Decoding the nature of Dark Matter
at current and future experiments

Alexander Belyaev

Southampton University & Rutherford Appleton Laboratory

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Decoding the nature of Dark Matter at current and future experiments

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Moscow State University 1993 graduation
Dark Matter is in the main focus after Higgs discovery (statistics of publications based on inSPIRE database)
Because while Higgs Discovery has finished the SM puzzle...
Because while Higgs Discovery has finished the SM puzzle... it became obvious that the SM itself is the piece of some (more) complete and consistent BSM theory.
Because while Higgs Discovery has finished the SM puzzle... it became obvious that the SM itself is the piece of some (more) complete and consistent BSM theory
And DM is strong and very appealing evidence for BSM!

**Galactic rotation curves**

**CMB: WMAP and PLANCK**

**Large Scale Structures**

**Bullet cluster**

**Gravitational lensing**

---

Decoding the nature of DM
DM is very appealing even though we know almost nothing about it!
How do we probe Dark Matter?
Decoding the nature of DM

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

DM

Signatures

Efficient annihilation now: Indirect Detection

Efficient production at colliders

Efficient scattering off nuclei: Direct Detection

Dark Matter (DM)

SM

Alexander Belyaev
Decoding the nature of DM
Complementarity of DM searches

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 have a way to determine the nature of DM
Complementarity of DM searches

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 have a way to determine the nature of DM

Efficient scattering off nuclei: DM Direct Detection (DD)

Example of DM interactions with negligible/suppressed DD rates
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
- create framework for mapping theory $\rightarrow$ signatures space (using effective multiple top $\rightarrow$ down simulation)
- using $[\text{theory} \rightarrow \text{signatures}]$ mapping data, perform
- $[\text{signatures} \rightarrow \text{theory}]$ identification using machine learning

We should prepare for DM discovery and identification!
Collaborators & Projects

- I.Ginzburg, D.Locke, A. Freegard, T. Hosken, A.Pukhov, AB to appear
- G.Cacciapaglia, J.McKay, D. Marin, A.Zerwekh, AB
- E.Bertuzzo, C.Caniu, G. di Cortona, O.Eboli, F. Iocco, A.Pukhov, AB
- T. Flacke, B. Jain, P. Schaefers, AB
- G. Cacciapaglia, I. Ivanov, F. Rojas, M. Thomas, AB
- I. Shapiro, M. Thomas, AB
- L. Panizzi, A. Pukhov, M. Thomas, AB
- D. Barducci, A.Bharucha, W. Porod, V. Sanz, AB

arXiv: 1809.00933
arXiv: 1808.10464
arXiv: 1807.03817
arXiv: 1707.07000
arXiv: 1612.00511
arXiv: 1611.03651
arXiv: 1610.07545
arXiv: 1504.02472
DM Mass range

- **m_{DM}**
- **m_{Planck} \sim 10^{19} \text{ GeV**

**10^{-22} \text{ eV**
- **non-thermal**
- **bosonic**

**\sim 100 \text{ eV**

**1 \sim 100 \text{ MeV**

**< 10 \text{ keV too hot**

**\sim 100 \text{ GeV**

**m_{Z} \sim 100 \text{ TeV too much**

**non-thermal**
- **composite**

Light DM

“WIMPs”
Spectrum of Theory Space

Effective Field Theories

Less Complete

Dipole Interactions

Contact Interactions

Simplified Models

Sketches of Models

Higgs portal

“Squarks”

Z'

dark photon

Models

UV Complete Models

More Complete

Little Higgs

UED

MSSM

mSUGRA

T. Tait
To test DM theory we need to realise

theory ↔ data

link

which is a non-trivial story
theory <-> data requires observables to be compared with data

THEORY ↔ OBSERVABLES

TOOLS

DATA
TOOLS
Tools for **theory → observables** link

- DM Model
- Feynman Rules
- LanHEP
- FeynRules
- SARAH
Tools for theory $\rightarrow$ observables link

DM Model $\rightarrow$ Feynman Rules $\rightarrow$ Matrix Element

LanHEP, FeynRules, SARAH $\rightarrow$ CalcHEP, CompHEP, FormCalc, MadGraph, MCFM, MC@NLO, Sherpa, WHizard
Tools for **theory** → **observables** link

- **DM Model**
  - LanHEP
  - FeynRules
  - SARAH

- **Feynman Rules**
  - CalcHEP, CompHEP
  - FormCalc, MadGraph, MCFM, MC@NLO

- **Matrix Element**
  - Pythia
  - HERWIG
  - ISAJET
  - Sherpa, WHizard

- **Events**
  - Sherpa
Tools for **theory → observables** link

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  - HERWIG
  - ISAJET
- **Events**
  - Sherpa
- **Detector**
  - FAST/FULL
  - Detector Simulation
  - PGS, Delphes
  - CMSSW, ATHENA
- **Collider signatures**
Tools for theory $\rightarrow$ observables link

DM Model $\rightarrow$ Feynman Rules $\rightarrow$ Matrix Element $\rightarrow$ Events $\rightarrow$ Detector

- LanHEP
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CalcHEP $\rightarrow$ Relic Density $\rightarrow$ DM Direct Detection $\rightarrow$ MadDM

Madgraph $\rightarrow$ Collider signatures

micrOMEGAs $\rightarrow$ DM Indirect Detection
Tools for theory $\rightarrow$ observables link

DM Model → Feynman Rules → Matrix Element → Events → Detector

LanHEP, FeynRules, SARAH → CalcHEP, CompHEP, FormCalc, MadGraph, MCFM, MC@NLO, Sherpa, WHizard → PYTHIA, HERWIG, ISAJET, Sherpa → FAST/FULL Detector Simulation, PGS, Delphes, CMSSW, ATHENA

Detector Simulation → Detector → Relic Density → DM Direct Detection → DM Indirect Detection

micrOMEGAs → MadDM → CMB constraint on $<\sigma v>$

“CMB constraints on Dark Matter models with large annihilation cross-section”
’09 Gallia, Iocco, Bertone, Melchiorri
MicrOMEGAs

http://lapth.in2p3.fr/micromegas
Belanger, Boudjema, Pukhov, Semenov
Goudelis, Zaldivar v5.0.8

- Comprehensive tool for dark matter studies: precise calculation of relic density, direct detection, indirect detection, cross section at colliders and decays
- Comes with models: MSSM, NMSSM, CPV-MSSM, RH-neutrino, Littlest Higgs, Inert doublet+singlet Z3,Z4; many more models are available at hepmdb.soton.ac.uk

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- Recent features
  - **Neutrino signal** from DM capture (for SuperKamiokande, IceCube), both neutrino flux and muon flux are computed
  - **Higgs 3-body decays** and loop-induced decays are included – a good agreement with HDECAY (Djouadi et al) for SM-like Higgs
  - Links to external packages: HiggsSignals/HiggsBounds (Bechtle et al), Smodels (Kraml et al)
  - Includes 3/4-body processes with one/two virtual W/Z
  - Z2,Z3,Z4,Z5 symmetries and **two DM candidates**
  - **Asymmetric DM**: option to define $\Delta Y = Y^+ - Y$
  - Collider limits for $Z'$ on-shell mediator (Barducci et al)
  - **Freeze-in DM scenario**: from v 5.0

![Graph](image-url)
MicrOMEGAs

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- Prospects:
  - Collider limits for any DM model (Belanger, Barducci, AB, Pukhov)
  - Improved propagation for ID DM signals, interface to USINE, GALPROP
  - $DMDM \rightarrow \gamma\gamma/\gamma Z$ with FormCalc (AB, Hahn, Pukhov, Semenov)
MadDM

http://susy.phsx.ku.edu/~mihailo/index.html
https://launchpad.net/maddm
Backovic, Martini, Kong, Mattelaer, Mohlabeng

- Was born in 2013, version 2.1: DM relic density, DM direct and directional detection

MadDM Status, MC4BSM 2015

- Urgent!
  - Link to Pythia/GALPROP
    - Still discussing...
- Finished!
  - Direct detection
- Indirect detection
- Model testing
- Relic density
- Database of experimental results (e.g. HiggsBounds)
- NLO
- Integration with MG5_aMC@NLO
- Web interface
Decoding the nature of DM

MadDM

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Backovic, Martini, Kong, Mattelaer, Mohlabeng

- Was born in 2013, version 2.1: DM relic density, DM direct and directional detection

MadDM Status, NOW

- Model testing (integration with MadAnalysis)
- Database of experimental results (e.g. HiggsBounds)
- NLO (colliders, ID)
- Web interface

In development!
- Link to Pythia/ GALPROP
- Full set of DD effective operators
- Direct detection
- Indirect detection
- Loop induced ID
- In development!
- Still discussing...

arXiv:1509.03683
arXiv:1308.4955
MicroMEGAs – MadDM comparison: DM DD
arXiv:1509.03683

<table>
<thead>
<tr>
<th>DM spin</th>
<th>Even</th>
<th>Odd</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI 0</td>
<td>scalar current $2M_X S S^* \bar{\psi}_q \psi_q$</td>
<td>vector current $i \left( \partial_\mu S S^* - S \partial_\mu S^* \right) \bar{\psi}_q \gamma^\mu \psi_q$</td>
</tr>
<tr>
<td>1/2</td>
<td>$\bar{\psi}<em>X \gamma</em>\mu \psi_X \bar{\psi}_q \gamma^\mu \psi_q$</td>
<td>$i \left( A_{X}^\alpha \partial_\mu A_{X\alpha} - A_{X}^\alpha \partial_\mu A_{X\alpha}^* \right) \bar{\psi}<em>q \gamma</em>\mu \psi_q$</td>
</tr>
<tr>
<td>1</td>
<td>$2M_X A_{X\mu}^* A_X^\mu \bar{\psi}_q \psi_q$</td>
<td></td>
</tr>
</tbody>
</table>

| SD 1/2 | axial-vector current $\bar{\psi}_X \gamma^\mu \gamma^5 \psi_X \bar{\psi}_q \gamma_\mu \psi_q$ | tensor current $-\frac{1}{2} \bar{\psi}_X \sigma_{\mu\nu} \psi_X \bar{\psi}_q \sigma^{\mu\nu} \psi_q$ |
| 1 | $\sqrt{6} \left( \partial_\alpha A_{X\beta}^* A_{X\nu} - A_{X\beta}^* \partial_\alpha A_{X\nu} \right) \epsilon^{\alpha\beta\mu\nu} \bar{\psi}_q \gamma_5 \gamma_\mu \psi_q$ | $i \frac{\sqrt{3}}{2} \left( A_{X\mu} A_{X\nu}^* - A_{X\mu}^* A_{X\nu} \right) \bar{\psi}_q \sigma_{\mu\nu} \psi_q$ |

- There is a good agreement between spin-Independent (SI) and spin-dependent (SD) rates.
Importance of the MicroMEGAs – MadDM comparison

- Actually the main message here is the importance of the fact that **two independent tools exist** and are being cross checked!
Importance of the MicroMEGAs – MadDM cross-check

Actually the main message here is the importance of the fact that two independent tools exist and are being cross checked!

A recent example of this importance are the results for the S-mediated model used with MadDM 2.0.5 in arXiv:1603.08525 and brought at DM LHC forum.

t-channel diagram was missed in MadDM 2.0.5, leading to the erroneous results.
CalcHEP for DM studies at colliders

A. Pukhov, AB, N. Christensen
http://theory.sinp.msu.ru/~pukhov/calchep.html

hep-ph/9908288
arXiv:1207.6082

Some highlights

- the “engine” of micOMEGAs
- has convenient graphical interface
- evaluates particle widths 'on the fly'
- allows to select diagrams (inducing squared diagram level) – important for the dedicated interference studies
- allows easily modify an existing model (GUI) or to implement the new one (LanHEP, FeynRules)
- powerful batch interface – connects production and decay processes, allows to perform multidimensional scan and produce LHE files in one run
- adopted to HPC cluster, symbolic and numerical evaluations/simulations are threads parallelized
- exports plots to GNUPLOT, PAW and ROOT
- numerous models are implemented, see CalcHEP's site and HEPMDB database
- modular structure, used in GAMBIT
CalcHEP for DM studies at colliders

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DM Models:
at CalcHEP, HEPMDB (hepmdb.soton.ac.uk) and FeynRules(feynrules.irmp.ucl.ac.be) sites

- **Extra dimensions**: 5D UED (MUED) with 2KK and 4KK layers, 6D UED with 2KK layers
- **SUSY**: CMSSM, MSSM, NMSSM, left-right symmetric MSSM, MSSM with CP violation, E6MSSM
- **Technicolor & Composite Higgs models**: TC with DM, VLQ with scalar DM
- **Little Higgs**: Littlest higgs model with T-parity
- **DM EFT operators**: The complete set of DIM5&6 operators with spin 0,1/2,1 DM

hep-ph/9908288
arXiv:1207.6082
Decoding the nature of DM

**MadGraph5\_aMC@NLO for DM studies at colliders**


http://madgraph.hep.uiuc.edu/
https://launchpad.net/mg5amcnlo

- the “engine” of MadDM
- has been most intensively used by ATLAS and CMS
- can perform NLO QCD corrections (not a generic for arbitrary model)
  but works for SM and NLO models located at FeynRules web site
- Includes matching to parton showers

**DM models: at FeynRules and HEPMDB sites**

- **Extra dimensions**: 5D UED (MUED)
- **SUSY**: MSSM NMSSM
- **DM EFT operators**: The complete set of DIM5&6 operators with spin 0,1/2,1 DM
- **NLO models at** feynrules.irmp.ucl.ac.be/wiki/NLOModels
  - DM simplified models (s-channel spin 0,1,2), SUSY-QCD

DM models at https://github.com/LHC-DMWG/model-repository

- **2HDM, EFT, ... →** MG models more specific to LHC-DMWG activity

We need models for both Magraph and CalcHEP for the cross-check & validation!
DM Direct detection interplay with colliders
Direct Dark Matter Detection

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

Elastic recoil energy

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

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

- Minimum WIMP speed required to produce a recoil energy - limitation in low DM mass region

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

\[ \frac{dR}{dE_R} = \frac{\sigma_0 F^2(E_R)}{2m_\chi \mu_x^2} \rho_\chi \eta(v_{\text{min}}, t) \]

halo integral
Power of DM DD to rule out theory space

ArXiv:1310.8327
Snowmass CF1 Summary
Power of DM DD to rule out theory space

Inert 2 Higgs Doublet Model

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

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

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

Inert 2 Higgs Doublet Model

Scalar DM

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

Cacciapaglia, Ivanov, Rojas, Thomas, AB arXiv:1610.07545
Novaes, Mercadante, Moon, Tomei, Moretti, Tomas, Panizzi, AB arXiv:1809.00933
Collider Searches

process

$q$

DM

$q$

detector

?
Collider Searches

process

q

q

DM

DM

detector

Nothing!
Collider Searches

process

q

DM

DM

detector

Large missing \( P_T \) (2DM)

High \( P_T \) jet

monojet signature

Decoding the nature of DM
Can we test DM properties at the LHC?

To 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
**Missing $E_T$ (MET) distributions: the large range of slopes**

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

<table>
<thead>
<tr>
<th>C1,C2</th>
<th>C1Q,C2Q</th>
<th>C3,C4</th>
<th>C5,C6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D1-D4</td>
<td>D1Q-D4Q</td>
<td>D1T-D4T</td>
</tr>
<tr>
<td></td>
<td>D5-D8</td>
<td>D9-D10</td>
<td></td>
</tr>
</tbody>
</table>

**AB, Panizzi, Pukhov, Thomas**

arXiv:1610.07545

### Missing $E_T$ (MET) Distributions

- **Scalar DM**
- **Fermion DM**
- **Vector DM**

<table>
<thead>
<tr>
<th>$E_{miss}$ (GeV)</th>
<th># Events (normalized to one)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>400</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>600</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>800</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>1200</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>1400</td>
<td>$10^{-2}$</td>
</tr>
</tbody>
</table>
Distinguishing DM operators/theories

The harder $M(DM,DM)$ distributions

The flatter MET shapes

operator energy dependence $\rightarrow$ $M_{DMDM}$ shape $\rightarrow$ MET shape

⇒ 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

⇒ 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 $2M_{DM}$

arXiv:1610.07545
Distinguishing the DM operators: $\chi^2$ for pairs of DM operators

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

: 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</td>
<td>1000 GeV C1</td>
<td>100 GeV D1</td>
<td>1000 GeV D1</td>
</tr>
<tr>
<td>Complex Scalar DM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 GeV C5</td>
<td>1000 GeV C5</td>
<td>100 GeV D9</td>
<td>1000 GeV D9</td>
</tr>
<tr>
<td>Dirac Fermion DM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| DM                   | 100 GeV C1        | 1000 GeV C1        | 100 GeV D1       | 1000 GeV D1        |
| Complex Scalar DM    | 100 GeV C5        | 1000 GeV C5        | 100 GeV D9       | 1000 GeV D9        |
| DM                   | 100 GeV C5        | 1000 GeV C5        | 100 GeV D9       | 1000 GeV D9        |
| Dirac Fermion DM     | 100 GeV D9        | 1000 GeV D9        | 100 GeV D9       | 1000 GeV D9        |

| Complex Scalar DM    | 0.0                | 19.7                | 25.54             | 74.63               |
|                      | 15.74              | 0.0                 | 0.37              | 16.25               |
| Dirac Fermion DM     | 11.73              | 41.79               | 25.78             | 52.58               |
|                      | 1.11               | 3.93                | 0.74              | 7.35                |

| Complex Scalar DM    | 19.89              | 0.36                | 0.0               | 11.82               |
|                      | 50.86              | 13.86               | 10.34             | 0.0                 |
| Dirac Fermion DM     | 2.33               | 2.09                | 0.27              | 4.58                |
|                      | 21.03              | 3.7                 | 11.18             | 1.53                |

| Complex Scalar DM    | 9.88               | 1.17                | 2.52              | 25.99               |
|                      | 30.49              | 3.59                | 1.96              | 3.96                |
| Dirac Fermion DM     | 0.0                | 9.23                | 2.4               | 14.17               |
|                      | 7.99               | 0.0                 | 2.71              | 0.52                |

| Complex Scalar DM    | 20.31              | 0.73                | 0.27              | 12.92               |
|                      | 37.38              | 6.54                | 4.18              | 1.6                 |
| Dirac Fermion DM     | 2.25               | 2.93                | 0.0               | 5.42                |
|                      | 11.96              | 0.5                 | 4.89              | 0.0                 |
DM DD ↔ Collider interplay

AB, Bertuzzo, Caniu, di Cortona, Eboli, Iocco, Pukhov 2018

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

non-collider constraints

\[ M_{DM,DM} = \Lambda \]
Beyond the EFT: SUSY
**Signal vs Background: SUSY scenario**

- difference in rates is pessimistic...

- but the difference in shapes is encouraging: large DM mass $\rightarrow$ bigger $M(DM,DM) \rightarrow$ flatter MET

---

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

- Normalised signal and $Zj$ background distributions for the 13 TeV LHC
Beyond the mono-jet signature

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

\[M_{Z'} = 3000 \text{ GeV}, \quad M_{T'} = 1200 \text{ GeV}\]

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

Flacke, Jaine, Schaefers, AB, 2017
Disappearing Charged Tracks (DCT): 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).
DCT allows to probe TeV DM at colliders

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
Frameworks for **observables → data link**

- **CheckMATE** V2 ([checkmate.hepforge.org](http://checkmate.hepforge.org))  
Drees, Schmeier, Dercks, Desai, Kim, Rolbiecki, Tattersall, Weber

- **MadAnalysis** ([madanalysis.irmp.ucl.ac.be](http://madanalysis.irmp.ucl.ac.be))  
Conte, Dumont, Fuks, Schmitt, Kraml, Bein, Chalons

  - quickly developing support from users (analysis validation)  
  - relies on Delphes fast simulation  
  - Incorporates projection analysis  
  - Great potential in creating **public library of the analysis**  
  - **Needs validation of more DM searches and boosted objects analysis**

- **GAMBIT** the Global and Modular Beyond-Standard Model Inference Tool  
[https://gambit.hepforge.org/collaboration](https://gambit.hepforge.org/collaboration)  
about 20 authors, see Andy Buckley’s talk  
is a global fitting code for generic Beyond the Standard Model theories, designed to allow  
fast and easy definition of new models, observables, likelihoods, scanners and backendphysics codes
The problem of data $\rightarrow$ theory link

- We have studied a lot of models, identified many potential signatures of DM, have powerful tools for theory $\rightarrow$ data exploration.

- But the inverse problem of decoding of the underlying theory from signal remains unexplored.

- Its solution requires:
  - database of models, database of signatures
  - framework with machine learning aiming to connect theory and signature space
  - effective creation of multidimensional set of signatures data in models space and in parameter space for each model
  - your input!
The problem of data $\rightarrow$ theory link

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HEPMDB (High Energy Physics Model Database) hepmdb.soton.ac.uk
created in 2011 to make the first step for decoding (AB, Daniel Locke at present)
- has a status of the permanent server at Southampton
- convenient centralized storage environment for HEP models
- linked to IRIDIS 5 HPC cluster at Southampton, 20K cores, 1.3 Petaflops
- it allows to evaluate the LHC predictions and perform event generation using CalcHEP, Madgraph for any model stored in the database via web interface
- users can upload their own model and perform simulation – became a very attractive feature for all range of researchers
- database of signatures is under development – your input is important!
Search Models :: Results for [MSSM]

   
   CalcHEP/MicrOMEGAs groups
   
   We present MSSM with SUGRA and AMSB scenario as well as MSSM with low energy input. Read file INSTALLATION for model installation and file CITE for references on scientific publications which pre...

2. **MSSM with bilinear R-Parity violation**  [2011-11-17 20:00:51] hepmdb:1111.0036
   
   Florian Staub
   
   The MSSM with bilinear R-Parity violating terms in the superpotential and for the soft-breaking terms. Model files created by SARAH 3.1.0 Support of SLHA+ functionality to read spectrum files...

   
   Florian Staub
   
   Triplet extended MSSM (including possibility of flavor violation) Model files created by SARAH 3.1.0 Support of
HEPMDB: setting batch file

```plaintext
# Process Info
# Process specifies the process. More than one process can be specified. Cuts, regularization and QCD scale should be specified for each one.
# Decay specifies decays. As many decays as are necessary are allowed.
# Composite specifies composite particles present in the processes or decays.

Process: p.p->W+,Z
Decay: W->le,n
Decay: Z->le,le

Composite: p=u,U,d,D,G
Composite: le=e,E,m,M
Composite: n=ne,Ne,nm,Nm
```

---

**Message**

02/03/12 03:21:58: You successfully submitted your job.
02/03/12 03:21:01: You don't have any job.
02/03/12 03:21:00: Logged In.

---

**Southampton**

**Durham University**

---

**Alexander Belyaev**

Decoding the nature of DM
HEPMDB: getting results

Validation

Job #1628195.blue30=Wednesday 01st of August 2012 09:55:37 PM=
CalcHEP Numerical Details
Done!

<table>
<thead>
<tr>
<th>Scans</th>
<th>sigma (fb)</th>
<th>Running</th>
<th>Finished</th>
<th>Time (hr)</th>
<th>N events</th>
</tr>
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<tbody>
<tr>
<td>Mh120</td>
<td>9.8870e+02</td>
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<td>13/13</td>
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<td>10000</td>
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<tr>
<td>Mh125</td>
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<td>0/13</td>
<td>13/13</td>
<td>0.01</td>
<td>10000</td>
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<tr>
<td>Mh130</td>
<td>9.6010e+02</td>
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<td>13/13</td>
<td>0.02</td>
<td>10000</td>
</tr>
</tbody>
</table>

Mh120.txt CalcHEP Numerical Details
Done!

<table>
<thead>
<tr>
<th>Processes</th>
<th>sigma (fb)</th>
<th>unc (%)</th>
<th>PID</th>
<th>Time (hr)</th>
<th>N events</th>
</tr>
</thead>
<tbody>
<tr>
<td>u,D-&gt;W+,b,B</td>
<td>1.3296e+03</td>
<td>4.59e-01</td>
<td>0</td>
<td>0.00</td>
<td>3258/3258</td>
</tr>
<tr>
<td>U,d-&gt;W-,b,B</td>
<td>7.2163e+02</td>
<td>5.03e-01</td>
<td>0</td>
<td>0.00</td>
<td>1822/1822</td>
</tr>
<tr>
<td>d,U-&gt;W-,b,B</td>
<td>7.1638e+02</td>
<td>4.39e-01</td>
<td>0</td>
<td>0.00</td>
<td>1810/1810</td>
</tr>
</tbody>
</table>

Message

01/08/12 : 21:56:05 : Nt_maker test-Mh120.lhe
01/08/12 : 21:56:04 : gunzip file test-Mh120.lhe.gz
01/08/12 : 21:55:38 : Job 1628195.blue30 was finished.
01/08/12 : 21:38:29 : You successfully submitted a job on HPCx : #1628195.blue30 . You will be notified by email when the job is finished.
HEPMDB: distributions from the files

HEPMDB
High Energy Physics Model Database

<table>
<thead>
<tr>
<th>CalcHEP (3.7)</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Messages**

- 12/03/19 : 07:29:31 : Conversion to n-tuple (.nt)
- 12/03/19 : 07:29:29 : Uncompressed file "HHMET_Sash RemoteException"
- 12/03/19 : 07:28:21 : You have no running jobs on this host.
- 12/03/19 : 07:28:18 : Logged In.

![Graph showing MET (GeV) distribution with ID, Entries, Mean, and RMS values]

**Download** [jpg] | [eps] | [pdf] | [data]
HEPMDB: geo and stats

last year activity: 200 users, 70M events, ~2K visits from over 60 countries
we have powerful tools to explore complementarity of collider and non-collider signatures and perform top-down exploration for theory → data link

there are observables 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, DCT, … )

not only tools but also models should be public - this will help us to validate and improve them - HEPMDB and FeynRules are good examples

model → signatures → data link is well explored, it is time to start tackling data → model problem
➤ requires machine learning framework over theory-signature space
➤ database of models and signatures (e.g. HEPMDB)
➤ your participation!
Thank you!
Backup Slides
We need HEP/DM “tools” first

- **Theory → Signature link**
  - MicrOMEGAs and MadDM
  - CalcHEP & MadGraph
  - models and repositories
  - Signatures, examples, remarks

- **Signature → Data link**
  - Checkmate, MadAnalysis, Gambit

- **Data → Theory link**
  - The inverse problem of decoding of the underlying theory from signal
### DIM5/6 operators (spin 0, 1/2, 1)

#### Complex scalar DM

<table>
<thead>
<tr>
<th>Operator</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\Lambda^2}{m_\phi} \phi^\dagger \phi q \bar{q}$</td>
<td>[C1]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\phi} \phi^\dagger \phi q i \gamma^5 q$</td>
<td>[C2]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\phi} \phi^\dagger \phi q i \partial_\mu \phi q i \gamma^\mu q$</td>
<td>[C3]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\phi} \phi^\dagger \phi q i \partial_\mu \phi q i \gamma^\mu i \gamma^5 q$</td>
<td>[C4]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\phi} \phi^\dagger \phi G^{\mu \nu} G_{\mu \nu}$</td>
<td>[C5]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\phi} \phi^\dagger \phi \tilde{G}^{\mu \nu} G_{\mu \nu}$</td>
<td>[C6]</td>
</tr>
</tbody>
</table>

#### Complex vector DM

<table>
<thead>
<tr>
<th>Operator</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\Lambda^2}{m_\mu} V^\dagger V \mu \bar{q} q$</td>
<td>[V1]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\mu} V^\dagger V \mu i \gamma^5 q$</td>
<td>[V2]</td>
</tr>
<tr>
<td>$\frac{1}{2\Lambda^2} (V^\dagger_\nu \partial_\mu V^\nu_\mu - V^\nu_\nu \partial_\mu V^\dagger_\nu_\nu) \bar{q} \gamma^\mu q$</td>
<td>[V3]</td>
</tr>
<tr>
<td>$\frac{1}{2\Lambda^2} (V^\dagger_\nu \partial_\mu V^\nu_\mu - V^\nu_\nu \partial_\mu V^\dagger_\nu_\nu) \bar{q} i \gamma^\mu i \gamma^5 q$</td>
<td>[V4]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\mu} V^\dagger_\nu V_\nu \bar{q} i \sigma^{\mu \nu} q$</td>
<td>[V5]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\mu} V^\dagger_\nu V_\nu \bar{q} i \gamma^\mu i \gamma^5 q$</td>
<td>[V6]</td>
</tr>
<tr>
<td>$\frac{1}{2\Lambda^2} (V^\dagger_\nu \partial_\mu V_\mu_\nu + V^\nu_\nu \partial_\mu V^\dagger_\mu_\nu) \bar{q} \gamma^\mu q$</td>
<td>[V7P]</td>
</tr>
<tr>
<td>$\frac{1}{2\Lambda^2} (V^\dagger_\nu \partial_\mu V_\mu_\nu - V^\nu_\nu \partial_\mu V^\dagger_\mu_\nu) \bar{q} i \gamma^\mu i \gamma^5 q$</td>
<td>[V7M]</td>
</tr>
<tr>
<td>$\frac{1}{2\Lambda^2} (V^\dagger_\nu \partial_\mu V_\mu_\nu + V^\nu_\nu \partial_\mu V^\dagger_\mu_\nu) \bar{q} \gamma^\mu i \gamma^5 q$</td>
<td>[V8P]</td>
</tr>
<tr>
<td>$\frac{1}{2\Lambda^2} (V^\dagger_\nu \partial_\mu V_\mu_\nu - V^\nu_\nu \partial_\mu V^\dagger_\mu_\nu) \bar{q} i \gamma^\mu i \gamma^5 q$</td>
<td>[V8M]</td>
</tr>
<tr>
<td>$\frac{1}{2\Lambda^2} \epsilon^{\mu \nu \rho \sigma} (V^\dagger_\nu \partial_\rho V_\sigma + V_\nu \partial_\rho V^\dagger_\sigma) \bar{q} \gamma_\mu q$</td>
<td>[V9P]</td>
</tr>
<tr>
<td>$\frac{1}{2\Lambda^2} \epsilon^{\mu \nu \rho \sigma} (V^\dagger_\nu \partial_\rho V_\mu + V_\nu \partial_\rho V^\dagger_\mu) \bar{q} i \gamma^\mu q$</td>
<td>[V9M]</td>
</tr>
<tr>
<td>$\frac{1}{2\Lambda^2} \epsilon^{\mu \nu \rho \sigma} (V^\dagger_\nu \partial_\rho V_\sigma + V_\nu \partial_\rho V^\dagger_\sigma) \bar{q} \gamma_\mu i \gamma^5 q$</td>
<td>[V10P]</td>
</tr>
<tr>
<td>$\frac{1}{2\Lambda^2} \epsilon^{\mu \nu \rho \sigma} (V^\dagger_\nu \partial_\rho V_\mu + V_\nu \partial_\rho V^\dagger_\mu) \bar{q} i \gamma_\mu i \gamma^5 q$</td>
<td>[V10M]</td>
</tr>
</tbody>
</table>

#### Dirac fermion DM

<table>
<thead>
<tr>
<th>Operator</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\Lambda^2}{m_\chi} \chi \bar{\chi} q \bar{q}$</td>
<td>[D1]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\chi} \chi i \gamma^5 \bar{\chi} q \bar{q}$</td>
<td>[D2]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\chi} \chi \bar{\chi} i \gamma^5 q \bar{q}$</td>
<td>[D3]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\chi} \chi \bar{\chi} \gamma^5 \bar{\chi} q \bar{q}$</td>
<td>[D4]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\chi} \chi \gamma^\mu \bar{\chi} q \bar{q} \gamma^\mu q$</td>
<td>[D5]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\chi} \chi \gamma^\mu i \gamma^5 \bar{\chi} q \bar{q} \gamma^\mu q$</td>
<td>[D6]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\chi} \chi \gamma^\mu \gamma^5 \bar{\chi} q \bar{q} \gamma^\mu q$</td>
<td>[D7]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\chi} \chi \gamma^\mu \gamma^5 \gamma^5 \bar{\chi} \gamma^\mu q \bar{q} \gamma^\mu q$</td>
<td>[D8]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\chi} \chi \sigma^{\mu \nu} \bar{\chi} q \bar{q} \sigma_{\mu \nu} q$</td>
<td>[D9]</td>
</tr>
<tr>
<td>$\frac{\Lambda^2}{m_\chi} \chi \sigma^{\mu \nu} i \gamma^5 \bar{\chi} q \bar{q} \sigma_{\mu \nu} q$</td>
<td>[D10]</td>
</tr>
</tbody>
</table>

* operators applicable to real DM fields, modulo a factor $1/2$


Mapping EFT operators to simplified models

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

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

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

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

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

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

\[ \frac{8}{\Lambda^2} \left[ \bar{\chi} q \bar{q} \chi - \frac{1}{4} \left( \bar{\chi} \chi \bar{q} q + \bar{\chi} \gamma^5 \chi \bar{q} \gamma^5 q + \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q - \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q \right) \right] \]
Distinguishing the DM operators: $\chi^2$ for pairs of DM operators

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

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

<table>
<thead>
<tr>
<th>Complex Scalar DM 100 GeV</th>
<th>Complex Scalar DM 1000 GeV</th>
<th>Dirac Fermion DM 100 GeV</th>
<th>Dirac Fermion DM 1000 GeV</th>
<th>Complex Vector DM 100 GeV</th>
<th>Complex Vector DM 1000 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>C5</td>
<td>C1</td>
<td>C5</td>
<td>D1</td>
<td>D9</td>
</tr>
<tr>
<td>100 GeV</td>
<td>0.0</td>
<td>19.7</td>
<td>25.54</td>
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<td>GeV</td>
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<td>0.37</td>
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<td>0.0</td>
<td>11.82</td>
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<td>GeV</td>
<td>50.86</td>
<td>13.86</td>
<td>10.34</td>
<td>0.0</td>
<td>21.03</td>
</tr>
<tr>
<td>Dirac Fermion DM 100 GeV</td>
<td>9.88</td>
<td>1.17</td>
<td>2.52</td>
<td>25.99</td>
<td>0.0</td>
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<tr>
<td>GeV</td>
<td>30.49</td>
<td>3.59</td>
<td>1.96</td>
<td>3.96</td>
<td>7.99</td>
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<td>1000 GeV</td>
<td>20.31</td>
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<td>12.92</td>
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<td>GeV</td>
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<td>1.6</td>
<td>11.96</td>
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<tr>
<td>V1</td>
<td>18.06</td>
<td>0.17</td>
<td>0.06</td>
<td>13.34</td>
<td>1.72</td>
</tr>
<tr>
<td>100 GeV</td>
<td>24.86</td>
<td>1.45</td>
<td>0.44</td>
<td>7.57</td>
<td>4.57</td>
</tr>
<tr>
<td>V5</td>
<td>38.36</td>
<td>7.24</td>
<td>4.79</td>
<td>1.3</td>
<td>12.86</td>
</tr>
<tr>
<td>GeV</td>
<td>50.03</td>
<td>13.43</td>
<td>10.0</td>
<td>0.01</td>
<td>20.55</td>
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<tr>
<td>V11</td>
<td>19.73</td>
<td>0.43</td>
<td>0.06</td>
<td>12.46</td>
<td>2.13</td>
</tr>
<tr>
<td>1000 GeV</td>
<td>25.96</td>
<td>1.78</td>
<td>0.65</td>
<td>6.72</td>
<td>5.21</td>
</tr>
<tr>
<td>GeV</td>
<td>37.33</td>
<td>6.47</td>
<td>4.04</td>
<td>1.68</td>
<td>11.72</td>
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<tr>
<td>V11</td>
<td>54.48</td>
<td>16.14</td>
<td>12.42</td>
<td>0.13</td>
<td>23.85</td>
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</tbody>
</table>
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>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10 GeV</td>
<td>100 GeV</td>
</tr>
<tr>
<td>Complex Scalar DM</td>
<td>C1 &amp; C2</td>
<td>$1/\Lambda$</td>
<td>456</td>
</tr>
<tr>
<td></td>
<td>C3 &amp; C4</td>
<td>$1/\Lambda^2$</td>
<td>750</td>
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<tr>
<td></td>
<td>C5 &amp; C6</td>
<td>$1/\Lambda^2$</td>
<td>1621</td>
</tr>
<tr>
<td>Dirac Fermion DM</td>
<td>D1 &amp; D3</td>
<td>$1/\Lambda^2$</td>
<td>931</td>
</tr>
<tr>
<td></td>
<td>D2 &amp; D4</td>
<td>$1/\Lambda^2$</td>
<td>952</td>
</tr>
<tr>
<td></td>
<td>D1T &amp; D4T</td>
<td>$1/\Lambda^2$</td>
<td>735</td>
</tr>
<tr>
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<td>D2T</td>
<td>$1/\Lambda^2$</td>
<td>637</td>
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<tr>
<td></td>
<td>D3T</td>
<td>$1/\Lambda^2$</td>
<td>586</td>
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<tr>
<td></td>
<td>D5 &amp; D7</td>
<td>$1/\Lambda^2$</td>
<td>1058</td>
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<tr>
<td></td>
<td>D6 &amp; D8</td>
<td>$1/\Lambda^2$</td>
<td>978</td>
</tr>
<tr>
<td></td>
<td>D9 &amp; D10</td>
<td>$1/\Lambda^2$</td>
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</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>$M_{DM}^2/\Lambda_D^4$</td>
<td>1435</td>
<td>1442</td>
</tr>
</tbody>
</table>

**Complex Vector DM**
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
Complementarity of LHC and non-LHC DM searches
for the model with Vector Resonances, Top Partners and Scalar DM

\[ \text{TT} \rightarrow \text{t t DM DM} \]

QCD TT production only

\[ \frac{M_{TT}}{m_\phi} \]

\[ m_\phi \text{ [GeV]} \]

\[ \lambda_{\phi H} = 0 \]

- Green: LHC, no Z'
- Yellow: Xenon1T, \( \lambda_{\phi T' t} = 10 \)
- Blue: \( \Omega h^2 = 0.12, \lambda_{\phi T' t} = 0.3 \)
- Red: \( \Omega h^2 = 0.12, \lambda_{\phi T' t} = 0.5 \)
- Dark grey: \( \Omega h^2 = 0.12, \lambda_{\phi T' t} = 1.0 \)
- Light grey: \( \Omega h^2 = 0.12, \lambda_{\phi T' t} = 10 \)

arXiv: 1707.07000

Decoding the nature of DM