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Astrophysical search strategies for accelerator blind dark matter

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Astrophysical search strategies for accelerator blind dark matter

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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 the dark matter is attractive [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 particle (LSP) is generically stable with $\mathcal{O}(\rho_c)$ relic abundance [2]. Rather than causing a problem, it provides a solution to the astrophysics concerns. Although axions and other dark matter 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 dark matter. This is purely aesthetic and only experimental probes are allowed to make these decisions.

In this talk I focus on the relationship between the supersymmetric 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 which will be difficult even to interpret conclusively as supersymmetry (or some other theory). Not only that, even if some chargeless dark matter particles were produced at the colliders we would only be able to say that it is stable on time scales less than the detector radius. Experiments devoted to discovering and confirming dark matter are necessary.

It could happen that the dark matter just won't be seen at the colliders, or that it is seen but it is difficult to say what its mass is. This is what I would like to address specifically in this talk. There are probably other reasons for why this would happen, but in the supersymmetric

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framework I can think of three good reasons: (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 supersymmetry, the expectation is that the LSP is near the weak scale. This is because the same supersymmetry breaking mass scale which 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 which 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 supersymmetry 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 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 which 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 galactic halo annihilations 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 $m_{\rm LSP} < m_t$ this chirality flip is highly suppressing: $(\sigma v)_S \propto m_f^2/\tilde{m}^4$. 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. So 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 dark matter observables [4] for this annihilation arises from $\chi\chi \to t\bar{t}$ where $t \to bW^+$ and then $W^+ \to e^+\nu$. 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 threshold of top pair production, there is a higher e^+ peak (near 30 GeV) corresponding to $W^+ \to e^+\nu$ decays and a lower peak corresponding to $b \to e^+\nu c$ 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 ~ 30 GeV region, although the most recent and precise measurements are not conclusive [5].

3. Dark matter with no gauge interactions

It is also possible that the dark matter 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 which 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.

The superpotential of a singlet Higgs supersymmetric theory contains the terms $W = \lambda S H_u \cdot H_d + \frac{\lambda'}{3} S^3$. The fermionic component (χ_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. One, in order for χ_S to be a good dark matter candidate it must be fairly heavy in order to annihilate into, for example, $h^0 + A^0$ final states. Two, 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 $\chi_S \chi_S \to \gamma\gamma$ can occur via a pure Higgsino internal loop of particles enhanced by λ^4, if λ 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 points in P. Ullio's talk [6] and multiply by roughly an order of magnitude for the highest flux models at a given LSP mass and estimate what the $\chi_S \chi_S$ signal is. A long exposure GLAST-like detector [7] with high energy resolution would be ideal to measure this signal.

4. Dark matter degenerate with other particles

If the dark matter is degenerate with other particles then it might be difficult to find any particle. This is the case with an 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 like Higgsinos – especially the two photon searches. The monochromatic signal is rather large in this scenario [6]. In addition to the excitement that would arise by seeing such a signal, it could provide mass resolution that the Tevatron and LHC just couldn't provide. The GLAST detector, for example, could resolve a ~ 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 $\chi_2^0 \to \mu^+\mu^-\chi_1^0$ the invariant mass distribution of the muons can tell us the mass difference between χ_2^0 and χ_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, I have said nothing about the $\bar{p}$ searches for dark matter. This is a very unique search strategy because the signal is never expected to have any energy peaking associate with it. In the case of the positron and photon searches for dark matter, 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 supersymmetry 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 causes all sorts of violence among protons and antiprotons with energies too low (< 1 GeV) to combat [8]. Thus, when a proton or antiproton with kinetic energy less than 1 GeV enters the heliosphere it might not be able to swim up the tide to the earth-based detector and if it does the energy could be drastically changed. Sophisticated modelling exists for these effects, but it would probably be difficult to obtain confidence of a signal over the skepticism of not understanding fully the solar modulation effects. 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 ~ 100 AU required to get unambiguous results, but it's 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.

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