Dark Matter Phenomenology

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PPC 2017, TAMU-CC

PH, C. Wagner arXiv:1404.0392
Neutralino Dark Matter Phenomenology

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Neutralino Dark Matter, (or anything with a Higgs exchange) -- Where is it?

- The direct detection experiments are pushing rapidly into the region with a Higgs exchange.
- Suppress the neutralino direct detection rate?

\[ \text{Direct Detection} \]
Outline

• How to suppress the neutralino direct detection rate?
  • Blind Spot scenarios

• Deviations from the Blind Spots
  • Current constraints
  • Future reaches

• How to probe the blind spot scenarios?
  • LHC
  • IceCube
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Suppress the Neutralino Direct Detection Rate

• Consider a neutralino scattering off a down-type quark.

In gauge eigenstates

\[ h = \frac{1}{\sqrt{2}}(\cos \alpha \ H_u - \sin \alpha \ H_d) \]

\[ H = \frac{1}{\sqrt{2}}(\sin \alpha \ H_d + \cos \alpha \ H_u). \]

Amplitude

\[ a_d \sim \frac{m_d}{\cos \beta} \left( \frac{-\sin \alpha \ g_{XXh}}{m_h^2} + \frac{\cos \alpha \ g_{XXH}}{m_H^2} \right) \]

\[ \bar{\chi} = N_{i1} \ B + N_{i2} \ \tilde{W} + N_{i3} \ \tilde{H}_d + N_{i4} \ \tilde{H}_u \quad L \supset -\sqrt{2}g' Y_{H_u} \ B \tilde{H}_u H^*_u - \sqrt{2}g \tilde{W}^u \tilde{H}_u e^a \tilde{H}^*_u + (u \leftrightarrow d) \]

Couplings

\[ g_{XXh} \sim (g_1 N_{i1} - g_2 N_{i2})(-\cos \alpha \ N_{i4} - \sin \alpha \ N_{i3}) \]

\[ g_{XXH} \sim (g_1 N_{i1} - g_2 N_{i2})(-\sin \alpha \ N_{i4} + \cos \alpha \ N_{i3}). \]
Suppress the neutralino direct detection rate

\[ a_d \sim \frac{m_d(g_1N_{i1} - g_2N_{i2})}{\cos \beta} \left[ N_{i4} \sin \alpha \cos \alpha \left( \frac{1}{m_h^2} - \frac{1}{m_H^2} \right) + N_{i3} \left( \frac{\sin^2 \alpha}{m_h^2} + \frac{\cos^2 \alpha}{m_H^2} \right) \right] \]

Loop Effects

\[ L = f_d \bar{d}_L d_R H_d^0 + \epsilon_d f_d \bar{d}_L d_R H_u^0 + h.c. \]

\[ a_d \sim \frac{\tilde{m}_d(g_1N_{i1} - g_2N_{i2})}{\cos \beta} \left[ N_{i4} \sin \alpha \cos \alpha \left( \frac{1 - \epsilon_d/\tan \alpha}{m_h^2} - 1 + \epsilon_d \tan \alpha \right) \right. \]

\[ + N_{i3} \left( \frac{\sin^2 \alpha(1 - \epsilon_d/\tan \alpha)}{m_h^2} + \frac{\cos^2 \alpha(1 + \epsilon_d \tan \alpha)}{m_H^2} \right) \]

\[ \tilde{m}_d = \frac{m_d}{1 + \epsilon_d \tan \beta} \quad \epsilon_d \approx \frac{2\alpha_s}{3\pi} M_3 \mu C_0(m_0^2, m_R^2, |M_3|^2) \]

\[ C_0(X, Y, Z) = \frac{y}{(x - y)(z - y)} \log(y/x) + \frac{z}{(x - z)(y - z)} \log(z/x). \]

When 1st&2nd gen squarks are heavy, \( \epsilon_d \) is suppressed
Suppress the Neutralino Direct Detection Rate

\[ a_d \sim \frac{m_d (g_1 N_{i1} - g_2 N_{i2})}{\cos \beta} \left[ N_{i4} \sin \alpha \cos \alpha \left( \frac{1}{m_h^2} - \frac{1}{m_H^2} \right) + N_{i3} \left( \frac{\sin^2 \alpha + \cos^2 \alpha}{m_h^2} \right) \right] \]

\[ N_{i3} \sim (m_\chi \cos \beta + \mu \sin \beta) \quad \sin \alpha \approx - \cos \beta \]

\[ N_{i4} \sim (m_\chi \sin \beta + \mu \cos \beta). \]

\[ a_d \sim \frac{m_d}{\cos \beta} \left[ \cos \beta (m_\chi + \mu \sin 2\beta) \frac{1}{m_h^2} - \mu \sin \beta \cos 2\beta \frac{1}{m_H^2} \right] \]

\[ a_u \sim \frac{m_u}{\sin \beta} \left[ \sin \beta (m_\chi + \mu \sin 2\beta) \frac{1}{m_h^2} + \mu \cos \beta \cos 2\beta \frac{1}{m_H^2} \right] \]

\[ a_p = \left( \sum_{q=u,d,s} f_{Tq}^{(p)} \frac{a_q}{m_q} + \frac{2}{27} f_{TC}^{(p)} \sum_{q=c,b,t} \frac{a_q}{m_q} \right) m_p \]

Blind Spot in Dark Matter Direct Detection

\[ \sigma_p^{SI} \sim \left( F_d^{(p)} + F_u^{(p)} \right) (m_\chi + \mu \sin 2\beta) \frac{1}{m_h^2} + \mu \tan \beta \cos 2\beta \left( -F_d^{(p)} + F_u^{(p)} / \tan^2 \beta \right) \frac{1}{m_h^2} \]

Blind Spot at

\[ (m_{\chi^0} + \mu \sin 2\beta) = 0 \]

Higgsino mass \( \mu < 0 \)

Suppress the lightest neutralino coupling to 125 GeV Higgs

Destructive interference between the 125 GeV Higgs and the heavy Higgs exchange

Reduce the pMSSM parameter space to \( M_1, \mu, \tan \beta, \) and \( m_A \)

For a full pMSSM study, see Cahill-Rowley et al, 1405.6716. For a loop level analysis, see Berlin, Hooper, and McDermott, arXiv:1508.05390
Blind Spot and the Relic Density

Relevant parameters:
$M_1, \mu, \tan\beta,$ and $m_A$

Under Abundant Over Abundant

$m_A$ is chosen to minimize the DD rate

$$2 \left( m_\chi + \mu \sin 2\beta \right) \frac{1}{m_h^2} \sim -\mu \tan \beta \frac{1}{m_H^2}$$

Two branches

- well tempered $M_1 \sim \mu$
- A-funnel $m_\chi \sim m_A/2$
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Current Direct Detection Constraints

\[ \sigma_{SI}^p \sim \left( F_d^{(p)} + F_u^{(p)} \right) \left( m_\chi + \mu \sin 2\beta \right) \frac{1}{m_h^2} + \mu \tan \beta \cos 2\beta \left( -F_d^{(p)} + F_u^{(p)}/\tan^2 \beta \right) \frac{1}{m_H^2} \right)^2 \]

Assume the right relic density

In the well-tempered region, \( m_A < 350 - 400 \text{ GeV} \)

The A-funnel region is allowed by LUX and relic density considerations

Neutralino higgs coupling vanishes
Current Direct Detection Constraints

\[ \sigma_{SI}^p \sim \left[ (F_d^{(p)} + F_u^{(p)})(m_X + \mu \sin 2\beta) \frac{1}{m_h^2} + \mu \tan \beta \cos 2\beta \left( -F_d^{(p)} + F_u^{(p)} / \tan^2 \beta \right) \frac{1}{m_H^2} \right]^2 \]

\( m_A \) upper bound

Rescale according to the local density

In the well-tempered region, \( m_A < 350\, \text{-} 400 \, \text{GeV} \)

relaxed mA bound to the left of the well-tempered region

Will discuss direct heavy Higgs search and precision Higgs later
Future Reach

next generation experiments will push $m_A$ to be smaller than 300 GeV in the well-tempered region
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Probe the Blind Spots Scenarios – Collider Searches

Well-tempered region:
- open for $\tan\beta < 6$
- completely ruled out for $\tan\beta \gtrsim 7$

A-funnel region starts to get excluded as $\tan\beta$ increases

$$2 \left( m_\chi + \mu \sin 2\beta \right) \frac{1}{m_h^2} = -\mu \tan\beta \frac{1}{m_H^2}$$
Probe the Blind Spots Scenarios – Collider Searches

- hbb coupling

\[
\frac{g_{hbb}}{g_{hbb}^\text{SM}} = -\frac{\sin \alpha}{\cos \beta} = \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha)
\]

hVV coupling \(\sim 1\) controls the modification

- One loop level, sizable tan\(\beta\)

\[
\tan \beta \cos(\beta - \alpha) \simeq \frac{-1}{m_H^2 - m_h^2} \left[ m_h^2 + m_Z^2 + \frac{3m_t^4}{4\pi^2 v^2 M_S^2} A_t \mu \tan \beta \left(1 - \frac{A_t^2}{6M_S^2}\right)\right]
\]

\(M_s \gtrsim \text{TeV}, \) proper Higgs mass

\(m_A \gtrsim 350 \text{ GeV}\) to be consistent with the current Higgs data.
In tension with the current Higgs data

Extended the Higgs sector

\[
\tan \beta \cos(\beta - \alpha) \simeq \frac{-1}{m_H^2 - m_h^2} \left[ m_h^2 + m_Z^2 + \frac{3m_t^4}{4\pi^2v^2M_S^2}A_t\mu \tan \beta \left( 1 - \frac{A_t^2}{6M_S^2} \right) \right]
\]

\[
\tan \beta \cos(\beta - \alpha) \simeq \frac{-1}{m_H^2 - m_h^2} \left[ m_h^2 + m_Z^2 - \lambda^2v^2 + \frac{3m_t^4}{4\pi^2v^2M_S^2}A_t\mu \tan \beta \left( 1 - \frac{A_t^2}{6M_S^2} \right) \right]
\]

\( \lambda \approx 0.6-07 \), even for \( m_H \approx 200 \text{ GeV} \), the modification in SM Higgs coupling is small enough.

Blind spot scenarios in NMSSM, see Badziak, Olechowski, and Szczerbiak, arXiv:1512.02472
Probe the Blind Spots Scenarios – Collider Searches

- 3 neutralinos, (mixtures of bino and Higgsinos), the lighest chargino(Higgsino-like)

\[ \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow WZ \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]
\[ \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow Wh \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]
Probe the Blind Spots scenarios – IceCube

**Figure 12:** Branching ratios for dark matter annihilation products, including $b\bar{b}$, weak, $t\bar{t}$, WH, ZH, hA, WW, ZZ.

**Table 1:**

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Branching Ratio</th>
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<tr>
<td>$b\bar{b}$</td>
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<tr>
<td>$t\bar{t}$</td>
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<tr>
<td>WH</td>
<td>0.6</td>
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<td>ZH</td>
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<td>hA</td>
<td>0.2</td>
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<tr>
<td>WW</td>
<td>0.1</td>
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<tr>
<td>ZZ</td>
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</table>

<table>
<thead>
<tr>
<th>$	an \beta = 7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\chi}$ (GeV)</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>600</td>
</tr>
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<td>800</td>
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<tr>
<td>1000</td>
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</tbody>
</table>

IceCube Collaboration, 2016
Probe the Blind Spots scenarios – IceCube

IC79

Spin-Dependent Constraints from IceCube, All $\tan\beta$

exclude the well-tempered region for $m_\chi \lesssim 200$ GeV
Conclusion

• Identify a blind spot scenario for neutralino dark matter

• Possible probes
  • LHC - Heavy Higgs searches, precision Higgs, and Electroweakinos searches
  • IceCube
backup
Positive $\mu$

Larger Higgs Neutralino coupling
Constructive interference

lower bound on $m_A$
A –funnel and the LUX limit

Figure. 6: Thermal relic density shown in color on $|\mu| - M_1$ plane for various $\tan\beta$. $M_A$ is taken to be at the center of blind spot (maximum cancellation). Note that $\mu$ is always negative for the blind spot to occur. The yellow region is consistent with the observed relic density. In the regions between the white dashed lines, $M_A$ can be adjusted to mediate resonant annihilation while keeping $\text{SI}_p < 10^{11}$ pb. Blind spots are not achieved in the gray area since the left hand side of Eq. 6 becomes negative and destructive interference cannot happen. In this region, the $\text{SI}_p < 10^{11}$ pb requirement does not set an upper bound for $M_A$ but only a lower bound, though it is still possible to tune $M_A$ to achieve resonant annihilation for $m$ high enough.

We have used MicroOMEGAs (with SuSpect 2.41) to calculate the spectrum, SI and
Exclusions

Figure 8: Net exclusion status of the well-tempered region and the A-funnel region. Each data point represents a point with the proper relic density. Data points are first checked for exclusion by CMS, then by ATLAS, then by the CMS electroweino searches (see the following section), with the color-coding of each data point corresponding to the method by which it is first excluded. Values of $M_A$ are labeled next to selected data points. The sparseness of points in the A-funnel region reflects its narrowness relative to the well-tempered region, as seen in Fig. 6.

B. Electroweino Search

The $\tau\tau$ searches leave open a small region of parameter space where $M_A$ is sufficiently large to avoid these constraints, with $M_{1/2}, |\mu| < 200$ GeV. The neutralinos and charginos are light in this region, so electroweino searches at LHC become relevant. The most stringent constraints are obtained from studying the decay products of the associated production of charginos and neutralinos, $e_0^2 \pm 1$. Since our slepton masses have been set high, the branching ratio for the decay of the second lightest neutralino and the lightest chargino into sleptons is negligible. In addition, since $m_{e_0^2}, e_0^\pm 1 < M_A$, the decay of $e_0^2, e_0^\pm 1$ into heavy Higgs bosons is also negligible. This leaves $e_0^2 e_0^\pm 1 \rightarrow WZ e_0^1 e_0^1$ and $e_0^2 e_0^\pm 1 \rightarrow Wh e_0^1 e_0^1$. 
Exclusions, mA upper bound

Figure 10: Plot analogous to Fig. 8 with $M_A$ chosen at the upper limit consistent with $\text{SI}_p = 10^{11}$ pb. Only exclusions from the CMS $\text{hl} \rightarrow \mu \mu$ search are shown.

Even considering there are two higgsinos, the total higgsino production cross section is about half the wino production cross section, so the true bounds on our data are weaker than those presented in [53]. We find that these electroweakino searches do constrain this region, as shown by the yellow points in Figs. 8-10. Although the displayed bounds are generous for the Higgsino-like electroweakinos in our data, we will show in subsection D that this region of parameters is also excluded by recent IceCube results [60].

The High Luminosity-LHC would extend the scope of the electroweakino searches, and could probe up to 150 GeV to 600 GeV depending on the mass of the LSP [59, 61]. A 100 TeV collider can further extend the reach. For instance, when $m_{\tilde{\chi}^0_1}$ is below 500 GeV, a 100 TeV collider with 3 ab$^{-1}$ can make a discovery of a higgsino on the order of 1.5 TeV.

For a recent analysis, see Ref. [59].
EW-ino production cross section

In the well-tempered region, where $M_1 \ll |\mu|$, a future 100 TeV collider with 3 ab$^{-1}$ can be sensitive to a mixed bino-higgsino LSP up to 1 TeV, and can reach 5 discovery for $m_{\tilde{\chi}_0^1}$ depending on the mass difference between the two lightest neutralinos and the treatment of systematics.

C. Precision Higgs Measurements

In the well-tempered region, as $M_A$ is light, there could be some tension with the precision Higgs data. At the tree level, the 125 GeV Higgs coupling to bottom-quarks in the MSSM is given by

$$g_{hbb}^S M = \sin \alpha \cos \alpha = \sin (\alpha) \tan \alpha \cos (\alpha).$$

(7)

The first term in the left-hand side of this expression, $\sin (\alpha)$, gives the ratio of the coupling of the Higgs to weak vector bosons to its SM value. In order to reproduce the