Physics Briefing Book

Input for the Strategy Group to draft the update of the
European Strategy for Particle Physics

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Contents

Chapter 1

Introduction

The first European Strategy for Particle Physics, consisting of 17 strategy statements, was adopted by the CERN Council at its special session in July 2006. Eight of the statements are devoted to scientific activities and include the LHC, accelerator research and development, the International Linear Collider, neutrinos, astroparticle physics, flavour physics and precision measurements, the interface of particle and nuclear physics, theory.

Concerning the LHC, its full exploitation was given as the highest priority for Europe. Since then, the LHC delivered the first data in pp collisions at $\sqrt{s} = 900$ GeV in November 2009. In 2010, the collision energy was increased to $\sqrt{s} = 7$ TeV and reached 8 TeV in 2012. At the same time, the machine has been running with peak luminosities above the design value expected for those energies. The LHC also achieved the highest energy Pb-Pb collisions in 2010.

The four major LHC experiments, ALICE, ATLAS, CMS and LHCb, have been taking excellent data with high efficiencies. The highlight of physics achievements is clearly the discovery of the new particle compatible with the long awaited Higgs boson by ATLAS and CMS. In flavour physics, the LHCb experiment has now overtaken the remarkable achievements of the B factories and Tevatron experiments. Physics studies of ultra relativistic heavy ion collisions by ALICE, ATLAS and CMS made a new step, opening a new horizon.

So far, no clear sign of physics beyond the Standard Model has been seen, neither by the ATLAS and CMS direct searches at the energy frontier, nor by experiments making precision measurements. On the other hand, investigation of the newly discovered particle has just started and further studies are needed to conclude whether it is the Standard Model Higgs particle or not. When the LHC starts running at $\sqrt{s} \approx 13$ TeV, the phase space for new particle searches will increase. Sensitivities for new physics searches by the precision experiments will further improve as well. However, a substantial upgrade would be needed for the machine and experiments in order to fully exploit the potential of LHC up to 2030 or even beyond. Based on the running experience, concrete upgrade plans can now be proposed. Such upgrades require time and resources. Therefore, a decision on the next phase of the LHC programme must be made soon.

Discovery of the new particle also triggered a proposal by the Japanese high energy physics community to host a 500 GeV International Linear Collider, starting as a Higgs factory with half of the energy. Also ideas to construct other types of machines such as circular e^+e^- colliders at various energies are now being suggested.

For the neutrino frontier, the Daya Bay experiment in China has established a non-zero value of the third mixing angle, θ_{13}, for neutrino flavour mixing, very closely followed by the RENO experiment in Korea. In both experiments, nuclear power reactors were used as the sources of neutrinos. The values of θ_{13} measured by them are in agreement with earlier but less accurate measurements by the two accelerator based long-baseline neutrino experiments, T2K in Japan and MINOS in the US, as well as by the reactor neutrino based Double Chooz experiment in France and with global fits to other neutrino data. With all three mixing angles measured, it is now possible to design the next generation of neutrino oscillation experiments using accelerator-generated long-baseline wide band beams to address the two key remaining issues of neutrino flavour mixing, i.e. the mass hierarchy and the value of the phase of the mixing matrix. The former subject is important to determine the basic properties of the neutrino. Depending on the result, it may even exclude the neutrino being a Majorana particle, when combined with future results from the experiments searching for neutrino-less double β decays. The latter measurements are related to CP violation in the neutrino sector.

Various proposals for a long-baseline experiment are being discussed in Europe, Japan and the US. At the same time, proposals for short baseline neutrino experiments to study the existence of sterile neutrinos and clarify some anomalies in reactor and accelerator neutrino data are being discussed at CERN, while proposed experiments to perform a similar study are being examined at FNAL. The European Strategy foresaw the importance of defining the optimal neutrino programme based on the new results in coming years.

Those new developments clearly indicated that the European Strategy needed to be updated. In order to provide scientific input to the strategy update process, a European Strategy Preparatory Group was set up. An Open Symposium was held in Cracow from 10th to 12th of September 2012 with about 500 participants to discuss scientific issues relevant for the European Strategy, i.e. physics at the high energy frontier, physics of flavour and symmetries, neutrino physics, strong interaction physics, astroparticle physics, and theoretical physics. There were also sessions devoted to accelerator science, and instrumentation and necessary infrastructure to construct and run large-scale experiments. Review talks on those subjects were followed by long discussions by the participants. In addition, the particle physics community, funding agencies and policy makers were invited to submit written contributions to express their ideas and opinions concerning the future of European particle physics. Over 150 contributions were submitted.

This Physics Briefing Book was written by the Preparatory Group and the scientific secretaries of the Open Symposium based on the material discussed during the Open Symposium and the submitted documents for updating the strategy. It is intended to serve as a reference for the next step of the process to draft the updated strategy statements during the European Strategy Group meeting in Erice in January 2013. The draft will then be submitted to the CERN Council for discussion and it is planned that the updated strategy will be adopted by the Council in May 2013.

Chapter 2

Energy Frontier

Relevant talks at the Open Symposium were given by G. Dissertori, C. Grojean, and T. Wyatt.

2.1 Accelerators for Exploring the TeV Scale

A plurality of accelerator facilities have been proposed to perform physics experiments at highest possible energies. This chapter will give an overview of the anticipated parameters of these machines. One should note, however, that the proposed facilities are in very different stages of development—from very detailed design reports to short written inputs to the strategy update, several being motivated by the recent discovery of a boson at 125 GeV. More detailed descriptions on the technological aspects of these accelerators are described in Chapter 8 on Accelerator Science and Technology.

2.1.1 Hadron Colliders

At the moment the LHC is the hadron collider at the energy forefront. The time line for the operation of the LHC including various steps to increase the luminosity has been laid out. Hadron colliders may be a possible route to a further increase of the collision energy. Possible hadron colliders beyond the LHC are being discussed and the R&D needed is being addressed. These are the energy-doubler for the LHC or colliders with larger circumferences than the LHC.

LHC current configuration In 2012 the LHC shows an excellent performance. The collision energy was raised from 7 TeV in 2011 to 8 TeV in 2012. The peak luminosity achieved in 2012, at the time this briefing book was written, was about $7.7\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. One should note that this peak luminosity is already above the design luminosity of the LHC at a beam energy of 4 TeV. Following the discovery of a Higgs-like Boson in July 2012, CERN decided to prolong the 2012 proton-proton run until the end of 2012 to provide the experiments with enough statistics to measure some crucial parameters of this new particle, i.e. spin and parity, before the first long shutdown. The general-purpose experiments ATLAS and CMS expect an integrated luminosity of up to 25 fb^{-1} until the end of the run in 2012. This will add to the 6 fb^{-1} at 7 TeV collected in 2011. The excellent performance of both the machine and the experiments provide a very positive outlook to the future LHC runs.

Reaching LHC design performance In 2013 the LHC will provide collisions of protons with Pb ions for one month before the machine enters the first long shutdown (LS1). In the following 18 months a long list of improvements will be carried out to bring all the equipment to the level needed for 7 TeV beam energy. It is foreseen to restart the LHC in January 2015 with a beam energy of 6.5 TeV and eventually reach the design energy of 7 TeV after retraining of the LHC magnets. For a running time of 148 days in 2015 the expectation is to deliver an integrated luminosity of 22 fb^{-1} (at a bunch spacing of 25 ns) or 29 fb^{-1} (50 ns). Until the start of long shutdown two (LS2) end of 2017 the experiments expect to collect about 90 fb^{-1} at a collision energy close to 14 TeV. In LS2 a first upgrade of the LHC including the installation of a new injector is foreseen. The goal of LHC running until about 2021 is to deliver a total of 300 fb^{-1} integrated luminosity for ATLAS and CMS. After that it is proposed that the LHC will stop again (LS3) for a further upgrade to higher luminosities, from now on called High Luminosity LHC (HL-LHC).

LHC high luminosity upgrade A series of improvements and upgrades to the machine are foreseen in the years from now to 2023 to reach the proposed high luminosity [ID153]. One should note, however, that some of these measures are needed in any case to guarantee the operation of the LHC even at the present luminosity. By exchanging aged parts with improved components (performance-improving consolidation) the upgrade will be done gradually. An example for this is the exchange of the new focusing magnets.

HL-LHC is proposed to be operated in the period of about 2023 to 2030 at 14 TeV with a luminosity of $5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$. In the presently proposed scenario a maximum integrated luminosity will be achieved by luminosity leveling, however this scheme is not fully tested yet and some concerns exist. The goal of HL-LHC is to deliver 3000 fb^{-1}. If the improvements to the accelerator are not implemented and the LHC continues to be operated at the original design luminosity only, an integrated luminosity of 1000 fb^{-1} could be delivered in the same time period.

The experiments will have to upgrade their detectors significantly to cope with the higher luminosity and the foreseen long running time. Also for the experiments some of the upgrades and replacements of detectors become necessary at around 2022 independent of the future increase in luminosity. Especially to be mentioned here is the exchange of the large inner tracking systems of ATLAS and CMS, which will reach the end of their lifetime by that time.

High Energy LHC A natural consideration is to exploit the CERN complex of accelerators beyond HL-LHC by installing magnets with higher fields in the existing LHC tunnel. Such a machine, called High-Energy LHC (HE-LHC) could reach a center-of-mass energy of 26–33 TeV [ID155]. The beam energy is set by the strength of the achievable dipole field of the superconducting magnets. The design luminosity of such a machine is $2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$. Assuming that a decision on the use of high temperature superconductors is made in 2016–17, followed by 3 years of prototyping, 7 years of industrialization, construction and testing, and finally 3 years of installation and commissioning after the termination of HL-LHC, physics production could start around 2035.

Table 2.1: Overview of proton-proton colliders.

Facility	Years	E_{cm} [TeV]	Luminosity $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Int. luminosity $[\mathrm{fb}^{-1}]$	Comments
Design LHC	2014–21	14	1–2	300	
HL-LHC	2024–30	14	5	3000	luminosity levelling
HE-LHC	>2035	26–33	2	100–300/yr	dipole fields 16–20 T
VHE-LHC	>2035	42–100			new 80 km tunnel

Very Large Hadron Collider A geological pre-feasibility study was done to examine possible new tunnels within the Geneva area for the hosting of a very large hadron collider (VHE-LHC) [ID165]. The study investigated two possible locations for a tunnel with a circumference of 80 km and one option with a circumference of 47 km and concluded with a list of recommendations and a comparison of risks of the three options. The achievable collision energy depends on the dipole field strength. With the present LHC magnet technology with 8.3 tesla an energy of 42 TeV can be reached in an 80 km tunnel. With 20 tesla magnet technology a collision energy up to 100 TeV is feasible.

2.1.2 Lepton Colliders

Due to the clean experimental environment, the precise knowledge of the collision energy, and the initial-state polarization, lepton colliders may provide measurements with precision otherwise not achievable. Several concepts for linear e^+e^- colliders are under study since many years. The R&D towards a design has been a priority in the European Strategy of Particle Physics defined 6 years ago. The recently discovered new boson has created a new momentum towards realization. Because of the rather low mass of this new particle a renaissance of circular machines is discussed as well.

The science community pursuing the design of an e^+e^- linear collider is presently setting up a new organization under the umbrella of ICFA. This organization will coordinate the effort towards the realization of a linear collider. Both machine concepts, ILC and CLIC, are represented in the new structure together with a common study group for Physics and Detectors. In June 2012 the new director of the Linear Collider Organization was appointed.

Muon colliders and $\gamma\gamma$ colliders may offer further options for future facilities.

International Linear Collider The physics case and the machine design of a linear e^+e^- collider has been under study for more than 20 years. The machine design has converged to the use of superconducting radio frequency cavities with an average gradient of about 31.5 MV/m. A full Technical Design Report (TDR) is being finalized for the end of 2012 [ID073], which will describe in detail the two main linear accelerators utilizing 1.3 GHz SCRF cavities, the polarized electron source, the undulator-based positron source, the damping ring, and the final focus system for one interaction region. The design of the ILC is based on superconducting cavities produced by a well established industrial production. Very similar cavities to the ones needed for ILC are already in operation at the FLASH superconducting free electron laser. The European XFEL accelerator under construction in DESY will also use these cavities and after completion the number installed will correspond to approximately 10% of those required for the ILC. The baseline design of the ILC foresees a center-of-mass energy of 500 GeV (design luminosity of $1.8 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$), with a possible upgrade to 1 TeV. The length of the facility to achieve 500 GeV is about 30 km ($\sim$ 50 km for 1 TeV). The ILC machine is a very flexible concept and can be built in stages and hence a low energy phase ($\sim$ 250 GeV) to study the new boson in detail could be a first step, with subsequent stages at higher energy.

In parallel to the machine design an international study group is preparing the Detailed Baseline Design (DBD) for the end of 2012, explaining the physics capability of the ILC and describing in detail the two detector concepts, ILD and SiD. ILD and SiD are proto-collaborations planning the two detectors to share the interaction point in a push-pull system.

As a response to the discovery of the Higgs-like boson the Japanese physics community has presented an initiative to host the ILC in Japan [ID121]. If a positive decision is made within a few years the ILC could start before 2030.

Compact Linear Collider The concept of the Compact Linear Collider (CLIC) is based on a novel two-beam acceleration technique in which the short, high power RF pulses (12 GHz) are extracted from a drive beam running parallel to the main linear accelerator structures [ID099]. The normal-conducting accelerator structures of the main linac would reach a gradient of 100 MV/m and thus limit the overall length of the machine. The key technologies of this concept have been addressed in experimental setups at KEK, SLAC and CERN. Conceptual Design Reports (CDR) for the machine and for Physics and the Detectors have been published in 2012 [1, 2]. The CDR describes the project in three possible stages and two scenarios for center-of-mass energies of 500 GeV, 1.4 (1.5) TeV and 3 TeV. The integrated luminosity targets are 500 fb^{-1}, 1.5 ab^{-1} and 2 ab^{-1} for the three envisaged energies. At each energy stage the collision energy can be tuned to lower values within a range of a factor of three with some loss on the achievable luminosity. The discovery of the Higgs-like Boson at a mass of 125 GeV has initiated a study for a klystron-based initial stage which could be implemented on a faster time schedule.

Site studies have shown that CLIC could be constructed underground in the CERN area. The length of the main tunnel is $\sim$ 13 km, $\sim$ 27 km, $\sim$ 48 km for center-of-mass energies of 500 GeV, 1.4 (1.5) TeV, 3 TeV, respectively. The detector studies for CLIC use the detector design for the ILC as a starting point. The unique time structure of CLIC with bunch trains in which individual bunch crossings are spaced by only 0.5 ns and the expected high rates of beam-induced background, poses challenges for the design of the detectors and their readout system. As for the ILC, CLIC foresees one interaction region with the two detectors operated alternately, moving in and out. The time line for the CLIC project foresees a focused R&D program in 2012–16 on the accelerator and the detectors. Provided sufficient resources are made available the project could advance in 2017–22 with finalizing all parameters, the verification of the drive beam and other systems, and the preparation for the industrial procurement of all components. The construction of stage one (500 GeV) could be accomplished in the years 2023–30, with commissioning starting in 2030.

Circular e^+e^- colliders Motivated by the discovery of the new boson with a rather low mass of 125 GeV a revival of circular $\mathrm{e^+e^-}$ colliders has taken place. A preliminary study has been done for a circular $\mathrm{e^+e^-}$ collider operating close to the ZH threshold at a centre-of-mass energy of 240 GeV [ID138, ID157]. This storage ring, called LEP3, could be installed in the existing LEP/LHC tunnel. A constant luminosity of $10^{34}\mathrm{cm^{-2}s^{-1}}$ is calculated. Operating the machine in a first stage at a lower energy at about the Z resonance a luminosity of several $10^{35}\,\mathrm{cm^{-2}s^{-1}}$ is predicted.

Alternative scenarios for the installation and the interplay with LHC are discussed. If LEP3 is installed during the lifetime of LHC a concurrent or alternating operation is proposed. The interference with the existing LHC infrastructure needs to be studied in detail. In the original LHC design some space in the tunnel on top of LHC was reserved for a possible future $\mathrm{e^+e^-}$ collider and the already mentioned LHeC study also identified space for an additional ring. Alternatively LEP3 could be installed after LHC operation has completed and the LHC is removed. In the LEP3 concept the two LHC multipurpose experiments ATLAS and CMS could be used as two detectors in the four possible interaction regions. In another preliminary study the performance and the suitability of the CMS detector was investigated. Assuming that 5–7 years are needed for a conceptual study, R&D on the critical items and the preparation of the technical design report, the earliest installation date of LEP 3 is during long shutdown LS3 around 2022/23 or more probably around 2025.

Perpetuating the concept of circular $\mathrm{e^+e^-}$ machines one could go further and consider the use of a possible new 80 km tunnel first for an e^+e^- collider before it is eventually used for a hadron machine. In such a tunnel an e^+e^- machine operating up to a center-of-mass energy of 350 GeV ($t\bar{t}$ threshold) is feasible (Triple-LEP, TLEP).

Muon colliders The use of muons instead of electron-positrons in a collider machine has many advantages. Due to the larger masses of muons synchrotron radiation is strongly suppressed allowing the construction of much smaller facilities with very small energy spread because of the reduced beamstrahlung. From the physics point of view muon colliders have the advantage over e^+e^- colliders that the s-channel production of the Higgs is also enhanced by a factor $(m_\mu/m_e)^2 \approx 40{,}000$.

The concept of a muon collider emerges from synergies with the intensity frontier, in particular neutrino physics. Future experiments in neutrino physics require extremely clean neutrino beams of one flavour. This can only be achieved with a muon storage ring, in which the decaying muons produce a clean muon-neutrino beam of high intensity. The muon storage ring could then be further developed into a muon collider [ID135]. The required R&D for the critical components is ongoing in several collaborations worldwide in connection with the studies for a neutrino factory. The International Design Study for a Neutrino Factory (IDS-NF) is targeting a Reference Design Report also on the 2013 timescale. The "entry point" for a neutrino factory may be the proposed facility νStorm.

Muon colliders could provide an alternative approach towards a Higgs factory. Multi-TeV muon colliders could even become the facility of choice to study Terascale physics after LHC.

Table 2.2: Overview of electron-positron colliders (*different scenarios)

Facility	Year	E_{cm} [GeV]	Luminosity [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	Int. luminosity [fb^{-1}]	Tunnel length [km]
ILC 250	<2030	250	0.75		
ILC 500		500	1.8		$\sim$ 30
ILC 1000		1000			$\sim$ 50
CLIC 500	>2030	500	2.3 (1.3)*	500	$\sim$ 13
CLIC 1400	>2038	1400 (1500)*	3.2 (3.7)*	1500	$\sim$ 27
CLIC 3000	>2047	3000	5.9	2000	$\sim$ 48
LEP3	>2024	240	1	100/year and exp.	LEP/LHC
TLEP		240	5		80 (ring)
TLEP		350	0.65		80 (ring)

$\gamma\gamma$ colliders The collisions of photons at high energy are regarded as adjuncts or by-products of linear e^+e^- colliders such as the ILC or CLIC. $\gamma\gamma$ colliders could, however, also be developed as Higgs factories. The advantage of a $\gamma\gamma$ Higgs factory is the lower beam energy required to produce a Higgs boson in the s-channel, about 80 GeV, as compared to the production mode in e^+e^- collisions where 120 GeV is required. The principle of a $\gamma\gamma$ collider is as follows. Electrons from a high energy electron beam interact with the light of a very intense laser beam producing the photon beam by Compton backscattering.

Two concepts for a $\gamma\gamma$ collider have been proposed. CLICHE (CLIC Higgs Experiment) [3] would use the development of a first full-scale module of the CLIC test setup. Electrons accelerated to 75 GeV by two such CLIC modules interacting with photons from a powerful mercury laser system would produce the photons for collision. Note that no positrons are needed, in contrast to an e^+e^- collider, simplifying the system. More recently SAPPHiRE (Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons) was proposed [ID145]. SAPPHiRE is based on a pair of $\sim$ 10 GeV recirculating electron linacs, similar in design to those proposed in the LHeC project. The electrons pass four times through two superconducting linacs acquiring about 80 GeV before they interact with the laser light. The footprint of such a machine shows two arcs with a circumference of about 2 km and with a total length of about 9 km (arcs plus straight sections). The target luminosity of SAPPHiRE is $\mathcal{L}_{ee} \sim 2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ resulting in $\mathcal{L}_{\gamma\gamma} \sim 3.6 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (for $E_{\gamma\gamma} > 0.6\ E_{\mathrm{cm}}$). The laser system requires 1 TW peak power and 5 ps pulse length at a wavelength of 351 nm. The laser system is the aspect of a $\gamma\gamma$ collider that requires the most R&D.

2.1.3 Lepton-hadron colliders

The Large Hadron Electron Collider (LHeC) study group has published a Conceptual Design Report (CDR) in 2012 [4, ID156]. The report describes in considerable detail the design of an electron or positron accelerator intercepting the proton or ion beam of LHC and the design of the experiment. The LHeC is designed to run synchronously with the LHC. The accelerator and the detector could be realized within about 10 years from now. To match the schedule of LHC the connection of the new machine to LHC and the installation of the experiment has to be done during the long shutdown LS3, currently scheduled for 2022 and a period of about 2 years. The target luminosity for e^-p is $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, whereas the e^+p luminosity would be about a factor 10 lower. This is a disadvantage of the linac-ring option. Within an operation period of 10 years a total luminosity of $O(100)\mathrm{fb}^{-1}$ may be collected.

2.2 Energy Frontier Physics at LHC

2.2.1 Current status

The excellent performance of the LHC and the extremely high overall efficiency of ATLAS and CMS made it possible in about two years of operation to achieve a first crucial step in our comprehension of the nature of Electro Weak Symmetry Breaking (EWSB). The impressive amount of data collected by each experiment (5.5 fb^{-1} at 7 TeV in six months of run and 6.5 fb^{-1} at 8 TeV in two months of run until June 2012) produced a number of solid and outstanding experimental results:

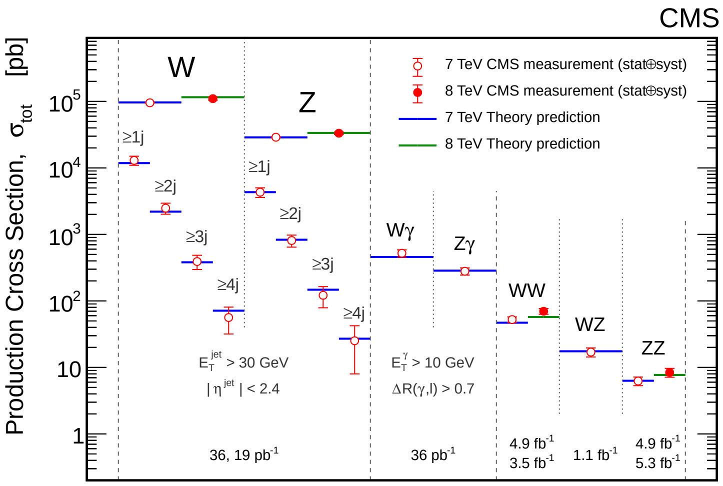
- confirmation up to the percent level of Standard Model (SM) predictions in the QCD and EW sectors
- observation of a new boson with a mass around 125 GeV [5] consistent within experimental errors with the SM Higgs boson
- exclusion of a wide area of parameter space in Supersymmetry (SUSY) models
- exclusion of the presence of exotic heavy objects up to masses of 2–3 TeV.

The priority set for the LHC in 2012 was to provide enough luminosity for an independent discovery of a SM Higgs Boson by ATLAS and CMS. At present a peak luminosity of $7.7 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ has been reached, at the price for the experiments to cope with high pile-up running conditions (20 events in average).

The consistency of the the standard measurements:

- jet production differential cross sections over a wide range of p_T and $m_{j_1 j_2}$ at different pseudorapidities
- W/Z (+ jet) production
- top production

with theory expectations in the new TeV energy domain provided by LHC give confidence in the reliability of calculations (which include NLO and NNLO QCD corrections) and in the detector performance. As an example Fig. 2.1 shows the production cross-section for vector bosons as measured by CMS at 7 TeV and 8 TeV compared with the SM theoretical expectations. This impressive agreement is the result of a gigantic work both on the theoretical and the experimental sides, and establishes solid foundations for the possible observation of future unexpected phenomena. Moreover, the experimental precision reached in measuring the production of standard objects in many cases starts to challenge theoretical uncertainties, for instance allowing to largely improve in the near future our knowledge of Parton Density Functions (PDF).



JHEP10(2011)132
JHEP01(2012)010
CMS-PAS-SMP-12-011 (W/Z 8 TeV)

PLB701(2011)535

CMS-PAS-EWK-11-010 (WZ)
CMS-PAS-SMP-12-005,
007, 013, 014 (WW ZZ)

Figure 2.1: Vector boson production cross-sections measured at 7 and 8 TeV by CMS. The SM predictions are also reported for comparison.

The quest for the Higgs boson Since the mass of the Higgs boson is a free parameter of the SM, the search of this particle has been performed by ATLAS and CMS on a wide range of mass. Several decay channels having different sensitivity depending on the mass of the Higgs have been combined.

On 4th of July 2012 both ATLAS and CMS announced the observation with 5σ significance of a new particle with a mass around 125–126 GeV. The results are compatible with the expectations from the production and subsequent decay of a SM Higgs boson. The significance of the discovery is driven by the two high resolution channels: $\gamma\gamma$ and ZZ^*. Figure 2.2 shows the excess around 125–126 GeV observed in the four lepton channel by ATLAS and in the two photon channel by CMS while Fig. 2.3 represents the statistical significance in terms of local p-value and number of standard deviations of the observations made by ATLAS and CMS.

This result is complemented by the exclusion at 95% CL of a SM Higgs boson outside a small range around 125 GeV, from the limit set by LEP up to masses of 600 GeV. The present values of the mass: 126.0 ± 0.4 (stat) ± 0.4 (syst) measured by ATLAS and 125.3 ± 0.4 (stat) ± 0.5 (syst) measured by CMS are consistent with each other, and locate the boson mass in a fortunate position where several decay channels are accessible and detectable, and thus will be studied in detail. The signal strengths ($\mu = \sigma/\sigma_{\rm SM}$) measured by the two experiments in the five channels $\gamma\gamma$, ZZ^*, WW^*, $\tau\tau$, bb are overall compatible with the expectations from a SM Higgs. It has to be noticed that the strength in $\gamma\gamma$ appears to be larger than predicted for both experiments and in both energy runs, but the present values (1.8 ± 0.5 ATLAS and 1.6 ± 0.4 CMS) are not yet significant enough to indicate an anomaly in this decay channel.

This discovery is the starting point of an extensive programme of measurements which will last several years to assess the nature of this particle:

- the mass
- the quantum numbers: spin and parity (J^P), CP (even, odd, or admixture?);

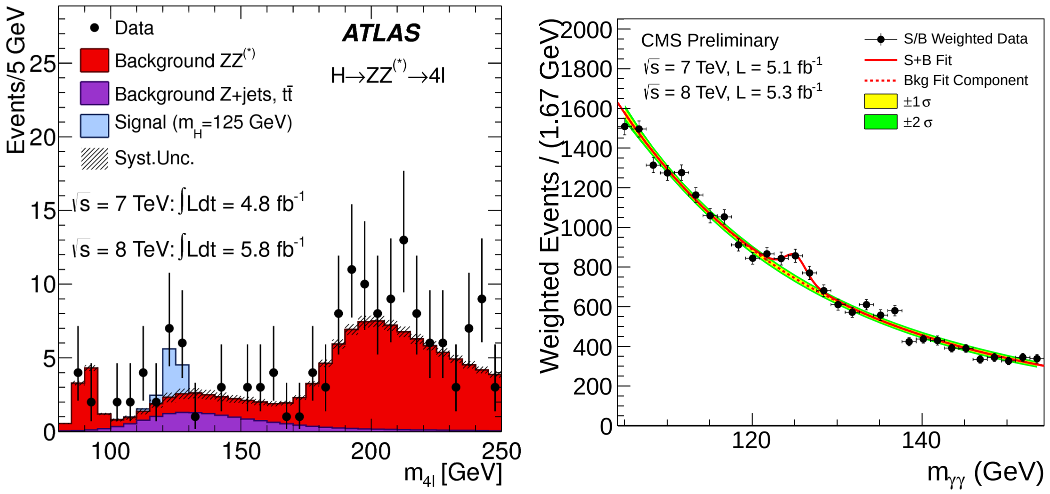


Figure 2.2: Excess observed by ATLAS (left) in the four lepton spectrum, the signal expected from a 125 GeV Higgs boson is also shown; CMS excess in the inclusive two photon spectrum (right). In both cases the expected background is shown.

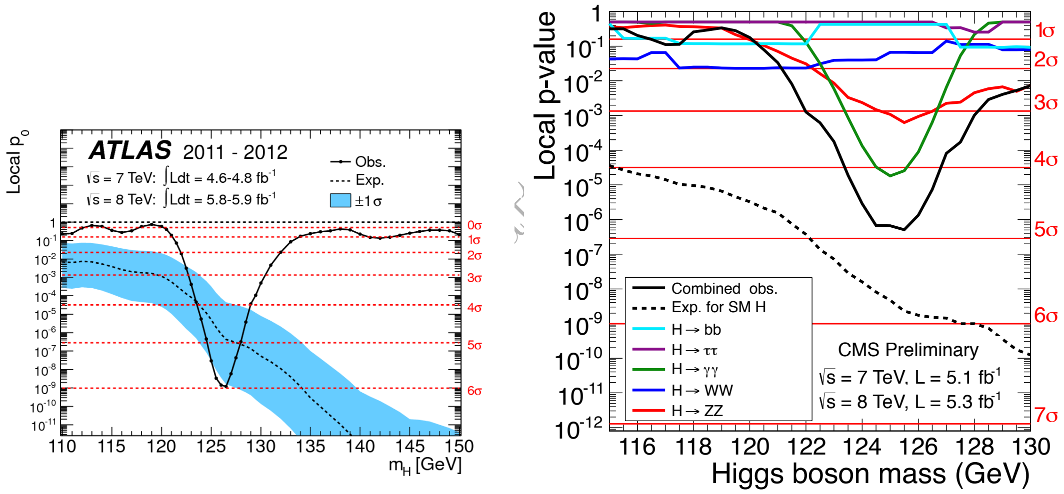


Figure 2.3: The observed local p-value p$_0$ for the overall combination of decay modes as a function of the SM Higgs boson mass as measured by ATLAS (left) and CMS (right). The dashed lines show the expected local p-value p$_0(m_H)$, should a Higgs boson with a mass m_H exist. CMS result reports also observed local p-value for the five subcombinations by decay mode.

- the couplings to vector bosons (is this boson related to EWSB and how much does it contribute to restoring unitarity in Vector Boson Scattering (VBS)?)
- the couplings to fermions (is their Yukawa interaction at work?)
- the self-interaction
- are the couplings proportional to mass?
- is there only one such state, or more?

- is it elementary or composite?

Some of these questions might be partially answered by the end of the 8 TeV run assuming about 35 fb^{-1} of collected integrated luminosity per experiment. We know already from its decay in two photons that the boson cannot be of spin 1, while J^P is being measured using angular correlation in ZZ^*, WW^* and $\gamma\gamma$ decays. It is expected to be able separate at 4σ 0^+ from 0^- and 0^+ from 2^+. After the discovery, a partial update has been given by ATLAS [7] and CMS [8] on the basis of 12–13 fb^{-1} collected at 8 TeV. ATLAS updated the signal strength measurement, the new results on the three low resolution channels (H decays in WW, $\tau\tau$, bb) are combined with the already published ones to give $\mu = 1.3 \pm 0.3$. CMS presented updated results for all the channels apart from $\gamma\gamma$. The significance of the observation is currently 6.9σ, the mass 125.8 ± 0.4 (stat) $\pm$ 0.4 (syst) and the combined signal strength $\mu = 0.88 \pm 0.21$. A summary of the status of the signal strength measured by the two experiments is given in Fig. 2.4. Using the decay of the boson in four leptons CMS performed a preliminary test of the J^P hypotheses 0^+ versus 0^-. Under the assumption that the observed boson has spin zero the data disfavour the pseudoscalar hypothesis 0^- with a CL$_\mathrm{s}$ value of 2.4%.

The picture emerging after an increase of statistics of a factor 1.5 per experiment is well coherent with the Standard Model.

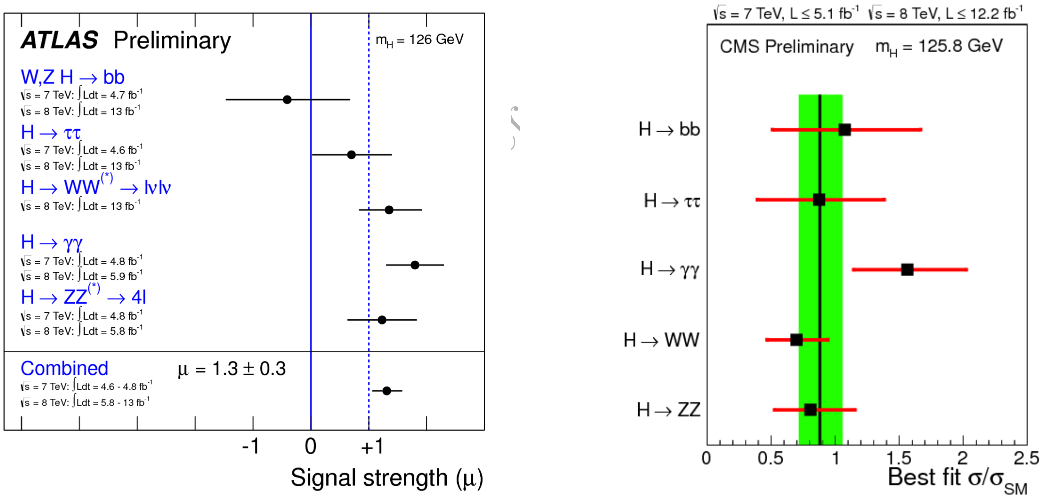


Figure 2.4: Measurements of the signal strength in the five measured channels and their combination for ATLAS (left) and CMS (right).

Searches for new phenomena The most promising theory proposed to solve the hierarchy problem, Supersymmetry (SUSY), has been the subject of many direct and also quite general searches. SUSY groups a plethora of models. The experimental approaches look for strongly produced heavy s-particles which then develop long decay chains characterized by several high p_T jets, and missing transverse energy (MET) due to a stable Lightest Supersymmetric Particle (LSP) escaping detection, with the possible additional presence of leptons and photons. A solid knowledge of the background based as much as possible on data, and a precise control of the detector response is needed in order to tell the presence of such spectacular SUSY events. Different interpretations of the experimental results translate into different model dependent constraints on SUSY parameters. The actual results, some already based on about 6 fb^{-1} of data collected at 8 TeV, and interpreted in the frame of simplified MSSM, set exclusion limits on squarks and gluinos at 1.4 TeV and 1.2 TeV respectively. Natural MSSM scenarios calls for a 3rd generation of light squarks: in that case the search is focused on direct or gluino mediated production of stop/sbottom by including a b-tag, required in the generic experimental search, and adding a specific search looking for $t\bar{t}$ in presence of high MET. In this framework mass limits on gluinos are typically reduced to 800 GeV for masses of LSP below 400 GeV and masses of 3rd generation squark in the range 300–500 GeV for a mass of LSP below 200 GeV. In scenarios with heavy squarks and gluinos, direct pair-production of weak gauginos (EWKinos) and/or sleptons dominates SUSY production. Typical limits exclude charginos with masses between 50 and 600 GeV and strongly depend on the assumptions about the intermediate states of the decay chain and on the value of the LSP mass. Assuming $M_{\rm LSP} = 0$, sleptons are excluded in a range of mass 90–180 GeV. Figure 2.5 shows the current status of SUSY searches from ATLAS. Similar results have been produced by CMS.

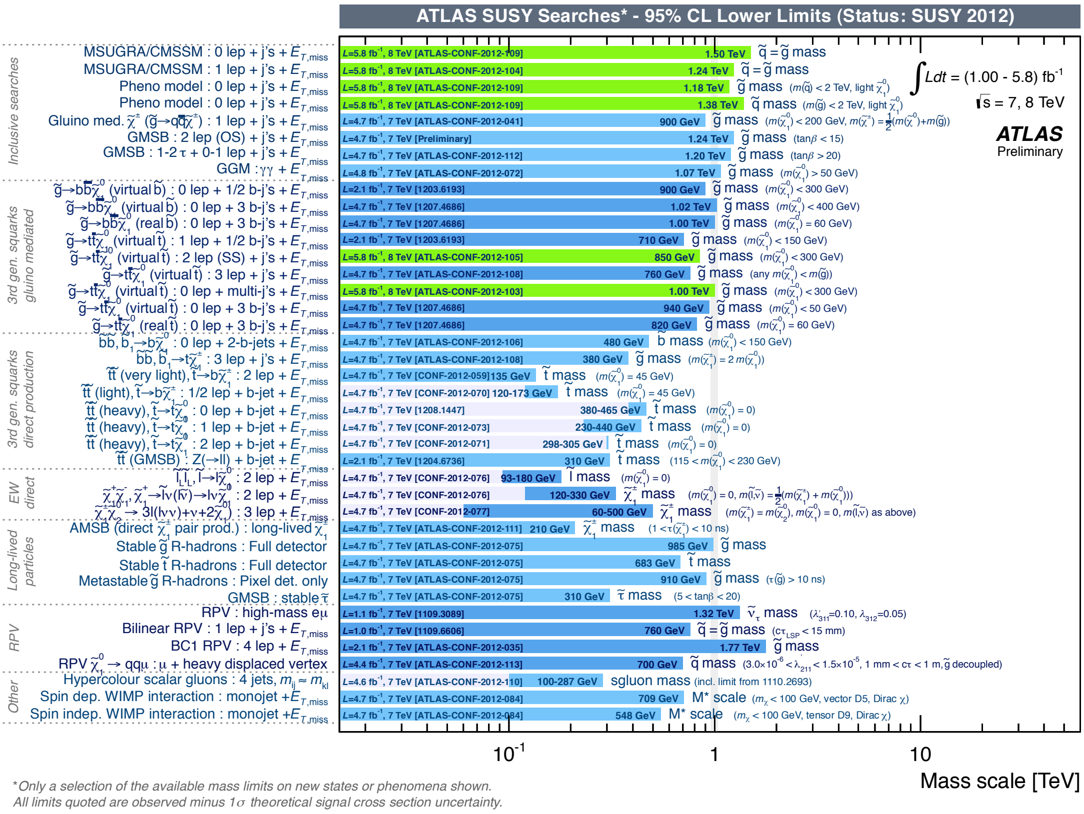


Figure 2.5: Mass reach of ATLAS searches for SUSY (SUSY 2012). Only a representative selection of the available results is shown.

Although it is certainly premature to decree a SUSY defeat, experimental results (direct limits on sparticle masses and the mass value found for the Higgs-like boson) put the constrained MSSM in an awkward position. However, other scenarios for natural supersymmetry at the TeV scale are still viable and about to be crucially tested.

The so called Exotica area collects all BSM models which are not based on minimal

SUSY or its extensions. This sector profited from the increase of 1 TeV in LHC energy. A non-exhaustive list includes searches for heavy resonances, composite objects, 4th generation quarks, long-lived particles, Leptoquarks, black holes as well as limits on contact interaction scales. Figure 2.6 shows a summary of the CMS exotica results. Similar results have been produced by ATLAS.

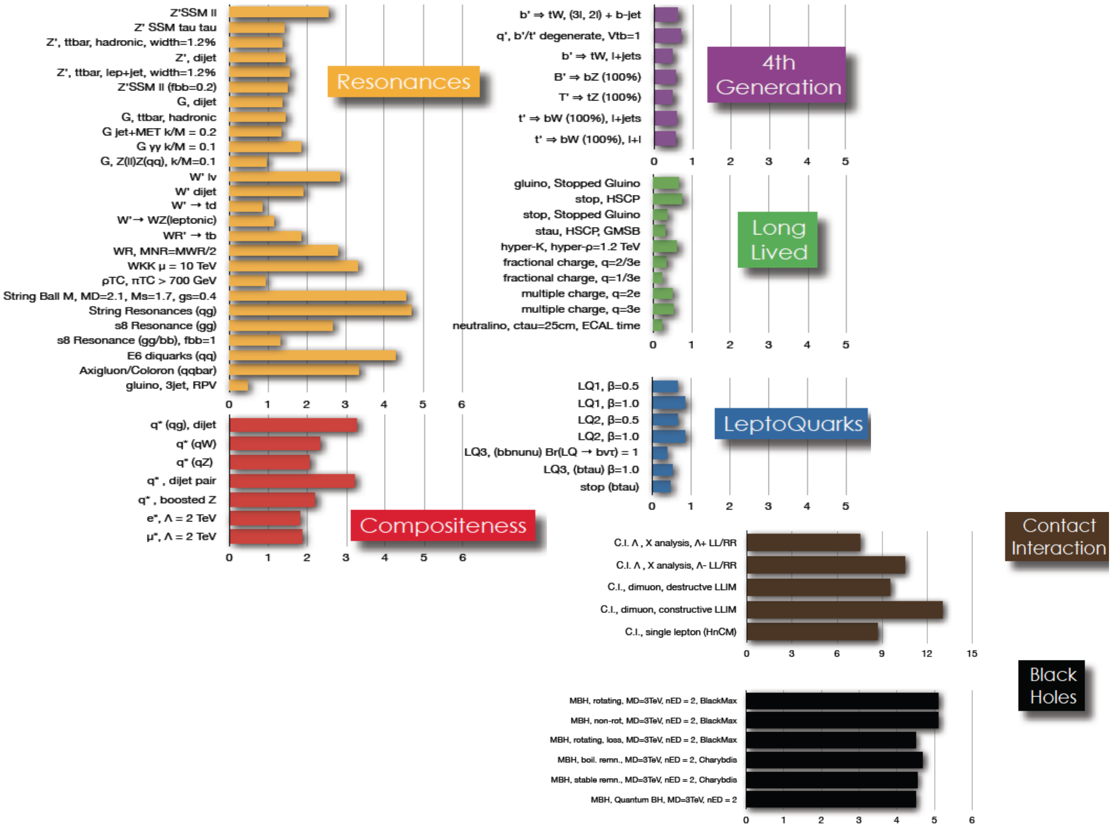


Figure 2.6: Summary of mass limits (TeV) at 95% CL in CMS exotica searches (ICHEP 2012)

Depending on the model and on the assumptions, exclusions of heavy objects range from 0.5 TeV to 5 TeV. It is worth to note the search of mono-jets and mono-photons in the frame of dark matter production which nicely complement the direct underground WIMP searches by extending the limits to very low masses (about 100 MeV).

2.2.2 Prospects with design performance

In March 2013 the LHC will stop for about 18 months (LS1) in order to prepare the machine for the next step: reaching the design energy of 14 TeV (or close to it) and the design luminosity of 10^{34} cm^{-2}s^{-1}. This will allow collecting an integrated luminosity of about 40 fb^{-1} per year of run. The main technical interventions during LS1 will be the repair of faulty interconnects, the consolidations of all interconnects with a new design, finishing installation of pressure release valves (DN200), setting up all the necessary equipment needed for 7 TeV/beam. ATLAS and CMS will perform a set of initial upgrades, design detector completions (parts foreseen in the original project that were then staged) and maintenance operations.

A one-year shutdown is foreseen in 2018 (LS2) to upgrade LHC equipment in order to allow the instantaneous luminosity to be doubled. An integrated luminosity around 300 fb^{-1} should be reached by about 2021. During LS2 ATLAS and CMS will perform major Phase-1 upgrades to cope with a luminosity higher by a factor of two with respect to the original accelerator design.

The gain in physics reach given by running LHC at 14 TeV can be seen in Fig. 2.7. What has been explored up to now is just a tiny region; the sensitivity for the detection of heavy objects will be significantly improved by the increase of the LHC energy, approximately scaling with c.m. energy. Based on what is known about the detectors' behaviour and assuming the actual analyses methodology it is also possible to extrapolate the physics reach achievable by a substantial increase in the collected luminosity. ATLAS and CMS produced extrapolations which should be considered as very preliminary studies, the results of these studies are consistent among the two experiments [ID141, ID144, ID174, ID177].

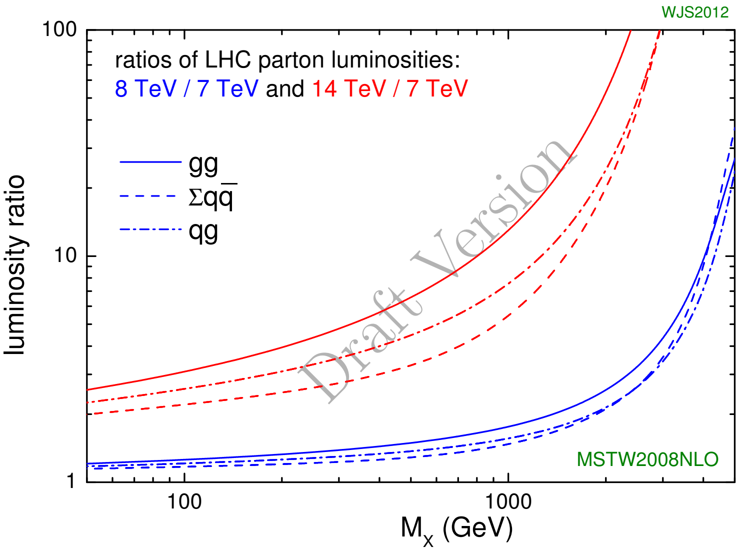


Figure 2.7: Ratio of parton luminosities [6] for the production of an object of mass M_X; the lower group of curves shows the ratio 8TeV/7TeV while the upper one shows the ratio 14TeV/7TeV. The dash-mode of the curves corresponds to different parton beams as indicated in the key.

An integrated luminosity of 300 fb^{-1} will not allow to access rare processes like double H production and consequently fundamental observables such as the Higgs trilinear self-coupling, or study the longitudinal vector boson scattering to understand in depth the EWSB mechanism. Nevertheless important progress can be made in the Higgs-like boson characterization. Quantum numbers (for non-mixed states) can be determined with a significance of more than 5σ. Signal strengths compatibility with SM can be tested to a precision of 5–10% as shown in Fig. 2.8 (left).

Assuming that boson and fermion couplings deviate from the SM by the same scale factors, κ_f and κ_V, these factors are expected to be determined to 10% precision. In that case the explicit assumption that no new physics is present and there are no additional loops in the production or decay of the Higgs boson has been made. In a more general approach deviations from SM predictions are searched for in the six couplings κ_γ, κ_V,

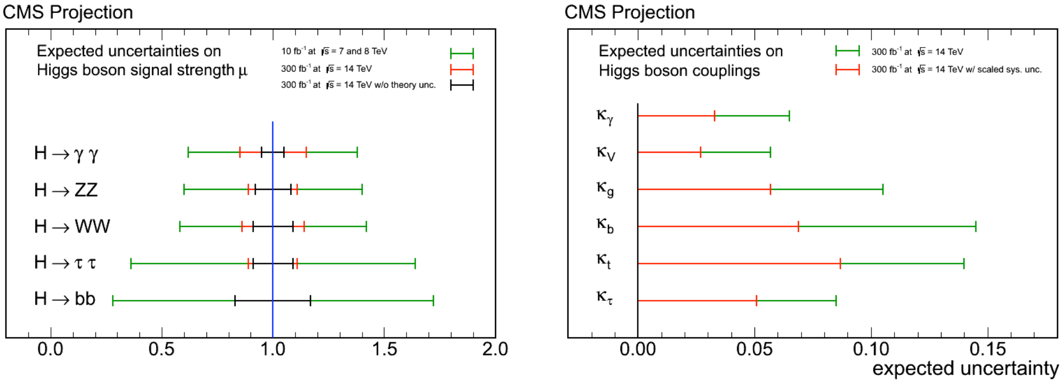


Figure 2.8: (Left) Estimated precision of the signal strength determination for a SM Higgs boson, from CMS. The projections assume $\sqrt{s} = 14$ TeV and an integrated luminosity of 300 fb^{-1}. They are shown including the current uncertainties and neglecting the systematic uncertainties from theory and are compared to the expected uncertainties of the measurement with 10 fb^{-1} at $\sqrt{s} = 7$ and 8 TeV. (Right) Estimated precision on the measurements of the couplings κ_γ, κ_V, κ_g, κ_b, κ_t, and κ_τ from CMS, for 300 fb^{-1} at $\sqrt{s} = 14$ TeV. The green line represents the precision attainable in the case where all systematic uncertainties are kept unchanged (present knowledge). The red line represents the precision achievable scaling the theoretical uncertainties by a factor of 1/2, while other systematic uncertainties are scaled by the square root of the integrated luminosity.

κ_g, κ_b, κ_t, and κ_τ, to photons, vector bosons, bottom quarks, top quarks, and τ leptons. If the systematic uncertainties are kept to the current values, these couplings can be checked to 5–15% as shown in Fig. 2.8 (right).

Using the decay in ZZ^* the CP nature of the boson can be better clarified. Assuming a 0^+ hypothesis, 300 fb^{-1} would be enough to exclude at 5σ a CP-violating state.

SUSY searches will extend the actual limits for generic squarks and gluinos up to 2.7 TeV and direct stop/sbottom production to 1.2 TeV. The sensitivity to direct stop/sbottom production will reach 1.2 TeV and EWKinos might be excluded up to about 800 GeV. Heavy narrow resonances like Z' will be probed up to typical values of 6.5 TeV (depending on models). Precise tests of the SM will in general benefit from the high statistics of data that might be collected, especially in the area of top studies.

2.2.3 Prospects with high luminosity upgrades (HL-LHC)

The roadmap of physics at the LHC beyond its initial design phase, with typically 300 fb^{-1} integrated luminosity until the early 2020s, has dramatically changed with the discovery of the Higgs-like boson. Not only will there be the unchallenged window for directly observable hypothetical heavy mass particles, messengers of new physics Beyond the Standard Model (BSM), but also a clear task to investigate in greatest details the properties of the new boson. Needless to say, this basic scenario could well be strongly enriched further if the forthcoming 14 TeV data of the current decade would reveal any new BSM physics, which then would be exploited of course the better the higher the available integrated luminosity.

In this section the LHC potential for detailed studies of the electroweak symmetry breaking mechanism will be discussed first, namely the precision measurements of the Higgs couplings, the Higgs self-coupling, and vector boson scattering at high energy. In a second part a few examples of extending the reach into exploratory BSM physics will be given, including SUSY and searches for massive heavy resonances. The ATLAS and CMS Collaborations have presented at the Symposium [ID141, ID144], and in subsequent updates [ID174, ID177], a wealth of evaluations for the physics reach with the anticipated luminosity of 3000 fb^{-1} for the HL-LHC era. These estimates, given here per single experiment, are based on a very substantial simulation effort taking into account realistic pile-up conditions. Both collaborations foresee substantial detector upgrade projects, including replacements of their trackers, that will maintain similar detector performances as at present, and which are needed in any case for critical components to allow operation beyond the initial LHC design era. The physics studies will be consolidated and expanded in the future as part of the upgrade Technical Design Reports.

Measurements of Higgs boson couplings While measurements of the Higgs boson couplings have already begun by ATLAS and CMS with the current 7 and 8 TeV data, and will remain a central topic within the approved LHC programme, the luminosity of the HL-LHC will provide substantially improved statistical precision for already established channels. Furthermore it will also allow one to study crucial rare Higgs boson production and decay modes.

Two examples for families of channels that will only become accessible in a quantitative way with the HL-LHC are mentioned here for illustration:

- WH/ZH, $H \to \gamma\gamma$ and ttH, $H \to \gamma\gamma$. These channels have a low signal rate at the LHC, but one can expect to observe more than 100 events at the HL-LHC. The ttH initial state gives the cleanest signal with a signal-to-background ratio (S/B) of 20%. It also provides a measurement of the top-Yukawa coupling, which is not easily accessible elsewhere. Figure 2.9(a) shows the expected signal.

- $H \to \mu\mu$. The S/B of this low-rate channel is only ~0.2% but the narrow peak allows one to extract a more than $6\,\sigma$ significant signal for an inclusive measurement, see Fig. 2.9(b). The exclusive ttH, $H \to \mu\mu$ would yield a clean (S/B > 1) sample of 30 events providing information on both top- and μ-Yukawa couplings.

An overview of the expected measurement precision on the signal rate in each channel is given in Fig. 2.10(a) comparing 300 and 3000 fb^{-1}. It should be stressed that only a limited selection of channels (initial and final states) were studied so far, and further improvements can be expected with future studies. The bb final state is not yet included in the current estimates. This mode is very challenging at LHC and its evaluation is not ready yet, as it requires particularly careful studies with realistic and well understood upgrade detector designs.

All measurements can be combined in a general coupling fit where no assumption is made about the particle content of the $gg \to H$ and $H \to \gamma\gamma$ loops. Furthermore, no assumption on possible BSM decay modes and hence the total width Γ is made, which allows only the measurement of ratios of coupling parameters, as shown in Fig. 2.10(b). This scenario is the most general case. With more constraints, e.g. assuming no additional BSM contributions to Γ and only two scale factors for the fermion (κ_f) and vector (κ_V) couplings, they can be measured to 2–3% precision.

Referring to an increased number of degrees of freedom in the coupling fits (κ_γ, κ_V, κ_g, κ_b, κ_t, and κ_τ, see Fig. 2.8) the estimated precision attainable with 3000 fb^{-1} is 5–10% keeping unchanged the actual systematic errors. An estimate of 1–4% on these

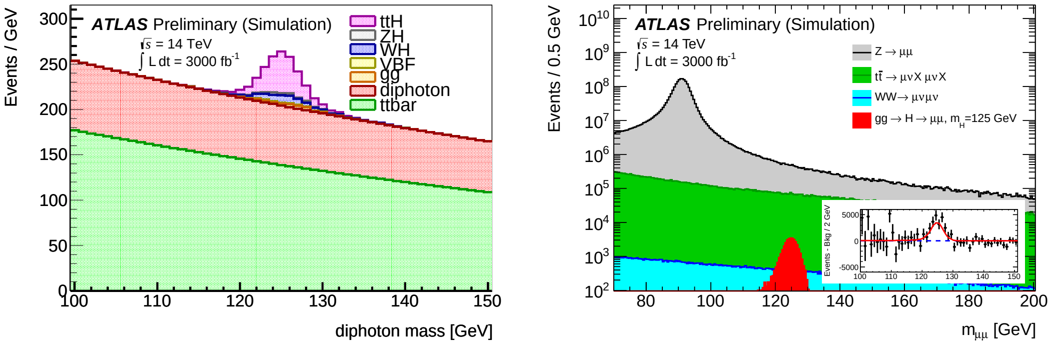


Figure 2.9: Examples of expected invariant mass distributions for 3000 fb^{-1}, (a) for ttH, $H \to \gamma\gamma$ selected with 1 lepton, and (b) inclusive $H \to \mu\mu$.

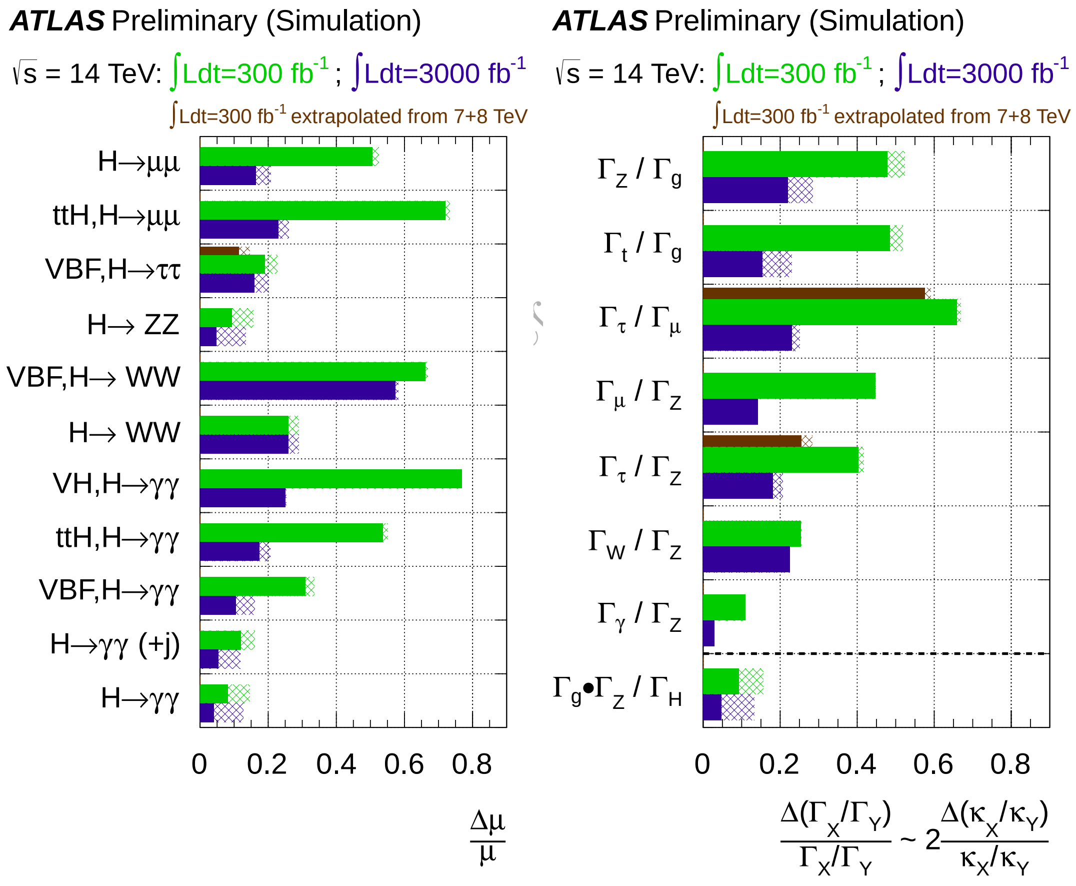


Figure 2.10: (a) Expected measurement precision on the signal strength in a selection of channels for 300 fb^{-1} and 3000 fb^{-1}. (b) Expected precisions on ratios of Higgs boson partial widths. In both figures the bars give the expected relative uncertainty for a SM Higgs with mass 125 GeV (dashed are current theory uncertainty from QCD scale and PDFs). The thin bars show extrapolations from current analysis to 300 fb^{-1}, instead of the dedicated studies for VBF channels.

coupling precisions can be obtained assuming an improvement of 50% in the theoretical uncertainties and the experimental one scaling with the square root of the integrated luminosity.

Observation of the Higgs self-coupling In order to fully determine the parameters of the SM and to establish the EW symmetry breaking mechanism, the measurement of the Higgs self-coupling is important. A direct analysis of the Higgs trilinear self-coupling λ_{HHH} can be done via the detection of Higgs boson pair production, through interference effects with the dominant pair production at LHC by gluon-gluon fusion. Initial sensitivity studies have been performed only on two channels so far, $HH \to bb\gamma\gamma$ and $bbWW$, for their clean signature and high branching ratio, respectively. Only the $bb\gamma\gamma$ final state has been found to be accessible with 3000 fb^{-1}, yielding a 3σ observation per experiment. Additional channels are under investigation. The expectation is that a 30% measurement on λ_{HHH} can be achieved by combining the HL-LHC measurements.

Vector boson scattering If the new boson discovered at LHC is confirmed to be the SM Higgs, then unitarity of scattering amplitudes in longitudinal Vector Boson Scattering (VBS) should be preserved at high energy. It is important to confirm this prediction experimentally. It would also be important to look for new physics contributing to the regularization of the cross-section or else enhancing it. For example, Technicolour or other models, such as partial compositeness or little Higgs, postulate TeV scale resonances to become observable.

At the LHC the VBS are tagged with two forward jets on either side, the remnants of the quarks that have emitted the vector bosons involved in the scattering process. Studies of several channels have been reported for different VB decay final states for $WW + 2\,\text{jet}$, $WZ + 2\,\text{jet}$, and $ZZ + 2\,\text{jet}$ events. As an example Fig. 2.11(a) shows the clean channel $ZZ + 2\,\text{jets} \to 4$ charged leptons + 2 jets, which would allow one to fully reconstruct a hypothetical 1 TeV mass ZZ resonance peak over the SM VBS events and non-VBS di-boson background. For the resonance search, in Fig. 2.11(b), a forward jet-jet mass requirement of at least 1 TeV (Fig. 2.11(a)) reduces the contribution from jets accompanying non-VBS di-boson production. For $m_{4l} > 500$ GeV the statistical precision that can be reached at HL-LHC on the SM contribution is about 15%.

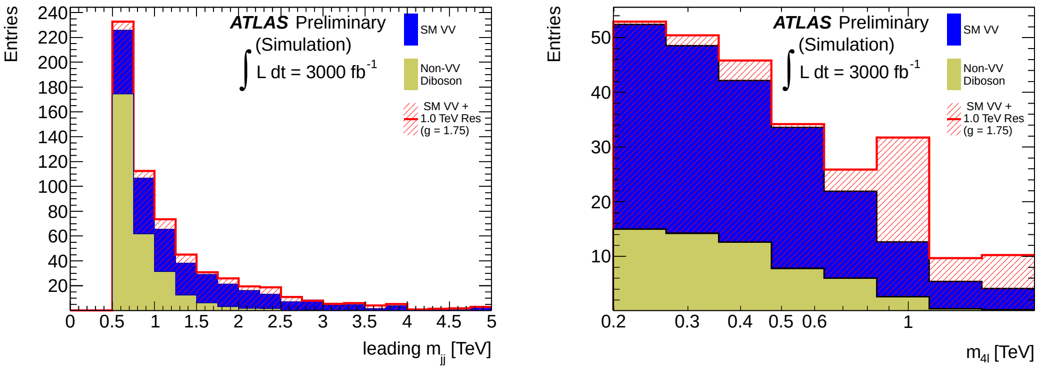


Figure 2.11: (a) Leading jet-jet invariant mass distribution for ZZ+2jets events, (b) reconstructed 4-lepton mass spectrum, with a hypothetical 1 TeV resonance superimposed (see text).

The strong increase in sensitivity provided by the HL-LHC for such an anomalous VBS ZZ resonance is illustrated in Table 2.3, for different masses and couplings g of reference [9].

Table 2.3: Increase in sensitivity provided by HL-LHC for anomalous VBS ZZ resonance.

Model	300 fb^{-1}	3000 fb^{-1}
$m_{\text{resonance}} = 500$ GeV, $g = 1.0$	2.4 σ	7.5 σ
$m_{\text{resonance}} = 1$ TeV, $g = 1.75$	1.7 σ	5.5 σ
$m_{\text{resonance}} = 1$ TeV, $g = 2.5$	3.0 σ	9.4 σ

Exploratory BSM physics at HL-LHC Exploratory reach for physics beyond the SM has always been a great motivation for the LHC, and that remains true also for the HL-LHC. Many quantitative studies exist, and have been refined now with sophisticated simulations by ATLAS and CMS with their realistic detector understanding, gained by the current LHC running in already very challenging pile-up conditions.

Considering first Supersymmetry (SUSY) searches, the new studies have confirmed that the mass reach in the generic searches for gluinos and squarks of the first two generations will be extended from typically 2.6 TeV to 3.2 TeV when adding the HL-LHC data. These results remain essentially unchanged for lightest supersymmetry particle (LSP) masses up to 1/3 of the mass of the strongly produced sparticles.

Naturalness arguments suggest the top squark to be light, preferably below 1 TeV. At 14 TeV the direct stop pair production cross-section for 600 GeV (1 TeV) stops is 240 fb (10 fb). An increase in the luminosity from 300 to 3000 fb^{-1} increases therefore the sensitivity significantly for heavy stop in the interesting region or, if stop candidates are found, will enable to measure their properties. As an illustrative example of a new detailed study the Fig. 2.12(a) summarizes the results in the stop-LSP plane for two decay chains. Both the 5 σ discovery range and the 95% CL exclusion limits are shown.

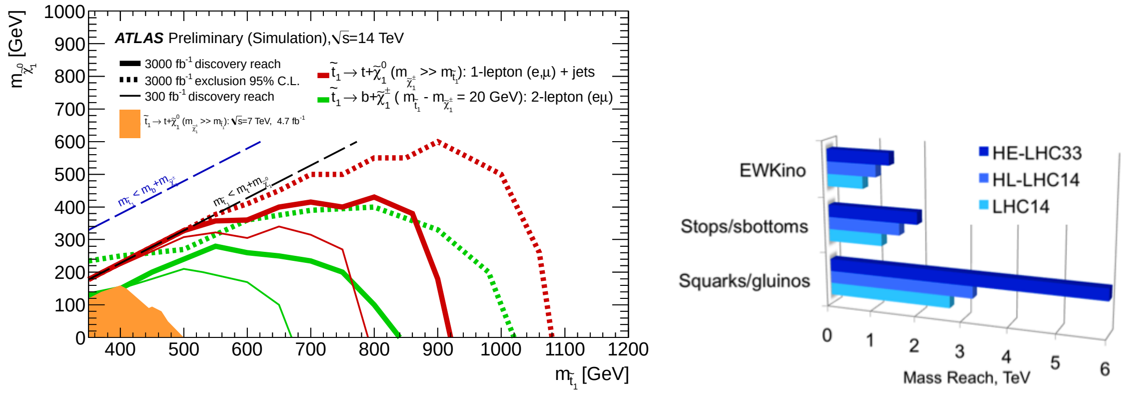


Figure 2.12: (a) 5σ discovery reach and 95% CL exclusion limits in the stop-LSP mass plane for two decay channels, as indicated, for direct stop pair production. (b) Indicative average mass reaches at the design luminosity (LHC14), the HL-LHC (HL-LHC14) and at a higher energy of 33 TeV (HE-LHC33).

The cross-sections for electroweak gaugino searches are small at the LHC, and the discovery potential would get strongly enhanced by the ten-fold luminosity increase. For example, the discovery potential for associated production of charginos and neutralinos extends to scenarios with chargino masses of about 800 GeV for neutralino masses below 300 GeV. Some overall indications of the average increases in mass range are given in Fig. 2.12(b), which illustrates also the gains that could be expected for an increased collision energy of 33 TeV.

A broad variety of resonances and other exotic signatures are sought for at the LHC. The reach for direct observations extends deep into the TeV mass scale, as a typical example one can quote the straight-forward searches for new sequential standard model like Z' decaying into charged lepton pairs. As important as extending the mass range is the substantial improvement in probing smaller couplings than those assumed for a sequential SM Z'. The mass reach of typically 6.5 TeV with 300 fb^{-1} will increase to 7.8 TeV with 3000 fb^{-1}. This improved reach of about 20% is very typical for many other searches.

A notable area of exotic physics that would benefit particularly from a HL-LHC phase is the sector of final states with top quarks. Strongly and weakly produced top-antitop resonances have been studied as an interesting benchmark. For example, strongly-produced Kaluza-Klein gluons in extra-dimension models could result in broad top-antitop resonance signals. The mass reach for them would increase very significantly from 4.3 TeV at 300 fb^{-1} to 6.7 TeV with 3000 fb^{-1}. The HL-LHC would provide huge samples of tops for searches of very rare top decays as a probe for new physics. In the SM the flavour-changing neutral current decays are predicted to be of the order of 10^{-12} or below compared to bW. While such a small branching ratio (BR) remains out of reach, BRs for $t \to q\gamma$ and qZ of a few times 10^{-5} would become accessible, an order of magnitude smaller than with the design luminosity only, and several magnitudes smaller than the ones currently probed.

2.3 Physics at e^+e^- Colliders

High-energy electron-positron collisions offer the opportunity to explore the TeV scale in a way complementary to hadron-hadron and lepton-hadron collisions. The simplicity of the initial state, the well-defined and tunable centre-of-mass energy, the low level of backgrounds due to the absence of colour in the initial state, and the possibility to polarize the incoming beams make electron-positron collisions a precision technique for the discovery of new physics.

For energies significantly above the maximum energy of LEP2 (209 GeV), the storage ring approach for an e^+e^- collider is challenged by huge synchrotron radiation losses (for $\sim$30 km circumference). Thus, in the past decades, linear colliders (LC) have been studied extensively in order to reach energies between 250 and 3000 GeV at high luminosity. The International Linear Collider (ILC) based on superconducting RF-cavities will submit the Technical Design Report (TDR) at the end of 2012 [ID075-077]. Within this TDR, the detailed technical design for a 500 GeV machine (tunable from 250 to 500 GeV and extendable to $\sim$ 1000 GeV is presented for a design luminosity of $1.8 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\sqrt{s} = 500$ GeV. The Compact Linear Collider (CLIC) is based on normal-conducting structures exploiting the two-beam concept for RF generation. CLIC finalized a Conceptional Design Report (CDR) after many years of targeted R&D [ID099]. A staged approached with centre-of-mass energies from 500 to 3000 GeV is proposed with luminosity of $1.4(2.0) \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 500 (3000) GeV (above 99% of $\sqrt{s}$). Very recently, variants of circular e^+e^- colliders have also been reconsidered [ID138, ID157].

The physics case for a LC has been studied extensively for more than 20 years. The conclusions [ID069] have been submitted as a contribution to the strategy update. The main goals of the LC physics programme are:

- precise measurements of the electro-weak symmetry breaking (EWSB) sector;
- precise measurements of the interactions of top quarks, gauge bosons, and new particles;
- searches for new physics beyond the SM in particular (but not only) for the pair production of colour-neutral states which extends significantly beyond the LHC;
- sensitivity to new physics through tree-level or quantum effects in high-precision observables.

2.3.1 Linear Colliders

The profile of the Higgs boson With the observation of a new particle by ATLAS and CMS consistent with the SM Higgs boson, there is a unique opportunity to study this boson in the clean environment of e^+e^- collisions. Since the boson has been seen in its ZZ-decay and given the indications that it also decays to WW, the main LC production modes, Higgs-strahlung and WW-fusion can be exploited, allowing for a model-independent reconstruction of the profile of this Higgs-like particle (hereafter called “Higgs boson” for simplicity).

For a LC, there are *qualitative* differences to the LHC which in turn lead to *quantitative* improvements for the determination of the parameters of the Higgs sector. The precise measurements of these parameters allows for the identification of the nature of underlying physics. The experimental anchor of LC Higgs physics is the possibility to observe the Higgs boson in Higgs-strahlung, $e^+e^- \to HZ$ as a resonance in the mass recoiling against a leptonically decaying Z-boson independent of a specific Higgs decay, see Fig. 2.13 (right). This allows for the direct reconstruction of g_{HZ}, the Higgs-Z coupling. Thus, inherently any Higgs branching ratios and couplings can be determined absolutely and without correlations. This includes potential beyond-SM decays such as e.g. invisible decays, decays into light quarks etc.

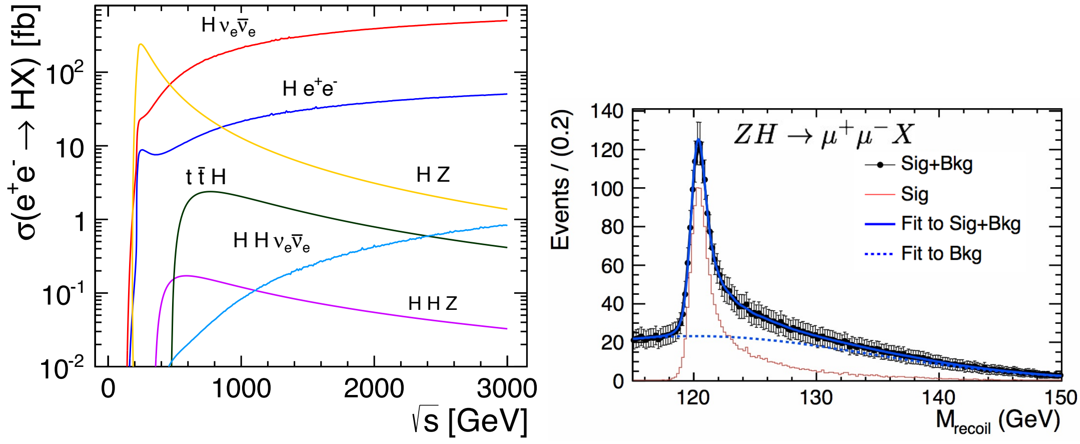


Figure 2.13: (Left) Cross-sections for various Higgs boson production processes in e^+e^- collisions. (Right) Recoil mass distribution for $e^+e^- \to ZH \to \mu^+\mu^-H$ events at the ILC for $m_H = 120$ GeV and 250 fb^{-1} at $\sqrt{s} = 250$ GeV.

The reconstruction of the Higgs boson profile requires different steps in centre-of-mass energy. The recoil mass spectrum as well as branching ratios (b, c, τ, g, W, Z, γ) can be measured in Higgs-strahlung where the maximum of the cross-section for a 125 GeV Higgs boson is around 250 GeV. Given the inherent, approximately linear, increase of instantaneous luminosity with $\sqrt{s}$, comparable accuracies can be achieved at 250 GeV and 350 GeV. The most precise method to reconstruct the total decay width involves the precise measurement of the WW-fusion cross section which rises logarithmically with $\sqrt{s}$ and requires at least 350 GeV.

Since the $H \to t\bar{t}$ decay is kinematically forbidden, the top Yukawa coupling needs to be measured in $e^+e^- \to t\bar{t}H$. The cross-section has a broad maximum around 700 GeV. The top Yukawa coupling can be measured with $\sim 15\%$ precision at $\sqrt{s} = 500$ GeV for 500 fb^{-1}[10].

The measurement of a non-zero trilinear Higgs coupling λ_{HHH} signals a non-trivial structure of the Higgs potential and thus spontaneous symmetry breaking. At the LC it can be accessed mainly through two different production mechanisms, $e^+e^- \to HHZ$ (maximum at $\sqrt{s} \approx 600$ GeV), and $e^+e^- \to HH\nu_e\bar{\nu}_e$ with logarithmically rising cross-section. Cross-sections for the various Higgs boson production processes are shown in Fig. 2.13 (left).

The precision achievable for the Higgs boson couplings is summarized in Table 2.4 and displayed in Fig. 2.14. It should be mentioned that the measurements are largely statistics-limited.

Table 2.4: Achievable LC precision on Higgs boson couplings, after [ID069]. Measurements are statistically limited; assumed integrated luminosity is 250/350/500/2000 fb^{-1} for $\sqrt{s}$ = 250/350/500/3000 GeV. Empty fields denote that no specific study at this energy has been performed, a dash denotes that the measurement is not possible.

	250/350 GeV	500 GeV	3 TeV
g_{Hbb}	1.6/1.4%		2%
g_{Hcc}	4/3%	2%	2%
$g_{H\tau\tau}$	3/3 %	2.5 %	
g_{HWW}	4/3%	1.4%	<2%
$g_{H\mu\mu}$	–	–	7.5%
g_{HZZ}	1.5–2%		
g_{HWW}/g_{HZZ}			<1%
g_{ttH}	–	15%	
g_{HHH}	–	30–40%	20%
Γ_H	11/7%	5%	

The Higgs boson mass can be measured both from the recoil mass distribution or from the direct reconstruction of its decay products to a precision better than 50 MeV, a factor of two better than current LHC projections. The spin can be unambiguously determined from a scan of the HZ threshold and from angular distributions of the Z boson and its decay products. Angular correlations in $H \to ZZ$ and $H \to \tau\tau$ can be exploited to study the CP properties of the Higgs boson with sensitivity to small (3–4%) CP-odd admixtures. While in HZ production CP-odd contributions may be suppressed, their study in ttH angular production allows for a model-independent analysis.

The percent-level sensitivity of the LC to Higgs boson couplings enables to explore the nature of the Higgs boson and can discriminate e.g. a fundamental Higgs boson from a

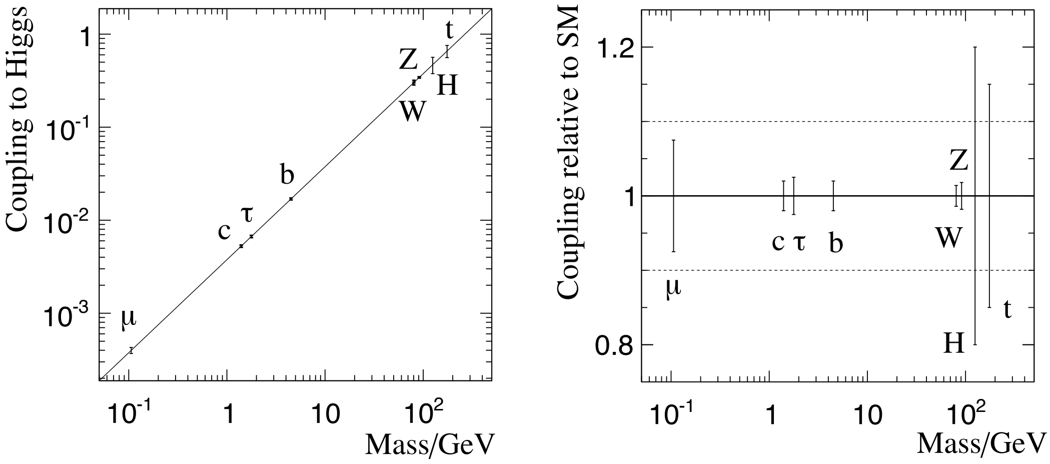


Figure 2.14: Typical precisions achievable at the ILC on model-independent Higgs boson couplings for $m_H = 120$ GeV.

composite object. The SM Higgs boson can be distinguished from BSM realizations of the Higgs sector, e.g. models with two Higgs doublets (with or without Supersymmetry). As a specific example, this discrimination power can be used to predict the masses of heavier Higgs bosons even in parameter regions where the LHC is insensitive to their direct production [11]. Deviations from the SM may occur through additional particles present in loops of the observed Higgs decays. Deviations may also occur as a consequence of the Higgs boson mixing with states from other new physics such as mixing with the radion appearing in extra-dimensional models.

Top quark physics The reaction $e^+e^- \to t\bar{t}$ both at the production threshold around $\sqrt{s} \approx 350$ GeV and in the continuum at $\sqrt{s} = 500$ GeV opens the possibility to study the heaviest quark in a way complementary to the LHC. Due to its large mass, the top quark plays an important role in radiative corrections to the ratio of the weak gauge boson masses and most notably in constraining the mass of the Higgs boson in the SM and in models beyond the SM. Precise measurements of top quark properties provide sensitivity to mass scales well beyond that of EWSB.

At the LC, a scan of the cross-section for $t\bar{t}$ production around its threshold of $\sqrt{s} \sim 2m_t$, yields a statistical precision of 20 MeV for the "threshold mass" of the top quark and 30 MeV for its width, see Fig. 2.15. In contrast to the mass measured at hadron colliders, where the transition from the measured observable to a theoretically well-defined mass gives rise to systematic uncertainties of $\mathcal{O}(1$ GeV$)$, the transition from the threshold mass to theoretically well-defined mass definitions is well understood yielding a precision for the latter better than 100 MeV, a factor 10 smaller than at hadron colliders. In the continuum, at $\sqrt{s} = 500$ GeV, forward-backward and (taking advantage of the polarized beams) left-right $t\bar{t}$ asymmetries can be measured to $\sim 5\%$ yielding, e.g., sensitivity to 10–20 TeV Kaluza-Klein excitations of the gluon. Recent anomalies observed at the Tevatron on top forward-backward asymmetries underline the importance of such measurements. The study of angular correlations of the decay products in $e^+e^- \to t\bar{t}$ can furthermore yield sub-percent sensitivity to BSM corrections of the $t\bar{t}\gamma$ and $t\bar{t}Z$ vertices while a sub-threshold measurement provides sensitivity to the

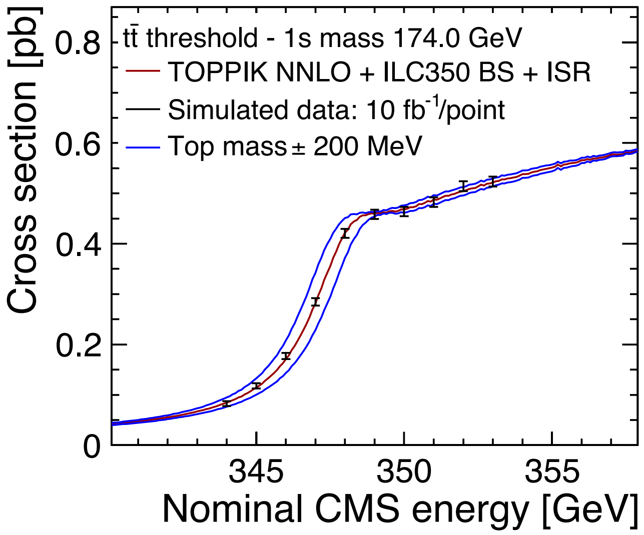


Figure 2.15: Simulation of the measurement of the $t\bar{t}$ cross section at the ILC around the production threshold.

tbW coupling with few percent precision. These measurements can probe various new physics models such as Little Higgs and top flavour models with better precision than the LHC.

Trilinear and quartic gauge boson couplings While the SM Higgs boson restores the unitarity of high-energy WW scattering completely, there are extensions of the SM where the Higgs boson fulfills this task only partially and is embedded into a strongly interacting sector. The restoration of unitarity can be already precisely checked by studying the Higgs boson couplings. However, in addition, it is important to study the trilinear and quartic gauge boson couplings to study such models. Through fully exploiting the possibility of beam polarization and the clean final states, the anomalous triple gauge couplings of the WWZ and $WW\gamma$ vertices can be measured to better than 1 permil precision with up to 1 ab^{-1} at 500 GeV extending the LHC reach by up to one order-of-magnitude, depending on the coupling. The measurement of quartic coupling in the $WW \to WW$ process requires energies significantly higher than 500 GeV and can be performed at a 1 TeV ILC upgrade or at 3 TeV CLIC.

Physics Beyond the SM The Higgs, top, and gauge boson programmes are guaranteed at a LC and serve as a window for the exploration of physics beyond the SM (BSM). In addition, new BSM states can be studied at a LC directly if they are kinematically accessible. Up to the date of writing, the LHC experiments have not yet revealed any direct signal of BSM. Strong constraints have been established on some of the standard BSM benchmarks, such as the constrained minimal supersymmetric model (CMSSM) where mass limits on (light flavour) squarks and gluinos around 1 TeV have been established. However, current LHC exclusions as well as sensitivity prospects at the LHC leave plenty of room for new particles still to be discovered, also in a mass range well accessible at a LC. In particular, the SUSY particles that are required to be light in order to retain the attractiveness of TeV-scale SUSY (third generation sfermions, charginos and neutralinos) are not yet strongly constrained by the LHC experiments.

In such a situation, the LC can (as shown for numerous examples) study these new particles in depth with great precision and discriminate between theoretical models. In the absence of direct LHC signals in the future, a LC has complementary discovery potential, in particular for new particles which carry only electroweak quantum numbers, such as (e.g.) neutralinos and charginos as well as sleptons in Supersymmetry and other pair-producable electroweak states of matter. This also holds for the pair-production of (non-SUSY) dark matter particles which can be searched for in $\chi\chi\gamma$ final states yielding sensitivity to the coupling of the DM particles to the Z which is superior to that at the LHC.

In addition to this direct discovery potential, discovery of NP through small deviations of SM observables is possible due to the high precision of SM measurements. These precision measurements often have a sensitivity to NP mass scale into the multi-ten-TeV regime and can thus serve to motivate and define collider programmes at such energies. The ILC can also be operated at on Z-pole ($\sqrt{s} = 91$ GeV) and the WW-threshold (160 GeV) allowing e.g. for a significantly improved measurement of the weak mixing angle and for a measurement of m_W to 6 MeV precision. These measurement are important to search for NP deviations from the SM predictions for EWSB, complementary to the direct study of the Higgs boson.

Linear Collider Detectors Intense R&D towards high-precision detectors for Linear Colliders has been pursued in the past decade. Two detector concepts, ILD [ID078] and SiD [ID079], have been validated in an international review process and are being supported by large international communities. Dedicated R&D collaborations (e.g. CALICE for particle flow calorimetry and LCTPC for a large TPC) are in place to address the development of detectors that meet the physics requirements of a Linear Collider detector. Both ILD and SiD adopt the particle flow concept for the reconstruction of final states. Calorimeters will consist of highly-granular silicon-tungsten electromagnetic and analog or digital steel or tungsten sampling calorimeters with different options for the active medium. Both concepts employ monolithic ultra-thin vertex detectors for the identification of bottom and charm quarks. In ILD, central tracking is based on a large TPC using MPGD readout in a 2T magnetic field while SiD uses a silicon strip tracker in a 5T magnet. Both concepts are working towards a Detector Baseline Document (DBD) to submitted for review together with the ILC Technical Design Report at the end of 2012. Both detector concepts emerged from the ILC effort but are also being adapted for their use within the CLIC concept. Drawings of the detectors are displayed in Fig. 2.16.

2.3.2 Circular Colliders

The fact that the newly discovered boson is only 11 GeV heavier than the SM Higgs limit from LEP2 revived the idea of producing e^+e^- collisions in storage rings. A submitted proposal [ID138, ID157, ID171, ID173] describes a high-luminosity e^+e^- storage ring in the LHC tunnel with $\sqrt{s}$ up to 240 GeV (LEP3) and one in a new 80 km tunnel with $\sqrt{s}$ up to 350 GeV (TLEP). LEP3 is dedicated to study Higgs boson production predominantly through the Higgs-strahlung process. At TLEP, in addition $t\bar{t}$ production at threshold can be studied and Higgs production in the WW fusion channel becomes accessible at a reasonable rate. The envisaged instantaneous luminosity for LEP3 is $1.1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ per interaction region. For TLEP the achievable luminosity is calculated

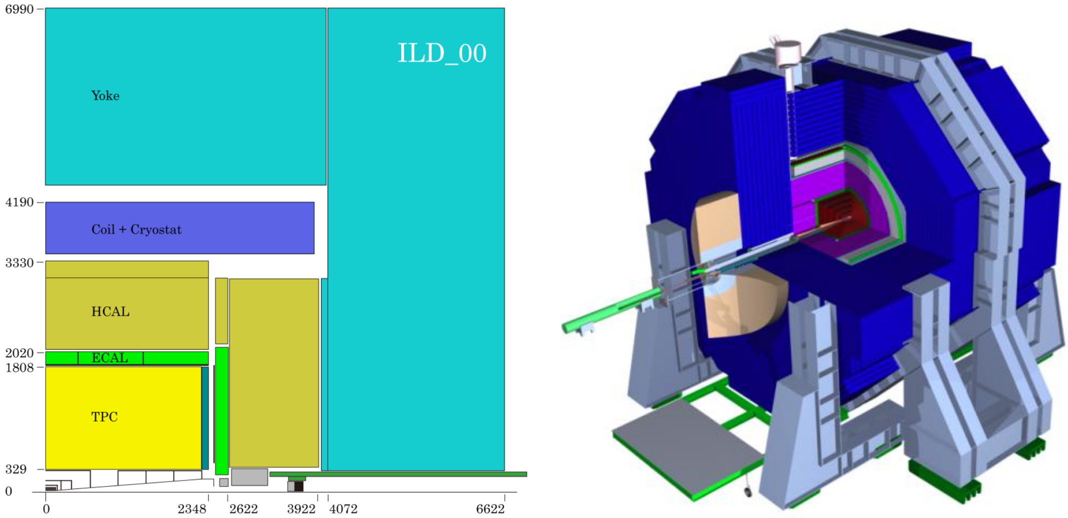


Figure 2.16: Linear Collider detector concepts: ILD (left) and SiD (right).

to be $\mathcal{L} = 6.5 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 350$ GeV and $\mathcal{L} = 4.9 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 240$ GeV. A study of the performance of the CMS detector for e^+e^- collisions has been submitted to the Open Symposium and was updated afterwards [ID101, ID171]. Due to short lifetime of the beams (10 minutes for 4 interaction points) polarization build-up is not possible above the Z. The physics potential of a circular collider is similar to that of an (unpolarized) Linear Collider at the same centre-of-mass energy. More than one detector can be operated simultaneously, allowing for a larger integrated luminosity when combining the results from different detectors. In addition beamstrahlung is smaller than at a LC. Both circular machine options offer the potential to run a $\sqrt{s} \sim m_Z$ with $> 10^{35}\text{cm}^{-2}\text{s}^{-1}$). The achievable precisions on Higgs branching fractions and the total width scale approximately with $1/\sqrt{\mathcal{L} \times n_{\text{IP}}}$. Consistent with this scaling, in [ID171], achievable precisions, e.g., of 0.6% (0.3%) on g_{HZZ} and 14% (9%) on $g_{H\mu\mu}$ at LEP3 with 4 IPs (TLEP with 2 IPs) are quoted.

2.3.3 Photon Colliders

The possibility of providing high-energy $\gamma\gamma$ collisions from laser Compton backscattering off high energy electron beams has been considered an option for linear colliders since a long time. In view of the newly discovered Higgs-like boson, a proposal (SAPPHiRE) for a dedicated photon collider has been submitted to the Open Symposium [ID145]. It exploits the potential to study the process $\gamma\gamma \rightarrow H$ with a luminosity of $\mathcal{L} = 0.36 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ at $\sqrt{s_{\gamma\gamma}} = 125$ GeV. With this process, additional measurements of the Higgs boson are provided through the measurement of the $b\bar{b}$, WW^*, and $\gamma\gamma$ final states, in particular the mass and the product of the $\gamma\gamma$ partial width with the respective Higgs boson branching ratio as well as the study of CP properties in the $H\gamma\gamma$ coupling.

2.4 Energy frontier physics at other proposed facilities

The LHC continues to yield measurements that will impact our understanding of the physics case for future energy frontier machines such as a multi-TeV lepton collider

[ID135] or a very high energy hadron collider with energies of the HE-LHC or beyond. The physics cases for these machines have been studied in the past [12]. A better understanding of the potential physics backgrounds, a plan for a detector R&D program and a program of R&D for the accelerator technologies, based on the experience gained with the LHC, are needed in the near term.

The physics goals of a muon collider are similar to those of a electron-positron collider of the same energy, but the suppression of radiative effects due to the muon mass could lead to some specific advantages. The overall size of a machine would be smaller for a comparable energy and the small energy spread provides the possibility of better beam-energy resolution. Following the recent announcement by the LHC experiments regarding the Higgs-like boson, there is interest in studying the direct production of the SM Higgs boson using a low-energy, high-luminosity muon collider. The muon collider offers some unique possibilities. For example, at a muon collider Higgs factory, a direct measurement of the width of the Higgs boson is possible. A multi-TeV muon collider offers the chance to study Terascale physics. The development of a muon collider program provides the potential for a staged program that could start with a Higgs factory or a neutrino factory as early stages each with significant physics potential.

A very large hadron collider with a center-of-mass energy in the range 100–200 TeV and luminosity that exceeds $10^{34}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$ will be of great interest in the post LHC era. If such a machine could be built, it would be able to directly explore the 10–100 TeV energy range, a scale that is 5–10 times larger than is possible at the design energy of the LHC. One expects such a machine would be able to greatly extend searches for new physics beyond the Standard Model and provide important information on supersymmetry, extra dimensions and compositeness. The greatest gains over the LHC will come in the searches for massive new particles. Rare top decays can be studied at a very large hadron collider since the $t\bar{t}$ cross sections are expected to be about 50 times larger at 200 TeV compared to the 14 TeV LHC. In addition, a high energy hadron collider offers potential for studying the trilinear Higgs self-coupling as well as provide information on $W_\mathrm{L}W_\mathrm{L}$, $W_\mathrm{L}Z_\mathrm{L}$ and $Z_\mathrm{L}Z_\mathrm{L}$ scattering with large data samples. More detailed studies are needed to understand the backgrounds for these processes and further complications from the pileup and underlying event in high energy collisions.

The LHeC Study Group submission to the Symposium outlines a physics program using ep and eA collisions at the proposed LHeC to study high density proton and nuclear dynamics and structure, as discussed in Chapter 5. The ep initial state can also be used for new particle searches and to investigate new phenomena that may be found by the LHC experiments. Examples are the spectroscopy of leptoquarks, the investigation of R-parity violating SUSY states, substructure and contact interaction phenomena, and the search for excited electron or neutrino states.

In ep collisions at the LHeC, Higgs bosons are produced through WW and ZZ fusion. These vector boson fusion (VBF) processes have sizeable cross sections, $O(100)$ fb for 126 GeV mass [ID147]. These production modes can be identified through the charged or neutral current process, and the decays are expected to have low backgrounds so it should be possible to measure the the dominant decay to bb with good precision.

Plasma wakefield acceleration has opened up the possibility of making fundamental physics measurements based on single laser shots. A contribution to the Symposium [ID91] considered physics topics that could be investigated at high energy colliders at low luminosities.

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Chapter 3

Physics of Flavour and Symmetries

Relevant talks at the Open Symposium were given by G. Isidori and F. Teubert, who also made contributions to this chapter.

3.1 Theory of Flavour Physics and Symmetries

One way to understand most particle physics phenomena is to use a simple effective theory which is composed of a gauge symmetry term and a symmetry-breaking term, as follows:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{sym.break.}} \; . \tag{3.1}$$

The first term is highly symmetric and can be predictable with high accuracy, while the second term, which encodes the flavour structure of the model, represents the connection to our natural world which is not fully symmetric. Flavour physics programs are aimed at understanding the second term. The evidence of a Higgs-like boson would suggest that the symmetry-breaking sector might have a minimal structure, and many of the particle physics problems could be included in the Higgs potential given by

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + Y^{ij}\Psi_L^i\Psi_R^j\Phi + \frac{g_{ij}}{\Lambda}\Psi_L^i\Psi_L^{jT}\Phi\Phi^T, \tag{3.2}$$

where Φ and Ψ are the Higgs and the fermions, respectively, and Y^{ij} is the Yukawa coupling. The last term represents the effective dimension-five neutrino mass term and Λ is its new physics scale. These third and fourth terms are responsible for masses and flavour mixing of both quarks and leptons.

The two key open questions concerning the "origin of flavour" in flavour physics are (1) *what determines the observed pattern of masses and mixing angles of quarks and leptons?* and (2) *which sources of flavour symmetry breaking are accessible at low energies?* Owing to the lack of theoretical guidance, even with the precise measurements of the quark mixing parameters it is difficult to address the first question so far. The second question is being studied by a series of high-precision measurements of flavour-changing processes.

In the quark sector, almost all measurements show overall agreement with the Cabibbo-Kobayashi-Maskawa (CKM) picture—a remarkable success of the model. On the other

Table 3.1: Sensitivity of the sources of flavour symmetry breaking accessible at low energy in the quark sector (from meson-antimeson mixing processes), given in Eq. (3.3). The observables include oscillation frequencies (Δm) and CP-violating parameters for the different systems. Taken from Ref. [1]; note that limits from the B_s have since been further tightened.

Operator	Limits on Λ (TeV) ($C_{\mathrm{NP}} = 1$)		Limits on C_{NP} ($\Lambda = 1\,\mathrm{TeV}$)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K, ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K, ε_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D, $\lvert q/p\rvert$, Φ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D, $\lvert q/p\rvert$, Φ_D
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}, $S_{\phi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}, $S_{\phi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}, $S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}, $S_{\psi\phi}$

hand, this success may be embarrassing since it could exclude possible large contributions of new physics at the TeV scale. For instance, new physics may be included as

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{C_{\mathrm{NP}}}{\Lambda^2} O_{ij}^{(6)} \ , \tag{3.3}$$

where the second term represents new physics contribution and C_{NP} and Λ are the coupling constant and the energy scale of new physics respectively, and $O_{ij}^{(6)}$ is a dimension-six operator. For example, from the measurements of Δm_K, Δm_D, Δm_{B_d}, Δm_{B_s}, CP violating parameters for K, D, B_d and B_s, the energy scale of new physics $\Lambda \sim O(10^3)$ TeV in the case of $C_{\mathrm{NP}} = 1$ is assumed, or C_{NP} is very small, of the order of $O(10^{-5})$ to $O(10^{-11})$ if $\Lambda = 1$ TeV is assumed (see Table 3.1).

For the charged lepton sector, the constraint from flavour-changing processes (charged lepton flavour violation) is even more severe. For instance, for $\mu^+ \to e^+\gamma$, one can consider

$$\frac{C_{\mathrm{NP}}}{\Lambda^2} O_{ij}^{(6)} \to \frac{C_{\mu e}}{\Lambda^2} \bar{e}_L \sigma^{\rho\nu} \mu_R \Phi F_{\rho\nu} \ . \tag{3.4}$$

The present upper limit of $B(\mu \to e\gamma) < 2.4 \times 10^{-12}$ gives

$$\Lambda > 2 \times 10^5\,\mathrm{TeV} \times (C_{\mu e})^{\frac{1}{2}} \ . \tag{3.5}$$

In the case of $C_{\mu e} = 1$, Λ can be $O(10^5)$ TeV.

The good overall consistency of the quark flavour-changing processes and the stringent limits of lepton flavour-changing processes indicates that there is not much room for new sources of flavour symmetry breaking close to the TeV scale, or the scale of new physics is very high. However, this is based on a very general argument. In some specific theoretical models the constraints of new physics should be determined in a model-dependent way, and sometimes the constraints could be less stringent.

In such theoretical models, we do expect small but detectable deviations from the SM predictions, in selected special flavour-changing processes. They are the flavour-changing processes with suppressed SM contributions, or the SM-forbidden processes with no SM contribution.

Table 3.2: List of key flavour-changing processes in the quark sector.

Observables	Comments	Physics issues
CKM angle γ	tree-level	SM input for ΔF=2 tests
$\lvert V_{ub}\rvert$	tree-level	SM input for ΔF=2 tests
$B_{(s,d)} \to \ell^+\ell^-$	$\Delta(f_B) < 5$ %	Higgs-mediated FCNC
CPV in B_s	$\sigma \sim 0.01$	new CPV
$B \to K^{(*)}\ell^+\ell^-, K^{(*)}\nu\nu$	$\sigma \leq 5$ %	non-standard FCNC
$B \to \tau\nu, \mu\nu$	$\Delta(f_B) < 5$ %	scalar charged currents
$K \to \pi\nu\overline{\nu}$	$\Delta(BR) < 5$ %	non MFV
CPV in charm	uncertainty needs work	new physics up-type quarks

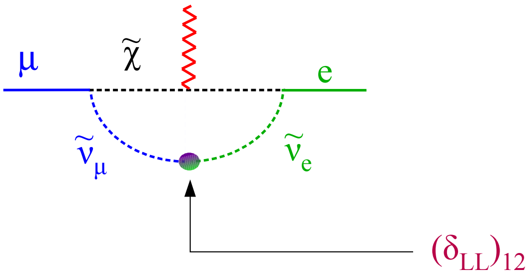

Figure 3.1: A SUSY diagram for CLFV ($\mu^+ \to e^+\gamma$); $(\delta_{LL})_{12}$ is the slepton mixing parameter between $\tilde{\mu}$ and $\tilde{e}$.

Some remarks on the selection of processes to study: firstly, the sensitivity to the energy scale Λ of new physics only grows slowly, with $N^{\frac{1}{4}}$, for statistics N. Facilities with high intensity are therefore needed.

Secondly, processes should be chosen with small uncertainty of the SM contribution. In particular, SM predictions in the quark sector often have large QCD uncertainties, but in some processes the theoretical QCD errors can be as small as the few-percent level. Some promising observables are listed in Table 3.2.

Charged lepton flavour violation (CLFV), which is a flavour-changing neutral current process in the lepton sector, is one of the most interesting and potentially rewarding searches in the flavour sector, after what has been learned from neutrino physics.

One of the virtues of CLFV is that the SM contribution from massive neutrino mixing is known to be too small to be detected, $O(10^{-54})$. This suppression comes from $(m^2_{\nu_l} - m^2_{\nu_k})/M^2_W$ where m_{ν_i} and M_W are the masses of the neutrino ν_i $(i = 1, 2, 3)$ and the W boson respectively. This process is therefore known to be theoretically clean.

The second virtue of CLFV is that various theoretical models predict sizable branching ratios for CLFV, being detectable in future experiments, if there are new particles carrying lepton flavour at an energy scale not far from the TeV scale. One class of the physics models are supersymmetric (SUSY) ones. In SUSY models, CLFV occurs e.g. through slepton mixing, $(\delta_{LL})_{12}$, as shown in Fig. 3.1, given by an off-diagonal element of the slepton mass matrix. In SUSY-GUT models, $(\delta_{LL})_{12}$ is proportional to $y_t^2 V_{13} V_{23}^*$, and in the SUSY see-saw models it is proportional to $y_{\nu_3}^2 U_{13} U_{23}^*$, where y_t and y_{ν_3} are the Yukawa couplings for the top quark and the neutrino ν_3 respectively, and V and U are the CKM quark-mixing matrix and PMNS neutrino-mixing matrix respectively. For example, the branching ratio (B) of $\mu^+ \to e^+\gamma$ can be given by

$$B \sim 10^{-13}\Big(\frac{\tan\beta}{10}\Big)^2\Big(\frac{0.5\text{TeV}}{\tilde{m}}\Big)^4\Big(\frac{\delta_{LL}}{10^{-4}}\Big)^2, \tag{3.6}$$

which could produce sizable branching ratios. Therefore, if SUSY exists, slepton mixing is sensitive to GUT (at 10^{16} GeV) or neutrino see-saw mechanisms (at 10^{13-14} GeV). As a result, CLFV has the potential to study physics at very high energy scale.

The current upper limit for $\mu^+ \to e^+\gamma$ from the MEG experiment is $B(\mu \to e\gamma) < 2.4 \times 10^{-12}$ [2]. This value can be taken as a reference value to estimate the potentially interesting level for future CLFV searches in different processes. $\tau \to \mu\gamma$ might occur through the same dynamics, but its branching ratio can be enhanced by either $O(10^3)$ for the CKM-type SUSY models, or $O(10)$ for the PMNS-type SUSY models, yielding $B(\tau \to \mu\gamma) \leq 4 \times 10^{-9}$. For the other muon CLFV processes such as $\mu^+ \to e^+e^+e^-$ and $\mu^-N \to e^-N$ having the same dynamics as $\mu^+ \to e^+\gamma$ are CLFV processes with the same muons, but the photonic dipole contribution is suppressed by $O(\alpha/\pi)$, although an additional non-dipole interaction could contribute. If the photonic dipole interaction dominates, $B(\mu N \to eN), B(\mu \to eee) \leq 10^{-14}$. Other tau CLFV processes are $\tau \to \mu\mu\mu$, which has the same $O(\alpha/\pi)$ suppression if the photonic dipole interaction dominates, and $\tau \to \mu\eta$ which can be interesting in models with no photonic dipole interaction.

The search for a permanent electric dipole moment (EDM) of fundamental particles, such as electrons, muons, neutrons, protons, and light ions, is another important search in particle physics at low energy. EDMs violate P (parity) and T (time reversal), and if CPT invariance is assumed they violate CP as well. We know that baryogenesis needs a new CP violation mechanism, in addition to the CKM CP violation which gives only a negligible contribution. The SM contribution to EDMs are known to be very small, and for instance that for the neutron EDM, $d_n^{\text{SM}} < 10^{-32}$ e·cm is much smaller than the current limit of $d_n < 2.9 \times 10^{-26}$ e·cm. Similarly to CLFV, various theoretical models predict EDM values which are close to the present upper bounds, e.g. SUSY models with a new CP violating phase at the TeV scale, or CP violation in the strong interaction.

3.2 Quark Flavour Physics

Quark flavour physics involves the study of transitions between quarks, mediated by the weak interaction. This is described in the SM by the CKM matrix, which quantifies the couplings between up-type (u, c, t) and down-type (d, s, b) quarks. It is a unitary matrix, implying relationships between its elements, that form triangles in the complex plane. The matrix has four parameters, which in one widely used parameterization [3] are denoted λ, A, ρ and η. The first of these is related to the Cabibbo angle: $\lambda = \sin\theta_{\text{C}} = 0.22$, determined from kaon decays, and $A = 0.81$ is extracted from the B lifetime, both known with percent-level precision [4]. The remaining two parameters, real and imaginary components, define the apex of the Unitarity Triangle shown in Fig. 3.2. The matrix has a single non-trivial phase, which is responsible for all CP violation in the SM. As a result there are strict relationships between the many observable CP asymmetries, providing sensitive tests of the model. Particle-antiparticle mixing and rare decays (flavour-changing neutral currents, FCNC) occur via loop diagrams, which

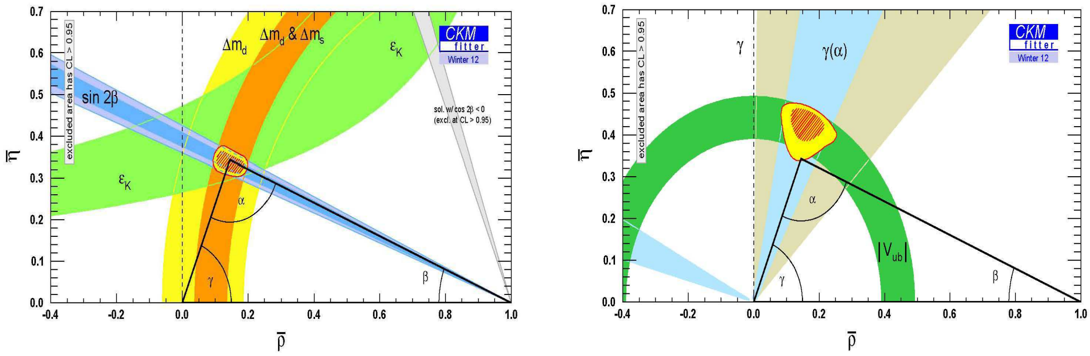

Figure 3.2: CKM Unitarity Triangle fit (left) from loop-mediated and (right) from tree-level processes. Taken from Ref. [5], similar results available from Ref. [6].

involve second-order transitions such as the “box” diagram that allows neutral mesons such as the B^0 (made up of a $\overline{b}$ and d quark) to transform into their antiparticles ($\overline{B}^0$, i.e. $b\overline{d}$). The dominant contributions from such loops involve the W and heavy quarks in the SM, but could include other particles from new physics, which would alter the observed rates. Precision measurements can thus shed light on the existence of new physics via the virtual effects of new particles in loop diagrams, so flavour physics is complementary to the direct search for the production of such particles, and can probe the phase structure of new physics.

The CP transformation is the combination of discrete symmetry transformations of charge conjugation (C) and parity (P). It was initially thought to be a symmetry of nature, after it was realized that parity was maximally violated by the weak interaction. The violation of CP was first observed as a small asymmetry $O(10^{-3})$ in kaon decays, in 1964. A large effect was predicted in B hadron decays (the angle β in Fig. 3.2) and subsequently observed by the B factory experiments in 2001, in triumphant agreement with the SM prediction. CP violation is a necessary ingredient for explaining baryogenesis, i.e. why the world is made up of matter, while both matter and antimatter are assumed to have been produced in equal quantities at the Big Bang. However, the level of CP violation from the CKM mechanism is found to be much too small to explain this, so other sources of CP violation are expected, and this is a good place to search for physics beyond the SM. The major focus of quark flavour physics is currently on the B system, where there is a rich set of observables. Charm physics is also studied by the same facilities, although complemented by studies made at charm resonances below the B threshold. In kaon physics the emphasis has moved towards the measurement of very rare decays, that provide clean observables in the search for new physics.

The CKM Unitarity Triangle relevant for B^0 decays is shown in Fig. 3.2, separated into loop-mediated and tree-level processes, where physics beyond the SM is expected to contribute to the former class of observables. At the current level of precision no significant inconsistency is seen, so there is no clear evidence of non-SM effects. This already puts tight constraints on new physics, and may indicate that such new physics (if it is to appear at the TeV scale) may involve Minimal Flavour Violation, where the Yukawa couplings of the new physics are similar to those of the SM, or the scale of new physics may be higher.

3.2.1 Recent and current experiments

B physics

Beauty (B) physics was initially studied at e^+e^- collider experiments, such as ARGUS (DESY) and CLEO (Cornell, US) which operated at the $\Upsilon(4S)$, and the LEP (CERN) experiments at the Z: they measured lifetimes and branching ratios of the various states, and observed B^0–$\overline{B}^0$ oscillation. This observation provides a good example of the power of flavour physics, as it demonstrated that the top quark was heavy, due to its influence on B^0–$\overline{B}^0$ rate through virtual loop diagrams, even though the top quark had not yet been observed directly. A major step forward was taken in sample sizes by the asymmetric B factories, PEP II (SLAC, US) and KEKB (KEK, Japan), which were dedicated to the study of B hadrons produced by e^+e^- collisions at the $\Upsilon(4S)$, the first $b\bar{b}$ resonance which is above threshold to decay to open beauty. The asymmetric beam energies allowed the decay products to be boosted, and the decay time to be observable—in fact the decay time *difference* between the B and $\overline{B}$ that are produced in a quantum-correlated fashion in the decay of the Υ. Following the observation of CP violation in B^0 decays by the B factory experiments, they continued to make many measurements, until they ceased operation in 2008 (BaBar) and 2010 (Belle). Their large data-sets of 0.5 ab^{-1} and 1 ab^{-1} respectively continue to be analysed. The $\Upsilon(4S)$ decays provided a clean environment, but limited them to the detailed study of B^0 and B^+ mesons (although the energy was increased to the $\Upsilon(5S)$, above B_s^0 production threshold, for special runs).

The feasibility of studying B physics at hadron colliders was established by experiments CDF and D0 at the Tevatron (Fermilab, US). At such machines one profits from the much larger production cross-section in hadronic collisions, which is typically 10^5 times greater than at the $\Upsilon(4S)$, and all b hadron species are produced (B^0, B^+, B_s^0, B_c^+, Λ_b^0 and other baryons, plus excited states). The large general-purpose experiment have excellent detectors, in particular high precision vertex detectors, that allow signals to be extracted from the more busy hadronic environment. B physics competes for bandwidth in trigger (and for offline analysis effort) with the high p_{T} physics that is also studied by these experiments: semileptonic decays in particular are more easily selected by the trigger. Nevertheless important steps were made, such as the observation of B_s^0–$\overline{B}_s^0$ oscillations by CDF, and an intriguing dilepton asymmetry by D0. With the termination of the Tevatron in 2011, their analyses are now winding down. However, the high p_{T} experiments at the LHC, ATLAS and CMS, continue in the same spirit. They can make strong contributions in particular for rare decays involving leptons in the final state, where their high operating luminosity can be an advantage [ID144].

LHC also has a dedicated flavour-physics experiment, LHCb [ID104]. It is a forward spectrometer, operating in pp collider mode, with flexible trigger that allows to select hadronic decays as well as semileptonic, and an excellent particle identification capability. The coverage of 2–5 in pseudorapidity is well matched to the forward production of b and c hadrons at the LHC. LHCb runs at a lower luminosity than ATLAS and CMS, to avoid excessive pile-up of pp interactions, since it is designed to study the vertex structure of events. Nevertheless the experiment has now accumulated $\sim 3\,\mathrm{fb}^{-1}$, about a factor of ten less than ATLAS and CMS, but corresponding to an enormous sample of order 10^{12} produced B decays; the LHCb output rate to storage is 5 kHz, compared to few hundred Hz for the general-purpose experiments. The LHC experiments will run at 8 TeV centre-of-mass energy until end-2012, then (after a few weeks of p–Pb collisions in early 2013) there will be a two year shutdown before the run starts again in 2015, at

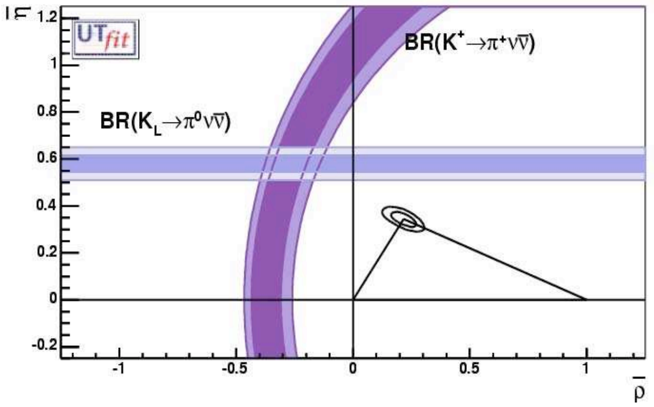

Figure 3.3: Potential impact of $K \to \pi\nu\overline{\nu}$ measurements, compared to recent fit to the CKM Unitarity Triangle, which are largely derived from measurements of B decays [7].

close to the design energy of 14 TeV.

Charm physics

The last phase of CLEO experiment, CLEO-c, focused on charm, with large dataset taken a centre-of-mass energies below the $B\overline{B}$ threshold. Those data samples have now been overtaken by BES III (BEPC, China) which has been running at a luminosity of $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, recording the world's largest samples of $O(10^8)$ J/ψ and $\psi(2S)$, and then taking 3 fb^{-1} at the $\psi(3770)$, which decays into open charm ($D\overline{D}$). They will also study the τ mass, and plan to run at higher energy to investigate the exotic spectroscopy of states discovered by the B factories that do not appear to fit into the expectations of the simple quark-model picture of $q\overline{q}$ states.

While being focused on B physics, the B factories also have a strong programme of charm studies. So does LHCb, that increased its output rate by 50% compared to the initial design, to provide extra bandwidth for charm. This has led to extremely high statistics samples for charged modes, which are of high purity straight from the trigger. For example, for the singly-Cabibbo suppressed modes $D^0 \to K^+K^-$, $\pi^+\pi^-$ that have been used in the study of CP violation discussed below, LHCb has samples of over 10^6 signal decays, despite their suppression compared to the Cabibbo-favoured modes.

Kaon physics

KLOE (Frascati) has accumulated a large number of kaon decays from $\phi \to K^+K^-$, $K^0_{\mathrm{L}}K^0_{\mathrm{S}}$, at the DAΦNE ϕ-factory, which have been used for studies of hadronic and semileptonic decays. Elsewhere the focus has moved to the study of rare kaon decays. This is recognized as important, since the SM contributions to flavour-changing neutral current decays are strongly suppressed, and also very precisely determined theoretically. The low momentum transfer involved in the transitions can be parameterized with chiral perturbation theory and lattice QCD, which has been proven to be satisfactory in such decays. The significance of such rare kaon studies is illustrated in Fig. 3.3, where the impact of the measurement of their branching ratios is shown on the (ρ, η) plane of the CKM Unitarity Triangle.

While the current flagship European experiment for B and charm flavour physics is LHCb, that for kaons is NA62 (CERN) [ID30]. The experiment is currently in preparation and nearing completion, and had a successful technical run at the end of 2012 with a partially-instrumented detector. NA62 is focused on the search for the very rare decay $K^+ \to \pi^+\nu\overline{\nu}$, using an in-flight technique with a high-intensity high-energy secondary beam from the SPS. The predicted SM branching ratio is $(7.8 \pm 0.9) \times 10^{-11}$, where a significant part of the uncertainty comes from knowledge of CKM matrix elements that should improve in the future. During the forthcoming long shutdown of the LHC the injector chain will also be off, including the SPS, so for NA62 the first physics run will start at end-2014. With two years of data taking, a 10% measurement of BR should be achieved at the SM branching ratio.

KOTO (J-PARC, Japan) is an experiment in preparation to search for the related (and even more challenging) neutral mode, $K^0_{\mathrm{L}} \to \pi^0\nu\overline{\nu}$. For this decay the predicted branching ratio is even smaller in the SM, $(2.5 \pm 0.4) \times 10^{-11}$, and the experimental signature is challenging due to the fully neutral initial and final states. The best limit on the branching ratio to date is from KEK experiment E391a, which observed no signal candidates and set the limit $< 2.6 \times 10^{-8}$ at 90% CL [8]. Its successor, KOTO, is starting its first physics run at the end of 2012, using the high-intensity proton beam from J-PARC to get more K^0_{L} decays. It is aiming to reach a sensitivity at the 10^{-9} level as a first step, and then eventually reaching 100 events at the SM branching ratio.

3.2.2 Recent progress

The B factory experiments made a dramatic step forward in the detailed understanding of B decays, as well as uncovering some non-standard states that do not fit into the expected quark model spectroscopy. Concerning the flavour physics results, most have been in good agreement with the SM expectations. An early indication that the value of $\sin 2\beta$ (the value of CP violation in the interference of B^0 mixing and decay) measured with the "golden" mode $B^0 \to J/\psi K^0_{\mathrm{S}}$ did not agree with that measured with other channels such as ϕK^0_{S} did not persist with increased statistics. More recently there has been tension between the value measured for the $B \to \tau\nu$ branching ratio, compared to the value inferred from $\sin 2\beta$, but the latest result from Belle does not confirm that discrepancy. There remain some interesting measurements from BaBar of $B \to D^{(*)}\tau\nu$ that are somewhat inconsistent with the SM expectation, that await confirmation [9].

With the start-up of the LHC, hopes were high for signs of new physics in the B^0_s sector, which had been little explored until then. Two results from the Tevatron experiments had hinted at effects beyond the SM: for the CP violating phase of mixing, corresponding to $\sin 2\beta$ for the B^0, which is known as ϕ_s for the B^0_s, and the dimuon asymmetry. The B^0_s and $\overline{B}^0_s$ mix to give mass eigenstates B_{H} and B_{L} (for heavy and light), and the oscillation frequency is proportional to their mass difference $\Delta m_s = m_{\mathrm{H}} - m_{\mathrm{L}}$. The oscillation frequency for the B^0_s was first measured by CDF, then confirmed by D0 and LHCb. Its value is a factor of 30 higher than that for the B^0, as expected in the SM. The B^0_s mass eigenstates also have different lifetimes, corresponding to a width difference $\Delta\Gamma_s = 1/\tau_{\mathrm{L}} - 1/\tau_{\mathrm{H}}$, and this parameter is measured in the same fits as ϕ_s (typically using the decay mode $B^0_s \to J/\psi\,\phi$). In the SM the CP asymmetry is expected to be very small, but precisely predicted: $\phi_s = -0.036 \pm 0.002\,\mathrm{rad}$. The first results from CDF and D0 had considerably larger central values, but as the precision improved the agreement with the SM prediction improved, see Fig. 3.4 (left).

D0 found evidence for an unexpected asymmetry in like-sign dimuons, from comparing the rates of $\mu^+\mu^+$ and $\mu^-\mu^-$, giving an asymmetry of $\sim 1\%$ (an excess of negative

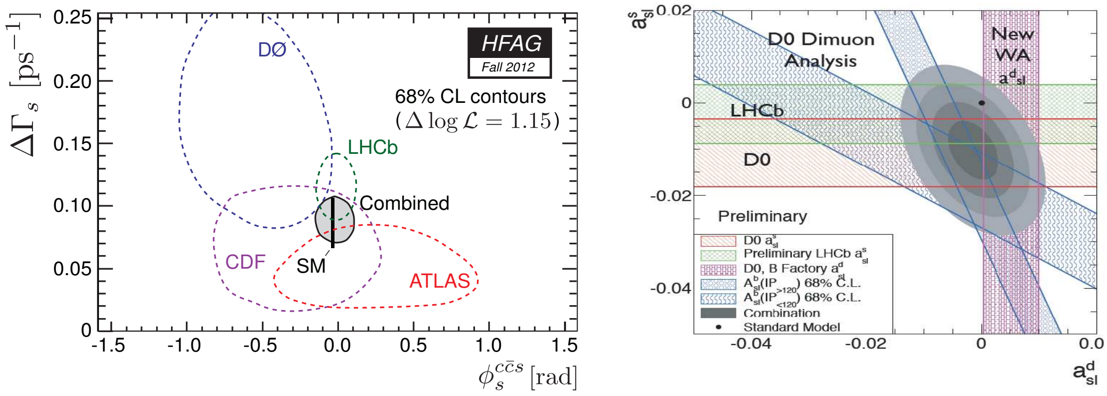

Figure 3.4: (Left) Constraints on the plane of $\Delta\Gamma_s$ vs. ϕ_s, the CP violating phase of B_s^0 mixing; as can be seen, the LHCb result dominates in the precision on ϕ_s, and is consistent with the small value expected in the SM, indicated by the thick line [17]. (Right) Semileptonic asymmetry in the B system: experimental constraints on the plane of asymmetry for the B_s^0 vs. B^0 are shown; the results for the dimuon asymmetry from D0 (indicated by the oblique bands) are inconsistent with the SM expectation of close to zero, but are not confirmed by the recent LHCb result [10].

dimuons, of almost 4 standard-deviation significance). This could be an indication of CP violation in B mixing, which is expected to be very small, $< 10^{-3}$, in the SM. As the source of the muons is not determined in the D0 analysis, the result corresponds to a combination of the asymmetries $a^d_{\rm sl}$ and $a^s_{\rm sl}$ for the B^0 and B_s^0 respectively, shown in Fig. 3.4 (right). Results from dedicated studies of the individual asymmetries from the B factories and LHCb have not confirmed this discrepancy with the SM, but higher precision is required for a definitive answer.

Discovery of the decay $B_s^0 \to \mu^+\mu^-$ has been one of the most eagerly anticipated results in flavour physics. It is a very rare FCNC decay in the SM, with precisely predicted branching ratio $B_{\mu\mu} = (3.2 \pm 0.3) \times 10^{-9}$, and is very sensitive to new physics contributions, which could significantly modify the decay rate. There have been a series of searches by the Tevatron experiments, and more recently the LHC experiments, as listed in Table 3.3. At the time of the Open Symposium the most stringent limit came from the combination of the LHC results, $B_{\mu\mu} < 4.2 \times 10^{-9}$. However, since then the LHCb result has been updated with over twice the statistics, and first evidence has been seen, as shown in Fig. 3.5 (left). The signal corresponds to $B_{\mu\mu} = (3.2\ ^{+1.5}_{-1.2}) \times 10^{-9}$, in good agreement with the SM prediction.

Another rare decay with high sensitivity to new physics is $B^0 \to K^{(*)}\mu^+\mu^-$, where the angular distributions of the decay products are sensitive to the helicity structure of the underlying theory. This decay has been studied by the B factory experiments and CDF, and more recently by LHCb. At present the distributions are in good agreement with the SM, apart from an intriguing difference between neutral and charged modes, the so-called isospin asymmetry, where a lower rate is seen for $B^0 \to K^0\mu^+\mu^-$ than for $B^+ \to K^+\mu^+\mu^-$, while the rates agree for the corresponding decays involving a K^* rather than K. Higher statistics, and further theoretical input, are needed to clarify this effect [ID104].

CP asymmetries in B decays correspond to angles of the CKM Unitarity Triangle, and the least well known of those is the angle γ (see Fig. 3.2). This can be determined from tree-level decays using $B \to DK$ decays, which should provide a point of reference for the SM, as it should be unaffected by new physics. The value has extremely low

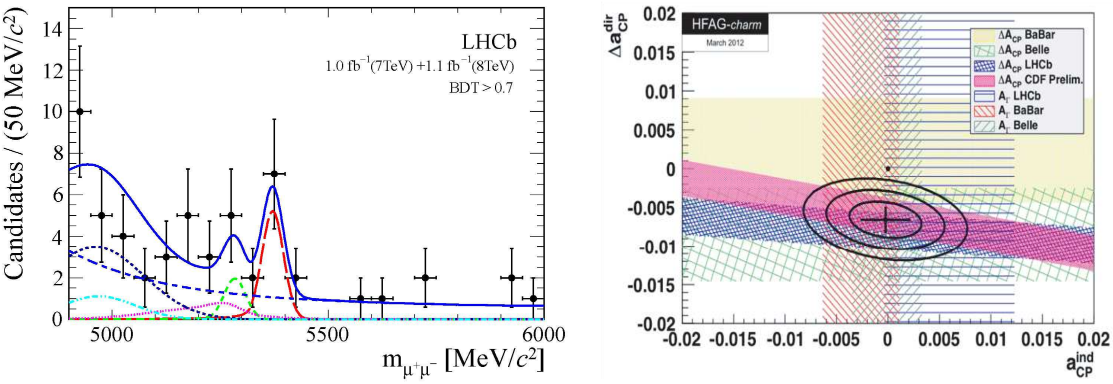

Figure 3.5: (Left) Candidates for the decay $B_s^0 \to \mu^+\mu^-$ from LHCb, in the $\mu^+\mu^-$ invariant mass plot; the excess over background is sufficient to claim 3.5 standard-deviation evidence for the decay [16]. (Right) CP violation in the D system: experimental constraints on the plane of indirect vs. direct CP violation are shown. The combination (marked by the error ellipses) indicates a non-zero direct CP contribution of about −0.6% [17].

theoretical uncertainty, and can be compared to γ measured through other loop-mediated channels, to search for new physics. At the recent CKM workshop, both BaBar and Belle updated their measurement of γ, and LHCb presented their first measurement, as listed in Table 3.4. All were in good agreement, and LHCb should be able to substantially improve on the precision using its full dataset and other modes.

Table 3.3: Limits on $B(B_s^0 \to \mu^+\mu^-)$ at 95% CL, at the time of the Open Symposium. Evidence for the decay has since been seen by LHCb, as described in the text.

Experiment	Limit ($\times 10^{-9}$)	Dataset	Ref.
D0	51	6 fb^{-1}	[11]
CDF	31	7 fb^{-1}	[12]
ATLAS	22	2 fb^{-1}	[13]
CMS	7.7	5 fb^{-1}	[14]
LHCb	4.5	1 fb^{-1}	[15]

Table 3.4: Measurements of the CKM angle γ, presented at the CKM workshop [19].

Experiment	Value [°]	Dataset
BaBar	$69\,^{+17}_{-16}$	0.5 ab^{-1}
Belle	$68\,^{+15}_{-14}$	1 ab^{-1}
LHCb	$71.1\,^{+16.6}_{-15.7}$	1 fb^{-1}

In charm physics, CLEO-c has made detailed measurements of $D^+_{(s)} \to \mu^+\nu$ decays to determine the decay constant f_D, which provides a stringent test of Lattice QCD, as the measurement can be compared to its prediction. BES III has made use of their large sample of $\psi(2S)$ decays to make first observation of new decays such as $\psi(2S) \to \gamma\eta_c(2S)$.

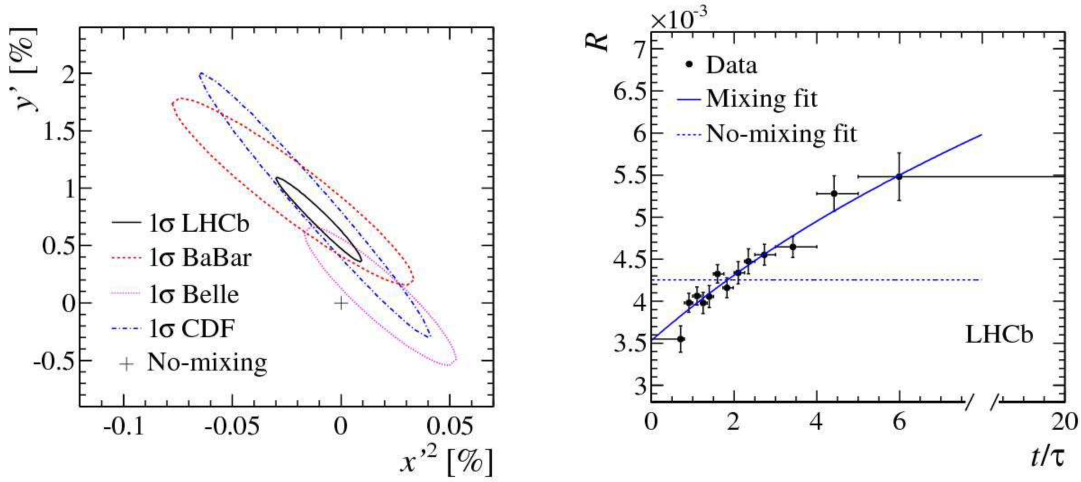

Figure 3.6: (Left) Charm mixing results from various experiments compared in the plane of parameters related to the width difference y vs. the mass difference squared x^2. (Right) Time dependence of the ratio R of wrong-sign to right-sign $D^0 \to K^{\pm}\pi^{\mp}$ decay rates, from LHCb, showing the clear signature of mixing [18].

With the large sample of D mesons produced at the $\psi(3770)$ they will extend the studies of CLEO-c.

CP violation is expected in charm decays, but only at a small (sub-percent) level in the SM. Evidence was recently seen for such an effect in the charm system by LHCb. The *difference* of time-integrated CP asymmetries measured in the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ modes was studied, known as $\Delta A_{\rm CP}$, since many systematic effects cancel in this quantity. A surprisingly large effect of -0.8% was seen, with 3.5 standard-deviation significance. This result has been corroborated by CDF and Belle, as shown in Fig. 3.5 (right), but still awaits to be definitively established with a 5 standard-deviation observation. After review by the theoretical community, although it is surprisingly large such a value is not yet considered to be a clear sign of new physics, and CP violation should be studied in other charm channels to confirm whether the signal indicates some contribution from beyond the SM.

Mixing between D^0 and $\overline{D}^0$ is very slow in the SM, and is parameterized in terms of $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where the mass and width differences are defined in a corresponding fashion to those for the B system. Evidence for D^0 mixing was seen by the B factories and CDF, but until recently there had not been an individual 5 standard-deviation observation. LHCb has now provided this: not just with 5 but over 9 standard-deviation significance, as shown in Fig. 3.6, illustrating the power of charm physics studies at that experiment.

3.2.3 Longer-term prospects

An upgrade of the B factory in Japan is in progress, Super-KEKB, with upgraded experiment Belle II [ID120]. The project was approved in 2011, and the collaboration has about 40% of its members from Europe [ID122]. The upgrade requires major redesign of the machine, for higher luminosity operation: the target luminosity is $8 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which will allow it to accumulate 50 ab^{-1} over a 6 year run, that is expected to start in 2016. The machine design involves innovative aspects including the strong squeezing of the beam size, to the nanometre level.

At the time of the Open Symposium a second upgraded B factory, Super$B$, had been planned at the University of Tor Vergata (Rome) [ID68, ID71]. Its completion date would have been later than that of Super-KEKB, and its status has since been revised by the Italian government. Although the excellence of the science involved was not questioned, the budget requested was found to be incompatible with the available research funding. The project has been discontinued, giving INFN the possibility to present alternative projects that could fit within the available budget.

LHCb is just reaching the end of its first three-year running period. In 2012 LHCb will have tripled the previous data set, to give a total of over $3\,\mathrm{fb}^{-1}$. The analysis of that full sample will take place during the long shutdown of the LHC. Then the accelerator will start up in 2015 with centre-of-mass energy of close to the design value of 14 TeV. For LHCb this implies increased signal cross-section, which scales roughly linearly with energy, and thus higher yields. A further doubling or more of the integrated luminosity can be expected in the years 2015–18, before the second long shutdown of the LHC. Then the data-doubling time would become long, so it is planned to upgrade the experiment in 2018, to provide an order-of-magnitude increase in yields [ID97].

In contrast to the upgraded B factories, the LHCb upgrade does not require substantial modifications of the accelerator, as the target luminosity of $1\text{–}2\times10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is already available from the LHC. Instead, the major requirement is to upgrade the trigger, to avoid saturation for hadronic modes as the luminosity is increased. This requires removing the current bottle-neck, the first (hardware-based) trigger level that reduces the rate to the current readout rate of 1 MHz. For the upgrade, this trigger level will be replaced by a new system with a tuneable output rate from 1–40 MHz (i.e. up to the bunch-crossing rate of the LHC, which should soon reach a bunch spacing of 25 ns). The entire experiment will be read out at 40 MHz, and the trigger performed in software on a large CPU farm. Along with the increased energy and luminosity, this will lead to higher signal yields by factors of 10–20 (for muonic and hadronic triggered events, respectively) compared to the yields in the current run. This constitutes a major upgrade, as the front-end electronics of most sub-detectors will need to be replaced, and a number of new technologies are under investigation to enhance the performance, while requiring them to be in time for installation in 2018. The LHCb upgrade has been fully endorsed by the LHCC, and funding is now being secured; the sub-system TDRs are expected in the next year. The upgraded LHCb experiment will run for a number of years, integrating $50\,\mathrm{fb}^{-1}$ of luminosity. In addition to flavour physics, it complements the coverage of the high-p_{T} experiments in the forward region, covering pseudorapidity range $2 < \eta < 5$ with excellent vertexing and particle identification, which is also of interest for electroweak and QCD physics, and exotic searches. It will therefore contribute to the full exploitation of the LHC in the upgrade era [ID104].

The improved precision that will be achieved in the upgrade era, both with upgraded B factory and the LHCb upgrade, is critical: if new physics has been discovered it will allow the character of that new physics to be explored, and if no sign of new physics beyond the SM has been seen then flavour physics will provide highly sensitive tests. In particular, there are a number of observables such as ϕ_s, $B(B^0_{(s)} \to \mu^+\mu^-)$, and γ, which are predicted with very high precision. For $B(B^0_{(s)} \to \mu^+\mu^-)$, the next step will be to measure the B^0_s branching ratio with high precision, and to search for the corresponding B^0 decay. Their ratio is a sensitive test of the flavour structure, and will

Table 3.5: Status and future prospects of selected B, D, K and LFV observables. The Super$B$ column refers to a generic upgraded B factory, collecting $75\,\mathrm{ab}^{-1}$ at the $\Upsilon(4S)$ and about $1\,\mathrm{ab}^{-1}$ at the $\Upsilon(5S)$. Table taken from Ref. [ID130].

Observable class of observables)	SM prediction	Ultimate th. error	Present result	Future (S)LHCb	Future SuperB	Future Other
$\vert V_{us}\vert$ $[K \to \pi\ell\nu]$	input	$0.1\%_{(\mathrm{Latt})}$	0.2252 ± 0.0009	-	-	
$\vert V_{cb}\vert$ $[\times 10^{-3}]$ $[B \to X_c\ell\nu]$	input	1%	40.9 ± 1.1	-	$1\%_{\mathrm{excl}}$, $0.5\%_{\mathrm{incl}}$	
$\vert V_{ub}\vert$ $[\times 10^{-3}][B \to \pi\ell\nu]$	input	$5\%_{(\mathrm{Latt})}$	4.15 ± 0.49	-	$3\%_{\mathrm{excl}}$, $2\%_{\mathrm{incl.}}$	
γ $[B \to DK]$	input	$< 1°$	$(70^{+27}_{-30})°$	$0.9°$	$1.5°$	
$S_{B_d \to \psi K}$	2β	$\lesssim 0.01$	0.671 ± 0.023	0.0035	0.0025	
$S_{B_s \to \psi\phi, \psi f_0(980)}$	$2\beta_s$	$\lesssim 0.01$	-0.002 ± 0.087	0.008	-	
$S_{[B_s \to \phi\phi]}$	$2\beta_s^{eff}$	$\lesssim 0.05$	-	0.03	-	
$S_{[B_s \to K^{*0}\bar{K}^{*0}]}$	$2\beta_s^{eff}$	$\lesssim 0.05$	-	0.02	-	
$S_{[B_d \to \phi K^0]}$	$2\beta^{eff}$	$\lesssim 0.05$	-	0.03	0.02	
$S_{[B_d \to K_S^0\pi^0\gamma]}$	0	$\lesssim 0.05$	-0.15 ± 0.20	-	0.02	
$S_{[B_s \to \phi\gamma]}$	0	$\lesssim 0.05$	-	0.02	-	
$A_{\mathrm{CP}}(b \to s\gamma)$	< 0.01	< 0.01	-0.012 ± 0.028	-	0.004	
$A_{\mathrm{CP}}(b \to (s+d)\gamma)$	$\sim 10^{-6}$	-	-0.060 ± 0.060	-	0.02	
$A^d_{\mathrm{SL}}[\times 10^{-3}]$	-0.5	0.1	-5.8 ± 3.4	0.2	4	
$A^s_{\mathrm{SL}}[\times 10^{-3}]$	2.0×10^{-2}	$< 10^{-2}$	-2.4 ± 6.3	0.2	~ 0.6	
$\mathcal{B}(B \to \tau\nu)[\times 10^{-4}]$	1	$5\%_{\mathrm{Latt}}$	(1.14 ± 0.23)	-	$4-5\%$	
$\mathcal{B}(B \to \mu\nu)[\times 10^{-7}]$	4	$5\%_{\mathrm{Latt}}$	< 13	-	$2-3\%$	
$\mathcal{B}(B \to D\tau\nu)[\times 10^{-2}]$	1.02 ± 0.17	$5\%_{\mathrm{Latt}}$	1.02 ± 0.17	[under study]	2%	
$\mathcal{B}(B \to D^*\tau\nu)[\times 10^{-2}]$	1.76 ± 0.18	$5\%_{\mathrm{Latt}}$	1.76 ± 0.17	[under study]	2%	
$\mathcal{B}(B_s \to \mu^+\mu^-)[\times 10^{-9}]$	3.2	$5\%_{\mathrm{Latt}}$	< 4.2	0.15	-	
$R(B_{s,d} \to \mu^+\mu^-)$	0.29	$\sim 5\%$	-	$\sim 35\%$	-	
$q_0(A^{FB}_{B \to K^*\mu^+\mu^-})[\mathrm{GeV}^2]$	4.26 ± 0.34			2%	[under study]	
$A^{(2)}_{\mathrm{T}}(B \to K^*\mu^+\mu^-)$	$< 10^{-3}$			0.04	[under study]	
$A_{\mathrm{CP}}(B \to K^*\mu^+\mu^-)$	$< 10^{-3}$			0.5%	1%	
$B \to K\nu\bar{\nu}[\times 10^{-6}]$	4	$10\%_{\mathrm{Latt}}$	< 16	-	0.7	
$\vert q/p\vert_{D-\mathrm{mixing}}$	1	$< 10^{-3}$	0.91 ± 0.17	$O(1\%)$	2.7%	
ϕ_D	$\lesssim 0.1\%$		$-$	$O(1°)$	$1.4°$	
$a^{\mathrm{dir}}_{\mathrm{CP}}(\pi\pi)(\%)$	$\lesssim 0.3$		0.20 ± 0.22	0.015	[under study]	
$a^{\mathrm{dir}}_{\mathrm{CP}}(KK)(\%)$	$\lesssim 0.3$		-0.23 ± 0.17	0.010	[under study]	
$a^{\mathrm{dir}}_{\mathrm{CP}}(\pi\pi\gamma, KK\gamma)$	$\lesssim 0.3\%$			[under study]	[under study]	
$\mathcal{B}(\tau \to \mu\gamma)[\times 10^{-9}]$	0		< 44	-	2.4	
$\mathcal{B}(\tau \to 3\mu)[\times 10^{-10}]$	0		$< 210(90\%\ \mathrm{CL})$	1-80	2	
$\mathcal{B}(\mu \to e\gamma)[\times 10^{-12}]$	0		$< 2.4(90\%\ \mathrm{CL})$			~ 0.1 MEG ~ 0.01 PSI-future ~ 0.01 Project X
$\mathcal{B}(\mu N \to eN)(Tl)$	0		$< 4.3 \times 10^{-12}$			10^{-18} PRISM
$\mathcal{B}(\mu N \to eN)(Al)$	0		-			10^{-16} COMET, Mu2e
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})[\times 10^{-11}]$	8.5	8%	$17.3^{+11.5}_{-10.5}$			$\sim 10\%$ NA62 $\sim 5\%$ ORKA $\sim 2\%$ Project X
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})[\times 10^{-11}]$	2.4	10%	< 2600			$\sim 100\%$ KOTO $\sim 5\%$ Project X
$\mathcal{B}(K_L \to \pi^0 e^+e^-)_{SD}$	1.4×10^{-11}	30%	$< 28 \times 10^{-11}$			$\sim 10\%$ Project X

only be accessible with the upgrade. The expected performance of future flavour physics experiments is compared in Table 3.5. The complementary sensitivities of the LHCb upgrade and the upgraded B factory is evident. An upgraded B factory is the machine of choice for decays involving neutrals or missing energy, due to their well constrained kinematics allowing full reconstruction, such as $B \to \tau\nu$ and $D^{(*)}\tau\nu$. The LHCb upgrade provides unbeatable statistics for the fully-charged final states, and is the machine of choice for the study of B_s^0 physics and that of heavier hadrons (including the B_c^+ and b baryons). LHCb will continue to study charm physics, with increased sensitivity, as will the upgraded B factory experiment, Belle II. A dedicated tau-charm factory has been proposed at Novosibirsk, Russia, as a continuation of the VEPP series of e^+e^- colliders [ID33].

The future of NA62 involves completing their charged kaon program in the period up to 2018. Once the in-flight technique has been established, and depending on the π^0 suppression achieved, the method could then be applied to the neutral mode $K_{\mathrm{L}}^0 \to \pi^0\nu\overline{\nu}$ [ID30]. This would require upgrades of the target and beam infrastructure, as well as the experimental apparatus. It would then be competing with KOTO for this measurement, which is aiming for 100 events at the SM branching ratio, and in the longer term could profit from the upgrade of J-PARC described below in the lepton flavour section.

The ORKA experiment has been proposed at Fermilab, to study the charged mode with a complementary technique to NA62, using a low momentum beam of kaons that are stopped in material and decay at rest [ID148]. This technique was used by the preceding experiment E949 (BNL) that observed 7 signal candidates, with less than one background event expected, that gave a branching ratio of $(1.73\ ^{+1.15}_{-1.05}) \times 10^{-10}$ [20]. ORKA is aiming for 5% precision at the SM BR, and has been granted Stage-1 approval at Fermilab, but is waiting for a decision on funding. Fermilab is focusing on the intensity frontier for their future, with Project-X, which will provide a high-powered beam for the long-baseline neutrino experiment LBNE. In parallel it will be able to provide high power beams at lower energies for kaon as well as muon and nuclear experiments [ID151]. The increased beam power would further increase the sensitivity of ORKA, and will open the possibility for a high sensitivity experiment to search for the neutral mode, at the 1000-event level.

3.3 Charged Lepton Flavour Physics

3.3.1 Current status

Charged lepton flavour violation (CLFV) is one of the most important and promising subjects in flavour physics in terms of finding new physics beyond the Standard Model (SM). The history of CLFV searches for muon decays is shown in Fig. 3.7.

It has been experimentally confirmed that neutral leptons are massive and mix among different neutrino flavour species, through the observation of the phenomenon of neutrino oscillation. Therefore, lepton flavour for neutrinos is known to be violated. However, CLFV has yet to be observed, and CLFV is one of the most interesting and potentially leading searches in the flavour sector. As mentioned in Section 3.1, the contribution from the SM with massive neutrinos is very tiny. As a result, it can be concluded that observation of CLFV would indicate a clean signal of new physics beyond the SM. CLFV is known to be sensitive to various extensions of new physics beyond the SM. It could

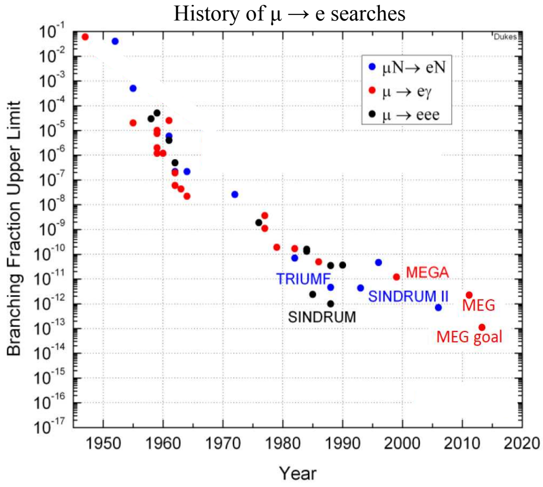

Figure 3.7: History of searches for muon CLFV.

have visible rates if there are new particles carrying lepton flavour not too far from the TeV energy scale.

$\mu^+ \to e^+\gamma$ decay

One of the important muon CLFV processes is the $\mu^+ \to e^+\gamma$ decay. Currently the MEG experiment at Paul Scherrer Institute (PSI) is running to search for $\mu^+ \to e^+\gamma$. The MEG experiment uses positive muons stopped in a thin target. The event signature of $\mu^+ \to e^+\gamma$ decay at rest is a positron and a photon moving back-to-back in coincidence with their energies equal to half that of the muon mass ($m_\mu/2 = 52.5$ MeV). There are two major backgrounds to the search for $\mu^+ \to e^+\gamma$ decay. One of them is a physics (prompt) background from radiative muon decay, $\mu \to e\nu\overline{\nu}\gamma$, when e^+ and photon are emitted back-to-back with the two neutrinos carrying off a small amount of energy. The other background is an accidental coincidence of an e^+ in a normal muon decay, $\mu \to e\nu\overline{\nu}$, accompanied by a high energy photon. Possible sources of the latter would be either $\mu \to e\nu\overline{\nu}\gamma$ decay, annihilation-in-flight or external bremsstrahlung of e^+ from a normal muon decay. For a high muon beam intensity, the latter background type becomes more serious. Therefore, a continuous muon beam is preferable to carry out a search for $\mu^+ \to e^+\gamma$ decay.

The MEG experiment uses a continuous muon beam from the PSI cyclotron at the πE5 beam line with a muon stopping rate of 3×10^7/s. In the data taken in 2009 and 2010 which include a total of 1.8×10^{14} muon decays, an upper limit is set of $B(\mu^+ \to e^+\gamma) < 2.4 \times 10^{-12}$ at 90 % CL [2]. The MEG results are shown in Fig. 3.8. This limit has already placed severe constraints on several theoretical models beyond the SM.

$\mu^- - e^-$ conversion

Another prominent muon CLFV processes is coherent neutrino-less conversion of a negative muon to an electron ($\mu^- - e^-$ conversion) in a muonic atom. When a negative muon is stopped in material, it is trapped by an atom, and a muonic atom is formed. After it cascades down energy levels in the muonic atom, the muon is bound in its 1*s*

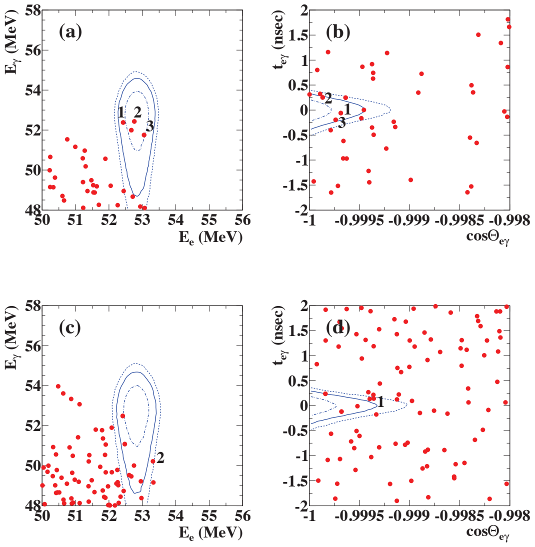

Figure 3.8: MEG results from their 2009 and 2010 data. (a) and (b) are E_γ vs. E_e and $t_{e\gamma}$ vs. cos$\theta_{e\gamma}$ respectively from the 2009 data and (c) and (d) are those from the 2010 data. The contours of the probability distribution for 1σ, $1.64\,\sigma$ and $2\,\sigma$.

ground state. The fate of the muon is then either decay in orbit (DIO) ($\mu^- \rightarrow e^-\nu_\mu\overline{\nu}_e$) or nuclear muon capture by a nucleus $N(A,Z)$ of mass number A and atomic number Z, namely, $\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)$. However, in the context of lepton flavour violation in physics beyond the Standard Model, the exotic process of neutrino-less muon capture, such as $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$, is also expected. This process violates the conservation of lepton flavour numbers, L_e and L_μ, by one unit, but the total lepton number, L, is conserved.

The event signature of coherent $\mu^- - e^-$ conversion in a muonic atom is a mono-energetic single electron emitted from the conversion with an energy ($E_{\mu e}$) of $E_{\mu e} = m_\mu - B_\mu - E_{\mathrm{recoil}}$, where m_μ is the muon mass, and B_μ is the binding energy of the 1s muonic atom. E_{recoil} is the nuclear recoil energy which is small and can be ignored. Since B_μ varies for various nuclei, $E_{\mu e}$ could be different. For instance, $E_{\mu e} = 104.3$ MeV for titanium (Ti) and $E_{\mu e} = 94.9$ MeV for lead (Pb).

From an experimental point of view, $\mu^- - e^-$ conversion is a very attractive process for the following reasons. First of all, the energy of the signal electron of about 105 MeV is far above the end-point energy of the normal muon decay spectrum (~ 52.8 MeV). Furthermore, since the event signature is a mono-energetic electron, no coincidence measurement is required. The search for this process has the potential to improve sensitivity by using a high muon rate without suffering from accidental background events, which would be serious for other processes, such as $\mu^+ \rightarrow e^+\gamma$ and $\mu^+ \rightarrow e^+e^+e^-$ decays.

The previous search for $\mu^- - e^-$ conversion was performed by the SINDRUM II collaboration at PSI. The SINDRUM II spectrometer consisted of a set of concentric cylindrical drift chambers inside a superconducting solenoid magnet of 1.2 tesla. They set an upper limit of $\mu^- - e^-$ conversion in Au of $B(\mu^- + \mathrm{Au} \rightarrow e^- + \mathrm{Au}) < 7 \times 10^{-13}$

[21].

τ CLFV Decays

CLFV in τ decays has been extensively studied at the B factories, and more recently at LHCb. The B factories, which operate mostly at the $\Upsilon(4S)$ resonance, can produce many τ leptons, since the production cross-sections for $\sigma_{\tau^+\tau^-} = 0.9$ nb whereas $\sigma_{b\bar{b}} = 1.05$ nb at the center of mass energy of 10.58 GeV. Almost as many τ pairs as b pairs are produced and thus the B factories serve as τ factories too. Moreover, the jet-like topology of $\tau^+\tau^-$ pairs can be easily distinguished from the spherical event shape of $B\bar{B}$ events. As a result, the B factories represent an optimal framework for the search for CLFV in τ decays due to their high statistics and the clean environment.

The signal events of CLFV decays of the τ leptons can be extracted by the measured energy of τ decay products and the total invariant mass (M_{rec}) of the τ decay products. The distributions of E_{rec} and M_{rec} might have non-Gaussian tails due to initial and final state radiation. Potential sources for background events come from radiative QED events (such as dimuon events and Bhabha processes) and continuum ($q\bar{q}$) events. There is hard initial-state radiation which contributes a background photon in the search for $\tau \to l\gamma$ ($l = e, \mu$). The best limits on some τ CLFV decay modes are summarized in Table 3.6.

Table 3.6: Best limits on τ CLFV decays at 90% CL.

Experiment	$B(\tau \to \mu\gamma)$	$B(\tau \to \mu\mu\mu)$
BELLE	4.5×10^{-8} [23]	2.1×10^{-8} [24]
BABAR	4.4×10^{-8} [25]	3.3×10^{-8} [26]
LHCb	–	6.3×10^{-8} [27]

3.3.2 Expected progress in near future

$\mu^+ \to e^+\gamma$ decay

The MEG experiment is running in 2012, expecting a sensitivity of $O(10^{-13})$ with the 2011 and 2012 combined data-sets. However the improvement of the MEG sensitivity reach is slowing down due to backgrounds and detector resolution. Therefore they are planning a detector upgrade to aim for a sensitivity of $O(10^{-14})$ (MEG-II). Better detector resolution is critical for MEG-II so as to reduce accidental backgrounds when they use a three-times higher beam intensity available at PSI. Possible detector upgrades would include, for instance, a single volume e^+ drift chamber with all stereo wires, a Xe photon detector with MPPC readout with higher granularity, a silicon pixel timing counter, and an active target made of silicon or fibres, etc. MEG-II is planning to start in 2015 or 2016 for a three-year running period, after a long shutdown in 2013 and 2014.

$\mu^- - e^-$ conversion

The next experimental projects to search for $\mu^- - e^-$ conversion with an anticipated sensitivity improvement of four orders of magnitude are being pursued in the Fermi National Laboratory (FNAL, US) and the the Japan Proton Accelerator Research Complex

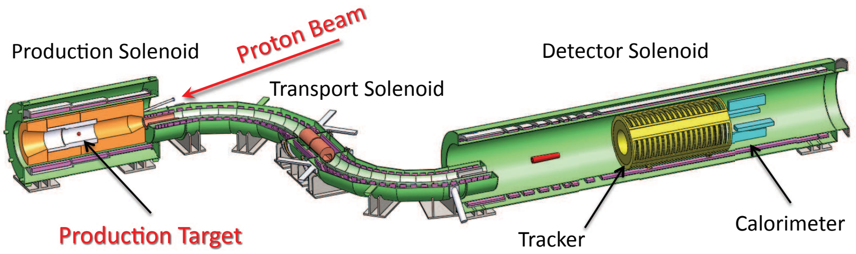

Figure 3.9: A schematic layout of the Mu2e experiment at FNAL.

(J-PARC, Japan).

The one in the US is the Mu2e experiment at FNAL [ID140]. It is largely based on the MELC design [28] and aimed to search for $\mu^- - e^-$ conversion at a single event sensitivity of 3×10^{-16}. It consists of the production solenoid system, the transport solenoid system and the detector solenoid system. The Mu2e experiment is planned to combat beam-related background events with the help of a 8 GeV/c proton beam of 7 kW beam power from the Booster machine at FNAL. The Mu2e experiment was approved at FNAL in 2009, and received the CD-1 approval from DOE in 2012. The Mu2e will start its measurement around 2020. A schematic layout of Mu2e is shown in Fig. 3.9.

The other experiment to search for $\mu^- - e^-$ conversion is called COMET (COherent Muon to Electron Transition), being prepared at J-PARC [ID89]. COMET uses a proton beam of 56 kW from the J-PARC main ring. The aimed for single event sensitivity of 3×10^{-17} for COMET is similar to that for Mu2e. A schematic layout of COMET is shown in Fig. 3.10.

For both Mu2e and COMET, in order to increase the muon beam intensity, a pion capture system will be used, where superconducting solenoid magnets of high magnetic field surround a proton target to capture pions in a large solid angle. It leads to a dramatic increase of muon yields by several orders of magnitude. An experimental demonstration of the pion capture system to increase a muon production efficiency by a factor of 1000 has been made at the MuSIC facility, Osaka University [ID89]. The muon transport solenoid system also maintains high transmission efficiency, resulting a significant increase of muon flux. At the same time, in order to suppress background events, in particular beam-related backgrounds, the following key elements have been adopted for both experiments. They are, first of all, beam pulsing, which is required to eliminate beam-related backgrounds by performing measurements between beam pulses. To eliminate beam-related backgrounds from proton leakage, proton beam extinction is required during the measurement interval. Secondary, curved solenoids for muon transport are needed to select charges and momenta of muons as well as removing neutral particles in the beam.

The differences of the designs between Mu2e and COMET exist in the adoption of C-shape curved solenoid magnets for both the muon beam line and the e^+ spectrometer in COMET. In Mu2e, after the first 90-degree bend, the muons of their momenta of interest are necessarily shifted back to the median plane in the second 90-degree bend

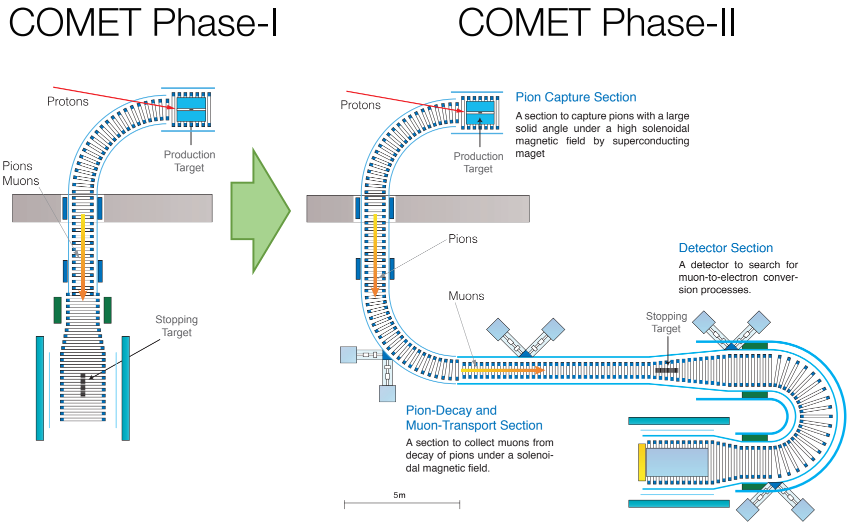

Figure 3.10: Schematic layouts of the COMET Phase-I (left) and Phase-II (right) at J-PARC.

with opposite bending direction (therefore an S-shape), whereas in COMET, by applying a magnetic field along the drift direction, the muons of interest can be kept on the median curved plane. As a result the opposite bending direction is not needed in COMET, and the 180-degree bend should provide larger dispersion to aid in momentum selection. Secondly, a curved solenoid spectrometer in COMET is used to eliminate low-energy events from muon decays in orbit before they reach the detector.

The COMET experiment has adopted a staged approach to realize COMET on an early time schedule. The COMET staging scenario has been approved at the J-PARC PAC and endorsed by the J-PARC review committee at MEXT in Japan. The COMET Phase-I would include the pion capture system and the muon transport system up to the end of the first 90-degree bend. The COMET Phase-I has two objectives, one of which is measurements of potential beam-related background sources, and the second is to search for $\mu^- - e^-$ conversion at an intermediate sensitivity, such as a single-event sensitivity of 3×10^{-15}, which is about a factor of 100 improvement over the previous limit, with 0.03 background events. At the COMET Phase-I, a muon beam intensity of 5×10^9 muons/s with a 3 kW proton beam power is expected, and about 1.5×10^6 s running period (18 days) is sufficient to achieve an improvement of about 100. KEK is planning to start the construction of the beam line in 2013. The COMET Phase-I will start in 2016, and COMET Phase-II (which is the full-sized COMET experiment) is planned to start around 2020. Figure 3.10 shows schematic layouts of COMET Phase-I and Phase-II.

It should be noted that although the Mu2e and COMET are experiments in the regions outside Europe, there are research groups from Europe, participating in these experiments as important and strong proponents. For instance, an Italian group participates in Mu2e, whereas UK and French groups participate in COMET.

$\mu^+ \to e^+e^+e^-$ *decay*

The rare decay $\mu^+ \to e^+e^+e^-$ is another important muon CLFV process. In a search for

$\mu^+ \to e^+e^+e^-$ decay, positive muons are stopped in a thin target, and two positrons and an electron are detected. To reconstruct $\mu^+ \to e^+e^+e^-$ events, kinematical constraints of momentum and energy conservation can be applied. Since the search for $\mu^+ \to e^+e^+e^-$ is limited by accidental backgrounds as in the case of $\mu^+ \to e^+\gamma$, it is best studied by using a continuous muon beam. The current limit of $B(\mu \to eee) < 10^{-12}$ at 90% CL was obtained by the SINDRUM experiment more than 20 years ago [22]. A letter of intent to carry out a new search for $\mu^+ \to e^+e^+e^-$ with a sensitivity of 10^{-16} has been submitted by the "Mu3e" collaboration to PSI, aiming at four orders of magnitude improvement [ID102]. They require a high-precision pixel detector capable of detecting high rates of more than $10^7\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Since the momentum resolution is dominated by multiple scattering, the pixel detector has to be thin, of 50 μm or less. Advanced detector technology of HV-MAPS is considered, allowing high-field charge collection in the pixel cells, hit digitization and the readout driver in one single silicon sensor. Also scintillating tiles and fibres with SiPM readout would allow an excellent timing resolution with low material budget and high granularity. The Mu3e collaboration will submit a proposal to PSI, aiming at the first stage to use the existing beam line by the end of 2014, and then the final sensitivity of 10^{-16} will be carried out with the installation of a new high-intensity muon beam line of at least 2×10^9 muons per second at the SINQ target, after 2017.

τ CLFV decays

CLFV in τ decays is one of the most important physics targets of the upgraded B factory and LHCb. Potential decay modes are $\tau \to \ell\gamma$ (where ℓ is either e or μ), $\tau \to \mu\mu\mu$, $\tau \to \mu\eta$ decays and so on. For $\tau \to \ell\gamma$ decay modes, the dominant background comes from $e^+e^- \to \tau^+\tau^-$ with initial state radiation. It is not negligible and the upper limit can be proportional to $1/\sqrt{N_\tau}$. With 50 ab^{-1} of data, about 5×10^{10} τ pairs can be available. If the current signal-to-background ratio is maintained, an expected upper limit could be about 3×10^{-9}. For the other modes where backgrounds are negligible, the upper limit can be proportional to $1/N_\tau$, yielding the upper limit of about $(0.2-1) \times 10^{-9}$. For $\tau \to \mu\mu\mu$ decay the LHCb upgrade with 50 fb^{-1} data-set should reach a sensitivity of $B(\tau \to \mu\mu\mu) < (0.1 - 8) \times 10^{-9}$, where the range reflects the current uncertainty on the background extrapolation.

3.3.3 Long term prospects

Project-X at FNAL (US) is a high-powered proton accelerator complex based on superconducting RF technology [ID151], that is described in the Accelerator chapter. It would ultimately provide beam powers of 3 MW at 3 GeV, 200 kW at 8 GeV and 2 MW at 120 GeV, simultaneously, and the beam can be configured with different pulsed structures. One of the physics topics is rare muon decays. With multi-MW beam power, Project-X could bring an additional 100 times more muons, about 10^{13} muons/s.

Currently J-PARC is planning to achieve the design beam power of 750 kW in approximately five years. It could be achieved by an increase of protons per bunch and high repetition rate of the J-PARC Main Ring (MR). At the same time, a study to realize a beam power in excess of 1 MW is also underway. Some plans include an increase of the injection energy to the MR. Once a proton beam power above 1 MW at J-PARC is available, a variety of new flavour physics studies could be performed there.

In addition to highly intense proton facilities, development of secondary beam lines

Table 3.7: The present best EDM limits for various fundamental particles [ID34]. The extraction of the electron EDM (d_e) or proton EDM (d_p) limits assumes a single source of CP violation.

	Upper limit [e·cm]	Ref.	Comment [e·cm]
n	2.9×10^{-26}	[29]	neutron
μ	1.9×10^{-19}	[30]	from muon $g-2$
^{199}Hg	3.1×10^{-29}	[31]	proton $d_p < 8 \times 10^{-25}$
^{205}Tl	9×10^{-25}	[32]	electron $d_e < 1.6 \times 10^{-27}$
YbF	1.1×10^{-22}	[33]	electron $d_e < 1.05 \times 10^{-27}$

would become critical to carry out future precision experiments with high statistics. There are several R&D studies of secondary beam lines going on world wide, in particular for muon beam lines. One example of such R&D programs is a muon beam with phase rotation [ID89], where fast muons are decelerated and slow muons are accelerated by RF in the muon storage ring. This R&D, based on a fixed field alternating gradient (FFAG) ring technology, is being undertaken by the PRISM collaboration in the UK and Japan for a future $\mu^- - e^-$ conversion search [ID89]. In the PRISM-FFAG ring, muons are phase-rotated by RF to make the muon beam-energy spread narrower. At the same time, pions contaminating muon beam, which would become a critical background for $\mu^- - e^-$ conversion search, decay out to make an ultra-pure muon beam. Using this novel technique, significant improvements for a search for $\mu^- - e^-$ conversion can be achieved, and an experiment with a 2×10^{-19} single-event sensitivity in $\mu^- - e^-$ conversion will be aimed at.

3.4 Fundamental Symmetries

3.4.1 Current status

EDM

A permanent electric dipole moment (EDM) of a fundamental particle violates P (parity) and T (time reversal). Once CPT is assumed, EDMs violate CP. Searches for EDMs are considered to be among the most important issues in particle physics at low energy. The searches for EDM range from neutrons, diamagnetic atoms, paramagnetic atoms, molecules, protons, deuterons, and muons. The SM contributions, which come from higher-order loop diagram, are five orders of magnitude smaller than the current limits, being too small to detect. EDM searches can provide one of the most sensitive tests of new physics beyond the SM. Therefore, the observation of any new CP-violating physics would be a very significant discovery. The current limits of the searches for EDM are summarized in Table 3.7, and already have sensitivity to new physics scales up to 10−100 TeV.

Interpretation of the experimental results are model-dependent at various levels. For

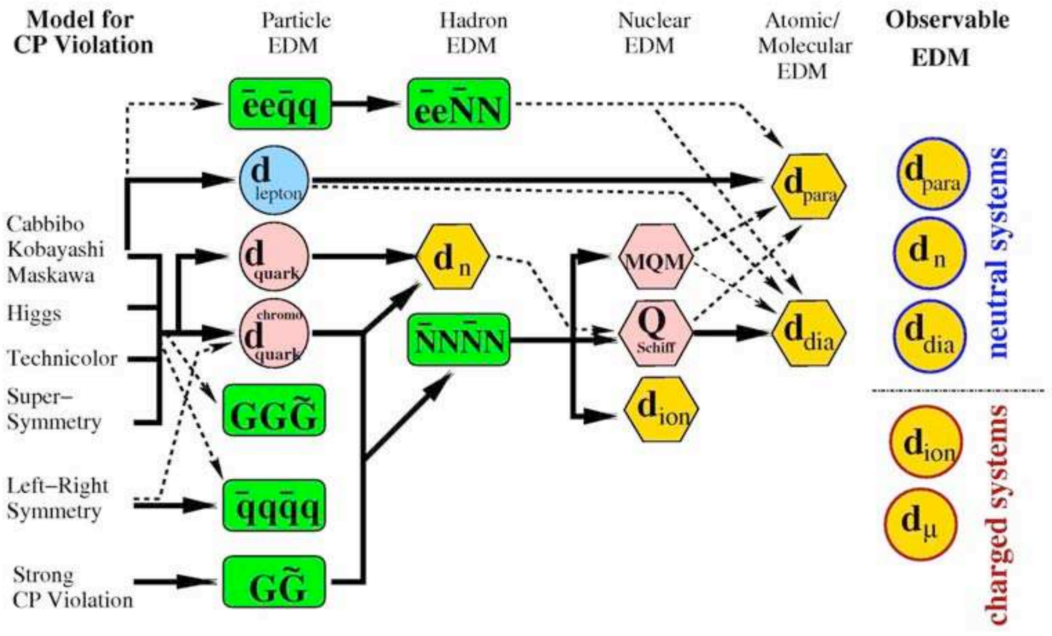

Figure 3.11: Various possible sources from the SM and new physics beyond the SM giving rise to an experimentally observable EDM [7].

instance, the limits of the electron EDM came from measurements with paramagnetic atoms such as ^{205}Tl [32] and molecules such as YbF [33] . However they are also sensitive to the electron-quark interaction as well as the intrinsic electron EDM. Similarly, for diamagnetic atoms such as ^{199}Hg, atomic and nuclear theory are required to extract the intrinsic nucleon EDM. Even for the neutron, proton and deuteron, the extraction of the EDM for fundamental fermions needs theoretical interpretation. This situation is illustrated in Fig. 3.11.

Muon $g-2$

Another important observable in the precision measurement is the muon anomalous magnetic moment. Since the muon is a Dirac particle, the g factor of its magnetic moment is 2, if radiative corrections are neglected. A deviation from 2, namely $g-2 \neq 0$, is very important for investigating quantum corrections. The present experimental value of $a_\mu = (g_\mu - 2)/2$ is given by

$$a_\mu^{\rm exp} = 116592089(63) \times 10^{-11} \ . \tag{3.7}$$

The experimental uncertainty is 0.5 ppm. Theoretically, this quantity can be calculated. The correction is divided into higher-order QED corrections, hadronic contributions and electroweak (EW) contributions. A recent update of theoretical calculations is given, for instance, in Ref. [34]:

$$a_\mu^{\rm SM} = 116591828(50) \times 10^{-11} \ , \tag{3.8}$$

with the hadronic correction from the light-by-light (LBL) contributions, $a_\mu^{\rm SM}({\rm LBL}) =$

$105(26) \times 10^{-11}$. From these, the deviation can be obtained as

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 261(80) \times 10^{-11} \ , \tag{3.9}$$

which gives about a 3.2 σ deviation. Note that the theoretical contribution to the uncertainty is almost as large as that from experiment.

Although the electron $g-2$ factor is experimentally measured with more accuracy than the muon $g-2$ factor, the latter is much more sensitive to short-distance physics. For example, the EW correction of $a_\mu^{\rm EW}$ is much larger than $a_e^{\rm EW}$ which is $O(10^{-14})$.

3.4.2 Expected progress in near future

EDM

The next round of experimental projects are aiming at a few orders of magnitude improvement over the current limits. Regarding the searches for neutron EDM, there are five projects which are in preparation in Europe. They are the projects at the reactor facilities of the ILL (Grenoble), PNPI (Gatchina), FRM-2 (Munich), and the neutron spallation facilities at PSI (Villigen). There are two further projects for the neutron EDM searches, one is at the SNS (Oak Ridge, US), and the other is a Japanese-Canadian collaboration at RCNP (Osaka, Japan) and TRIUMF (Vancouver, Canada).

Regarding the measurements of the EDMs of protons, deuterons and other light ions, a method to use a storage ring is pursued by two collaborations, one at the Brookhaven National Laboratory (BNL) in the US (srEDM-US collaboration) and the Forschungszentrum Jülich (FZJ) in Europe (JEDI collaboration, Jülich Electric Dipole moment Investigations) [ID15]. The aimed for sensitivities of these projects are at the 10^{-29} e·cm level, probing new physics at the 10^3 TeV scale. The advantage of the storage-ring EDM measurement comes from the fact that high intensity ($> 10^{10}$/s) and high polarization (> 80 %) can be available. In a storage ring, at the rest frame of the stored particle, there exist strong electric fields acting on the particle spin, even in a purely magnetic storage ring. The srEDM-US aims at the measurement of the proton EDM in an all-electric ring at BNL, and then will probe the deuteron and ^{3}He by replacing electric field plates. On a short time scale, the srEDM collaboration has submitted a proposal to measure the proton and deuteron EDM with an intermediate goal of 10^{-24} e·cm by using the existing but upgraded Cooler Synchrotron COSY at FZJ. In the long term, JEDI plan to construct a dedicated all-in-one storage ring that uses a combination of magnetic and electric fields, in order to probe the EDMs of the proton, deuteron, and ^{3}He at the 10^{-29} e·cm level. The muon EDM can be measured as a byproduct of the next muon $g-2$ experiments, either at FNAL or at J-PARC. The dedicated measurements for the muon EDM are also being discussed at J-PARC and at PSI.

The measurements of atomic and molecular EDMs can be done in small groups at the university level. Measurements in Europe would include the YbF molecule and ^{129}Xe in Munich and Mainz.

Muon $g-2$

Regarding the muon $g-2$ measurements, a new experiment, E989, is currently in preparation at FNAL aiming at 0.14 ppm, a reduction of the experimental error by a factor

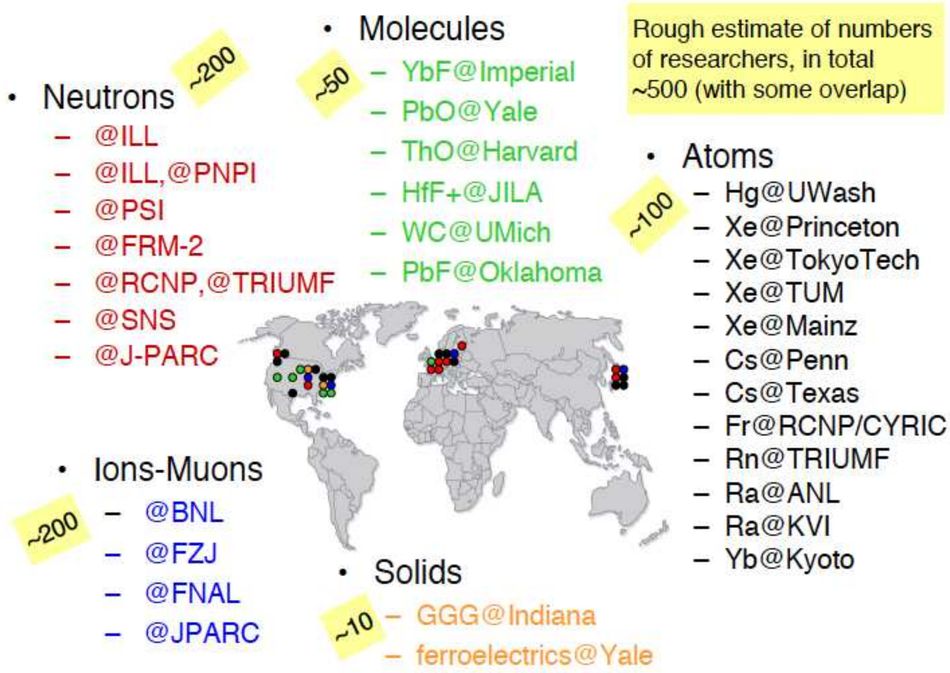

Figure 3.12: Various activities to search for EDMs in the world [ID34].

of 4. They received CD-0 approval from the DOE in Summer 2012.

Antiprotons

Regarding precision experiments with antimatter, the AEGIS and GBAR experiments at CERN plan to study the gravitational effect on antimatter. Both experiments are approved at the CERN AD, which provides slow antiprotons. They will then use different techniques, aiming to test $\overline{g}$ at the percent level at a first step.

3.4.3 Long term prospects

Figure 3.12 shows all the research activities to search for EDMs in the world. Some of them are large-size experiments, others are small at the university group level. In the long term, the srEDM collaboration is studying the possibility of an upgrade to reach 10^{-30} e·cm using stochastic cooling.

Also in the long term, the muon $g-2$/EDM measurement could be performed using ultra-slow positive muons, which are produced by laser ionization of muonium (a μ^+e^- atom). Owing to small beam emittance, they will not need any electric field focusing, allowing the muon momentum to be away from the $g-2$ magic momentum of 3 GeV/c. The measurement apparatus could be smaller, resulting in improved control of systematic errors. The proposal has been submitted to J-PARC.

3.5 Summary

There has been substantial recent progress in flavour physics, since the last European Strategy in Particle Physics in 2006, including the following achievements. The B fac-

Table 3.8: List of the top-ten important flavour-changing measurements chosen by G. Isidori, with wished for sensitivity (not listed in order of importance); SES stands for single-event sensitivity, and σ is the uncertainty.

Process	Sensitivity
$B(\mu \to e\gamma)$	SES$< 10^{-13}$
$B(\mu N \to eN)$	SES$< 10^{-16}$
$B(\tau \to \mu\gamma)$	SES $< 10^{-9}$
$B(B_s \to \mu^+\mu^-)$	$\sigma_{\rm rel} < 5$ %
ϕ_s	$\sigma < 0.01$
$B(K \to \pi\nu\overline{\nu})$ $(K^+ \& K_{\rm L})$	$\sigma_{\rm rel} < 5$ %
$B(B^+ \to \ell\nu)$	$\sigma_{\rm rel} < 5$ %
$a_{\rm CP}(D \to \pi\pi\gamma)$	$\sigma < 0.005$
$\lvert V_{ub}\rvert$	$\sigma_{\rm rel} < 5$ %
CKM angle γ	$\sigma < 1^\circ$

tories (both Belle and BaBar) have completed data-taking and continue to provide a wide range of interesting physics results, including CP violation and rare decays. Experiments designed for high-$p_{\rm T}$ physics (CDF, D0, ATLAS and CMS) also do excellent flavour physics. The dedicated flavour physics experiment at the LHC, LHCb, has demonstrated that precision flavour physics is possible at a hadron collider, and has now overtaken the results of previous experiments. A detailed study of CP violation and rare decays in the B system (including the B_s) has been made. No clear deviation from the Standard Model has yet been seen, although the results for $B \to D^{(*)}\tau\nu$, the dilepton asymmetry, the isospin asymmetry of $K\mu\mu$, and CP violation in charm decays all require further study. NA62 at CERN is completing its preparation for precision kaon physics ($K^+ \to \pi^+\nu\overline{\nu}$). For CLFV, the MEG experiment at PSI is improving the search for $\mu^+ \to e^+\gamma$ down to a sensitivity of $< 2.4 \times 10^{-12}$.

The success of the SM in describing flavour-changing processes of both quarks and charged leptons implies that a large new source of flavour symmetry breaking at the TeV scale is excluded. However, the two key questions about the origin of flavour are still open: what determines the observed pattern of masses and mixing angles of quarks and leptons, and which sources of flavour symmetry breaking are accessible at low energies?

With the high intensity/luminosity facilities running or planned, future experiments in flavour physics may well find deviations from the SM. The key approach to make progress in flavour physics is to push forward the precision in the cleanest observables, such as rare B and K decays, CLFV and EDMs. Table 3.8 shows a wish list of achievements for the potential top-ten important flavour-changing measurements. They are complementary to high-energy/high-$p_{\rm T}$ physics, and also complementary amongst themselves, and are required to understand the dynamics of new physics beyond the SM.

Towards a strategic plan, LHCb and its upgrade form an important part of the exploitation of the LHC. An upgraded B factory will give complementary physics coverage. CLFV for muons and taus at highly intense facilities and various advanced EDM searches could provide a clean demonstration of new physics beyond the SM. Flavour physics experiments are typically on a smaller scale than those for Higgs or neutrino physics, and sometimes they are ambitious single-goal experiments. But flavour physics is crucial in the search for new physics, and to understand new physics once it is found. It is therefore essential to maintain a diverse programme for muons, B, D, K mesons and fundamental symmetry measurements such as EDMs, both within Europe and also encouraging international collaboration when scientific research opportunities are available in the other regions.

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Chapter 4

Neutrino Physics

Relevant talks at the Open Symposium were given by C. Hagner, P. Hernandez, H. Robertson, and M. Zito.

4.1 Theoretical Introduction

While the LHC quest for new physics has only begun and will hopefully discover some evidence of new physics in the near future, the neutrino flavour change observed in neutrino oscillation experiments has already testified the incompleteness of the SM through the discovery of neutrino masses. Indeed, if neutrinos are massive particles and their flavour eigenstates ν_α $(\alpha = e, \mu, \tau)$ and mass eigenstates ν_i $(i = 1, 2, 3)$ do not coincide but are related through a unitary rotation similar to the one observed in the quark sector:

$$\nu_\alpha = \sum_i U^*_{\alpha i}\, \nu_i \,, \tag{4.1}$$

then, since each mass eigenstate will acquire a different propagation phase after travelling for a baseline L, it would lead to a non-zero probability of flavour change, given in vacuum by:

$$\begin{aligned} \mathrm{P}(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) \quad &= \quad \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j})\, \sin^2(\Delta m^2_{ij}\frac{L}{4E}) \\ &\quad \underset{(-)}{+}\, 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j})\, \sin(\Delta m^2_{ij}\frac{L}{2E}) \quad , \end{aligned} \tag{4.2}$$

with $\Delta m^2_{ij} = m^2_j - m^2_i$ and $U_{\alpha i}$ are the elements of the lepton mixing matrix, that can be parametrized by 3 mixing angles θ_{12}, θ_{23} and θ_{13} as well as 1 CP violating phase δ:

$$\begin{array}{ccccc} & & \text{Atmospheric/Accel.} & \text{Reactor/Accel.} & \text{Solar/Reactor} \\ U & = & \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} & \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} & \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{array} \tag{4.3}$$

Here, $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$. Thus, the experimental observation of neutrino flavour change and its dependence on the neutrino energy E and baseline L demonstrates that neutrinos have non-zero (and non-degenerate) masses and the existence of non-zero mixing angles relating the flavour and mass eigenstates, indicating the incompleteness of the SM with massless neutrinos. As we will discuss later, neutrino oscillations have already determined the values of $\Delta m^2_{21} \simeq 7.5 \times 10^{-5}$ eV^2, $|\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}$ eV^2, $\sin^2\theta_{12} \simeq 0.3$, $\sin^2 2\theta_{23} \simeq 0.97$ and, very recently, $\sin^2\theta_{13} \simeq 0.023$. The main goals of the next generation of neutrino oscillation experiments will be to determine the values of the CP-violating phase δ and the neutrino mass hierarchy, i.e. the sign of Δm^2_{31}.

It is perhaps not surprising that one of the first solid experimental evidences of physics beyond the SM came in this form. Indeed, we expect that the low energy effects of the higher, more fundamental theory of Nature can be encoded in a series of effective operators built with the SM particle content and its symmetries, and with mass dimension larger than 4. The effects of these effective operators at low energies will be suppressed by inverse powers of the new physics scale Λ with the higher dimension operators suffering a correspondingly stronger suppression:

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\mathcal{L}^{d=6} + \dots \tag{4.4}$$

While dozens of different $d = 6$ effective operators can be built from the SM particle content, only one such $d = 5$ gauge and Lorentz invariant operator exists: the Weinberg operator [1]:

$$\mathcal{L}^{d=5} = \frac{1}{\Lambda}\left(\overline{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right) + \text{h.c.}\,, \tag{4.5}$$

where L is the left-handed lepton doublet, $\tilde{\phi} = i\tau_2\phi^*$ and ϕ is the SM Higgs doublet. Thus, since the low energy suppression through Λ is weakest for the Weinberg operator, it is to be expected that it corresponds to one of the first evidences of physics beyond the SM. Indeed, when the Higgs doublet $\tilde{\phi}$ develops a vacuum expectation value, the Weinberg operator reduces to a Majorana mass term for neutrinos of the form $(v^2/\Lambda)\,\overline{\nu^c}_\alpha\nu_\beta$, which nicely accommodates our only present direct experimental evidence for particle physics beyond the Standard Model: neutrino oscillations. From this effective theory point of view, the neutrino sector and, in particular, its masses and mixings thus represent the least suppressed contribution, and therefore the best window for study, of physics beyond the SM.

While the addition of neutrino masses and mixings to the SM so as to account for neutrino oscillations may seem a small extension that can be easily accomplished by just including right-handed neutrinos ν_R to the SM particle content, this simple addition triggers the possibility of entirely new phenomena in the neutrino sector that could hold the answers to much more fundamental questions in particle physics. Indeed, even if the addition of the ν_R only seems to make the lepton sector of the SM an exact copy of the quark sector with no significantly new phenomenology, the gauge singlet nature of the ν_R allows the existence of a Majorana mass term of the form $M\overline{\nu^c}_R\nu_R$, forbidden for any other fermion in the SM due to gauge invariance. The mass parameter M introduces a completely new scale in the theory, unrelated to the electroweak scale and the Higgs mechanism, unlike all other fermion masses. This Majorana mass term also violates lepton number L. Its running is therefore protected by lepton number symmetry and this scale will be stable under radiative corrections. The mass scale M can thus take any possible value and the corresponding phenomenology will be very different in each case and can shed light on other fundamental puzzles:

- For $M = 0$ the Majorana mass term vanishes which implies that the accidental lepton number symmetry of the SM should be promoted to a fundamental symmetry of the theory in order to forbid it.

- For small $M \sim$ eV, extra sterile neutrinos could be present around the eV scale. These extra states could drive very short baseline oscillations and help to understand the anomalies observed by some experiments like LSND, MiniBOONE and reactors.
- For $M \sim$ keV, extra sterile neutrinos could be present around the keV scale. These states are considered viable warm dark matter candidates and could explain the mysterious dark matter component of the Universe, which the SM cannot accommodate [2]. In this case they could be searched for through their decay to lighter neutrinos and photons through gamma ray searches [3, 4].
- For $M \sim$ MeV–GeV the extra sterile states could lead to important contributions to flavour-changing processes in the lepton sector that would lead to characteristic signals in rare lepton flavour violating processes such as $\mu \to e\gamma$, $\mu \to 3e$ or $\mu \to e$ conversion in nuclei as well as alternative channels involving the τ lepton [5, 6, 7, 8]. Or even more striking lepton-number violating processess [9].
- For $M > v$ the electroweak scale, the extra sterile states are heavy and can be integrated out at low energies. In this case, not surprisingly, the Weinberg operator of Eq. (4.5) emerges as the least suppressed low energy effect with $\Lambda = M$. In particular, light neutrino masses will be given by $m_\nu = m_D^t M^{-1} m_D$, where $m_D = Yv$ is the Dirac mass of the neutrinos obtained through their Yukawa couplings Y and the vacuum expectation value of the Higgs v, as for any other fermion. In this case, the smallness of neutrino masses can be attributed to a hierarchy of scales between M and v. This is known as the "Seesaw mechanism" for the generation of ν masses [10, 11, 12, 13].

The only way to discern the value of this new physics scale is to test for the associated phenomenological consequences that such new states would predict. In any of these cases, the discovery of neutrino masses and mixings introduces a plethora of new flavour parameters to the "flavour puzzle", making these measurements crucial to its understanding. In the limit of the popular Seesaw scenario, the flavour puzzle is alleviated, since very small Yukawa couplings are not needed to explain the smallness of neutrino masses. Indeed, for $M \sim 1$ TeV, the required neutrino Yukawa couplings would be of the same order as for the electron, while for $M \sim 10^{16}$ GeV, as inspired by GUT models, the neutrino Yukawa couplings would be order 1, as for the top quark.

The Seesaw limit also offers the tantalizing possibility of explaining the observed baryon asymmetry of the Universe (BAU) through the leptogenesis mechanism. In order for a matter-antimatter asymmetry to be generated in the early Universe the three Sakharov conditions [14], namely deviation from thermal equilibrium, CP violation and baryon number violation, need to be fulfilled. While the SM has, in principle, these three ingredients, it has been shown that the CP violation in the quark sector, encoded in the Jarlskog invariant $J = (2.96^{+0.20}_{-0.16}) \times 10^{-5}$ [15], is not enough to account for the observed BAU [16, 17]. The recent measurement of θ_{13} indicates that the corresponding quantity in the neutrino sector is $J \sim 0.29 \sin\delta$, potentially four orders of magnitude larger. Furthermore, extra CP violating phases will be present in the matrix M. Thus, the out-of-equilibrium decays in the early Universe of heavy ν_R could violate CP and lepton number (given their Majorana masses) and induce a lepton number asymmetry that would be later partially transformed into the BAU by the SM sphaleron processes. This mechanism of baryogenesis induced by the lepton sector is known as leptogenesis [18] and constitutes one of the most popular theories for the generation of the BAU. The presence of the extra phases in the M matrix implies that the CP violating phase that controls the lepogenesis mechanism does not have a direct mapping to the δ phase accessible in neutrino oscillation experiments except in very specific models. However, a demonstration of the existence of leptonic CP violation would be an important step towards showing that the main elements required by the leptogenesis mechanism can indeed be present in Nature. CP violating effects driven by δ in neutrino oscillation experiments are suppressed by $\sin\theta_{13}$ and thus, before its recent discovery, the feasibility of these searches was an open issue. However, the recent discovery of non-zero θ_{13} and its size guarantees that measurements of δ with 1σ errors ranging from 5° to 30°, depending on the facility and the actual value of δ, are possible.

Regarding the Majorana nature of neutrinos, its more characteristic phenomenological signal is the violation of lepton number by two units, since the Majorana mass terms mix a particle with its antiparticle. Thus, processes in which lepton number is violated by two units would be allowed through a neutrino Majorana mass insertion. In particular, the most promising of those possible processes is neutrinoless double beta decay ($0\nu\beta\beta$) in which a nucleus decays via a double β process emitting two electrons but no neutrinos. The experimental signal of such a decay would be a monochromatic peak at the end of the electron spectrum, since all the decay energy is shared among the two electrons without missing energy carried away by the neutrinos. The $0\nu\beta\beta$ decay rate is proportional to the following combination of neutrino masses and mixings:

$$m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_1} + m_3 s_{13}^2 e^{2i\alpha_2}, \tag{4.6}$$

where α_1 and α_2 are additional "Majorana" CP-violating phases that are only physical if neutrinos are Majorana particles and do not play a role in lepton number conserving processes such as neutrino oscillations. Notice that for an inverted mass hierarchy ($\Delta m_{31}^2 < 0$) m_1 and m_2 are larger than m_3 and, since their contributions are not suppressed by s_{13}, the decay rate of $0\nu\beta\beta$ could be sizable. In fact, the value of $m_{\beta\beta}$ is bounded from below by present oscillation data for an inverted hierarchy scenario by $m_{\beta\beta} \gtrsim 0.01$ eV at the 1σ level. Conversely, for a normal mass hierarchy ($\Delta m_{31}^2 > 0$), m_3 is the largest eigenstate but its contribution is suppressed by s_{13} and, for particular values of m_1 and the Majorana phases, the contributions of the three terms can be similar and cancel among each other, yielding a non-observable $0\nu\beta\beta$ rate even if neutrinos are Majorana particles. In fact, with present data, $m_{\beta\beta} \lesssim 0.007$ eV for a normal mass hierarchy and $m_1 < 0.01$ eV. Thus, the determination of the neutrino mass hierarchy is a fundamental parameter to combine with the searches for $0\nu\beta\beta$ since its value determines the expected rate of the process when neutrinos are Majorana particles. Thus, if the mass hierarchy is found to be inverted but $m_{\beta\beta} \gtrsim 0.01$ eV is excluded, the explanation of neutrino masses via a high-energy Seesaw mechanism would be ruled out together with the simplest leptogenesis mechanisms.

The neutrino sector could also hold the key to the understanding of dark matter. Indeed, as already mentioned, a keV sterile neutrino is a valid warm dark matter candidate. Moreover, since right-handed neutrinos are gauge singlets, they are allowed to communicate with hypothetical dark or hidden sectors through lower dimension, and hence less suppressed, couplings than the rest of the SM fields, with the exception of the Higgs and the photon. For this reason the Higgs, photon and neutrino portals are considered the best probes into hidden sectors and are most susceptible of being affected by new physics. Finally, all the rich and, as yet, unexplored phenomenology discussed here, stemmed only from the simplest explanation of the observed neutrino masses: the addition of right-handed neutrinos to the SM content. However, this is not the only possibility. At tree level, neutrino masses can also be explained by the addition of scalar or fermion SU(2) triplets. These options are usually dubbed type-II and type-III Seesaw mechanisms, as opposed to the type-I Seesaw with right-handed neutrinos, and come with a similarly rich phenomenology to be probed for in the neutrino sector. Furthermore, different extensions of the SM leading to neutrino masses are possible at loop level.

To summarize, the extension of the SM that gives rise to the observed neutrino masses remains unknown. The simplest and most popular possibility, namely, the addition of right-handed neutrinos to the SM particle content, already implies an extremely rich range of possible phenomenologies, depending on the Majorana nature and scale of the ν_R. In particular, the neutrino sector may hold the key to the understanding of the flavour puzzle, the origin and nature of dark matter and the origin of the baryon asymmetry of the Universe and the probes for the Majorana nature of neutrinos and the existence of leptonic CP violation are crucial milestones for the unraveling of these mysteries. While the present generation of neutrino experiments, such as T2K and NOνA, will start providing the first $\sim 2\sigma$ hints of the existence of CP violation and the mass hierarchy [19], we will not be able to unlock the secrets buried in the neutrino sector with them alone, and experiments of realistic scale that can address these issues have already been proposed. The great potential impact on fundamental theory of the results of such experiments supplies a compelling argument for their careful consideration.

4.2 Status of Neutrino Experiments

Due to the smallness of θ_{13} when compared with the other two mixing angles and to the hierarchy between the two mass splittings: $|\Delta m^2_{31}| \gg |\Delta m^2_{21}|$, the three blocks in Eq. (4.3) tend to decouple and the neutrino oscillation phenomenon can be described with enough accuracy with simple, two-family approximations of Eq. (4.2) in many regimes that only depend on one mixing angle and one mass splitting:

$$\mathrm{P}(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right) \tag{4.7}$$

and $\mathrm{P}(\nu_\alpha \to \nu_\alpha) = 1 - \mathrm{P}(\nu_\alpha \to \nu_\beta)$. In particular, given the size of θ_{23} and θ_{12}, sizable oscillations well described by the two family approximation have been observed in two regimes.

For large L/E (the "solar regime") the smallest of the two mass splittings, Δm^2_{21}, drives sizable oscillations between the ν_e and the other flavours through the θ_{12} mixing angle. Since the energy needs to be low to reach the necessary values of L/E for these oscillations to develop, CC interactions of ν_μ and ν_τ cannot be exploited and this regime has only been observed through the disappearance of ν_e in solar neutrino detectors [20, 21, 22, 23, 24, 25, 26, 27] and confirmed by the KamLAND detection of reactor antineutrinos at $L \sim 100$ km [28]. From the interplay between solar and KamLAND data we have obtained very precise measurements of θ_{12} and Δm^2_{21}, as well as some hints of θ_{13}, since the subleading three-family effects seem to reconcile better the two datasets [29, 30, 31].

For smaller values of L/E (the "atmospheric regime") the larger mass splitting, Δm^2_{31}, drives the near maximal oscillations of ν_μ into ν_τ via the θ_{23} mixing angle. These oscillations were discovered in atmospheric neutrino oscillations, where a significant depletion of the ν_μ flavour is observed [32], and has later been confirmed by several accelerator experiments such as K2K [33], MINOS [34] and T2K [35], providing our present measurements of θ_{23} and $|\Delta m^2_{31}|$. Similarly to the solar sector, the subleading effects of θ_{13} start to be important with our current level of experimental precision and the two flavour approximation of Eq. (4.7) needs to be extended to:

$$P_{\nu_\mu \to \nu_\mu} = 1 - 4|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2) \sin^2 \frac{\Delta m^2_{31} L}{4E} \,, \qquad |U_{\mu 3}|^2 = \sin^2 \theta_{23} \cos^2 \theta_{13} \,. \tag{4.8}$$

In the two family approximation, $\theta_{13} = 0$, a degeneracy (called the octant degeneracy) appears since θ_{23} is only measured through $\sin^2 2\theta_{23}$, so two values of θ_{23} equally spaced on either side of the maximal mixing value of $\theta_{23} = \pi/4$ will produce the same mixing probability. The effects induced by non-zero θ_{13} cause an asymmetry between the two octants and, indeed, present data now slightly favour the first over the second octant for a normal mass hierarchy. In the atmospheric regime Δm^2_{31} also drives the subleading oscillations of ν_e into the other flavours through θ_{13}. Given the smallness of this last mixing angle, the discovery of these oscillations has been challenging and a 5σ significance on non-zero θ_{13} was only reached this year with the data from the Daya Bay [36] and RENO [37] detectors. Both experiments have exploited the disappearance of reactor $\bar{\nu}_e$ through the oscillation probability:

$$\begin{aligned} P_{\nu_e \to \nu_e} \quad \simeq \quad & 1 - \sin^2 2\theta_{13} \left(\cos^2 \theta_{12} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right) + \sin^2 \theta_{12} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right) \right) \\ & - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{21} L}{4E} \right) . \end{aligned} \tag{4.9}$$

For small L/E the term with Δm^2_{21} can be neglected and $\Delta m^2_{31} \approx \Delta m^2_{31}$ so that the dependence on θ_{12} disappears, and this channel provides a clean measurement of θ_{13}. Its discovery by Daya Bay and RENO has been confirmed at lower significance by a third reactor experiment, Double CHOOZ [38], as well as by the appearance of ν_e in two accelerator ν_μ experiments: MINOS [39] and T2K [40]. Conversely, for large L/E the term in Eq. (4.9) driven by Δm^2_{21} dominates and θ_{12} can instead be probed. This is the regime corresponding to the measurements by the KamLAND detector [28]. If enough energy resolution at the detector is achieved at this larger L/E regime, the interplay between the terms oscillating with Δm^2_{31} and Δm^2_{32} could provide sensitivity to the mass hierarchy. Indeed, for a normal hierarchy $|\Delta m^2_{31}| > |\Delta m^2_{32}|$ while the opposite is true for inverted hierarchy and, since $\cos\theta_{12} > \sin\theta_{12}$ the two terms can in principle by distinguished by their different amplitudes and a measurement of their relative frequencies would imply a determination of the mass hierarchy.

A global fit to all solar, atmospheric, reactor and accelerator neutrino oscillation data was performed in Ref. [41] (see also Refs. [42, 43]) and its results constraining all oscillation parameters are summarized in Fig. 4.1 extracted from that reference. Since, at present, the theoretical expectation for the ν fluxes from reactors seems to be higher than the observation from very short baseline reactors [44, 45, 46], two different assumptions of the reactor fluxes have been used in the global fit. In one case (solid coloured regions in Fig. 4.1), the flux is left free and normalized to the rates measured by the very short baseline reactor detectors (RSBL), in particular the Bugey4 [47], ROVNO4 [48], Bugey3 [49], Krasnoyarsk [50, 51], ILL [52], Gösgen [53], SRP [54], and ROVNO88 [55] detectors. In the other case these experiments are not included in the fit but the fluxes from Ref. [46] are assumed.

It is clear from Fig. 4.1 that the main targets of the next generation of oscillation experiments to complete the three-family neutrino oscillation picture are:

- The mass hierarchy, that is, the sign of Δm^2_{31}.
- The existence of leptonic CP violation and the value of δ.
- The deviation of θ_{23} from $\pi/4$, which is a very important parameter to discriminate among different models addressing the flavour puzzle, and, if it turns out not to be maximal, its octant.

It should be remembered that neutrino physics has made many unexpected discoveries in the past. Any neutrino experiment which extends our sensitivity reach to any parameter is therefore a search for new physics, and we should always keep an open mind (for instance about Non-Standard Interactions [93]) and try to improve the precision of measurements across the board.

Why is there a single value of Δm^2_{21}, but not Δm^2_{31}, in Fig. 4.1? The reason for having two values should be clear from Eq. (4.7). The oscillation probability depends on the square of the sin of Δm^2_{ij}, so the sign of Δm^2_{ij} is undetermined. Luckily, oscillations are modified by the passage of the neutrinos through matter because ν_e have different interactions with the electrons in matter than the other flavours. These modifications, called the MSW effect or just matter effects, depend on the sign of the Δm^2_{ij}'s as well as their magnitudes. Solar neutrino oscillations are heavily modified by matter effects in the dense matter of the sun, so the sign of Δm^2_{21} is determined in the fit. So far there have not been clean enough observations of matter effects in the atmospheric sector to determine the sign of Δm^2_{31}, so observing such matter effects is a major target for future experiments.

To discover leptonic CP violation we will be required to go even further beyond the purely atmospheric or solar regimes. Indeed, as for the quark sector, CP violation through flavour mixing is encoded in the Jarlskog invariant $J = c_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$ so all three mixing angles need to be involved in the process. The sensitivity to CP violation will thus stem from the interference between the solar and atmospheric contributions to the oscillation probability. The best channel to observe this is the so-called "golden channel", the $\nu_\mu \to \nu_e$ oscillation (or its T conjugate $\nu_e \to \nu_\mu$) which, expanded to second order in the small parameters $\sin\theta_{13}$ and $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and assuming a constant matter density reads [56, 57, 58]:

$$\begin{aligned} P_{\nu_\mu\to\nu_e} \quad &\approx \quad \sin^2 2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha^2 \sin^2 2\theta_{12}\,\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2} \\ &\qquad + \alpha\, J \cos(\Delta \pm \delta)\,\frac{\sin\Delta A}{A}\,\frac{\sin\Delta(1-A)}{1-A}\,, \end{aligned} \tag{4.10}$$

with the definitions

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}\,, \quad A \equiv \frac{2EV}{\Delta m^2_{31}}\,, \tag{4.11}$$

where V is the effective matter potential [59]. As mentioned above, note that α, Δ, and A, which appear in the terms that arise from matter effects, are sensitive to the sign of Δm^2_{31} (i.e., the mass hierarchy). The plus (minus) sign in Eq. (4.10) applies for

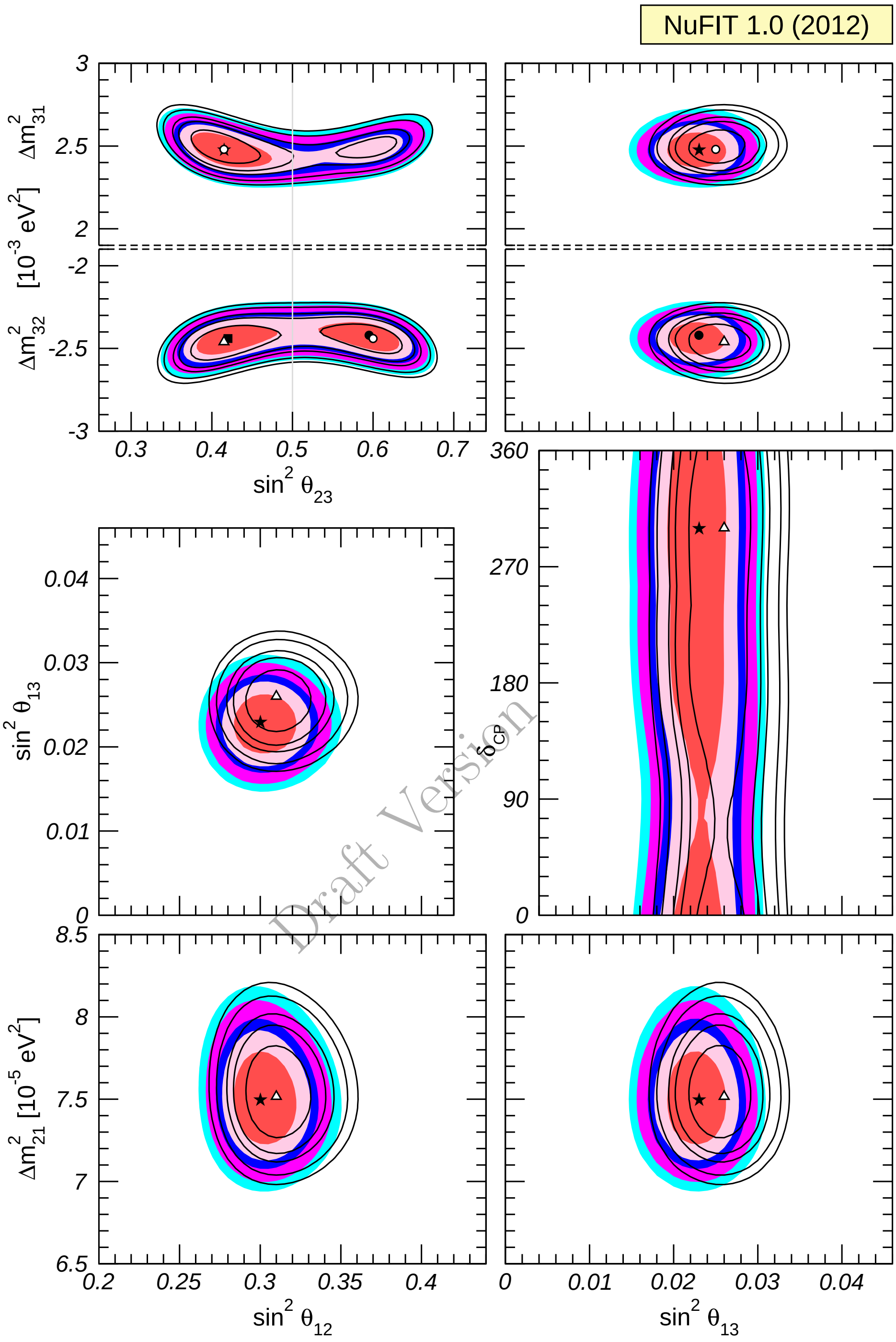

Figure 4.1: Global 3ν oscillation analysis. Each panel shows a two-dimensional projection of the allowed six-dimensional region after marginalization with respect to the undisplayed parameters. The different contours correspond to the two-dimensional allowed regions at 1σ, 90%, 2σ, 99% and 3σ CL (2 dof). Results for different assumptions concerning the analysis of data from reactor experiments are shown: full regions correspond to analysis with the normalization of reactor fluxes left free and data from short-baseline (less than 100 m) reactor experiments are included. For void regions short-baseline reactor data are not included but reactor fluxes as predicted in [46] are assumed. Note that as atmospheric mass-squared splitting Δm^2_{31} is used for normal hierarchy and Δm^2_{32} for inverted hierarchy. Figure taken from Ref. [41].

neutrinos (antineutrinos), and for antineutrinos $V \to -V$, which implies $A \to -A$. The importance of matter effects is encoded in the size of A, which grows with energy.

The first term of Eq. (4.10) oscillates with the fast atmospheric frequency, is suppressed by $\sin^2 2\theta_{13}$ and, for significant matter effects $A \geq 1$, contains a strong dependence on the mass hierarchy. Indeed, for $A = 1$, which is possible either for neutrinos and a normal hierarchy or antineutrinos and inverted hierarchy, the oscillation probability becomes resonant [60], as can be seen from the denominators, which would provide a very clear determination of the mass hierarchy. The second term is driven by the solar mass splitting and thus its oscillations develop much more slowly with L/E. The last term is the linear interference between the atmospheric and solar terms and, thus, is suppressed by one power of $\sin 2\theta_{13}$ (contained in J) and one power of α. As anticipated, the interference term contains all the dependence on the CP-violating phase δ and also depends on the mass hierarchy. Had θ_{13} turned out to vanish, the search for leptonic CP and the mass hierarchy through neutrino oscillations would have failed. For this reason, only one year ago the feasibility of this measurements was an open issue. The recent discovery of non-zero θ_{13} changes the situation and guarantees that searches within our current technological reach could provide a definite determination of the mass hierarchy (MH) and significant sensitivity to δ.

The actual value of θ_{13} is not only non-zero, but also comparatively large, saturating the previous upper bounds on it. This "large θ_{13}" has important consequences for the requirements and optimization strategy of the measurement of both CP violation and the mass hierarchy. Firstly, notice that matter effects in the atmospheric and interference terms grow with the value of θ_{13} quadratically and linearly respectively. This means that matter effects turn out to be significant even at relatively short baselines and low energies. The advantage is that the determination of the mass hierarchy becomes much easier than it would have been for smaller values of θ_{13} and therefore could almost be in reach of existing or near-term experiments.

Regarding the determination of δ, the non-zero value of θ_{13} guarantees that its determination at the next generation of oscillation facilities is feasible. However, since $\sin 2\theta_{13} \sim 0.3$ turned out to be larger than $\alpha \sim 0.03$, the "atmospheric", CP-conserving term of Eq. (4.10) will dominate over the "solar" term and the interference term and a very good control of the systematic uncertainties on the signal become a necessity, so that the δ dependence in the interference term is not hidden under the leading atmospheric oscillation. Before we consider the details of entirely new long-baseline experiments aimed at CP and MH determination, in the next section we turn to what we will learn from existing (or under construction) long baseline experiments and from other experiments on atmospheric or reactor neutrinos.

4.2.1 Present Generation of Accelerator and Reactor Experiments

Over the next few years there will be seven experiments that are likely to significantly contribute to improving our knowledge of the PMNS matrix. They are the three reactor experiments with ~ 1 km baselines (Daya Bay, Double Chooz, and RENO); two off-axis long baseline neutrino oscillation experiments (T2K and NOνA), and two continuing atmospheric neutrino experiments (Super Kamiokande and MINOS, continuing as MINOS+). To understand what these are likely to tell us (and how we will make further progress beyond them) it is helpful to look at the various simplified versions of the 3ν oscillation probabilities in Eqs. (4.8), (4.9) and (4.10). Equation (4.10) governs the ap-

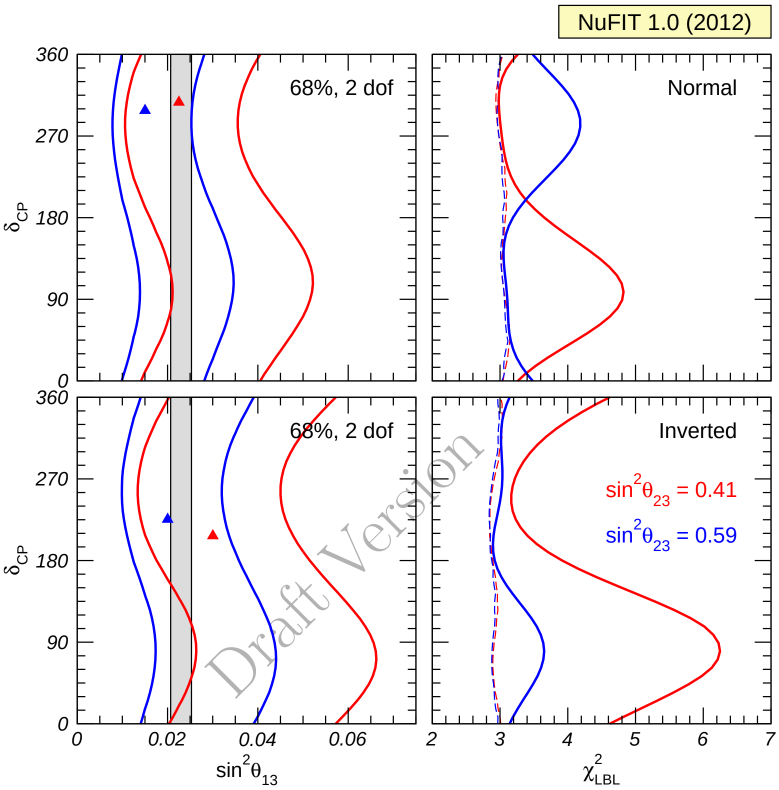

Figure 4.2: (Left) Preferred regions at 68% CL in the $\sin^2 2\theta_{13} - \delta_{\rm CP}$ plane. The contour curves correspond to T2K + MINOS appearance data, where $\sin^2\theta_{23}$ is fixed to the two degenerate solution in the 1st (red) and 2nd (blue) octant. We define contours for 2 dof with respect to the global minimum which is indicated by a triangle. The gray region corresponds to the θ_{13} determination from the reactors Double Chooz, Daya Bay, Reno (1σ band for $\sin^2\theta_{13}$, 1 dof). (Right) $\chi^2(\delta)$ from beams (dashed) and beams+reactors (solid) with the same colour coding as in the left panels. The solid curves are computed by adding $\Delta\chi^2_{\theta_{13}} = (\sin^2\theta_{13} - 0.023)^2/(0.0023)^2$ to the χ^2 from T2K and MINOS appearance data. Upper (lower) panels are for NH (IH). The other oscillation parameters are fixed to their best fit values. Figure taken from Ref. [41].

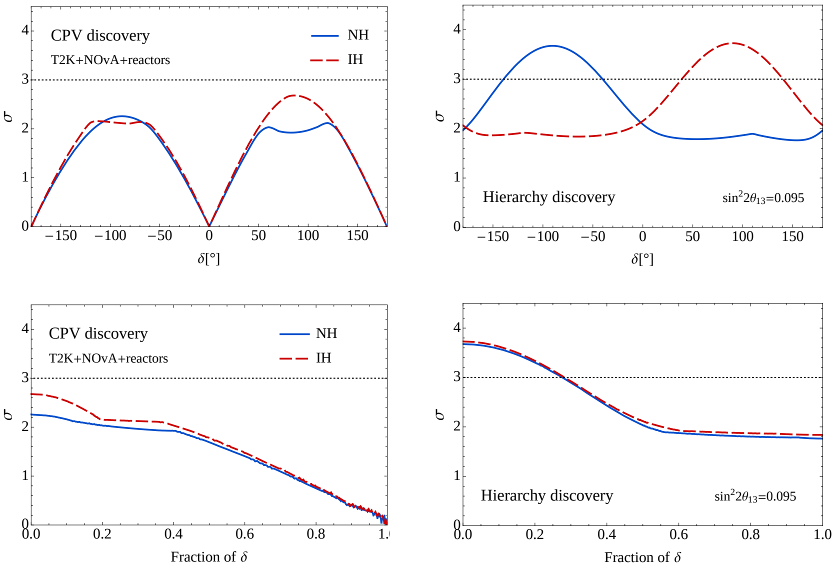

Figure 4.3: CP violation and MH sensitivity of the combination of T2K and NOνA with existing information (including the reactor experiments). Only for favourable values of δ does the significance reach 3σ for MH, and there is no 3σ CP sensitivity. Matter effects at NOνA provide most of the sensitivity to the MH. Plot courtesy of P. Coloma, the simulation of the facilities follows Refs [19, 61]. Notice that the nominal intensity of 700 kW for T2K has been assumed in those references but this intensity is yet to be reached.

pearance channel in long-baseline experiments, and it is this channel which allows the search for CP violation. However, the equation reveals one problem immediately—the appearance probability depends on many parameters in addition to δ, including all the mixing angles and the value and sign of Δm^2_{31}, both directly and through the matter effects. This produces covariances and degeneracies in the oscillation parameters derived from a fit to any particular measurement of the appearance probability, which means that more than one measurement (and type of measurement) of the oscillation probabilities will be needed to unambiguously measure all the parameters.

This covariance has already begun to be apparent when one considers the first way to try to extract a value for δ from the data—a comparison of reactor to long-baseline experiments [62, 63]. Fig. 4.2, taken from Ref. [41], shows the values of δ and $\sin^2\theta_{13}$ which are consistent with the reactor experiments (in the grey band) and with the MINOS and T2K appearance measurements. The three reactor experiments plotted here are at such short baselines that their oscillations are only sensitive to θ_{13}, so they appear as vertical bands. The long-baseline experiments, on the other hand, show the effects of covariance so different values of δ fit to different values of $\sin^2\theta_{13}$, the fits also depending on θ_{23} (the red and blue bands) and the MH (top and bottom plots). The panels on the right show a simple $\Delta\chi^2$ analysis. The dashed curves show the result considering only the beam experiments, with the flat values of $\Delta\chi^2$ showing that the covariance completely cancels any sensitivity to δ for the current statistics from these experiments alone. However when the reactors are added in (solid curves), the combined fit is already starting to show differences in χ^2 with δ, but the errors are currently too large and the additional covariances with θ_{23} and the MH too great to allow any sensitivity. This shows the need to determine the MH and the θ_{23} octant, and the need for greater sensitivity in the long-baseline experiments (the long-baseline curves on these plots are dominated by the 11 events from T2K, clearly there is a long way to go). The reactor experiments continue to run, and the current errors on $\sin^2\theta_{13}$ of $\sim 10\%$ should decrease to $\sim 4-5\%$ (or even slightly better when combining the three experiments, assuming they continue to agree). Meanwhile the T2K and NOνA experiments will improve our knowledge of the appearance probability (as well as make more accurate measurements of θ_{23}). The combination of these experiments, however, cannot provide more than an indication of the MH and of CP violation, as shown in Fig. 4.3.

4.3 Next Generation of Reactor and Atmospheric Neutrino Experiments

How could we do better? T2K and NOνA were both originally designed to search for θ_{13}, thus further optimization for the search of the MH or CP is possible. They both use off-axis beams, which produce narrow-band beams concentrated right at the oscillation maximum. This helps reduce backgrounds at the price of spectral information and statistics, which is the correct choice for optimizing sensitivity to small θ_{13} since it reduces the beam-induced background, but almost eliminates any sensitivity to the shape of the neutrino spectrum. Since θ_{13} turned out to be relatively large, this further reduction of the background at the expense of statistics and shape information is not optimal. The experiments have 295 km (T2K) and 810 km (NOvA) baselines, so matter effects are not large (in fact to some degree they are large enough to interfere with sensitivity to CP violation without being big enough to cleanly measure, particularly in the case of T2K). This can be seen in Fig. 4.4, which shows the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance oscillation probabilities for different values of δ and MH for different baselines. The first thing which is obvious is the matter effect. As you go to longer baselines the blue lines diverge from the red lines, with the neutrino rates becoming larger for the NH and the anti-neutrino rates for the IH, thus longer baselines are extremely useful for distinguishing the MH. For the measurement of CP, the most obvious effect is that the curves shift with δ in opposite ways for neutrinos and anti-neutrinos, thus the primary way to determine CP is by the comparison of the neutrino and antineutrino rates. This comparison becomes more challenging in presence of matter effects. For small matter effects the neutrino-antineutrino asymmetry coming from CP violation is of the same order as the one induced by the matter effects and disentangling the two can be hard, giving rise to parametric degeneracies. For large matter effects the MH can be clearly determined, but the price to pay is a strong depletion of the neutrino (antineutrino) sample for IH (NH) and a reduction of the relative dependence on δ of the rates, so the sensitivity to CP can diminish. An examination of the plot also shows that spectral information would also be useful for determining δ, in particular, the second oscillation maximum (which moves to high enough energy to be measured as the baseline is increased) changes differently than the first oscillation maximum as δ is varied, and the shape of the spectrum is distorted. This supplies complementary information to the neutrino/anti-neutrino differences. Getting information from the spectrum requires a broad-band beam, so most future long-baseline experiments want to use on-axis beams.

Longer baselines affect two other key experimental parameters—energy and rate. Obviously longer baselines require higher energies to keep a constant value of L/E and

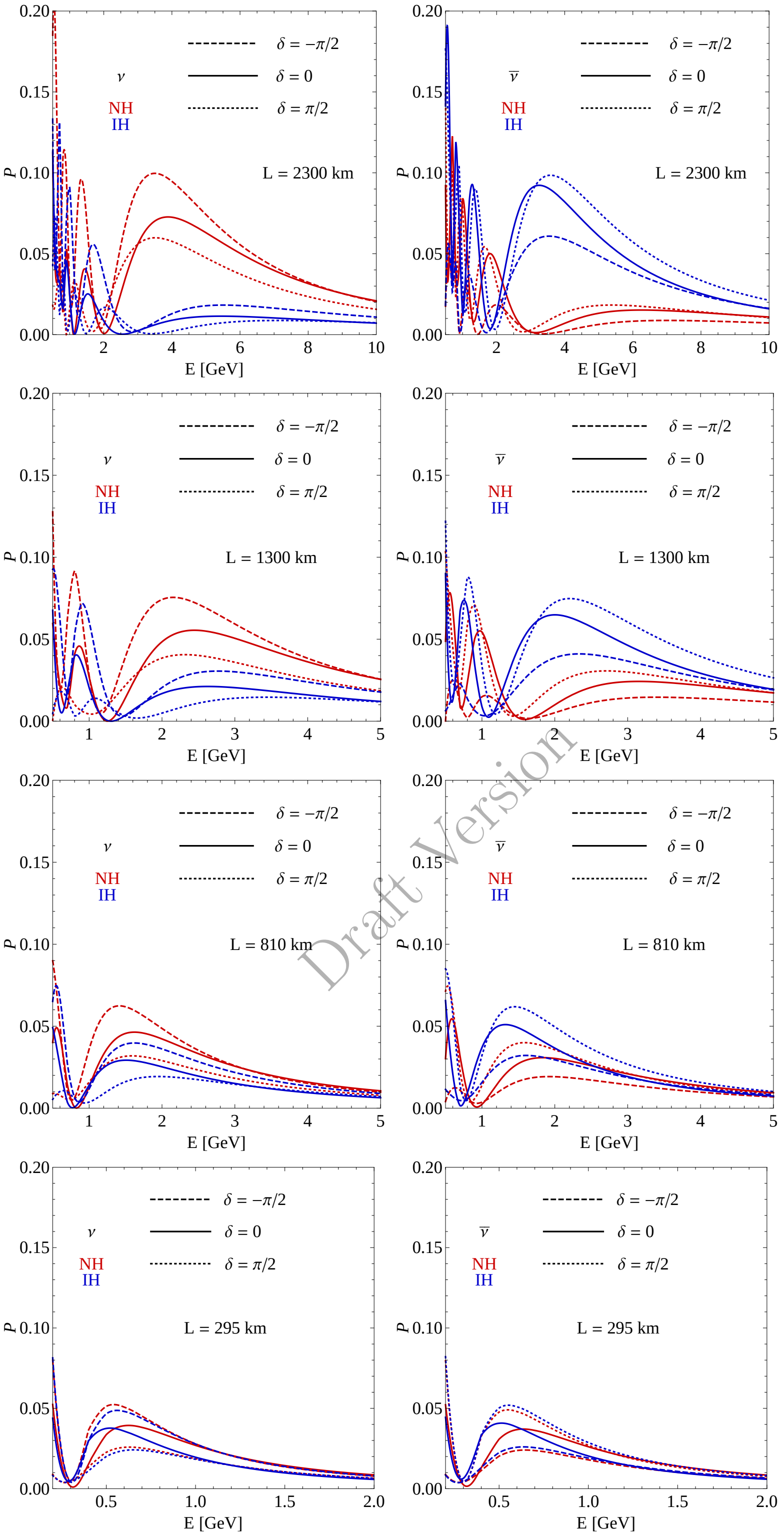

Figure 4.4: Oscillation appearance probability for the baselines (from top to bottom) of 2300, 1300, 810 and 295 km. Red and blue curves refer to the Normal and Inverted Hierarchy respectively, while the left panels are for neutrinos and the right for antineutrinos, and the different types of line are for different values of δ.

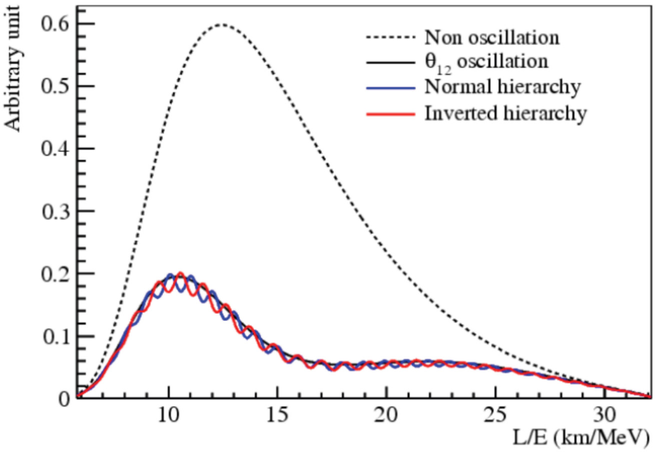

Figure 4.5: Reactor anti-neutrino spectrum on a 60 km baseline showing the non-oscillated spectrum, the spectrum corresponding to just oscillations driven by θ_{12}, and the result of full oscillations for the different values of the MH and $\sin^2 2\theta_{13} = 0.1$.

therefore remain on the oscillation maximum. Naively the rates would be expected to fall as L^{-2}, however two effects from the higher energies compensate for this. Firstly, the higher energy neutrinos are more effectively focused in the beam, and secondly, the total cross-section for neutrino interactions rises linearly with energy. The combination of these two effects almost cancels the L^{-2}, so the rates fall only slowly with baseline. The higher energy has another effect, however, which is that the events become more complicated with more particles in the final state (and therefore more difficult to reconstruct) as the energy increases. This is important, because of course the oscillation probability varies with neutrino energy, so it is critical to correctly reconstruct the neutrino energy from the observed events. This is relatively easy for a charged-current quasi-elastic (CCQE) event, where the neutrino energy can be uniquely reconstructed from the energy and angle of the outgoing lepton, however it is much harder for the more complicated resonance or deep-inelastic scattering events that dominate the sample above a GeV or so. That is why the experiments have settled on water Cerenkov detectors for baselines of a few hundred kilometres, where CCQE dominates (although there is still a significant experimental issue with quantifying non-CCQE backgrounds), while for longer baselines they have chosen liquid argon tracking calorimeters, with their ability to give bubble-chamber like reconstruction of all the tracks in complex events and thereby (at least in principle) greatly improve the reconstruction efficiency.

The three proposed conventional long-baseline experiments which are most advanced (T2HK, LBNE, and LBNO) will be described in more detail below, but first let us consider whether other experiments might give information about CP or the MH first. As mentioned above (in the text following Eq. (4.9)), a reactor experiment with a baseline of ~ 60 km would be able to make a very precise measurement of θ_{12}, however, in principle, it might also be sensitive to the MH. The probability from Eq. (4.9) for such a baseline is shown in Fig. 4.5. The large oscillation minimum caused by θ_{12} and driven by Δm^2_{21} has a small modulation caused by θ_{13} and driven by Δm^2_{31}, which is sensitive to the mass hierarchy. However, note that it is a small effect and that the frequency of the modulation is “high”, i.e., the width of the modulation peaks are comparable to the theoretical limit for the experimental energy resolution of an organic liquid scintillator detector at these energies. Recent papers [64, 65, 66, 67] quantify the difficulties in this measurement, and it is not clear that the unprecedented energy resolution ($\sim$ factor of two better than Borexino) and in particular the great improvement in energy linearity (an order of magnitude better than KamLAND) needed to resolve the MH can be achieved in such a large detector. An analysis of a 20 kT detector, 60 km from a 40 GW reactor, with energy resolution near the theoretical limit and perfect linearity, predicts the ability to distinguish the MH at 99% [66]. The Daya Bay collaboration are planning to build a new detector (Daya Bay II) for this measurement, and the improved knowledge of θ_{12} certainly justifies such a detector. To understand how much additional information it will give about the MH will require further R&D, but a sensitivity beyond 3σ would appear very challenging.

Another source of what are effectively long-baseline measurements with a wide range of baselines (but a flavour-impure and uncontrolled beam) are provided by atmospheric neutrinos. Could these improve our knowledge of the MH, CP violation or the θ_{23} octant? Atmospheric neutrino oscillations are dominated by $\nu_\mu \to \nu_\tau$ oscillations governed by Eq. (4.8), which is basically a two-neutrino oscillation and therefore insensitive to the MH. However there are sub-leading effects that depend on all three flavours in atmospheric neutrinos as well, and these, in principle, can help pin down the unmeasured quantities. Existing atmospheric neutrino results from the Super Kamiokande and MINOS experiments are included in the fits in Fig. 4.1. Both these experiments will continue taking data, but as they have already been running for many years the improvements will probably not be highly significant. A new large magnetized iron/RPC tracking calorimeter called INO is planned for a new underground laboratory in India, however it is unlikely to reach 3σ sensitivity to the MH prior to $\sim$ 2030 [68, 69].

Another idea that has been put forward is to use atmospheric neutrinos to address the MH using the vast water- or ice-based Cerenkov detectors built to detect very high energy cosmic ray neutrinos. These experiments cannot reconstruct neutrino events in sufficient detail to look for ν_e appearance. However, they have such vast statistics that the sub-leading effects in the ν_μ disappearance may be measurable just from counting the number of “track-like” events (which are dominated by muons) as a function of energy and angle. Interest in this idea was greatly increased by a recent paper [70], which showed that a very simple analysis binning the track-like events by neutrino energy and zenith angle showed a very large statistical separation between the hierarchies if the energy threshold of these detectors could be lowered to the point that events near the matter effect resonance around 6 GeV could be reconstructed. Efficient reconstruction of such “low” (for a high-energy neutrino telescope) energy events requires a denser packing of the phototubes, and two proposals are being prepared to accomplish that. The first, called PINGU, would build a dense core in the existing Icecube detector at the South Pole, the second, called ORCA [ID42] would build a dense core in the proposed KM3NeT detector in the Mediterranean. While these ideas are certainly very interesting, it should be emphasized that so far the analyses have not been based on full reconstructions and have not done a complete quantification of the systematics. Such full analyses are ongoing, however trying to determine the MH this way will always suffer from the drawback that it will be done by comparing data to Monte Carlo without any independent calibration of the energy scale or reconstruction efficiencies for different types of neutrino interaction and with no comparison of neutrinos to anti-neutrinos (they cannot be distinguished in this type of detector).

To summarize, the large matter effects implied by the value of θ_{13} recently discovered grants some sensitivity to the MH to a wide range of different search strategies. Thus, many new ideas have been put forward very recently (including the idea of measuring the MH by observations of supernova neutrinos, should a convenient supernova occur). More time and R&D are needed to determine the final sensitivity achievable at these proposals, however at the moment none of these ideas appears likely to provide a $> 3\sigma$ determination of the MH in the next 15 years, except perhaps the combination of T2K/NOνA/reactors for a narrow range of values of δ. The possible exception to that statement are the PINGU/ORCA proposals, but they also require further analysis to determine their likely sensitivity.

4.4 Next Generation Long-Baseline Projects from Conventional Beams

4.4.1 Options in Japan

Japan has a long and successful history in neutrino physics, particularly in long-baseline oscillation physics with the K2K and T2K experiments. It is worth noting that the Final Report of the Subcommittee on Future Projects of High Energy Physics from the Japanese HEP community submitted prior to the Krakow meeting states that “Should the neutrino mixing angle θ_{13} be confirmed as large”, as its second priority (behind an ILC) Japan “Should aim to realize a large-scale neutrino detector through international cooperation, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations” [ID121].

Two new experiments have been proposed to continue from T2K, both based on the existing T2K neutrino beam (a third possibility, which is to put a far detector in Korea, is not being actively considered but remains a long-term possibility). One idea is to put a LAr tracking calorimeter on the island of Okinoshima off the west coast of Japan [71]. The baseline would 658 km and the off-axis angle is small (0.8), giving it a broad-band beam for a measurement of the ν_e appearance spectral shape. The detector would be a LAr tracking calorimeter as discussed below for LBNO (Japanese and Swiss groups are jointly developing this technology, which has already been deployed in a test detector at KEK). In Japan significant effort is focused on increasing the available power on target at J-PARC, which will be critical to justifying this (or any upgraded long-baseline experiment).

Meanwhile progress continues towards a full international proposal to build the Hyper Kamiokande experiment [72, ID86], which would have a full range of physics goals including astrophysical measurements and proton decay (as discussed in Chapter 6). Since Hyper Kamiokande will reuse the T2K neutrino beamline, the T2K 280 m near detector, which was built with major European contributions, will likely be re-used as well. More than half of the members of the T2K collaboration are from European institutions, so a substantial European involvement in T2HK (if it goes ahead) seems probable.

The proposed detector is a huge water Cerenkov detector with a fiducial volume of 560 kT (compare 22.1 kT for Super Kamiokande). The proposed location is in the Tochibora mine near the site of Super Kamiokande, selected so that it has the same off-axis angle (but on the left side of the beam as viewed in the beam direction, while Super Kamiokande is on the right side). With a narrow-band beam and “short” (295 km)

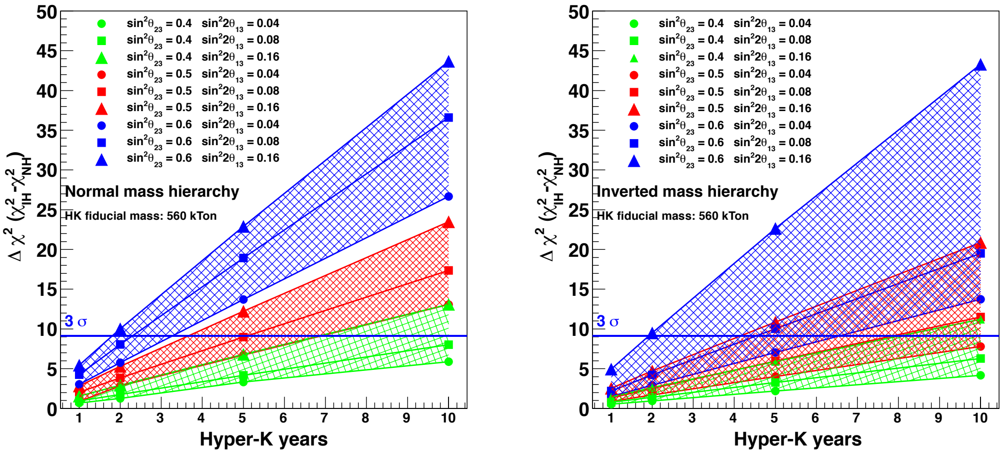

Figure 4.6: Significance in Hyper Kamiokande of an upward-going electron neutrino excess for determining the MH as a function of θ_{23}. Figure taken from Ref. [72].

baseline, Hyper Kamiokande would concentrate on extremely accurate measurements of the rates near the oscillation maximum for ν_e and $\bar{\nu}_e$ appearance. As one can see from examining the bottom two panels in Fig. 4.4, these rates are very sensitive to δ, but only if the MH is known. Indeed, the dotted and dashed lines diverge from the solid lines in the opposite ways for ν_e and $\bar{\nu}_e$, thus giving sensitivity to δ, but the dashed, dotted, and solid lines for each MH are hard to distinguish in each panel, thus providing little sensitivity to MH. Moreover, the solid blue and red curves are different enough from each other to confuse the search for δ if the MH is unknown.

The predicted sensitivity of T2HK to δ will be discussed below, but a critical question is whether the MH will be measured before the results are known. Some possibilities were mentioned above, but Hyper Kamiokande may have the capability of determining the MH itself using atmospheric neutrinos. As mentioned above, there are sub-leading effects that are sensitive to the MH, in particular there is an enhancement of the reconstructed number of upward going electrons that is larger for the IH than for the NH. However, this enhancement is also sensitive to the value of the octant degeneracy, being greater for $\theta_{23} > 45°$. If the MH is known this is valuable in that it gives information that can help resolve the octant degeneracy, however the impact on determining the MH with atmospheric neutrinos is significant, as shown in Fig. 4.6. If θ_{23} is less than 45° (as indicated in the current global fits, although with very low significance) this measurement becomes much less significant and another method is probably required.

4.4.2 LBNE

Groups in the US have been working for many years on an ambitious set of plans to build a new long-baseline neutrino experiment (LBNE) between Fermilab and a new underground laboratory in Homestake [73, ID150]. After the NSF withdrew from supporting a new lab in Homestake the DOE has requested that the collaboration reconfigure their programme with staged development which was affordable at each stage. As a consequence the LBNE collaboration is moving towards DOE CD-1 approval for an experiment consisting of a new 700 kW neutrino beam at Fermilab, and a 10 kT LAr tracking calorimeter on the surface in Homestake on a baseline of 1300 km. The beamline is very similar in intent to the successful NuMI beamline, although it utilizes a clever geometry with an artificial hill to minimize cost by keeping the elements at the far end of the beamline as near to the surface as possible. There is currently no provision for a near detector in the initial phase of the project, although the option exists if further funding can be found (and forms part of the plan for later phases of the project).

The far detector is based on a wire-plane readout similar to the ICARUS detector, with a non-evacuable membrane cryostat. For cost reasons, the designs of most planned large LAr calorimeters feature non-evacuable cryostats, and it is therefore very encouraging that the results of Fermilab's Liquid Argon Purity Demonstrator (LArPD) detector have shown that it is possible to reach acceptable levels of purity by repeated purging of a cryostat with evacuation. The placement of the detector on the surface is obviously non-optimal, as it means there would be no sensitivity to proton decay or to the various astrophysical measurements. Another concern is whether cosmic ray induced backgrounds near the surface would mask the rare ν_e appearance events. Since the duty cycle of the beam is very small, such backgrounds can be very well measured during beam-off so are unlikely to produce a false signal. The collaboration has Monte Carlo studies which indicate that it should be possible to reduce any such backgrounds sufficiently during the beam-on periods that they will be much smaller than the signal and should be easily subtracted. Obviously more work on this point is needed, and experience with the planned LAr detectors at Fermilab such as MicroBooNE (see below) will be very valuable.

The appearance probabilities for a 1300 km baseline are shown in Fig. 4.4. The predicted beam flux, spectrum, and composition must be modified by these probabilities and then used to generate a prediction of the measured spectrum and composition taking into account the detectors size, efficiency, resolution, and other properties. The result for LBNE as currently configured is shown in Fig. 4.7 (note that the plot shows the rates for a 34 kT detector, not the 10 kT currently planned, so the statistics are too optimistic by a factor of 3.4 for the stated run time).

The first phase of this experiment, as designed, will have limited statistics, particularly in the anti-neutrino channel. However it is intended to be the first phase of a continuing programme that would feature a 34 kT far detector underground at the 4850 ft level in the Homestake mine coupled to a staged increase of the beam power from 700 kW to 2.3 MW using the new Project-X accelerators (see Chapter 8), and a capable near detector to minimize the systematic uncertainties that provide the ultimate limit to the sensitivity to oscillation parameters. An obvious concern arises over how long all this will all take. In their submission to this Strategy Process Fermilab and the LBNE Collaboration have welcomed European contributions (beyond the few European groups already involved) to the programme to help accelerate progress and, in particular, to increase the capability of Phase I by putting the 10 kT detector underground. These contributions (stated to be 15% of the Phase I cost) would presumably have to be defined before the experiment receives CD-2 status, in about two years' time.

4.4.3 LAGUNA-LBNO

The existing European expertise in long-baseline experiments has built on the outcome of the FP7-funded LAGUNA study of potential deep underground sites in Europe for

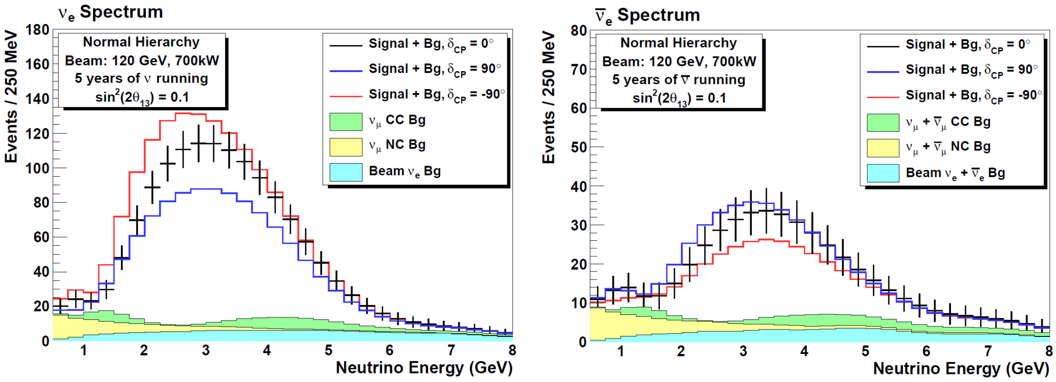

Figure 4.7: The expected spectrum of ν_e or $\bar{\nu}_e$ oscillation events in a 34 kt LAr for 5 years of neutrino (left) and antineutrino (right) running with a 700 kW beam and 1300 km baseline, assuming $\sin^2 2\theta_{13} = 0.1$ and normal mass ordering. Backgrounds from intrinsic beam ν_e (cyan), ν_μ NC (yellow), and ν_μ CC (green) are displayed as stacked histograms. The points with error bars are the expected total even rates for $\delta = 0$; the red (blue) histogram is the total event rate with $\delta = -\pi/2$ ($\pi/2$).

a combined long-baseline neutrino oscillation, proton decay, and astrophysical neutrino detector. LAGUNA studied three different detector technologies (water Cerenkov, liquid scintillator, and LAr) at seven different sites with baselines ranging from 130 to 2300 km from CERN. While all the sites and technologies had some advantages and disadvantages, the conclusion of the study was that two potential projects (the shortest baseline to a water Cerenkov detector in Frejus, and the longest baseline to a LAr detector in Pyhasalmi, Finland) provided the best options for beam physics and that a large liquid scintillator detector had many advantages as a detector for astrophysical neutrinos. These projects (along with a medium-baseline option to a new laboratory near the Gran Sasso) were then approved for further study in the FP7 LAGUNA-LBNO project. While the beam to Frejus would require the SPL to achieve its science goals, the beam to Finland could be built off of the existing SPS accelerator. It was decided that for the next generation it would be appropriate to concentrate on CN2PY, the beam to Pyhasalmi. This has resulted in an EoI [74, ID74] submitted to CERN by ~230 authors at 51 European institutions to build (in the first instance) a 20 kT LAr tracking calorimeter in the Pyhasalmi mine for long-baseline, proton decay, and astrophysics.

Optimization of the beam design is ongoing (as is also the case for LBNE) to increase the neutrino flux at low energies (around the second oscillation maximum) in order to improve CP sensitivity. Initially the protons would come from the current SPS, with an annual target of 0.8–1.3 × 10^{20} protons on target (cf CNGS target of 0.45 × 10^{20} pot). Further upgrades to the beam could be provided by an upgrade to the SPS. Another very exciting possibility is the addition of a second neutrino beam from Protvino with a baseline of 1160 km, which has been discussed recently in Russia. This would obviously add tremendously to the power of the experiment, as it would combine two different baselines to a single detector, canceling a broad range of systematics, while approximately doubling the statistics.

The far detector site would be in the Inmet Mine in Pyhasalmi, Finland. The mine is an excellent place for underground physics. It is a compact mine with very little water ingress, is the deepest mine in Europe, and has first-rate modern infrastructure with both lift and ramp access to depths down to 1400 m (4000 m.w.e). The rock is excellent, allowing large cavities to be safely constructed at reasonable cost. The ore reserves are expected to be exhausted in $\sim$ 2018, after which the Inmet Mining have offered to explore donating the mine to the Finnish Government for underground science. The regional government has already committed funds to exploratory drilling in support of laboratory planning. This mine would be an excellent site for additional deep underground lab space in Europe, and in particular, would make an excellent location for the LENA [ID70] detector. LENA has very strong astrophysics and proton decay capabilities, and preliminary studies also indicate that it may have some capability for beam physics as well, so the added benefits of securing the Pyhasalmi mine for physics should be kept in mind when evaluating the total physics return of CN2PY. The 2300 km baseline from CERN is also excellent for a Neutrino Factory, thereby keeping long-term options open at CERN.

The planned detector is a LAr tracking calorimeter which is proposed to use a novel readout technology. Rather than collecting the charge on wires as in ICARUS or the proposed LBNE detector, the LBNO detector plans to extract the charge from the liquid into the gas phase and then multiply it in the small holes of a LEM micropattern charge readout plane. This technique gives much higher signal/noise and "pixel" readout of the events (as opposed to the "strip" readout from wires), hopefully allowing finer details of complex neutrino interactions to be reconstructed. Another benefit of this technique is that, since it amplifies the signal, it can tolerate the inevitable attenuation of the deposited charge caused by drifting over many metres. It therefore is better for mass scaling, as mass can be added in the drift direction without adding channels (and also does not suffer from the risk of a broken wire shorting a large section of the detector). This amplification also supplies a safety factor in case the purity of the LAr is lower than expected. Surprisingly the amplification may mean that you would require fewer electronics channels as well, because the lack of amplification in the ICARUS-style readout means that multiple induction views are necessary to recover efficiency, multiplying the number of channels. A numerical comparison demonstrating the mass scaling advantage arising from these two effects (longer drift and fewer views) is that a T300 ICARUS module has 240 tons instrumented mass and 27,000 readout channels, while a $3{\times}3{\times}3$ m prototype being discussed at CERN would instrument mass at the same spatial resolution with just 7680 channels. The new technique has been demonstrated in test experiments at CERN and J-PARC. In addition the detector would have a MINOS-like iron/scintillator tracking calorimeter behind it to act as a muon ranger. Various designs are being studied for the near detector, with a magnetized high-pressure Ar gas TPC surrounded by an ECAL as one option. In addition there would likely be a need to conduct further hadron production measurements as NA61 [ID29] has done for T2K in order to reach the aggressive targets for the systematic uncertainties of the experiment.

Predicted measured spectra are shown in Fig. 4.8 for one particular set of neutrino parameters corresponding approximately to their current best fit values and $\delta = 180°$. Note that the anti-neutrino run is three times as long as the neutrino run to compensate for the poorer statistics for anti-neutrinos, although this would be revisited after a few years as the MH sensitivity is so high that within two years 5σ should be achieved and the remaining run time could then be optimized. This ability to determine the MH so quickly is a major advantage, both from the point of view of making the discovery first, but also from the point of view of giving early guidance to the rest of the neutrino

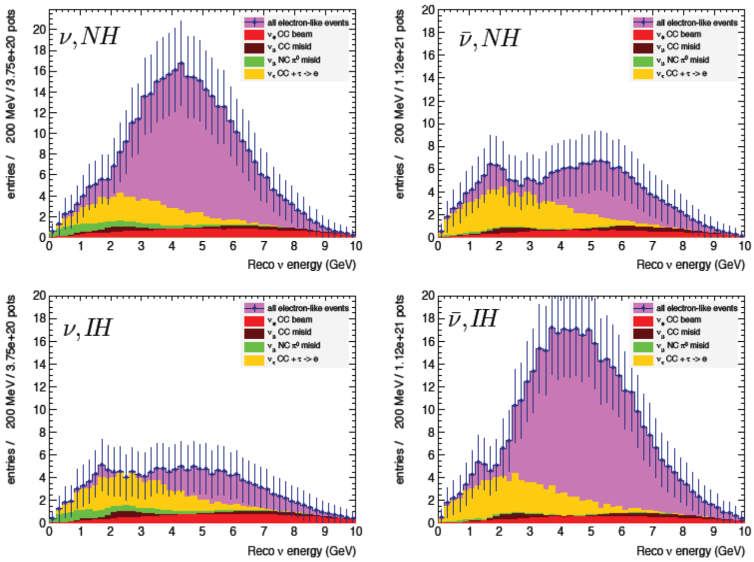

Figure 4.8: Possible observed spectra for one set of oscillations parameters to demonstrate the power of the proposed CN2PY experiment to distinguish the MH.

programme. Note the yellow part of the spectrum, which corresponds to electrons from the decays of τ's produces from ν_τ appearance. Whether this is considered background or signal (it is, after all, the signature the CNGS programme was built to find), it is quite easy to precisely quantify and subtract because the ν_μ flux is well-measured in the disappearance channel.

As of now the largest LAr tracking calorimeter ever built is the 600 ton ICARUS detector. The 20 kT LBNO detector therefore represents a substantial scale-up in detector size, and (as pointed out above) the European collaborators currently plan on building any new LAr detectors using LEM-TPC readout. More R&D and intermediate size prototypes (currently under discussion at CERN) thus represent a critical step to any potential approval of a CN2PY proposal, however it may be even more time critical if Europe is to participate in LBNE.

4.4.4 Predicted Sensitivity from Next Generation Experiments

An analysis of the predicted sensitivity or the three experiments discussed above is shown in Fig. 4.9. The two top panels show $\Delta\chi^2$ for CP violation, on the right for the case when the MH is independently known by some other means, on the left if it is not. The bottom panels show the measured uncertainty on δ (for comparison the current value from the CKM matrix is $\approx 6^\circ$) and the $\Delta\chi^2$ to reject the wrong value of the MH. Several things are apparent from the plots. First, the sensitivity to the MH increases strongly with baseline, with LBNO able to achieve $> 5\sigma$ for any value of δ. As mentioned above, an important point is that LBNO can achieve this in only two years of running, allowing the rest of the running time to be optimized for whichever MH is observed (which will produce better sensitivity to δ than is shown in this plot, which assumes equal neutrino and anti-neutrino running). Second, as mentioned above, the CP sensitivity of T2HK is compromised if the MH is unknown (note that this plot does not include atmospheric neutrinos). Third, the CP sensitivity of LBNE and LBNO in this analysis is approximately equal. The CP sensitivity of T2HK, with its much shorter baseline and weaker matter effects, is about as good as the upgraded or Phase II versions of the other experiments. This derives in part because of the much bigger proposed detector than the Phase I versions of LBNO/E and in part because of the weaker matter effects. At least in this analysis, T2HK is more sensitive to assumptions about systematic uncertainties, as shown by the width of the band - this will require further study by the T2HK Collaboration. Fourth, achieving a $5\,\sigma$ demonstration of CP violation will be challenging for these experiments for all but the most favourable values of δ, which nicely makes the case for the longer-term projects discussed in Section 4.5.

As an alternative to the CERN-Pyhasalmi baseline, the SPS could be exploited to produce instead a lower energy beam to match shorter baseline oscillations with weaker matter effects and thus increased sensitivity to CP violation (and reduced to the MH). Proposals along these lines were submitted to the Krakow meeting. A LAr detector, similar to the one proposed for LBNO could be hosted in a new laboratory near the existing Gran Sasso laboratory ($\sim$ 730 km baseline) [76, ID11] or a large WC detector (MEMPHYS) at the Canfranc laboratory [ID19] under the Pyrenees ($\sim$ 650 km baseline) [77, ID24]. To have significant CP coverage these projects assume a new dedicated high-power proton driver as discussed below.

4.5 3ν Oscillations from more Advanced Beams

As can be seen in Fig. 4.9, a 5σ demonstration of CP violation from experiments based on conventional beams requires huge detectors (and/or beam powers) and would only be possible over a rather narrow range of values of δ. This has caused a number of ideas to be proposed to produce intense, cleaner, more predictable neutrino beams from other sources. Two such novel beams consist of electron neutrinos and anti-neutrinos from the decays of stored beams of nuclei which are unstable against beta-decay or electron capture (called Beta Beams [78], or BB); and producing beams of neutrinos from the decays of stored muon beams (a Neutrino Factory [79, 80, 81, 82], or NF). Very high power conventional “superbeam”, or SB, have also been proposed for the next generation of oscillation facilities, this increase in statistics also makes them good candidates for a high-significance demonstration of CP violation despite their unavoidable intrinsic contamination. This is due to the relatively large value of θ_{13}, which guarantees that the intrinsic beam background will not dominate the signal. The types of neutrinos and oscillation channels available from these three facilities are shown in Fig. 4.10. The resulting experiments are rather different in the cases of a BB, SB or NF. As the electron (anti-)neutrinos in the case of a BB arise from the decays of stored ions, it is difficult to reach very high energies. This results in relatively short oscillation lengths (few hundred kilometres), and therefore the matter effects are small and MH determination is difficult (although presumably the MH will have already been measured before a BB could be built). The low energy neutrinos ($\sim$100’s of MeV) have relatively smaller cross-sections, so large detectors are required, but produce simple final states as they are dominated by CCQE. This means the BB is well matched to a large water Cerenkov detector, and the proposal is to build such a detector (MEMPHYS [83]) in the Frejus underground laboratory. Furthermore, the high-statistics atmospheric neutrino sample available at the MEMPHYS detector could also greatly improve the MH determination (as discussed above for Hyper Kamiokande), otherwise limited at the BB [84]. A similar setup can be

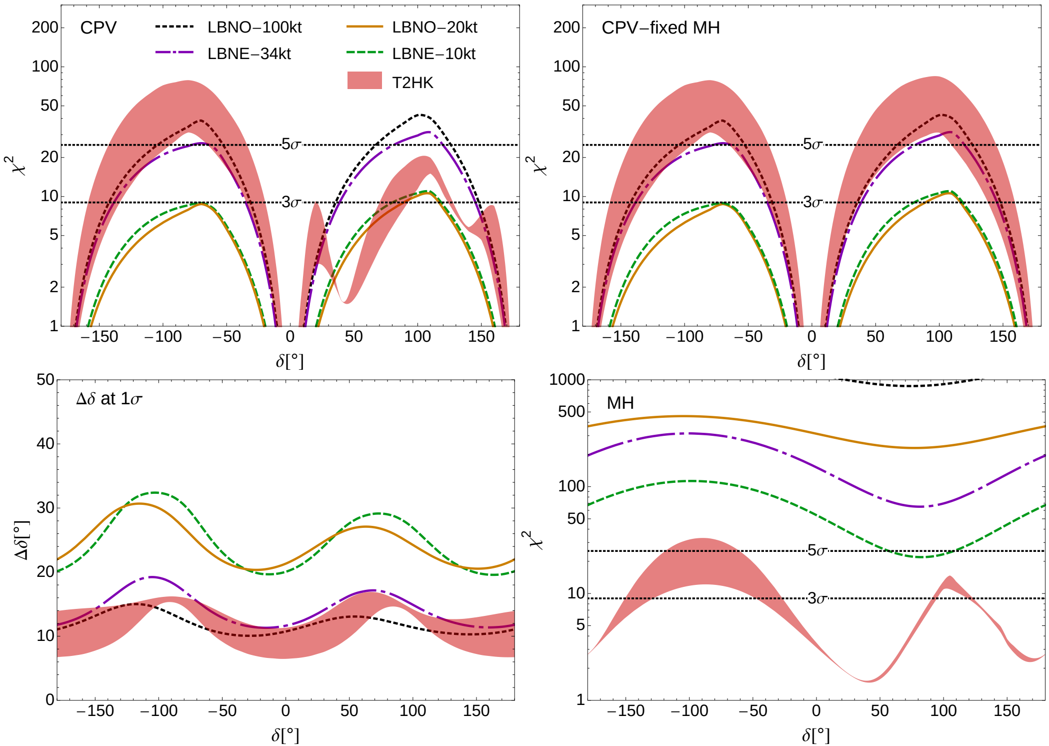

Figure 4.9: Comparative performance of LBNE (with 34 and 10 kt and a 700 kW beam, 10 years data), LBNO (with 100 and 20 kt and a 800 kW beam, 10 years data) and T2HK (with 560 kt and a 1.66 MW beam, 5 years data) in terms of achievable discovery potential for CP violation (top panels), precision for a measurement in delta (bottom, left panel), and sensitivity to the mass hierarchy (bottom, right panel). The top right panel shows the improvement in the CP violation discovery potential when the MH is known while in the top left panel is left free. Simulation details as well as systematic uncertainties have been implemented according to Ref. [75]: correlations have been fully taken into account, and a near detector has also been considered for all experiments. The lines show the results assuming "default" systematics as defined in Table 2 in Ref. [75] have been considered; while the bands show the possible improvement when the values of the systematics are changed from the default to the optimistic values in the same table. Marginalization has been performed over the solar and atmospheric oscillation parameters including Gaussian priors around the central values, in agreement with present best fit values and uncertainties at 1σ. For the matter density, a Gaussian uncertainty of a 2% (for the default systematics) and a 1% (for the optimistic systematics) has also been considered. Normal mass hierarchy has been assumed. Finally, θ_{13} and δ are left completely free during marginalization. Figures courtesy of P. Coloma.

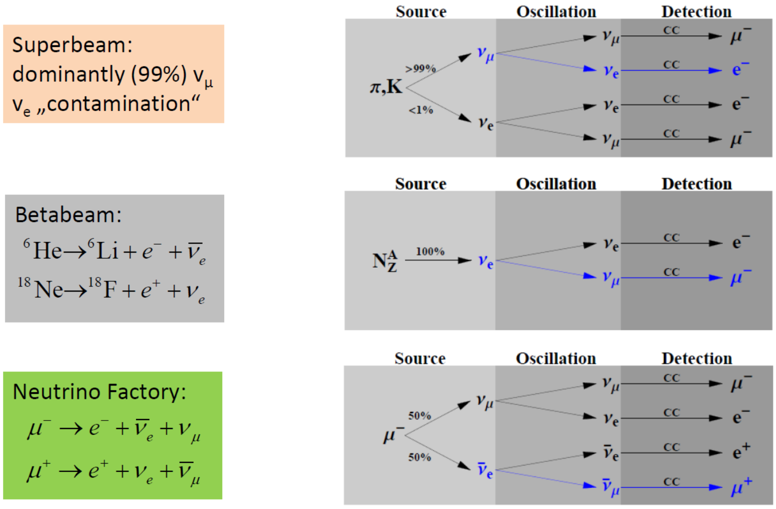

Figure 4.10: The sources of neutrinos and the oscillation channels available from a conventional SB, a BB and a NF.

envisioned for a low energy SB [85, 86, 84, 87]. Given that both facilities can exploit the same detector and that the BB could profit from the SB proton driver for ion production, the BB setup is usually considered in combination with a companion SB (as in Fig. 4.11).

In the case of the NF, the muons can be accelerated to produce higher-energy neutrinos, with the baseline proposed ending up somewhere around 2000 km (although the exact energy/baseline does not appear critical, and somewhat shorter or longer baselines would be almost equivalent). For the NF the “golden” channel is to observe (in the case of a μ^- beam) the $\bar{\nu}_e \to \bar{\nu}_\mu$ appearance oscillation (the normal $\nu_\mu \to \nu_e$ appearance oscillation is difficult to observe as it is hard to distinguish the electrons produced by ν_e from the positrons produced by unoscillated $\bar{\nu}_e$ which are in the beam to start with). This requires the detector to be magnetized, as you must distinguish the μ^+ arising from oscillations from the μ^- in the original beam. With currently practicable technology that leads to a MINOS-like magnetized sampling calorimeter, or MIND (Magnetized Iron Neutrino Detector).

Proposed versions of a BB, SB, and NF are being studied in the FP7 Design Study EUROnu. The final report from this study should be available in time for the Erice meeting, but preliminary findings were submitted as input to the Krakow meeting [ID35]. The predicted CP-violation coverage of the various options, and the accuracy with which they could determine δ, are shown in Fig. 4.11. Clearly the LENF (Low Energy Neutrino Factory) option has the best reach and accuracy for δ, and is in fact the only proposed programme that could determine the δ from the PMNS matrix to a precision of $\sim 6°$, similar accuracy as the existing determinations of the δ from the CKM matrix, a useful benchmark as it would mean that the accuracy of the neutrino determination of δ would not be the limiting factor for testing flavour models. This, along with preliminary information about costs (where more information should be available at Erice),

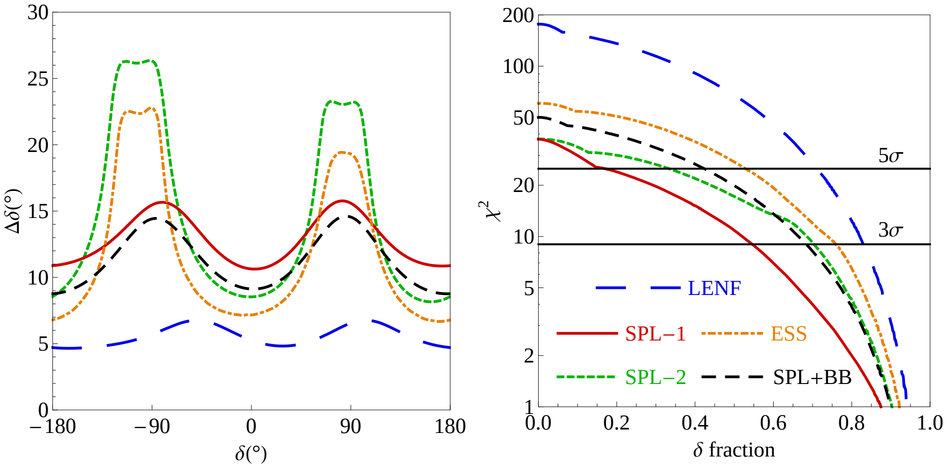

Figure 4.11: (Left) The 1σ precision with which δ could be measured as a function of its true value at different facilities. (Right) The χ^2 with which CP-conservation could be excluded at the same facilities as a function of the fraction of value of δ for which this exclusion is possible. The details of the different facilities are as follows. LENF: the low energy Neutrino Factory with a flux from 10^{21} muon decays per year at 10 GeV and a 100 kt MIND detector at a 2000 km baseline. SPL-1: a 4 MW low energy SB with a 500 kt fiducial water Cerenkov detector at a baseline of 130 km, matching the CERN-Frejus distance and roughly at the first oscillation peak. SPL-2: a 4 MW low energy SB with a 500 kt fiducial water Cerenkov detector at a baseline of 650 km, matching the CERN-Canfranc distance and roughly at the second oscillation peak. BB+SPL: the combination of the SPL with a BB from the decay of 1.3 (3.5)$\times10^{18}$ ^{18}Ne (^{6}He) decays per year at $\gamma = 100$ aimed at the same 500 kt fiducial water Cerenkov detector at a baseline of 130 km. ESS: a 5 MW low energy SB from the ESS linac with a 500 kt fiducial water Cerenkov detector at a baseline of 540 km, matching the ESS-Garpenberg distance. In all cases 10 years of data taking have been considered. This figure corresponds to the final EUROnu comparison of facilities [ID35] with the line for the ESS from Ref. [ID82] added.

has led the EUROnu group to issue the strong recommendation to proceed along the path towards a staged construction of a LENF as the definitive facility for long-baseline neutrino oscillation physics.

Given the current status of R&D, it seems unlikely that a decision to build such a facility could be made prior to the next CERN Strategy process. The EUROnu group is therefore recommending a strong continued programme of R&D leading to a proposal for a LENF to be submitted to the next CERN Strategy process. Such R&D is already going on world-wide, and it is a prime opportunity for CERN to collaborate with the world neutrino community. Proposed elements of an R&D programme from the Euronu group are:

- Further R&D on the design and layout of a NF in preparation for writing a full proposal.
- Support for the νStorm project. νStorm is a proposal to use an existing proton driver to produce a pion beam that will be focused into a storage ring where some of the muons from their decay will be circulated to produce a baby version of a NF. νStorm is an important step along the way to a LENF, but it also has two strong physics goals. The first (to search for sterile neutrinos) will be discussed

below. The second is to produce an intense beam of ν_e and $\bar{\nu}_e$ which can be used to make precision measurements of electron neutrino cross-sections ($\sim 1\%$) [ID108]. Knowledge of these cross-sections is essential for achieving the ambitious systematic uncertainty targets of future long-baseline projects, and this would be by far the best way to experimentally determine them.

- R&D towards the design of the type of high-power (4 MW) proton driver needed for the ultimate LENF design. This high-power proton upgrade would be preferable via the High Power SPL route that would provide the neutrino SB with high sensitivity to CP violation, as depicted in Fig. 4.11. While superseded by the LENF, the SPL SB can, on its own, potentially provide a high-significance discovery of CP-violation, reaching the 5σ (3σ) level for a $\sim 20\%$ ($\sim 55\%$) of the possible values of δ when the detector is placed at Frejus, close to first oscillation peak. This sensitivity can be further improved to $\sim 30\%$ ($\sim 70\%$) if the detector is instead placed closer to the second oscillation peak, at the Canfranc underground laboratory [88], although the lower statistics at this location hinders the precision with which δ could be measured if it turned out to be maximally CP violating ($\delta = \pm 90°$) [89], as can be seen in the left panel of Fig. 4.11.

Another important step towards the construction of the LENF is the MICE (Muon Ionization-Cooling Experiment) at the Rutherford Lab. This is an essential step in demonstrating muon cooling which is important for a high-flux NF and essential to the long-term plans to build a Muon Collider. MICE has seen its schedule stretched until 2019, largely due to funding constraints, and a CERN contribution could be useful to bringing that into the period of the coming CERN strategy.

A recent interesting alternative for the SPL SB would be to exploit the European Spallation Source facility [ID10] (ESS) linac. The ESS has already been approved to deliver 5 MW 2.5 GeV protons to produce neutrons for various applications. The ESS proton linac can also be used in sharing mode to deliver protons to an SB equivalent to those of CERN-SPL [ID82]. Profiting from the EUROnu Design Study work on the SPL SB hardware and physics, the proposed ESS SB is found to have similar but slightly better performance on CP violation discovery potential and the determination of δ than the SPL-2 (Fig. 4.11). The optimization of the ESS setup has only just started and further improvements are to be expected.

4.6 Sterile Neutrinos

The LEP results on the width of the Z limit the number of light weakly-interacting neutrinos to the three already known, but many BSM models allow for the existence of additional neutrinos which do not couple weakly, known as “sterile” neutrinos. A large number of experimental anomalies exist which could be explained by oscillations to sterile neutrinos, the oldest of which is the observation of the LSND experiment at Los Alamos of an excess of $\bar{\nu}_e$ induced events in a flux of neutrinos from stopped pion decay. A similar experiment with similar sensitivity at the Rutherford Lab, called KARMEN, saw no effect, however it was unable to rule out the LSND result. The unexplained LSND result was the motivation for the MiniBooNE experiment at Fermilab, which was intended to look for such appearance in a low-energy conventional neutrino beam at the same L/E as LSND (but different L and E). MiniBooNE initially ran with neutrinos, and while they saw an excess of unexplained events at low energy, these were not consistent with the simplest interpretations of the LSND experiment and were not interpreted as evidence for sterile neutrinos. However a second run with anti-neutrinos saw a small excess (1.7σ) consistent with LSND, and a re-analysis of both data sets now claims a 3.8σ overall excess which is interpreted as evidence for sterile neutrinos.

To these appearance results must be added a number of disappearance results. A new calculation of the expected flux of anti-neutrinos from reactors has yielded a value which is about 3% higher than the average of the value measured by many experiments ($2.7\,\sigma$), which can be interpreted in terms of $\sim 5\%$ of the reactor anti-neutrinos oscillating to a sterile state before reaching the detectors. In addition the SAGE and GALLEX gallium radiochemical solar neutrino experiments were calibrated with very strong neutrino sources, but the detected rate was about $2.9\,\sigma$ low compared to the predictions, which can once again be interpreted as oscillations to a sterile state. In addition recent analyses of cosmological data imply at $> 95\%$ CL that there are more than 3 light neutrinos, with 4 giving a better fit to the data (although this could be satisfied by any light degree of freedom, so is not necessarily evidence for a sterile neutrino).

Many people see this large number of independent pieces of evidence and conclude that there is likely to be an underlying physics cause, however a problem exists in the interpretation. If you attempt to explain all these results via oscillations to sterile neutrinos then the appearance and disappearance rates have to be related. When the fits are actually done the appearance and disappearance results are in very strong tension, and no satisfactory fit to either a 3+1 model with one light sterile neutrino or even a 3+2 model with two light sterile neutrinos exists [90, 91, 92, 93]. However, appearance and disappearance experiments are usually compared separately to the each other and to existing experimental results using a phenomenological 3+1 model.

4.6.1 Experimental Tests for Sterile Neutrinos

A very large number of different ways to search for sterile neutrinos have been proposed using a multitude of different neutrino sources ranging from reactors to very strong radioactive sources to stopped pions or kaons to conventional and even un-conventional neutrino beams. To give some feel for the number of proposals, Fig. 4.12 shows the predicted sensitivity of a subset of the proposed experiments compared to the disappearance claim. It is impossible to discuss all the proposed experiments here, so the interested reader is referred to the White Paper [93] for details. We will limit our discussion to three sets of experiments which are directly relevant to CERN.

4.6.2 Proposed Short-baseline Experiments at Fermilab

Two LAr TPC detectors are already proposed at Fermilab for other purposes. The MicroBooNE [ID149] detector was originally designed to use the excellent photon/electron separation capability of such detectors to see if the low-energy excess seen in the MiniBooNE beam arises from an unexpected source of photons. There was a plan to build a ~ 1 kT fiducial prototype (LAr1) for the LBNE experiment (although it is not now felt that such a prototype is needed). A proposal now exists to combine these two detectors (with MicroBooNE moved to a position 200 m from the target) to perform a sensitive sterile neutrino search using the MiniBooNE beam. The expected sensitivity in appearance mode for neutrinos and anti-neutrinos is shown in Fig. 4.13 (left panels). The LSND region is completely covered at $3\,\sigma$, and almost completely covered at $5\,\sigma$.

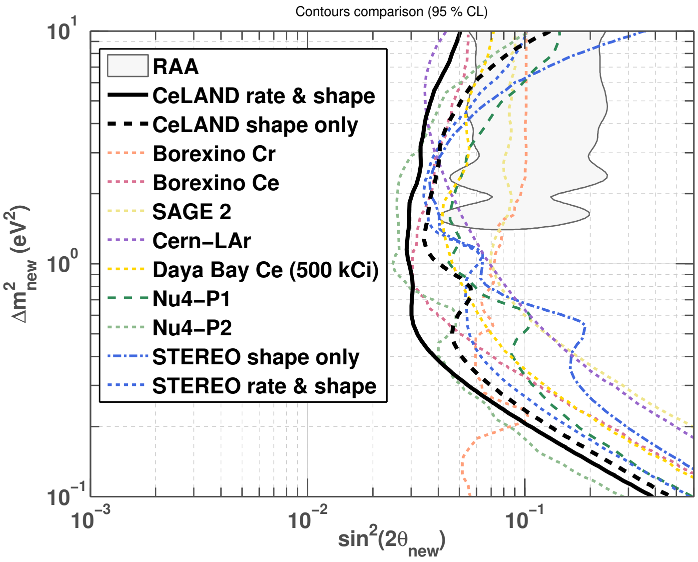

Figure 4.12: Compilation of the claimed sensitivity of various experiments to the parameters which are consistent with the disappearance results from reactors. Note the sensitivity of the CERN SBL proposal discussed below. Adapted by G. Mention from Ref. [93].

4.6.3 Proposed Short-baseline Experiments at CERN

A proposal has been submitted to the SPSC (SPSC-P-343) to perform a similar experiment at CERN by moving the well-tested ICARUS detector from LNGS to a new position in the North Area at the end of a new neutrino beamline, 1600 m from the target [ID38]. A new LAr detector based on the ICARUS design but 1/4 the size (150 tons) would be placed 330 m from the detector. Both of these LAr detectors would have behind them a magnetized iron/scintillator muon spectrometer (SPSC-P-343) allowing charge identification and momentum measurement of muons emitted in interactions in the LAr detectors (and in the spectrometers themselves), opening up the disappearance mode as well as improving the appearance mode. The experiment would have an additional sensitivity to sterile oscillations by comparing the NC/CC ratio in the near and far detectors. The sensitivity to electron appearance is shown in Fig. 4.13, while the disappearance sensitivity is shown in Fig. 4.12 above. This proposal, like the CN2PY proposal discussed above, both would involve building a new neutrino beamline in the CERN North Area. While it may be an obvious point, it should be noted that these are not the *same* new neutrino beamlines, as the short-baseline beam for a sterile search would be roughly horizontal (the far detector, ICARUS, would be near the surface), while in the case of LBNO the beam must be inclined into the ground at an angle of 10.4°. Thus the decay volumes (physically the largest parts of a neutrino beam line) could not be in common. It remains to be seen whether a single target station could be designed to accommodate both beamlines. The transfer beamline to bring protons from the SPS to the target certainly could be in common. An intermediate position on the SBL beam would be available as a location for the CN2PY prototype detector, which would be very valuable for testing. The level of commonality or interference between the two proposals on the beamlines has not been fully worked out. Common expertise on

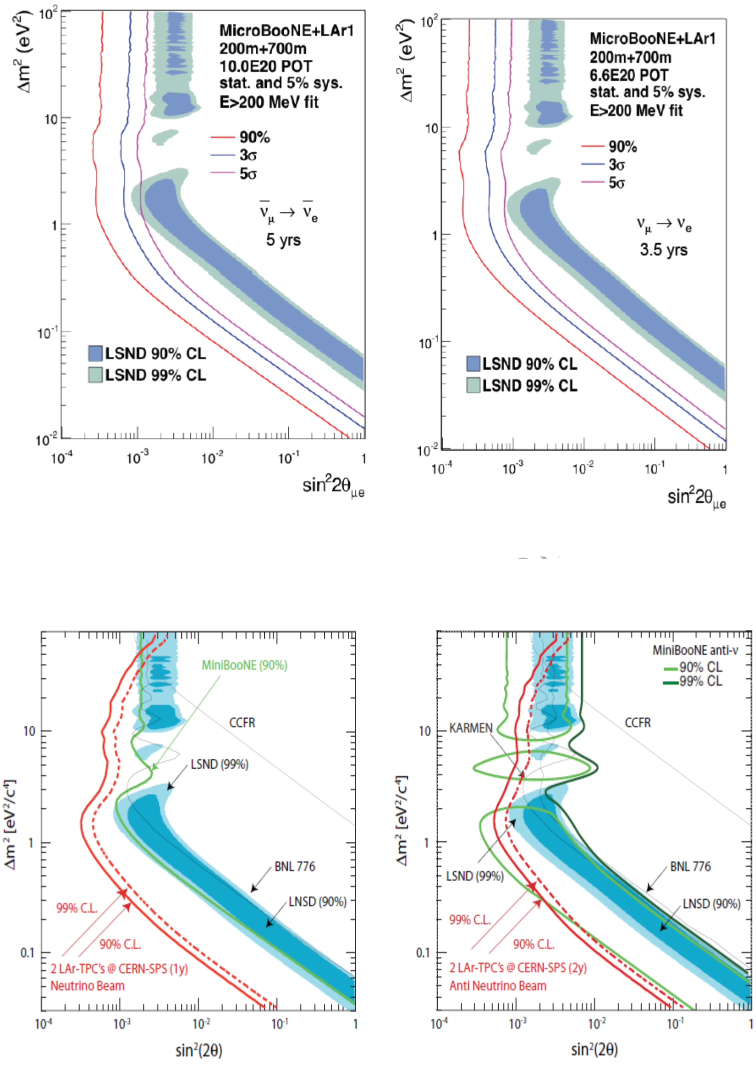

Figure 4.13: (Top) Sensitivity to electron (anti-)neutrino appearance in the proposed MicroBooNE/LAr1 experiment, for antineutrinos (left) and neutrinos (right). (Bottom) Sensitivity to electron (anti-)neutrino appearance in proposed experiment exposed to the CERN-SPS neutrino beam (left) and antineutrino (right) for 4.5×10^{19} pot (1 year) and $9 \cdot 10^{19}$ pot (2 years), respectively. The LSND allowed region is fully explored in both cases.

LAr techniques (purification, cryogenics, electronics, etc.) and a critical mass of physicists trained in those techniques would certainly be very valuable to both projects, and indeed to involvement in European physicists on LAr anywhere in the world.

4.6.4 νStorm and Sterile Neutrinos

As mentioned above, a proposal has been put forth to build a very low energy Neutrino Factory called νStorm [94, ID108] at Fermilab (although there is also discussion of bidding to host such a facility at CERN). The main purpose of this facility is as an initial step towards a Neutrino Factory, however it also has two strong physics motivations. The first is the precision measurement of ν_e and $\bar{\nu}_e$ interaction cross-sections (a precise knowledge of which is assumed in most long-baseline proposals, but for which there is no other realistic prospect of accurate measurements). The second physics motivation of νStorm would be to perform an extremely sensitive search for sterile neutrino oscillations. Conventional ν_μ neutrino beams, as assumed for both of the proposed experiments above, always suffer from contamination of ν_e that reduce the sensitivity of appearance searches. In the case of νStorm, the ν_μ beam is free from $\bar{\nu}_\mu$ (or vice versa for storing the opposite charge muons). The ν_μ beam, however, has an equal flux of $\bar{\nu}_e$, which would undergo the CPT-invariant appearance oscillation and produce $\bar{\nu}_\mu$ which could be observed with a detector capable of charge-discrimination. νStorm would therefore concentrate on the appearance measurement.

The plan is to build a muon storage ring that will be filled by muons arising from pions decaying in the ring itself (thereby avoiding complicated capture and cooling schemes). Pions would be produced by proton collisions on a target and then transferred directly into the decay ring. The detector would be a 1.3 kT MINOS-like magnetized iron tracking calorimeter. This proposal is based largely on already-existing technology, and therefore could be delivered quickly and with minimal risk. The resulting sensitivity to appearance is shown in Fig. 4.14. This proposal would produce $\sim 10\,\sigma$ sensitivity to appearance, allowing a truly definitive test of the claimed LSND/MiniBooNE effect.

4.7 Absolute Neutrino Mass

Neutrino oscillations experiments measure only the differences in the masses of the mass eigenstates, however their absolute mass is a topic of great interest to particle physics and astrophysics. There are three methods of trying to measure the absolute mass which have the sensitivity to add interesting new information on the time scale of this strategy—astrophysical determinations, kinematic measurements, and neutrinoless double-beta decay.

4.7.1 Astrophysical Determination of Neutrino Mass

Neutrinos created in the Big Bang are the second most numerous particles in the Universe (after the CMBR photons). In the early Universe the neutrinos are relativistic and free-stream, and if they have mass they constitute a significant fraction of hot dark matter that tends to prevent matter from clumping and damps structure formation. This can leave an imprint on the large scale structure of the universe, and therefore cosmological measurements of the matter distribution in the universe as a function of time are potentially sensitive to the mass of neutrinos (or rather, at the current levels of

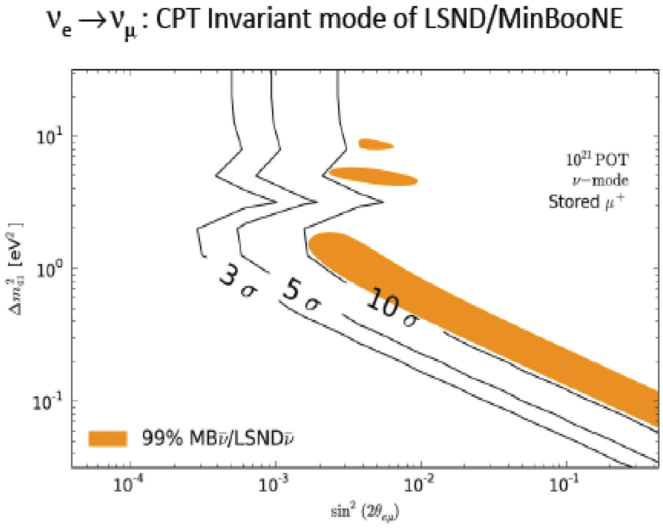

Figure 4.14: Sensitivity of νStorm to electron neutrino appearance via the CPT invariant appearance channel.

precision, to the sum of the masses of the three mass eigenstates). There is at present no hint for non-zero neutrino masses from cosmology, however the precise bound that can be derived from data strongly depends on the cosmological model assumptions. At present, the most conservative and least model-dependent bounds are slightly below ~ 1 eV at 95% CL for the sum of the neutrino masses Σm_ν [95]. Future data from Planck combined with galaxy redshift surveys and weak gravitational lensing observations could improve the sensitivity of these determinations down to $\Sigma m_\nu < 0.04$ eV in the most optimistic case [95], which would in principle begin to give sensitivity to the MH (as the IH, with two heavy neutrinos and one light neutrino, produces roughly twice the contribution to the mass density as the NH), however proving that any effect seen is not in any way dependent on potential over-simplification of the assumed cosmological model will be challenging.

4.7.2 Kinematic Measurements of Absolute Neutrino Mass

The classic, and most model-independent, way to measure neutrino masses is by decay kinematics. With the measurements of the Δm^2_{ij} values in oscillations it is now clear that only measurements of electron neutrinos offer useful sensitivity. The most sensitive measurements come from tritium beta decay, where the current limit is $m_\nu < 1.8$ eV (95% CL). An ambitious new experiment, KATRIN, in being commissioned in Karlsruhe with a goal of reaching sensitivity such that (if no effect is seen) they will set a limit of $m_\nu < 0.2$ eV. Very strong scaling arguments exist making it very difficult to extend this technique further, so KATRIN is likely to be the last tritium beta decay experiment built with a magnetic spectrometer. Another project, called Project 8, is being developed which would measure the electron energies by looking at their synchrotron emission in the radio, which can evade those scaling laws and in principle offer greater sensitivity. Another method, using cryogenic bolometers, is also being developed but as of yet cannot

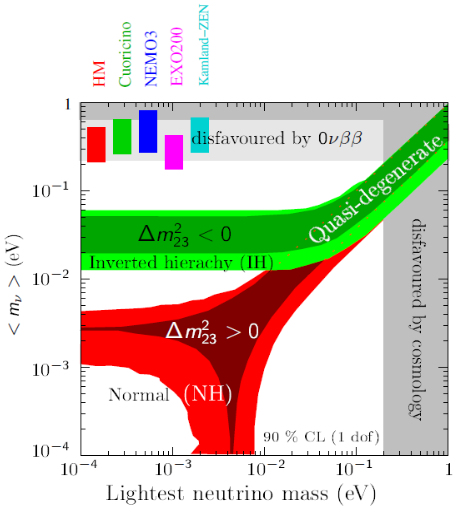

Figure 4.15: Results for the current round of $0\nu\beta\beta$ experiments. HM is the Heidleberg-Moscow ^{76}Ge experiment. The definition of the axes is provided in the text. Figure provided by Francois Mauger.

approach the sensitivity from tritium beta decay.

4.7.3 $0\nu\beta\beta$ Decay

As mentioned in Section 4.1 above, if neutrinos are Majorana particles another process which is extremely sensitive to the absolute mass of neutrinos ($0\nu\beta\beta$ decay) becomes possible. It is hard to overestimate the importance of searches for $0\nu\beta\beta$ decay, as its discovery would not only determine the absolute mass of neutrinos, it would demonstrate the existence of an entirely new type of fundamental particle (a Majorana particle). The experimental signature of $0\nu\beta\beta$ decay is the emission of two electrons from the same decaying nucleus with a discrete summed energy equal to the endpoint energy of the electrons emitted in the competing Standard Model process of $2\nu\beta\beta$ decay. Two main types of $\beta\beta$ decay experiments exist, one where the decaying nucleus is the detector (such as an intrinsic Ge detector measuring the $\beta\beta$ decay of ^{76}Ge), and one where this nucleus is in a source foil viewed by a separate electron detector (such as the NEMO3 experiment, which has made beautiful studies of $0\nu\beta\beta$.

The current experimental situation is summarized in Fig. 4.15. The effective mass parameter controlling the $0\nu\beta\beta$ decay rate from Eq. (4.6) is plotted against the mass of the lightest mass eigenstate. Given the known neutrino mixing parameters the right answer (for Majorana neutrinos) must lie in either the green (IH) or red (NH) bands on the plot. Limits on the rates for $0\nu\beta\beta$ translate into limits on $\langle m_\nu \rangle$, however there is a range of values caused by uncertainties in the nuclear matrix elements for each transition (which are only known from calculation). Thus, each experimental result produces a range of limits (or, if $0\nu\beta\beta$ is finally observed, a range of values) shown by the coloured bars for each experiment. At the moment experiments are probing the quasi-degenerate regime where the neutrino masses are larger than their splittings, however the next generation of experiments should begin to probe the IH region [ID14]. There is thus a strong synergy between long-baseline experiments and $0\nu\beta\beta$ decay experiments, as if the IH is demonstrated by long baseline but $0\nu\beta\beta$ is not observed for values of $\langle m_\nu \rangle$ down to 10^{-2} eV the explanation of neutrino masses via a high-energy Seesaw mechanism would be ruled out together with the simplest leptogenesis mechanisms. On the other hand, if long-baseline experiments demonstrate the NH it will set an ambitious target for the size of necessary $0\nu\beta\beta$ experiments (or if $0\nu\beta\beta$ is observed in the next round of experiments it will provide a strong hint to the long-baseline experiments that the IH is the correct solution).

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[ID10] Contribution 10: “Fundamental Science at the European Spallation Source”

[ID11] Contribution 11: “Conclusions from the NUTURN 2012 Workshop”

[ID14] Contribution 14: “NEXT a high-pressured Xenon-based experiments for ultimate sensitivity to a Majorana neutrino”

[ID19] Contribution 19: “The Canfranc Underground Laboratory (LSC)e”

[ID24] Contribution 24: “A realistic next-generation nucleon decay and neutrino experiment capable to probe leptonic CP violation”

[ID29] Contribution 29: “NA61/SHINE plans beyond the approved program”

[ID35] Contribution 35: “Input to the European Strategy for Particle Physics from the EUROnu FP7 Design Study of a High Intensity Neutrino Oscillation Facility in Europe”

[ID38] Contribution 38: “Search for anomalies in the neutrino sector with muon spectrometers and large LArTPC imaging detectors at CERNe”

[ID42] Contribution 42: “ORCA: Oscillation Research with Cosmics in the Abyss”

[ID70] Contribution 70: "LENA - Low Energy Neutrino Astronomy"

[ID74] Contribution 74: "A new CERN long baseline conventional neutrino beam (CN2PY) aimed at a deep underground research infrastructure for large scale detectors at Pyhasalmi: an opportunity for Particle and Astroparticle Neutrino and Grand Unification Physics"

[ID82] Contribution 82: "Proposal to use a high intensity neutrino beam from the ESS proton linac for measurements of neutrino CP violation and mass hierarchy"

[ID86] Contribution 86: "The Hyper-Kamiokande Experiment"

[ID108] Contribution 108: "nuSTORM: input to the update of the European Strategy for Particle Physics"

[ID121] Contribution 121: "Future Strategy of Japanese High Energy Physics Community"

[ID149] Contribution 149: "Opportunities for Collaboration at Fermilab: The MicroBooNE Experiment"

[ID150] Contribution 150: "The Long Baseline Neutrino Experiment"

Chapter 5

Strong Interaction Physics

Relevant talks at the Open Symposium were given by H. Appelshaeuser and P. Newman, and further contributions to this chapter were given by B. Badelek and A. Cooper-Sarkar.

5.1 Introduction

The strong interaction is responsible for the existence of nucleons and nuclei, and for their interactions. Strong interactions also determine the mass spectra of hadrons and their internal structure through the interactions among their constituents, the quarks and gluons. A detailed understanding of strong interactions is therefore important for our comprehension of the Universe. That is why we aim for investigations of phenomena mediated by the strong interaction for the widest possible selection of processes and over the widest possible energy range.

The theory of Strong Interactions, Quantum ChromoDynamics (QCD), was established almost 40 years ago. The key features of QCD, resulting from the non-abelian gauge group, are "asymptotic freedom" in the high energy limit and "colour confinement" in the low energy domain. The former implies that the coupling constant of the strong interaction decreases for increasing energies (momentum transfers), providing a framework for accurate perturbative predictions for hadronic cross-sections. This aspect is crucial for exploring new phenomena at the high energy frontier: at the LHC, in high energy cosmic ray studies, as well as with future lepton colliders. Asymptotic freedom also implies the existence of a new state of matter, the quark-gluon plasma (QGP), which existed in the early universe until about 10 μs after the Big Bang and where quarks and gluons roam freely (are "deconfined"). Its properties can be studied by colliding atomic nuclei at high energy fixed target and collider accelerators. To-date there is, despite tremendous progress, still no in-depth understanding of the nature of quark confinement, of the transition from a confined hadron gas to a deconfined QGP, and of the detailed structure of hadrons in terms of quarks and gluons. In particular, for the partonic structure of hadrons, described in terms of Parton Distribution Functions (PDFs), QCD provides only a prediction of the evolution of their structure with the energy scale. Determination of PDFs, which are an indispensable ingredient of cross section calculations for hadronic interactions, has to be based on experimental data.

Enormous progress in our understanding of strong interactions and the description of the structure of proton was due to important contributions by the H1 and ZEUS experiments at the HERA facility, running from 1992 to 2007. Almost 1 fb^{-1} of data on

Deep Inelastic electron- and positron-proton Scattering (DIS) have been used both to investigate predictions of the theory of the strong interaction and to determine parton distributions within the proton. While fixed-target measurements still give significant constraints, data from HERA dominate all current QCD analyses aiming at parametrization of proton PDFs. This is mainly because of their large coverage in kinematic range: in Q^2 (the negative of the invariant mass squared of the exchanged virtual boson) from below 1 GeV^2 up to about $3 \cdot 10^4$ GeV^2 and in Bjorken x from 0.4 down to about 10^{-6} (10^{-4} for $Q^2 \geq 1$ GeV^2), much extended compared to the fixed-target deep inelastic experiments, which only covered a Q^2 range up to about 200 GeV^2. Furthermore, by combining data on electron and positron scattering, as well as on charged current (CC) and neutral current (NC) processes, additional information on flavour composition could be gained. All data collected at HERA are very well described by QCD evolution and the resulting PDFs were successfully used to describe data on jet, as well as W and Z production at the Tevatron and the LHC. Still, extrapolation of PDFs to the LHC kinematic range results in significant systematic uncertainties for many precision measurements and searches.

In the field of QGP enormous progress was made by the four major experiments BRAHMS, PHENIX, PHOBOS, and STAR, operating at the RHIC accelerator in the USA. In particular, the RHIC experiments discovered the “jet quenching” phenomenon, implying large parton energy loss in the QGP, and established the “ideal fluid” scenario by demonstrating that the fireball formed at RHIC energy behaves more like an ideal fluid than a weakly interacting gas of quarks and gluons.

Since the Fall of 2010 dramatic new progress was made by the LHC experiments ALICE, ATLAS, and CMS with the start of the Pb beam program at the LHC. Because of the excellent preparation of all three experiments and impressive performance of the LHC accelerator striking new results were obtained very quickly, particularly for high p_T processes as well as in physics with heavy quarks and quarkonia.

On going research in strong interaction physics has two main goals. The first is to understand the basics of QCD and address fundamental questions such as as the nature of confinement, the generation of hadron masses, the existence of exotic QCD states (glueballs, hybrids, pentaquarks, instantons), and the elucidation of the origin of the spin of the nucleon. The search for novel physics at high parton densities (issue of high energy unitarity) and for the possible unification of coupling constants constitutes another active research field. A major priority is also the investigation of the behaviour and properties of hadronic matter and the QGP at very high densities and/or temperatures, as is investigated with high energy heavy-ion collisions, in particular at the US RHIC collider and at the LHC. The second class of goals is of more practical concern, related to the knowledge which is needed for particular measurements or experiments, such as the determination of proton (also photon, pomeron, nuclear) parton densities, the modeling of hadronisation and fragmentation processes, the description of underlying events, as well as the study of multi-parton interactions and diffraction. The results of these studies will contribute to the development of a more detailed description of hadron structure and to more accurate Monte Carlo simulation tools, with the goal to model hadron interactions with increasing precision. Both experimental input and theoretical development are needed here.

It is clear that, in the coming years, the majority (though not all) of the new results concerning strong interactions will come from the LHC experiments. In fact, most QCD studies do not need ab^{-1} level luminosities, as the corresponding cross sections are large.

On the contrary, the large pile-up coming with high-luminosity running (~ 200) may be prohibitive for some studies, especially those requiring low energy thresholds (jets at low and moderate p_T, forward physics, low-x parton densities). Therefore, short dedicated runs with small pile-up may be needed for precision QCD studies and to reduce systematic uncertainties.

Both in the case of the envisioned High Energy LHC (HE-LHC) upgrade ($\sqrt{s} \sim 33$ TeV) as well as at a possible future *pp* collider in a new 80 km tunnel ($\sqrt{s} \sim 80$ TeV) we can expect that the detailed studies of QCD and related phenomena will continue. However, no dedicated studies were presented so far.

Various proposed lepton collider configurations would provide a clean environment to measure α_s and other fundamental QCD parameters via e.g. event shapes or jet studies. Also top quark and heavy-flavour production, multi-jet final states and other precision QCD topics can be investigated. The clean environment and high measurement precision possible with e^+e^- colliders make them a perfect testing ground for further verification of NNLO or NN(N)LL QCD predicitions, as well as for studying fragmentation, hadronisation etc.

Submitted to the strategy update were also proposals for new research infrastructures mainly dedicated to studies of strong interactions. The “Report on a Large Hadron Electron Collider at CERN (LHeC)” [ID147, 12] opens a perspective for very detailed measurement of the partonic structure of nucleons and nuclei in completely new kinematic domains and with precision vastly surpassing what was achieved at HERA. There are also proposals for “A Fixed-Target ExpeRiment at the LHC (AFTER@LHC)” [ID117] and for a “New *ep* collider based on the SPS” [ID12]. Research programmes related to strong interaction physics were also submitted by numerous existing and/or approved experiments. Selected prospects for QCD measurements within these projects are described in the following sections.

5.2 Parton Densities

5.2.1 Deep Inelastic Scattering

The most precise and complete information on parton distribution functions of the nucleon is obtained from global fits to large sets of data, combining measurements of different electro- and hadroproduction processes: deep inelastic scattering (DIS), Drell-Yan (DY), gauge boson production and jet production. The combination of the information from different processes allows the determination of quark and gluon distributions in the nucleon. The Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations, as derived within QCD, can be used to extract the PDFs, parametrized at a chosen reference energy scale, from the analysis of experimental measurements. The more data are available, coming from diverse processes, collected with different beams and at different energy scales, the fewer assumptions are needed to constrain the parton densities with high accuracy. A recent PDF parametrization developed by the HERAPDF group [15] (see also [16, 17]) includes HERA data on NC and CC e^+p and e^-p DIS cross sections, on the longitudinal structure function F_L, the heavy flavour structure functions F_2^c and F_2^b as well as jet data. Other parametrizations (as MSTW08 [13] or CT10 [14]) include also data from fixed-target experiments (electron and neutrino scattering) and the Tevatron (Drell-Yan, W asymmetry, Z rapidity distribution, inclusive jet cross-sections). Each of the measurements is sensitive to one particular combination of parton densities. It is

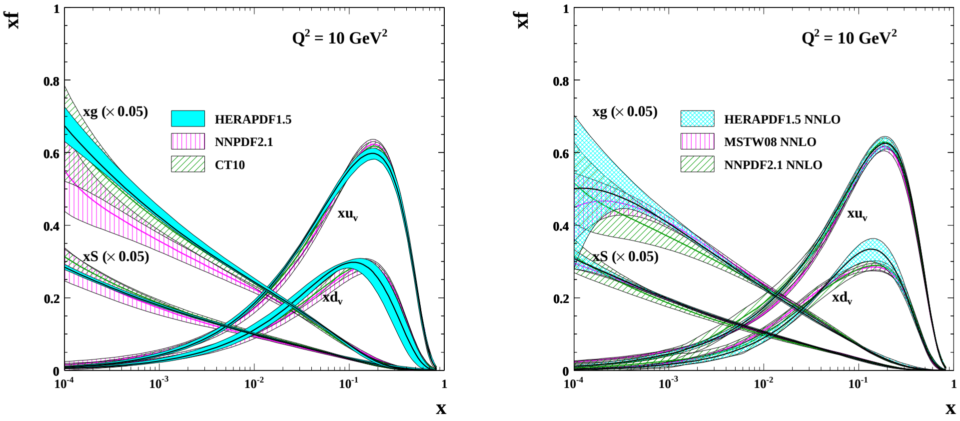

Figure 5.1: Comparison of different PDF parametrizations at $Q^2 = 10$ GeV^2, as obtained at NLO level: HERAPDF1.5, NNPDF2.1 and CT10 (left plot), and at NNLO level: HERAPDF1.5, MSTW08 and NNPDF2.1 (right plot). Indicated bands represent total PDF uncertainties. Adopted from [17].

their combination, together with the QCD evolution equations, which leads to precise information on quark, anti-quark and gluon distributions. A comparison of selected PDF sets including their respective uncertainties is shown in Fig. 5.1. Different parametrizations are largely consistent within the quoted uncertainties. However, as they are based on the same (or largely overlapping) data sets, the observed differences indicate that model assumptions still result in uncertainties. The theoretical uncertainties have been significantly reduced recently, by moving from NLO to NNLO QCD level, and small differences between NLO and NNLO results confirm that there is currently no need to go beyond NNLO. All results indicate that the QCD evolution equations discussed above work very well in the kinematical domains explored so far, and the precision of the calculated parton densities depends solely on the quality of input data. The largest uncertainties are visible for gluon densities at low and very high x, where also differences between parametrizations are largest. This is because gluon densities are not directly measured in NC DIS and are mainly constrained from the PDF evolution.

Unfortunately, DIS measurements at HERA and at fixed target experiments cover only a part of the kinematical domain where accurate PDF modeling is required for LHC experiments, as shown in Fig. 5.2 [19]. In particular, the luminosity delivered by HERA was not sufficient for precise cross section measurements in the high-x ($x > 0.4$) domain and PDF determination is statistically limited there. There are high-x measurements available from the fixed target experiments, but they are subject to additional uncertainties due to nuclear corrections and are primarily sensitive to quark densities. Also, in the case of low-x ($x < 10^{-4}$) DIS measurements, the limited Q^2 coverage results in an insufficient lever-arm in PDF evolution for gluon density determination with high precision. Moreover, high precision HERA NC DIS data are only weakly sensitive to the quark flavour decomposition in the proton and this information can only be accessed with statistically limited measurements at the highest Q^2 and CC DIS, or from direct measurements of heavy flavour production. Data on fixed-target DIS measurements with neutrino beams would allow access to flavour information but they are again statistically

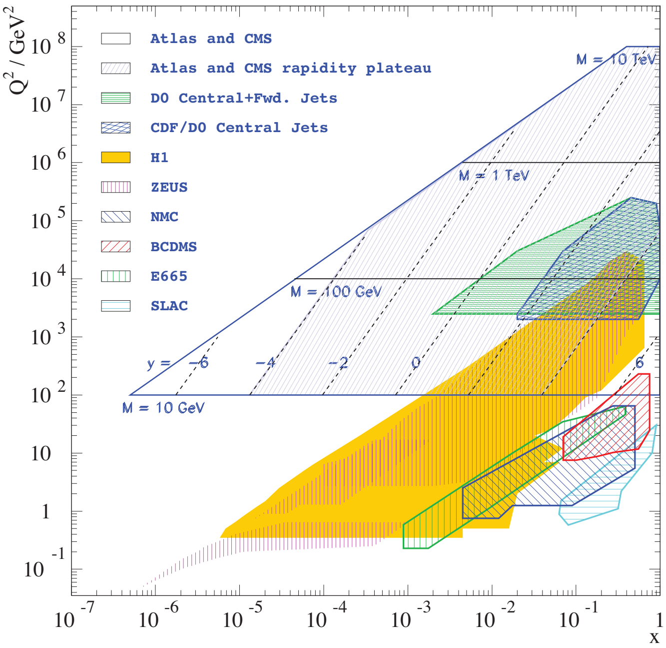

Figure 5.2: Kinematic coverage of the DIS and collider $pp/p\bar{p}$ experiments. For pp and $p\bar{p}$ colliders, the Bjorken x and Q^2 scale are those corresponding to the production of the Drell-Yan pair with mass M at rapidity y [19].

limited. As a result, PDF uncertainties significantly affect many theoretical predictions for Standard Model processes at the LHC, including Higgs boson production, as estimated with the currently available parametrizations [ID174, ID177]. Also searches near the LHC kinematic boundary may become limited by uncertainties in SM background predictions due to PDF, especially if they involve contiuum measurements. For future precision measurements and for searches for New Physics phenomena, especially in the High Luminosity LHC phase (HL-LHC), more precise PDF determination in the LHC domain than is possible with currently available data would be useful.

Experiments at the LHC, and at the High Energy Frontier in general, are sensitive to quark (anti-quark) and gluon momentum distributions in the nucleon and its quark flavour decomposition. However, there are many processes which reveal much more details of the complicated structure of the proton. One of the fundamental problems which is still far from being well understood is how the quark and gluon spins and their orbital angular momentum contribute to the spin $\frac{1}{2}$ of nucleons. Dedicated measurements were performed for the last 25 years to constrain quark and gluon contributions to the nucleon spin. The quark contribution is now confirmed to be around 30%, while the average gluon polarisation measured is small, consistent with zero within large uncertainties. This leaves a large orbital angular momentum in the proton as currently the only possible explanation of the "proton spin puzzle", but this still remains to be demonstrated experimentally.

Nevertheless, emphasis on nucleon structure studies is being shifted from longitudinal spin structure functions to transversity and observables sensitive to correlations between partons. One of the main experimental targets, which could help us to access the quark angular momenta in the proton, are measurements of Generalised Parton Distributions

(GPDs). GPDs correlate the longitudinal momenta of partons with their transverse positions and are often referred to as “nucleon tomography” or “3D distributions”. They can be measured with Deeply Virtual Compton Scattering (DVCS) or Deeply Virtual Meson Production (DVMP; also referred to as Hard Exclusive Meson Production, HEMP) processes in DIS experiments. Generalized Parton Distributions provide a much more comprehensive description of the partonic structure of the nucleon than the “standard” distributions of parton densities in longitudinal momenta (1D PDFs) though experimental knowledge is very limited so far. Additional information about nucleon structure can be obtained by studying parton transverse-momentum-dependent (TMD) effects, which can be accessed with spin and azimuthal asymmetries in semi-inclusive deep inelastic scattering (SIDIS) and polarised Drell-Yan (DY) processes. Comparison of the TMD PDFs extracted from SIDIS and DY data will be a crucial test of QCD in the non-perturbative regime. In particular, the fundamental prediction of QCD is that the Sivers and the Boer-Mulders TMD PDFs should reverse sign between these two reactions. At the moment, the precision of TMD PDF and GPD measurements is much worse, compared to the “standard” PDFs, and a dedicated experimental effort is clearly needed in this domain.

One experiment which is planning to address these issues in the coming years is COMPASS [ID60]. The first COMPASS measurement of TMD PDFs was based on deuteron SIDIS data collected in 2004 and showed strong kinematic dependencies, which should be studied in detail. The approved running programme for 2014 includes determination of TMD PDFs from the measurement of Drell-Yan muon pairs via negative pion scattering off a polarised target. The results can be compared with the previous SIDIS analysis. However, to reduce statistical uncertainties, measurements of azimuthal asymmetries for π and K mesons in SIDIS are also planned in 2015 and 2016. With full statistics, a complete decomposition of TMD PDFs over 4 kinematic variables can be achieved with high accuracy. This will be done in parallel with the programme for GPD measurement via DVCS and DVMP. The pilot DVCS run took place in November 2012. Proposals for future COMPASS running, beyond 2016, include additional measurements with a deuteron target (higher statistics needed for QCD analysis) as well as measurements of DY production with light and heavy nuclear targets [ID60].

The COMPASS experiment presented a unique programme for hadron structure and spectroscopy measurements till at least 2020. It is complementary to other existing and planned infrastructures worldwide. Outside Europe, the study of GPD and TMD PDFs will also be possible at JLab and BNL. The approved CEBAF upgrade at JLab will allow scattering of an intense 12 GeV electron beam off diverse targets, with focus on high-x nucleon and nuclear structure, nucleon tomography, meson spectroscopy and confinement. At RHIC, nucleon spin and GPD studies are planned with polarised pp scattering at $\sqrt{s} = 500$ GeV.

5.2.2 Parton Densities at the LHC

As already mentioned above, parton distribution functions are a crucial ingredient for the LHC physics programme. Much progress in the PDF determination has been made in the last years, in terms of additional constraints from different data sets, improved theory calculations as well as updated methodology and statistical treatment of the QCD fits. However, PDF systematics are still expected to dominate both experimental and theoretical uncertainties in a number of cases. Many measurements at LHC would benefit greatly from reducing the PDF uncertainties. They include Higgs production, precision EW observables, heavy flavour production and searches for new physics. With the expected performance of the HL-LHC a much higher level of precision in PDF analyses will be needed, to match the experimental needs.

It is clear that the LHC experiments will accumulate themselves large amounts of data which can be used to constrain parton densities in the proton. In fact, each relevant aspect of the proton PDFs can be addressed with a dedicated measurement. A preliminary review presented by the CMS collaboration [ID177] indicates that the following measurements can be used to reduce PDF uncertainties at LHC: inclusive jet and dijet production (can be used to constrain quark and gluon densities at large x), W/Z, and double-differential Drell-Yan pair production (quarks at medium and small x, and quark flavor separation), top-quark distributions (gluons at medium and large x), single-top-quark production (gluon and bottom-quark PDFs), direct photon productions (gluons at medium and small x), transverse momentum of the Z boson (quarks at small x), W production in association with jets (gluons at small x), $W + c$ production (strange-quark PDFs), $Z + c$ and $\gamma + c$ production (intrinsic charm PDFs). Several of these measurements can be performed already in the near future, as they do not require high luminosity.

Already with the first LHC data collected at 7 TeV some constraints were obtained: the CMS analysis of electron charge asymmetry in inclusive W production could discriminate between different PDF models considered in calculating Standard Model predictions [2], whereas the ATLAS collaboration was able to estimate the ratio of the strange to down sea quark distributions from measurements of the $W \to l\nu$ and $Z \to ll$ cross sections [1], although with large uncertainty. Also a recent global QCD analysis including LHC data demonstrated that LHC data are likely to play an increasing role in future refinements of PDF sets [18]. With the excellent performance of the LHC and its experiments, not only data on the usual inclusive processes will become more precise, but also new processes will be incorporated. However, systematic uncertainties are expected to dominate and it is not clear to what extent LHC experiments will be able to give model independent PDF constraints.

Dedicated studies on the LHC potential in constraining PDFs are ongoing. Without further detailed analysis, taking into account all relevant experimental and theoretical aspects, it is currently not possible to judge if LHC data by themselves will be sufficient to constrain PDF uncertainties to the level comparable with statistical and theoretical ones.

5.2.3 A Large Hadron Electron Collider at CERN

The proposal "A Large Hadron electron Collider at CERN (LHeC)" contains a programme for a next-generation high energy electron-proton and electron-ion collider [ID147, 12]. In its default design configuration LHeC uses a 60 GeV electron beam of high intensity, accelerated using two 10 GeV Energy Recovery Linacs (ERL) in a racetrack configuration, for collisions with the intense, high energy beam of the LHC. The main processes to be studied are deep inelastic ep and eA scattering, which is the cleanest probe of a partonic structure of nucleons and nuclei. LHeC is expected to exceed the luminosity of HERA by a factor of 100 and extend the energy reach to a maximum Q^2 of above 1 TeV^2, as compared to a maximum of 0.03 TeV^2 at HERA. For eA scattering the extension of the kinematic coverage amounts to nearly 4 orders

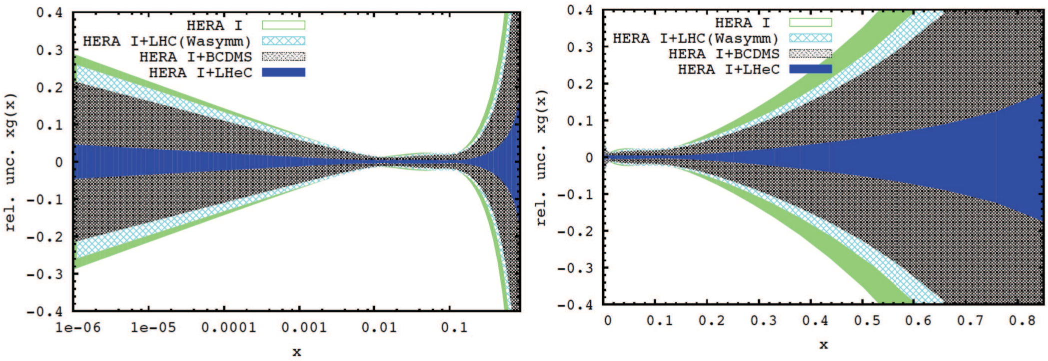

Figure 5.3: Relative uncertainty of the gluon distribution at $Q^2 = 1.9$ GeV^2, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x scale, right: linear x scale [ID175].

of magnitude in Q^2 and x, as nuclear targets were not available at HERA. With such a high collision energy accurate measurements in the perturbative domain are possible down to $x \sim 10^{-6}$ (for $Q^2 \approx 1$ GeV^2) .

The high luminosity and the wide kinematic coverage, overlapping to a much higher extent with the LHC kinematic domain than was the case for HERA, will provide very precise PDF constraints, complementing and extending what can be done at LHC. QCD analysis of LHeC data will include not only very precise measurements of NC DIS (sensitive to electroweak corrections at high Q^2) but also jet and heavy quark production cross sections. LHeC should be able to provide the neccessary constraints on all parton (quark and gluon) distributions to determine them completely, free of any QCD fit assumptions, which has hitherto not been possible. It is clear that LHeC will allow determination of PDFs with even higher precision than is possible at the LHC and with much smaller theoretical uncertainties. In particular, the gluon density can be precisely mapped between $x \sim 10^{-5}$ and almost 1, as shown in Figure 5.3 [ID175]. This spans the currently inaccessible regions of low x, where saturation effects are expected, and high x, where precise PDF determination of the gluon density will be essential for some LHC searches close to the kinematic boundary.

The LHeC by its nature is an upgrade to the LHC, but the design is built on the assumption that the LHC will continue to run in *pp* mode when an electron beam becomes operational. This would allow to maximize the possible impact of LHeC on the LHC exploration potential and significantly reduce running costs. As proposed in the LHeC CDR [12] the accelerator and experiment installation could already take place during the long shutdown LS3 currently scheduled for 2022/23, with no extra downtime to the overall HL-LHC programme. However, this schedule has to take into account plans of the ALICE collaboration [ID128, ID55], which assume collection of at least 10 nb^{-1} for Pb–Pb collisions, implying ALICE running until the mid 2020ties, following its detector upgrade in LS2.

As described above, significant PDF information can be extracted from the LHC data itself, although the systematic uncertainties are likely to dominate. Detailed requirements of the HL-LHC physics programme concerning the precision of PDF determination have not been presented yet. Substantially more detailed studies on the LHC side are needed to ascertain the value added by the LHeC to the main physics goals of the LHC.

In addition to the PDF studies, LHeC has a very rich and diverse physics programme by itself, addressing variuos important aspects of strong interaction physics. The broad programme includes the exploration of the high-density, low-coupling parton regime at low x, where parton saturation is expected, experimental determination of α_s at the per mille level and an unprecedented precision and kinematic coverage of the partonic structure of nuclei. The knowledge of nuclear PDFs from DIS is currently limited to fixed target data. With eA scattering LHeC will provide a huge extension of kinematic range (4 orders of magnitude in x or Q^2) covering lower x for nuclear PDFs than achievable in pA at LHC. Clean final states and reduced theoretical uncertainties will again allow for a detailed flavour decompostition of nuclear PDFs. The low x saturation effects are expected to set in earlier in nuclear PDFs than in their proton counterparts, and comparison between ep and eA scattering can reveal new effects pointing, e.g., to the breakdown of factorisation, new dynamics of high parton densities or the physics of the Color Glass Condensate (CGC). Understanding the low x proton structure is also important for precision studies of cosmic ray air showers and ultra-high energy neutrino interactions. These aspects, combined with a competitive sensitivity to new physics in channels where initial state lepton quantum numbers are an advantage, make the LHeC a very interesting option for the future. Some of the LHeC measurements not related to PDF determinations will be discussed in the following sections. The detailed directions of that programme will surely be influenced by the results of future LHC running campaigns.

5.2.4 Other projects

Two proposals for an Electron Ion Collider (EIC) are also considered in the US: at JLab (ELIC) and at BNL(eRHIC). Both machines would operate at rather low energy (at most half of the HERA CMS energy, an order of magnitude below LHeC), but with > 100 times HERA luminosity. Moreover, the use of polarised protons would allow detailed spin structure studies, as well as GPD determination in the new kinematic regime. For eA scattering EIC would still result in a large step forward in kinematic range, compared to data from fixed target experiments available today.

Detailed information on the isospin asymmetry of the quark sea could also be obtained in AFTER@LHC, from precision measurements of Drell-Yan pairs with LHC protons scattered on both hydrogen and deuterium targets. Moreover, independent determination of the gluon content in the proton and the neutron should be possible, based on the measurement of quarkonium production and prompt photons [ID117]. A programme focusing on the exploration of the structure of nucleons and nuclei by elastic and inelastic scattering of electrons was also proposed in [ID12]. The concept of the experiment assumes scattering of 20 GeV electron beam from an ERL on protons and ions from the SPS or PS. Detailed study of inclusive quark and gluon structure functions, fragmentation functions, flavour effects and nuclear media effects would be possible for Q^2 from $4 \cdot 10^{-6}$ to $4 \cdot 10^{2}$ GeV^2. One of the main goals of the proposed programme is also to study effects related to the phenomenon of confinement.

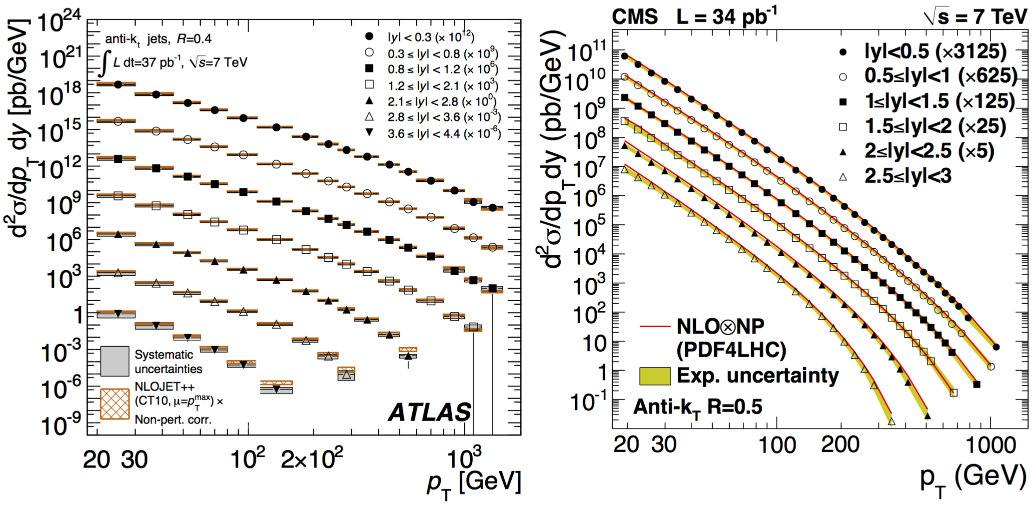

Figure 5.4: Inclusive jet cross sections as a function of jet p_T in different regions of rapidity y, for pp scattering at $\sqrt{s} = 7$ TeV, as measured by ATLAS [4] (left) and CMS [3] (right).

5.3 Other QCD Studies at LHC and Future Accelerators

Modeling of the partonic structure of the proton is a key element of all physics studies at the LHC as it is required for proper description of the collision initial state. Similar is the case for all existing and future collider and fixed target experiments, except for lepton colliders. However, for most processes being studied strong interactions contribute also to the scattering process itself, as well as to the final state formation. This opens a wide range of possibilities for detailed tests of perturbative and non-perturbative QCD predictions.

5.3.1 Jet Production

As already mentioned above, jet production measurements at LHC can provide significant constraints on the quark and gluon densities in the proton. In addition, jet and multi-jet cross sections are also important tools for understanding the strong interactions and testing QCD predictions. The kinematic domain for these studies has been significantly extended at the LHC, both in jet transverse momentum and in rapidity, compared to the previous measurements at the Tevatron. Already with 2010 LHC data, inclusive jet and dijet cross sections were measured over two orders of magnitude in p_T, spanning ten orders of magnitude in cross section values, see Fig. 5.4. Comparison of results to NLO pQCD calculations, as well as to parton shower Monte Carlo simulations with NLO matrix elements showed significant effects of the parton shower in some regions of the phase space. Studies of dijet production at highest invariant masses, probing parton densities at largest x and at largest virtuality scales, seem to be particularly important for a detailed understanding of soft gluon radiation. This is because, due to phase-space limits, the PDFs evolve with strongly suppressed real gluon emissions in this region [ID144]. These studies will profit from the high luminosity LHC running.

On the other hand, jet production at low p_T is more sensitive to non-perturbative QCD effects. With decreasing minimum jet transverse momentum required, the jet cross section, as given by perturbative QCD, should rise and eventually overshoot the total inelastic pp cross section. For LHC running at $\sqrt{s} = 14$ TeV this should happen for p_T around 4–5 GeV/c. Proper cross section behaviour can be restored by a combination of multi-parton interactions, gluon saturation and color screening effects which are expected to be maximal around a “saturation scale” of a few GeV [ID144]. The luminosity required for relevant measurements is small, since the cross section is very large, but the pileup has to be minimal in order to be able to measure jets down to the minimum p_T reachable. A short dedicated low-pileup run with integrated luminosity of the order of 0.1 pb^{-1} would be required for these studies. Signatures of double parton scattering and multi-parton interactions can also be searched for at high luminosities with double J/Ψ [37] or Υ production, double Z production, as well as same sign lepton pairs coming from same-sign W production. Similarly, studies of the charged particle multiplicity dependence of J/Ψ, Υ and open charm production can help to understand the role of multi-parton interactions, as indicated by recent results from ALICE [9] and LHCb [38].

The strength of the strong coupling, α_s is not given by theory, but must be determined by experiment[1]. Within QCD one is only able to predict its energy dependence. Measurements of α_s from different processes, performed at different energy scales, test the global nature of QCD and its characteristic predictions of “asymptotic freedom” and “confinement”. Determination of α_s running in the high-p_T regime from jet production cross sections, in particular from the 3 to 2 jet production ratio is complementary to its extraction from PDF evolution. Measurements at the LHC are likely to be unique in this domain, due to the highest energy scales reachable. Even more precise determination of α_s, down to the per mille level, will be possible at LHeC. Through ultra-precise determination of parton distributions, complemented by measurements of parameters such as the charm mass, experimental uncertainties can be reduced to the required level. A similar level of precision is expected at future lepton colliders from jet production and event shape measurements. These prospects are also a major challenge for the further development of perturbative QCD to the N^{3}LO level, which will be required to match the experimental precision [20].

5.3.2 Forward Physics and Diffraction

The Large Hadron Collider offers an opportunity to study jet production not only at an increased centre-of-mass energy but also with a much wider coverage in rapidity. Jets emitted at small polar angles ($|\eta| > 3$) usually arise from collisions between partons of significantly different momentum fractions, in particular probing the low-x region. New effects in QCD evolution are expected, to limit the rise of low-x parton densities. At high gluon densities we hope to see clear signatures of saturation effects, as well as possible signs of non-linear parton evolution dynamics.

Particularly suited for perturbative QCD tests are measurements of jet pair production, with one of the jets in the forward and one in the central region, or with a large rapidity gap between jets. Corresponding measurements have already been performed with LHC 2010 data [6, 5]. The effects of wide-angle soft-gluon radiation can be studied, as well as the contribution from colour singlet exchange. Such event topologies may also show deviations from the parton radiation patterns expected

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[1] An alternative approach within the framework of lattice QCD is to calculate α_s directly from the QCD lagrangian and Schwinger-Dyson equations. However, precise results of these calculations have to be verified by experiment as well.

from the standard DGLAP evolution equations of QCD, and point to the alternative approaches of e.g. Balitski-Fadin-Kuraev-Lipatov (BFKL) [21], Ciafaloni-Catani-Fiorani-Marchesini (CCFM) [22], or taking into account gluon saturation like Balitsky-Kovchegov (BK) [23], Kutak-Golec-Biernat-Jadach-Skrzypek (KGBJS) [24] and Jalilian-Marian-Ianku-Milhano-Weigert-Leonidov-Kovner (JIMWLK) [25]. Moreover, understanding the dynamics of forward jet production, either with or without accompanying central jets, is essential for modeling multi-jet processes at the LHC. Also in this case dedicated runs with low-pileup would be advisable.

A significant fraction of the total inelastic proton-proton cross section at high energies is attributed to diffractive scattering, mediated, as described in the framework of Regge theory, by a strongly interacting colour-singlet exchange, the so called Pomeron. Since vacuum quantum numbers are exchanged, no particles are produced in a large rapidity range adjacent to the scattered proton, implying a so-called "rapidity gap", which is the signature of diffractive scattering. Hard diffractive processes can be described within perturbative QCD by introducing a concept of diffractive parton distribution functions (dPDFs), which model parton densities in the Pomeron. Diffraction with a hard scale has been studied in proton-antiproton ($p\bar{p}$) and electron-proton (ep) collisions at the CERN SPS, the Tevatron and at HERA. QCD evolution equations were successfully used to describe different hard diffractive processes in ep collisions. In hard diffractive hadron-hadron scattering, suppression of the diffractive cross section was observed, quantified by the so-called "rapidity gap survival probability", which can be of the order of 10% (diffractive dijet production at the Tevatron). First measurements, based on the 2010 data from the LHC, confirm significant contributions from diffractive dijet production for events with a large rapidity gap [7]. Diffractive event generators based on dPDFs from the HERA experiments properly describe LHC events, but their normalisation needs to be scaled down by a factor of ~ 5. LHC experiments, with their large coverage in rapidity, allow very detailed studies of diffractive phenomena. Unfortunately, an unbiased measurement of diffractive processes is only possible in low-pileup running conditions.

Detailed studies of DIS at very low x values, $x \sim 10^{-5}$, where deviations from the DGLAP evolution are expected, are also one of the key points of the LHeC physics programme. The LHeC will offer a huge lever arm in x and also a possibility of changing the matter density at fixed values of x (ep vs eA running). This will allow to pin down and compare the small x and saturation phenomena both in protons and nuclei and will offer an excellent testing ground for theoretical predictions. Unambiguous observation of saturation can be based on comparison between different observables e.g. F_2 vs F_L in ep or F_2 in ep vs eA, and observation of their deviations from the DGLAP evolution. LHeC should be able to distinguish between different parton level models for the onset of non-linear dynamics.

One should however also recognize that part of the saturation physics will also be addressed by the current LHC experiments through the study of pPb collisions. These will provide access to very low x processes, in particular at forward rapidity ($2 < \eta < 5$ for LHCb). First results are expected from the pPb run in early 2013, and the results are eagerly awaited by the nuclear and particle physics community.

Also diffractive processes, as previously at HERA, are expected to play an important role at LHeC. At the LHeC they can be studied in a substantially increased kinematic range, which will allow new insights into inclusive diffraction and low-x dynamics. Structure of the Pomeron, in terms of dPDFs, can be precisely determined, its universality checked and validity of factorization verified. Studying QCD evolution of dPDFs can point to significant non-linear effects, which are expected in diffraction.

5.3.3 Particle spectra

Detailed modeling of strong interactions requires not only adequate understanding of parton densities and hard scattering cross sections, which can be measured on the level of hadronic jets. It is also important to understand how the partonic final state of quarks and gluons produced in hard scattering evolves to form the final state hadrons observed in the experiment. Hadronisation and fragmentation studies based on diverse processes are included in the physics programmes of all collider projects described above. Proper modeling of particle production is crucial for reducing systematic uncertainties in many measurements at the high energy frontier, neutrino experiments, as well as for understanding the Cosmic Ray (CR) spectra at the highest energies. For example, it was pointed out that comparison with LHC data should allow to verify if the "knee" observed in the CR spectra is not due to a change in QCD dynamics at large scales [ID5].

The NA61/SHINE set-up at the CERN SPS is particularly suited for particle spectra measurements, being capable of both precise particle momentum measurements and particle identification. One of the goals of the experiment is a measurement of charged pion and kaon spectra in $p+{}^{12}_{6}\mathrm{C}$ interactions at 31 GeV/c for the T2K neutrino oscillation experiment at J-PARC. After analysis of the full data sample, collected with both thin (4% of a nuclear interaction length) and replica targets, the required precision of 5% on the absolute neutrino flux predictions in the near and far neutrino detectors should be achieved. Future long baseline neutrino experiments in Europe and United States would require corresponding measurements to be performed also at higher energies (400 GeV for LAGUNA-LBNO, up to 120 GeV for LBNE) and for different target materials. Precise hadroproduction measurements in this energy range are possible in NA61/SHINE with only minor upgrades to the detector [ID29].

Better understanding of the structure and dynamics of hadrons is also among the main goals of the COMPASS experiment at the CERN SPS. High-statistics measurements from COMPASS, with a beam of pions, kaons and protons, allow for detailed studies of meson and baryon spectra up to 2.5 GeV/c^2, to verify lattice calculations and search for possible exotic states. Of special interest is a search for exotic mesons which do not fit into the $q\bar{q}'$ scheme of the quark model, but are allowed by QCD: hybrids and glueballs. Several new states have been claimed in the past, but still lack an unambiguous explanation. COMPASS is expected to contribute significantly to understanding the light meson spectrum. Study of Coulomb scattering at very small momentum transfer (Primakoff reactions) also provides a unique tool for testing theory predictions. Future plans of the COMPASS collaboration, extending beyond 2016, include increase of the beam momentum for enhanced production of exotic states, higher luminosity and more efficient kaon tagging for strange and charm hadron spectroscopy. Study of doubly charmed baryon production is also considered, but would require installation of high-resolution Silicon vertex detectors [ID119].

Detailed studied of quarkonia and open heavy-flavour production are also among the goals of the proposed AFTER@LHC. With the similar energy range ($\sqrt{s} \approx 115$ GeV for pp) as RHIC but with luminosity 3 order of magnitude higher, and thanks to high acceptance and energy resolution, AFTER@LHC should be able to carry out precise measurements of most of the S - and P-wave quarkonia. Correlation measurements of quarkonia with heavy flavour productions and prompt photons are also at reach [ID117].

5.3.4 Monte Carlo generators

General purpose Monte Carlo generators are probably the most crucial tools for experiments in HEP, indispensable to fully exploit the experimental data. They combine perturbative theoretical calculations with non-perturbative models and parametrizations based on experimental results. They effectively summarize our theoretical and experimental knowledge about the processes being studied. Their further development, following the advancement in experimental methods and improving precision of measurements, is essential for future progress not only at the high energy frontier, but also in relativistic heavy ion collisions and high energy cosmic rays.

With increasing complexity of the hadronic final states being studied, modeling of strong interactions in the perturbative domain remains a challenge. Precision measurements and searches for faint signals of new physics require generators to be available at least at next-to-leading order both for signal and background processes. Particular emphasis is put on developing algorithms for matching parton showers with NLO, and possibly even NNLO matrix elements for multi-jet processes. It is also important to assure consistent treatment of NLO electroweak corrections. In the non-perturbative regime more effort is required to improve modeling of diffractive processes and multi-parton interactions, as well as correlations and fluctuations in the underlying events [ID106].

As already mentioned above, proper modeling of the hadronic final state on the single particle level is crucial for many measurements. Hadronisation is an intrinsically non-perturbative process, still poorly understood, for which we only have models at present. The general assumption is that the hadron level distributions should correspond to the energy-momentum and flavor distributions at the parton level. The main and most successful approaches are currently string and cluster hadronisation models as implemented in PYTHIA and HERWIG, respectively. Comparison with the first LHC data show that, although most models considered describe general event properties well, none of them is able to reproduce both the p_T and multiplicity quantities simultaneously, especially for production of strange particles [8]. This clearly indicates the need for further experimental studies as well as for model development. Continued coordination of these efforts on European level should be supported to assure that the generator development keeps pace with the requirements of experiments [ID106].

5.4 Relativistic Heavy-Ion Collisions

The field of quark-matter studies and QGP research took on a new dimension with the start of the Pb-beam program at the LHC by ALICE, ATLAS, and CMS. With the campaigns in 2010 and 2011 many new results were obtained in all areas. They are briefly described in the sections below and have led to completely new insights, both in the understanding of the hydrodynamic response of the fireball formed in Pb–Pb collisions, and particularly in the physics of hard probes and quarkonia, where the LHC program offers world-wide unique opportunities. This quite dramatic success has been made possible by the spectacular performance of the LHC as a Pb-Pb collider - already in 2011 the Pb–Pb luminosity exceeded design by a factor of two - and by the excellent detector and analysis performance of all three experiments. This led to very quick publications. By all accounts the results from the LHC heavy ion program have dominated the last two 'Quark Matter' conferences, and many exciting results are in store, once the full energy program starts in 2015.

Meanwhile, the two major RHIC experiments have continued to produce important results at lower energy, focussing more and more on rare probes as well as on a beam energy scan program to elucidate other aspects of the QCD phase diagram. At the center of attention is a search for signatures of a possible critical endpoint in the phase diagram. To date no clear sign of such a structure has emerged, and also the theoretical state of affairs is ambiguous, but it is also fair to say that the relevant energy range between $\sqrt{s_{NN}} = 5$ and 40 GeV has not been well covered.

5.4.1 Future Opportunities for Colliders and Fixed Target Experiments

To plot the course for the intermediate and long term future of the relativistic heavy ion program a town meeting was convened on June 30, 2012 at CERN, with the participation of representatives of all major laboratories and experiments world-wide as well as with a strong part of the theoretical community. Overall more than 160 members of the world-wide heavy ion community attended in person, many more via video-conferences.

As a result of this town meeting, a white paper was produced which contains the major conclusions for the program and was submitted as contribution [ID55] to the ESG list of documents. We summarize the main conclusions here, for a detailed discussion see below and the full document.

1. The top priority for future quark matter research in Europe is the full exploitation of the physics potential of colliding heavy ions in the LHC.
2. At lower center of mass energies where the highest baryon densities are reached, advances in accelerator and detector technologies provide opportunities for a new generation of precision measurements that address central questions about the QCD phase diagram.
3. The complementarity of LHC and RHIC is an essential resource in efforts to quantify properties of the Quark-Gluon Plasma.
4. Dedicated investments in theoretical research are needed to fully exploit the opportunities arising from the upcoming precision era of nuclear research at collider and fixed target energies.

The top priority is reflected in the fact that all three LHC heavy ion experiments now plan to run beyond LS3, with a brief overview given in the three contributions [ID128, ID142, ID144] to the ESG, see also below. In addition, the ALICE collaboration has submitted to the LHCC detailed Letters of Intent on the 'Upgrade of the ALICE Experiment' [10] as well as on the 'Upgrade of the Inner Tracking System' [11]. Both documents were recently endorsed by the LHCC and the ALICE collaboration is now in the process of producing detailed Technical Design Reports, with a timeline for submission in 2013.

All three LHC experiments now plan to make use of increased Pb–Pb luminosities at the LHC with a goal to reach an integrated luminosity of about 10 nb^{-1} by about 2025.

For the RHIC accelerator, physics plans for the coming years have been outlined in a recent town meeting on August 18, 2012 in Washington, D.C., USA, with presentations available on the web [26]. For the future of the European Strategy in this area, it is important to note the complementarity of the RHIC and LHC programs, as outlined above.

At lower center of mass energies fixed target experiments at the Brookhaven AGS and the CERN SPS have explored the energy range between 2 to 200 GeV/nucleon to characterize the transition from a hadronic to a partonic state of matter produced in the collision. With a new approach centered on studies of fluctuations as well as on collisions between smaller mass nuclei, the NA61/SHINE experiment at the CERN SPS and the RHIC Beam Energy Scan program focus on a detailed characterization of fluctuations in hadronic distributions, with the aim to study a possible critical endpoint in the QCD phase diagram. Both the RHIC programs and NA61/SHINE have upgrade programs which are outlined in the US town meeting documents above, and in contribution [ID29] to the ESG, see below.

The study of rare penetrating (electro-magnetic) probes as well as very detailed hadronic probe measurements are planned to be performed in the region of large baryon density at the SIS 100 facility at FAIR. This will allow, in the next decade, the HADES and CBM collaborations to investigate these probes at beam energies up to 10 GeV/nucleon. In the long term, construction of the SIS 300 accelerator at FAIR would extend the energy reach to 35 GeV/nucleon.

Based on existing heavy ion beams at the Nuclotron accelerator, the NICA project at JINR in Dubna will make accessible energies up to $\sqrt{s_{NN}} = 11$ GeV in collider mode at luminosities up to $10^{27}/\text{cm}^2\text{s}$, as well as fixed target experiments with $\text{E}_{Lab} =$ 2–4.5 GeV/nucleon, offering experimental studies in the coming decade which are complementary to the beam energy scan program at RHIC and the programs at FAIR.

In discussions at the heavy ion town meeting at CERN and at the ESG Open Symposium in Cracow in Sep. 2012 it was emphasized that the CERN SPS will remain also in the future the only fixed target accelerator capable of delivering heavy ion beams with energies exceeding 30 GeV/nucleon, and the potential of investigating rare penetrating probes at this machine is attractive. In general, there are still many interesting opportunities at lower energy accelerators, and a good coordination among the various planned programs would be very important.

In the following we briefly describe the major findings of the LHC heavy ion program from the past 2 years. A summary of the major new results from the LHC heavy ion experiments can be found in the proceedings of the two recent Quark Matter conferences in Annecy 2011 [27] and in Washington, D.C., in 2012 [28].

5.4.2 Soft probes and Flow and Hydrodynamic Response of the Medium

Here we collect only the major points on soft probes from the LHC heavy ion programme:

1. the multiplicity per participating nucleons of charged particles in central Pb–Pb collisions increases with energy significantly more rapidly than that in pp collisions, reaching $\text{dN}/\text{d}\eta = 1600$ at $\sqrt{s_{NN}} = 2.76$ TeV.

2. analysis of the production probabilities of non-strange and strange hadrons in central Pb–Pb collisions reveals that they are produced from a thermal state with temperature close to 160 MeV and vanishing baryo-chemical potential as expected

from extrapolation of lower energy results. Surprizingly, proton and anti-proton distributions exhibit a somewhat reduced production probability compared to all other hadrons, which may be related to annihilation close to the QCD phase boundary.

3. detailed measurements of transverse momentum and azimuthal distributions reveal increased radial flow at LHC energy and provide strong support for the 'nearly ideal fluid' scenario also at LHC energy.

4. investigations of higher Fourier components of azimuthal distributions reveal for the first time direct access to quantum fluctuations in the very early state of a nucleus-nucleus collision at very high energy, akin to analysis of fluctuations in the cosmic microwave background of the early universe.

An emerging topic for nucleus-nucleus collisions at collider energies is the investigation of penetrating probes, i.e. particles which participate in electro-weak interactions only. First results have been shown from the RHIC experiments for high p_T photns and from the ATLAS and CMS experiments on the nuclear modification factor for high p_T photons and Z and W gauge bosons. As expected, the results imply little or no modification in the hot and dense fireball. Of particular importance for the study of the QGP and the chiral phase transition is a characterization of the electromagnetic radiation spectrum at low transverse momentum. A first measurement of direct photons in this kinematical domain indicates a significant thermal contribution, pointing to temperatures significantly higher than the critical or transition temperature where hadrons are formed. Much more detailed information can be obtained from the measurement of lepton pairs at low and intermediate invariant masses, providing access to the initial temperature, the partonic equation of state, and the chiral nature of the phase transition. Such measurements, which are complementary to studies of particle production at high transverse momentum and heavy flavors, will become possible at the LHC with the upgraded ALICE detector after LS2.

5.4.3 Hard probes and Quarkonia

Here we collect the major points on hard probes and quarkonia from the LHC heavy ion programme, as presented at recent conferences [27, 28].

We first focus on high transverse momentum particle spectra and jets:

1. the transverse momentum distributions of charged particles in central Pb–Pb collisions are very strongly suppressed compared to appropriately scaled results in pp collisions. The suppression reaches nearly a factor of 10 near a transverse momentum of 6 GeV, then increases until about 50 GeV, where it appears to saturate at a suppression factor of about 2. No such suppression is observed in the first pPb measurements, demonstrating that the effect is produced in the matter (fireball) formed in the collision, and is strongly linked to large parton energy loss in the hot medium.

2. above a transverse momentum of about 10 GeV/c, the suppression factor exhibits little dependence on the hadronic species observed, implying that the partons fragment in the vacuum, after energy loss in the medium.

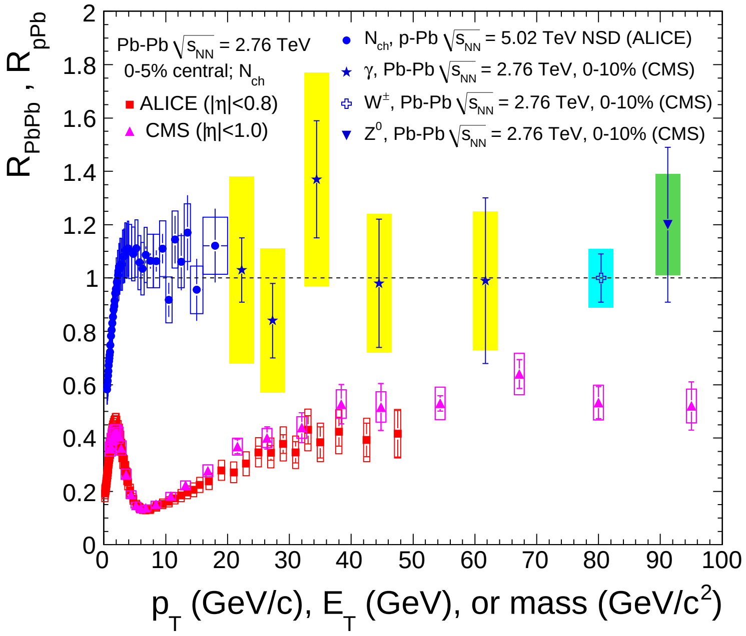

Figure 5.5: Compilation of nuclear suppression factors R_{PbPb} and R_{pPb} for different observed species as function of the transverse scale (p_T, E_T, or M_T. The data are from ALICE pPb [29], ALICE charged particles [30], CMS charged particles [31], CMS γ [32], CMS W [33], CMS Z [34].

3. measurements of reconstructed jets imply suppression of about a factor of two for jet energies up to 300 GeV.

4. studies of electromagnetically and weakly interacting probes such as photons and intermediate vector bosons exhibit no suppression, corroborating the above picture.

To illustrate the dramatic changes observed when comparing pp or pPb collisions with Pb–Pb collisions, we show, in Fig. 5.5 a compilation of nuclear suppression factors R_{PbPb} and R_{pPb} for different observed species as function of the transverse scale (p_T, E_T, or M_T. We observe that the measured nuclear suppression factors are close to unity for pPb collisions as well as in Pb–Pb collisions for weakly or electromagnetically interacting probes (γ, Z, W), strong suppression is observed in Pb–Pb collisions for strongly interacting particles, even for very high values of transverse momentum. As a second example we present, in Fig. 5.6, the large jet quenching (suppression with respect to the pp reference) in Pb–Pb collisions as a function of transverse momentum for different collision centralities. Note that the suppression persists up to very large ($>$ 200 GeV/c transverse momenta. The two examples demonstrate the very strong influence of the fireball (QGP) on strongly interacting probes: the QGP is opaque to even very high momentum partons.

Secondly we report on the most important findings for heavy quarks and quarkonia:

1. measurements of fully reconstructed D mesons show very similar suppression pat-

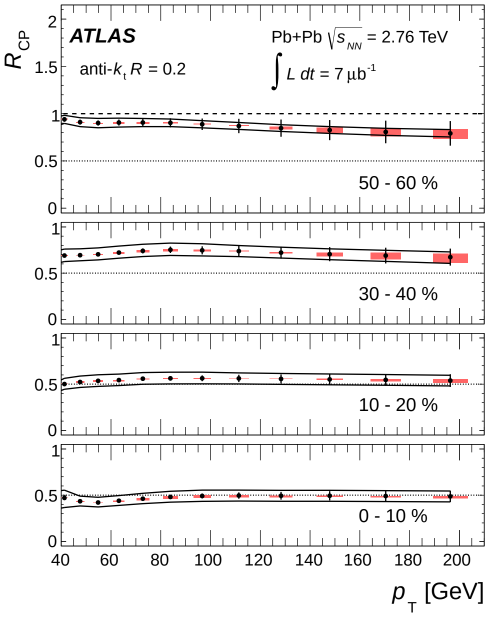

Figure 5.6: Jet quenching via R_{CP} as a function of jet p_T for different centralities, as measured by ATLAS [35]. For details see the ATLAS reference.

terns to those observed for hadrons made from light quarks, implying that charm quarks lose energy nearly at the same rate as other partons.

2. the suppression pattern observed for J/ψ mesons is spectacularly different from that observed for all other hadrons, exhibiting less suppression than measured at lower (RHIC and SPS) energies and little centrality dependence. The pattern is consistent with complete color screening of the charmonium states in the partonic fireball and with their assembly at the QCD phase boundary from previously deconfined charm quarks.

3. transverse momentum distributions of J/ψ mesons exhibit a narrowing with increasing centrality of the collision. This feature is not observed at lower energies, and is consistent with thermalization of charm quarks.

4. the azimuthal distributions of D and J/ψ mesons imply that heavy quarks participate in the hydrodynamic flow of the hot fireball, lending further support to the thermalization scenario.

5. the Υ states exhibit a suppression which increases with increasing excitation energy. The observed pattern is qualitatively akin to a sequential supression in the hot fireball, but also consistent with reduced feeding from excited states. There is little direct indication of thermalization of beauty quarks.

We illustrate, in particular, the striking new phenomena observed in the charmonium sector by presenting, in Fig. 5.7, the transverse momentum dependence of the nuclear

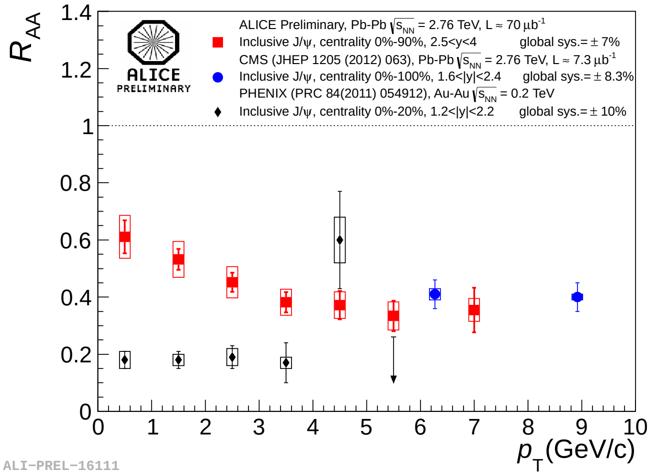

Figure 5.7: Nuclear suppression factor R$_{AA}$ for J/ψ production in central Au–Au (Pb–Pb) collisions. The figure is taken from [36].

suppression factor R$_{AA}$ for J/ψ production in central nucleus-nucleus collisions at RHIC and LHC energy.

Note, in particular, the strongly reduced suppression at LHC energy compared to RHIC results. This observation is consistent with J/ψ production at the QCD phase boundary from previously deconfined charm quarks, following complete color screening.

5.5 Discussion at the Open Symposium

5.5.1 Strong Interactions and QCD at the High Energy Frontier

Most of the discussion during the Strong Interaction Physics session focused on issues related to the LHeC project, its physics case, its complementarity to the LHC, and advantages compared with eRHIC at BNL and ELIC at JLab. It was pointed out that the LHeC is a very flexible precision machine, with a much wider kinematical range compared to eRHIC and ELIC. It is complementary to LHC, allowing for the determination of parton densities with much higher precision. Results from LHeC will motivate theoretical calculations of some observables at NNLO and beyond. Apart from probing a much extended kinematical range as compared to HERA, LHeC will allow the investigation of effects due to saturation of parton densities in *ep* and *eA* collisions, and test probe dependence of the saturation scale.

5.5.2 Relativistic Heavy Ion Collisions

Questions and suggestions on: issues of the future of QGP experiments, fixed target vs. collider experiments, studies of nuclear effects at low energies and specific processes, studies of properties of QGP.

With a general agreement on the major priority for experiments at LHC energy and, in particular, on the high luminosity upgrade of the ALICE experiment, the discussion concentrated on plans for new experiments like NICA at JINR, Dubna, and CBM at FAIR. The special interest in such low energy experiments is the possibility to investigate the phase diagram of QCD also in areas of large net baryon density and to search for signatures of a possible critical endpoint. In this context the availability of the CERN SPS accelerator was also pointed out. This facility covers a much wider energy range than either of the above facilites at substantial luminosities. A coordination of the worldwide strategy for experiments at lower energy should take place, also taking into account the beam energy scan program at the RHIC facility.

The experimental studies at all facilities need to be supported by a strong theoretical effort in the area of QCD and QGP phenomenology and with improved numerical solutions of QCD on the lattice.

5.6 Strategy issues

The following points could be considered in the discussion on the strategy update:

- for the upgrade of the LHC Pb beam program after LS2, luminosities of order $6 \cdot 10^{27}/\mathrm{cm}^2\mathrm{s}$ are essential to reach the proposed physics goals.
- some of the possible LHC measurements, which are crucial for understanding of strong interactions, require dedicated low-pileup running. The resulting loss in the total luminosity is expected to be small.
- dedicated analysis, taking into account all relevant experimental and theoretical aspects, should be performed to give quantitative estimates of the PDF accuracy which can be ultimately reached with the LHC data. This is required for comparison with LHeC capabilities, against the background of the exact requirements of HL-LHC for PDF uncertainties, which should be established as well.
- the LHeC project offers, in addition to the PDF studies motivated by LHC needs, a very rich and diverse physics programme by itself. If the project is to be considered as one of the future collider options, dedicated effort towards the preparation of TDR is needed.
- the fixed target programme at CERN gives a very valuable contribution to research in strong interaction physics. It offers unique measurement possibilities which can not be covered at other facilities.

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[ID12] Contribution 12: “Exploring Confinement”

[ID29] Contribution 29: “NA61/SHINE plans beyond the approved program”

[ID55] Contribution55: “Conclusions of the Town Meeting: Relativistic Heavy Ion Collision”

[ID60] Contribution 60: “COMPASS planned measurements in the next five years and longer term perspectives on the study of the nucleon structure”

[ID106] Contribution 106: “The future of Monte Carlo Event Generators”

[ID117] Contribution 117: “A Fixed-Target ExpeRiment at the LHC: AFTER@LHC”

[ID119] Contribution 119: “COMPASS Plans and Perspectives for Physics with Hadron Beams”

[ID128] Contribution 128: “Long term plans of the ALICE collaboration”

[ID142] Contribution 142: “Future of the ATLAS heavy ion program”

[ID144] Contribution 144: “CMS Submission to the ESPG”

[ID147] Contribution 147: “A Large Hadron Electron Collider at CERN”

[ID174] Contribution 174: “Physics at a High-Luminosity LHC with ATLAS”

[ID175] Contribution 175: “On the Relation of the LHeC and the LHC”

[ID177] Contribution 177: “CMS at the High-Energy Frontier”

Chapter 6

Astroparticle and non-accelerator Particle Physics

Relevant talks at the Open Symposium were given by C. Spiering and S. Katsanevas, who also made contributions to this chapter.

6.1 Introduction

In Europe the Astroparticle Physics activities are coordinated by ApPEC (Astroparticle Physics European Consortium, [1]). At the global level discussions are performed within the APIF (Astroparticle Physics International Forum) committee of the Global Science Forum of OECD.

At the previous European Strategy for Particle Physics, statement 7 states:

"A range of very important non-accelerator experiments take place at the overlap between particle and astroparticle physics exploring otherwise inaccessible phenomena; *Council will seek to work with ApPEC to develop a coordinated strategy in these areas of mutual interest.*"

The scientific enlargement of CERN is under discussion. In 2011, the proposal for *A joint CERN-ApPEC Workplan for the period until the next update of the European Strategy for Particle Physics (2011-2012)* has been endorsed by CERN Council (see CERN-Council-S/0066/Rev). ApPEC is represented in the CERN Council Strategy Session and CERN is represented in ApPEC. ApPEC is in charge of the roadmap for Astroparticle Physics in Europe. Moreover, ASPERA is a network of national government agencies responsible for coordinating and funding national research efforts in Astroparticle Physics. In this chapter we summarize the ApPEC/ASPERA roadmap in section 6.2.

Several of the Astroparticle Physics experiments are now CERN recognized experiments. These collaborations benefit from logistics support, like the use of meeting rooms, access to computers, etc. The question can be asked whether this support should be enlarged. In addition to this indirect support, the question can be asked whether CERN should directly engage in Astroparticle Physics experiments.

For the European Strategy update process four research domains have been identified: dark matter, proton decay, high- energy cosmic particles (neutrino, gamma ray, charged particles) and neutrino physics. The latter is discussed in the neutrino chapter. The three other topics are discussed in the sections 6.3 to 6.5. Astroparticle Physics experiments and experiments at accelerators have a number of common tools, like detectors, theory support, etc. This is discussed in section 6.6.

During the Open Symposium in Krakow the question was raised whether CERN would help in strengthening the collaboration between the Astroparticle Physics and Particle Physics communities. Common training was cited as well.

6.2 Overview of Astroparticle Physics in Europe

6.2.1 What is Astroparticle Physics in Europe ?

Astroparticle physics deals with the study of particles provided by the Universe - cosmic rays and radioactivity.

On the one hand, these particles, and the phenomena they are revealing, can bring information on the intimate structure of matter and the fundamental laws that govern their interactions. In this respect these studies fully pertain to the field of particle physics.

On the other hand, detection of cosmic rays such as high-energy particles or gammas, neutrinos, or gravitational waves, are or will be opening up new observing windows in astronomy. This is of paramount importance since astrophysical objects often demand multi-wavelength and multi- messenger approach for their comprehension.

Furthermore, astrophysical sites of violent phenomena from the big bang to black holes and in fact the whole Universe history, i.e. cosmology, are laboratories to test the structure of the fundamental laws of particle physics and gravitation.

There are about 3000 European full-time equivalent scientists involved in the field in some 50 laboratories. The consolidated cost of the current European program is close to 220 million Euros per year [2]. The investment cost of current experiments range from ten to a hundred million euros per experiment. Future projects will increase the scale of investment by at least a factor 5. The consolidation of the existing coordination of the various projects at the European level has become a necessity.

A European governance has been set up over the past decade, starting in 2001 as an informal coordination committee and transformed in 2012 into an Astroparticle Physics European Consortium (ApPEC). It is the outcome of the preparatory work carried out by a consortium of ministry and agency representatives and of the intense work provided by the EU funded ERANETs ASPERA and ASPERA-2 (from 2006 to 2012, [3]) that paved the way through a series of funding mechanism studies, common roadmap elaborations, common calls for R&D proposals, and common outreach and communication endeavours.

6.2.2 Key questions

ASPERA/ApPEC has produced, through a community effort, a roadmap in 2008 and an updated version in 2011 describing the status and perspective of the field within Europe and links it to activities in other parts of the world [4]. It aims to promote Astroparticle Physics within the member states of ASPERA, to stimulate coordination and cooperation within the European Astroparticle Physics community and to prepare future decisions at National and European levels. This roadmap covers the next ten years, with a focus on the next five.

The ASPERA/ApPEC prospective has identified 6 key issues to be addressed with the highest priority:

- **What is the Universe made of?**

  Only 4% of the Universe is made of ordinary matter. Following the latest measurements and cosmological models, 73% of the cosmic energy budget seems to consist of dark energy and 23% of dark matter. The 2011 Nobel Prize in Physics went to S. Perlmutter, A. Riess, and B. Schmidt for the discovery of the acceleration of the Universe. The nature of dark energy and dark matter remains a mystery.

- **Do protons have a finite lifetime?**

  Grand Unified Theories (GUTs) of particle physics predict that the proton has a finite lifetime. Proton decay is one of the most generic and verifiable implications arising from GUTs. This phenomenon has not yet been observed despite huge efforts. An increase of one or two orders in sensitivity will cover a large part of the possible theoretical values, although one would not be in a position to exclude proton decay theories altogether.

- **What are the properties of neutrinos? What is their role in cosmic evolution?**

  A major breakthrough of the past decade has been the discovery that neutrinos, contrary to what is expected from the Standard Model, are massive and are produced in a mixed state by weak interactions. Many mysteries remain: their mass hierarchy, their absolute masses, the properties of antineutrinos compared to neutrinos (CP violation and their Dirac or Majorana nature), the possible existence of a fourth type of neutrino, and their role in cosmology.

- **What do neutrinos tell us about the interior of Sun and Earth, and about Supernova explosions?**

  In 2002, Ray Davis and Masatoshi Koshiba were awarded the Nobel Prize in Physics for opening the neutrino window on the Universe, specifically for the detection of neutrinos from the Sun and Supernovae. Since neutrinos travel almost unaffected through the Universe, being only deviated by the gravity, they provide a unique tool to look deep into the astrophysical objects and far in the past history of the Universe.

- **What is the origin of high-energy cosmic rays?**

  Nearly a century ago, the Austrian physicist Victor Hess discovered cosmic rays, charged particles that hit our atmosphere like a steady rain from space. Later, it turned out that some of these particles have energies a hundred million times greater than that achievable by terrestrial accelerators. Their origin is still a mystery.

- **Can we detect gravitational waves? What will they tell us about violent cosmic processes and basic physics laws ?**

  Gravitation governs the large scale behaviour of the Universe but is weak compared to all other forces at the microscopic level. At large scale it is understood through Einstein theory. Einstein theory predicts the emission of gravitational waves. They have not been yet observed directly but there is strong hope that the projected sensitivities will give the first detection in the next 10 years. The penetrating character of gravitational waves would clearly open a new window of observation and a new type of astronomy. The link to the subatomic scales will have to wait for the unification of gravitation with quantum mechanics.

We note that not all of these questions are going to be answered exclusively by experiments belonging to the field we define as "Astroparticle Physics".

Consider dark matter searches as an example. First evidence for dark matter has been obtained from the kinematics of Galaxies as revealed by ground-based optical observations in the first half of the 20th century. Since then, dark matter has become a keystone of the standard cosmology model based on much wider evidence than optical astronomy alone, notably on radio-astronomy. The ultimate answer on the nature of dark matter will likely come from the observation of exotic particles constituting dark matter. These particles may be first observed in subterranean laboratories, by the planned detectors recording the nuclear recoils due to the impact of dark matter particles ("direct detection"). Alternatively, signs of dark matter particles may arise as products of their annihilation in celestial bodies and may be detected by gamma telescopes at ground level or in space, by neutrino telescopes deep underwater or ice, or by cosmic ray spectrometers in space ("indirect detection"). Last but not least, it may well be that the LHC provides first evidence for dark matter candidates through their production in accelerator based experiments. From an experimental point of view, optical and radio observations are assigned to the field of astronomy, and accelerator research to that of particle physics. Direct searches makes use of laboratories deep underground which is the traditional environment of astroparticle and non-accelerator particle physics. Other dark matter search techniques use neutrino and gamma telescopes, whose methods have evolved from particle physics. It is this part of the search for dark matter that we assign to the field of Astroparticle Physics.

6.2.3 European roadmap for Astroparticle Physics

On 29 September 2008, ASPERA published the first *European roadmap for Astroparticle Physics*, presenting the seven large infrastructures expected to address the 6 key issues stressed above. Most of these projects are currently under design study or in preparatory phase. In the updated version in 2011, the Scientific Advisory Committee of ASPERA decided to classify the projects into two categories:

1. Medium scale projects or upgrades being at different stages of realization (investment funds in the category of tens of Meuros)
    - **Gravitational waves**: Advanced VIRGO, Advanced LIGO and GEO-HF are long-baseline interferometers. They do have a discovery potential in the next five years.
    - **Dark Matter**: The liquid-xenon technology with XENON100 and next XENON1T experiments at Gran Sasso is producing the most sensitive results. The EURECA project with bolometric experiments will reach the same sensitivity later. DARWIN, a program aiming to extend the target mass of noble liquids to several tons, is strongly supported.
    - **Neutrino properties**: GERDA, CUORE, NEXT and the demonstrator for SuperNEMO will search for neutrino-less double beta decay, KATRIN for neutrino mass via single beta decay. Double CHOOZ, a nuclear reactor experiment, is studying neutrino oscillations.

2. Large scale projects whose construction needs to start towards the middle of the current decade (investment funds on the scale of hundreds of Meuro).
    - **TeV gamma-ray astrophysics**: The Cherenkov Telescope Array (CTA) –a large array of Cherenkov telescopes for detection of cosmic high-energy gamma– is the worldwide priority project of this field.
    - **High energy neutrinos**: The KM3NeT collaboration is working towards a technical proposal for a neutrino telescope of a few cubic kilometer size to be built in the Mediterranean sea, with a substantially larger sensitivity than IceCube.
    - **High energy cosmic rays**: The cosmic-ray community, including the Pierre Auger collaboration, is working towards a next-generation ground-based observatory.
    - **Low-energy neutrino astrophysics and proton decay**: A megaton-scale low-energy neutrino astrophysics and proton-decay detector for Astroparticle and accelerator- based neutrino measurements is addressed by the LAGUNA design study. It is to be installed deep underground.

Astroparticle physicists play a major role in many international dark energy programs, e.g. the predominantly US-funded LSST observatory (first light ca. 2020) or the ESA satellite EUCLID (launch 2020/23).

The path for research in gravitational waves beyond the advanced detectors foresees two very large-scale projects: the Earth-bound Einstein Telescope (E.T.) and the space-bound eLISA/NGO project.

6.2.4 Topics to be covered

For details about the ASPERA/ApPEC forward look and roadmap we refer the reader to the associated web site (http://www.aspera-eu.org/).

In the present document we focus on topics directly linked to the particle physics research, namely :

- The neutrino properties which are presented in the neutrino chapter.
- The dark matter search.
- The large underground detector for proton decay and neutrinos.
- The high energy cosmic rays.

These studies are also relevant for searching for new particles, and physics beyond the Standard Model.

6.3 Dark Matter

6.3.1 The missing mass problem

The imprints of dark matter are observed at all cosmological scales, from the cosmic microwave background, to galaxy clusters down to the smallest dwarf galaxies. Combinations of cosmological measurements indicate that the matter budget in the Universe is the following: 0.4% of the total matter emits light (stars essentially), 15.6% is non-luminous matter of known type (baryonic dark matter), and 84% is dark matter of unknown type (non-baryonic dark matter). A reasonable assumption is that this global budget is valid in our Galaxy. Moreover, conventional matter, e.g. cold hydrogen or compact objects, has been ruled out to be a significant fraction of the Galactic dark matter.

Although dark matter is seen only through its gravitational effects, no modification of the laws of gravitational dynamics can account for the observations without the need to introduce a new type of particle. This is true in particular with the observation of collisions of galaxy clusters such as the so-called bullet cluster. In figure 6.1, one can see the result of a collision of galaxy clusters. The blue patches indicate the location of the mass, deduced from the gravitational shear of background objects, and the red parts are hot gas observed in X-ray. Prior to the collision the mass and the gas were mixed within the clusters. During the inter-penetration of the clusters, the gas has been compressed, slowed down and heated. The mass on the other hand continued its way. The simplest interpretation of this kind of observation is that the mass is composed of weakly interacting massive particles (WIMPs). In this process the source of the gravitational potential is physically separated from the conventional matter (the gas), it is then impossible to explain in a simple way what happens here by modifying the laws of dynamics. The current best working hypothesis is that 84% of the matter mass of the Universe is made of a new (or a set of), yet undiscovered, particle(s). Therefore, the Universe missing mass problem is a matter for particle physics. Particle physics models beyond the Standard Model are well known to contain **particle dark matter** candidates. This is for example the case for the lightest supersymmetric particle (often the neutralino) or some excitation of a Standard Model field in extra-dimensions (it can be for example an extra-photon or a right-handed Dirac neutrino). Those particles would be massive and possess weak interactions, as required to compose dark matter. They would fulfill yet another condition that imposes that those particles are cold, indeed for galaxies to form in the gravitational potential wells of dark matter (it is that point that excludes Standard Model neutrinos as potential candidates). These **WIMP** candidates are well motivated also by their production mechanism in the early Universe. The condition for them to decouple from the primordial bath at the right moment to

Figure 6.1: The Bullet cluster (NASA/Chandra/STScI/ESO)

account for the observed dark matter density is that their self-interaction strength is of order the weak interaction. This condition provides a natural scale for the value of the annihilation cross- section that is discussed in the following.

Another limitation of the Standard Model is that is does not explain why strong interactions are exactly CP-invariant. The question of this so-called strong CP problem is addressed also in the section dealing with flavor physics. A possible solution to the strong CP problem is the Peccei-Quinn mechanism, which predicts the existence of a new particle that couples to photons, the **axion**. The axion can be copiously produced in the early universe and it can have the required properties to be the dark matter. Extensions of the Peccei-Quinn mechanism, as well as high-energy models such as string theories, predict light particles with similar interactions, they are called axion-like particles.

6.3.2 Identification of dark matter strategies

There are three main avenues to unravel the nature of the dark matter. In the case of WIMPs, new particles can be sought at colliders. Two cases can be distinguished: model-dependent searches for which the particle dark matter model predicts other charged particles, and model-independent approach through effective lagrangians. In the first case, it is easier to search for the charged particles and try to identify the underlying model. As an example, one can imagine a dark matter particle that is an excitation of a Standard Model field in extra-dimensions, then charged Kaluza-Klein states with given mass spectra can be searched for. The non-observation of those can constrain the assumed dark matter state. The same applies for SUSY searches. Concerning the effective approach, missing transverse energy can be searched for at the LHC. The events are tagged through an initial-state radiation, a single photon or a single jet for instance. This approach allows constraining effective contact interactions that can be later related to model predictions. The energy budget implies that these strategies are limited to WIMP masses of order a fraction of the centre-of-mass energy.

The search for WIMPs is also performed with fixed targets. In that case, the observable would be an interaction between a dark matter particle and a nucleus within a medium very sensitive to some energy deposition. The source of the dark matter particles is the galactic halo itself, inside which the Solar system orbits. The detectors have to be shielded against cosmic rays and be built in materials with very low activity. The experiments are thus placed in underground labs and make use of very sensitive detectors that detect either nuclear recoil induced scintillation, ionization, heat, or a combination of those. In the absence of a dark matter signal, sets of parameters like the mass of the particle and the WIMP-nucleon cross section are excluded and compared to models.

The last research line is indirect searches in astrophysical environments. In regions where the dark matter density is large like in the centre of galaxies or in dark matter clumps, the annihilation process that set the cosmological density in the early Universe can occur at an appreciable rate. Dark matter annihilations lead to the exotic production of particles in astrophysical environments. If unstable, the produced particles will decay into stable particles and constitute a new source of charged cosmic rays, gamma rays or neutrinos. Observations of the cosmos with these messengers then provide possible constraints on the properties of the assumed dark matter particle. In that case, the constraints typically lie in a mass / annihilation cross-section plane. As mentioned earlier, one advantage of this line of research is that cosmology provides a natural scale for the annihilation cross-section, as an identified target. The three mentioned ways to

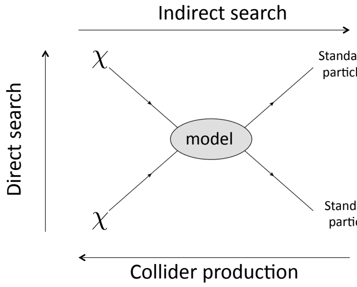


Figure 6.2: Three strategies for identification of dark matter.

search for WIMP dark matter can be summarized with the diagram in figure 6.2. Here χ represents dark matter particles and SM stands for Standard Model particles. One can see that by rotating the diagram it is possible to retrieve the three search strategies. The central circle represents the particle physics model that can be either effective or embedded in a larger theory. It is very important to keep in mind the complementarity between the different lines of research. For example, a direct detection signal should be compared to astrophysical data (indirect searches) to verify that the particle observed in the underground labs is also responsible for the dynamics of the largest objects in the Universe.

In the case of axions, numerous search strategies can be considered. The bottom line of all axion searches is the use of their two-photon vertex. That interaction can be used to search for conversion from axions to photons in magnetic fields. This process can happen in astrophysical environments or in laboratory experiments. Assuming axions are the dark matter, the source of axions can be the Galactic halo itself. In that case axions can be converted into photons in a dedicated apparatus, like the ADMX experiment. Axions might be thermally produced in the Sun, in which case they can be converted back in the magnetic field of an experiment, as done with CAST. Other searches include the study of the cooling of stars, or the propagation of high-energy gamma-rays.

The dark matter could also be sterile neutrinos, which are discussed in the neutrino section. In that case, detection strategies mostly rely on specific models. Dedicated space-based X-ray observation could be sensitive to sterile neutrinos in some specific models.

6.3.3 Current constraints

For dark matter direct searches the constraints are expressed in a WIMP-nucleon cross-section / WIMP mass plane. The current best constraints on the nucleon-WIMP cross-section are obtained with Xenon detectors and are of order $10^{-45}\ cm^2$ for 50 GeV WIMPs (see the left panel of figure 6.3). This allows to exclude some new physics model parameters. On the same figure some contours are closed. The corresponding experiments claim detection of a signal, due to the observation of annual modulation matching with expectations from the Earth motion in the Galaxy. Xenon 100 and Edelweiss experiments both exclude the corresponding parameters. From effective lagrangians and using

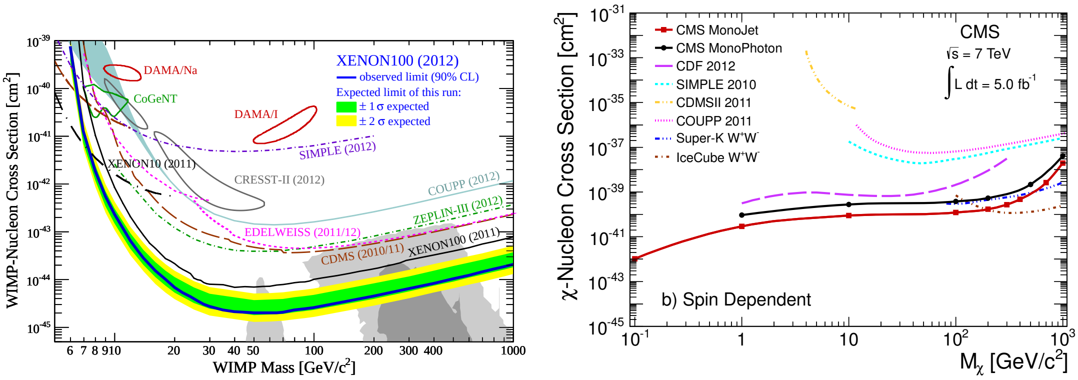


Figure 6.3: Current constraints on nucleon-WIMP cross-section from direct searches experiments (left, XENON100 collaboration 2012) and LHC and indirect neutrino searches (right, CMS collaboration 2012)

monojet events at the LHC, similar constraints can be obtained with ATLAS and CMS, as show in figure 6.3 in the case of CMS.

The searches for axions and axion-like particles try to benefit from their two-photon vertex. In particular axions can convert into photons in magnetic fields and vice-versa. There are many ways in which axions can manifest, for instance in astrophysical environments. The imprints of axions could be found in star evolution or high-energy gamma-ray astronomy for instance. A way to perform laboratory searches for axion-like particles is to assume a local density of axions (here considered as dark matter) and try to convert them into photons. Another possibility is to perform light-shining-through-wall experiments with LASERs and magnetic fields. Finally, one can use helioscopes. In that case axions are supposed to be thermally produced in the Sun. A magnet is pointed towards the Sun and traces of conversion from axions to photons are searched for. That is what the CAST experiment at CERN is based on. In the absence of positive results, the constraints are expressed in a coupling-to-photons/mass plane. Figure 6.4 displays a compilation of constraints from various experiments and probes [ID105]. On that figure light blue and grey areas are exclusions coming from astrophysical probes, current constraints from CAST are displayed in dark green and vertical lines at the micro-eV level are from resonant cavities. The oblique yellow band corresponds to axions that solve the strong CP problem.

6.3.4 European strategy issues

The Preparatory Group has received some input from the community concerning the search for dark matter. The inputs mention most of the prospects in the field and are briefly summarized here. In the case of direct searches different groups have been set up proposing ton-scale experiments, either with Xenon (Xenon 1T) or with bolometers (EURECA). Those could be installed in Gran-Sasso, in an extension of the LSM in Modane or in the Canfranc underground laboratory. R&D is on-going for searches with directional sensitivity, which would allow a better signal discrimination. Prospects for future constraints in indirect searches will be addressed in the section devoted to the high-energy Universe, as they will appear as by-products of future observatories. Note, however, that proposals exist for dedicated cosmic missions to test scenarios alternative

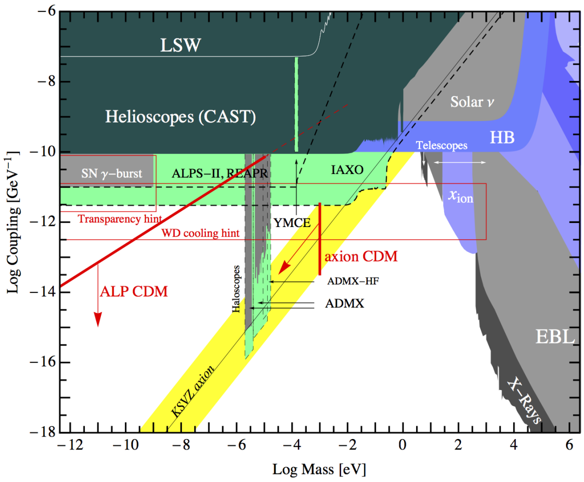


Figure 6.4: Current and future constraints on axion-like particles parameters

to annihilating WIMPs, such as decaying dark matter and sterile neutrino dark matter.

In the search for axion-like particles, prospects include a variety of approaches, some of which are mentioned in the high-energy Universe section. Concerning laboratory experiments, one can mention ALPS-II in DESY and upgrades of resonant cavities ADMX in the US. An upgrade of CAST is foreseen in the near future, the next step will require the building of a dedicated, helioscope-optimized magnet. The IAXO proposal goes in that direction, expectations for its sensitivity appear in light green on the previous figure.

Concerning dark matter searches, ApPEC has made some recommendations, which are summarised here [ID57].

- Based on the good sensitivity of direct dark matter searches with Xenon, DARWIN, a program to further extend the target mass of noble liquids to 10-20 tons, should be supported. If the competitiveness of liquid Argon is confirmed, a double-target option should be chosen.

- The Bolometric approach remaining competitive with the noble liquid approach, the development of a multi-target experiment like EURECA is recommended.

- R&D activities aiming at the directional detection of nuclear recoils should be supported.

- Improvements of the DAMA/LIBRA experiments are recommended, as well as a fully independent experiment based on the same technology, to better understand the modulation signal.

- In the field of axions, a CAST follow-up is considered. The associated R&D programs are supported as well as smaller activities on the search for axion-like particles.

The large-scale projects of this roadmap have not been funded yet. Should a scientific enlargement of CERN be decided towards Astroparticle Physics, these recommendations could be used as a basis for a common strategic plan.

6.4 Large underground detectors

In this section, we discuss detectors sensitive to MeV-GeV neutrinos, to be installed deep underground. The detectors for high-energy (tens of GeV and higher) neutrino astronomy are discussed in section 6.5.

The Scientific Advisory Committee of ApPEC/ASPERA recognizes the high cost of underground laboratories on the one hand and the unique capabilities of a large neutrino detector in particle physics (proton decay) and Astroparticle Physics (solar neutrinos, supernovae, dark matter, geo-neutrinos) on the other hand. It recommends that the program with neutrino beams be flanked by a strong Astroparticle Physics program to justify the high investment. The physics to be performed with a long baseline neutrino beam and with atmospheric neutrinos is discussed in the chapter on neutrino physics. In the present section we concentrate on the Astroparticle Physics aspects.

Large underground detectors have produced a very rich harvest of discoveries. This legacy is intended to be continued by one or several multi-purpose detectors on the mass scale of 20-500 ktons.

Several conceptual ideas for next-generation very massive, multi-purpose underground detectors have emerged worldwide over the last years. All the designs consist of large liquid volumes observed by detectors which are arranged on the inner surfaces of the vessels. In Europe, seven underground sites and three detector options have been investigated in the framework of the LAGUNA design study [ID74].

6.4.1 Search for proton decay

The observation of proton decay would be one of the most fundamental discoveries for particle physics and cosmology. Presently, the most sensitive lower limits on the proton lifetime are of the order of 10^{33} yr (depending on the decay mode) and were obtained by the Super-Kamiokande experiment. The simplest non-SUSY grand unification theory (GUT) model, the Georgi-Glashow SU(5) model, which predicted proton charged lepton decay modes such as $p \to e^+\pi^0$ and a proton lifetime of the order of 10^{31} yr has been ruled out in the 1980s. More complicated non-SUSY or SUSY models predict proton lifetime in the range $10^{33} - 10^{38}$ yr. In SUSY models, decay modes such as $p \to \bar{\nu}K^+$ can become dominant because of additional diagrams involving Higgsino exchanges. The progress in the verification of GUTs calls for an improvement in sensitivity of 1-5 orders of magnitude and the possibility to explore decay modes preferred by SUSY scenarios. Interactions of atmospheric neutrinos are the main background to proton decay searches. The detectors for proton decay searches have thus to be installed in deep underground laboratories. The sensitivity of the searches can be improved by increasing the active volume relative to the present Super-Kamiokande detector. This is what is proposed for the MEMPHYS water Cherenkov detector. A drawback is that the charged kaon from proton decay is under the Cherenkov threshold in water detectors, so that the $p \to \bar{\nu}K^+$ decay mode does not have a very clear signature. An alternative strategy to increasing the active volume is to improve the pattern recognition and particle identification with a liquid argon TPC such as GLACIER or a liquid scintillator detector such as LENA. The comparison of expected limits of MEMPHYS, GLACIER and LENA for a 10-year search is shown in the table.

6.4.2 Facility for low energy neutrino astrophysics

The different aspects of neutrino physics which can be performed on long-baseline neutrino beams are discussed in the chapter on neutrino physics. If the far detector is placed deep underground, it will allow to detect and study neutrinos from astrophysical sources, or from nuclear decay in the Earth.

- Solar neutrinos

  There are presently three devices with an active solar neutrino programme:

  - Super-Kamiokande (22 kt fiducial volume water Cherenkov, Japan, ^{8}B-neutrinos).
  - BOREXINO (270 t scintillator, Gran Sasso Laboratory, Italy, ^{7}Be-neutrinos).
  - SAGE (GaGe radiochemical detector, Russian Baksan Laboratory, pp neutrinos).

  The scientific programme includes measurement of the predicted matter effects from neutrino oscillations, precision measurement of solar fusion processes and long-term monitoring of the solar fusion process. The main goals of the present solar neutrino experiments which can be within reach in a few years are: measurement of the up-turn of the survival probability; improved measurement of the pep flux and first measurement of the CNO flux by BOREXINO, resolving the metallicity controversy.

  A large next generation underground detector would allow to study the details of the processes in the solar interior with high statistics and the details of the Standard Solar Model would be determined with per cent accuracy.

- Neutrinos from Supernovae

  Today, a galactic supernova (10 kpc distance) of the SN1987A-type would result in nearly ten thousand of detected neutrino events worldwide:

  - Super-Kamiokande (8500) and KamLAND (350) in Japan.
  - LVD (400), BOREXINO (100) and ICARUS (50) in Italy.
  - MiniBOONE (200) in the US.
  - The Baksan detector (70) in Russia.

  In a large multi-purpose detector (50-500 kton) a few tens of thousand of fully reconstructed neutrino events would be detected, which would provide incredibly detailed information on the early phase of the supernova explosion.

  A diffuse flux of past supernova would probe the cosmological star formation rate and the average features of neutrino emission from a variety of core collapse events.

- Geo-neutrinos

  The so-called geo-neutrinos originate in the Earth crust and mantle from Th, K and U decays. Most of the decay energy is transformed to heat the planet, but about 20% of the neutrinos are able to escape. Geo-neutrinos from U and Th decays have been observed by Kamland and Borexino. The study of geo-neutrinos is still in its infancy. Future detectors will allow to measure geo-neutrinos with much-increased statistical accuracy compared to today, which should help discriminate among various geophysical models.

6.4.3 The global scene

Projects which are planned or are in R&D phase outside Europe are:

- Hyper-Kamiokande in Japan

  The proposal [ID86] is to build a Mton water Cherenkov detector for atmospheric and solar neutrino physics, a study of neutrinos from other astrophysical origins and for proton decay and indirect dark matter searches. It will serve as far detector on the J-PARC long- baseline neutrino beam. This is based on the well-known technique used in Super-K. It would be located 8 km south of Super-K, 295 km from J-PARC and 1750 mwe deep. A proposal has been submitted for funding.

- LBNE in the US

  The proposal is to build a far detector on a 1300 km long-baseline neutrino beam from Fermilab to the Homestake site in South Dakota. This will be a liquid argon TPC detector. If the funding allows it, the detector will be put deep underground.

- PINGU, high density insert in IceCube

  This is a proposal to add a dense array of photomultipliers (20 strings) to the IceCube neutrino detector at the South Pole. PINGU is optimised for 1-50 GeV neutrinos and may allow measuring the neutrino mass hierarchy, to detect SN neutrinos and to search for dark matter. A feasibility study in on the way and a proposal for funding will be prepared towards Fall 2013.

- ORCA in the Mediterranean Sea

  An input ([ID42]) to the strategy process proposes to optimise the geometry of KM3NeT phase-1 by deploying a dense array of photomultipliers in order to detect 3-30 GeV neutrinos and to study the neutrino mass hierarchy. The deployment of ORCA (50-70 lines) could be done by the end of 2016, with the funding already allocated to KM3NeT. The R&D developments are done in collaboration with PINGU.

- Liquid scintillator envisaged in Baksan (Russia)

  The Baksan Neutrino Observatory (see [ID45]) is the only underground low-background site in Russia. It is at 5000 mwe depth, and far from nuclear power plants. There is a proposal to build a 50 kton liquid scintillator detector.

6.4.4 The LAGUNA-LBNO design study

In Europe, seven underground sites and three detector options have been investigated in the LAGUNA and LAGUNA-LBNO design studies (see [ID74]). All the designs consist of large liquid volumes observed by detectors which are arranged on the inner surfaces of the vessels. The liquid simultaneously acts as the target and the detection medium.

The techniques investigated are:

- **MEMPHYS**: Water, following the concept of Super-Kamiokande

  In the LAGUNA design study this option is called the MEMPHYS detector. The main cost comes from the PMTs. The technique is also proposed for Hyper-Kamiokande in Japan.

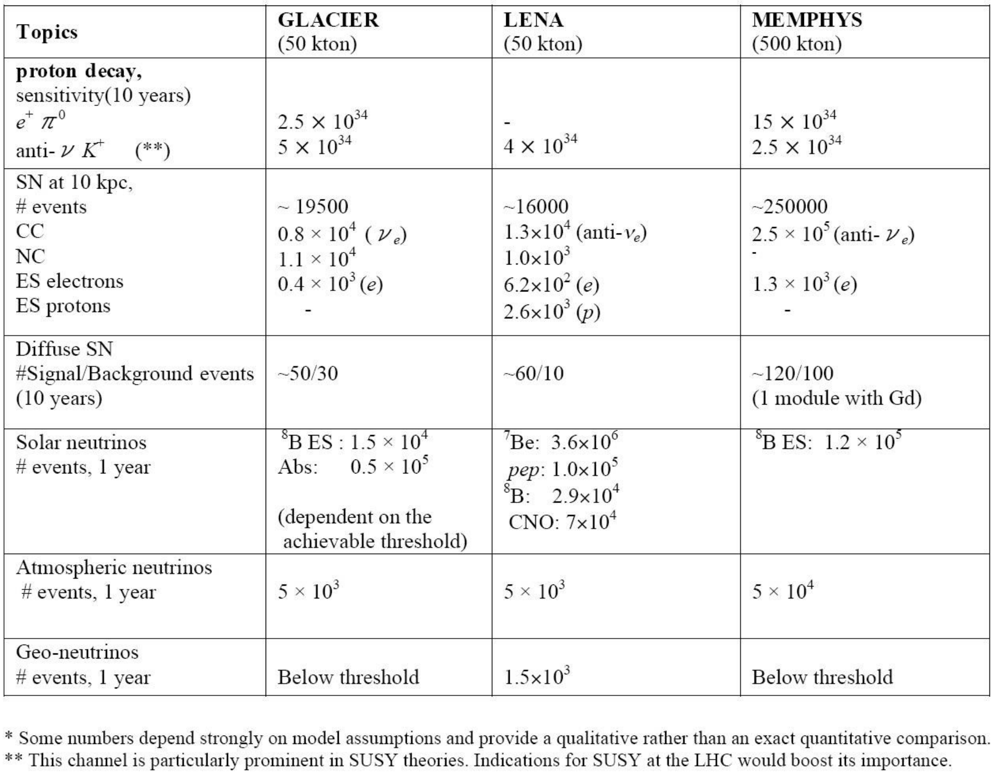
- **LENA**: Liquid scintillator, following the expertise gained in Borexino and Kamland

  In the LAGUNA design study this option is called the LENA detector. For financial reasons the technique is limited to several kilotons. The main challenge is the radio-purity of scintillator.

- **GLACIER**: Liquid argon TPC, pioneered by ICARUS

  In the LAGUNA design study this option is called the GLACIER detector. A liquid argon TPC allows to image rare events with the quality of a bubble chamber. The technique has been shown to work in the ICARUS experiment.

The liquid argon TPC is the best technique for long-baseline neutrino physics while the liquid scintillator technique is the best for neutrino astrophysics. A summary of the performance in Astroparticle Physics of the different detector options is given in the table (from [ID57]).



Topics	**GLACIER** (50 kton)	**LENA** (50 kton)	**MEMPHYS** (500 kton)
proton decay,			
sensitivity(10 years)			
$e^+ \pi^0$	2.5×10^{34}	-	15×10^{34}
anti- ν K^+ (**)	5×10^{34}	4×10^{34}	2.5×10^{34}
SN at 10 kpc,			
# events	~ 19500	~16000	~250000
CC	0.8×10^4 (ν_e)	1.3×10^4 (anti-ν_e)	2.5×10^5 (anti- ν_e)
NC	1.1×10^4	1.0×10^3	-
ES electrons	0.4×10^3 (e)	6.2×10^2 (e)	1.3×10^3 (e)
ES protons	-	2.6×10^3 (p)	-
Diffuse SN #Signal/Background events (10 years)	~50/30	~60/10	~120/100 (1 module with Gd)
Solar neutrinos # events, 1 year	^{8}B ES : 1.5×10^4 Abs: 0.5×10^5 (dependent on the achievable threshold)	^{7}Be: 3.6×10^6 *pep*: 1.0×10^5 ^{8}B: 2.9×10^4 CNO: 7×10^4	^{8}B ES: 1.2×10^5
Atmospheric neutrinos # events, 1 year	5×10^3	5×10^3	5×10^4
Geo-neutrinos # events, 1 year	Below threshold	1.5×10^3	Below threshold

* Some numbers depend strongly on model assumptions and provide a qualitative rather than an exact quantitative comparison.
** This channel is particularly prominent in SUSY theories. Indications for SUSY at the LHC would boost its importance.

The sites which have been considered in the LAGUNA design study are the following. Europe has currently 4 national underground sites: Boulby (UK), Canfranc (Spain), Gran Sasso (Italy), Modane (France). None of these sites is large enough to host a next generation neutrino detector.

LAGUNA has investigated 7 potential sites:

Boulby (UK), Canfranc (Spain), Modane (France), Pyhälsalmi (Finland), Sierocziwice (Poland), Slanic (Romania), Umbria (Italy). Three detector options, GLACIER, MEMPHIS, and LENA were considered for each site. It was found that all 7 sites were in principle technically feasible and able to host the desired type of detectors.

The LAGUNA-LBNO design study concentrates on a neutrino beam from CERN and the two deepest sites: Modane and Pyhälsalmi with a focus on the later.

6.4.5 Recommendations of ApPEC/ASPERA [ID57]

- CERN and the national agencies, as well as ApPEC, should support a vigorous R&D program on neutrino detectors and beam design studies, in anticipation of a critical decision in 2015;
- ApPEC supports the Astroparticle Physics program that will profit from the synergy with the accelerator-based programme (eg liquid scintillator detector in Pyhälsalmi), as well as medium-scale astroparticle physics detectors (including feasibility studies for high-density infills of high energy neutrino telescopes) which can in principle determine the neutrino mass hierarchy and other neutrino parameters;
- In parallel, given the obvious worldwide interest as well as the high project costs, it is recommended that CERN, together with key European agencies and ApPEC, enter into discussions with their US and Asian counterparts in order to develop a coherent international strategy for this field.

6.5 The high energy universe

Besides the search for new phenomena or new particles, Astroparticle Physics allows to open new windows on the Universe. For instance, in the last decade gamma ray astronomy experienced a significant leap with some experimental techniques reaching maturity. Thanks to ground-based Cherenkov telescopes and the Fermi gamma ray observatory, the high and very-high energy picture of the Universe has become clearer. That represents a first step towards the understanding of non-thermal phenomena such as the ones at the origin of the acceleration of cosmic rays in our galaxy. Within the national and European roadmaps an advanced Cherenkov telescope array (CTA) is recognised as a high priority. CTA will become the first ground-based gamma-ray observatory. At higher energies, water Cherenkov detectors such as HAWC are promising as they provide a large field of view coverage with a very good duty cycle. At lower energies but still of great interest for particle physics and cosmology, the study of gamma ray bursts is important and a successor to Fermi should be prepared.

Gamma rays are potentially not the only messengers from the cosmos. In particular, neutrino telescopes search for high-energy neutrino sources in the Universe. They so far failed to do so but efforts are pursued in this direction, as neutrino astronomy would provide information about violent phenomena in the Universe that are complementary to gamma ray observations. Currently running experiments use very large volumes of water or ice. Those include ANTARES in the Mediterranean, IceCube in Antarctica and NT 200 in Lake Baikal in Russia. The next global step in this direction is the construction of a large undersea neutrino telescope like KM3NeT. Gravitational wave detection might be around the corner with the upgrades of current generation of ground-based interferometers. A global effort is currently made with large interferometers (LIGO in the US and VIRGO in Italy). The community now shares all data from different sites to reach the best possible sensitivity. The next step would be the construction of the Einstein Telescope, which could allow deep studies of gravitational emissions. Finally, the other messengers that can be used to observe the Universe are cosmic rays. In the

GeV to TeV range, space spectrometers like PAMELA and AMS-02 allow measuring the composition of cosmic rays, to measure light antimatter particles and to search for new types of particles (exotic particle or antimatter nuclei). AMS-02 is expected to take data for more than a decade and no successor is discussed at the moment. If they carry few charges and are energetic enough, cosmic rays could travel straight from the sources, allowing performing charged particle astronomy. The Pierre Auger Observatory results concerning the anisotropy of cosmic ray arrival directions are not completely conclusive and might need a new generation experiment. Promising proposals include JEM-EUSO, which intends to observe atmospheric cosmic ray showers from space. Ground networks such as LHAASO are also discussed for energies up to 10^{18} eV.

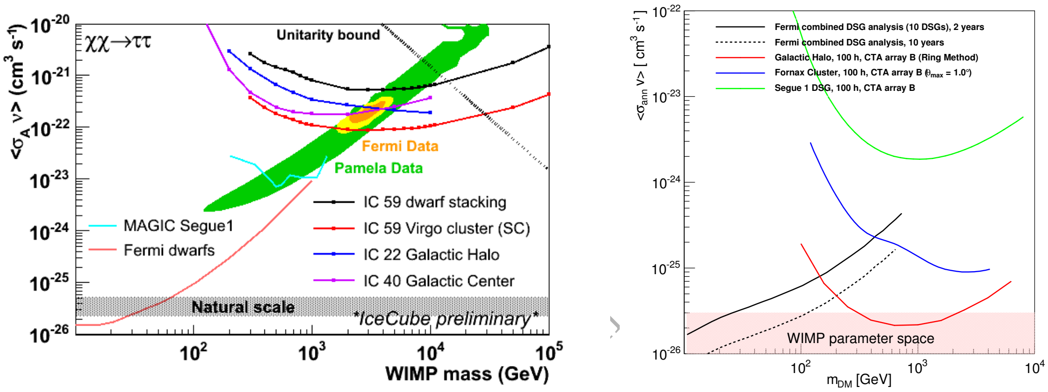


Figure 6.5: Current IceCube and Fermi constraints on WIMP annihilation cross-section (left, IceCube collaboration 2012), and future constraints with CTA (right, CTA collaboration 2012).

One should note that the physics topics related to CERN research are not the main drivers of these observatories. However, they will offer invaluable opportunities to search for new physics complementary to CERN results. In that sense, the Astroparticle Physics experiments related to the high-energy universe cannot be justified for particle physics only but have great discovery potential. The overlap between CERN core business and Astroparticle Physics experiments related to the high-energy observation of the Universe has been discussed at the Krakow meeting and it appears in the documents submitted by the community. Some of these topics are summarized in the following. Gamma ray astronomy and neutrino astronomy allow searching for WIMP annihilations (see figure 6.5). Those are expected to happen in astrophysical environments with large dark matter density (e.g. central part of the galactic halo, dwarf galaxies, dark matter clumps). The large sensitivity of CTA will allow further searches for axion-like particles. Photon/ALPs oscillations can occur in astrophysical environments offering large magnetic fields and long baselines. CTA improved sensitivity will open a window on a large number of sources, giving the opportunity of finding one that has characteristics fitting perfectly the needs or searching for effects in the stacking of more data. The same considerations apply to the search for Lorentz invariance violation with gamma rays.

Cosmic ray research also has the potential to provide particles physics measurements and probe for new physics. One example is the search for primary cosmic rays that would be produced by WIMP annihilations. In addition, the highest energy cosmic radiation constitutes a test bed for possible Planck-scale effects that may violate Lorentz invariance at energies unattainable in the laboratory. Such effects could be distinguished from astrophysical processes and would give insights into quantum field theory at very high energy. In a less speculative approach, a recent result by the Pierre Auger Observatory illustrates the nice complementarity between LHC physics and what can be achieved by studying atmospheric shower. They indeed managed to measure the proton- proton cross-section at an energy of 57 TeV, well above the reach of Terrestrial accelerators (figure 6.6). In principle, similar analyses can be conducted to probe center of mass energies up to 400 TeV. Comparison of nearly horizontal air showers from PeV-EeV neutrinos interacting in the atmosphere, with up-going showers from Earth-skimming tau neutrinos would allow measurement of the neutrino-nucleon cross-section at energies high enough to probe non-perturbative QCD effects or new physics at the TeV scale.

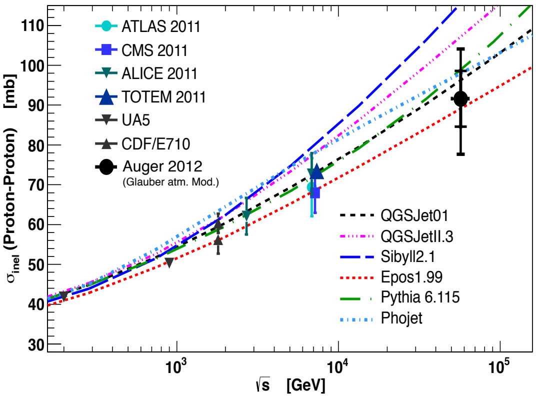


Figure 6.6: Measurement of the total proton-proton inelastic cross-section (P. Auger collaboration, 2012).

Other even wider synergies can be found, e.g. with climate science with the CLOUD experiment, which studies the effects of cosmic rays on aerosols related to cloud formation using PS beams.

In conclusion to this part, not all physics subjects in the high-energy Universe are interesting for CERN. The question was raised how to explore ways of collaboration between the high-energy Astrophysics community and CERN. Constant dialog between the different groups that have common interests would stimulate the research in the fields related to fundamental physics. One example of such a synergy is the LHCf experiment installed in the very forward region near the ATLAS detector [5]. The aim of LHCf is to study the forward production of neutral particles in proton-proton collisions, providing information to be used in the modeling of cosmic ray interactions in the Earth atmosphere.

6.6 Transversal activities

Current and certainly next generation Astroparticle Physics experiments are run by large collaborations which are comparable in size to those running HEP experiments. They face similar problems of management of large collaborations. The question can be asked whether CERN should help in setting up the governance of large projects.

Several techniques used in the Astroparticle Physics experiments originate from HEP experiments, or are very similar: detector techniques, data acquisition, management of large data samples, data reconstruction, Monte-Carlo simulation. It seems advisable that collaboration is sought between HEP and Astroparticle Physics experiments for the sharing of for example test beams, large computing clusters (GRID), etc. (remark: should CERN play a role and provide this?)

It has been shown in the previous sections that in several topics of Astroparticle Physics there is a clear synergy and complementarity with accelerator-based research. During the Krakow Open Symposium the different communities have asked CERN to play a role in enhancing the exchange of information between the two communities.

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[ID86] Contribution 86: *The Hyper-Kamiokande Experiment*

[ID42] Contribution 42: *Oscillation Research with Cosmics in the Abyss*

[ID45] Contribution 45: *Neutrino and Astroparticle Physics program of JINR and Russian Institutes*

Chapter 7

Particle Physics Theory

The particle theory relevant for the physics topics of the previous sections has already been summarized in the repsective section. In this section we review those aspects of theory that may require some strategic action at the European level, on the basis of the submissions from the community [ID18, ID46, ID59, ID93, ID106, ID116, ID137, 1], of the presentations at the Open Symposium [2, 3] and of the ensuing discussions [4].

We begin with a general assessment of the implementation of the current strategy and of the recent evolution of the field. We continue with the description of some organizational aspects of particle physics theory in Europe, commenting on the role of the CERN Theory Unit, on the relations with the EU Programmes and on the relations with experiment. We conclude with two special topics that do require a higher level of coordination than the rest of theory: lattice quantum field theory and the development of software packages.

7.1 General Assessment

The current European Strategy for particle physics contains the following statement:

> "European theoretical physics has played a crucial role in shaping and consolidating the Standard Model and in formulating possible scenarios for future discoveries. Strong theoretical research and close collaboration with experimentalists are essential to the advancement of particle physics and to take full advantage of experimental progress; *the forthcoming LHC results will open new opportunities for theoretical developments, and create new needs for theoretical calculations, which should be widely supported.*"

The first part of the statement found recently a dramatic confirmation in the discovery of a new particle, so far compatible with the Standard Model Higgs boson, by the ATLAS and CMS Collaborations at the LHC. The theoretical foundations for such a discovery were first laid down, almost fifty years ago, by three theorists working in Europe: Englert, Brout and Higgs. In more recent times, many European theorists have played a crucial role in the characterization of the direct and indirect signals of such a particle, both in the Standard Model and in some of its extensions, and in the computation of the relevant backgrounds.

With the start of the LHC, the collaboration between phenomenology-oriented theorists and experimentalists became more intense, also thanks to new initiatives such as the LPCC (LHC Physics Centre at CERN): the benefits extend not only to CERN scientists but also to CERN Users belonging to European and non-European laboratories and universities.

The particle theory community is a global and well connected community. The history of the arXiv provides a relatively recent example: the arXiv, founded by the US theorist Paul Ginsparg in 1991, was very rapidly adopted by the large majority of theorists worldwide, whilst it took more time to influence experimentalists and other scientific communities to a comparable extent. Also, various special-purpose working groups typically have broad international composition. Theorists, however, do not have a history of working in large groups. This is becoming more prevalent now in certain fields, such as those discussed in the Section 2.7.3, and may affect the sociology of the community in the future.

Variety, independence and complexity are perceived as virtues of the theoretical research activities: there should be room for initiatives out of the mainstream by individuals or small groups. Very often theoretical progress is not planned, but arises unpredictably from formal theoretical research: a recent example is the connection between the fluid dynamical properties of the quark-gluon plasma and the AdS/CFT correspondence, originally developed in the context of superstring theories.

A diverse and vibrant programme of theoretical physics, encompassing formal theory of all the fundamental interactions including gravity, phenomenology and model building, as well as the related areas of cosmology and astroparticle physics, should remain an essential ingredient of any future particle physics programme. The shifts in the paradigms that the experimental results of the LHC are progressively imposing will presumably require a higher investment in theory than before. For example, a revision of the standard approaches to the concept of naturalness has already started, and the connections of particle theory with astrophysics and cosmology are becoming increasingly important.

An activity where theorists are playing a crucial role is training. Common graduate workshops and summer institutes for theoretical and experimental students coming from different institutions are a good example of optimization in the use of resources. There are international schools with decades of tradition (Cargèse, Les Houches, Erice, Jerusalem, etc) that have been playing a major role in educating future leaders of the field: these activities need a stable source of funding. General education and outreach are also activities where theorists are increasingly engaged.

7.2 Organizational Aspects

Theoretical research groups are organized in several ways and vary largely in size, from individuals to relatively large groups, which gives a lot of flexibility in the organization of work.

Collaborations working on precision calculations, on event simulation tools, on lattice calculations, on the automation of calculations and on the confrontation of new models with data can be large in size (at least for the standards of theoretical physics), and there may be problems in identifying individual contributions, similarly to experimental groups. In addition, many challenging calculations that are arguably most relevant to the experiments (e.g., those of complicated background processes) tend to be very time-consuming and to have lower publication and citation returns, especially in their early stages, than topics such as model building. These two tendencies combine to reduce the visibility and hamper the career prospects of the young theorists involved in challenging, long-term and crucial tasks for particle physics. The superficial use of bibliometric data by selection or evaluation committees not involving specialists of the field may increase further the risk of privileging the theoretical activities on those topics that guarantee quick results and a steady rate of publications and citations. A possible corrective step could consist of longer post-doctoral appointments, allowing young theorists to complete long-term projects and reap their benefits before they have to apply for the next job.

Maintaining the quality of theory groups is not trivial. Active and stimulating environments are needed for both students and postdocs in order to maintain high quality research and education. One possibility is to share and optimise resources, as done at GGI-Florence and IPPP-Durham, in the DESY programmes, in the CERN-TH institutes, in the TASI program in the US. However, it is of great importance for Europe that thriving scientific communities with a broad spectrum of research exist in all of its sizeable regions.

7.2.1 The CERN Theory Unit

CERN is an important hub of European theory research. It has several roles: a) its staff conducts forefront theoretical research, as in any leading institute; b) it provides a central meeting point for the European/worldwide theoretical particle physics community, and a natural interaction point between theorists and experimentalists; c) CERN, including the TH unit, has a Europe-wide role in scientific and technical education.

Research in CERN TH covers all fields that are of direct relevance for high-energy physics or that are essential for the innovative transfer of knowledge and tools to and from HEP. The theory unit is a centre of excellence in theoretical high-energy physics and related areas, including cosmology, high-energy astrophysics, field and string theory.

For the world-wide theoretical HEP community, CERN TH serves as a unique forum for discussion and exchange of ideas amongst theorists, and between theorists and the experimentalists in the Laboratory and elsewhere. CERN TH hosts top theorists from all over the world as their presence is a primary seed for attaining and maintaining excellence both at CERN and in the home institutions of the visitors. CERN TH hosts more than 150 visitors per year for periods exceeding one month. Complementary to the short-term visitor programme, the CERN programme of paid associates provides approximately 150 person months subsistence per year for extended research visits. In addition to the scientific visits that are supported by the CERN programmes, an increasingly large number of scientific visitors come to CERN TH with external support. With the increasing number of external short- and long- term visitors in CERN TH, suitable office space has become - in particular during the summer months - an important limiting factor for the role of CERN TH as a meeting point of the theoretical HEP community.

CERN TH organizes and hosts workshops of various duration and size, often in collaboration with experimentalists at CERN and often responding to or anticipating the needs of the Laboratory. CERN TH also organizes and hosts workshops of the European and worldwide community in fields beyond those directly related to LHC physics (e.g. on supergravity, strings and gauge theory; interconnection between particle physics and cosmology; astroparticle physics).

To safeguard high quality scientific achievements in the future, education is an important activity. CERN TH currently regards the training of doctoral students as primarily the responsibility of universities and it does not offer a PhD program. However, CERN TH offers a complement to this training by accepting a limited number of students on secondment from their home universities to gain extra experience before returning to complete their thesis. CERN TH is prepared to make the supervisory resources of its staff available to complement the training of doctoral students and it welcomes funding schemes that allow to host students, in joint supervision with their home institutions, for specialized training on secondment.

CERN TH advocates a stronger engagement of the theory community in the development of outreach resources to explain the meaning of LHC discoveries and conceptual revolutions to the greater public.

7.2.2 Relations with the EU Programmes

EU actions for particle theory in the past have been lacking the coordination, the scale and the continuity that have benefitted other aspects of particle physics. The two main instruments used so far by particle theory research have been individual grants (Marie Curie Fellowships and ERC Grants) and Initial Training Networks. The ERC grants are attributed on a personal basis, which is well suited for theoretical research. Also, they typically allow to support or exchange students and postdocs on flexible time scales, which is well suited for evolving project needs and which makes, e.g., the supervisory resources offered by theory groups at CERN and other laboratories available to the European HEP community. While the award of several particle theory projects in the individual grant schemes is clearly encouraging, the Initial Training Networks appear to be difficult to match with the needs of the theory research community. With their principal emphasis on the training of very young pre-doctoral researchers, and their mixture of scientific and applied training, they are clearly successful in the preparation of future professionals, but fail to provide the appropriate framework for the advanced and longer-term training of post-doctoral researchers through their involvement in forefront theory projects. The combination of rigid recruitment rules, industrial partner requirements and lack of continuity of funding for follow-up proposals make these projects of rather limited use from the point of view of basic theoretical research. Before FP7, instead, Research Training Networks emphasising postdocs were available and played a very important role in unifying European efforts, helping European competitiveness and establishing an impressive mobility at the postdoc and then at the faculty level.

In general, European funding for fundamental research, in particular particle physics theory, should not be penalized by the increased attention to applied research. At the level of EU actions, a better coordination of theoretical research between particle physics and astroparticle physics, including the connections to experimental results, could be proposed. Also, one should find appropriate ratios of EU funding among Ph.D. student, postdoc and junior faculty positions.

Theory has been largely neglected in the EU research policy. Theorists have been successful in open calls such as ERC grants, Marie-Curie Fellowships and Training Networks. However, the largest fraction of the EU research funding goes to "strategic" areas that have excluded theory (and particle physics in general). Some strategic EU actions for theory would reinforce scientific competitiveness with other world regions.

7.2.3 Relations with Experiment

Particle theory research will develop jointly with experimental discoveries in particle physics, astroparticle physics and cosmology.

In the near future, several challenges demand progress in particle theory. The LHC experimental programme will continue to provide information on particle interactions at three frontiers: energy, intensity and precision. To obtain a reliable interpretation of LHC measurements, theory predictions will have to match the precision of the experimental measurements. Given the large number of potentially interesting observables and the increasing complexity of final states, calculations of Standard Model predictions will have to become increasingly automated. Continuous advances in the understanding of the mathematical properties of quantum field theories, of perturbation theory and of renormalization are crucial for this task. Likewise, new models have to respect a large number of constraints resulting from measurements at past and present experiments, thereby turning the construction and validation of new models into a very challenging task.

To help the interaction between theorists and experimentalists, a common training of students in theory and in experiment is useful. This can happen in common graduate workshops, summer institutes, etc. Given the current age-profile of permanent researchers in Europe, a slight, but continuous increase in positions will be required to ensure proper career perspectives for the next generation of research leaders. Attempts at organizing the particle physics research landscape at the national level (such as the Helmholtz Alliance in Germany) have been very beneficial. A similar initiative at the European level would be excellent.

CERN is a focal point for European theory activities. LPCC provides a forum for the collaborative effort of experiment and theory to exploit the LHC physics results. A better institutional collaboration of CERN with European universities (which is at present largely based on initiatives of individual staff members) could be of enormous benefit for both sides.

Scientific collaborations of theorists with experimental teams, motivated by the interest and competence of theorists, take shape within laboratories in many countries. For example, the DESY theory groups in Hamburg and Zeuthen cover a large spectrum of research in particle physics, and their phenomenological activities proceed in close contact with experimentalists.

7.3 Special Topics

7.3.1 Lattice Field theory

The applications of lattice field theory straddle the fields of particle physics, nuclear physics and astrophysics. Lattice-QCD computations already provide some of the most accurate determinations of the strong gauge coupling α_s and of the masses of the five lightest quarks, as well as a wealth of non-perturbative hadronic parameters (e.g., meson decay constants) that are necessary to interpret the experimental results, notably in flavour physics. In some cases, the predictions of lattice QCD are so accurate that they match the precision of the last generation of dedicated flavour-physics experiments. Lattice field theory also allows to study matter at extreme densities and temperatures, characterizing for example the early stages of the Universe. More generally, lattice calculations provide insights into the properties of strongly coupled quantum field theories, offering the opportunity to understand non-perturbative questions in the Standard Model and beyond. The possibility of checking on the lattice non-perturbative results originating from string theory is only starting to be systematically exploited.

Progress in lattice computations requires increases both in raw computing power and in the sophistication of algorithms and methods. Since the last strategy review, substantial advances have been made - especially for what concerns the inclusion of physically light up and down quarks in the sea. Further increases in computing power would allow to achieve lattice spacings small enough to be suited for precision studies of b-quark physics, as well as volumes large enough to study extended hadronic systems such as resonances, multi-hadron states or small nuclei. Very high statistics would also give access to the properties of more difficult systems such as flavour singlets or glueballs.

While the cost of the computer facilities required for lattice computations is a small fraction of the cost of high-energy physics experiments, it exceeds by far the budget of any theory group. Thus, lattice theorists need recourse to multi-purpose centers for high-performance computing (HPC). Currently, Europe has seven of the world's top-20 computers, with computing speeds at the level of the petaflops. Most of these computers are available on a national basis, and the Partnership for Advanced Computing in Europe (PRACE) provides resources for large projects on a Europe-wide scale. However, fundamental physics is not currently a top priority of PRACE - e.g., lattice QCD was not chosen as an application area for the recent Dynamical Exascale Entry Platform (DEEP) project. Moreover, the allocation of computer resources at the European level is usually based on the model of 1-2 year projects, which does not necessarily match the needs of QCD computations.

To gain access to large-scale computing resources, lattice theorists organize themselves in large collaborations, which in some cases are further organized in national consortia (e.g., UKQCD). What appears to be lacking at the moment is some sort of Europe-wide coordination, which would allow lattice theorists to effectively negotiate with funding agencies for the required investment (the latter is of the order of 10M-20M EUR/year for dedicated hardware, and 4M EUR/year for software and theoretical development). On the other hand, some success at bringing lattice theorists across Europe together comes from EU Initial Training Networks such as StrongNET and, formerly, Flavianet.

Finally, it should be stressed that lattice calculations are on the cutting edge of HPC, thus they provide a unique training environment for researchers who may eventually move on to other fields. Besides the obvious benefits for particle physics, an investment in lattice field theory has the potential to bring additional returns in terms of software and, perhaps to a larger extent, hardware developments.

7.3.2 Development of Software Packages

High-energy particle physics has reached such a level of complexity that it is practically impossible to carry out phenomenological analyses of the Standard Model (SM) and its extensions without making recourse to sophisticated computing tools. For example: many extensions of the SM (e.g., supersymmetry) introduce a large number of new fundamental parameters, which greatly complicates their analysis; high-precision calculations of physical observables often involve hundreds if not thousands of Feynman diagrams, making automated methods indispensable; in the simulation of the collider signatures of the different models, the calculations of matrix elements for high-multiplicity signal and background events need to be matched to accurate descriptions of parton showering and of initial and final hadronic states.

The tools for particle physics analyses that are developed (mostly) by theorists can be grouped in several broad categories:

- Codes that compute the mass spectrum and the decays rates in extensions of the SM, starting from the fundamental parameters of the model and including higher-order corrections;
- Codes that compute the predictions of a given model for individual observables that can be used to constrain its parameter space (e.g., flavour-violating processes, electroweak precision observables, Dark Matter relic abundance);
- Global fitting codes that combine the information from a number of predictions to test how well a given model can describe all the available experimental information;
- Matrix element generators that compute total or differential cross sections for signals and backgrounds at colliders and/or produce the amplitudes for the individual "hard" events, starting from the Lagrangian of a given model;
- Monte Carlo (MC) event generators that implement the amplitude for the hard event, then simulate randomly its development, i.e.: the decays of the particles involved in the hard event; the parton showering of coloured particles in the initial and final states; the hadronization of the partons in the showers.

While some of the existing codes perform several of the tasks listed above, no single code currently performs all of the tasks, therefore it is often necessary to link different codes to each other. To simplify the passing of information between codes (which might be written in different languages and make use of different conventions), several accords have been developed. They generally consist of agreed-upon file formats and sets of conventions with which developers should comply for the input and output of their codes.

Among the categories of codes listed above, MC event generators occupy a special place, in that - while developed by theorists - they are used mainly by experimentalists, at all stages of an experiment. Indeed, almost every measurement, discovery and search for new physics at colliders has relied on MC event generators (examples include the discovery of a Higgs-like particle at the LHC; the discovery of the top quark and the measurement of its mass at the Tevatron; the electroweak measurements at the LEP; the searches for Dark Matter particles at the LHC). Also, theoretical progress in the understanding and precision of MC event generators will be necessary to further several aspects of the research program at the LHC, including the measurement of the properties of the Higgs-like particle, the searches for new physics in channels with large backgrounds and the precise measurements of the top-quark and W-boson masses.

In a sense, MC event generators serve as a conduit of knowledge between theory and experiments. That is why, in parallel to the efforts devoted to theoretical improvements (e.g., towards a consistent NLO matching of matrix elements and parton showers), the MC community is actively engaged in training the experimentalists to the use of event generators and to the understanding of the physics behind them. Over 300 experimental students have been trained at the six editions of the annual school organized by the MCnet collaboration – which was an EU-funded Research Training Network in the period 2007-2010 – and many have gone on to positions such as convenors of the MC working groups in the collider experiments.

In summary, the development of software packages has become an essential component of particle physics research. It would be important to find the proper framework to evaluate and fund these activities, and to ensure adequate career prospects for the researchers involved.

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Chapter 8

Accelerator Science and Technology

Relevant talks at the Open Symposium were given by C. Biscari and M. Lindroos, and further contributions to this chapter were given by L. Rivkin.

8.1 Energy Frontier Challenges

8.1.1 Introduction

Over the last few years—between the first and second process of the European Strategy Group—the international collider panorama has significantly changed (Fig. 8.1). While in 2006 several particle-physics accelerators were operating in Asia, Europe and the US, in 2012 LHC is the outstanding flagship of collider physics, and few e^+e^- colliders in Asia and Europe, together with RHIC in the US, complete the picture.

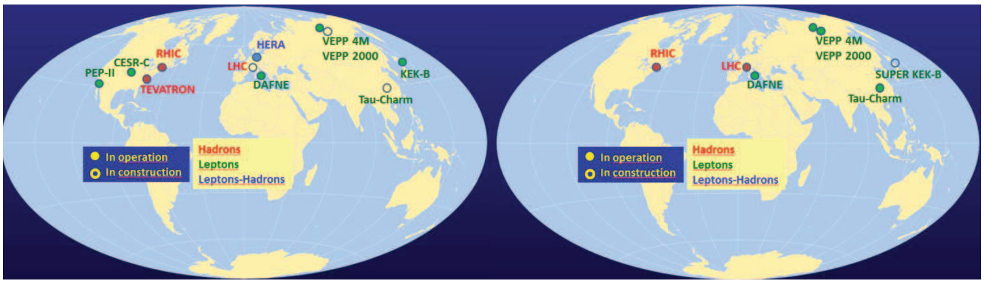

Figure 8.1: Collider panorama in 2006 and 2012

Going to higher and higher beam energies—the so-called energy frontier—has been the main source of discoveries. Over the last fifty years the collider energy has been increased by five orders of magnitude and the luminosity by about seven orders. The maximum energy of lepton and hadron colliders has followed roughly an exponential growth, up to LEP and the LHC. Only five hadron colliders have been built so far: ISR, SPS, Tevatron, RHIC and the LHC. Figure 8.2 shows the energy and luminosity of past, present and proposed future colliders as a function of year. It is likely that from the "flock" of possible future projects only very few will eventually be realized.

Amongst the most important limits one can note for electron-positron circular colliders the synchrotron radiation losses, for linear colliders the beam size, and for hadron colliders the magnet technology. All three types of colliders can reach higher energy through larger size. The size, complexity and cost of the next generation of energy-frontier colliders call for extended international collaboration to master their construction and operation. In parallel, numerous laboratories are performing R&D on novel acceleration methods aimed at creating the basis for colliders at much higher energy.

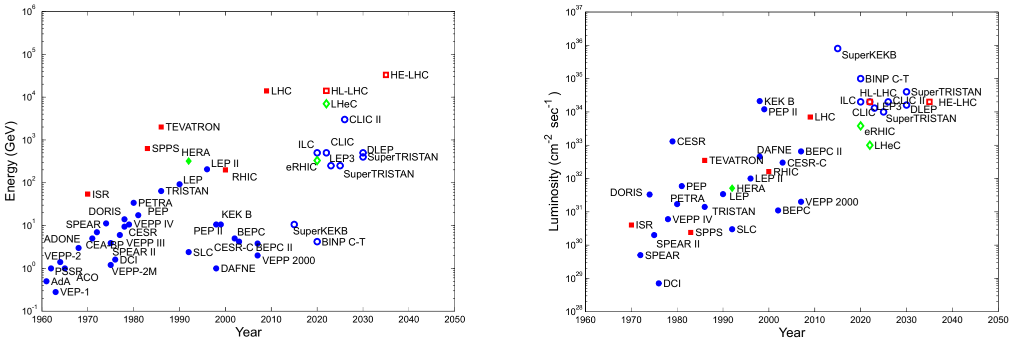

Figure 8.2: Energy and luminosity of particle colliders

8.1.2 Hadron Colliders

This section is dedicated to the LHC, its planned upgrades, and RHIC.

LHC (14 TeV): Presently the LHC is running at energies lower than nominal due to the awareness of critical splice junctions between SC magnets since the 2008 incident. At this reduced energy (7 TeV c.m. in 2011, 8 TeV in 2012, to be compared with the 14 TeV design value) the LHC performance is well above the design expectations, in terms of luminosity, reliability, β^*, integrated luminosity, etc. High beam-beam tune shifts have been demonstrated without any negative impact on luminosity lifetime (total beam-beam tune-shift values $\Delta Q_{\mathrm{bb}} > 0.03$ have been routinely reached in 2011-12 machine studies).

The next Long Shutdown "LS1" starting in March 2013, will be mainly dedicated to splice consolidation, after which the beam energy will be gradually increased up to the nominal energy. The programme through 2021 is already defined: the running period 2015-2017 will be dedicated to increasing the luminosity while limiting the maximum event pile up in the experiments (either by transiting from 50 to 25-ns bunch spacing or by luminosity leveling).

After LS2 (2018) both luminosity and reliability will be further increased, with the aim of a total integrated luminosity of 300 fb^{-1} by 2021.

HL-LHC [ID153]: The inner quadrupole triplets at the interaction points (IPs) 1 and 5 of the LHC are expected to be destroyed by radiation from collision debris when a luminosity of 300–400 fb^{-1} has been accumulated. Replacing them twice, about every 5 years, with identical magnets, and carrying out the necessary consolidation work of the present LHC accelerator complex, would allow reaching an integrated luminosity of 1000 fb^{-1} by about 2030. The proposed project of a High Luminosity LHC (HL-LHC) aims at making some additional improvements to the accelerator in order to provide a leveled luminosity of 5×10^{34} cm^{-2}s^{-1}, and to accomplish an integrated luminosity of 3000 fb^{-1} on the same time scale (2030), at about 20% higher cost for the accelerator modifications.

The HL-LHC project includes the following main hardware items:

- larger-aperture final quadrupoles with a peak field of 13 T, based on Nb_3Sn superconductor, to replace the existing inner triplets at IPs 1 and 5;
- new shorter 11-T dipoles in the dispersion suppressors, also based on Nb_3Sn, to free space for a more robust collimation system, which can support higher beam currents and higher luminosity;
- novel compact 400-MHz SC *Nb* crab cavities to recover the luminosity loss due to the crossing angle (which becomes more pronounced for smaller β^*); and
- a superconducting link, based on high temperature superconductor (*HTS*), to relocate the radiation-sensitive power converters away from the LHC tunnel.

Furthermore, the cryogenics system will be upgraded to include a dedicated cooling system for the interaction regions (IRs), required for higher luminosity. In parallel to the design of the HL-LHC final quadrupoles, a new LHC optics is being developed to support the chromatic correction for β^* values of 30 cm or below. In addition to HL-LHC, a substantial upgrade of the LHC injector complex (LHC Injector Upgrade – LIU [ID154]) is planned by 2018, comprising the new Linac4, increased injection energies for the PS booster and modifications to the PS to overcome space-charge limitations and enhancements of the various RF systems for handling higher beam intensity, etc.

The R&D on high field magnets started years ago, stimulated by the VLHC and ITER projects. It has grown into multi-laboratory and industrial collaborations. Example collaborations are the US-LARP effort, which has been, and is, developing a series of HL-LHC prototype quadrupoles, the FRESCA test facility at CERN, and the European EuCARD WP7 HFM.

A short summary of the present magnet technologies (Fig. 8.3) follows:

- *Nb-Ti:* Robust, ductile, well established technology for fields lower than 10 T. Most SC magnets in present accelerators are based on this technology.
- Nb_3Sn: This SC can reach a magnetic field up to 16 T. The production of cables is well advanced. Robust programs of R&D aim at defining heat treatment, etc., to reduce its brittleness. Magnet prototyping is also well advanced and a few Nb_3Sn magnets will be used in the HL-LHC.
- Nb_3Al: KEK and Hitachi are building a subscale magnet for demonstration ($B =$ 13 T).
- *HTS* may withstand fields up to 45 T. R&D on wires is ongoing. There still is a long road for HTS high-field magnets. Challenges include mechanical weakness, magnetization, ac losses, establishment of quench detection and protection techniques, unit length and cost.

Other applications of high-field magnets include polarized ultra-cold neutrons, gantries for hadron therapy, NMR magnets, high-field wigglers and undulators for light sources, and linear-collider damping rings.

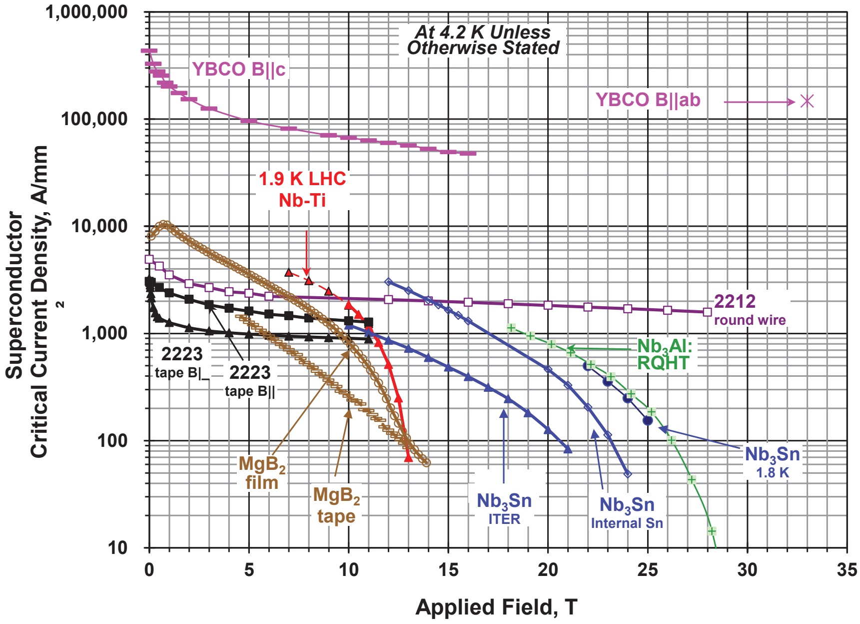

Figure 8.3: Critical current density for SC cables as a function of applied field [1].

HE-LHC and VHE-LHC [ID155] : Different proposals exist for the possible use of present CERN infrastructure after the completion of the HL-LHC programme. Two of them are the High Energy LHC (HE-LHC) and the Very High Energy LHC (VHE-LHC), both aiming at increasing the proton energy far beyond 7 TeV. A possible time line is shown in Fig. 8.4. In 2010 a CERN study group and a EuCARD workshop addressed the feasibility and critical R&D issues. Arguments in favour are the reuse of the CERN infrastructure as well as the practical and technical experience gained with LHC. The beam energy is set by the SC magnets dipole: fields of 16-20 T will allow beam energies up to 26-33 TeV in the centre of mass, for a collider inside the present LHC tunnel. Fields of order 16 T are within the reach of $Nb3Sn$ SC magnets. 20-T fields would require additional segments of *HTS* conductor, for which presently the Bi-2212 round wire, and the ReBCO (YBCO or GdBCO) coated conductors are the most promising. Though HTS solenoid insert coils have been built and tested, a long road still lies ahead with R&D on dipole fabrication and quench protection scheme. Other applications of high-field superconductors have appeared in the meantime (e.g. SC power transmission lines), which are interesting also from the commercial point of view.

HE-LHC needs further R&D advances in several other domains: accelerator physics, collimation (with increased beam energy and energy density), beam injection including the replacement of the SPS by a SC machine with energy above 1 TeV and SC transfer lines to the LHC, beam dumping, vacuum and cryogenics for increased synchrotron radiation. The latter will also represent an advantage: for the first time a hadron collider will benefit from a short damping time of 1 hour to be compared with 13 h for the present LHC.

Table 8.1 compares parameters of LHC, HL-LHC, HE-LHC and VHE-LHC.

The VHE-LHC would require a new tunnel in the CERN vicinity of up to 80 km circumference, which could allow *pp* colliders of 42 TeV c.m. with the present 8.3-T LHC magnets, 75 TeV with 15-T magnets, and 100 TeV with 20-T magnets (very high field

Table 8.1: Parameters of LHC, HL-LHC, HE-LHC, and VHE-LHC (examples)

parameter	**LHC**	**HL-LHC**		**HE-LHC**	**VHE-LHC**
c.m. energy [TeV]	14			33	100
circumference C [km]	26.7				80
dipole field [T]	8.33			20	20
dipole coil aperture [mm]	56			40	40
beam half aperture [cm]	2.2 (x), 1.8 (y)			1.3	1.3
injection energy [TeV]	0.45			>1.0	7.0
no. of bunches	2808	2808	1404	1404	4210
bunch population [10^{11}]	1.125	2.2	3.5	1.29	1.34
init. transv. norm. emit. [μm]	3.73,	2.5	3.0	2.59	1.53
initial longitudinal emit. [eVs]	2.5			4.0	17.2
no. IPs contributing to tune shift	3	2	2	2	2
max. total beam-beam tune shift	0.01	0.015	0.019	0.01	0.01
beam circulating current [A]	0.584	1.12	0.089	0.328	0.338
RF voltage [MV]	16			32	32
rms bunch length [cm]	7.55			6.5	7.7
IP beta function [m]	0.55	0.15		0.6	1.5
init. rms IP spot size [μm]	16.7	7.1	7.8	9.4	6.5
full crossing angle [μrad]	285	590		175	52.3
Piwinski angle	0.65	3.13	2.86	0.65	0.3
geometric luminosity loss	0.84	> 0.9	> 0.9	0.84	0.96
stored beam energy [MJ]	362	694	552	480.7	4573
SR power per ring [kW]	3.6	6.9	5.5	66.0	1991
arc SR heat load dW/ds	0.21	0.40	0.32	2.8	84
energy loss per turn [keV]	6.7			201.3	5857
critical photon energy [eV]	44			575	5474
photon flux [10^{17}/m/s]	1.0	1.9	1.5	1.3	1.3
longit. SR emit. damping time [h]	12.9			0.98	0.32
horiz. SR emit. damping time [h]	25.8			1.9	0.64
init. longit. IBS emit. rise time [h]	57	21.0	16.4	68	305
init. transv. IBS emit. rise time [h]	103	15.4	14.3	$\sim$60	72.2
events per crossing	19	140 (lev.)	140 (lev.)	76	193
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	7.4	3.7	2.0	5.0
beam lifetime due to burn off [h]	45	11.6	18.4	12.6	15.5
optimum run time [h]	15.2	8.9	14.3	10.4	11.8
opt. av. int. luminosity / day [fb^{-1}]	0.47	3.7	2.3	0.8	2.1

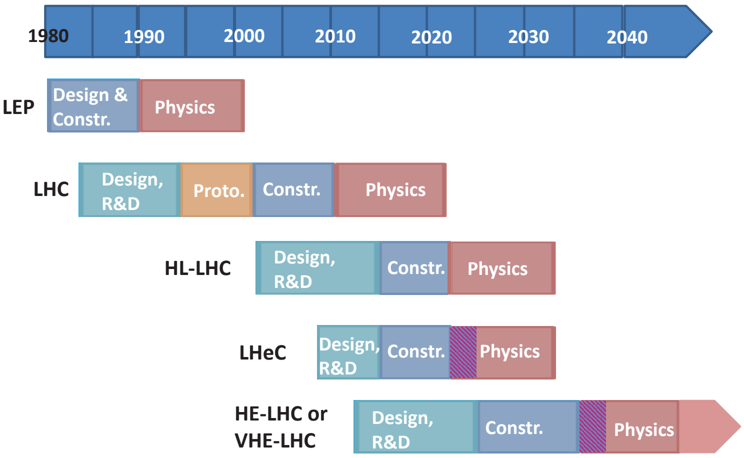

Figure 8.4: Possible time line of LHC and its proposed upgrades or extensions

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hybrid magnets based on *HTS*, Nb_3Sn and *Nb-Ti*). Some geological studies to identify the best locations in the Geneva area for such a large infrastructure are underway [ID165]. Preliminary conclusions on the feasibility of an 80-km tunnel are encouraging.

Heavy ions in the LHC [ID164]: The heavy-ion programme in the present LHC configuration will contrinue until 10 fb^{-1} have been accumulated in *Pb-Pb* collisions, implying 50-kHz interaction rates. A number of options for colliding various species are possible besides further higher-energy and higher-luminosity *Pb-Pb* and *p-Pb* runs.

A future HE-LHC could also be a very high-performance heavy-ion collider. At the nominal LHC energy, synchrotron radiation damping rates are comparable with intra-beam scattering (IBS) growth rates. At twice the nominal LHC energy, damping will cool the emittance 8 times faster and overcome IBS, which at the LHC is an important component of the luminosity decay.

RHIC – a High Luminosity (Polarized) Hadron Collider [2]: RHIC, at BNL, is unique in that it may collide longitudinally polarized protons or light ions in addition to heavy ions.

Recent upgrades for heavy-ion operation at RHIC include 3D stochastic cooling and an electron beam ion source. Peak luminosities of 50×10^{26} $cm^{-2}s^{-1}$ have been achieved in *Au-Au* collisions. Further improvements include a 56 MHz SRF, electron cooling for low-energy operation, and *p-Au* collisions.

In *pp* collisions peak luminosities of 165×10^{30} $cm^{-2}s^{-1}$ have been achieved with an average polarization of 52-58%. Further plans comprise an upgrade of the polarized source, electron lenses, and polarized ^{3}He beams.

8.1.3 Lepton Colliders

Linear Colliders: ILC and CLIC Several proposed technologies include the ILC based on SuperConducting (SC) RF cavities and CLIC based on two-beam acceleration, as well as a lower-energy CLIC using klystrons.

ILC [ID73]: After a decision taken in 2004 on the technology to be used for a future e^+e^- linear collider, and also thanks to the European XFEL project at DESY, the SC RF technology has been developed in global collaboration. The three world regions have worked together under the direction of the Global Design Effort (GDE). The GDE has addressed not only the technical challenges, but also the industrialization and the mass production of a large number of elements. The 1.3-GHz ILC RF cavities are based on the TESLA design and have a nominal accelerating gradient of 31.5 MV/m.

A TDR is being produced. The ILC design foresees a maximum energy of 1 TeV c.m., but it is optimized for an initial phase at 0.5 TeV with a length of 31 km, and energy staging is planned. The design is site independent. The SC RF gradient is the primary cost driver, since the linac and the civil construction amount to 75% of the total cost.

The feasibility of the ILC SC cavity has been demonstrated. Significant progress in the achievable gradient has been made possible by the development of standardized recipes for electron beam welding, purification (thermal conductivity), and chemical polishing (see Fig. 8.5). Further improvements of the yield are being pursued.

Outstanding challenges are the deployment and technology industrialization around the world. R&D is still continuing with slightly modified objectives, i.e. technology transfer, mass industrialization, high pressure, high purity rinsing, solvent/detergent rinse, use of large-grain *Nb* sheets, diagnostics, and mechanical grinding/tumbling for surface repair. For 500 GeV c.m. about 15,000 9-cell cavities will be used, with 1680 cryomodules and 560 RF units (10-MW klystrons) [ID73].

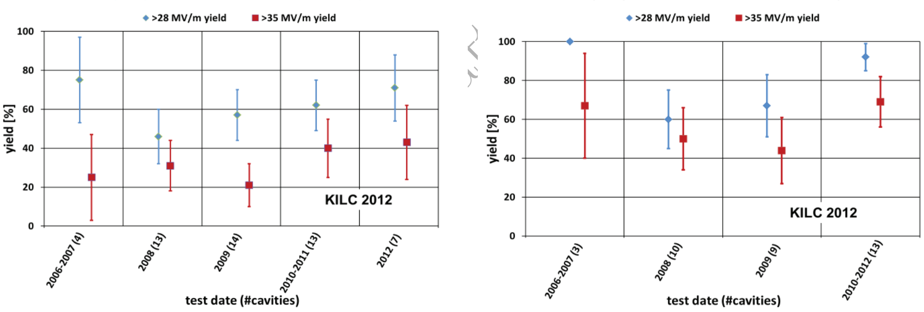

Figure 8.5: SC 1.3-GHz RF cavity gradient yields in first (left) and second pass (right) [3].

Other ILC challenges include: achieving and maintaining the 6–8 nm vertical design IP spot sizes (the smallest spot size so far achieved at the KEK-ATF2 test facility is 166 ± 7 nm, to be compared with an ATF2 design goal of 37 nm, which would optically correspond to the ILC final focus); delivering a high integrated luminosity; extracting 1312 bunches per pulse one by one from a 6.7-km damping ring using ultrafast kickers; and achieving the required average positron production rate. The high flux of positrons should be obtained from photons produced by sending the high-energy electron beam of at least 150 GeV through a small-aperture 147-m long SC helical undulator, or, alternatively, a 125-GeV beam through a 250-m long undulator.

The ILC design luminosity at 500 GeV c.m. is 1.8×10^{34} cm^{-2}s^{-1} in the baseline design (1312 bunches) with 162 MW of electrical power (Table 8.3). It could be doubled with 2625 bunches per pulse (requiring 205 MW). At 250 GeV c.m. a luminosity of 0.75×10^{34} cm^{-2}s^{-1} is expected with about 120 MW of electrical power. The ILC baseline design considers a highly polarized electron beam (80%) and positrons with moderate polarization (30%) from the helical undulator source. As a consequence of the undulator scheme adopted for the e^+ production, for collisions at lower energies, such as 250 GeV c.m., the ILC electron-linac repetition rate needs to be doubled to 10 Hz (5 Hz for collision, 5 Hz for positron generation), or the length of the undulator be increased.

CLIC [ID99]: The two-beam acceleration technology has been the subject of more than 25 years of R&D centered at CERN. The CLIC technology is based on normal conducting cavities at 12 GHz with a nominal accelerating gradient of 100 MV/m. The nominal energy of the CLIC collider is 3 TeV c.m., passing through initial phases at lower energy, of which the 0.5-TeV option has been outlined in greater detail (Table 8.3). A possible ultimate upgrade to 5 TeV has also been considered. Lower-energy machines can run most of the time during the construction of the following stage.

The CLIC group is an international collaboration gathered around CTF3, the third CLIC Test Facility at CERN, which has been, and is, addressing the major technical challenges of the two-beam acceleration and of the high RF gradient at high frequency. The CTF2/CTF3 teams obtained results on two-beam acceleration, drive-beam generation (Table 8.2), and long-pulse high-gradient operation of X-band cavities.

Table 8.2: Comparison between CLIC and CTF3 Drive Beam Parameters

parameter	CLIC	CTF3
accelerated current [A]	4.2	3.5
combined currrent [A]	101	28
final energy [MeV]	2400	120
acceleration pulse length [μs]	140	1.2
final pulse length [ns]	240	149
acceleration frequency [GHz]	1	3
final bunch freqency [GHz]	12	12

The most critical points for the CLIC machine design are: achieving the high main-linac gradient of 100 MV/m, with sufficiently low breakdown rate; generation of the drive beam, production of RF power, stable deceleration, and main beam acceleration; generation of the ultra-low emittances of the main beam in the damping rings and their preservation during beam transport and acceleration in the main linac (prealignment and active magnet stabilization); machine protection; and focusing and colliding nm-scale beams, with the implied stability requirements for final focus and linac; and delivering a high integrated luminosity. The CLIC CDR has been recently published [4] and a comprehensive project implementation plan for CLIC is foreseen for 2016.

The CLIC design luminosity at 500 GeV c.m. is 2.3×10^{34} cm^{-2}s^{-1} with 270 MW of electrical power (Table 8.3)[1]. For CLIC the design electron-beam polarization at the IP is 80% as for the ILC. The baseline design for the CLIC positron source provides only unpolarized positrons, though preliminary studies indicate the possibility to also produce positrons with moderate (30%) polarization, using either a Compton or an undulator source [4].

Since 2008 a strong collaboration exists between the ILC and CLIC groups (accelerator and detector). A new Linear-Collider organization will be created in 2013 to take over from the current GDE and to coordinate the R&D efforts of ILC and CLIC towards realizing an e^+e^- linear collider as a worldwide collaborative project.

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[1] Various preliminary scenarios for CLIC operation at 250 GeV c.m. can be found in [5].

Table 8.3: ILC and CLIC main parameters for different energies

	ILC			CLIC (two-beam acc.)	
centre-of-mass energy [TeV]	0.25	0.5	1.0	0.5	3.0
total (peak 1%) luminosity [10^{34} cm^{-2}s^{-1}]	0.75 (0.63)	1.8 (1.5)	4.9	2.3 (1.4)	5 (2)
repetition rate [Hz]	5	5	4	50	50
loaded acc. gradient [MV/m]	31.5	31.5	45.0	80	100
m. linac RF frequ. [GHz]	1.3 (SC)			12	
bunch population [10^9]	20	20	17.4	6.8	3.72
beam pulse duration [μs]	727	727	897	0.177	0.155
beam power / linac [MW]	5.1	10.2	27.2	4.9	14
hor. norm. emit. [μm]	10	10	10	2.4	0.66
vert. norm. emit. [μm]	0.035	0.035	0.030	0.025	0.020
hor., vert. IP beta f. [mm]	13, 0.41	11, 0.5	11, 0.23	8, 0.1	4, 0.07
hor., vert. IP spot size [nm]	729, 7.7	474, 5.9	335, 2.7	202, 2.3	40, 1.0
BDS length [km]	~ 1.1	2.23 (1 TeV)	2.23	1.87	2.75
total site length [km]	16 (or 31)	31	46	13.0	48.3
wall plug to beam transf. eff.	9.0%	9.6%	13%	7.5%	6.8%
total wall-plug power [MW]	$\leq$100	162	300	270	589

Circular e^+e^- colliders [ID157, ID138, 6, 7] : For a long time LEP2 was considered the last circular e^+e^- collider at the high energy frontier, limited by the synchrotron radiation emission. Lately new proposals of high-energy circular e^+e^- colliders have emerged. The recent discovery of a Higgs-like boson at an energy reachable by a collider slightly more powerful than LEP, together with the excellent performances of lepton factories delivering very high luminosities, which have set new standards for e^+e^- collisions, are the driving motivation behind such proposals based on well-known and established technologies.

LEP3 is proposed to be built in the LEP-LHC tunnel, the existence of which, together with the associated infrastructure and the LHC detectors, is an attractive starting point. The LEP3 parameters shown in Table 8.4 provide a peak luminosity of 10^{34} cm^{-2}s^{-1}.

The short beam lifetime, with 4 IPs of the order of 10 minutes, limited by radiative Bhabha scattering, asks for a booster inside the tunnel, and a top-up operation mode, as successfully demonstrated in synchrotron light sources and the two B factories. There would, therefore, be two rings in the LHC tunnel, based on light-weight magnets. An additional beam lifetime limitation arises from beamstrahlung [8]. This effect can be mitigated by developing an optics with an energy acceptance of around 2%, or by operating with flatter beams (smaller vertical emittance), or by fast top up.

At CERN there are very preliminary studies for e^+e^- circular colliders fitting different larger tunnels that are being considered for high energy hadron colliders. The cost of any of these very large hadron infrastructures, the time needed to build them, and the collaborative efforts are such that it appears a reasonable approach to exploit them at maximum, with the coexistence of different machines. In this spirit the TLEP proposal (three times longer than LEP) aims at exploring the Z, the W, the Higgs, and the $t\bar{t}$ threshold at 90, 160, 240 and 350 GeV c.m., respectively. The TLEP luminosity at the "Higgs threshold" (240 GeV c.m.) is at least 5×10^{34} cm^{-2}s^{-1} in each of up to four collision points, and about 7×10^{33} cm^{-2}s^{-1} at 350 GeV c.m. For both TLEP

Table 8.4: Parameters of circular e^+e^- colliders

	LEP2	LEP3			TLEP			
c.m. energy [GeV]	209	90	160	240	90	160	240	350
number of IPs	4	4			4			
L [10^{33}cm^{-2}s^{-1}]	0.1	250	50	10	1000	250	50	7
beam lifetime [min] (4 IPs)	360	14	8	8	37	16	16	27
circumference [km]	26.7	26.7			80			
ΔE/turn [GeV]	3.5	0.1	1.4	7	0.04	0.4	2.1	9.3
RF voltage [GV]	3.6	1	4	12	2	2	6	12
RF frequency [MHz]	352	700						
SR power [MW]	23	100			100			

and LEP3 at the Z pole significant longitudinal polarization of both beams is possible, up to 80% [9], but this requires further investigation when operating with very high luminosity. Similar studies of circular e^+e^- Higgs factories are being pursued in Japan (SuperTRISTAN), China, Russia, and in the US [7].

Muon Collider [ID135] Several facilities for neutrino physics, based on high power proton beam accelerators (see Chapter 8.2), are operational or are being developed. One of the possible outcomes of these facilities is a future muon collider. The technology is not yet mature, especially the muon cooling process, for which a dedicated test facility (MICE) is being commissioned. The advantages of a muon collider, apart from direct Higgs production, are compactness, low synchrotron-radiation power, small energy spread at the interaction point, and negligible beamstrahlung.

Studies to fit a multi-TeV machine at Fermilab, in the framework of the development of the neutrino physics program, are ongoing. Key parameters of this study are listed in Table 8.5. It should be noted that, amongst the challenges that should be overcome, the cooling is particularly severe. One needs to reduce the phase space by six orders of magnitude in the cooling channels composed of hundreds of very high-field solenoids (30–40 T) and of high-gradient RF cavities operating in multi-Tesla fields.

Table 8.5: Muon-collider parameters

parameter	value
c.m. energy [TeV]	1.5
luminosity [10^{34} cm^{-2}s^{-1}]	1.25
beam-beam tune shift	0.087
muons / bunch [10^{12}]	2
muon power (both beams) [MW]	7.2
normalized transverse rms emittance [μm]	25
normalized longitudinal rms emittance [mm]	72
repetition rate [Hz]	15
proton driver power [MW]	4

Plasma and dielectric accelerators [ID110] The possibility of using plasmas to produce very high gradient electric fields which can accelerate charged particles is established (Fig. 8.6). The accelerating gradients in plasmas can be orders of magnitude higher than in RF cavities. R&D is going on in several laboratories, since a multitude of possible applications appears realizable at a small scale. The focus is on beam quality, stability, staging and continuous operation.

In the last decade a breakthrough of the plasma acceleration techniques has come on one side from advances in laser technology, especially the invention of chirped-pulse amplification, and on another side from important advances in the field of plasma computer simulations, in particular the prediction of the bubble regime to produce beams with reduced energy spread.

The accelerating field in a plasma can be driven by different techniques: lasers, e^- beams, and p beams.

Dielectric structures with much higher gradients than conventional RF strucures represent another approach, where the field is also excited by e^- beams.

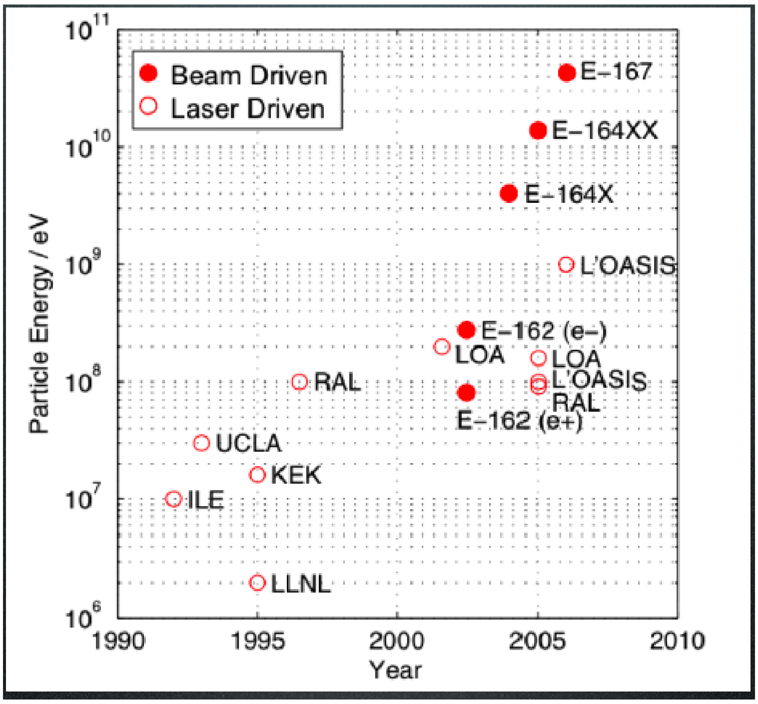


Figure 8.6: Experimental results on plasma acceleration [ID110]

In **Laser Wake Field Acceleration (LWFA)** an intense laser light pulse in a dilute plasma expels electrons from its axis of propagation by its ponderomotive force, creating a plasma wake, with longitudinal fields above 10 GV/m. Powerful lasers are becoming tools for fundamental physics (see for example ELI with its 10^{23-25} W/cm^2 laser [10]). Electron beams from 100 MeV to 1 GeV, have been obtained in mm to cm long plasmas, with a relative energy spread of the order of 1%, a femtosecond duration, and emittances of the order of 1 μm for bunch charges between 10 and 100 pC. This technology is not yet ready for a proposal for a high energy accelerator.

e^- **driven:** High brilliance, short pulse e^- beams are the main ingredient of e^- driven plasma accelerators, where the accelerating gradient is proportional to the bunch charge and inversely proportional to the square of the bunch length. Accelerations over longer distances ($\sim$ 50 cm) than LWFA have been obtained, although with higher final energy spread. The maximum energy gain is limited to twice the incoming energy.

Several methods are being studied to increase the accelerating gradient, as for example the ramped bunch train, with variable bunch charge along the train, or the *weak blow out* regime with low charge and very small size e^- bunches. All regimes need advanced methods for electron-beam parameter control.

p **driven:** Recently it has been proposed to use a powerful proton beam to drive a plasma wakefield e^- beam accelerator [11]. Simulations indicate that an accelerating gradient in excess of 100 GV/m could be produced. A beam experiment at CERN is being prepared [ID168]. Very high energy transfer and absence of staging are the main advantages of this technique.

Dielectric wakefields: The electromagnetic power radiated by an ultrashort, intense “driving” electron bunch propagating in a hollow dielectric fiber can be used to accelerate another “witness” bunch as in the case of the plasma wakefield accelerator. Dieletric accelerators need high peak currents, a small inner radius of the hollow dielectric fiber, a drive beam with high charge, short bunch duration and a very low emittance. Preliminary experiments are underway at SLAC-FACET [12].

While plasma acceleration can be considered embryonic compared with high-energy colliders, there already exist concept proposals for linear colliders based on these techniques. An active international community, involving different laboratories, and merging photon factories, industrial applications, medical applications and HEP, looks forward to following this road. Power-conversion efficiency and luminosity are two of the key challenges. Several decades of intense R&D are likely to be necessary before a viable linear-collider project using this technology could materialize.

8.1.4 Hadron-Lepton Colliders [ID147, ID156]

The Large Hadron electron Collider (LHeC) [13] plans to collide the high-energy protons and heavy-ions in the LHC with 60 GeV polarized electrons or positrons. The baseline scheme for this facility adds to the LHC a separate 9-km long recirculating SC lepton linac with energy recovery, delivering an electron current of 6.4 mA. The new LHeC tunnel must be arranged tangential to the LHC. It turns out that the only practicable solution for the LHeC interaction point is IP2 (ALICE). Hence a transition from ALICE to the LHeC experiment would become mandatory. With 60-GeV lepton beam energy and using the 7 TeV proton (and few TeV / nucleon ion) beam, LHeC attains c.m. energies in the TeV range. The LHeC ep target luminosity is 10^{33} cm^{-2}s^{-1}. Extensions to 10^{34} cm^{-2}s^{-1} are being considered. The total electrical power for the LHeC lepton branch has been limited to 100 MW. A Conceptual Design Report (CDR) has been published recently [9]. This CDR considered both ERL-ring and ring-ring options. Recently [14] the ring-ring design has been dropped, due to interference with the LHC physics programme. A slightly reconfigured LHeC recirculating linac (without energy recovery) could operate as Higgs factory $\gamma\gamma$ collider (“SAPPHiRE”) [15, ID145].

The electron-hadron collider project eRHIC [16] aims to collide polarized (and unpolarized) electrons with a current of 50 (220) mA and electron energies in the range 5–30 GeV with a variety of hadron beams — heavy ions as well as polarized light ions — stored in the existing RHIC at BNL. The eRHIC electron beam will be generated in an energy recovery linac (ERL) installed inside the RHIC tunnel. The ultimate eRHIC luminosity per nucleon, achieved with lower hadron-beam emittances and with larger electron-beam currents than for the LHeC, is a factor 100–400 higher, assuming a novel scheme of Coherent Electron Cooling (CEC) [17].

8.1.5 Higgs Factories

The announcement at CERN of a clear signal for a new particle with a mass of ∼126 GeV, has stimulated interest in a dedicated facility, a so-called "Higgs factory,". This facility should be focused on producing a large number of events in a clean environment. Possible Higgs factories include e^+e^- colliders, muon colliders and $\gamma\gamma$ colliders.

e^+e^- collider Higgs factory: The relatively low energy of the Higgs-like particle signal has revived the possibility of using a circular collider, and it has led the linear-collider community to downsizing and staging their proposed projects.

The c.m. energy of an e^+e^- collider Higgs factory is around 240 GeV, which is about 10% higher than LEP2. LEP3, with 240 GeV c.m. and luminosity in the 10^{34} cm^{-2}s^{-1} range, is proposed to be installed in the LHC tunnel. Short beam lifetimes (of the order of 20 minutes) call for a top-up mode of operation. Also TLEP with three times the LEP circumference is a possible contender, with very interesting luminosities (5×10^{34} cm^{-2}s^{-1} at 240 GeV c.m.) and energy reach (up to 400 GeV c.m.). Proposals similar to TLEP are being studied around the world.

Operating the ILC for a low energy around 240 GeV c.m. implies changes to the electron linac repetition rate or to the undulator of the positron source. CLIC has been optimised for 3 TeV. An initial klystron-based low-energy stage could provide fast access to the Higgs particle, realizing substantial synergy with high gradient X-band development for photon factories in several laboratories.

Muon colliders have also been considered as Higgs factories, and there indeed is a recent proposal from Fermilab for a low-energy Higgs factory, at 126 GeV c.m. energy. The amount of R&D still needed renders these muon-collider Higgs factories not competitive over the next decade.

Finally the $\gamma\gamma$ **option** is another possible future collision scheme, where the Higgs boson is produced in the s-channel. Two proposals have been submitted to the European Strategy Group Open Symposium, one based on a recirculaging SC linac in possible synergy with LHeC [ID145] and the other using CLIC technology [ID146]. $\gamma\gamma$ collisions are realized through Compton backscattering of laser (or FEL) photons off the high energy electron beams close to the IP. Advantages with respect to the e^+e^- collision scheme are that the electron beam energy is lower, and positrons are not required. Electron beam energies of 80 GeV, with high repetition rate, are the basis of the $\gamma\gamma$ Higgs collider, and are within reach of present accelerator technology. At a beam energy of 80 GeV, the laser wavelength should be 300-400 nm. For efficient conversion the total energy of the Compton-scattering laser pulse should be a few Joule, e.g., 1 TW peak power and 5 ps pulse length, implying 1 MW average power at 200-kHz repetition rate. Stacking laser pulses in a high-finesse optical cavity reduces the input laser power required by two orders of magnitude, to about 10 kW. An economic way to produce the required e^- energy is by means of a SC recirculating linac [ID145]. Operating a recirculating linac with much higher electron current in energy-recovery mode would also, or further, decrease the needed laser power [18]. The Compton IR layout with integrated optical cavity and the production of the required photon beam using a laser or FEL need strong R&D investments.

8.2 Intensity Frontier Challenges

8.2.1 Introduction

The particle accelerator intensity frontier has moved from a few kW to a few MW in the last 30 years. High-intensity applications such as neutrino oscillation physics, neutron spallation sources, nuclear physics, accelerator driven energy amplifiers and flavor factories drive the future of the field. The facilities can be split into lepton and hadron beams, but also into short-pulse and longer-pulse beams.

Particle physics at the high intensity frontier can broadly be divided into neutrino physics, other single flavor beam physics and flavor factory physics. Neutrino physics requires short pulses of very high intensity at a beam energy above the production threshold. The short pulse is needed to suppress the background in the detectors. Figure 8.7 (left) gives an overview of operating and planned short pulse facilities in the world.

Other single flavor beam physics such as neutron and muon physics can often make use of all or most of the machine duty cycle and can be done with long pulse or continuous accelerator sources. Figure 8.7 (right) gives an overview of operating, planned and studied facilities for the high average intensity physics. The flavor factories require very high luminosity with continuous electron and positron beams.

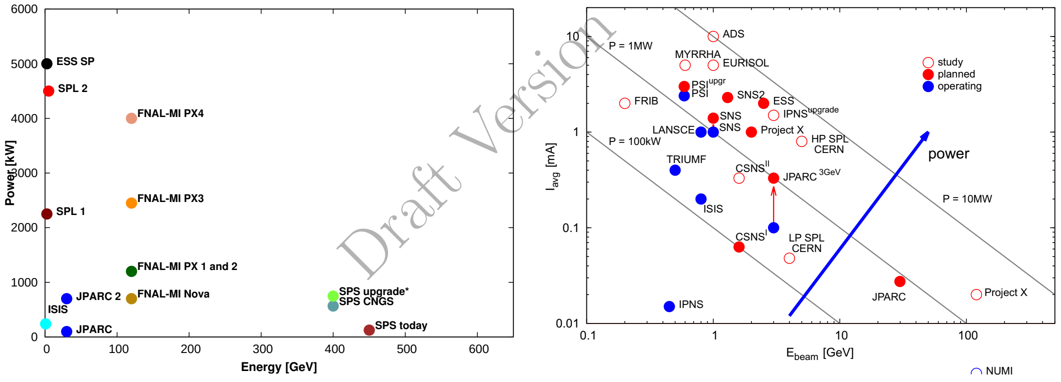


Figure 8.7: Short pulse high intensity facilities in operation (SPS at CERN, J-PARC in Japan and the Main Injector at FNAL), planned upgrades (Main Injector with Project X, CERN after the luminosity upgrade for LHC) and new projects under study (SPL and the Short Pulse (SP) ESS with accumulator and compressor rings) [19] [left]. High average intensity facilities in the world, operating, project and/or study [19] [right]. The high intensity frontier has moved from a few kW to MW in the last 30 years.

From a machine perspective, the particle accelerators at the high intensity frontier today can be grouped as:

- High intensity linacs for high intensity, high brightness single flavor beams e.g. neutrinos, anti-protons, muons and neutrons for EDM measurements. Examples of facilities are the European Spallation Source (ESS) [ID10], SPL at CERN [ID161], Project X at FNAL [ID151] and MYRRHA in Belgium [20].
- High intensity cyclotrons for high intensity single beams e.g. neutrons for EDM measurements and high brightness muons. Examples of facilities are PSI [21, 22, 23] and TRIUMF.

- High-intensity hadron rings with high-intensity single beams and flavor factories for rare decay and CP violation measurements, e.g. anti-protons, neutrinos, and muons. Examples of facilities are the Main Injector at FNAL, PS/SPS at CERN, ISIS and FAIR.

- High intensity electron/positron rings for high luminosity flavor factories. Examples of facilities are DAFNE at LNF, VEPP-2000 and VEPP-4M at BINP, BEPCII at IHEP, and SuperKEKB at KEK. Other proposed projects include a Super tau-charm factory at BINP.

8.2.2 High Intensity Neutrino Facilities

The next high-intensity long base-line experiments will be T2K with the J-PARC main ring reaching 300 kW at 30 GeV in 2014, gradually increased to 750 kW in 2018, and NOνA, which will start in 2013, with the goal to reach 700 kW from the 120-GeV FNAL Main Injector [ID135].

The European Design study EUROnu [ID35] has made a physics performance and cost comparison between a 4 MW CERN to Frejus Super-Beam, a 10 GeV Neutrino Factory and a $\gamma = 100$ beta beam, all based at CERN. The physics comparison has demonstrated that the Neutrino Factory has the best physics reach for CP-violation and the mass hierarchy, while a combination of the Super-Beam and Beta Beam is required to be competitive (see Chapter 4).

A cost comparison is still being worked out and will be provided for the January 2013 Erice meeting of the Strategy Group. Nevertheless, it has been demonstrated that there is no significant cost advantage in building the Super-Beam and Beta Beam combination, rather than the Neutrino Factory. As a result, the recommendation of EUROnu is the construction and operation of a 10 GeV Neutrino Factory as soon as possible, implemented using the following staged approach:

1. Completion of the necessary R&D and design work required to produce a full proposal in 5 years.
2. The completion and operation of MICE to study ionization cooling of muons.
3. The construction and operation of the νSTORM project [ID135] and other necessary R&D (see Section 8.2.2).
4. The construction and operation of the low power version of the Neutrino Factory [ID35].
5. The construction of the high power version [ID35].

Upgrade of existing facilities: Scenarios are being studied in Europe, Japan, and USA for long and short base line experiments with upgraded injectors and detectors:

- A short (1.6 km) and a very-long (2300 km) baseline are investigated as post-CNGS neutrino facilities in the sub-MW range [ID159, ID81]. The short-baseline would use the presently available beam from the SPS, operating with a 100 GeV protons at 120 kW of beam power using the technology validated at CNGS. A very-long baseline is proposed in a staged approach, based on the LHC injector upgrade [ID154], which would ultimately permit operation at 700 kW at 400 GeV, and later using new injectors being studied at CERN (see Section 8.2.2).

- In Japan an upgrade of the J-PARC facility to 1.6 MW and a new detector, Hyper-Kamiokande [ID86], are being studied.
- In the USA upgrades of the Main Injector at 120 GeV to some 700 kW through a proton improvement programme is underway and a long base line facility is under study for use with that beam [ID150]. Ultimately much higher beam power would become available after the construction of new injectors, such as Project X [ID151] (see Section 8.2.2).

Main issues for high intensity beams required by future neutrino experiments are related to beam losses. Most of the CERN accelerator upgrades planned by the LHC Injector Upgrade project [ID154] will also be beneficial for other users. They include the Linac4 leading to higher injection energy of the PS Booster and smaller transverse emittances, an upgrade of the PS Booster for increasing the injection energy of the PS, and an upgrade of the RF systems in the SPS. However, production of the CNGS-type beams is much more demanding for both PS and SPS and additional measures should be implemented before intensities close to 7×10^{13} protons can be accelerated to 400 GeV in a 6-s cycle. Beam losses at extraction in the PS are the main limiting factor for the present CNGS beam, with half the intensity. Stable operation of the new PS Multi-Turn Extraction is an indispensable step for their reduction. Transition crossing in both machines is another area of concern. Dedicated studies are required to define all necessary steps towards these high beam intensities.

Super-Beams: Super-Beams are usually defined as conventional broadband neutrino beams from facilities with a beam power exceeding 1 MW.

Project X is the key element of the Fermilab strategy and would in the long term permit the Main Injector to reach a beam power beyond 2.4 MW, maybe up to 4 MW. R&D is underway with significant investment in SRF development and front system tests.

A compressor ring at ESS has been proposed as a possible future upgrade of the facility and would open up new possibilities for neutron scattering physics. It would also open the possibility for a medium base-line neutrino experiment at ESS. The ring would have to be complemented with an additional extraction beam line, a target & horn assembly and a decay tunnel as well as a beam stopper. At 2.5 GeV extraction energy from the compressor ring, the neutrino detector should be located somewhere between 300 and 600 km from the ESS site. Two mines in Sweden, respectively at 365 km and 540 km from Lund/ESS, are being investigated as possible underground sites for the megaton water Cherenkov detector [ID10, 24]. Critical R&D issues for this project are the accumulator ring, the neutrino target and horn assembly, and the detector [ID10, 24].

The SPL study at CERN was initially aimed at a 4-5 GeV superconducting linac which, combined with a new 50 GeV synchrotron, would replace the PS Booster and PS and boost the beam characteristics for LHC. While a low power version of the SPL (LP-SPL) would be sufficient in the LHC injector complex, it could be upgraded to high beam power and serve as a multi-MW proton driver for a Super-Beam (4 GeV – 4 MW), a neutrino factory (5 GeV – 4 MW) and/or a Radioactive Ion Beam facility (2.5 GeV – 5 MW) . The SPL-based Super-Beam option to Frejus has been studied by EuroNu [ID35]. Another possibility is a Super-Beam to Canfranc (or similar distance) which was not covered by EuroNu and which gives very good reach for both the CP violating phase and for the mass hierarchy.

In close collaboration with similar developments worldwide (ESS [ID10], Project X [ID151], MYRRHA . . .), the SPL R&D [ID161] is addressing essential components of the future linac (Superconducting RF and associated equipment, RF power sources. . .) and contributing to the upgrade of the CERN infrastructure (diagnostics, workshop tools, test place. . .) to ensure that any of these potential projects could start smoothly whenever required.

A ∼50-GeV 2-MW proton driver using the LP-SPL and a new high power 50 GeV synchrotron (HP-PS) is under study for a long baseline experiment studied within the LAGUNA-LBNO Design Study [ID74, ID159]. This proton driver would serve for a second generation Super-Beam aimed at a remote experiment in Finland. The design of the HP-PS machine is rather challenging where among others, R&D issues on the fast ramping magnets and RF systems need to be addressed.

The interesting neutrino beam potential from a higher-energy successor of the SPS for a possible future energy upgrade of the LHC has not been studied in any detail yet. This is likely to be done in the near future.

For the new generation of Super-Beams the development of a multi-MW target station and the capture system is required. Present R&D on high-power targets is focusing on the use of segmented or granular targets that seem to be viable solutions for the required regime. Tests of prototypes in special facilities, like HiRadMat at CERN, would be required to validate the proposed designs. To address the stringent operational conditions for the horns in a multi-MW target station arising from the radiation levels and the pulsing, solutions using multiple horns are proposed where each assembly sees 1 MW of beam power.

Common for all super-beam facilities which use a linac at a few GeV as injector is the need of an accumulator and compressor ring. At MW level the design of such a ring is far from trivial. Space charge issues in the ring will be challenging, but multiple rings offer one possible solution. Injection is more challenging as the high power will require new injection schemes such as laser stripping of H^- beams. Development of such schemes could be shared.

Beta Beams: A beta-beam facility for a Gamma 100 has been studied in the European Design Studies EURISOL [ID160] and EURONU [ID35]. The studies were limited to a γ factor of 100 to avoid the construction of a new SPS for higher γ and too challenging a decay ring (with very high field magnets and large circumference). Several new ideas for the ion production have been studied recently. Collimation of the radioactive ion beam in the decay ring is another challenge as well as beam instabilities for the high space charge in the injector chain. Collimation systems for the injectors need to be further studied.

Neutrino Factories: The International Design Study for a Neutrino Factory (IDS-NF) is undertaking a conceptual design for the Neutrino Factory, with the aim of producing a reference design report (RDR) and costing in 2013. EUROnu is an integral and very important part of this. The RDR will identify the critical R&D that will need to be done before the machine can be constructed, but it is likely that further work will be required on the proton driver (see Section 8.2.2), the target and pion collection system, the muon front end and cooling system and the muon acceleration system. The construction of the Neutrino Factory itself could happen in stages. The first stage would be the simplest possible implementation of the Neutrino Factory concept. It would consist of a conventional target station and then pion capture and transport to a racetrack-like decay ring which would store muons from pion decay. Neutrinos from the decay of the stored muons could be used to perform an exciting physics programme complementary to any long-baseline neutrino program. This concept has been proposed in the US as the νSTORM project [ID135] (neutrinos from STORed Muons, see below). The Neutrino Factory itself could then be built in a number of stages where the first stage would be a lower power option, employing a lower power proton driver (around 1 MW), no cooling and a smaller far detector (40 kt).

The νSTORM project has arisen out of a desire to address the results of LSND and MiniBooNE, along with the recent papers on a possible reactor neutrino flux anomaly which give tantalizing hints of new physics. Initial studies indicate that with 10^{21} protons on target, νSTORM can provide near 10σ confirmation or rejection of the LSND/MiniBooNE results. In addition, νSTORM presents a unique opportunity for the study of neutrino (particularly ν_e) interactions. νSTORM does not require the development of any new technologies and thus could be built in the near term. It provides, however, a test bed to study muon production and muon decay-ring instrumentation necessary for a future Neutrino Factory.

8.2.3 High Luminosity Flavor Factories

Flavor factories are today operating at LNF in Italy (DAFNE), at BINP in Novosibirsk (VEPP-2000) and at IHEP in China (BEPCII). The physics targeted at the different facilities depends on the energy range of the machine, the experiments and the luminosity. The upgrade issues are common for all facilities e.g. new collision schemes which require R&D on large crossing angle and very small beam sizes.

Phi-Factories The operational facilities today are showing the way towards higher luminosity. The “crab-waist sextupole” option with a large Piwinski angle was developed and tested at DAFNE (LNF). Another idea for higher luminosity was realized at VEPP-2000 (BINP) operating with “round beams” scheme which allows a very high tune shift.

DAFNE at LNF is operating at a fixed energy $2E \sim 1$ GeV c.m. with $L = 4 \times 10^{32}$ cm^{-2}s^{-1} [25, 26] and VEPP-2000 at BINP is operating at $2E$ =0.3-2.0 GeV with $L = 10^{31}$ cm^{-2}s^{-1} at $2E = 1.0$ GeV, $L = 3 \times 10^{31}$ cm^{-2}s^{-1} at $2E$=1.8 GeV [27]. The VEPP-2000 luminosity is expected to be increased by an order of magnitude when a new injector will come into operation in 2013.

Tau-Charm factories The Tau and Charm factory BEPCII at IHEP is operating at 2.5–4.0 GeV c.m. ($L = 6.5 \times 10^{32}$ cm^{-2}s^{-1} at $2E = 3.8$ GeV). The Super tau-charm factory at BINP is proposed to operate with a variable energy at 2.0–5.0 GeV c.m. ($L = 1.5 \times 10^{35}$ cm^{-2}s^{-1} at $2E = 5.0$ GeV, longitudinal polarization). The project is preliminarily approved by the Russian government.

B-Factory: For high precision measurements in flavor physics a high luminosity facility, SuperKEKB in Japan, is being constructed, by upgrading the existing KEKB collider. SuperKEKB will be operational in 2015. Its design luminosity is $L = 8 \times 10^{35}$ cm^{-2}s^{-1}. A primary challenge will be achieving the targeted small emittance, typical for Synchrotron Light Sources and for the Damping Rings of planned Linear Colliders (ILC, CLIC), in colliding-beam storage rings.

8.2.4 High Intensity Single Beams

***e*, muon, *K*, *p* (*p*bar), *n*-beams** Single flavor beams are in most cases best produced at very high average intensity facilities. The leading high intensity facilities today are the cyclotrons at PSI and TRIUMF and the Superconducting linac at SNS. The future of the field depends ultimately on increased beam power at existing drivers and the construction of new and more powerful drivers.

The ILL Grenoble continues to be the leading reactor facility for ultra cold neutrons (UCNs), while presently PSI [21] is the leading accelerator facility. In short the status of the ultra-cold neutron (UCN) facilities is:

1. SNS-based collaboration [28, 29]. In this project, cold neutrons (specifically neutrons in narrow band near 1 meV) are extracted and sent to an EDM apparatus via a long neutron guide. The cold neutrons are "down-converted" to UCNs in superfluid He in the EDM apparatus. The measurement is performed in the superfluid He.
2. PSI-based collaboration [30]. Here the UCNs are created in a dedicated source adjacent to a spallation source. The UCN source is a block of solid D_2 at ∼5 K. The UCNs are extracted and the experiment is done at room temperature at some distance from the source. The target takes high power beam, but only for a short pulse after which the beam is off for several minutes. The cryogenic properties of solid D_2 preclude continuous beam operation at high power.
3. RCNP- and TRIUMF-based collaboration [31]. An auxiliary spallation target adjacent to the UCN source is used. UCNs are extracted and the measurement is done at room temperature at some distance from the source. Again the very low temperature required by the LHe source precludes continuous high power beam delivery. This project (in collaboration with Japan) is still under development. The RCNP UCN source will be moved to TRIUMF.
4. ESS. A UCN facility is being studied [ID10].
5. LANL. Presently LANSCE has a UCN source working.
6. J-PARC. A UCN facility at J-PARC is considered.
7. ILL (reactor) based effort. In addition to these accelerator facilities, there are 2 significant reactor based efforts at the ILL in Grenoble. One of these is similar in concept to the SNS experiment in that cold neutrons are down converted in the experimental apparatus. The other uses UCNs created in the experiment itself.
8. UCN efforts at reactors also include the TRIGA reactor in Mainz (running), WWRM reactor in Gatchina (sometimes running and under an upgrade program), the PULSTAR reactor in North Carolina (starting about 2013), and FRM-2 in Germany (starting UCN in 2014 or 2015).

Presently the leading accelerator facilities for muons are PSI in Switzerland, TRIUMF in Canada, ISIS in UK, RCNP and J-PARC in Japan. Work is in progress for muons at FNAL and studies are being done for muons at ESS [ID10]. The various facilities provide muons at different energies and with different emittance (including low energy cooling at some facilities).

Rare kaon decays provide probes of new physics beyond the Standard Model at energy scales ranging from 100-1000 TeV. Beam power of the order of 1 MW at an energy between 3-8 GeV is ideal for these investigations.

At CERN the NA62 experiment is about to start data taking using an upgraded Kaon (K^+) beam, at 75 GeV/c. Further upgrades of the beam are foreseen for a simultaneous K^+K^- beam and/or a neutral K_L^0 beam in future stages of the experiment.

The PSI high intensity proton accelerator generates a proton beam with 590 MeV kinetic energy and presently 1.3 MW average beam power. In practice, the performance is limited by the beam losses at the extraction of the Ring cyclotron. The relative losses are kept within the lower 10^{-4} range to avoid excessive activation of accelerator components in the extraction region. The PSI accelerator consists of a Cockcroft-Walton pre-accelerator and a chain of two isochronous cyclotrons, the Injector II and the Ring cyclotron. The beam is produced in continuous wave (CW) mode at a frequency of 50.6 MHz. The high intensity proton beam is used to produce pions and muons. Muon beam intensities up to 5×10^8 s^{-1} are achieved [23]. The polarized muons are mainly used for muon spectroscopy experiments. After collimation the remaining beam with roughly 1 MW is then used to produce neutrons in a spallation target

The TRIUMF cyclotron continues to benefit from the H^- extraction and thus several simultaneous beams. The intensity goal of the machine for routine operation is 450–500 microamps, providing beam to three primary beamlines for studies in molecular and material science, fundamental symmetries, and nuclear physics. An e-linac is being built. It will begin with 100 kW and eventually reach 500 kW. The power is limited by target development. A possible upgrade includes an energy recovery ring.

Project-X at FNAL is a future facility under planning and it will be a unique facility for providing MW-class beams to multiple experiments simultaneously. Project-X is based on a 1 mA CW linac accelerating beam to 3 GeV, followed by a 3–8 GeV pulsed linac (4.3% duty factor) for delivery of beams to the existing Main Injector complex. The full capabilities of Project-X are 3 MW of beam power at 3 GeV, simultaneous with 2.4 MW of beam power at 60–120 GeV. In parallel the 3 GeV program will provide opportunities for world leading experiments utilizing muons, kaons, and nuclei. Project-X is currently planned as a staged project with construction of a CW linac initially, followed by a pulsed linac. The primary R&D challenges are related to development of a wideband (6 nsec rise time) chopper, H^- injection, halo formation and mitigation, and development of high Q_0 accelerating structures of six different types at four different frequencies.

The European Spallation Source linac will be the world's most powerful proton source at 5 MW. It will be commissioned in stages with full 5 MW capability from around 2022. Beside the aggressive schedule, the major challenges are quality control issues for SC cavities to assure sufficiently high Q_0 and gradient, energy efficient RF sources and the available manufacturing capacity for e.g.cavities, klystrons, modulators and high power Inductive Output Tubes (IOTs).

Presently the only anti-proton source operating is the AD facility at CERN. It provides beams for several experiments and an upgrade with a low energy cooling and storage ring is planned (ELENA). The ring provides further deceleration of antiprotons from the AD from 5.3 MeV to 100 keV and a reduction of emittances by electron cooling (at 650 keV and 100 keV). It will improve capture efficiency at the trap experiments and it creates opportunities for new experiments on gravitational effects with antihydrogen. Several experiments will be operating in parallel at the ring with approximately

0.7×10^7 antiprotons (pbars) per experiment and cycle within a physical rms emittance of approximately 1 mm. This infrastructure will be unique in the world.

In 2018 the future anti-proton facility at FAIR will come into operation. It will enable an anti-proton physics program with a unique system of storage rings. The main driver of FAIR — the heavy ion synchrotron SIS100 — will provide short bunches of up to 4×10^{13} protons to the anti-proton target. About 10^9 antiprotons will be produced and guided towards a cooler storage ring, where phase space cooling is applied to provide brilliant beams to the high energy storage ring (HESR). In the HESR up to 10^{11} antiprotons will be captured by a new injection scheme using a barrier bucket method. The energy of the antiprotons in the HESR can vary between 831 MeV and 14 GeV. The injection energy of 3 GeV is determined by the collector ring.

8.3 Organization of Accelerator R&D for HEP in Europe

8.3.1 Accelerator R&D Coordination and Collaborative Programmes

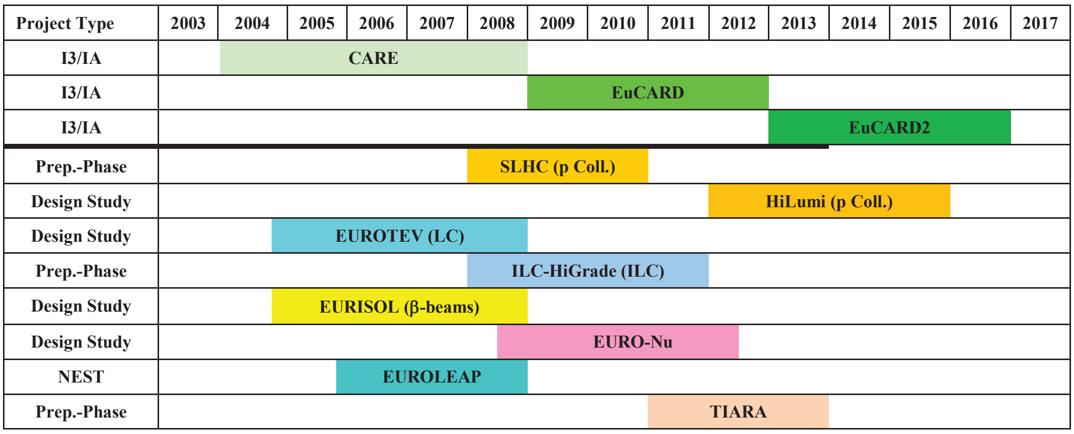
The realization of current and planned state-of-the-art accelerator-based research infrastructures, such as LHC upgrades, XFEL, FAIR, SPIRAL2, ESS, IFMIF-EVEDA, serving the needs of a vast range of research communities, is only made possible by continuous progress in accelerator science and technology supported by strong and sustainable R&D activities. It is thus not surprising that strengthening Europe‘s capability in accelerator R&D is identified as a very high priority issue within many of the communities using accelerator-based research infrastructures. This is, in particular, the case for Particle Physics, for which the CERN Council has ranked accelerator R&D as a top priority in its 2006 European Strategy document, and also applies to a large number of projects included in the ESFRI roadmap.

The realization of new accelerators needed for studying particle physics relies crucially on a strong and steady RTD program, the magnitude and diversity of which surpasses the intellectual, technical and financial resources of a single laboratory or institution and requires a large international effort.

The R&D on accelerators for high energy physics is organized for a large part around several possible future projects:

1. Facilities providing proton beams with ultra-high intensities and energies, aiming at very large hadron colliders, and covering as well luminosity and energy upgrades of the LHC at CERN.
2. Electron-positron colliders with energies ranging between 250 and 3000 GeV in the centre-of-mass system, using combinations of
   (a) technologies developed for B factories,
   (b) technologies for SC high gradient acceleration structures, initially developed by the **TESLA** international collaboration [32] and continued by the **Global Design Effort** (GDE),
   (c) and technologies exploiting the two-beam acceleration technique using very-high gradient room-temperature cavities developed by the **CLIC** international collaboration [33].

Table 8.6: Accelerator R&D projects co-financed by the EC



Project Type	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
I3/IA		CARE													
I3/IA							EuCARD								
I3/IA											EuCARD2				
Prep.-Phase						SLHC (p Coll.)									
Design Study										HiLumi (p Coll.)					
Design Study		EUROTEV (LC)													
Prep.-Phase						ILC-HiGrade (ILC)									
Design Study		EURISOL (β-beams)													
Design Study						EURO-Nu									
NEST			EUROLEAP												
Prep.-Phase									TIARA						

3. Facilities providing intense neutrino beams (see for example **Neutrino** Factory [34]), using improvements to the existing methods based on intense proton beams accompanied with the generation of muon beams investigated within the International Design Study (IDS).

4. Low energy facilities delivering very high luminosity for the study of specific physics topics such as flavor physics with **SuperB Factories**.

In Europe, these efforts are accompanied by large collaborative projects partially supported by the European Commission, including in addition activities related to novel technologies such as plasma acceleration. The coordination and submission of these projects is carried out by the European Steering Group for Accelerator R&D (ESGARD). A total of eleven R&D projects have been developed and launched covering the high priority technological aspects for future accelerators over a period of ten years and amounting to a total cost of about 228 M€, out of which 68 M€ is financed by the EC (see Table 8.6).

The work carried out within these projects has already been instrumental for enabling the construction of large infrastructures such as Linac4 at CERN and ESS in Lund.

While carrying out these projects, it has become increasingly clear that establishing an efficient, structured and sustainable coordination of activities in this area is crucial for the optimal use and development (upgrades and construction of new facilities) of this broad variety of large scale test infrastructures. The TIARA project [ID51, 35] has been initiated to this end, with the objective of establishing a distributed pan-European Test Infrastructure and Accelerator Research Area, covering Particle-Physics and other-fields needs related to particle accelerator developments.

A first TIARA survey has identified the Key Accelerator Research Areas, which are summarized in Table 8.7.

As can be seen from this table, several R&D topics (such as high field superconducting magnets, RF acceleration structures, particle sources and injectors. . .) are critical for building several types of facilities.

Chapter 9 reviews global collaborative efforts detector R&D, construction of large-scale projects, and computing for particle physics.

Table 8.7: Key Accelerator Research Areas identified by TIARA

Domain	**Projects** / **KARA**	ESFRI Project List										
		XFEL	FAIR	ESS	LHC Upgrades (HL-HE)	Linear Colliders (ILC, CLIC)	Flavour Factories (SuperB)	Neutrino Factories Muon Colliders	High Intensity Hadron Facilities (Eurisol, ADS/MYRRHA, IFMIF)	3^{rd} Generation radiation sources	4^{th} Generation radiation sources, FEL, ERL	5^{th} Generation radiation sources
Accelerator Components	Sources and Injectors	x	x	x	x	x	x	X	x	x	x	
	RF Structures	x	x	x	x	x	x	X	x		x	
	RF Systems	x		x		x	x		x		x	
	SC Magnets		x		x	x	x	X				
	Conventional NC Magnet Systems		x			x				x	x	x
	Diagnostic and Instrumentation	x	x	x	x	x	x	X	x	x	x	x
	Targetry		x	x	x	x		X	x			
	Radiation Issues		x	x	x	x		X	x			
Accelerator Technologies	Electronics and Software	x	x	x	x	x	x	X	x	x	x	x
	UHV	x	x	x	x	x	x	X	x	x	x	x
	RF Sources	x	x	x	x	x	x	X	x	x	x	x
	Cryogenics	x	x	x	x	x		X	x			
	Alignment and Stabilization	x	x	x	x	x	x	X	x	x	x	x
Accelerator Concepts	Accelerator Design		x	x		x	x	X	x			x
	Beam Dynamics		x	x	x		x	X	x			x
	FEL Processes	x									x	x
	Beam Cooling		x					X				
	New Techniques for High Gradient Acceleration					x						x
	Medical and Industrial Accelerators	N/A										

8.3.2 Synergies with Other Fields of Science

Thanks to the technical progress made in the development of accelerators, important breakthroughs in other fields of science have been made possible as well. Both particle accelerators producing intense light and neutron sources are now indispensable tools for biologists and solid-state physicists. Similarly, NMR based on high-field SC magnets has become a common device in biochemistry and medical science and accelerator-based hadron-therapy centers are being developed. Finally, accelerators have become very efficient tools for the industrial sector and lead to innovation in many areas. The use of accelerators is also studied in the energy and environment domain. One can expect this trend to continue in the future following the current development of new generations of accelerators.

As already mentioned the on-going projects LHC upgrades, XFEL, FAIR, SPIRAL2, ESS, IFMIF-EVEDA can benefit from joint efforts as far as the accelerator technologies are concerned. Other projects are also planned such as ILC, CLIC, LEP3/TLEP, SwissFEL, MYRRHA…

It is thus highly desirable to further encourage the synergies by establishing the proper structure facilitating the exchange of knowledge and expertise and enabling the gathering of common efforts. The aim of TIARA is to establish such a structure.

8.3.3 Education and Training

The R&D in Accelerator Science and Technologies as well as the construction of particle accelerators span over long time periods. It is thus vital to include education and training as part of the sustainable R&D programme to be established. A recent survey carried out within TIARA over 88 institutes in 13 countries has identified only a handful of dedicated full-time formal training programmes in accelerator science. Furthermore, even with the inclusion of the programmes providing some partial time training in accelerator science, the number of trainees remains limited. This is illustrated in Figs. 8.8 and 8.9, which present results of a survey in 13 European countries [36].

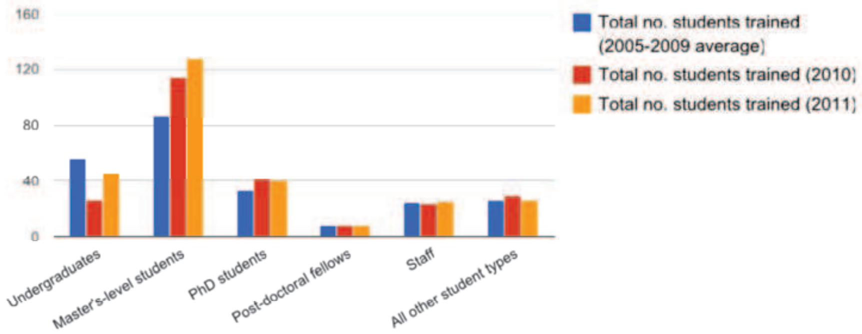


Figure 8.8: Number of trainees by type receiving more than 70 hours per year in accelerator science and technologies (average 2005-2009 in blue, 2010 in red, 2011 in orange) [36]

Moreover, one sees large differences from one country to the other.

A particular effort is thus required for developing further Training and Educational programmes, aiming at spreading and sharing the knowledge base in the community at large (including both academia and associated industrial partners), in view of strengthen-

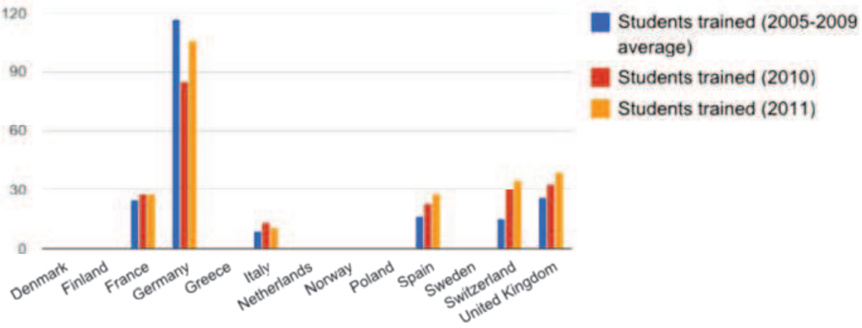


Figure 8.9: Number of trainees by countries receiving more than 70 hours per year in accelerator science and technologies [36]

ing and enhancing the community of accelerator physicists and engineers at the European level.

As a corollary, the dissemination of the information and of the outcomes of the R&D in the scientific community at large, as well as outreach activities directed towards the society (particularly in high-schools and universities) are of prime importance in order to popularize the achievements in the field and help promote the attractiveness of scientific careers among young Europeans.

8.3.4 Applications to Societal Challenges

Particle accelerators are indispensable tools for a very large range of applications. Besides fundamental research (e.g. Particle and Nuclear Physics, condensed matter, biology, cultural heritage…) many other vital domains for our society require accelerators:

Energy and Environment with for example the utilization of accelerators for material irradiation for the development of ITER (IFMIF), for transmutation (MYRRHA) or Accelerator Driven Reactors, control of power plant gas emission…

Health and Medicine with accelerators for sterilization, production of radioisotopes for imaging as well as for clinical applications for cancer therapy (i.e. radiotherapy and hadron therapy…)

Industry with the utilization of accelerators for a very large and broad number of applications such as ion implantation in the silicon industry, high performance electron beam welding, material hardening for cars, cargo scanning…

While the construction of particle accelerators for basic research represents a yearly consolidated “market” of about one B€, it is of the order of 3 B€ for the other applications mentioned above. Furthermore, the market generated by the end products is more than 100 times larger. TIARA has recently developed a brochure “accelerators for society”, which will be linked to a website for highlighting these points and raising the awareness of the public and the governments.

To enhance further the benefits for the society, it is of prime importance to strengthen the relation between the academic and public sector with the industry to ensure that the progress made in the research domain can be used by the industry as quickly as possible.

8.3.5 Relation with industry

Although some significant progress has been done for improving the collaboration of the academic and public sector with industry, the establishment of a framework intellectually and economically attractive to develop industrial products both for the research facilities and medical and industrial accelerators is missing. An open and recognized way of communication would enable industry to give valuable inputs for defining the most useful R&D direction for industrial-medical applications. The aim of such a framework would be to increase the impact of R&D in accelerator science and technology and the speed of the industrialization of breakthrough by facilitating the technology and knowledge transfer.

Furthermore, several actions could be useful for enhancing the collaboration with the industry, such as:

- The definition of a technology roadmap for the development of future accelerator components in industry, including the critical requirements and the main targets which are aimed at (costs, reliability etc.), as well as the technology alternatives should be pursued. To ensure the sustainability and timely relevance of such roadmap, periodic revision is needed.
- The opening of the R&D infrastructures of the public sector to industry for the enabling cost effective R&D projects should be promoted.
- The joint development with industry of cost effective accelerators for industrial & medical applications is to be encouraged.

Interesting initiatives promoting the involvement industry in accelerator R&D exist, such as DOE-SBIR in the USA. It would be desirable to develop mechanisms appropriate for Europe, taking into account the specific present context in which some of the strong national institutes or agencies have already developed their own mechanisms for technology transfer and close cooperation with industry.

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Chapter 9

Instrumentation, Computing, and Infrastructure

Relevant talks at the Open Symposium were given by T. Boccali, A. Cattai, and T. Virdee, who also made contributions to this chapter.

9.1 Introduction

Discoveries in particle physics are often the result of innovations in detector technologies, computing or accelerators. Members of particle physics community have developed the skills and expertise to design, construct and commission complex technical systems and infrastructure needed to meet the challenges of the physics program. The community continually innovates to find solutions to technical challenges and to train the next generation. Since it often takes a decade or more to bring a new technology from a successful R&D phase to become a reliable system ready for production, to prepare the discoveries of the next decade, the field must continually plan ahead to examine the essential R&D, the infrastructure and workforce that will be required.

The long time scales of particle physics projects and the complexity of the required technologies drive the need for strong support for technical infrastructure at the national laboratories and larger institutions. Preparation of a skilled technical workforce remains a priority in the field is to continue to meet the challenges of R&D for detectors, accelerators and computing systems in addition to the design, construction and operations of new or upgraded detector and computing systems.

The success of the LHC experiments offers compelling examples of how the community has leveraged international resources to create large detectors for discovery science. The upgrades for the experiments and other future projects such as the linear collider will require the field to make a plan to coordinate R&D efforts, to train the next generation and to support the infrastructure so the field will be prepared for the discoveries made by the detectors, computers and accelerators of tomorrow.

9.2 Detector R&D

Development of novel detector concepts has always played a major role in supporting and enabling scientific research. In the forthcoming phase of particle physics, its role will be even more enhanced by the harsh environmental conditions to be faced by proposed future detectors and the challenging requests from the physics needs: improved spatial resolution, speed and radiation hardness, minimal power consumption, ultra-light structures and more.

The ICFA Instrumentation Panel and ECFA recently carried out a European survey on detectors R&D. The survey reflects the work of about 2300 hardware-oriented scientists of which 85% work in experiments and 40% carry out the R&D activities within international consortia that gather scientists from several branches of physics. The preliminary results indicate that almost 40% of the scientists are involved in the development of tracking or vertex detectors, 15% work on gas detectors, 10% on particle identification and 7% on calorimetry. About 15% of scientists are involved in R&D on photo-detectors correlated to tracking, calorimetry or particle identification at the energy, intensity and cosmic frontiers.

One can distinguish two major drivers for detector R&D in the short-term: the upgrade of the LHC detectors and the possible development of new high precision detectors for the next generation lepton collider. The former pushes developments in the direction of high granularity of the tracker, higher data transfer speed, higher trigger and data readout rates, and radiation hardness, with the constraints of integrating the new instrumentation within already existing experiments and infrastructures, thus reducing the freedom of technological choices. The latter imposes strong requirements for R&D in the fields of high granularity or segmentation in the calorimeters, energy- time- and space-resolution, reduced material budget, robustness and integration of large and complex systems.

9.2.1 Technologies for the Next Generation Experiments

Key elements to enable future physics programs are vertex and tracking detectors. Primary and secondary vertex reconstruction of unprecedented accuracy and minimal multiple scattering are required together with high efficiency for track reconstruction in high multiplicity events.

In this framework, silicon pixels have become the standard for vertex tracking in the proximity of the interaction region of HEP experiments. The number and diversity of pixel technologies are growing, as new facilities call for emphasis on different specifications such as frame rate, radiation tolerance and space-time resolution. Hybrid pixel detector technology has reached an excellent level of maturity at an industrial level together with high radiation tolerance, still the bump bonding may be a limiting approach and investment is necessary on emerging interconnect technologies (small pitch bump bonding, Through Silicon Via and 3D assembly and more) enabling assembly at extremely small pixel pitches (less than 10 μm). Although our requirements in terms of density and performance are not very different from those of commercial applications, the access to these technologies and the adaptation to our specific needs (reliability and radiation hardness, size, etc.) require a solid development program. This problematic challenge is overcome by using advanced monolithic pixel technologies, a major alternative for vertex reconstruction, that, although needing further investigations on radiation tolerance, remain particularly attractive since they combine high speed and complex signal processing while improving spatial resolution and reducing the material budget[ID103].

The trend in the outer tracking domain clearly indicates that the future will bring higher granularity devices to instrument large tracker volumes in order to provide the necessary spatial resolution. The more demanding physics performance requirements will impose additional constraints to future tracker systems: reduced material to keep high track-purity and efficiency, higher readout speed and complex on-detector electronics to generate prompt first level trigger and timing information[ID143]. Excellent spatial resolution, lighter mass and increased functionality, can be achieved by a careful balancing of microelectronics, integrated assembly technologies, low powering schemes, integrated cooling, material selection and integration choices. R&D in all these fields are pursued across many communities and efforts are expected to increase in the future including fostering, within new consortia, mechanical engineering and searches for common technological platforms.

The fast pace of development of industrial semiconductor processes and microelectronics provides us with opportunities and challenges for ongoing R&D on vertex and tracking detectors for future projects. Very deep-submicron technologies open new possibilities for meeting the requirements of future experiments, but their complexity and cost, as well as their qualification for our harsh environment, will require a very substantial financial investment and manpower[ID66].

Particle identification plays a prominent role in the determination of quark flavors and in the enhancement of signal from background. The most significant advances and the most promising future directions have been achieved in the following major sectors of research: the large surface Time-of-Flight detectors based on Multi-gap Resistive Plate Chambers that aim to achieve time resolution of the order of 20 ps; the outstanding performances of the TPC, which combines tracking and ionization energy loss measurements, and that will be further improved with the innovative read-out plane composed of Micro Pattern Gaseous Detectors (MPGD); the measurement of the Cherenkov angles via the direct imaging of the emitted photons that has become a well-established technique frequently employed in high-energy and astro-particle physics experiments to identify charged particles in a vast momentum range from few hundreds MeV/c up to several hundreds GeV/c.

The community has admirably mastered the technology of radiators and optical transport of photons along complicated paths and media; nevertheless, some space for improvement remains in the domain of photo-detection. Many techniques under investigation share a strong interest in large area MCP or solid state photo-sensors and there is a continuous push for higher efficiency, dynamic range, radiation hardness, lower noise and improved time resolution [ID120],[ID143],[ID14]. Many different and dislocated activities have arisen around these topics and the cooperation between laboratories, universities and industry is becoming vital to make significant progress sparing financial and human resources. In the case of large surface gaseous photo-detections, the exploitation of MPGD, with appropriate photo-cathodes, is a promising option to be explored, providing a substantial investment to actuate a cost-effective production of large area micro-structures.

Micro Pattern Gaseous Detectors have become well established in the fertile field of gaseous detectors and are acknowledged as a high performing technique that has been successfully exploited in many recent experiments. As a result, all flavours of MPGDs are in high demand for future applications including as the active plane in cryogenic noble Ar/Xe liquid detectors[ID74]. Hence, industrial manufacturing has become mandatory and remains a central issue to be solved for these techniques [ID115], [ID128], [1], [2], [ID78], [ID79].

In recent years, R&D in calorimetry has been primarily a lepton collider driven effort, but it is highly relevant also for future upgrades of the LHC experiments particularly in the forward region. The precise measurement of hadron and jet energies is a major challenge for future experiments at the energy frontier and represents the most critical point in future HEP detectors. The hadronic energy resolution of today's calorimeters is fundamentally limited by intrinsic event-to-event fluctuations of the shower development. Two main directions are followed to overcome this weakness: the particle flow and the dual read-out methods. Both take an integrated approach to electromagnetic and hadronic calorimetry, are complementary and can ultimately be combined.

The particle flow approach to calorimetry aims at reconstructing each particle in a jet individually and thus optimizing the jet energy resolution by combining tracking and calorimetric measurements exploiting the unprecedented segmentation of the detectors in 3 dimensions. This technique, proven in many test-beams and experiments with segmentation lower than the one foreseen in lepton colliders, now enters the challenging phase of achieving a cost-effective handling of large numbers of modules with integrated circuitry [ID78],[ID79]. Quality assurance, testing and calibration campaigns are the upcoming areas to be sustained and supported in this sector.

The dual readout approach aims at improving the hadronic energy resolution by simultaneously measuring the total deposited energy by means of scintillation light and the electromagnetic component by means of Cherenkov light. This allows correcting for fluctuations of the shower composition event-by-event, which otherwise limits the resolution in non-compensating calorimeters. This method has promising ultimate potential, but several technical issues have still to be investigated. The idea of a totally absorbing crystal-based hadronic calorimeter with dual readout is also being pursued. Research on dual read out methods, crystals, ceramics, metamaterials are rapidly increasing, fostered by the needs of future experiments, upgrades to existing detectors, and the exploitation of these techniques for medical applications.

9.2.2 Generic Detector R&D

Despite the diversity of the technologies and approaches, there are many common areas of R&D, including the use of simulation tools, the exploitation of off-detectors electronics and DAQ systems, testing and quality assurance protocols during development or production time and more. Cooperation between laboratories and universities and the creation of common infrastructures and facilities that can provide global support to the communities that share common needs, would be most advantageous. Some specific examples can be given: a) simulations have become more and more reliable tools for quantitative detectors optimisation. It can be foreseen that with the increasing complexity of future detectors, the requirements for realistic simulations will sharpen even more. Since probing detector performance already at an early design phase would spare financial and prototyping efforts, a plan for long-term support of simulation tools is a fruitful investment; b) on the electronics side it can be noticed that the cost of the readout and control electronics of current HEP experiments represents about 25% of the total experiment cost. This will not decrease in the future and the anticipation of such a level of funding merits a corresponding substantial investment in R&D activities and collaborative efforts with scientific and industrial partners [ID66].

It has been demonstrated through many examples that it can take 10-15 years to mature a technology from the original idea to an established technique suited for implementation in an experiment. Recent examples include a variety of highly performing vertex detectors. It is therefore important to maintain an active generic R&D community that fosters new ideas for future detectors. Experience shows that additional time is needed to move from an established technology to the industrialization of a product and to mass production. This step can be significantly sped up if adequate attention is given to early technology transfer and close collaboration with industry.

It is in the interest of the community to invest early and to invest, when possible, on long lasting technologies. As an example: microelectronics technologies have been key enabling technologies for designing and building detectors with increasing capabilities and performance, but the field evolves very rapidly, is driven by industry and we have marginal impact on it. This requires that our community selects and pursues R&D on alternative technological options in parallel, choosing among the technological nodes expected to be available for a long time. Furthermore, there is a need to coordinate our efforts so as to provide a common technical and administrative support to the institutes working on microelectronics, namely: simplify the access to technical information, use common simulation tools and design services, aggregate the demand for shared engineering and production runs, and provide support for frame contracts established with a foundry supplier.

9.2.3 Interface to other fields and Industry

Particle physics advances often require breakthrough innovation in detector technologies [ID80]. The particle physics community has been a leader in detector technologies, but still can benefit greatly from interactions with other fields and vice versa. Often it is other fields of physics or other scientists who provide the catalyst or required technique and there are already many successful examples of collaborations worth to increase in the future.

HEP-driven R&D on vertex detectors with pixels technologies has given rise to a broad spectrum of applications of these detectors in fields outside fundamental physics: imaging at light sources and free electron lasers, transmission electron microscopy, plasma diagnostics, fluorescence microscopy, auto-radiography, biological and medical imaging, neutron detection and radiography, radiation monitoring and dosimetry, real-time dose delivery assessment and quality assurance in hadron therapy. There are examples where the interplay between HEP and imaging applications with pixels technologies is a two-way process: Medipix, one of the first pioneering projects originally developed for particle physics detectors was successfully applied to medical X-ray imaging, later successfully transferred to industry for commercial X-ray diffraction cameras and now is back to HEP for LHC upgrade applications [ID66], [ID103].

HEP-driven R&D has always played a prominent role in providing cutting-edge detectors to medical applications. A few very recent examples are calorimeters, solid-state photodetectors, and gamma-camera. Fine-grained imaging calorimeters, not imaginable a decade ago, and made possible through the advent of solid state photo-detectors are of great importance for the Proton Computed Tomography (pCT). pCT is very much like a fixed target experiment: a proton beam is measured before it hits a target, in this case part of the human body, and its direction and energy is measured when it exits the target. CsI crystals are commonly used to measure the energy of the outgoing protons. The new pCT detector concepts use miniature calorimeters with SiPM readout as detectors for the protons. This allows for cheaper experimental setups with faster readout providing more accurate images[ID80]. Another medical imaging technique with potentially huge benefits from the application of the SiPMs is Positron Emission Tomography (PET) assisted by time-of-flight (TOF) measurements for the reduction of noise and eventually the refinement of position resolution. As an aside, it should be noted that the crystals used in PET systems, generally BGO or LYSO crystals, already came out of basic detector R&D in the field of particle physics. Very promising applications of HEP-driven R&D is the lympho-scintigraphy in which lymph nodes containing metastases are counted and located precisely by means of a gamma-camera. In case of a biopsy, the surgeon checks the position of the sentinel lymph node prior to making an incision and after ablation, to confirm the absence of any residual radioactivity. Many other examples of probes constituted by particle detectors, exploiting last-generation scintillating crystals or fibres and last generation electronic to detect radio-tracer exist; the very advanced ones are also conceived to work inside the human body. HEP-driven R&D allowed the acquisition of the expertise necessary to progress in the field of medical research, continued support of these studies will continue to generate visible and substantial progress otherwise not in reach by the community of medical doctors alone. Additionally it may be noticed that European funded projects offer the ideal support to bring small-medium companies into contact with communities of physicists fostering the development of instrumentation for application outside fundamental physics.

Last but not least, the earth and environment sciences are facing more and more challenging questions from both the scientific community and society in general [ID124]. Acute societal problems nowadays concern, among others, the understanding of the changes in the climate, the forecast of devastating natural hazards, the treatment and potential recycling of nuclear waste, the impact of natural or artificial radiations on living bodies. These are wide and open problems which require dedicated observation and modelling programs over longer and longer time scales. The complexity of the systems under study naturally implies a permanent search for new observables, new detection and data analysis methods. Alternative methods may come from inter-disciplinary approaches and the physicist community can bring key elements because of the vast expertise developed over decades on large-scale long-lasting experiments, through wide international collaborations. A non-exhaustive list of investigations that will profit from a more global scientific approach with existing projects in physics is: geosciences, geoparticles and oceans science exploiting muons tomography and neutrinos experiments; atmosphere physics [ID16] in synergy with the cosmic frontier experiments; environmental metrology exploiting radioactivity measurements and radio-chemistry; forests fires early detection, gas emissions monitoring in synergy with gaseous or solid-state detector R&D. Technology transfer between fundamental physics and earth and environment sciences in the above mentioned fields (detectors development, data analysis, software simulation etc) would be highly profitable. As well, a long-term and dedicated involvement of large physics facilities in research and observation programmes of earth and environment sciences may provide unprecedented data sets on underwater or atmosphere physics and are worthy to be promoted and encouraged.

9.2.4 Test Facilities

Test beam facilities are vital for R&D in fundamental physics. They are the places where new ideas and future technologies are developed, state-of the-art prototypes are tested, new concepts are validated and detectors are commissioned and calibrated. Basic performances studies, long-term tests under specific conditions or verification of radiation hardness of active detectors, electronics or passive materials, can only be done at test beam and irradiation facilities. The development of novel detector concepts always necessitated large test beam and irradiation campaigns and in the forthcoming phase of HEP, with the expected enhanced harsh environmental conditions, radiation hardness studies will be even more indispensable to guarantee the integrity of the response of complex apparatus.

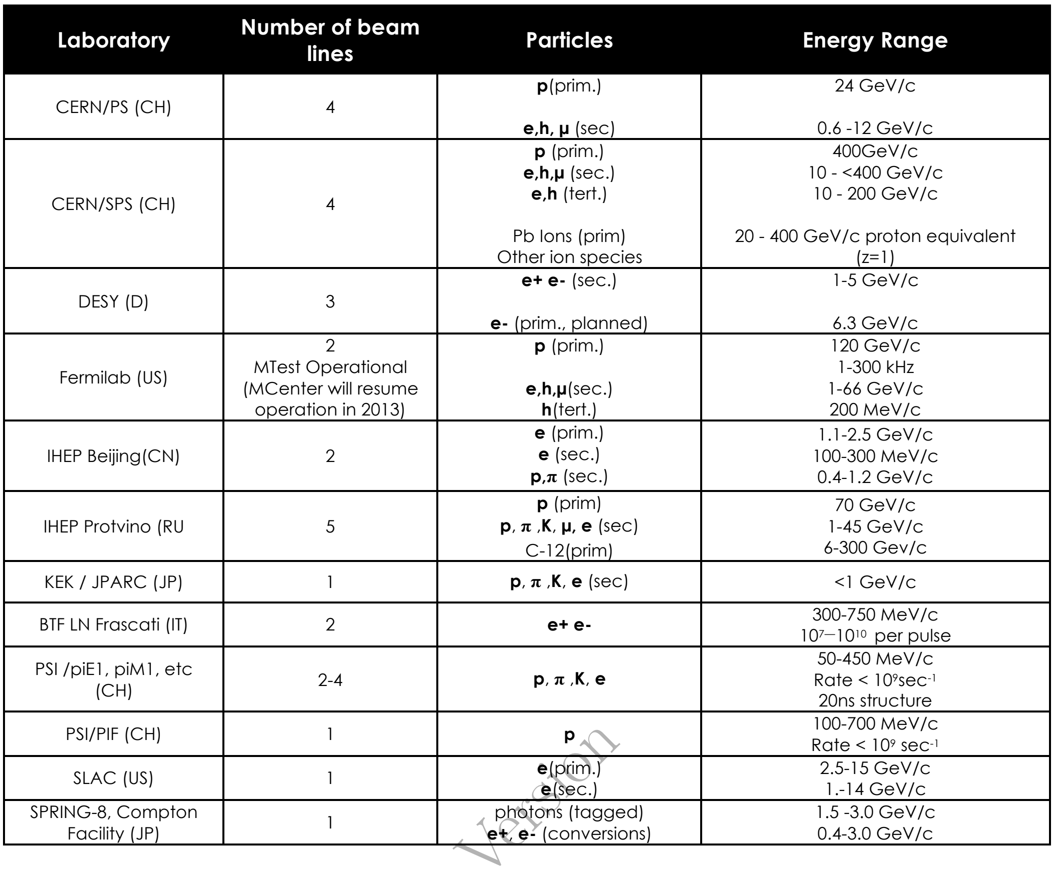
Well-defined experimental conditions at test beam facilities also allow improvements to Monte Carlo simulations that aim to model the interactions of particles with detector materials. This synergy promotes a better understanding of the detector response leading to improvements to the simulation tools used to develop new ideas and to verify the potential of new technologies already at the design phase.

Present and future generation accelerators will operate with a stored beam power that imposes stringent conditions on materials used for near-beam devices such as collimators, scrapers, targets, beam windows and beam dumps. R&D on materials for these devices and validation of prototypes with robustness tests in dedicated test facilities under well-controlled conditions is required. Furthermore, the safe and efficient operation of accelerators requires more and more electronics (e.g, for functional control, monitoring) to be installed close to beam-line. The development and maintenance of these electronics requires a careful radiation tolerant design, thus making radiation tests mandatory. The failure of a single piece of equipment can alter the accelerator operation and induce a beam-dump, imposing the requirement of high individual and overall reliability. Modern accelerators sustain a strong mixed particle radiation field ranging from thermal to very high energies, thus requiring radiation tests in equivalent fields or individual tests for each of the field components. For the latter, external facilities exist, however often their availability is limited and the costs are significant. Dedicated accelerator test facilities and access to external test complexes are therefore considered as mandatory to allow for safe and efficient operation of existing accelerators, as well for ensuring the developments towards the next generation of particle accelerators and experiments.

Over the past ten years the demand for test beams and irradiation facilities has increased and permanent installations of test set-ups are necessary to host the huge long-term developments and tests for future detectors and accelerators. Table 1 illustrates the various test beam facilities around the world; particle types, energies and beam intensities are different but complementary. The largest facilities are available at CERN, DESY, Fermilab and SLAC with requests that may exceed by large the available beam time. As an example, at CERN, in a typical year: 80% of the available beam time is used at the PS, and at the SPS the requests exceed the available beam time by a factor 1.5. The extensive use of the test beam facilities is only possible because of the outstanding technical support, the expertise and the excellent conditions of the infrastructure and beam instrumentation. For the latter, a large number of beam tests around the world exploit pixel telescopes developed by a common effort to provide high-quality beam instrumentation[ID62].

9.2.5 Outlook and Conclusions

Detector R&D is the vital backbone for the success of the upcoming large and complex experiments. Similar technological choices are, very often, the baseline for the detectors envisaged in future experiments at the Intensity, Energy and Cosmic Frontiers. Hence,



Laboratory	Number of beam lines	Particles	Energy Range
CERN/PS (CH)	4	**p**(prim.) **e,h, μ** (sec)	24 GeV/c 0.6 -12 GeV/c
CERN/SPS (CH)	4	**p** (prim.) **e,h,μ** (sec.) **e,h** (tert.) Pb Ions (prim) Other ion species	400GeV/c 10 - <400 GeV/c 10 - 200 GeV/c 20 - 400 GeV/c proton equivalent (z=1)
DESY (D)	3	**e+ e-** (sec.) **e-** (prim., planned)	1-5 GeV/c 6.3 GeV/c
Fermilab (US)	2 MTest Operational (MCenter will resume operation in 2013)	**p** (prim.) **e,h,μ**(sec.) **h**(tert.)	120 GeV/c 1-300 kHz 1-66 GeV/c 200 MeV/c
IHEP Beijing(CN)	2	**e** (prim.) **e** (sec.) **p,π** (sec.)	1.1-2.5 GeV/c 100-300 MeV/c 0.4-1.2 GeV/c
IHEP Protvino (RU	5	**p** (prim) **p**, **π** ,**K**, **μ**, **e** (sec) C-12(prim)	70 GeV/c 1-45 GeV/c 6-300 Gev/c
KEK / JPARC (JP)	1	**p**, **π** ,**K**, **e** (sec)	<1 GeV/c
BTF LN Frascati (IT)	2	**e+ e-**	300-750 MeV/c 10^{7}—10^{10} per pulse
PSI /piE1, piM1, etc (CH)	2-4	**p**, **π** ,**K**, **e**	50-450 MeV/c Rate < 10^{9}sec^{-1} 20ns structure
PSI/PIF (CH)	1	**p**	100-700 MeV/c Rate < 10^{9} sec^{-1}
SLAC (US)	1	**e**(prim.) **e**(sec.)	2.5-15 GeV/c 1.-14 GeV/c
SPRING-8, Compton Facility (JP)	1	photons (tagged) **e+**, **e-** (conversions)	1.5 -3.0 GeV/c 0.4-3.0 GeV/c

Figure 9.1: An overview of beams with energies above 100 MeV/c (status as of August 2012).

for a bright future, high priority needs to be given to the development of instrumentation in a coordinated way across laboratories, universities, international partners within fundamental physics and other disciplines. In this framework, establishing common interdisciplinary forums of discussion, global technological platforms and consortia would be of invaluable help for optimising the financial and human resources. Noting that detector R&D is mainly done within the larger experiments where funding levels facilitate interactions with industry, it can be argued that through common frameworks for R&D, small groups could more easily profit from the investments and achievements done by the large collaborations.

Detector R&D is expensive by nature, as are the final complex systems. Nowadays, prototypes of detectors and electronics can not always be built by individual institutes alone, but require collaborative forms of organisation and global coordination, common support services and facilitated access, when possible, to shared production and frame contracts. As well, the groups need a stable framework in which they can reliably plan the optimal use of scarce resources and the long term investments.

All detectors and electronics developments need test beam and irradiation facilities to prove the performances and to verify radiation effects on active parts and passive materials. Existing facilities have constantly been over-subscribed in the previous years and will need continuous if not increased support for meeting future demands. Irradiation/testing facilities and associated infrastructures, covering a large ranges of energies and particle types, need to be actively sustained.

High priority must be given to the training of the next generation of young talented researchers, to be able to cope with the future challenges in instrumentation. Due to the very long timescales of today's research, the opportunities to participate to all phases of an experiment are becoming more and more scarce. Hence, additional investment is needed for the specialized education of young physicists and providing maximal support to the organization of schools in instrumentation would be highly beneficial [ID49]. In addition, excellence in instrumentation development is not recognized enough at the universities so as to foster the participation of young people to this branch of research. It would be highly fruitful to encourage, with respect to the academy, a plan that allows equal-opportunity careers in instrumentation at the universities, for both students and professors.

9.3 Construction of Large Scale Projects

9.3.1 Introduction

The particle physics community can proudly look back on a long history of successful realization of ever increasingly complex instruments that were crucial for the advances of our field. The LHC detectors can be taken as a culmination of this evolution. They operate in a truly impressive manner, as it was demonstrated convincingly with the discovery of a new Higgs-like boson, announced in summer 2012 by the ATLAS and CMS Collaborations. Both detectors record data with very high efficiency, and they have reached full design performances already after less than two years from the turn-on of the collider, in spite of their unprecedented complexity. The central role of the detector performances, together with the computing infrastructure and the whole data preparation and analysis chain, cannot be stressed enough for the timely delivery of the discovery physics.

However, the show-cases of the LHC detector construction projects also make very clear that one cannot assume that future projects can be realized without innovation. Analyzing the multitude of challenges that ATLAS and CMS in particular had to face and overcome, one has rather to assume that much careful thinking and planning is necessary before embarking into future large scale projects. Without conscious and deliberate efforts the necessary ingredients for a successful project design and execution may well be missing in the future within our community. A special challenge that has to be addressed is the growing complexity of the detector systems, requiring an integrated engineering effort, starting from the design phase, and including more and more expertise from outside than what is traditionally available in our community. The long time scales involved in the life cycle of the projects makes the traditional transfer of knowledge and experience from senior to junior physicists and engineers much more problematic: there is a clear concern about building up the next generation of engineers and physicists with the competences required for leading the construction of the next large scale projects.

Some of the major aspects will be addressed in this section. It follows in many parts directly the presentation given at the Open Symposium by T. Virdee, who took the largest and most complex particle physics detector projects realized so far, ATLAS and CMS, as examples to illustrate the considerations that have to be kept in mind for future projects. It also reflects the points raised by a couple of dedicated written contributions submitted to the Strategy Update [ID48, ID115].

9.3.2 Framework for the construction of the LHC experiments

The LHC experiments are the largest truly global construction projects ever undertaken in our field, each of ATLAS and CMS having typically about 180 Institutions (with 3000 scientists) from 40 countries with more than 40 Funding Agencies involved. It took about 20 years from the first detector concepts to full operation, and the most important driver to overcome many challenges discussed in the following was of course the extraordinarily strong physics case for the construction of the LHC.

Given the long time scale involved, a key element in achieving success was to plan and prepare these projects within a framework of stability of resources, both financial and human resources. This stability was the necessary backbone to face and adapt solutions to many unforeseen changes and surprises during the different phases, from initial prototyping, serial production of components to installation and commissioning. This resources framework was provided at the top level by the regular meetings, twice a year, of the Resources Review Boards (RRBs) with executive representatives of all funding partners monitoring the construction progress in line with the Memorandum of Understanding, under the authority of CERN, and under the chairpersonship of the CERN Director of Research. This also implied that a large part of the legal and contractual matters were thereby embedded into the framework of CERN. The RRBs were also crucial to develop, and agree on, the funding modes (common funds, in-kind contributions, shared funding between different countries, operation funds etc).

9.3.3 Facilities for the construction of large detectors

The experience of the large LHC experiments is that there are three elements, inside the HEP community, that contributed to the successful construction of the detectors, together with industry, namely CERN as a host laboratory, large national laboratories, and last but not least the universities. All of them were crucial, and their respective roles must be preserved for future projects.

A strong host laboratory was pivotal not only to provide the resources framework mentioned above, but also to provide the necessary technical expertise, operating in partnership with national laboratories and those universities with good technical infrastructure. This was very fruitful for the highly distributed construction of components, and even critical to overcome unforeseeable technical difficulties during fabrication of components in industry. There are many examples where the LHC experiments would have failed with industry working on its own, with the concomitant probability of leading to large delays and cost increases, without the technical experts from the projects directly taking corrective actions with the industrial partners.

The large national laboratories often provided unique and precious technical expertise, for example in superconducting magnets, cryogenics, integrated electronics, experience in constructions of large detector components etc. They often also played a very important role in hosting locally the construction and assembly efforts of national communities. This partnership between the host laboratory, the large national laboratories, and the universities allowed the collaborations to exploit most efficiently all the available talent, including that from groups too small to contribute on their own to detector construction.

A question, brought up in the discussion at the Open Symposium, is how to provide the best possible infrastructure and support for new experiments on greenfield sites, for which novel models of operation will have to be developed.

9.3.4 Integration and Project Management

The traditional lean top-layer management for particle physics experiments run in Europe has turned out to work well for the LHC Collaborations. The Experiment Management is led (at CERN) typically by a Spokesperson, elected by the Collaboration, operating independently of the host laboratory, albeit in close consultation. Then there is a strong host laboratory interface with the experiments through the Technical and Resources Coordinators, each appointed by, and answerable to, both the Collaboration and the host laboratory. An important lesson learned from the LHC experiments is that it is crucial to set up already early in the design phase a central project office, led by the Technical Coordinator, which includes engineering expertise. A primary role of a central project office is that a coherent systems approach, including overall integration, be implemented from the onset. This will avoid later-on painful design changes that could become necessary when understanding too late the constraints from, for example, services such as cables and cryogenics fluids, magnetic environments, thermal environments etc. The central project office must also have the authority to define the standards to be followed in the project as a whole. These concern technical documentation (design data base management, change tracking, resource-loaded scheduling) as well as the Quality Assurance and Quality Control procedures. In the CERN experiments the Technical Coordinator is responsible for all safety aspects, the oversight of which is then also naturally embedded in the project offices.

It was pointed out in written contributions to the Strategy Update [ID48, ID115] that modern project design practice involves a lot of system simulation analyses and 3D modeling that need often also interdisciplinary competences. This modeling must go well beyond the traditional mechanical engineering design, and include such aspects as for example thermal, magnetic and vibration behaviours. One can expect that the central project office takes a leading role in bringing together this expertise available in some of the major partner laboratories collaborating on the project. A strong dialogue between the engineering and physicist teams is crucial through all phases of the project, but certainly also very early on when simulations are playing a central role in the design. A common data base platform for engineering and physics simulations, not fully achieved for the developments of the LHC experiments, remains a very desirable goal that would, for example, avoid later surprises in term of (usually larger) material budgets in trackers than assumed by the physicists.

A very important role in the LHC detector construction process was played by internal and external technical reviews. Whereas the scientific peer reviews were conducted very regularly (six times a year) by the LHC Experiments Committee (LHCC) on an overview level, the large experiments, through their technical coordination (project office), conducted dedicated experts reviews on the engineering level which were truly crucial for the success of the construction and installation of the complex instruments. They were typically conducted for sub-detector systems before authorization of start of fabrication, after some 10-20% of completion in order to possibly still implement corrective actions if needed, and then at a more advanced stage to monitor construction completion and installation issues. These review processes followed the projects from design to construction to installation and commissioning.

9.3.5 Preserving Knowledge and Technical Expertise

Dedicated in-house technical expertise at CERN, the national laboratories and in large university teams was indispensable for the delivery of the large LHC detector systems. It is vital that these are preserved for future large projects, not least to guarantee the direct and efficient interactions and interfaces between the scientists, engineers and industry.

There are areas of technical competences linked to the specific applications for large particle physics detectors that cannot be found readily outside our community. Just to name a few examples: large transparent superconducting magnet designs, large-scale radiation-hard semiconductor tracking detectors, integrated electronic designs, integrated data flow and triggering systems. This precious knowledge can only be preserved for our field by investing into the required infrastructure and expertise at the Institutions that will hopefully also play leading roles in future construction projects. In-house experts also ensure that our field remains aware of the evolution of emerging potentially useful technologies for particle physics experiments by active technology tracking.

An issue of great concern has been identified, that of training the next generation of engineers and physicists knowledgeable to lead the conception and the realization of future projects. The skills and experience of the typically 10 to 15 years of effort it took to realize instruments like ATLAS and CMS must be passed on to a new generation. Needless to say, the best way to preserve and create knowledge and expertise would be to have ongoing construction projects, concurrently with the exploitation of the previous generation of detectors. The LHC detector upgrades are an excellent opportunity to give the younger generation of engineers and physicists a chance to acquire such technical and managerial knowledge for successful realization of cutting edge projects. A support of small size experiments certainly adds also in a beneficial way to provide platforms for the next generation project engineers and technical coordinators.

However, the scarcity of projects, and the long time scales involved, are reasons that there is no more a natural transmission of knowledge, and active pursuit of corrective actions is required if the community wants to assure availability of specific expert knowledge needed for the realization of future detectors. Fortunately there exist schools and workshops in technical areas such as accelerators, instrumentation, electronics, data acquisition and computing. But there are only very limited chances for young engineers and physicists to learn about overall system designs for large particle physics detectors, and it is a legitimate question whether a dedicated school would be useful to attract new talent, in particular from universities where they often cannot get exposed to such challenges. There is also an issue of encouraging a better culture in our field in which people working on R&D, building detectors, operating and maintaining them should get proper recognition, with job opportunities and promotions. Putting too high a weight only on achievements in physics analysis is detrimental in the long-term for the health of our community.

9.3.6 Summing up some key points

Largely based on the successful construction of the LHC experiments, arguably with the most complex detectors built in the recent decades in our community, one can make the following observations which most likely apply to future large projects.

1. To deliver challenging large projects it is pivotal to have a technically strong host laboratory and a strong collaboration structure (project office) which work coher-

ently hand-in-hand, within well understood and defined interfaces and responsibilities.

2. The roles of national laboratories and universities with large construction capabilities are absolutely crucial for the successful distributed construction. Naturally they provide the largest fraction of human resources, which must be embedded in partnership with the central project management.

3. Funding Agencies, CERN, national laboratories and those universities with large construction capabilities should assure that the required expertise and infrastructures are preserved and maintained at the state-of-art level for future construction projects.

4. Bringing-in and training of the new generation capable of taking responsibilities in leading the design and execution of large complex instruments is a must to maintain the vitality of our field, and to preserve a good chance of success in the construction of future large projects.

9.4 Computing for Particle Physics 2020

Particle physics has relied on advances in computing in order to record and handle the large amounts of information generated by modern detectors and to model the physics processes and to simulate the interactions of particles in the detectors. The field has taken advantage of and at times helped to develop new technologies. The global computing infrastructure assembled for processing and analysis of LHC data has been hugely successful, and is an example of global planning and international partnerships for development, operations and funding of computing for science.

The LHC has been a great computing challenge for the particle physics community. Experiments at LHC generate petabytes (PB) of data each year that are then processed, stored and made available to physicists around the world for analysis. The data also will be archived for many years - at least for the lifetime of the experiments which could span several decades. CERN and the rest of the HEP community responded to the computing challenge and developed the Worldwide LHC Computing Grid (WLCG). This collaboration of institutes and national GRID consortia includes scientists and computing specialists from CERN, from computer centers across Europe and from around the world. The WLCG came together to build and operate the infrastructure to manage the data produced by the LHC detectors and enabled the 1000s of scientists on the LHC to produce physics results and new discoveries at remarkable speed.

The rapid evolution of computing technology is again expected to create many new challenges over the next decade. At the same time the LHC experiments will continue to push the data rates to accommodate high intensity operations. The field needs to update its computing strategy to be prepared to support the development and infrastructure needed to meet these upcoming challenges.

9.4.1 Computing Models

The model of HEP computing changed with the preparations for the LHC era. Computing for particle physics is now distributed and takes advantage of excellent network bandwidth between sites and within each institutes campus. This global infrastructure was essentially a dream at the time the LHC experiments were initially planned. The GRID was an R&D project that held promise, but had not been tested at full scale. It took more than a decade to develop the plan and the corresponding core computing and software infrastructure to achieve the computing systems we nearly take for granted today.

LHC computing routinely uses nearly 250,000 CPU processor cores, and nearly 170 petabytes of disk storage in addition to large multi petabyte tape libraries. These resources are spread over many continents with prompt data processing and initial archiving of the data located at CERN. The LHC model was based on the MONARC report [3] that advocated a distributed system noting that power and cooling at CERN was limited. It was also seen as beneficial to distribute the computing resources in order to take advantage of local expertise and funding. The GRID was to provide the glue between the sites and good network connectivity was foreseen to be expensive with limited bandwidth between many sites. The initial models were strictly hierarchical (Tier-0, Tier-1, Tier-2) with specific functionality assigned to each tier. Data distribution had to be pre-planned and the computing tasks were sent to the data. The computing models of today are based on an evolution of this paradigm that takes advantage of the excellent networking that is now available between most sites.

The operations of the LHC computing GRID worked well due to careful planning, adequate preparation of the sites and sufficient funding across the WLCG collaboration. The funding for WLCG comes from a variety of sources including CERN, the EU, national funding agencies, regional GRID projects and local institutes. The software and computing systems for physics analysis at the LHC were the result of a large worldwide effort that took years to plan and skilled scientists and engineers to commission it. The coordinated effort paid off. The LHC experiments had an accurate simulation based on GEANT4 at the time of first collisions and a tested data processing chain working at the right scale. As a result, physicists from around the world could participate in analysis and the first physics papers were prepared within a few months. The LHC experiments plan for their computing systems to be in continuous operations throughout the next two decades. There is a continuous need to improve the systems to make the most effective use of resources. It is vital that the funding for the WLCG Tier-1 and Tier-2 centers be maintained at a level to ensure the full exploitation of the data produced by the LHC in the coming years.

Looking ahead to the computing challenges for the next decade, the HL-LHC stands out as a significant challenge. The expected increases in trigger rate, pile-up and detector complexity (number of channels) could increase the data rates by a about a factor of 10 or more. This order of magnitude increase in storage and CPU requirements presents a new challenge for the computing infrastructure and the community will need time to prepare for it. The LHC community is beginning to review their computing models as they make plans for the next decade. It is anticipated that the general design will be an evolution from the current models with the computing resources distributed at computing centers around the world.

The general particle physics community should be able to profit from the LHC computing infrastructure set up by the WLCG. The community needs a broader HEP-wide forum where strategic issues for computing for the next decade can be discussed and the common work coordinated [ID58]. It may be the right time to review the organizational structure of the WLCG in anticipation of the LHC future planning and development work that is getting underway.

9.4.2 R&D for HEP Computing and Software

The development of the software for the LHC experiments spanned more than a decade and involved an international effort that partnered computing specialists with physicists to design, develop and commission the software systems. The hardware components that were assembled into the computer centres were commercial products, but the software infrastructure to process, transport and manage the data was largely developed by the experiments or by the HEP GRID community and the related projects. The funding for this development and deployment came from a variety of sources including the EU, CERN and the national funding agencies.

For the past several decades, the community has been able to take advantage of developments in commercial computing components to expand dramatically the processing power, the storage capacity and network bandwidth capacity each year without a fundamental change in the software paradigm and without dramatic increases in funding. Rapid improvements in CPU clock speeds and I/O speed are not expected to continue into the next decade. We anticipate a need to reengineer many HEP software codes to adapt to the new computer architectures of the future since machines are expected to have many more cores per processor. One of the consequences is that single event-by-event parallelism will no longer be efficient and we will need to adapt event processing software to implement sub-event parallelism and to take best advantage of the multi-core systems.

The exploration of parallelism at the level of the individual algorithms demands software expertise beyond the skill of most physics graduate students and postdocs. Software experts within the experiments are working to develop enhanced frameworks that mask the complications of parallelism from the users. Simple schemes for module parallelism may not always be possible due to software module interdependence through algorithms such as for instance particle flow that combine tracking and calorimetry algorithms. For critical algorithms such as tracking, a partnership of physicists and experienced parallel programming experts will be needed to develop effective parallel codes. The complete transformation of our physics software packages will take time, expertise and an adequate level of support. There is already a CERN based HEP effort (Concurrency Forum [4]) working in this direction [ID40].

9.4.3 Infrastructure and Data Management

The LHC experiments and the WLCG have demonstrated that the particle physics community is able to manage large data samples effectively. Particle physics has been a leader in this area within the science community for some time. Many challenges lie ahead as data volumes continue to grow. The community should continue to build on its successes and work to improve the efficiency through the development of optimized models for data placement, data caching and data access.

The HEP computing and software community should take a leadership role in building collaborations with industry and with other data intensive sciences. If the science community could identify more synergies among the communities and target specific areas where common tools for data management could be utilized, support and maintenance of the infrastructure could become more sustainable. The community should develop a plan to work with the wider scientific community to identify common data management solutions that could become open standards for scientific data management.

The WLCG infrastructure developed for the LHC should be open and available to the whole particle physics community. This openness has already been partially achieved within many of the national grids. Further technical development and planning is needed to make access to the global computing infrastructure more user-friendly for smaller collaborations. One possible bi-product of HEP-wide sharing would be to make the e-infrastructure more open and attractive to other sciences.

Cloud computing is under extensive consideration as a possible component of HEP computing models of the future. Although commercial clouds are not yet economically viable for large scale data intensive HEP computing, cloud computing, perhaps a science cloud could well be a significant component of future HEP computing systems. A pilot project to evaluate the use of cloud technologies for data processing has been launched as part of a European Cloud Computing partnership, Helix Nebula [5]. Network connectivity is expected to continue to improve and we can expect to have seamless remote access to data. This will have an impact on the computing models for analysis and should lead to more efficient use of resources.

In general it takes 5 to 10 years to develop facilities and computing infrastructure. The facilities of the next decade will have to be planned soon. We need a strategic plan that captures HEP computing needs for the next decade. CERN should work with the leaders of the national research infrastructure centres to develop the plan and that best fits the needs of our science.

9.4.4 Data Preservation and Data Access

Many HEP experiments have a lifecycle that is beyond the lifecycle of the computing technology we use. Ideally data preservation should be built into each collaborations software plans from the beginning. It is also becoming increasingly important to provide open access not only to science publications but also to the data. It is not adequate to preserve an archived copy of the data; the associated software and software libraries also need to be preserved and well documented. The HEP collaborations are aware of the need to develop clear policies and plans for data preservation and for open access. This task has been taken up by the LHC experiments, where work is underway within the collaborations.

The Study Group for Data Preservation and Long Term Analysis in High Energy Physics (DPHEP) [6] [ID125] has taken the lead in this important area. HEP collaborations have traditionally tackled the preservation of data near the end of the experiments lifecycle. This trend is changing since the need for data preservation and access is more widely recognized in large projects with long timescales. CERN is working with DPHEP to provide some guidance for policies and leadership in the technical strategies for the current experiments.

The HEP community has long advocated for open access to scientific publications in the field. LHC results are published with Open Access and there are plans to convert all HEP literature. Open access to the data produced by particle physics experiments is becoming a requirement and will need to be built into models for data presevation. Access to the raw data requires very specific knowledge of the characteristics of the decectors and accompanying detailed simulations and will not be as useful as processed and calibrated datasets.

INSPIRE [7] is the HEP digital library developed and operated in partnership among HEP institutions: CERN, DESY, Fermilab, and SLAC [ID22]. INSPIRE is widely used in the HEP community and is a model of successful infrastructure for scientific communication and knowledge management for other fields. A sustainable funding model for these efforts is required for their continued success.

9.4.5 Particle Physics Software Libraries

Software libraries developed by particle physicists such as GEANT4 [ID170], ROOT and event generators are widely used in the particle physics community and beyond. They represent the work of years of many scientists and computing specialists. These libraries are a repository of many of the tools and algorithms we need to do our work. With adequate support, they will continue to evolve in order to to keep up with the needs of the experiments. They also need to run efficiently and to operate reliably on modern computer systems, which requires a model for sustained support. It is essential that the community find a way to maintain and support these libraries, particularly the major toolkits and libraries that are in general use.

GEANT4 has been a very successful detector simulation toolkit. It was developed by a group of particle physicists working in a global collaboration. The project has enjoyed the support of the experimental HEP community and many of the major laboratories in the field participate in the GEANT4 collaboration. GEANT4 is widely used in the particle physics community (and also by many other communities including medical, radiation protection, space and homeland security) and provides us with an unprecedented detailed understanding of detector systems. In fact, detector simulations using GEANT4 code is responsible for a large part of the CPU cycles used by HEP. Therefore, it is important that it runs very efficiently. The core code and algorithms will need to be updated to take advantage of new computer architectures. The codes will also have to accommodate descriptions of new devices and materials used in next generation detector R&D and new experiments [ID133]. Continued support is vital to this program.

CERN has been a leader in the development and preservation of the physics software libraries, mathematics and analysis toolkits libraries that have been developed for HEP specific applications and analysis. There are now examples of software collaboration that involve more support from the HEP community. It is important to foster this collaboration and to develop a sustainable model for support of our software over the long term.

9.4.6 Concluding remarks

Computing for particle physics faces a number of new challenges including securing adequate funding for infrastructure, development and operations. It is important that the community tackles the challenges coming from the expected transition to future computing architectures. It is vital that the support for the operations teams and the WLCG centers be maintained at a level to ensure the full exploitation of the data produced by the LHC in the coming years.

References

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[6] DPHEP website: www.dphep.org

[7] INSPIRE website: inspirehep.net

[ID14] ESPG document 14, NEXT a high-pressured Xenon-based experiments for ultimate sensitivity to a Majorana neutrino

[ID16] ESPG document 16, Synergy of Particle Physics with other disciplines; the CERN CLOUD experiment

[ID22] ESPG document 22, Open Infrastructures for Scholarly Communication

[ID40] ESPG document 40, Addressing the challenges posed to HEP software due to the emergence of new CPU architectures

[ID48] ESPG document 48, Large-system Engineering

[ID49] ESPG document 49, Excellence in Detectors and Instrumentation Technologies: Network Project

[ID58] ESPG document 58, CERN IT & WLCG Input to the European Strategy for Particle Physics Update

[ID62] ESPG document 62, AIDA contribution to European Strategy on Infrastructure for detector R&D

[ID66] ESPG document 66, Neutrino Physics in Finland

[ID74] ESPG document 74, A new CERN long baseline conventional neutrino beam (CN2PY) aimed at a deep underground research infrastructure for large scale detectors at Pyhasalmi: an opportunity for Particle and Astroparticle Neutrino and Grand Unification Physics

[ID78] ESPG document 78, The ILD Detector Concept for the ILC

[ID79] ESPG document 79, The SiD concept for the ILC

[ID80] ESPG document 80, European Strategy for Accelerator Based Neutrino Physics

[ID103] ESPG document 103, R&D Paths of Pixel Detectors for Vertex Tracking and Radiation Imaging

[ID115] ESPG document 115, Instrumentation & Detection. Contribution from the French engineers and physicists

[ID120] ESPG document 120, The Belle II experiment at SuperKEKB

[ID124] ESPG document 124, Interfaces with Earth sciences. Input from the French community.

[ID125] ESPG document 125, Towards a Global Effort for Sustainable Data Preservation in High Energy Physics [DPHEP Study Group]

[ID128] ESPG document 128, Long-term plans of the ALICE Collaboration

[ID133] ESPG document 133, Monte Carlo Simulation for Particle Detectors

[ID143] ESPG document 143, Trends and perspectives for detectors in Fundamental Physics

[ID170] ESPG document 170, Geant4 Near and Medium Term Strategy

Appendix A

Open Symposium Scientific Programme

Monday, September 10, 2012

Overview Talk	A. Masiero (INFN)

Physics at High Energy Frontier and Flavour Physics I

Kuno Y (Chair), R. Forty (Scientific Secretary)

HEF Experiment Results	G. Dissertori (ETH Zuerich)
Flavour and Symmetries; Experiment Results	F. Teubert (CERN)
Charged Lepton Flavor and Symmetry Physics Implications	G. Isidori (INFN)

Physics at High Energy Frontier and Flavour Physics II

K. Desch (Co-Chair), M. Diemoz (Co-chair), A. Lister (Scientific Secretary)

Implications on Possible New Physics from Direct and Indirect Measurements	C. Grojean (CERN)
Next Step Facilities	T. Wyatt (Manchester)

Strong Interaction Physics

P. Braun-Munzinger (Chair), K. Kutak (Scientific Secretary)

Strong Interactions and QCD at the High Energy Frontier	P. Newman (Birmingham)
Relativistic Heavy Ion Collisions	H. Appelshaeuser (Johann-Wolfgang-Goethe Univ.)

Tuesday, September 11, 2012

Astroparticle Physics, Gravitation and Cosmology	
C. De Clercq (Chair), Pierre Brun (Scientific Secretary)	
European Astroparticle Physics: Status and Vision	C. Spiering (DESY)
Summary of Activities in Regions Beyond Europe	S. Katsanevas (IN2P3)

Physics of Neutrinos	
D. Wark (Chair), E. Fernandez Martinez (Scientific Secretary)	
Phenomenology of Neutrino Oscillations and Current Situation	P. Hernandez (Valencia)
Neutrino Mass Measurements	H. Robertson (Washington)
Next Generation Accelerator Neutrino Projects - Long and Short Baseline	M. Zito (IRFU Saclay)
Longer-term Accelerator and Future Reactor Neutrino Projects	C. Hagner (Hamburg)

Accelerator Science and Technology	
R. Aleksan (Chair), F. Zimmermann (Scientific Secretary)	
High Energy	C. Biscari(INFN)
High Intensity	M. Lindroos (ESS, on leave from CERN)

Instrumentation, Computing and General Infrastructure	
P. McBride (Chair), E. Garutti (Scientific Secretary)	
Detector R&D for Discovery Science	A. Cattai (CERN)
Construction of Large Scale Projects - Technical Capabilities and Infrastructure	T. Virdee (Imperial College)
Computing and Data Management for Particle Physics in 2020	Tommaso Boccali (INFN)

Wednesday, September 12, 2012

IParticle Physics Theory	
K. Huitu (Chair), P. Slavich (Scientific Secretary)	
The Role of Theory for Particle Physics	L. Alvarez-Gaume (CERN)
Quantum Field Theory on the Lattice	Ch. Davies (Glasgow)

Status of Other Regions and Closing Discussion	
T. Nakada (Chair)	
Americas	A. J. Lankford (UC Irvine)
Asia Pacific	M. Yamauchi (KEK)
Closing Discussion	

Appendix B

Open Symposium Contributions

ID	Title	Primary Authors
5	The QGSM Monitoring of Standard Model Baryon Spectra in High Energy Proton Collisions at LHC	PISKUNOVA Olga
10	Fundamental Science at the European Spallation Source	LINDROOS Mats RATHSMAN Johan CHRISTIANSEN Peter
11	Conclusions from the NUTURN 2012 Workshop (LNGS, 8?10 May 2012)	TERRANOVA Francesco
12	Exploring Confinement	KRASNY Mieczyslaw Witold
13	What if there is no Higgs?	KRASNY Mieczyslaw Witold
14	NEXT a high-pressured Xenon-based experiments for ultimate sensitivity to a Majorana neutrino	GOMEZ CADENAS Juan Jose
15	Storage Ring Electric Dipole Moment Methods: The road to the next sensitivity level of hadronic EDMs.	SEMERTZIDIS Yannis
16	Synergy of Particle Physics with other disciplines; the CERN CLOUD experiment	KIRKBY Jasper
17	Search for GeV-scale sterile neutrinos responsible for active neutrino masses and baryon asymmetry of the Universe	SHAPOSHNIKOV Mikhail
18	High-energy physics in Finland Strategical outlook for Helsinki Institute of Physics	AYSTO Juha
19	The Canfranc Underground Laboratory (LSC)	BETTINI Alessandro
20	Statement of Interest and Support from the Brazilian HEP Community	FREIRE JUNIOR Fernando Lazaro
21	Thermal Neutron Accelerator	CHUNDURU Amareshwar Prasad
22	Open Infrastructures for Scholarly Communication	MELE Salvatore
24	A realistic next-generation nucleon decay and neutrino experiment capable to probe leptonic CP violation	FERNANDEZ MARTINEZ Enrique LABARGA Luis
25	Suggestion from a Taiwan physicist	HOU George Wei-shu
26	Dirac magnetic monopole (new arrangement of experiment)	KUKHTIN Victor
27	Swiss contribution to the Update of the European Strategy for Particle Physics	KIRCH Klaus
28	JAI input for the European Strategy	SERYI Andrei
29	NA61/SHINE plans beyond the approved program	ABGRALL Nicolas

30	The Scientific Program in Particle and Nuclear Physics at the CERN injectors and its foreseable future	BLOCH Philippe
31	Neutrinos: masses, oscillations; proton decay. A roadmap proposal by the French physicists.	DUCHESNEAU Dominique
32	Statement from NuPECC regarding the LHeC and ALICE	BRACCO Angela NYSTRAND Joakim
33	Particle Physics at Budker INP	TIKHONOV Iouri
34	Searches for Permanent Electric Dipole Moments	KIRCH Klaus HARRIS Philip
35	Input to the European Strategy for Particle Physics from the EUROnu FP7 Design Study of a High Intensity Neutrino Oscillation Facility in Europe	EDGECOCK Rob
36	Nucleon Structure and QCD at High Energy. A roadmap proposal by the French physicists.	SABATI Franck
37	CP violation, matter-antimatter and heavy flavours. A roadmap proposal by the French physicists.	ARNAUD Nicolas
38	Search for anomalies in the neutrino sector with muon spectrometers and large LArTPC imaging detectors at CERN	RUBBIA Carlo
39	Standard Model: precision measurements and electroweak symmetry breaking, roadmap elements by the French physicists	MALCLES Julie
40	Addressing the challenges posed to HEP software due to the emergence of new CPU architectures	HARVEY John CARMINATI Federico MATO VILA Pere
41	European strategy for long-baseline neutrino-oscillation experiments; The UK perspective	BARKER Gary
42	ORCA: Oscillation Research with Cosmics in the Abyss	COYLE Paschal
43	NICA at JINR Dubna	MATVEEV Victor KEKELIDZE Vladimir
44	Cosmology and Dark Matter. A roadmap proposal by the French physicists.	ARMENGAUD Eric
45	Neutrino and Astroparticle Physics Program of JINR and Russian Institutes	MATVEEV Viktor
46	Particle and Astroparticle Physics in Poland	ZALEWSKA Agnieszka
47	A case for a very large circular electron-positron collider	GLOVER Edward VAN DER BIJ Jochum
48	Large-system Engineering	ARDELLIER-DESAGES Florence
49	Excellence in Detectors and Instrumentation Technologies: Network Project	CATTAI Ariella
50	JINR Activity in Future Linear Colliders	SHIRKOV Grigori
51	TIARA contribution to the European Strategy for Particle Physics	TIARA Collaboration
52	Strategy for Experimental Particle Physics to 2040: University of Liverpool	ALLPORT Philip Patrick BOWCOCK Themis DAINTON John KLEIN Max TOURAMANIS Christos GREENSHAW Timothy John

53	FRENCH MEMORANDUM ON A FAST TRACK SCENARIO FOR BUILDING A GLOBAL LC	BRIENT Jean-claude
54	Contribution of the Spanish network for Future Linear Colliders to the Update of the European Strategy for Particle Physics	RUIZ-JIMENO Alberto
55	Conclusions of the Town Meeting: Relativistic Heavy Ion Collision	WIEDEMANN Urs REDLICH Krzysztof WAMBACH Jochen BLAIZOT Jean-paul
56	NICA at JINR Dubna	MATVEEV Viktor KEKELIDZE Vladimir TRUBNIKOV Grigory
57	ApPEC/ASPERA Scientific Advisory Commitee (SAC) Recommendations	SPIERING Christian
58	CERN IT & WLCG Input to the European Strategy for Particle Physics Update (Computing)	BIRD Ian HEMMER Frederic
59	UK input to European Particle Physics Strategy Update	BURROWS Philip
60	COMPASS planned measurements in the next five years and longer term perspectives on the study of the nucleon structure	KUNNE Fabienne BRESSAN Andrea
61	The SuperB Computing Model	BIANCHI Fabrizio
62	AIDA contribution to European Strategy on Infrastructure for detector R D	SERIN Laurent
63	Advanced technologies for components of future accelerators	SPATARO Bruno MARCELLI Augusto
64	Imaging and Imagination, how to exploit semiconductor technology for particle physics	HEIJNE Erik H.m.
65	Neutrino Physics in Finland	MAALAMPI Jukka TRZASKA Wladyslaw Henryk
66	R&D Activities in Electronics for future HEP Experiments	ANGHINOLFI Francis CAMPBELL Michael CHRISTIANSEN Jorgen FARTHOUAT Philippe MARCHIORO Alessandro VASEY Francois
67	Computing : A contribution from the French community	BOUTIGNY Dominique
68	SuperB Physics Programme	BEVAN Adrian GIORGI Marcello CIUCHINI Marco LUSIANI Alberto WALSH John FACCINI Riccardo RONEY Michael BIGI Ikaros

69	The Physics Case for an e+e- Linear Collider	BRAU Jim GODBOLE Rohini LE DIBERDER Francois THOMSON Mark WEERTS Harry WEIGLEIN Georg Ralf WELLS James YAMAMOTO Hitoshi
70	LENA - Low Energy Neutrino Astronomy	STAHL Achim
71	Opportunities Offered by the SuperB Detector Development	FORTI Francesco
72	Covering letter summary, International Linear Collider submissions to Open Symposium	FOSTER Brian
73	Summary of the International Linear Collider Technical Design Report	FOSTER Brian
74	A new CERN long baseline conventional neutrino beam (CN2PY) aimed at a deep underground research infrastructure for large scale detectors at Pyhasalmi: an opportunity for Particle and Astroparticle Neutrino and Grand Unification Physics	RUBBIA Andre
75	ILC Project Implementation Planning I: Introduction, Governance and Funding	FOSTER Brian
76	ILC Project Implementation Planning II: Management, Siting Host responsibilities, In-kind Contributions.	FOSTER Brian
77	ILC Project Implementation Planning III: Industrialisation, Schedule Future R D	FOSTER Brian
78	The ILD Detector Concept for the ILC	BEHNKE Ties
79	The SiD concept for the ILC	JAROS John
80	ILC Detector R&D: its impact	DEMARTEAU Marcel
81	EUROPEAN STRATEGY FOR ACCELERATOR BASED NEUTRINO PHYSICS	BLONDEL Alain
82	Proposal to use a high intensity neutrino beam from the ESS proton linac for measurements of neutrino CP violation and mass hierarchy	EKELF Tord DRACOS Marcos
83	Beyond the standard model. Contribution by the French physicists	BESANON Marc
84	Opportunities for Collaboration at Fermilab: Input to the European Strategy for Particle Physics, 2012	ODDONE Pier
85	Input of Nikhef to the European Particle Physics Strategy Discussion 2012	DE JONG Paul
86	The Hyper-Kamiokande Experiment	NAKAYA Tsuyoshi
88	TIMING TRACKERS FOR HIGH LUMINOSITY HADRON COLLIDERS	CHIODINI Gabriele
89	COMET and PRISM - Search for muon to electron Conversion in Japan	SATO Akira
91	Particle Physics at High Energies but Low Luminosities	CALDWELL Allen

92	Input for European Strategy for Particle Physics from IFIN-HH, Romania	IFIN-HH Directorate
93	The CERN Theory Unit and the future of European High Energy Physics	ALVAREZ-GAUME Luis ANTONIADIS Ignatios DRUMMOND James DVALI Georgi FRIXIONE Stefano GIUDICE Gian GROJEAN Christophe LAMBERT Neil LERCHE Wolfgang LESGOURGUES Julien LUESCHER Martin MANGANO Michelangelo PEREZ Gilad PIOLINE Boris Samuel SALAM Gavin Phillip SCHAEFER Stefan SERVANT Geraldine SKANDS Peter WELLS James WIEDEMANN Urs
94	An Accelerator Science Perspective on Experimental Particle Physics to 2040	CHATTOPADHYAY Swapan
96	The fourth generation, linac-ring type colliders, preons and so on	SULTANSOY Saleh
97	The LHCb Upgrade	CAMPANA Pierluigi FORTY Roger SCHMIDT Burkhard
98	Input from CPAN on behalf of the Spanish community	CERRADA Marcos
99	CLIC e+e- Linear Collider Studies	STAPNES Steinar DANNHEIM Dominik LEBRUN Philippe LINSSEN Lucie SCHULTE Daniel SIMON Frank TOGE Nobu WEERTS Harry WELLS James
101	Prospective Studies for LEP3 with the CMS Detector	JANOT Patrick
102	A New Search for the Decay mu-¿eee	SCHOENING Andre
103	R&D Paths of Pixel Detectors for Vertex Tracking and Radiation Imaging	BATTAGLIA Marco DA VIA Cinzia
104	Implications of LHCb measurements and future prospects	GERSHON Tim CAMPANA Pierluigi
105	Fundamental physics at low energies – The quest for axions and other new light particles	DBRICH Babette
106	The future of Monte Carlo Event Generators	SEYMOUR Mike
107	Imperial College London HEP Group Submission to the ESPG	NASH Jordan VIRDEE Jim EGEDE Ulrik PATEL Mitesh WASCKO Morgan UCHIDA Yoshi

108	nuSTORM: input to the update of the European Strategy for Particle Physics	LONG Kenneth
109	Higgs/top factory and Planck physics	BEZRUKOV Fedor KALMYKOV Mikhail KNIEHL Bernd SHAPOSHNIKOV Mikhail
110	On the Prospect and Vision of Ultra-High Gradient Plasma Accelerators for High Energy Physics	ASSMANN Ralph Wolfgang CALDWELL Allen FERRARIO Massimo TAJIMA Toshi OSTERHOFF Jens VIDEAU Henri
111	Particle accelerators	BOUSSON Sbastien
112	Implications of LHC results for TeV-scale physics: Exotics	GROJEAN Christophe SANTIAGO Jose SAVARD Pierre WORM Steven
113	Statement by the German Committee for Particle Physics (KET)	SPAAN Bernhard
114	Scalable CaloTracker (SCT) proposal for universal particle detector from zero till practically infinite energies	AGOCS Adam VESZTERGOMBI Gyorgy
115	Instrumentation & Detection. Contribution from the French engineers and physicists	COLAS Paul
116	Theoretical physics in France (particle physics, nuclear physics, astroparticle physics and cosmology)	MATHIOT Jean-franois
117	A Fixed-Target ExpeRiment at the LHC: AFTER @ LHC	ANSELMINO Mauro ARLEO Francois ARNALDI Roberta BOER Daniel BRODSKY Stanley J. CHAMBERT Valerie DIDELEZ Jean-pierre FERREIRO Elena G. FLEURET Frdric GENOLINI Bernard HADJIDAKIS Cynthia LANSBERG Jean-philippe LORC Cdric PEIGNE Stephane RAKOTOZAFINDRABE Andry ROSIER Philippe SCHIENBEIN Ingo SCOMPARIN Enrico UGGERHOJ Ulrik
118	High-energy universe, gravitational waves, multi-messangers	STOLARCZYK Thierry
119	COMPASS Plans and Perspectives for Physics with Hadron Beams	BRESSAN Andrea KUNNE Fabienne
120	The Belle II experiment at SuperKEKB	DOLEZAL Zdenek
121	Future Strategy of Japanese High Energy Physics Community	MORI Toshinori

122	The Belle II experiment at SuperKEKB: Importance for the European Particle Physics Institutions	DOLEZAL Zdenek
123	Quark-gluon plasma. Input from the French community	CASTILLO CASTELLANOS Javier FURGET Christophe MARTINEZ Gines
124	Interfaces with Earth sciences. Input from the French community.	CARLOGANU Cristina MARTEAU Jacques
125	Towards a Global Effort for Sustainable Data Preservation in High Energy Physics [DPHEP Study Group]	DIACONU Cristinel
127	Searching for Dark Matter	BOYARSKY Alexey RUCHAYSKIY Oleg SHAPOSHNIKOV Mikhail
128	Long-term plans of the ALICE Collaboration	SAFARIK Karel
130	Implications of LHC results for TeV-scale physics: flavor-changing processes at low energies	ISIDORI Gino
131	Implications of LHC results for TeV-scale physics: signals of electroweak symmetry breaking	HEINEMEYER Sven KADO Marumi MARIOTTI Chiara WEIGLEIN Georg Ralf WEILER Andreas
133	Monte Carlo Simulation for Particle Detectors	PIA Maria Grazia WEIDENSPOINTNER Georg
134	Particle Physics at DESY: Strategy and Plans	MNICH Joachim
135	A Staged Muon-Based Neutrino and Collider Physics Program	KAPLAN Daniel
136	A view from the INFN National Scientific Committee 1	BEDESCHI Franco
137	Input for the European Strategy Update from the DESY theory groups	DIEHL Markus BLUEMLEIN Johannes SOMMER Rainer
138	LEP3: A High Luminosity e+e- Collider to Study the Higgs Boson	BLONDEL Alain KORATZINOS M ZANETTI Marco ZIMMERMANN Frank
139	Implications of LHC results for TeV-scale physics: new physics with missing energy signatures	CAVANAUGH Richard HEWETT Joanne KRAML Sabine MANGANO Michelangelo POLESELLO Giacomo
140	Opportunities for Collaboration in the FNAL Charged Lepton Flavor Violation Program	BERNSTEIN Robert
141	Physics at a High-Luminosity LHC with ATLAS	ATLAS COLLABORATION The
142	Future of the ATLAS heavy ion program	ATLAS COLLABORATION The
143	Trends and perspectives for detectors in Fundamental Physics	CASSE Gianluigi CATTAI Ariella NAPPI Eugenio KRIZAN Peter SEFKOW Felix TITOV Maxim
144	CMS Submission to the European Strategy Preparatory Group	LANDSBERG Greg

145	SAPPHiRE: a Small gamma gamma Higgs Factory	ELLIS John
146	A “Higgs” Factory at the Greek-Turkish Border	UNEL Gokhan
147	A Large Hadron Electron Collider at CERN	KLEIN Max BRUNING Oliver
148	ORKA: Measurement of the Rare Kaon Decay K+-¿pi+ nu nubar at Fermilab	BRYMAN Douglas
149	Opportunities for Collaboration at Fermilab: The MicroBooNE Experiment	ZELLER Geralyn
150	The Long Baseline Neutrino Experiment	STRAIT James
151	Opportunities for Collaboration in the Design and Development of the Project-X Accelerator Complex and Research Program	HOLMES Stephen TSCHIRHART Bob
153	High Luminosity Large Hadron Collider	BRUNING Oliver ROSSI Lucio
154	LIU Project at CERN	GAROBY Roland
155	High Energy LHC	BRUNING Oliver GODDARD Brennan MANGANO Michelangelo MYERS Steve ROSSI Lucio TODESCO Ezio ZIMMERMANN Frank
156	LHeC - Preparations for a Future Proton-Lepton Collider in the TeV CM Regime	BRUNING Oliver KLEIN Max
157	LEP3 - Higgs factory in the LHC tunnel	ZIMMERMANN Frank
159	CERN Accelerator Infrastructure for Neutrino Physics	CORNELIS Karel EFTHYMIOPOULOS Ilias FERRARI Alfredo GAROBY Roland GILARDONI Simone GODDARD Brennan GSCHWENDTNER Edda PAPAPHILIPPOU Yannis SHAPOSHNIKOVA Elena STEERENBERG Rende STORA Thierry WILDNER Elena
160	Physics and Technology for the Next Generation of Radioactive Ion Beam Facilities: EURISOL	KADI Yacine
161	R&D related to the High Power Superconducting Proton Linac (HP-SPL)	GAROBY Roland GERIGK Frank
162	CERN Beam Test Facilities Infrastructure	EFTHYMIOPOULOS Ilias
163	Applications of Accelerators	MYERS Steve
164	LHC heavy ion programme	JOWETT John
165	Pre-Feasability Assessment for an 80 km Tunnel Project at CERN	OSBORNE John Andrew WAAIJER Caroline Sieao

166	National Research Centre 'Kurchatov Institute' input to the European Particle Physics Strategy Update	IVANOV Sergey TYURIN Nikolai ZAITSEV Alexandre KORSHENINNIKOV Alexey POPOV Mikhail SHEVCHENKO Vladimir SKOROKHVATOV Mikhail VASILIEV Andrei DANILOV Mikhail ZAKHAROV Valentin LIPATOV Lev VOROBYOV Alexey
167	Geant4 Near and Medium Term Strategy	VERDERI Marc
168	Proton Driven Plasma Wakefield Acceleration (AWAKE)	GSCHWENDTNER Edda
169	Executive Summary of the German Roadmap on Astroparticle Physics	SPIERING Christian
170	Geant4 Near and Medium Term Strategy	VERDERI Marc
171	Prospective Studies for LEP3 with the CMS Detector	JANOT Patrick
172	Swiss contribution to the Update of the European Strategy for Particle Physics (Part 2)	KIRCH Klaus
173	LEP3 and TLEP: High luminosity e+e- circular colliders for precise Higgs and other measurements	ELLIS Jonathan R.
174	Physics at a High-Luminosity LHC with ATLAS (Update)	ATLAS COLLABORATION The
175	On the Relation of the LHeC and the LHC	KLEIN Max
176	Higgs cross sections in pp collisions at very high energy	MANGANO Michelangelo
177	CMS at the High-Energy Frontier	CMS COLLABORATION The