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Overview of high energy physics and prospective dark matter detections at HL-LHC and CEPC

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Abstract. This paper first takes an overview of the current development of high-energy physics, including an introduction to the fundamental particles and forces described by the standard model, physics beyond the standard model like super-symmetry and matter-antimatter asymmetry, and current high-energy physics experiments such as ATLAS and CMS at the large hadron collider. Then we focus on the prospective dark matter detections at the high-luminosity large hadron collider (HL-LHC) and circular electron-positron collider (CEPC), especially the upgrades of the current LHC and different working modes of the CEPC. Finally, the paper discusses the prospects of dark matter detection and possibly dark matter candidates.

Keywords: high energy physics, dark matter, HL-LHC, CEPC, the standard model.

1. Introduction

The idea that matters in the universe consist of small fundamental building blocks can be traced back to the ancient Greek philosopher Democritus who proposed an atomic theory of the universe. Then, John Dalton, an English chemist and physicist in the 19th century, concluded that every element was made up of a unique type of particle called an atom. In the early 20th century, the discovery of electrons, protons, and neutrons begins the study of subatomic particles. In the 1950s and 1960s, various new particles were discovered through the collisions between particle beams with high energy. Although these discoveries were incredible, it was the proposition of the Standard Model, which was framed in the context of quantum field theories, during the 1970s that began the age of modern particle physics (high energy physics).

High Energy Physics (HEP) goals include answering some of the most significant and fundamental questions about the universe. For example, what is our world made of? What are the fundamental forces that govern our universe? Is there a Grand Unified Theory of the universe? Through HEP experiments and the development of HEP theories, it is possible that someday we will find the answers to these big questions. Therefore, large circular accelerators and colliders were built, among which the largest is the Large Hadron Collider (LHC) located in the European Organization for Nuclear Research (CERN). Remarkably, one of the most incredible discoveries in HEP, the discovery of the Higgs Boson, was made at CERN.

So far, the Standard Model has incorporated all fundamental particles we have discovered and the most fundamental forces except for gravity. However, many questions remain unclear, including matter-antimatter asymmetry, the exclusion of gravity, and the nature of dark matter and dark energy.

Furthermore, there are 19 free parameters that we cannot calculate with the model, and the explanation of particle masses has not been verified.

2. Overview of High Energy Physics (HEP)

2.1. The standard model [1]

Despite its deficiencies, the Standard Model is the most successful theory in high-energy physics. According to the Standard Model, there are, in total, twelve fundamental fermions (fermions are particles that follow the Fermi-Dirac statistics) with spin $\frac{1}{2}$. Specifically, there are three generations of Quarks and three generations of leptons (Table 1-3):

Table 1. Quarks.

up (u)	charm (c)	top (t)
down (d)	strange (s)	bottom (b)

Table 2. Leptons.

electron (e^-)	muon (μ^-)	tau (τ^-)
electron neutrino	muon neutrino	tau neutrino

Besides the 12 fermions, there are four bosons that mediate the four fundamental interactions:

Table 3. Fundamental Forces and Corresponding Bosons.

Strong force	Electromagnetic force	Weak force	Gravitational force
gluon (g)	photon (γ)	W and Z bosons	graviton (not yet detected)

Finally, the Higgs Boson completed the current Standard Model when it was discovered in 2012 at the LHC.

2.1.1. Quarks. The defining characteristic of quarks is that they carry color charge, a property related to the strong interaction in quantum chromodynamics (QCD). Both quarks and gluons carry color charges, and quarks appear in different "colors." The combination of different colors describes how quarks will combine to form larger particles. To create a "colorless" particle, the only possibilities are mesons (formed by the combination of a quark and an antiquark) and baryons. Furthermore, quarks are "confined, " meaning they never appear alone. This phenomenon is called "quark confinement." Finally, according to the Standard Model, the up, charm, and top quarks all have $+\frac{2}{3}$ charge, and the down, strange, and bottom quarks have $-\frac{1}{3}$ control, which explains the charges of protons and neutrons.

2.1.2. The Higgs Boson. In modern particle physics, every particle is a wave in a particular field, and so is the Higgs Boson. The concept of a “Higgs field” was first proposed in 1964, and it was described as a field that fills every corner of the universe and gives all elementary particles their mass. By the "Higgs field" theory, what gives particles mass is the interaction between mass particles, and by the "Higgs field," particles like photons do not interact and thus have zero groups. The discovery of the Higgs Boson in 2012 is evidence of the "Higgs field."

2.2. Physics beyond the standard model

Physics beyond the Standard Model are new theories and possibilities to explain the current deficiencies of the Standard Model.

2.2.1. Matter antimatter asymmetry. The constituents of our universe --- the stars, planets, asteroids, and so on --- are made of matter, while no antimatter is found. The extreme imbalance between matter and antimatter is a mystery, and physicists believe that this imbalance is the result of the violations of a symmetry called charge-parity reversal (CP), which means that the universe flipped in a mirror does not have ultimately the same physics laws as the universe outside of the mirror [2]. There seems to be a natural way for CP symmetry to be broken within the current Standard Model. However, the prediction made by the standard model about the amount of violation is far less than enough to help us explain the matter-antimatter asymmetry in our universe.

This fact shows the deficiency of the Standard Model. Currently, two new accelerators, which will be able to probe violations of CP, are being built on understanding whether the Standard Model needs to be revamped or replaced.

2.2.2. Supersymmetry. The theory of supersymmetry is welcomed by physicists mainly because there are two things the Standard Model cannot explain. First, why the Standard Model takes the form it does, or precisely why the theory's mathematical structure is elegant and surprisingly simple, cannot be explained. Second, we do not understand the nature of mass and the fundamental interactions' strength [3]. So far, we can only use experiments to measure these quantities instead of calculating them with theories. The search for evidence of supersymmetry mainly focuses on the hunt for new particles because this theory requires every ordinary particle to have a “super-partner” with identical properties other than spin, which differs by half a unit. Supersymmetry is exceptional because it relates fermions and bosons together.

2.2.3. What is dark matter? About 27 percent of our universe is made up of dark matter, roughly six times the amount of ordinary matter. However, it does not emit light, reflect light, or interact with electromagnetic force. So far, the only way we can confirm the existence of dark matter is through its gravitational effects. This means that even if we created dark matter in our experiments, our detectors would not be able to discover it. However, since dark matter carries energy and momentum, we can infer its existence by measuring the missing power and rate after collisions. Candidates of the nature of dark matter are usually related to physics beyond the Standard Model.

2.3. Current and prospective HEP experiments

Modern HEP experiments are primarily based on circular accelerators and colliders, where high-energy particle rays collide with each other to produce subatomic particles. With detectors, we can know the properties, such as electric charge, mass, and spin, of the particles produced so that we can discover new particles and make more precise measurements of the properties of known particles. Many experiments are going on at the LHC, among which the two main collaborations are the ATLAS and CMS experiments.

2.3.1. ATLAS. ATLAS is one of the main experiments and collaborations at the LHC, and it investigates physics in various areas. During its operation, particles collide with each other in the form of beams at the center point of the ATLAS detector, producing new particles that fly out of the colliding point. The new particles are then captured by six detecting subsystems around the colliding point. The detectors include the tracking system, the solenoid magnet, the electromagnetic calorimeter, the hadronic calorimeter, and the muon spectrometer. First, all particles pass through the tracking system and the magnet, during which particles with electric charges are bent. Next, the particles enter the electromagnetic calorimeter, where all the electrons and photons experience an electromagnetic shower and are stopped. Then, the particles go into the hadronic calorimeter, where hadrons experience the hadronic shower, and their properties are measured. Finally, the muons and neutrinos go on since they are not stopped in any previous detectors. The muon is measured in the muon spectrometer, and neutrinos go through the entire detector without being seen. The operation of ATLAS needs an advanced “trigger” system to automatically tell which data to be kept and which to be disposed of because a huge amount of data is created, and not all of them are useful. As a result, the "trigger" system helps increase the experiment's efficiency [4].

2.3.2. The CMS experiment. The Compact Muon Solenoid (CMS), like ATLAS, is a general-purpose detector. The goals of their research are similar, but they are technically different. Specifically, the CMS uses a different magnetic system design; lies in the center of the CMS is a giant cylindrical solenoid magnet that generates a magnetic field of about 4 Tesla [5].

3. The High-Luminosity Large Hadron Collider (HL-LHC)

The LHC run 2 ended in 2018, followed by a Phase-I upgrade, and then run 3 begins in 2022. Four years later, the LHC will enter a new phase of operation, namely the HL-LHC phase. After the upgrade, the HL-LHC will deliver photon-photon collisions at $\sqrt{s} = 14\,\mathrm{TeV}$ with a baseline instantaneous luminosity of $5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ and maximum instantaneous luminosity of $7.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$. The HL-LHC is expected to enable ATLAS experiment to achieve a final integrated luminosity of about $3000\ \mathrm{fb^{-1}}$.

3.1. Upgrade overview

This section takes the upgrade of ATLAS as an example of how the LHC will be upgraded. The ATLAS Inner Tracker will be replaced entirely with the new silicon-only design, improving the momentum resolution, extending the pseudo-rapidity coverage, and reducing the material budget [6]. The hardware trigger system will be primarily redesigned, allowing for higher data granularity and enhanced flexibility beyond what will be afforded during Run 3 data taking. The Liquid Argon (LAr) Calorimeter will have a new frontend and readout electronics, and additional muon chambers will be built. Finally, the high-granularity timing detector will be installed in front of the LAr calorimeter.

3.2. Prospective dark matter searches at HL-LHC

This section will overview the searches for dark matter at ATLAS. Searches for dark matter at ATLAS can be divided into three main categories: (1) direct searches; (2) indirect searches; and (3) searches for light DM signals from dark sectors. Here, direct and indirect searches differ by whether dark matter particles are present in the final state. Search (1) focuses on the mono-X searches where the dark matter mass is smaller than the mediator, while case (2) occurs when the dark matter mass is heavier than the mediator. For case (3), new theories with hidden dark sectors included may be able to explain how the light dark matter particles escape our current searches [7]. In addition, the Higgs Boson could potentially provide us with new methods of searching for dark matter particles at LHC. Dark matter searches at the LHC are strongly complementary to the direct and indirect detections, so all three are significant in finding out the entire parameter space of a range of prospective theoretical models of dark matter.

4. The Circular Electron-Positron Collider (CEPC)

4.1. Introduction to the CEPC

The discovery of the Higgs Boson in 2012 was a milestone in the development of HEP because the Higgs Boson could potentially reveal the answers to some of the most fundamental questions about our universe, such as why the gravitational force is so weak compared to other basic details. Therefore, we will need a new collider that can help us better understand the Higgs Boson. This is the CEPC. At the current LHC and expected HL-LHC, which rely on proton-proton collisions, systematic uncertainty is inevitable and could lead to limitations on the measurements and detections. However, at CEPC, which studies electron-positron collisions, the frequent delays are practically avoided and, therefore, more precise and reliable [8]. In addition to its advantage in studying the Higgs Boson, the CEPC also has a crucial and irreplaceable role in detecting dark matter particles. It is possible that electroweak dark matter is missed by direct detections but seen by the CEPC. Also, even if current detectors discover the dark matter before the CEPC, it is still crucial because it can answer questions like what it is and how it interacts with other particles [8].

4.2. Prospective dark matter searches at CEPC

There are three different proposed running modes for CEPC, as shown in the table below (Table 4-5):

$\boldsymbol{\sqrt{s}}$.

Table 4. Total luminosity and duration of three modes.

Mode	$\sqrt{s}$ (GeV)	Total Luminosity (ab^{-1})	Duration (years)
Higgs Factory (H-mode)	240	~ 5.6	7
Z Factory (Z-mode)	91.2	~ 16	2
WW Threshold Scan (WW-mode)	~ 158-172	~ 2.6	1

Table 5. Processes in three .odes.

Mode	Process
Higgs Factory (H-mode)	$e^+e^- \to ZH$
Z Factory (Z-mode)	$e^+e^- \to Z$
WW Threshold Scan (WW-mode)	$e^+e^- \to W^+W^-$

In this section, we focus on the three types of dark matter models: (1) millicharged DM; (2) Z' portal DM; and (3) DM interactions with Standard Model via effective-field-theory (EFT) operators [9]. In most cases, dark matter particles fly through the detectors without being detected. Therefore, to see the dark matter in collisions, we need some detectable particles to be produced together with dark matter particles. Here, the monophoton process of dark matter particles is used.

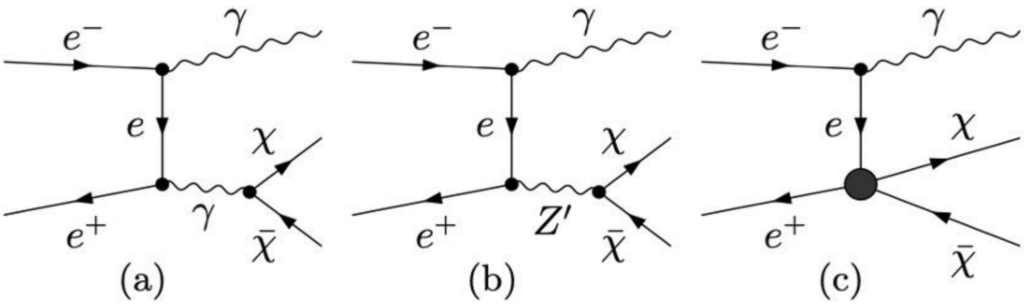

Figure 1. Feynman diagrams for the $e^+e^- \to \chi\bar{\chi}\gamma$ process in (a) millicharged. DM models; (b) Z' portal DM models; and (c) EFT DM models

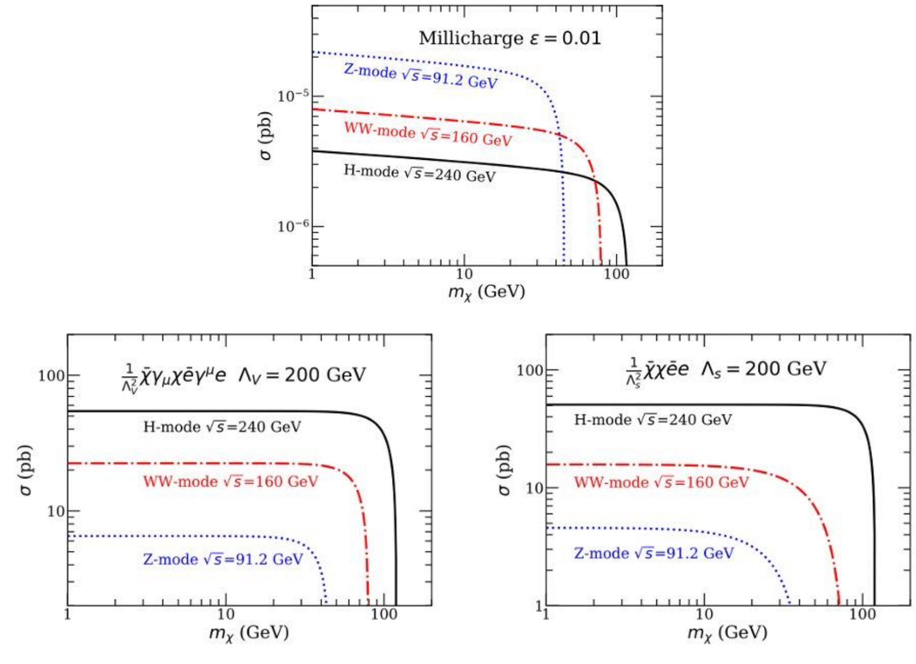

Figure 2 Total monophoton cross-section $\sigma(e^+e^- \to \chi\bar{\chi}\gamma)$ at CEPC in millicharged

DM models (upper panel) and EFT DM models (lower two panels)

From the upper panel of Figure 2, we can see that for dark matter lighter than 40 GeV, $\sqrt{}$ the monophoton cross-section increases as the value of s decreases. Therefore, Z-mode is the most sensitive among the three regarding the delicate millicharged dark matter. From the lower two panels of Figure 2, we can see an opposite trend: as $\sqrt{s}$ increases, the monophoton cross-section also increases. As a result, H-mode is the most sensitive among the three when it comes to probing four-fermion EFT dark matter models [9].

5. Prospects and conclusion

High-energy physics is an area that has the potential to answer some of the biggest questions in science. Although the Standard Model, one of the core models in high energy physics, has so far been successful in that it matches all the experimental measurements well, a significant number of mysteries remain unsolved. For example, what is dark matter? Is it a new group of particles or something we already knew? This is one of our main research directions. With the firm astronomical evidence of the existence of dark matter in our universe, we are not sure what its nature is. One of the DM candidates, the Weakly Interacting Massive Particles, is the leading search direction in current experiments [10]. We hope the oncoming upgrades of the LHC and the new prospective CEPC will help us detect dark matter particles and explain the nature of dark matter and other mysteries of the universe.

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