Search for dark matter candidates produced in $Z(\ell\ell) + E_T^{\text{miss}}$ events with the ATLAS detector at the LHC

Kayla McLean

Puzzle of Dark Matter Conference
DESY, Hamburg, Germany
October 29-31, 2018
Searching for dark matter in the ATLAS detector

- The LHC has been delivering 13 TeV proton-proton collisions to the ATLAS detector since 2015
  - Analysis of the full 2015-2018 Run 2 dataset (149 fb$^{-1}$) has started and is ongoing
  - This talk will cover results with the 2015+2016 dataset with integrated luminosity = 36.1 fb$^{-1}$

Invisible dark matter will manifest in the missing transverse momentum, $\vec{E}_T^{miss}$
Signal models

• The dark matter models studied are coordinated by the LHC Dark Matter Working Group
• For this particular analysis we study “mono-Z” events with $Z(\ell\ell) + E_T^{\text{miss}}$ final states ($\ell\ell = ee$ or $\mu\mu$)

\begin{itemize}
\item \textbf{s-channel simplified models} \\
\textbf{“Standard” benchmark DM model in Run 2}
\item \textbf{Two-Higgs-doublet + pseudoscalar model} \\
Newer benchmark, more theoretically complete
\item \textbf{t-channel simplified models} \\
To be studied
\end{itemize}
Event selection

- Event selection criteria are optimized to isolate potential signal events with large $E_T^{\text{miss}}$ recoiling against $Z \rightarrow \text{ee}$ or $Z \rightarrow \mu\mu$, while also reducing backgrounds.

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Background reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exactly one $\ell\ell$ ($= \text{ee or } \mu\mu$) pair with opposite charge</td>
<td></td>
</tr>
<tr>
<td>Veto events with 3rd lepton (e or $\mu$) with $p_T &gt; 7$ GeV</td>
<td>$WZ$</td>
</tr>
<tr>
<td>$Z$ mass window: $76 &lt; m_{\ell\ell} &lt; 106$ GeV</td>
<td>$WW/WT/tt/Z(\tau\tau)$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 90$ GeV</td>
<td>$Z+\text{jets}$</td>
</tr>
<tr>
<td>$\Delta R(\ell\ell) &lt; 1.8$</td>
<td>$Z+\text{jets}$, $WW/WT/tt/Z(\tau\tau)$</td>
</tr>
<tr>
<td>$\Delta\phi(Z,E_T^{\text{miss}}) &gt; 2.7$</td>
<td>$Z+\text{jets}$, $WW/WT/tt/Z(\tau\tau)$</td>
</tr>
<tr>
<td>$</td>
<td>p_T(\ell\ell) -</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/H_T &gt; 0.6$ ($H_T = p_T(\text{jets}) + p_T(\ell_1) + p_T(\ell_2)$)</td>
<td>$Z+\text{jets}$</td>
</tr>
<tr>
<td>b-jet veto</td>
<td>$tt$</td>
</tr>
</tbody>
</table>
### Backgrounds

- **Standard Model ** **background processes** **also produce** \(Z(\ell\ell)+E_T^{\text{miss}}\), **mimicking** the DM signal of interest

<table>
<thead>
<tr>
<th>Background</th>
<th>Source</th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ZZ)</td>
<td>(ZZ \rightarrow \ell\ell\nu\nu, \text{irreducible})</td>
<td>MC</td>
</tr>
<tr>
<td>(WZ)</td>
<td>(WZ \rightarrow \ell\nu\ell^+\ell^-)\n(\ell) \text{from} (W) not reconstructed</td>
<td>Data (yield), MC (shape)</td>
</tr>
<tr>
<td>(Z+\text{jets})</td>
<td>(Z(\text{ee}) / Z(\mu\mu) + \text{jets})\njets mis-measured as fake (E_T^{\text{miss}})</td>
<td>Data (yield), MC (shape)</td>
</tr>
<tr>
<td>(W/\text{top})</td>
<td>(WW / Wt / tt / Z(\tau\tau) \rightarrow \ell^+\nu\ell^-\nu)\n(\ell\ell) \text{do not come from} a (Z)</td>
<td>Data</td>
</tr>
<tr>
<td>(W+\text{jets})</td>
<td>(W(\ell\nu) + \text{jets})\n(\ell) \text{mis-identified from a jet})</td>
<td>Data</td>
</tr>
<tr>
<td>(ttV/\text{ttVV/VVV}\ (V=Z,W))</td>
<td>e.g. (ttW \rightarrow (\ell^+\nu b)(q_1q_2b)(\ell^-\nu))</td>
<td>MC</td>
</tr>
</tbody>
</table>
• Perform **statistical analysis** on signal region

• Inputs: observed data, background estimates, all sources of systematic errors

• Small overall excess in $\mu\mu$ channel => **worse observed limits** compared to expected

• Since **no significant excess** is observed, we set **limits** using the $CL_s$ method
Simplified model mass exclusion limits (axial-vector)

ATLAS
\( \gamma S = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)
Axial-vector, Dirac, \( g_q = 0.25, g_\chi = 1.0 \)
\( ee+\mu\mu \)

LO
PT limit
\( m_{\chi} = 2m_\gamma \)

NLO

Expected limit (±1\sigma)
Observed limit
Relic density

\( m_\chi \text{ [GeV]} \)
0 50 100 150 200 250 300 350 400

\( m_{\text{med}} \text{ [GeV]} \)
0 100 200 300 400 500 600 700 800 900

ATLAS Preliminary
\( \gamma S = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)
Axial-vector, Dirac, \( g_q = 0.25, g_\chi = 1.0 \)
\( ee+\mu\mu \)

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ATLAS-CONF-2018-051

10/30/18
Kayla McLean (UVic)
Simplified model mass exclusion limits (vector)

ATLAS
\( \bar{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)
Vector, Dirac, \( g_q = 0.25, g_\chi = 1.0 \)
ee+\( \mu \mu \)

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ATLAS Preliminary
\( \bar{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)
Vector, Dirac, \( g_q = 0.25, g_\chi = 1.0 \)
ee+\( \mu \mu \)

ATLAS-CONF-2018-051

10/30/18
Kayla McLean (UVic)
Mono-$Z(\ell\ell)$ limits compared to direct detection expts

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV, } 36.1 \text{ fb}^{-1} \]
Axial-vector, Dirac
\[ g_\text{q} = 0.25, \ g_\chi = 1.0 \]

- Black line: Observed 90% CL
- Green line: LUX 2013+2014-16
- Blue line: PICO-2L 2016
- Red line: PICO-60 2017

\[ \sigma_{SD} (\chi\text{-proton}) \text{ [cm}^2\text{]} \]

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV, } 36.1 \text{ fb}^{-1} \]
Vector, Dirac
\[ g_\text{q} = 0.25, \ g_\chi = 1.0 \]

- Black line: Observed 90% CL
- Cyan line: CRESST-II 2015
- Pink line: CDMSlite 2015
- Green line: PandaX-II 2016
- Blue line: LUX 2013+2014-16
- Red line: XENON1T 2017

\[ \sigma_{SI} (\chi\text{-proton}) \text{ [cm}^2\text{]} \]

**Axial-vector (LO)**

**Vector (LO)**

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Mono-\(Z(\ell\ell)\) limits compared to other ATLAS searches

\[ m_{Z'} \text{ [TeV]} \]

\[ m_{\chi} \text{ [TeV]} \]

All limits at 95\% CL

**Axial-vector mediator, Dirac DM**
- \( g_q = 0.25, g_0 = 0, \ g_\chi = 1 \)

ATLAS Preliminary

**Vector (NLO)**
- \( g_q = 0.25, g_0 = 0, \ g_\chi = 1 \)

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• Mono-$Z(\ell \ell)$ one of the most sensitive channels in the 2HDM+a model studied

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Conclusions

• Overview of the analysis and results with 36.1 fb\(^{-1}\) (2015+16) has been presented

• Work is ongoing in the mono-\(Z(\ell\ell)\) analysis towards unblinding the full dataset = 149 fb\(^{-1}\)
  • **More DM models** to be studied
    • In addition to simplified models, pursue models with diagrams unique to mono-\(Z\)
      (2HDM+a, \(t\)-channel, \(\ldots\))
  • **Signal region optimization**
    • New object-based \(E_T^{\text{miss}}\) significance – better discriminating power for events with fake \(E_T^{\text{miss}}\)
      (see Dilia’s mono-\(H(bb)\) talk later today)
  • New **background estimation** techniques being studied
    • \(Z\gamma\) data-driven estimate of \(ZZ\) background
    • \(\gamma+\text{jet}\) data-driven estimate of \(Z+\text{jet}\) background
  • More potential for discovery than ever before!
Invisible Higgs limits

- Look for deviations in SM $BR(H\rightarrow ZZ\rightarrow 4\nu) = 1.06\times10^{-3} = 0.1\%$

- **At most** the branching ratio is 67% or else we would have seen something… at the 95% confidence level

- Small data excess in $\mu\mu$ channel => **worse observed** upper limits compared to expected

<table>
<thead>
<tr>
<th>Obs. $B_{H\rightarrow inv}$ Limit</th>
<th>Exp. $B_{H\rightarrow inv}$ Limit ±1σ ±2σ</th>
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<tbody>
<tr>
<td>ee 59%</td>
<td>(51 $^{+21}<em>{-15}$ $^{+49}</em>{-24}$) %</td>
</tr>
<tr>
<td>$\mu\mu$ 97%</td>
<td>(48 $^{+20}<em>{-14}$ $^{+46}</em>{-22}$) %</td>
</tr>
<tr>
<td>ee + $\mu\mu$ 67%</td>
<td>(39 $^{+17}<em>{-11}$ $^{+38}</em>{-18}$) %</td>
</tr>
</tbody>
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