ATLAS Dark Matter Search

Tony Weidberg (Oxford) on behalf of the ATLAS Collaboration

Outline

• Introduction
  – Theory
  – Experiments
• ATLAS and LHC Run 2.
• ATLAS Searches
  – Explain principles
  – Example searches (not comprehensive)
  – pMSSM and direct DM searches
• Summary and outlook.
Dark Matter: Theory

• Convincing evidence for dark matter. Assume WIMP but no compelling WIMP theory \( \rightarrow \) model independent. Effective Field Theory (EFT) attractive.

• Example: Fermi 4 point interaction as approximation to W exchange.
  – Good if \( Q^2 << M_W^2 \) for low energy \( \nu \) scattering but not for W production at high energy, e.g. LHC.

• EFT reliable for direct dark matter searches but in general not appropriate for LHC for which \( Q^2 \) can be bigger than \( M(WIMP) \).

• Use many different simplified models. See arxiv/1507.0096
Dark Matter: Theory (2)

- Example simplified models:
  - V or A coupling to SM and DM
- $\chi$ are WIMPs $\Rightarrow$ don’t interact in detector.
- Different mediator spins possible.
- t-channel production also possible with spin-0 mediators.
  - Quarks could be b or t.
- SUSY: R parity conserving $\Rightarrow$ natural WIMP candidate, e.g. $\chi^0_1$
- Higgs portal
Dark Matter: Experiment

- Direct dark matter detection
- Annihilation dark matter
- Production WIMPS @ LHC
  - Weakly interacting $\Rightarrow$ doesn’t interact in detector $\Rightarrow$ apparent missing transverse momentum $E_T^{miss}$
- Complementarity.
Collider Searches (1)

• Use missing transverse momentum.
• Use Initial State Radiation (ISR)
  \( E_T^{\text{miss}} \)
  – Mono-X signatures
  – X can be, \( g, \gamma, W, Z \) etc.
• In some models (e.g. SUSY) complex cascades \( E_T^{\text{miss}} \)
  without ISR.
  – One of many possible examples shown.
Collider Searches (2)

- Can also search for DM mediator using resonant decays to SM.
- More indirect, but sensitive to DM in context of a particular model.
- e.g. Dijet resonance search, sensitive to DM mediator.
- Complementary to mono-X searches.
Backgrounds

- Reducible: Fake $E_T^{miss}$ from mismeasurements, mainly jets.
  - Reduce to very low level with cuts on $E_T^{miss}$ and event topology.
- Irreducible: $\nu$ don’t interact in detector $\Rightarrow$ real $E_T^{miss}$
- Many SM process give $\nu$
  - $Z \rightarrow \nu\nu, W \rightarrow l\nu, t \rightarrow bl\nu$
- Essential to estimate background accurately.
  - Define control regions (CR): background dominated, use to normalise MC prediction to data.
  - Use MC to extrapolate to signal region (SR) to predict background. Systematic errors tend to cancel.
ATLAS & LHC Performance

- **Superb performance of LHC in 2016.**
  - Luminosity > design.
  - $\mathcal{L}_{\text{max}} = 1.4 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1}$

- **High pile-up:**
  - Challenges for detector operation and analysis.
  - Low dead time
  - Detector live times ~ 99%

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**ATLAS Online Luminosity**

- $\sqrt{s} = 13 \, \text{TeV}$
- Total Delivered: 38.5 fb$^{-1}$
- Total Recorded: 35.6 fb$^{-1}$

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**ATLAS pp 25ns run: April-October 2016**

<table>
<thead>
<tr>
<th>Inner Tracker</th>
<th>Calorimeters</th>
<th>Muon Spectrometer</th>
<th>Magnets</th>
<th>Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>SCT</td>
<td>TRT</td>
<td>LAr</td>
<td>Tile</td>
</tr>
<tr>
<td>98.9</td>
<td>99.9</td>
<td>99.7</td>
<td>99.3</td>
<td>98.9</td>
</tr>
</tbody>
</table>
$E_T^{\text{miss}}$ Performance and pile-up

- $E_T^{\text{miss}}$ reconstructed from
  - high $p_T$ objects: leptons, $\gamma$, jets
  - Underlying event, soft particles

- Use tracks to minimise pile-up dependence “soft term”.

\[ \gamma s = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]
\[ \text{Data 2012, } Z \rightarrow \mu \mu \text{ Inclusive} \]
\[ E_T^{\text{miss}} \] Performance and pile-up

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Calorimeter

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]
Data 2012, \( Z \rightarrow \mu \mu \) Inclusive
Performance and pile-up

- $E_{T}^{\text{miss}}$ reconstructed from
  - high $p_T$ objects: leptons, $\gamma$, jets
  - Underlying event, soft particles

- Use tracks to minimise pile-up dependence “soft term”.

![Diagram showing $E_{T}^{\text{miss}}$ and its components: lepton, jet, and $E_{T}^{\text{miss}}$.]

Calorimeter

ATLAS
$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$
Data 2012, $Z\rightarrow\mu\mu$ Inclusive

Tracks

Data / MC

Number of Reconstructed Vertices ($N_{PV}$)

0 5 10 15 20 25 30 35 40

0.8 1.0 1.2

CST
TST
STVF
EJAF
Track
ATLAS Searches

- $\gamma + E_T^{miss}$
- $bb + E_T^{miss}$
- $tt + E_T^{miss}$
- Dijet resonances
- pMSSM search summary and DM
- Higgs portal:
  - $(H \rightarrow \gamma\gamma) + E_T^{miss}$ talk by Vivek Jain.
  - $(H \rightarrow bb) + E_T^{miss}$
- Others in backup
Mono-Photon Search

- Select $E_T^{\gamma} > 150\text{GeV}$
  (140 GeV @ single $\gamma$ trigger)
- Suppress $\gamma$+jet background with "fake" $E_T^{\text{miss}}$
  $\Delta\phi(\gamma, E_T^{\text{miss}}) > 0.4$
  $E_T^{\text{miss}} / \sqrt{\sum E_T} > 8.5\text{GeV}^{1/2}$
- Contributes less than 10% total background. Measured in CR
  $85 < E_T^{\text{miss}} < 110\text{GeV}$
  $\Delta\phi(\gamma, E_T^{\text{miss}}) < 3.0$
- MC extrapolation $\rightarrow$ SR

arxiv:1704.03848
SM Backgrounds

- SM processes with $\nu \rightarrow$ genuine $E_T^{miss}$
- Largest background is $(Z\rightarrow \nu\nu)+\gamma$.
- Use $Z\rightarrow l^+l^-\text{CR}$.
  - Remove leptons from reconstructed $E_T^{miss}$
- MC extrapolation $\rightarrow$ SR (BR, $\eta$ and $\varepsilon$)
- Other SM: $(W\rightarrow l\nu)+$jets.

2-muon CR: $E_T^{miss}$
Mono-Photon Results

- Different signal regions optimised for different masses $m_{\text{med}}$ and $m_\chi$.
- Fitted backgrounds compatible with data.

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ (GeV)</th>
<th>&gt; 150</th>
<th>&gt; 225</th>
<th>&gt; 300</th>
<th>150-225</th>
<th>225-300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>2400</td>
<td>729</td>
<td>236</td>
<td>1671</td>
<td>493</td>
</tr>
<tr>
<td>Background</td>
<td>2600 ± 160</td>
<td>765 ± 59</td>
<td>273 ± 37</td>
<td>1900 ± 140</td>
<td>501 ± 44</td>
</tr>
</tbody>
</table>

- Set improved limits for mediator and DM masses (more $\mathcal{L}$ and multi-bin fit).
- Use simplified model to compare with direct DM searches (limits in EFT also given).
Dark Matter-Mediator Limits

- **Axial vector**

- **Vector**

ATLAS

$\sqrt{s}=13 \text{ TeV, } 36.1 \text{ fb}^{-1}$

Axial-vector mediator
Dirac DM
$g_q=0.25, \ g_\chi=1, \ g_L=0$

Observed 95\% CL
Expected 95\% CL
Relic density

Vector mediator
Dirac DM
$g_q=0.25, \ g_\chi=1, \ g_L=0$

Observed 95\% CL
Expected 95\% CL
Relic density

PPC 2017

ATLAS Dark Matter
Comparison with direct DM

- **Axial Vector**
  - ATLAS
  - $\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$
  - Exclusion at 90% CL
  - Axial-vector mediator
  - Dirac DM
  - $g_q=0.25$, $g_x=1$

- **Vector**
  - ATLAS
  - $\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$
  - Exclusion at 90% CL
  - Vector mediator
  - Dirac DM
  - $g_q=0.25$, $g_x=1$
b-quarks + $E_T^{\text{miss}}$

- Spin-0 mediator coupling to SM and DM.
  - Assume Yukawa couplings mediator to SM fermions $\rightarrow$ search for $E_T^{\text{miss}} + 2$ b quarks.

- Backgrounds
  - Fake $E_T^{\text{miss}}$
  - Genuine $E_T^{\text{miss}}$ from SM: $Z \rightarrow \nu\nu$, $W \rightarrow l\nu$, $t \rightarrow b\nu$.

ATLAS CONF-2016-086
Signal & Backgrounds

• Similar approach to reject fake $E_T^{\text{miss}}$
  
  $E_T^{\text{miss}} > 150 \text{ GeV}$
  
  $\Delta \varphi^j = \Delta \varphi(jet_j,E_T^{\text{miss}})$ ; $\Delta \varphi_{\text{min}} = \min(\Delta \varphi^j) > 0.4$

• Select two tagged b-jets, veto 3$^{\text{rd}}$ jet (suppress $\bar{t}t$).

• Backgrounds
  – Fake $E_T^{\text{miss}}$
  – Genuine $E_T^{\text{miss}}$ from SM: $Z\rightarrow \nu\nu$, $W\rightarrow l\nu$, $t\rightarrow b\nu$.
  – Similar strategy of CR, VR and SR to determine backgrounds.
CR & SR

- Example CR: \((Z \rightarrow l^+ l^-)b\)
  - Treat \(l^\pm\) as \(\nu\)
  - Plot \(E_T^{\text{miss}}\)

- SR: imbalance between two b-jets and angular separation jets
  \[
  \text{Im}(b_1, b_2) = \frac{p_T(b_1) - p_T(b_2)}{p_T(b_1) + p_T(b_2)} > 0.5
  \]
  \[
  \min(\Delta R_{ij}) = \min \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} > 2.8
  \]
Results

- SR Observed

<table>
<thead>
<tr>
<th>Observed</th>
<th>33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Background</td>
<td>31.0 ± 0.6</td>
</tr>
<tr>
<td>W+jets</td>
<td>1.2 ± 0.8</td>
</tr>
<tr>
<td>Z+jets</td>
<td>22.6 ± 5.7</td>
</tr>
<tr>
<td>ttbar</td>
<td>4.7 ± 1.4</td>
</tr>
<tr>
<td>Single top</td>
<td>2.6 ± 1.1</td>
</tr>
</tbody>
</table>

- Place limits on $\sigma$ vs DM mediator mass for $M(DM) = 1$ GeV.

**Pseudoscalar**

- **Exp. ±1 $\sigma$**
- **Exp. ±2 $\sigma$**
- **Expected 95% CL**
- **Observed 95% CL**

$\chi \rightarrow bb, a \rightarrow \chi \chi$

$g = 1.0, \ m_{\chi} = 1$ GeV

$\sqrt{s} = 13$ TeV, $L_{int} = 13.3$ fb$^{-1}$
t-quarks + $E_T^{\text{miss}}$

- Spin-0 mediator coupling to SM and DM.
  - Search for $E_T^{\text{miss}} + t\bar{t}$
- Select large $E_T^{\text{miss}}$, topology and b-tagging.
- Backgrounds: genuine $E_T^{\text{miss}}$:
  - e.g. $t\bar{t}$, $t\bar{t} + (Z \rightarrow \nu\nu)$
- Example CR for $ttZ$ with $Z \rightarrow l^+l^-$. 
- No significant excess in SRs $\Rightarrow$ set exclusion limits

ATLAS-CONF-2017-046
Limits for Mediator and DM Mass

- Fix $m_\chi = 1$ GeV
- Limit on $\sigma$ vs $m_\phi$

Fix $m_\phi = 10$ GeV
Limit on $\sigma$ vs $m_\chi$

Similar limits for pseudo-scalar
Resonance Search for DM Mediators

- Search for bump in di-jet mass spectra
- Use Z’ mediator model.
- Complementary approaches
  - Di-jets + ISR: covers broader range at low mass [ATLAS-CONF-2016-070](https://atlas.cern.ch/Conf/2016/070/)
  - Di-jets: Trigger Level Analysis (TLA): most sensitive limits at intermediate mass. [ATLAS-CONF-2016-030](https://atlas.cern.ch/Conf/2016/030/)
- Looking for bumps on top of smooth mass spectra.
  - Also have non-DM interpretations
High Mass Di-jets

- High Mass:

  - ISR + di-jets

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**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 37.0 \text{ fb}^{-1} \)

- Data
- Background fit
- BumpHunter interval

\( q^*, m_{q^*} = 4.0 \text{ TeV} \)

\( q^*, m_{q^*} = 5.0 \text{ TeV} \)

\( p\text{-value} = 0.63 \)

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 3.4 \text{ fb}^{-1} \)

- Data
- Background fit
- BumpHunter interval

\( p\text{-value} = 0.44 \)

**ATLAS Dark Matter**
Limits from Di-jets

- Complementarity
  - dijets best at high mass
  - Dijet+ISR best at low mass.
- Use $\gamma$ and jet
- TLA better in intermediate mass region
DM Exclusion Summary

- Using s-channel exchange of DM mediator.
- Di-jets very sensitive to mediator mass but not to DM mass.
- Complementarity with DM production searches.
SUSY

- Many different searches targeting different regions of SUSY parameter space.
- Example search: $\tilde{g} \rightarrow q\bar{q} \chi_1^0$
- Combining 22 run 1 SUSY analysis: pMSSM.
- Allows comparison with direct DM searches.
- JHEP09 (2016) 175
pMSSM

- 19 parameter pMSSM
- Generate points in parameter space consistent with existing collider and direct DM search constraints.
- Project surviving models to regions in $\sigma$ vs DM mass
- Examine how many of these models are excluded by ATLAS run 1.
pMSSM

• 19 parameter pMSSM
• Generate points in parameter space consistent with existing collider and direct DM search constraints.
• Project surviving models to regions in $\sigma$ vs DM mass
• Examine how many of these models are excluded by ATLAS run 1.
Higgs Portal

- Dark matter production in association with Higgs.
- Simplified model.
  - 2HDM, DM production via $Z' \rightarrow hA, A \rightarrow \chi\chi$.
- Signature is $H + E_T^{miss}$.
  - This analysis: $H \rightarrow bb$ (see Vivek Jain’s talk for $H \rightarrow \gamma\gamma$).
  - b-tagging and $E_T^{miss}$ to reduce backgrounds.
- Discriminant variable: $m(bb)$
  - Look for peak at $m(H)$.

ATLAS-CONF-2017-028
Higgs portal: exclusion Limits

- Main backgrounds: $(Z \rightarrow \nu\nu)$+jets, W+jets, ttbar.
- No excess $\Rightarrow$ set limits in plane of masses of $A$ and $Z'$ assuming $m_\chi = 100$ GeV.
Summary and Outlook

- Many different searches targeting different dark matter models. No significant signals yet but powerful constraints in simplified models
  - Vector, axial vector, scalar mediators
  - Limits related to direct DM searches in $\sigma$ vs $M(WIMP)$ plane. Complementarity of collider and direct DM searches.
- Limits from pMSSM analysis from run 1 data.
- Hadron collider: more luminosity $\Rightarrow$ more reach in parton-parton energy. LHC has only acquired $\sim 1\%$ luminosity from full HL-LHC programme.
Backup Slides
Other DM Searches (1)


• Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at 13 TeV using the ATLAS detector *PRD* 94 (2016) 032005

• Search for dark matter produced in association with a hadronically decaying vector boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC ATLAS-CONF-2015-080

• Search for dark matter in events with heavy quarks and missing transverse momentum in pp collisions with the ATLAS detector *EPJC* 75 (2015) 92

• Higgs portal: see talk by Vivek Jain.
Other DM Searches (2)

• Search for dark matter in events with a Z boson and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector PRD 90, 012004 (2014)

• Search for dark matter in events with a hadronically decaying W or Z boson and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector PRL 112, 041802 (2014)

• Search for dark matter pair production in events with a hadronically decaying W or Z boson and missing transverse momentum in pp collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector ATLAS-CONF-2013-073
pMSSM

• Constraints: LEP, precision EW, DM searches ...
• Assumptions (e.g. R-parity conservation) reduced MSSM to 19 parameter space.
• $5 \times 10^8$ models considered with flat sampling.
• $3 \times 10^3$ models satisfied pre-ATLAS constraints.
• 40.9% of models excluded by ATLAS run 1.
• DM cross sections scaled: DM searches assume WIMP saturates relic density but LSP might be only one of several contributors to DM.

\[ R_\Omega = \frac{\Omega(\tilde{\chi}_1^0)h^2}{\Omega_{\text{Planck}}h^2} \]

• [JHEP 10 (2015) 134](#)
MET Resolution 2016

ATLAS Preliminary

Data 2016, \( \sqrt{s} = 13 \text{ TeV} \)

\[ Z \rightarrow \text{ee}, \ 8.5 \text{ fb}^{-1} \]

0 jets, \( p_T > 20 \text{ GeV} \)

Number of primary vertices \( N_{PV} \)

Data

\[ Z(\rightarrow \text{ee}) \text{ MC} \]
Contact Interactions

- cf Fermi theory and SM

\[ G_F = \frac{\sqrt{2}}{8} \frac{g_w^2}{M_W^2} \]

- 4 point interaction valid for \( q^2 \ll M_W^2 \)