LHC physics with displaced vertices

Giovanna Cottin

NCTS Annual Theory Meeting 2017, Hsinchu, Taiwan
The world is full of long-lived particles

Their presence comes from conserved symmetries, small couplings or heavy mediators.

Source: B.Shuve @ LHC-LLP workshop, CERN
Why shouldn’t an exotic/dark sector have the same structure?

Many BSM models predict LLPs, including RPV, split SUSY, GMSB, hidden sectors/portals

Baryogenesis, dark matter and neutrinos: same old strong motivations to invest in a dedicated long-lived particle (LLP) program at colliders

See for example:
Shuve, Cui *JHEP* **1502** (2015) 049
Strassler, Zurek *PRD* **94** (2016) no.1, 011504
Co, D’Eramo, Hall, Pappadopulo *JCAP* **1512** (2015) no.12, 024
The lifetime frontier is theoretically and also experimentally well motivated

The lack of evidence of any new physics at the LHC motivates unconventional searches, such as displaced vertices arising from the decay of a LLP

The null results at the LHC may point that the new physics is so feebly coupled to our SM that its signatures may have been overlooked or misidentified by searches not dedicated to LLPs
Recasting Displaced Searches @ LHC
Displaced Searches @ the ATLAS detector looks for displaced signatures inside inner tracker (lifetimes of order picosecond to a nanosecond)

**Analysis strategy:**
* Look for high-mass and track multiplicity DVs in inner tracker \( mDV > 10 \text{ GeV}, \ nTrk > 5 \)
* Standard ATLAS tracking is run again with looser cuts to gain efficiency for high-d0 tracks
* Veto vertices in material layers (dominant background vertices) with a 3D material. After this, ZERO background search

The DGS (NMSSM + GMSB) Model

The only free parameter is the messenger scale, which controls the phenomenology

$$c\tau_{\tilde{N}_1} \approx 2.5 \text{ cm} \left(\frac{100 \text{ GeV}}{M_{\tilde{N}_1}}\right)^5 \left(\frac{M}{10^6 \text{ GeV}}\right)^2 \left(\frac{\tilde{m}}{\text{ TeV}}\right)^2$$
Our Simulation shows LOW sensitivity to the model

After some optimization of the cuts, discovery of NMGMSB with \( \sim 2 \text{ TeV} \) gluino is possible with 300 fb-1 @ 13 TeV with displaced searches.

Source: EPJ C76 (2016)
What else could be measured at colliders (and what could thus be inferred about the nature of dark matter) given a displaced vertex signal?
Construction of a kinematic mass variable that takes into account the displaced vertex information, starting with the following hypothesis
Historic example of a kinematic mass variable, the transverse mass

\[ m_W^2 = m_e^2 + m_\nu^2 + 2(E_e E_\nu - 2\vec{p}_e \cdot \vec{p}_\nu) \]

\[ m_e^2 = E_e^2 - p_e^2 \]
\[ m_\nu^2 = E_\nu^2 - p_\nu^2 \]
\[ p_T \equiv (p_x, p_y) \]

\[ m_W^2 = (E_e + E_\nu)^2 - (\vec{p}_{Te} + \vec{p}_{T\nu})^2 - (p_{ze} + p_{z\nu})^2 \]

\[ m_T^2 \equiv (E_e + E_\nu)^2 - (\vec{p}_{Te} + \vec{p}_{T\nu})^2 \]

\[ m_T^2 \equiv m_e^2 + m_\nu^2 + 2(E_e E_\nu - \vec{p}_{Te} \cdot \vec{p}_{T\nu}) \]
Can not directly compute $W$ mass from the lepton and neutrino. But can know a lower limit as

$$m_T^2 \leq m_W^2$$

Cuts on this variable also had a big role in LHC Higgs searches

Source: d0.fnal.gov
Work in collaboration with Chris Lester \textbf{(in preparation)}

Our displaced case

\[ m_{\chi_1}^2 = p_{\chi_1}^2 = p_{\chi_1'}^2 \]

\[ m_{\chi_2}^2 = (p_V + p_{\chi_1})^2 = (p_{V'} + p_{\chi_1'})^2 \]

Including information on the displaced vertex positions \( \mathbf{r} \), we get extra knowledge on the direction of the momentum of the parent

\[ p_{\chi_2} = \frac{|p_{\chi_2}|}{\mathbf{r}} = \frac{|p_{\chi_2}|}{|\mathbf{r}|} \]
Define projections of three momenta of daughter and visible along the directions of the parent to help solve the system

\[(p_{\chi_1})_{\parallel \chi_2} = (p_{\chi_1} \cdot \hat{r})\hat{r}\]

\[(p_V)_{\parallel \chi_2} = (p_V \cdot \hat{r})\hat{r}\]

\[(p_{\chi_1})_{\perp \chi_2} = p_{\chi_1} - (p_{\chi_1} \cdot \hat{r})\hat{r}\]

\[(p_V)_{\perp \chi_2} = p_V - (p_V \cdot \hat{r})\hat{r}.\]
We can solve for $A$ and $C$

Assuming missing transverse momenta comes only from daughters

$\mathbf{p}_{X_1} = (A + B)\hat{r} - \mathbf{p}_V$

$\mathbf{p}_{X'_1} = (C + D)\hat{r}' - \mathbf{p}_{V'}$

$\mathbf{p}_T^{\text{miss}} = [(A + B)\hat{r} - \mathbf{p}_V + (C + D)\hat{r}' - \mathbf{p}_{V'}]_\perp$

We can solve for $A$ and $C$

$A = A(p^\text{miss}_X, p^\text{miss}_Y, \hat{r}, \hat{r}', \mathbf{p}_V, \mathbf{p}_{V'})$

$C = C(p^\text{miss}_X, p^\text{miss}_Y, \hat{r}, \hat{r}', \mathbf{p}_V, \mathbf{p}_{V'})$
We can rewrite the system as

\begin{align*}
m_{\chi_2}^2 &= m_{\chi_1}^2 + \alpha \sqrt{m_{\chi_1}^2 + \beta + \gamma} \\
m_{\chi_2}^2 &= m_{\chi_1}^2 + \delta \sqrt{m_{\chi_1}^2 + \epsilon + \zeta}
\end{align*}

So we can solve event-by-event, the system is fully constrained.

\[
\alpha \equiv 2E_V \\
\delta \equiv 2E_{V'} \\
\beta \equiv A^2 - B^2 + |p_V|^2 \\
\epsilon \equiv C^2 - D^2 + |p_{V'}|^2 \\
\gamma \equiv m_V^2 - 2(A + B)B + 2|p_V|^2 \\
\zeta \equiv m_{V'}^2 - 2(C + D)D + 2|p_{V'}|^2
\]

In principle we have 8 solutions for the pair \((m_{\chi_1}, m_{\chi_2})\)
But we are interested in the two requiring positive masses. We will see zero, one or sometimes two solutions per event.
Displaced Dark Matter Simplified Model

We use for our study the simplified displaced dark matter model in

**JHEP 1709 (2017) 076** (Buchmueller, De Roeck, Hahn, McCullough, Schwaller, Sung, Yu)

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**Figure 3.** A representative diagram from the DisplacedDM model that produces displaced vertices plus $E_T$. The subscripts on $Y$ indicate the spin of the mediator.
We first study events at truth level

Event input

\[(r, r', p_V, p_{V'}, p_x^{\text{miss}}, p_y^{\text{miss}})\]

\[r \rightarrow r + \theta p_V\]

\[\theta = [-0.1, 0.1]\]

\[r \rightarrow r + \theta_1 p_V\]

\[r' \rightarrow r' + \theta_2 p_{V'}\]

\[\theta_1 \text{ and } \theta_2 \text{ are sampled from two different Normal distributions}\]
We do a detector simulation and generate the smeared quantities to solve the system again. Smeared quantities \((r, r', pV, pV', p^\text{miss}_x, p^\text{miss}_y)\)

Mass Estimation based on the 1st percentile: i.e \((2.4, 49.2)\) for truth masses \((1, 50)\)

Our goal is to be able to extract both masses from the data.

Constructing a confidence region based on our mass estimates.
Conclusions

- We have found low sensitivity for current displaced LHC searches on a NMGMSB model. If (displaced) SUSY exists at all in this way, we are currently not seeing it!

- We propose a method to reconstruct the mass of a (invisible, dark matter) particle and its long-lived parent. If displaced events are seen at the LHC, the method can be applied.

- We need a dedicated program to systematize LLP searches, to ensure coverage and to make sure LLP analysis are optimal for recasting. New methods/ideas are coming from both theoretical and experimental fronts (LHC-LLP Community White paper in preparation!).

The lifetime frontier is the cutting edge of LHC physics!
Backup
Long-lived/Displaced Searches

Different lifetimes/charge/velocity give rise to different detector signatures that require special triggers, reconstruction and/or simulation.
<table>
<thead>
<tr>
<th>Signature</th>
<th>Model</th>
<th>Decay length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late decaying</td>
<td>Split-SUSY, Hidden Valley</td>
<td>-</td>
</tr>
<tr>
<td>low $\beta$, large $dE/dx$</td>
<td>Split-SUSY, GMSB, Stealth SUSY, HIPs, AMSB</td>
<td>$&gt;1000$</td>
</tr>
<tr>
<td>Disappearing Tracks</td>
<td>AMSB</td>
<td>$O(100-1000)$</td>
</tr>
<tr>
<td>Non-pointing $\gamma$</td>
<td>GMSB</td>
<td>$O(100-1000)$</td>
</tr>
<tr>
<td>Displaced Vertex</td>
<td>Split-SUSY, RPV SUSY, GMSB, Hidden Valley</td>
<td>$O(10-100)$</td>
</tr>
</tbody>
</table>
ATLAS DV analysis strategy

* Look for high-mass, high-track multiplicity displaced vertices in inner tracker with mass $>10$ GeV and at least 5 tracks

* Standard ATLAS tracking algorithms are re-run with looser cuts to gain efficiency for high-$d_0$ tracks

* Veto vertices in material layers (dominant background vertices) with a 3D material. After this, almost zero background search

Source: PRD92 (2015) 7, 072004
How to get a natural 125 GeV Higgs in SUSY?

<table>
<thead>
<tr>
<th>Naturally accommodate a 125 GeV Higgs via</th>
<th>with Gauge Mediation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MSSM</strong></td>
<td>large At</td>
</tr>
<tr>
<td><strong>NMSSM</strong></td>
<td>new contributions to Higgs mass</td>
</tr>
</tbody>
</table>


this talk, DGS Model!
The DGS Model

\[ W_{\text{NMSSM}} = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \]

\[ W_{\text{GM}} = X \sum_{i=1,2} (\kappa_D \Phi_i^D \Phi_i^D + \kappa_T \Phi_i^T \Phi_i^T) \]

\[ W_{\text{DGS}} = S \left( \xi_D \Phi_1^D \Phi_2^D + \xi_T \Phi_1^T \Phi_2^T \right) \]

\[ m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + m_{h,\text{mix}}^2 + m_{h,\text{loop}}^2 \]

Maximising the tree level contribution to the SM-like Higgs mass fixes the higgs sector parameters.

\[ m_{h_1} \approx 94 \text{ GeV} \quad \cos \theta \approx 0.88 \]

\[ m_{h_2} \approx 125 \text{ GeV} \]

\[ \lambda, \xi \quad \tilde{m} \]

\[ \sim 10^{-2} \quad \sim 1 \text{ TeV} \]

light singlet-like pseudo scalar (\(~20 \text{ GeV}\)) and a \(\sim 100 \text{ GeV}\) singlino NLSP.


Allanach, Badziak, Hugonie, Ziegler (2015) PRD 92, 015006
Benchmark P0
Model input via NMSSMTools

\[ \xi = 0.01 \]
\[ \lambda(M_{SUSY}) = 0.009 \]
\[ \tan \beta = 28.8 \]
\[ \tilde{m} = 863 \text{ GeV} \]
\[ c r \tilde{N}_1 = 99 \text{ mm} \]
\[ M = 1.4 \times 10^6 \text{ GeV} \]

<table>
<thead>
<tr>
<th>( m_{H_1^0} )</th>
<th>( m_{H_2^0} )</th>
<th>( m_{\tilde{t}_1} )</th>
<th>( m_{\tilde{N}_1} )</th>
<th>( m_{\tilde{N}_2} )</th>
<th>( m_{\tilde{e}_1} )</th>
<th>( m_{\tilde{\tau}_1} )</th>
<th>( m_{\tilde{g}} )</th>
<th>( m_{\tilde{a}_R} )</th>
<th>( m_{\tilde{b}_1} )</th>
<th>( m_{\tilde{G}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>122.1</td>
<td>23</td>
<td>97.6</td>
<td>373</td>
<td>348</td>
<td>323</td>
<td>1966</td>
<td>2045</td>
<td>1992</td>
<td>1866</td>
</tr>
</tbody>
</table>

\[ \tilde{q}_L \]
\[ \tilde{q}_R \]
\[ \tilde{g} \]
\[ \tilde{b}_2 \]
\[ \tilde{b}_1 \]

\[ H^0_3 \]
\[ H^0_1 \]
\[ H^\pm \]
\[ \tilde{\nu}_L \]
\[ \tilde{\nu}_T \]
\[ \tilde{\ell}_L \]
\[ \tilde{\ell}_R \]
\[ \tilde{\tau}_2 \]
\[ \tilde{N}^0_2 \]
\[ \tilde{N}^0_3 \]
\[ \tilde{N}^0_1 \]


Giovanna Cottin - DAMPT Seminar

Prompt Signals and Displaced Vertices in the NMSSM
Our Simulation

Source: EPJ C76 (2016)
1) Sensitivity is affected due to low pseudo scalar mass, less tracks

2) Sensitivity is affected due to the presence of additional displaced b-vertices

\[ \tilde{N}_1 \rightarrow a_1 \tilde{G} \rightarrow b\bar{b}\tilde{G} \]

b-hadrons are themselves long-lived, and both b’s from the neutralino decay have less than 5 tracks* and are almost always more than 1 mm apart! This effect in sensitivity has also been noticed before**

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* 18.1 (tracks after hadronisation) x 0.06 (displaced track efficiency) = 1.2 visible tracks per displaced b

Our Simulation shows LOW sensitivity, How to improve it?

Increase merging distance of DV reconstruction to catch the two bs

Loosen up invariant mass and track multiplicity cuts. Control backgrounds (such as random track crossings) by adding standard jet+MET prompt searches cuts

After this, discovery of NMGMSB with ~2 TeV gluino is possible with 300 fb-1 @ 13 TeV
Can not directly compute $W$ mass from the lepton and neutrino. But can know a lower limit as $m_T^2 \leq m_W^2$.

Cuts on this variable also had a big role in LHC Higgs searches.

Source: d0.fnal.gov

Source: ATLAS-CONF-2011-005
Displaced Dark Matter Simplified Model

We use for our study the simplified displaced dark matter model in JHEP 1709 (2017) 076 (Buchmueller, De Roeck, Hahn, McCullough, Schwaller, Sung, Yu)

<table>
<thead>
<tr>
<th>Simplified DM models</th>
<th>Variables</th>
<th>DM candidate</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m_{\phi}$</td>
<td>Dirac</td>
<td>Vector</td>
</tr>
<tr>
<td></td>
<td>$m_1$</td>
<td>Majorana</td>
<td>Axial-Vector</td>
</tr>
<tr>
<td></td>
<td>$g_\chi$</td>
<td>Scalar-real</td>
<td>Scalar</td>
</tr>
<tr>
<td></td>
<td>$g_\phi$</td>
<td>Scalar-complex</td>
<td>Pseudoscalar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Displaced signature extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau, m_2$</td>
</tr>
<tr>
<td>Decay of $\chi_2 \rightarrow \chi_1 X$</td>
</tr>
</tbody>
</table>

Table 1. Overview of the different building blocks that form simplified DM models. The lower part of this table lists the kinematic variables, lifetime ($\tau$) and mass ($m_2$) of the excited state $\chi_2$ and its decay $\chi_2 \rightarrow \chi_1 X$, which are required to add the displaced signature to the standard simplified DM models.
Table 4. Minimal set of dMETs searches for neutral displaced SM particles. To facilitate the trigger acceptance for these topologies, especially for soft $X$ systems, the dMETs can be combined with an ISR signature, such as an additional hard jet or hard $\gamma$. A list of basic operators that would give rise to such topologies is shown in table 2.

Figure 3. A representative diagram from the DisplacedDM model that produces displaced vertices plus $E_T$. The subscripts on $Y$ indicate the spin of the mediator.
Simulation

$q\bar{q} \rightarrow Y_1 \rightarrow \chi_2 \bar{\chi}_2 \rightarrow \chi_1 Y_0 \chi_1 Y_0 \rightarrow \chi_1 f \bar{f} \chi_1 f \bar{f}$.

Simulation is done in two stages. We use the UFO model provided by the authors and simulate with MadGraph5

$$pp \rightarrow Y_1 \rightarrow \chi_2 \bar{\chi}_2 \text{ at } \sqrt{s} = 13 \text{ TeV}$$

The output corresponds to events in LHE format that includes the lifetime of the LLP. The LHE events are passed to Pythia8 to compute the decays

$$\chi_2 \rightarrow \chi_1 f \bar{f}$$

The Pythia output is saved to be further processed with python routines to solve the system of equations
\[
A = \frac{(r_x r'_y - r_y r'_x)(p^x_V r_x + p^y_V r_y + p^z_V r_z) + [(p^y_V + p^y_{V'}, + p^\text{miss}_y)r'_x - (p^x_V + p^z_{V'}, + p^\text{miss}_x)r'_y]}{(r_y r'_x - r_x r'_y)\sqrt{r'^2_x + r'^2_y + r'^2_z}} (r^2_x + r^2_y + r^2_z)
\]

(2.19)

\[
C = \frac{(r_x r'_y - r_y r'_x)(p^x_V r'_x + p^x_{V'} r'_y + p^z_{V'} r'_z) + [(p^x_V + p^x_{V'}, + p^\text{miss}_x)r_y - (p^y_V + p^y_{V'}, + p^\text{miss}_y)r'_x]}{(r_y r'_x - r_x r'_y)\sqrt{r'^2_x + r'^2_y + r'^2_z}} (r'^2_x + r'^2_y + r'^2_z)
\]

(2.20)

with \( \mathbf{r} = (r_x, r_y, r_z) \), \( \mathbf{r}' = (r'_x, r'_y, r'_z) \), \( \mathbf{p}_V = (p^x_V, p^y_V, p^z_V) \) and \( \mathbf{p}_{V'} = (p^x_{V'}, p^y_{V'}, p^z_{V'}) \).
Evt: 0 mChiarr: [49.982214626459556] mBarr: [399.9957020056687]
Evt: 1 mChiarr: [49.997847802846437] mBarr: [399.9975823914735]
Evt: 2 mChiarr: [50.006630432827031] mBarr: [400.003734724441]
Evt: 3 mChiarr: [50.010177086819461] mBarr: [400.00606265816737]
Evt: 4 mChiarr: [50.109659799175979] mBarr: [400.0158016364571]
Evt: 5 mChiarr: [50.997122013410426] mBarr: [399.99826691166845]
Evt: 6 mChiarr: [50.014707822323942] mBarr: [400.00453952926358]
Evt: 7 mChiarr: [50.393634925910867] mBarr: [400.0589860549436]
Evt: 8 mChiarr: [49.999410112510134] mBarr: [399.9994289843388]
Evt: 9 mChiarr: [49.992738898517388] mBarr: [399.99698845905823]
Evt: 10 mChiarr: [49.967349760165789] mBarr: [399.99126243588614]
Evt: 11 mChiarr: [50.036957798806178] mBarr: [400.01016603669729]
Evt: 12 mChiarr: [49.992303389461341] mBarr: [399.999283417041]
Evt: 13 mChiarr: [49.997471931884832] mBarr: [399.99875121728917]
Evt: 14 mChiarr: [50.007923489783266] mBarr: [400.00258707240448]
Evt: 15 mChiarr: [50.0027814353576274] mBarr: [400.00207547616282]
Evt: 16 mChiarr: [50.017625778919367, 1572.2137433762121] mBarr: [400.00510826769192, 1902.2536858290978]
Evt: 17 mChiarr: [49.94209890061183, 3295.9536543266059] mBarr: [399.98833105254397, 3517.5543137848449]
Evt: 18 mChiarr: [49.998777778621744] mBarr: [399.99790453719328]
Evt: 19 mChiarr: [49.986317180114575] mBarr: [399.99608835930223]
Evt: 20 mChiarr: [50.010826027572556, 929.13531166417124] mBarr: [400.0018834655807, 1189.0032178162496]
<table>
<thead>
<tr>
<th>Final state $X$</th>
<th>$\mathcal{O}_F$</th>
<th>$\mathcal{O}_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma/\gamma^*$</td>
<td>$\frac{1}{\Lambda^2} \overline{\chi}<em>2 \sigma</em>{\mu\nu} \chi_1 F^{\mu\nu}$</td>
<td>$\frac{1}{\Lambda^2} (\partial_{\mu} \phi_2 \partial_{\nu} \phi_1) F^{\mu\nu}$</td>
</tr>
<tr>
<td>$Z$</td>
<td>$\frac{1}{\Lambda^2} \overline{\chi}<em>2 \sigma</em>{\mu\nu} \chi_1 Z^{\mu\nu}$</td>
<td>$\frac{1}{\Lambda^2} (\partial_{\mu} \phi_2 \partial_{\nu} \phi_1) Z^{\mu\nu}$</td>
</tr>
<tr>
<td>$h$</td>
<td>$\overline{\chi}_2 \chi_1 h$</td>
<td>$\Lambda \phi_2 \phi_1 h$</td>
</tr>
<tr>
<td>$jj$</td>
<td>$\frac{1}{\Lambda^3} \overline{\chi}<em>2 \chi_1 \text{Tr}[G^{\mu\nu} G</em>{\mu\nu}]$</td>
<td>$\frac{1}{\Lambda^2} \phi_2 \phi_1 \text{Tr}[G^{\mu\nu} G_{\mu\nu}]$</td>
</tr>
<tr>
<td>$\bar{ll}$</td>
<td>$\frac{1}{\Lambda^2} \bar{l}l \overline{\chi}_2 \chi_1$</td>
<td>$\frac{1}{\Lambda} \phi_2 \phi_1 \bar{l}l$</td>
</tr>
<tr>
<td>$\bar{bb}$</td>
<td>$\frac{1}{\Lambda^2} \bar{b}b \overline{\chi}_2 \chi_1$</td>
<td>$\frac{1}{\Lambda} \phi_2 \phi_1 \bar{b}b$</td>
</tr>
<tr>
<td>$\bar{tt}$</td>
<td>$\frac{1}{\Lambda^2} \bar{t}t \overline{\chi}_2 \chi_1$</td>
<td>$\frac{1}{\Lambda} \phi_2 \phi_1 \bar{t}t$</td>
</tr>
</tbody>
</table>

**Table 2.** List of example effective operators for the decay $\chi_2 \rightarrow \chi_1 X$ for fermionic (middle column) and scalar (right column) DM particles. Each of these operators corresponds to different final state $X$ (left column). Note that this is not an exhaustive list. For example, one could also have diboson final states. Furthermore, the scalar charge radius operator gives decays only to off-shell photons, $\gamma^* \rightarrow \bar{f}f$, $W^+W^-$.
Figure 2. Topology for the decay of $\chi_2$ into $\chi_1$ and SM particles ($X$) through a light mediator $\phi_D$.

<table>
<thead>
<tr>
<th>Final state</th>
<th>$\mathcal{O}<em>{\text{DM}} + \mathcal{O}</em>{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{f}f$</td>
<td>$-g_{12}\phi_D^\mu\bar{\chi}<em>1 \gamma</em>\mu \chi_2 - g_q \phi_D^\mu \bar{q} \gamma_\mu q$</td>
</tr>
<tr>
<td></td>
<td>$-g_{12}\phi_D^\mu\bar{\chi}_1 \gamma_5 \chi_2 - g_q \phi_D^\mu \bar{q} \gamma_5 q$</td>
</tr>
<tr>
<td></td>
<td>$-g_{12}\phi_D \bar{\chi}_1 \chi_2 - g_q \phi_D \bar{q} q$</td>
</tr>
<tr>
<td></td>
<td>$-i g_{12} \phi_D \bar{\chi}_1 \gamma^5 \chi_2 - g_q \phi_D \bar{q} \gamma^5 q$</td>
</tr>
</tbody>
</table>

Table 3. A small sample list of example vector, axial-vector, scalar, and pseudo-scalar decay mediator couplings for fermionic DM particles. Similar models may also be constructed for bosons.
\[ \mathcal{L}_n = \bar{\chi} \gamma_{\mu} (g_\chi + g_\chi \gamma_5) \chi + h.c. \]

\[ \mathcal{L}_D^{Y_0_{SM}} = \sum_{i,j} \left[ \bar{d}_i \frac{y_{i,j}^d}{\sqrt{2}} (g_{d_{ij}}^S + ig_{d_{ij}}^P \gamma_5) d_j + \bar{u}_i \frac{y_{i,j}^u}{\sqrt{2}} (g_{u_{ij}}^S + ig_{u_{ij}}^P \gamma_5) u_j \right] Y_0, \]

\[ \mathcal{L}_D^{Y_1_{SM}} = \sum_{i,j} \left[ \bar{d}_i \gamma_\mu (g_{d_{ij}}^V + g_{d_{ij}}^A \gamma_5) d_j + \bar{u}_i \gamma_\mu (g_{u_{ij}}^V + g_{u_{ij}}^A \gamma_5) u_j \right] Y_1^\mu, \]

\[ \mathcal{L}_D^{Y_1_{DM}} = \bar{\chi} \gamma_\mu (g_\chi + g_\chi \gamma_5) \chi Y_1^\mu. \]
Smearings inside the detector simulation in Pythia8 goes like this:

Jet energy resolution: Use 20% for jets at 50 GeV, falling linearly to 10% at 100 GeV, then flat 10%.

Jet energy scale: For jets with $|\eta| > 2$, use 3% flat, for jets with $|\eta| < 2$, use 1% flat (I am assuming the jets are above 20-30 GeV by which point this is probably quite accurate)

Electron resolution: use 2% at 10 GeV, falling linearly to 1% at 100 GeV, and then 1% flat. Electron scale is effectively 0 so we can forget it.
We also require

- At least 4 electrons in each event
- Each electron has to be truth matched to a displaced track with deltaR in $(\eta, \phi)$ to be less than 0.1
- $|d_0| > 2 \text{ mm and } p_T > 1 \text{ GeV}$

Source: EPJ C76 (2016)
We do a detector simulation and generate the smeared quantities to solve the system again

Smeared \((r, r', p_V, p_{V'}, p_x^{\text{miss}}, p_y^{\text{miss}})\) quantities

Mass Estimation based on the 1st percentile

Smearings for jets and leptons include energy scales/resolutions. DV resolution of \(\sigma=0.3\) mm

At least 4 electrons in each event
Each electron has to be truth matched to a displaced track with \(\Delta R\) less than 0.1
Our goal is to be able to extract both masses from the data. Estimated region for every truth mass pair that gets estimated

Estimated mass plane from truth mass pair (1,50)

Next step is to construct a confidence region based on our maps in estimation space, to guarantee that, given an observation, the real masses will lie in the region at least some fixed fraction of the time (e.g. 95%)
Extending the mass range, is the higher mass grid model-wise feasible?