Searches for Dark Matter mediators with the ATLAS Detector

Peter McNamara
On behalf of the ATLAS Collaboration
Dark Matter searches at the LHC use simplified models
• Production of Dark matter goes via a mediator

Resonance searches are complimentary to these direct DM searches
• Look for mediators decaying into quarks (dijet resonance)
Dijet Searches

QCD predicts smoothly falling dijet invariant mass ($m_{jj}$)
- New mediator decaying to jets will introduce a bump

Benchmark Leptophobic $Z'$ model parameters
- Axial-vector (or vector) mediator ($Z'$)
- Coupling to quarks - $g_q$ (universal)
- Coupling to leptons - $g_\ell = 0$ (leptophobic)
- Coupling to dark matter – $g_{DM}$
- Mediator mass - $m_{Z'}$
- Dark matter mass - $m_{DM}$

See Sébastien Rettie’s talk for dilepton resonance searches
Limits are dependent on a number of factors

- More Events Recorded
- Higher collision energies
- Lower trigger thresholds
Baseline Dijet Search

Selections are applied to

- Reduce backgrounds (y* rapidity difference)
- Ensure trigger and selection efficiency

Estimate background from sliding window fit using

\[ f(z) = p_1 (1-z)^{p_2} z^{p_3} \]

\[ z = m_{jj} / \sqrt{s} \]

Search for excess with bumphunter algorithm

### Selections

<table>
<thead>
<tr>
<th>Selections</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Jet pT</td>
<td>&gt; 440 GeV</td>
</tr>
<tr>
<td>Second Jet pT</td>
<td>&gt; 60 GeV</td>
</tr>
<tr>
<td>( m_{jj} )</td>
<td>&gt; 1.1 TeV</td>
</tr>
<tr>
<td>(</td>
<td>y^*</td>
</tr>
</tbody>
</table>

**Limit on axial vector Z' quark coupling**

Probing Lower Masses

How do you access lower masses?

Trigger Level Analysis (TLA)
Lower the trigger threshold by reducing amount of data saved per event, keep only trigger level objects

Initial State Radiation (ISR) Selection
Examine a boosted signature by requiring an ISR photon or jet to pass the trigger threshold
First stage hardware trigger identifies jets using coarse calorimeter information.

Second stage software trigger then reconstructs jets using the same algorithm as offline jets (anti $k_t$).

Limited bandwidth so high threshold required to save entire event.

Save only trigger jets:
- Small size
- Higher rate
- Similar bandwidth

Hardware trigger threshold requires offline jet $p_T > 220$ GeV.

Software trigger threshold requires offline jet $p_T > 440$ GeV.

- $40$ MHz Collision Rate
- $\sim 3$ kHz
- Save only trigger jets ($<0.5\%$ size)
- $\sim 30$ Hz
- Save data from entire detector

**ATLAS** Trigger Operations

$\sqrt{s} = 13$ TeV

Peak luminosity: $4 \times 10^{33}$ cm$^2$ s$^{-1}$ From single run

- Red: Data Scouting chain seeded by L1_J75
- Green: Rate of j360 (lowest unprescaled trigger)
Jet energies are calibrated similarly to offline jets (Eur. Phys. J. C 76 (2016) 581)

**Calibration Steps:**
- **Jet-area based pileup correction**
  - Applied as a function of event pileup $p_T$ density and jet area only
- **Absolute MC-based calibration**
  - Corrects the jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated
- **Global sequential calibration**
  - Reduces flavor dependence and energy leakage using calorimeter variables only
- **Eta intercalibration**
  - Corrects the scale of forward jets in data to that of central jets, using the $p_T$ balance ratio between data and simulation, applied only to data
- **Trigger-to-offline data-derived correction**
  - Corrects trigger-level jets to the scale of offline jets, applied only to data

**Residual in-situ calibration**
- Derived for offline jets
- Derived specifically for trigger jets

Calibrate using momentum balance of offline jets against well calibrated objects
- Needs to be smooth as can introduce bumps
- Use polynomial fit in log($p_T$) rather than spline

After calibration energy of trigger and offline jets agree within 0.05%

Jet energy scale uncertainty is 1-2%, similar to that of offline jets
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- Eta intercalibration: Corrects the scale of forward jets in data to that of central jets, using the $p_T$ balance ratio between data and simulation.
- Trigger-to-offline data-derived correction: Corrects trigger-level jets to the scale of offline jets, applied only to data.

Residual in-situ calibration:
- A smooth residual calibration is derived by fitting in-situ measurements and applied only to data.
- Derived specifically for trigger jets.

Calibrate using momentum balance of offline jets against well calibrated objects:
- Needs to be smooth as can introduce bumps.
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After calibration energy of trigger and offline jets agree within 0.05%

Jet energy scale uncertainty is 1-2%, similar to that of offline jets
Two selections based on trigger threshold target different mass ranges

Fit background and look for bumps

Set Bayesian limit

<table>
<thead>
<tr>
<th>Selections</th>
<th>HW 75 GeV Trigger (3.6 fb⁻¹)</th>
<th>HW 100 GeV Trigger (29.3 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Jet pT</td>
<td>&gt; 185 GeV</td>
<td>&gt; 220 GeV</td>
</tr>
<tr>
<td>Second Jet pT</td>
<td>&gt; 85 GeV</td>
<td>&gt; 85 GeV</td>
</tr>
<tr>
<td>$m_{jj}$</td>
<td>&gt; 450 GeV</td>
<td>&gt; 700 GeV</td>
</tr>
<tr>
<td>$</td>
<td>y^*</td>
<td>= 0.5</td>
</tr>
</tbody>
</table>

Limit on axial vector Z' coupling

arxiv: 1804.03496
Add energetic ISR photon or jet to signature to allow better sensitivity to light resonances

- satisfies the trigger threshold
- allows lower masses to be examined
- reduced production rates

**Selections**

<table>
<thead>
<tr>
<th>ISR Photon</th>
<th>ISR Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISR Object</td>
<td>&gt; 150 GeV</td>
</tr>
<tr>
<td>First (Second) Jet $p_T$</td>
<td>&gt; 25 GeV</td>
</tr>
<tr>
<td>Second (Third) Jet $p_T$</td>
<td>&gt; 25 GeV</td>
</tr>
<tr>
<td>$</td>
<td>y^*</td>
</tr>
</tbody>
</table>
Boosted ISR Dijet Search

ISR selection has allowed masses down to 200 GeV to be examined
• Targets regime where jets from the mediator are separated
• To go lower examine a larger single jet instead

To reduce pileup and soft radiation effects, large radius jets are trimmed
• Reclustered with smaller radius using kt algorithm
• Removed if smaller clusters if carry < 5% of total jet pT

Use jet substructure to reduce background and select the signal

Signal has two particles in the jet vs one for the background

- $\tau_N$ is a measure of jet’s compatibility with having $N$ subjets
- $\tau_{21} = \tau_2 / \tau_1$ discriminates between jets due to one particle and two

However, $\tau_{21}$ is correlated with the large radius jet’s mass ($m_j$)

Use designated decorrelated tagger method

$$\rho^{DDT} \equiv \log \left( \frac{m_j^2}{p_T \times \mu} \right)$$

Define $\tau_{21}^{DDT}$, a linearly corrected version of $\tau_{21}$

Now independent of jet mass
## Boosted ISR Dijet Search

### Signal Region Selections

<table>
<thead>
<tr>
<th>Selection</th>
<th>ISR Photon</th>
<th>ISR Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISR Object pT</td>
<td>&gt; 155 GeV</td>
<td>&gt; 420 GeV</td>
</tr>
<tr>
<td>Large Radius Jet pT</td>
<td>&gt; 200 GeV</td>
<td>&gt; 450 GeV</td>
</tr>
<tr>
<td>$\Delta \phi$(Large Jet, photon/jet)</td>
<td>&gt; $\pi/2$</td>
<td></td>
</tr>
<tr>
<td>Large jet momentum</td>
<td>&gt; 2 x the jet mass</td>
<td></td>
</tr>
<tr>
<td>$c_{DDT}^{21}$</td>
<td>&lt; 0.5</td>
<td></td>
</tr>
<tr>
<td>$\rho_{DDT}$</td>
<td>&gt; 1.5</td>
<td></td>
</tr>
</tbody>
</table>

Probes Z' masses down to 100 GeV

**arxiv: 1801.0876**
Specific final state quarks

Specific searches for resonances with pairs bottom or top quarks in the final dijet resonance

For lower mediator masses
Excludes masses up to 1.02 TeV ($g_q=0.1$)

For higher mediator masses
Excludes masses up to 2.1 TeV ($g_q=0.25$)
assumes only $Z' \rightarrow bb$

70% b-tagging efficiency

85% b-tagging efficiency

EXOT-2016-33

See Siyuan Sun’s talk for details
Specific searches for resonances with pairs bottom or top quarks in the final dijet resonance

See Siyuan Sun’s talk for details

Search for top quark pairs

Vector Mediator

\[ g_q = 0.25 \]

\[ g_{DM} = 1 \]

\[ g_{\ell} = 0 \]

Axial vector Mediator

Excludes masses up to 1.4 TeV

Excludes masses up to 1.2 TeV

arxiv: 1804.10823
Dijet Summary

ATLAS Preliminary April 2018

\( \sqrt{s} = 13 \text{ TeV}, 3.6-37.0 \text{ fb}^{-1} \)

95% CL upper limits
- Observed
- Expected

Axial vector mediator
Dirac Dark Matter
\( m_{DM} = 10 \text{ TeV} \)

\(|y_{12}| < 0.3\)
\(|y_{12}'| < 0.6\)

Baseline Dijet

Large-\(R\) jet + ISR, 36.1 fb^{-1}
arXiv: 1801.08769

Dijet + ISR (\(\gamma\)), 15.5 fb^{-1}
ATLAS-CONF-2016-070

Dijet + ISR (jet), 15.5 fb^{-1}
ATLAS-CONF-2016-070

Dijet TLA, 3.6-29.7 fb^{-1}
arXiv: 1804.03496

Dijet, 37.0 fb^{-1}
Summary

\( g_q = 0.25 \quad g_{DM} = 1 \quad g_\zeta = 0 \)

\( g_q = 0.1 \quad g_{DM} = 1 \quad g_\zeta = 0.01 \)

Not updated for latest TLA and ISR results

See Sébastien Rettie’s talk

See Young-Kee Kim’s talk

Summary

\[ g_q = 0.25 \quad g_{DM} = 1 \quad g_\gamma = 0 \]

\[ g_q = 0.1 \quad g_{DM} = 1 \quad g_\gamma = 0.01 \]

Not updated for latest TLA and ISR results
ATLAS has an extensive program of searches for dark matter mediators in run 2

- Complementarity between dedicated searches for mediators and dark matter candidates

Searches for mediators with dijets in run 2 are examining:

- **Lower couplings** thanks to a large number of recorded events
- **Higher masses** thanks to higher collision energies
- **Lower masses** thanks to new experimental techniques
  - *Trigger level analysis* extending to *lower masses and low couplings*
  - *ISR search* extends search to *lower masses*
  - *Boosted ISR* further extends search to *even lower masses*

Searches cover all mediator masses between 100 GeV and 3.5 TeV

Looking forward to the full run 2 results
**Summary**

- $g_q = 0.25$  
- $g_{DM} = 1$  
- $g_{\ell} = 0$

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**DM Simplified Model Exclusions**

- **ATLAS Preliminary July 2017**

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For further reading:
- See Sébastien Rettie’s talk
- See Young-Kee Kim’s talk
Translation to DD plane

\[
\sigma_{SI} \approx 6.9 \times 10^{-41} \text{ cm}^2 \cdot \left( \frac{g_q g_{DM}}{0.25} \right)^2 \left( \frac{1 \text{ TeV}}{M_{med}} \right)^4 \left( \frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2
\]

\[
\sigma^{SD} \approx 2.4 \times 10^{-42} \text{ cm}^2 \cdot \left( \frac{g_q g_{DM}}{0.25} \right)^2 \left( \frac{1 \text{ TeV}}{M_{med}} \right)^4 \left( \frac{\mu_{n\chi}}{1 \text{ GeV}} \right)^2
\]

\[
\mu_{n\chi} = \frac{m_n m_{DM}}{m_n + m_{DM}}
\]

Arxiv: 1603.04156
$g_q = 0.25$  \hspace{1cm}  $g_{DM} = 1$  \hspace{1cm}  $g_\gamma = 0$

---

$g_q = 0.1$  \hspace{1cm}  $g_{DM} = 1$  \hspace{1cm}  $g_\gamma = 0.1$

---

Not updated for latest TLA and ISR results
**Summary**

\[
g_q = 0.25 \quad g_{DM} = 1 \quad g_\gamma = 0
\]

\[
g_q = 0.1 \quad g_{DM} = 1 \quad g_\gamma = 0.1
\]

---

Not updated for latest TLA and ISR results
Uses (at trigger level)

- Energy fraction in Electromagnetic Calorimeter
- Energy fraction in Hadronic Calorimeter
- Minimum number of Calorimeter cells which contain 90% of the jet energy

No track based variables available
Correction factor applied to trigger-level jets using the \( p_T \) response between trigger-level and offline jets split by \( \eta \) and \( p_T \) of the jet.

Data 2016, \( \sqrt{s} = 13 \text{ TeV} \)
anti-\( k_t \), \( R = 0.4 \), EM+JES + relative \textit{in situ} correction

ATLAS
Data 2016, \( \sqrt{s} = 13 \) TeV
anti-\( k_t \), \( R = 0.4 \), EM+JES + in situ correction
\( \eta = 0.0 \)

- Total Uncertainty, Trigger
- Total Uncertainty, Offline
- Absolute in situ JES, fitted
- Relative in situ JES
- Trigger Flav. composition, dijet events
- Trigger Flav. response, dijet events
- Trigger Pileup, average 2016 conditions
- Trigger data-derived correction
Fit over mjJ performed in a sliding window to estimate background

Three functions are used to fit to the data

- Final function used has best chi squared over the full range
- Systematic uncertainty uses alternate function

$|y^*| < 0.6$ (0.3) uses first (second) function

$$f(x) = p_1 (1 - x)^{p_2 x^{p_3} + p_4 ln x + p_5 ln x^2}$$

(ISR)

$$f(x) = p_1 (1 - x)^{p_2 x^{p_3} + p_4 ln x}$$

$$f(x) = \frac{p_1}{x^{p_2}} e^{-p_3 x - p_4 x^2}$$
Control region inverts $\tau_{21}^{DDT}$ selection

- Background estimated in SR using transfer factor
- Method Validated on W/Z peak

Largest (systematic) uncertainty is from the transfer factor
- 90% for $M_{Z'}$ of 160 GeV
\[ BG = TF \times (\text{Number in CR} - \text{Expected number from production with an associated vector boson}) \]

Transfer factor = expected ratio of events which pass \( \tau_{21}^{DDT} \) to those which fail

- Data measured away from Z’ mass under consideration (20% buffer)
- Parameterised by \( \log(\text{Large radius jet } pT / \mu) \) and \( \rho^{DDT} \)
Boosted ISR - Uncertainty

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta\mu/\mu$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m_{Z'} = 160$ GeV</td>
</tr>
<tr>
<td>Transfer factor</td>
<td>90</td>
</tr>
<tr>
<td>Large-$R$ jet</td>
<td>25</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>93</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>10</td>
</tr>
</tbody>
</table>
Boosted ISR - mj Shape

Boosted requirement of large jet momentum > 2 x the jet mass results in altered slope

Large Radius Jet $p_T$ > 200 GeV > 450 GeV
Leptophobic Z’

\[ \mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{X} \gamma^\mu X - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q, \]

\[ \mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{X} \gamma^\mu \gamma^5 X - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q. \]