Ph.D. Thesis

Probing Electroweakly Interacting Massive Particles with Drell-Yan Process at 100 TeV Colliders

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December 2019

Abstract

(♣ To be written ♣) The main part of this thesis is based on our works [1,2].

Acknowledgments

I would like to thank my supervisor, Takeo Moroi, who provided stimulating discussions, helpful comments, fruitful suggestions and collaboration and proofread the earlier version of this thesis.

(♣ Appreciate more ♣)

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Section 1
Introduction

1.1 Overview

There are many models that extend the standard model (SM) of the particle physics by introducing weakly interacting massive particles (WIMPs), which have interactions with SM particles whose size is comparable to the electroweak gauge coupling. We have many theoretical motivations to introduce WIMPs, some of which are listed below.

- One of the motivations is the existence of the dark matter (DM) in our universe. When we assume a stable WIMP with its interaction strength comparable to the electroweak gauge coupling, its thermal relic abundance agrees with the observation if its mass is of $\mathcal{O}(\text{TeV})$ or so.

- Such $\mathcal{O}(\text{TeV})$ WIMPs often appear in well-motivated models beyond the standard model (BSM). For example, the following two models contain such WIMPs: the minimally supersymmetric standard model (MSSM) introduced to solve the hierarchy problem and the minimal dark matter (MDM) model that can explain the existence and stability of the DM in a minimal extension of the SM.

Besides, models with WIMPs are also phenomenologically interesting because

- Such $\mathcal{O}(\text{TeV})$ WIMPs are likely to be discovered by many kinds of experiments such as the dark matter searches and the particle colliders.

Considering the second point, many of the WIMPs in the BSM models mentioned above have non-zero electroweak charges, which explain its weak interaction with SM particles. In this thesis, we would like to focus on such kind of WIMPs and seek ways to search for them.[♮1]

In the MSSM, it is known that the supersymmetric (SUSY) partner of the electroweak gauge bosons or the Higgs boson can be the lightest supersymmetric particles (LSP) and are natural DM candidate. In particular, there are well motivated scenarios where the so-called Higgsino or Wino play the role of the LSP, which transform as doublet and triplet under

[♮1] The word "WIMPs" is usually used in a broader sense that includes particles with some unknown weak interactions with SM particles. To distinguish this usage with ours, which only denotes some particles with non-zero electroweak charge, it may be better to call them as "WIMPs", abbreviation of electroweakly interacting massive particles. However, within this thesis, we will just use "WIMPs" in a narrow sense obeying the widely spread custom.

the weak $SU(2)_L$ gauge symmetry, respectively; light Higgsino is preferred to reduce the amount of the fine-tuning of the electroweak scale as in the "natural SUSY" set up [3–6], while the so-called "mini-split" spectrum [7–12] with anomaly mediation [13,14] makes Wino LSP. Another example, the MDM scenario [15–17], introduces a larger $SU(2)_L$ multiplet, whose stability is automatically ensured by the charge assignment. In particular, a 5-plet Majorana fermion with hypercharge zero is a good DM candidate that escape from the DM search experiments so far.

To search for WIMPs, several different approaches are adopted. One way is to rely on DM search experiments, assuming that the WIMPs are the dominant component of the DM. Firstly, there exist several direct detection experiments that utilize a scattering between the DM and the nucleus [18–20]. Wino is one of the promising targets of these experiments, whose spin independent scattering cross section with a nucleon is almost mass independently given as $\sigma_p^{\mathrm{SI}} \simeq 2.3 \times 10^{-47}\,\mathrm{cm}^2$ [21–25], which is still an order of magnitude below the current experimental limit. The situation for Higgsino highly depends on the size of the mixing between Higgsino and SUSY partners of electroweak gauge bosons (or electroweakinos). However, it is particularly difficult to detect (almost) pure Higgsino DM since its scattering cross section is comparable to or below that of the neutrino background [22]. The detection of MDM may also be difficult [26] since its possibly larger mass of $\mathcal{O}(10)$ TeV weakens the sensitivity of direct detection experiments.

Secondly, a lot of efforts are devoted to detecting cosmic rays resulting from DM annihilation, namely the DM indirect detection [27–30]. Although the results suffer from some astrophysical uncertainties, they have already excluded, for example, Wino with mass less than 400 GeV and also around 2 TeV [31]. On the other hand, the corresponding Higgsino bound is weaker and it has been probed only up to 350 GeV [32] again due to the smallness of its $SU(2)_L$ charge. For the MDM, 5-plet fermion is analyzed as an example in [33] and the mass less than 2 TeV and several narrow regions are excluded. Note again that the WIMPs must be the dominant component of the DM for these approaches to be sensitive.

Another way of probing WIMPs is the direct production at the large hadron collider (LHC). One of the good strategies of the collider search for WIMPs is to use the disappearing charged track signal, which indicates a long-lived charged particle, the charged components of the WIMP in the current case. Both ATLAS and CMS collaborations announced a result of this method with the data of $\sqrt{s} = 13\,\mathrm{TeV}$ LHC [34–36]. The current lower bound on the mass of the pure Higgsino-like (Wino-like) state is 152 (460) GeV at 95 % C.L. We can obtain a similar bound for the MDM using the same method [37]. In this method, however, the bound strongly depends on the lifetime of the charged component, which is sensitive to the mass difference between the charged and the neutral components. In particular, it is often the case in the SUSY model that the Higgsino-like LSP and its charged counterpart possess a non-negligible fraction of electroweakinos, which significantly enhances the mass difference compared to the pure Higgsino case. In such a case, the lifetime of the charged component is extremely short, making the disappearing track search challenging. There is another option called mono-X search to search for a new physics signal in general. However, the corresponding bound is usually very weak due to the large SM background and no bound is imposed on Higgsino at $\sqrt{s} = 14\,\mathrm{TeV}$ LHC [38].

Given this situation, it has been discussed that indirect search for WIMPs using precision measurement is useful [39–45]. It utilizes a pair production of charged leptons or that of a charged lepton and a neutrino, where WIMPs affect the pair production processes through the vacuum polarizations of the electroweak gauge bosons. The current status and future prospects have been analyzed for several different setups, indicating that it provides a promising way to probe Higgsino as well as the other WIMPs. A virtue of this method is that it is robust against the change of the lifetime and the decay modes of WIMPs and whether an WIMP constitutes a sizable portion of the DM or not. Another important point is that, due to WIMPs, the invariant mass distributions of the final state particles show sharp dip-like behavior at the invariant mass close to twice the WIMP mass. It helps us to distinguish the WIMP effects from backgrounds and systematic errors. This second point, however, also indicates that we need sufficiently large number of events with TeV-scale or sub-TeV invariant masses. As a result, the prospect of the reach for Higgsino is still unsatisfactory; $m_\chi \lesssim 100 - 200\,\mathrm{GeV}$ for the high luminosity LHC [43, 45] and $m_\chi \lesssim 500\,\mathrm{GeV}$ for lepton colliders with $\sqrt{s} = 1\,\mathrm{TeV}$ assuming $1\,\%$ systematic errors [42].

Thus, it is important to consider the application of this method for higher energy colliders. In particular, in this thesis, we study the prospect of the indirect search method at future $100\,\mathrm{TeV}$ hadron colliders such as FCC-hh at CERN [46–48] or SppC in China [49, 50]. We concentrate on the lepton pair production processes since they provide a very clean signal without any hadronic jets at least from the final state particles. We will show that it provides a comparable or better experimental reach for Higgsino compared to the direct production search of WIMPs at future colliders [51–54]. This method also provides independent and additional information about Wino and the MDM. Besides, we will reveal that this method is useful to investigate WIMP properties, such as charges, masses, and spins.

1.2 Organization of this thesis

This thesis is organized as follows.

In Sec. ??, we briefly review models with WIMPs considered in the thesis. Sec. ?? is devoted to the minimally supersymmetric standard model, while Sec. ?? to the minimal dark matter model. The mass splitting among the multiplet, which is a phenomenologically important property of WIMPs, is described in Sec. ??. The WIMP properties are summarized in Sec. ??.

In Sec. ??, we summarize the WIMP properties as a DM candidate. We show the calculation of thermal relic abundance and derive the required mass for WIMP DMs in Sec. ??. Then, we review two different approaches to search for WIMP DMs, called the direct detection described in Sec. ?? and the indirect detection in Sec. ??. We summarize the situation of the WIMP DM searches in Sec. ??.

In Sec. ??, we study the WIMP production at the hadron collider experiments and its detection. Possible production processes and the kinematics of the produced WIMPs are summarized in Sec. ??. Using the production processes described here, the current status and the prospect at the future 100 TeV colliders are reviewed in the following subsections. Sec. ?? and Sec. ?? are devoted to the description of one of the most promising ways for the WIMP search called the disappearing track search and the mono-jet search, respectively.

In Sec. ??, we discuss our own ideas [1, 2] to probe the one-loop effect of WIMPs on the lepton pair production processes through the precise measurement at 100 TeV colliders. Here, we will describe our statistical analysis, show the obtained reach for WIMPs, and see the possibility to determine the WIMP properties after its discovery. Conclusions of the thesis are presented in Sec. ??.

In Appendices, we first summarize the conventions and notations used in the thesis in ??. Then, we briefly review the $\mathcal{N} = 1$ supersymmetry in Appendix ??, the procedure we have adopted to perform the collider simulation on the MDM models in Appendix ??, the properties of the so-called transverse mass used in our analysis in Appendix ??, and the statistical analysis method called the profile likelihood method in Sec. ??.

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