Jet energy scale uncertainty and resolution in the ATLAS experiment

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Outline

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

Motivation:

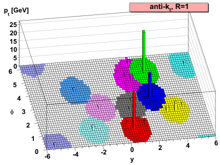
- **Hadronic jets**: hard objects widely produced at the LHC
- Understanding of jets and QCD crucial for physics at the LHC:
  - Standard Model jet measurements in a new kinematic regime (P. Francavilla, D. Miller's talks)
  - Dijet/multijet: possible hints to new physics (A. Gibson, A. Taffard's talks)
  - 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 reconstruction in ATLAS

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



[Cacciari, Salam, Soyez JHEP 0804:063,2008]

Energy deposits → noise-suppressed **3D clusters**: 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...

Calibration schemes in ATLAS

Baseline calorimeter energy scale: `electromagnetic` **scale**

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

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

- Data-derived offset pile-up subtraction [ATLAS-CONF-2011-030]
- Restore average JES with (η, 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

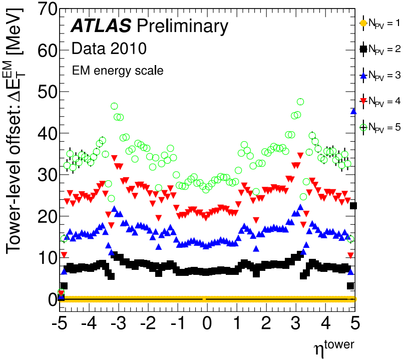
Global Cell Weighting (GCW) :
Use cell energy density to weight cells within jet

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
$\rightarrow$ *additional soft diffuse radiation*

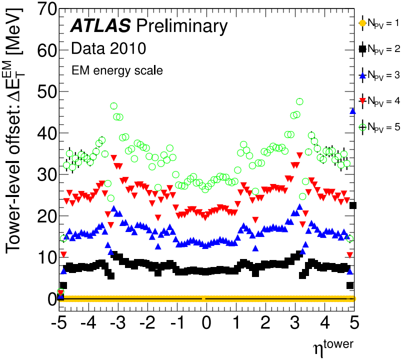
- Measure extra energy per calorimeter tower ($\Delta\phi \times \Delta\eta = 0.1 \times 0.1$) from minimum bias data (*Tower-level offset:* ΔE_T^{EM})
- Subtract additional per-jet, per vertex offset (for 2010 EM+JES jets only)
- Validate correction using jets with tracks from primary vertex

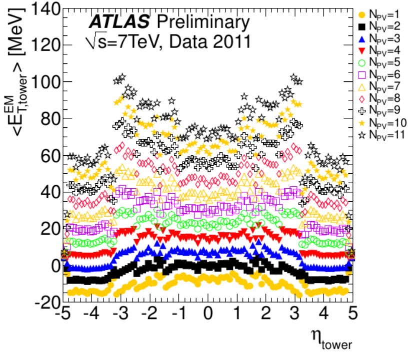


Pile-up in jet reconstruction and calibration

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

- Compensation of in-time/out-of-time pile-up in ATLAS calorimeter readout
  $\rightarrow$ 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





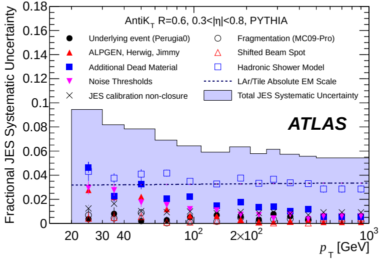
Jet energy scale uncertainty in ATLAS (EM+JES)

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:

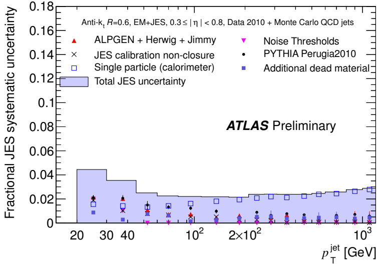
<**6.5%** for central jets, p_T=200 GeV
<**10%** for endcap jets



[ATLAS-CONF-2010-056 , EPJC]

After analysis of 2010 collision data:

<**2.5%** for central jets, p_T =100 GeV
<**9 (14)%** for endcap (forward) jets



[ATLAS-CONF-2011-032]

Jet energy scale uncertainty in ATLAS (EM+JES)

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  (added separately as f(N_{PV}), on average <3% for low p_T central jets)

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** Δ_{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]
- 2004 combined ATLAS test-beam: $20 < p < 350$ GeV [ATL-TILECAL-PUB-2009-007]

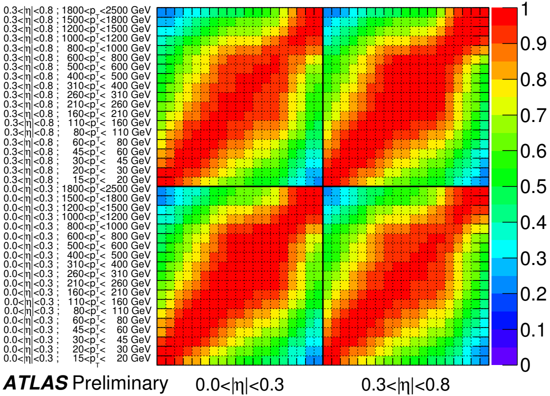
Additional sources of single hadron uncertainties include:
calorimeter acceptance, absolute EM energy scale, dead material

Total calorimeter contribution to JES uncertainty: **1.5-4%**

JES uncertainty due to calorimeter EM response

Propagate single isolated hadron uncertainties to jets
to obtain estimate of **calorimeter** Δ_{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

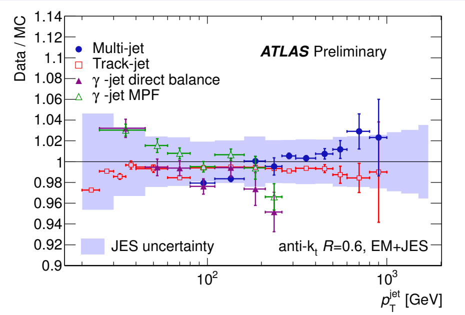
In-situ validation of the JES: 2010 data

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:

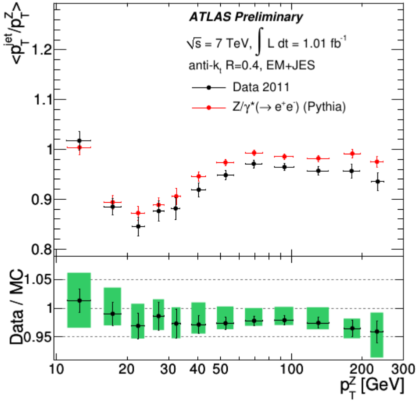
- Balance high p_T jet with recoil system (*Multi-jet / MJB*) [ATLAS-CONF-2011-029]
- γ-jet direct p_T balance [ATLAS-CONF-2011-031]
- Missing-E$_T$ projection fraction (*MPF*) [ATLAS-CONF-2011-031]
- Compare calorimeter jets to track-jets [ATLAS-CONF-2011-068]
- $Z \to ee$-jet p_T balance (2011 only)

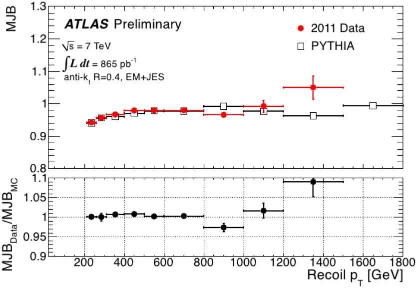


In-situ balance for EM+JES calibrated jets in data vs Monte Carlo
$\rightarrow$ cross-check of JES uncertainty up to jet $p_T \approx 1$ TeV

In-situ validation of the JES: 2011 data

Increased pile-up in 2011 data
⇒ **new** jet energy scale, no pile-up correction
Need to **validate** MC-based JES
with **in-situ** techniques





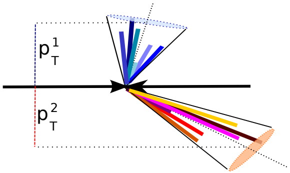
- MPF, Z+jets:
  data/MC differences in 2011 baseline JES **covered** by 2011 JES uncertainty
- Multi-jet balance:
  good understanding of JES up to p_T=1.4 TeV

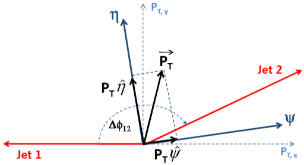
Estimating the jet energy resolution (JER)

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): ≈ 5-8%



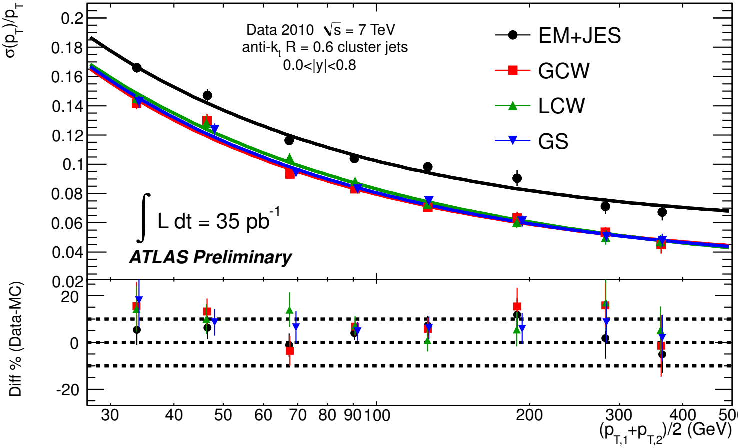


Bisector method [UA2, CERN-EP-83-94]

- Based on decomposition of vector sum of two leading jets
- Method systematics (2010): ≈ 3-4%

Jet energy resolution in 2010

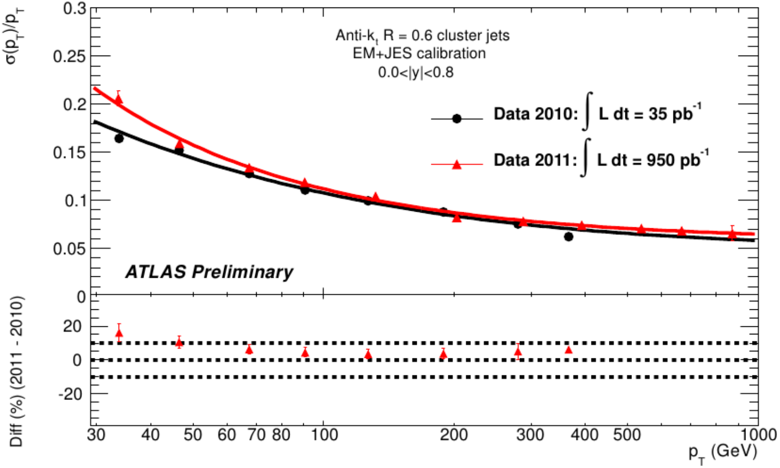
Data (points) / MC (fit) agreement within uncertainties for EM+JES jets (bisector method shown)



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 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

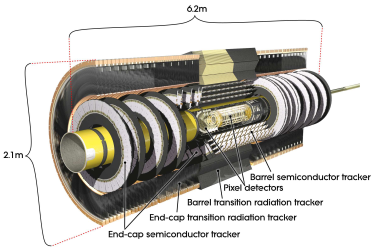
The ATLAS inner detector and calorimeters

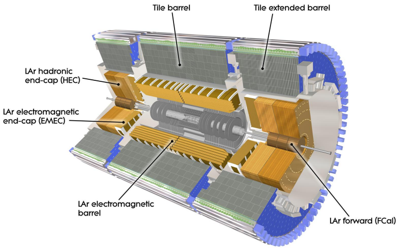
Inner detector

- 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

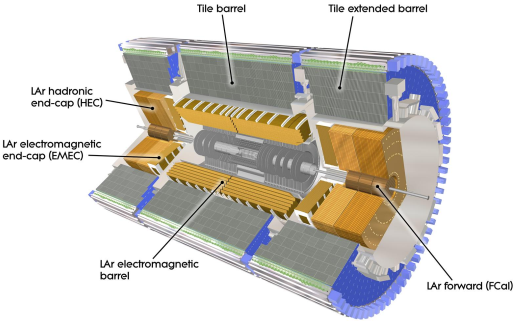
- Subsystem technology and granularity $\leftrightarrow$ shower characteristics
  - **transverse** and **longitudinal** sampling
  - fine granularity: $\approx$ 200 000 *readout cells* up to $|\eta| < 4.9$
- Energy deposits grouped in noise-suppressed **3D topological clusters**





ATLAS calorimeters: expected performance

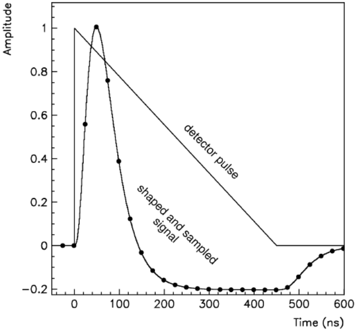
- EM barrel/endcap (LAr/EMEC): Pb/LAr accordion $\sigma/E \approx 10-17\%/\sqrt{E} \oplus 0.7\%$
- HAD barrel (Tile): Fe/scintillator tiles: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$
- HAD endcap (HEC): Cu/LAr $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$
- EM/HAD forward (FCal): Cu/W-LAr $\sigma/E \approx 100\%/\sqrt{E} \oplus 10\%$



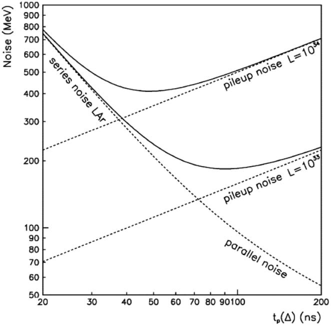
Performance of the ATLAS detector: [JINST 2008 3 S08001, JHEP 09 (2010) 056]

ATLAS LAr calorimeters: out-of-time pile-up

- Signal readout time for LAr calorimeters: 500 ns:
- Use bipolar shaping with time constant to minimize electronics + pile-up noise [IEEE Trans. Nucl. Sci. 53 (2006) 735-740]
- 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

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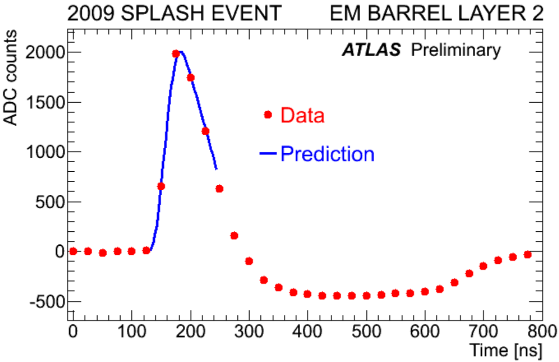
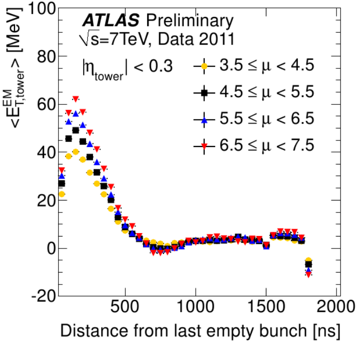
Pulse shape in 2009 beam splash events



Effect of pileup on mean tower energy

Average calorimeter tower transverse energy $< E^{EM}_{T,tower} >$ as a function of the distance from the last empty bunch in the current bunch train for different average number of interactions $< \mu >$



- Beginning of bunch train: larger $< E^{EM}_{T,tower} >$ due to incomplete cancellation in calorimeter read-out $\Rightarrow$ out-of-time pileup
- Variation of peak amplitude with $< \mu >$: depends on conditions of current bunch $\Rightarrow$ in-time pileup
- Cancellation of in/out-of-time pileup happens away from train beginning/end

Jet calibration chain in ATLAS in 2010

Calorimeter energy deposits → Jets (uncalibrated) → Offset correction → Origin correction → EM+JES Energy, eta correction → Jets (EM+JES)

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 (η)
   - Derive correction factors from Monte Carlo Pythia sample tuned to ATLAS data

Pile-up offset correction

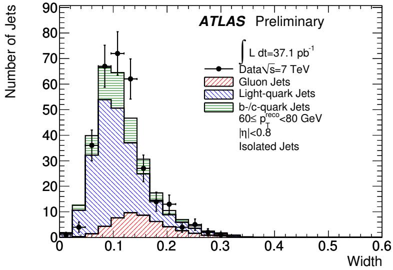
For a given luminosity $\mathcal{L}$, number of primary vertices N_{PV} , η :

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: $O(\eta, N_{PV}, \mathcal{L}) = \langle \Delta E_{T,tower} \rangle \cdot N_{towers}$
   $\Rightarrow$ Correction only applied on events with N_{PV} >1 in 2010 data

JES flavour and topology dependence

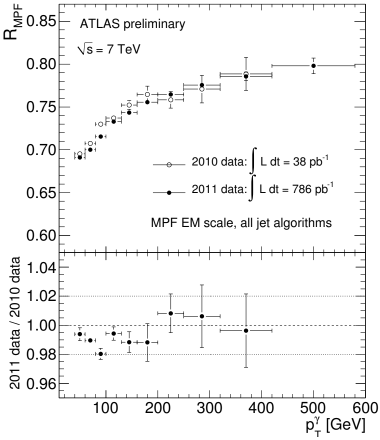
JES and uncertainty: derived assuming q/g composition in MC, isolated jets
⇒ consider dependence of response of jet on parton initiating the jet
(specific fragmentation/showering) [ATLAS-CONF-2011-053]
⇒ consider effect due to close-by jets [ATLAS-CONF-2011-062]

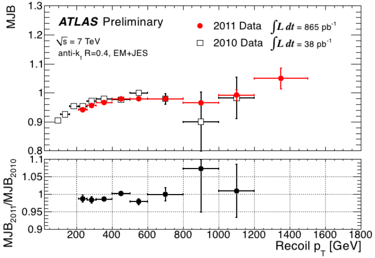
- Determine sample flavour composition using template fits to jet properties (not yet applied)
- Compare calorimeter jets to track jets with close-by topologies
- Additional JES uncertainty contributions:
  - Flavour uncertainty:
    How much does the response of the sample differ from the response of 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).

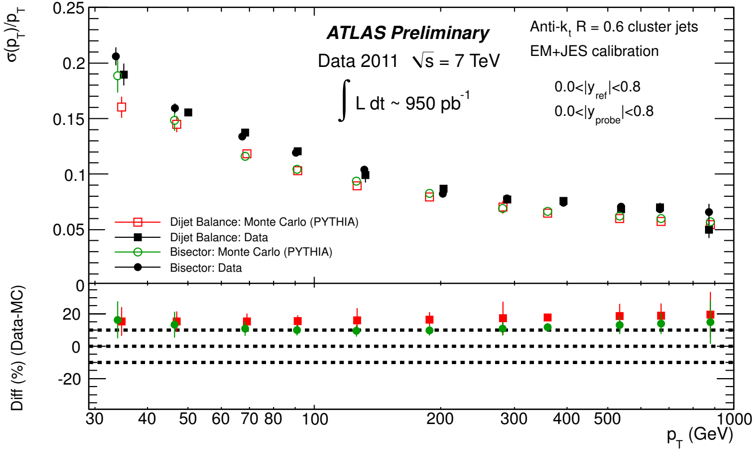
In-situ validation of the JES: 2011 vs 2010





- Multi-jet balance (right): p_T reach, statistical precision improve significantly in 2011 wrt 2010

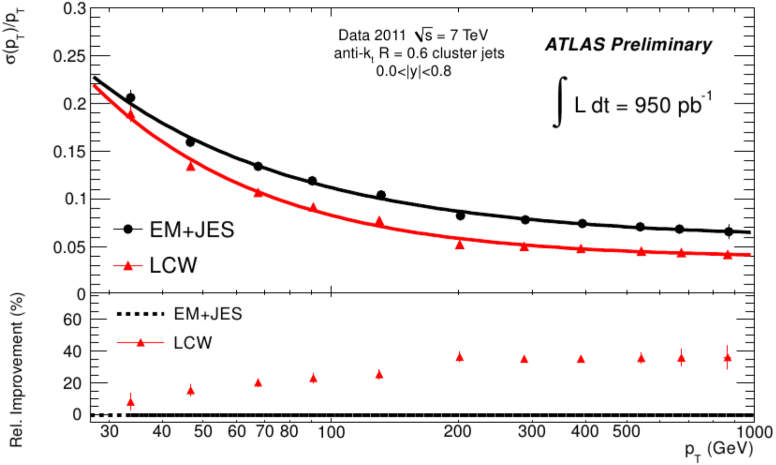
Jet energy resolution in 2011: data vs MC



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