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ATLAS Jet and Missing ET Reconstruction, Calibration, and Performance

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Jets and $E_T^{\text{miss}}$ at the ATLAS experiment

- **Jet reconstruction and calibration**
  - Jets - key ingredients of many Standard Model measurements and New Physics searches,
  - Jet energy scale uncertainty - main contribution to the systematic uncertainty of many physics results,

- **Jet substructure and jet tagging**
  - Identification of hadronically decaying boosted objects,
  - Quark- and gluon-initiated jet discrimination,

- **Missing transverse energy** ($E_T^{\text{miss}}$)
  - Important signature for many physics processes.
Jet Reconstruction and Calibration
Jet reconstruction and calibration steps

1. finding and calibration of topological calorimeter clusters (topo-clusters),
2. jet clustering of topo-clusters,
3. correction for pile-up,
4. calibration of the jet pseudorapidity and energy - Jet Energy Scale (JES),
5. residual calibration using *in situ* measurements.
Step 1: Topo-clusters

- group of calorimeter cells topologically connected,
- topo-cluster finding:
  - optimized to noise and pile-up suppression
  - procedure:
    1. seeds - cells with $E > 4\sigma_{\text{noise}}$,
    2. neighbors - all cells with $E > 2\sigma_{\text{noise}}$ neighboring seed or other neighbors,
    3. perimeter cells - all cells with $E > 0$ on the perimeter of the group of seed and neighbors,

\[
E > 4\sigma_{\text{noise}} \quad \Rightarrow \quad \phi \cos \times |\theta| \tan \theta \in [-0.05, 0.05] \\
E > 2\sigma_{\text{noise}} \quad \Rightarrow \quad \phi \cos \times |\theta| \tan \theta
\]

topo-clusters (one layer)
Step 1: Topo-cluster calibration

Two options:

- electromagnetic scale (**EM topo-clusters**)
  - all topo-clusters calibrated to the response for electrons,
  - zero topo-cluster mass,
- local calibration weighting (**LCW topo-clusters**):
  - each topo-cluster classified as electromagnetic or hadronic deposit (depending on its energy density and depth),
  - a weighting scheme corrects for the different $e/\pi$ response in the calorimeters,
  - out-of-cluster correction,
  - dead material correction,
  - zero topo-cluster mass.
Step 2: Jet clustering

- using anti-$k_t$ ($R = 0.4$ or $R = 0.6$) jet clustering algorithm,
- input: EM or LCW topo-clusters,
- output: EM or LCW jets,
- further pile-up correction and calibration necessary.
Step 3: Pile-up correction

- offset correction for 2011 data
  - corrected jet $p_T$:
    \[
    p_T^{\text{corr}} = p_T - \alpha \cdot (N_{PV} - 1) - \beta \cdot \mu \quad (1)
    \]
  - $N_{PV}$ - number of primary vertices,
  - $\mu$ - mean number of interactions,
  - $\alpha$ and $\beta$ - parameters obtained from MC
  - reliance on the correct identification of tracks and vertices

- jet-area-based correction + residual offset correction for 2012 data
  - corrected jet $p_T$:
    \[
    p_T^{\text{corr}} = p_T - A \cdot \rho \quad (2)
    \]
  - $A$ - jet area, $\rho$ - pile-up $p_T$ density
  - after it, residual offset correction similarly as for 2011 data
Step 4: Jet calibration

- jet pseudorapidity calibration - addition of a correction factor obtained from MC.
- jet energy calibration - multiplication by a correction factor obtained from MC:

**correction factor = inverse of average energy response:**

\[
R_{\text{EM(LCW)}}^{\text{EM(LCW)}} = \left\langle \frac{E_{\text{jet}}^{\text{EM(LCW)}}}{E_{\text{truth}}^{\text{jet}}} \right\rangle
\]

(3)
Step 5: Residual in situ calibration

- applied to Data only,
- jet $p_T$ correction: multiplication by the response ratio of the MC to the Data:

\[
\frac{\text{Response}_{\text{MC}}}{\text{Response}_{\text{Data}}} = \left( \frac{\langle p_T^{\text{jet}} / p_T^{\text{ref}} \rangle_{\text{MC}}}{\langle p_T^{\text{jet}} / p_T^{\text{ref}} \rangle_{\text{Data}}} \right)
\]

(4)

Response $\langle p_T^{\text{jet}} / p_T^{\text{ref}} \rangle$ obtained from transverse momentum balance between jet and a reference object.

- several methods to cover large kinematic phase space:
  - dijet $\eta$-intercalibration,
  - $\gamma$+jet balance,
  - $Z$+jet balance,
  - multijet balance.

![Graph showing response vs. $p_T$](image)
Jet energy scale uncertainty

- several components:
  - in situ calibration uncertainties
  - pile-up uncertainty
  - flavor composition uncertainty
  - flavor response uncertainty
- total uncertainty = components summed in quadrature
- central jets uncertainties:
  - $< 4\%$ for $p_T > 20$ GeV
  - $< 2\%$ for $p_T \in [100, 1000]$ GeV
Jet energy resolution

- measured with the dijet balance and bisector in situ techniques,
- improved jet energy resolution for LCW calibrated topo-clusters wrt. EM calibrated topo-clusters.
Suppression of pile-up jets

- **Jet Vertex Fraction (JVF)**
  - quantity to filter pile-up jets,
  - evaluated from tracks associated to a given jet:
    \[
    JVF = \frac{\sum_{i \in PV0} p_T^{\text{track } i}}{\sum_j p_T^{\text{track } j}} \quad (5)
    \]
  - \(i \in PV0\) - only tracks matched to the hard-scatter vertex (primary vertex with the highest \(\sum_j \left(p_T^{\text{track } j}\right)^2\))
  - JVF = −1 in case of no associated tracks.

- **Jet Vertex Tagger (JVT)**
  - multivariate combination of two track-based variables,
  - hard-scatter jet efficiency is stable as a function of \(N_{PV}\).
Jet Substructure and Jet Tagging
Jet Substructure Techniques

- identification of hadronically decaying boosted objects \((W, Z, H, \text{top})\),
- using jet algorithms with large distance parameter (anti-\(k_t\) with \(R = 1.0\) and \(C/A\) with \(R = 1.2\)),
- better energy and mass resolution with **jet grooming** techniques - selective removal of soft radiation, e.g. trimming.

![ATLAS Simulation](image-url)

**ATLAS Simulation**

- anti-\(k_t\) LCW jets, \(600 \leq p_T^{\text{jet}} < 800\) GeV
- Comparison of ungroomed and trimmed jets for \(Z\) and dijets.
Jet Substructure Techniques

- many jet substructure techniques and variables tested and validated:
  - identification of boosted $W$ bosons: momentum balance $\sqrt{y_f}$, mass drop $\mu_{12}$, Q-jets, splitting scale $\sqrt{d_{12}}$, ...
  - identification of boosted top quarks: shower deconstruction (SD), HEPTopTagger (HTT),subjettiness $\tau_{32}$, ...

$W$ boson tagging performance
Discrimination between quark- and gluon-initiated jets

- useful for identification of hadronic decays of $W$ and $Z$ bosons,
- likelihood based discriminant using two variables constructed from associated tracks (number of charged tracks, $n_{\text{trk}}$, and jet width),
- light-quark tagging efficiency of $\sim 50\%$ with gluon mistag rate of $\sim 25\%$
- Data/MC disagreement is observed.
Missing Transverse Energy
Missing transverse energy $E_T^{\text{miss}}$

- event quantity based on momentum conservation in the transverse plane:

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}$$  \hspace{1cm} (6)

$$E_{x(y)}^{\text{miss}} = - \left( E_{x(y)}^{\text{jets}} + E_{x(y)}^{e} + E_{x(y)}^{\gamma} + E_{x(y)}^{\tau} + E_{x(y)}^{\mu} + E_{x(y)}^{\text{Soft Term}} \right)$$  \hspace{1cm} (7)

- $E_{x(y)}^{\text{jets}}$, $E_{x(y)}^{e}$, $E_{x(y)}^{\gamma}$, $E_{x(y)}^{\tau}$ and $E_{x(y)}^{\mu}$ - sum of $x(y)$-component of the momentum of all jets, electrons, photons, taus and muons, respectively,
  - using anti-$k_t$ $R = 0.4$ jets calibrated with LCW+JES scheme with $p_T > 20$ GeV,
  - all objects are corrected for pile-up and calibrated,
  - suppression of pile-up jets: rejecting jets with JVF = 0, $p_T < 50$ GeV and $|\eta| < 2.4$,
- Soft Term $E_{x(y)}^{\text{Soft Term}}$ - sum of $x(y)$-component of the momentum of all topo-clusters and tracks not associated to above physics objects - avoiding double counting.
large effect of pile-up on $E_T^{miss}$,
several correction methods for the Soft Term $E_x^{\text{Soft Term}}$:

- Soft-Vertex-Fraction (STVF) - multiplication by a factor constructed from all tracks in the event:

$$\text{STVF} = \frac{\sum_{i \in \text{PV0}} p_T^{\text{track } i}}{\sum_j p_T^{\text{track } j}}$$

Jet-area-based methods:
- jet clustering of Soft Term constituents,
- jet-area-based pile-up correction,
- optionally apply JVF-based selection,
- various setups (EJA, EJAF, JAF).

$E_T^{miss}$ corrected with STVF method - the smallest bias and the best resolution.
$E_T^{\text{miss}}$, Data/MC agreement

- Good Data/MC agreement before and after STVF pile-up correction,
- Worse Data/MC agreement after EJAF pile-up correction.
$E_T^{\text{miss}}$, linearity

- positive bias for low true $E_T^{\text{miss}}$,
- larger negative bias for true $E_T^{\text{miss}} > 40$ GeV corrected with STVF method.
Summary

- **jet reconstruction and calibration**
  - calorimeter-based topological clustering,
  - powerful pile-up subtraction methods,
  - in-situ techniques for Jet Energy Scale uncertainty up to 1.5 TeV,
  - testbeam-based beyond,
  - high precision on Jet Energy Scale,
  - good data/MC agreement,

- **jet substructure and jet tagging**
  - wealth of substructure techniques for identification of boosted hadronically decaying top quarks, Higgs, W and Z bosons,
  - quark/gluon jet discrimination,

- **missing transverse energy**
  - exploiting object-based $E_T^{\text{miss}}$,
  - many techniques for Soft Term pile-up correction investigated,
  - use of tracks for the Soft Term so far provides optimal performance.
Liquid-Argon Calorimeter Plots:
http://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArCaloPublicResultsDetStatus

topo-clusters:
ATL-LARG-PUB-2008-002

LCW calibration:
ATL-LARG-PUB-2009-001-2

pile-up correction and suppression:
ATLAS-CONF-2012-064
ATLAS-CONF-2013-083
ATLAS-CONF-2014-018

jet area based pile-up correction:
arXiv:0707.1378

jet energy scale and its uncertainty, in situ calibrations:
arXiv:1406.0076
http://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013JESUncertainty
References

- jet energy resolution:
  arXiv:1210.6210
- jet substructure techniques:
  arXiv:1306.4945
- W boson tagging:
  ATL-PHYS-PUB-2014-004
- shower deconstruction:
  ATLAS-CONF-2014-003
- Q-jets:
  ATLAS-CONF-2013-087
- boosted top quark identification:
  ATLAS-CONF-2013-084
- light-quark/gluon jet discrimination:
  arXiv:1405.6583
- missing transverse energy:
  ATLAS-CONF-2013-082
  ATLAS-CONF-2014-019
BACKUP
Pile-up

- additional proton-proton (pp) interactions in bunch crossings:
  - in-time pile-up - pp interactions in the same bunch crossing, characterized by number of primary vertices, \(N_{PV}\),
  - out-of-time pile-up - pp interactions in preceding bunch crossings, characterized by mean number of interactions, \(\mu\),
- one of the main challenges for jets due to additional energy deposits in calorimeters causing:
  - jet energy offset and worse resolution,
  - additional (fake) jets.

![ATLAS Online Luminosity](image)
Pile-up

- out-of-time pile-up due to long charge collection and the specific choice of signal shaping in the Liquid Argon calorimeters (600 ns wrt. 50 ns bunch spacing)

Ionization Pulse Shape in the front EM Barrel layer
Topo-clusters

- noise

\[ \sigma_{\text{noise}} = \sqrt{\left(\sigma_{\text{electronic}}\right)^2 + \left(\sigma_{\text{pile-up}}\right)^2} \] (9)

Pseudorapidity dependence of noise in Liquid Argon calorimeters at the electron scale for \( \mu = 14 \)
Pile-up Correction

- jet area, $A$, computation:
  - ghosts (infinitesimally soft particles uniformly distributed in the $y - \phi$ space) added to the event
  - ghosts are clustered into the jets - area 4-vector can be obtained:
    \[
    A_\mu = \frac{1}{\nu p_T^g} \sum_{j \in \text{ghosts}} p_{\mu,j}^g \tag{10}
    \]
    \[\nu p_T^g\] - transverse momentum density of the ghosts
  - jet area $= \text{transverse component of } A_\mu$

- pile-up $p_T$ density, $\rho$, estimation:
  \[
  \rho = \text{median}_i \left\{ \frac{p_{T,i}^{\text{jet}}}{A_i^{\text{jet}}} \right\} \tag{11}
  \]
  median over $k_t R = 0.4$ jets.
Jet origin correction

- Correction to the calorimeter jet direction
- Makes the jet pointing back to the primary event vertex instead of the nominal center of the ATLAS detector.
Jet Vertex Tagger

- Jet Vertex Tagger - multivariate combination of two variables:
  - corrJVF

\[
\text{corrJVF} = \frac{\sum_{i \in \text{PV0}} p_T^{\text{track } i}}{\sum_{k \in \text{PV0}} p_T^{\text{track } k} + \frac{\sum_{m \notin \text{PV0}} p_T^{\text{track } m}}{k \cdot n_{\text{PU}}^{\text{track}}}}
\]  \hspace{1cm} (12)

- $k$ - scaling factor ($k = 0.01$)
- $n_{\text{PU}}^{\text{track}}$ - number of pile-up tracks
- $R_{pT}$

\[
R_{pT} = \frac{\sum_{i \in \text{PV0}} p_T^{\text{track } i}}{p_T^{\text{jet}}}
\]  \hspace{1cm} (13)

pile-up jets

hard-scatter jets
Residual in situ calibration: $Z+\text{jet}$ method

- using events with one $Z$ boson and one jet $\rightarrow$ momentum balance in the transverse plane between the two objects,
- reference: $Z$ boson decaying $Z \rightarrow e^-e^+$,
- probes the jet response at low $p_T$ (low background),

![Graph](image)

ATLAS

$\sqrt{s} = 7$ TeV, $\int L \, dt = 4.7$ fb$^{-1}$

anti-$k_t$ R=0.4, EM+JES

- Data 2011
  - $Z(\rightarrow e^+e^-)$ (PYTHIA)

![Graph](image)

ATLAS

$\sqrt{s} = 7$ TeV, $\int L \, dt = 4.7$ fb$^{-1}$

anti-$k_t$ R=0.4, EM+JES

- Data 2011
  - Total uncertainty

$\langle p_T^{\text{jet}} / p_T^{\text{ref}} \rangle$

$\langle p_T^{\text{jet}} / p_T^{\text{ref}} \rangle_{\text{Data}}$

$\langle p_T^{\text{jet}} / p_T^{\text{ref}} \rangle_{\text{PYTHIA}}$

$p_T^{\text{ref}}$ [GeV]

$p_T^{\text{jet}}$ [GeV]
Jet Substructure Techniques

trimming:

$| \eta | < 0.8$  
$| \eta | < 800 \text{ GeV}$,  
$p_T \leq 600$  

no trimming

with trimming
W boson tagging

- splitting scale:

\[ \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \cdot \Delta R_{12}, \]

where \( p_{T1} \) and \( p_{T2} \) in the last clustering step of the \( k_t \) algorithm and \( \Delta R_{12} \) is their distance.

- momentum balance:

\[ \sqrt{y_f} = \sqrt{d_{12}} / m \]

- mass-drop

\[ \mu_{12} = \frac{\max(m_1, m_2)}{m} \]

combined effect of jet grooming and W-tagging: the various combinations have similar performance
Top quark tagging

- shower deconstructions
  - input are subjets reconstructed with the C/A algorithm with $R = 0.2$ from the constituents of large-$R$ jet,
  - all possible shower histories are created for background and signal hypothesis,
  - calculates the probability that a given shower history was realized in a given jet,
  - likelihood ratio between probabilities given the signal and background hypothesis is the discriminating variable,

- subjettiness

\[
\tau_N = \frac{1}{d_0} \sum_k p_{Tk} \cdot \min(\delta R_{1k}, \delta R_{2k}, \ldots, \delta R_{Nk}), \quad \text{with} \quad d_0 \equiv \sum_k p_{Tk} \cdot R
\]  

where $R$ is the jet radius parameter in the jet algorithm, $p_{Tk}$ is the $p_T$ of constituent $k$ and $\delta R_{ik}$ is the distance from a subjet $i$ to constituent $k$.

- subjettiness ratio

\[
\tau_{ij} = \tau_i / \tau_j
\]
$E_T^{\text{miss}}$, linearity, sample comparison

**ATLAS Simulation Preliminary**

$\sqrt{s} = 8$ TeV

- No pile-up suppression
- Pile-up suppression STVF
- SVTF correction

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ATLAS Jet and Missing ET

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