Guaranteed Rates for Dark Matter Production at Colliders

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Dark Matter (DM)

- Non-baryonic
- Stable
- Neutral
- Cold

\[ \Omega_{DM} h^2 = 0.112 \pm 0.009 \]

- Can not be any of the known particles
- Microscopic identity of DM?

**WIMP** and **superWIMP**

- Appear in particle physics models motivated independently by attempts to solve EWSB
- Relic density are determined by \( M_{pl} \) and \( M_{\text{weak}} \)
  - Naturally around the observed value
  - No need to introduce and adjust new energy scale
Neutral WIMP

- \( m_{\text{WIMP}} \gg M_{\text{weak}} \)
- \( \sigma_{\text{an}} \gg \alpha_{\text{weak}}^2 M_{\text{weak}}^{-2} \)

\( \Omega_{\text{WIMP}} \gg h \sigma_{\text{an}} v i^{-1} \)
	naturally around the observed value

e.g. neutralino LSP

![Graph showing the comoving number density over time with increasing \( \langle \sigma_A v \rangle \)]
superWIMP

WIMP → superWIMP + SM particles

$10^4 \text{ s} < t < 10^8 \text{ s}$

$\Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}}$

superWIMP

- e.g. Gravitino LSP
- LKK graviton

WIMP

- neutral
- charged
WIMP production (I)

- \( \Omega_{\text{WIMP}}, \Omega_{\text{SWIMP}} \leq \Omega_{\text{DM}} \)
- WIMP annihilate efficiently in early universe
- WIMP be produced efficiently at colliders

Upper bound on \( \Omega \)
Lower bound on rates


- neutral WIMP at ILC: see Perelstein's talk
- both ILC and LHC
- consider superWIMP scenario: more promising
WIMP production (II)

**WIMP annihilation**

\[
\sigma_{\text{tot}} = \sum_{ij} \sigma(X \bar{X} \rightarrow ij; \hat{s})
\]

\[
\langle \sigma_{\text{tot}} v_X \rangle = \sigma_{\text{an}} v_X^{2n} + O(v_X^{2n+2}) = \sigma_0 x^{-n} + O(x^{-n-1})
\]

\(n=0: \text{S-wave}; \ n=1, \text{P-wave}\)

\[x = \frac{m_{\text{WIMP}}}{T}\]

**WIMP relic density**

\[
\Omega_{\text{WIMP}} h^2 \simeq 1.07 \times 10^9 \text{ GeV}^{-1} \frac{n + 1}{\sqrt{g_* M_{\text{Pl}}}} \frac{x_F^{n+1}}{\sigma_0}
\]

\[
\sigma_0 = \frac{1}{c^2 - 1} \sqrt{\frac{8}{45}} \frac{2\pi^3 g_*^{1/2}}{g} \frac{x_F^{n+1/2}}{m_{\text{WIMP}} M_{\text{Pl}}} e^{x_F}
\]

\[x_F = \frac{m_{\text{WIMP}}}{T_F}\]

**WIMP pair production:** via detailed balance

\[
\sigma(ij \rightarrow X \bar{X}; \hat{s}) = \frac{\eta_{ij} v_X^2 (2S_X + 1)^2}{4(2S_i + 1)(2S_j + 1)} \sigma(X \bar{X} \rightarrow ij; \hat{s}) = \frac{\eta_{ij} (2S_X + 1)^2}{4(2S_i + 1)(2S_j + 1)} \frac{\kappa_{ij} \sigma_{\text{an}} v_X^{2n+1}}{\sigma_{\text{tot}}}
\]

\[\eta = 1: \text{identical}; \ \eta = 1: \text{otherwise}\]

\[\kappa_{ij} = \frac{\sigma(X \bar{X} \rightarrow ij; \hat{s})}{\sigma_{\text{tot}}}
\]
SuperWIMP with charged WIMP

LHC production

\[ \bar{\sigma}(pp \rightarrow X \bar{X}; s) = \int_{4m_X^2/s}^{3m_X^2/s} du \int_u^1 dx \frac{1}{1-v_{max}^2/4} x \]

\[ \times \sum_{ij} \left[ f_{q_i}^P(x) f_{\bar{q}_j}^P(u/x) + f_{\bar{q}_j}^P(x) f_{q_i}^P(u/x) \right] \times \bar{\sigma}(q_i \bar{q}_j \rightarrow X \bar{X}; s) \]

Signal: two isolated charged track, free of hadron activity
- \( |n| < 2.5 \)
- detect the track
- \( \beta < 0.7 \)
- ionization -dE/dx more than double minimum-ionizing

Background free!
SuperWIMP with charged WIMP at LHC

- **P-wave vs. S-wave**
  - $V_X^2$ suppression compensated by $\sigma_{an}$
- **$S_X=0**
  - $\sigma / (2S_X+1)^2$
- **$\kappa_{qq}=0.2$ for $q=u,d,s,c,b$**
  - $\sigma / \kappa_{qq}$
- **$m_{SWIMP}/m_{WIMP}=0.6$**
  - $\sigma / m_{SWIMP}/m_{WIMP}$
- **isotropic distribution**
  - 10% variation for $\sin^2\theta$ or $(1-\cos\theta)^2$
- **$\eta_{CUT}$ dependence**
  - drop by 20% for $|\eta|<0.5$
- **$\beta_{CUT}$ dependence**
  - drop by factor of 2-5 for $\beta<0.6$
SuperWIMP with charged WIMP at ILC

\[ \beta > 0.7, \ V_x^2 > 2 \]

unreliable
**superWIMP: Discovery limit**

10 events reach

P-wave

\( S_X = 0 \)

\( m_{SWIMP}/m_{WIMP} = 0.6 \)

Scale as

\((2 S_X + 1)^{-2} \) and

\((m_{SWIMP}/m_{WIMP})^{-1} \)
Neutral WIMP at LHC

- WIMP pair production is invisible
- Consider monojet event: $pp \rightarrow X \bar{X} j$

\[
\frac{d}{dz \, d\cos \theta} \bar{\sigma}(q(\bar{q} \rightarrow \bar{q}g) \rightarrow X \bar{X} g; \hat{s}) \approx F_{\bar{q} \rightarrow g}(z, \theta) \bar{\sigma}(q \bar{q} \rightarrow X \bar{X}; (1 - z)\hat{s})
\]

- Irreducible SM background: $pp \rightarrow \nu \nu j$

\[
\frac{d}{dz \, d\cos \theta} \bar{\sigma}(q(g \rightarrow \bar{q}q) \rightarrow X \bar{X} q; \hat{s}) \approx F_{g \rightarrow q}(z, \theta) \frac{2S_q + 1}{2S_g + 1} \bar{\sigma}(q \bar{q} \rightarrow X \bar{X}; (1 - z)\hat{s})
\]

<table>
<thead>
<tr>
<th>$p_T^{\text{min}}$ (GeV)</th>
<th>$B$ (fb)</th>
<th>$1300$ pb</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>19</td>
<td>1300</td>
<td>0.51</td>
</tr>
<tr>
<td>100</td>
<td>4.1</td>
<td>130</td>
<td>0.36</td>
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</tbody>
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Difficult!
Conclusions

If stable WIMP or superWIMP exist, cosmology provides model-independent lower bounds on production rates of new particles at colliders.

In superWIMP scenario with charged WIMP, spectacular signals at LHC and ILC.

In standard WIMP scenario, $XXj$ signal is swamped by monojet background.