Performance of Jets and Missing Transverse Energy with the ATLAS detector in pp Collisions at $\sqrt{s} = 7$ TeV

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Outline

■ Jet performance
  • Inputs to jet reconstruction
  • shapes and internal structure
  • calibration
  • energy scale and uncertainty
  • energy resolution

■ Missing transverse energy performance
  • reconstruction
  • resolution
Motivation

Understanding and measuring the performance of jets and missing transverse energy is crucial for the understanding of physics at the LHC

- Jet energy scale is an input to many physics analyses
- Jet energy scale uncertainty is the dominant experimental uncertainty for many measurements including
  - Di-jet cross section
  - Top quark mass
  - New physics searches with jets in the final state
- Events with large missing transverse energy are expected to be the key signature for new physics such as
  - Supersymmetry
  - Extra dimensions
- For example, good missing transverse energy is also important in the mass reconstruction
  - The top quark in ttbar events with one top decaying semi-leptonically
  - To Higgs boson mass when the Higgs decays into a tau pair
The ATLAS Calorimeter System

Cu-LAr
1.5 < |η| < 3.2

LAr hadronic end-cap (HEC)

Cu/W-LAr
3.2 < |η| < 4.9

Fe-Scintillator
|η| < 1.7

Tile barrel

Tile extended barrel

Pb-LAr
|η| < 1.4

LAr electromagnetic barrel

Pb-LAr
1.375 < |η| < 3.2

LAr electromagnetic end-cap (EMEC)

LAr forward (FCal)

Segmented in pseudo-rapidity η and azimuthal angle φ

η = − ln \[ \tan \left( \frac{\theta}{2} \right) \]

- LAr system: 182,468 cells
- Tile system: 10,364 cells

Over 98% of all cells used for event reconstruction

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Inputs to Jet Reconstruction

- **Topological clusters**
  - Dynamically formed calorimeters cell clusters optimized to follow the shower development
  - High calorimeter granularity requires noise suppression

- **Noise suppressed towers**
  - Calorimeter cells belonging to topological clusters projected on a fixed geometry grid $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ of 6,400 towers

- **Tracks**
  - Independent from calorimeter measurements
  - Vertex information (also for pileup effects control)

- **Jets**
  - Reconstructed using the anti-$k_T$ algorithm with size parameter $R$ set at 0.4 or 0.6

- **3D clusters use 4-2-0 suppression:**
  - Cells with $|E| > 4\sigma_{\text{noise}}$ seed the cluster
  - Neighbouring cells with $|E| > 2\sigma_{\text{noise}}$ added iteratively
  - Single layer of neighbouring cells added

Noisy cells (~0.1%) are masked and not used.

Cluster:

```
1 0 0 1 0 0
0 0 1 2 3 1 0 0
1 0 2 4 7 4 3 0
1 0 1 3 5 2 1 0
0 0 1 1 0 2 1 0 1
0 1 1 1 1 0 0 0 0
0 1 0 1 3 2 1 1 0 0
1 0 2 0 0 0 0 0
0 1 0 0 0 0 0 0
0 0 1 1 1
```

In units of $|E|/\sigma_{\text{noise}}$.

Not a Cluster.
Inputs to Jet Reconstruction

- Mean number of clusters per jet is about 1/4 of the mean number of towers for central jets; in both cases a shift is observed leading to a deficiency of 4.0% and 6.4% in the simulation.
- Difference between MC and data probably connected to deficiencies in the physics description in the MC.
Inputs to Jet Reconstruction

- Charged particle tracks matched to jets provide information on the fraction of neutral and charged energy contained in the jet.
- For softer tracks, there is indication that the treatment of fragmentation and underlying event in MC generators may need tuning (MC underestimates the number of tracks in a jet by ~5% for $p_T^{\text{track}} > 0.5$ GeV).

$\not{p}_T > 1$ GeV
Inputs to Jet Reconstruction

- The total scalar sum of track transverse momenta associated with a jet is used to further study the calorimeter response to jets.
- ~3-4% higher mean predicted by MC, primarily localized to low jet $p_T$ and forward regions.

\[ f_{\text{track}} = \frac{\sum p_{T}^{\text{track}}}{p_{T}^{\text{jet}}} \]
Jet Reconstruction Efficiency

Calorimeter jet reconstruction an identification efficiency relative to track-jets

- tag and probe method, valid for $|\eta| < 2.3$
Jet Shapes and Properties

- Measurement of jet shapes and properties are used to test how well the simulation models physics and detector effects
  - Jet fragmentation, detector response to low energy particles, inputs to jet reconstruction, soft underlying event, pileup
  - Calorimeter and track measurements are independent and can be used to disentangle physics and detector effects

- Example of quantities studied
  - Longitudinal and transverse jet profiles
  - Jet internal structure (annuli)
  - Effects of close-by jets
  - Total tracks momentum compared to jet momentum

- Jets are observed to be broader in data than in Monte Carlo simulation
Jet Longitudinal Profile

- Mean energy deposited longitudinally in cluster jets as a function of the calorimeter depth of each layer in the barrel region for two different jet $p_T$ ranges.

- Indication that, in the barrel region, hadronic showers are deeper in data compared to MC simulation.
Jet Transverse Profile

\[
\text{width} = \frac{\sum_i r_i^2 E_T^i}{\sum_i E_T^i}
\]

\[
r_i^2 = (\phi^i - \phi^\text{jet})^2 + (\eta^i - \eta^\text{jet})^2
\]

- Sum over constituents (here clusters)
- Jets wider in data by about \(\sim 10\%\) compared with MC, even for isolated jets
Jet Internal Structure

- Differential transverse jet energy distribution provides a more detailed study of the jet transverse structure.
- Less energy observed in the core of the jet and more in the periphery in data compared to Monte Carlo.
- Similar results for clusters, towers, tracks, and all rapidity regions.
- Difference between MC and data probably connected to deficiencies in the physics description in the MC.

\[
\left\langle \frac{1}{r} \frac{dp_T}{dr} \right\rangle_{\text{jets}} = \frac{1}{AN_{\text{jets}}} \sum_{\text{jets}} p_T \left( r - \frac{\Delta r}{2}, r + \frac{\Delta r}{2} \right)
\]

Annulus of area \( A \) and radius \( r \) and width \( \Delta r = 0.1 \) for \( 0 \leq r \leq R = 0.6 \)
Jet Energy Calibration

The energy of jets needs to be corrected for calorimeter non-compensation, energy losses in dead material, shower leakage, "out of cone" energy, and pileup.

Jets are calibrated using Monte Carlo particle-level truth jets as reference.

Three calibration schemes are being explored by ATLAS:

- **EM+JES**
  - simple $p_T$ and $\eta$-dependent correction to jet energy scale (JES) applied to jets measured at EM scale.

- **Global cell weighting: GCW+JES**
  - use cell weights based on cell energy density to compensate for the different calorimeter response to hadronic (low E-density) and electromagnetic depositions.

- **Local cluster weighting: LCW+JES**
  - use properties of topological clusters (including energy density and position) to classify them and calibrate them individually.
  - cluster calibration derived from Monte Carlo simulations of single charged and neutral pions.

For all three schemes, *global sequential calibration* can be used to improve *jet-by-jet fluctuations* by correcting for the dependence on jet shapes and other properties. Correction done such that the mean energy does not change.
Jet Calibration Schemes

- Mean ratio of calibrated over un-calibrated jet energies as a function of calibrated jet $p_T$ (here shown for central region)
  - same average correction for all three calibration schemes
  - the agreement between the correction factors applied to data and Monte Carlo is better than 2%
  - similar agreement in the whole rapidity range
Jet Energy Scale Uncertainty

- Jet energy scale uncertainty evaluated by comparing Monte Carlo using various detector configurations, hadronic shower models and physics models.
- Dominant sources of uncertainty are due to:
  - dead material (5%)
  - noise description (3%)
  - hadronic shower model (5%)
  - LAr/Tile absolute EM scale (3%)
  - $\eta$ inter-calibration (3%)
- Jet energy scale uncertainty smaller that 7% for jets with $p_T > 100$ GeV.
- Uncertainty assessed to $|\eta| < 4.5$ using in-situ di-jet balance measurements.
- The uncertainty is cross-checked with $E/p$ measurements.
- Expect reduction of the systematic uncertainty in the near future.
  - for example by propagating single particle response measurements in data to jets.

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Jet Energy Scale Uncertainty

- Energy scale uncertainty cross-checked with calorimeter response to single isolated hadrons measured in data
  - $E/p$ with $p$ obtained from isolated tracks
  - Correlate a particle jet to a reconstructed jet using Monte Carlo
  - Propagate the response and uncertainty of the single particles (as measured in data) in the jet (using Monte Carlo)
- Jet energy scale uncertainty of 3-4% is expected for jets in $|\eta| < 0.8$ and $20 \text{ GeV} < p_T < 1 \text{ TeV}$
Jet energy resolution measured in-situ using di-jet balance and bisector techniques.

The Monte Carlo simulation describes the jet energy resolution measured from data within 14% for jets with $20 < p_T < 80$ GeV and $|y| < 2.8$. 

ATLAS Preliminary
Missing E_T Reconstruction

- Missing transverse energy (Missing E_T) is reconstructed from:
  - cells belonging to topological clusters
  - use of clusters ensures noise suppression (required by high granularity of calorimeter)
  - reconstructed muons
  - barrel cryostat term (only for GCW calibration)
    - important only for high p_T jet events

\[
E_{\text{miss}}^{x(y)} = E_{\text{miss,calo}}^{x(y)} + E_{\text{miss,cryo}}^{x(y)} + E_{\text{miss,muon}}^{x(y)}
\]

\[
E_{\text{miss,calo}}^{x} = - \sum_{i=1}^{N_{\text{cell}}} E_{i} \sin \theta_{i} \cos \phi_{i}
\]

\[
E_{\text{miss,calo}}^{y} = - \sum_{i=1}^{N_{\text{cell}}} E_{i} \sin \theta_{i} \sin \phi_{i}
\]

\[
E_{T}^{\text{miss}} = \sqrt{(E_{x}^{\text{miss}})^2 + (E_{y}^{\text{miss}})^2}
\]
Missing $E_T$: Calorimeter Term

- Cells used can either be
  - at EM scale (no compensation!)
  - calibrated with GCW
  - calibrated with LCW (which includes dead material corrections)

- The calorimeter term can be further improved using energy corrections of physics objects
  - apply overlap removal between objects at cell level
  - objects calibrated independently, then use cells from objects

```
Electrons    Photons    Taus    Jets    Muons    Unused TopoClusters

Go back to constituent Calorimeter Cells → apply overlap removal at Cell level →
Cell calibration weights dependent on the object → add them to calculate partial terms

MET_RefEle + MET_Refγ + MET_RefTaus + MET_RefJets + MET_RefMuons + MET_CellOut

+ MET_Cryo + MET_Muon = MET_RefFinal
```
Missing $E_T$ Performance

- Calibrated missing $E_T$ distributions and tails in minimum bias events are well described by the simulation.
- Missing $E_T$ resolution in the data in good agreement with the simulation before and after cluster and cell level calibrations.
Missing $E_T$ Performance

**Dependence on event topology**
- in events with large hadronic activity, for example with high $p_T$ jets, the missing $E_T$ resolution degrades
- applying calibration (LCW shown here) restores some of the lost resolution
Conclusions and Outlook

- ATLAS has developed several jet and missing $E_T$ reconstruction and calibration schemes, with different level of complexity and sensitivity to systematic effects
  - inputs to jet and missing $E_T$ reconstruction and calibration are well described by the simulation within 10%
  - in data slightly higher soft activity is found around jets
  - in data hadronic showers appear to go deeper in the barrel region
  - an initial ATLAS jet energy scale has been determined with an uncertainty smaller than 7% for jets with $p_T > 100$ GeV
  - the Monte Carlo simulation describes the jet energy resolution within 14% for jets with $20 < p_T < 80$ GeV

- Improvements expected very soon
  - more complex calibration schemes
  - the use of tracks and single particle response measurements
  - objects-based missing $E_T$ reconstruction
Material Budget

The diagram shows the interaction lengths of different regions as a function of pseudorapidity. The regions include Tile1, Tile2, Tile3, HEC0, HEC1, HEC2, HEC3, FCal1, FCal2, FCal3, and EM calo. Each region is represented by a different color and the interaction lengths are plotted on the y-axis against pseudorapidity on the x-axis.
Electromagnetic Energy Scale

- Calorimeters measure energy at the electromagnetic (EM) scale
  - EM scale established using beam tests for electrons and muons
  - Z->ee and E/p studied and soon to be used also

- This energy scale accounts correctly for the energy of electrons and photons, but for jets it does not correct for detector effects including:
  - calorimeter non-compensation
  - energy losses in dead material
  - shower leakage
  - energy not collected in the jet reconstruction (“out if cone”)
  - inefficiencies in calorimeter clustering and jet reconstruction
  - pile-up
Jet Reconstruction

- Jets are reconstructed using the anti-\( k_T \) algorithm\(^1\)
  - Clusters and towers form massless 4 vectors
  - Use clusters or towers or tracks as proto-jets and define a distance measure:

  \[
  d_{ij} = \min \left( \frac{1}{p_T^2}, \frac{1}{p_T'^2} \right) \left( \frac{\Delta_{ij}^2}{R^2} \right) \tag{1}
  \]

  \[
  d_{ii} = \frac{1}{p_T^2} \tag{2}
  \]

  where:
  - \( \Delta_{ij} = (\phi_i - \phi_j)^2 + (y_i - y_j)^2 \)
  - \( p_T, y, \) and \( \phi \) are the transverse momentum, rapidity and azimuth of proto-jet \( i \)
  - \( R = 0.6 \) (0.4) in ATLAS reconstruction

  Until no proto-jet are left compute all \( d_{ij} \) and take smallest \( d_{ij} \):
  - \( i \neq j \) Remove proto-jet \( i \) and \( j \) and add 4-vector sum as new proto-jet
  - \( i = j \) Remove proto-jet \( i \) and call it a final jet

Inputs to Jet Reconstruction

**Event selection**
- at least one hit in the minimum bias trigger scintillators
  - located $2.09 < |\eta| < 3.84$
- in coincidence with a proton bunch passing through ATLAS
  - using the electrostatic beam sensor
- calorimeters, inner detector and solenoid fully operational
- require at least one good event vertex
  - with at least 5 tracks with $p_{T_{\text{track}}} > 150 \text{ MeV}$
  - $|z_{\text{vertex}}| < 100 \text{ mm}$

**Monte Carlo Simulation**
- non-diffractive pp collisions describing hard 2->2 processes using a matrix-element plus parton-shower model in a leading log approximation generated with the PYTHIA event generator at 7 TeV center of mass energy
- the transverse momentum of outgoing partons (in the hard scatter rest frame) is restricted to 7 GeV
Inputs to Jet Reconstruction

- Mean number of clusters per jet is about 1/4 of the mean number of towers for central jets; in both cases a shift is observed leading to a deficiency of 4.0% and 6.4% in the simulation.
- Difference between MC and data probably connected to deficiencies in the physics description in the MC.
Jet Longitudinal Profile

- Distribution of energy deposited longitudinally in cluster jets
- Good agreement with MC observed in the barrel and in the endcap region, and over the whole $p_T$ range probed
Jet Longitudinal Profile

Mean energy deposited longitudinally in cluster jets as a function of $p_{T}^{\text{jet}}$

With other measurements, this seems to indicate that, in the barrel region, hadronic showers are deeper in data compared to MC simulation.
Local Cluster Weighting

- Local cluster weighting calibration allows to improve the jet energy resolution by calibrating clusters individually before jet reconstruction
  - uses a discriminant to classify clusters as EM or hadronic, based on cluster $\eta$, depth, and cell energy density
  - cluster weights obtained for each of these effects separately:
    - hadronic response (based on cell E-density and cluster energy)
    - out-of-cluster energy (based on depth and energy around the cluster)
    - dead material (based on cluster energy and fractional energy deposited in each calorimeter layer)
- 2% agreement between data and Monte Carlo simulation for the ratio of calibrated over the un-calibrated cluster energy after each calibration step
- Very good agreement between data and simulation for all inputs to LCW
Global Cell Weighting

- Global cell weighting applies cell weights according to the energy density of the cells
- This method compensates for lower calorimeter response to hadrons and energy loss in dead material
- Jet energy scale correction in data and simulation agrees within 2%

- less cells with high energy density in data than predicted by the simulation in the EM calorimeter
- good agreement between data and simulation for the cell energy density in the hadronic calorimeter
Jet Energy Scale Correction

\[ p_T^{\text{jet}} = K p_T^{\text{jet,EM}} \]

EM+JES

Increased in electromagnetic content in jets of higher energies

ATLAS Preliminary
Monte Carlo QCD jets
Jet Energy Scale Uncertainty

- Uncertainties due to material description and experimental conditions
  - material budget and distorted geometry
  - topological cluster noise thresholds
    - 10% noise threshold uncertainty from the stability of the noise spread in dedicated noise runs and the comparison of the noise distribution in data and Monte Carlo
  - shifted beam spot
Jet Energy Scale Uncertainty

Other jet energy scale uncertainties

- hadronic shower model
  - beam test single pion response measurement lie within QGSP and FTFP_BERT model (nominal hadronic shower model is QGSP_BERT)
- uncertainty assessed to $|\eta| < 4.5$ using in-situ di-jet balance measurements
  - in $|\eta| < 1.8$, MC and data agree to better than 2%
  - in $1.8 < |\eta| < 2.8$, the agreement is within 2.8%, larger un forward region
Pile-up Jet Response Offset

- multiple pp interactions in the same bunch crossing (in-time pile-up) add extra energy to jets

- measure the mean tower energy as a function of $\eta$ and of the number of primary vertices

- estimate the additional tower energy as a function of the number of interactions by subtracting the average tower energy for events with one vertex from the average tower energy for events with $N$ additional interactions

- estimate the average number of towers in jets as a function of $\eta$

- estimate the average number of additional interactions as

$$\langle N_{\text{pile-up}} \rangle = \langle N \rangle + \sigma_N$$

- then, for a run, estimate the pile-up extra contribution to the transverse energy of jets as a function of $\eta$ from the additional energy per tower per additional interactions, the average number of towers in jets and the average number of additional interactions

- event by event and jet by jet corrections techniques are also being commissioned

Data 2010, $\sqrt{s}=7$ TeV

ATLAS Preliminary
Jet Energy Scale Uncertainty

The jet energy scale was derived using a simulated sample of QCD jets:
- particular mixture of quark and gluon initiated jets
- particular fraction of isolated and non-isolated jets

- the response of non-isolated jets is lower than that of isolated jets; all $\eta$ regions
- gluon initiated jets have a lower response than quark jets (gluon jets fragment into more and softer particles than quark initiated jets)
- corrections and systematic uncertainty must be evaluated for each physics analysis
Jet Energy Resolution (di-jet balance)

- $p_T$ asymmetry measured in back-to-back di-jet events as a function of the third jet $p_T$ threshold values $p_T^{\text{cut}}$

- Resolution obtained from different $p_T^{\text{cut}}$ is fitted and extrapolated to $p_T^{\text{cut}}=0$ for each $p_T$ bin

\[ A \equiv \frac{p_T^1 - p_T^2}{p_T^1 + p_T^2} \quad \frac{\sigma_{p_T}}{p_T} = \sqrt{2} \sigma_A \]

\[ K(p_T) = \left( \frac{\sigma_{p_T}}{p_T} \right)_{p_T^3 \to 0} \left( \frac{\sigma_{p_T}}{p_T} \right)_{p_T^3 < 10 \text{ GeV}} \]

\[ \left( \frac{\sigma_{p_T}}{p_T} \right)_{\text{corrected}} = K(p_T) \times \left( \frac{\sigma_{p_T}}{p_T} \right)_{p_T^3 < 10 \text{ GeV}} \]
Jet Energy Resolution (bisector)

\[ \vec{p}_T = \vec{p}_{T1} + \vec{p}_{T2} \]

- The imbalance transverse momentum vector is projected along an orthogonal coordinate system in the transverse plane
  - the \( \eta \)-axis is chosen to bisect the two leading jet directions

- Basic assumption of the method: the variances of \( p_{T\psi} \) and \( p_{T\eta} \) both contain identical isotropic contributions

- An estimate of the jet \( p_T \) resolution is given by

\[
\sigma^2_{p_T} = \frac{\sigma^2_{\psi} - \sigma^2_{\eta}}{-2 \cos (\Delta \phi)}
\]

\[\text{ATLAS Preliminary}\]

\[\text{ATLAS-CONF-2010-054}\]
Missing $E_T$ Performance

- Minimum bias events
  - cells in clusters used
  - LCW calibration used

- A sample enriched in high $p_T$ jets (anti-$k_T$ $R=0.4$) contains outliers, all of which with a high $p_T$ jet aligned or anti-aligned with the missing transverse energy vector
  - similar events are found in Monte Carlo
  - mainly mis-measured jets in calorimeter transition regions