IN2P3 contribution for the update of European Strategy for Particle Physics

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Abstract:

The "Institut de Physique Nucléaire et de Physique des Particules" (IN2P3) comprises 25 laboratories located in major universities. IN2P3 is in charge of coordinating nuclear, particle and astro-particles physics in France. The number of people working at IN2P3 is 3200, about half of them PhDs. This represents 600 CNRS physicists, 400 professors from universities and 1500 engineers, technicians and administrative staff. This document contains two parts: an executive summary and the main contributions from IN2P3 physicists.

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Executive Summary

The understanding of electroweak symmetry breaking, of the origin of CP violation, of strong interactions and of the neutrino sector, and the ability to explore physics beyond the standard model at the energy frontier, are the key ingredients which should primarily be addressed by this update of the European Strategy for Particle Physics.
In order to continue to play a leading role in this field, Europe should engage in a dedicated and focused R&D program in view of building a new accelerator, which will take-over the HL-LHC around the end of the 2030's. At this stage, the most promising and yet achievable project is the Future Circular Collider, with an e^+e^- option to start with, which would be operated before the hh collider. The FCC project would have to be planned and organised as a world project. A new e^+e^- collider targeting Higgs physics is largely supported by IN2P3 particle physicists. In case of a positive announcement by the Japanese government regarding the ILC project, we recommend establishing a strong European participation in the experimental program. The ILC will be a complementary machine to the HL-LHC and the European contribution to the ILC would therefore have to be compatible with maintaining Europe's full capacity to host the FCC. The same applies if another e^+e^- project is launched by China. More specifically, we would like to provide the following recommendations in each domain.

SM and BSM physics at the high energy frontier:

- Ensure the success of the HL-LHC, i.e., the upgrade of the machine, the detectors and the exploitation of the data with a special attention to computing aspects.
- Support the building of an e^+e^- collider running at the Higgs production resonance. This machine should be upgradable to higher energies in order to reach the top pair production, as well as the associated top and Higgs production thresholds.
- Support accelerator R&D toward a project at CERN after the HL-LHC. In order to plan for a FCC-hh, it is essential to continue a strong R&D program on high field magnets, in particular high temperature superconducting magnets. Further R&D on improved accelerating concepts should be supported (energy recovery linac, muon colliders, laser plasma acceleration).

Flavour physics and the intensity frontier:

- Exploit the two large-scale facilities with a wide flavour physics programme, LHCb and Belle-2, which are in particular expected to provide further insights into the nature of the current flavor anomalies.
- Pursue a long-term intensity frontier physics programme with possibly upgrades of LHCb and/or Belle-2 experiments, a FCC-ee running at the Z pole and beam dump experiments or upgrades of experiments searching for long-lived particles.
- Support experiments dedicated to specific measurements of fundamental observables, in particular Electric Dipole Moments and Lepton Flavour Violation.

Neutrinos physics:

- The neutrino platform at CERN is a unique facility in the world. This facility and its access to European physicists should be strongly supported in order to keep leadership in neutrino detector R&D.
- Develop and support a strong European participation in the DUNE project in the US; in particular, the involvement of European teams in the construction of dual phase detectors.
- Support T2K in Japan and the upgrades of its near detector, as well as possible contribution to the planned T2Hyper-K experiment.

Exploring QCD Matter:

- Exploit LHC run 3 & 4 to characterize with high precision QCD matter beyond the QGP phase transition at zero baryon density and search for the origin of collective effects.
- Investigate the possibilities offered by possible upgrades of existing experiments and facilities, as well as the building of new facilities beyond 2030 to further explore the QCD phase diagram and the conditions for the QGP phase transition.

The European strategy should also address the following items, which are important for the development of particle physics:

- Continue to support innovative and high quality programs in theoretical physics.
- Support experimental search for dark matter, and experiments aiming at characterizing dark energy
- Develop stronger ties with gravitational waves projects and particle astrophysics experiments.
- Strongly support R&D for detector developments beyond the approved programs.
- Support generic R&D for computing and software developments, essential for future projects.

Introduction

In recent years, using data from numerous facilities – high-energy, high-intensity and neutrino dedicated experiments – the validity of the Standard Model (SM) as an underlying fundamental theory has been probed. The discovery of a neutral scalar (Higgs) boson supports the SM description of electroweak (EW) symmetry breaking, and the CKM paradigm allows to predict and interpret most of the observables associated with quark flavours and CP violation. Despite its success in describing the properties of fundamental particles, and in predicting with unprecedented precision numerous observables, the SM has to be extended to explain neutrino oscillation phenomena, account for the baryon asymmetry of the Universe, and provide a viable dark matter candidate. Several theoretical puzzles (grand unification, hierarchy, fine-tuning, naturalness, completeness issues and restoration of broken symmetries in QCD) remain to be addressed. Searches for new phenomena (NP) beyond the Standard Model, either in precision measurements or via direct searches, have so far remained inconclusive.

Nonetheless, several tensions between the SM and observation have emerged – these include the proton radius, the anomalous magnetic moment of the muon, and several "anomalies" related to B-meson decays, which could suggest a possible violation of lepton flavour universality. Cosmology also provides strong motivations to search for new physics at the high-energy and at the high-intensity frontiers. If the baryon asymmetry of the Universe is explained via electroweak baryogenesis, new sources of CP violation and an enlarged scalar sector are expected be present. This strengthens the need to pursue the quest for NP, while at the same time to further probe the validity of the SM.

While direct searches at the high-energy frontier aim at discovering new particles, precision tests of the SM, as well as indirect searches for new physics at the high-intensity frontier provide crucial inputs to the nature of the new physics model. In this sense, the study of flavours (in both the quark and lepton sectors) and CP violation are expected to play a crucial role in unveiling further deviations from the SM expectations.

In the neutrino sector, many fundamental parameters and properties remain to be determined, among them the absolute mass scale, the ordering of the neutrino spectrum, the existence of CP violation in the lepton sector, and finally, the very nature of neutrinos (Dirac or Majorana). If they are Majorana fermions, neutrinos violate the conservation of total lepton number (LNV); new sources of CP violation in the lepton sector (the Dirac δ_{CP}, which can be determined in oscillation experiments, and possibly extra Majorana phases) are a further appealing possibility, as LNV and CPV are (necessary) conditions to explain the baryon asymmetry of the Universe via leptogenesis.

Many open questions also remain to be addressed in order to improve the understanding of strong interactions. The Quark-Gluon-Plasma (QGP) must be fully characterized at vanishing values of the baryo-chemical potential and the QCD phase diagram thoroughly explored and understood. Furthermore, collective-like phenomena observed in high-multiplicity proton-proton and proton-lead collisions open the road for the search of universal mechanisms at work in many-body QCD physics.

SM and BSM physics at the high-energy frontier

At high-energy colliders a two-fold approach is followed:

- Precision tests of the Standard Model: precise determination of the Higgs properties and couplings, EW measurements, tests of QCD

The current knowledge of the SM allows to make theoretical predictions for a wide array of quantities. If the measurements are in agreement with the Standard Model, increasingly stringent constraints on models of new physics can be drawn; should deviations with respect to the SM be observed, classes of new phenomenological models that are compatible with the pattern of deviations can be singled out. This requires that the electroweak precision observables be experimentally determined as precisely as possible. The determination of the strong coupling constant with an increased precision (possibly reaching the per mille level) is an important ingredient for further precision tests of the SM. For processes involving hadron initial states (as in pp collisions), a complete high-precision determination of the parton distribution functions (PDFs), is a crucial input to high-energy measurements in the Higgs sector and for the computation of multi-TeV SM and BSM cross sections.

In order to fully characterize the scalar sector, an increase of the precision of the Higgs couplings to SM gauge bosons and fermions, as well as a measurement of its width, will lead to further insight. Determining the Higgs self-coupling (trilinear coupling) is of paramount importance. The measurements of $H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$ and $H \to \gamma Z$ are crucial to test the SM; the determination calls for precise measurements of production cross-sections times branching ratios. Measuring the Higgs couplings to fermions, in particular the coupling to the 3rd family ($H \to bb$, $H \to \tau\tau$) with higher precision, as well as searching and measuring the coupling to the 2nd family (i.e. $H \to \mu\mu$) will give a more complete picture of the scalar sector.
Together with searches for rare flavour violating decays, these measurements allow to infer strong constraints on the SM flavour structure, further allowing to reveal new phenomena. Rare Higgs decays to mesons must also be searched for to fully constrain NP contributions. The modulation of the spin and CP components of the final states provides additional elements to fully characterize the Higgs interactions to both matter fermions and gauge bosons.
Invisible Higgs decays play a crucial role in relation with a possible (light) dark matter portal and neutrino physics - other than decays into SM-like $\nu\nu$ pairs, the Higgs can also decay into pairs of heavy neutral fermions. The latter includes WIMP-like DM candidates such as neutralinos in SUSY models, or heavy neutral leptons possibly involved in the mechanism of neutrino mass generation.

Current observations do not exclude the possibility that the discovered Higgs boson be the SM-like component of an extended Higgs sector. Other than the direct searches for other scalar and pseudoscalar neutral states, as well as for charged (or even doubly charged) states, rare exotic decays of the SM-like state to a pair of light (pseudo)scalars might also reveal the presence of NP.
Due to its very large mass, the top quark is a privileged messenger of NP. A precise determination of its couplings to SM fermions and bosons is crucial to reveal possible deviations from the SM expectations. Rare decays must be searched for in order to identify (or constrain) NP leading to CP violating and/or flavour violating top neutral current interactions, such as in the decays $t \to Hc$, $t \to Zq$, $t \to gq$ or $t \to \gamma q$. A precise determination of the top (bare) mass – possibly down to O(50 MeV) – will shed light SM theoretical issues such as the metastability of the EW vacuum.

- Direct searches for the new states

Searches for new heavy resonances as those predicted in extensions of the Standard Model, such as supersymmetry or extra dimensions, rely on direct production at very high energies. A wide variety of signatures can be probed at high energies, and these strongly depend on the predicted particle content, the spectrum and the couplings. The experimental sensitivity further depends on the decay pattern of the resonances.
The mass spectrum of the new states – and more crucially, the size of their couplings – might lead to NP scenarios which can be extremely difficult to unveil. For instance, the new states might be considerably light, e.g. axions, or axion-like particles (ALPs), having so far escaped detection due to their very small interactions with SM fields. Corresponding searches must then be focused on achieving a very high sensitivity to the various exotic decay modes.
Likewise, non-conventional search channels must be explored to discover “invisible” states (for example potential DM candidates): these include associate production with a single object such as mono-jet, mono-Z, mono-photon, mono-Higgs or mono-top searches. The future BSM programme must also include dedicated searches for heavy, long-lived particles (LLP), via displaced vertex signatures, or the delayed emission of photons or Z bosons. An important connection to neutrino physics might also be established from dedicated searches for heavy neutral leptons, which might be an integral part of the mechanism of neutrino mass generation. These points will be subsequently addressed in the High-Intensity section of this document.
Should new states be discovered, the reconstruction of their properties (determination of the quantum numbers, precise measurement of masses and couplings) will be paramount to identify the NP model.

Colliders

Lepton and hadron colliders are the two categories first considered here. Hadron colliders reach in general higher centre-of-mass energies where the transverse state is fully constrained. The effective centre-of-mass energy is reduced by parton distribution functions. Lepton colliders collide elementary (point-like) particles so that the full initial state is well known; they are sensitive to synchrotron radiation and/or beamstrahlung. For lepton colliders two different schemes are proposed: linear and circular. While circular colliders offer a high luminosity, which decreases with increasing energy, the luminosity delivered by a linear collider is smaller but increases as function of the beam energy. In a linear collider longitudinal polarization can be achieved which can in turn reduce the background for certain measurements and thus increase the signal strength.

The nature of the colliding beams (consisting of hadrons or leptons) also has consequences on the calculation of phenomenological predictions such as cross sections and differential distributions. In hadron machines the theoretical uncertainties on certain measurements are typically larger than at lepton colliders.

Present:

- HL-LHC: The high-luminosity upgrade of the LHC, coupled with a modest increase of its centre-of-mass energy is the top priority. A successful continuation of the LHC programme requires an investment in the upgrades of the ATLAS and CMS detectors (electronics, new trackers, calorimeters and timing detectors) as well as in the corresponding computing infrastructures, which are essential to enable an optimal exploitation of the large data sets to be delivered post-2025. The program will lead to improved precision measurements of the Higgs and top sectors and will allow to probe unexplored regions of several NP models.

Future lepton colliders:

- The ILC with a centre-of-mass energy of at least 250 GeV (Japanese government proposal) will allow to significantly improve the precision of the Higgs coupling measurements, thus complementing the LHC program. It will also measure with high precision the width of the Higgs boson. The ILC can also carry direct searches for light NP states which only have EW interactions. In order to further study the Higgs sector and the top sector with sub-percent level precision, the possibility of an energy upgrade to about 500 GeV should not be excluded.
  Extensive R&D work has been performed over the last decade (cavities, power couplers), some of which has already been used in other physics fields (XFEL). To fully exploit the ILC, which may come into operation in somewhat more than 12 years from now, a new generation of dedicated, highly granular, detectors is mandatory. Vigorous R&D is going on since many years in international collaborations to demonstrate the detector feasibility. Based on the achieved proofs of principle, these efforts ought to be pursued.
- The CLIC machine is designed for centre-of-mass energies starting at 380 GeV. It is currently the only lepton collider, which could reach the multi-TeV energy range. It can provide further insights on the Higgs sector as well as on the top sector and play an important role in direct searches for new resonances.
- The FCC-ee is a 100 km circumference circular collider at CERN. The FCC-ee could continue the comprehensive study of the electroweak scale, driven by the high luminosity at the four electroweak thresholds crossed (Z, W, H, top).
- The CEPC is a proposal to build a 100 km circumference circular collider in China. Its baseline programme includes runs at the Higgs boson resonance (240 GeV), at the Z boson resonance (91.2GeV), as well as at the W pair production threshold, continuing the study of the electroweak scale with high precision.

In addition to electron-positron colliders, R&D has been performed for a muon collider. While a muon collider allows s-channel production of the Higgs boson and extensive searches for NP (via direct production and exotic decays), such a machine remains a technical challenge.

Future hadron collider:

The FCC program comprises two machines: HE-LHC and FCC-hh. Common to both of them is the development and use of high field magnets.

  - The HE-LHC proposes to increase the centre-of-mass energy of the LHC using magnets of the same technology as developed for the FCC-hh.

- The FCC-hh is a 100 km circumference hadron collider, which requires magnets with a field as high as 16 Teslas. Its centre-or-mass energy is 100 TeV, allowing exploring a new range in the search of NP. To be able to build such a machine, an important investment in magnet development should be made.
- The SppC is also a proposal for a 100 km circumference hadron collider in China.

Beyond the needs of approved projects, it is essential to continue generic R&D developments. This includes classical acceleration schemes as well as new concepts such as Plasma Acceleration.

Flavour physics and the intensity frontier

Research at the intensity frontier allows the detection and interpretation of signs of new physics using large datasets of some of the rarest processes in nature. If new particles are found by direct searches, then indirect tests are needed to study the new physics structure and couplings. If on the other hand no direct evidence for new physics is found in collisions, which has been the case so far at the LHC, higher scales and/or smaller couplings can be probed by experiments at the intensity frontier. Lately the case for the intensity frontier has further been strengthened by several anomalies observed in measurements of rare B decays, the anomalous magnetic moment of the muon and the proton radius.
The IN2P3 physicists working on the intensity frontier support an experimental strategy based on two complementary pillars: large facilities with a wide physics program (LHC, SuperKEKB, HL-LHC) and experiments dedicated to specific measurements of crucial observables (EDM, g-2, LFV experiments). This section provides an overview of the experiments in which the IN2P3 and its partners are involved, and that IN2P3 physicists wish to see endorsed by the European Strategy for Particle Physics.

Experiments with a wide physics program

The major players in flavor physics in the upcoming years will be LHCb (and its upgrade) and Belle-II : the former exploiting the unprecedented number of b-hadrons produced at the LHC, the latter profiting from the clean e^+e^- environment of SuperKEKB. These will improve our understanding of the flavour picture, and probe new physics in a complementary way with high precision measurements of a plethora of observables, part of a well recognized physics program. In particular they will allow the clarification of the nature of the intriguing anomalies in some rare B decays via independent measurements, a priority today in particle physics. Traditionally France has strongly contributed to flavor physics. Today five IN2P3 laboratories play a major role in LHCb. Two laboratories joining Belle II was an important step towards consolidating the French involvement in this field. We fully support the exploitation of the data from LHCb, its phase I upgrades and Belle II in the next 5-10 years. In addition, Belle II will have to undergo several upgrades of detector systems before 2025, and we expect that IN2P3 will contribute to these detector developments.

For the future, we believe that the priority is to guarantee the pursuit of a long-term flavor physics program at the HL-LHC, considering that, according to the current schedule, Belle II will end its operations in 2026, and LHCb Upgrade I operations are approved until 2029. The LHCb Upgrade II is a proposal, which could be implemented during the fourth long shutdown of the LHC in 2030. It would operate at a factor 10 higher luminosity, fully exploiting the large luminosity of the accelerator, to reach unprecedented precision in key measurements, e.g. CP violation phases and b->sll and b->dll observables, probing a 90% higher new physics mass scale for fixed couplings. The LHCb Upgrade II would be the only general flavor experiment at that time horizon; it is strongly supported by IN2P3 physicists.

One way to search for new physics at the intensity frontier relies on the quest for long-lived particles (LLPs), arising naturally in many models, with masses and lifetimes that span many orders of magnitude. Both collider and beam-dump based experiments are needed to probe the large area of parameter space. Additionally, different experiments have complementary backgrounds, providing a powerful crosscheck in the event of a discovery. The strong institutional support for such experiments would be welcome whether these might be at the LHC with present detectors and new experiments (e.g. CODEX-b at LHCb) or at the SPS (e.g. SHiP).

CODEX-b will take advantage of the DELPHI cavern, located behind a concrete wall next to the LHCb experimental area. If data taking occurs throughout the LHCb Upgrade II, CODEX-b would cover a significant region of the parameter space reached by other much bigger and more expensive dedicated LLPs experiments, which have been proposed. If integrated into the LHCb readout, the rest of the event could even be analyzed by LHCb.

SHiP, in the CERN North Area, involves the dumping of a 400 GeV proton beam from SPS on a heavy target. With 2x10^{20} p.o.t. integrated in 5 years, it will probe LLPs with masses below O(10) GeV/c^2, potentially unveiling Hidden Portals e.g. dark photons, light scalars and pseudo-scalars or heavy neutrinos. The sensitivity to heavy neutrinos in the mass range between the kaon and the charm mesons will probe for the first time couplings that could also explain baryogenesis and active neutrino masses. Additionally, neutrino cross-sections and angular distributions measurements with large statistics can be performed.

In addition to SM precision tests and searches of new physics states, large colliders (such as the ILC and FCC) are also an integral part of long-term strategies for the intensity frontier. The flavour physics program of the FCC-ee in the quark and lepton sectors is an invaluable complement to the electroweak physics case, and will benefit from the unprecedented statistics at the Z pole, the large boost of the b-hadrons produced in Z decays, the cleanliness of the e^+e^- experimental environment, the production of all heavy-flavoured hadrons and the highly-resolved vertexing of heavy-flavoured weakly-decaying particles. For example, if the current flavour anomalies persist, FCC-ee will allow the analysis of the $B \to K^*\tau\tau$ decay, as well as the search for lepton flavour violating Z decays.

Experiments dedicated to specific measurements of crucial observables

IN2P3 is involved in a programme dedicated to the search for permanent electric dipole Moments (EDM), probing new physics at energy scales between 1 TeV and 10^3 TeV. Measuring a non-zero value for the EDM for any spin 1/2 particle would reveal flavor diagonal CP violation. To broaden the search for CP-violating new physics, the EDM of various systems (neutron, electrons, atoms, protons and muons) are targeted by different projects. This will allow eventually disentangling the origin of CP violation in case of a discovery in one system. For example, a non-zero neutron EDM could be induced either by genuine new physics at the multi-TeV scale or by a tiny value of the θ QCD parameter in the Standard Model. Current and future experiments are sensitive to new physics involved in the electroweak baryogenesis scenario, which form an important class of theories to explain the matter-antimatter asymmetry.

The most sensitive neutron EDM experiment to date has been performed using the ultra-cold neutron source of the Paul Scherrer Institute (PSI). The data, with a statistical sensitivity of about 10^{-26} ecm, is being analyzed. Three French laboratories are strongly involved in the project. A new experiment, n2EDM, is under construction at PSI and it will start operating in 2021, improving the sensitivity by one order of magnitude in the next decade and exploring the 10^{-28} ecm region in its second phase in 2030.

The muon g-2/EDM experiment at J-PARC sees also contributions from French physicists. Using a design different from the concurrent experiment at FNAL, it is expected to provide a new measurement for the muon anomalous magnetic moment, a quantity with one of the largest, most puzzling and durable deviations from the standard model predictions at the moment. Some technological challenges are shared with COMET (Coherent Muon to Electron Transition) at J-PARC, in which three IN2P3 laboratories are involved. COMET will improve the current limits on $\mu \to e$ conversion by two to four orders of magnitude in five years from now, with a strong impact on models predicting lepton flavor violation (LFV). LFV in charged leptons is extremely suppressed in the standard model. Nevertheless, it could be largely enhanced in some new physics scenarios, additionally motivated by the recent lepton flavor non-universality anomalies in rare B decays. COMET will provide insights complementary to those from LHCb and Belle II, the latter being particularly adapted to measure LFV processes in tau decays.

Unique experiments could be performed using low energy antiprotons. IN2P3 is involved in the projects Gbar and AEgIS to measure the free fall of anti-hydrogen in Earth's gravitational field to test the Weak Equivalence principle of General Relativity for the first time with antimatter.

A super tau-charm factory with expected luminosity two order of magnitude higher than BES III and a possibility to scan e^+e^- center-of-mass energy between 2 and 7 GeV is considered as a complementary tool for performing important measurements in flavor physics, including precision studies of τ lepton properties, rare charm and τ decays, mixing and CPV in the charm sector, properties of charmed hadrons and exotic particles.

There are other important intensity frontier experiments in which IN2P3 physicists are not directly involved, namely g-2 at FNAL; NA62, KLEVER, KOTO and KLOE for the search of rare kaon decays; BES III for the study of charmed mesons; direct axion searches; LFV experiments Mu2e, MEG and Mu3e. These are considered relevant for the field and we encourage the ESPP to endorse them as well.

Neutrino physics

The challenge of observing CP violation in the leptonic sector can be met by long baseline neutrino oscillation experiments. These experiments make use of intense ν_μ beams with detectors at short baselines to determine the beam composition, flux and cross-sections, and gigantic detectors at long baselines to measure the disappearance of ν_μ, appearance of ν_e and potentially ν_τ appearance. Changing the beam mode from neutrino to anti-neutrino allows measuring the asymmetry in the oscillation probabilities $\nu_\mu \rightarrow \nu_e$ vs $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities. Current and future searches allow precision measurements of the involved parameters of the neutrino mixing matrix and mass splittings, and current unknowns - the octant of θ_{23}, the neutrino mass ordering and the δ_{CP} phase.

Such searches are in progress with current experiments T2K in Japan and NOvA in the US which are expected to dominate the field for the next 8-10 years.
T2K has been taking data in both neutrino (since 2010) and anti-neutrino mode (since 2014) and has recently reported first hints of CP violation, excluding CP conserving values ($\delta_{CP} = 0$ or π) at more than 2σ and favoring $\delta CP \sim -\pi/2$ the maximum $\nu_\mu \rightarrow \nu_e$ appearance probability (and minimizing the anti-neutrino equivalent).
Both NOνA and T2K show a preference for the normal mass ordering, and favour large CP violation. The collaborations plan to perform a joint oscillation analysis by 2021, which should provide the best constraints on the mass ordering and CP violation.

Phase II of T2K, expected to operate from 2021 to 2026, with upgraded beamline and off-axis near detector (ND280), should be capable of arriving (assuming the current favoured value) to a significance of more than 3σ. French researchers are actively involved in T2K, and intend to continue with involvements in T2K II and upgrades of ND280. Their contributions span from R&D towards detectors for precision flux and cross-section measurements, to the development of analysis tools and finally the oscillation analysis.

To profit more from the running experiments, a better understanding of the systematic uncertainties on the neutrino fluxes and cross-sections is required. To this end, French researchers also participate to the NA61/SHINE experiment at the CERN SPS, focused on the precise measurements of hadron production for neutrino flux predictions for T2K and Fermilab experiments. Two targets have so far been measured for T2K: a thin carbon target and the T2K replica target. Including the NA61/SHINE results from the thin carbon target, has brought the neutrino flux systematic uncertainty at the far detector – SuperK - down from 25% to 10%. Recent work, using results from the T2K replica target, drop further this systematic uncertainty to 5%. Even better knowledge is needed for future experiments such as T2K-II, and new measurements are planned for future experiments Hyper-K and DUNE. NA61/SHINE is a major European contribution to the current and future worldwide neutrino program.

Currently the only financed future long baseline experiment is DUNE, which is the result of a worldwide effort, obtained by merging the European design study LAGUNA-LBNO and the US effort LBNE. European, including French, physicists have made major contributions to the design and optimization of the physics reach.
The experiment is conceived to be highly sensitive to the matter effect with a long baseline of 1300 km where Mass Hierarchy and δ_{CP} effects can be disentangled. At the far site, four modules of liquid argon TPCs each with a 10-kton fiducial mass modules will provide fine-grained tracking giving excellent identification of final state products and hence neutrino flavour and energy determination. The first two modules are planned to operate from 2024. Thanks to the wide-band high intensity neutrino (anti-neutrino) beam from Fermilab, planned to start in 2026, DUNE will make a spectral measurement, covering both the first and second oscillation maxima, allowing to unambiguously determining both the mass hierarchy and δ_{CP} at 5σ with 5 years of exposure at a δ_{CP} of $\pm\pi/2$.

IN2P3 researchers are heavily involved with the instrumental development of the dual phase technology. They have been contributing to the 3x1x1m prototype and to the 6x6x6m proto-DUNE dual phase detector at CERN. Analysis efforts are also focused on the three flavor oscillation physics, study of the selection of supernovae burst neutrinos, search for n-nbar oscillations, events reconstruction and the propagation of light in the DUNE 10 kton dual-phase module. The French accelerator groups are also willing to contribute to the production of the beam through the Fermilab-PIP-II program.
IN2P3 physicists also encourage the pursuit of Hyper-K, a proposed 187 kton water Cherenkov detector located deep in the Tochibora mine, 295 km from the J-PARC complex in Tokai, Japan. The J-PARC beam is narrow band, tuned to the first oscillation maximum at 600 MeV, matching well to the water Cherenkov detection providing excellent e/μ separation, high background rejection, and high signal efficiency. Due to its shorter baseline and lower neutrino energy than DUNE, the contribution of the matter effect is smaller, so the experiment targets the measurement of CP-asymmetry. Assuming a favourable funding decision, construction is expected to take 8 years, with start of operations at similar time scales to DUNE. Due to the different technology, baseline and beam, the experiments are extremely complementary.

As neutrino physics enters the precision era, long-baseline accelerator experiments will have excellent knowledge on the final state interactions but still a rough knowledge (with systematic uncertainties of 5% at best) on the initial neutrino fluxes and beam contaminations. Lowering the systematics to 1% would automatically improve the sensitivity to the CP phase and mass ordering. Supporting experiments and future opportunities are being explored.

ENUBET (Enhanced NeUtrino BEam for kaon Tagging) is a proposed narrow band neutrino beam featuring an instrumented decay tunnel. The objective is to obtain both a superior control of the flux and flavor composition at source and a high level of tunability and precision in the selection of the outgoing neutrinos. The project is currently in a design phase funded by an ERC grant. Such a facility could be implemented at CERN, Fermilab and JPARC for a new generation of cross section experiments in the energy range of interest for DUNE and Hyper-K with a precision on the incoming neutrino energies ranging from 8% at 1 GeV to 22% at 4 GeV.

Towards the longer term, studies are ongoing on the production of a European neutrino superbeam at the European Spallation Source. This facility would produce an almost pure ν_μ beam which coupled with a near and far detector (water Cherenkov) at a baseline of 500 km would be ideal for a CP violation search. This distance corresponds to the second oscillation maximum where the matter-antimatter asymmetry is almost 3 times higher than at the first oscillation maximum, a position which is also significantly less sensitive to systematic uncertainties. Studies, assuming current T2K-like systematics on signal and background, indicate the discovery of CP violation at the level of 5σ for 60% of possible values, and an accuracy of the δ_{CP} phase of 6 degrees for angles of 0 and 180 degrees.

Groups involved in the megaton-scale European neutrino detector KM3NeT ORCA, have also studied the physics potential of the development of a Russian neutrino beam, at the Institute for High Energy Physics at Protvino. This beam-detector combination would have the longest baseline, some 2590 km. A second phase, with beam upgrades and further densification of the ORCA detector is also being explored.

Non-accelerator experiments are highly complementary to the accelerator programme, as they allow to address open questions such as the determination of the ordering of the light neutrino spectrum, shed light on the nature of neutrinos (Dirac or Majorana), and look for the presence of light sterile states. IN2P3 physicists are involved in several experiments dedicated to exploring the above points. JUNO is a medium-baseline (53km) reactor anti-neutrino disappearance experiments which will exploit vacuum oscillations to determine, as well as precision measurements of the solar parameters, the mass ordering, whereas KM3NeT/ORCA, will exploit the matter effect with ~GeV atmospheric neutrinos. French groups are also heavily invested in experimental searches for neutrinoless double beta decays (as induced by Majorana fermions); this is the case of SuperNEMO, CUORE/CUPID and Lucifer, with R&D activities based on a variety of technologies. Currently, there is also a strong participation in STEREO and SOLID, both searching for the presence of light sterile states in short baseline oscillations at nuclear reactors.

Exploring QCD matter

The physics of ultra-relativistic heavy-ion collisions is dedicated to the study of strongly interacting matter under extreme conditions of temperature and energy density at which a new state of QCD matter is formed: the Quark-Gluon-Plasma (QGP). Theoretically, the parameters of the phase transition between ordinary matter and the QGP is calculated at vanishing values of the baryo-chemical potential, from lattice QCD, a discrete formulation of QCD.
Experimentally, the CERN-LHC heavy-ion programme extends, thanks to much larger collision energies, the QGP discovery phase initiated at CERN-SPS and continued at BNL-RHIC to an exploratory phase of the longest-lived deconfined medium with the highest energy density over the largest volume ever produced in the laboratory, at vanishing baryo-chemical potential i.e. under conditions that prevailed in the early universe. In addition, the large centre-of-mass collision energies also lead to abundant yields of hard probes such as jets, heavy-flavour particles, direct photons and electroweak bosons, opening new opportunities for exploring the properties of the QGP.

The rich sets of results obtained with LHC Run 1 and Run 2 have refined through unprecedented high precision measurements the physical picture established at RHIC: a nearly-perfect liquid with vanishing mean-free path and high color charge density and a high opacity blocking even the most energetic colored particles. Strikingly, at LHC, collective-like dynamics in high-multiplicity proton-proton and proton-lead collisions have been discovered, questioning the existence of universal mechanisms at the origin of collective patterns. These phenomena and the clarification of their origin have now become a major pillar of the interest in many-body QCD physics.

In the 2020's, the LHC integrated luminosity increase and the ambitious detector upgrades will allow us to address some key questions:

1. Is there a common origin of soft particles production from pp to AA collisions? Is the prevailing description via fluid dynamics the correct approach? What is the dynamical origin of collectivity?
2. Can signatures of chiral symmetry restoration be found and thermal radiations of the QGP be identified?
3. How can jet and jet-substructure measurements characterize medium properties?
4. Do heavy flavours participate in the medium dynamics and how do they probe the medium properties?
5. How can we progress in the precise determination of parameters calculable from first QCD principles with refined measurements of very exclusive observables?
6. What role plays the initial state of the colliding nuclei in the formation of the QGP ?

In this period, with LHC Run 3 and 4, large data samples of PbPb, pPb and pp collisions will be collected. High-multiplicity pp and pPb results, and increased precision of multiparticle correlations measurements will challenge the hydrodynamic scenario of PbPb collisions. Dilepton measurements will aim at the extraction of the thermal radiation from the QGP and the isolation of the in-medium modified spectral function of the rho meson triggered by the chiral-symmetry restoration. The study of new observables in high-p_T jets (at the TeV scale), charm- and beauty-tagged jets as well as jets in correlation with photon, W or Z, will provide insight of energy loss and fragmentation mechanism, revealing the nature of the QGP degrees of freedom. The detailed measurements of the suppression of the different quarkonium states will allow to probe different regions of the heavy-quark potential, giving information on the in-medium modification of the QCD force and on the ordering of their production through regeneration mechanisms. Accurate measurements will be performed of open heavy-flavours production down to low p_T, and on exotic charm and beauty hadrons, to better understand the transport properties of heavy quarks in the QGP. Increased luminosity in proton-lead collisions will provide precise measurements of beauty hadron productions, which are more accurately calculable in perturbative QCD, down to low p_T. At high-Q^2, the W and Z probes will be measured with much better precisions, providing unique constraints on initial state effect.

At this stage, theory developments and further synergies between theory and experimental communities will permit to achieve a comprehensive and coherent description of the QGP properties together with the collective dynamics of collisions involving light to heavy nuclei.

Beyond Run 4, in the 2030's, several opportunities at the LHC are explored in order to add new dimensions to the heavy-ion programme. Running lighter ions and lower energies at LHC will allow to explore the conditions of QGP formation. Thanks to higher luminosity, precise measurements of not-yet exploited multi-heavy quark states such as B_c as well as precise measurements of quarkonium 1P states such as χ_c will become accessible. Measurement of top-quark decays in heavy-ion environment could be exploited to study the time dependence of the energy loss mechanism. In proton-nucleus collisions, extended runs with lower mass number ions (including proton) will allow us to map collective-like effect as a function of mass and further explore the roots of collectivity.

IN2P3 teams have been active contributors to this field, since its inception. At LHC, they have a key contribution to the construction and operation of the ALICE experiment and play a leading role in several analyses. They also play a key role in the CMS and LHCb heavy-ion programmes as well as in the development of a LHC fixed-target programme and its first implementation with LHCb.

In addition to a major involvement in the exploitation of LHC Run 3 and 4, IN2P3 teams will investigate the experimental implementation of future programmes at the LHC, such as the development of a new compact silicon detector with very high momentum resolution over a broad range of p_T and particle identification capabilities, or the discussed LHCb phase 2 upgrade and its fixed-target programme, while the CMS experiment will naturally benefit from the upgrades already scheduled for pp collisions. A fixed-target programme is also under investigation within ALICE.

Possible contributions to future electron-ion colliders (EIC and LHeC), that would provide an accurate description of the partonic content of nuclei, are under discussions. The LHeC can be achieved by colliding protons (ions) circulating in the HL-LHC, HE-LHC or FCC-hh with a 60 GeV polarised electron beam. provided by a dedicated multi-pass recirculating energy-recovery linac (ERL). The conjunction of multi-pass and high current, needed for the LHeC, is very challenging and has never been proved. A demonstrator at lower energy (400-500) MeV, named PERLE@Orsay, is actually proposed, and IN2P3 teams are leading this effort.

At the frontier of large baryonic densities, the exploration of the QCD phase diagram can be performed by the already approved HADES experiment, to which IN2P3 is already contributing, and the CBM experiment, at the SIS100-FAIR-GSI facility, and the NA60+ experiment at SPS-CERN, which proposal is currently under discussion.

In the longer term at HE-LHC and FCC, with a step in collision energy of a factor 2 and 8, respectively, the properties of the QGP under new experimental conditions could be studied.

Role of theory

Theoretical predictions and interpretations, crucial for advances in the field, may involve a large variety of tools, from formal approaches to phenomenological and numerical techniques. While most theoretical activities essentially require only person-power, numerical simulations are also demanding in terms of computing power and algorithmic techniques. The interpretation of experimental results, whether this be model independent in terms of effective field theories or model dependent, serves as inspiration for model building and further leads to new ideas for experiments. Theoretical progress is clearly dependent on experiments for guidance, but inversely theoretical ideas can frame future experiments. Therefore, any strategy on the future of experimental particle physics must be accompanied by a vision concerning the support to provide to particle theory and furthermore to European initiatives promoting theory-experiment collaborations.