CEA-Irfu contribution to the 2020 update of the European Strategy for Particle Physics

This document summarizes the scientific and technological position of CEA-Irfu teams on the main projects for particle physics, including neutrino physics and QGP physics.
The achievement of the HL-LHC and its scientific exploitation is the immediate priority. The crucial question is therefore the definition of the next generation of collider able to pursue an ambitious search for new physics.

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Particle physics at future colliders

Scientific goals

In the LHC era, particle physics is facing an unprecedented situation. The Standard Model (SM) spectrum is complete and so far, there is no hint of new physics. Furthermore, the mass of the Higgs boson is such that the SM remains theoretically consistent up to phenomenally high energy scales. One can identify two main, complementary avenues: the exploration of the energy frontier in search for yet unknown new physics (NP) phenomena, and the comprehensive set of ultimate measurements at the Fermi scale. The latter includes measurements of the Higgs boson properties and couplings, as well as measurements of the properties of the top quark and electroweak vector bosons. Searches for new physics hints, such as dark matter particles, new interactions, excited fermions, new dimensions of space .., at high-energy colliders are strongly motivated by remaining open key questions.

The LHC is today the only machine at the energy frontier, and yet an extraordinary place for precision measurements. Thanks to its impressive operation and outstanding experiments, particle physics at CERN is living a golden age, with an unprecedented production of results of the highest quality in QCD, electroweak, flavor, top, supersymmetry and BSM physics. The successful completion of the HL-LHC program is the priority for particle physics in Europe, and will allow to reach in particular an impressive level of precision. The electron-proton option for the LHC would help to reduce the theoretical uncertainties on electroweak measurements.

However, given the timescales involved, it is vital for Europe and CERN to decide on which major project to invest next.

Going beyond 14TeV in proton-proton collision is mandatory to extend the direct new physics reach, to elucidate the electroweak symmetry breaking sector at the TeV scale, and to perform measurements of the Higgs self-coupling and the top Yukawa coupling. With twice the energy of the LHC and five times its luminosity, HE-LHC presents a solid physics case.

A 100-TeV pp collider (FCC-hh) represents the ultimate energy frontier mankind can envision with affordable tunnel size and foreseeable magnet technologies. The potential of such a machine is immense, but a complete physics case can only be built once the TeV scale has been explored and a certain confidence has emerged that NP is within reach of such a machine.

The energy scale at which NP might be expected could result from ultimate precision measurements performed at electron-positron (e^+e^-) colliders. The choice between linear and circular (e^+e^-) colliders depends on priorities that reflect different questionings. The anticipated precisions on Higgs coupling measurements are similar, but otherwise, the physics cases for linear and circular colliders are complementary.

In particular, circular collider projects insist on the utter importance of ultimate precision measurements that are needed to complete the global electroweak fit, which can only be performed at circular colliders thanks to ultra-high luminosity and beam energy control at the Z pole and WW threshold. A circular e^+e^- collider (FCC-ee), with an energy reach extended to the top quark pair production threshold, is a promising and ambitious project.

Having a machine ready to deliver physics not later than 5 years after the completion of HL-LHC requires to take decisions by the timescale of the next European Strategy Update. The FCC-ee/FCC-hh scenario provides the broadest range of opportunities but presents the weakness of postponing the exploration of beyond-LHC energies in pp collisions at CERN to the 2060s.

CEA involvement in present and future collider projects

The Large Hadron Collider (LHC) is the only running high-energy proton-proton and heavy ion collider. Its stunning success relies on the existing complex of accelerators and infrastructures at CERN, which is now the main laboratory for high-energy physics in the world. For more than thirty years, CEA has contributed to all phases of the LHC project, from design to commissioning, on both accelerator and detector sides, and is involved in the physics harvest.

On the detector side, CEA-Irfu is now focusing on upgrades of the ATLAS and CMS detectors for the high-luminosity phases of the LHC. For the ATLAS phase-I upgrades, CEA-Irfu is involved in the production of large Micromegas detectors for the New Small Wheels of the muon spectrometer and in the production of the new digital level-one trigger board of the liquid argon calorimeter. CEA-Irfu contributes to LAr and muon spectrometer phase-II upgrades and will host a clean room facility for the assembly of modules of the new pixel detector. For the CMS phase-II upgrades, the main project is the design, production and qualification of new very front-end electronics for the barrel ECAL. CEA-Irfu also participates in the design of a high-speed electronics for the new high-granularity end-cap calorimeters, and a clock distribution system that can be extended to a novel timing detector inserted between the tracker and the calorimeters.

To reach higher energies at future colliders, CERN and its partners, including CEA, are developing the next generation of magnets based on niobium-tin, a superconducting metallic chemical compound that can sustain twice higher fields than the present LHC dipole magnets. Recently the FRESCA2 prototype, a 1.5-m long magnet with 100-mm aperture developed in the framework of the European EuCARD programme, has reached a record magnetic field of 14.6 T. This is an important step towards the development of future 16 T dipole magnets using niobium-tin and perhaps high critical temperature (HTS) superconductors.

These 16-T dipole magnets are meant to equip the next generation high-energy hadron collider at CERN, which would be hosted either in the LHC tunnel (HE-LHC) or in a new tunnel 100 km in circumference (FCC-hh). The latter would necessitate detectors capable of covering the physics at 100 TeV and performing in unprecedented conditions. FCC-hh detector design is already ongoing at CERN and its partners, including CEA.

The International Linear Collider (ILC) is an advanced electron-positron linear collider project. The decision process for its construction is dependent on a statement from the Japanese government on the intent to host the ILC in Japan as an international project. In case of a positive decision, based on its experience gained with the successful E-XFEL construction, CEA-Irfu is expected to contribute in particular to the cryo-module assembly as part of a European contribution. On the detector side, CEA-Irfu could capitalize on R&D programmes carried out over a decade on Micromegas readout, electronics and dual-phase CO_2 cooling for the TPC central tracker, and on CMOS active sensors for the pixel detector. The recognized expertise in the design of large superconducting magnets (ATLAS, CMS) could lead CEA-Irfu to participate in the design of the ILD detector solenoid.

The challenges of neutrino physics

Neutrinos play a special role in the Standard Model as they are the only neutral elementary fermion. The discovery of neutrino masses indeed requires an important addition to the minimal version of the Standard Model: either new particles (like new neutrino states) or new interactions are necessary to explain this mass term. The exciting perspective of these future discoveries motivates a renewed interest in neutrino physics reaching out in several directions.

The most obvious direction for further investigation is the precision measurement of the lepton flavor, namely the parameters governing the oscillation, the mixing angles and the neutrino masses. While the quark flavor sector with the CKM matrix has been studied in depth to high precision, the corresponding PMNS matrix in the neutrino sector deserves to be fully explored and tested.

Long baseline experiments

In the investigation of the PMNS matrix, the long baseline experiments play a leading role. Indeed, they are the only way to probe CP violation effects related to the PMNS phase δ. Leptogenesis, based on CP violation in the lepton sector at very high scales, is today the most plausible model to explain the baryon asymmetry in the Universe.

The current generation of experiments, T2K and NOVA, has already provided the first evidence of the θ_{13} mixing angle being non-zero, a precision measurement of the θ_{13} mixing angle and the first indications concerning the neutrino mass ordering. They have also provided tantalizing indications of CP-violating effects. This would be the first evidence of a new source of CP violation in Nature beyond the CKM matrix.

Both experiments will continue to take data in the next years. T2K phase II will extend until 2026 and might provide 3σ evidence for CP violation for 36% of the phase space.

To meet the challenge of that measurement, the T2K collaboration has launched an upgrade of its near detector ND280. CEA-Irfu has already made a major contribution to the three large TPCs equipped with Micromegas, a pivotal detector for ND280. Today CEA-Irfu is strongly committed to this upgrade and will provide in collaboration with CERN the innovative resistive bulk Micromegas detectors for the readout of the two High-Angle TPCs.

For the preparation of the DUNE experiment, CEA-Irfu is playing a major role in the R&D and construction of the ProtoDUNE-Double Phase (ProtoDUNE-DP) prototype. It has designed, procured and installed all the Large Electron Multipliers (LEMs), the charge amplification devices for the 600 tons ProtoDune-DP that will be commissioned at CERN in early 2019. Based on that experience, CEA-Irfu proposes to build a large fraction of the LEMs for a Double Phase DUNE 10-kt module, to be deployed in SURF (South Dakota) around 2024. CEA-Irfu is in addition strongly interested by a possible contribution to the construction of a superconducting Linac (PIP-II project).

The Hyper-Kamiokande project offers complementary technology and sensitivity to DUNE for what concerns the CP violation reach. Hyper-Kamiokande will also provide unprecedented detail on the neutrino burst of the next possible core-collapse supernova in our galaxy and offer a window on GUT physics with a high sensitivity for proton decay. CEA-Irfu physicists may contribute to this project.

The search for new neutrino states

At the moment theory gives no indication on the mass scale of possible new neutrino states that would be singlets under the Standard Model gauge group and therefore "sterile". Since several decades investigations have been focused on the eV scale, in connection with some experimental anomalies, mainly the LSND anomaly and the reactor anomaly. These investigations are continuing, with a strong activity in the search for very short baseline oscillations at nuclear reactors. CEA-Irfu is playing a leading role in the STEREO experiment at ILL Grenoble. The important short baseline experimental program at FERMILAB will also contribute to shed light on these anomalies.

The nature of neutrinos

The neutrino, the only elementary neutral fermion, could acquire a mass term through a totally different mechanism, first studied by Majorana. This mass term could also explain the smallness of neutrino masses. In this case, lepton violation processes could occur, for instance in the neutrino-less double beta decays. CEA-Irfu is active in several R&D: one of these aims at developing new enriched scintillating bolometers for the next-generation experiment CUPID to search for this decay. After the R&D phase, a technology will be selected for a large experiment.

Synergies at the European level

Throughout the different neutrino experiments several common techniques and methods have emerged. In France, the Neutrino Groupement de Recherche (GdR) is the forum where neutrino physicists regularly meet, present their recent results and have fruitful discussions.

In the few years since the last European strategy document, the CERN Neutrino Platform has emerged as an important hub for European physicists involved in this field. It supports the European physicists active in experiments in USA and Japan. One of its roles is to help the R&D on future neutrino detectors.

Another common effort is emerging around a new reliable model for neutrino-nucleus interactions, as the next generation long baseline experiments will require an unprecedented control of systematic uncertainties at the percent level.

This effort for precision models and measurements is developing at the phenomenological level but requires also the development of supporting experiments. These comprise:

- precision hadroproduction experiments like NA61-SHINE;
- accelerators for very intense beams, as well as the related targetry and instrumentation;
- innovative detector R&D for superior performance in near detectors;
- ancillary experiments for neutrino cross-section determination.

CEA-Irfu is already playing an important role in several of these avenues and will continue to do so in the next years.

Quark-Gluon Plasma studies

Collisions of heavy ions at high center-of-mass energies per nucleon pair are used to study the deconfined phase of nuclear matter, the Quark-Gluon Plasma (QGP), which is achieved at extreme conditions of temperature and density. The study of the QGP in the laboratory could provide important insights to the evolution of the early Universe as well the dynamics of neutron stars. Past and ongoing experimental programs at BNL-RHIC and CERN-LHC, have allowed important progress in the understanding of the strongly coupled QGP. Studies of heavy quarks such as charm and beauty, as probes of the QGP, have played a major role in these studies. On the one hand, they have proven the suppression of primary produced quarkonia by interactions with the QGP constituents. On the other hand, the regeneration of quarkonia by recombination of deconfined charm quarks in the QGP has been unveiled. Last but not least, studies of proton-proton and proton-lead collisions, besides providing crucial constrains to theoretical models and necessary input for lead-lead studies, have also revealed striking features. Indeed, collective effects, which in lead-lead collisions were attributed to the early thermalization of the dense medium, are also seen in small systems such as proton-proton and proton-lead collisions, at high-multiplicity.

CEA-IRFU involvement in past, present and future QGP projects

CEA-Irfu has played major roles in this field at both RHIC and the LHC, where CEA-Irfu is among the main contributors to the muon spectrometer of the ALICE experiment and related analyses. CEA-Irfu is also one of the driving forces of the major upgrades ALICE is performing in view of ten-fold increase of luminosity in lead-lead collisions for the LHC Runs 3 and 4. The CEA-Irfu team will exploit the upgrade of the muon spectrometer and the addition of the new pixel-based forward tracking device MFT, to continue investigating the properties of the QGP. The key objectives can be summarized as: (i) study of the in-medium modification of the QCD force, (ii) properties of the transport of heavy quarks in the QGP, and (iii) hadronization mechanisms. Extended running time in proton-proton and proton-lead collisions will also allow exploring collective phenomena in small systems.

ALICE beyond Run 4

Beyond LHC Run 4, in addition to further increasing the integrated luminosity, it appears essential to exploit the flexibility of the machine in producing collisions with lighter ions or at lower energies as well as to develop a fixed-target program. In the heavy-quark sector, the under- exploited probes like multi-heavy-quark states could finally be addressed. The ideal detectors to pursue these investigations have to be cautiously studied. In the longer term, the very high collision energies foreseen at HE-LHC or FCC, could open up thermal charm production. Also, the increased production cross section of beauty and anti-beauty pairs could lead to significant regeneration of Y. The properties of such a qualitatively different QGP could be studied.

Electron-Ion Collider

The context of US scientific strategy is highly favorable to the construction of an EIC. In 2015 the Nuclear Science Advisory Committee emitted a positive recommendation. In 2018 the Consensus Study Report by the National Academy of Sciences recognized an EIC as a unique facility in the world that would uniquely address profound, fundamental questions about nucleons and their assembly into nuclei of atoms, and would push the frontiers of accelerator science and technology. EIC could start operating around 2030. EIC would achieve two world premieres: being the first electron-nucleus collider and being the first polarized electron - polarized proton collider. Scientific topics include for instance the study of the gluonic content of the nucleon including its 3D imaging, the study of the gluonic-saturated matter at low-x, which is essential to understand the initial state of the QGP studied at ALICE, the measurement high-x quark PDF essential to BSM searches at the LHC.

CEA-Irfu involvement

Based on its experience at Jefferson Lab and COMPASS, CEA-Irfu teams have been deeply involved in the EIC project since its inception, both in the definition of the physics case concentrating on the 3D nucleon imaging possibilities of this future machine, and in the R&D on novel tracking chambers for the central region of the EIC detector. Physics topics linked to the study of the initial state of the QGP provide the link with the QGP group working at ALICE.

In summary, the EIC project is clearly the ultimate cold-QCD machine, both as a support of LHC physics but also for its striking capability to revolutionize hadronic physics achieved at Jefferson Lab, COMPASS and HERA in the past.

Conclusion

In the next decades, a deep understanding of the fundamental laws of the Universe requires, for what concern particle physics, to scrutinize the Standard Model with high precision measurements, to search for new physics at the energy frontier, to address the different questions raised in the neutrino sector, and to continue the study of strong interactions in particular through QGP experiments. The CERN role in the achievement of this scientific roadmap is crucial.

The HL-LHC program is the immediate priority of the community. CEA is fully committed to its technological and scientific success. The European Strategy update for particle physics should be focused on the definition of the next ambitious collider based at CERN, involving all the actors around the world. This task requires a detailed comparison of all the options in terms of achievable precision on branching ratios and of new physics energy range either directly produced or indirectly explored via precision measurement. The definition of such a project should start when the European Strategy is presented, in order to be ready within 15 years from now. The Future Circular Collider, starting with an e^+e^- option reaching high luminosities and allowing impressive precision measurements, followed by a h-h collider, is a promising scenario, even if it would postpone the high energy physics to a long term horizon. If such a project cannot be achieved, the HE-LHC project should be considered with interest. Finally, the European community should play a key role in the possible collider projects outside Europe (ILC, CEPC), possibly under the CERN umbrella.

The construction of future colliders requires a strong support to the development of accelerator science and technology, in several domains: high-energy gradient acceleration systems, high beam intensity and efficient radiofrequency systems, use of new superconductor materials for accelerator magnets. CEA is already strongly involved in this effort, in collaboration with its main partners, in particle physics and beyond. Alternative concepts, such as muon colliders, should also be studied in details.

Key questions will be addressed by the future neutrino physics experiments; CEA is in particular strongly supporting the DUNE project. Interest is also expressed for the Hyper-Kamiokande program. Europe should also coordinate itself strongly to prepare the 1-ton double beta decay experiment.

CEA considers with interest the emerging EIC project, allowing deeper studied of QGP matter beyond LHC programs.

Finally, as a crucial insight for the open questions on particle physics, theory should remain strongly supported and well-coordinated at the European level.