INFN National Scientific Committee for High Energy Particle Physics with Accelerators

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Abstract

High energy colliders offer the opportunity to widen our investigation of sub-nuclear phenomena to the highest unexplored energy regimes and shortest interaction scales. They consequently have the strongest potential for discovering new heavy particles and forces, allowing more accurate precision tests of Standard Model objects, and detecting new elusive signatures like the ones associated with dark matter particles.
In 2014-2015 the INFN National Scientific Committee for High Energy Physics with Accelerator (CSN1) discussed and prepared an extensive document [1] to describe the present understanding of the scientific scenarios and to propose recommendations towards future experiments at high energy particle accelerators.
Dedicated physics studies and R&D on innovative technologies are longstanding activities for the CSN1 community of over one thousand physicists and engineers. This valuable work has been exploited as a contribution in the context of international collaborations, preparing the dedicated inputs for the update of the European Strategy for Particle Physics.
The present document is the outcome of several workshops and discussions, during the past three years, devoted to study different opportunities both at the high energy and high intensity frontiers.

The update of the European Strategy for the future of high energy physics must be based on the most recent physics results produced by the Large Hadron Collider (LHC) at CERN.
The most striking result from LHC is the discovery of the 125 GeV scalar particle, to date consistent with the Higgs boson predicted by the Standard Model (SM) of particles and fields. Very recently, the ATLAS and CMS experiments have observed the production of the Higgs boson in association with a top quark pair as well as the Higgs boson decay in a pair of bottom quarks.
The HL-LHC luminosity upgrade will allow the comparison with SM predictions of Higgs boson couplings to elementary fermions and bosons at the level of a few %, both in the measurement of both absolute couplings (which are model-dependent at the LHC) and coupling ratios (which are largely model independent) [2]. Moreover a first direct measurement of the Higgs boson self-coupling strength λ_{HHH} will be possible.
Data so far produced by the LHC are well described by the SM predictions. No deviation from SM predictions has been observed yet. Strong exclusion limits have been set by ATLAS and CMS on the mass and production cross sections of new particles hypothesized by several beyond-the-SM theories. When coupled with indications from indirect limits, this scenario could likely indicate that the energy scale of new physics is larger than the one accessible by LHC collisions.

The recently discovered Higgs boson particle has opened a new era in the exploration of particle physics. This is the first elementary scalar observed in nature, if confirmed to be elementary.
A precision study of Higgs boson properties, with an accuracy significantly higher than that expected by the HL-LHC will be crucial to establish the internal consistency of the SM theory. Possible deviations from the SM expectations and their pattern will characterize the energy scale at which this theory breaks and provide discrimination among new physics models. These investigations are essential for clarifying the nature of the electroweak phase transition (EWPT) in the cosmological evolution of the Universe.
In particular, a measurement of the Higgs boson self-coupling strength λ_{HHH} is crucial to test the shape of the Higgs potential away from its minimum. **The most powerful method to directly measure λ_{HHH} is the challenging study of Higgs boson pair direct production (HH). This requires the highest possible available center-of-mass collision energy. Any mid- and far-future high-energy collider project should take into account this process.**
Under the assumption that the discovered Higgs boson is the SM one, the present experimental uncertainties on other fundamental SM parameters like the vector bosons and top quark masses or the electroweak mixing angle, from LEP, Tevatron and LHC measurements, exceed those of theoretical predictions from electroweak fits [3]. Improving the uncertainties on the measurements of these parameters to a level comparable to that of their theoretical predictions allows the validation at the highest possible precision of the SM and probe the presence of new physics through deviations in the electroweak precision observables (EWPO).

Lepton machines are the best tool to explore in depth and in an almost fully model independent manner the physics properties of the 125 GeV Higgs boson, in particular, its couplings to elementary fermions and bosons. It is worthwhile to highlight that these measurements allow to extract from data a direct measurement of its natural width.

A large circular e^+e^- collider could provide ZH pairs with high rate, allowing sub-percent measurements of the Higgs boson couplings [4, 5]. A physics program which includes collisions at the Z pole as well as at the WW and top anti-top thresholds would improve the present accuracy on

many electroweak observables by one or two orders of magnitude, as well as significantly reduce parametric uncertainties in the associated theory predictions.
A preliminary estimate of λ_{HHH} could be obtained from an analysis of the loop corrections to the Higgs couplings [3]. A center-of-mass energy around 1 TeV or possibly beyond is however needed in order to explore that parameter in detail. Linear e^+e^- colliders are currently limited to a center-of-mass energy of a few TeV, with an enormous power consumption at their top energy.

A very attractive possibility to clarify the self-interaction structure of the Higgs field is the construction of a circular muon collider.
A machine with a center-of-mass energy of 10-30 TeV can be studied, exploiting either of two different technologies: proton- or positron-driven muon production. Both approaches still need an extensive R&D, yet we believe that such a collider has a significant chance to open completely new physics scenarios. The Higgs pair production cross section grows significantly with center-of-mass energy of up to 10 TeV, allowing for an accurate determination of the trilinear Higgs self-coupling. At these energies the vector boson fusion cross section also becomes large, thus making this machine a sort of unprecedent vector boson collider (Figure 1 left). A very high energy muon collider is a unique discovery machine. If a sufficient instantaneous luminosity can be achieved, a 14 TeV center-of-mass energy muon machine is equivalent to a 100 TeV hadron collider in terms of direct discovery potential, due to the steeply-falling parton luminosity functions (Figure 1 right).

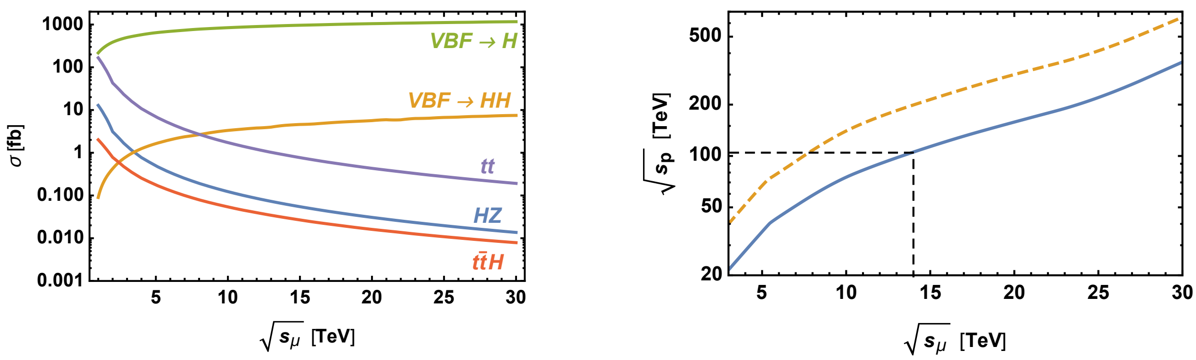

Figure 1: Left panel: Higgs and top-quark production cross-sections at high energy lepton colliders.
Right panel: the energy at which the proton collider cross-section equals that of a muon collider. The dashed line assumes comparable Feynman amplitudes for the muon and the proton production processes. A factor of ten enhancement of the proton production amplitude squared, possibly due to QCD production, is considered in the continuous line.

There is no doubt that a circular muon collider is ideal for the physics reach potential.
This new accelerator complex requires further dedicated studies and innovative concepts to overcome many machine and experimental challenges, before a Comprehensive Design Report can be written [6]**.**
The design of a high-intensity, low-emittance muon source is the first demanding requirement to be faced. Due to the short muon lifetime, a high induced background level will affect both machine and detector components. Moreover neutrino-induced radiological hazard must be taken into account while designing the accelerator system. Appropriate physics benchmarks are presently discussed to be established in order to optimize a detector design that can deal both with the physics and the machine backgrounds. The latter is critically depending on machine layout.

An extensive R&D campaign must be fully supported at international level to exploit existing studies and move forward. So far, the USA Muon Accelerator Project (MAP) [7] deeply investigated the proton-driver technology and the MICE collaboration [8] demonstrated the feasibility of ionization cooling, but the aim to reach multi-TeV center-of-mass energy could still be jeopardized by the difficulty to design an efficient final cooling system.
The new very promising Low Emittance Muon Accelerator (LEMMA) concept [9], based on the production at threshold of muon pairs from a 45 GeV positron beam colliding on the electrons of a target system, has the potential to eliminate a demanding cooling system, but has the drawback of a low muon production efficiency. An upgraded layout of a positron driven muon source should be studied and fully designed to demonstrate its feasibility.
CSN1 is fully supporting the ongoing effort to prepare an end-to-end scheme of a LEMMA concept muon collider, where the critical issues should be investigated with dedicated studies.

A hadron collider with an energy of 100 TeV or higher is in principle feasible provided magnets with critical currents much larger than those currently available can be built. Such a machine would have a direct discovery potential in the tens of TeV range and explore a large area of physics, including the dark sector. There is a strong synergy between this machine and the large circular e^+e^- collider. Indeed a 100-TeV-class proton collider could be located in the same tunnel of the previous electron machine.
New 16 T magnets could be obtained by further developing the 11 T Nb_3Sn magnets, which have been already under study to produce the eight magnets needed for HL-LHC. Even higher fields and easier construction could be obtained by using a new generation of High Temperature Superconductors (HTS).

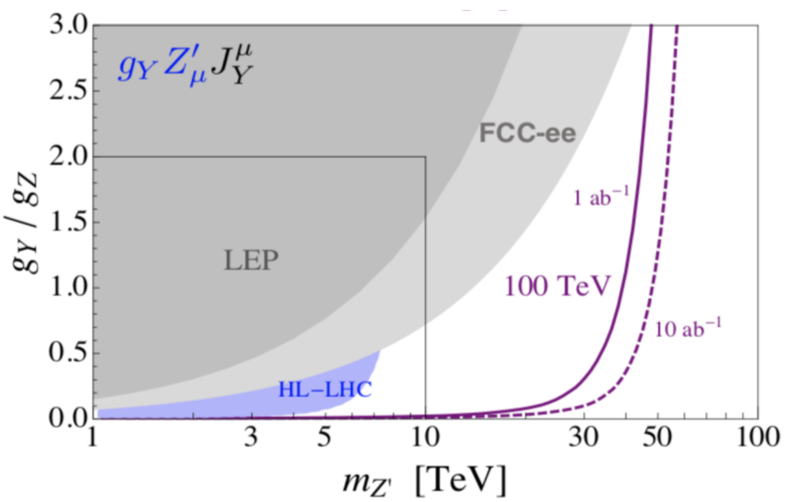

Figure 2: 95% CL exclusion limits for a Z’ compared to other proton and electron-positron colliders

It is widely recognized within the particle physics community that the complementary approaches of expanding at the energy and intensity frontier must be both pursued in the search for physics Beyond the Standard Model (BSM).
The method of testing the SM through precision measurements in flavor physics is fully complementary to that of searching for on-shell production of new particles in high-energy collisions and is in general able to probe energy scales unreachable by colliders. This vast field is heterogeneous, involving general-purpose experiments and dedicated facilities.

The vast campaign of measurements performed in the past years in this field has not only led to exclusion limits on BSM effects at higher mass scales, but also revealed a few hints of anomalies in B physics, which both Belle2 and LHCb will be able to independently confirm or dismiss in a couple of years from now.
In a longer perspective, the B-physics capabilities of the ATLAS and CMS experiments will be enhanced by their Phase II Upgrades. These improvements, together with the very large data sets that are foreseen, will allow for precise measurements to be performed, in particular in final states including muons. The evolution of flavor physics suggests a more extensive program of precise measurements and supports a dedicated new LHCb Phase II Upgrade, which has the capability of fully exploiting the flavor physics potential of the LHC [10].
Moreover, studies on rare and forbidden kaon decays within the high intensity fixed target physics program of the SPS may explore BSM scenarios in a complementary and independent way, as certain processes are extremely clean and potentially sensitive to mass scales of hundreds of TeV [11]. Similarly, the search for charged lepton-flavor-violating processes in the muon sector with upgraded accelerator facilities at PSI and Fermilab offer unique probes of physics beyond the SM, reaching mass scales of thousands of TeV [1].

Pursuing this vast and diverse program in the next decade not only will imply a discovery potential at energy scales comparable with the future colliders, but will also allow the structure of BSM physics to be precisely identified.

In the context of Dark Sector searches, future high energy colliders will explore a large number of signatures and cover a large fraction of the parameter space for the high-mass regime (above 10 GeV). **Complementary opportunities to explore a lower mass (1 MeV−10 GeV) regime have been summarized within the CERN-driven Physics Beyond Colliders effort** [12].
The proposed SHiP experiment at the Beam Dump Facility is aiming at performing an investigation of the hidden sector based on a high-intensity, high-energy, and slowly extracted SPS proton beam.
A summary of the projected sensitivities from future proposed experiments is shown in Figure 3, for a muon-coupling ($U\mu$) dominated, heavy neutral lepton of mass m_N [12].

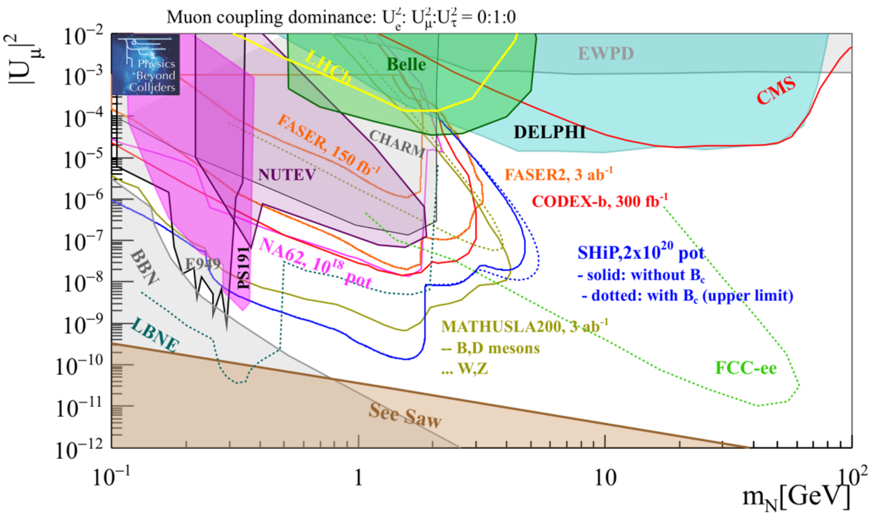

Figure 3: Sensitivity for Heavy Neutral Leptons coupling to the second lepton generation only, in the plane coupling $|U_\mu|^2$ versus HNL mass m_N, for future proposed experiments discussed within the Physics Beyond Colliders study group.

The future physics program, both at the high energy and high intensity frontier, requires dedicated efforts in the next years to develop new technologies for particle detection, front-end electronics, data acquisition and data handling systems.
Important aspects which have to be taken into account are also the scalability of the proposed solutions, and their maturity in terms of the industrialization process, which represents the only way to guarantee an affordable funding profile.

Channeling of high-energy hadrons in bent crystals demonstrated the possibility to extract and collimate the particle beams at worldwide circulating accelerators [13], allowing to consider this technology as an option for future collimators at the HL-LHC.
INFN have now developed the know-how to produce series of bent crystals with well controlled parameters. Furthermore, there is a proposition to exploit crystals as components of intense positron sources for future colliders such as CLIC, FCC-ee, CEPC, LEMMA [14], and as innovative compact detectors [15], offering a reduced volume and costs as compared to the state-of-the-art detectors.

A strong R&D program should be pursued on technologies that can enable the next generations of accelerators. In particular a new generation of magnets based on high temperature superconductors and the technology enabling the construction of a muon collider with adequate energy and luminosity.

Nowadays, a crucial ingredient of any physics program is the computing. Already now the simulation of physics process and detectors performance necessary to determine the physics reaches are so demanding that new parametric tools have been developed. In the future, data management and processing has to be designed together with the detectors and the data acquisition systems to guarantee that the events bringing high level of information will be analysed. The trend of moving towards trigger-less infrastructures makes the full system design mandatory. **The adoption of new computing technologies, like HPC now and Quantum Computers and Quantum Simulators in a near future, may help if enough R&D and manpower investment will be dedicated at any level.**

Conclusions

The European Strategy for particle physics in the post-LHC era should be based on a new collider at CERN, that can be made operational on the time scale of the completion of the HL-LHC program.

A circular electron-positron collider in a 100 km tunnel, operating from 90 to 365 GeV at high luminosity, provides an outstanding program of precision and discovery physics. Such a collider is feasible with current technology at an acceptable cost.
<u>The practical feasibility of building such a collider at CERN should be understood as soon as possible and, in case of a positive conclusion, a decision to go ahead with the construction will be fully supported.</u>

A muon collider in a multi-TeV range has the extraordinary advantage to open up a new territory for discovery only if the feasibility of the technology could be fully demonstrated in a few years on an international coordinated effort.
<u>Extensive studies must be focused to address necessary R&D, which are mandatory to demonstrate the feasibility of a machine and detector complex design.</u>

A complementary physics program, enabling to address all the searches and dedicated rare measurements which could offer unique probes of physics beyond the standard model, has been always supported by CSN1, whenever a strong physics case has been presented by a motivated community.

A constant commitment in cutting-edge technology for particle accelerators, detectors and computing has been so far one of the key ingredients which made INFN a driving force in the high-energy physics community.
This central role must be recognized with concrete actions since it will be even more relevant in the future, due to the increasing importance of the technology-transfer process from research to society. Cross-fertilization among different scientific communities and scientific and industrial sources of high-technologies requires further support to grow up the next generation of scientists.

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