Searches for Dark Matter with the ATLAS detector

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Deep Inelastic Scattering 2017, Birmingham
Motivation

Why search for 'dark matter'? 
- strong evidence from several observations: rotational velocities in spiral galaxies, galaxy clusters, bullet cluster...
- cosmic microwave background: \( \sim 26\% \) of universe made up by dark matter

What is dark matter?
- at least gravitational interaction, at most weak interaction with SM sector
- stable on cosmological time scale

⇒ focus on WIMP model for dark matter: weakly interacting, massive (non relativistic), stable

→ production at colliders possible
Dark Matter Searches at the LHC

How to look for dark matter?

WIMPs can only be recognised as $E_T$ at the LHC: need a recoiling object: jets, $W/Z$, $\gamma$, Higgs boson

- event signatures denoted as **Mono-X**:  
  - jet $+ E_T$  
  - $\gamma$ $+ E_T$  
  - $W/Z$ $+ E_T$  
  $\leftrightarrow$ different decay modes

- Higgs $+ E_T$  

$\leftrightarrow$ different decay modes

$\leftrightarrow$ Higgs directly involved in WIMP production

- dark matter+heavy flavour production:

- di-jet resonant production:
  mediator can also decay to quarks
Strategy: search for an abundance of events with high $E_T$, a high $p_T$ jet and 0 leptons

- at most four jets ($p_T > 30$ GeV)
- $E_T > 250$ GeV
- leading jet $p_T > 250$ GeV

- control regions defined to estimate $W/Z+$jets background: lepton veto inverted, $E_T$ defined to mimic $p_T(W/Z$-boson)

- simultaneous fit to $E_T$: $\rightarrow E_T$-dependent scale factors for background normalisation

- dominant background: $Z(\nu\nu)+$jets: normalised via $W(\mu\nu)+$jets scale factor, theory transfer uncertainty applied in signal region
No excess found: limit on dark matter production via $Z'$-like mediator:

$\leftrightarrow$ axial-vector coupling with $g_\chi = 1.0$ and $g_q = 0.25$

$\leftrightarrow$ derivation of scattering cross section limit: ATLAS constraint competitive for low DM masses
Monophoton Search \((36.1 \text{ fb}^{-1})\)  

**Brand NEW Link**

Similar to monojet: instead of high energetic jet, require high energetic photon

- 1 isolated photon with \(p_T > 150\) GeV, no leptons
- \(E_T > 150\) GeV, at most one jet with \(p_T > 30\) GeV
- combination of data-driven methods and MC
- fit to \(E_T\): \(W/Z\gamma\) backgrounds scale factors
- Dominant background \(Z(\nu\nu)\gamma\) normalised by \(Z(\ell\ell)\gamma\) scale factors
Monophoton Search (36.1 fb$^{-1}$)

Use binned fit to $E_T$-distribution to interpret results in terms of DM models:

Axial-vector mediator

Effective Theory: $\gamma\gamma\chi\chi$ interaction

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

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

Preliminary
ATLAS
=13 TeV, 36.1 fb$^{-1}$

EFT model
$\gamma\gamma\chi\chi$

→ analysis sensitivity dominated by statistical uncertainty in control regions
Mono-\(V(\rightarrow\text{hadrons})\) Search (3.2 fb\(^{-1}\))

Search for \(W/Z+\not{E}_T\) with hadronically decaying \(W/Z\)

\(\rightarrow\) analysis similar to monojet search but with focus on \textbf{large-}R \textbf{jets}

- require \textbf{large-}R \textbf{jets}: both decay products of \(W/Z\) contained \((R = 1.0, \text{anti-}\kappa_t)\)
  \(\rightarrow\) substructure described by jet mass and \(D_2\) (two distinct energy concentrations)

- \(p_T(\text{large-}R \text{ jet}) > 200 \text{ GeV, } |\eta| < 2.0, \not{E}_T > 250 \text{ GeV}\)

- no leptons allowed

- dominant background \(Z(\nu\nu)+\text{jets}\)
  \(\rightarrow\) normalised via \(Z(\mu\mu)+\text{jets}\) estimation
Background-prediction in agreement with data: limits are set on effective field theory and simplified models:

\[ \int L = 3.2 \text{ fb}^{-1} \quad \sqrt{s} = 13 \text{ TeV} \]

\[ VV\chi\chi \text{ EFT} \]

\[ \text{Observed} \quad \text{Expected} \]

\[ \begin{array}{c}
\text{± 1σ} \\
\text{± 2σ}
\end{array} \]

\[ \text{ATLAS} \]

\[ \text{95\% C.L. lower limit on } M \]

\[ \begin{array}{c}
200 \\
400 \\
600 \\
800 \\
1000
\end{array} \quad \begin{array}{c}
\text{GeV}
\end{array} \]

\[ \text{Observed} \quad \text{Expected} \]

\[ \sigma \quad 1\pm\sigma \\
2\pm\text{ATLAS} \]

\[ \text{L=3.2 fb}^{-1} \quad \int = 13 \text{ TeV} \]

\[ E_{T}^{\text{miss}} + W/Z: \text{vector model} \]

\[ g_{SM} = 0.25, \quad g_{DM} = 1 \]

\[ \text{95\% C.L. upper limit on } \mu \]

\[ \begin{array}{c}
10^{-2} \\
10^{-1} \\
10^0
\end{array} \quad \begin{array}{c}
10
\end{array} \]

\[ \text{ATLAS} \]

\[ \int L = 3.2 \text{ fb}^{-1} \quad \sqrt{s} = 13 \text{ TeV} \]

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\[ \text{95\% C.L. upper limit on } \mu \]

\[ \begin{array}{c}
10^{-2} \\
10^{-1} \\
10^0
\end{array} \quad \begin{array}{c}
10
\end{array} \]

\[ \text{main limitations: statistics, modelling of large-}R\text{ jet observables} \]
Signature: opposite sign leptons and $E_T$

- require $E_T > 90$ GeV, boosted $Z$-boson with $\Delta R(\ell\ell) < 1.8$, $b$-veto
- dominant background: $ZZ \rightarrow \ell\ell\nu\nu$ production
- differential $m_{ZZ}$ cross section corrected to NNLO QCD and NLO EW calculation
- $WZ$ background normalized to NNLO QCD and fitted in control regions with 3 leptons
- $Z$+jets background data driven, non resonant background from $e\mu$ control regions
- $Z$+jets uncertainty dominates
- limit on vector mediator in simplified model of WIMP production
Mono-Higgs, \( H \to \gamma \gamma \) (13.3 fb\(^{-1}\))

ATLAS-CONF-2016-087

Higgs involved in WIMP production:

- different models: coupling to heavy mediator \( Z' \), coupling to \( Z' \) and pseudo-scalar \( A^0 \) (2HDM)
  - two photons with \( p_T > 25 \) GeV, \( 105 < m_{\gamma \gamma} < 160 \) GeV
  - categories in \( E_T / \sqrt{\sum E_T} \) and \( p_T^{\gamma \gamma} \)
    \( \rightarrow \) highest sensitivity to vector mediator \( (Z'_B) \) for high \( E_T / \sqrt{\sum E_T} \)
    and \( p_T^{\gamma \gamma} \)
  - background in \( m_{\gamma \gamma} \) fitted with exponential function+double sided crystal ball (Higgs resonance)
  - signal (crystal ball) fitted to \( 0 \rightarrow \) upper cross section limits as function of heavy mediator masses derived

Higgs ISR suppressed due to Yukawa coupling
Mono-Higgs, $H \rightarrow bb$ (36.1 fb$^{-1}$)  

Brand NEW Link

Search similar to mono-$H(\rightarrow \gamma\gamma)$: final state now with $b$-jets

- **resolved** region: two distinct $b$-jets, $E_T < 500$ GeV
- **merged** region: $E_T > 500$ GeV: boosted Higgs $\rightarrow$ large-$R$ jet with substructure
- shape-fit to $m_{jj}$ or $m_J$ in different categories of $E_T$ and $\# b$-jets, two dedicated control regions
- main backgrounds: $W/Z+\text{jets}$, $t\bar{t}$
- dominant uncertainty: $b$-tagging, luminosity, JES, jet mass
DM+Heavy Flavour Searches (13.3 fb$^{-1}$)

Searches for $b\bar{b} + E_T$ and $t\bar{t} + E_T$ production:
¬ sensitive to *(pseudo-*)scalar mediator

- **DM+bb**: ATLAS-CONF-2016-086
  ¬ exactly two $b$-jets, 3rd jet veto, no leptons
  ¬ dominant background $Z(\nu\nu) + b$ reduced by cut requiring separated $b$-jets, momentum imbalance
  ¬ 3 CR, $Z(\nu\nu) + b$ constrained from $Z(\ell\ell) + b$

- **DM+tt**: ATLAS-CONF-2016-077, ATLAS-CONF-2016-050, ATLAS-CONF-2016-076
  ¬ 0-leptons, 1-lepton or 2-leptons channels
  ¬ many signal regions defined with help of different variables: $E_T / \sqrt{H_T}, m_T$, razor variables...
  ¬ dominant background is SM $t\bar{t}$ production: estimated in control regions
Limits shown on **pseudo-scalar** mediator models (similar to scalar mediator):

**bb + E_T**

**tt + E_T**

*similar sensitivities*
Search for resonance in di-jet invariant mass spectrum

- see talk by Hanno Meyer zu Theenhausen (Wed. 2 pm)
- limits are set on excited quarks $q^*$, quantum black holes, $W', Z', W^*$, generic Gauss-shaped resonances
- in context of simplified models: limit on coupling $g_q$ to standard model particles as a function of the mediator mass $m_{Z'}$
Combining dark matter searches in terms of simplified models with an axial-vector mediator model:

- **Dijet**: \( \sqrt{s} = 13 \text{ TeV}, \ 37.0 \text{ fb}^{-1} \), [arXiv:1703.09127 [hep-ex]]
- **Dijet 8 TeV**: \( \sqrt{s} = 8 \text{ TeV}, \ 20.3 \text{ fb}^{-1} \), Phys. Rev. D. 91 052007 (2015)
- **Dijet TLA**: \( \sqrt{s} = 13 \text{ TeV}, \ 3.4 \text{ fb}^{-1} \), ATLAS-CONF-2016-030
- **Dijet + ISR**: \( \sqrt{s} = 13 \text{ TeV}, \ 15.5 \text{ fb}^{-1} \), ATLAS-CONF-2016-070
- **E_T^{miss} + \gamma**: \( \sqrt{s} = 13 \text{ TeV}, \ 36.4 \text{ fb}^{-1} \), CERN-EP-2017-044
- **E_T^{miss} + jet**: \( \sqrt{s} = 13 \text{ TeV}, \ 3.2 \text{ fb}^{-1} \), JHEP 06 (2016) 059

Axial-vector mediator, Dirac DM
\[ g_q = 0.25, \ g_l = 0, \ g_{DM} = 1 \]
All limits at 95% CL
Combination of Exclusions II

With less 'optimistic' coupling to standard model quarks: $g_q = 0.1$:

→ dilepton results shown, coupling suppressed: $g_\ell = 0.01$
Combination of Exclusions III

Limit on spin-dependent WIMP-proton scattering cross section:

\[
\begin{array}{cccc}
\text{DM Mass [GeV]} & 1 & 10 & 2 \\
\text{σ_{SD} (DM-proton) [cm}^2] & 10^{-42} & 10^{-41} & 10^{-40} \\
\end{array}
\]

ATLAS Simplified Model Exclusions

Preliminary March 2017

ATLAS

- Dijet TLA
  - \( \sqrt{s} = 13 \text{ TeV}, 3.4 \text{ fb}^{-1} \)
  - ATLAS-CONF-2016-030
- Dijet 8 TeV
  - \( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)
- Dijet
  - \( \sqrt{s} = 13 \text{ TeV}, 37.0 \text{ fb}^{-1} \)
  - arXiv:1702.07666v1 [hep-ex]
- PICO-60 C\textsubscript{3}F\textsubscript{8}
  - \( \sqrt{s} = 13 \text{ TeV}, 36.4 \text{ fb}^{-1} \)

Axial-vector mediator, Dirac DM

\( g_q = 0.25, g_l = 0, g_{DM} = 1 \)

ATLAS limits at 95% CL, direct detection limits at 90% CL
Summary and Outlook

- a variety of dark matter searches carried out throughout 2015 and 2016 data taking
  - many new results, many new results to come soon with full 2015+2016 data set

- interpretations focused on simplified models: dark matter production via heavy mediator
  - model dependent approach
  - complementary sensitivity compared to direct dark matter searches
  - constraints from di-jet resonance searches

- no evidence for dark matter found so far
  - stay tuned for new results with 3-10× increased data sets
BACKUP
Monophoton Search (36.1 fb\(^{-1}\))

Similar to monojet: instead of high energetic jet, require high energetic photon

- 1 isolated photon with \( p_T > 150 \) GeV, no leptons
- \( \slashed{E}_T > 150 \) GeV, at most one jet with \( p_T > 30 \) GeV
- 4 control regions to estimate \( W/Z\gamma \) and \( \gamma + \)jets background: use low-\( \slashed{E}_T \) region
- fake photon estimation data-driven: ABCD method for jets faking \( \gamma \), \( Ze\gamma/Zee \) ratio measurement for \( e \) faking \( \gamma \)

Simultaneous fit in control regions and signal regions to \( \slashed{E}_T \): independent normalisation factors per \( \slashed{E}_T \)-bin for \( W/Z\gamma \) backgrounds

Dominant background \( Z(\nu\nu)\gamma \) normalised by \( Z(ll)\gamma \) scale factors
require large-$R$ jets: both decay products of $W/Z$ contained ($R = 1.0$, anti-$k_t$)
$\rightarrow$ substructure described by jet mass and $D_2$ (two distinct energy concentrations)

$P_T$ (large-$R$ jet) $> 200$ GeV, $|\eta| < 2.0$, $E_T > 250$ GeV, $\Delta\phi(E_T, \text{narrow jet}) > 0.6$

no leptons

dominant background $Z(\nu\nu)+\text{jets}$
$\rightarrow$ three control regions defined
$\rightarrow$ simultaneous fit to $E_T$-distribution performed: single normalisation factors for $W/Z+\text{jets}$, $t\bar{t}$ backgrounds
$\rightarrow$ $Z(\nu\nu)+\text{jets}$ normalised with $Z(\mu\mu)+\text{jets}$ scale factor
Search for resonance in di-jet invariant mass spectrum

- background completely data-driven: *sliding window fit* with \( f(x) = p_1(1 - x)^p_2 x^{p_3} \)
- limits are set on excited quarks \( q^* \), quantum black holes, \( W' \), \( Z' \), \( W^* \)
- limits are also set on generic Gauss-shaped resonances with mass \( m_G \) (truth level)
- in context of simplified models: limit on coupling \( g_q \) to standard model particles as a function of the mediator mass \( m_{Z'} \)

### Observed 95% CL upper limit

<table>
<thead>
<tr>
<th>Mass (TeV)</th>
<th>Observed 95% CL upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.30</td>
</tr>
<tr>
<td>2.0</td>
<td>0.25</td>
</tr>
<tr>
<td>2.5</td>
<td>0.20</td>
</tr>
<tr>
<td>3.0</td>
<td>0.15</td>
</tr>
<tr>
<td>3.5</td>
<td>0.10</td>
</tr>
</tbody>
</table>

### Expected 95% CL upper limit

- \( \sigma / m_G = 0.15 \)
- \( \sigma / m_G = 0.10 \)
- \( \sigma / m_G = 0.07 \)
- \( \sigma / m_G = 0.03 \)
- \( \sigma / m_G = 0 \)