Initial INFN input on the update of the European Strategy for Particle Physics

The INFN Board of Directors

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Abstract

This document contains some initial input from INFN to the update of the European Strategy for Particle Physics. It does not aim at providing a comprehensive overview of the INFN position on all the relevant aspects of the Strategy: this will be defined with the other actors all along the update process, from the Open Symposium of May 2019 to the Strategy Drafting Session of January 2020. It aims instead at emphasizing the INFN position on three key issues that according to INFN deserve special attention:

- An ambitious post-LHC accelerator project at CERN
- The relation between CERN and AstroParticle Physics
- The CERN laboratory and the laboratories in the Member States

The content of this document takes into account the information presented and the extensive discussions held at a National INFN "Town Meeting", which took place in Rome on 6-7 September 2018: https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=15968
Independent and more detailed input is being submitted by some of the National INFN Scientific Committees and Laboratories, in particular CSN1 (Particle Physics), CSN2 (AstroParticle Physics), CSN3 (Hadronic Physics), C3S (Physics and Computing) and LNF (Frascati).

An ambitious post-LHC accelerator project at CERN

The 2013 Strategy Update identified three high-priority large-scale activities with high-energy particle colliders.

The top priority was motivated by the fact that "*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*", and consisted in "*the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view of collecting ten more times data than in the initial design, by around 2030.*"

It was further mentioned that "*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.*"

This was followed by the statement that "*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.*"

Since 2013, significant developments connected with the above priorities have occurred

- in the implementation of the Strategy
- in our understanding of the relevant physics landscape
- in the studies for future accelerators

These developments must be fully taken into account in the present Strategy update.

The first of the three recommendations described above has essentially been implemented. Run 2 has increased the LHC cm energy from 8 to 13 TeV, delivering an integrated luminosity in excess of 150 fb^{-1} to each of the two general-purpose experiments. After LS2, twice as much integrated luminosity will be collected at 14 TeV in Run3. HL-LHC was approved by the CERN Council in 2016: after upgrading the LHC Injectors and the experiments, it will deliver 3000 fb^{-1} at 14 (or possibly slightly more) TeV, well into the mid-2030s.

In the meantime, the Japanese decision on the ILC, possibly de-scoped from 500 to 250 GeV cm energy, is still pending, and is expected at the beginning of 2019. Another linear electron-positron collider studied at CERN is CLIC, with staged cm energy of 380 GeV, 1.5 and 3 TeV, for which a CDR has been published in 2012 and updated in 2016. Since 2014 CERN has been studying future circular colliders (FCC) to be hosted in a 100km long tunnel: among them FCC-ee, which could operate with high-luminosity at the Z-boson peak, at the threshold for WW-production, at the optimal energy of 240 GeV for ZH production, and finally at 365 GeV, slightly above the top-antitop threshold. A very similar project, called CepC, is under study in China, and a decision to build it could be possibly taken within the next few years.

R&D on superconducting high-field magnets has also been making progress: magnets based on conventional superconductors such as Nb_3Sn could reach 14T shortly and perhaps be pushed up to 16T after some years of focused R&D; magnets based on High-T Superconductors look even more promising: they could aim at 20T and be of interest also to other communities, but their cost is still very high and at least a decade of focused R&D would be required. This has led to the study of two possible scenarios for a future pp-collider: the so-called HE-LHC, at 24(27) TeV cm energy with 14(16)T magnets, or a possible 100 TeV pp-collider in a 100km long new tunnel, called FCC-hh in the CERN version, mirrored by a similar Chinese project called SppC.

The projects described above have different levels of technical readiness, different costs, different physics reach, and in some cases are mutually exclusive. The decision among them should be driven by today's physics landscape, which is significantly different from that of the previous Strategy update, keeping of course awareness of the financial and technical feasibility.

The main development in collider physics since 2013 is that the Run2 data collected and analysed so far by the LHC experiments have extended the validity of the Standard Model (SM) to higher energy scales and higher levels of precision than in 2013. The couplings of the Higgs particle to massive gauge bosons and to the third generation fermions have all been measured and are in agreement with those predicted by the SM within the errors. The searches for direct and indirect signals of new physics near the weak scale have not found any exotic particle or any confirmed discrepancy with the SM, challenging conventional solutions to the weak scale Naturalness problem of the SM, such as Supersymmetry and Compositeness. Achieving a precise understanding of the physics of electroweak symmetry breaking and ascertaining whether the Naturalness and Dark Matter problems find their solution with new particles near the weak scale remains as important as ever. However, the spectrum of possibilities to be explored is now much broader than in 2013 and does not point to a definite model or physics threshold. HL-LHC will bring important progress both in precision and in the effectively reachable energy scale, but it is not unlikely that the relevant new physics to be discovered is beyond its reach. We have moved from a validation to an exploratory phase, where many directions need to be explored and no single machine/experiment can probe all of them and guarantee discoveries.

This calls for a broad and ambitious post-LHC program, with a long-term perspective capable of motivating the young generations and focused on the following two physics drivers: 1) precision studies of the SM, especially of the properties of the recently discovered Higgs boson, to a level of precision at least an order of magnitude better than what can be reached at HL-LHC, as motivated by the present stringent and largely model-independent constraints on new physics near the TeV scale connected with a possible solution of the SM Naturalness problem; these studies should also test the triple Higgs boson coupling (also relevant for clarifying the nature of the electroweak phase transition in the cosmological evolution of the Universe), to which HL-LHC will be only marginally sensitive through Higgs pair (HH) production; 2) exploration of energy scales significantly higher than those reached at the LHC and reachable at HL-LHC, for a conclusive search of a possible solution of the Naturalness and/or Dark Matter problems with new physics connected with the weak scale. .

For these reasons, **in the INFN view, the European Strategy for particle physics must have as a first priority a new collider at CERN that can be made operational on the time scale of the completion of the HL-LHC program. A machine such as FCC-ee would provide an outstanding program of precision and discovery physics, and would be feasible with current technology at an acceptable cost. The practical feasibility of building such a collider at CERN should be understood as soon as possible. The possibility of exceptional contributions to the tunnel excavation, which would bring the machine cost within the boundaries of the normal CERN budget if spread over a long enough period, should be actively explored. In the case of a positive conclusion, a decision to go ahead should be taken without delay.** On a longer term basis, this strategy would pave the way for a FCC-hh in the more distant future. Such a machine could be installed in the same tunnel when, after intensive and focused R&D, industrial production of HTS magnets above 16T would become possible at affordable costs.

The European strategy cannot be decoupled from the roadmaps of the other regions of the world, therefore a decision by Japan to build the ILC or a decision by China to build CepC would be new elements to be taken into account in the definition and implementation of the European priorities.

A very attractive possibility to be explored now for the longer term is a high-energy circular Muon Collider with a cm energy of 10-30 TeV. Such a machine is under study exploiting either of two different technologies, proton- or positron-driven muon production. Both approaches still need extensive dedicated studies and R&D before overcoming many machine and experimental challenges and making a viable design possible. The possibility of installing a muon collider either in the present LHC tunnel or in the 100km FCC tunnel has been considered and should be explored in depth. Such a collider would open completely new physics scenarios, both for precision studies of electroweak physics, including the triple Higgs boson coupling, and for its direct discovery potential. A “dream-machine” such as a 30 TeV muon collider would have a reach for new physics going well beyond that of FCC-hh at 100 TeV. **A priority of the updated European Strategy for Particle Physics should be a systematic, extensive and adequately financed R&D campaign to go beyond the existing studies for a multi-TeV Muon Collider, both in the proton-driven and in the positron-driven option for muon production, and head towards a Conceptual Design Report.** As discussed in the final section of this document, a joint and well-organized effort of CERN and of national laboratories in the Member (as well as Associate and Observer) States will be required to progress swiftly.

The relation between CERN and AstroParticle Physics

The last decades have witnessed a series of expected and unexpected major discoveries in AstroParticle physics, the field at the interface between Particle Physics, Astrophysics and Cosmology. Just to mention the most relevant ones: the discovery of the CMB fluctuations and of the accelerated expansion of the Universe, the confirmation with high precision of the validity of the ΛCDM cosmological model, the recent detection of cosmic neutrinos and gravitational waves with the advent of the multi-messenger astronomy. This impressive series of discoveries has been either prompted or accompanied by an intense theoretical effort, overcoming the traditional boundaries among the disciplines constituting what we now call AstroParticle physics. The experimental and theoretical successes of AstroParticle physics have been made possible by the unprecedented level of sensitivity reached by the various AstroParticle experiments, making this road to the exploration of the fundamental interactions fully synergistic with the more traditional roads of the high-energy and intensity frontiers.

In summary, it is becoming more and more evident that addressing the challenge of finding new physics beyond the SM demands a broadened approach, overcoming traditional borders among disciplines and fully exploiting the enormous technological, experimental and theoretical synergies between Particle and AstroParticle Physics.

The APPEC AstroParticle Physics EU Strategy 2017-2026 individuates three main research fronts: the multi-messenger astronomy (cosmic rays, HE photons and neutrinos, gravitational waves), the study of the neutrino properties (masses, mixings, CP violation, nature of the neutrino particle), the cosmological exploration - the dark side of the Universe (Dark Matter and Dark Energy) and the CMB. All these research topics provide a substantial contribution to the Particle Physics investigation of the fundamental properties of the elementary particles and of their interactions. Indeed, the cultural domain where the Particle Physics community (and in particular its theoretical component) is operating is already (and is becoming more and more) strongly affected by the presence of the abovementioned AstroParticle subjects addressing fundamental questions beyond the Standard Model of Particle Physics.

The 2013 Strategy Update states "*The exchange of information between CERN and ApPEC has progressed since 2006. In the coming years, CERN should seek a closer collaboration with ApPEC on detector R&D with a view to maintaining the community' s capability for unique projects in this field.*" In that Update we find also an explicit indication for CERN to develop a research programme along the abovementioned neutrino research line of the APPEC roadmap: *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."*

Together with the recommendation for a vigorous continuation and full development of the CERN involvement in neutrino physics (neutrino platform at CERN as well as involvement of particle physicists and engineers for global collaboration on neutrino oscillation physics), we recommend an extension of such effort to some AstroParticle sectors, with particular emphasis on gravitational waves and Dark Matter searches.

Notice that the next-generation experiments on gravitational waves and Dark Matter searches are going to involve large or very large research infrastructures. In particular, the proposed next-generation underground gravitational interferometer (Einstein Telescope – ET project – the first AstroParticle large research infrastructure to reach the threshold cost of the order of one billion euro) would strongly benefit from the great CERN expertise on infrastructural aspects such as the building of the tunnel, vacuum techniques, cryogenics, etc. More generally, next-generation AstroParticle experiments need innovative detectors (e.g., advanced photodetector techniques and large intelligent sensor networks), a sharp increase in computing power, etc: undoubtedly, they would strongly benefit from the exploitation of vast areas of synergy with the achievements or R&D developed by the Particle Physics community.

In summary, in addition to the continuation and development of the CERN effort in neutrino physics, **we recommend that CERN and European Particle Physics:**

- **Reinforce the current level of participation in Dark Matter (DM) searches in the framework of a global programme. This should include not only multi-ton experiments aimed at direct detection of WIMP DM, but also fixed-target experiments searching for DM candidates such as sterile neutrinos and dark photons, as well as axion searches. CERN should exploit the synergies with other laboratories that are already actively engaged. In particular, for experiments making use of noble liquid targets, CERN could build on the experience and collaborations developed with the neutrino platform, and its participation should include, but not necessarily be limited to, infrastructural and technological support (e.g., underground civil infrastructures, photodetectors, cryogenic detectors).**
- **Participate in the next generation of observatories of Multi-Messenger Physics, with particular consideration for the third generation gravitational wave observatory Einstein Telescope (ET). The involvement of CERN, which would be made easier by the acquisition of additional dedicated resources, can extend over a broad spectrum of topics ranging from science to detector R&D, computing, governance and infrastructural aspects.**

The CERN Laboratory and the Laboratories in the Member States

The 2013 Strategy Update stated that *the success of the LHC is proof of the effectiveness of the European organisational model for particle physics, founded on the sustained long-term commitment of the CERN Member States and of the national institutes, laboratories and universities closely collaborating with CERN.*

The ongoing Strategy Update should go beyond this generic statement and define more precisely, within CERN as an organisation, the role of the CERN laboratory and of the laboratories in the Member States, with the aim of reinforcing also the latter. CERN should keep its central role as the leading common infrastructure for Particle Physics and as example of best practice. However, the health of the CERN laboratory and of Particle Physics in Europe also depends on the health of the national laboratories in the Member States: an example is the training of young physicists, engineers, specialized technicians, which often occurs first in the different Member States and then provides strength and support to the core activities at CERN. Centralizing at CERN activities that could performed equally well in the Member States should be avoided. Systematic collaborations between CERN and national laboratories in fields such as detector R&D, accelerator R&D (including the development of new superconducting magnets), applications and medical physics, computing, should be reinforced or established. They should make optimal use of the available infrastructures and human resources and exploit in a coordinated way the resulting broad spectrum of opportunities for Technology Transfer.

An ideal ground for this reinforced synergy between CERN and national laboratories are the detailed studies and R&D efforts required to identify a viable design for a high-energy Muon Collider, either in the proton-driven or in the positron-driven option. A second major opportunity for this reinforced synergy, and an important investment for the long-term future of Particle Physics, which requires the development of radically new types of accelerators to overcome the limitations of the traditional ones, is the continuation and scale-up of a strong accelerator R&D on Plasma WakeField Acceleration (PWFA), exploiting the expertise and the resources available in the national laboratories.