Next Generation Dark Matter Models

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DM Landscape

- Dark Sector
- Mediating Sector
- Standard Model
Effective operators

Obfuscates Mediating sector, replaced with general scale

Captures kinematics of coupling to standard model

Limited range of validity

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$\bar{\chi}\chi q\bar{q}$</td>
<td>$m_q/M_\ast^3$</td>
</tr>
<tr>
<td>D2</td>
<td>$\bar{\chi}\gamma^5\chi q\bar{q}$</td>
<td>$i m_q/M_\ast^3$</td>
</tr>
<tr>
<td>D3</td>
<td>$\bar{\chi}\chi q\gamma^5\bar{q}$</td>
<td>$i m_q/M_\ast^3$</td>
</tr>
<tr>
<td>D4</td>
<td>$\bar{\chi}\gamma^5\chi q\bar{q}$</td>
<td>$m_q/M_\ast^3$</td>
</tr>
<tr>
<td>D5</td>
<td>$\bar{\chi}\gamma^\mu\chi q\bar{q}\gamma^\mu\bar{q}$</td>
<td>$1/M_\ast^2$</td>
</tr>
<tr>
<td>D6</td>
<td>$\bar{\chi}\gamma^\mu\gamma^5\chi q\bar{q}\gamma^\mu\bar{q}$</td>
<td>$1/M_\ast^2$</td>
</tr>
<tr>
<td>D7</td>
<td>$\bar{\chi}\gamma^\mu q\gamma^\mu q\gamma^5\bar{q}$</td>
<td>$1/M_\ast^2$</td>
</tr>
<tr>
<td>D8</td>
<td>$\bar{\chi}\gamma^\mu\gamma^5\chi q\bar{q}\gamma^\mu\gamma^5\bar{q}$</td>
<td>$1/M_\ast^2$</td>
</tr>
<tr>
<td>D9</td>
<td>$\bar{\chi}\sigma^{\mu\nu}\chi q\sigma^{\mu\nu}\bar{q}$</td>
<td>$1/M_\ast^2$</td>
</tr>
<tr>
<td>D10</td>
<td>$\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi q\sigma^{\alpha\beta}\bar{q}$</td>
<td>$i/M_\ast^2$</td>
</tr>
<tr>
<td>D11</td>
<td>$\bar{\chi}\chi G_{\mu\nu} G^{\mu\nu}$</td>
<td>$\alpha_s/4 M_\ast^3$</td>
</tr>
<tr>
<td>D12</td>
<td>$\bar{\chi}\gamma^5\chi G_{\mu\nu} G^{\mu\nu}$</td>
<td>$i\alpha_s/4 M_\ast^3$</td>
</tr>
<tr>
<td>D13</td>
<td>$\bar{\chi}\chi G_{\mu\nu} \tilde{G}^{\mu\nu}$</td>
<td>$i\alpha_s/4 M_\ast^3$</td>
</tr>
<tr>
<td>D14</td>
<td>$\bar{\chi}\gamma^5\chi G_{\mu\nu} \tilde{G}^{\mu\nu}$</td>
<td>$\alpha_s/4 M_\ast^3$</td>
</tr>
</tbody>
</table>
EFT breaks down at high momentum transfer

Truncation procedure removes events with momentum transfer > M*

ATLAS (arXiv:1411.1559v2)
Simplified Models

• Chooses a mediating mechanism
• Considers limited number of interactions
• Issue with arbitrarity and theoretical consistancy (unitarity, gauge invariance)
• Not every simplified model can be realized in UV completion
Next Generation Models

- Theoretically consistent extension of a simplified model
- Generic enough to be used in the context of broader, more complete theoretical frameworks
- Varied phenomenology to encourage comparison of different experimental signals and to search for DM in new, unexplored channels
- Be of interest beyond the DM community, to the point that other direct and indirect constraints can be identified.

ArXiv:1810:09420
Pseudoscalar Mediator

- **EFT**

\[
\bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q \quad \bar{\chi} \chi \bar{q} q
\]

D1 and D3 operators

\[
\sum_{f=u,d,s,c,b,t,c,\mu,\tau} \left( \frac{C_1}{\Lambda^2} \bar{f} f \bar{\chi} \chi + \frac{C_2}{\Lambda^2} \bar{f} \gamma^5 f \bar{\chi} \gamma^5 \chi + \ldots \right)
\]

- **Simplified Model**

\[
\mathcal{L}_{\text{DM-simp}} = -ig_\chi a \bar{\chi} \gamma_5 \chi - ia \sum_j \left( g_u y_j^u \bar{u}_j \gamma_5 u_j + g_d y_j^d \bar{d}_j \gamma_5 d_j + g_e y_j^e \bar{e}_j \gamma_5 e_j \right)
\]

Violates gauge invariance!
Remove arbitrariness by selecting BSM scenario that naturally contains the mediating particle. Fix gauge invariance by requiring proper quantum numbers in mediator sector.

2HDM containing 2 complex doublet fields $H_1$ and $H_2$ plus new pseudoscalar $P$, yielding 6 fields $h, H, H^{+-}, A, a$. 

H, h, H^+, A, a

DARK SECTOR  ↔  MEDIATING SECTOR  ↔  STANDARD MODEL
DM coupling to pseudoscalar

\[ \mathcal{L}_\chi = -iy_\chi P\bar{\chi}\gamma_5\chi \]

Pseudoscalar mixing with SM

\[ V_{HP} = P \left( i b_P H_1^\dagger H_2 + \text{h.c.} \right) + P^2 \left( \lambda_{P1} H_1^\dagger H_1 + \lambda_{P2} H_2^\dagger H_2 \right) \]

Higgs coupling to SM

\[ \mathcal{L}_Y = - \sum_{i=1,2} \left( \bar{Q}_Y^i \tilde{H}_i u_R + \bar{Q}_Y^i H_i d_R + \bar{L}_Y^i H_i \ell_R + \text{h.c.} \right) \]
Consequences of Next Generation Models for DM coupling and Indirect detection

- Multiple coupling between DM and the SM
- Complex DM annihilation spectrum
- Multibody kinematics
- Extremely variable Relic Density
DM couplings to SM and BSM states

BSM states in the extended Higgs sector
Indirect Detection Constraints

Dark Matter Annihilation channels through pseudoscalar

\[ f \bar{f}, hA, HA, HZ, H^{\pm}W^{\mp}, ha, H a, AA, aa \text{ and } Aa \]

\[ M_H = M_A = M_{H^\pm} = 600 \text{ GeV}, \quad M_a = 250 \text{ GeV} \]
$R_X$ annihilation fraction

$M_H = M_A = M_{H^*} = 600 \text{ GeV}, \ M_a = 250 \text{ GeV}$

\[ \sum <\sigma v>_{i} = <\sigma v>_{\text{Total}} \quad R_i = <\sigma v>_{i} / <\sigma v>_{\text{Total}} \quad \sum R_i = 1 \]
DM couplings to SM and Mediator states

3 final state cascade

4 final state cascade
Cascades shift spectrum

![Graph showing Generic Cascade with different steps](image)

Slatyer group PhysRevD.91.103531

$2^N$ Cascade
Relic Density Calculation

Orders Of magnitude

\[ \Omega h^2 = 0.12 \]

\[ M_{DM} = M_{a}/2 \]

\[ M_{DM} = M_{top} \]

\[ M_{DM} = M_{A}/2 \]

\[ M_{DM} = (M_{a} + M_{h})/2 \]

\[ M_{DM} = (M_{A} + M_{h})/2 \]
Conclusions

Next Generation Models require more complexity in the mediator sector

Consequences for ID and DD detection are manifold

Great multiplicity of DM couplings to SM particles

DM annihilation process becomes complex, multiple final states and cascade decays

Extreme variation in Relic Density calculation