Dark Matter searches with the ATLAS Detector

Will Kalderon, Lund University (SE)

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!

In a hadron collider, “SM” initial state = quarks and gluons

X = q, γ, W, h, …

We can see this

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

“Mono-X searches”
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>$\gamma$</td>
<td>36.1 fb^{-1}</td>
<td>Eur. Phys. J. C 77 (2017) 393</td>
</tr>
<tr>
<td>$Z (\rightarrow \ell\ell)$</td>
<td>36.1 fb^{-1}</td>
<td>PLB 776 (2017) 318</td>
</tr>
<tr>
<td>$W/Z (\rightarrow qq)$</td>
<td>3.2 fb^{-1}</td>
<td>PLB 763 (2016) 251</td>
</tr>
<tr>
<td>$h (\rightarrow bb)$</td>
<td>36.1 fb^{-1}</td>
<td>PRL 119 (2017) 181804</td>
</tr>
<tr>
<td>$h (\rightarrow \gamma\gamma)$</td>
<td>36.1 fb^{-1}</td>
<td>PRD 96, 112004 (2017)</td>
</tr>
<tr>
<td>$Z' (\rightarrow qq)$</td>
<td>36.1 fb^{-1}</td>
<td>ATLAS-CONF-2018-005</td>
</tr>
</tbody>
</table>

### Associated production Dataset

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

$Z' \sim Z_B$ $M_{Z'}[GeV]$
Dijet limits, run 1 vs run 2

\[ g_q \]

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

\[ 300 \quad 400 \quad 1000 \quad 2000 \quad 3000 \]

**ATLAS** Preliminary March 2017
\[ \sqrt{s} = 13 \text{ TeV}; 3.4-37.0 \text{ fb}^{-1} \]

- Run 1 dijet
- Run 2 dijet

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

95% CL upper limits
- Expected
- Observed

\[ \text{Prescaled*: only a fraction of events accepted by a trigger are recorded} \]
\[ \text{Delayed stream**: events accepted by some triggers are written to a separate stream that is not reconstructed until computing resources become available over a shutdown} \]

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

Higher bottom mass edge to exclusion: trigger limitations
What limits the ATLAS trigger?

30* MHz → L1 → ~100 kHz → HLT → ~1.5 kHz → storage for offline analysis

~20-40 Hz single jet

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
Overcoming trigger 1: ISR

- 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
Dijet (merged & resolved) + ISR limits

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

\[ \text{ATLAS} \ Preliminary \ March \ 2018 \]

95% CL upper limits
- Observed
- Expected

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

200 GeV = crossover between merged and resolved

**Large-R jet -> takes this down to 100 GeV**

**Axial vector mediator**

**Dirac Dark Matter**

\[ m_{\text{DM}} = 10 \text{ TeV} \]
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\(^{-1}\)

Requiring ISR reduces signal cross-section -> lower sensitivity than pure dijet

Gap in run 2 sensitivity from \(~1000-1500\)
2: Revisit trigger limitations

Limitations:

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
Evade trigger bandwidth limits

**ATLAS** Trigger Operation

**HLT Stream Rates** (with overlaps)

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*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

**ATLAS** Trigger Operation

pp Data July 2016, $\sqrt{s}=13$ TeV

---

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

```

```

4x10^7 events in first bin in 29.3 fb^-1 of 2016 data
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 recalibrated trigger $m_{jj}$**

### 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
  - $|y^*|<0.3$: 27 bins, $|y^*|<0.6$: 19

Functional form

\[
\begin{align*}
f(x) &= p_1 (1 - x)^{p_2} x^{p_3} \\
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}
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ATLAS

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

Data
Fit window
Fit for this bin

animation here
Background estimation

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  f(x) &= p_1 (1 - x)^{p_2} x^{p_3} + p_4 \ln x \cdot p_5 \ln x^2 \\
  f(x) &= \frac{p_1}{x^{p_2}} e^{-p_3 x - p_4 x^2}
\end{align*}
\]
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
Limits, March 2018

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

ATL-DATA-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 scale as 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

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)
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)
- 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

\[
\begin{align*}
\chi_2 & \to q & q \\
\chi_1 & \to Z' & q
\end{align*}
\]

Dark Higgs

\[
\begin{align*}
\chi & \to Z' & h_D & \to q \\
\chi_1 & \to Z' & q
\end{align*}
\]

Dijet resonance + MET

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Dark-fermion model</th>
<th>Dark-Higgs model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(m_{\chi_1} = 5 \text{ GeV})</td>
<td>(m_X = 5 \text{ GeV})</td>
</tr>
<tr>
<td>Light dark sector</td>
<td>(m_{\chi_2} = m_{\chi_1} + m_{Z'} + 25 \text{ GeV})</td>
<td>(m_{h_D} = \begin{cases} m_{Z'}, &amp; m_{Z'} &lt; 125 \text{ GeV} \ 125 \text{ GeV}, &amp; m_{Z'} &gt; 125 \text{ GeV} \end{cases})</td>
</tr>
<tr>
<td>Heavy dark sector</td>
<td>(m_{\chi_1} = m_{Z'}/2)</td>
<td>(m_X = 5 \text{ GeV})</td>
</tr>
<tr>
<td></td>
<td>(m_{\chi_2} = 2m_{Z'})</td>
<td>(m_{h_D} = \begin{cases} 125 \text{ GeV}, &amp; m_{Z'} &lt; 125 \text{ GeV} \ m_{Z'}, &amp; m_{Z'} &gt; 125 \text{ 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 => foresee improvement
Resonance search

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 $E_T$
- 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)
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
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

**Jet calibration**

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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**
TLA fitting

- 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

\[ \frac{\Delta m_{jj}}{\sigma(m_{jj})} \]

TLA

ATLAS Simulation Preliminary
Pythia 8 QCD
|y*| < 0.6

 offline
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 $|y^*|<0.3$ => higher $<p_T>$ from given $Z'$ mass => 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

<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>

2. Decide rate allocation

3. Adjust jet $p_T$ threshold to fit

4. Evaluate performance of this trigger to determine analysis selections
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 (eg restricted / no tracking)
- trigger calibrations determined before data-taking, offline afterwards!
Jet trigger calibration

- **Calibration**
  - Origin correction
  - Pileup subtraction
  - Jet Energy Scale correction
  - Global Sequential Correction
  - 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

- **Start with offline calibration chain**
Jet trigger calibration

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

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

- 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

Status in 2015 and 2016 data
Jet trigger calibration

- **Origin correction**: Move jet origin to vertex
- **Pileup subtraction**: Remove contributions from pileup
- **Jet Energy Scale correction**: Restore hadronic energy
- **Global Sequential Correction**: Reduce flavour (quark / gluon) dependence
- **In-situ eta intercalibration**: Corrects detector effects along eta to central region
- **In-situ JES correction**: Calorimeter response corrected to MC truth scale

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

**Status in 2017 data**

- 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
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

Calibration

- Origin correction
- Pileup subtraction
- Jet Energy Scale correction
- Global Sequential Correction
- 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

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

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<th>Purpose</th>
<th>Applied to?</th>
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<tbody>
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<td>Origin correction</td>
<td>Move jet origin to vertex</td>
<td>Offline, applied to trigger jets</td>
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<tr>
<td>Pileup subtraction</td>
<td>Remove contributions from pileup</td>
<td>Offline, trigger-jet specific</td>
</tr>
<tr>
<td>Jet Energy Scale correction</td>
<td>Restore hadronic energy</td>
<td>trigger - offline correction</td>
</tr>
<tr>
<td>Global Sequential Correction</td>
<td>Reduce flavour (quark / gluon) dependence</td>
<td>Offline only - needs tracks</td>
</tr>
<tr>
<td>In-situ eta intercalibration</td>
<td>Corrects detector effects along eta to central region</td>
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<td>In-situ JES correction</td>
<td>Calorimeter response corrected to MC truth scale</td>
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Offline trigger jet calibration

**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
- 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

- 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
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 \( \rho^{DDT} \approx 1 \)

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

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

\( m_j \) is defined as

\[ m_j = \frac{\sigma^2}{\langle \rho^{DDT} \rangle} \]

The mean value of \( m_j \) is 0.2

Simulation

\( \rho^{DDT} \) is an arbitrary scale parameter. For \( \rho^{DDT} \), there is a linear relationship between \( \rho^{DDT} \) and \( m_j \).

The resonance candidate, and at least one large-\( R \), jet must satisfy these requirements, the jet with the lower ranges of large-\( R \) jet mass 

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\[ \rho^{DDT} \]
• 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

ATLAS TLA updated since this plot
**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