Dark Matter Implications for Linear Colliders

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Abstract. The existence of dark matter is currently one of the strongest motivations for physics beyond the standard model. Its implications for future colliders are discussed. In the case of neutralino dark matter, cosmological bounds do not provide useful upper limits on superpartner masses. However, in simple models, cosmological considerations do imply that for supersymmetry to be observable at a 500 GeV linear collider, some signature of supersymmetry must appear *before* the LHC.

INTRODUCTION

In evaluating any large-scale future project in high energy physics, the critical question at present is its ability to discover and explore physics beyond the standard model. While many theoretical motivations for such physics exist, one of the most compelling phenomenologically (along with neutrino oscillations) is the evidence for dark matter. The energy density of luminous matter in the universe is $\Omega_{\rm lum} \approx 0.005$. At the same time, measurements of mass in galactic clusters, expected to be the largest virialized structures in the universe, require $\Omega_m \approx 0.2$ [1], and recent measurements of supernovae luminosities and CMB anisotropies imply $0.2 \lesssim \Omega_m \lesssim 0.4$ [2]. Additional observations require most of the dark matter to be cold and non-baryonic. No particles of the standard model (even suitably extended to include neutrino masses) are even remotely plausible candidates.

Among the most promising particles beyond the standard model are two motivated by fine-tuning problems — the lightest neutralino and the axion. Dark matter may be composed of either, neither, or both. Axion dark matter is of little relevance for high energy colliders (but is the subject of another vigorous experimental program [3]). In contrast, neutralino dark matter has strong implications for colliders and has even been argued to provide stringent upper bounds on superpartner masses. We will see that this is overly optimistic even in simple models [4].

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However, we will find that the requirement of neutralino dark matter does strongly constrain parameter space. In simple models like minimal supergravity, if superpartners are accessible at a 500 GeV linear collider, some hint of supersymmetry must appear before the LHC [5].

NEUTRALINO DARK MATTER

The lightest neutralino χ, is well-known to be an excellent dark matter candidate in R-parity conserving supergravity models [6]. In addition to being stable, neutral, and non-baryonic, its annihilation cross section gives, very roughly, the desired thermal relic density:

$$\Omega_\chi \approx \frac{10^{-10}\ \text{GeV}^{-2}}{\langle \sigma_A v \rangle} \sim \frac{10^{-10}\ \text{GeV}^{-2}}{(\alpha^2/m_W^2) \times 0.1} \sim 0.1\ . \tag{1}$$

To go beyond such general statements, one must specify precisely all of the many supersymmetry parameters that determine neutralino properties. The full parameter space is unwieldy. However, many important insights may be gained by considering the simple example of minimal supergravity. In this framework, the weak scale values of the Bino and Wino masses satisfy $2M_1 \approx M_2$, and $|\mu|$ is fixed by electroweak symmetry breaking and the universal scalar mass m_0 [7]:

$$\frac{1}{2} m_Z^2 \approx -0.04\ m_0^2 + 8.8\ M_1^2 - \mu^2\ . \tag{2}$$

The neutralino thermal relic density in minimal supergravity is given in Fig. 1. In the region $m_0 \lesssim 1$ TeV, an upper bound of, say, $\Omega_\chi h^2 \lesssim 0.3$ leads to upper bounds on both the universal scalar and gaugino masses. This is easy to understand qualitatively: in this region, Eq. (2) implies $M_1 < \mu$, and so $\chi \approx \tilde{B}$. Bino-like dark matter annihilates dominantly to fermion pairs through t-channel $\tilde{f}$ exchange, and so $\Omega_\chi h^2$ grows as m_0 increases. This line of reasoning seemingly leads to the conclusion that cosmology implies that some superpartners must be within reach of a TeV linear collider.

However, for $m_0 \gtrsim 1$ TeV, it is possible to satisfy Eq. (2) with $M_1 \sim \mu$, and χ may be a gaugino-Higgsino mixture. Such neutralinos dominantly annihilate through t-channel charginos and neutralinos to gauge bosons, and so another branch of parameter space with cosmologically-preferred $\Omega_\chi h^2$ exists. This branch extends to $m_\chi \sim 2.5$ TeV [4], where unitarity ultimately limits $\Omega_\chi h^2$. Thus, while cosmology does provide upper bounds on superpartner masses, the upper bounds are not stringent enough to guarantee supersymmetry at any foreseeable linear collider.

The $m_0 \gtrsim 1$ TeV branch, often neglected, is comparable in size to the conventional $m_0 \lesssim 1$ TeV branch and has significant virtues [8]: undesirable contributions to proton decay and electric dipole moments are suppressed, and heavy top and bottom squarks naturally predict Higgs boson masses of 115 GeV $\lesssim m_h \lesssim$ 120 GeV,

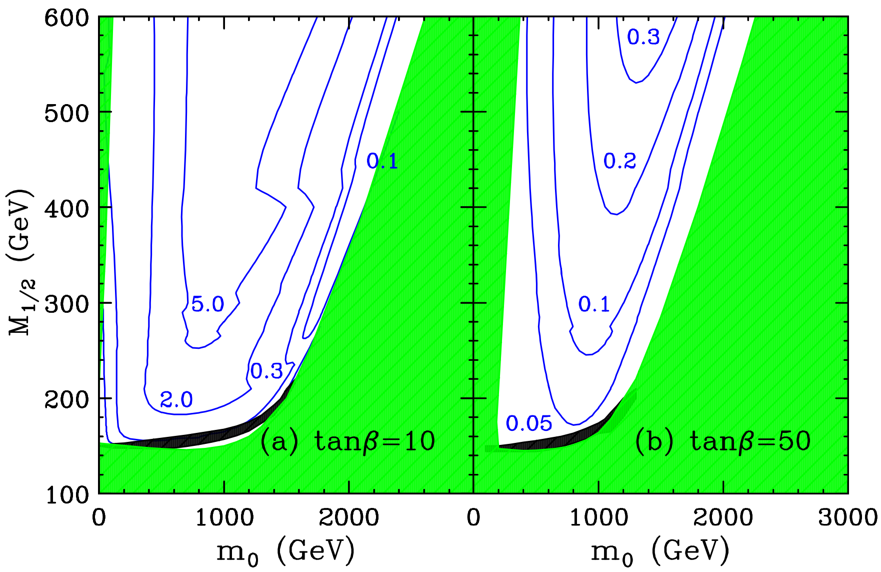

FIGURE 1. Contours of $\Omega_\chi h^2$ [4]. We fix $A_0 = 0$ and $\mu > 0$, and choose representative values of $\tan\beta$ as indicated. The shaded regions are excluded by the requirements of a neutral LSP (left) and the 103 GeV chargino mass bound (right and bottom). In the black region, neutralinos annihilate through the light Higgs pole. (Heavy Higgs poles also play a role in limited regions with $\tan\beta = 50$ and $m_0 < 1$ TeV.) Effects of co-annihilation, important along the boundaries of the excluded regions, have not been included.

the range preferred by current data. In addition, in a sense precisely defined in Ref. [7], no additional fine-tuning is required as a result of the interesting 'coincidence' that the top quark mass is $m_t \approx 180$ GeV [7,9].

PROSPECTS FOR SUPERSYMMETRY DISCOVERY

If neutralinos account for a significant fraction of the dark matter, many experiments have the potential to discover supersymmetry. On the $m_0 \lesssim 1$ TeV branch, traditional particle physics experiments are sensitive. On the other hand, for large m_0, many dark matter searches are especially powerful. The projected reaches of both particle physics experiments and dark matter searches by the year 2006 are given in Fig. 2. The observable signals, associated experiments, and expected sensitivities are given in Table 1.

In addition to the complementarity of the particle and astrophysical experiments, it is notable that all of the cosmologically-preferred parameter space accessible to a 500 GeV linear collider will lead to at least one hint of supersymmetry before the LHC begins operation. This conclusion applies for all $\tan\beta$ in minimal supergravity, and its qualitative structure suggests that similar conclusions will remain valid in alternative frameworks.

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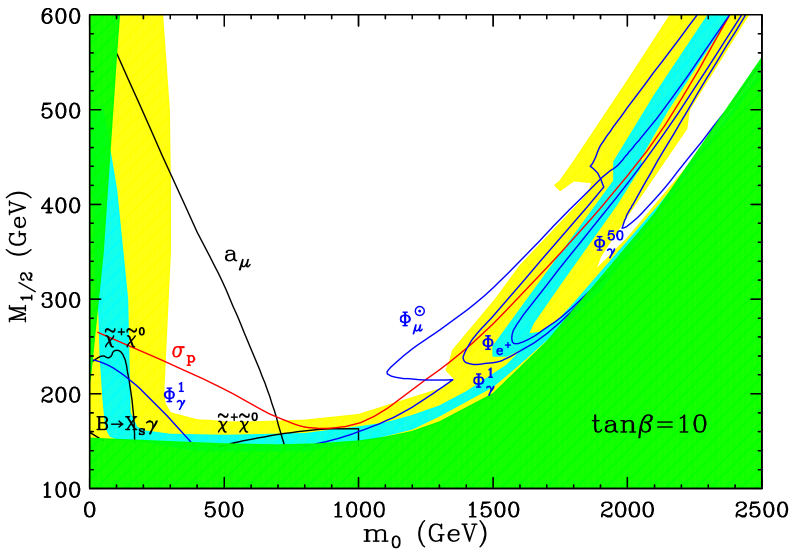

FIGURE 2. Reaches of various astrophysical and particle physics experiments expected by 2006 [5]. The excluded regions are as in Fig. 1. In the light (dark) shaded region, $0.025 \lesssim \Omega_\chi h^2 \lesssim 1$ ($0.1 \lesssim \Omega_\chi h^2 \lesssim 0.3$). The regions probed extend the curves toward the excluded regions.

TABLE 1. Supersymmetric signals and experimental sensitivities assumed in Fig. 2.

Observable	Type	Sensitivity	Experiment(s)
$\tilde{\chi}^{\pm}\tilde{\chi}^{0}$	Collider	See Ref. [5]	Tevatron: CDF, D0
$B \to X_s \gamma$	Low energy	$\lvert\Delta B(B \to X_s\gamma)\rvert < 1.2 \times 10^{-4}$	BaBar, BELLE
Muon MDM	Low energy	$\lvert a_\mu^{\rm SUSY}\rvert < 8 \times 10^{-10}$	Brookhaven E821
$\sigma_{\rm proton}$	Direct DM	$\sim 10^{-8}$ pb (See Ref. [5])	CDMS, CRESST, GENIUS
ν from Earth	Indirect DM	$\Phi_\mu^{\oplus} < 100$ km^{-2} yr^{-1}	Amanda, Nestor, Antares
ν from Sun	Indirect DM	$\Phi_\mu^{\odot} < 100$ km^{-2} yr^{-1}	Amanda, Nestor, Antares
γ (gal. center)	Indirect DM	$\Phi_\gamma(1) < 1.5 \times 10^{-10}$ cm^{-2} s^{-1}	GLAST
γ (gal. center)	Indirect DM	$\Phi_\gamma(50) < 7 \times 10^{-12}$ cm^{-2} s^{-1}	MAGIC
e^+ cosmic rays	Indirect DM	$(S/B)_{\rm max} < 0.01$	AMS-02

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