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Implications of Direct Dark Matter Searches for MSSM Higgs Searches at the Tevatron

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Searches for the Minimal Supersymmetric Standard Model (MSSM) Higgs bosons are among the most promising channels for exploring new physics at the Tevatron. In particular, interesting regions of large $\tan\beta$ and small m_A are probed by searches for heavy neutral Higgs bosons, A and H, when they decay to $\tau^+\tau^-$ and $b\bar{b}$. At the same time, direct searches for dark matter, such as CDMS, attempt to observe neutralino dark matter particles scattering elastically off nuclei. This can occur through t-channel Higgs exchange, which has a large cross section in the case of large $\tan\beta$ and small m_A. As a result, there is a natural interplay between the heavy, neutral Higgs searches at the Tevatron and the region of parameter space explored by CDMS. We show that if the lightest neutralino makes up the dark matter of our universe, current limits from CDMS strongly constrain the prospects of heavy, neutral MSSM Higgs discovery at the Tevatron (at 3σ with 4 fb^{-1} per experiment) unless $|\mu| \gtrsim 400$ GeV. The limits of CDMS projected for 2007 will increase this constraint to $|\mu| \gtrsim 800$ GeV. On the other hand, if CDMS does observe neutralino dark matter in the near future, it will make the discovery of heavy, neutral MSSM Higgs bosons far more likely at the Tevatron.

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Introduction — Searches for Higgs bosons and supersymmetric particles are among the most exciting challenges for the Tevatron collider experiments. Of particular interest are searches for CP-even and CP-odd Higgs bosons with enhanced couplings to b-quarks and τ-leptons.

Tevatron limits on the production of heavy, neutral MSSM Higgs bosons have recently been published [1]. The inclusive process $p\bar{p} \to A/H\,X \to \tau^+\tau^-\,X$ relies on τ-lepton reconstruction to suppress backgrounds, and includes both the gluon-fusion process and the radiation of the Higgs from a final-state b-quark. The process $p\bar{p} \to A/H\ b\bar{b}$ followed by $A/H \to b\bar{b}$ relies on the tagging of multiple b-jets to isolate a signal. The constraints from both of these Higgs searches exclude values of $\tan\beta$ as low as ~ 40 for m_A $\sim$100 GeV. While this represents only a corner of parameter space, a wider range of models will be tested as the integrated luminosity grows. With 4 fb^{-1}, values of $\tan\beta$ as small as $\sim$30 and values of m_A as large as $\sim$250 GeV will be within reach of the Tevatron [2]. Tevatron searches for the decay $B_s \to \mu^+\mu^-$ also cover a significant portion of the $\tan\beta$-m_A plane [3].

Concurrently, dark matter experiments are also searching for supersymmetry, in the form of a stable neutralino. These experiments [4, 5] have begun to constrain supersymmetric models by providing limits on the spin-independent elastic scattering cross section of the lightest neutralino with nuclei. When the elastic scattering cross section, $\sigma_{\rm SI}$, is large enough to be detected by current experiments, this process is generally dominated by the t-channel exchange of CP-even Higgs bosons, H and h, coupling to strange quarks and to gluons through a bottom quark loop. The cross section from this contribution is enhanced at large $\tan\beta$ through the s and b Yukawa couplings. Within the MSSM at large $\tan\beta$, the mass of the CP-odd Higgs is related to that of the CP-even Higgs with enhanced couplings to down-type fermions, hence this cross section is also enhanced for small values of m_A.

Comparing direct dark matter experiments to Tevatron searches, we see that the prospects for both of these techniques depend to a certain extent on the same parameters, $\tan\beta$ and m_A. We explore the interplay of direct dark matter searches and the Tevatron Higgs searches and find that, modulo certain caveats discussed below, current and future constraints from CDMS limit the prospects for the discovery of neutral Higgs bosons with enhanced couplings to down-type fermions at the Tevatron. A positive detection in the near future by CDMS, on the other hand, would be very encouraging for Tevatron searches.

Neutralino Elastic Scattering Cross Section — The CDMS experiment is primarily sensitive to the neutralino's spin-independent (scalar) elastic scattering cross section:

$$\sigma_{SI} \approx \frac{4m_r^2}{\pi}[Zf_p + (A-Z)f_n]^2, \tag{1}$$

where $m_r = m_N m_\chi/(m_N + m_\chi)$ is the reduced mass, Z is the atomic number of the nucleus, A is the atomic mass of the nucleus, and f_p and f_n are the neutralino couplings to protons and neutrons, given by:

$$f_{p,n} = \sum_{q=u,d,s} f_{T_q}^{(p,n)} a_q \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{q=c,b,t} a_q \frac{m_{p,n}}{m_q}, \tag{2}$$

where a_q are the neutralino-quark couplings and $f_{T_u}^{(p)} \approx 0.020 \pm 0.004$, $f_{T_d}^{(p)} \approx 0.026 \pm 0.005$, $f_{T_s}^{(p)} \approx 0.118 \pm 0.062$, $f_{T_u}^{(n)} \approx 0.014 \pm 0.003$, $f_{T_d}^{(n)} \approx 0.036 \pm 0.008$, and $f_{T_s}^{(n)} \approx 0.118 \pm 0.062$ [6]. The first term in Eq. 2 corresponds to interactions with the quarks in the target, either through t-channel CP-even Higgs exchange, or s-channel squark exchange. The second term corresponds to interactions with the gluons in the target through a quark/squark loop diagram. $f_{TG}^{(p)}$ is given by $1 - f_{T_u}^{(p)} - f_{T_d}^{(p)} - f_{T_s}^{(p)} \approx 0.84$, and analogously, $f_{TG}^{(n)} \approx 0.83$.

The contribution to the neutralino-quark coupling from Higgs exchange is given by [6]:

$$a_q^{(\rm Higgs)} =$$

$$- \frac{g_2 m_q}{4 m_W B}\left[Re\left(\delta_1[g_2 N_{12} - g_1 N_{11}]\right) DC\left(\frac{1}{m_h^2} - \frac{1}{m_H^2}\right)\right.$$
$$\left. + \; Re\left(\delta_2[g_2 N_{12} - g_1 N_{11}]\right)\left(\frac{D^2}{m_h^2} + \frac{C^2}{m_H^2}\right)\right]. \qquad (3)$$

For up-type quarks, $\delta_1 = N_{13}$, $\delta_2 = N_{14}$, $B = \sin\beta$, $C = \sin\alpha$ and $D = \cos\alpha$, whereas for down-type quarks, $\delta_1 = N_{14}$, $\delta_2 = -N_{13}$, $B = \cos\beta$, $C = \cos\alpha$ and $D = -\sin\alpha$. α is the Higgs mixing angle. N_{11}^2, N_{12}^2, N_{13}^2 and N_{14}^2 are the bino, wino and two Higgsino fractions of the lightest neutralino, respectively.

Supersymmetric models which are within the current or near-future reach of CDMS generally have an elastic scattering cross section that is dominated by CP-even Higgs exchange. For illustration, consider a bino-like neutralino (with a small Higgsino admixture) and large to moderate $\tan\beta$ and $\cos\alpha \sim 1$. In this case, the neutralino-nucleon cross section from CP-even Higgs exchange is approximately given by:

$$\sigma_{SI} \sim \frac{0.1\, m_p^4\, g_1^2\, g_2^2\, N_{11}^2\, N_{13}^2\, \tan^2\beta}{4\pi\, m_W^2\, m_A^4}$$
$$\sim 4 \times 10^{-7}\,\mathrm{pb}\left(\frac{\mathrm{N}_{11}^2}{0.9}\right)\left(\frac{\mathrm{N}_{13}^2}{0.1}\right)\left(\frac{300\,\mathrm{GeV}}{\mathrm{m_A}}\right)^4\left(\frac{\tan\beta}{50}\right)^2 \qquad (4)$$

where the mass of the CP-even Higgs with enhanced couplings to down-type fermions is approximately m_A. Below, we shall express the neutralino mass and composition in terms of $M_1 = M_2/2$ and μ. Generally, the relation is not compact, but *e.g.* in the limiting case of a light, bino-like LSP ($N_{11}^2 \approx 1$), one has $N_{13}^2 \approx \sin^2\theta_W \sin^2\beta\, m_Z^2/\mu^2$.

Eq. 4 demonstrates that if m_A and $\tan\beta$ are within the range of Tevatron searches, then a substantial elastic scattering cross section can be expected for the lightest neutralino, unless it is a very pure bino (*ie.* $|\mu|$ is very large).

Implications of CDMS — CDMS currently provides the strongest constraints on σ_{SI}. For a 50–100 GeV neutralino, this result excludes $\sigma_{SI} \gtrsim 2 \times 10^{-7}$ pb, whereas the limit is about a factor of ten weaker for a 1 TeV neutralino [4].

In the top frame of Fig. 1, we have plotted as a solid line the current exclusion limit of the Tevatron for $p\bar{p} \to A/H\, X \to \tau^+\tau^-\, X$ in the $\tan\beta - m_A$ plane and compared this to the current limits from CDMS, for various choices of M_2 and μ. The Tevatron constraint from the inclusive $\tau^+\tau^-$ channel is quite robust against variations of the MSSM parameters, while the channel $p\bar{p} \to A/H\; b\bar{b}$ followed by $A/H \to b\bar{b}$ is more susceptible to radiative corrections and is weaker, unless both $|\mu|$ is large and $\mu M_3 < 0$ [7].

σ_{SI} was calculated using the DarkSUSY program [9] assuming the central values of the f_T's appearing in Eq.2. The squarks have been decoupled and the GUT-relation between the gaugino masses was adopted. Note also that we do not address the neutralino relic abundance in Figs. 1 and 2, since we have only specified those supersymmetric parameters which are relevant to elastic scattering through Higgs exchange.

In the lower frame of Fig. 1, we show the projected 3σ discovery reach at the Tevatron (4 fb^{-1} per experiment) compared with the 2007 projected limits from CDMS [8]. For a wide range of M_2 and μ, we find that CDMS is able to test the entire region of the $\tan\beta - m_A$ plane in which the Tevatron will be capable of observing $p\bar{p} \to A/H\, X \to \tau^+\tau^-\, X$.

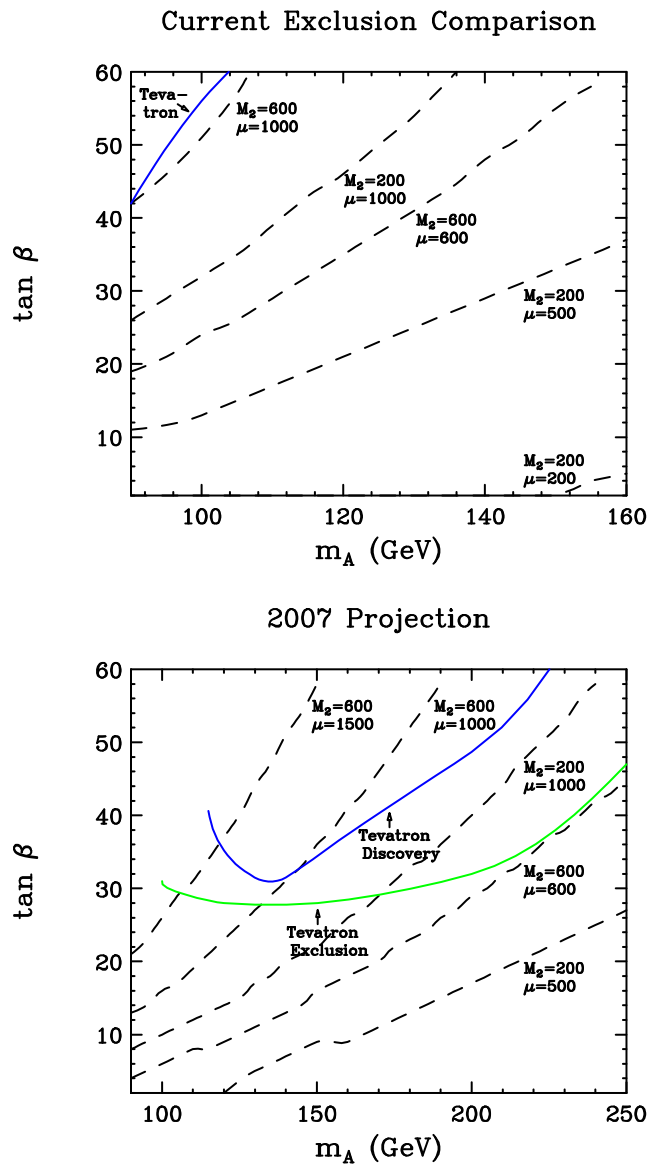

FIG. 1: Top-frame: The current Tevatron limit from $p\bar{p} \to A/H\; X \to \tau^+\tau^-\; X$ [1] compared to the currently excluded regions from CDMS for various combinations of M_2 and μ. Bottom-frame: The projected Tevatron 3σ discovery and 95% exclusion reach for $p\bar{p} \to A/H\; X \to \tau^+\tau^-\; X$ [2] compared to the 2007 projection of the CDMS limits.

It is clear that (unless $\mu \gg M_2$) the lack of a signal at CDMS disfavors the possibility of discovering heavy, neutral MSSM Higgs bosons at the Tevatron. We show these results in the M_2-μ plane in Fig. 2. For the models in the lightly shaded regions, A/H is not expected to be observed in the inclusive $\tau^+\tau^-$ channel, for any values of $\tan\beta$ and m_A, given the current constraints from CDMS. This would be expanded to the black regions, if indeed CDMS observes no signal in 2007.

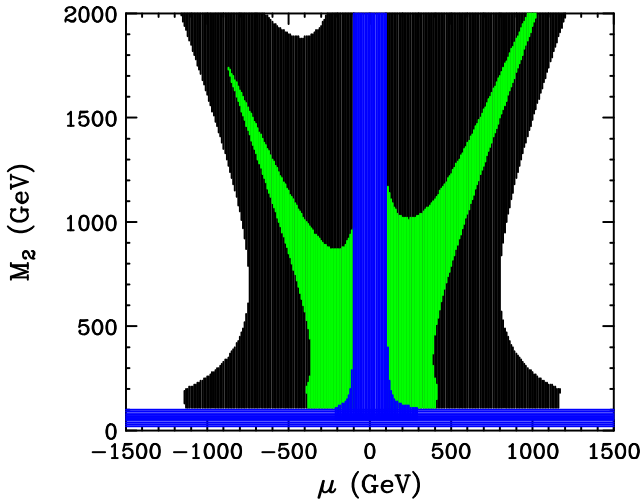

FIG. 2: The regions in the M_2-μ plane in which the possibility of discovering heavy, neutral MSSM Higgs boson at the Tevatron (4 fb^{-1} per experiment) through $p\bar{p} \to A/H\,X \to \tau^+\tau^-\,X$ is excluded due to current CDMS limits (light shaded) and the projected 2007 CDMS limits (black). The shaded region along the bottom of the figure and extending upward for small μ is excluded by LEP chargino limits [10].

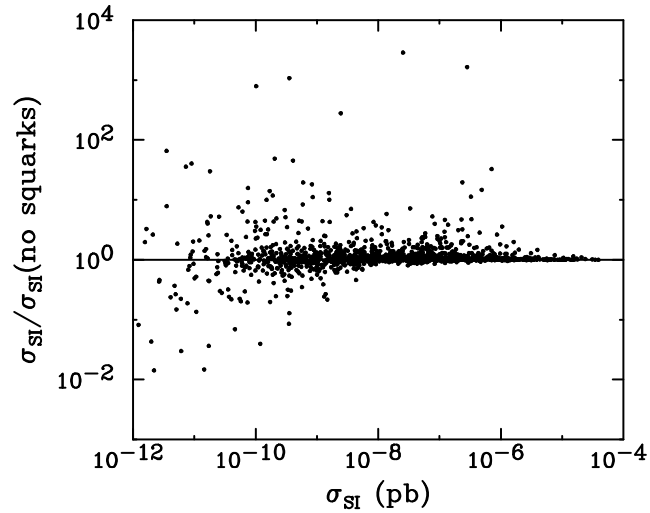

FIG. 3: The neutralino's elastic scattering cross section compared to the value found if all squark contributions are neglected, for a random sample of supersymmetric models. Each point shown respects all current collider constraints and does not predict a thermal density of neutralinos in excess of WMAP measurements.

If χ^0 had a large Higgsino component, such as in the upper region of Fig. 2 where $M_2/2 \gg |\mu|$, then it would be produced below the measured dark matter density [12]. Consequently, we focus on the lower region of the plot, in which $M_2/2 \lesssim |\mu|$. In the case when $M_2/2 \ll |\mu|$, the lightest neutralino is mostly bino-like, and the elastic scattering cross section is gradually reduced. For example, for M_2 =200 GeV, the Higgsino fraction of the lightest neutralino is approximately 15%, 1% and 0.2% for μ =200, 500 and 1000 GeV, respectively, corresponding to $\sigma_{\rm SI} \sim 6\times10^{-7}$, 4×10^{-8} and 10^{-8} pb, for $\tan\beta = 50$ and $m_A = 300$ GeV (see Eq. 4).

A positive signal at CDMS would be very encouraging for Tevatron Higgs searches. For example, if a neutralino were detected at CDMS with $\sigma_{SI} \sim 10^{-7}$ pb, then 3σ evidence for A/H in the inclusive $\tau^+\tau^-$ channel would be obtained as long as the Higgsino fraction of the lightest neutralino is greater than about 0.5% and m_A is heavier than about 140 GeV (as inferred from Fig. 1 and Eq. 4). On the other hand, evidence for the production of heavy neutral Higgs bosons at the Tevatron, without an observation at CDMS by 2007, could give very valuable information about the MSSM particle spectrum. In particular, it would suggest that $|\mu|$ is large, *e.g.* greater than about 800 GeV.

Caveats — These conclusions are subject to a number of assumptions. Most obviously, if the dominant component of our universe's dark matter is not made up of neutralinos, then the constraints placed by CDMS do not affect collider searches.

The results from CDMS involve substantial astrophysical uncertainties, including the local dark matter density, which we have taken to be 0.3 GeV/cm^3, as implied by the dynamics of our galaxy. Halo profiles consistent with observations have been proposed in which the dark matter density at the radius of the solar circle is as large as 0.8 GeV/cm^3 and as small as 0.2 GeV/cm^3. Experiments such as CDMS measure the product of the local dark matter density and the cross section averaged over the relative neutralino velocity.

If dark matter is not distributed homogeneously, but in dense clumps or tidal streams, then the density and velocity distribution of neutralinos at Earth could be different from the values we have used. Simulations suggest, however, that the dark matter distribution in the local vicinity consists of a superposition of a very large number of substructures, making substantial deviations from homogeneity unlikely [11].

We have neglected squark exchange diagrams in the calculation of σ_{rmSI} thus far. In Fig. 3 we demonstrate that these contributions, once included, generally increase rather than decrease the cross section, thus making our conclusions stronger. The figure shows the elastic scattering cross section for a random sample of lightest neutralinos compared to the value found if all squark contributions are neglected. Here we have scanned over M_2, μ, $\tan\beta$, m_A, sfermion masses and trilinear couplings (up to 2 TeV). M_1 and M_3 have been set by the GUT relationship. In the range of cross sections for which CDMS is likely to be sensitive to in the near future ($\sigma_{SI} \gtrsim 10^{-8}$ pb), neglecting squarks either has little effect or slightly underestimates the cross section in each model found.

We also consider our MSSM model assumptions, and alternatives which might lead to smaller elastic cross sections. For example, we assumed the GUT relationship between the gaugino masses ($M_1 : M_2 : M_3 \approx 1 : 2 : 7.5$), which leads to a very small wino component for the lightest neutralino. If, instead, we consider $M_2 \lesssim M_1$, then the lightest neutralino could be wino-like (such as in models of Anomaly Mediated Supersymmetry Breaking), and the cross section will be mod-

ified accordingly [13]. We have also assumed all MSSM parameters to be purely real. If, for example, μ has a non-trivial phase, then the Higgs states will mix and the Higgs-neutralino couplings can vary widely with that phase [14]. In such a scenario, the elastic scattering of neutralinos could be substantially suppressed.

Also, throughout our analysis we have used the central values [6] for the $f_T^{(p,n)}$ parameters appearing in Eq. 2. For σ_{SI}, the dominant contributions come from f_{T_s} and f_{TG}. Since these are related by a sum rule, our results are slightly more stable than would be inferred from the large uncertainty on f_{T_s} alone. Varying f_{T_s} by 1σ, for example, causes a factor of roughly 2 change in σ_{SI}, in either direction. Note that a larger π-nucleon Σ term [15] would increase f_{T_s} and thereby σ_{SI}, hence the values used here are conservative in this regard.

Finally, we point out that we have neglected radiative corrections to the down-type Yukawa couplings, which can be important at the largest values of $\tan\beta$ considered here. They will impact slightly the discovery reach of the Tevatron Higgs searches in the inclusive-τ channel, and more significantly the value of $\sigma_{\rm SI}$ [7], although the impact is generally small compared to the astrophysical uncertainties discussed above.

Summary and Conclusion — In this letter, we have explored the interplay of direct dark matter searches such as CDMS and the search for heavy, neutral MSSM Higgs bosons at the Tevatron. Both search techniques are most sensitive to supersymmetric models with large $\tan\beta$ and small m_A. We find that, modulo the caveats we have discussed, for small and moderate values of $|\mu|$, this region of MSSM parameter space is being probed first by CDMS. If a neutralino signal is seen in the near future by CDMS, then the expectations for the discovery of heavy, neutral Higgs bosons at the Tevatron will be high. On the other hand, the lack of a signal in CDMS would suggest that the observation of Higgs bosons will be unlikely, unless the lightest neutralino is a nearly pure bino, as would be the case if $|\mu| \gg M_2/2$. The current constraints from CDMS disfavor the discovery of heavy, neutral MSSM Higgs bosons at the Tevatron unless $|\mu| \gtrsim 400$ GeV, and the 2007 projected limits of CDMS will extend this to $|\mu| \gtrsim 800$ GeV.

Collider searches for heavy, neutral MSSM Higgs bosons and direct dark matter searches can, together, be used to extract valuable information about the supersymmetric spectrum. An observation of $p\bar{p} \to A/H \to \tau^+\tau^-$ at the Tevatron along with an accompanying discovery at CDMS, for example, could potentially be used to infer the higgsino fraction of the lightest neutralino. An observation of $p\bar{p} \to A/H \to \tau^+\tau^-$ at the Tevatron without an accompanying discovery at CDMS, on the other hand, would imply a very small higgsino fraction for the lightest neutralino (a large value of $|\mu|$), or that the nature of dark matter is not as assumed.

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