Dark Matter searches with the ATLAS Detector

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on behalf of the ATLAS Collaboration

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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
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**
  - We don't know what the higher-scale physics is, but we can integrate it out.
  - EFTs often have validity issues at LHC energy scales.

- **“Simplified Models”**
  - We introduce a few additional degrees of freedom, but don't try to make statements about the complete theory.
  - I'll focus mainly on simplified models.

- **Complete Theories**
  - We add a full set of new DoF's and expect them to explain everything (e.g. SUSY).
  - Typically require targeted model-specific searches. More details in the various ATLAS SUSY talks!
ATLAS Strategy

ATLAS has a broad program of searches for dark matter.

- We often consider “simplified models” with an additional mediator*.

*The SM Higgs can be the mediator, more on this later.
“Direct” Searches
Jets + MET

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

- $\gamma$
- $Z \rightarrow ll$
- $W \rightarrow qq$
- $H \rightarrow bb$
- $\rightarrow YY$

**Results:**
- $36.1 \text{ fb}^{-1}$
- $36.1 \text{ fb}^{-1}$
- $36.1 \text{ fb}^{-1}$
- $80 \text{ fb}^{-1}$
- $36.1 \text{ fb}^{-1}$

**References:**
  - arXiv: 1704.03848
  - arXiv: 1708.09624
- JHEP 10 (2018) 180
  - arXiv: 1807.11471
- ATLAS-CONF-2018-039
- Phys. Rev. D 96 (2017) 112004
  - arXiv: 1706.03948
Heavy Flavor + MET

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

- Set limits on scalar/pseudoscalar models
Mediator Searches
Dijets

Most obvious place to look for mediators is the dijet final state.

New 140 fb\(^{-1}\) resonant result now public ([ATLAS-CONF-2019-007](https://atlas.cern.ch/Publications/CONF-2019-007))

![Dijet Diagram]

Also, in previous results:

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!

<table>
<thead>
<tr>
<th>$\sigma$</th>
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<tbody>
<tr>
<td>0.2</td>
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<tr>
<td>0.18</td>
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<tr>
<td>0.16</td>
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<tr>
<td>0.14</td>
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<td>0.12</td>
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<td>0.06</td>
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<td>0.04</td>
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<td>0.02</td>
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$\sqrt{s} = 13$ TeV

95% CL upper limits

<table>
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<th>ATLAS</th>
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<tr>
<td>3.6 fb$^{-1}$</td>
</tr>
<tr>
<td>29.3 fb$^{-1}$</td>
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</table>

$|y^*| < 0.3$

$|y^*| < 0.6$

Dijet Observed

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


**Boosted dijet system**

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


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.

Explore dilepton spectrum from 250 GeV – 6 TeV
- Earlier versions have gone down to 80 GeV.
Some models have the mediator preferentially coupling to top quarks.

- Interpret various top-related searches in terms of DM mediators.

same-sign $t\bar{t}$

$g_{SM}$

$V$

$t\bar{t}$ resonance

$\bar{q} q$

$Z'$

4-top production

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

**SUSY search results**

- JHEP 12 (2018) 039
  - arXiv: 1807.11883
  - $36.1 \text{ fb}^{-1}$

  - arXiv: 1804.10823
  - $36.1 \text{ fb}^{-1}$

- JHEP 09 (2017) 088
  - arXiv: 1704.08493
  - $36.1 \text{ fb}^{-1}$
Higgs As The Mediator
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.
Higgs \rightarrow\text{Invisible}

Also search using \textit{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.

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>
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For full details, see our new summary paper (arXiv:1903.01400, accepted by JHEP)
Vector Models

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 ($a$, $A$)
Future Prospects

Many of the flagship dark matter searches are becoming systematics-limited now.

- Jet+MET, VBF $H \rightarrow \text{invisible}$, etc.
- Taking full advantage of HL-LHC data will require improvements in reconstruction and analysis techniques (and in some cases, theoretical calculations).

A few DM searches automatically get a large benefit from statistics.

- Mainly channels which use EW or Higgs interactions (small cross sections)
- $Z(\rightarrow ll)H(\rightarrow \text{invisible}), H(\rightarrow \gamma\gamma)+\text{MET}$, etc.

We'll continue pursuing as broad a search program as we can through the end of the LHC lifetime.

- Have an interesting idea we haven't covered? Let us know!
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!