Dark Matter: Colliders (and Direct Detection)

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Dark Matter Puzzle:

- About 25% of the energy in the universe is dark, non-relativistic matter
- Non-particle explanations unlikely
- $\chi$ has to be stable (or at least $\tau \geq 10$ bln. years)
- $\chi$ cannot have strong interactions (otherwise $p\chi$ exotic nuclei) or electric charge (dark)
- $\chi$ cannot be a Standard Model neutrino (free streaming)
- Have to invent (at least one) new particle
**WIMP: a Perfect Fit**

- $\chi$’s interact with the SM matter via weak forces (or a new interaction of similar strength/range)

- $\chi$ is massive (1 GeV – 10 TeV range) → $\chi$’s are in thermal equilibrium with the SM matter as long as $T > M(\chi)$: $n_\chi \sigma v > H$

- When $T < M(\chi)$, $n_\chi \propto \exp(-M/T)$ (Boltzmann suppression) and $\chi$’s decouple

- Energy density of $\chi$’s today: $\rho_\chi \approx \frac{T_0^3}{M_{pl}\sigma} \sim \rho_c$
WIMPs at Colliders

• Much of the reasonable mass range for WIMPs is within reach of the LHC and ILC/CLIC

• Two basic ways to produce WIMPs at colliders:
  • In decay of heavier exotic particles: for example
  • Direct production: for example

• Production in decay can dominate (e.g. if decaying particle is colored high rate) but is more model-dependent (assumptions beyond WIMP!)

• Strong LHC bounds on colored exotic states decaying to MET+SM shrinking parameter space for observing WIMPs in decays...

• Direct production is less model-dependent, and is not yet strongly constrained. Will be my focus in this talk.
Predicting WIMP Signatures: “Model-Independent” Approach

- Many particle physics models contain WIMPs: SUSY, Extra Dimensions, Little Higgs, etc.

- Direct (radiative) WIMP production can be described within a model-independent formalism [Birkedal, Matchev, MP, hep-ph/0403004]

\[
\text{WMAP } \Omega_{\text{dm}} \Rightarrow \begin{array}{c}
\chi \rightarrow e^- \\
\chi \rightarrow e^+ \\
\chi \rightarrow e^-
\end{array} \Rightarrow \begin{array}{c}
\chi \rightarrow e^+ \\
\chi \rightarrow e^- \\
\chi \rightarrow \gamma
\end{array} \Rightarrow \text{ILC } \sigma(\gamma + \bar{\nu})
\]
Assumptions:

- Assume **generic** mass spectrum (no resonances, no coannihilations)

- At the time of $\chi$ decoupling, the only important reactions are $\chi\chi \leftrightarrow X_i \bar{X}_j$, where $X_i$ is SM

- For non-relativistic WIMPs, can be expanded as:

\[
\sigma_i v = \sigma_i^{(0)} + \sigma_i^{(1)} v^2 + \ldots
\]

- Dominated by either **s-wave** or **p-wave**

- Define

\[
\sigma_{an} = \sum_i \sigma_i^{J_0}
\]
$\Omega_{dm}$ determines $\sigma_{an}$

$2\sigma$ constraint using $\Omega_{dm}h^2 = 0.112 \pm 0.009$ (WMAP)
From Cosmology to Colliders

Cosmology provides a precise, model-independent measurement of $\sigma_{\text{an}}$

Idea: use this information to predict $\chi$ production rate at a collider!

Step 1: Detailed Balancing (DB)

$$\frac{\sigma(\chi\chi \rightarrow e^+e^-)}{\sigma(e^+e^- \rightarrow \chi\chi)} = 2 \frac{v_e^2(2S_e + 1)^2}{v_\chi^2(2S_\chi + 1)^2}$$

Define annihilation fraction: $\kappa_e = \frac{\sigma_{e^+e^-}}{\sigma_{\text{an}}}$
Tagging and Factorization

 Obtain a \textbf{prediction}:

\[ \sigma(e^+e^- \rightarrow \chi\chi) = \frac{2^{2(J_0+1)}}{(2S_\chi + 1)^2} \kappa_i \sigma_{an} \left(1 - \frac{4M_\chi^2}{s}\right)^{1/2+J_0} \]

 \[ d\sigma(e^+e^- \rightarrow 2\chi + \gamma) \approx \mathcal{F}(x, \cos \theta) \hat{\sigma}(e^+e^- \rightarrow 2\chi) \]

 \[ \mathcal{F}(x, \cos \theta) = \frac{\alpha}{\pi} \frac{1 + (1 - x)^2}{x} \frac{1}{\sin^2 \theta}, \quad x = 2E_\gamma/\sqrt{s} \]

This is unobservable (like \( e^+e^- \rightarrow \nu\bar{\nu} \))

Consider instead \( e^+e^- \rightarrow \chi\chi + \gamma \)

\textbf{Step 2: Use \textit{soft/collinear factorization}:}

\[ \frac{d\sigma(e^+e^- \rightarrow \chi\chi + \gamma)}{dx \, d\cos \theta} \approx \mathcal{F}(x, \cos \theta) \hat{\sigma}(e^+e^- \rightarrow \chi\chi + \gamma) \]
Experimental Strategy for a Model-Independent WIMP Search at the ILC

- Look for photon + missing energy events
- Impose $p_{\gamma}^{\text{min}}(\gamma)$ cut to eliminate fakes (mainly Bhabha)
- Impose $E_{\gamma}^{\text{min}}$ cut to ensure non-relativistic WIMPs
- Compute and subtract the irreducible background (mainly $e^+e^- \rightarrow \nu\bar{\nu}\gamma$)
- Look for deviations from zero!
The Reach of a 500 GeV LC

Dash – stat. only \((L = 500 \text{ fb}^{-1})\), Solid – stat. + 0.3% syst.

Cuts: \(\sin \theta > 0.1\), \(p_T^\gamma > 7.5\text{ GeV}\), \(x_\gamma \in [1 - 8M_\chi^2/s, 1 - 4M_\chi^2/s]\)
Detector-Level Studies

Figure 4: 3σ observation reach of the ILC for a Spin-$\frac{1}{2}$ WIMP in terms of WIMP mass and $\kappa_e$ for three different assumptions on the chirality of the electron-WIMP coupling, see text. Full line: $P_{e^-} = P_{e^+} = 0$, dotted line: $P_{e^-} = 0.8, P_{e^+} = 0$, dashed line: $P_{e^-} = 0.8, P_{e^+} = 0.6$. Regions above the curves are accessible.

[ Bartels, List, 0709.2629]
Reach down to $\kappa_e \sim 10^{-2}$!

[ Bartels, Berggren, List, 1206.6639]
Percent-level mass measurement!
Alternative: Effective Operator Approach

- The formalism I just reviewed makes no reference to a Lagrangian

- Alternative: Model DM-SM couplings with effective operators in a Lagrangian [Beltran et al. 1002.4137; Goodman et al. 1005.1286; Bai, Fox, Harnik, 1005.3797; Fox et al. 1109.4398]

- Example: Spin-1/2 Dirac WIMP, some of the possible electron-DM couplings are
  \[ \mathcal{O}_V = (\bar{\chi} \gamma_\mu \chi)(\bar{\ell} \gamma^\mu \ell) \, , \quad \mathcal{O}_A = (\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{\ell} \gamma^\mu \gamma^5 \ell) \, , \]
  \[ \mathcal{O}_S = (\bar{\chi} \chi)(\bar{\ell} \ell) \, , \quad \mathcal{O}_t = (\bar{\chi} \ell)(\bar{\ell} \chi) \, . \]

- Parameterizes the effect of heavy particles mediating WIMP-DM interactions (e.g. t-channel selectrons in the MSSM), in a model-independent way

- Works if the scale \( \Lambda \) is above the energy scale of the experiment

- Does not require NR WIMPs - broader kinematic validity

- Applicable to more processes - e.g. \( qX \) elastic scattering (direct detection!)
Direct Detection Status

[XENON100, 1207.5988]
LHC Limits

[ATLAS, 1210.4491; see also CMS, 1206.5663]

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial state</th>
<th>Type</th>
<th>Operator</th>
</tr>
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<tbody>
<tr>
<td>D1</td>
<td>$qq$</td>
<td>scalar</td>
<td>$\frac{m_\chi}{M_Z^2} \bar{\chi} \chi q \bar{q}$</td>
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<tr>
<td>D5</td>
<td>$qq$</td>
<td>vector</td>
<td>$\frac{1}{M_Z^2} \bar{\chi} \gamma^\mu \chi \gamma_{\mu} \bar{q} q$</td>
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<tr>
<td>D8</td>
<td>$qq$</td>
<td>axial-vector</td>
<td>$\frac{1}{M_Z^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \gamma_{\mu} \gamma^5 \bar{q} q$</td>
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<tr>
<td>D9</td>
<td>$qq$</td>
<td>tensor</td>
<td>$\frac{1}{M_Z^2} \bar{\chi} \sigma^{\mu \nu} \chi \gamma_{\mu} \sigma_{\nu\lambda} \bar{q} q$</td>
</tr>
<tr>
<td>D11</td>
<td>$gg$</td>
<td>scalar</td>
<td>$\frac{1}{4M_Z^2} \bar{\chi} \chi \alpha_S (G_{\mu \nu}^a)^2$</td>
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![Graph of LHC limits](image)
LHC vs. Direct Detection

[ATLAS, 1210.4491; see also CMS, 1206.5663]

Collider Searches are more sensitive in two regimes:

Low WIMP mass (<10 GeV)

Coupling via Spin-Dep. operators
LEP-2 Limits

[Fox, Harnik, Kopp, Tsai, 1103.0240]
Expected ILC Limits

[Yoonseok Chae, MP, to appear]
Direct Detection/Tuning in (N)MSSM

[Shakya, MP, 1107.5048; 1208.0833]

“Purity”: fraction of the subdominant (gaugino or Higgsino) component in the LSP

Fine-tuning in EWSB (tree-level)

Tension is already developing in (N)MSSM from null result of direct detection searches!