The Circular Electron Positron Collider (CEPC) Project: The Physics Reach and Reference Detector Design

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ABSTRACT

After the discovery of the Higgs boson, electron positron colliders that can precisely measure properties of the Higgs boson and electroweak (EW) observables became a natural choice in the development and construction of new facilities. Electron positron colliders allow for the possibility of groundbreaking scientific exploration, where a much more profound understanding of the Standard Model may lead to discoveries regarding underlying fundamental principles of physics. The proposed Circular Electron Positron Collider (CEPC) aims to be one such facility.

This paper includes an introduction to the physics motivations and physics potential of the CEPC project. The physics requirements and one reference performance assessment of the detector is also presented.

INTRODUCTION

The Standard Model (SM) of the particle physics is one of the most successful physics models ever constructed [1]. Using a simple and beautiful mathematical structure, the SM explains and predicts almost all of the phenomena observed in collider experiments. In 2012, the last missing piece of the SM particle spectrum, the Higgs boson, was discovered [2, 3]. This historic discovery marked the beginning of a new era – the post-Higgs era – where the SM particle spectrum had been completed, yet exploration using the Higgs boson, which can be used as an extremely powerful probe, had just begin.

Despite its enormous success, the SM is hardly a satisfactory theory. The SM includes a series of bizarre coincidences and is incapable of explaining many observed or anticipated physics phenomena. These coincidences include too many hand-put free parameters, the naturalness/hierarchy problem, and vacuum stability problems, etc. [4] The latter contains the famous Baryon-Asymmetry, dark matter and dark energy, non-vanishing neutrino masses, and, to some extent, the unification between gravity and gauge interactions. To put it simply, there must be fundamental physics principles explaining why nature chooses the SM in the electroweak energy scale. The exploration toward these unknown fundamental laws certainly becomes a priority for particle physics in the post-Higgs era.

This exploration involves a combination of direct searches (via the production of particles beyond the SM) and precision measurements (by searching for deviations from the SM), especially toward Higgs boson properties and electroweak (EW) measurements. In fact, the Higgs boson is responsible, or at least correlated with most of the theoretical defects in the SM. In other words, the Higgs boson serves as an excellent probe. It has been well established that the physics landscape of the TeV level could be revealed once the precision of Higgs boson property measurements reaches percentage level [5]. The electroweak observations, once combined with measurements of Higgs properties, could significantly enhance the physics reach [6, 7]. Therefore, these precision measurements become key physics objectives for both the on-going LHC programs and the proposals for high-precision future facilities.

The Circular Electron Positron Collider (CEPC) is one

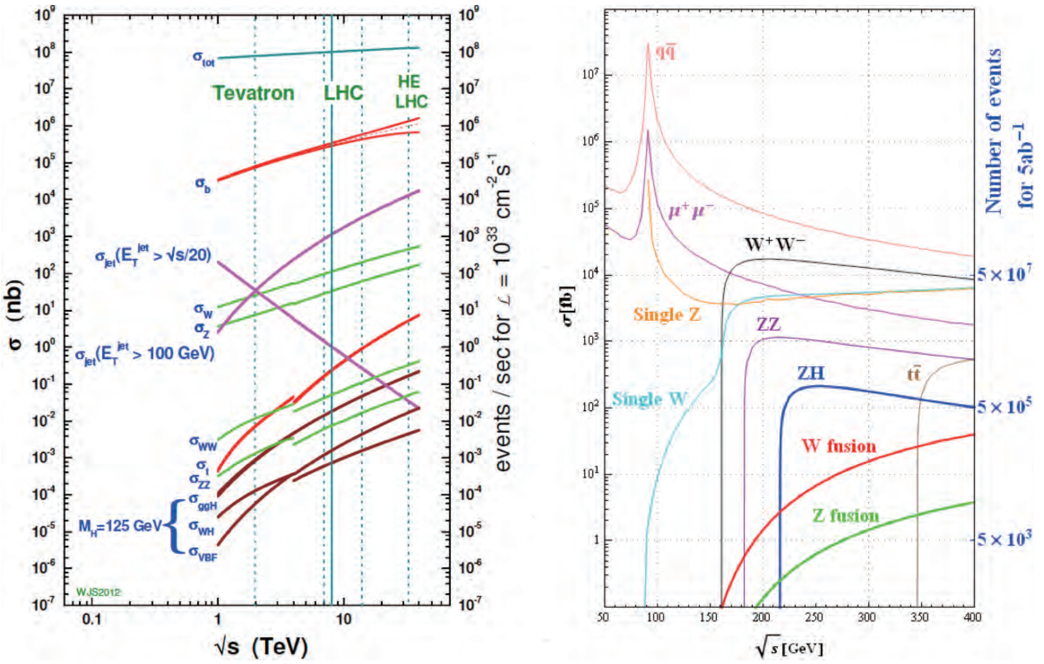

Fig. 1: Physics cross sections at different center of mass energies at LHC (left) and at an electron positron collider without beam polarization (right).

of these future facilities [8]. The idea is straightforward: in a tunnel with a total circumference of roughly 100 km, a high luminosity electron positron collider will be installed and serve as a precise telescope toward Higgs boson properties and EW observables. CEPC could produce 1 million Higgs bosons in 10 years of operation at two interaction points. Downgrading the center of mass energy to 91.2 GeV, this accelerator could produce 10^{10} Z bosons in 1 year. The electron positron collider could be upgraded to a proton collider (Super Proton Proton Collider, SPPC) with a center of mass energy of 100 TeV that would directly search in the high-energy frontier. A careful overall design could enable a heavy ion, and even an electron-proton program. Therefore, CEPC could provide inclusive information from high-precision frontier, the high-energy frontier, and also the high-density frontier. This program could certainly lead to a significant leap in our understanding of nature.

This article provides a brief introduction to the physics motivations and the anticipated detector performance of CEPC. We will compare the Higgs program at LHC with other electron positron colliders, and report on a reference detector's design and performance assessment.

HIGGS FACTORY: THE ELECTRON POSITRON COLLIDERS VS THE HADRON COLLIDER

The LHC is a very powerful Higgs factory. It has already produced millions of Higgs bosons, while two orders of magnitudes more Higgs bosons are anticipated in the coming HL-LHC program [9]. However, the huge QCD background limits the precision of Higgs boson measurements at the LHC and HL-LHC. The background is so high that one Higgs event is produced in roughly 10 billion proton-proton collisions (see the left plot of Fig. 1). The physics events are overlapped with tens or even hundreds of pile-up events. Therefore, only Higgs events with clear and, for the most part, pre-defined final states could be identified and recorded. The typical event reconstruction efficiency at the proton collider is roughly at the per mille level. As a result, the ultimate precision of the Higgs boson measurements, characterized by the measurements of signal strengths (the ratio between measured events rates and that of the SM prediction), are limited to relative accuracies at the 10% level [10, 11]. Meanwhile, the requirement of pre-defined final states makes the interpretation of experimental data always model dependent; tagging for unexpected Higgs decay modes at the LHC is a bit difficult.

Comparing to the LHC, an electron positron Higgs factory is much clearer since the beam particles are blind to the strong interaction. The typical ratio between the event rates of the Higgs signal and the inclusive SM background is roughly at 10^{-2} to 10^{-3} level (see the right plot of Fig. 1) [12]. In fact, its total event rate is so low that all the physics events could be recorded, making the search for unexpected Higgs decay modes – the smoking guns of the new physics laws – much easier than at the LHC. Meanwhile, the initial condition of the electron positron collider is well known and adjustable. The SM backgrounds are usually well understood. The theoretical errors at the electron positron collider could be controlled to a precision much better than that at the LHC. In addition, at an electron positron collider, a significant portion of the Higgs boson are generated via the Higgsstrahlung (ZH) process – which allows the Higgs event to be identified using only Z boson information – therefore no pre-knowledge of the Higgs boson behavior is required. This technology is also known as the model-independent measurement, which determines the absolute values of the $g(HZZ)$ coupling, the Higgs boson width and the couplings between the Higgs boson and its decay final states in the SM. To conclude, an electron positron Higgs factory has significant advantages compared to the LHC, and it certainly brings lots of information on top of the LHC measurements.

For these reasons, many electron positron facilities have been proposed, including linear colliders (ILC[13] and CLIC[14]) and circular ones (FCC[15, 16] and CEPC[8]). Typically, these colliders could produce 10^5 – 10^6 Higgs bosons. Since almost all the Higgs events could be recorded, the Higgs boson properties – in terms of the absolute value of their couplings – could be determined to a percentage or even a per mille level accuracy, which would be roughly one order of magnitude better than the anticipated signal strength measurements at HL-LHC. In addition, these electron positron colliders, especially circular ones, could also produce huge statistic of W and Z bosons for precision EW measurements. Dedicated studies show that the precisions of EW measurements could be improved by at least one order of magnitude with respect to current levels of precision [8, 16, 17].

In summation, the discovery of the Higgs boson strongly promotes the development of electron positron Higgs factories, which could improve the precision of measurements of Higgs properties by one order of magnitude with respect to the HL-LHC, and also could significantly improve the precision of EW measurements. Such precision would reveal the physics landscape in TeV or even higher energy scales, and would strongly enhance our understanding of the physical laws underlying the SM.

DETECTOR REQUIREMENTS AND PERFORMANCE AT CEPC

A high luminosity accelerator and well-suited detectors are the pillars for the CEPC project. In this section, we will discuss the physics requirements for the CEPC detectors and introduce one of the designs for a reference detector.

The Higgs events at CEPC have many different topologies. The Higgs boson could be generated accompanied by a pair of leptons, or jets, or missing energy/momentum. Meanwhile, giving the mass of 125 GeV, the SM Higgs boson has multiple decay final states with significant branching ratios. A successful CEPC detector should be able to distinguish the Higgs signal from the SM background. In addition, it should also be capable of reconstructing and classifying the Higgs signal according to its generation mode and decay products. In other words, a CEPC detector should be able to reconstruct the following physics objects with high efficiency, high purity, and high accuracy.

Leptons: Leptons could be generated, directly or via cascade, in the Higgs boson decay. Meanwhile, about 7% of Higgs bosons are produced with an electron-positron pair or muons. These events enable a model-independent tagging of the Higgs signal via the recoil mass method, which is of key importance for the CEPC Higgs program. In addition, roughly 200 $H \to \mu\mu$ events are anticipated at CEPC, where precise momentum measurement and excellent muon identification would lead to the determination of $g(H\mu\mu)$ with relative accuracy better than 10% [8].

Photons: The SM Higgs boson has a branching ratio of 0.2% to decay into a pair of photons (which, incidentally, is the golden channel for the Higgs search at the LHC). A precise determination of $g(H\gamma\gamma)$ allows insight into the heavy charged particle spectrum. Furthermore, the photon is a key component of the jets; better photon energy resolution is appreciated for jet energy reconstruction.

Taus: Being the most massive lepton in the SM, the tau is extremely intriguing and is crucial to the CEPC physics program. More than 6% of SM Higgs bosons decay into a pair of tau, which leads to the percentage level determination of $g(H\tau\tau)$. Precise reconstruction of final tau decay probably leads to the best measurements for a set of EW parameters [17]. Therefore, a detector that can efficiently reconstruct the tau lepton and distinguish its different final decay states is required at CEPC.

Jets/MET: Roughly 80% of the SM Higgs bosons decay into final states with jets ($H \to bb, cc, gg$ events and the hadronic/semi-leptonic decay cascade of $H \to WW, ZZ$ events). Efficient identification of jet candidates and precise reconstruction of their energies are essential for the corresponding couplings and branching ratio measurements. Good jet energy resolution means good missing energy/momentum measurements, which leads to better reconstruction of Higgs events with neutrinos in their final states.

Large solid angle coverage is certainly important for the CEPC detector. In addition, the ability to distinguish kaons from pions, and to identify different flavor jets is highly valued. The former would enable a rich flavor physics program, while the latter would be essential for the measurement of $g(Hbb)$, $g(Hcc)$, and $g(Hgg)$.

To fulfill these requirements, many detector concepts have been proposed. Thanks to the development of microelectronics and detector technology, the particle flow principle became a trend for collider detector studies and has played a key role in detector R&D efforts toward future electron positron colliders [8, 13-14, 18-20].

The idea of particle flow is to reconstruct all the final state particles in the most suited sub-detectors and to provide a list of reconstructed particles. From this very list, all the physics objects, both simple ones (i.e, photons and leptons) and composed ones (taus and jets), could be reconstructed from the same basis. Therefore, the particle flow principle provides a global, coherent interpretation of the entire physics event from the reconstructed particles – which eventually leads to high efficient/purity physics object identification and precise energy/momenta determination for the composed objects. This is especially significant for the jets, since the charged particles, which dominate the jet energy, are usually much better measured by trackers as compared to calorimeters.

The anticipated typical performance of the PFA oriented detector design for the CEPC is presented in Table 1. Validated with full simulation study tools, this design is projected to achieve superior performance as compared to previous experiments. For instance, the misidentification rate in lepton identification is controlled to a rate roughly 3 times better than the ALEPH experiments, while the jet energy resolution is roughly 3 times better than that of the LHC [23, 24].

Identification Performance		
Leptons (E > 2GeV)	Efficiency	99.5-99.9%
	Mis-id from hadron	< 1%
Photons (E > 0.5 GeV)	Efficiency	99.5%
	Mis-id from neutron	0.1 – 1%
Charge kaon (2-20 GeV)	Efficiency	90 – 99%
	Purity at $Z \to qq$ sample	90 – 99%
b-jets	Efficiency	80%
	Purity at $Z \to qq$ sample	90%
c-jets	Efficiency	60%
	Purity at $Z \to qq$ sample	60%
Measurement Performance		
Photons	$\delta M/M$ at $H \to \gamma\gamma$	1.7-2.4%
Jets	$\delta M/M$ at $H \to gg$	<4%

Table I: Typical performance of the PFA oriented detector concept at full reconstruction level.

CONCLUSION AND DISCUSSION

The discovery of the Higgs boson has boosted particle physics into the post-Higgs era, where the achievement of precision measurements has become a critical experimental frontier. Electron positron colliders, due to their clean collision environments and well-defined initial states, are anticipated to provide crucial information beyond that which is anticipated to arise from the LHC/HL-LHC, and therefore electron positron colliders are a natural choice for the future exploration of particle physics.

The proposed CEPC project could produce 1 million Higgs bosons, o(10^8) W bosons, and o(10^{10}) Z bosons. In addition, being a circular collider, CEPC could be upgraded into a high-energy proton collider. Therefore, this project combines the possibility of direct searches as a proton collider, precision measurements as a electron-positron collider, and potential heavy ion programs, thus providing the opportunity for an extremely intriguing physics program.

In the electron-positron collision phase, almost all the physics events could be recorded and analyzed at CEPC. To fully appreciate the physics opportunity provided by CEPC, its detector(s) would be required to be able to reconstruct all the key physics objects with high efficiency, high purity and high accuracy. It has been demonstrated that a reference detector concept, designed following the particle flow principle, could fulfill the physics requirements of the CEPC program. As a result, CEPC could resolve the Higgs boson properties at accuracies roughly 1 order of magnitude better than the ultimate limit at HL-LHC, and boost the current precision of EW observations by at least 1 order of magnitude [8].

It should also be emphasized that circular colliders can easily host multiple interaction points. Therefore, different detector geometry concepts, following different principle and physics ideas, are always welcome for this future project.

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