Jet and $E_T^{\text{miss}}$ Reconstruction with the ATLAS Experiment at LHC

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Roadmap for this Talk

Jet reconstruction in ATLAS
  Basic signals and reconstruction sequences

Small-\(R\) & large-\(R\) jets calibration
  MC-based calibration
  In situ calibration methods for jets in data

\(E_T^{\text{miss}}\) reconstruction
  Signal ambiguity resolution
  Selected performance

Conclusions and outlook
Anti-$k_t$ jets with $R = 0.4$

Two choices for input signals

Calorimeter only: clusters of topologically connected cells (topo-cluster) with signals on a basic electromagnetic (EM) scale – **EMTopo jets**

Calorimeter and Tracking: particle flow signals (PFlow) combining reconstructed tracks with EM-scale topo-clusters – **EMPFlow jets**

Clustering uses four-momentum recombination

**Jet energy scale (JES) calibration sequence**

- **Origin correction**: Changes the topological cluster direction to point to the hard-scatter vertex. No change of cluster signal.
- **EM-scale jets**: Jet finding applied to topological clusters (EM scale) or to neutral (EM scale) and charged PFlow objects.
- **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 $N_{PV}$.

- **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.

**Residual in situ calibration** calibrates $p_T - (E, \vec{p})$ rescaled
Large-\( R \) Jet Reconstruction in ATLAS

**Anti-\( k_t \) jets with \( R = 1.0 \)**

**Input signals**

Calorimeter only: clusters of topologically connected cells (topo-cluster) with signals on a locally calibrated hadronic (LCW) scale – **LCTopo jets**

Clustering uses four-momentum recombination

**JES and jet mass (JMS) calibration sequence**

1. **Calorimeter energy clusters (LCW scale)**
   - Large-\( R \) jet reconstruction
     - Large-\( R \) jets are reconstructed using the anti-\( k_t \) algorithm with \( R = 1.0 \).

2. **Groomed large-\( R \) jets (LCW scale)**
   - \( E, \eta & m \) calibration
     - A correction to the jet energy, pseudorapidity and mass is derived from MC to bring the reconstructed jet to the particle jet scale.

3. **Ungroomed large-\( R \) jets (LCW scale)**
   - Residual in situ calibration
     - Residual correction determined using in situ measurements to bring data in agreement with MC. Applied only to data.

4. **Jet grooming**
   - Soft subjets are removed from the reconstructed jets.

5. **Groomed large-\( R \) jets (LCW+JES+JMS scale)**
   - calibrates \( p_T \) and \( m \) – first \((E, \vec{p})\) rescaled by \( p_T \)-calibration, then \( m \) calibrated & \( p_T \) rescaled with \( E \) unchanged
Response Before MC-based Calibration

$R = 0.4$ EMTopo

$R = 0.4$ EMPFlow

$R = 1.0$ LCTopo

$R = 1.0$ LCTopo

$E_{\text{Truth}} = 30$ GeV
$E_{\text{Truth}} = 60$ GeV
$E_{\text{Truth}} = 110$ GeV
$E_{\text{Truth}} = 400$ GeV
$E_{\text{Truth}} = 1200$ GeV

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, \) Pythia Dijet
anti-\( k_t \) \( R = 0.4 \), EM scale

$\mathcal{R}_{\text{Topo}} = 0.4$

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, \) Pythia dijets
Trimmed anti-\( k_t \), \( R = 1.0 \), LCW
\( m_{\text{Truth}} = 40 \text{ GeV} \)

\[ m_{\text{Truth}} \approx m_W / 2 \]

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, \) Pythia dijets
Trimmed anti-\( k_t \), \( R = 1.0 \), LCW
\( m_{\text{Truth}} = 80.4 \text{ GeV} \)

\[ m_{\text{Truth}} = m_W \]

$\mathcal{R}_{\text{Topo}} = 1.0$

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, \) Pythia dijets
Trimmed anti-\( k_t \), \( R = 1.0 \), LCW
\( m_{\text{Truth}} = 10^{-20} \times p_T^{\text{jet}} \) for \( q/g \) jet

\( m_{\text{jet}} \approx (10 - 20)\% \times p_T^{\text{jet}} \) for \( q/g \) jet

(NLO, \( R = 1.0 \))

$\mathcal{R}_{\text{Collects boosted particle decay products into jet of size } R}$
In situ Jet Calibration (Data Only)

In-situ calibration

(1) Relative $\eta$-intercalibration
Dijets with central jet balancing probed (forward) jet – removes $\eta$-dependent data/MC response variations

(2) Full response calibration
Combining various final states for full phase space coverage – scales central response of data to MC

Final state selection

Same topologies data & MC
Back-to-back reference and probe
Suppression of events with additional jet(s) above threshold

$Z$ or $\gamma$, $p_T^{\text{ref}} = p_T^{Z/\gamma}$

$Z$ + jet:
$20 \text{ GeV} < p_T^{\text{jet}} \lesssim 1.0 \text{ TeV}$

$\gamma$ + jet:
$35 \text{ GeV} \lesssim p_T^{\text{jet}} \lesssim 1.2 \text{ TeV}$

$\Delta\phi$

Multi-jets

$\sum_{\text{recoil}} p_T^{\text{jet}}$

Small-$R$ or large-$R$ probe jet

Multi-jets:
$300 \text{ GeV} < p_T^{\text{jet}} \lesssim 2 \text{ TeV}$
In situ Jet Energy Scale

**In situ corrections relative to MC**

Derived from DB or MPF

Depends on phase space coverage and precision

\[ r_{\text{in situ}} = \frac{p_T^{\text{jet}}}{p_T^{\text{ref}}} \left( \frac{p_T^{\text{ref}}}{p_T^{\text{ref}}} \right) - \text{direct balance (DB)} \]

\[ R_{\text{MPF}} = 1 + \left( \frac{p_T^{\text{ref}} \cdot E_T^{\text{miss}}}{|p_T^{\text{ref}}|} \right)^2 - \text{missing projection fraction (MPF)} \]

Calibration functions

(Powheg+)Pythia8/data ratio reflects nominal calibration function for data – near flat (~2%) correction for \( p_T^{\text{jet}} > 40 \text{ GeV} \) both for small- and large-\( R \) jets

Differences to other MC generators and variations of topology selections contribute to systematic uncertainties
Combination of results
Various final states and methodologies
Most precise configuration gets highest weight

Contribution weights
Some dependency on jet definition, collected luminosity (statistical precision), algorithm choice (MPF, DB) and detector signal choice
Statistical limitations towards phase space limits

\( \mathcal{R} = 0.4 \)

ATLAS JETM-2019-02 (Fig.4)

\( s = 13 \text{ TeV}, 80 \text{ fb}^{-1} \)
EMPFlow, \((R = 0.4)\)

\( \gamma + \text{jet} \)
\( Z + \text{jet}, Z \rightarrow ee \)
\( Z + \text{jet}, Z \rightarrow \mu\mu \)
Multijet

ATLAS Preliminary
\( s = 13 \text{ TeV}, 80 \text{ fb}^{-1} \)
Anti-\( k_t, R = 0.4 \) (PFlow+JES)

ATLAS JETM-2019-05 (Fig.1b)

\( s = 13 \text{ TeV}, 80 \text{ fb}^{-1} \)
Trimmed anti-\( k_t, R = 1.0 \) (LCW+JES+JMS)

\( \gamma + \text{jet} \)
\( Z + \text{jet}, Z \rightarrow ee \)
\( Z + \text{jet}, Z \rightarrow \mu\mu \)
Multijet

EMTopo, \((R = 0.4)\)

\( s = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

ATLAS Preliminary
\( s = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
anti-\( k_t, R = 0.4, \text{ EM+JES} \)

\( \gamma + \text{jet} \)
\( Z + \text{jet} \)
\( Z + \text{jet}, Z \rightarrow ee \)
\( Z + \text{jet}, Z \rightarrow \mu\mu \)
MJB

ATLAS JETM-2019-02 (Fig.4)

ATLAS JETM-2019-05 (Fig.1b)

Extracting Jet Calibration for Full Phase Space

Combination of results
Various final states and methodologies
Most precise configuration gets highest weight

Calibration functions
From response curves from weighted combination
Gaussian Kernel smoothing
Calibration and uncertainties very comparable between small-$R$ and large-$R$ jets
Relative Jet Energy Resolution

Measured with $p_T$ asymmetry in di-jet balance

PFlow shows expected improvements at low $p_T$

- Significantly reduced fluctuations from pile-up
- Significantly reduced uncertainties at low $p_T$

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 43.6 \text{ fb}^{-1} \)
\( 0.2 \leq |\eta| < 0.7 \)

Dijet in situ

- Total uncertainty
- MC prediction

EMTopo, \( (R = 0.4) \)

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 43.6 \text{ fb}^{-1} \)
\( 0.2 \leq |\eta| < 0.7 \)

Dijet in situ

- Total uncertainty
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EMPFlow, \( (R = 0.4) \)

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 43.6 \text{ fb}^{-1} \)
\( 0.2 \leq |\eta| < 0.7 \)

- Imperfect pile-up modeling – larger fluctuations in MC simulation than in data

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV} \)
2.4 pb\(^{-1}\), zero-bias data
Random cones \( (R = 0.4) \)
Open markers – MC

\( |\eta_{\text{incl}}| < 0.7 \)
**$E_T^{\text{miss}}$ Reconstruction in ATLAS**

**Object-based approach**
- Fully reconstructed and calibrated particles and jets
  - Require signal ambiguity resolution to avoid double counting
- **Soft signals**
  - Signals below reconstruction threshold(s) still contribute to the event $p_T$ flow
  - can be important for $E_T^{\text{miss}}$ resolution, bias and significance

**Signal ambiguity resolution**
- Priority ranking of object contributing to $E_T^{\text{miss}}$
  - Higher priority to object with higher reconstruction quality
  - Analysis goals determine the ranking and particular object selections
- **Reasons for rejection of lower priority objects for $E_T^{\text{miss}}$ reconstruction**
  - A – use of same detector signal
  - B – association with detector signals used for reconstruction of accepted objects
  - C – other significant phase space overlap with accepted object

**Soft signal collection**
- Signals not associated or used by accepted objects
  - Basic signals or signal remnants from rejected objects – e.g., accepted electron removes only part of jet
  - Topo-clusters in Run 1 – now primary vertex tracks due to higher stability to increased pile-up
**$E_T^{\text{miss}}$ Response**

**Response & resolution**

$Z \rightarrow \ell\ell + (0, \ldots, N_{\text{jet}}) \text{ jet(s)}$

Reconstructed $E_T^{\text{miss}}$ is projected onto $p_T^Z$

$N_{\text{jet}}(p_T > 20 \text{ GeV}) \geq 0$

Turn on of jets in recoil improves recoil reconstruction

$(p_T^\text{jet} > 20 \text{ GeV})$

**Pile-up stability**

Soft term using tracks performs well – soft calorimeter signals strongly affected by pile-up

$N_{\text{jet}}(p_T > 20 \text{ GeV}) = 0$

Jets in recoil improve resolution but introduce a pile-up dependence

$N_{\text{jet}}(p_T > 20 \text{ GeV}) = 0$
**$E_T^{\text{miss}}$ in Data & Simulations in LHC Run 2**

**Good agreement observed**

$E_T^{\text{miss}}$ spectrum

Important for e.g. phase space selections

$E_T^{\text{miss}}$ significance (**ATLAS-CONF-2018-038**)

Relates observed $E_T^{\text{miss}}$ to accumulated signal fluctuations in underlying objects – including correlations

Important tool for e.g. searches for non-interacting or weakly interacting particles
Conclusions & Outlook

Jets in ATLAS in LHC Run 2

Following principal approaches developed in Run 1
  MC-based calibrations followed by *in situ* data-only calibrations

Similar small and large $R$ jet performance
  Uncertainties at $\mathcal{O}(1\%)$ comparable to Run 1
  Well controlled and precise measurement of overall jet kinematics
  Effects from increased pile-up in Run 2 appropriately mitigated using well-established tools

PFlow jets
  Improved pile-up suppression for $p_T \lesssim 100$ GeV – similar or higher precision
  New standard and basis of the final precision recommendations for physics analysis

Further improvements
  Several projects looking at one-step calibration approaches and the application of machine learning in jet calibration
  Improved pile-up mitigation techniques considering correlations between the out-of-time signal remnants and the in-time pile-up signals
$E_T^{\text{miss}}$ reconstruction

Object-based approach carried from Run 1 to higher luminosity

- Works very well even at highest luminosities (so far)
- Extension to PFlow – mainly affects jets
- Investigation of Machine Learning in reconstruction
- Improved fJVT measure removes pile-up jets outside of tracking acceptance more efficiently
Recent and relevant publications


Conference & public notes

ATLAS Coll., *Simultaneous jet energy scale and jet mass scale calibration using generalized numerical inversion*, ATLAS-PHYS-PUB-2020-001


Additional Material
**Anti-$k_t$ jets with $R = 0.4$**

Two choices for input signals

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Clustering uses four-momentum recombination

**Jet energy scale (JES) calibration sequence**

**MC-based**

- **Pile-up suppression**: removes diffuse emissions from pile-up into jet (jet-area-based – pile-up represented as median $p_T$ density of given event)
- **Energy calibration and direction correction**: scales the reconstructed jet energy to the truth expectation and corrects small directional deflections
- **Global sequential calibration**: reduces jet-by-jet response variations introduced by jet flavor, fragmentation and longitudinal energy leakage

**In situ calibration**: data only – relative to MC

- **$\eta$-intercalibration using $p_T$ balance in dijet events**: corrects data-MC response ratio variations in calorimeter regions, relative to central region
- **$p_T$ balance in $\gamma/Z + \text{jet(s)}$ & multi-jet final states**: calibrates data to jet response in MC simulations – removes residual data-MC differences
Large-\(R\) Jet Reconstruction in ATLAS

Anti-\(k_t\) jets with \(R = 1.0\)

Input signals

Calorimeter only: clusters of topologically connected cells (topo-cluster) with signals on a locally calibrated hadronic (LCW) scale – LCTopo jets

Clustering uses four-momentum recombination

JES and jet mass (JMS) calibration sequence

Pile-up suppression by jet grooming

Removing soft subjets by trimming \( (p_T^{\text{subject}} / p_T^{\text{jet}} > f_{\text{cut}} = 5\%, R_{\text{subj}} = 0.2) \)

MC-based

Energy and mass calibration and direction correction: scales the reconstructed jet energy and mass to the truth expectations; corrects small directional deflections (truth particle jet is trimmed as well)

In situ calibration: data only – relative to MC

In situ JES similar to small-\(R\) jets approach: using \(p_T\) balance with well-calibrated reference(s)

In situ JMS: applied after in situ JES – corrects \(m_{\text{jet}}^{\text{data}}\) with scale factors determined by forward-folding \(m_{W \rightarrow jj}^{\text{MC}}\) and \(m_{t \rightarrow j j j}^{\text{MC}}\) distributions from MC to data in \(t\bar{t} \rightarrow (Wb)(Wb) \rightarrow (qqb)(\ell \ell b)\) final states
Total weight: 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid + (varying) toroid field

ATLAS at the LHC

A multi-purpose detector system

Muon Detectors   Tile Calorimeter   Liquid Argon Calorimeter

Toroid Magnets   Solenoid Magnet   SCT Tracker   Pixel Detector   TRT Tracker
Detectors for Hadronic Final State Reconstruction

Calorimeters

Provides principal signals for $e^\pm/\tau^\pm$ and jet kinematics – and other measurements

- Full coverage within $|\eta| < 4.9$ with depth $\geq 10 \lambda_{\text{int}}$
- Highly segmented for energy flow measurements (~188,000 cells)
  - High granularity in $\Delta\eta \times \Delta\varphi = 0.025 \times \pi/128$ (central EM)
  - Up to seven depth layers (samplings)

Inner detector

Provides charged particle tracks and vertices

- Coverage $|\eta| < 2.5$

Jet energy calibration refinement

- Provides vertex for jet origin correction/jet vertex association/jet vertex tagging (JVT)
- Flavor/fragmentation sensitive response measures – mitigation of jet flavor response dependencies

Particle flow

- Replace charged response in calorimeter with kinematics from well-measured tracks

Missing transverse momentum soft contributions

- Tracks not used or associated with (hard) reconstructed particles and jets

Muon spectrometer

Reconstructed muons

- Contribution to missing transverse momentum reconstruction

Track segments

- Proxy for energy leakage behind a jet
Why Particle Flow Jets?

Angular resolution improvements

Improved jet energy resolution

Better lower $p_T$ performance especially in pile-up
### In situ JES Calibration Overview

<table>
<thead>
<tr>
<th>Method</th>
<th>Validity range</th>
<th>Reference jet calibration</th>
<th>Probe jet calibration</th>
<th>Applied to jets with ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$-intercalibration</td>
<td>full accessible $p_T^{\text{jet}}$ range</td>
<td>MC calibrations</td>
<td>MC calibrations</td>
<td>MC calibrations</td>
</tr>
<tr>
<td>$Z + \text{jet}$ (MPF)</td>
<td>$20 \text{ GeV} &lt; p_T^{\text{jet}} \leq 1.0 \text{ TeV}$</td>
<td>n/a</td>
<td>No probe – full final state response</td>
<td>MC calibrations + $\eta$-intercalibration</td>
</tr>
<tr>
<td>$Z + \text{jet}$ (DB)</td>
<td></td>
<td></td>
<td>MC calibrations + $\eta$-intercalibration</td>
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</tr>
<tr>
<td>$\gamma + \text{jet}$ (MPF)</td>
<td>$35 \text{ GeV} \leq p_T^{\text{jet}} \leq 1.2 \text{ TeV}$</td>
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</tr>
<tr>
<td>Multi-jet (MJB)</td>
<td>$300 \text{ GeV} \leq p_T^{\text{jet}} \leq 2 \text{ TeV}$</td>
<td>full calibration</td>
<td>MC calibrations + $\eta$-intercalibration</td>
<td>MC calibrations + $\eta$-intercalibration</td>
</tr>
</tbody>
</table>
Extracting Jet Calibration for Full Phase Space

Systematic uncertainties

Dominant sources

- Absolute in-situ data-to-MC calibration
- Flavor response variations and pile-up corrections for low $p_T R = 0.4$ jets
- High precision for $R = 1.0$ jet response
- Less sensitivity to flavor response (fragmentation)

EMPFlow, ($R = 0.4$)

EMTopo, ($R = 0.4$)

LCTopo, ($R = 1.0$)
**$E_T^{\text{miss}}$ Reconstruction in ATLAS**

**Principal observables**

\[ E_{x(y)}^{\text{miss}} = - \sum_{i \in \{\text{hard objects}\}} p_{x(y),i} - \sum_{j \in \{\text{soft signals}\}} p_{x(y),j} \]

\[ E_T^{\text{miss}} = (E_x^{\text{miss}}, E_y^{\text{miss}}) \]

\[ E_T^{\text{miss}} = |E_T^{\text{miss}}| = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \]

\[ \phi^{\text{miss}} = \tan^{-1}(E_y^{\text{miss}}/E_x^{\text{miss}}) \]

**Signal contributions**

\[ E_T^{\text{miss}} = - \sum_{\text{selected electrons}} p_T^e - \sum_{\text{accepted photons}} p_T^\gamma - \sum_{\text{accepted } \tau\text{-leptons}} p_T^{\tau_{\text{had}}} - \sum_{\text{selected muons}} p_T^\mu - \sum_{\text{accepted jets}} p_T^{\text{jet}} - \sum_{\text{untused tracks}} p_T^{\text{track}} \]

\[ E_T^{\text{miss},e} \quad E_T^{\text{miss},\gamma} \quad E_T^{\text{miss},\tau_{\text{had}}} \quad E_T^{\text{miss},\mu} \quad E_T^{\text{miss},\text{jet}} \quad E_T^{\text{miss},\text{soft}} \]

hard term \quad soft term