Future physics prospects with CEPC and HL-LHC synergy

Chonglun Xu

Departments of Physics, University of Hong Kong, HK, China

u3583473@connect.hku.hk

Abstract. After constructing the Circular Electron Positron Collider (CEPC) and the High-Luminosity Large Hadron Collider (HL-LHC), particle physics experiments will reach a new mass region with more incredible energy. Both types of colliders have the unique duty of searching for new particles or estimating the coupling constants of the reactions based on their different structures, providing a different focus. This presentation will discuss and cover the regions of CEPC and HL-LHC to show their complementary functions. The CEPC can answer the Higgs particle, whether it is a composite particle, how it contributes to the dark matter mass, and whether its field provides enough matter mass for the universe. It can generally provide detections below 10 TeV, leading to possible new theories. For the HL-LHC, the upgraded HL-LHC has a higher luminosity and data acquisition capability, ten times higher than predicted. It is expected to produce 15 million Higgs particles annually, five times more than the LHC. The large number of collision events provides more opportunities to measure the characteristics of the Higgs particles.

Keywords: CEPC, HL-LHC, Higgs Boson.

1. Study the purpose of the collider.

The Standard Model in particle physics is a theory that describes the three fundamental forces - strong interaction, weak interaction, and electromagnetic interaction - and the fundamental particles that make up all matter. In the Standard Model, the Higgs boson is a scalar boson with mass, an essential cornerstone of the Standard Model. Since the discovery of the Standard Model (SM) in the 1970s, it reached its most tremendous success with the discovery of the Higgs particle at the Large Hadron Collider in 2012. This event brought the world's attention to particle physics. The Standard Model has withstood the precise test of many experiments over the past decades, making it one of the most successful fundamental theories. However, success does not mean perfection, and it still has many problems, such as inducing symmetry-breaking Higgs particles that are still experimentally undiscovered etc. In addition, in recent years, some experimental results and the predictions of the Standard Model also have a certain degree of deviation, which makes people must consider that there is still new physics in nature not included in the Standard Model and how to use colliders to discover or exclude the possible new physics has become the main direction of people to explore the laws of physics. However, the old Large Hadron Collider failed to meet the inquiry's needs and led to colossal background noise. Therefore, a new collider will be upgraded and built to improve the collision and detection efficiency.

2. About the physics of CEPC

CEPC works as a high-sensitivity Higgs plant with great physics promise. It has a significant advantage over other colliders because of its unique mechanism. The positions and electrons from the SM have accurate information from the initial state. CEPC is also a clean background noise Higgs factory, providing a much higher Higgs event signal than the LHC, and the events can be detected and recorded with high precision. It can accurately determine the initial and final states of the Higgs boson event and use them to measure the Higgs boson signature. At the same time, the advantages of CEPC allow it to perform measurements of the width and decay trajectory of the Higgs boson, which is impossible with other colliders.

CEPC has a wide range of uses in particle physics because it provides high detection sensitivity in events. CPEC provides many Z particles for flour physics, which later produce charm quark pairs, top quark pairs, and tau leptons pair events. This provides opportunities for measurements in flour physics. In addition, CEPC measures the coupling constants of strong interactions by studying quark and gluon events and the QCD vacuum. The potential of CEPC can be improved by future upgrades of luminosity and central mass energies above 240 GeV.

2.1. About the accuracy of CEPC

The main ring of CEPC has a circumference of 100 km, which is nearly four times larger than that of the LHC. CEPC will produce one million Higgs particles at a center-of-mass energy of 240 GeV, a yield almost six times larger than that of ILC, the representative of linear colliders, which means that it has a massive advantage in accuracy. While the Standard Model does not accurately predict the properties of the Higgs boson. The precise measurement of the Higgs boson is an integral part of current high-energy physics. The equation is.

$$\text{Deviation} = \frac{cv^2}{M^2} \tag{1}$$

It is shown that the LHC cannot achieve accuracy below one percent of the new physics field when measuring the Higgs coupling.

At relatively low center-of-mass energies, CEPC allows for rich physical measurements: CEPC is expected to produce hundreds of millions of W particles and hundreds of billions of Z particles under highly demanding conditions. CEPC can do better than the LHC for Higgs boson candidates. Its cleaner environment facilitates better and more exclusive measurements of the Higgs boson decay channel. It eliminates the need for a series of labeling of decay products, making the study smoother. In general, CEPC plans to improve the precision of the Higgs coupling strength and other electroweak parameters by about an order of magnitude. The accuracy will be less than one-hundredth of a percent, the so-called sub-percent accuracy. And CEPC is very likely to measure the Higgs coupling to the Z boson, even if the degree of accuracy substantially exceeds that of HL-LHC.

The following figures show the predictions of the accuracy of the Higgs coupling extraction and Z-pole measurements in the kappa frame, respectively[1] (Figure 1 and Figure 2).

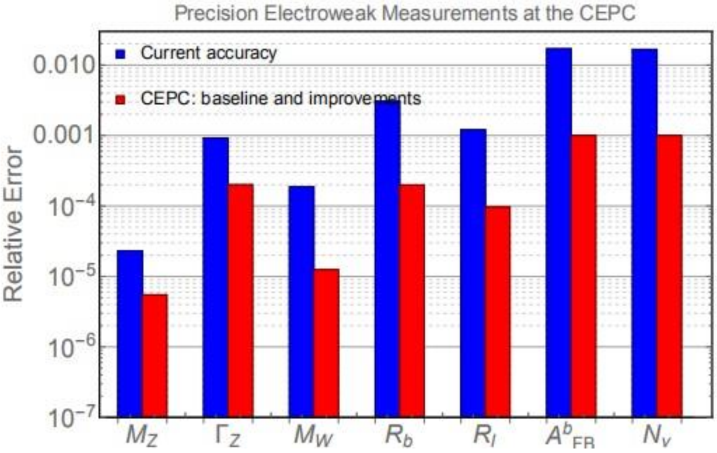

Figure 1. Precision Electroweak Measurements at the CEPC.

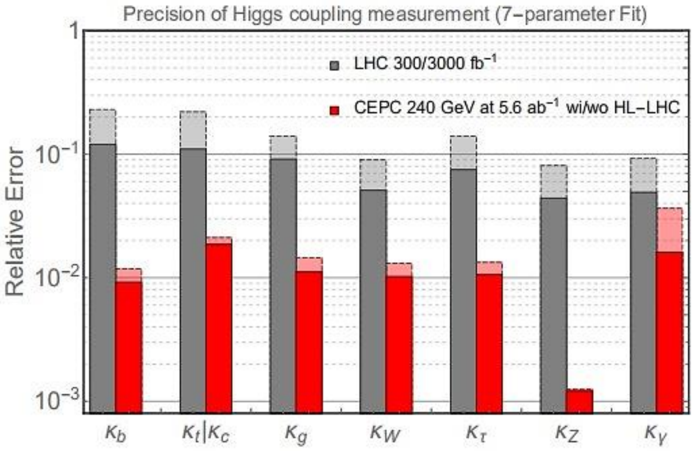

Figure 2. The precision of Higgs coupling measurement (7-parameter Fit).

2.2. New physics study on CEPC

The high central mass energy and high sensitivity of CEPC allow it to step into new areas of physics. The different physics options are to make exotic particles carrying the charge of the standard model, normalizable classic model portals, portals with additional standard model sector physics or SM charged groups of new gauge models, and practical theories and high dimensional operators, the approach being which of the three options above we consider. The first section is discussed mainly in this report, as the Higgs boson can be an essential portal to new physics beyond the Standard Model.

CEPC is a collider that studies the Higgs and electroweak physics and provides sensitive detection of electroweak multiplets. An example of an electroweak multiplet is dark matter. Although neutrally charged, it can also be part of the SU(2) group of multiplets with charged particles. e+ +e− -Z* -ZH is the Higgs produced through the Z boson. It is described as.

$$\sigma = \frac{G_F^2 M_Z^4}{24s\pi}\left[(g_V^e)^2 + (g_A^e)^2\right]\lambda^{\frac{1}{2}}\frac{\left(\lambda + \frac{12M_Z^2}{s}\right)}{\left(1 - \frac{M_Z^2}{s}\right)^2} \tag{2}$$

g_V^e and g_A^e is the coupling constant between Z and electron? The recoil mass technique is used to find the Higgs boson's label from the Z boson's visible decay. Thus, further selection and labeling of the Higgs boson decay products can achieve high signal efficiency, while the main background will come from the SM decays of the Higgs boson, which were introduced in [2].

The exotic decays of a set of Higgs bosons and their predicted LHC constraints and limits are derived from Table 1 summarizes the comparison of the CEPC with the 5.6 ab^{-1} integrated luminosity. It demonstrates the mass difference between the high-brightness LHC and the toroidal positron collider.

Table 1. Current and predicted limits of the Higgs boson heterodyne decay modes for the 5.6 ab^{-1} integrated luminosity of HL-LHC and CEPC.

Decay		95% CL limit on BR	
Mode	LHC(current)	LHC(projections)	CEPC
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.23	0.056	0.003
$(b\bar{b}) + E_{\mathrm{T}}^{\mathrm{miss}}$	_	[0.2]	1x10^{-4}
$(jj) + E_{\mathrm{T}}^{\mathrm{miss}}$	_	_	4x10^{-4}
$(\tau^+\tau^-) + E_{\mathrm{T}}^{\mathrm{miss}}$	_	[1]	8x10^{-5}
$b\bar{b} + E_{\mathrm{T}}^{\mathrm{miss}}$	_	[0.2]	2x10-^{4}
$jj + E_{\mathrm{T}}^{\mathrm{miss}}$	_	_	5x10^{-4}
$\tau^+\tau^- + E_{\mathrm{T}}^{\mathrm{miss}}$	_	_	8x10^{-5}
$(b\bar{b})(b\bar{b})$	1.7	(0.2) 90.2	6x10^{-4}
$(c\bar{c})(c\bar{c})$	_	(0.2)	8x10^{-4}
$(jj)(jj)$	_	[0.1]	2x10^{-3}
$(b\bar{b})(\tau^+\tau^-)$	[0.1]	[0.15]	4x10^{-4}
$(\tau^+\tau^-)(\tau^+\tau^-)$	[1.2]	[0.2~0.4]	2x10^{-4}
$(jj)(\gamma\gamma)$	_	[0.01]	1x10^{-4}
$(\gamma\gamma)(\gamma\gamma)$	[7x10^{-3}]	4x10^{-4}	8x10^{-5}

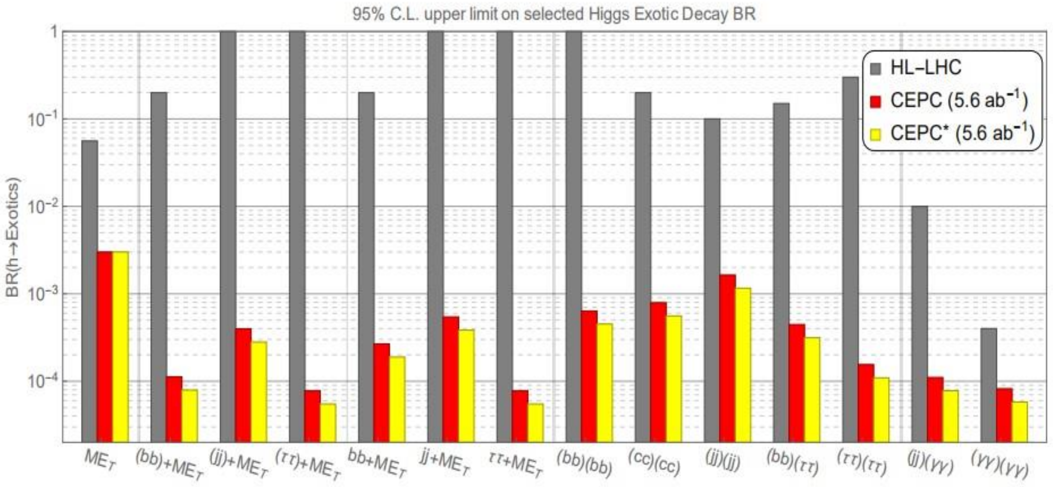

Figure 3. 95%C.L. upper limit on selected Higgs Exotic Decay BR.

Table 1 shows the current and predicted limits of the Higgs boson heterodyne decay modes for the 5.6 ab^{-1} integrated luminosity of HL-LHC and CEPC, as calculated from [2]. In the first column seen, the particles in the same brackets indicate the decay products of the intermediate resonances. The predictions for future runs of the LHC are collected in the third column, and the data are shown in its limits in the cases of 100 fb^{-1} and 300 fb^{-1}, respectively. Figure 3 shows one of the most challenging modes to constrain in the LHC, reflecting the considerable sensitivity of the CEPC. The coverage of the exotic branching fraction of the Higgs boson has improved considerably compared to the HL-LHC, by roughly 1 to 4 orders of magnitude.

2.3. *About CPC's dark matter research*

Although many astronomical observations have shown the existence of dark matter in the universe [3], we still know too little about them. According to the available words, the main properties of dark matter that we know so far are: (1) it must be electrically and chromatically neutral on large scales, with weak interactions with ordinary baryonic matter; (2) it must be stable particles in the age range of the universe, (3) it constitutes about 27% of the mass of the universe (4) it plays the role of a gravitational seed in the formation of human-type celestial structures, in which dark matter must form clumps and not spread out.

So far, our discussion of dark matter has been organized according to the details of the model. The smallest charge unit in the standard model is 1/3; experiments by lower group quarks carrying the actual Milligan oil droplet have never found a non-integer charge. Thus the quantization of payment has been accepted as a fundamental experimental fact and embodied in various physical theories. Some theorists also point out that the quantization of charge is related to magnetic monopoles. Still, unfortunately, there is no experimental evidence to support the existence of magnetic monopoles as well. However, we can also take a portal agnostic or "model-independent" approach and simply look for a generic signal; this could occur if the DM is part of an electroweak multiplet due to the cycling of charged SU(2)L partners of dark matter and W bosons. This may also occur if completely new charged particles independent of the DM exist and couple to the DM. In the practical theory approach, this signal comes from the seventh-dimensional effective operator that couples fermionic dark matter to SM gauge boson pairs. Panels (a) (b) show DM masses of m = 4 (10) GeV. Figure 4 and Figure 5 further indicates the direct and indirect detection limits and the CEPC in-plane constraints. For direct detection, we calculated the spin-independent scattering rate through the scalar operator [4], which considers the contribution of the dominant two-photon exchange.

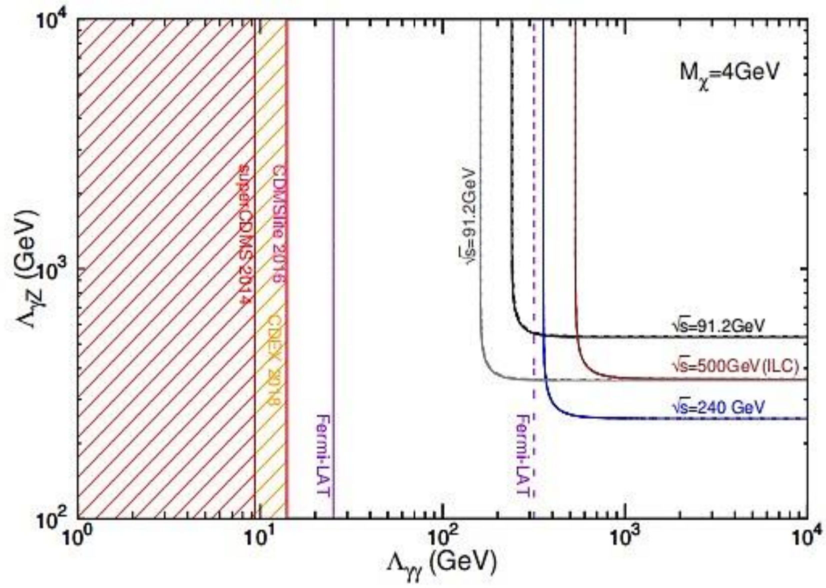

Figure 4. CEPC test for the ability of dark matter to couple to SM photons operators.

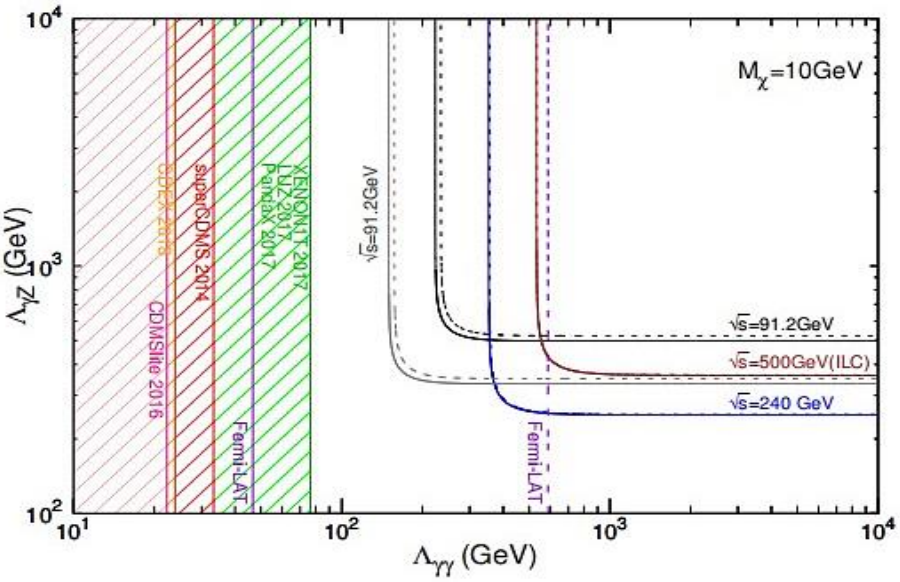

Figure 5. CEPC test for the ability of dark matter to couple to Z bosons via.

2.4. *QCD accuracy on CEPC*

QCD is a canonical theory of strong interactions that describes the interactions of quarks that make up strong-acting particles (hadrons) and canonical fields associated with color quantum numbers that can describe the structure of hadrons and the strong interactions between them in a unified way and is considered a promising fundamental theory of strong interactions in which the vital force is mainly responsible for producing the mass of protons. Among the positron colliders that humanity has built so far, the Large Positron Collider (LEP) is the closest to the CEPC in terms of center-of-mass energy and collider scale. Potential improvements in detector design could lead to better experimental systematics, most notably particle identification capabilities. Thus, CEPC will provide the opportunity to perform QCD studies with unprecedented precision while giving new constraints on understanding hadronization in high-energy processes.

The following figures show the four-jet production cross section versus the resolution parameter y and the expected statistical uncertainty for the Durham jet algorithm in CEPC, respectively (Figure 6 and Figure 7).

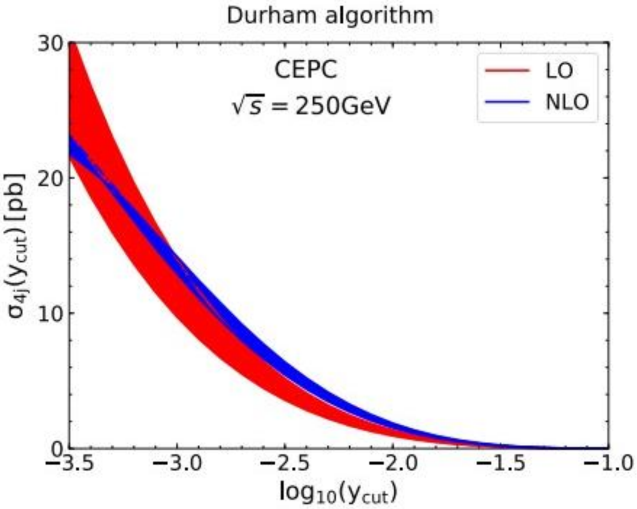

Figure 6. the four-jet production cross section versus the resolution parameter y.

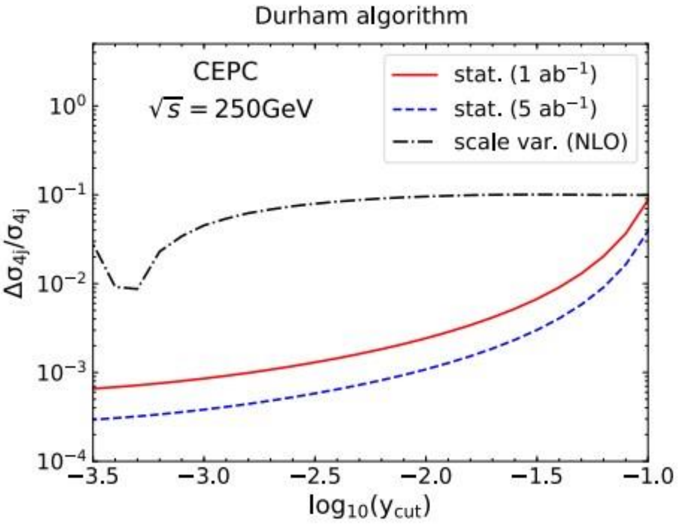

Figure 7. The expected statistical uncertainty for the Durham jet algorithm.

2.5. CEPC on Flavor Physics

The high-energy proton collisions produce many hadrons containing heavy quarks (b or c quarks). Measuring the decay properties of these particles allows precise experimental tests of the Standard Model to uncover signs of new physics, a type of exploration often referred to as flavor physics research. The high-brightness Z factory produces 10^{12} Z bosons, and this factory offers a unique opportunity for various measurements. The decay of 10^{12} of these Z bosons will have about 10^{11} b hadrons, comparable to the number of B mesons expected from Belle II.

Table 2. The Tara-Z plant of CEPC.

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
BR $(B_s \to ee)$	2.8x10^{-7}(CDF)[438]	~7x10^{-10}(LHCb)[435]	~fewx 10^{-10}
BR$(B_s \to \mu\mu)$	0.7x10^{-9}(LHCb)[437]	~1.6x10^{-10}(LHCb)[435]	~fewx 10^{-10}
BR$(B_s \to \tau\tau)$	5.2x10^{-3}(LHCb)[441]	~5x10^{-4}(LHCb)[435]	~10^{-5}
R_K, R_{K^*}	~10%(LHCb)[443,444]	~few%(LHCb/Belle II)[435,442]	~few %
BR$(B \to K^*\tau\tau)$	_	~10^{-5}(Belle II)[442]	~10^{-8}
BR $(B \to K^*\nu\nu)$	4.0x10^{-5}(Belle)[449]	~10^{-6}(Belle II)[442]	~10^{-6}
BR $(B_s \to \phi\nu\bar{\nu})$	1.0x10^{-3}(LEP)[452]	_	~10^{-6}
BR $(\Lambda_b \to \Lambda\nu\bar{\nu})$	_	_	~10^{-6}
BR $(\tau \to \mu\gamma)$	4.4x10^{-8}(BaBar)[475]	~10^{-9}(Belle II)[442]	~10^{-9}
BR $(\tau \to 3\mu)$	2.1x10^{-8}(Belle)[476]	~few x10^{-10}(Belle II)[442]	~fewx 10^{-10}
$\frac{\text{BR }(\tau \to \mu\nu\bar{\nu})}{\text{BR }(\tau \to e\nu\bar{\nu})}$	3.9x10^{-3}(BaBar)[464]	~10^{-3}(Belle II)[442]	~10^{-4}
BR $(Z \to \mu e)$	7.5x10^{-7}(ATLAS)[471]	~10^{-8}(ATLAS/CMS)	~10^{-9}-10^{-11}
BR $(Z \to \tau e)$	9.8x10^{-6}(LEP)[469]	~10^{-6}(ATLAS/CMS)	~10^{-8}-10^{-11}
BR $(Z \to \tau\mu)$	1.2x10^{-5}(LEP)[470]	~10^{-6}(ATLAS/CMS)	~10^{-8}-10^{-10}

Note: Order of magnitude estimates of the sensitivities of several key observables that may have interesting capabilities for the Tara-Z plant of CEPC.

3. HL-LHC

The Hadron Collider mainly refers to the Proton-Antiproton Collider and Proton-Proton Collider, which are easier to reach higher center-of-mass energies than the positron collider and are suitable for measuring particle properties and discovering new particles in higher energy regions. The Proton-Proton Collider now refers to the operating Large Hadron Collider, the international highest-energy, and largest experimental facility. The LHC has brought human exploration of the microscopic world to a new frontier where the standard model theory of particle physics is again validated. After discovering the Higgs particle at the LHC, it has become a logical choice to continue to upgrade the LHC to study the nature of the Higgs particle and to search for new physics beyond the standard model. Many new physics theories beyond the standard model have been predicted. Many new physics theories beyond the Standard Model predict the existence of new particles beyond the Standard Model. These new particles have distinctive features in their production and decay, thus becoming the most direct signal to search for new physics. Therefore, the Hadron Collider was upgraded, and the next generation is HL-LHC[5].

The HL-LHC aims to improve the performance of the LHC. In addition to the center-of-mass collision energy, brightness is also one of the critical indicators of the collider performance. The intelligence of the collider refers to the number of collisions per square centimeter per second when two beam clusters collide. In theory, if the brightness of the LHC is increased by a factor of 5 to 10, then in principle, the data acquisition capability of the HL-LHC needs to be raised by a factor of 5 to 10. The massive amount of data generated by the HL-LHC will then open up great opportunities for research and possibly discoveries in several fields, including the search for new particles and new interactions in the Super Standard Model, precise measurements of electroweak physics, studies of the properties of the Higgs particle, studies of positive and negative matter asymmetries, and studies of the structure and properties of hadrons.

3.1. Higgs coupling measurements on HL-LHC

Accurate measurement of the properties of Higgs particles is the most crucial topic of LHC experiments. A central task in the study of Higgs particle properties is the measurement of their coupling constants with other elementary particle processes. Experiments have received particular attention because many new physics models predict that these coupling constants can deviate from the predicted values of the Standard Model. However, the experimental measurements of the coupling constants are not yet very accurate, and the observed errors are mostly above 15%. Many theories beyond the Standard Model predict that these coupling constants may deviate from the predicted values of the Standard Model. Still, they generally do not exceed 5%, and the current experimental precision is insufficient to test these theories substantially. Therefore, accurate measurements of the coupling strength of Higgs particles to other particles and the self-coupling strength of Higgs particles will continue throughout the HL-LHC experimental studies in the future. The high brightness of the HL-LHC will improve the statistical accuracy substantially and allow exploring the rare Higgs boson production and decay patterns. By studying the combination of the observed rates of different channels, we will extract a more accurate coupling strength measurement corresponding to it. To estimate the precision of the SM Higgs boson coupling with other particles that can be measured at the HL-LHC[6], the predicted results based on the available special decays at 7 and 8 TeV are carried out as shown in the figure below (Figure 8 and Figure 9).

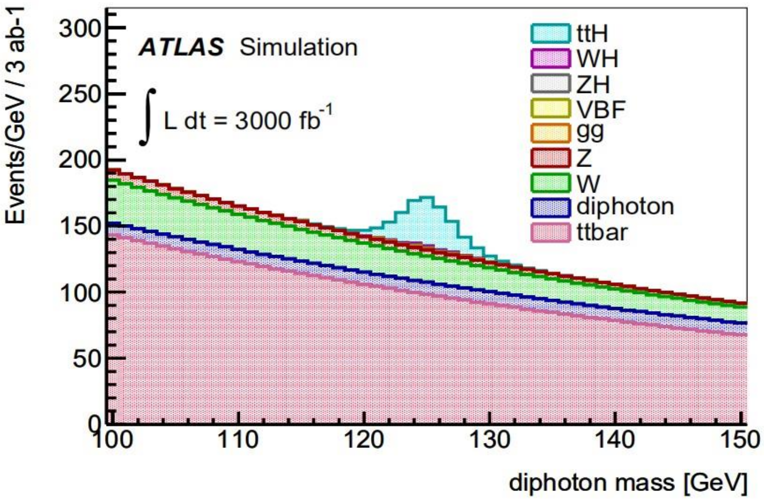

Figure 8. Accurate prediction of the coupling of the SM Higgs boson to other particles.

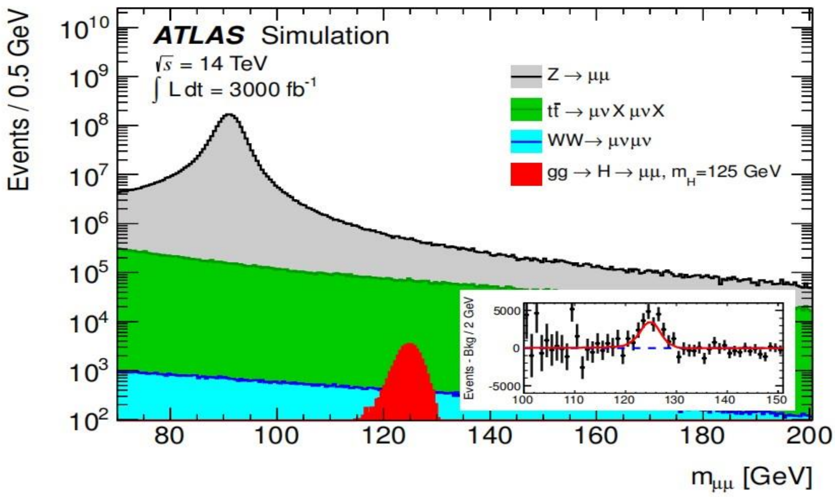

Figure 9. Accurate prediction of the coupling of the SM Higgs boson to other particles.

3.2. Quark and Gluon Search

To search for dark matter, we first need to know how it is produced by colliders, which also reflects the physical properties of it. In general, dark matter production theories can be divided into the following three categories according to models: effective field models, simplified models, and complete models. In many practical and simplified field models, the standard model particles co-produced with dark matter particles may come from the initial quark or gluon radiation or directly from intermediate propagators. Generally, the chances of a single standard model particle being produced from such are high. So, the search for quarks and gluons is equally essential. In the past, the generic search for quarks and gluons was performed in the event of final states with multiple jets and sizeable transverse momentum deficit features [7]. And in the future, HL-LHC will improve the sensitivity of both particles in the following figure. If significant deviations relative to the SM background estimates are observed, the kinematic properties of the events can be studied, and thus the dark matter can be investigated [8]. Figure 10: 95CL exclusion limit and 5σ discovery range in the simplified square-guino model with massless neutrons, 300 fb^{-1} and 3000 fb^{-1}, Figure 11: The mbb-invariant mass distribution of the baseline SUSY model compared to the SM background process with an integrated luminosity of 3000 fb^{-1}

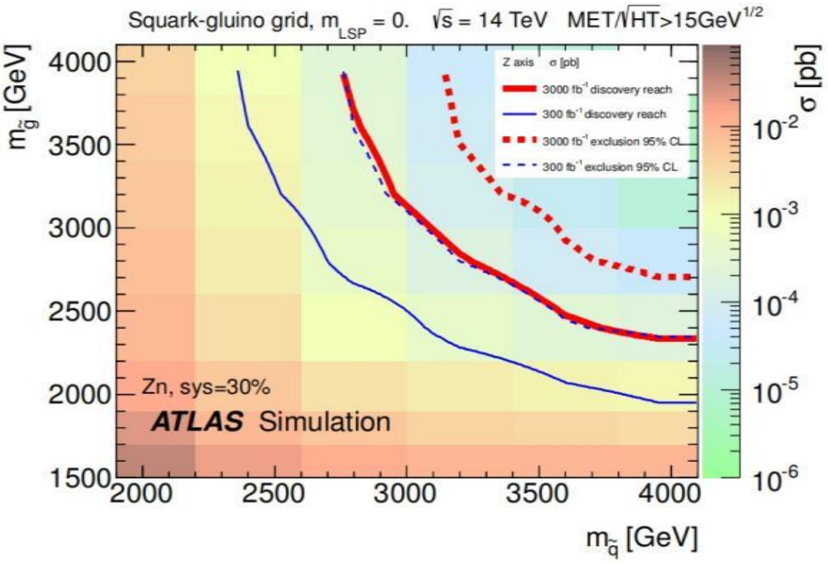

Figure 10. The simplified square-guino model.

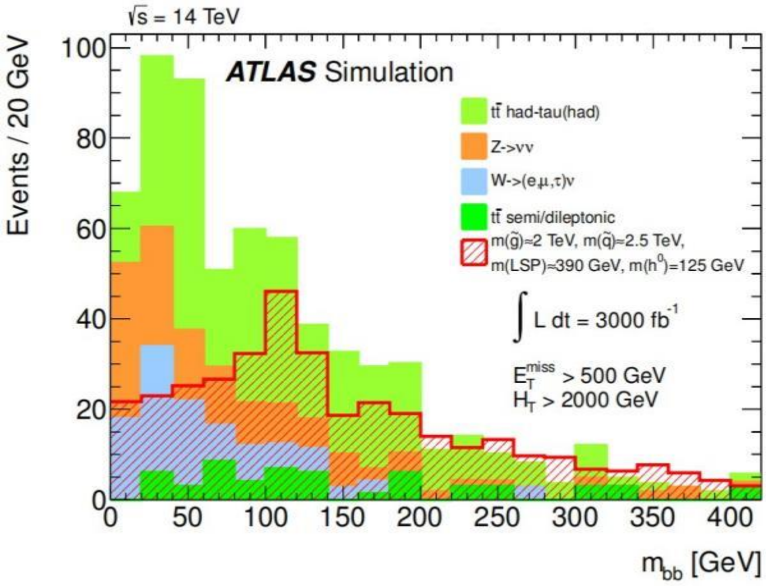

Figure 11. The mbb-invariant mass distribution.

The naturalness argument requires that the top quark is light below 1 TeV. The integrated luminosity at the HL-LHC will improve the sensitivity to the stops, and the stop candidates will be able to measure their properties. Figure 12 shows the discovery and exclusion potential in two studies concerning t˜ and X_1^0 masses. Figure 13 shows the m_T2 distribution of the dual leptonic channel, which helps distinguish the SUSY signal from the SM background processes. A 10-fold increase in integrated luminosity increases the range of sensitive stop masses to 200 GeV. They further improve the analysis technique by using specific features that distinguish the signal from the SM background.

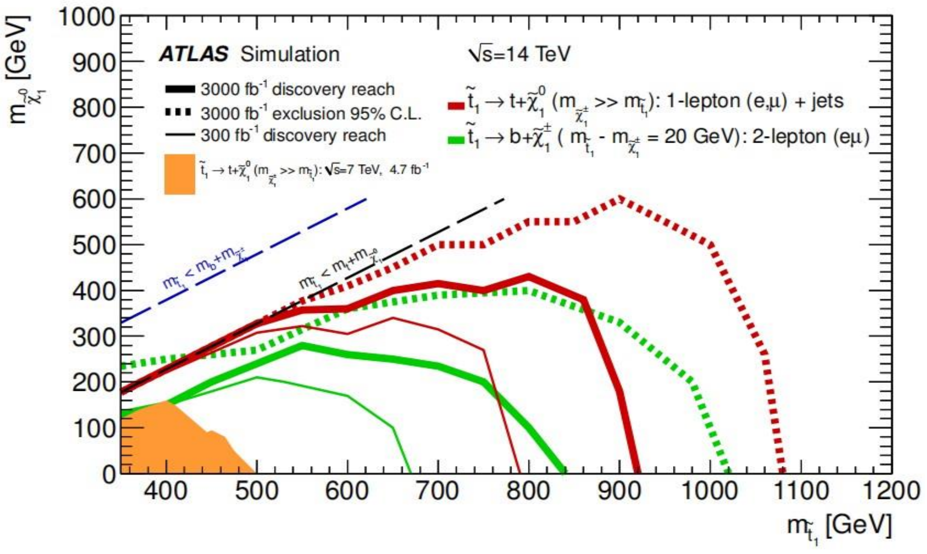

Figure 12. The Discovery and exclusion potential in two studies.

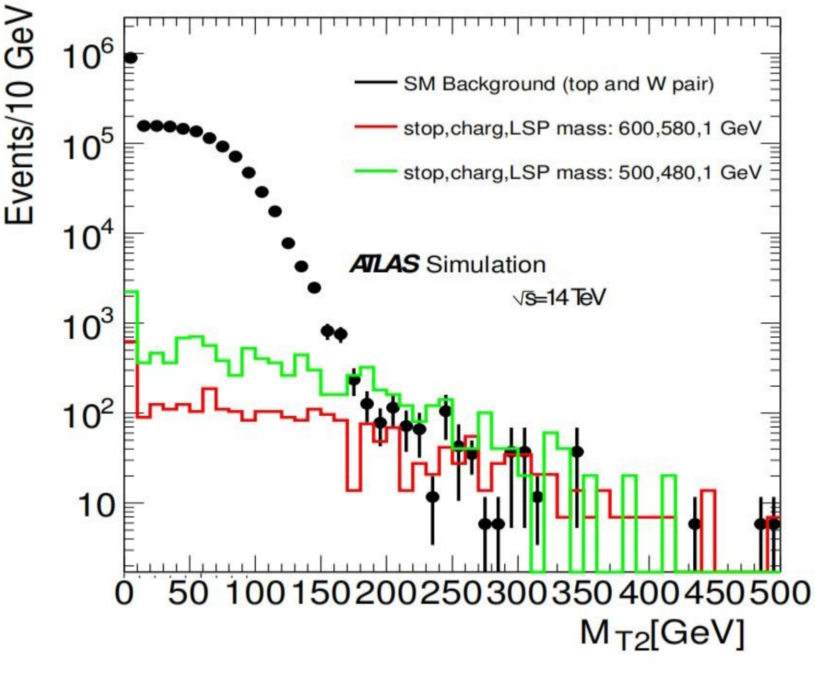

Figure 13. distribution of the double leptonic channel.

4. Conclusion

In general, CEPC covers a broader field of physics. By studying CEPC's exploration of Higgs measurements and new physics and external regions of the Standard Model, the authors summarize the characteristics of CEPC's research on the Higgs particle, whose experimental depth and precision are unmatched by other colliders. CEPC can perform a complete planarization of the Higgs particle, allowing a full range of empirical studies, such as the in-depth study and decryption of the Standard Model and the study of new physics and dark matter. The authors have studied the upgraded collider, the HL-LHC, by understanding the LHC, which focuses more on Higgs production. The HL-LHC is five to ten times brighter, which means that the research data will increase by the same factor, substantially improving the statistical accuracy and providing a vast amount of data for research, giving it a massive advantage in studying multiple particles. The collaboration between the two colliders will provide a comprehensive framework, from the interior of the Standard Model to other particles, such as dark matter. In the future, through their study of them, the author is sure it will allow us to learn more about the mysteries of the universe and the wonders of nature, an advancement in physics that will leave a profound mark on our human history.

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