Decoding the nature of Dark Matter

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Casa do Sol Hotel, Hazyview, South Africa
Can we decode the Nature of DM?
Can we decode the Nature of DM?
we do not know yet ...
Can we decode the Nature of DM?
we do not know yet ...
but we are very excited exploring all options
Can we decode the Nature of DM? we do not know yet ... but we are very excited exploring all options

And we will be even more excited when we will find out what it is!
Higgs Boson Discovery has finished the SM puzzle
Higgs Boson Discovery has finished the SM puzzle, but it is just a piece of some (more) complete and consistent one!
Why we are so keen to study DM?
Why we are so keen to study DM?

Alexander Belyaev

Decoding the nature of DM
Why we are so keen to study DM?
Because the existence of DM is the strongest evidence for BSM!

Galactic rotation curves

CMB: WMAP and PLANCK

Large Scale Structures

Bullet cluster

Gravitational lensing

DARK ENERGY ~72%

~23% DARK MATTER

ordinary matter
Even though we know almost nothing about it!

<table>
<thead>
<tr>
<th>Spin</th>
<th>?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>?</td>
</tr>
<tr>
<td>Stable</td>
<td>Yes</td>
</tr>
<tr>
<td>Thermal relic</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- **Spin**
- **Mass**
- **Couplings**
  - gravity: Yes
  - Weak: ?
  - Higgs: ?
  - Quarks/gluons: ?
  - Leptons: ?
  - New mediators: ?
- **Stability**
- **Thermal relic**
How we can decode the fundamental nature of Dark Matter?
How we can decode the fundamental nature of Dark Matter?

We need a DM signal first!
How we can decode the fundamental nature of Dark Matter?

We need a DM signal first!

But at the moment we can:

- understand what kind of DM is already excluded
- explore theory space and prepare ourselves to discovery and decoding of DM
Collaborators & Projects

- I.Ginzburg, D.Locke, A. Freegard, T. Hosken, AB to appear
- I. Shapiro, M. Thomas, AB arXiv:1611.03651
- L. Panizzi, A. Pukhov, M. Thomas, AB arXiv:1610.07545
- D. Barducci, A.Bharucha, W. Porod, V. Sanz, AB arXiv:1504.02472
DM candidates: interaction vs mass

- Planck mass BH remnants: tiny black holes protected by gravity effects [Chen '04] from decay via Hawking radiation
- Wimpzillas: very massive non-thermal WIMPs [Kolb, Chung, Riotto'98]
- Q-balls: topological solitons that occur in QFT [Coleman '86]
- EW scale WIMPs, protected by parity – LSP, LKP, LTP particles
- SuperWIMPs: electrically and color neutral DM interacting with much smaller strength (perhaps only gravitationally)
- Neutrinos: usual neutrinos are too light - HDM, subdominant component only (to be consistent with large scale structures); but heavier gauge singlet neutrinos can be CDM
- Axions: \( \theta_{QCD} \) is replaced by a quantum field, the potential energy allows the field to relax to near zero strength, axion as a consequence
DM candidates: interaction vs mass

- **Planck mass BH** remnants: tiny black holes protected by gravity effects [Chen '04] from decay via Hawking radiation
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- **Q-balls**: topological solitons that occur in QFT [Coleman '86]
- **EW scale WIMPs**, protected by parity – LSP, LKP, LTP particles
- **SuperWIMPs**: electrically and color neutral DM interacting with much smaller strength (perhaps only gravitationally)
- **Neutrinos**: usual neutrinos are too light- HDM, subdominant component only (to be consistent with large scale structures); but heavier gauge singlet neutrinos can be CDM
- **Axions**: \( \frac{\theta_{QCD}}{32\pi^2} F_{\mu\nu} \tilde{F}_{\mu\nu} \)

\( \theta_{QCD} \) is replaced by a quantum field, the potential energy allows the field to relax to near zero strength, axion as a consequence
Mass range for thermal DM

\[ m_{DM} \]

\[ 10^{-22} \text{ eV} \rightarrow \sim 100 \text{ eV} \rightarrow \sim 100 \text{ MeV} \rightarrow \sim 100 \text{ GeV} \rightarrow >100 \text{ TeV} \]

- bosonic
- composite

< 10 keV: too hot

\[ m_{\text{Planck}} \sim 10^{19} \text{ GeV} \]

Light DM

“WIMPs”
Spectrum of Theory Space

Effective Field Theories
- Dipole Interactions
- Contact Interactions

Simplified Models
- Higgs portal
- “Squarks”
- Z’
- dark photon

Models
- UED
- MSSM
- mSUGRA
- Little Higgs

Less Complete

Sketches of Models

T. Tait

Decoding DM at the LHC
Correct Relic density: efficient (co)annihilation at the time of early Universe

Efficient annihilation now: Indirect Detection

Dark Matter (DM) Observables
Correct Relic density: efficient (co) annihilation at the time of early Universe

Dark Matter (DM) Observables
Correct Relic density: efficient (co) annihilation at the time of early Universe

Dark Matter (DM) Observables

Efficient scattering off nuclei: Direct Detection
Correct Relic density: efficient (co)annihilation at the time of early Universe

Dark Matter (DM) Observables
Correct Relic density: efficient (co) annihilation at the time of early Universe

Efficient production at colliders

Dark Matter (DM) Observables

Alexander Belyaev
Correct Relic density: efficient (co)annihilation at the time of early Universe
Complementarity of DM searches

Efficient scattering off nuclei:
DM Direct Detection (DD)

Efficient production at colliders

Important: there is no 100% correlation between signatures above. E.g. 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
Complementarity of DM searches

Efficient scattering off nuclei:
DM Direct Detection (DD)

DM Direct Detection (DD)
Efficient production at colliders

Example of DM interactions with negligible/suppressed DD rates

Important: there is no 100% correlation between signatures above. E.g. 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
Direct Dark Matter Detection

See also Maria Martinez' talk

- Search for the recoil energy of a nucleus in an underground detector after collision with a WIMP

  Elastic recoil energy
  
  \[ E_R = \frac{2\mu_{\chi N}^2 v^2}{m_N} \cos^2 \theta \]

- Minimum WIMP speed required to produce a recoil energy
  
  \[ v_{\text{min}} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}} \]

- The differential event rate (per unit detector mass):

  \[ \frac{dR}{dE_R} = \frac{\rho_{\chi}}{m_{\chi} m_N} \int_{v > v_{\text{min}}} d^3v \frac{d\sigma_{\chi N}}{dE_R} v f_{\text{det}}(v, t) \]
Direct Dark Matter Detection

- Search for the recoil energy of a nucleus in an underground detector after collision with a WIMP

Elastic recoil energy

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- The differential event rate (per unit detector mass):

\[ \frac{dR}{dE_R} = \frac{\sigma_0 F^2(E_R)}{2m_{\chi} \mu_{\chi N}^2} \rho_{\chi} \eta(v_{\text{min}}, t) \]
Direct Dark Matter Detection

• Search for the recoil energy of a nucleus in an underground detector after collision with a WIMP

Elastic recoil energy

\[ E_R = \frac{2\mu^2\chi_N v^2}{m_N} \cos^2 \theta \]

• Minimum WIMP speed required to produce a recoil energy

\[ v_{\text{min}} = \sqrt{\frac{m_N E_R}{2\mu^2\chi_N}} \]

• The differential event rate (per unit detector mass):

\[ \frac{dR}{dE_R} = \frac{\sigma_0 F^2(E_R)}{2m_\chi \mu^2\chi_N} \rho_\chi \eta(v_{\text{min}}, t) \]
Power of DM DD to rule out theory space

ArXiv:1310.8327
Snowmass CF1 Summary
Latest XENON 1T results

$10^{-46} \text{ cm}^2 = 10^{-10} \text{ pb}$

The limit scales linearly with $M_{\text{DM}}$

arXiv:1805.12562
Power of DM DD to rule out theory space

Inert 2 Higgs Doublet Model

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

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

\[ \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5 \]
Power of DM DD to rule out theory space

Inert 2 Higgs Doublet Model

\[ \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5 \]

Cacciapaglia, Ivanov, Rojas, Thomas, AB arXiv:1610.07545
Novaes, Mercadante, Moon, Tomei, Moretti, Tomas, Panizzi, AB arXiv:1809.00933
Power of DM DD to rule out theory space

Vector DM Model

\[ \mathcal{L} = \mathcal{L}_{SM} - Tr \{ D_\mu V_\nu D^\mu V^\nu \} + Tr \{ D_\mu V_\nu D^\mu V^\nu \} \]
\[ - \frac{g^2}{2} Tr \{ [V_\mu, V_\nu] [V^\mu, V^\nu] \} \]
\[ - ig Tr \{ W_{\mu\nu} [V^\mu, V^\nu] \} + \tilde{M}^2 Tr \{ V_\nu V^\nu \} \]
\[ + a (\Phi^\dagger \Phi) Tr \{ V_\nu V^\nu \} \]

- DM from vector triplet
- SM gauge coupling
- \( V_{DM} V_{DM}^* \) H coupling is the only free parameter

AB, Cacciapaglia, McKay, Martin, Zerwekh

Decoding the nature of DM
Power of DM DD to rule out theory space

Vector DM Model

Direct detection constraints

- **ZENON 1T** excludes both large $H_{\text{DM}}V_{\text{DM}}$ couplings and large $M_{\text{DM}}$
- **The lower masses** (rest of space) can be covered at future colliders
Power of DM DD to rule out theory space

- DM Interaction with SM particles is very limited, mainly from DM DD experiments
  
- E.g. coupling of Dirac Fermion DM interaction with Z-boson is excluded above $10^{-3}$ level with DM DD searches
  
- Majorana Fermion DM does not have this problem, the limit comes from Higgs interactions, the coupling above 0.1 is excluded
Decoding the nature of DM

DM DD interplay with Collider Searches

process

detector

q

q

DM

DM

?
Hunting for DM at Colliders

process

q

DM

DM

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?

We explore the LHC potential to probe DM operators with different DM spin using the shape missing transverse momentum (MET)

- we use the EFT approach: simplicity and model independence
- explore the complete set of DIM5/DIM6 operators involving two SM quarks (gluons) and two DM particles
- consider DM with spin=0, 1/2, 1
- use mono-jet signature at the LHC
Mono-jet diagrams from EFT operators
<table>
<thead>
<tr>
<th>Complex scalar DM†</th>
<th>Complex vector DM‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{1}{\Lambda^2} \phi^{\dagger} \phi q \bar{q} )</td>
<td>( \frac{\Lambda}{m} V^{\dagger} \mu V^\mu \bar{q} q )</td>
</tr>
<tr>
<td>( \frac{1}{\Lambda^2} \phi^{\dagger} \phi q \gamma^5 q )</td>
<td>( \frac{\Lambda}{m} V^{\dagger} \mu V^\mu q \bar{q} )</td>
</tr>
<tr>
<td>( \frac{1}{\Lambda^2} \phi^{\dagger} i \partial_\mu \phi \gamma^\mu q )</td>
<td>( \frac{1}{2\Lambda^2} (V^{\dagger}<em>\nu V</em>\mu - V^\mu V^{\dagger}_\nu) q \gamma^\mu q )</td>
</tr>
<tr>
<td>( \frac{1}{\Lambda^2} \phi^{\dagger} i \partial_\mu \phi \gamma^\mu \gamma^5 q )</td>
<td>( \frac{1}{2\Lambda^2} (V^{\dagger}<em>\nu V</em>\mu - V^\mu V^{\dagger}_\nu) \bar{q} \gamma^\mu \gamma^5 q )</td>
</tr>
<tr>
<td>( \frac{1}{\Lambda^2} \phi^{\dagger} G^{\mu\nu} G_{\mu\nu} )</td>
<td>( \frac{\Lambda}{m} V^{\dagger}_\nu \sigma q \gamma^\mu q )</td>
</tr>
<tr>
<td>( \frac{1}{\Lambda^2} \phi^{\dagger} \tilde{G}^{\mu\nu} G_{\mu\nu} )</td>
<td>( \frac{\Lambda}{m} V^{\dagger}_\nu \sigma q \gamma^\mu \gamma^5 q )</td>
</tr>
</tbody>
</table>

| Dirac fermion DM† | 
| \( \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q \) | \( \frac{1}{\Lambda^2} \bar{V} \mu V^\mu \bar{q} q \) |
| \( \frac{1}{\Lambda^2} \bar{\chi} i \gamma^5 \chi \bar{q} q \) | \( \frac{1}{\Lambda^2} \bar{V} \mu V^\mu \bar{q} q \) |
| \( \frac{1}{\Lambda^2} \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q \) | \( \frac{1}{\Lambda^2} \bar{V} \mu V^\mu \bar{q} \gamma^\mu \gamma^5 q \) |
| \( \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma^\mu q \) | \( \frac{1}{\Lambda^2} \bar{V} \mu V^\mu \bar{q} \gamma^\mu \gamma^5 q \) |
| \( \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma^\mu q \) | \( \frac{1}{\Lambda^2} \bar{V} \mu V^\mu \bar{q} \gamma^\mu \gamma^5 q \) |
| \( \frac{1}{\Lambda^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q \) | \( \frac{1}{\Lambda^2} \bar{V} \mu V^\mu \bar{q} \sigma_{\mu\nu} \sigma_{\mu\nu} q \) |
| \( \frac{1}{\Lambda^2} \bar{\chi} \sigma^{\mu\nu} i \gamma^5 \chi \bar{q} \sigma_{\mu\nu} q \) | \( \frac{1}{\Lambda^2} \bar{V} \mu V^\mu \bar{q} \sigma_{\mu\nu} \sigma_{\mu\nu} q \) |

* 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]
Mapping EFT operators to simplified models

\[
\frac{1}{\Lambda^2} \phi^* \phi G^{\mu\nu} G^{\mu\nu}, \quad \frac{1}{\Lambda^2} \phi^* \phi \tilde{G}^{\mu\nu} G^{\mu\nu}
\]
Mapping EFT operators to simplified models

C5,C5A
\[ \frac{1}{\Lambda^2} \phi^* \phi G^{\mu\nu} G^{\mu\nu}, \quad \frac{1}{\Lambda^2} \phi^* \phi \tilde{G}^{\mu\nu} G^{\mu\nu} \]

D1T-D4T
\[ \frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi \]

Scalar mediator

\[ q \rightarrow \chi_{DM} \]
\[ \bar{q} \rightarrow \chi_{DM} \]
Mapping EFT operators to simplified models

C5,C5A \[ \frac{1}{\Lambda^2} \phi^* \phi G^{\mu\nu} G^{\mu\nu}, \quad \frac{1}{\Lambda^2} \phi^* \phi \tilde{G}^{\mu\nu} \tilde{G}^{\mu\nu} \]

D1T-D4T \[ \frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi \]

C3 \[ \frac{i}{\Lambda^2} [\phi^* (\partial_\mu \phi - (\partial_\mu \phi^*) \phi)] \bar{q} \gamma^\mu q \]
Mapping EFT operators to simplified models

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

C5,C5A

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

D1T-D4T

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

C3

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

D1-D4, D5-D8

\[ \gamma^0, S_{DM} \]

Scalar mediator

\[ \phi^0, S_{DM} \]

Vector mediator

\[ \chi_{DM} \]
Mapping EFT operators to simplified models

C5,C5A  
\[ \frac{1}{\Lambda^2} \phi^* \phi G^{\mu\nu} G^{\mu\nu} \rightarrow \frac{1}{\Lambda^2} \phi^* \phi \tilde{G}^{\mu\nu} G^{\mu\nu} \]

D1T-D4T  
\[ \frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi \rightarrow \bar{q} \Rightarrow \text{Scalar mediator} \]

C3  
\[ \frac{i}{\Lambda^2} [\phi^*(\partial_\mu \phi - \partial_\mu \phi^*)\phi] \bar{q} \gamma^\mu q \]

D1-D4, D5-D8  
\[ \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{\gamma}_\mu q \rightarrow \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q \]

C1  
\[ \frac{1}{\Lambda^2} \phi^* \phi \bar{q} q \Phi \Rightarrow \frac{\nu}{\Lambda^2} \phi^* \phi \bar{q} q \rightarrow \text{Scalar mediator} \]
**Mapping EFT operators to simplified models**

**C5,C5A**
\[ \frac{1}{\Lambda^2} \phi^* \phi G^{\mu\nu} G^{\mu\nu} \]
\[ \frac{1}{\Lambda^2} \phi^* \tilde{\phi} G^{\mu\nu} G^{\mu\nu} \]

**D1T-D4T**
\[ \frac{1}{\Lambda^2} \bar{\chi} q \bar{q} \chi \]
\[ \frac{i}{\Lambda^2} [\phi^* (\partial_\mu \phi - (\partial_\mu \phi^*) \phi)] q \gamma^\mu q \]

**C3**
\[ \frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{\gamma}_\mu q \]
\[ \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q \]

**D1-D4, D5-D8**
\[ \frac{1}{\Lambda^2} \phi^* \bar{\phi} q \bar{q} \Phi \]
\[ \frac{1}{\Lambda^2} \phi^* \bar{\phi} \bar{q} q \]

**D9,D10**
\[ \frac{1}{\Lambda^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q \]
\[ \frac{8}{\Lambda^2} [\bar{\chi} q \bar{q} \chi - \frac{1}{4} (\bar{\chi} \chi \bar{q} q + \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q + \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q - \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q) \]
Missing $E_T$ (MET) distributions: the large range of slopes

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

$E_{miss} \text{ vs. } # \text{Events (normalized to one)}$

AB, Panizzi, Pukhov, Thomas
arXiv:1610.07545
Properties of MET distributions:

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

Properties of MET distributions:

\[
\frac{\tilde{m}}{\Lambda^2} \phi^* \phi \bar{q} q \quad [C1]
\]
\[
\frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q \quad [D1]
\]
\[
\frac{\tilde{m}}{\Lambda^2} V^+ \mu \mu V_\mu \bar{q} q \quad [V1]
\]
\[
\frac{1}{\Lambda^2} \phi^\dagger i \bar{D}_\mu \phi \bar{q} \gamma^\mu q \quad [C3]
\]
\[
\frac{1}{\Lambda^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma^\mu q \quad [D5]
\]
\[
\frac{1}{\Lambda^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q \quad [D9]
\]
\[
\frac{\tilde{m}}{\Lambda^2} V^\dagger_\mu V_\nu \bar{q} i \sigma^{\mu\nu} q \quad [V5]
\]
Properties of MET distributions for small and large $M(DM,DM)$

- MET distributions are the same for the fixed mass of DM pair $M(DM,DM)$ & fixed SM operator
- With the increase of $M(DM,DM)$, MET slope decreases (PDF effect)

For $p_T(g)$ increase

$\Delta (x_1 x_2)/(x_1 x_2)$ is large and MET slope is steep
Properties of MET distributions for small and large $M(\text{DM,DM})$

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

For $p_T(g)$ increase, $\Delta (x_1 x_2)/(x_1 x_2)$ is large and MET slope is steep

For $p_T(g)$ increase, $\Delta (x_1 x_2)/(x_1 x_2)$ is small and MET slope is gradual
On the other hand, $M(\text{DM},\text{DM})$ distributions, defined by the EFT operators are different!

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

**The harder M(DM,DM) distributions**

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

**The flatter MET shapes**

\[ M_{DM} = 10, \sqrt{s} = 13 \text{ TeV} \]

\[ \text{arXiv:1610.07545} \]

operator energy dependence \( \rightarrow \) \( M_{DMDM} \) shape \( \rightarrow \) MET shape

\( \Rightarrow \) projection for 300 fb\(^{-1}\): some operators C1-C2, C5-C6, D9-D10, V1-V2, V3-V4, V5-V6 and V11-12 can be distinguished from each other

\( \Rightarrow \) 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 2\( M_{DM} \)

Alexander Belyaev

Decoding the nature of DM
LHC@13TeV reach projected $100 \text{ fb}^{-1}$

LanHEP → CalcHEP → LHE → CheckMATE

ATLAS@13 TeV, 1604.07773

analysis cuts

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

ATLAS @ 13 TeV

300/fb projection

AB, Panizzi, Pukhov, Thomas arXiv:1610.07545

$\Lambda \ [\text{GeV}]$
Decoding the nature of DM

Distinguishing the DM operators: $\chi^2$ for pairs of DM operators

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

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

<table>
<thead>
<tr>
<th></th>
<th>Complex Scalar DM</th>
<th></th>
<th>Dirac Fermion DM</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 GeV C1 C5</td>
<td>1000 GeV C1 C5</td>
<td>100 GeV D1 D9</td>
<td>1000 GeV D1 D9</td>
</tr>
<tr>
<td>Complex Scalar DM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM 100 GeV C1</td>
<td>0.0</td>
<td>19.7</td>
<td>11.73</td>
<td>41.79</td>
</tr>
<tr>
<td>DM 1000 GeV C5</td>
<td>15.74</td>
<td>0.0</td>
<td>1.11</td>
<td>3.93</td>
</tr>
<tr>
<td>DM 1000 GeV C5</td>
<td>19.89</td>
<td>0.36</td>
<td>0.27</td>
<td>4.58</td>
</tr>
<tr>
<td>DM 1000 GeV C5</td>
<td>50.86</td>
<td>13.86</td>
<td>11.18</td>
<td>1.53</td>
</tr>
<tr>
<td>Dirac Fermion DM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM 100 GeV D1</td>
<td>9.88</td>
<td>1.17</td>
<td>0.0</td>
<td>9.23</td>
</tr>
<tr>
<td>DM 100 GeV D9</td>
<td>30.49</td>
<td>3.59</td>
<td>7.99</td>
<td>0.0</td>
</tr>
<tr>
<td>DM 1000 GeV D1</td>
<td>20.31</td>
<td>0.73</td>
<td>2.25</td>
<td>0.0</td>
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Distinguishing the DM operators: $\chi^2$ for pairs of DM operators

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

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

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Importance of the operator running in the DM DD ↔ Collider interplay

- In case of axial operators, e.g.

\[ c_A^{(q)} c_\chi \overline{\chi} \gamma^\mu \chi \overline{q} \gamma_\mu \gamma_5 q \]  \hspace{1cm} \text{(D7)}

or

\[ c_A^{(q)} c_\phi \phi^\dagger \partial_\mu \phi \overline{q} \gamma^\mu \gamma_5 q \]  \hspace{1cm} \text{(C4)}

couplings \( c_v^{(q)} \) arise due to the running of the wilson coefficient \( c_A^{(q)} \)
leading to sizable constraints on the DM DD constraints.
Importance of the operator running in the DM DD ↔ Collider interplay

- In case of axial operators, e.g.

\[ c_{A}^{(q)} c_{\chi \bar{X} \gamma^{\mu} \chi \bar{q} \gamma_{\mu} \gamma_{5} q} \quad (D7) \]  
or \[ c_{A}^{(q)} c_{\phi \phi \gamma^{\mu} \phi \bar{q} \gamma_{\mu} \gamma_{5} q} \quad (C4) \]

couplings \( c_{V}^{(q)} \) arise due to the running of the wilson coefficient \( c_{A}^{(q)} \) leading to sizable constraints on the DM DD constraints

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

runDM program (github.com/bradkav/runDM) by D’Eramo, Kavanagh Panci
Importance of the operator running in the DM DD ↔ Collider interplay

- In case of axial operators, e.g.

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

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AB, Bertuzzo, Caniu, di Cortona, Eboli, Iocco, Pukhov 2018
DM DD ↔ Collider interplay

\[ \frac{1}{\Lambda} \bar{\chi}\gamma^\mu \bar{q}\gamma_\mu \gamma^5 q \]

\[ M_{DM,DM} = \Lambda \]

\[ \Omega h^2 = 0.118 \]

CMB: \( p_{\text{ann}} < 4.1 \times 10^{-28} \text{ cm}^3 \text{s GeV} \) at 95% C.L., where \( p_{\text{ann}} = \sum_j f_j(600, m_{DM}) \frac{\langle \sigma v \rangle_j(600)}{m_{DM}} \)

Galli, Iocco, Bertone, Melchiorri 2009

AB, Bertuzzo, Caniu, di Cortona, Eboli, Iocco, Pukhov 2018
DM DD ↔ Collider interplay

\[ \frac{1}{\Lambda} \bar{\chi} \gamma^\mu \bar{q} \gamma_\mu \gamma^5 q \]

non-collider constraints

D7: \( \frac{g_s^2}{\Lambda^2} (\bar{\chi} \gamma^\mu \chi)(\bar{q} \gamma^\nu \gamma^5 q) \)

- \( g_s = 4 \pi \) (blue)
- \( g_s = 1 \) (red)
- \( g_s = 6 \) (orange)
- non-coll. (purple)

\( \Lambda \) [GeV]

LHC

\( m_{DM} \) [GeV]
DM DD ↔ Collider interplay

(a) 

(b) 

(c) 

(d) 

D1: \( \frac{\lambda^2}{s} (\chi \chi) (\psi \psi) \) 
- \( g_\ast = 4 \pi \) 
- \( g_\ast = 1 \) 
- \( g_\ast = 6 \) 
- non-coll.

D2: \( \frac{\lambda^2}{s} (\chi y \chi) (\psi \psi) \) 
- \( g_\ast = 4 \pi \) 
- \( g_\ast = 1 \) 
- \( g_\ast = 6 \) 
- non-coll.

D3: \( \frac{\lambda^2}{s} (\chi \chi) (\chi y \psi) \) 
- \( g_\ast = 4 \pi \) 
- \( g_\ast = 1 \) 
- \( g_\ast = 6 \)

D4: \( \frac{\lambda^2}{s} (\chi y \chi) (\psi \psi) \) 
- \( g_\ast = 4 \pi \) 
- \( g_\ast = 1 \) 
- \( g_\ast = 6 \) 
- non-coll.
Beyond the EFT: SUSY
There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 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 leptonic signatures.

- 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.
Signal vs Background

- difference in rates is pessimistic ...
- but the difference in shapes is encouraging: large DM mass → bigger $M(DM,DM) →$ flatter MET

$pp\rightarrow \nu\nu j$ vs. $pp\rightarrow \chi\chi j$

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

![Signal and Zj background $p_T$ distributions for the 13 TeV LHC](image)

- normalised signal and Zj background distributions

$pp\rightarrow \nu\nu j$ vs. $pp\rightarrow \chi\chi j$
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

AB, Barducci, Bharucha, Porod, Sanz  JHEP, 1504.02472
Beyond the mono-jet signature

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

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

Current LHC reach with $tt + \text{MET}$ signature based on ATLAS_CONF_2016_050 results

Flacke, Jaine, Schaefers, AB, 2017
The role of Z' vs QCD for $pp \rightarrow TT \rightarrow tt$ 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

DM DD rates are loop-suppressed
Disappearing Charged Tracks from: VDM as an example

The small mass gap (~ pion mass) between DM and its charged partner will lead to the disappearing charge tracks signatures

The life-time should be properly evaluated using W-pion mixing (otherwise overestimated by factor of 10)
Collider sensitivity to VDM mass

Collider sensitivity to VDM mass

Current bound from LHC on DM mass from the minimal vector triplet model: **1.3 TeV**!

100 TeV FCC will cover DM mass **beyond 4 TeV**: will discover or close the model

AB, Cacciapaglia, McKay, Martin, Zerwekh
arXiv:1808.10464
Decoding the nature of DM at the ILC

muon spectrum from the models with scalar and fermion DM

e^+e^- → D^+ D^- → DM DM W^+ W^- → DM DM jj μ ν

Normalized No. Events vs Energy of Muon, $M_{D^\pm} = 150$ GeV

- Green: Fermion, 2→4, ISR + Beamstrahlung, $\sigma = 9.5 \times 10^{-2}$ pb
- Red: Scalar, 2→4, ISR + Beamstrahlung, $\sigma = 7.2 \times 10^{-3}$ pb
- Black: Analytical, simplified case

$M_{DM} = 100$ GeV
$M_{D^+} = 150$ GeV

AB, Ginzburg, Locke, Freegard, Hosken, Pukhov preliminary
Decoding Problem: Data → Theory

- 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
Decoding Problem: Data → Theory link

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HEPMDB (High Energy Physics Model Database) was created in 2011 hepmdb.soton.ac.uk
  - 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
  - you can upload their own model and perform simulation
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As a HEPMDB spin-off the **PhenoData** project was created
hepmdb.soton.ac.uk/phenodata
  - stores data (digitized curves from figures, tables etc) from those HEP papers which did not provide data in arXiv or HEPData
  - has an easy search interface and paper identification via arXiv, DOI or preprint numbers
**Summary**

- DM DD detection provides a very powerful probe of DM theory space – in general provides DM mass probe beyond the collider reach.

- Colliders – provide DM detection power in the region “blind” for DM DD, typically below 1 TeV.

- Several ways to decode DM nature from the signal which we hope to observe soon (slopes of MET- beyond EFT approach, cross sections, beyond mono-X signatures, …).

- New prospects: new DD experiments, new ideas, prospects for directional DM detection, new signatures at colliders (VFB, LLPs, …), future colliders (great potential of ILC and FCC).

- Great synergy of collider and non-collider experiments (DD, CMB, relic density).
Thank you!
Backup Slides
DM DD: directional detection – going beyond the neutrino floor

- The idea is to measure both the energy and the direction of the recoil.

- Most mature technology is the gaseous Time Projection Chamber (TPC) : DRIFT, MIMAC, DMTPC, NEWAGE, D3.

Detecting recoil tracks in nuclear emulsion (e.g. NEWS experiment)
Aleksandrov et al. [1604.04199]

- Directional detection is HARD, But it is also very POWERFUL.
Relation of the actual dimension (D) and the naive one (d) for VDM operators

<table>
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<tr>
<th>$V_{DM}$ Operator</th>
<th>$\Lambda_d$</th>
<th>d</th>
<th>$\Lambda_D$</th>
<th>D</th>
<th>$\Delta_\sigma (\sigma_{\nu\nu} \propto E^{\Delta_\sigma})$</th>
<th>Amplitude Enhancement</th>
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<td>V1, V2, V5, V6</td>
<td>$\frac{1}{\Lambda}$</td>
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<td>$\frac{M_{DM}^2}{\Lambda^3}$</td>
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<td>4</td>
<td>$(E/M_{DM})^2$</td>
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<td>$\frac{M_{DM}^2}{\Lambda^4}$</td>
<td>8</td>
<td>6</td>
<td>$(E/M_{DM})^2$</td>
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<tr>
<td>V7P, V8P, V9, V10</td>
<td>$\frac{1}{\Lambda^2}$</td>
<td>6</td>
<td>$\frac{M_{DM}}{\Lambda^3}$</td>
<td>7</td>
<td>4</td>
<td>$E/M_{DM}$</td>
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</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 $M_{DM} = 1$ 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:

  \[
  \Lambda_D = \left( \Lambda_d^{d-4} M_{DM}^{d-D} \right)^{\frac{1}{D-4}} \quad \text{and} \quad \Lambda_d = \left( \Lambda_D^{D-4} M_{DM}^{D-d} \right)^{\frac{1}{d-4}}
  \]
Distinguishing DM operators

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

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

# of events consistent with 95% CL

MET cut (GeV) $\rightarrow$

$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7$

Signal region, IM

$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7$

# of events consistent with 95% CL

$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7$

$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7$
The BG is statistically driven, e.g. pp->Zj \to nnj BG is defined from the pp \to Zj \to l^+l^-j one

## CMS-PAS-EXO-16-013

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<th>$E_{T}^{\text{miss}}$ Range (GeV)</th>
<th>$Z(\nu)+\text{jets}$</th>
<th>$W(\nu)+\text{jets}$</th>
<th>$Z(\ell)+\text{jets}$</th>
<th>$\gamma+\text{jets}$</th>
<th>Top</th>
<th>Diboson</th>
<th>QCD</th>
<th>Total (Post-fit)</th>
<th>Total (Pre-fit)</th>
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<td>11976 ± 196</td>
<td>207 ± 13</td>
<td>230 ± 14</td>
<td>564 ± 55</td>
<td>251 ± 41</td>
<td>508 ± 171</td>
<td>27761 ± 1464</td>
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<td>230 – 260</td>
<td>7974 ± 116</td>
<td>5776 ± 101</td>
<td>92.9 ± 5.7</td>
<td>101 ± 6</td>
<td>267 ± 26</td>
<td>157 ± 26</td>
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<td>4467 ± 70</td>
<td>2867 ± 50</td>
<td>37.9 ± 2.3</td>
<td>63.7 ± 3.9</td>
<td>116 ± 11</td>
<td>77.3 ± 12.7</td>
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<td>290 – 320</td>
<td>2518 ± 46</td>
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<td>29.8 ± 10.5</td>
<td>4083 ± 204</td>
<td>4215 ± 48</td>
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<td>320 – 350</td>
<td>1496 ± 35</td>
<td>818 ± 20</td>
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<td>19.7 ± 1.2</td>
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<td>2407 ± 37</td>
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<td>350 – 390</td>
<td>1204 ± 31</td>
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<td>3.9 ± 0.2</td>
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<td>24.5 ± 2.4</td>
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<td>589 ± 30</td>
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<td>430 – 470</td>
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<td>0.8 ± 0.04</td>
<td>337 ± 15</td>
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<td>470 – 510</td>
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<td>2.2 ± 0.4</td>
<td>0.28 ± 0.19</td>
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<td>134 ± 7</td>
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<td>550 – 590</td>
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<td>1.0 ± 0.1</td>
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<td>0.46 ± 0.01</td>
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<td>0.017 ± 0.001</td>
<td>0.19 ± 0.01</td>
<td>0.94 ± 0.09</td>
<td>1.5 ± 0.2</td>
<td>0.06 ± 0.05</td>
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<td>0.23 ± 0.02</td>
<td>0.11 ± 0.02</td>
<td>0.02 ± 0.02</td>
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<td>790 – 840</td>
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http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-16-013/#AddFig
Complementarity of LHC and non-LHC DM searches

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

\( TT \rightarrow t \bar{t} \, \text{DM DM} \)

arXiv: 1707.07000
## LHC@13TeV Reach for spin 0 and $\frac{1}{2}$ 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>
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<td>C1 &amp; C2</td>
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<td>C5 &amp; C6</td>
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<td>Dirac Fermion DM</td>
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<td>D1T &amp; D4T</td>
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<td>D6 &amp; D8</td>
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# LHC@13TeV Reach for spin 1 DM

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<td>V1 &amp; V2</td>
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<td>V3 &amp; V4</td>
<td>$M_{DM}^2/\Lambda_D^4$</td>
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<td>V5 &amp; V6</td>
<td>$M_{DM}^2/\Lambda_D^3$</td>
<td>784</td>
<td>791</td>
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<td>V7M &amp; V8M</td>
<td>$M_{DM}^2/\Lambda_D^4$</td>
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<tr>
<td>V7P &amp; V8P</td>
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<td>V9M &amp; V10M</td>
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<td>$M_{DM}^2/\Lambda_D^4$</td>
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Complex Vector DM
Disappearing Charged Tracks from DM

The small mass gap between (~ pion mass) DM and its charged partner will lead to the disappearing charge tracks

The life-time should be properly evaluated using W-pion mixing

\[ \mathcal{L}_{\pi^-V^+V^0} = \frac{g^2 f_\pi}{2\sqrt{2} M_W^2} [g_{\beta\gamma}(p_{V^+} - p_{V^0})_\alpha + g_{\alpha\gamma}(p_{V^+} - p_{V^0})_\beta] p_{\pi^-}^\alpha - \pi^- V^+ V^0 \gamma \]

\[ pp \rightarrow V^+ V^- / V^\pm V^0 @ 13 \text{ TeV} \]