Jet energy scale uncertainty and resolution in the ATLAS experiment

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Jet energy scale and resolution in the ATLAS experiment:
Quantifying the performance of jet reconstruction

Motivation:

- **Hadronic jets**: hard objects widely produced at the LHC
- Understanding of jets and QCD crucial for physics at the LHC:
  - **Standard Model** jet measurements in a new kinematic regime
    (P. Francavilla, D. Miller’s talks)
  - Dijet/multijet: possible hints to **new physics**
    (A. Gibson, A. Taffard’s talks)
  - Jets are essential ingredient in **top** analyses
    (M. Costa, P. Ferrari, D. Hirschbuel’s talks)

This talk:

**Selected** ATLAS results on **jet reconstruction performance**:
jet energy scale and resolution
Jet energy scale – Jet calibration

Jet reconstruction in ATLAS

Jet finding: from partons/particles/energy deposits to jets

Energy deposits → noise-suppressed 3D clusters: you exploit transverse and longitudinal calorimeter segmentation

Jet inputs clustered with anti-\( k_T \) algorithm:
- Infrared safe, collinear safe (⇒ NLO comparisons)
- Regular, cone-like jets in calorimeters
- Distance parameter 0.4, 0.6

Jet calibration: restore the jet energy scale (JES)

Calorimeter jet response needs to be corrected for:
- **Non-compensating** calorimeters
- **Inactive** material
- **Out-of-cone** effects

⇒ calibrate the jet kinematics to the **hadronic scale**

JES uncertainty:

Main uncertainty source for many physics measurements:
jet/dijet cross section, top mass...
Baseline calorimeter energy scale: electromagnetic scale

Extracted from $Z \rightarrow ee$, electron test beams, MIP $\mu$

**ATLAS default:** EM+JES Calibration [ATLAS-CONF-2011-032]

- Data-derived offset pile-up subtraction [ATLAS-CONF-2011-030]
- Restore average JES with $(\eta, E)$-dependent calibration constants from MC
- Allows direct estimation of JES uncertainty

**Undergoing commissioning** (improved performance) [ATLAS-CONF-2010-053]:

- **Global Sequential Calibration (GS):**
  Exploit longitudinal and transverse energy deposition in calorimeter layers

- **Global Cell Weighting (GCW):**
  Use cell energy density to weight cells within jet

- **Local Cluster Weighting (LCW):**
  Factorized corrections derived from cluster properties in single pion MC, independent from jet context
Pile-up in jet reconstruction and calibration

In-time pile-up (2010 and 2011): multiple interactions in same bunch crossing → additional soft diffuse radiation

- **Measure** extra energy per calorimeter tower ($\Delta \phi \times \Delta \eta = 0.1 \times 0.1$) from minimum bias data (*Tower-level offset: $\Delta E_T^{EM}$*)
- **Subtract** additional per-jet, per vertex offset (for 2010 EM+JES jets only)
- **Validate** correction using jets with tracks from primary vertex

![Graph showing EM energy scale with different number of vertices (N_V)]
Jet energy scale – Jet calibration

Pile-up in jet reconstruction and calibration

Out-of-time pile-up (2011): overlapping signal from collisions in other bunch crossings
→ affects calorimeter energy reconstruction

- Compensation of in-time/out-of-time pile-up in ATLAS calorimeter readout
  → Negative energy contribution to signal from other bunch crossings
- Change in the baseline energy scale accounted for in jet calibration
- Offset used to estimate additional JES uncertainty
Jet energy scale – Jet energy scale

Jet energy scale uncertainty in ATLAS (EM+JES)

Estimate JES uncertainty using:
- isolated hadron response uncertainties (in-situ/test beam)
- Monte Carlo samples with systematic variations
- $p_T$ balance in dijet events
- in-situ measurements in case of pile-up
  (added separately as $f(N_{PV})$, on average $<3\%$ for low $p_T$ central jets)

Before collisions:
$< 6.5\%$ for central jets, $p_T = 200 \text{ GeV}$
$< 10\%$ for endcap jets

After analysis of 2010 collision data:
$< 2.5\%$ for central jets, $p_T = 100 \text{ GeV}$
$< 9 \ (14)\%$ for endcap (forward) jets

[ATLAS-CONF-2011-032]
C. Doglioni - 21/07/2011 - EPS HEP, Grenoble
Jet energy scale uncertainty in ATLAS (EM+JES)

Estimate JES uncertainty using:
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2011 analyses: initial estimate of pile-up uncertainty

- **Keep** 2010 JES uncertainty as baseline
- **Add** pile-up uncertainty from data/MC comparison of expected offset:
  - $20 < p_T^{jet} < 50$ GeV: $\oplus 5\%$ for central jets, $\oplus 7\%$ for forward jets
  - $50 < p_T^{jet} < 100$ GeV: $\oplus 2\%$ for central jets, $\oplus 3\%$ for forward jets
- **Validate** average JES and uncertainty using in-situ measurements
JES uncertainty due to calorimeter EM response

Propagate single isolated hadron uncertainties to jets to obtain estimate of calorimeter $\Delta_{JES}$

$\Rightarrow$ uncertainty constrained by in-situ measurements

Data used to evaluate calorimeter uncertainties:

- Isolated tracks matched to calorimeter clusters ($E/p$): $0.5 < p < 20$ GeV
  - Average hadronic response in calorimeters described by MC within 2-5% [ATLAS-CONF-2011-028]
  - Use of resonances for particle identification [ATLAS-CONF-2011-019]

Additional sources of single hadron uncertainties include:
calorimeter acceptance, absolute EM energy scale, dead material

Total calorimeter contribution to JES uncertainty: 1.5-4%
Jet energy scale – Jet energy scale

JES uncertainty due to calorimeter EM response

Propagate single isolated hadron uncertainties to jets to obtain estimate of calorimeter $\Delta_{JES}$

$\Rightarrow$ uncertainty constrained by in-situ measurements

Full bin-by-bin correlation matrix available for calorimeter uncertainty:

Relevant correlations for jets close in $p_T$, limited for low vs high $p_T$ jets
In-situ validation of the JES: 2010 data

In-situ techniques used to validate JES and its uncertainty

- use well calibrated object(s) as reference for jet $p_T$
- compare calibrated jets in data and Monte Carlo simulation

Techniques used in ATLAS:

- Balance high $p_T$ jet with recoil system ($Multi$-$jet$ / $MJB$) [ATLAS-CONF-2011-029]
- $\gamma$-jet direct $p_T$ balance [ATLAS-CONF-2011-031]
- Missing-$E_T$ projection fraction ($MPF$) [ATLAS-CONF-2011-031]
- Compare calorimeter jets to track-jets [ATLAS-CONF-2011-068]
- $Z \rightarrow ee$-jet $p_T$ balance (2011 only)

In-situ balance for EM+JES calibrated jets in data vs Monte Carlo → cross-check of JES uncertainty up to jet $p_T \approx 1$ TeV
Increased pile-up in 2011 data
⇒ new jet energy scale, no pile-up correction
Need to validate MC-based JES with in-situ techniques

- MPF, Z+jets: data/MC differences in 2011 baseline
  JES covered by 2011 JES uncertainty

- Multi-jet balance: good understanding of JES up to $p_T = 1.4$ TeV
Knowledge of JER necessary for data unfolding/evaluating systematics
Two independent in-situ techniques to estimate JER and compare to MC

**Dijet balance method** [D0, hep-ex/0012046v2]
- Based on momentum conservation in transverse plane for dijet events
- Method systematics (2010): $\approx 5\text{-}8\%$

**Bisector method** [UA2, CERN-EP-83-94]
- Based on decomposition of vector sum of two leading jets
- Method systematics (2010): $\approx 3\text{-}4\%$
Jet energy resolution – Results for 2010 and 2011 data

Jet energy resolution in 2010

Data (points) / MC (fit) agreement within uncertainties for EM+JES jets (bisector method shown)

\[ \frac{\sigma(p_T)}{p_T} \]

Data 2010 \( \sqrt{s} = 7 \text{ TeV} \)
anti-\( k_t \) \( R = 0.6 \) cluster jets
0.0<|y|<0.8

\[ \int L \, dt = 35 \text{ pb}^{-1} \]

ATLAS Preliminary

Up to 30% improvement if using refined calibration techniques
Jet energy resolution in 2011

Comparison with 2010 resolution:

Increase of JER at low $p_T$ wrt 2010, within 10% elsewhere
Conclusions

Conclusions and outlook

Good understanding of the **jet energy scale** and **resolution** in **2010** and **2011** ATLAS data

**Jet energy scale and uncertainty**

- Default **MC-based calibration** allows for direct estimate of JES uncertainty
- Average **pile-up** conditions accounted for in calibration:
  - Pile-up correction in place for 2010, being developed for 2011
- Current JES uncertainty: **3-4%** for central jets with $p_T > 100$ GeV
- JES and uncertainty validated with in-situ techniques

**Jet energy resolution (JER)**

- Two independent techniques to measure JER with data
- Comparison to MC: **good agreement** for 2010 data
- Expect **improvements** in JER when refined jet calibrations applied
Backup slides
**Inner detector**
- Pixel detectors, semiconductor tracker (SCT), transition radiation tracker
  - $\approx 87M$ readout channels, coverage up to $|\eta| < 2.5$
  - Immersed in 2T solenoidal magnetic field

**Electromagnetic and hadronic calorimeters**
- Subsystem technology and granularity $\leftrightarrow$ shower characteristics
  - Transverse and longitudinal sampling
  - Fine granularity: $\approx 200\,000$ readout cells up to $|\eta| < 4.9$
- Energy deposits grouped in noise-suppressed **3D topological clusters**
ATLAS calorimeters: expected performance

- EM barrel/endcap (LAr/EMEC):
  Pb/LAr accordion
  $\sigma/E \approx 10 - 17\%/\sqrt{E} + 0.7\%$

- HAD barrel (Tile):
  Fe/scintillator tiles:
  $\sigma/E \approx 50\%/\sqrt{E} + 3\%$

- HAD endcap (HEC):
  Cu/LAr
  $\sigma/E \approx 50\%/\sqrt{E} + 3\%$

- EM/HAD forward (FCal):
  Cu/W-LAr
  $\sigma/E \approx 100\%/\sqrt{E} + 10\%$

Signal readout time for LAr calorimeters: 500 ns:

- Shaping leads to negative contribution in pulse shape

(a) Triangular pulse of the current for a LAr cell and output signal after bi-polar shaping.

(b) Noise level as function of peak shaping time $t_p$ for various LHC luminosities, with bunch crossings every 25 ns
Signal readout time for LAr calorimeters: 500 ns:

- Shaping leads to negative contribution in pulse shape

Pulse shape in 2009 beam splash events
Backup slides – ATLAS calorimeters and out-of-time pile-up

**Effect of pileup on mean tower energy**

Average calorimeter tower transverse energy \( \langle E_{T,tower}^{EM} \rangle \) as a function of the distance from the last empty bunch in the current bunch train for different average number of interactions \( \langle \mu \rangle \):

- **Beginning of bunch train**: larger \( \langle E_{T,tower}^{EM} \rangle \) due to incomplete cancellation in calorimeter read-out ⇒ **out-of-time pileup**
- **Variation of peak amplitude with \( \langle \mu \rangle \)**: depends on conditions of current bunch ⇒ **in-time pileup**
- **Cancellation of in/out-of-time pileup** happens away from train beginning/end

![Graph showing the effect of pileup on mean tower energy](image)
Jet calibration chain in ATLAS in 2010

1. **Pileup OFFSET correction**: subtract average additional energy due to pile-up
   - Use correction constants measured in-situ
2. **ORIGIN correction**: correct jet position
   - Jet originates from primary interaction vertex
3. **EM+JES calibration**: restore jet energy/position ($\eta$)
   - Derive correction factors from Monte Carlo Pythia sample tuned to ATLAS data

**Pile-up offset correction**

For a given luminosity $L$, number of primary vertices $N_{PV}$, $\eta$:

1. Calculate average extra energy per tower as a function of NPV: $\langle \Delta E_{T,tower} \rangle$
2. Calculate number of towers per jet (take average for topocluster jet): $N_{towers}$
3. Derive offset to subtract jet by jet: $O(\eta, N_{PV}, L) = \langle \Delta E_{T,tower} \rangle \cdot N_{towers}$
   $\Rightarrow$ Correction only applied on events with $N_{PV} > 1$ in 2010 data
JES and uncertainty: derived assuming q/g composition in MC, isolated jets
⇒ consider dependence of response of jet on parton initiating the jet
   (specific fragmentation/showering) [ATLAS-CONF-2011-053]
⇒ consider effect due to close-by jets [ATLAS-CONF-2011-062]

- Determine sample flavour composition using template fits to jet properties (not yet applied)
- Compare calorimeter jets to track jets with close-by topologies
- Additional JES uncertainty contributions:
  - Flavour uncertainty:
    How much does the response of the sample differ from the response of the inclusive jet sample?
  - Flavour composition:
    How well is the average flavour content of the sample known?
  - Close-by jets:
    How well does the MC describe the response of close-by jets?

Template fit to jet width on γ-jet data sample using templates derived from di-jet MC sample (fraction of HQ-jets is taken from simulation).
In-situ validation of the JES: 2011 vs 2010

ATLAS preliminary
\( \sqrt{s} = 7 \) TeV

\[ R_{\text{MPF}} \]

\[
\begin{align*}
\text{2010 data: } & \int L \ dt = 38 \text{ pb}^{-1} \\
\text{2011 data: } & \int L \ dt = 786 \text{ pb}^{-1}
\end{align*}
\]

MPF EM scale, all jet algorithms

\[
\begin{align*}
2011 \text{ data} / 2010 \text{ data} & \approx 1.00
\end{align*}
\]

Multi-jet balance (right): \( p_T \) reach, statistical precision improve significantly in 2011 wrt 2010
Jet energy resolution in 2011: data vs MC

ATLAS Preliminary
Data 2011 $\sqrt{s} = 7$ TeV
\[ \int L \, dt \sim 950 \text{ pb}^{-1} \]

Anti-$k_t$ $R = 0.6$ cluster jets
EM+JES calibration

$0.0 < |y_{\text{ref}}| < 0.8$
$0.0 < |y_{\text{probe}}| < 0.8$

Increased pile-up conditions affects data/MC comparison in jet resolution
Jet energy resolution in 2011

EM+JES vs Local Cluster Weighting:

Relative improvement of more than 30% if using Local Cluster Weighting

Data 2011 $\sqrt{s} = 7$ TeV
anti-$k_t$, $R = 0.6$ cluster jets
$0.0<|y|<0.8$

$\int L \, dt = 950 \, \text{pb}^{-1}$

ATLAS Preliminary