Dark Matter Characterisation at the LHC

Alexander Belyaev

Southampton University & Rutherford Appleton Laboratory

Rencontres de Moriond, QCD session
LA THUILE, 19-26 March 2016
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Many thanks to the organisers!
Collaborators

- Daniele D. Barducci, AB, A.Bharucha, W. Porod, V. Sanz, arXiv:1504.02472
- AB, M. Thomas, Luca Panizzi, Alexander Pukhov, (DM spin, th) work in progress
- AB, S. Novaes, M. Gregores, P. Mercadante, S. Quazi, S. Moon, S. Santos, T. Tomei, (DM spin, i2HDM, exp) work in progress
- AB, G. Cacciapaglia, I. Ivanov, F. Rojas, M. Thomas (i2HDM, th) work in progress
While Higgs Boson Discovery has completed the puzzle of the Standard model ...
While Higgs Boson Discovery has completed the puzzle of the Standard model, the SM can be seen as a piece of a bigger puzzle – BSM one!
What do we know about Dark Matter?

- Spin
- Mass
- Stable:
  - Yes
  - No
- Couplings:
  - gravity: Yes
  - Weak: Yes
  - Higgs: No
  - Quarks/gluons: No
  - Leptons: No
  - New sector: No
- Thermal relic:
  - Yes
  - No
The most competing subjects/theories

[Graph showing the number of papers for SUSY, Higgs, Top, DM, and EXD from 1980 to 2010, with logarithmic scaling on the y-axis.]
The most competing subjects/theories

The graph shows the number of papers published over time for various subjects. The y-axis represents the number of papers on a logarithmic scale, ranging from $10^2$ to $10^3$. The x-axis represents the years from 1980 to 2010.

The subjects are indicated by different lines:
- SUSY (Super Symmetry)
- Higgs
- Top
- EXD
- DM (Dark Matter)

The graph highlights how these subjects have gained or lost traction over time, with peaks indicating periods of increased research activity and drops indicating reduced interest. The 750 GeV line indicates a significant event in 2011.
This talk is about DM though, which is well established.
LHC sensitivity to SUSY DM
LHC sensitivity to SUSY DM

There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above $\sim 1 \text{ TeV}$
Low $\mu$ is required by low fine tuning measure

$$L_{\text{MSSM}} = \mu \tilde{H}_u \tilde{H}_d + \text{h.c.} + (m_{H_u}^2 + |\mu|^2) |H_u|^2 + (m_{H_d}^2 + |\mu|^2) |H_d|^2 + \ldots$$

Low EW FT $\leftrightarrow$ no large/unnatural cancellations in deriving $m_Z$ from the weak scale scalar potential:

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{(\tan^2 \beta - 1)} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

using fine-tuning definition which became standard

Ellis, Enqvist, Nanopoulos, Zwirner '86; Barbieri, Giudice '88

$$\Delta_{FT} = \max [c_i], \quad c_i = \left| \frac{\partial \ln m_Z^2}{\partial \ln p_i} \right| = \left| \frac{p_i}{m_Z^2} \frac{\partial m_Z^2}{\partial p_i} \right|$$

one finds $\Delta_{FT} \simeq \Delta_{EW}$ which requires as well as

$$\left| \mu^2 \right| \simeq M_Z^2$$
$$|m_{H_u}^2| \simeq M_Z^2$$

The last one is GUT model-dependent, so we consider the value $|\mu^2|$ as a measure of the minimal fine-tuning
\[ \Delta m_\sigma = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx m_Z^2 \left( \frac{s_W^2}{M_1} + \frac{c_W^2}{M_2} \right) \]

\[ \Delta m_{\pm} = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \approx \frac{\Delta m}{2} + \mu \frac{\alpha(m_Z)}{\pi} \left( 2 + \ln \frac{m_Z^2}{\mu^2} \right) \]

|μ| ≪ |M1|, |M2|

\[ \Delta m < 1 \text{ GeV} \]

→ displaced vertices \( \sim 0.1 \text{mm} \)

\[ \Delta m < 0.1 \text{ GeV} \]

→ DM is collider stable
The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature.

The only way to probe CHS is a mono-jet signature [“Where the Sidewalk Ends? ...” Alves, Izaguirre, Wacker ’11], which has been used in studies on compressed SUSY spectra, e.g. Dreiner, Kramer, Tattersall ’12; Han, Kobakhidze, Liu, Saavedra, Wu ’13; Han, Kribs, Martin, Menon ’14.
Mass Spectrum and Challenge for the LHC

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Note that $W^*$ decay products do not get large boost - it is proportional to the mass of $W^*$ which is much smaller than the mass of the LSP.
What is the LHC potential to probe NSUSY space through the $pp \rightarrow \chi \chi j : \chi = \chi^0_{1,2}, \chi^\pm_1$ process?
DM relic density and Direct Detection

- DM relic density is below the measured one because of intense LSP annihilation and co-annihilation processes
- IDD cross section rescaled with the relic density is low for the small DM region. Chance for the LHC?
Signal vs Background analysis

difference in rates is quite pessimistic ...

but the difference in shapes is quite encouraging!

\[ pp \rightarrow \nu \nu j \text{ vs. } pp \rightarrow \chi \chi j \]

13 TeV LHC

\[ 100 \text{ fb}^{-1} \]
**S/B vs Signal significance**

There is a strong tension between S/B and signal significance.

Higher S/B needs high \( E_T^{\text{miss}} \) cut to reach an acceptable systematic.

Higher significance needs low (< 500 GeV) \( E_T^{\text{miss}} \) cut.
LHC@13 Reach for NSUSY

- 3% and 5% S/B BM for 3 ab\(^{-1}\) and 100 fb\(^{-1}\) integrated luminosity

- LUX and XENON1T are sensitive to the upper end (larger \(\Delta M\)) of NSUSY

- For S/B \(\sim\) 3% (based on ATLAS studies), LHC will be sensitive to DM mass up to 250 GeV @95% CL with 3 ab\(^{-1}\) integrated luminosity
LHC@13 Reach for NSUSY

- 3% and 5% S/B BM for 3 ab^{-1} and 100 fb^{-1} integrated luminosity

- LUX and XENON1T are sensitive to the upper end (larger $\Delta M$) of NSUSY

- For S/B ~ 3% (based on ATLAS studies), LHC can discover DM with the mass up to 200 GeV with 3 ab^{-1} integrated luminosity
Characterisation of DM in generic models
Motivation for generic DM study

- If DM is produced at the LHC:
  - We need to be able to identify the underlying model.
    - SUSY?, Extra Dimensions?, Inert Two Higgs Doublet Model?
  - We need to know:
    - Mass, Spin, Mediator properties.

- Also: From LHC DM forum (arXiv:1507.00966)
  - “Different spins of Dark Matter particles will typically give similar results..... Thus the choice of Dirac fermion Dark Matter should be sufficient as benchmarks for the upcoming Run-2 searches.”

- Crucial to understand if this is true: Important for future exclusion and discovery DM studies.

- Study the effects of DM spin on observables at the LHC for Spin=0 and Spin=1/2, for events with a mono-jet (more generally mono-X).
- Consider contact interactions first: simplest case.
  - Complete set of DIM6 operators involving two SM quarks (gluons) and two DM particles.
- Extend to consider simplified models.
- Explore LHC potential to differentiate DM spins. (ongoing work)
### DIM6 operators

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$\bar{\chi} \chi \bar{q} q$</td>
<td>$m_q/M_3^2$</td>
</tr>
<tr>
<td>D2</td>
<td>$\bar{\chi} \gamma^5 \chi \bar{q} q$</td>
<td>$i m_q/M_3^2$</td>
</tr>
<tr>
<td>D3</td>
<td>$\bar{\chi} \chi \bar{q} \gamma^5 q$</td>
<td>$i m_q/M_3^2$</td>
</tr>
<tr>
<td>D4</td>
<td>$\bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q$</td>
<td>$m_q/M_3^2$</td>
</tr>
<tr>
<td>D5</td>
<td>$\bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q$</td>
<td>$1/M_2^2$</td>
</tr>
<tr>
<td>D6</td>
<td>$\bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu q$</td>
<td>$1/M_2^2$</td>
</tr>
<tr>
<td>D7</td>
<td>$\bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu \gamma^5 q$</td>
<td>$1/M_2^2$</td>
</tr>
<tr>
<td>D8</td>
<td>$\bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$</td>
<td>$1/M_2^2$</td>
</tr>
<tr>
<td>D9</td>
<td>$\bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$</td>
<td>$1/M_2^2$</td>
</tr>
<tr>
<td>D10</td>
<td>$\bar{\chi} \sigma^{\mu\nu} \gamma^5 \chi \bar{q} \sigma_{\alpha\beta} q$</td>
<td>$i/M_2^2$</td>
</tr>
<tr>
<td>D11</td>
<td>$\bar{\chi} \chi G_{\mu\nu} G^{\mu\nu}$</td>
<td>$\alpha_s/4M_2^3$</td>
</tr>
<tr>
<td>D12</td>
<td>$\bar{\chi} \gamma^5 \chi \bar{G} G_{\mu\nu} G^{\mu\nu}$</td>
<td>$i \alpha_s/4M_2^3$</td>
</tr>
<tr>
<td>D13</td>
<td>$\bar{\chi} \chi G_{\mu\nu} G^{\mu\nu}$</td>
<td>$i \alpha_s/4M_2^3$</td>
</tr>
<tr>
<td>D14</td>
<td>$\bar{\chi} \gamma^5 \chi \bar{G} G^{\mu\nu}$</td>
<td>$\alpha_s/4M_2^3$</td>
</tr>
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</table>

### Dimension-7 operators

<table>
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<tr>
<th>Name</th>
<th>Operator</th>
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</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>$\chi^\dagger \chi \bar{q} q$</td>
<td>$m_q/M_2^2$</td>
</tr>
<tr>
<td>C2</td>
<td>$\chi^\dagger \chi \bar{q} \gamma^5 q$</td>
<td>$i m_q/M_2^2$</td>
</tr>
<tr>
<td>C3</td>
<td>$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu q$</td>
<td>$1/M_2^2$</td>
</tr>
<tr>
<td>C4</td>
<td>$\chi^\dagger \partial_\mu \chi \bar{G} \gamma_\mu \gamma^5 q$</td>
<td>$1/M_2^2$</td>
</tr>
<tr>
<td>C5</td>
<td>$\chi^\dagger \chi G_{\mu\nu} G^{\mu\nu}$</td>
<td>$\alpha_s/4M_2^2$</td>
</tr>
<tr>
<td>C6</td>
<td>$\chi^\dagger \chi G_{\mu\nu} \bar{G}^{\mu\nu}$</td>
<td>$i \alpha_s/4M_2^2$</td>
</tr>
<tr>
<td>R1</td>
<td>$\chi^2 \bar{q} q$</td>
<td>$m_q/2M_2^2$</td>
</tr>
<tr>
<td>R2</td>
<td>$\chi^2 \bar{q} \gamma^5 q$</td>
<td>$i m_q/2M_2^2$</td>
</tr>
<tr>
<td>R3</td>
<td>$\chi^2 G_{\mu\nu} G^{\mu\nu}$</td>
<td>$\alpha_s/8M_2^2$</td>
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</tr>
</tbody>
</table>

Jessica Goodman, Masahiro Ibe, Arvind Rajaraman, William Shepherd, Tim M.P. Tait and Hai-Bo Yu, arXiv:1008.1783
**DIM6 operators – an update**

<table>
<thead>
<tr>
<th>Dirac Fermion DM</th>
<th>Real or Complex Scalar DM</th>
</tr>
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<tr>
<td>$\frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q$</td>
<td>$\frac{1}{\Lambda^2} \partial_\mu (\phi(\dagger) \phi) \bar{q} \gamma^\mu q$</td>
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<td>$\frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} \gamma^5 q$</td>
<td>$\frac{i}{\Lambda^2} [\phi(\dagger) (\partial_\mu \phi) - (\partial_\mu \phi(\dagger)) \phi] \bar{q} \gamma^\mu q$</td>
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<td>$\frac{1}{\Lambda^2} \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q$</td>
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<tr>
<td>$\frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi$</td>
<td>$\frac{i}{\Lambda^2} \phi(\dagger) \phi(q \not{D} q)$</td>
</tr>
<tr>
<td>$\frac{2\Lambda^2}{\Lambda^2} (\bar{\chi} \gamma^5 q \bar{q} \chi + \bar{\chi} q \bar{q} \gamma^5 \chi)$</td>
<td>$\frac{i}{\Lambda^2} \phi(\dagger) \phi(q \not{D} \gamma^5 q)$</td>
</tr>
<tr>
<td>$\frac{1}{\Lambda^2} (\bar{\chi} \gamma^5 q \bar{q} \chi - \bar{\chi} q \bar{q} \gamma^5 \chi)$</td>
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<td>$\frac{1}{\Lambda^2} \bar{\chi} \gamma^5 q \bar{q} \gamma^5 \chi$</td>
<td>$\frac{1}{\Lambda^2} \phi(\dagger) \phi(q \bar{q} \Phi) \rightarrow \frac{\tilde{m}}{\Lambda^2} \phi(\dagger) \phi(q \bar{q} \Phi)$</td>
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</tr>
</tbody>
</table>
DIM6 operators – an update

Dirac Fermion DM

\[ \begin{align*}
\frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q & \quad [D1] \\
\frac{1}{\Lambda^2} \bar{\chi} \gamma^5 \chi \bar{q} q & \quad [D2] \\
\frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} \gamma^5 q & \quad [D3] \\
\frac{1}{\Lambda^2} \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q & \quad [D4] \\
\frac{1}{\Lambda^2} \bar{\chi} \bar{\chi} & \quad [D1T] \\
\frac{i}{2\Lambda^2} (\bar{\chi} \gamma^5 q \bar{q} \chi + \bar{\chi} q \bar{q} \gamma^5 \chi) & \quad [D2T] \\
\frac{1}{\Lambda^2} (\bar{\chi} \gamma^5 q \bar{q} \chi - \bar{\chi} q \bar{q} \gamma^5 \chi) & \quad [D3T] \\
\frac{1}{\Lambda^2} \bar{\chi} \gamma^5 q \bar{q} \gamma^5 \chi & \quad [D4T] \\
\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma^\mu q & \quad [D5] \\
\frac{1}{\Lambda^2} \bar{\chi} \gamma^5 \chi \bar{q} \gamma^\mu q & \quad [D6] \\
\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma^5 q & \quad [D7] \\
\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma^\mu q & \quad [D8] \\
\frac{1}{\Lambda^2} \bar{\chi} \sigma_{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q & \quad [D9] \\
\frac{i}{\Lambda^2} \bar{\chi} \sigma_{\mu\nu} \gamma^5 \chi \bar{q} \sigma_{\mu\nu} q & \quad [D10]
\end{align*} \]

Real or Complex Scalar DM

\[ \begin{align*}
\frac{1}{\Lambda^2} \partial_\mu (\phi^{(\dagger)} \phi) \bar{q} \gamma^\mu q & \quad [S1] \\
\frac{1}{\Lambda^2} \partial_\mu (\phi^{(\dagger)} \phi) \bar{q} \gamma^5 q & \quad [S1.A] \\
\frac{i}{\Lambda^2} [\phi^{(\dagger)} (\partial_\mu \phi) - (\partial_\mu \phi^{(\dagger)}) \phi] \bar{q} \gamma^\mu q & \quad [S2] \\
\frac{i}{\Lambda^2} [\phi^{(\dagger)} (\partial_\mu \phi) - (\partial_\mu \phi^{(\dagger)}) \phi] \bar{q} \gamma^5 q & \quad [S2.A] \\
\frac{i}{\Lambda^2} \phi^{(\dagger)} (\bar{q} \not{D} q) & \quad [S3] \\
\frac{i}{\Lambda^2} \phi^{(\dagger)} (\bar{q} \not{D} \gamma^5 q) & \quad [S3.A] \\
\frac{1}{\Lambda^2} \phi^{(\dagger)} \phi \bar{q} q & \quad [S4] \\
\frac{1}{\Lambda^2} \phi^{(\dagger)} \phi \bar{q} \gamma^5 q & \quad [S4.A] \\
\frac{1}{\Lambda^2} \phi^{(\dagger)} \phi G^{\mu\nu} G^{\mu\nu} & \quad [S5] \\
\frac{1}{\Lambda^2} \phi^{(\dagger)} \phi \tilde{G}^{\mu\nu} G^{\mu\nu} & \quad [S5.A]
\end{align*} \]
Model Implementation

* Both models – DM od Spin=0 and Spin=1/2 have been implemented into CalcHEP/Madgraph using LanHEP package
* publicly available at High Energy Physics Model Database: https://hepmdb.soton.ac.uk/ - search for “DM-contact”

Search Models :: Results for [DM-contact]


   Alexander Belyaev

   ...


   Alexander Belyaev

* you can generate LHE events at HEPMDB!
MET distributions for Contact interactions

DM Mass = 100 GeV

Normalised to same number of events

Large kinematic differences between Distinct Groups of operators

- D9, D10
- S5, S5A
- D1T-D4T
- S2-S2A
- D1-D4, D5-D8
- S4, S4A
**MET distributions for Contact interactions**

DM Mass = 100 GeV

- Normalised to same number of events

- Large kinematic differences between Distinct Groups of operators

- D9, D10
- S5, S5A
- D1T-D4T
- S2-S2A
- D4-D8

---

**Graph Details**

- X-axis: Missing Transverse Momentum
- Y-axis: # Events / (100 GeV)
- Legend:
  - D9, D10
  - S4, S4A
  - S5
  - D1-D4
  - D1T-D4T
  - S2-S2A
  - D5-D8

---

**Graph Notes**

- Large kinematic differences between distinct groups of operators.
- Differences persist for wide range of DM mass

- Over 1 order magnitude difference between operators for MET = 1000 GeV

- Differences remain after fast Detector simulation (Delphes!)
Mapping CI with Simplified models

- Ordered according the height of the hi-PT tails (Least steep first)

\[
\begin{align*}
\text{D9} \quad & \frac{1}{\Lambda^2} \bar{\chi} \sigma^{\mu\nu} \chi q \sigma_{\mu\nu} q \\
\text{D10} \quad & \frac{1}{\Lambda^2} \phi^* \phi G^{\mu\nu} G^{\mu\nu} \quad \frac{1}{\Lambda^2} \phi^* \phi \tilde{G}^{\mu\nu} G^{\mu\nu} \\
\text{S5, S5A} \quad & \frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi \\
\text{D1T-D4T} \quad & \frac{i}{\Lambda^2} \left[ \phi^* \left( \partial_\mu \phi - (\partial_\mu \phi^*) \phi \right) \bar{q} \gamma^\mu q \right] \\
\text{S2-S2A} \quad & \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q \quad \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q \\
\text{D1-D4} \quad & \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q \quad \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q \\
\text{D5-D8} \quad & \frac{1}{\Lambda^2} \phi^* \phi \bar{q} q \Phi \quad \frac{\nu}{\Lambda^2} \phi^* \phi \bar{q} q
\end{align*}
\]
Mapping CI with Simplified models

\[ \frac{1}{\Lambda^2} \bar{\chi} \sigma^{\mu \nu} \chi \bar{q} \sigma_{\mu \nu} q \]

\[ \frac{1}{\Lambda^2} \phi^* \phi G^{\mu \nu} G^{\mu \nu} \]

\[ \frac{1}{\Lambda^2} \phi^* \phi \tilde{G}^{\mu \nu} G^{\mu \nu} \]

\[ \frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi \]

\[ \frac{i}{\Lambda^2} [\phi^* (\partial_\mu \phi - (\partial_\mu \phi^*) \phi)] \bar{q} \gamma^\mu q \]

\[ \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q \]

\[ \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q \]

\[ \frac{1}{\Lambda^2} \phi^* \phi \bar{q} q \Phi \rightarrow \frac{1}{\Lambda^2} \phi^* \phi \bar{q} q \]
Effects for Signal vs BG analysis

DM Mass = 100 GeV

- Different signal vs background MET distributions.
- Increase S/B ratio for large MET cuts.
- Large differences in efficiencies of different operators.

Important for exclusion/discovery studies.

MET > 200:
  - D10 eff = 0.30
  - D1 eff = 0.20
  - S4 eff = 0.13
  - D10/S4 = 2.3

MET > 500:
  - D10 eff = 0.074
  - D1 eff = 0.031
  - S4 eff = 0.014
  - D10/S4 = 5.5

MET > 1000:
  - D10 eff = 0.012
  - D1 eff = 0.0033
  - S4 eff = 0.0010
  - D10/S4 = 12
DM relic density and DD rates

- Coupling=1, Lambda=1 TeV, MDM=100-500 GeV give the right order of magnitude for relic density.

- Operators with no $\gamma^5$ are excluded by LUX (SI detection):
  - $D1, D1TD5, S2, S4$

- Operators with even number of $\gamma^5$ are excluded by SD DM search, i.e. neutrino telescopes:
  - $D4, D4T, D8, D9$

- Operators top which DD (SI or SD) searches are not sensitive are:
  - $D2, D3, D2T, D3T, D6, D7, D10, S2A, S3A$
  - can be probed at the LHC - great complementarity
Beyond mono-jet signature: mono-$Z$

Different set of topologies/diagrams for different DM

- different mono-$Z$ distributions
- complementary to mono-jet signature in resolving the nature of DM (work in progress)
Summary

- Weakly Interacting DM is hard to probe at the LHC: even 100-200 GeV DM discovery requires very high luminosity - Light Higgsino (LH) MSSM is an example
  - if S/B ~ 3% control is possible LHC@13 can probe LH DM up to 250 GeV @ 95% CL or discover LH DM with the mass up to 200 GeV
  - DDM search experiments - LUX and XENON1T are very complementary to LHC - they probe LH DM space with $\Delta M > 5$ GeV

- Generic models: starting from CI and using mono-jet signature one can potentially distinguish different operators and related DM spins
  - 1) D9/10 2) S5 3) D1T-D2T 4) S2 5) D5-8 6) S4 give different MET distributions, difference retains at the level of simplified models
  - spin of the mediator and its s/t-channel nature define MET
  - spin of the t-channel mediator is uniquely related to the spin of DM
  - an order of magnitude difference for the efficiencies/discovery potential for different operators/DM spins
  - Models are publicly available at HEPMDB (download/event generation)
Thank you!
Backup
$\Delta M$ pattern for $M_1 > 0$ and $M_1 < 0$ cases
DM relic density is below the measured one because of intense LSP annihilation and co-annihilation processes.

- Independent of tanb
DD cross section rescaled with the relic density is low for the small $\Delta M$ region. Chance for the LHC?
Direct Detection Prospects

- LUX
  - $\tan\beta = 5$
  - $M_1 = \mu$
  - $M_1 = \mu + 600$
  - $M_1 = \mu - 600$

- XENON1T
  - $M_1 = -\mu$

$\log(\sigma_{SI})$ vs $\mu [\text{GeV}]$ for $M_1 > 0$ and $M_1 < 0$.
LHC@13 Reach for NSUSY
LHC@13 Reach for NSUSY

LHC13 2\sigma contour (M1>0)

LHC13 5\sigma contour (M1>0)

\Delta M [\text{GeV}]

m_{\chi_1^0} [\text{GeV}]

LUX

XENON1T

LEP

LHC13 3 ab^{-1} (3\%)

LHC13 100 fb^{-1} (3\%)

LHC13 3 ab^{-1} (5\%)

LHC13 3 ab^{-1} (5\%)

Alexander Belyaev

Dark Matter Characterisation at the LHC
Similar recent studies:

- Han, Kobakhidze, Liu, Saavedra, Wu, Yang '13:
  “NSUSY can be probed up to 200 GeV at 5 sigma level with 1.5 ab^{-1}”
  but S/B < 1% for 200 GeV LSP – not quite realistic to probe

- Baer, Mustafayev, Tata '14:
  “NSUSY can not be probed at the LHC, since S/B ~ 1%”
  too conservative, since S/B can be improved with high P_T cuts, this however requires
  high luminosity to keep statistics up

- Han, Kribs, Martin, Menon '14
  interpreted LHC@8TeV results, found sensitivity up to 70-90 GeV
  study was done at the parton level
  At the detector level (as we have found) both S/B and significance are too low for
  LHC@8TeV to be sensitive to NSUSY
Analysis Setup

MSSM
- **SPHENO** for mass spectrum, cross checked with **ISAJET**
- **micrOMEGAs** for DM relic density, DM DD and ID
- **MadGraph** for parton level simulations, cross checked with **CalcHEP**
- **PYTHIA6** for hadronization and parton-showering
- **Delphes3** for fast detector simulation
- **CTEQ6L1 PDF**

Main backgrounds for $p_T$ jet + high MET signature

- Irreducible $Z + \text{jet} \rightarrow \nu \nu + \text{jet}$ ($Zj$)
- Reducible $W + \text{jet} \rightarrow \ell \nu + \text{jet}$ ($Wj$) when $\ell$ is missed
\[ \Delta M = m_{\chi^\pm} - m_{\chi^0} \text{ VS } M_1 \text{ plane} \]
LHC sensitivity to CHS

through the $pp \rightarrow \chi \chi j : \chi = \chi^{0}_{1,2}, \chi^{\pm}_{1}$ process

\[ \sigma (fb) \]

\[ P_T > 50 \text{ GeV} \]

\[ P_T > 600 \text{ GeV} \]
DD in $M_1 - \mu$ plane

$m_{\chi_1^0}$ and $m_{\chi_1^+} - m_{\chi_1^0}$ [GeV]

$m_{\chi_1^0}$ and $m_{\chi_1^+} - m_{\chi_1^0}$ [GeV]
Both S/B and Significance are too low – so LHC@8 is unfortunately not sensitive to NSUSY space ...
What is the minimal S/B value one can deal with?

- **S/B systematic study by ATLAS and CMS LHC@8:**
  sources of systematic uncertainty and their contributions (in %) to the total uncertainty on the $Z(\nu \nu)$ background from CMS PAS EXO-12-048

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ (GeV)</th>
<th>&gt; 250</th>
<th>&gt; 300</th>
<th>&gt; 350</th>
<th>&gt; 400</th>
<th>&gt; 450</th>
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<tbody>
<tr>
<td>Statistics ($N^{\text{obs}}$)</td>
<td>1.7</td>
<td>2.6</td>
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<td>2.4</td>
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- So, the realistic S/B ratio we can afford is $\sim 5\%$ or more
OUTLINE

- Dark Matter as the evidence of BSM physics
- Sensitivity to DM in Natural SUSY scenario – example of LHC & direct detection interplay
- Characterisation of DM spin from Contact Interactions using mono-jet signature
- Connection between Contact Interactions and Simplified models
- Going beyond the mono-jet signature
Supersymmetry (SUSY)

boson-fermion symmetry aimed to unify all forces in nature

\[ Q |\text{BOSON}\rangle = |\text{FERMIION}\rangle, \quad Q |\text{FERMIION}\rangle = |\text{BOSON}\rangle \]

extends Poincare algebra to Super-Poincare Algebra:

the most general set of space-time symmetries! (1971-74)

\[ \{f, f\} = 0, \quad [B, B] = 0, \quad \{Q_\alpha, \bar{Q}_\beta\} = 2\gamma^\mu_{\alpha\beta} P_\mu \]

Golfand and Likhtman'71; Ramond'71; Neveu,Schwarz'71; Volkov and Akulov'73; Wess and Zumino'74