ATLAS Jet Reconstruction, Calibration, and Tagging

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On behalf of the ATLAS Collaboration

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Introduction to jets

- Jets are a tool to represent hadronic showers in a detector.
- ATLAS primarily uses the anti-$k_t$ algorithm, with topo-cluster inputs.
  - Topo-clusters: topological groups of noise-suppressed calorimeter cells.
  - Topo-clusters can be EM-scale or LCW-scale (hadronic scale).
- Depending on physics intent, different types of jets are useful.
  - Primarily small-$R$ ($R = 0.4$) EM jets and large-$R$ ($R = 1.0$) LCW jets.
- Jets can have different underlying sources $\rightarrow$ jet tagging.
  - Small-$R$ mostly for quarks/gluons, large-$R$ for energetic W/Z/H/top/X.

![Jet Reconstruction Diagram]

**ATLAS simulation 2010**

Pythia 6.425 dijet event

$E$ [MeV]

$|\tan \theta| \times \sin \phi$

$|\tan \theta| \times \cos \phi$
Jet inputs

- Jets can be built from any set of 4-vectors
  - Topo-clusters, tracks, particle flow objects, truth particles, ...
- Topo-clusters can be pileup-suppressed (several techniques)
  - SoftKiller, Voronoi ($\times 2$), Constituent Sub, Cluster Vertex Fraction, ...
- Large improvements in low-$p_T$ jet resolution in high lumi environments
- (Larger) jets can even be built from (smaller) jets: reclustering
  - Take advantage of well-known and well-measured small-$R$ jets
- Unless mentioned, following slides use standard topo-clusters

![Diagram](image_url)
Jet calibration overview

- Jets need to be calibrated to account for several effects
  - Pileup, non-compensating calorimeter response, data/MC diffs, etc
- The calibration chain is different for small-$R$ and large-$R$ jets
  - In particular, Large-$R$ jets include mass calibrations, not just energy
- Calibrations are becoming more similar as large-$R$ jet usage grows
  - First results of large-$R$ jet *in situ* calibrations will be presented

**Diagram:**
- EM-scale small-$R$ jets ($R=0.4$) → Origin correction → Pileup correction → MC-based energy calibration → Global sequential calibration → Residual in situ energy calibration → Fully calibrated small-$R$ jet
- LCW-scale large-$R$ jets ($R=1.0$) → Jet grooming (trimming) → MC-based energy calibration → Residual in situ energy calibration → Fully calibrated large-$R$ jet

Standard approach
First results

Calibration and uncertainties

Small-\(R\) jet pileup suppression

- Suppress pileup jets by exploiting tracking information
  - Jet Vertex Tagger (JVT): veto if most tracks from additional vertices
  - Particle flow: build jets from a mix of track and cluster information
- Dynamically remove pileup energy from hard-scatter jets
  \[
  p_T^{\text{corr}} = p_T - \rho A_{\text{jet}} - \alpha (N_{\text{PV}} - 1) - \beta \mu
  \]

\[\langle \mu \rangle \sim 22\]
\[s = 13 \text{ TeV} \]
\[p_T^{\text{jet}} > 20 \text{ GeV}\]
\[\langle \text{Fake Jets} / 0.2 / \text{Event} \rangle\]
Larger $R$ jet pileup suppression

- Larger radius means more susceptible to pileup
- Significant impact on key variables, even at high $p_T$
- ATLAS uses trimming to counteract pileup effects
  - Build $R = 0.2$ sub-jets
  - Check if $\frac{p_T^{R=0.2}}{p_T^{R=1.0}} < 5$
  - Remove such sub-jets
- Resulting jets are very stable with respect to pileup
  - Even stable for $\langle \mu \rangle = 200$
Monte Carlo (MC) calibration

- A substantial fraction of hadronic shower energy is not measured
  - Nuclear binding energy from strong interactions, inactive material, etc
- MC information is used to correct for such effects
  - Response: $X_{\text{reco}}/X_{\text{true}}$, numerical inversion gives calibration factor
  - After energy calibration, average jet is at the truth scale
- Small-$R$ jets: further energy corrections to fix residual effects (GSC)
  - Shower development, flavour differences (q vs g), punch-through
- Large-$R$ jets: subsequent mass calibration

\[ \text{Energy Response} \]

\[ \text{Mass response before calibration} \]
Relative *in situ* correction

- Previous calibration steps assume that MC perfectly represents data
- It is important to fix residual data/MC differences
- Small-$R$ jets use $\eta$-intercalibration to do this
  - Correct scale of forward jets with respect to well-known central jets
  - Do in both data and MC to fix data/MC differences
- Large-$R$ jets: first studies demonstrate $\eta$ dependence
  - Balance of photon and jet varies, requires a correction for $|\eta| \gtrsim 1.2$

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**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, $L = 24.8$ fb$^{-1}$

$|\eta| \lesssim 1.2$, EM+JES

$85 \leq p_T^{\text{avg}} < 115$ GeV

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 32 fb$^{-1}$

$\gamma$-jet Events, Data 2016

$|\eta| \lesssim 1.2$, EM+JES

$145 \leq p_T^{\text{avg}} < 1000$ GeV

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Absolute \textit{in situ} correction

- Relative scale of jets across the detector is now fixed
- The absolute scale may still differ between data and MC
- Investigate with three methods, using well-known reference objects
  - Balance of $Z \rightarrow \ell\ell$ and a jet, for low $p_T$ jets
  - Balance of a photon $\gamma$ and a jet, for medium $p_T$ jets
  - Multi-jet balance, using a recoil system of $Z/\gamma$ calibrated jets
- The results are then combined, providing a final calibration
Small-$R$ jet uncertainties

- The *in situ* corrections (relative and absolute) correct data to MC
  - This correction has uncertainties, which are evaluated
- There are additional uncertainties beyond the *in situ*
  - Flavour dependence, pileup, and punch-through are also considered
- 1-2% uncertainty on the energy scale from $p_T$ of 50 GeV to 2 TeV

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**ATLAS**

**Data 2015, $\sqrt{s} = 13$ TeV**

- **Anti-$k$, $R = 0.4$, EM+JES + in situ**
  - $\eta = 0.0$

**Total uncertainty**
- **Absolute in situ JES**
- **Relative in situ JES**
- **Flav. composition, inclusive jets**
- **Flav. response, inclusive jets**
- **Pile-up, average 2015 conditions**
- **Punch-through, average 2015 conditions**

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**ATLAS**

**Data 2015, $\sqrt{s} = 13$ TeV**

- **Anti-$k$, $R = 0.4$, EM+JES + in situ**
  - $p_T^{jet} = 80$ GeV

**Total uncertainty**
- **Absolute in situ JES**
- **Relative in situ JES**
- **Flav. composition, inclusive jets**
- **Flav. response, inclusive jets**
- **Pile-up, average 2015 conditions**
- **Punch-through, average 2015 conditions**
$R_{\text{trk}}$ and large-$R$ jet uncertainties

- First look at large-$R$ jet \textit{in situ} corrections was shown
  - However, do not yet cover full kinematic range (lack of $\eta$ correction)
  - Different procedure for uncertainty on $X$: $R_{\text{trk}} = \frac{(X_{\text{calo}}/X_{\text{track}})_{\text{data}}}{(X_{\text{calo}}/X_{\text{track}})_{\text{MC}}}$
  - Does not correct data/MC differences, only an uncertainty on them
  - \textbf{Baseline}: raw $R_{\text{trk}}$ difference from 1 between data and Pythia8
  - \textbf{Modelling}: Pythia8 vs Herwig++ difference in $R_{\text{trk}}$
  - \textbf{Tracking}: tracking efficiency, momentum, and fake tracks
  - Larger uncertainties, but quick and can be used for any variable

\[ R_{\text{trk}} \text{ uncertainty} \]

\[ \text{Jet} \quad \text{jet} \quad T_p^2 \quad 10^{3} \times 10^{3} \quad 10^{3} \times 10^{3} \quad 10^{3} \times 3 \quad 10^{3} \times 3 \]

\[ \text{Jet} \quad \text{Jet} \quad \text{Track} \quad \text{Statistical} \]

\[ \text{Data 2016, } \sqrt{s} = 13 \text{ TeV} \quad \text{anti-k, } R = 1.0 \text{ jets, LC+JES+JMS} \quad \text{Trimmed (} \mu = 0.05 \text{, } R_{\text{sub}} = 0.2) \]

\[ |m_{\text{jet}}| < 2, m_{\text{jet}} / p_T^\text{jet} = 0.10 \]

\[ \text{Fractional JPS uncertainty} \]

\[ \text{Baseline} \quad \text{Total uncertainty} \quad \text{Modelling} \quad \text{Tracking} \quad \text{Statistical} \]
Jet mass and forward folding

- Forward folding allows for measuring the mass scale and resolution
- Idea: construct high-purity W or top selection, look at data and MC
  - Shift and smear the distribution until data and MC agree
  - This gives the mass scale and resolution data/MC difference
- Forward folding is very limited in where it can be derived (statistics)
  - $R_{\text{trk}}$ is used to extrapolate to other kinematic regimes
Hadronic object tagging

- Hadronic decays of massive particles can come from many sources
  - Main examples: $W \rightarrow qq'$, $Z \rightarrow q\bar{q}$, $H \rightarrow b\bar{b}$, top$\rightarrow bW \rightarrow bqq'$
  - Higher parent particle energy $\implies$ decay product collimation
  - Idea of “boosted decays”, rule-of-thumb $\Delta R \gtrsim 2m^X/p_T^X$
  - Results in all decay products within a single jet
    - *Jet substructure* distinguishes different parent particles (or $q$ vs $g$)

![Graphical representation of jet substructure and tagging](image)
Combined jet mass

- Jet mass is the most intuitive substructure variable
  - Signal jets should have the mass of the parent particle
- Mass defined by energy and angular separation between constituents
- At very high $p_T$, calorimeter may not resolve the constituents
  - *Track-assisted* jet mass addresses this, $m_{\text{jet}}^{\text{TA}} = m_{\text{jet}}^{\text{track}} \frac{p_{\text{calo}}}{p_{\text{track}}}$
- Combination $m_{\text{jet}}^{\text{comb}} = A(p_T) \times m_{\text{jet}}^{\text{calo}} + B(p_T) \times m_{\text{jet}}^{\text{TA}}$ is best of both worlds
Jet substructure

- Combined mass provides good separation between QCD, $W$, and top
  - A good first step to tagging a hadronic decay
- Other substructure variables quantify further differences
  - $D_{2}^{β=1}$ is the most powerful variable (after mass) for W/Z tagging
  - $τ_{32}^{wta}$ is the most powerful variable (after mass) for top tagging
- Both quantify consistency of jet angular distribution with signal
W-boson and top-quark tagging

- W and top taggers are optimized with two-variable cuts
- Plots show QCD rejection as a function of $p_T$
  - W-tagging is for a 50% signal efficiency, top uses 80% signal efficiency
- Boosted Decision Trees and Deep Neural Networks also studied
  - Use roughly 10 substructure variables as inputs
  - Reasonable gains with respect to simpler methods

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**ATLAS** Simulation Preliminary

- $\sqrt{s} = 13$ TeV
- anti-$k_t$, $R=1.0$ jets, $|\eta^{\text{truth}}| < 2.0$
- Trimmed ($f_{\text{cut}} = 0.05$, $R_{\text{sub}} = 0.2$)
- W tagging at $\epsilon_{\text{sig}} = 50$

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**ATLAS** Simulation Preliminary

- $\sqrt{s} = 13$ TeV
- anti-$k_t$, $R=1.0$ jets, $|\eta^{\text{truth}}| < 2.0$
- Trimmed ($f_{\text{cut}} = 0.05$, $R_{\text{sub}} = 0.2$)
- Top tagging at $\epsilon_{\text{sig}} = 80$
W-bosons and top-quarks in data

- BDT and DNN discriminants agree nicely between data and MC
- Shown for W-tagging using a DNN
- Application of taggers can select high purity regions
- Shown for top-tagging using a two-variable tagger

### ATLAS Preliminary

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- $\Delta R$(large jet, $b$-jet) $> 1.0$
- Jet $p_T > 200$ GeV
- Jet $m_{comb} > 40$ GeV

**Data 2015+2016**
- $t\bar{t}$ (top)
- $W$ (W)
- $t\bar{t}$ (other)
- Single Top (W)
- Single Top (other)
- $W$+jets
- $VV$, $Z$+jets, QCD
- Total uncert. (no large-$R$)
- Stat. uncert.
- $t\bar{t}$ modelling uncert.

**Data/Pred.**

- 0.5
- 1
- 1.5

### ATLAS Preliminary

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- $\Delta R$(large jet, $b$-jet) $< 1.0$
- Jet $p_T > 350$ GeV
- $\tau_{32} + \sqrt{d_{23}}$ ($e_{sig} = 80\%$)
- Top tag pass

**Data 2015+2016**
- $t\bar{t}$ (top)
- $W$ (W)
- $t\bar{t}$ (other)
- Single Top (W)
- Single Top (other)
- $W$+jets
- $VV$, $Z$+jets, QCD
- Total uncert.
- Stat. uncert.
- $t\bar{t}$ modelling uncert.

**Data/Pred.**

- 0.5
- 1
- 1.5

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H→bb tagging

- H-tagging uses $b$-tagging and substructure information
  - $b$-tagging: QCD rejection
  - Substructure: top, $g \rightarrow bb$
- At high $p_T$, track-jets for $b$-tagging merge (truth-level)
  - New jet types recover eff.

**ATLAS Simulation Preliminary**

- **Higgs-jet efficiency**
  - MV2c10 $b$-tagging at 77% WP
    - 1 b-tag, Loose $m_{bb}$ window
    - 2 b-tags, No $m_{bb}$ selection
    - 2 b-tags, Loose $m_{bb}$ window
    - 2 b-tags, Tight $m_{bb}$ window, $D_{s}$ sel.
  - $p_T$ [GeV]

- **Hadronic top rejection**
  - MV2c10 $b$-tagging at 77% WP
    - 1 b-tag, Loose $m_{bb}$ window
    - 2 b-tags, No $m_{bb}$ selection
    - 2 b-tags, Loose $m_{bb}$ window
    - 2 b-tags, Tight $m_{bb}$ window, $D_{s}$ sel.
  - $p_T$ [GeV]
Quark vs gluon tagging

- Differentiating quarks from gluons is different in several ways
  - Jet mass is not useful (not a hadronically decaying massive particle)
  - Uses small-$R$ jets rather than large-$R$ jets
- Best single variable is track multiplicity (gluons radiate more)
- Also tried a convolutional neural network (CNN)
  - Some gains over a two-variable tagger for high quark efficiencies

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<tr>
<th>Normalized Entries</th>
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<tbody>
<tr>
<td>ATLAS Simulation Preliminary</td>
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<td>Anti-$k_t$, EM+JES $R=0.4$</td>
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Quark Jet
Gluon Jet

- $50 < p_T < 100$ GeV
- $400 < p_T < 500$ GeV
- $1200 < p_T < 1500$ GeV

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<table>
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- CNN EM Towers + Tracks
- LLH (# Charged Particles + Jet Width)
- # Charged Particles
- Jet Width

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Tagging into the future

- Calorimeter’s ability to resolve highly boosted decays is degraded
  - Ideal: angular resolution of the tracker and scale of the calorimeter
- ATLAS is developing a substructure-oriented particle flow “TCC”
  - Combined mass currently superior at low $p_T$, TCC better at high $p_T$
  - TCC vastly superior for non-mass substructure variables
- TCC algorithm promises large gains to future hadronic object tagging
ATLAS jets are typically built of calorimeter topo-clusters
  - Jets built using particle flow objects are also starting to be used

ATLAS makes use of small-$R$ (0.4) and large-$R$ (1.0) jets
  - Both jet types are calibrated in several steps
  - Account for pileup, calorimeter response, and data/MC differences

Jets are also used to tag hadronic showers
  - $W$, $Z$, $H$, and top tagging using large-$R$ jets
  - Quark vs gluon discrimination using small-$R$ jets
  - Machine learning methods (BDTs, DNNs, CNNs) studied for tagging
  - Work ongoing to improve highly boosted jet substructure and tagging

This talk focused on current techniques, used in 2015 and 2016
  - Lots of work is ongoing to prepare for the future!
Backup Material
Constituent-level pileup suppression

- Small gains compared to nominal (jet areas) in low pileup environment
- Large gains by $\langle \mu \rangle = 200$
Trimming at high luminosity

**ATLAS Simulation Preliminary**

- anti-k, LCW jets with $R=1.0$
- No jet grooming, no pileup correction
- $\sqrt{s} = 14$ TeV, 25 ns bunch spacing
- $|\eta^{\text{jet}}| < 1.2$, $500 < p_{\text{T}}^{\text{jet}} < 1000$ GeV
- Pythia8 dijets

**ATLAS Simulation Preliminary**

- anti-k, LCW jets with $R=1.0$
- Trimmed, pileup corrected
- $\sqrt{s} = 14$ TeV, 25 ns bunch spacing
- $|\eta^{\text{jet}}| < 1.2$, $500 < p_{\text{T}}^{\text{jet}} < 1000$ GeV
- Pythia8 dijets

- $m_{Z'}$ ($m_t \to t\bar{t}$) (2 TeV)}
Jet substructure uncertainties

- The $R_{\text{trk}}$ method is used to derive substructure uncertainties
- Shown for $D_2^{\beta=1}$ (W/Z tagging) and $\tau_{32}^{\text{wta}}$ (top tagging)
- Plots are older (2015 data only), and thus are statistically limited
  - Update with 2016 data reduces the statistical component significantly
- Uncertainties are under control, so they can be used for object tagging
Jet reclustering

- Idea: small-$R$ jets are already carefully calibrated and understood
  - Build large-$R$ jets from them, take advantage of small-$R$ knowledge
  - Allows for choosing the jet radius you want, not only $R = 1.0$

- Typically smaller uncertainties in the range of interest ($p_T \lesssim 1 \text{ TeV}$)
- Also improved mass resolution, compared to $m_{\text{jet}}^{\text{calo}}$ (not $m_{\text{jet}}^{\text{comb}}$)
- Performance degrades at higher $p_T$ (increased boost)
  - Effective reclustered jet size becomes one small-$R$ jet

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ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$

$W' \rightarrow WZ, m_{\text{jet}}^1 > 50 \text{ GeV}$

Reclustered ($R=1.0, f_{\text{cut}} = 5\%$) from anti-$k_t$, $R=0.4 \text{ EM+JES+GSC+JMS jets}$

Trimmed ($f_{\text{cut}} = 5\%, R_{\text{cut}} = 0.2$) anti-$k_t$, $R=1.0 \text{ LC+JES+JMS jets}$

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ATLAS Simulation Preliminary

Pythia 8 $W' \rightarrow WZ; W \rightarrow qq; |\eta| < 0.4$

Calorimeter-only jet mass

Reclustered ($R=1.0, f_{\text{cut}} = 5\%$) from anti-$k_t$, $R=0.4 \text{ EM+JES+GSC+JMS jets}$

Trimmed ($f_{\text{cut}} = 5\%, R_{\text{cut}} = 0.2$) anti-$k_t$, $R=1.0 \text{ LC+JES+JMS jets}$

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