Accelerating Science and Innovation

Introduction
Science
A Forward Look
Introduction

Accelerating Science and Innovation

CERN
The Mission of CERN

- **Push back** the frontiers of knowledge
  
  E.g. the secrets of the Big Bang … what was the matter like within the first moments of the Universe’s existence?

- **Develop** new technologies for accelerators and detectors
  
  Information technology - the Web and the GRID
  Medicine - diagnosis and therapy

- **Train** scientists and engineers of tomorrow

- **Unite** people from different countries and cultures
CERN was founded 1954: 12 European States “Science for Peace”

Today: 21 Member States

- 2300 staff
- 1600 other paid personnel
- 10500 scientific users

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

States in accession to Membership: Romania, Serbia

Applicant States for Membership or Associate Membership:
Brazil, Croatia, Cyprus, Pakistan, Russia, Slovenia, Turkey, Ukraine

Observers to Council: India, Japan, Russia, Turkey, United States of America; European Commission and UNESCO
Breaking the Walls between Cultures and Nations since 1954

Science is a universal language
CERN: Particle Physics and Innovation

- **Interfacing** between fundamental science and key technological developments

- **CERN Technologies and Innovation**
  - Accelerating particle beams
  - Detecting particles
  - Large-scale computing (Grid)
Combining Physics, ICT, Biology and Medicine to fight cancer

**Hadron Therapy**

- Leadership in Ion Beam Therapy now in Europe and Japan
- >70,000 patients treated worldwide (30 facilities)
- >21,000 patients treated in Europe (9 facilities)

**Imaging**

- Clinical trial in Portugal for new breast imaging system (ClearPEM)

**Detecting particles**

- Accelerating particle beams
  - ~30,000 accelerators worldwide
  - ~17,000 used for medicine

**PET Scanner**

- Example: Medical applications
- Example: PET Scanner
- X-ray, Protons, light ions

- Brain Metabolism in Alzheimer's Disease: PET Scan
Science
Particle Physics at CERN: Experiments and Theory
Main emphasis: High energy frontier, i.e. LHC and beyond
But: rich program of accelerator based particle physics

LHC: 27 km circumference
The Particle Physics Landscape at CERN

**High Energy Frontier**

*LHC*

**Hadronic Matter**
deconfinement
non-perturbative QCD
hadron structure

**Low Energy**
heavy flavours / rare decays
neutrino oscillations
anti-matter

**Non-accelerator**
dark matter
astroparticles

**Multidisciplinary**
climate, medicine

Non-LHC Particle Physics = o(1000) physicists / o(20) experiments

In the past few years

Several breakthroughs !

Steady progress of other programs

New mid-term and long-term projects started or in discussion

C. Vallee SPC-274

Non-LHC Particle Physics at CERN 10
AD (current situation)

Antiproton decelerator

1. Antiproton production
   \(10^{13} p @ 26 \text{ GeV/c}^2\)

2. Injection at 3.5 GeV/c

3. Deceleration and cooling
   (3.5 - 0.1 GeV/c)

4. Extraction
   \(\approx 2 \times 10^7\) in 200 ns

AEgIS
ATRAP
ASACUSA
ALPHA

0 10 20 m

Electron cooling

Stochastic Cooling
Spectroscopy with trapped antihydrogen?

Antihydrogen atom trapping time

Spectroscopy: HFS via microwave

but: B-field varies strongly over trap

(ALPHA) 2012

Next steps: better cooling, more atoms, laser spectroscopy
increasing & continuous demand for antiprotons, current methods for trapping them are very inefficient

➔ ELENA (will start 2017)

• dramatically slows down the antiprotons from the AD
• increases the trapping efficiency x 100
• allows 4 experiments to run in parallel
High Energy Frontier

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Several breakthroughs !
Steady progress of other programs
New mid-term and long-term projects started or in discussion
First $\nu_\tau$ Candidate

Data taking now terminated, analysis still ongoing. Area at CERN used for new experiment (AWAKE).

Up to now: 4 tau-candidates seen (one hadronic decay)

Muonless event 9234119599, taken on 22 August 2009, 19:27 (UTC) (as seen by the electronic detectors)
The Particle Physics Landscape at CERN

High Energy Frontier

**LHC**

Hadronic Matter
- deconfinement
- non-perturbative QCD
- hadron structure

Low Energy
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- anti-matter

Non-accelerator
- dark matter
- astroparticles

Multidisciplinary
- climate, medicine

Non-LHC Particle Physics = o(1000) physicists / o(20) experiments

In the past few years

Several breakthroughs!

Steady progress of other programs

New mid-term and long-term projects started or in discussion
Research with radioactive nuclides

More than 700 nuclides of over 70 chemical elements delivered

Techniques: all available at ISOLDE

Upgrade underway: HIE-ISOLDE

Nuclear physics and atomic physics

Material science and life sciences

Fundamental interactions

Nuclear astrophysics

Neutrons
Protons

Laser spectroscopy
Beta-detected NMR
NMR
Ion traps
Decay spectroscopy
Laser spectroscopy
Coulomb excitation
Nucleon transfer reactions

Transition probability
Spin, parity
Half-life
Mass
Decay pattern

Circle chart highlighting: TOF, (126) Sn, (50) Ca, (28) Cu, and (20) Co.
n_TOF physics

100 members, 32 institutions

Nuclear technologies

Nuclear Astrophysics

Medical applications

Basic Nucl. Phys.

FF Ang. Distribution

237Np, 234,235,238U

Fission

240,242Pu, 235U

Neutron capture

25Mg, 88Sr, 93Zr, 235U

(n,chnp)

10B, 27Al, 33S, 59Ni,

Experimental Area 2 (EAR2) ready in 2014

- New vertical line for neutrons and target at shorter distance than in EAR1
- Neutron fluence 20x larger than in EAR1 but lower resolution due to shorter TOF
Accelerating Science and Innovation

Energy Frontier

LHC
The study of LHC data will allow us to answer some of the key questions ...

Will we understand the **primordial state of matter** after the Big Bang before protons and neutrons formed?

Have we found the **Higgs particle** that is ‘responsible for giving mass’ to all particles?

Will we find the reason why **antimatter and matter did not completely destroy each other**?

Will we find the **particle(s)** that make up the mysterious ‘dark matter’ in our Universe? And what’s ‘dark energy’?
2010: a New Era in Fundamental Science

Exploration of a new energy frontier
Proton-proton and Heavy Ion collisions
at $E_{CM}$ up to 14 TeV

LHC ring:
27 km circumference

CMS
LHCb
ALICE
LHCF
TOTEM
MOEDAL
ATLAS
LHC Experiments → complementary

Specialised detector to study b-quarks → CPV

General purpose detectors

Specialised detector to study heavy ion collisions
LHC Experiments → complementary

Overlap in physics reach

Key feature: reconstruct secondary vertex

CMS

ALICE

ATLAS

LHCb

ATLAS

LHCb
LHC Experiments \(\rightarrow\) complementary

Overlap in physics reach

Key feature: reconstruct > 20’000 charged tracks in one event
Versatility of LHC & complementarities of experiments make the whole of LHC a more powerful instrument than the sum of its parts.
LHC run 1 at 7 and 8 TeV

a great success

p-p / Pb-Pb / p-Pb

Discovery of a Higgs-boson, messenger of the BEH mechanism
S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
- B is integral of background model over a constant signal fraction interval
Evolution of the excess with time

[Graph showing the evolution of the excess with time for different periods and energy levels.]

**ATLAS**

$\sqrt{s} = 7$ TeV (2011), $\int L dt = 4.8$ fb$^{-1}$

$\sqrt{s} = 8$ TeV (2012), $\int L dt = 5.9$ fb$^{-1}$

07/11 EPS Prel.
- Observed
- Expected

12/11 CERN Prel.
- Observed
- Expected

Spring 2012 PRD
- Observed
- Expected

04/12 CERN Prel.
- Observed
- Expected

PLB 07/12
- Observed
- Expected

$m_H$ [GeV]
The new particle is a Higgs boson

ATLAS and CMS have verified the two “fingerprints”

1) To accomplish its job (providing mass) it interacts with other particles (in particular W, Z) with strength proportional to their masses

2) It has spin 0, it is representing a scalar field

It completes the Standard Model, thus describing ~5% of the Universe

What about the “Dark Universe”?

The detailed study of the properties of this Higgs Boson could give

… information on Dark Matter
… first hints on Dark Energy
Strong evidence for fermionic ($\tau\tau$) decays of the Higgs boson, at the 4.1$\sigma$ level

Confirms and strengthens previous evidence from CMS (3.4$\sigma$ excess at 125 GeV combining $bb$ and $\tau\tau$), now updated to combined 4.0$\sigma$ excess

Our new boson decays to fermions as well as to bosons!

published (Nature)  preliminary
LHCb 2012:

The search for $B_s (d) \rightarrow \mu \mu$

Predicted to be very rare in SM due to GIM & helicity suppression:

Precise predictions in SM:
- $\text{BR}(B_s \rightarrow \mu \mu) = 3.5 \pm 0.2 \times 10^{-9}$
- $\text{BR}(B_d \rightarrow \mu \mu) = 1.1 \pm 0.2 \times 10^{-10}$

“Golden channel” for New Physics effects

$$\text{Br}_{\text{MSSM}}(B_q \rightarrow \ell^+ \ell^-) \propto \frac{M_b^2 M_\ell^2 \tan^6 \beta}{M_A^4}$$

With 2011+2012 data (2.1/ fb) LHCb has got the first evidence of $B_s \rightarrow \mu \mu$ decay at $\sim 3.5 \sigma$

$$\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

in agreement with SM.

“Background only” $p$ value $\sim 5 \times 10^{-4}$

Also best limit on $B_d \rightarrow \mu \mu$

$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 9.4 \times 10^{-10} \text{ at } 95\% \text{ CL}$$
The study of LHC data will allow us to answer some of the key questions ...

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Have we found the **Higgs particle** that is ‘responsible for giving mass’ to all particles?

Will we find the reason why **antimatter and matter** did not completely destroy each other?

Will we find the **particle(s)** that make up the **mysterious ‘dark matter’** in our Universe? And what’s ‘**dark energy**’?
Low $p_T$ direct photons → a direct thermometer for the temperature of the fireball

Integrated over fireball history: $T = 304$ MeV
initial temperature $> 450$ MeV
highest temperature ever measured in the laboratory

around $3.5 \times 10^{12}$ K
Results keep flowing

- A huge scientific output
  - 77 ALICE papers on arXiv

- **High impact papers:** the top cited paper at the LHC after the Higgs discovery ones is the ALICE paper on flow in HI collisions, and out of the 10 top cited physics papers at the LHC 3 are from ALICE and one from ATLAS-Heavy Ion program (source: ISI)

- **Several hundred** presentations at international conferences *each* year
1) We have **consolidated** the Standard Model
(wealth of measurements at 7-8 TeV, including the rare $B_s \rightarrow \mu\mu$ decay, very sensitive to New Physics)
→ it works BEAUTIFULLY …

2) We have **completed** the Standard Model: Discovery of the messenger of the BEH-field, the Higgs boson discovery
(over 50 years of theoretical and experimental efforts !)

3) We found interesting properties of the hot dense matter

4) We have no evidence of new physics (YET)

What’s next ?
LS 1 from 16th Feb. 2013 to Dec. 2014

- LHC
- SPS
- PS
- PS Booster

Available for works:
- Physics
- Beam commissioning

- Shutdown
- Powering tests
The main 2013-14 LHC consolidations

Opening: 100% 1695 Openings and final reclosures of the interconnections Closure: 100%

1. Opening 100% done
   Complete reconstruction of 3000 of these splices
   18th June

2. Consolidation 100% done
   Consolidation of the 10170 13kA splices, installing 27000 shunts

3. Installation 100% done
   Installation of 5000 consolidated electrical insulation systems

4. Measurements 100% done
   300 000 electrical resistance measurements

5. Orbital 100% done
   10170 orbital welding of stainless steel lines

6. Leak 80% done
   10170 leak tightness tests

7. Tests 90% done
   18 000 electrical Quality Assurance tests

8. Magnets 3 quadrupole magnets to be replaced

9. Replacement 15 dipole magnets to be replaced

10. Pressure 100% done
    612 pressure relief devices to bring the total to 1344

11. Feedboxes 98% done
    Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

12. Feedboxes Completed
post- $H(126)$-discovery

- Good reasons to expect more
  - We have really just begun the searches
  - Much space has yet to be accessed
  - And there are important new physics models yet-to-be invented
- Precision and rare physics
  - Beyond our direct production reach
    - LHC is a superb intensity frontier machine
- Investment
  - Powerful detectors, triggers, computing
    - A sustained period of important results
    - And practical applications

**The LHC is the only Higgs, (top, Z, W...) factory on the planet for many years to come!**
LHC --> HL-LHC: *THE* Higgs factory

- Measure as many Higgs couplings to fermions and bosons as precisely as possible
- **Measure Higgs self-couplings** (give access to $\lambda$)
- Verify that the Higgs boson fixes the SM problems with W and Z scattering at high E

Today: ATLAS+CMS have 1400 Higgs events
HL-LHC: $(3000\text{fb}^{-1}) > 3\text{M}/170\text{M}$ useful for precise measurement

Couplings
- $ttH$  → $\gamma\gamma$
- $H$  → $\mu\mu$

Self-coupling
- $g_{HHH} \sim \lambda v$

Difficult measurement precision $30\%$? for $3000\text{fb}^{-1}$

Access to rare processes

Vector boson fusion
- Check if Higgs does the (whole) job of cancelling divergences

x 1.5 to 2 for $300 \rightarrow 3000\text{fb}^{-1}$

Fabiola:
High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.

*Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*
Strategic Plan for U.S. Particle Physics

- Charge: A strategic plan, executable over 10 years, in the context of a 20-year global vision
- US community has come together to make a plan
  - Driven by the science
  - Meets fiscal
  - Considers the global context
- Recommendations in line with the European Strategy
  - Resolves key issues for the field
  - Provides a continuous flow of results while making essential investments for the future
From the P5 report

**Recommendation 10:**
Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.
**LHC schedule beyond LS1**

**LS2** starting in **2018 (July)**  
=> 18 months + 3 months BC

**LS3** LHC: starting in **2023**  
=> 30 months + 3 months BC

**Injectors:** in **2024**  
=> 13 months + 3 months BC

### 2015 - 2021

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**The CERN LHC Roadmap**
There is a program at the energy frontier with the LHC beyond 2030:
- 7 and 8 TeV (essentially done)
- 14 TeV design luminosity
- 14 TeV high luminosity (HL-LHC)

Upgrades to accelerator complex, detectors, and computing Grid are vital to fully exploit the physics potential of LHC.
Energy Frontier
Beyond LHC

Accelerating Science and Innovation
d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*
European Strategy: “CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines.”

FCC Study: p-p towards 100 TeV

Kick-off meeting: February 2014
(Univ. Geneva)
Future Circular Collider Study - SCOPE CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- **pp-collider (FCC-hh)** → defining infrastructure requirements
  - $\sim 16$ T ⇒ $100$ TeV $pp$ in $100$ km
  - $\sim 20$ T ⇒ $100$ TeV $pp$ in $80$ km

- **$e^+e^-$ collider (FCC-ee)** as potential intermediate step

- **$p$-$e$ (FCC-he)** option

- **80-100 km infrastructure in Geneva area**
CLIC near CERN

Conceptual Design Report published

R&D continues (accelerator and detector) in the framework of the LC effort and the CLIC collaboration (e.g. high gradient accelerating structures)
High-priority large-scale scientific activities

At CERN ILC efforts continue in the framework of the LC efforts.

Hosting LCC Director(ate) at CERN

There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation.
Linear Collider(s)

Continue working on the technical design report for CLIC and common research on ILC (machine and detectors)

**P5 Recommendation 11:** Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should **engage in modest and appropriate levels of ILC accelerator and detector design** in areas where the U.S. can contribute critical expertise. **Consider higher levels of collaboration if ILC proceeds.**

This parallel research (CLIC and ILC) aims to be ready to decide on the way forward at the time of the next European Strategy update (around 2018)
Intensity Frontier

Accelerating Science and Innovation
High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector.

*CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*
Neutrino Platform

Create a platform to pave the way for a European contribution in a neutrino facility in the US or Asia

Financial scenario with an allocation to allow for
- Extension of the experimental area of the SPS complex (North Area)
- (liquid argon) detector R&D for neutrino experiments
- Preparing detectors at CERN for transport to US

P 5 Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. **LBNF is the highest-priority large project in its timeframe.**
Accelerating Science and Innovation

Diversity
European Strategy for Particle Physics

A variety of research lines at the boundary between particle and nuclear physics require dedicated experiments. The CERN Laboratory should maintain its capability to perform unique experiments. CERN should continue to work with NuPECC on topics of mutual interest.

- Honor ongoing obligations at unique facilities
  - Na61, Na62
  - N_Tof area 2
  - HIE-ISOLDE construction
  - ELENA construction including consolidation of the AD facility
  - Maintain experimental areas for fixed-target experiments
Conclusion

With the European Strategy, approved by Council May 2013, with the P5 recommendations, approved by HEPAP in the US, with the Japanese roadmap

we have (for the first time) a global vision for our field going beyond regional boundaries

CERN is playing a major role in this global endeavour