PROCEEDINGS OF SCIENCE

# Particle Dark Matter at Hadron Colliders

**Matthew Low***
*Department of Physics, Enrico Fermi Institute, and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637*
*E-mail:* mattlow@uchicago.edu

**Lian-Tao Wang**
*Department of Physics, Enrico Fermi Institute, and Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637*
*E-mail:* liantaow@uchicago.edu

In weak-scale theories of beyond the Standard Model physics, particle dark matter is ubiquitous. This is for good reason as the simplest interpretation of observations point towards TeV-scale dark matter with weak-strength interactions. One promising way to search of this type of dark matter is via production at hadron colliders. In these proceedings we will discuss strategies for searching for dark matter at hadron colliders and present projections on the sensitivity of colliders to simplified models and to neutralino dark matter.

*XXIII International Workshop on Deep-Inelastic Scattering*
*27 April - May 1 2015*
*Dallas, Texas*

*Speaker.





PoS(DIS2015)111

## 1. Introduction

There is a substantial body of evidence for the existence of dark matter [1]. Its effects have been observed in galactic rotation curves, in the cosmic microwave background, and in gravitational lensing, just to name a few cases. While its identity is unknown, a compelling possibility is that it is a TeV-scale particle charged under the SU(2) of the standard model. This scenario is one of the most widely studied because particles of this type, weakly interacting massive particles (WIMP), both come naturally from many models of new physics and produce signals in a wide variety of experiments.

Assuming thermal production, reproducing the correct relic density yields the relation

$$M_{\rm DM} \lesssim 1.8 \text{ TeV} \left(\frac{g_{\rm eff}^2}{0.3}\right). \tag{1.1}$$

This provides us with the expectation that the interesting parameter space for thermal WIMPs is the TeV scale. This also roughly coincides with the mass scales that will be probed at hadron collider experiments in the near and next-to-near future. Specifically, the Large Hadron Collider (LHC) will provide crucial input into WIMP searches. Unfortunately, as we will point out, the LHC is insufficient to reach masses required for the correct thermal relic abundance, but a proposed 100 TeV collider would cover most of the parameter space [2, 3, 4].

In this study we would like to avoid assumptions about dark matter production that are closely tied to the full spectrum of new particles so we will consider simplified models. There are three common approaches to dark matter simplified models: dark matter production from effective operators, dark matter production with new mediators, and dark matter production with standard model mediators. In this work we study dark matter production with standard model mediators, namely the $W$ and $Z$ bosons. This is most simply implemented by considering dark matter particles in SU(2) multiplets.

In Section 2 the collider reach for doublets and triplets will be presented. Singlets are discussed after, in Section 3, because they require another particle in the spectrum. Finally, Section 4 will summarize and present conclusions. Note that minimal low energy supersymmetry contains particles in these multiplets so we will frequently refer to these particles by their supersymmetric names. The results, however, are general and do not depend on an implementation inside of a supersymmetric model.

## 2. Doublets and Triplets

We start with the SU(2) triplet case, which is also called the wino. For this dark matter candidate there are three states which assemble themselves into a charged state $\chi^{\pm}$ and a neutral Majorana state $\chi^0$. They are nearly mass degenerate but the charged state is heavier, due to infrared effects, by an amount $\Delta m \simeq 166$ MeV (in the heavy mass limit) [5]. For a thermally produced wino, a mass of $m_\chi = 3$ TeV saturates the relic density. It will be some time before direct detection experiments are sensitive to winos because of their low cross-section, but winos may already be ruled out by indirect detection, depending on the halo profile [6, 7].

At a hadron collider there are two main searches that can be performed in searching for pure winos. The first consists of considering the pair production of winos along with initial state radiation (ISR). The signal is missing energy from the winos recoiling against the ISR emission. We only consider the case for an ISR emission of jets, known as the monojet signature, but other ISR emissions are expected, such as photons and $W/Z$'s. Due to the higher rates, the monojet signature is more sensitive than the other mono-$X$ searches.

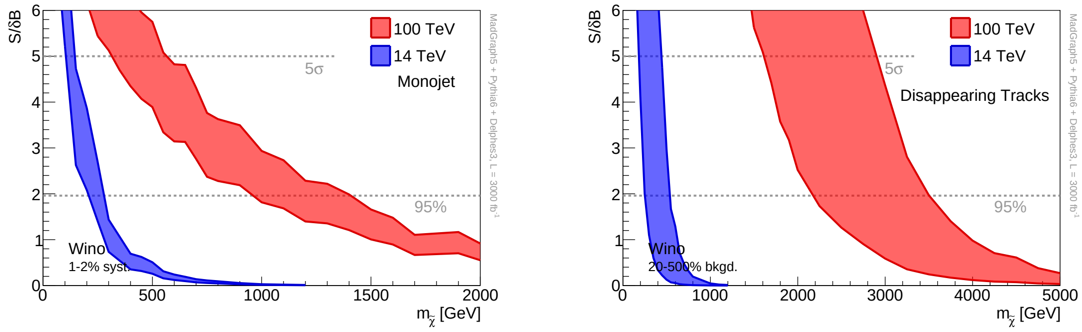


**Figure 1:** Wino projections from [2] in the monojet channel (left) and disappearing tracks channel (right).

The main backgrounds for monojet searches are $Z$+jets where the $Z$ decays to a pair of neutrinos and $W$+jets where the $W$ decays to a lepton and neutrino and the lepton is outside of the acceptance. The search then consists of triggering on a hard ISR jet, looking for large missing energy, and vetoing on additional leptons and jets. ATLAS and CMS have done these searches in their 7 and 8 TeV data, although not for this particular signal [8, 9]. In Figure 1 (left) we show the LHC reach at 14 TeV in blue. The width of the band is generated by varying the assumed systematic uncertainty whose impact on the search significance is given by

$$\text{significance} = \frac{S}{\delta B} = \frac{S}{\sqrt{B + \lambda^2 B^2 + \gamma^2 S^2}}, \tag{2.1}$$

where $S$ is the number of signal events, $B$ is the number of background events, $\lambda$ is the systematic uncertainty on the background, and $\gamma$ is the systematic uncertainty on the signal. Throughout we assume a 10% systematic uncertainty on the signal.

From the results we see that the mass reach is 200 - 280 GeV, depending on the systematics. Such a strong dependence on systematics indicates that this result is systematics dominated which means that there is room for potential improvement depending on the level to which the experiments can lower their systematic uncertainties. In any case, the reach falls far short of the 3 TeV mark and in fact even in the entire future LHC dataset one does not expect to produce a single 3 TeV wino. For this reason, the reach using a 100 TeV proton-proton collider is shown in red and reaches 1.0 - 1.4 TeV.

The second search one can perform is called a disappearing tracks search. In this case one uses the fact that the small charged-neutral splitting between the wino states results in long lifetime for the charged state before it decays to the neutral state and a soft pion. In a detector one can see the partial track from the charged state until the track disappears due to the decay. The efficacy of this search crucially depends on the mass splitting and for the wino the splitting yields a chargino lifetime of $c\tau \simeq 6$ cm.

The projected reach for the disappearing tracks search in shown in Figure 1 (right) and is about 400 GeV at 14 TeV and 3 TeV at 100 TeV. These searches are much more sensitive because there is no physics background in this channel, only detector backgrounds. As such, this makes the projection much less certain because the backgrounds in different detector configurations could be drastically different, although ATLAS and CMS appear to have similar backgrounds in their 8 TeV searches [10, 11]. Accordingly, the bands in Figure 1 vary over a wide range of possible systematic uncertainties. In any case, it is clear that this channel holds the most potential for discovering or ruling out winos at colliders.

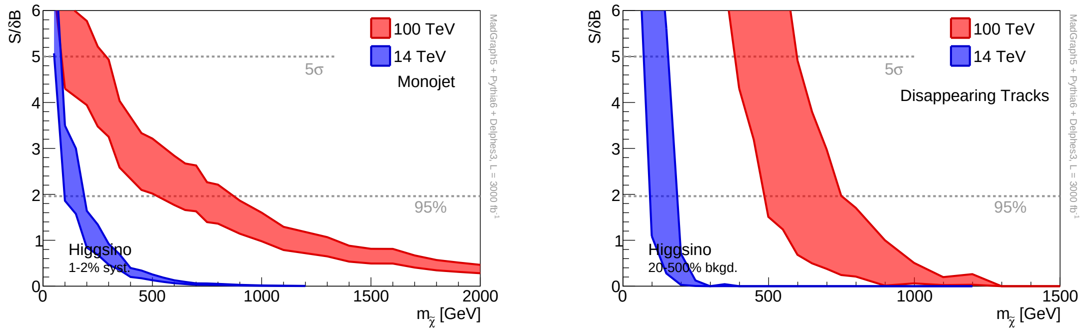


**Figure 2:** Higgsino projections from [2] in the monojet channel (left) and disappearing tracks channel (right).

Next we discuss the SU(2) doublet case, known as the Higgsino, which actually contains two doublets with opposite hypercharge, as is necessary to obtain an electrically neutral state. One now has a charged state $\chi^{\pm}$ and two neutral states $\chi_1^0$ and $\chi_2^0$. For a thermal relic, one needs a 1 TeV Higgsino. Our collider statements about the wino carry over the Higgsino with two small modifications. The first is that Higgsinos are produced with a smaller rate, due to the smaller effective SU(2) charge and the second is that there is a different charged-neutral mass splitting. The lower rate corresponds to less sensitivity compared to winos. The mass splitting (in the heavy mass limit) is $\Delta m \simeq 355$ MeV resulting in a chargino lifetime of $c\tau \simeq 6$ mm [12]. Unfortunately, this is also less favorable because most the tracks are no longer produce a sufficient number of hits in the tracker to show up as a disappearing track. Even on the direct detection side the Higgsino will be very difficult to observe because of a cancellation that makes the direct detection rate close to zero [13].

Figure 2 (left) shows the sensitivity in the monojet channel which is 100 - 200 GeV at 14 TeV and 600 - 900 GeV at 100 TeV. The disappearing tracks channel in shown in Figure 2 (right) and has a reach of about 150 GeV at 14 TeV and 600 GeV at 100 TeV. The qualitative expectation for reduced sensitivity is reflected in the reach. The reduction in reach in disappearing tracks is more substantially because it suffers from both a reduced rate and a less favorable lifetime.

## 3. Coannihilation

Considering only renormalizable interactions a singlet fermion does not interact with the standard model. Thus for the singlet, also called the bino, to be dark matter it requires an additional state. The thermal relic density is then set by the mass splitting between the bino and the coannihilator and the identity of the coannihilator. For colored coannihilators the collider reach can be quite good compared to the doublet and triplet case because the rate is largely controlled by the production rate of the colored particle which is produced via QCD rather than through the electroweak interaction.

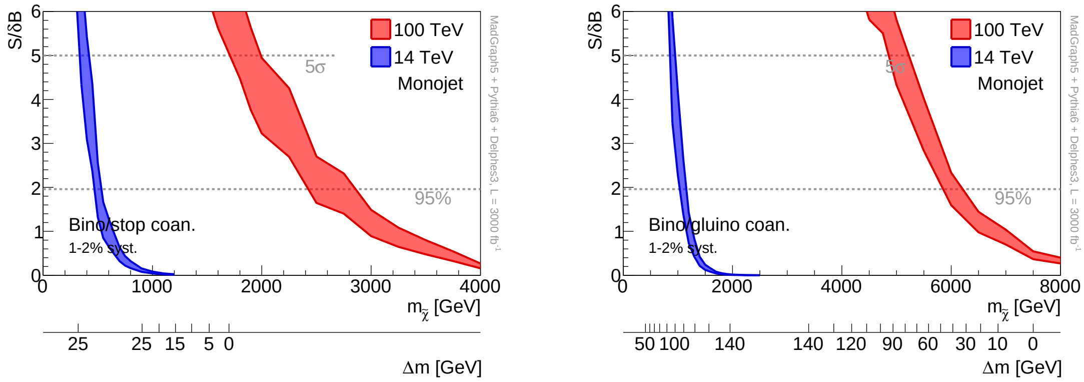


**Figure 3:** Monojet projections from [2] for bino/stop coannihilation (left) and bino/gluino coannihilation (right).

We consider stop/bino and gluino/bino coannihilation here, but additional scenarios are considered in [2]. For bino/stop coannihilation, a range of bino and stop masses can produce the correct relic density as a function of the splitting between them. The relation between the bino mass and the splitting was calculated in [14, 15] and is shown in the $x$-axes of Figure 3 (left). The LHC reaches about 500 GeV corresponding to splitting of about 25 GeV and a 100 TeV collider would reach 2.4 - 2.8 TeV which fully covers the allowed range. This is a nice case where colliders will give a certain answer as to whether this spectrum is realized or not.

For bino/gluino coannihilation, the results are shown in Figure 3 (right). Again, the $x$-axes relate the splitting to the bino mass as was calculated in [15]. A 1 TeV bino could be excluded at the LHC while a 6 TeV bino could be excluded at 100 TeV. While this does not cover the full parameter space it is worth noting that our search is the most conservative search possible. In particular, we assume in the decay of $\tilde{g} \to \tilde{B} + X$ that the $X$ is undetectable. Depending on exactly the identity of $X$ one can imagine looking for additional features in the event. While the signal acceptance would decrease slightly, the background would decrease by much more.

## 4. Conclusions

We addressed the dark matter scenarios of a wino, a higgsino, a bino and a stop, and a bino and gluinos. For winos, the potential of colliders is determined by the disappearing tracks search for which we have made rough estimates that predict that the wino parameter space can be covered at 100 TeV. On the other hand, for Higgsinos, the outlook is not as optimistic and it is unlikely one can observe pure Higgsinos even at 100 TeV. One possibility that would allow Higgsino dark matter to be observed is if there were also winos in the low energy spectrum that were light enough to be produced directly [16].

For stop and gluino coannihilation we found that even being agnostic as to the decay products of the stop and gluino both the LHC and a 100 TeV could cover reasonable regions of the open parameter space. This is because the cross-sections are controlled by the stop and gluino which are higher than the direct electroweak production of electroweakinos.

Ref. [2] also investigated a few other possible identities of the dark matter including bino/Higgsino mixtures and bino/wino mixtures. The results are summarized in Figure 4.

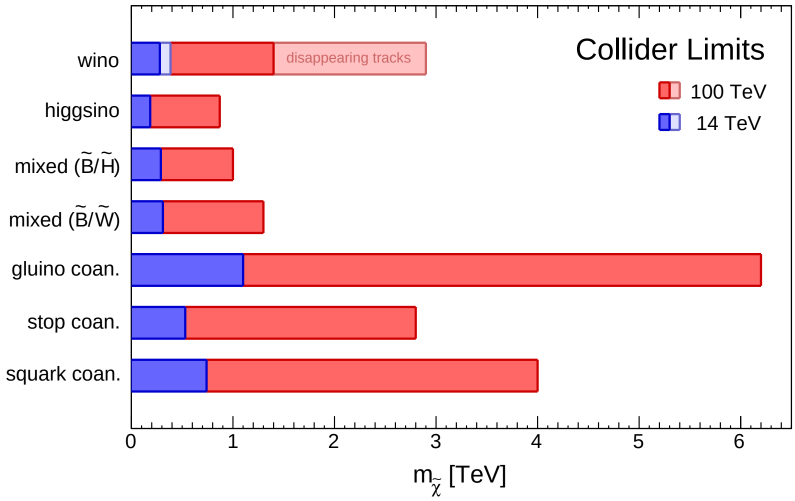


**Figure 4:** Summary of limits for neutralino dark matter at 14 TeV and 100 TeV [2].



## References

[1] G. Bertone, D. Hooper and J. Silk, Phys. Rept. **405**, 279 (2005) [hep-ph/0404175].

[2] M. Low and L. T. Wang, JHEP **1408**, 161 (2014) [arXiv:1404.0682 [hep-ph]].

[3] M. Cirelli, F. Sala and M. Taoso, JHEP **1410**, 033 (2014) [JHEP **1501**, 041 (2015)] [arXiv:1407.7058 [hep-ph]].

[4] A. Berlin, T. Lin, M. Low and L. T. Wang, Phys. Rev. D **91**, no. 11, 115002 (2015) [arXiv:1502.05044 [hep-ph]].

[5] M. Ibe, S. Matsumoto and R. Sato, Phys. Lett. B **721**, 252 (2013) [arXiv:1212.5989 [hep-ph]].

[6] T. Cohen, M. Lisanti, A. Pierce and T. R. Slatyer, JCAP **1310**, 061 (2013) [arXiv:1307.4082].

[7] J. Fan and M. Reece, JHEP **1310**, 124 (2013) [arXiv:1307.4400 [hep-ph]].

[8] V. Khachatryan *et al.* [CMS Collaboration], Eur. Phys. J. C **75**, no. 5, 235 (2015) [arXiv:1408.3583 [hep-ex]].

[9] G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **75**, no. 7, 299 (2015) [Eur. Phys. J. C **75**, no. 9, 408 (2015)] [arXiv:1502.01518 [hep-ex]].

[10] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **88**, no. 11, 112006 (2013) [arXiv:1310.3675 [hep-ex]].

[11] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1501**, 096 (2015) [arXiv:1411.6006 [hep-ex]].

[12] S. D. Thomas and J. D. Wells, Phys. Rev. Lett. **81**, 34 (1998) [hep-ph/9804359].

[13] R. J. Hill and M. P. Solon, Phys. Rev. Lett. **112**, 211602 (2014) [arXiv:1309.4092 [hep-ph]].

[14] K. Harigaya, K. Kaneta and S. Matsumoto, Phys. Rev. D **89**, no. 11, 115021 (2014) [arXiv:1403.0715 [hep-ph]].

[15] A. De Simone, G. F. Giudice and A. Strumia, JHEP **1406**, 081 (2014) [arXiv:1402.6287 [hep-ph]].

[16] S. Gori, S. Jung, L. T. Wang and J. D. Wells, JHEP **1412**, 108 (2014) [arXiv:1410.6287 [hep-ph]].

PoS(DIS2015)111