Towards Decoding the Nature of Dark Matter at the LHC

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NExT Physics meeting
RHUL
1st of November 2017
Collaborators & Projects

- D. Barducci, A. Bharucha, W. Porod, V. Sanz, AB – arXiv:1504.02472
- M. Brede, D. Locke, L. Panizzi, M. Thomas, AB – follow up 1610.07545
- E. Bertuzzo, C. Caniu, O. Eboli, G. di Cortona, AB – follow up 1610.07545
- I. Ginzburg, D. Locke, A. Freegard, T. Hosken, AB – distinguishing DM spin at the ILC
While Higgs Boson Discovery has completed the SM, the SM itself can be viewed itself as a piece of a bigger puzzle since SM is theoretically and empirically incomplete.
Why we are so keen to study DM?

The diagram shows the number of papers published over the years from 1970 to 2020. The categories include SUSY, Higgs, Top, DM, and EXD. The number of papers is plotted on a logarithmic scale, with the range from $10^2$ to $10^3$. The number of papers increases over time, with DM and Higgs showing a particularly sharp rise in the latter years.
Why we are so keen to study DM?

![Graph showing the number of papers on various topics over the years, including SUSY, Higgs, Top, EXD, and DM, with a peak interest around 2015-2020 for DM.]
Why we are so keen to study DM?

![Graph showing the number of papers over the years for different topics including SUSY, Higgs, Top, EXD, and DM. The x-axis represents the years from 1970 to 2020, and the y-axis represents the number of papers with a logarithmic scale.]
Because the existence of DM is the strongest evidence for BSM, even though we know almost nothing about it!

- Spin & question mark
- Mass & question mark
- Stable & question mark
- Couplings & question mark
- Gravity & question mark
- Weak & question mark
- Higgs & question mark
- Quarks/gluons & question mark
- Leptons & question mark
- New mediators & question mark
- Thermal relic & question mark
- Yes & question mark
- No & question mark

Symmetry behind stability & question mark
Theories of Dark Matter

- MSSM
- NMSSM
- Supersymmetry
- WIMPless DM
- Self-Interacting DM
- Technibaryons
- Dark Photons
- Asymmetric DM
- Warm DM
- Axion DM
- T-odd DM
- Solitonic DM
- Q-balls
- Dirac DM
- QCD Axions
- Axion-like Particles
- Littlest Higgs
- UED DM
- Dynamical DM
- RS DM
- Warped Extra Dimensions
- Sterile Neutrinos
- Light Force Carriers

T.Tait

Decoding DM at the LHC
Spectrum of Theory Space

Effective Field Theories

Less Complete

Dipole Interactions

Contact Interactions

Simplified Models

Higgs portal

“Squarks”

dark photon

Z’

Models

UV Complete Models

UED

MSSM

mSUGRA

Sketches of Models

Little Higgs

More Complete

T. Tait

Decoding DM at the LHC
DM Observables: the power of WIMP

Correct Relic density: efficient (co) annihilation
WMAP, Planck; annihilation to photons can affect CMB

\[
\begin{array}{c}
\text{DM} \\
\text{SM}
\end{array}
\quad \quad
\begin{array}{c}
\text{DM} \\
\text{SM}
\end{array}
\]
DM Observables: the power of WIMP

Correct Relic density: efficient (co) annihilation
WMAP, Planck; annihilation to photons can affect CMB

Signatures from neutralino annihilation in halo, core of the Earth and Sun
- photons,
- Anti-protons
- positrons,
- Neutrinos

Neutrino telescopes:
- Amanda
- Icecube
- Antares

Efficient annihilation now: Indirect (ID) DM Detection

DM

SM

DM

SM
DM Observables: the power of WIMP

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Efficient scattering off nuclei:
DM Direct Detection (DD)

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,
DM Observables: the power of WIMP

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Efficient annihilation now: Indirect (ID) DM Detection
Efficient scattering off nuclei: DM Direct Detection (DD)
Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,

LHC signatures
- mono-jet
- mono-photon
- mono-Z
- mono Higgs
- VBF+MET
- soft leptons+MET
- ....
DM Observables: the power of WIMP

Signatures from neutralino annihilation in halo, core of the Earth and Sun
- photons,
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Correct Relic density: efficient (co) annihilation WMAP, Planck; annihilation to photons can affect CMB

Efficient scattering off nuclei: DM Direct Detection (DD)

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,

LHC signatures
- mono-jet
- mono-photon
- mono-Z
- mono Higgs
- VBF+MET
- soft leptons+MET
- ...

Note: there is no 100% correlation between signatures above. For example, the high rate of annihilation does not always guarantee high rate for DD!

Actually there is a great complementarity in this:
- In case of NO DM Signal – we can efficiently exclude DM models
- In case of DM signal – we can efficiently determine the nature of DM
Hunting for DM at Colliders

process

detector

q

DM

DM

q

?
Hunting for DM at Colliders

process

detector

Nothing!
Hunting for DM at Colliders

**process**
- q
- g
- DM

**detector**
- Large missing $P_T$ (2DM)
- High $P_T$ jet

monojet signature
Can we test DM properties at the LHC?

- 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.”

- Let us check the effects of DM spin on Missing transverse momentum (MET) distributions at the LHC:
  - let us start with EFT approach first – the simplest model-independent approach:
  - Complete set of DIM5/DIM6 operators involving two SM quarks (gluons) and two DM particles
  - consider spin=0, 1/2, 1 DM
  - mono-jet signature
  - explore LHC discovery potential for scenarios with different DM spins and potential to distinguish these scenarios
Mono-jet diagrams from EFT operators
### Complex scalar DM\(^+\)

\[
\begin{align*}
\frac{\tilde{m}}{\Lambda^2} & \phi^\dagger \phi \bar{q} q & [C1]^* \\
\frac{\tilde{m}}{\Lambda^2} & \phi^\dagger \phi q i \gamma^5 q & [C2]^* \\
\frac{1}{\Lambda^2} & \phi^\dagger i \partial_\mu \phi q \gamma^\mu q & [C3] \\
\frac{1}{\Lambda^2} & \phi^\dagger i \partial_\mu \phi q \gamma^\mu \gamma^5 q & [C4] \\
\frac{1}{\Lambda^2} & \phi^\dagger \phi G^{\mu \nu} G_{\mu \nu} & [C5]^* \\
\frac{1}{\Lambda^2} & \phi^\dagger \tilde{G}^{\mu \nu} G_{\mu \nu} & [C6]^* \\
\end{align*}
\]

### Complex vector DM\(^+\)

\[
\begin{align*}
\frac{\tilde{m}}{\Lambda^2} & V_\mu^\dagger V_{\nu} q & [V1]^* \\
\frac{\tilde{m}}{\Lambda^2} & V_\mu^\dagger V_{\nu} q i \gamma^5 q & [V2]^* \\
\frac{1}{2\Lambda^2} & (V_\nu^\dagger \partial_\mu V_{\nu} - V_\nu^\dagger \partial_\mu V_{\nu}^\dagger) \bar{q} \gamma^\mu q & [V3] \\
\frac{1}{2\Lambda^2} & (V_\nu^\dagger \partial_\mu V_{\nu} - V_\nu^\dagger \partial_\mu V_{\nu}^\dagger) q i \gamma^\mu \gamma^5 q & [V4] \\
\frac{1}{\Lambda^2} & V_\nu^\dagger V_{\nu} q i \sigma^\mu \sigma^\nu q & [V5] \\
\frac{1}{\Lambda^2} & V_\nu^\dagger V_{\nu} q \gamma^5 \gamma^\mu \gamma^5 q & [V6] \\
\frac{1}{2\Lambda^2} & (V_\nu^\dagger \partial_\nu V_{\mu} + V_\nu^\dagger \partial_\nu V_{\mu}^\dagger) \bar{q} \gamma^\mu q & [V7P] \\
\frac{1}{2\Lambda^2} & (V_\nu^\dagger \partial_\nu V_{\mu} - V_\nu^\dagger \partial_\nu V_{\mu}^\dagger) \bar{q} i \gamma^\mu q & [V7M] \\
\frac{1}{2\Lambda^2} & (V_\nu^\dagger \partial_\nu V_{\mu} + V_\nu^\dagger \partial_\nu V_{\mu}^\dagger) \bar{q} \gamma^\mu \gamma^5 q & [V8P] \\
\frac{1}{2\Lambda^2} & (V_\nu^\dagger \partial_\nu V_{\mu} - V_\nu^\dagger \partial_\nu V_{\mu}^\dagger) \bar{q} i \gamma^\mu \gamma^5 q & [V8M] \\
\frac{1}{\Lambda^2} & \epsilon^{\mu \nu \rho \sigma} (V_\nu^\dagger \partial_\rho V_{\sigma} + V_\nu \partial_\rho V_{\sigma}^\dagger) \bar{q} \gamma^\mu q & [V9P] \\
\frac{1}{\Lambda^2} & \epsilon^{\mu \nu \rho \sigma} (V_\nu^\dagger \partial_\rho V_{\mu} + V_\nu^\dagger \partial_\rho V_{\mu}^\dagger) \bar{q} i \gamma^\mu q & [V9M] \\
\frac{1}{\Lambda^2} & \epsilon^{\mu \nu \rho \sigma} (V_\nu^\dagger \partial_\rho V_{\sigma} + V_\nu \partial_\rho V_{\sigma}^\dagger) \bar{q} \gamma^\mu \gamma^5 q & [V10P] \\
\frac{1}{\Lambda^2} & \epsilon^{\mu \nu \rho \sigma} (V_\nu^\dagger \partial_\rho V_{\mu} + V_\nu^\dagger \partial_\rho V_{\mu}^\dagger) \bar{q} i \gamma^\mu \gamma^5 q & [V10M] \\
\frac{1}{\Lambda^2} & V_\mu^\dagger V_{\nu} G^{\rho \sigma} G_{\rho \sigma} & [V11]^* \\
\frac{1}{\Lambda^2} & V_\mu^\dagger V_{\nu} \tilde{G}^{\rho \sigma} G_{\rho \sigma} & [V12]^* \\
\end{align*}
\]

* operators applicable to real DM fields, modulo a factor \(1/2\)

\(^+\) Listed in J. Goodman et al., Constraints on Dark Matter from Colliders, Phys.Rev. D82 (2010) 116010, [arXiv:1008.1783]

\(^\dagger\) All but V11 and V12 listed in Kumar et al., Vector dark matter at the LHC, Phys. Rev. D92 (2015) 095027, [arXiv:1508.04466]
Mapping EFT operators to simplified models

\( \frac{1}{\Lambda^2} \phi \phi G_{\mu\nu} G^{\mu\nu} \), \( \frac{1}{\Lambda^2} \phi \phi \tilde{G}_{\mu\nu} G^{\mu\nu} \)

\( \frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi \)

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

\( \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q \)

\( \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} q \)

\( \frac{1}{\Lambda^2} \bar{\chi} \sigma_{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q \)

\( \frac{8}{\Lambda^2} \left[ \bar{\chi} q \bar{q} \chi - \frac{1}{4} \left( \bar{\chi} \chi q q + \bar{\chi} \gamma^5 \chi q \gamma^5 q + \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q - \bar{\chi} \gamma^\mu \chi \bar{q} \gamma^5_\mu q \right) \right] \)
Missing $E_T$ (MET) distributions: the large range of slopes

$$M_{DM} = 10 \text{ GeV}, \quad \sqrt{s} = 13 \text{ TeV}$$

L. Panizzi, A. Pukhov, M. Thomas, AB
arXiv:1610.07545
$M_{\text{DM}}$ dependence is weak for 10-100 GeV range

$M_{\text{DM}} = 100$ GeV, $\sqrt{s} = 13$ TeV

L. Panizzi, A. Pukhov, M. Thomas, AB
arXiv:1610.07545

#Events (normalized to one)

$E_{\text{miss}}$
Properties of MET distributions:

- MET distributions are the same for the fixed mass of DM pair \([\text{M}(\text{DM,DM})]\) & fixed SM operator.
- With the increase of \([\text{M}(\text{DM,DM})]\), MET slope decreases (PDF effect).

\[
\frac{\tilde{m}}{\Lambda^2} \phi^* \phi q q \quad \text{[C1]}
\]
\[
\frac{1}{\Lambda^2} \chi \chi q q \quad \text{[D1]}
\]
\[
\frac{\tilde{m}}{\Lambda^2} V^\dagger \mu V_{\mu} \bar{q} q \quad \text{[V1]}
\]
\[
\frac{1}{\Lambda^2} \phi^* i \partial_{\mu} \phi \bar{q} \gamma^\mu q \quad \text{[C1]}
\]
\[
\frac{1}{\Lambda^2} \chi \gamma^\mu \chi \bar{q} \gamma^\mu q \quad \text{[D5]}
\]
\[
\frac{1}{\Lambda^2} \chi \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q \quad \text{[D9]}
\]
\[
\frac{\tilde{m}}{\Lambda^2} V^\dagger V_{\nu} \bar{q} i \sigma^{\mu\nu} q \quad \text{[V5]}
\]
On the other hand, $M(\text{DM,DM})$ distributions, defined by the EFT operators are different!

$$M_{\text{DM}} = 10 \text{ GeV}, \sqrt{s} = 13 \text{ TeV}, \text{MET} > 500\text{GeV}$$
Distinguishing DM operators/theories

M(DM,DM) distributions are correlated with Different MET shapes

$M_{DM} = 10$ GeV, $\sqrt{s} = 13$ TeV, $MET > 500$ GeV

- Energy dependence of the DM operator $\rightarrow$ $M_{DMDM}$ distributions $\rightarrow$ slopes of MET
- Projection for $300$ fb$^{-1}$: some operators $C1$-$C2$, $C5$-$C6$, $D9$-$D10$, $V1$-$V2$, $V3$-$V4$, $V5$-$V6$ and $V11$-$V12$ can be distinguished from each other
- Application beyond EFT: when the DM mediator is not produced on-the-mass-shell and $M_{DMDM}$ is not fixed: t-channel mediator or mediators with mass below $2M_{DM}$
Absolute values of the cross sections provide an additional information to distinguish EFT operators

\[ \Lambda = 1 \text{TeV} \]

\[ \text{MET} > 100 \text{ GeV} \]

\[ pp \rightarrow \text{DM DM jet} \ @ \ 13 \text{ TeV} \]
LHC@13TeV reach at 3.2 fb$^{-1}$

LanHEP $\rightarrow$ CalcHEP/ Madgraph $\rightarrow$ LHE $\rightarrow$ CheckMATE 2 chain

- Scalar DM
- Fermion DM
- Vector DM

$M_{DM}=100\text{GeV}$

ATLAS@13 TeV, 1604.07773

Analysis cuts
LHC@13TeV reach projected 100 fb$^{-1}$

LanHEP → CalcHEP/ Madgraph → LHE → CheckMATE 2 chain

LHC@13TeV

ATLAS@13 TeV, 1604.07773
analysis cuts

scalar DM

fermion DM

vector DM

$M_{DM}=100\text{GeV}$

ATLAS @ 13 TeV
300/fb projection
# LHC@13TeV Reach for spin 0 and $\frac{1}{2}$ DM

<table>
<thead>
<tr>
<th>Complex Scalar DM</th>
<th>Operators</th>
<th>Coefficient</th>
<th>Excluded $\Lambda$ (GeV) at 3.2 fb$^{-1}$</th>
<th>Excluded $\Lambda$ (GeV) at 100 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 GeV</td>
<td>DM Mass</td>
</tr>
<tr>
<td>C1 &amp; C2</td>
<td>$1/\Lambda$</td>
<td>456</td>
<td>424</td>
<td>98</td>
</tr>
<tr>
<td>C3 &amp; C4</td>
<td>$1/\Lambda^2$</td>
<td>750</td>
<td>746</td>
<td>400</td>
</tr>
<tr>
<td>C5 &amp; C6</td>
<td>$1/\Lambda^2$</td>
<td>1621</td>
<td>1576</td>
<td>850</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dirac Fermion DM</th>
<th>Operators</th>
<th>Coefficient</th>
<th>Excluded $\Lambda$ (GeV) at 3.2 fb$^{-1}$</th>
<th>Excluded $\Lambda$ (GeV) at 100 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 GeV</td>
<td>DM Mass</td>
</tr>
<tr>
<td>D1 &amp; D3</td>
<td>$1/\Lambda^2$</td>
<td>931</td>
<td>940</td>
<td>522</td>
</tr>
<tr>
<td>D2 &amp; D4</td>
<td>$1/\Lambda^2$</td>
<td>952</td>
<td>936</td>
<td>620</td>
</tr>
<tr>
<td>D1T &amp; D4T</td>
<td>$1/\Lambda^2$</td>
<td>735</td>
<td>729</td>
<td>476</td>
</tr>
<tr>
<td>D2T</td>
<td>$1/\Lambda^2$</td>
<td>637</td>
<td>638</td>
<td>407</td>
</tr>
<tr>
<td>D3T</td>
<td>$1/\Lambda^2$</td>
<td>586</td>
<td>625</td>
<td>391</td>
</tr>
<tr>
<td>D5 &amp; D7</td>
<td>$1/\Lambda^2$</td>
<td>1058</td>
<td>967</td>
<td>721</td>
</tr>
<tr>
<td>D6 &amp; D8</td>
<td>$1/\Lambda^2$</td>
<td>978</td>
<td>1050</td>
<td>579</td>
</tr>
<tr>
<td>D9 &amp; D10</td>
<td>$1/\Lambda^2$</td>
<td>1587</td>
<td>1592</td>
<td>958</td>
</tr>
</tbody>
</table>
# LHC@13TeV Reach for spin 1 DM

<table>
<thead>
<tr>
<th>Operators</th>
<th>Coefficient</th>
<th>Excluded $\Lambda$ (GeV) at 3.2 fb$^{-1}$</th>
<th>Excluded $\Lambda$ (GeV) at 100 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10 GeV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>V1 &amp; V2</td>
<td>$M_{DM}^2/\Lambda_D^3$</td>
<td>831</td>
<td>833</td>
</tr>
<tr>
<td>V3 &amp; V4</td>
<td>$M_{DM}^2/\Lambda_D^4$</td>
<td>930</td>
<td>931</td>
</tr>
<tr>
<td>V5 &amp; V6</td>
<td>$M_{DM}^2/\Lambda_D^3$</td>
<td>784</td>
<td>791</td>
</tr>
<tr>
<td>V7M &amp; V8M</td>
<td>$M_{DM}^2/\Lambda_D^4$</td>
<td>930</td>
<td>926</td>
</tr>
<tr>
<td>V7P &amp; V8P</td>
<td>$M_{DM}/\Lambda_D^3$</td>
<td>796</td>
<td>791</td>
</tr>
<tr>
<td>V9M &amp; V10M</td>
<td>$M_{DM}/\Lambda_D^3$</td>
<td>796</td>
<td>799</td>
</tr>
<tr>
<td>V9P &amp; V10P</td>
<td>$M_{DM}/\Lambda_D^3$</td>
<td>794</td>
<td>782</td>
</tr>
<tr>
<td>V11 &amp; V11A</td>
<td>$M_{DM}/\Lambda_D^4$</td>
<td>1435</td>
<td>1442</td>
</tr>
</tbody>
</table>

**Complex Vector DM**
Distinguishing DM operators

energy dependence of the operator $\rightarrow M_{DM \ DM}$ shape $\rightarrow$ MET shape

$pp \rightarrow$ DM DM + jet @ 13 TeV, $M_{DM} = 100$ GeV

![Graph showing the number of events vs. Signal region, IM and MET cut (GeV) with different DM operators labeled.](image)
On the BG uncertainty

- The BG is statistically driven, e.g. pp→Zj→nnj BG is defined from the pp→Zj→l^+l^-j one

<table>
<thead>
<tr>
<th>$E_T^{miss}$ Range (GeV)</th>
<th>Z(νν)+jets</th>
<th>W(ℓν)+jets</th>
<th>Total (Pre-fit)</th>
<th>Total (Post-fit)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 – 230</td>
<td>14919 ± 221</td>
<td>11976 ± 196</td>
<td>27761 ± 1464</td>
<td>28654 ± 171</td>
<td>28601</td>
</tr>
<tr>
<td>230 – 260</td>
<td>7974 ± 116</td>
<td>5776 ± 101</td>
<td>14114 ± 757</td>
<td>14675 ± 97</td>
<td>14756</td>
</tr>
<tr>
<td>260 – 290</td>
<td>4467 ± 70</td>
<td>2867 ± 50</td>
<td>7193 ± 351</td>
<td>7666 ± 68</td>
<td>7770</td>
</tr>
<tr>
<td>290 – 320</td>
<td>2518 ± 46</td>
<td>1520 ± 34</td>
<td>4083 ± 204</td>
<td>4215 ± 48</td>
<td>4195</td>
</tr>
<tr>
<td>320 – 350</td>
<td>1496 ± 35</td>
<td>818 ± 20</td>
<td>2385 ± 118</td>
<td>2407 ± 37</td>
<td>2364</td>
</tr>
<tr>
<td>350 – 390</td>
<td>1204 ± 31</td>
<td>555 ± 15</td>
<td>1817 ± 87</td>
<td>1826 ± 32</td>
<td>1875</td>
</tr>
<tr>
<td>390 – 430</td>
<td>684 ± 20</td>
<td>275 ± 9</td>
<td>978 ± 45</td>
<td>998 ± 23</td>
<td>1006</td>
</tr>
<tr>
<td>430 – 470</td>
<td>382 ± 14</td>
<td>155 ± 6</td>
<td>589 ± 30</td>
<td>574 ± 17</td>
<td>543</td>
</tr>
<tr>
<td>470 – 510</td>
<td>248 ± 11</td>
<td>87.3 ± 3.8</td>
<td>337 ± 15</td>
<td>344 ± 12</td>
<td>349</td>
</tr>
<tr>
<td>510 – 550</td>
<td>160 ± 8</td>
<td>52.2 ± 2.7</td>
<td>211 ± 9</td>
<td>219 ± 9</td>
<td>216</td>
</tr>
<tr>
<td>550 – 590</td>
<td>99.5 ± 6.0</td>
<td>29.2 ± 1.9</td>
<td>134 ± 6</td>
<td>134 ± 7</td>
<td>142</td>
</tr>
<tr>
<td>590 – 640</td>
<td>77.3 ± 4.9</td>
<td>18.9 ± 1.4</td>
<td>100 ± 4</td>
<td>98.5 ± 5.8</td>
<td>111</td>
</tr>
<tr>
<td>640 – 690</td>
<td>44.8 ± 3.5</td>
<td>11.2 ± 0.9</td>
<td>59.6 ± 2.6</td>
<td>58.0 ± 4.1</td>
<td>61</td>
</tr>
<tr>
<td>690 – 740</td>
<td>27.8 ± 2.5</td>
<td>6.1 ± 0.6</td>
<td>36.6 ± 1.5</td>
<td>35.2 ± 2.9</td>
<td>32</td>
</tr>
<tr>
<td>740 – 790</td>
<td>21.8 ± 2.3</td>
<td>5.3 ± 0.6</td>
<td>23.8 ± 1.0</td>
<td>27.7 ± 2.7</td>
<td>28</td>
</tr>
<tr>
<td>790 – 840</td>
<td>13.5 ± 1.9</td>
<td>2.8 ± 0.4</td>
<td>15.3 ± 0.7</td>
<td>16.8 ± 2.2</td>
<td>14</td>
</tr>
<tr>
<td>840 – 900</td>
<td>9.5 ± 1.4</td>
<td>2.0 ± 0.3</td>
<td>12.2 ± 0.6</td>
<td>12.0 ± 1.6</td>
<td>13</td>
</tr>
<tr>
<td>900 – 960</td>
<td>5.4 ± 1.0</td>
<td>1.1 ± 0.2</td>
<td>7.6 ± 0.3</td>
<td>6.9 ± 1.2</td>
<td>7</td>
</tr>
<tr>
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<td>3.3 ± 0.8</td>
<td>0.77 ± 0.21</td>
<td>5.2 ± 0.3</td>
<td>4.5 ± 1.0</td>
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<td>1020 – 1160</td>
<td>2.5 ± 0.8</td>
<td>0.52 ± 0.16</td>
<td>3.6 ± 0.2</td>
<td>3.2 ± 0.9</td>
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<td>1160 – 1250</td>
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<td>0.3 ± 0.11</td>
<td>2.3 ± 0.1</td>
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<td>&gt; 1250</td>
<td>1.4 ± 0.5</td>
<td>0.19 ± 0.08</td>
<td>1.6 ± 0.1</td>
<td>1.6 ± 0.6</td>
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On the BG uncertainty

- The BG is statistically driven, e.g. \( pp \rightarrow Z_j \rightarrow n nj \) BG is defined from the \( pp \rightarrow Z_j \rightarrow l^+l^-j \) one.

- For the high enough statistics the BG error can be as low as 1%, but not much lower than this!

- Once \( \sim 1\% \) dBG is reached (we assume as a floor), the increase of luminosity does not improve LHC sensitivity: the BG uncertainty linearly grows with luminosity together with signal.

- At about 300 fb\(^{-1}\) such saturation is reached for all operators for current LHC cuts.
### Distinguishing the DM operators: $\chi^2$ for pairs of DM operators

$$\chi^2_{k,l} = \min_\kappa \sum_{i=3}^7 [(\frac{1}{2} N_i^k - \kappa \cdot N_i^l)/(10^{-2} BG_i)]^2$$

: if $\chi^2 > 9.48$ (95%CL for 4 DOF) – operators can be distinguished!

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</tbody>
</table>

Alexander Belyaev

Dark Matter Characterisation at the LHC
Importance of the operator running in the DM DD ↔ Collider interplay

- the connection between physics at high and low energy is crucial to properly explore complementarity collider and non-collider DM experiments
- RGEs for the EFT introduce the mixing between different operators

Kopp, Niro, Schwetz, Zupan (2009); Hill, Solon (2012); Frandsen, Haisch, Kahlhoefer, Mertsch, Schmidt-Hoberg (2012); Kopp, Michaels, Smirnov (2014); Crivellin, D’Eramo, Procura (2014); Crivellin, Haisch (2014); Berlin, Robertson, Solon, Zurek (2016); D’Eramo, de Vries, Panci (2016); D’Eramo, Kavanagh, Panci (2016)

\[
\mathcal{L} \supset -\frac{J_{DM} J_{SM,\mu}}{\Lambda^2}, \quad J_{SM} = \sum_{q} \left[ c_{Vq}(\Lambda) \bar{q}(i) \gamma_\mu q(i) + c_{Aq}(\Lambda) \bar{u}(i) \gamma_\mu \gamma_5 u(i) + \ldots \right]
\]

let us take, for example,

\[
J_{DM} = c_{V\chi} \bar{\chi} \gamma^\mu \chi + c_{A\chi} \bar{\chi} \gamma^\mu \gamma_5 \chi
\]

Once the wilson coefficient are evolved at the low scale, we need to match the low energy parton-level lagrangian with the low energy nucleon one

\[
\mathcal{L} \supset -\frac{J_{DM}^{(N)}}{\Lambda^2} \left( c_{V}(^{(N)} ) \bar{N} \gamma_\mu N + c_{A}^{(N)} \bar{N} \gamma_\mu \gamma_5 N \right) \quad \text{and} \quad \sigma_{SI} = \frac{\mu^2_N}{\pi} \frac{(c_{V\chi} c_V^{(N)})^2}{\Lambda^4}
\]

where

\[
\mu_N = m_\chi m_N / (m_\chi + m_N)
\]
Importance of the operator running in the DM DD ↔ Collider interplay

- In case of axial operators, e.g.

\[ c_A^{(q)} c_{\chi\chi\gamma^\mu\chi q} \gamma \gamma_5 q \quad (D7) \quad \text{or} \quad c_A^{(q)} c_{\phi\phi^\dagger \partial_\mu \phi q} \gamma^\mu \gamma_5 q \quad (C4) \]

...couplings \( c_V^{(a)} \) arise due to the running of the wilson coefficient \( c_A^{(a)} \)

leading to sizable constraints on the DM DD constraints.

- One can use runDM program (github.com/bradkav/runDM) by

F. D’Eramo, B. J. Kavanagh & P. Panci

\[ c_A^{(u)}, c_A^{(d)}, c_V^{(u)}, c_V^{(d)} = (1, 1, 0, 0)[5\text{TeV}] \rightarrow (1.1, 1.1, 0.04, -0.07)[1\text{GeV}] \]
Importance of the operator running in the DM DD ↔ Collider interplay

- In case of axial operators, e.g.

\[ c_A^{(q)} c_{\chi \bar{\chi} \gamma^\mu \chi \bar{q} \gamma^\mu q} \]  \hspace{1cm} (D7) \hspace{1cm} \text{or} \hspace{1cm} \[ c_A^{(q)} c_{\phi \phi^\dagger \bar{\phi} q} \]  \hspace{1cm} (C4)

 couplings \( c_{\gamma} \) arise due to the running of the wilson coefficient \( c_A^{(a)} \) leading to sizable constraints on the DM DD constraints.

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\( c_A^{(u)}, c_A^{(d)}, c_{V}^{(u)}, c_{V}^{(d)}=(1,1,0,0) \)\[5\text{TeV}] \rightarrow (1.1, 1.1, 0.04, -0.07) \[1\text{GeV}]

\( \Lambda \) vs. \( m_{DM} \) for complex scalar and Dirac fermion dark matter.
Beyond EFT: SUSY
There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above $\sim 1.9$ TeV.
Susy Compressed Mass Spectrum scenario

- 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.
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Signal vs Background

- difference in rates is pessimistic ...

- but the difference in shapes is encouraging, especially for large DM mass → bigger $M(DM,DM)$ → flatter MET

S and BG number of events for 100 fb$^{-1}$

Signal and Zj background parton-level $p_T$ distributions for the 13 TeV LHC
LHC/DM direct detection sensitivity


- SUSY DM, can be around the corner (~100 GeV), but it is hard to detect it!
- Great complementarity of DD and LHC for small DM (NSUSY) region
Case of inert 2 Higgs Doublet Model (i2HDM): consistent model with scalar DM

\[
\begin{align*}
\phi_1 &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \\
\phi_2 &= \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}h^+ \\ h_1 + ih_2 \end{pmatrix}
\end{align*}
\]

\[
V = -m_1^2(\phi_1^\dagger \phi_1) - m_2^2(\phi_2^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_1)^2 + \lambda_2(\phi_2^\dagger \phi_2)^2 + \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_2^\dagger \phi_1)(\phi_1^\dagger \phi_2) + \frac{\lambda_5}{2} \left[ (\phi_1^\dagger \phi_2)^2 + (\phi_2^\dagger \phi_1)^2 \right]
\]

\[
\begin{align*}
g &\to g \\
g &\to g \\
g &\to H \\
g &\to h_1 \\
g &\to H \\
g &\to h_1 \\
g &\to H \\
g &\to h_1 \\
q &\to g \\
\bar{q} &\to g \\
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\]
LHC reach for I2HDM with mono-jet signature

LHC is sensitive only to low DM masses – similar BG & signal shapes, poor improvement with luminosity increase

\[ \sigma(pp \rightarrow h_1 h_1 j) \text{ (fb) at 13 TeV} \]

- \( \lambda_{345} = 0.1 \)
- \( \lambda_{345} = -0.01 \)
- \( \lambda_{345} = \text{maximum} \)

- 95% CL (20 fb\(^{-1}\))
- 95% CL (100 fb\(^{-1}\))
- 95% CL (3000 fb\(^{-1}\))

G. Cacciapaglia, I. Ivanov, F. Rojas, M. Thomas, AB
arXiv:1612.00511
Beyond the mono-jet signature

Example of the vector resonance in the Composite Higgs model: $Z' \rightarrow TT \rightarrow t\bar{t} \, DM \, DM$ signature

$M_{Z'} = 3000$ GeV, $M_{T'} = 1200$ GeV

Current LHC reach with $tt + \not{E}_T$ signature based on ATLAS_CONF_2016_050 results

Flacke, Jaine, Schaefers, AB
arXiv: 1707.07000
Complementarity of LHC and non-LHC DM searches

for the model with Vector Resonances, Top Partners and Scalar DM

TT→ t t DM DM

arXiv: 1707.07000
The role of Z' vs QCD for $pp \rightarrow TT \rightarrow t \bar{t} \text{ DM DM}$

LHC is probing now DM and top partner masses up to about 0.9 and 1.5 TeV respectively: above bounds from QCD production alone by ~ factor of two!
Decoding the nature of DM at the ILC

muon spectrum from the models with scalar and fermion DM

\[ e^+e^- \rightarrow D^+ D^- \rightarrow DM \quad DM \quad W^+ W^- \rightarrow DM \quad DM \quad jj \mu \nu \]

*Normalised No. Events vs Energy of Muon, \( M_{D^\pm} = 150 \, \text{GeV} \)*

- **Fermion**, 2 → 4, ISR + Beamstrahlung, \( \sigma = 9.5 \times 10^{-2} \, \text{pb} \)
- **Scalar**, 2 → 4, ISR + Beamstrahlung, \( \sigma = 7.2 \times 10^{-3} \, \text{pb} \)
- *Analytical, simplified case*

I. Ginzburg, D. Locke, A. Freegard, T. Hosken, AB, preliminary
Data → Theory link

- probably the most challenging problem to solve – **the inverse problem of decoding of the underlying theory from signal**
  - requires database of models, database of signatures
  - requires smart procedure based on machine learning of matching signal from data with the pattern of the signal from data

**HEPMDB (High Energy Physics Model Database)** was created in 2011 to make the first step towards this: [hepmdb.soton.ac.uk/phenodata](http://hepmdb.soton.ac.uk/phenodata)
  - recently has got a status of the permanent server at Southampton
  - convenient centralized storage environment for HEP models
  - it allows to evaluate the LHC predictions and perform event generation using CalcHEP, Madgraph for any model stored in the database
  - users can upload their own model and perform simulation – became a very attractive feature for all range of researchers
  - **no database of signatures yet** (is under development) – you input could play and important role

- As a HEPMDB spin-off the **PhenoData** project was created [hepmdb.soton.ac.uk/phenodata](http://hepmdb.soton.ac.uk/phenodata) (thanks to Dan Locke and James Blandford)
  - stores data (digitized curves from figures, tables etc) from those HEP papers which did not provide data in arXiv or HEPData, and to avoid duplication of work of HEP researchers on digitizing plots.
  - has an easy search interface and paper identification via arXiv, DOI or preprint numbers. PhenoData is not intended to be a replication of any existing archive
Different DM spin → different energy dependence of the DM component of the EFT operator, different $M_{DMDM}$ distributions → different MET distributions: thus the MET is related to the DM spin and respective operator and can characterise it

At the LHC from 300 fb$^{-1}$ it is possible to distinguish several classes of operators, all models are public at HEPMDB https://hepmdb.soton.ac.uk/

The strategy on distinguishing EFT DM operators is generically applicable beyond EFT, when the DM mediator is not produced on-the-mass-shell - $M_{DMDM}$ is not fixed: t-channel mediator or mediators with mass below 2$M_{DM}$

We should explore more signatures and models – to prepare more complete framework on decoding LHC signatures

ILC is very complementary to the LHC in exploration of DM properties
Thank you!
Backup Slides
Parametrisation of the Vector DM operators

- The cross section for $qq(gg) \rightarrow \text{DM DM}$ process with a power of the energy asymptotic power, $\Delta_s$ takes a form:
  $$\sigma_{2\rightarrow 2} \propto \frac{1}{\Lambda^2} \times \left( \frac{E}{\Lambda} \right)^{\Delta_\sigma}$$

- On the other hand, from EFT operator we have:
  $$\sigma_{2\rightarrow 2} \propto \frac{1}{E^2} \times \left( \frac{E^{D-4}}{\Lambda^{D-4}} \right)^2$$
  where $D$ is the actual energy dimension of the EFT operator

- So, one finds: $\Delta_\sigma = 2(D - 5) \implies D = \frac{\Delta_\sigma}{2} + 5$

  - **Note:** $D$ can be different from naive dimension $d = 5$ or 6
  - consider V7P as an example:
    $$\frac{1}{2\Lambda^2} (V^\dagger_\nu \partial^\nu V_{\mu} + V^\nu \partial^\nu V^\dagger_{\mu}) \bar{q} \gamma^\mu q$$
  - with $d=6$, however for each (allowed) VDM longitudinal polarisation there is an additional $(E/M_{\text{DM}})$ factor, so the actual energy scaling of VDM EFT operator, $D$ is different!
Relation of the actual dimension (D) and the naive one (d) for VDM operators

<table>
<thead>
<tr>
<th>$V_{DM}$ Operator</th>
<th>$\Lambda_d$</th>
<th>$d$</th>
<th>$\Lambda_D$</th>
<th>$D$</th>
<th>$\Delta_\sigma (\sigma_{2\rightarrow 2} \propto E^{\Delta_\sigma})$</th>
<th>Amplitude Enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1, V2, V5, V6</td>
<td>$1/\Lambda$</td>
<td>5</td>
<td>$M_{DM}^2/\Lambda^3$</td>
<td>7</td>
<td>4</td>
<td>$(E/M_{DM})^2$</td>
</tr>
<tr>
<td>V3, V4, V7M, V8M, V11, V12</td>
<td>$1/\Lambda^2$</td>
<td>6</td>
<td>$M_{DM}^2/\Lambda^4$</td>
<td>8</td>
<td>6</td>
<td>$(E/M_{DM})^2$</td>
</tr>
<tr>
<td>V7P, V8P, V9, V10</td>
<td>$1/\Lambda^2$</td>
<td>6</td>
<td>$M_{DM}/\Lambda^3$</td>
<td>7</td>
<td>4</td>
<td>$E/M_{DM}$</td>
</tr>
</tbody>
</table>

- we suggest a *new parametrisation* of VDM operators: since the energy $E$ and the collider limit on $L$ are of the same order, it is natural to use an additional $M_{DM}/\Lambda$ factor for each power of $E/M_{DM}$ enhancement, so collider limits are *not artificially enhanced* [~100 TeV !!! for MDM =1 GeV, see Kumar, Marfatia, Yaylali 1508.04466] and will be of the same order as limits for other operators

- Dictionary between limits on $\Lambda$ in different parametrisations:

$$\Lambda_D = (\Lambda_d^{d-4} M_{DM}^{D-d})^{1/(D-4)}$$

and

$$\Lambda_d = (\Lambda^{D-4} M_{DM}^{d-D})^{1/(d-4)}$$
## i2HDM benchmarks

<table>
<thead>
<tr>
<th>BM</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{h_1}$ (GeV)</td>
<td>55</td>
<td>55</td>
<td>50</td>
<td>70</td>
<td>100</td>
<td>100</td>
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<tr>
<td>$M_{h_2}$ (GeV)</td>
<td>63</td>
<td>63</td>
<td>150</td>
<td>170</td>
<td>105</td>
<td>105</td>
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<tr>
<td>$M_{h_+}$ (GeV)</td>
<td>150</td>
<td>150</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
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<tr>
<td>$\lambda_{345}$</td>
<td>$1.0 \times 10^{-4}$</td>
<td>0.027</td>
<td>0.015</td>
<td>0.02</td>
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<tr>
<td>$\lambda_2$</td>
<td>1.0</td>
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<td>1.0</td>
<td>1.0</td>
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<tr>
<td>$\Omega h^2$</td>
<td>$9.2 \times 10^{-2}$</td>
<td>$1.5 \times 10^{-2}$</td>
<td>$9.9 \times 10^{-2}$</td>
<td>$9.7 \times 10^{-2}$</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$1.7 \times 10^{-3}$</td>
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<tr>
<td>$\sigma_{SI}^p$ (pb)</td>
<td>$1.7 \times 10^{-14}$</td>
<td>$1.3 \times 10^{-9}$</td>
<td>$4.8 \times 10^{-10}$</td>
<td>$4.3 \times 10^{-10}$</td>
<td>$5.3 \times 10^{-7}$</td>
<td>$2.1 \times 10^{-12}$</td>
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<tr>
<td>$R_{SI}^{LUX}$</td>
<td>$1.6 \times 10^{-5}$</td>
<td>0.19</td>
<td>0.51</td>
<td>0.37</td>
<td>0.48</td>
<td>$2.5 \times 10^{-5}$</td>
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<tr>
<td>$Br(H \to h_1 h_1)$</td>
<td>$5.2 \times 10^{-6}$</td>
<td>0.27</td>
<td>0.13</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>$\sigma_{LHC8}$ (fb)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h_1 h_1 j$</td>
<td>5.44 $\times 10^{-3}$</td>
<td>288.</td>
<td>134.</td>
<td>6.05 $\times 10^{-3}$</td>
<td>1.80</td>
<td>7.23 $\times 10^{-6}$</td>
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<tr>
<td>$h_1 h_2 j$</td>
<td>36.7</td>
<td>36.7</td>
<td>6.48</td>
<td>3.90</td>
<td>6.93</td>
<td>6.93</td>
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<tr>
<td>$h_1 h_1 Z$</td>
<td>6.14 $\times 10^{-2}$</td>
<td>21.4</td>
<td>30.7</td>
<td>12.2</td>
<td>0.101</td>
<td>2.52 $\times 10^{-2}$</td>
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<tr>
<td>$h_1 h_1 H$</td>
<td>1.70 $\times 10^{-4}$</td>
<td>8.98</td>
<td>4.21</td>
<td>2.19 $\times 10^{-4}$</td>
<td>0.100</td>
<td>3.33 $\times 10^{-7}$</td>
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<tr>
<td>$h_1 h_2 H$</td>
<td>5.35 $\times 10^{-3}$</td>
<td>6.31 $\times 10^{-3}$</td>
<td>9.80 $\times 10^{-3}$</td>
<td>7.54 $\times 10^{-3}$</td>
<td>3.86 $\times 10^{-2}$</td>
<td>5.51 $\times 10^{-4}$</td>
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<tr>
<td>$h_1 h_1 j j$</td>
<td>2.39 $\times 10^{-2}$</td>
<td>17.2</td>
<td>8.11</td>
<td>4.44 $\times 10^{-2}$</td>
<td>0.212</td>
<td>1.62 $\times 10^{-2}$</td>
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<tr>
<td>$\sigma_{LHC13}$ (fb)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$h_1 h_1 j$</td>
<td>1.67 $\times 10^{-2}$</td>
<td>878.</td>
<td>411.</td>
<td>1.93 $\times 10^{-2}$</td>
<td>6.25</td>
<td>2.50 $\times 10^{-5}$</td>
</tr>
<tr>
<td>$h_1 h_2 j$</td>
<td>92.4</td>
<td>92.4</td>
<td>17.8</td>
<td>11.1</td>
<td>19.1</td>
<td>19.1</td>
</tr>
<tr>
<td>$h_1 h_1 Z$</td>
<td>0.153</td>
<td>46.2</td>
<td>66.9</td>
<td>28.3</td>
<td>0.241</td>
<td>6.47 $\times 10^{-2}$</td>
</tr>
<tr>
<td>$h_1 h_1 H$</td>
<td>6.69 $\times 10^{-4}$</td>
<td>35.3</td>
<td>16.5</td>
<td>9.08 $\times 10^{-4}$</td>
<td>0.441</td>
<td>1.51 $\times 10^{-6}$</td>
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<tr>
<td>$h_1 h_2 H$</td>
<td>1.18 $\times 10^{-2}$</td>
<td>1.40 $\times 10^{-2}$</td>
<td>2.47 $\times 10^{-2}$</td>
<td>1.99 $\times 10^{-2}$</td>
<td>9.82 $\times 10^{-2}$</td>
<td>1.34 $\times 10^{-3}$</td>
</tr>
<tr>
<td>$h_1 h_1 j j$</td>
<td>0.101</td>
<td>62.7</td>
<td>29.6</td>
<td>0.189</td>
<td>0.904</td>
<td>7.49 $\times 10^{-2}$</td>
</tr>
</tbody>
</table>
A Simplified Model with Vector Resonances, Top Partners and Scalar DM

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin} + \mathcal{L}_{Z'q} + \mathcal{L}_{Z'\ell} + \mathcal{L}_{Z'Q'} + \mathcal{L}_{\phi Q'} - V_{\phi} \]

\[ \mathcal{L}_{kin} = -\frac{1}{4} \left( \partial_\mu Z'_\nu - \partial_\nu Z'_\mu \right) \left( \partial^\mu Z'^\nu - \partial^\nu Z'^\mu \right) + \frac{M_{Z'}^2}{2} Z'_\mu Z'^\mu \]

\[ + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{m_\phi^2}{2} \phi^2 \]

\[ + \overline{T'_s} \left( i \overline{\ell} - M_{T'_s} \right) T'_s + \overline{Q'_d} \left( i \overline{Q} - M_{T'_d} \right) Q'_d , \]

\[ \mathcal{L}_{Z'q} = \lambda_{Z'q}^q \overline{q}_L/R Z'_\mu \left( \overline{q}_L/R \gamma^\mu q_L/R \right) , \]

\[ \mathcal{L}_{Z'\ell} = \lambda_{Z'\ell}^\ell \overline{\ell}^c_L/R Z'_\mu \left( \overline{\ell}^c_L/R \gamma^\mu \ell_L/R \right) , \]

\[ \mathcal{L}_{Z'Q'} = \lambda_{Z'T'_sT'_s}^\ell \overline{T'_s,L/R} Z'_\mu \left( \overline{T'_s,L/R} \gamma^\mu q_L/R \right) \]

\[ + \lambda_{Z'T'_dT'_d}^\ell \overline{T'_d,L/R} Z'_\mu \left( \overline{T'_d,L/R} \gamma^\mu T'_d,L/R \right) \]

\[ + \lambda_{Z'T'_dT'_d}^\ell \overline{T'_d,L/R} Z'_\mu \left( \overline{B'_d,L/R} \gamma^\mu B'_d,L/R \right) , \]

\[ \mathcal{L}_{\phi Q'} = \left( \lambda_{\phi T'_s t} \phi \overline{T'_s,R} T'_s,R + \lambda_{\phi T'_d t} \phi \overline{T'_d,L} T'_d,L + \lambda_{\phi T'_d t} \phi \overline{b}_L B'_d,L \right) + \text{h.c.} , \]

\[ V_{\phi} = \frac{\lambda_{\phi} \phi^4}{4!} + \frac{\lambda_{\phi H} \phi^2}{2} \left( |H|^2 - \frac{v^2}{2} \right) . \]