Review of the status and future prospects for dark matter searches at colliders

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Composition of the Universe

- What we are made of
- What we know about
- Insignificant? Do we matter?

- Dark matter
- Hydrogen & helium gas
- Stars etc
- Dark energy
Our place in the Universe

Copernicus: Earth is not the center of the Universe!
Our place in the Universe

Galileo: use of telescope, confirmed Copernican model, Jupiter has orbiting moons, Earth just another planet
Our place in the Universe

Hubble: each speck of light is another galaxy, our galaxy one of billions.
Our place in the Universe

We only make up 4% of the Universe

How did we come to know that the most common form of matter in the universe is ‘invisible’ to us?
Evidence for Dark Matter
how do we know its there?
Not enough mass

Fritz Zwicky
Rotation curves of galaxies

Vera Rubin

Observed

Expected
Gravitational lensing
Gravitational lensing

- foreground galaxy acts like gravitational lens
- bending of light from background galaxies to give multiple images

All experimental evidence for dark matter has come from observation of its gravitational influence:

- Can a modification of the laws of gravity explain this?
  OR
- Do we need to introduce a new form of matter?
Optical image from Magellan and Hubble

Optical + X-ray
hot gas detected by Chandra, containing most of normal matter

Optical + gravitational lensing
Most of the mass in the cluster, measured by gravitational lensing, shown in blue
Dark matter exists
What is it made of?
What properties should a DM candidate have?

- non-relativistic
- long lived
- interacts gravitationally
- no electric charge or color charge
The Standard Model

**Remarkably successful theory!**
Passed rigorous tests performed by decades of experiments

SM provides no candidate to explain the most common form of matter - no neutral, heavy, non-relativistic and long-lived particle
Weakly Interacting Massive Particles (WIMPs)

- Postulate a new species of elementary particles
- They are produced in the Big Bang and interact via: $\chi + \chi \leftrightarrow \text{SM} + \text{SM}$.
- As the universe expands and the temperature falls, they become diluted, and eventually can’t find each other, so they ‘freeze out’.
- Their relic density is measured by their interaction strength, inversely proportional to the annihilation cross-section ($<\sigma_A v>$).

Weakly interacting particles with weak-scale masses naturally provide the right relic abundance - “WIMP miracle”
Searches for dark matter
Searching for dark matter

- $\chi + \chi \rightarrow \text{SM} + \text{SM}$ is the only process important for determination of relic abundance

*All three approaches to detecting dark matter probing the same interaction*
Searching for dark matter

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Searching for dark matter

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Direct detection experiments

- Aim to observe recoil of dark matter off nucleus
- Typical recoil energy 1-100 keV
- Elastic scattering can be spin-dependent or spin-independent
Direct detection experiments: Status and challenges

WIMP-nucleon cross section
Challenges for direct detection experiments

- Low mass region difficult
- Collider does not have low energy threshold
Challenges for direct detection experiments

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- Much weaker sensitivity to Spin-dependent interactions.
- Collider has similar sensitivity to spin-dependent and spin-independent
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Irreducible neutrino background

WIMP discovery limit
Challenges for direct detection experiments

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- Irreducible neutrino background
- WIMP discovery limit

- Excesses observed by several experiments
  - Need independent verification from non-astrophysical expts
Searches at colliders
LHC can directly produce WIMP pairs

LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC cannot produce WIMPs

Searching for dark matter at colliders

Slide adapted from Tim Tait talk at Moriond
LHC can directly produce WIMP pairs

LHC cannot produce WIMPs

LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles
LHC can directly produce WIMP pairs

LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC cannot produce WIMPs

Supersymmetry
- symmetry between fermions and bosons
- heavy super-partners for each SM particle
- lightest SUSY particle (LSP) is neutral, stable. Good candidate for dark matter

Extra dimensions
- In UED, the dark matter candidate is a massive vector particle which is stable
- In Randall-Sundrum, the right-handed neutrino is stable

Theories designed to address the gauge hierarchy problem naturally
- predict stable, weakly interacting particles with mass ~ weak scale
- the correct relic abundance required to be dark matter.
LHC can produce heavier particles beyond the SM that decay to WIMP pairs and SM particles

LHC can directly produce WIMP pairs

LHC cannot produce WIMPs
Assumptions:
- DM particle is only new state accessible to the collider
- Effective field theory so interaction between DM and SM particles is contact interaction
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- Mediator can be integrated out

Phenomenology

Fermi 4-fermion contact interaction

Below the weak interaction scale

strength of interaction represented by $G_F$

$$M_{fi} = G_F g_{\mu\nu} [\bar{\psi} \gamma^\mu \psi][\bar{\psi} \gamma^\nu \psi]$$
Assumptions:
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**Phenomenology**

Fermi 4-fermion contact interaction

\[ u \quad g \quad \nu \]
\[ d \quad g \quad e^- \]

Below the weak interaction scale

After discovery of parity violation in 1957

**Equation**

\[ M_{fi} = \frac{G_F}{\sqrt{2}} g_{\mu\nu} [\bar{\psi} \gamma^\mu (1 - \gamma^5) \psi] [\bar{\psi} \gamma^\nu (1 - \gamma^5) \psi] \]
After discovery of $W$ boson........

$M_{fi} = \frac{g_{w}}{\sqrt{2}} \bar{\psi} \gamma^{\mu} (1 - \gamma^{5}) \psi \frac{g_{\mu \nu} - q_{\mu} q_{\nu}/M_{W}^{2}}{q^{2} - m_{W}^{2}} \frac{g_{w}^{2}}{M_{W}^{2}}$
Assumptions:
- DM particle is only new state accessible to the collider
- Effective field theory so interaction between DM and SM particles is contact interaction

\[ \mathcal{L} = \mathcal{L}_{SM} + i \bar{X} \gamma^\mu \partial_\mu X - M_X \bar{X}X + \sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} [\bar{X} \Gamma_{i}^{X} X] [\bar{q} \Gamma_{q}^{j} q], \]

Operators \( \Gamma \) describe scalar, pseudoscalar, vector, axial, vector, tensor interactions
DM neutral and weakly interacting, escape detection.
- only infer presence from imbalance in transverse momentum of all visible particles
- Search for DM particles recoiling off a jet/photon/X from the initial state
Signatures for dark matter searches: Mono-X

Mono-photon

Mono-jet

Mono-W

Mono-Z

Mono-top

Mono-Higgs
A monojet event

- one jet $p_T$ 900 GeV
- MET of 900 GeV

Missing transverse momentum
Monojet search
Monojet search

At the heart of all DM searches at colliders: Missing transverse energy (MET)

- challenging quantity to measure
- sensitive to mis-measurements, detector effects, backgrounds
- but well controlled
Collider limits comparable and complementary to direct detection experiments
Many different signatures employed to search for dark matter at LHC, will become especially important if signal is observed by collider/DD/DDID experiments.
DM at colliders phenomenology

From Tim Tait
Effective field theories

Simplified models

UV complete models

DM at colliders phenomenology

From Tim Tait

Can we meet in the middle?

Spectrum of Theory Space
Effective field theory

- Assume mediator heavy enough to be integrated out
- Use EFT operators to describe SM-DM interaction
- Pro: Limited number of degrees of freedom (interaction scale, DM mass).
- Con: Given energy scales being probed by collider, not always a valid assumption for us

Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286
Bai, Fox, Harnik, 1005.3797
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1008.1783
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1009.0008
Fox, Harnik, Kopp, Tsai, 1103.0240
Fortin, Tait, 1103.3289
Cheung, Tseng, Yuan, 1104.5329
Shoemaker, Vecchi, 1112.5457
Beyond EFT: Simplified models of dark matter

For Run-2: focus shifted to simplified models

EFT

Simplified model

SM → DM → SM

SM → DM → SM

arXiv:1403.4634
Minimal Simplified model of dark matter

Define simplified model with (minimum) 4 parameters

<table>
<thead>
<tr>
<th>Mediator mass ($M_{\text{med}}$)</th>
<th>DM mass ($M_{\text{DM}}$)</th>
<th>$g_q$</th>
<th>$g_{\text{DM}}$</th>
</tr>
</thead>
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DM

<table>
<thead>
<tr>
<th>Dirac fermion</th>
<th>Scalar - real</th>
</tr>
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<tbody>
<tr>
<td>Majorana fermion</td>
<td>Scalar - complex</td>
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Consider comprehensive set of diagrams for mediator

<table>
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<tr>
<th>Vector</th>
<th>Axial-vector</th>
</tr>
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<tbody>
<tr>
<td>Scalar</td>
<td>Pseudoscalar</td>
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Simplified models of dark matter

**VECTOR**

\[ g_{\text{DM}} Z'_\mu \bar{\chi} \gamma^\mu \chi \]

DD competitive

**AXIAL-VECTOR**

\[ g_{\text{DM}} Z''_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi \]

DD less sensitive

**SCALAR**

\[ g_{\text{DM}} S \bar{\chi} \chi \]

Yukawa style coupling (Mass based coupling)

complementarity with DD

**PSEUDOSCALAR**

\[ g_{\text{DM}} P \bar{\chi} \gamma^5 \chi \]

Yukawa style coupling (Mass based coupling)

No bounds from DD

Only Cosmic bounds exist
Beyond EFT : Simplified models of dark matter

For Run-2 : focus shifted to simplified models

With simplified models, several additional things come into play:
- Searches for the mediator itself
- Additional search signatures
- Enables a more equal footing comparison with direct detection experiments.

ATLAS-CMS Dark Matter Forum formed; to reach consensus on prioritised, benchmark set of simplified models for early Run2 searches
Elucidates more accurately the complementarity between collider and direct detection experiments
Complementarity between colliders and DD

arXiv:1407.8257, O. Buchmueller, M. Dolan, S. Malik, C. McCabe

Elucidates more accurately the complementarity between collider and direct detection experiments
Complementarity between colliders and DD

Scalar

Pseudoscalar

$M_{\text{med}}$

$g_q$

$g_\chi$

$g_{\chi}$

$g_q$

$M_{\text{med}}$
Complementarity between colliders and DD

Complementarity between collider and direct/indirect searches

- Fermi Large Area Telescope (Fermi-LAT) see a gamma-ray excess around the galactic center - generated much interest
- Mass and annihilation cross section required to explain excess consistent with WIMPs
- Large astrophysical uncertainties - need corroborative evidence from colliders or direct detection experiments
- Many models proposed to explain excess, common feature is pseudoscalar mediator (inaccessible to direct detection expts, gives suppressed spin-dependent interactions)
Complementarity between collider and direct/indirect searches

arXiv:1505.07826,
O. Buchmueller, S. Malik, C. McCabe, B. Penning

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<tr>
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<th>2012</th>
<th>2015-2016</th>
<th>~2020</th>
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<tr>
<td><strong>Energy</strong></td>
<td>8 TeV</td>
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</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>20 fb$^{-1}$</td>
<td>30 fb$^{-1}$?</td>
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Graphs showing different energy and luminosity levels.
Searches for mediator - constraints from dijet searches

- Dijet searches take out sizeable region of parameter space for low coupling
- If we open up decay channels of mediator to leptons etc, then dilepton searches also become relevant
Invisible Higgs searches

DM can couple to the Higgs sector; $H \rightarrow \chi\chi$
- Limits on branching fraction of Higgs to “invisible” particles used for limits on DM
- Limits only up to DM mass $M_\chi < M_H/2$

BF($H \rightarrow \text{invisible}$) < 0.58 @ 95% CL
assuming SM production cross section and kinematics
Invisible Higgs searches

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CMS-PAS-HIG-15-012
Future projections
## LHC scenarios

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<td><strong>Integrated luminosity</strong></td>
<td>20 fb(^{-1})</td>
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Future projections: direct detection experiments

XENON1T
- backgrounds 2 orders of magnitude lower than XENON100
- increase sensitivity by factor of 100
- expected to come online 2016

LZ: LUX-ZEPLIN
- increase sensitivity by factor of 100 compared to LUX
- expected to come online 2019

Next generation of direct detection experiments also expected to come online
Future projections: direct detection experiments
LHC - Run I

S.Malik et al.
arXiv:1409.4075

Axial vector

Vector

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LHC - Run 2

Axial vector

Vector

S. Malik et. al.
arXiv:1409.4075

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LHC - Run 2

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Axial vector

Vector
Colliders able to probe all the way up to and beyond neutrino barrier with HL-LHC

reach of next generation of DD expt
Studies on future projections with 14 TeV, High Luminosity LHC 3000 fb\(^{-1}\) show that we may be able to constrain BF(H\(_{125}\) \rightarrow\) invisible) at few-% level.
Summary

➡ Searches for Dark matter at collider:
- via UV complete models like SUSY
- via generic mono-X signatures
- Higgs invisible decays

➡ Interpretation of searches:
- Shift from effective field theory approach which has several limitations to simplified models
- Mediator also accessible to collider, can be constrained from other collider searches

➡ Complementarity with direct detection experiments
- low mass DM
- spin-dependent interactions of DM

➡ Future projections, similar complementarity between collider and DD experiments
- Collider can probe all the way upto and beyond neutrino floor for some DM models
- Exclude/confirm an excess in the direct/indirect detection experiments