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Higgsino Cold Dark Matter Motivated by Collider Data

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Abstract

Motivated by the supersymmetric interpretation of the CDF $ee\gamma\gamma+\not{E}_T$ event and the reported $Z\to b\bar{b}$ excess at LEP, we analyze the Higgsino as a cold dark matter candidate. We examine the constraints as implied by the collider experiments, and then calculate its relic density. We find that this Higgsino-like lightest supersymmetric particle is a viable cold dark matter candidate ($0.05 < \Omega h^2 < 1$), and we discuss its favorable prospects for laboratory detection.

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Introduction

One of the successes of the supersymmetric version of the standard model is that it provides a natural candidate for the cold dark matter of the universe. Many authors [1] have lauded this feature of supersymmetry. Studies often assume that the lightest supersymmetric particle (LSP) is the bino ($\tilde{B}$), the supersymmetric partner of the hypercharge gauge boson, for two reasons. Bino annihilation can give about the right relic density. Second, minimal supergravity models with gauge coupling unification and with universal scalar and gaugino masses at the unification scale generically produce a Bino LSP after the full renormalization group flow of all sparticle masses, Yukawas, and gauge couplings [2]. In general, Higgsino-like LSP's annihilate too efficiently to provide cosmologically interesting amounts of cold dark matter.

In this paper we are instead motivated primarily by data rather than by general theory, mainly by the $ee\gamma\gamma + \not{E}_T$ event reported by CDF [3]. This event has two different possible supersymmetric interpretations. One [4, 5] is that two selectrons are created which ultimately decay into electrons, photons, and a very light gravitino (less than about 1 keV) as would happen in low scale gauge-mediated supersymmetry breaking models. However, these models have not as yet produced a compelling cold dark matter candidate, and so we do not consider the light gravitino interpretation further for this paper.

The second supersymmetric interpretation of this event [5] is based on ordinary gravity communicated supersymmetry breaking where the gravitino is sufficiently heavy to not be the LSP. In this interpretation, the decay chain which produces $ee\gamma\gamma + \not{E}_T$ is

$$\tilde{e}^+\tilde{e}^- \rightarrow e^+N_2e^-N_2 \rightarrow e^+e^-\gamma\gamma N_1N_1 \tag{1}$$

where the photino-like second-lightest neutralino N_2 decays radiatively [6] into the lightest neutralino (N_1) and a photon. Thus, N_1 is the LSP. Here, motivated by the desire for a simple notation (and one suitable for e-mail) we denote neutralinos by N_i (and charginos by C_i). If the supersymmetric interpretation of the FNAL $ee\gamma\gamma\not{E}_T$ event is correct, then N_1 has been observed at FNAL. Of course, that it escapes the detector only proves it lives longer than $\sim 10^{-8}$ sec, so its direct detection would be necessary before it could be finally accepted as the cold dark matter. In this paper we will demonstrate that N_1 can be an interesting dark matter candidate, despite the fact that it is Higgsino-like, and we also discuss the direct detection prospects for such a particle. Our analysis assumes a general low scale supersymmetric Lagrangian, with no presumed relations among parameters. No assumptions are made about the exact form of the high scale theory except that it exists perturbatively, and no assumptions are made about common gaugino or scalar masses. Rather, we assume that the low energy theory can be described by a superpotential plus general soft-breaking terms. We use the results of ref. [5] for the mass and coupling requirements of the light supersymmetric states.

N_1 as the LSP

In order to proceed with a discussion about the dark matter qualities of the N_1 LSP, we must discuss its composition and mass. For convention purposes we write down the neutralino mass matrix

$$\begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -\mu \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix} \tag{2}$$

in the $\left\{\tilde{B}, \tilde{W}^3, -i\tilde{H}_d^0, -i\tilde{H}_u^0\right\}$ basis. If $0 < -\mu < (M_1 \simeq M_2)$, and $\tan\beta$ is near one, then the two lightest eigenstates of the neutralino mass matrix are $N_2 \sim \tilde{\gamma}$ (photino-like), and $N_1 \sim \sin\beta\tilde{H}_d^0 + \cos\beta\tilde{H}_u^0 + \delta\tilde{Z}$ (Higgsino-like), where $\delta < 0.1$.

This arrangement of lightest neutralino mass eigenstates enhances the important radiative neutralino decay $N_2 \to N_1\gamma$, and along with the $ee\gamma\gamma + \not{E}_T$ event of ref. [3] implies $m_{N_2} - m_{N_1} \gtrsim 30\,\text{GeV}$ and $30 \lesssim m_{N_1} \lesssim 55\,\text{GeV}$ [5]. We shall see that with $\tan\beta$ near one the Z invisible width constraint is satisfied and N_1 provides an interesting amount of dark matter as well.

From the invisible width determinations at LEP, the Z is not allowed to decay into N_1N_1 with a partial width more than about 5 MeV (at 2σ) [7]. In our approximation, the formula for the partial width is

$$\Gamma_{\text{inv}} = \frac{\alpha M_Z}{24\sin^2\theta_W\cos^2\theta_W}\cos^2 2\beta\left(1 - 4\frac{m_{N_1}^2}{M_Z^2}\right)^{3/2}. \tag{3}$$

Figure 1 has contours of the invisible width in units of MeV. As can be

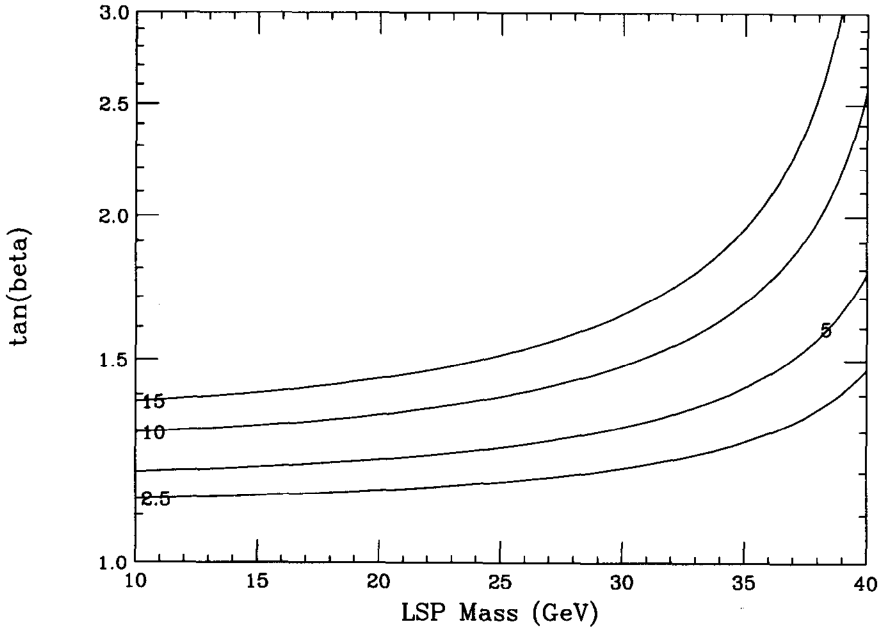

Figure 1: Contours of constant invisible width due to $Z \to N_1 N_1$. The labelled lines are in units of MeV, and the current 2σ bound at LEP on the invisible width is 5 MeV.

seen from the above equation as long as $\tan\beta$ is close enough to 1 then the invisible width constraint can be satisfied. We think this constraint should not be applied too tightly at this stage since it could be affected by new physics. However, since $\tan\beta \simeq 1$ is the natural region for the radiative decay requirements in ref. [5], this constraint does not cause any problems for our analysis here, even if it is applied with the most stringent assumptions [8].

N_1 pairs annihilate through the Z into fermion pairs. To look at the prediction for Ωh^2, we can expand the thermally averaged annihilation cross section [9] into fermions (f) in the following way:

$$(\sigma v)(x) = \cos^2 2\beta \sum_f (a_f + b_f x) \tag{4}$$

where a_f and b_f depend only on one unknown, the LSP mass. Applying the usual approximation method [10] to solve the Boltzmann equation, the relic abundance can be found:

$$\Omega h^2 = (2.5 \times 10^{-11}) \left(\frac{T_{N_1}}{T_\gamma}\right)^3 \left(\frac{T_\gamma}{2.7\,\mathrm{K}}\right)^3 \frac{\sqrt{N_F}}{\cos^2 2\beta} \left(\frac{\mathrm{GeV}^{-2}}{a x_f + \frac{1}{2} b x_f^2}\right) \tag{5}$$

where N_F, $(T_{N_1}/T_\gamma)^3$ and x_f must be solved for self-consistently. Calculations such as these could be valid to a factor of two or better.

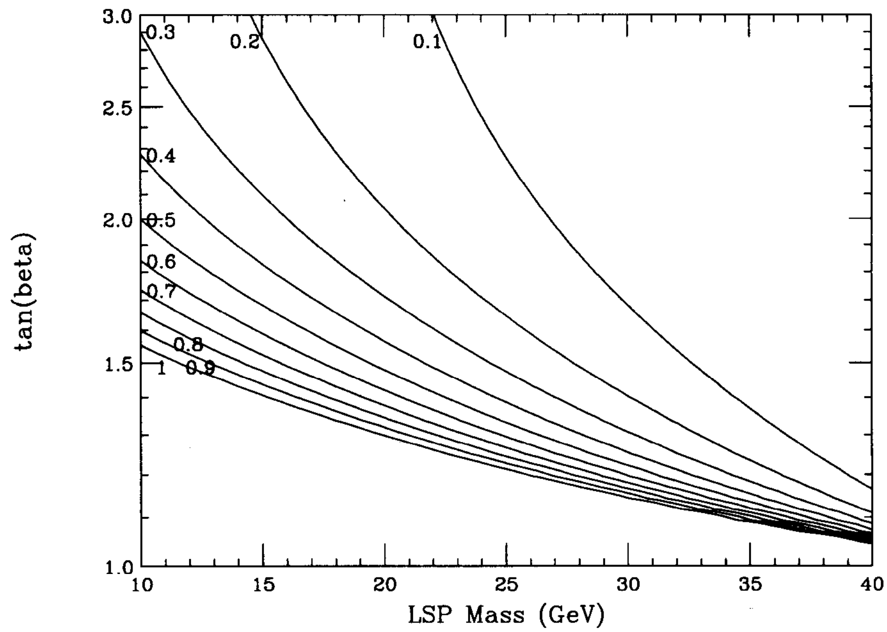

Figure 2: Contours of constant Ωh^2 for the Higgsino-like LSP described in the text.

In Fig. 2 contours of Ωh^2 are plotted in the $\tan\beta - m_{N_1}$ plane. Since the annihilation cross section is proportional to $\cos^2 2\beta$, when $\tan\beta$ gets closer to 1, Ωh^2 begins to exceed one. The t channel sfermion exchange is greatly suppressed (since N_1 is mainly Higgsino-like), but if the $\tilde{Z}$ fraction of N_1 is large enough, then a t channel sfermion diagram which couples like the $SU(2)_L$ gauge coupling could start to become important. However, this potentially efficient annihilation channel is suppressed by a factor of δ^4 and δ is less than about 0.1 [5]. Comparing $\delta^4/m_{\tilde{f}}^4$ with $\cos^2 2\beta/M_Z^4$, we find that this channel can compete with the s channel Z exchange only when $\tan\beta$ is less than about 1.05. Furthermore, as $\tan\beta$ gets closer and closer to 1, δ necessarily becomes smaller and smaller, and the number $\tan\beta < 1.05$ is actually an overestimate. At $\tan\beta = 1.05$ we find that the annihilation cross section is too small for all values of m_{N_1} in Fig. 2, and therefore we set this as our lower bound on allowed $\tan\beta$ in this scenario. Consequently, the sfermion annihilation channel is not numerically important.

The s channel Higgs exchange diagrams might possibly play an important role in the annihilation cross section. However, if the pseudo-scalar (A^0) is sufficiently heavy then the pseudo-scalar and heavy scalar (H^0) Higgses will decouple; in the absence of information about the heavy Higgs bosons we assume they effectively decouple. In this limit it can be shown that the $N_1 N_1 h^0$ also vertex decouples. Furthermore, since the LSP is sufficiently light not to annihilate into top quarks, or vector bosons, the light final state fermion masses contribute a further suppression of the h^0 mediated annihilation cross section.

The allowed mass range for N_1 from ref. [5] overlaps $M_Z/2$. If consistency with the supersymmetry interpretation of the LEP $Z \to b\bar{b}$ excess is required, probably $M_{N_1} \lesssim 40\,\mathrm{GeV}$, but it is premature to assume that. If $M_{N_1} \simeq M_Z/2$ it is necessary to do the resonant calculation very carefully [11]. There is always a value of $\tan\beta$ for which the curves of Fig. 2 continue across $M_Z/2$ smoothly, so we will wait until m_{N_1} and $\tan\beta$ are better measured to do the more precise calculations needed. We show results in Fig. 2 for $M_{N_1} < M_Z/2$, which we expect is the most relevant region. Given the results of reference [5], the only channel that could complicate the simple analysis is coannihilation of the N_1 with the $\tilde{t}_1$ [13], if $m_{\tilde{t}_1} \simeq m_{N_1}$ ($\tilde{t}_1$ is the lightest stop mass eigenstate). We expect $m_{\tilde{t}_1} \gtrsim M_Z/2$ and $M_{N_1} \lesssim M_Z/2$, so probably this complication can be ignored, but until the masses are better determined it should be kept in mind.

The Hubble constant h is probably between about 0.5 and 0.8. Assuming the cold dark matter constitutes 0.4 to 0.8 of Ω_{tot}, we expect that $\Omega_{N_1} h^2$ should lie somewhere between 0.08 and 0.5 in Fig. 2 (e.g. $0.57^2 \times .75 = 0.25$). We emphasize that Fig. 2 follows from the results of ref. [5], and that apart from the approximations mentioned above this is a prediction of the supersymmetric interpretation of the CDF event. Further, we note that the supersymmetric interpretation of the reported excess of $Z \to b\bar{b}$ decays at LEP leads to the same region of parameters as ref. [5], with Higgsino-like N_1 and with $\tan\beta$ near 1 [12], and therefore can conservatively be viewed as consistent with this prediction, or optimistically as additional evidence for its correctness.

Detecting N_1 as the Cold Dark Matter

We have established that the same N_1 which is necessary to explain the $ee\gamma\gamma + \not{E}_T$ event at Fermilab, and independently the LEP R_b excess, is also a viable cold dark matter candidate. Future experiments at Fermilab and

LEP will be able to determine if the supersymmetric interpretation of the CDF event is a valid one. However, these colliders cannot determine experimentally if N_1 particles in fact are stable and comprise a significant portion of the cold dark matter in the universe. In this section we discuss some of the direct detection prospects for this particle.

From kinematic analyses of the galactic rotation curves it has been estimated [14] that the local density of cold dark matter is approximately $0.3 < \rho < 0.7\,\mathrm{GeV/cm^3}$. (We will use the lower number in our subsequent calculations.) Several experiments are under way to look for weakly interacting massive particles (WIMPs) floating around our part of the galaxy. Neutrino telescopes at AMANDA, etc., hope to see the effects of WIMP annihilations in the sun. The light Higgsino dark matter candidate, which we propose here, would be difficult to detect at the large area neutrino telescopes since the muon threshold energy is about $30\,\mathrm{GeV}$, roughly equivalent to the LSP mass range we are considering. The neutrinos produced by the LSP annihilations in the sun will be at energies below this threshold, and so the converted muons will not be energetic enough to be detected.

Other experiments [15] are designed to measure direct annihilations of LSPs in the galactic halo by seeing an excess of photons, electrons, protons, etc. in the spectrum. The steeply rising photon background (as energy decreases) makes the photon signal difficult to extract, and the broad energy spread of the electron/positron signal for $N_1 N_1$ annihilations in the galactic halo also complicates this detection possibility.

Lastly, numerous table-top experiments [16] are being set up with the hope of seeing WIMPs interact with different nuclei. It is this last set of experiments that we wish to focus on in this analysis. We also wish to urge one change in notation, namely that the acronym WISP (weakly interacting supersymmetric particle) be used when the particle in question is known to be a possible state following from a supersymmetric Lagrangian and consistent with phenomenological constraints; many WIMP's discussed in the literature are not WISP's.

Since we have argued that the Z coupling is the most important one, we concentrate on ^{29}Si and ^{73}Ge which are well-suited for spin-dependent scattering of LSP's with nucleons, and are currently being considered by experimentalists for larger scale designs. The spin-dependent cross section

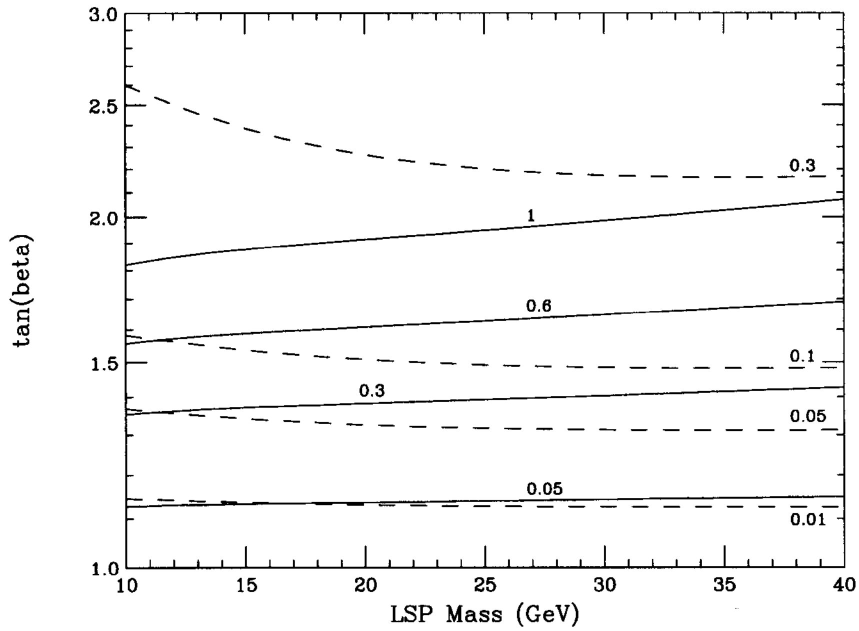

Figure 3: Event rate contours for ^{29}Si (solid lines) and ^{73}Ge (dashed lines) in units of /kg/day.

in this scenario can be written as

$$\sigma^{\rm sd} = \frac{g_2^4}{16\pi}\frac{\cos^2 2\beta}{M_W^4}\frac{m_{N_1}^2 m_A^2}{(m_{N_1}+m_A)^2}\lambda^2 J(J+1)[\Delta_n u - \Delta_n d - \Delta_n s]^2 \qquad (6)$$

where $\Delta_n q$ is the spin content of the neutron [18] carried by quark q, and m_A is the mass of a silicon atom. From this we can estimate [16] the rate of interactions per day:

$$R = \frac{\sigma\xi}{m_{N_1} m_A}\left(\frac{1.8\times 10^{11}\mathrm{GeV}^4}{\mathrm{kg}\cdot\mathrm{day}}\right) \qquad (7)$$

where ξ quantifies the nuclear form factor suppression. We are not considering the spin-independent cross section in this analysis since, as we argued above, the couplings of N_1 to all scalar particles are very small. It is possible with a lighter pseudo-scalar mass to have larger couplings of N_1 to the Higgs particles, which would contribute to a spin-independent cross-section, but to be conservative we have assumed that the Higgs effects are decoupled.

Figure 3 is a plot of the event rate per kilogram per day of N_1 interacting on ^{29}Si and ^{73}Ge. The expected sensitivity [17] for ^{73}Ge is at about the 0.3 events contour in the near future, and about 0.01 in the next round of experiments. Thus, the entire region of the plot above about the 0.01

event contour will soon be probed in the table-top detector. This is a good demonstration of how the table top experiment can sometimes do better than collider limits (see Fig. 1) for an interesting part of parameter space. ^{73}Ge has a reduced event rate compared to Silicon mainly because the nuclear Landé $\lambda^2 J(J+1)$ factor is smaller, and the nucleus mass is heavier. We interpret Fig. 3 as implying that Si and Ge and related detectors may be able to observe a cold dark matter signal in the next round of attempts.

Summary

It is remarkable that these calculations (which *a priori* could have given much smaller or much larger Ωh^2, and are essentially free of parameters) imply a WISP cold dark matter candidate that is cosmologically interesting, possibly detectable using table-top experiments, possibly already observed at FNAL, and possibly associated with loop effects seen at LEP.

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