Different Detection Methods for Dark Matter

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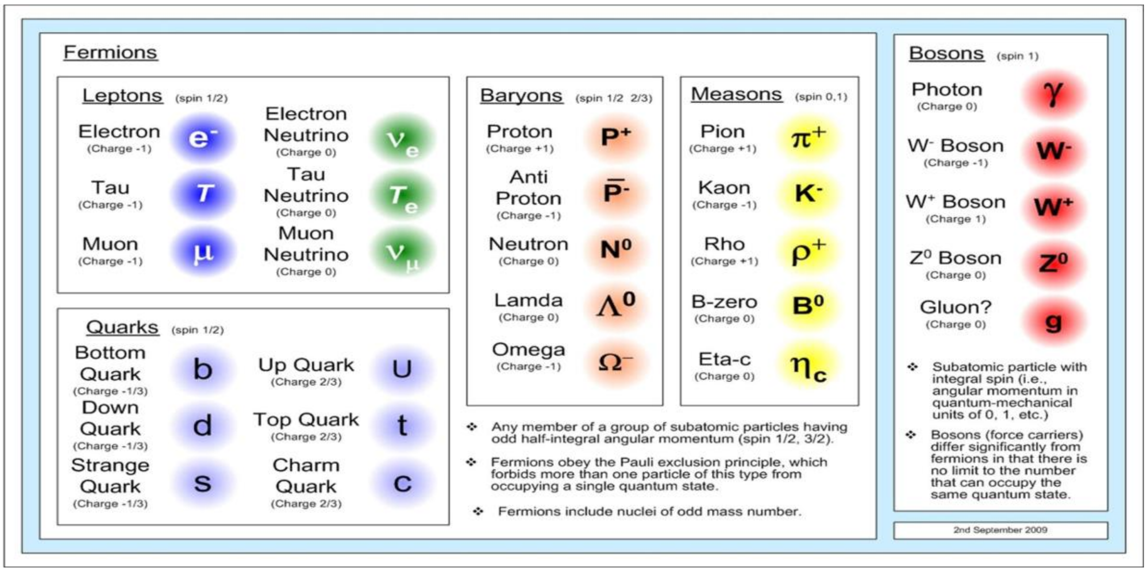
Abstract. Dark matter has been proposed to fulfill the missing mass from Astro-observation. Many theories have been raised to explain dark matter, and weakly interacting massive particles (WIMPs) are one of them. In recent decades, dark matter detection sensitivity has improved significantly. However, solid evidence for their existence has not come yet. This paper outlines some methods for detecting dark matter, including direct detections, collider searches with the ATLAS detector at LHC, and collider searches with CEPC.

Keywords: Dark Matter, Direct Detection, ATLAS, CEPC.

1. Introduction



- Any member of a group of subatomic particles having odd half-integral angular momentum (spin 1/2, 3/2).
- Fermions obey the Pauli exclusion principle, which forbids more than one particle of this type from occupying a single quantum state.
- Fermions include nuclei of odd mass number.

- Subatomic particle with integral spin (i.e., angular momentum in quantum-mechanical units of 0, 1, etc.)
- Bosons (force carriers) differ significantly from fermions in that there is no limit to the number that can occupy the same quantum state.

Figure 1. Standard Model.

Physicists have always sought to provide a comprehensive explanation for our world. Among all the theories, the Standard Model is thought to be the most updated and sound theory in interpreting the physical world. Under the Standard Model framework, the world consists of two different particles: three generations of fermions with a spin of n+1/2 and bosons with an integral spin. While the firstgeneration leptons combine to form atoms, the bosons are in charge of the fundamental forces. The Standard Model could explain all three fundamental interactions except for the carrier for gravity. Details about Standard Model particles are shown in Figure 1. However, the Standard Model is not perfect. There are still many questions that cannot be explained, for example, the natureless problem, the dark matter, and the matter-antimatter asymmetry of the universe. In this passage, I will discuss the detections of dark matter, which will provide significant evidence for models beyond the Standard Model.

2. Dark Matter

2.1. The Missing Mass

According to general relativity, a massive object, such as clusters of galaxies, can bend light reaching us from a more distant galaxy, producing the so-called gravitational lens effect. This enables us to observe multiple distorted images of the same galaxy. Using this effect, scientists calculate that the universe's mass is more than ordinary observable matter. The unexpected rotation curves of spiral galaxies also show that there should be additional mass in the universe. This additional mass is assumed to be dark matter. Scientists have calculated that there should be five times as much dark matter as ordinary.

2.2. Theoretical Framework

There are serval models that should be considered during the detection of dark matter. The most popular among them is the Weakly Interacting Massive Particles (WIMPs), the soundest and widely accepted model. WIMPs theory assumes that dark matter is a new, massive, stable particle that interacts only through gravity and any unknown forces that are not part of the Standard Model. The new interaction should be weaker, or at least as weak, as the weak interaction. Particle from the supersymmetry (SUSY) model is one of the best candidates for WIMPs. It is also called the 'WIMP miracle. While the WIMPs present us with their basic properties, the SUSY explains the behaviors in detail using its complete models. However, recent direct detection and experiments at LHC have placed limits and cast doubt on the theory.

Another kind of approach includes entirely new models. The SUSY and the Universal Extra Dimension (USD) are the most popular. These models not only explain the existence of dark matter but also offer self-consistent extensions to the Standard Model. Take the SUSY as an example; it assumes the existence of a superpartner to every Standard Model particle. For example, the spin 1/2 electron and the quark have a superpartner with spin 0 named selectron and squark, while spin 1 photon and gluon have a superpartner with spin 1/2 named photino and gluino [1]. Since the super-particles interact weakly with the Standard Model particles, they could be possible candidates for dark matter. However, these models need many details to prove their validity, and the realization of dark matter depends on those details. As a result, these models lack generality.

Scientists have also used the practical field theory (EFT) to describe the interaction between the dark matter candidates and the Standard Model particles. Moreover, the possible mediator for the new force is considered heavy. In the EFT, the dark matter could also interact with Higgs and vector bosons at colliders. However, the EFT is limited to interactions with small momentum transfer because it makes an unphysical prediction. In this passage, I am mainly going to focus on the detection of WIMPs.

3. Detection Methods

There are three main detection methods for possible dark matter candidates. The three methods include direct detection (though detecting the nuclear recoil energy from a scattering of dark matter), indirect detection (though detecting the annihilation of dark matter into ordinary matter), and high-energy collisions (though the missing energy and Standard Model particles produced among with dark matter). In this paper, I will mainly discuss direct detection and detection at different colliders (Figure 2).

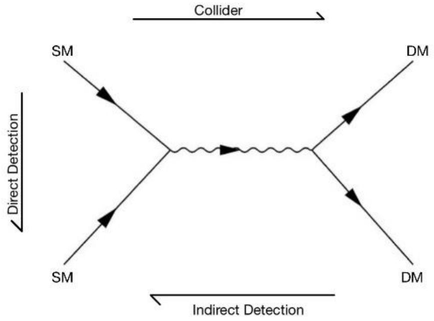


Figure 2. Detection Methods for Dark Matter.

4. Direct Detection for Dark Matter

4.1. Method

The direct detection experiments use the nuclear recoil energy from the galactic WIMPs' elastic scattering of the nucleus. According to the WIMPs model, this interaction should not have a nuclear spin or a proton-neutron dependence. Instead, the recoil energy can be transferred into thermal motion, ionization, or scintillation photons through the charged nucleus [2]. Most experiments will simultaneously detect two types of energy for a signal to suppress the effect of the electron recoil background. Also, the detector should be located deep underground to eliminate the background produced by cosmic rays; for example, the PandaX-II detector is 2400 meters underground [3]. The detector components should be constructed using high-purity materials to prevent influences from the experimental equipment. Due to the lack of technology to avoid solar and atmospheric neutrinos, the uncertainty caused by neutrinos scattering off the nucleus limits the sensitivity of direct detection. Although there has not been solid evidence for dark matter though direct detection, experiments have placed limits on different theoretical models. There are also possibilities that direct detection experiments cannot detect dark matter. The dark matter may be pure electroweak multiplets, which have minimal interaction with the Higgs boson. Another possibility is that even if it is a mixed multiplet, it could still interact with Higgs weakly, which is called the *blindspot* for direct detection.

4.2. Xenon and Argon detectors

One of the most widely used detectors is the dual-phase xenon dark matter detector. These detectors have pushed the sensitivity for the elastic spin-independent WIMP-nucleon scattering. Scientists make use of the ^{136}Xe element's double-beta decay. This kind of decay has negligible influence on the experiments' detection. Scientists also use the two arrays of photomultiplier tubes in the liquid-xenon time projection chamber to produce significant vertex reconstruction, enabling them to distinguish between nuclear and electron recoil signals. There have been serval xenon detectors around the world. The LUX, a 250kg xenon detector, and a half-ton PandaX-II are among them. While the LUX presented a minimum of 1.1×10^{-46} limit cross-section for a WIMP mass of 50 GeV/c^2[4], the PandaX-II has a limit of 2.5×10^{-46} at 40GeV/c^2 [3]. In addition, at this sensitivity level, the effect of underground sources of minerals begins to play a role. Scientists are trying to find a way to eliminate their influences. The LZ, the successor of LUX, a 7-ton detector, is expected to have a sensitivity limit of 3×10^{-48} at 40GeV/c^2. Moreover, China plans to build PandaX-4T and PandaX-30T with 4 tons and 30 tons of xenon, respectively.

Another element used in the direct detection of dark matter is Argon. Compared to ^{136}Xe, Ar takes advantage of its low cost and mainly focuses on detecting high-mass WIMPs. People are able to construct detectors with serval tons of argon, even detectors with a few hundred-ton are foreseeable. For example, the DarkSide-20k detector is expected to have 20-ton of argon and a sensitivity of 9×10^{-48} at 1TeV/c^2.

5. Dark Matter Detection with ATLAS at LHC

5.1. The ATLAS Detector

The ATLAS detector is the largest general-purpose detector on the Large Hadronic Collider. The detector is forward-backward symmetric concerning the interaction point (IP). It mainly consists of 4 parts: the inner detector, the calorimeters, the muon spectrometers, and the magnet system [5]. The inner detector tracks the charged particles with great accuracy, detecting their interaction with points on the detector; the calorimeters measure the energy of easily stopped and 'stable' particles; the muon system measures that of muons which are highly penetrating; the magnet system that bends the charged particles and allows us to detect their charge and momentum though curved direction and curvature (Figure 3).

For energy measurement, the basic idea is pretty simple. When the particles from the interaction point travel through the detector materials, they will either knock out some atomic electrons or emit a photon that carries away energy if the particles' energy is high enough. The rate for the relativistic particle to lose energy while traversing the matter is described by the Bethe-Bloch equation [6]:

$$-\langle\frac{dE}{dx}\rangle = \frac{4\pi}{m_e c^2}\cdot\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right)-\beta^2\right]$$

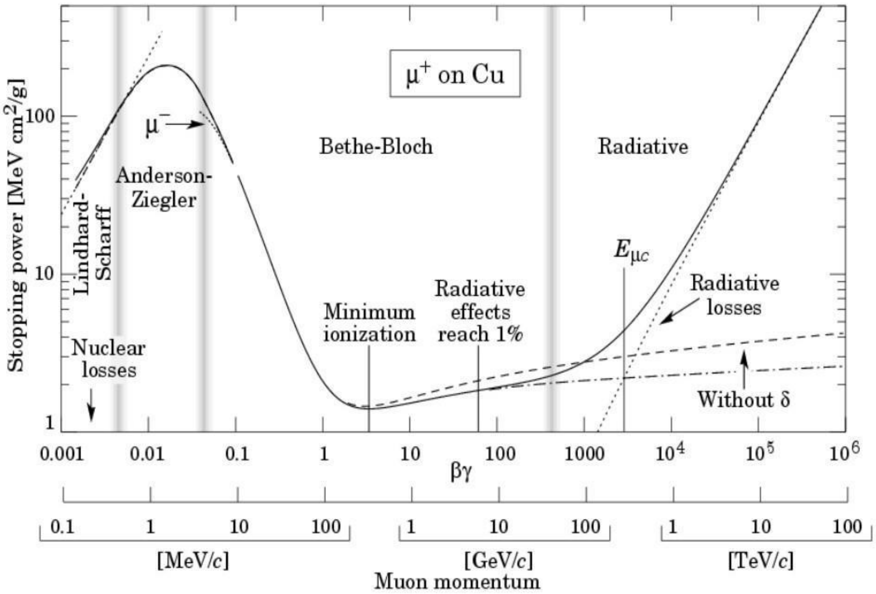


Figure 3. Graph for Bethe-Bloch formula.

We can see from Figure 4, the stopping power first rises and then fall to the minimum ionization. Then, it rises slowly and then increases rapidly. It is apparent that as the power increase, radiative plays the dominant role, and the equation is getting closer and closer to the red line for radiative alone.

For tracking, scientists just have to look at all the points certain particles pass through and then use the computer to calculate the track. The general machine layout of the ATLAS detector is shown in Figure 5.

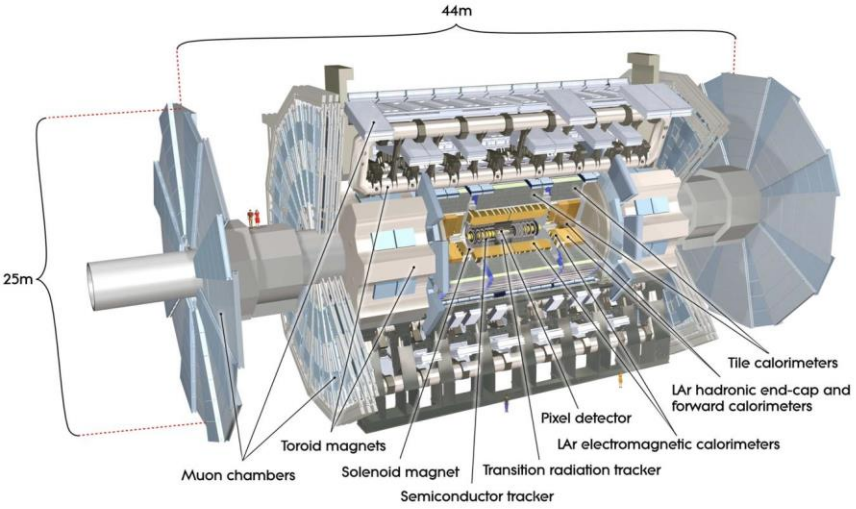


Figure 4. Cutaway view of the ATLAS detector.

5.2. Detection of Dark Matter at ATLAS

There are three main categories of searches for dark matter at ATLAS: searches in final states with dark matter, searches without dark matter, and searches for light dark matter signals from dark sectors [8]. When the dark matter particle's mass is small compared to the mediator, WIMP in the opposite direction of visible particles will be produced, resulting in the mono-X signature [7]. When the mediator's mass is smaller, the constraint from mono-X searches will be weaker. This is when searches in final states without dark matter play a role; for example, searches for the unexpected signals in the di-jet invariant mass spectrum or angular momentum. At the same time, the last category is valid when the dark matter particle is hidden in the dark sector for different complete extension models. I will not discuss the dark matter in the dark sectors in this passage. Because the QCD coupling significantly with other interactions and they have a distinctive experimental signature, the LHC has studied these events extensively. The expected signals for this kind of event are the difference in the distribution of miss transverse momentum (E_T^{miss}). Dark matter is expected to produce the distribution of E_T^{miss} that is significantly different from the Standard Model's prediction [7]. When dark matter interacts mainly with the heavy quarks, Yukawa-like couplings are preferred. Furthermore, the discovery of the Higgs boson provides an additional way for detecting in final states with dark matter, which is the invisible Higgs decay.

We could conduct indirect searches for the mediator for final states without dark matter. If dark matter is produced at the LHC, the mediator for this process will decay back to ordinary matter like quarks, gluons, or leptons. Therefore, we could interpret the results for narrow resonances and look for evidence of dark matter mediators. Backgrounds under scenarios are modeled using MC samples.

6. Dark matter searches at CEPC

6.1. The General Machine Layout

The Circular Electron-Positron Collider (CEPC) is a double-ring collider proposed in 2012. The collider is expected to start construction in 2022 and be complete in 2030. After it is completed, it will be the largest electron-positron collider in the world. The CEPC is designed to serve as a Higgs factory at 240GeV. It will also be able to operate as Z boson factory at 91GeV and W boson factory at 160GeV [8]. In addition, the tunnel of CEPC is large enough to accommodate the future SPPC.

The CEPC is 100km long. It mainly consists of the linear accelerator (Linac), the booster, the collider, and eight straight sections. The eight straight sections are two interaction points, two RF stations, and four injection regions. The beams of electrons and positrons will first be accelerated at the Linac, and then injected into the booster for further acceleration. After they reach enough speed, they will finally be injected into the collider and collide at the interaction points. While the off-axis injection is for all three modes, the on-axis injection is only used for the Higgs mode. While the RF cavities are used for the acceleration of electrons and positrons, the interaction points of SPPC will be placed in the same straight regions.

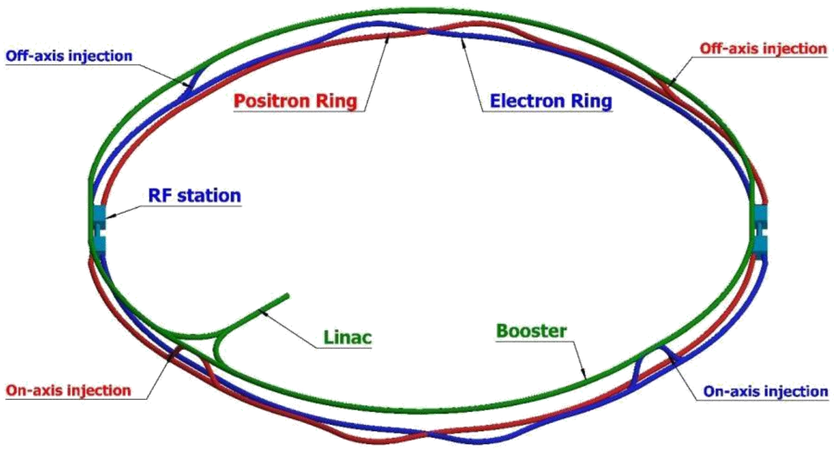
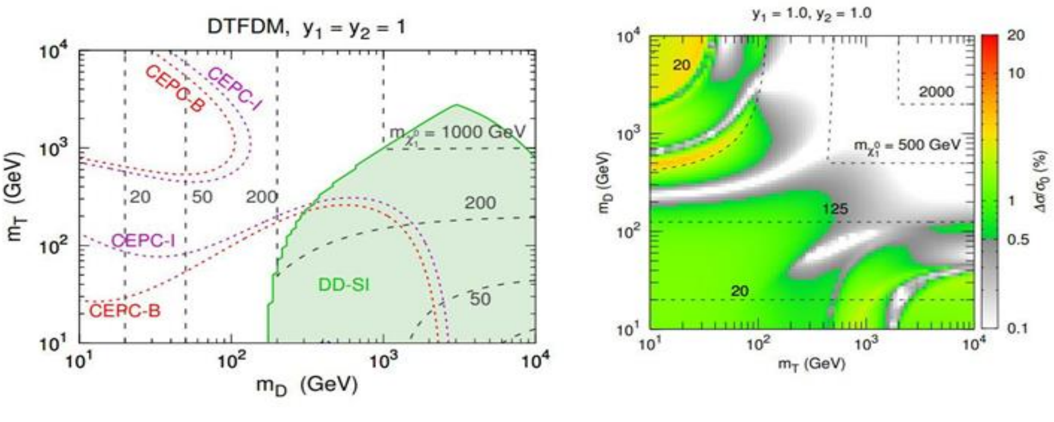


Figure 5. CEPC layout.

6.2. Detection of Dark Matter at the CEPC

Possible dark matter particles could interact with the Standard Model in various ways that can be detected at CEPC. First, the new particles may carry standard model charges. Although the dark matter must not contain charges, it may belong to an SU (2) multiplet that contains charges [9]. As we have mentioned above, for pure multiplets and the blind spot scenario, direct detection will not be effective detection method. Thus, I am going to focus on this. Second, through renormalizable standard model portals. Third, through portals with additional standard model sector physics or new charged groups that the Standard Model is charged under. Even though the dark matter candidates do not interact with existing bosons, new force carriers may lead to couplings between the dark matter and the Standard Model particles [9]. The last way is the practical theory. This model-independent approach simply looks for the missing energy plus some Standard Model particles.



(a) (b)

Figure 6. (a) The CEPC electroweak precision (S , T) fit probe of the doublet-triplet model at the custodially symmetry point[10]. (b) CEPC's sensitivity to the same scenario via the Higgsstrahlung cross-section σ [11].

Since the CEPC is a machine designed for Higgs and electroweak physics, it is especially sensitive for detecting dark matter particles that belong to electroweak multiplets. Two of the models are doublet-singlet models and doublet-triplet models. Both of the models have a blind spot for either spin-dependent or spin-independent direct detection. In the context of SUSY, we assume the fields S , D, T to be bino, higgsino, and wino. Although the couplings may be small in the case of SUSY, which leads to small signals, it is reasonable to consider the Minimum Supersymmetric Model (MSSM). The MSSM provides us with why the mass of the Higgs is heavier than that predicted by SUSY. We can see from figure 6 that CEPC can test dark matter theories to a large degree below 200GeV. While *the S* parameter is sensitive to the region hidden from direct detection, the custodial symmetry also suppresses the T parameter.

7. Conclusion and Future Perspective

Although scientists have tried to prove the existence of dark matter through various methods, no solid evidence has been found. More sensitive searches for dark matter are still on the way: the XENON1T direct detector, the CEPC, and the upgraded LHC. All the experiments share a possibility for detecting dark matter. Moreover, only a few dark matter theories have been tested. There are more models ready to be explored.

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