Dark Matter searches with the ATLAS Detector

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DIS Kobe
18.04.18

on behalf of the ATLAS Collaboration
DM signatures

Gravitational: ✓
Electromagnetic: ✗
Strong: ✗
Weak-strength: ?
How to search for them

Direct detection

Indirect detection

Collider production

Collider: how do we search for nothing?
Option 1: require something to happen!

We can see this

Which also allows us to notice this as $p_T^{\text{miss}}$

“Mono-X searches”

In a hadron collider, “SM” initial state = quarks and gluons
ATLAS mono-X / associated production

### mono-X Dataset

<table>
<thead>
<tr>
<th>mono-X</th>
<th>Dataset</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>jet</td>
<td>36.1 fb⁻¹</td>
<td>JHEP 01 (2018) 126</td>
</tr>
<tr>
<td>Z (→ ℓℓ)</td>
<td>36.1 fb⁻¹</td>
<td>PLB 776 (2017) 318</td>
</tr>
<tr>
<td>W/Z (→ qq)</td>
<td>3.2 fb⁻¹</td>
<td>PLB 763 (2016) 251</td>
</tr>
<tr>
<td>h (→ bb)</td>
<td>36.1 fb⁻¹</td>
<td>PRL 119 (2017) 181804</td>
</tr>
<tr>
<td>h (→ γγ)</td>
<td>36.1 fb⁻¹</td>
<td>PRD 96, 112004 (2017)</td>
</tr>
<tr>
<td>Z' (→ qq)</td>
<td>36.1 fb⁻¹</td>
<td>ATLAS-CONF-2018-005</td>
</tr>
</tbody>
</table>

### Associated production

<table>
<thead>
<tr>
<th>Associated production</th>
<th>Dataset</th>
<th>Reference</th>
</tr>
</thead>
</table>

scalar mediator, 3rd-gen couplings
Option 2: dark matter? What dark matter?

If there is a mediator that couples to quarks and DM...

...then we can forget about the DM and look for the mediator

“Dijet* resonance searches”

*One can also imagine the Z’ coupling to leptons -> dilepton resonances, lower BR to dijet
Dijet limits on Z’, at end of run 1

Model has **four parameters**:

1. Mediator coupling to quarks $g_q$ (usually assumed universal, but dijets ignore Z’ $\to$ tt)
2. Mediator mass $m_{Z'}$
3. Dark Matter mass $m_{DM}$ - set well above 0.5 $m_{Z'}$ (eg 10 TeV) -> kinematically inaccessible
4. Mediator coupling to Dark Matter, $g_{DM}$ - not very relevant given 3, often set to 1

$$g_B = 6g_q$$

**References:**

Prescaled* triggers (with extensive use of delayed stream**)

Axial vector mediator
Dirac DM, $m_{DM} = 10$ TeV

Lower coupling $g_q$ for given mass $m_{Z'}$:
more data ($\sigma \sim g_q^2 \Rightarrow \text{limit}(g_q) \sim \text{data}^{1/4}$), better mass resolution

Higher bottom mass edge to exclusion: trigger limitations

* Prescaled: only a fraction of events accepted by a trigger are recorded
** Delayed stream: events accepted by some triggers are written to a separate stream that is not reconstructed until computing resources become available over a shutdown
What limits the ATLAS trigger?

Limitations:
- detector readout
- total: storage & processing cost
- single jet: competing demands

Higher instantaneous luminosity -> higher rate of high-$p_T$ jet production

=> with rising instantaneous luminosity, must raise jet $p_T$ threshold for recording events

- Empirical observation: at high $p_T$ (>100 GeV or so), rate $\sim p_T^{-5}$
- 2016: record events containing jets with $E_T > 380$ GeV -> efficient by $p_T > 440$ GeV in analysis

* 25ns bunch spacing gives 40 MHz, but the ring is not full
• ATLAS has preliminary results (ATLAS-CONF-2016-070) using photon and jet using initial state radiation to trigger on => resonance can be much lower $p_T$ (lead resonance jet $p_T > 25$ GeV, vs 440 GeV)

• At $Z'$ masses below ~ 200 GeV, resonance jets merge -> large-R jet
Quick overview: Large-R + ISR

- Use substructure $\tau_{21}$ to distinguish 2-subjet signal from single-subjet QCD background
- Use “designed decorrelated tagger” method to decorrelate from jet mass
- Main background QCD
  - Data-driven method for background estimation based on inverted $\tau_{21}^{DDT}$
  - Method validated on W/Z peak
  - Separate signal region for each mass point

**ATLAS Simulation**
\( \sqrt{s} = 13 \text{ TeV} \)

Jet channel

- Bkg., 500 < $p_T^j$ < 700 GeV
- Sig., 500 < $p_T^j$ < 700 GeV
- Bkg., 700 < $p_T^j$ < 900 GeV
- Sig., 700 < $p_T^j$ < 900 GeV
- Bkg., 900 < $p_T^j$ < 1300 GeV
- Sig., 900 < $p_T^j$ < 1300 GeV

**ATLAS**
\( \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \)

Jet channel

- Data
- Background est.
- W/Z + jets
- $Z'$ (160 GeV)
- Bkg. stat. uncert.
- Bkg. stat. ⊕ syst.

Data / est.

- 0.98
- 0.99
- 1
- 1.01
- 1.02

Events / GeV

- 10
- 10^3
- 10^6
- 10^9
- 10^12
Dijet (merged & resolved) + ISR limits

ATLAS Preliminary March 2018
\(\sqrt{s} = 13\) TeV, 3.6-37.0 fb\(^{-1}\)

95\% CL upper limits

- **Observed**
- **Expected**

- 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, 20.3 fb\(^{-1}\) 8 TeV
- Dijet, 37.0 fb\(^{-1}\)

**ISR -> sensitivity down to 200 GeV**

200 GeV = crossover between merged and resolved

**Large-R jet -> takes this down to 100 GeV**
Dijet (merged & resolved) + ISR limits

Requiring ISR reduces signal cross-section -> lower sensitivity than pure dijet
2: Revisit trigger limitations

- 30\(^*\) MHz
- L1: \(~100\ kHz\)
- HLT: \(~1.5\ kHz\)

Limitations:

- Total: storage & processing cost
- Single jet: competing demands

**Storage and processing drives 1.5 kHz limit for ATLAS**

- Dijet resonance search only uses jets - no leptons, no p\(T\)\(_{\text{miss}}\), etc.
- We already build and calibrate jets in the trigger... just save these
- Record minimal events at high rate

* 25ns bunch spacing gives 40 MHz, but the ring is not full

\(~20-40\ Hz\) single jet
Evade trigger bandwidth limits

**ATLAS Trigger Operation**

**HLT Stream Rates (with overlaps)**

*pp Data July 2016, √s = 13 TeV*

**LHCb: “Turbo stream” [1]**

**CMS: “Data Scouting” [2]**

**ATLAS: “Trigger Level Analysis”**

(arXiv: 1804.03496, April 11th!)

Huge TLA rate but tiny bandwidth since ~0.5% of full event size

Instead of 20-40 Hz for a dijet resonance search, we now have 1-3 kHz!

jump: sometimes recorded more TLA data once the luminosity had fallen

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The payoff

"standard"

dijet

TLA

lead jet $p_T > 440$

sublead jet $p_T > 60$

$m_{jj} > 1100$

$4 \times 10^7$ events in first bin

in 29.3 fb$^{-1}$ of 2016 data

$\sqrt{s} = 13$ TeV, 29.3 fb$^{-1}$

$|y^*| < 0.6$

ATLAS Preliminary

Data 2016

Data 2015

$|y| < 2.8$

Offline central jet $p_T$ [GeV]

3.0

2.5

2.0
**TLA calibration**

**EM-scale jets**
Jet finding applied to topological clusters at the electromagnetic scale

**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**
A smooth residual calibration is derived by fitting in-situ measurements and applied only to data

- Write out sufficient information to be able to redo calibration offline
- Some parts rederived since TLA data lacks eg track information
- End result: excellent agreement between offline and recalibrate trigger $mjj$

---

**ATLAS**
$\sqrt{s}=13$ TeV, 29.3 fb$^{-1}$
$|y^*| < 0.6$
Background estimation

- Fit to functional form
  - Choose one with best $\chi^2$
- Very large number of events -> very little scope for QCD to deviate from functional form
- In 2015, could not fit whole $m_{jj}$ range, hence truncated fit at 1250 GeV
- Solution, also used by high-mass dijet 37 fb$^{-1}$ result: fit sub-ranges
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\[
\begin{align*}
    f(x) &= p_1(1 - x)^p_2x^p_3 \\
    f(x) &= p_1(1 - x)^p_2x^p_3 + p_4 \ln x \\
    f(x) &= p_1(1 - x)^p_2x^p_3 + p_4 \ln x + p_5 \ln x^2 \\
    f(x) &= \frac{p_1}{x^p_2} e^{-p_3x - p_4x^2}
\end{align*}
\]

ATLAS
\[\sqrt{s} = 13\text{ TeV}, 29.3\text{ fb}^{-1}\]
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Data

Fit window

Fit for this bin

animation here
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$$f(x) = p_1 (1 - x)^{p_2} x^{p_3} + p_4 \ln x$$
$$f(x) = p_1 (1 - x)^{p_2} x^{p_3} + p_4 \ln x + p_5 \ln x^2$$
$$f(x) = \frac{p_1}{x^{p_2}} e^{-p_3 x - p_4 x^2}$$

ATLAS
√s=13 TeV, 29.3 fb$^{-1}$
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- In 2015, could not fit whole $m_{jj}$ range, hence truncated fit at 1250 GeV
- Solution, also used by high-mass dijet 37 fb$^{-1}$ result: fit sub-ranges
  - $|y^*|<0.3$: 27 bins, $|y^*|<0.6$: 19
Results

• “BumpHunter” with background-only fit: no significant excesses found

• Signal + Background fit: set limits (areas of flexibility give observed - expected differences)

• Similar sensitivity to conventional dijet resonance search at 1.5 TeV

• Can go much lower in m_{Z'}:
  • 450-700 GeV using dedicated signal region with L1_J75 for some of 2016
Trigger-level analysis greatly improves sensitivity

New results mean that we surpass pre-LHC constraints everywhere
Prospects, TLA

- 2017/8: improve calibration of trigger jets, take advantage of unused L1 rate towards end of fill to run new triggers allowing lower masses to be probed (J50 vs J75/J100)
- Run 3: improve reconstruction of L1 objects with new hardware => can probe lower mass for given rate
- Run 3: FTK -> full tracking at HLT -> pileup rejection possible -> can go well below 85 GeV

ATLAS Preliminary April 2018

$\sqrt{s} = 13$ TeV, 3.6-37.0 fb$^{-1}$

ATLAS Trigger Operation

HLT Stream Rates (with overlaps)

pp Data July 2016

$\sqrt{s} = 13$ TeV

ATLAS-CONF-2016-070

$\gamma$, 15.5 fb$^{-1}$

arXiv: 1804.03496

Dijet TLA, 15.5 fb$^{-1}$

arXiv: 1801.08769

10 TeV, 3.6-37.0 fb$^{-1}$

ATLAS-CONF-2016-070

$\gamma$, 15.5 fb$^{-1}$

arXiv: 1804.03496

Dijet, 37.0 fb$^{-1}$


ATL-DAQ-PUB-2017-003
**Prospects, resolved dijet + ISR**

- $g_q$ limit scales as data$^{1/4}$ => 15.5 to 120 fb$^{-1}$ = factor 1.7
- Higher instantaneous luminosity -> higher trigger thresholds, mitigated by improved jet trigger performance
- Combinatorics in jet channel can improve mass reach and sensitivity
- Potential for TLA technique in run 3 with FTK
Prospects, merged dijet + ISR

- $g_q$ limit scales as $\text{data}^{1/4} \Rightarrow 37$ to 120 fb$^{-1} = \text{factor 1.3}$
- New trigger strategies for large-R, including substructure information in the trigger (2017 has mass, run 3 will have more) => much more data
- Optimised grooming methods ATL-PHYS-PUB-2017-020 => better S/B
- Also improvements in jet substructure resolution thanks to track information in jet reconstruction inputs ATL-PHYS-PUB-2017-015

More details on substructure in Jason Veatch's WG4 talk yesterday
Complementarity between DM searches

DM Simplified Model Exclusions

ATLAS Preliminary July 2017

DM Mass [TeV]

0

0.5

1

1.5

2

2.5

3

Mediator Mass [TeV]

Axial-vector mediator, Dirac DM

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

All limits at 95% CL

Caveats:
- plot is ~ 1 year old, doesn’t include latest TLA, large-R+ISR or mono-X results

mono-X and resonance searches complement each other
Complementarity between DM searches

Caveats:
- plots are ~ 1 year old, don’t include latest TLA, large-R+ISR or mono-X results
- very model-dependent (eg non-zero lepton coupling causes large changes)

other channels (eg dilepton resonance) cover other model scenarios
Complementarity between DM searches

- plots are ~ 1 year old, don’t include latest TLA, large-R+ISR or mono-X results
- very model-dependent (eg non-zero lepton coupling causes large changes)
- DD limits 90% CL, collider 95%

also complementarity with direct detection
Conclusions

• Broad set of approaches to searching for Dark Matter with ATLAS

• Various new techniques being exploited to go lower in mass
  • Initial state radiation to evade trigger limitations
  • Substructure to take this into the merged regime
  • Borrowing methods from LHCb and CMS to make the best use of jet trigger system and do a dijet analysis with partial events

• New methods can all take advantage of LS2 trigger upgrades for sensitivity scaling much better than integrated luminosity alone

• Can also help with significant computing and storage pressures in the future
Backup
New: mono-$Z'$

ATLAS-CONF-2018-005, April 4th

Dark Fermion

Dijet resonance + MET

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Dark-fermion model</th>
<th>Dark-Higgs model</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_{X_1} = 5 GeV</td>
<td>m_{X} = 5 GeV</td>
<td></td>
</tr>
<tr>
<td>Light dark sector</td>
<td>m_{X_2} = m_{X_1} + m_{Z'} + 25 GeV</td>
<td>m_{h_D} = \begin{cases} m_{Z'} , m_{Z'} &lt; 125 GeV \ 125 GeV , m_{Z'} &gt; 125 GeV \end{cases}</td>
</tr>
<tr>
<td>m_{X_1} = m_{Z'}/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy dark sector</td>
<td>m_{X_2} = 2m_{Z'}</td>
<td>m_{h_D} = \begin{cases} 125 GeV , m_{Z'} &lt; 125 GeV \ m_{Z'} , m_{Z'} &gt; 125 GeV \end{cases}</td>
</tr>
</tbody>
</table>
Quick overview: Mono-Z’

- $E_T^{\text{miss}}$ trigger
- Merged and resolved jet resonance search
- Use of btagging to enhance sensitivity to $Z’ \rightarrow bb$
- Combined fit of MC normalisations in 1&2-lepton CRs and 0-lepton SRs
- Limits: heavy dark sector comparable to dijet searches, stronger with light dark sector
- Systematically limited $\Rightarrow$ foresee improvement
Resonance search

$q \rightarrow Z' \rightarrow q\bar{q}\rightarrow hadronisation$ of final state quarks

“pile-up” - simultaneous p-p interactions

highest-mass dijet event in 2016
$p_T(j1,j2) = 3.79$
$m_{jj} = 8.12$ TeV
Jet reconstruction

- Seed from cells with S/N > 4
- Grow with cells S/N > 2
- Split local maxima (EM calorimeter)

“topological clusters” - 3D energy blobs

- Sequentially merge topoclusters
- Start from highest ET
- Size controlled by ‘radius’ parameter, \( \Delta R = \Delta \eta \oplus \Delta \phi = 0.4 \)
- End with a 2D object - ~ circular in \( \eta \)-\( \phi \) (except when touch)
- Built from raw energy recorded by calorimeter
- **sampling**
  calorimeters -> don’t record all the energy
- Also have energy deposits from other p-p collisions in same event
Jet calibration

- Built from raw energy recorded by calorimeter
- **sampling**
  calorimeters ->
don’t record all the energy
- Also have energy deposits from other p-p collisions in same event

**Origin correction**
Changes the jet direction to point to the hard-scatter vertex. Does not affect $E$.

**Jet area-based pile-up correction**
Applied as a function of event pile-up $p_T$ density and jet area.

**Residual pile-up correction**
Removes residual pile-up dependence, as a function of $\mu$ and $N_{PV}$.

look at average $p_T$ density of event in the calorimeter, subtract this approximated pileup contribution
Jet calibration

- Built from raw energy recorded by calorimeter
- **Sampling** calorimeters -> don’t record all the energy
- Also have energy deposits from other p-p collisions in same event

---

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---

**Absolute MC-based calibration**
Corrects 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 effects using calorimeter, track, and muon-segment variables.

**Residual in situ calibration**
A residual calibration is derived using in situ measurements and is applied only to data.

---

at this point, have only discriminated based on event pileup and jet origin, $\eta$ and $p_T$. We have more information than this!

---

final corrections to get back to “truth” scale
• Very large number of events -> very little scope for QCD to deviate from functional form

• In 2015, could not fit whole $m_{jj}$ range, hence truncated fit at 1250 GeV
BumpHunter - high-mass dijet

- “BumpHunter” - scans all widths from 1 to Nbins/2, finds maximally discrepant interval
- $p$-value < 0.05 => there is something there with 95% confidence
- $p$-value > 0.05 => there is not something there
Limits on the limits: $m_{jj}$ resolution

**Good resolution**

**Bad resolution**

Bad resolution: signal smears out, covers wider $m_{jj}$ range, trying to extract same number of signal events from more background events
m_{jj} resolution

Cartoon because offline plot is internal… but you can read it from m_{jj} bins

\[ \sigma(\sqrt{m_{jj}}) / m_{jj} \]

TLA

offline

\[ |y^*| < 0.6 \]

ATLAS Simulation Preliminary

Pythia 8 QCD
Lower still: exploiting the Kinematics

The dijet searches use $|y^*| < 0.6$

$y^* = \frac{1}{2} (y_1 - y_2)$

Imagine a centrally produced $Z'$:

i.e. quarks back to back, $y_1 = -y_2$, $y^* = y_1$

small $\Delta y$, large $p_T$

large $\Delta y$, small $p_T$

TLA: Imposing $|y^*| < 0.3 \Rightarrow$ higher $<p_T>$ from given $Z'$ mass $\Rightarrow$ sensitive to lower $Z'$ mass for given $p_T$ (394 vs 443)

(signal and background both lose a factor of $\sim 2-3$)
### Trigger evolution over time

1. LHC performance increases
2. Decide rate allocation
3. Adjust jet $p_T$ threshold to fit
4. Evaluate performance of this trigger to determine analysis selections

<table>
<thead>
<tr>
<th>Year</th>
<th>$L / 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</th>
<th>Jet $p_T$ Threshold</th>
<th>Single Jet Trigger Rate</th>
<th>Offline Turnon</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>0.5</td>
<td>260</td>
<td>18</td>
<td>400</td>
</tr>
<tr>
<td>2016</td>
<td>1.2</td>
<td>380</td>
<td>38</td>
<td>420</td>
</tr>
<tr>
<td>2017</td>
<td>1.7</td>
<td>420</td>
<td>33</td>
<td>435</td>
</tr>
</tbody>
</table>
Jet trigger performance

Before: offline - truth resolutions for width of $m_{jj}$ peak

For triggers: trigger - offline resolution, i.e. how good are we at selecting the events we want to analyse?

This is set by how similar we can make trigger jets to offline jets, given:

- partial event information (e.g. restricted / no tracking)
- trigger calibrations determined before data-taking, offline afterwards!
Jet trigger calibration

<table>
<thead>
<tr>
<th>Calibration</th>
<th>Purpose</th>
</tr>
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<tbody>
<tr>
<td>Origin correction</td>
<td>Move jet origin to vertex</td>
</tr>
<tr>
<td>Pileup subtraction瘠</td>
<td>Remove contributions from pileup</td>
</tr>
<tr>
<td>Jet Energy Scale correction</td>
<td>Restore hadronic energy</td>
</tr>
<tr>
<td>Global Sequential Correction</td>
<td>Reduce flavour (quark / gluon) dependence</td>
</tr>
<tr>
<td>In-situ eta intercalibration</td>
<td>Corrects detector effects along eta to central region</td>
</tr>
<tr>
<td>In-situ JES correction</td>
<td>Calorimeter response corrected to MC truth scale</td>
</tr>
</tbody>
</table>

Applied to?

Offline

- Start with offline calibration chain
Jet trigger calibration

- Start with offline calibration chain
- No GSC or in-situ in 2015/16 data (developed using 2015 data!)

### Calibration
- Origin correction
- Jet area
- Residual
- Jet Energy Scale correction
- Jet area
- Residual
- Global Sequential Correction
- Calo-only with tracks
- In-situ eta intercalibration
- In-situ JES correction

### Purpose
- Move jet origin to vertex
- Remove contributions from pileup
- Restore hadronic energy
- Reduce flavour (quark / gluon) dependence
- Corrects detector effects along eta to central region
- Calorimeter response corrected to MC truth scale

### Applied to?
- Offline and HLT (2015 and 2016)
- Offline only - not implemented in time
Jet trigger calibration

**Calibration**
- Origin correction
- Pileup subtraction
- Jet Energy Scale correction
- Global Sequential Correction
- In-situ eta intercalibration
- In-situ JES correction

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- Move jet origin to vertex
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- Restore hadronic energy
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- Corrects detector effects along eta to central region
- Calorimeter response corrected to MC truth scale

**Applied to?**
- Offline and HLT (2015 and 2016)
- Offline only - not implemented in time
- Offline only - needs tracks

**Status in 2015 and 2016 data**

- Start with offline calibration chain
- No GSC or in-situ in 2015/16 data (developed using 2015 data!)
- Also: no tracks!
  - very CPU intensive in ATLAS trigger -> infeasible to run full tracking
Jet trigger calibration

- **Purpose**: Move jet origin to vertex
  - Remove contributions from pileup
  - Restore hadronic energy
  - Reduce flavour (quark / gluon) dependence
  - Corrects detector effects along eta to central region
  - Calorimeter response corrected to MC truth scale

- **Origin correction**: Move jet origin to vertex
- **Pileup subtraction**: Jet area, Residual
- **Jet Energy Scale correction**: Calo-only, with tracks
- **Global Sequential Correction**: Calo-only with tracks
- **In-situ eta intercalibration**: Calo-only with tracks
- **In-situ JES correction**: Calo-only with tracks

- **Applied to?**
  - Offline and HLT (2015-2017)
  - Offline and HLT (all 2017)
  - Offline and HLT (some 2017)
  - Offline only

- **New in 2017**
- **Apply partial GSC and in-situ calibrations to all trigger jets**
- **Some HLT tracking in jets is possible within CPU constraints - can apply GSC to some trigger jets**

**Status in 2017 data**
Jet trigger calibration

- Application of more steps in calibration chain hugely improves resolution and turnon
- Partially offsets threshold increases required from luminosity increases
Offline trigger jet calibration

- We save enough information to be able to (re)do most of the calibration offline.

- Offline and HLT (2015 and 2016)

- Offline only - not implemented in time
Offline trigger jet calibration

- We save enough information to be able to (re)do most of the calibration offline
- Some parts specifically redefined for trigger jets
Offline trigger jet calibration

- We save enough information to be able to (re)do most of the calibration offline
- Some parts specifically redefined for trigger jets
- Apply scale factor between trigger and offline jets to correct residual differences

### Calibration
- Origin correction
- Pileup subtraction
- Jet Energy Scale correction
- Global Sequential Correction
- trigger - offline scale factor
- In-situ JES correction

### Purpose
- Move jet origin to vertex
- Remove contributions from pileup
- Restore hadronic energy
- Reduce flavour (quark / gluon) dependence
- Corrects residual differences (binned in \( p_T \) and \( \eta \))
- Calorimeter response corrected to MC truth scale

### Applied to?
- Offline, applied to trigger jets
- Offline, trigger-jet specific
- trigger - offline correction
- Offline only - needs tracks
TLA trigger jet calibration

Custom “in-situ” step to ensure smoothness - statistical fluctuation in normal spline-based combination leads to bump in $p_T$ and hence $m_{jj}$

Excellent trigger : offline agreement
Expected limits fluctuations

- Real signal can exist in data, but expected limits need to represent signal-free background
  - Fit signal+background model for each signal point
  - Set signal component to zero & throw toys for expected limit
- Thus the model used to generate the expected limits is **different for each signal point**, since a different signal is included in each signal+background fit
  - Results in wobbly expected limits
    - More pronounced the more “flexible” the background estimation is
Observed and expected limits at 95% confidence level on the coupling ($g_q$), for the combination of the ISR jet and ISR $\gamma$ channels.
Large-R + ISR DDT

\[ \rho_{DDT} \equiv \log \left( \frac{m_J^2}{p_T \times \mu} \right) \]

Linear relationship between \( \rho_{DDT} \) and \( < \tau_{21} > \) for \( \rho_{DDT} > \sim 1 \)

Define \( \tau_{21}^{DDT} \) : linearly corrected version of \( \tau_{21} \)

\( \tau_{21}^{DDT} \) independent of jet mass

\( \begin{align*}
&DATLAS \text{ Simulation} \\
&\sqrt{s} = 13 \text{ TeV} \\
&\text{Jet channel}
\end{align*} \)

arXiv:1801.08769

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV} \)
Jet channel

- Bkg., 500 < \( p_T^J < 700 \text{ GeV} \)
- Sig., 500 < \( p_T^J < 700 \text{ GeV} \)
- Bkg., 700 < \( p_T^J < 900 \text{ GeV} \)
- Sig., 700 < \( p_T^J < 900 \text{ GeV} \)
- Bkg., 900 < \( p_T^J < 1300 \text{ GeV} \)
- Sig., 900 < \( p_T^J < 1300 \text{ GeV} \)
Tracking in CaloClusters

- Improvements in jet substructure resolution thanks to track information in jet reconstruction inputs ATL-PHYS-PUB-2017-015

- Black -> Red
  - Mostly low p_T -> improvement in D2, degradation in mass
CMS and ATLAS limits

CMS Preliminary

95% CL exclusions

$\Gamma_{Z'}/M_{Z'} = 100\%$

$\Gamma_{Z'}/M_{Z'} = 50\%$

$\Gamma_{Z'}/M_{Z'} = 30\%$

$\Gamma_{Z'}/M_{Z'} = 10\%$

$\Gamma_{Z'}/M_{Z'} = 5\%$

boosted dijet (ATLAS)

b-tagged

8 TeV

Dijet

Dijet ATLAS

Z'→qq

Dijet X

CMS Dijet, 13 TeV [EXO-16-056]

ATLAS Dijet+ISR, 13 TeV [ATLAS-CONF-2016-070]

ATLAS TLA, 13 TeV [ATLAS-CONF-2016-030]

CMS Dijet, 13 TeV [ATLAS-EXOT-2017-01]

ATLAS Boosted Dijet, 13 TeV [ATLAS-EXOT-2016-21]

ATLAS Dijet+ISR γ, 13 TeV [ATLAS-CONF-2016-070]

CMS Dijet, 8 TeV [EXO-14-005]

ATLAS Dijet+ISR γ, 13 TeV [ATLAS-CONF-2016-070]

CMS Dijet b tagged, 8 TeV [EXO-16-057]

UA2 [Nucl. Phys. B 400, 3 (1993)]

UA2

CDF Run1


CDF Run2


CDF Run2


[arXiv:1404.3947]

95% CL exclusions

$\Gamma_{Z'}/M_{Z'} < 10\%$

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Wider context

Sensitivity decreases as DM mass decreases
(Z' branching ratio to dijets decreases)
-> covered by mono-X searches

Interpretation is very model-dependent

Sensitivity decreases as lepton coupling $g_l$ increases and quark coupling $g_q$ decreases
-> covered by dilepton resonance searches
Even wider context

Interpretation is even more model-dependent

Nice complementarity between direct detection, collider production with mono-X and “indirect searches” with dijet resonances
8 TeV 20.3 fb$^{-1}$ triggers

**ATLAS**

- Normal stream only
- Delayed stream added

Prescaled single jet triggers plus delayed stream