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SUPERSYMMETRIC DARK MATTER AND CONSTRAINTS FROM LEP

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Accelerator constraints on the parameter space of the Minimal Supersymmetric extension of the Standard Model are analyzed and contrasted with the parameter space yielding dark matter which is allowed by the cosmological constraints on the relic density. The most important accelerator limits are those from searches for charginos $\chi^\pm$, neutralinos χ_i and Higgs bosons at LEP. Constraints derived from $b \to s\gamma$ decay are also incorporated. It is found that $m_\chi > 51$ GeV and $\tan\beta > 2.7$ if all soft supersymmetry-breaking scalar masses are universal, including those of the Higgs bosons, and that these limits weaken to $m_\chi > 47$ GeV and $\tan\beta > 2.1$ if non-universal scalar masses are allowed.

It is will known that supersymmetry with unbroken R-parity offers a natural cold dark matter candidate with a cosmologically significant relic density [1]. Indeed, one of the reasons that supersymmetric dark matter is the main focus of many direct detection searches for dark matter, is that over a wide range of the supersymmetric parameter space (with mass parameters $\lesssim 1$ TeV), the relic density (in units of the critical density) takes values of order $\Omega_\chi \sim$ a few tenths. In fact, until recently, some of the strongest constraints on the susy parameter space came from the cosmological upper limit $\Omega_\chi h^2 \leq 0.3$. In addition, if the neutralino is responsible for the dark matter, then we should have $\Omega_\chi h^2 > 0.1$ The final runs at LEP [2] combined with the current bounds from $b \to s\gamma$ [3], further constrain the available susy parameter space. Here I will briefly summarize the combined cosmological and accelerator constraints [4].

In the analysis below, I will distinguish between two simplifications of the minimal supersymmetric standard model (MSSM). One in which all soft scalar masses (including the Higgs soft masses) are unified at the GUT scale denoted as UHM (for universal Higgs masses) or the constrained MSSM (CMSSM). In the second case, the Higgs soft masses are not unified with the the squark and slepton soft masses which remain universal at the GUT scale. This case will be denoted as nUHM or simply the MSSM. In addition to the parameters common to both models, the ratio of the two Higgs vevs, $\tan\beta$, and the trilinear soft mass terms, A (also assumed to be unified at the GUT scale, there are several other key parameters which determine the susy particle spectrum.

In the UHM model, there is one common soft scalar mass at the GUT scale, m_o. The gaugino masses are also unified at the GUT scale so that $M_1 = M_2 = M_3 = m_{1/2}$. Finally in the UHM model, the sign of the Higgs mixing mass parameter, μ, is arbitrary. The values of the magnitude of μ and the pseudoscalar Higgs mass, m_A, are determined by the conditions of electro-weak symmetry breaking. In contrast, in the nUHM model, since the soft Higgs masses, $m_1, m_2 \neq m_0$, the values of μ and m_A are free parameters. It is also common to use the SU(2) gaugino mass, M_2 at the weak scale as the free parameter rather than $m_{1/2}$. M_2 is easily related to $m_{1/2}$ through $M_2 = (\alpha_2/\alpha_{GUT}) \times m_{1/2}$. In the figures, $m_o - m_{1/2}$ plots will always refer to UHM models, and $M_2 - \mu$ plots will refer to nUHM models.

The accelerator bounds used in the analysis below can be summarized as follows:

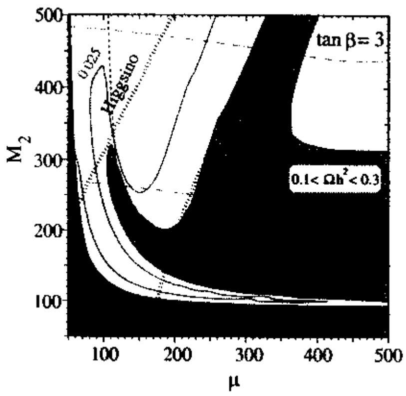

Figure 1. The μ, M_2 plane for $\tan\beta = 3$, $m_0 = 100$ GeV and $m_A = 1$ TeV.

- Chargino mass limit:
  $m_{\chi^\pm} \geq 101 - 102$ GeV
  mainly constrains $m_{1/2}$ (M_2 and μ) in the UHM (nUHM).
- Higgs mass limit:
  $m_h \geq 107 - 112$ GeV; $\tan\beta = 3$
  $m_h \geq 103 - 111$ GeV; $\tan\beta = 5$
  mainly constrains $m_{1/2}$ (m_A, M_2 and A) at low $\tan\beta$.
- $b \to s\gamma$
  mainly constrains $m_{1/2}$ (m_A) particularly at high $\tan\beta$ and $\mu < 0$.

The ranges for the chargino and Higgs mass limits refer to the difference between the established LEP limits and preliminary (but expected limits) [2]. Note that the LEP sensitivity to detecting the Higgs diminishes at high $\tan\beta$. At $\tan\beta \gtrsim 8$, the limit is only 89 GeV. Furthermore, due to theoretical uncertainty in the calculation of the Higgs mass, the constraints imposed are about 3 GeV less than the stated experimental constraint. It is also required that sfermions masses are larger than 98 GeV, and that the neutralino is the LSP.

Constraints from the chargino and Higgs searches are shown in Fig. 1 and Fig. 2, for the nUHM and UHM respectively [4] for selected values of $\tan\beta$ and $sgn(\mu)$. In Fig. 1, contours of $\Omega_\chi h^2 = 0.025, 0.1$ and 0.3 are shown as solid lines, and the preferred region with $0.1 < \Omega_\chi h^2 < 0.3$ is shown light-shaded. The dashed line corresponds to $m_{\chi^\pm} = 100$ GeV. The near-horizontal dot-dashed lines are Higgs mass contours, and the hashed lines are 0.9 Higgsino and gaugino purity contours. The dark shaded region has $m_{\chi^\pm} < m_Z/2$. It is apparent that the bulk of the cosmological region with $0.1 \leq \Omega_\chi h^2 \leq 0.3$ has $\mu \gtrsim M_2$, indicating that LSP dark matter is generically a gaugino: in these regions, it is mainly a Bino. There are, however, small regions at smaller $|\mu|$ (for given M_2), where the LSP is mainly a Higgsino. However, as can be seen in Fig. 1, this Higgsino possibility is under severe pressure from several LEP constraints, including the chargino and Higgs searches. Careful analysis [4] has shown that predominantly Higgsino dark matter is excluded and the gaugino content must be at least 30%.

In Fig 2, the region allowed by the cosmological constraint $0.1 \leq \Omega_\chi h^2 \leq 0.3$, after including coannihilations [5], has medium shading. Dotted lines delineate the announced LEP constraint on the $\tilde{e}$ mass and the disallowed region where $m_{\tilde{\tau}_1} < m_\chi$ has dark shading. The contour $m_{\chi^\pm} = 102$ GeV is shown as a near-vertical dashed line in each panel. Also shown as dot-dashed lines are relevant Higgs mass contours. The long dashed curves in panels (a), (b) represent the anticipated limits from trilepton searches at Run II of the Tevatron [6].

Though not shown in Figs. 1 and 2, contributions $b \to s\gamma$ come from chargino-stop and charged Higgsino exchanges [7]. When $\mu > 0$, these contributions interfere destructively, and the limits are weakened, that is the supersymmetric contributions are with the experimental uncertainty for moderately low $\tan\beta \lesssim 10$ in the UHM. At $\tan\beta = 20$, and $m_0 \lesssim 400$ GeV, even for $\mu > 0$, we obtain $m_{1/2} \gtrsim 200$ GeV from $b \to s\gamma$ [4]. For negative μ, we find $m_{1/2} \gtrsim 230$ GeV at $\tan\beta = 3$ and $m_{1/2} \gtrsim 450 - 500$ GeV at $\tan\beta = 20$.

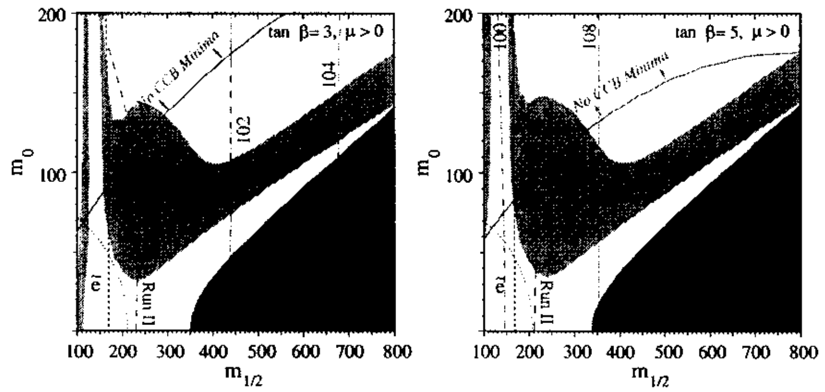

Figure 2. *The $m_{1/2}, m_0$ plane for $\mu > 0$, $A = -m_{1/2}$ and $\tan\beta$ = (a) 3, (b) 5.*

In the nUHM, the constraint from $b \to s\gamma$, can be greatly diminished by choosing large ($\gtrsim 350 - 500$ GeV) m_A.

From the accelerator bounds on the chargino and Higgs masses, one can place lower bounds on the neutralino mass. The limits are summarized in Fig. 3 for $\mu > 0$, under various different assumptions: UHM or nUHM and (in the former case) whether one requires the present vacuum to be stable against transition to a charge- and colour-breaking (CCB) vacuum (best achieved when $A_0 = -m_{1/2}$) or not ($\mathrm{UHM_{min}}$, where A_0 is left free). Also, limits are given for both the available 1999 LEP data and for a 'realistic' assessment of the likely sensitivity of data to be taken in 2K [4].

In all cases, for both positive and negative μ, the lower limits on m_χ are relatively insensitive to $\tan\beta$ at large $\tan\beta$. Here, they are determined by the LEP chargino bound, as the LEP Higgs mass bound is weaker than the chargino bound at large $\tan\beta$. In fact, in the two UHM cases shown, the points at which the limiting curves bend upward, as one decreases $\tan\beta$, are precisely the points at which the Higgs mass bound becomes more stringent than the chargino bound. In the UHM cases, the neutralino mass limits are strong at intermediate values of $\tan\beta \simeq$ 4–7 because the cosmological bound on the relic density prohibits going to large values of m_0, and ensures that the Higgs bound places a strong constraint. Below this break point, the lower limit on m_χ increases rapidly with decreasing $\tan\beta$. Above this break point, the limit on m_χ is relatively insensitive to the additional theoretical assumptions made, such as UHM vs. $\mathrm{UHM_{min}}$ or nUHM. However, in the nUHM cases, because one can increase m_0 sufficiently to weaken the Higgs mass bound, the break point occurs at a lower value of $\tan\beta$. To go to lower values of $\tan\beta$ then requires a substantial increase in m_χ.

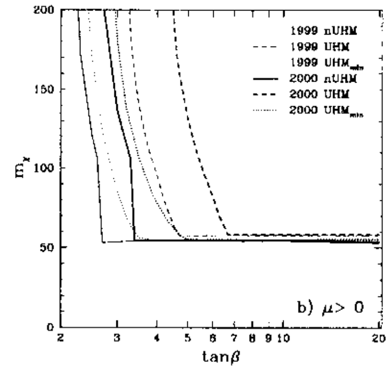

Figure 3. *Lower limits on the neutralino mass m_χ as functions of $\tan\beta$ for $\mu > 0$.*

One can also place an upper limit on the neutralino mass from relic density considerations. In the nUHM, the upper limit on a mostly bino LSP is about 300 GeV [8]. This limit is somewhat soft and can be avoided if the LSP is sitting on a pole (e.g. the pseudo-scalar Higgs pole) or is nearly degenerate with a squark such as the stop [9]. In the UHM, co-annihilations increase the upper limit to about 600 GeV [5].

In the UHM cases with and without the restriction forbidding CCB vacua, the lower limit on the lightest MSSM Higgs mass, in particular, implies lower limits on $\tan\beta$ which are plotted in Fig. 4. Recall that the existing Higgs mass calculations in the MSSM are believed to be accurate to about 3 GeV. Therefore in computing the bounds on $\tan\beta$ one should shift the experimental bound down by 3 GeV before reading the values of $\tan\beta$ off of Fig. 4. We also show in Fig. 4 the lower bound on $\tan\beta$ obtained in the nUHM, which is significantly weaker than in the UHM cases, and essentially independent of the sign of μ.

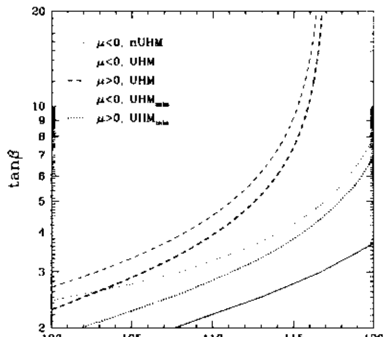

Figure 4. *Lower limit on* $\tan\beta$ *imposed by the experimental and cosmological constraints, as a function of the experimental Higgs mass limit. The UHM,* UHM_{min} *and nUHM labels are the same as in Fig. 3.*

The current 2K limits on $\tan\beta$ are summarized in Table 1.

	UHM	UHM_{min}	nUHM
$\mu < 0$	4.0	3.1	2.1
$\mu > 0$	3.6	2.7	2.1

Table 1. *Limits on* $\tan\beta$*, assuming the 'realistic' 2K energies and luminosities .*

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