Dark Matter searches with the ATLAS Detector

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Overview

Introduction to the ATLAS dark matter strategy

Searches for DM production

Mediator-based searches

The SM Higgs as a mediator

Making sense of it all

Conclusions
Background

WIMPs remain the “most popular” dark matter candidate.

- Generally expected that there should be some (small) interaction with SM particles.

For ~TeV masses and below, it should be possible to produce DM at the LHC.

- If the cross section isn't too small, we can measure this.
- Complements other methods, which can have limited sensitivity at lower DM masses and for some DM-nucleon scenarios.
Background

3 broad classes of DM models:

- **Effective Field Theories**
  - We don't know what the higher-scale physics is, but we can integrate it out.

- "**Simplified Models**"
  - We introduce a few additional degrees of freedom, but don't try to make statements about the complete theory.

- **Complete Theories**
  - We add a full set of new DoF's and expect them to explain everything (e.g. SUSY).
3 broad classes of DM models:

**Effective Field Theories**
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**Complete Theories**
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- EFTs often have validity issues at LHC energy scales.
- I'll focus mainly on simplified models.
- Typically require targeted model-specific searches. More details in the various ATLAS SUSY talks!
What ATLAS Can Do

We've collected ~140 fb\(^{-1}\) of \(pp\) collision data at 13 TeV.

- Most results so far use the first 36 fb\(^{-1}\) (2015+2016 data)
- Some results with all 140 fb\(^{-1}\) done, many more on the way!

We can reconstruct:

- Electrons
- Muons
- Photons
- Jets (i.e. quarks & gluons)
- MET (“Missing Transverse Energy”)
- Anything that decays into the above
ATLAS Strategy

ATLAS has a broad program of searches for dark matter.
- Specific strategies depend on the model in question.

We often consider “simplified models” with an additional mediator.
- These are intended as benchmarks for interpretation.
- Direct interactions with only SM particles are largely ruled out (except for the Higgs*).

* More on the Higgs mediator case later...
Depending on the model and its parameters, it's often easier to search for the mediator itself.

Jet + MET

\[ q \xrightarrow{g} g_{q} \xrightarrow{Z_{A}} g_{\chi} \xrightarrow{\chi} \bar{q} \]

Dijet Resonance

\[ q \xrightarrow{g} g_{q} \xrightarrow{Z_{A}} g_{\chi} g_{q} \xrightarrow{\chi} \bar{q} \]

Here, if \( g_{\chi} \) is small and \( g_{q} \) is large, then the best search method involves no DM at all!

ATLAS does both direct searches and mediator searches.
- This includes re-interpreting other analyses as mediator searches.
“Direct” Searches
LHC makes lots of jets, this is the most obvious place to look!

Jet required to boost the invisible system

Measure MET spectrum

Constrain W and Z backgrounds using lepton control regions

Many models produce this signature!

Latest result is with 36.1 fb$^{-1}$ (2015+2016 dataset).

Full Run-2 (140 fb$^{-1}$) analysis in the works!
Bosons + MET

\[
\begin{align*}
\text{MET} + \ldots & \quad \rightarrow \gamma \gamma \\
\gamma & \quad \text{Eur. Phys. J. C 77 (2017) 393} \\
& \quad \text{arXiv: 1704.03848} \\
& \quad 36.1 \text{ fb}^{-1} \\
Z & \quad \rightarrow \text{ll} \\
& \quad \text{Phys. Lett. B 776 (2018) 318} \\
& \quad \text{arXiv: 1708.09624} \\
& \quad 36.1 \text{ fb}^{-1} \\
W & \quad \rightarrow \text{qq} \\
& \quad \text{JHEP 10 (2018) 180} \\
& \quad \text{arXiv: 1807.11471} \\
& \quad 36.1 \text{ fb}^{-1} \\
H & \quad \rightarrow \text{bb} \\
& \quad \text{ATLAS-CONF-2018-039} \\
& \quad 80 \text{ fb}^{-1} \\
& \quad \rightarrow \text{YY} \\
& \quad \text{Phys. Rev. D 96 (2017) 112004} \\
& \quad \text{arXiv: 1706.03948} \\
& \quad 36.1 \text{ fb}^{-1}
\end{align*}
\]
Heavy Flavor + MET

Dedicated search for cases where the mediator couples preferentially to heavy-flavor quarks

  - Set limits on scalar/pseudoscalar models
Mediator Searches
Most obvious place to look for mediators is the dijet final state.

New 140 fb$^{-1}$ resonant result now public (ATLAS-CONF-2019-007)

Also, in previous results:
- Angular analysis for signals that aren't narrow resonances (Phys. Rev. D 96 (2017) 052004)
Dijets – Probing lower masses

Standard dijet search is limited to high masses by trigger thresholds.
→ We use 2 methods to access lighter mediators:

**Trigger-Level Analysis**

Save only trigger-level jet information to allow recording more events!

**Boosted dijet system**

The latest: photon+dijet with 80 fb$^{-1}$
- includes new b-tagged channel


One Run-2 result so far with 29.3 fb$^{-1}$


SM physics provides the boost, so the recoiling object is model-independent.

See also: jet+di-bjet with 80 fb$^{-1}$ (ATL-CONF-2018-052)
Dileptons

Search for generic resonances which couple to leptons.
- Not “traditionally” thought of as a DM mediator search, but easy to reinterpret.

**Electrons**

**Muons**

Explore dilepton spectrum from 250 GeV – 6 TeV
- Earlier versions have gone down to 80 GeV.
Top final states

Some models have the mediator preferentially coupling to top quarks.
- Interpret various top-related searches in terms of DM mediators.

\[ g_{\text{SM}} \]
\[ V \]
\[ g_{\text{SM}} \]

\[ u \rightarrow t \]
\[ u \rightarrow t \]

same-sign $t\bar{t}$

\[ g \rightarrow Z' \rightarrow t\bar{t} \]

$t\bar{t}$ resonance

4-top production

SUSY search re-interpreted in terms of non-minimal 2HDM mediator scenarios

**JHEP 12 (2018) 039**  
**36.1 fb\(^{-1}\)**

**36.1 fb\(^{-1}\)**

**JHEP 09 (2017) 088**  
**36.1 fb\(^{-1}\)**
Higgs As The Mediator
Higgs → Invisible

If DM couples directly to the Higgs and is lighter than \(~62\) GeV, then H can decay into pairs of DM particles.

- VBF is currently the most sensitive channel for this at LHC.

Leverage VBF topology (forward jets) to discriminate against large SM backgrounds.

Accepted by *Phys. Lett. B* (arXiv: 1809.06682)
Also search using W/Z associated production.

- **New combination with Run 1 + 2015 + 2016 data results!**

\[ \text{BR}(H \rightarrow \text{inv}) < 26\% \quad (17^{+7}_{-5} \% \text{ expected}) \]

Constraints weaker than Run 1 due to excesses in every Run 2 channel.

Full 140 fb\(^{-1}\) analyses in the works, with final combination to follow.

Higgs → Invisible

Sensitivity complements direct detection at low DM mass.

Note: We don't have any searches for DM over ~60 GeV with the SM Higgs as the mediator!
Putting It All Together
ATLAS's DM search program is really broad!

- To help navigate, we've interpreted all of these in terms of a few benchmark scenarios:

<table>
<thead>
<tr>
<th>(Pseudo)scalar mediator</th>
<th>(Axial) vector mediator</th>
<th>Extended Higgs sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral interaction</td>
<td>Color-neutral interaction</td>
<td>2HDM + Vector</td>
</tr>
<tr>
<td>Baryon-charged interaction</td>
<td>Color-charged</td>
<td>2HDM + Pseudoscalar</td>
</tr>
<tr>
<td>Flavor-changing interaction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For full details, see our new summary paper (arXiv:1903.01400, accepted by JHEP)
We've re-interpreted existing searches in terms of these models.

- Exclusion plots computed for a few representative parameter choices.
Axial Vector Models

Collider limits generally much stronger than direct detection for spin-dependent interactions!

Caveat: comparisons are model-dependent.

Shown here for DM-neutron interactions; protons look very similar.
This model aims to be a little less “simplified” / more realistic.

Results in 3 new physical scalars \((H, H^+, H^-)\), and 2 new pseudoscalars \((a, A)\).
Collider searches provide complementary coverage with respect to other methods (like direct detection).

ATLAS has a very broad dark matter search program!
- Includes searches for DM production as well as for mediators.
- Recently beginning to include less minimal models in our interpretations.

We recently released a new summary paper combining everything into a few benchmark interpretations.
- Intended as the definitive reference for dark matter at ATLAS.

We're continuing to produce new results with the Run 2 dataset!