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INFN National Committee for Particle Physics (CSN1): Input to the European Strategy for Particle Physics Update

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Summary

1 Introduction

Particle physics at accelerators has entered a new historical phase with the discovery of what seems to be, to all effects, the first fundamental scalar field [I1]. This phase encompasses three aspects already present in fundamental science in the past two hundred years. The *discovery of the Higgs boson* recalls the excitement of the discovery of the positron in the thirties, which proved that the anti-electron of Dirac's equation was not just a mere mathematical artifact. The *triumph of the Standard Model* recalls the success of classical electrodynamics at the end of the XIX century, which made scientists believe that a model, which could potentially explain all phenomena in a laboratory, was at hand. The evidence of phenomena, which cannot be explained by the Standard Model, recalls the experimental evidence of radioactivity, *new physics* at the time, in Curie's laboratory at the dawn of the XX century.

There is no doubt that *new physics* exists, beyond the Standard Model, as indicated by the inconsistency with two experimental observations: 1) Standard Model fermions constitute only about one sixth of the total matter in galaxies, according to astrophysical observation [I2]; 2) neutrinos oscillate and therefore have mass [I3], while within the Standard Model they are predicted to be strictly massless. This evidence for new physics is further reinforced by the lack of *natural explanations* for some observed phenomena: a) baryons in our known universe are not matched by an equal amount of anti-baryons; b) the hierarchical pattern of quark and lepton masses are completely unexplained, as well as the approximate symmetries exhibited by the quarks and neutrinos mixing matrices; c) the lightness of the Higgs boson mass compared to the Planck scale requires an unnatural fine-tuning of the mass term in the Higgs potential.

The three aspects mentioned above, *i) important discovery*, *ii) precise verification of a model*, *iii) unexplained phenomena* co-exist at the present time, making this period a special one. There is a fourth aspect that, again, is not new to fundamental physics. Having found experimental evidence of all the building blocks of the Standard Model, we have somewhat lost guidance in the search for new fundamental constituents, and we must rely, rather than on model-dependent prejudices, on the *traditional way of discovering new physics by exploring new frontiers*, i.e., making new experimental observations or improving the precision of existing measurements.

From the above considerations, two main drivers for particle physics at accelerators can be identified, on a time scale relevant for the current update of the European Strategy for Particle Physics [I4]. The first one is, rather obviously, to understand the role of the new discovered scalar in electroweak symmetry breaking. The properties of the Higgs boson must be studied with high precision, similarly to what has been done, in the past, for vector bosons. It is of paramount importance to understand if the newly discovered scalar particle is indeed the Higgs boson, fully responsible for the Brout-Engler-Higgs mechanism in the Standard Model, or if it is something else, e.g., composite or part of a doublet. Furthermore, the role of the scalar in its interactions with other particles (and with itself!) should be clarified.

The second major physics driver is evident, too, and it is related to the need to clarify the experimental observations and the theoretical arguments, which are pointing to the existence of physics beyond the Standard Model. As an example, experiments at accelerators have a considerable potential to reveal the nature of dark matter (DM) by producing it in high energy interactions or to detect new particles that could shed light on the stabilization mechanism of the Higgs mass parameter. Another example is the direct study of neutrino oscillations at a long baseline experiment, which can unveil the origin of these phenomena and its relationship with beyond Standard Model (BSM) physics. Last but not least, the search for deviations from the Standard Model predictions in flavour-changing transitions of quarks or leptons could reveal new dynamics responsible for the approximate flavour symmetries observed in nature.

This short document represents the input of the INFN CSN1 [I5], the INFN scientific committee in charge of High Energy Physics experiments and projects at accelerators, to the European Strategy for Particle Physics Update (ESPPU). The projects supported on the mid-term, in construction or approved, dominated by experiments at LHC, are briefly described, followed by neutrino oscillations experiments and future colliders projects. The CSN1 vision for next strategy is presented in the conclusions.

2 LHC and other projects on the mid-term

By far the most important CSN1 commitments, human and resource-wise, are currently within the CERN's Large Hadron Collider (LHC) experiments and their foreseen upgrades. About 400 physicists in 20 INFN sections and national laboratories are constructing key elements of the ATLAS and CMS phase 2 upgrades [H1] for HL-LHC. In the next decade each of the two upgraded experiments is expected to collect at least 3 ab^{-1} each of integrated luminosity at a centre-of-mass energy close to 14 TeV. With this wealth of data, the measurement of Higgs couplings to vector bosons and third-generation fermions will reach the O(1%) level, the Higgs trilinear self-coupling will be constrained at better than 50%, rare decays of Standard Model particles (such as, e.g., top quark flavour-changing neutral-currents decays) will be searched for with unprecedented sensitivity and the search for BSM particles (such as, e.g., stop, vector-like quarks or other exotic states) will enter unexplored territory [H2]. These are a few examples on how HL-LHC will progress on precision measurements and exploration, following the two physics drivers previously mentioned.

In the same period the LHCb experiment at the same accelerator [H3] and the BELLE II experiment at SuperKEKB [H4], both with significant CSN1 support, will expand the search for deviations from the Standard Model predictions in flavour-changing transitions of quarks or leptons, with the potential of revealing new dynamics responsible for the approximate flavour symmetries observed in nature. The precise and complementary studies done by these two experiments, in pp and e^+e^- collisions, will provide an effective tool for indirect searches of new particles, even at mass scales well above those directly accessible at the LHC. Flavour-changing transitions of leptons will also be studied by the MEG 2 experiment at PSI [H5] and the MU2E experiment at Fermilab [H6], continuing and starting, respectively, their investigation of $\mu \to e\gamma$ transitions in the next few years.

While the analysis of the full dataset collected by the Muon g-2 experiment at Fermilab [H7] is being completed, the MUonE experiment [H8] will investigate the robustness of g-2 theory predictions and the muEDM experiment in preparation at the PSI [H9] is expected to search for a possible muon electric dipole moment with unprecedented sensitivity. Our knowledge of QCD and hadron structure will continuously progress thanks to data provided by BES III at BEPC [H10], exploring exotic hadron states, by AMBER at CERN [H11], precisely measuring the pion and proton structure and, at the highest energy, by the LHC experiments. In this realm important projects are also being followed by the INFN CSN3 such as, e.g., EIC [H12], as described in the corresponding documentation [H13].

HL-LHC and other mid-term projects mentioned in this section are essentially all already approved and they represent a concrete step in progressing with our knowledge along the main physics drivers of experimental particle physics: precision and exploration. At the same time, they provide unvaluable training opportunities to a generation of young physicists, the generation that will oversee and steer fundamental research at longer-term projects. These projects have also developed new ground-breaking detector techniques (e.g., radiation-hard high-resolution silicon detectors, timing detectors providing for the first time 4-D tracking, etc.), which will be used for the first time in realistic experimental environments, a necessary step for further progress at future colliders.

3 Exploring neutrinos at accelerator experiments

Accelerator neutrino physics has entered its precision era after the measurement of the mixing angle between the first and third neutrino mass eigenstates - θ_{13} [N1]. This breakthrough opens the door to exploring the entire Lepton Yukawa sector of the Standard Model with accelerator beams, including the establishment of CP violation in neutrinos and determining the neutrino mass hierarchy. The facilities currently under construction for long-baseline experiments, such as DUNE [N2] and HyperKamiokande [N3], are comparable in complexity and cost to collider experiments and were supported by the previous European Strategy.

DUNE has successfully completed the construction of the underground laboratory at SURF and is expected to begin data-taking around 2030. The experiment is built upon the liquid argon TPC technology, which was pioneered by C. Rubbia in the 1970s [N4] and brought to maturity by INFN through the realization of the ICARUS detector at LNGS and Fermilab [N5]. The DUNE Near Detector includes the SAND apparatus, which exploits relevant components of the INFN LNF KLOE apparatus (most noticeably the magnet and electromagnetic calorimeter). To fully realize its potential—especially in studying CP violation—DUNE is committed to executing Phase II [N6], which includes building the third and fourth Far Detector TPCs and deploying the Near Detector complex. The US P5 process [N7] has identified DUNE Phase II as the top priority for neutrino physics in the United States, with INFN playing a crucial role in its realization. Completing Phase II is essential to establish CP violation with a precision of approximately 10° and to fully leverage the significant investments made thus far. The third and fourth DUNE TPCs, along with the DUNE Near Detector, will employ advanced technologies currently under development. Reaffirming CERN as the central hub for validating these technologies—following the success of ProtoDUNE-HD and ProtoDUNE-VD for Phase I—is crucial. Achieving this vision requires robust support for the CERN Neutrino Platform over the next five years.

INFN has also provided substantial support to the design and construction of HyperKamiokande. Unlike DUNE, HyperKamiokande relies on a conventional and fully proven technology—the water Cherenkov detector—which has already led to groundbreaking discoveries, including the first observation of supernova neutrinos (Kamiokande) [N8], the observation of neutrino oscillations with natural and artificial sources (SuperKamiokande and K2K) [N9, N10], and the discovery of $\theta_{13} \neq 0$ (T2K) [N11]. The HyperKamiokande experiment builds on INFN's contributions to the T2K near detector ND280 and leverages INFN's expertise in developing the multi-PMT systems employed by KM3Net, as well as the front-end electronics for 20” PMTs. Specifically optimized to probe CP violation with unprecedented precision, HyperKamiokande is poised to achieve significant results even before DUNE begins its data-taking phase.

The previous European Strategy identified a new generation of high-precision cross-section experiments as a crucial step toward significantly reducing systematic uncertainties in DUNE and HyperKamiokande, and addressing electroweak nuclear physics [N12]. ENUBET [N13] and NuSTORM [N14] were recognized as the most advanced candidates for such a facility. In recent years, ENUBET, supported by CSN1, has successfully completed its R&D phase and is now preparing a proposal for a high-precision short-baseline experiment at CERN, designed to operate alongside DUNE and HyperKamiokande. This project, known as SBN@PBC, brings together the expertise of ENUBET, NuTAG [15], and the CERN Neutrino Platform and is being developed within the framework of Physics Beyond Colliders (PBC). Its implementation at CERN would leverage existing infrastructures, such as the CERN-SPS, and detectors like ProtoDUNE and WCTE [N16], enabling this ambitious program to be executed at a sustainable cost.

The unique capabilities of the CERN accelerator complex, particularly the LHC, provide an opportunity to explore neutrino cross sections at energy ranges significantly higher than those accessible to DUNE and HyperKamiokande. These opportunities were recently realized by the FASER [N17] and SND@LHC [N18] experiments, which achieved the first-ever observation of neutrinos produced in colliders. SND@LHC, in particular, is an INFN-supported experiment that builds on expertise in nuclear emulsions and fast-tracking detectors. It paves the way for precise measurements of high-energy neutrino cross sections, including during the high-luminosity phase of the LHC, as proposed in the AdvSND framework [N19].

4 Future Colliders

The previous update of the European Strategy [F0] gave priority to *investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage*. Since then, the feasibility study of FCC, which passed the mid-term phase [F1] and is expected to be completed in time for the current European Strategy, has developed in detail the design of a possible infrastructure in the Geneva region, close to CERN, for a circular e^+e^- collider running at a centre-of-mass energy ranging from the Z pole (91 GeV) to above the top-pair production threshold (365 GeV), with a circumference of 90.7 km. Higgs boson production would be achieved at 240 GeV in the HZ Higgstrahlung mode and at the highest energy in the vector boson fusion mode. The infrastructure would be ready to host, in a second phase, a pp collider with a centre-of-mass energy of about 100 TeV, the exact value depending on the choice and technical availability of the superconducting dipole magnets.

The circular e^+e^- collider (FCC-ee) [F2] would be able to reach the permil level for the *absolute* couplings of the Higgs boson to Z and W bosons and to improve the present knowledge of key electroweak observables (e.g, Z mass, W mass, $\sin^2\theta_W$) by one-two order of magnitudes. Some important couplings (e.g., $\alpha_{QED}(m_Z)$) would be measured for the first time and direct search for new particles (e.g. heavy neutral leptons, potentially responsible for the tiny neutrino mass through the see-saw mechanism) would be considerably extended. The hadron collider (FCC-hh) [F3] would reach a 5% precision for the Higgs boson self-coupling and extend by a factor of ≈ 7 the territory for new particle searches (as an example for the relevance of this physics reach extension, the entire mass region for WIMP dark matter candidates would be covered). It has been clarified [F4] that the precision of FCC-hh measurements, such as the measurement of the Higgs boson self-coupling or of the top-Higgs Yukawa coupling, depends crucially on observables precisely measured at FCC-ee. On the other hand, parameters measured at FCC-ee at various centre-of-mass energies, for example the Wilson coefficients in an EFT framework, show strong correlations among each-other [F5], calling for the necessity of *an integrated* FCC-ee + FCC-hh programme.

Since the start of FCC preparatory studies, about ten years ago, CSN1 has supported dedicated activities at INFN labs. In particular, for FCC-ee the INFN teams have proposed an innovative type of detector concept for one of the four interaction points, called IDEA (Innovative Detector for e^+e^- Accelerator) [F6]. IDEA consists of a vertex tracker placed immediately around the IP, a large and ultra-light wire drift chamber, a silicon wrapper used to improve the overall momentum resolution, a crystal electromagnetic calorimeter read in dual readout (DR) mode, a thin high temperature superconducting (HTS) solenoid providing a magnetic field up to 3 T, followed by a hadronic fibre calorimeter read in DR mode, and then a muon detection system housed within the iron yoke closing the magnetic field. IDEA promises to have an extremely good charged-track momentum resolution, an exquisite PID provided mainly by the cluster counting technique exploited in the drift chamber, an outstanding energy resolution for both the electromagnetic showers as well as the hadronic showers, matching the requirements of FCC-ee physics. Finally, it proposes highly performant trackers in the muon detection system that, apart from identifying and tracking muons, can also be effective to identify and track long living particles, predicted by many new-physics scenarios. INFN, through CSN1 and other Committees (e.g. CSN5, MAC), started also a robust program of R&D for FCC accelerator components, specifically for the FCC-ee machine-detector interface (MDI), for FCC-ee RF cavities and for FCC-hh dipole magnets. The latter covers several activities aimed at developing superconducting magnets in both Nb_3Sn and HTS-based technologies.

CSN1 commitments to a conceptual design of a multi-TeV Muon Collider date back to the previous ESPPU [F7], which led to the present International Muon Collider Collaboration (IMCC) hosted at CERN. A Muon Collider offers an attractive and sustainable solution for high-energy lepton-collisions and is, in fact, the only viable machine for lepton colliders at a centre-of-mass energies above 3 TeV. The physics reach of a Muon Collider with centre-of-mass energies above 10 TeV is complementary to a 100 TeV hadron collider: it would provide similar parton energies with complementary production mechanisms, being essentially a WW collider. It would uniquely pursue the quantum imprint of new phenomena (e.g., Higgs compositeness) in novel observables by combining precision with energy. Additionally, it would provide access to new physics coupled to muons and enable highly accurate measurements of the trilinear Higgs coupling [F8]. To exploit the unique physics potential of a muon collider, the detector requires a dedicated design to mitigate the Beam Induced Background (BIB) due to decay of the muons. The ongoing R&D is focused on reaching high granularity and time resolution in the tracker and calorimeters, beyond the present target of HL-LHC. INFN groups are contributing on leading activities on developing new technologies with dedicated accelerator and detector R&Ds [F9].

The development of a Muon Collider project, ultimately aiming to achieve high-energy high-luminosity muon collisions, faces several challenges an requires dedicated R&Ds [F10], including an ionizing muon cooling demonstrator to produce low-emittance and high-flux muon beams. A 6D muon ionization experiment will be included in this facility; a collimated, low-energy neutrino beam would be an interesting byproduct, which might be employed for neutrino cross section measurements [F11]. The construction and operation of the full-power *demonstrator* will proceed in stages, starting with a target and a few cooling cells, along with system integration tests. To this end, INFN is supporting the development of a cooling cell test facility to address the technological challenges, mainly concerning the requirements of high accelerating gradients in high magnetic fields exploiting HTS technologies. Among others, INFN R&D activities related to the development of high-field HTS magnets are in full synergy with FCC-hh.

5 Conclusions: mid- and long-term vision

Building a strategy for particle physics in Europe involves aspects related to physics, technology, and geopolitics. The latter is relevant, as discussed in Mario Draghi’s report on the future of Europe competitiveness published by the European Commission [C1], but outside the scope of this document. The current physics landscape, outlined in the introductory section, calls for increased precision in a broad set of electroweak measurements, including obviously the Higgs boson sector, and for a substantial extension of the territory explored seeking for new phenomena. On the mid-term a series of already-approved projects exists, most noticeably HL-LHC and neutrino oscillations experiments, to continue the path marked by the two physics drivers of precision and exploration. Many of these projects and experiments are supported by INFN CSN1, as mentioned in the second and third section, and they have a strong potential of producing very significant physics results. They should be sustained and play a significant role (also) in the next strategy; beyond physics results they contribute to the growing of the next generation of physicists, the leaders of future projects.

Nevertheless, it is already clear that the challenges of nowadays particle physics require a new generation of experiments and a long-term vision. When discussing new projects, technology plays an important role in any decision: there are projects whose design and construction could start essentially now (e.g. an electroweak/Higgs/top e^+e^- collider) and other very relevant projects requiring significant, although realistic, technological steps (e.g. a 100 TeV pp collider or a muon collider). The *integrated* FCC-ee + FCC-hh programme represents the best solution to answer to a broad set of significant physics questions in an optimal way; the construction of the tunnel and of the e^+e^- collider could start relatively soon, minimizing the gap between the end of HL-LHC physics and the start of physics at the following frontier project. A long-term *European* vision, incorporating the FCC project, requires dedicated efforts in physics studies, detector, and accelerator R&D that INFN CSN1 has already started supporting. In terms of detector R&D, these efforts align with the implementation of the ECFA Roadmap [C2] through the implementation of the DRD projects. Such *European* vision is also in complete synergy with our support to other *Worldwide* projects as described, for example, in the recent US P5 report [C3].

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