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Future electron-positron and Hadron Colliders

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The discovery of the Higgs boson at Large Hadron Collider (LHC) at CERN in July 2012 raised new requirements and opportunities for large-scale future electron positron and hadron colliders. The Higgs boson is the heart of the Standard Model (SM) and is at the center of most fundamental mysteries of universe. In this paper we will give a very brief review of the proposed electron positron colliders as Higss factories, such as CEPC, FCC_{ee}, ILC, CLIC, and C^3, and future hadron colliders of center of mass energy around 100TeV, such as SppC and FCC_{hh}. Their development status, synergies and the complementarities among them are discussed.

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1. Introduction

Higgs boson is the heart of the Standard Model (SM), and is at the center of our understanding the most fundamental mysteries of universe. The discovery of the Higgs boson at CERN's Large Hadron Collider (LHC) in July 2012 raised new requirements and opportunities for future large-scale colliders. The historical developments of both electron positron colliders and hadron colliders are shown in Figs. 1 and 2 [1]. In the next generation Higgs factories, precise measurements of the properties of the Higgs boson serve as probes of the underlying fundamental physics principles of the SM and beyond. Due to the modest Higgs boson mass of 125 GeV, it is possible to produce it not only by electron positron linear colliders, but also by circular electron–positron colliders with higher luminosity and multi detectors. The advantages of linear colliders are that they have great potential to reach the center of mass energy up to 1TeV and beyond, such as ILC, CLIC and C^3. As for the circular electron positron colliders as Higgs factories, such as CEPC and FCC_{ee}, they have big advantages of high luminosities at Higgs, W and Z energies. For the proposed electron positron colliders shown in Fig. 3, their luminosities vs energy have been compared as shown in Fig. 4 [2].

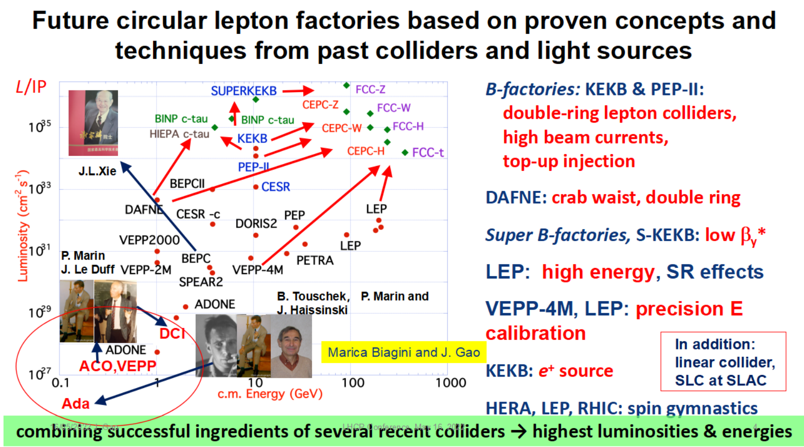

Figure 1: The history of electron-positron colliders.

For the circular electron positron colliders, it is difficult to operate beyond the ttbar energy due to the intolerable synchrotron radiation energy loss. The optimized circumferences of circular electron positron colliders as Higgs factories are found to be around 100km based on the scientific outputs (accumulated physical events) and cost of the machine (including construction and operation costs) [3]. Concerning the aspects of the green colliders, the detailed comparisons of carbon footprint of future Higgs boson studies through Higgs factories have been given in Ref. [4]. As for the staging possibilities of circular electron positron colliders, proton proton colliders are the ideal options for these machines, such as CEPC and FCC_{ee}, to use the same tunnels to build the hadron colliders to reach the center of mass energy up to 100TeV with SppC and FCC_{hh}. The difference between CEPC-SppC and FCC_{ee}/FCC_{hh} is that CEPC and SppC will be installed in the same tunnel side by side for future electron proton collision option.

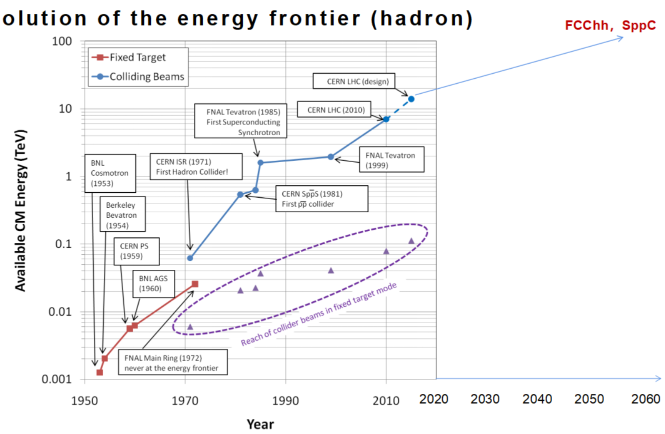

Figure 2: The history of hadron colliders.

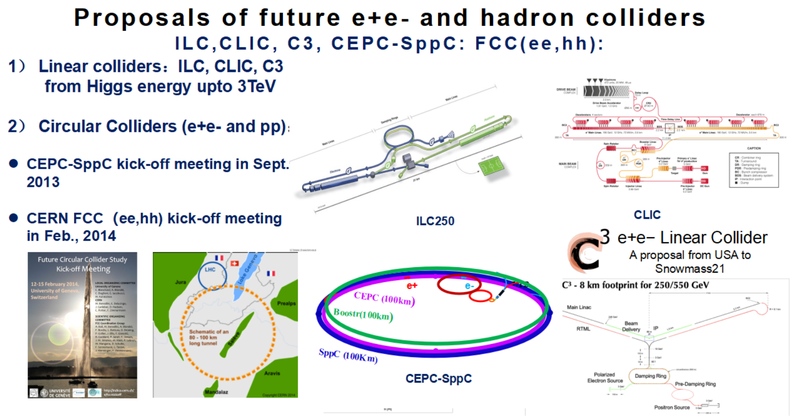

Figure 3: The proposed electron-positron and hadron colliders.

2. CEPC-SppC

In September 2012, Chinese scientists proposed a 240 GeV Circular Electron Positron Collider (CEPC), serving two large detectors for Higgs studies and other topics as shown in Fig. 3. The CEPC kick-off meeting was held in Sept. 2013 in Beijing. The 100 km tunnel for such a machine could also host a Super Proton Proton Collider (SppC) to reach center of mass energy about 125 TeV with 20T iron base high temperature superconducting magnet technologies. The design features of CEPC are that Higgs energy is the optimization point, and the collider could switch from Higgs energy to W and Z-pole energies freely without changing hardwares. The ttbar operation is as an upgrade possibility at the last phase of operation of CEPC.

The CEPC Conceptual Design Report (CDR) was formally relased in Nov. 2018 [5] and the Technical Design Report (TDR) will be released in 2023. As an international project proposed by Chinese scientists, CEPC has actively participated and contributed to international high energy strategy planning activities, such as the European Strategy for Particle Physics [6] and the Snowmass21 of US [7]. According to CEPC timeline, from 2023-2025 CEPC will enter into Engineering

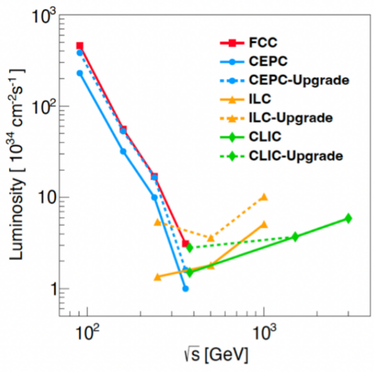

Figure 4: The luminosity comparison results of different electron positron colliders.

Design Phase (EDR) aiming to start of construction around 2026 (the beginning of the 15th five year plan of China) and put CEPC into operation around 2035. Concerning the site of CEPC, there are several candidates have been carefully studied with the supports from the local governments, which satisfy the construction requirements. The CDR cost of CEPC is about 5Billion USD.

3. FCC

FCC was proposed by CERN in the beginning of 2013, and the FCC kick-off meeting was held in April 2014 in Geneva as shown in Fig. 3. The main feature of FCC_{ee} is that it is a Higgs factory optimized at ttbar energy with 2 or 4 interaction points, but its operation starts from Z-pole energy all the way up to ttbar, with each energy step accompanied with hardware changing. Another feature is that FCC_{ee} will be dismantled at the moment when FCC_{hh} starts to be constructed. The FCC Conceptual Design Report (CDR) was published in the beginning of 2019 [8] , and European Strategy for Particle Physics released in 2020 [9] states that Higgs factory is the first priority, which is different from the beginning of FCC proposal, where FCC_{hh} had the higher priority. The site of FCC is located near CERN, which is good for less uncertainty but with less freedom in circumference choice. Right now the FCC circumference is about 91.17km [10]. The FCC_{ee} cost is around 11Billion CHF. The feasibility study of FCC_{ee} will be completed in 2025 and operation time is around 2045. As for the center of mass energy of FCC_{hh} is 100TeV with 17T superconducting magnets.

4. ILC

International Linear Collider is an L-band superconducting technology based electron positron linear collider with accelerating gradient of 31.5 MV/m. ILC baseline has been adjusted from center of mass energy of 500GeV to Higgs energy of 250GeV as first phase with total collider length of 20km since 2018. The construction cost of ILC250 is around 5Billion USD. Since the ILC TDR completion in June 2013, after LCC phase development, ILC is a technically matured Higgs factor with center of mass energy upgradable to 1TeV [11]. As future electron positron linear collider to be hosted by Japan, ILC International Development Team (IDT) has been established in 2020, and a four years of pre-lab preparation phase before construction is still pending. The optimum operation time for ILC is around 2037.

5. CLIC

CLIC as a two beam normal conducting X-band electron positron linear collider is proposed by CERN, and as starting point of center of mass energy of 380GeV, CLIC has the first phase total length of 11km with accelerating gradient of 72MV/m. CLIC has the potential to raise the center of mass energy up to 3TeV with accelerating gradient of up to 100MV/m. The cost of CLIC at 380GeV with two beam scheme is around 5.9Billion CHF [12]. CLIC TDR will be completed around 2026 and estimated construction time is around 2030 and operation time around 2040.

6. C3

The electron positron Cool Copper Collider (C^3) has been proposed in USA in 2021 [13][14]. The C^3 is a Higgs factory based on C band copper linear accelerator cooled by Nitrogen at 77K in order to reduce the rate of electric sparking at high accelerating gradient of 120MV/m and increase the quality factor Q by a factor of above 2. The design features of C^3 are that with 8 km footprint, with accelerating gradient of 70-120 MeV/m, the center of mass energy could reach 250-550 GeV, and by using high precision numerical milling machine for C band accelerating structure fabrication, the collider cost could be reduced. Many existing experiences from ILC, CLIC and NLC could be beneficial for C^3 design and cost estimations. For a 250GeV C^3 Higgs factory, a preliminary cost is around 4Billion USD. Taking the Fermi National Lab site 7 km footprint for example, at accelerating gradient of 155 MeV/m, a center of mass energy of 550 GeV can be achieved. The attracting point of C^3 electron positron linear collider is its high energy potential of reaching several TeV, say 4TeV, which catches up the low end of a muon collider. In terms of technology preparations, C^3 still needs to go through different phases, such CDR and TDR, etc., before starting the construction, and the optimal operation time for C^3 is around 2040.

7. Conclusions

In this paper we have seen that many Higgs factory projects (proposals) have been made worldwide, from Asia, to Europe and America, due to the extraordinary importance of the Higgs boson related partice physics and sciences in general. Tremendous efforts and progresses have been made towards their final realisations. The synergies and the complementarity in physics reaches among them are enormous in promoting each other with healthy competitions and collaborations towards a common goal.

8. Acknowledgments

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