Astrophysical search strategies for accelerator blind dark matter

James D. Wells\textsuperscript{a} *

\textsuperscript{a}Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Abstract. A weakly interacting dark-matter particle may be very difficult to discover at an accelerator because it either (1) is too heavy, (2) has no standard-model gauge interactions, or (3) is almost degenerate with other states. In each of these cases, searches for annihilation products in the Galactic halo are useful probes of dark-matter properties. Using the example of supersymmetric dark matter, I demonstrate how astrophysical searches for dark matter may provide discovery and mass information inaccessible to collider physics programs such as the Tevatron and LHC.

1. Introduction

A stable, weakly interacting particle explanation for dark matter (DM) is attractive \cite{1}. This is because the astrophysics community declares its favorability from galaxy rotation curves, structure formation, etc., and the particle physics community has recognized that the lightest supersymmetric (SUSY) particle (LSP) is generically stable with $\mathcal{O}(\rho_c)$ relic abundance \cite{2}. Rather than causing a problem, the LSP provides a solution to the astrophysics concerns. Although axions and other DM candidates can be made to fit the data just as well as the LSP, it is perhaps a little less compelling since arbitrary axion parameters do not yield viable DM. This is purely aesthetic, and only experimental probes are allowed to make these decisions.

The focus of this article is the relationship between the SUSY theory of dark matter and the experimental probes of it. Often particle physicists think of the large hadron collider (LHC) as a kind of death for good people: when it happens we'll know all the answers. It is true that the LHC will have a tremendous mass reach for supersymmetry, and if nothing is found then it will be an unpleasant few weeks for particle physicists. However, these two extremes of thinking are not likely to be relevant. More likely, we will experience with the Tevatron and LHC a large collection of interesting observables that will be difficult even to interpret conclusively as supersymmetry (or some other theory). Not only that, even if some chargeless DM particles were produced at the colliders, we would only be able to say that the particles are stable on time scales less than the detector radius. Experiments devoted to discovering and confirming DM are necessary.

It could happen that the DM will not be seen at the colliders; or, it is seen but it will be difficult to say what its mass is. This is addressed specifically in this paper. There are probably other reasons why this could happen, but in the SUSY framework there are three good reasons:

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(1) The LSP is too heavy to be produced, (2) the LSP has no standard-model gauge interactions, and (3) the LSP is stable with other particles.

2. Heavy dark matter

In SUSY, the expectation is that the LSP is near the weak scale. This is because the same SUSY-breaking mass scale that sets the LSP mass also sets the $W$ mass. However, one immediately encounters the question: is 200 GeV “near the weak scale”? Or, is 2 TeV “near the weak scale”? The question is morphed into a response by devising a fine-tuning parameter that essentially indicates how far above the weak scale one is allowed to go and still call it “near the weak scale.” Again, the largest allowed mass scale of the LSP is not a question that humans are supposed to sound confident answering.

A question that we can answer is how far above the weak scale would SUSY have to be for us not to see it? Given a well-formulated theory, we can analyze it and answer this question. In so-called minimal supergravity scenarios with common scalar and common gaugino masses, the answer is that the gluinos and squarks have to be less than a few hundred GeV at the Tevatron and 2 TeV at the LHC [3]. Using renormalization group relations that predict the LSP mass in terms of these masses, we can conclude that the mass of the LSP must be below about 150 GeV to be seen at the Tevatron and perhaps 350 GeV to be seen at the LHC.

In minimal supergravity theories, the bino (superpartner of the hypercharge gauge boson) is generally the LSP [2]. It has some small mixing with the superpartners of the Higgs boson, which can play an interesting role in some observables (especially LSP scattering off nuclei in cryogenic detectors). For accelerator physics and annihilations in the Galactic halo, the bino component of the LSP is usually most important.

Since the LSP is a Majorana particle, annihilations into final state fermions must flip chirality in the $S$-wave. For $m_{\text{LSP}} < m_t$ this chirality flip is highly suppressing: $(\sigma v)_S \propto m_t^2/\tilde{m}^4$. Therefore, the annihilation proceeds through a $P$-wave, which is velocity suppressed (the LSP is a “cold relic” with non-relativistic energies). However, the annihilation rate in the galactic halo must proceed through the $S$-wave since the virial velocity today of the LSPs is only a few hundred kilometers per second (highly non-relativistic). So, it becomes a little tricky to correlate the relic abundance of a particle with its annihilation rate in the Galactic halo.

When the LSP is much heavier, this correlation becomes easier. The relic abundance now has a potentially large $S$-wave diagram proportional to $m_t^2$, and annihilations of the LSP in the Galactic halo do the same. Therefore, a one-to-one correspondence can be written for the two. Since binos cannot couple to winos or vector bosons, heavy LSP dark matter will want to annihilate almost 100% of the time into top quark pairs. One of the best DM observables [4] for this annihilation arises from $\chi\chi \rightarrow t\bar{t}$, where $t \rightarrow bW^+$ and then $W^+ \rightarrow e^+\nu$. The positrons can have an interesting energy profile from this annihilation signal. When contrasted with the energy profile of positrons from ordinary QED processes, a bump or shoulder is expected in the spectrum.

For LSP annihilations near the threshold of top pair production, there is a higher $e^+$ peak (near 30 GeV) corresponding to $W^+ \rightarrow e^+\nu$ decays and a lower peak corresponding to $b \rightarrow e^+\nu c$ decays in the $t\bar{t}$ events. Positrons from fragmentation of jets also contribute a continuum spectrum at the lower energies. These continuum positrons are difficult to separate from background positrons.
The all-electron spectrum measurements appeared to be slightly peaking in the $\sim 30$ GeV region, although the most recent and precise measurements are not conclusive [4].

3. Dark matter with no gauge interactions

It is also possible that the DM has no gauge interactions allowed. In the case of the bino, since it is the superpartner of the hypercharge gauge boson, one expects it to interact by gauge interactions with the right-handed sleptons, for example. Indeed, it is these gauge interactions that set the relic abundance of the bino LSP. However, if the dark matter is the superpartner of a Higgs singlet, then it has no gauge interactions at all, and cascade decays of MSSM states may not terminate with the true LSP inside the detector volume.

The superpotential of a singlet Higgs SUSY theory contains the terms $W = \lambda S H_u H_d + \lambda' S^3/3$. The fermionic component, $\chi_S$, of the $S$ chiral superfield could be the dark matter and it could annihilate into Higgs bosons if heavy enough. This possibility does not preclude interesting studies at colliders; however, I have separated it out as a good theory for astrophysical searches for two reasons. (1) In order for $\chi_S$ to be a good DM candidate it must be fairly heavy in order to annihilate into, for example, $h^0 + A^0$ final states. (2) These theories could have a significantly larger monochromatic two-photon signature from annihilations in the Galactic halo compared to ordinary minimal supergravity models.

The annihilation of $\chi_S \chi_S \rightarrow \gamma \gamma$ can occur via a pure Higgsino internal loop of particles enhanced by $\lambda^4$, if $\lambda$ is rather large. Even if it is 1, the enhancement over minimal supergravity models is at least as high as $g_1^2 \sim 10$. One can compare the scatter-plot points in P. Ullio’s results [6] for monochromatic photon flux and multiply by roughly an order of magnitude for the highest flux models at a given LSP mass and estimate the $\chi_S \chi_S$ signal. A long-exposure GLAST-like detector [7] with high energy resolution would be ideal to measure this signal.

4. Dark matter mass-degenerate with other particles

If the dark matter is degenerate with other particles, it might be difficult to find any particle. This is the case with the Higgsino LSP. The LSP is a singlet state of the Higgsinos and there is a triplet multiplet of Higgsinos just above the LSP. In collider experiments one often relies on the leptons from cascades of the next heaviest chargino or neutralino into the lightest neutralino (LSP). If there is mass degeneracy between these states, then the leptons will be very soft and undetected.

Astrophysical searches are good probes of the Higgsino LSP. The monochromatic two-photon searches [6] are especially useful, since the signal is expected to be rather large. In addition to the excitement that would arise by seeing such a signal, it could provide mass resolution that the Tevatron and LHC just could not provide. The GLAST detector, for example, could resolve an $\sim 100$ GeV dark-matter peak on the order of a percent or two mass resolution [7]. Tevatron and LHC have no absolute scale capabilities to measure the mass of the LSP, but rather can do fairly well with mass differences. For example in the decay $\chi_2^0 \rightarrow \mu^+ \mu^- \chi_1^0$, the invariant mass distribution of the muons can tell us the mass difference between $\chi_2^0$ and $\chi_1^0$ (the LSP). The absolute mass scale is difficult to extract in a general approach to LHC observables. However, the two photon peak can tell us this number to within a few percent.
5. Conclusion

So far, the usefulness of the $\bar{p}$-searches for DM has not been discussed. This is a very unique search strategy, because the signal is never expected to have any energy peaking associated with it. In the case of the positron and photon searches for DM, the energy peaks were necessary to resolve the signal from background. In the $\bar{p}$ observables, it is the background that has an energy peak. The secondary $\bar{p}$ flux from spallation peaks at about 1 GeV. This is easily derived from maintaining Lorentz invariance and baryon number conservation in $pp$ collisions. The interstellar $\bar{p}$ spectrum quickly falls above and below 1 GeV [8]. Above 1 GeV the SUSY prediction falls rapidly as well, and so it is not as useful; however, below 1 GeV the supersymmetric LSP annihilations can produce a large interstellar $\bar{p}$ flux measurable above the background.

The challenge with antiproton searches is solar modulation. The solar wind slows low-energy protons and antiprotons [8]. Thus when a proton or antiproton with kinetic energy less than 1 GeV enters the heliosphere, it might not be able to “swim upstream” to the earth-based detector, and if it does the energy could be drastically changed. Sophisticated modelling exists for these complicated effects, but it might be difficult to have confidence in a signal. For this reason, it could be useful to put an antiproton spectrometer on the recently considered interstellar probe [9]. It might take a few decades to reach beyond the $\sim 100$ AU required to get unambiguous results, but it is a relatively inexpensive piggy-back payload that has potentially enormous payoffs [10]. For example, primordial black holes, which (hopefully) have no chance of being produced at a collider experiment can evaporate antiprotons at a significant rate. Probing their existence is perhaps best accomplished with an interstellar antiproton spectrometer.

References

[1] V. Trimble, Ann. Rev. Astron. Astrophys. 25 (1987) 425.
[2] For discussion and references, see J. D. Wells, Nucl. Phys. Proc. Suppl. B 62 (1998) 235.
[3] H. Baer, C.-h. Chen, F. Paige, and X. Tata, Phys. Rev. D 52 (1995) 2746.
[4] E. Diehl, G. L. Kane, C. Kolda, and J. D. Wells, Phys. Rev. D 52 (1995) 4223; also see G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rept. 267 (1996) 195.
[5] S. W. Barwick et al. (The HEAT Collaboration), ApJ 482 (1997) L191 and astro-ph/9712324.
[6] P. Ullio, these proceedings; also see L. Bergström, P. Ullio, and J. H. Buckley, astro-ph/9712318.
[7] GLAST Collaboration (E. D. Bloom, G. Godfrey, and S. Ritz, eds.), SLAC report 522 (1998).
[8] T. K. Gaisser and R. K. Schaefer, ApJ 394 (1992) 174; also see A. W. Labrador and R. A. Mewaldt, ApJ 480 (1997) 371.
[9] R. A. Mewaldt, J. Kangas, S. Kerridge, and M. Neubebauer, “Small interstellar probe: a mission to the boundary of the heliosphere and nearby interstellar space,” presented at IAA Conf. on Low Cost Planetary Missions, APL/JHU, Laurel, MD, April 1994.
[10] J. D. Wells, A. Moiseev, and J. F. Ormes, SLAC report SLAC-PUB-7806.