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Future circular collider studies

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Summary. — With the end of the High-Luminosity LHC (HL-LHC) run, the physics potential of *pp* colliders at an energy of about 14 TeV will be completely exploited. Nevertheless important fundamental questions about the Standard Model, in case of missing evidences of new physics, still would need to be addressed. One possible option to continue the investiagtion of fundamental physics is the building up of higher-energy e^+e^- and *pp* machines. The physics potential and motivations of such machines will be summarised in this contribution.

1. – The status of the Standard Model at the end of HL-LHC

In the present work we assume that no new physics effect will be seen in the current LHC Run-2 run and the following HL-LHC program. Such assumption is not based on a scientific prejudice about the LHC outcome, but it is just a working assumption, being evident that in case new physics will show up at HL-LHC, it is very difficult to figure out now what would be the best choice to study such new phenomena.

HL-LHC will be able to constrain Higgs boson couplings to bosons, b quark and τ leptons at few % level, observe the $h \to \mu^+\mu^-$ decay channel, probably have a first evidence of di-Higgs production.

Concerning supersimmetry, it should be possible to exclude s-top and gluino masses up to 3 TeV.

2. – The next physics target after the Higgs boson discovery

After the Higgs boson has been discovered, all particle needed for the Standard Model description of the law of physics have been found. Neverthless, the validation of the Standard Model description itself is still failry incomplete. While Higgs couplings to photon, Z and W and the Higgs boson spin and parity have been completely estabilished, the couplings to leptons and quarks are still largely experimentally unknown. In particular top, b and τ lepton couplings should have been completely certified at the end of Run-2 and the coupling to muon should have been observed at HL-LHC. Nevethless, the coupling of the Higgs boson to electrons, c and light quarks will be completely untested. Furthermore, the Higgs symmtry breaking mechanism relies on the presence of an energy potential for the Higgs scalar field that has a well-defined shape. The SM strictly predicts the shape of such potential that depends only from the Higgs mass and the Higgs vacuum expectation value. The last quantity is determined from the Fermi coupling constant extracted from the muon decay G_μ. Neverthless, nowadays, and most likely even at the end of HL-LHC, this last fundamental piece of the fundamental theory of nature will remain untested.

3. – Relevance of the Higgs potential for cosmology

It has been known for several years [1] that due to the running of the Higgs self-coupling constant with the energy scale at which it is computed, the Higgs potential gets a shape that deviates from the simple $\lambda\Phi^4$ form and acquires a non-trivial Φ-dependence. Assuming no new physics at least up to the Planck scale, the present values of the top and Higgs masses imply the presence of a second, and deeper, minimum in the Higgs potential. Therefore, there is a non-null probability that the Higgs boson field has a transition to the stable minimum changing the law of physics as we know them in the present universe. The lifetime of such transition is extremely long and many orders of magnitude longer than the age of the Universe, neverthless it is interesting to know if the present Universe really has been shaped in such instability condition. Furthermore, it is known that to explain all comsologial parameters today, an inflationary epoch needs to be postulated during which the Universe undertook an exponential expantion and became extremely cold and uniform. Inflation models postulate the existence of a scalar boson with a properly shaped potential. Being the Higgs boson a scalar with its relative potential term, it is a natural inflaton candidate [2, 3]. The goodness of the Higgs boson as an inflaton candidate strongly depends on the potential shape, and at the moment there is an open discussion about the goodness of the Higgs potential to explain all the aspects of the inflationary theories. It is therefore important to have a direct probe of the potential, in order to determine its shape and test it against inflationary theories.

4. – How to determine the Higgs potential

The Higgs potential can be probed at pp and e^+e^- colliders by looking at the di-Higgs production processes. Di-Higgs production can be mediated by a top-box diagram, with the emission of a Higgs boson at each of the two box diagram vertices, and by a top triangle diagram with the Higgs boson propagating from the initial to the di-Higgs final state, with a coupling constant proportional to the λ parameter of the $\lambda\Phi^4$ SM potential term. In pp interactions the hh production strongly increases with the center-of-mass energy, going from 40 fb at 13 TeV to 1750 fb at 100 TeV. This huge cross-section increase makes a 100 TeV pp collider an ideal candidate for studies of di-Higgs boson production.

5. – The 100 TeV *pp* collider project

In the recent years, a strong effort has been started to study the feasibility and the physics potential of a 100 TeV proton-proton collider. It is quite clear that in the relatively far future, 16 T Nb_3Sn could become available for industrial productions and studies are on-going to obtain 20 T high-temperature superconducting coil magnets.

Extrapolating the LHC energies with these configurations, a maximum energy of 100 TeV or 130 TeV is reachable depending on the used magnet technology.

5·1. *Physics deliverables.* – The physics reaches of a 100 TeV collider have been deeply exploited in [4]. Using the $\gamma\gamma bb$ final state, a fractional error of 13% can be reached on the hh production cross-section that translates to a 2.5% error on the self-coupling λ using a total integrated luminosity of $30\,\mathrm{ab}^{-1}$. Such study has been performed without taking into account pile-up effects and a realistic detector simulation, therefore, it will need to be redone in the near future. Neverthless it clearly sets the measurement of the Higgs self-coupling as a clear reachable target of a 100 TeV pp collider. In order to try improving this result, with the target to reduce the needed integrated luminosity and, therefore, the running time of the machine, more channels are under study, like the $WWbb$ and the $ZZbb$ decay channels. A 100 TeV collider is also a unique opportunity to extend the explorable region for new particles up to 10 TeV, for example the s-quarks and gluinos supersymmetric particles.

6. – The e^+e^- 100 km option

The timeline needed to develop and industrialise magnets able to provide a magnetic field up to 16–20 T is still uncertain, therefore it is of interest to explore the physics reach of other options. An e^+e^- 100 km collider would allow to start the building up of the tunnel and the facilities for a following pp collider when the technology and the higher budget needed for the pp collider would become available. A circumference larger than the previous LEP circumference allows to reduce the impact of photon radiation on the beam energy loss. Studies for the e^+e^- option are performed assuming a constant power consumption of 100 MW. With such power a luminosty of $1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is reachable at the $t\bar{t}$ production threshold, 2×10^{35} at the Z mass and 10^{34} at the Zh threshold. A collider of this type could set precision measurements on the Higgs couplings at sub-percent level, a measurement of the W mass at 0.5 MeV level and of the top mass at 10 MeV level, to compare with the present, systematic dominated measurements of 15 MeV for the W mass and 500 Mev for the top mass.

7. – Current on-going studies and conclusions

The possibility to build up an e^+e^- collider followed by a pp collider is under consideration by both European and Chinese physics communities. The two projects are nowadays becoming more and more similar, with a 100 km circumference length in both cases and a design of the e^+e^- collider based on a double-ring for the accumulation of the beams plus a booster for the acceleration to high energies. For the pp case, while the European community is concentrating on the Nb_3Sn-based magnets, the Chinese community is working more on the high-temperature superconductors. The e^+e^- and the pp options look nowadays the only two possibilities to boost forward the knowledge in particle physics at the energy frontier, the first one setting the best measurements of the Higgs couplings, the second allowing to probe new physics up to the 10 TeV scale and being able to probe the Higgs boson potential through the Higgs self-coupling measuerement at percent level.

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