

Particle and Astroparticle Searches for Supersymmetry

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Supersymmetry may be discovered at high energy colliders, through low energy precision measurements, and by dark matter searches. We present a comprehensive analysis of all available probes in minimal supergravity. This work extends previous analyses by including the focus point branch of parameter space and the full array of promising indirect dark matter searches. We find that particle and astrophysical searches underway are highly complementary: each separately provides only partial coverage of the available parameter space, but together they probe almost all models. Cosmology does *not* provide upper bounds on superpartner masses useful for future colliders. At the same time, in the cosmologically preferred region, if supersymmetry is to be observable at a 500 GeV linear collider, some signature of supersymmetry must appear *before* the LHC.

Weak-scale supersymmetry has consequences for a wide variety of particle physics experiments. At the same time, it is now well-established that luminous matter makes up only a small fraction of the mass of the observed universe [1]. Neutralinos in supersymmetry are well-motivated candidates to provide much or all of the non-baryonic dark matter. While it is conceivable that all standard model superpartners are unstable, decaying, for example, into gravitinos or axinos, in many model frameworks, a neutralino is the lightest supersymmetric particle (LSP) and stable. Further, neutralino thermal relic densities of the desired amount are remarkably generic in supergravity models [2]. If neutralinos make up a significant portion of the halo dark matter, astrophysical searches for dark matter open up many additional avenues for the discovery of supersymmetry.

Here we summarize results of two studies of current and near future prospects for supersymmetry searches [3, 4]. We consider minimal supergravity, a simple framework that is conservative in the sense that many low energy signals generic in supersymmetry are suppressed. This work extends previous analyses in two ways. First, we include the focus point branch of supersymmetry parameter space [5], previously neglected. As we will see, neutralino dark matter in the focus point region has novel properties, with strong, positive implications for dark matter searches. Second, we consider not only collider experiments, low energy probes, and direct dark matter searches, but also the full array of indirect dark matter searches. We find that the various searches are highly complementary, and this comprehensive approach leads to strong conclusions that may be reached only by considering all available experiments.

The signals we consider, the projected sensitivities, and the experiments likely to achieve them, are listed in Table I. Conventional particle physics probes include searches at LEP and the Tevatron, the improved measurement of the the $B \rightarrow X_s \gamma$ branching ratio at B factories, as well as the projected final sensitivity of the Brookhaven $g_\mu - 2$ experiment. On the astrophysics side, we consider the projected reach of detectors searching for direct dark matter interactions, including the CDMS [6], CRESST [7] and GENIUS [8] experiments.

We also include the most promising indirect dark matter searches. In the next five years, an astounding array of experiments will be sensitive to potential neutralino annihilation products. These include under-ice and underwater neutrino telescopes (AMANDA [9], NESTOR [10], ANTARES [11]), which will be sensitive to muons produced by neutrinos from relic annihilations in the cores of the Sun and Earth [12]; atmospheric Cherenkov telescopes (STACEE [13], CELESTE [14], ARGO-YBJ [15], MAGIC [16], HESS [17], CANGAROO [18], VERITAS [19]), and space-based γ ray detectors (AGILE [20], AMS/ γ [21], GLAST [22]), which may detect gamma rays from the galactic center [23]; and anti-matter/anti-particle experiments (PAMELA [24], AMS [25]), which may detect positrons [26], antiprotons [27] and antideuterium [28] from the galactic halo. In many cases, these experiments will improve current sensitivities by several orders of magnitude. The search for supersymmetric dark matter is reviewed in a number of excellent articles [29]; see also Refs. [30, 31, 32] and the bibliographies of Refs. [3, 4].

The main results from our combined study [4] of dark matter and collider signals in supersymmetry *prior to the start of the LHC* are shown in Fig. 1. The regions of cosmologically interesting relic densities are shown; see Ref. [3] for details. A generous range is $0.025 \leq \Omega_\chi h^2 \leq 1$, where the lower bound is the requirement that neutralino dark matter explain galactic rotation curves and the upper bound follows from the lifetime of the

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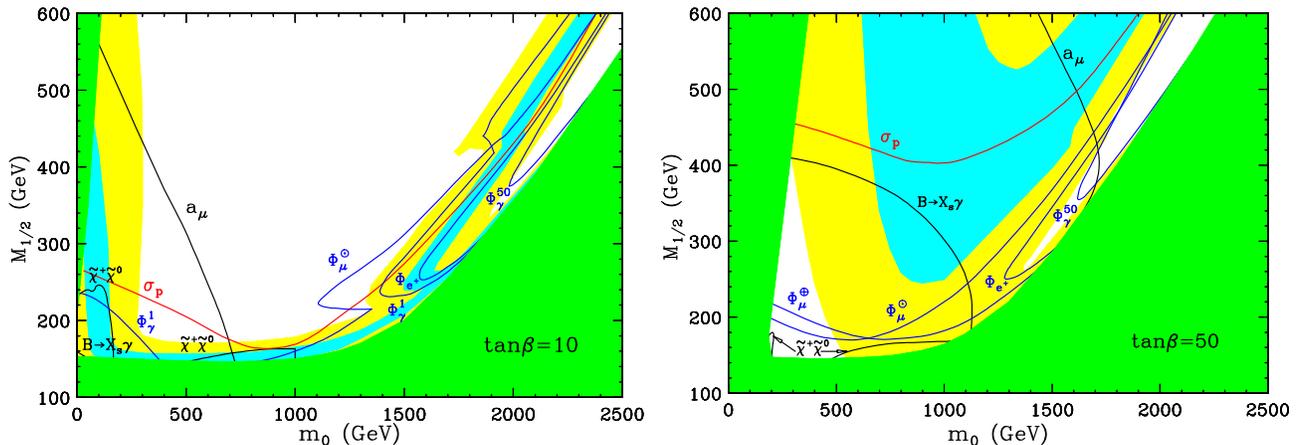


FIG. 1: Estimated reaches of various high-energy collider and low-energy precision searches, direct dark matter searches, and indirect dark matter searches before the LHC begins operation, for $\tan\beta = 10$ (left) and $\tan\beta = 50$ (right). The projected sensitivities used are given in Table I. The darker shaded (green) regions are excluded by the requirement that the LSP be neutral (left) and by the LEP chargino mass limit (bottom and right). We have also delineated the regions with potentially interesting values of the LSP relic abundance: $0.025 \leq \Omega_\chi h^2 \leq 1$ (light-shaded, yellow) and $0.1 \leq \Omega_\chi h^2 \leq 0.3$ (medium-shaded, light blue). The regions probed extend the curves toward the forbidden regions. The dark matter reaches are not modulated by the thermal relic density. Bounds from photons from the galactic center are highly halo model-dependent; we assume a moderate halo profile parameter $\bar{J} = 500$ [33]. (From Ref. [4].)

TABLE I: Constraints used in Fig. 1, and experiments likely to reach these sensitivities by 2006.

| Observable | Type | Bound | Experiment(s) |
|-----------------------------------|-------------|---|------------------------------|
| $\tilde{\chi}^+ \tilde{\chi}^-$ | Collider | $m_{\tilde{\chi}}^\pm > 100$ GeV | LEP: ALEPH, DELPHI, L3, OPAL |
| $\tilde{\chi}^\pm \tilde{\chi}^0$ | Collider | from [34] | Tevatron: CDF, DØ |
| $B \rightarrow X_s \gamma$ | Low energy | $ \Delta B(B \rightarrow X_s \gamma) < 1.2 \times 10^{-4}$ | BaBar, BELLE |
| Muon MDM | Low energy | $ a_\mu^{\text{SUSY}} < 8 \times 10^{-10}$ | Brookhaven E821 |
| σ_{proton} | Direct DM | from [35, 36] | CDMS, CRESST, GENIUS |
| ν from Earth | Indirect DM | $\Phi_\mu^\oplus < 100$ km $^{-2}$ yr $^{-1}$ | AMANDA, NESTOR, ANTARES |
| ν from Sun | Indirect DM | $\Phi_\mu^\ominus < 100$ 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 | $(S/B)_{\text{max}} < 0.01$ | AMS-02 |

universe. Above this shaded region, $\Omega h^2 > 1$; below, $\Omega h^2 < 0.025$. The range $0.1 \leq \Omega_\chi h^2 \leq 0.3$, preferred by current limits, is also shown.

Several striking conclusions follow from Fig. 1:

No Useful Upper Bounds from Cosmology. For all $\tan\beta$, cosmologically interesting densities are possible for either relatively small m_0 , where the dark matter is Bino-like and coannihilation effects may be relevant [37], or in the focus point region at large $m_0 \gtrsim 1$ TeV, where the dark matter contains a small but phenomenologically significant Higgsino component. As is evident from Fig. 1, for all values of $\tan\beta$, the cosmologically preferred region extends to very large m_0 and $M_{1/2}$; discovery at near future colliders cannot be guaranteed by cosmological arguments. The cosmologically preferred region is ultimately cutoff around $M_{1/2} \sim 6$ TeV, but this is far beyond the reach of the LHC and planned linear colliders.

Excellent Prospects for Combined Searches. At the same time, by combining all available searches, nearly all of the cosmologically preferred models predict signals in at least one experiment. This is strictly true for $\tan\beta = 10$. For $\tan\beta = 50$, some of the preferred region escapes all probes, but this requires $M_{1/2} \gtrsim 450$ GeV and $m_0 \gtrsim 1.5$ TeV, and requires significant fine-tuning of the electroweak scale. In the most natural regions, all models with significant neutralino dark matter will yield some signal before the LHC begins operation.

Complementarity of Particle and Astrophysical Searches. Also noteworthy is the complementarity of traditional particle physics searches and indirect dark matter searches. Collider searches require, of course, light superpartners. High precision probes at low energy also require light superpartners, as the virtual effects of superpartners quickly decouple as they become heavy. Thus, the LEP and Tevatron reaches are confined to

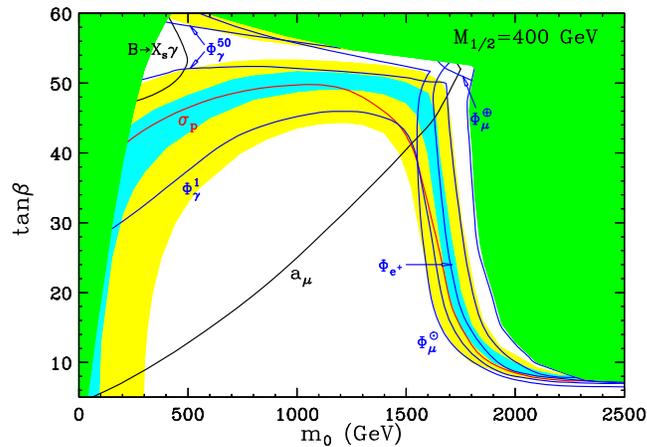


FIG. 2: As in Fig. 1, but in the $(m_0, \tan \beta)$ plane for fixed $M_{1/2} = 400$ GeV, $A_0 = 0$, and $\mu > 0$. The regions probed are toward the green regions, except for Φ_γ^{50} , where it is between the two contours. The top excluded region is forbidden by limits on the CP-odd Higgs scalar mass.

the lower left-hand corner, as are, to a lesser extent, the searches for deviations in $B \rightarrow X_s \gamma$ and a_μ . These bounds, and all others of this type, are easily satisfied in the focus point models with large m_0 , and indeed this is one of the virtues of these models. However, in the focus point models, *all* of the indirect searches are maximally sensitive, as the dark matter contains a significant Higgsino component. Direct dark matter probes share features with both traditional and indirect searches, and have sensitivity in both regions. It is only by combining all of these experiments, that the preferred region may be explored completely.

Implications for Linear Colliders. Finally, these results have implications for future colliders. In the cosmologically preferred regions of parameter space with $0.1 < \Omega_\chi h^2 < 0.3$, all models with charginos or sleptons lighter than 300 GeV will produce observable signals in at least one experiment. This is evident for $\tan \beta = 10$ and 50 in Fig. 1. In Fig. 2, we vary $\tan \beta$, fixing $M_{1/2}$ to 400 GeV, which roughly corresponds to 300 GeV charginos. We see that the preferred region is probed for any choice of $\tan \beta$. (For extremely low $\tan \beta$ and m_0 , there appears to be a region that is not probed. However, this is excluded by current Higgs mass limits for $A_0 = 0$. These limits might be evaded if A_0 is also tuned to some extreme value, but in this case, top squark searches in Run II of the Tevatron [38] will provide an additional constraint.) These results imply that if any superpartners are to be within reach of a 500 GeV lepton collider, some hint of supersymmetry must be seen before the LHC begins collecting data. This conclusion is independent of naturalness considerations.

While our quantitative analysis is confined to minimal supergravity, we expect this result to be valid more generally. For moderate values of $\tan \beta$, if the dark matter is made up of neutralinos, they must either be light, Bino-like, or a gaugino-Higgsino mixture. If they are light, charginos are typically also light, and can be discovered at colliders. If the dark matter is Bino-like, light sfermions are required to mediate their annihilation, and there will be anomalies in low energy precision measurements. And if they are a gaugino-Higgsino mixture, at least one indirect dark matter search will see a signal. For large $\tan \beta$, low energy probes become much more effective and again there is sensitivity to all superpartner spectra with light superpartners. These conclusions are not airtight — they may be evaded by highly split charginos and neutralinos, highly split sfermions, or enhanced annihilation from Higgs poles. For example, in the case of highly split sfermions, one could arrange for light staus to mediate neutralino annihilation, but very heavy smuons to suppress $g_\mu - 2$. Barring such possibilities, however, if supersymmetry exists at the weak scale and neutralinos provide the bulk of dark matter, there are excellent prospects for supersymmetry discovery prior to LHC operation.

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