Higgsino Cold Dark Matter Motivated by Collider Data

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Motivated by a supersymmetric interpretation of the CDF $ee\gamma\gamma + \not{E}_T$ event and the reported $Z \to b\overline{b}$ excess at LEP, we analyze the implied Higgsino-like lightest supersymmetric partner as a cold dark matter candidate. We examine constraints and calculate its relic density, obtaining $0.05 < \Omega h^2 < 1$. Thus it is a viable cold dark matter candidate, and we discuss its favorable prospects for laboratory detection. [S0031-9007(96)00381-X]

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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. Although Higgsino dark matter was studied in the past [2,3], recent studies have often assumed that the lightest supersymmetric particle (LSP) is the B-ino ($\tilde{B}$), the supersymmetric partner of the hypercharge gauge boson. Furthermore, the old studies did not take into account coannihilation effects [4], which in general cause Higgsino-like LSP's to annihilate too efficiently [5] to provide cosmologically interesting amounts of cold dark matter.

In this paper we revisit this question mainly because of the recent $ee\gamma\gamma + \not{E}_T$ event reported by CDF [6]. This event has two different possible supersymmetric interpretations. One [7,8] 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 [8] assumes the gravitino is not light, and then the LSP is the lightest neutralino. Then the decay chain which produces $ee\gamma\gamma + \not{E}_T$ is $\tilde{e}^+(\to e^+N_2)\tilde{e}^-(\to e^-N_2)$, followed by the photinolike second-lightest neutralino N_2 decaying radiatively [9] into the lightest neutralino (N_1) and a photon. N_1 is the LSP. Here, 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. [8] for the mass and coupling requirements of the light supersymmetric states.

We emphasize that here we are not doing just another study of cold dark matter, we are calculating the prediction of the supersymmetric interpretation of the CDF event for the cold dark matter. In order for the event to have the selection interpretation, the mass parameters must be in the range $45 \lesssim M_2 \lesssim 85$, $60 \lesssim M_1 \lesssim 85$, $-55 \lesssim \mu \lesssim -35$, $30 \lesssim M_{N_1} \lesssim 55$ (all masses in GeV), and $\tan\beta < 2$. In addition, $M_1 = M_2$ (within 15%) is needed rather than satisfying the gauge unification condition $M_1 \simeq M_2/2$. The analysis of Ref. [8] was checked against all LEP and rare decay data and other collider data. The values for M_1, M_2, μ, $\tan\beta$ are correlated so one must use consistent sets from the above ranges. LEP160 could see events that confirm the supersymmetry interpretation of the FNAL event, but with 25 pb^{-1} or so of data they do not cover the whole space.

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

$$\begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -\mu \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix} \tag{1}$$

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in the $\{\tilde{B}, \tilde{W}^3, -i\tilde{H}_d^0, -i\tilde{H}_u^0\}$ basis. If $0 < -\mu < M_1 \simeq M_2$, and $\tan\beta$ is near 1, then the two lightest eigenstates of the neutralino mass matrix are $N_2 \sim \tilde{\gamma}$ (photinolike), 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. [6] implies $m_{N_2} - m_{N_1} \gtrsim 30$ GeV and $30 \lesssim m_{N_1} \lesssim 55$ GeV [8].

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) [10]. In our approximation,

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

Figure 1 has contours (dashed lines) of the invisible width in units of MeV. Since $\tan\beta \simeq 1$ is the natural region for the radiative decay requirements in Ref. [8], the invisible width constraint is easily satisfied even if it is applied with the most stringent assumptions [11].

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 [12] into fermions (f) in the following way:

$$(\sigma v)(x) = \cos^2 2\beta \sum_f (a_f + b_f x), \qquad (3)$$

where a_f and b_f depend only on one unknown, the LSP mass. Applying the usual approximation method [2] to solve the Boltzmann equation, the relic abundance can be found:

$$\Omega h^2 = (2.5 \times 10^{-11})\left(\frac{T_{N_1}}{T_\gamma}\right)^3\left(\frac{T_\gamma}{2.7\ \text{K}}\right)^3\frac{\sqrt{N_F}}{\cos^2 2\beta} \times \left(\frac{\text{GeV}^{-2}}{ax_f + \frac{1}{2}bx_f^2}\right), \qquad (4)$$

where N_f, $(T_{N_1}/T_\gamma)^3$, and x_f must be solved for self-consistency. Calculations such as these could be valid to a factor of 2 or better.

In Fig. 1 contours of Ωh^2 (solid lines) 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 1. 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 [8]. Comparing $\delta^4/m_{\tilde{f}}^4$ with $\cos^2 2\beta/M_Z^4$, this channel can compete with the s channel Z exchange only when $\tan\beta$ is less than about 1.05. At $\tan\beta = 1.05$ the annihilation cross section is too small for all values of m_{N_1} in Fig. 1, so we set this as our lower bound on allowed $\tan\beta$.

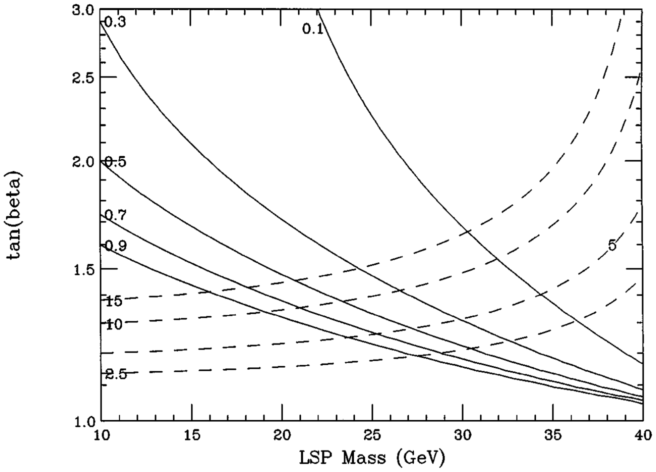

FIG. 1. Contours of constant Ωh^2 (solid lines) and constant invisible width (dashed lines) due to $Z \to N_1N_1$ in units of MeV. The current 2σ bound at LEP on the invisible width is 5 MeV.

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 pseudoscalar (A^0) is sufficiently heavy then the pseudoscalar and heavy scalar (H^0) Higgs bosons 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 $N_1N_1h^0$ vertex also 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. [8] overlaps $M_Z/2$. If consistency with the supersymmetry interpretation of the LEP $Z \to b\overline{b}$ excess is required, probably $M_{N_1} \lesssim 40$ 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 [4,13]. There is always a value of $\tan\beta$ for which the curves of Fig. 1 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. 1 for $M_{N_1} < M_Z/2$, which we expect is the most relevant region. Given the results of Ref. [8], the only channel that could complicate the simple analysis is coannihilation of the N_1 with the $\tilde{t}_1$ [14], if $m_{\tilde{t}_1} \simeq m_{N_1}$ ($\tilde{t}_1$ is the lightest stop mass eigenstate). We expect $m_{\tilde{t}_1} \gtrsim M_Z/2$, 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. 1 (e.g., $0.57^2 \times 0.75 = 0.25$). We emphasize that Fig. 1 follows from the results of Ref. [8], 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. [8], with Higgsino-like N_1 and with $\tan\beta$ near 1 [15], 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. Now we discuss some of the direct detection prospects for this particle.

From kinematic analyses of the galactic rotation curves it has been estimated [16] 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). Several experiments are under way to look for weakly interacting massive particles (WIMP's) floating around our part of the Galaxy. Neutrino telescopes hope to see the effects of WIMP annihilations in the Sun. Our light Higgsino dark matter candidate would be difficult to detect at the large area neutrino telescopes since the muon threshold energy is about 30 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 [17] are designed to measure direct annihilations of LSPs in the galactic halo by seeing an excess of photons, electrons, antiprotons, 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_1N_1 annihilations in the galactic halo also complicates this detection possibility.

Lastly, numerous tabletop experiments [18] are being set up with the hope of seeing WIMP's interact with different nuclei. It is these experiments that we focus on here. We also urge a 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 the Z coupling is the most important one, we concentrate on ^{19}F 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 in this scenario can be written as

$$\sigma^{\mathrm{sd}} = \frac{g_2^4}{16\pi}\,\frac{\cos^2 2\beta}{M_W^4}\,\frac{m_{N_1}^2 m_A^2}{(m_{N_1} + m_A)^2}\,\lambda^2 J(J+1) \times [\Delta d - \Delta u - \Delta s]^2, \tag{5}$$

where $\Delta_n q$ is the spin content of the proton [19] carried by quark q, and m_A is the mass of the fluorine atom. (Substitute $\Delta u \leftrightarrow \Delta d$ for Ge.) From this we can estimate [18] the rate of interactions per day:

$$R = \frac{\sigma\xi}{m_{N_1} m_A}\left(\frac{1.8 \times 10^{11}\ \mathrm{GeV}^4}{\mathrm{kg\,day}}\right), \tag{6}$$

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 pseudoscalar mass to have larger couplings of N_1 to the Higgs particles, which would increase the spin-independent cross section, but to be conservative we have assumed that the Higgs effects are decoupled.

Figure 2 is a plot of the event rate per kilogram per day of N_1 interacting on ^{19}Fe and ^{73}Ge. The expected sensitivity [20] for ^{73}Ge is at about the 0.3 event 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 tabletop detector; the tabletop 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 fluorine mainly because of the nuclear Landé $\lambda^2 J(J+1)$ factor is smaller, and the nucleus mass is heavier. We interpret Fig. 2 as implying that fluorine, germanium, and related detectors may be able to observe a cold dark matter signal in the next round of attempts.

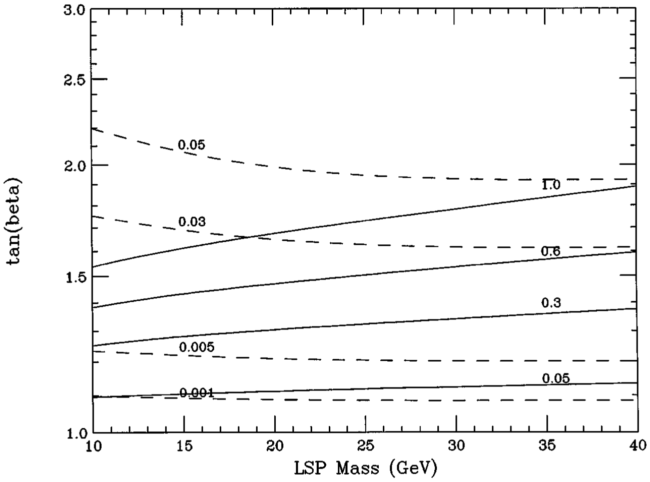

FIG. 2. Event rate contours for ^{19}F (solid lines) and ^{73}Ge (dashed lines) in units of kg/day.

In summary, our analysis is not just a study of the parameter space for cold dark matter, but a report of the implications of the CDF slepton candidate event and/or the LEP $Z \rightarrow b\bar{b}$ excess for cold dark matter. Both imply the LSP is the superpartner of a Higgs boson. 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 tabletop experiments, possibly already observed at FNAL, and possibly associated with loop effects seen at LEP.

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