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

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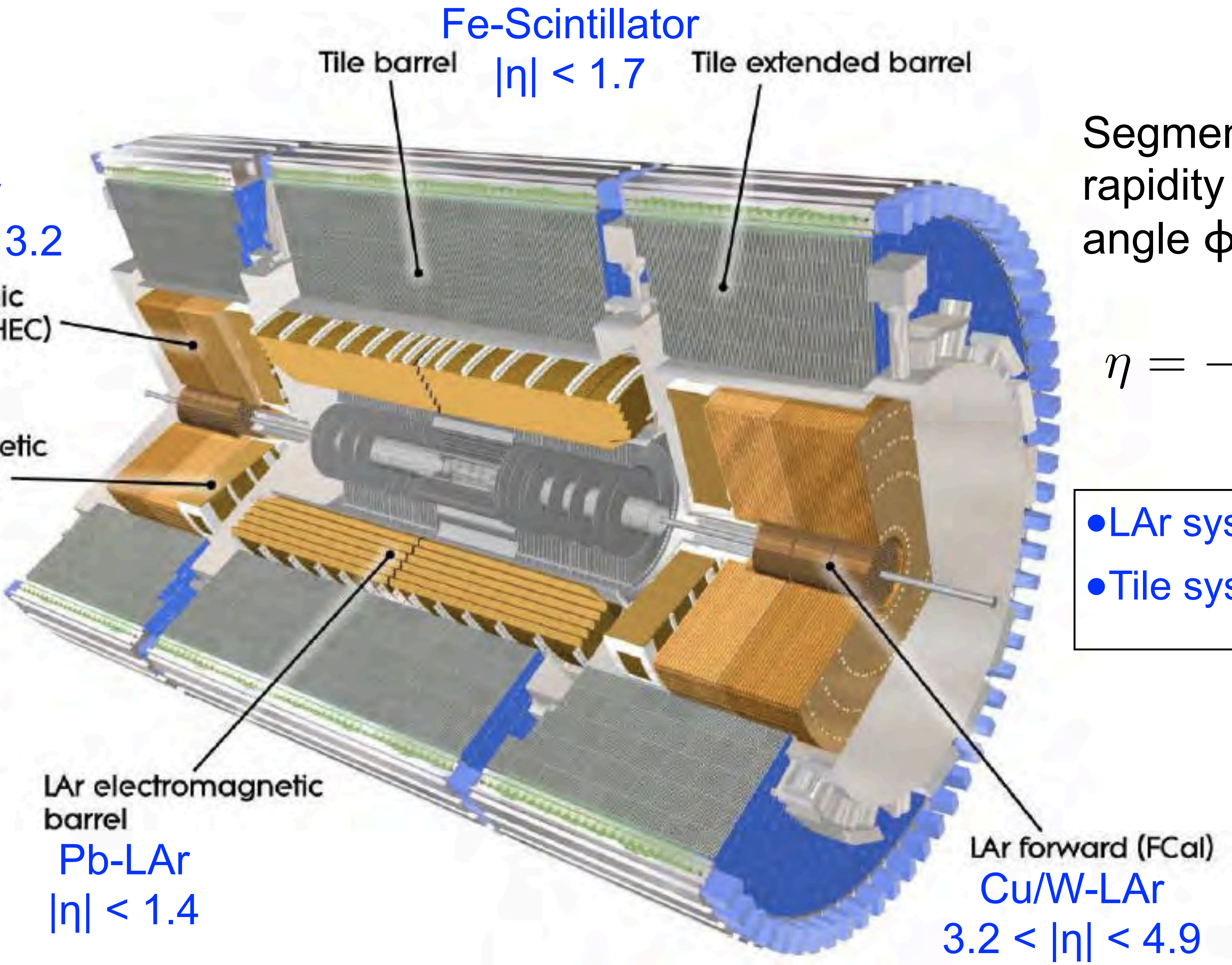
Outline

- 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



Segmented in pseudo-rapidity η and azimuthal angle ϕ

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

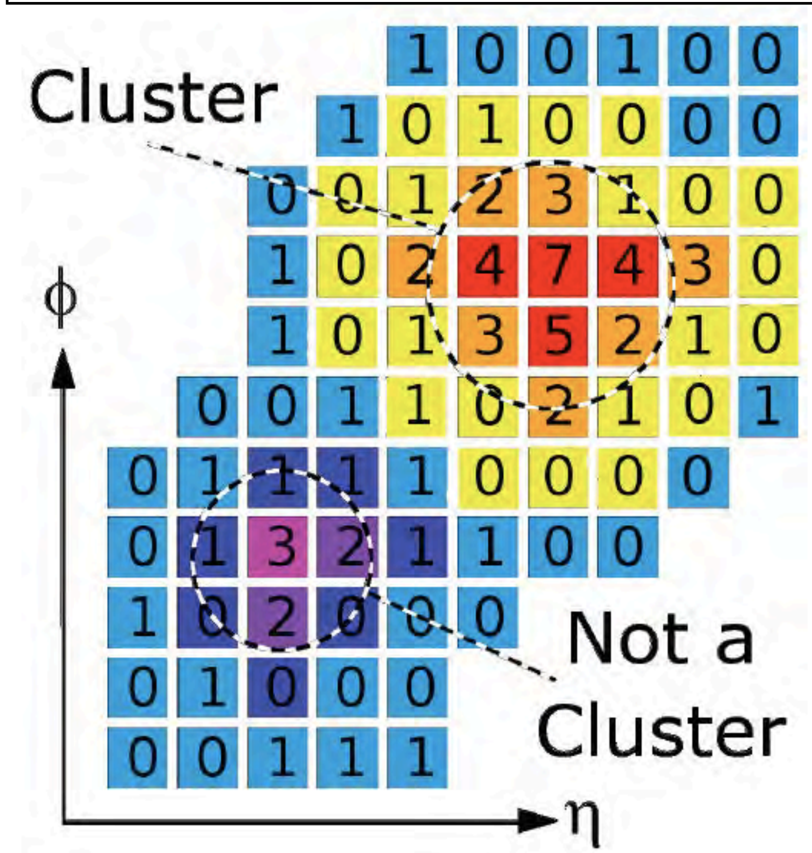
- LAr system: 182,468 cells
- Tile system: 10,364 cells

Over 98% of all cells used for event reconstruction

Inputs to Jet Reconstruction

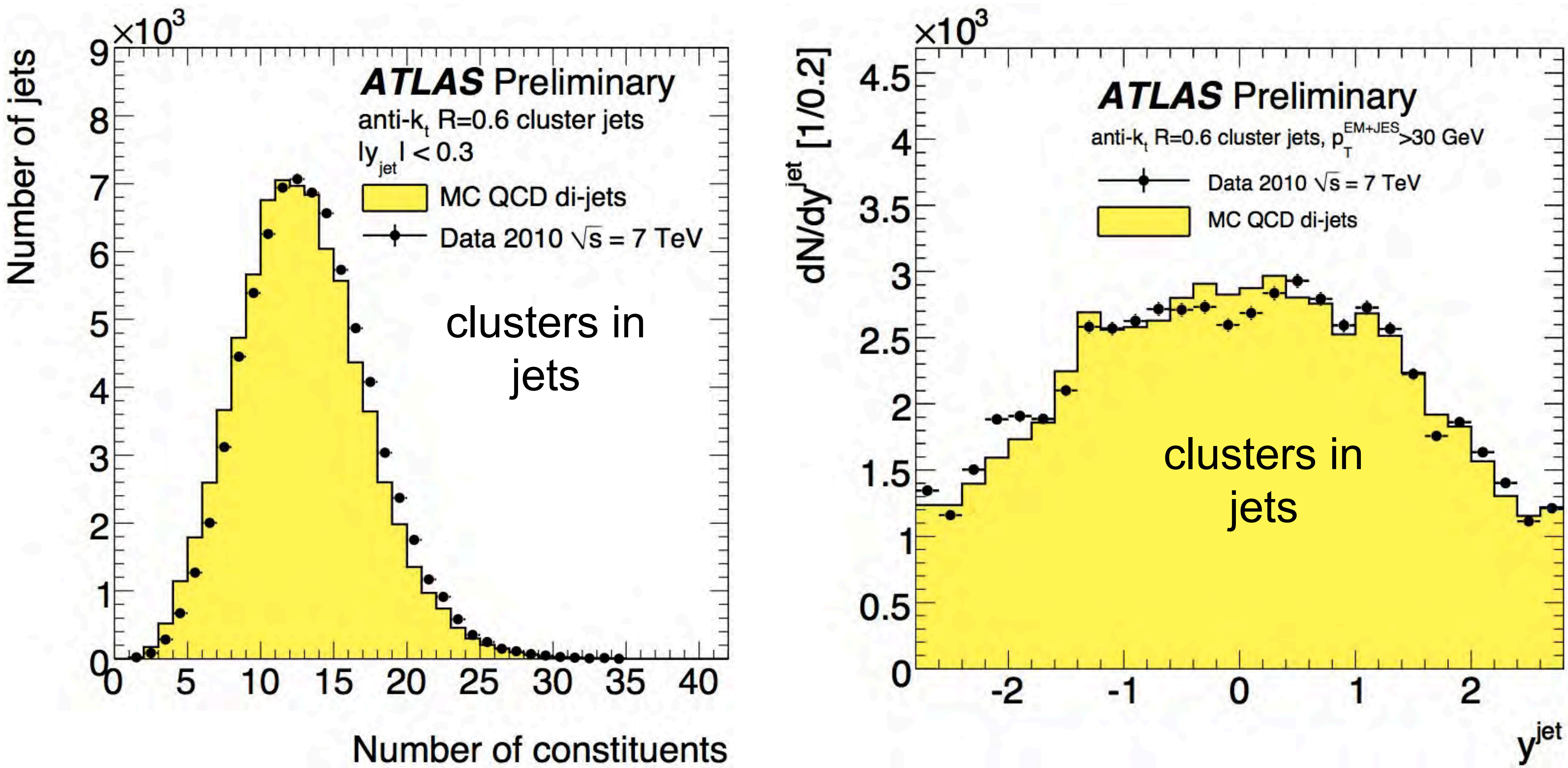
- Topological clusters
  - Dynamically formed calorimeters cell clusters optimized to follow the shower development
  - High calorimeter granularity requires noise suppression
- Noise suppressed towers
  - Calorimeter cells belonging to topological clusters projected on a fixed geometry grid $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ of 6,400 towers
- Tracks
  - Independent from calorimeter measurements
  - Vertex information (also for pileup effects control)
- Jets are reconstructed using the anti-k_T algorithm with size parameter R set at 0.4 or 0.6
  - M. Cacciari and G. P. Salam, Phys. Lett. B 641, 57 (2006)

- 3D clusters use 4-2-0 suppression:
  - cells with $|E| > 4\sigma_{noise}$ seed the cluster
  - neighbouring cells with $|E| > 2\sigma_{noise}$ added iteratively
  - single layer of neighbouring cells added
- Noisy cells (~0.1%) are masked and not used



in units of $|E|/\sigma_{noise}$

Inputs to Jet Reconstruction



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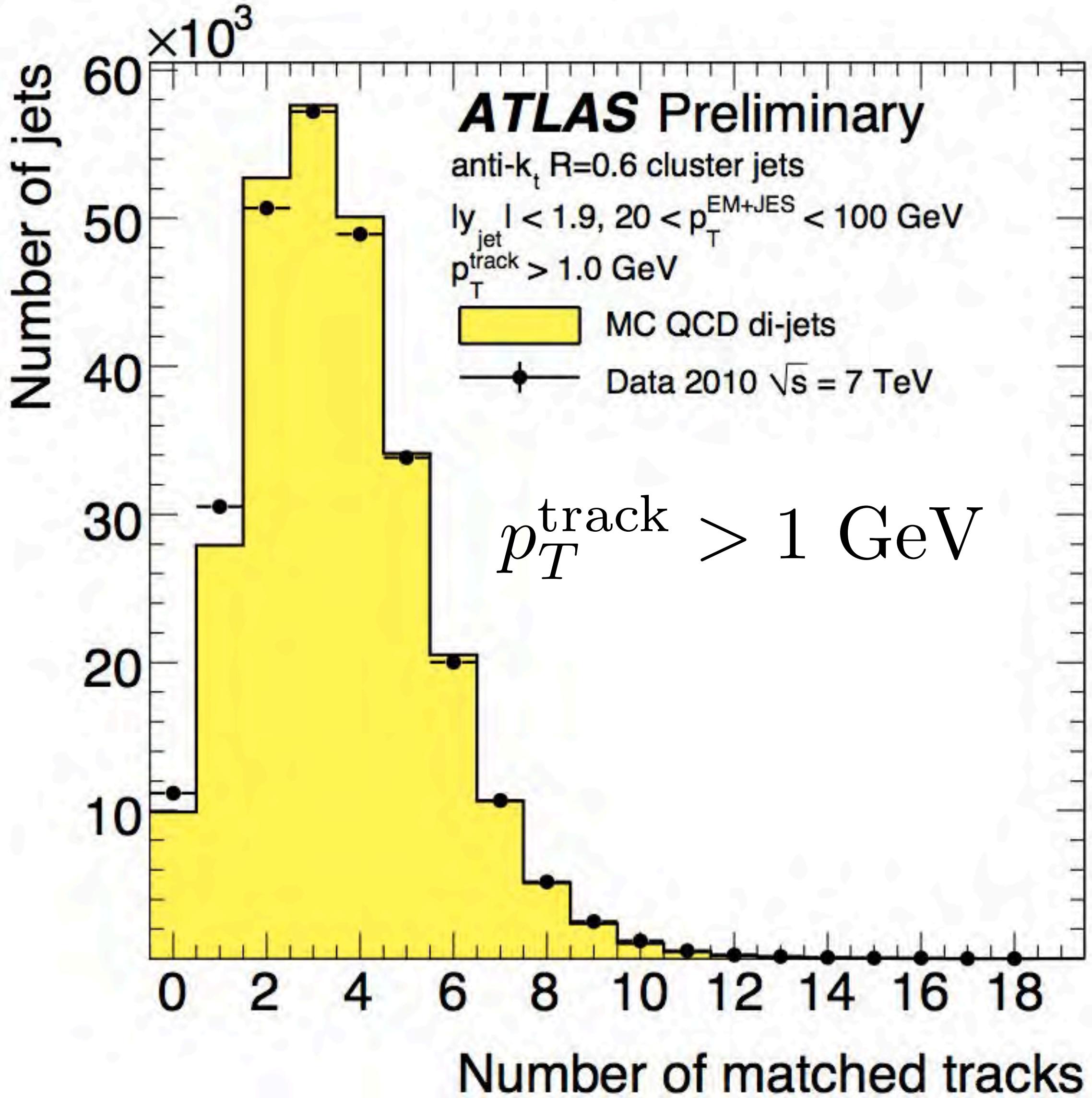
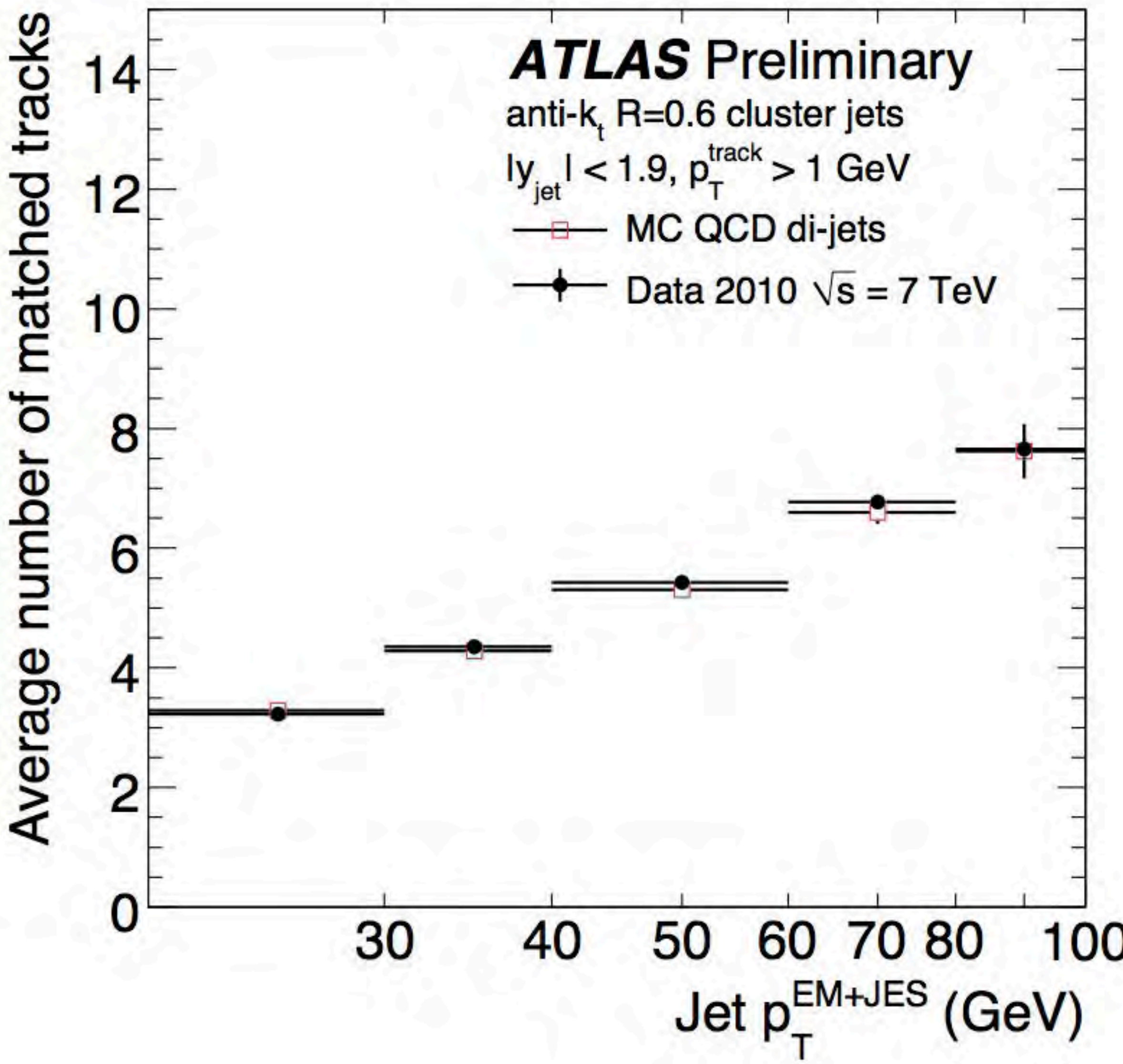
- Mean number of clusters per jet is about 1/4 of the mean number of towers for central jets; in both cases a shift is observed leading to a deficiency of 4.0% and 6.4% in the simulation
- Difference between MC and data probably connected to deficiencies in the physics description in the MC

Inputs to Jet Reconstruction





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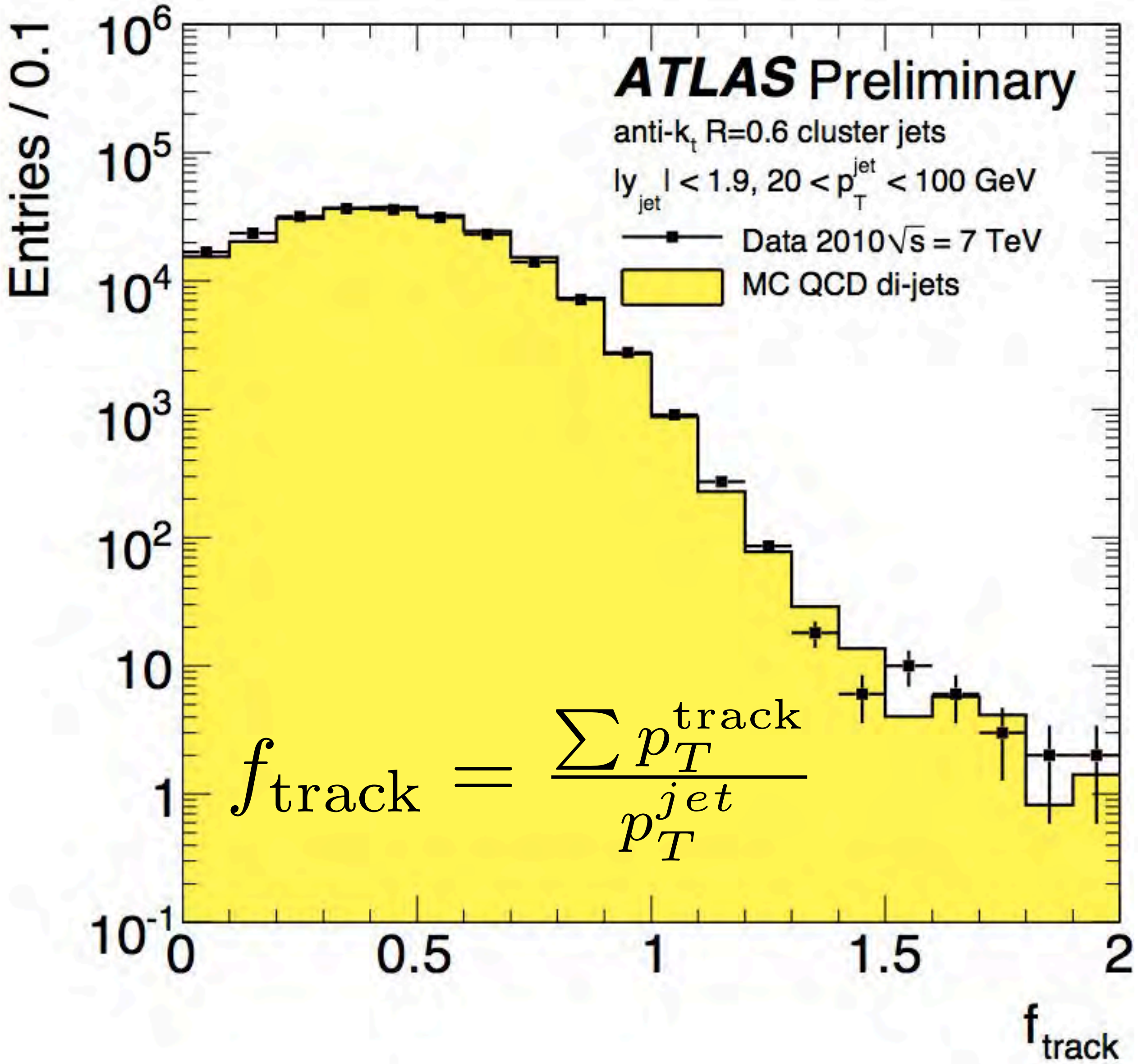
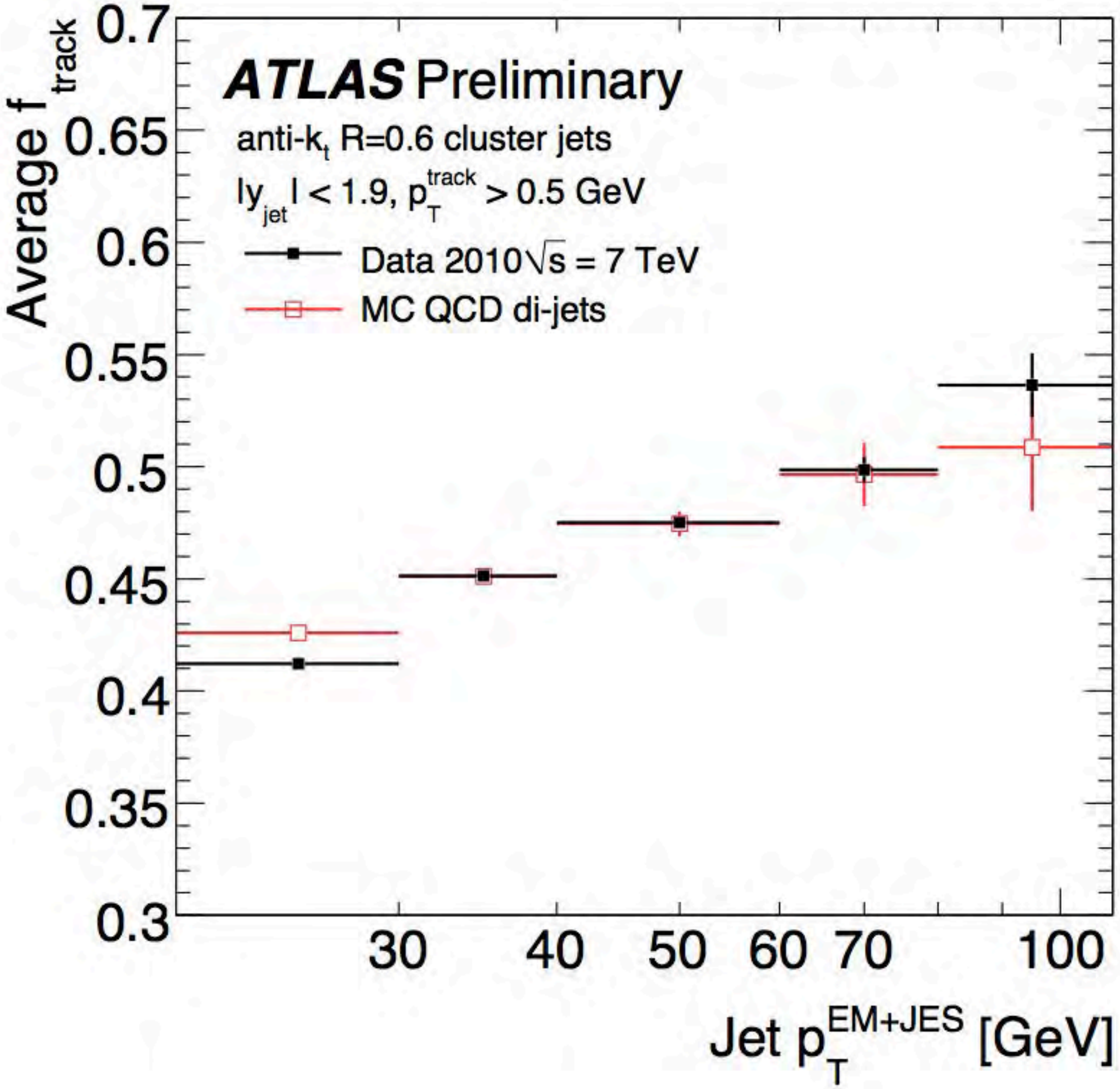
- Charged particle tracks matched to jets provide information on the fraction of neutral and charged energy contained in the jet.
- For softer tracks, there is indication that the treatment of fragmentation and underlying event in MC generators may need tuning (MC underestimates the number of tracks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





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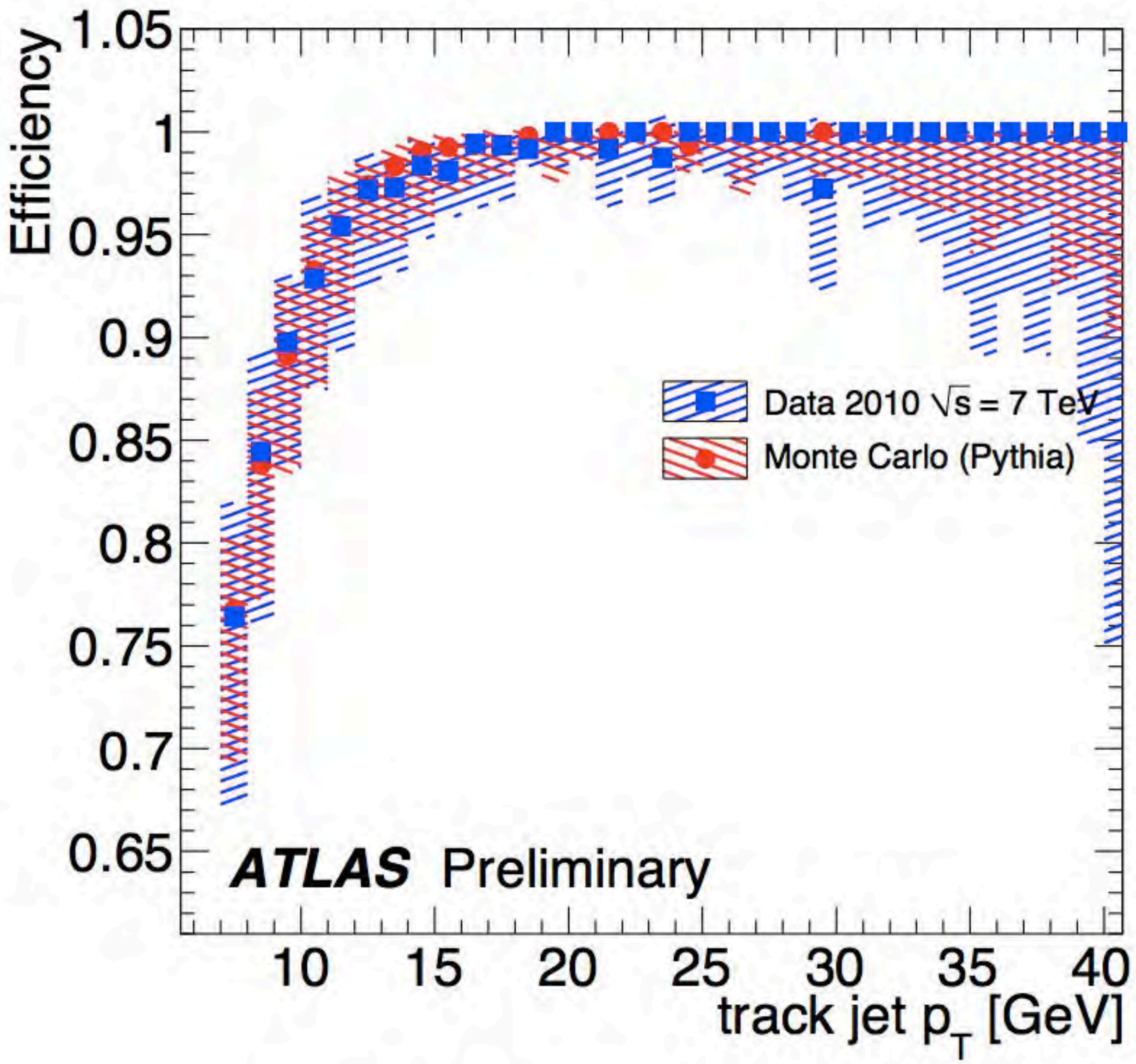
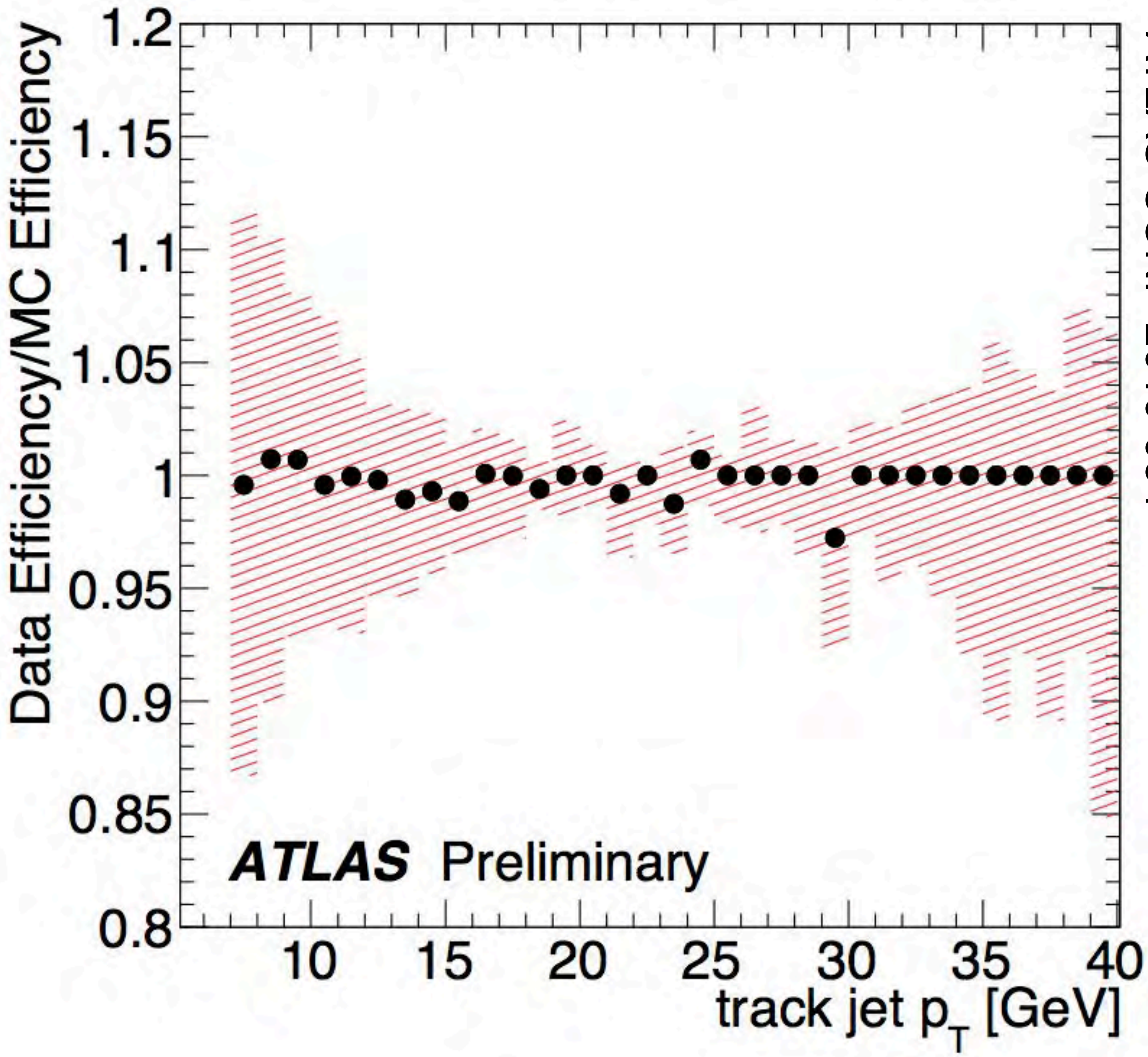
Jet Reconstruction Efficiency





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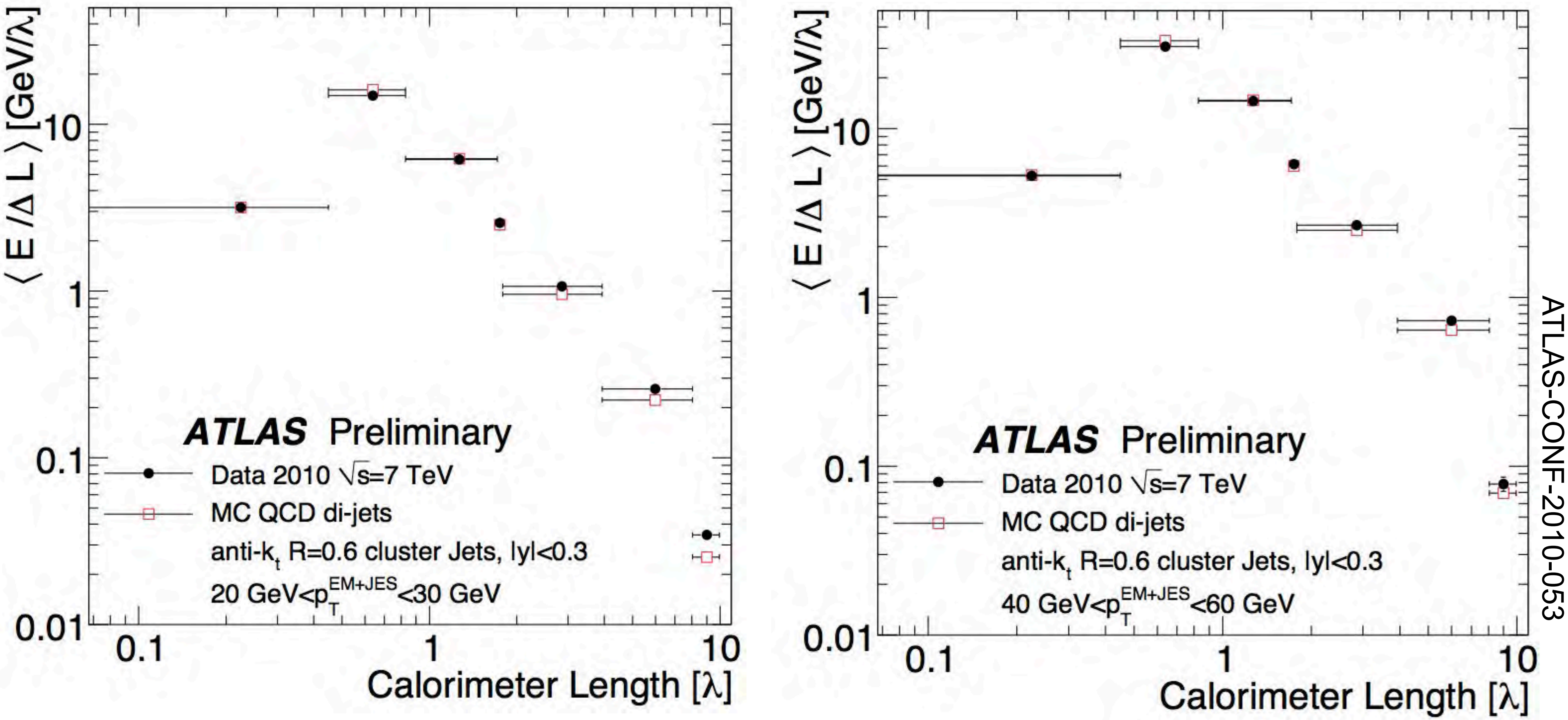
- Calorimeter jet reconstruction an identification efficiency relative to track-jets
  - tag and probe method, valid for $|\eta| < 2.3$

Jet Shapes and Properties

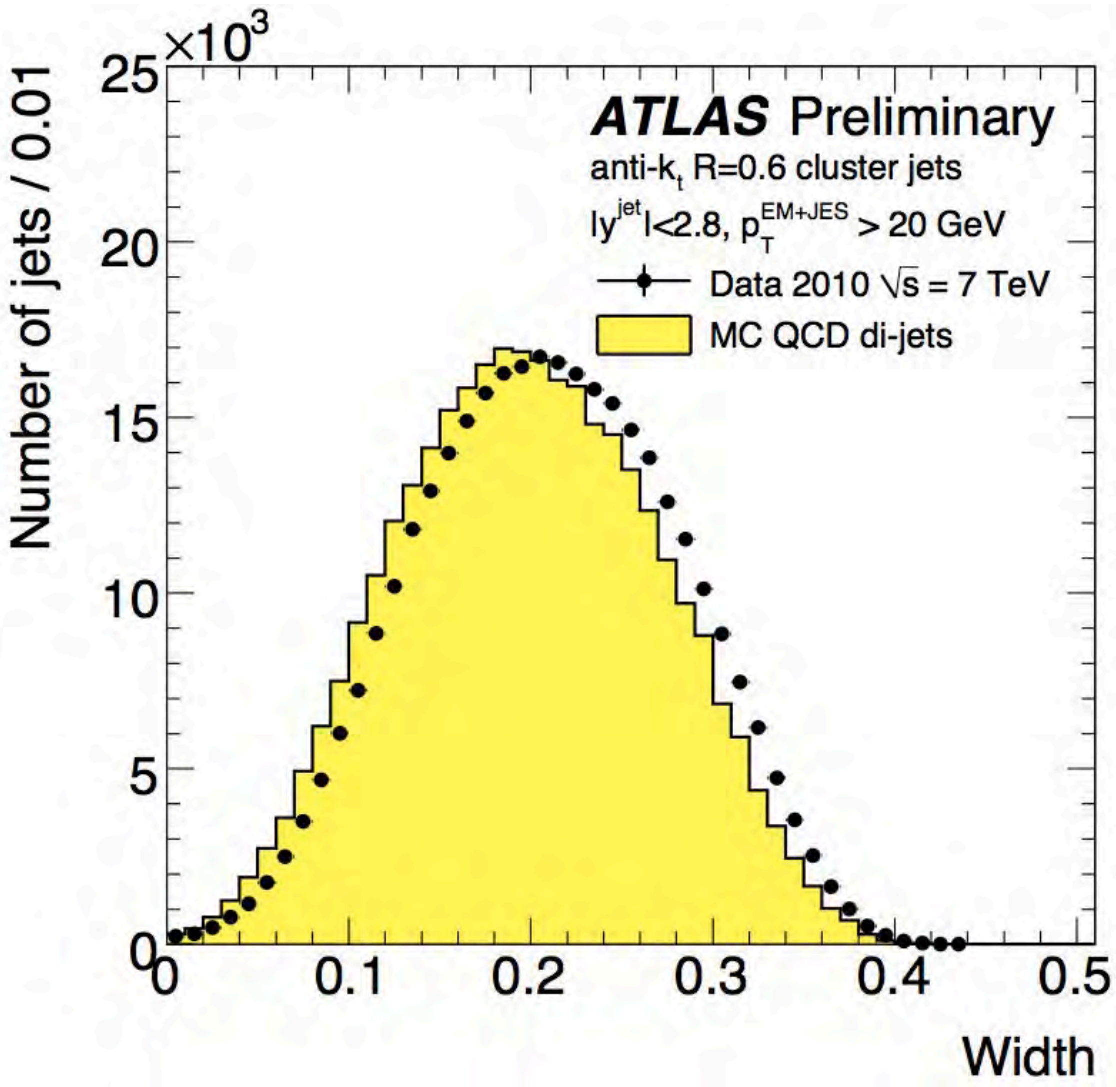
- Measurement of jet shapes and properties are used to test how well the simulation models physics and detector effects
  - Jet fragmentation, detector response to low energy particles, inputs to jet reconstruction, soft underlying event, pileup
  - Calorimeter and track measurements are independent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

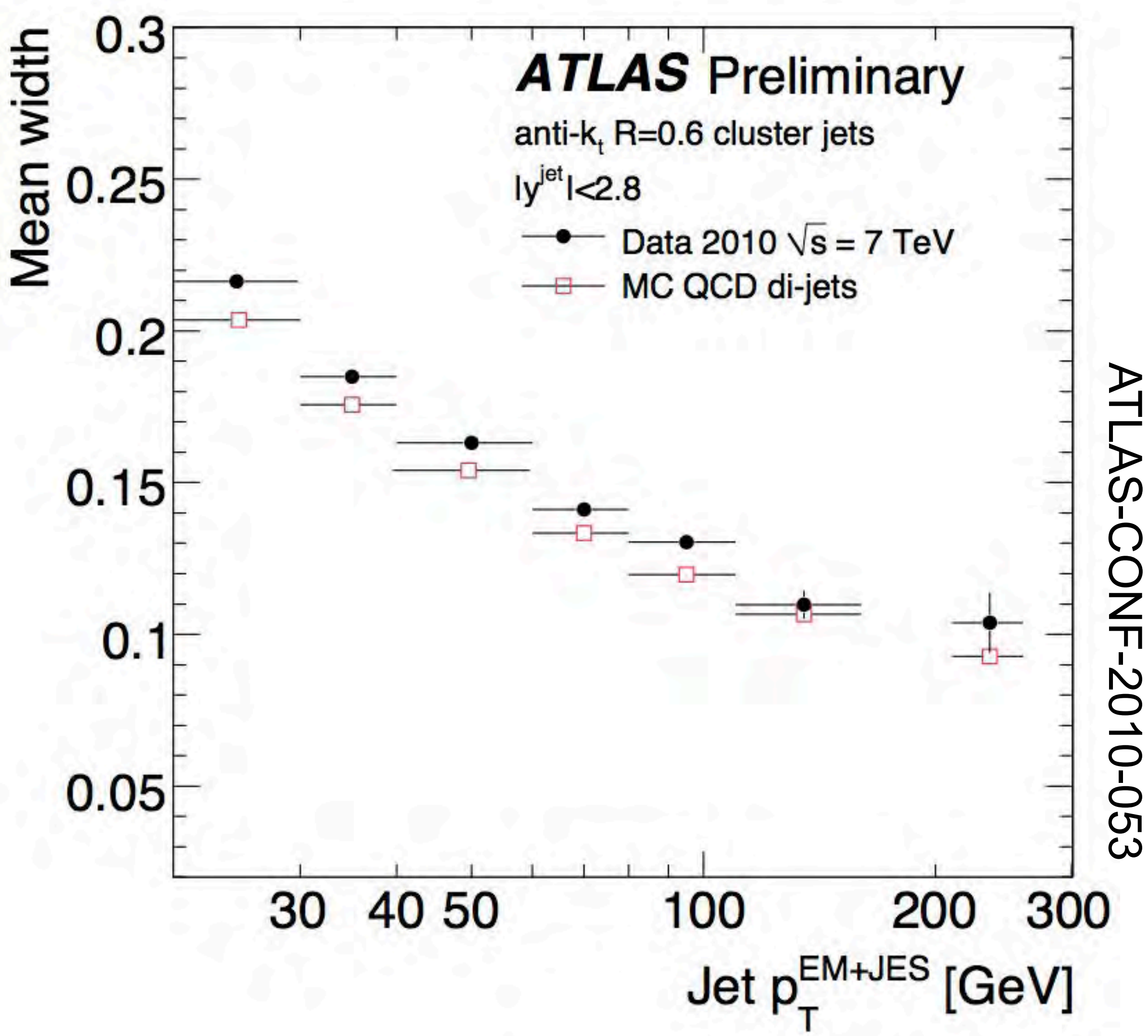
Jet Longitudinal Profile



- 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





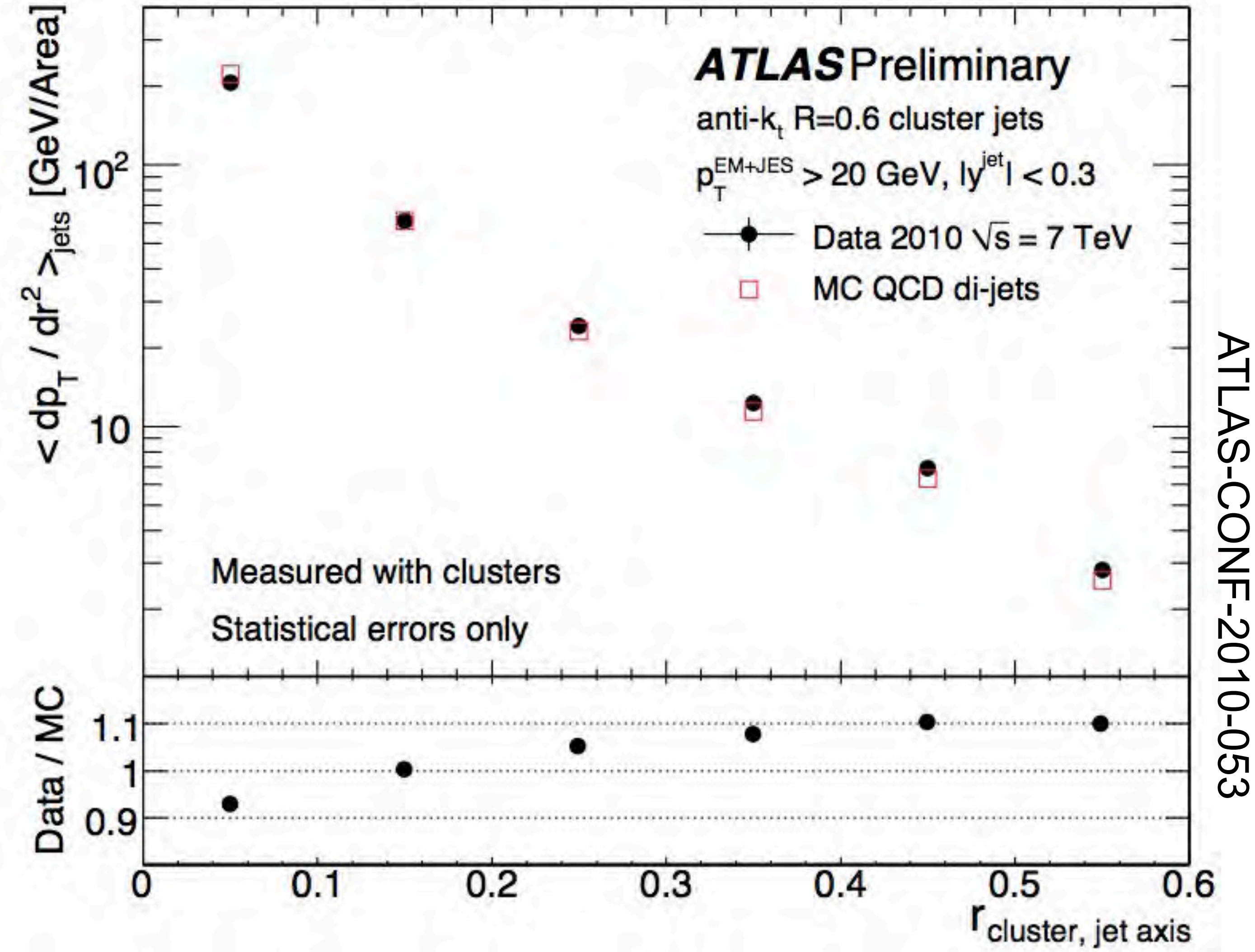
$$\text{width} = \frac{\sum_i r_i E_T^i}{\sum_i E_T^i}$$

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

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

Jet Internal Structure

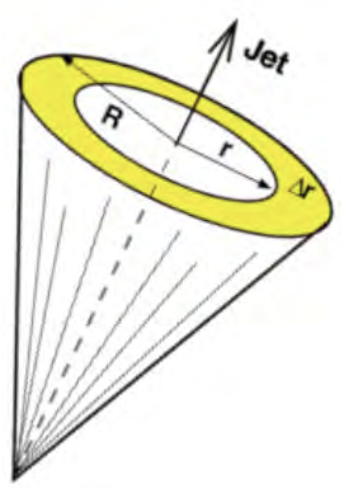
- Differential transverse jet energy distribution provides a more detailed study of the jet transverse structure
- Less energy observed in the core of the jet and more in the periphery in data compared to Monte Carlo
- Similar results for clusters, towers, tracks, and all rapidity regions
- Difference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



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

annulus of area A and radius r and

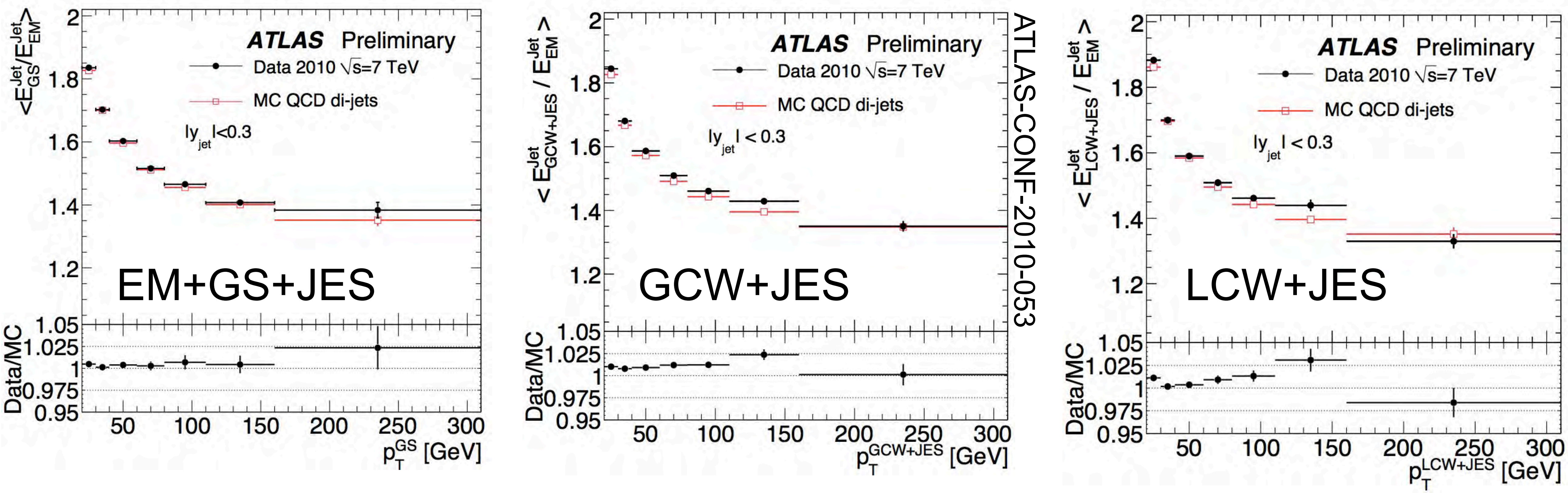
width $\Delta r = 0.1$ for $0 \leq r \leq R = 0.6$



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 η-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

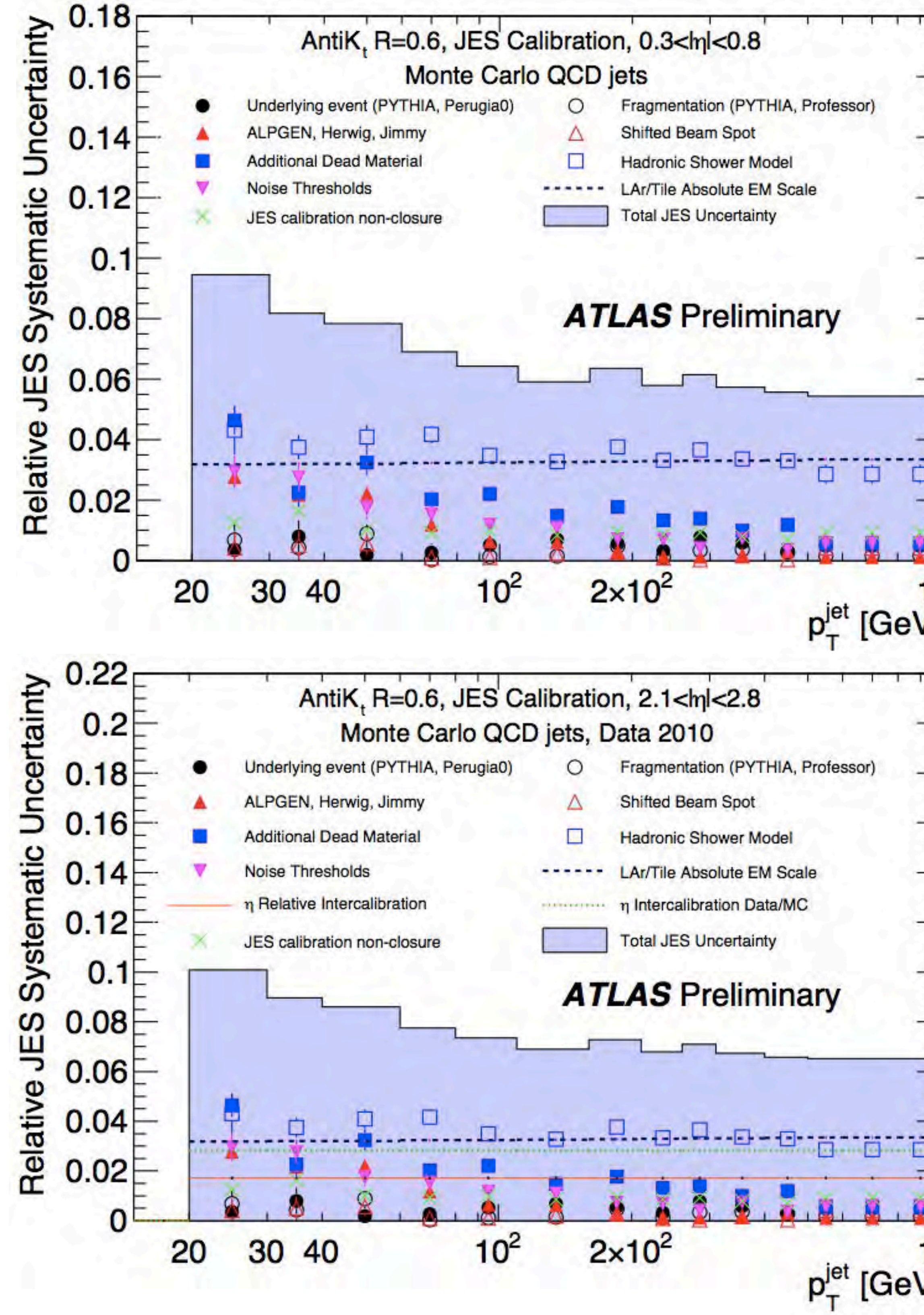
Jet Calibration Schemes



- 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%)
  - η inter-calibration (3%)
- Jet energy scale uncertainty smaller that 7% for jets with p_T > 100 GeV
- Uncertainty assessed to |η| < 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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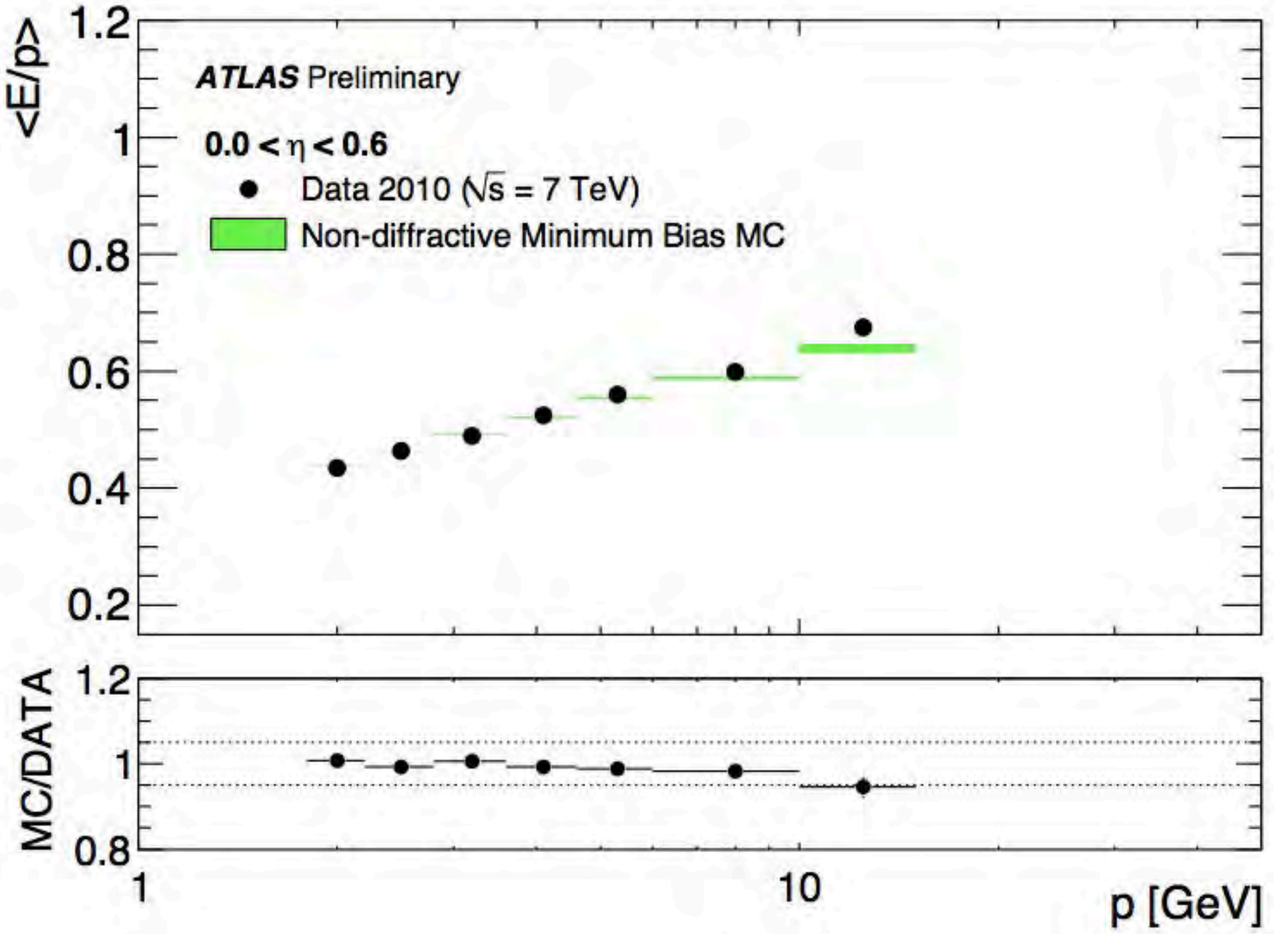
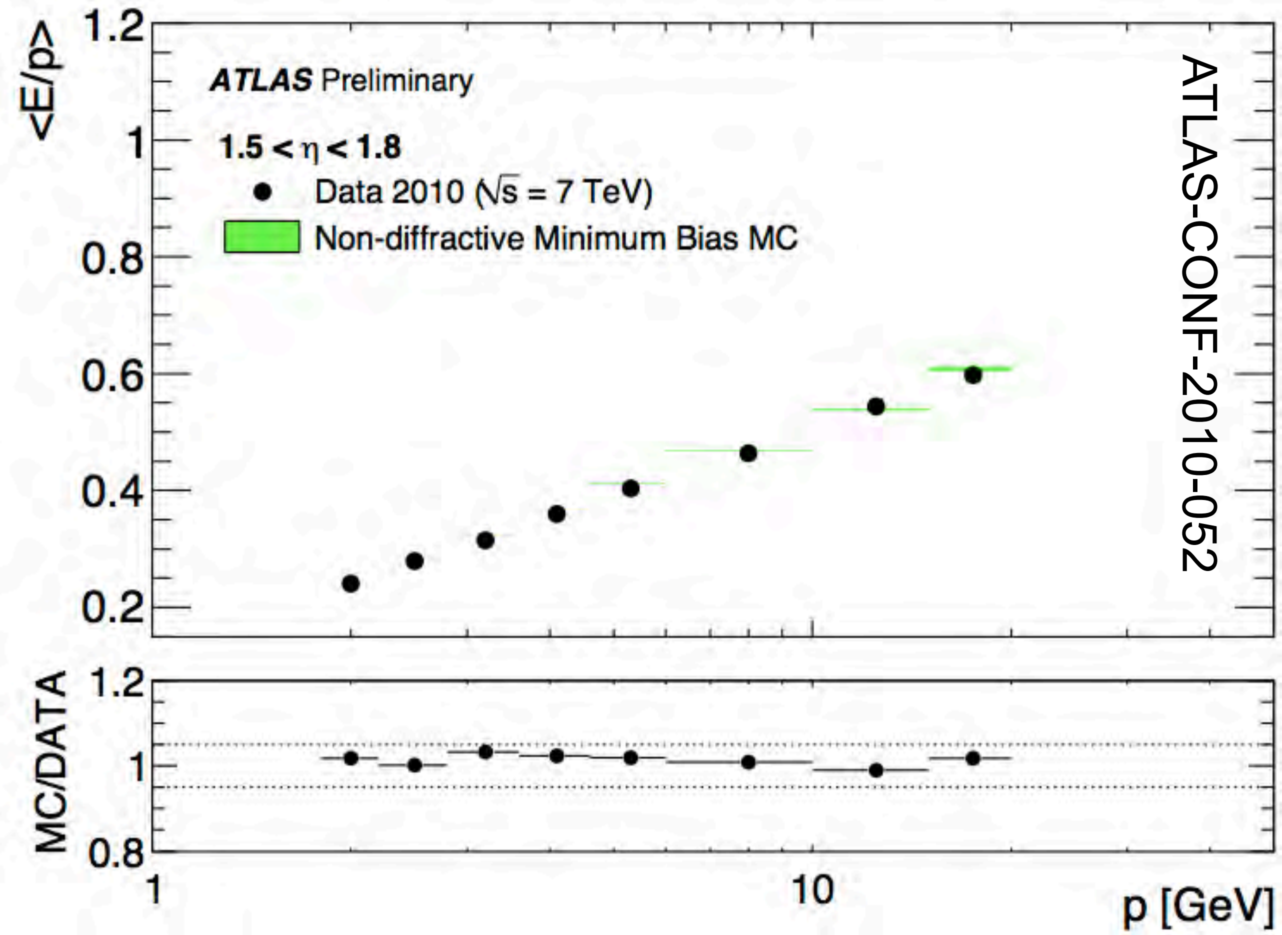
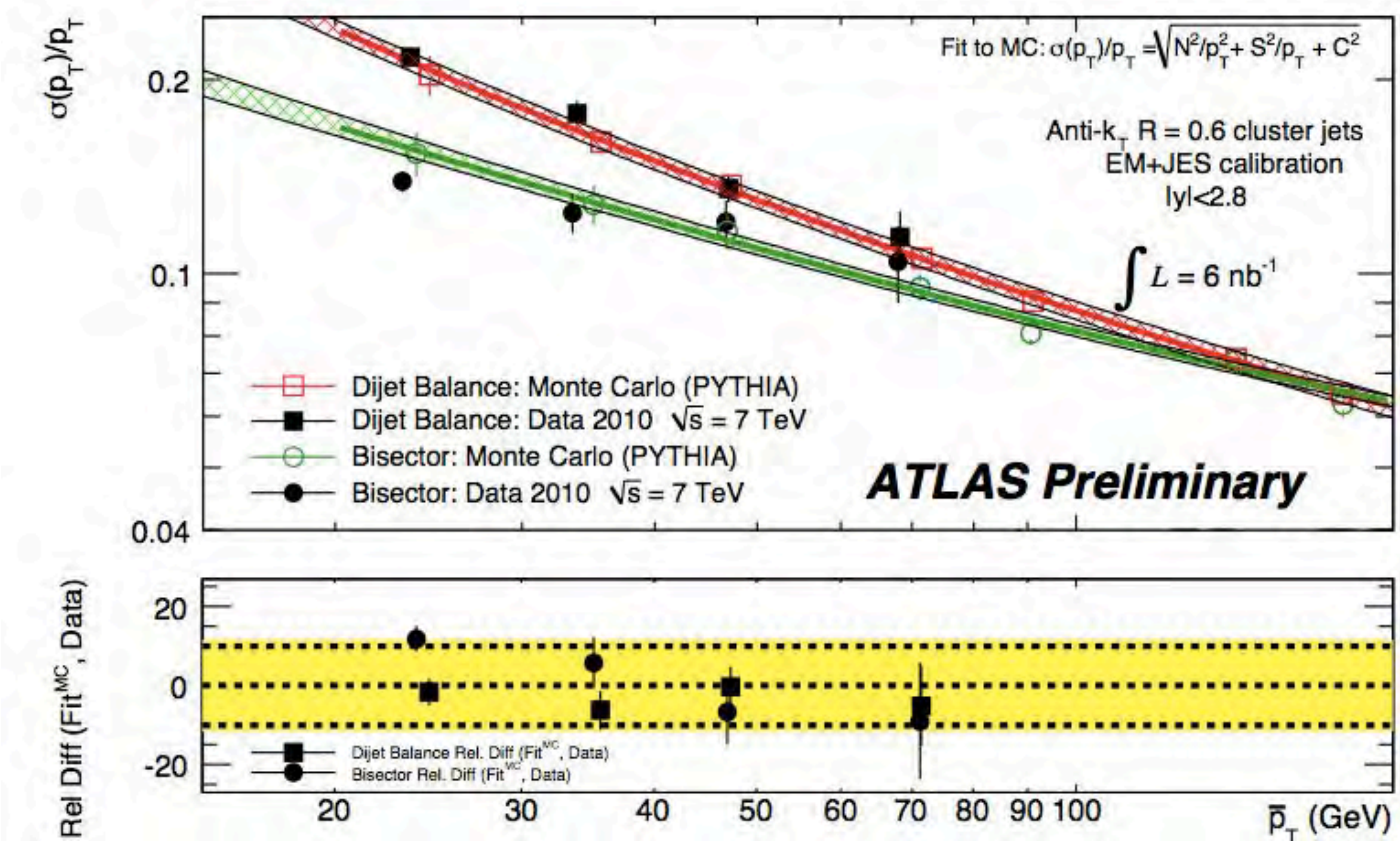
Jet Energy Scale Uncertainty





- 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 GeV $< p_T <$ 1 TeV

Jet Energy Resolution



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- 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 $|y| < 2.8$

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

$$E_{x(y)}^{\mathrm{miss}} = E_{x(y)}^{\mathrm{miss,calo}} + E_{x(y)}^{\mathrm{miss,cryo}} + E_{x(y)}^{\mathrm{miss,muon}}$$

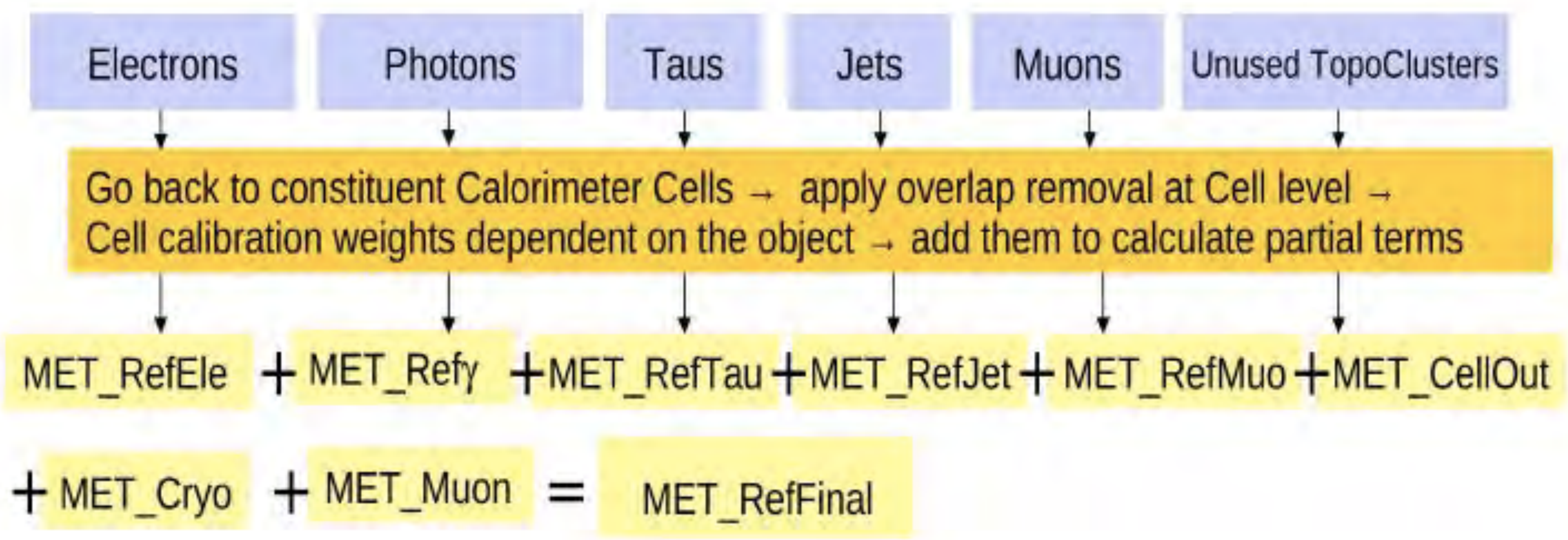
$$E_x^{\mathrm{miss,calo}} = -\sum_{i=1}^{N_{\mathrm{cell}}} E_i \sin\theta_i \cos\phi_i$$

$$E_y^{\mathrm{miss,calo}} = -\sum_{i=1}^{N_{\mathrm{cell}}} E_i \sin\theta_i \sin\phi_i$$

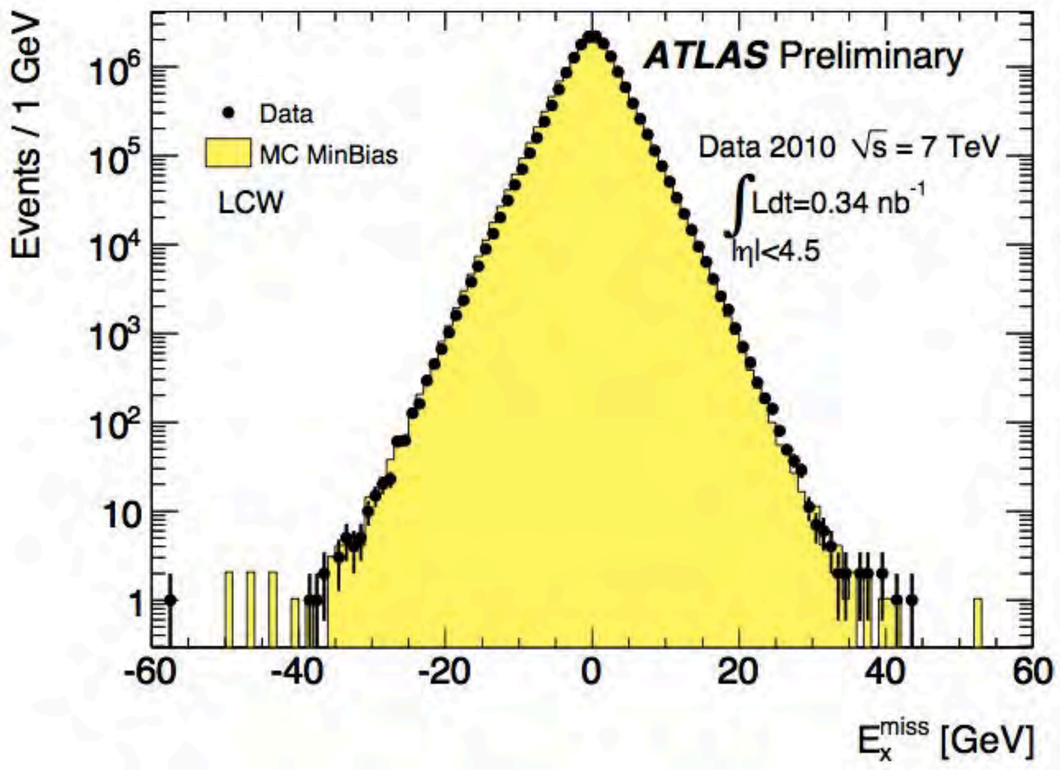
$$E_T^{\mathrm{miss}} = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2}$$

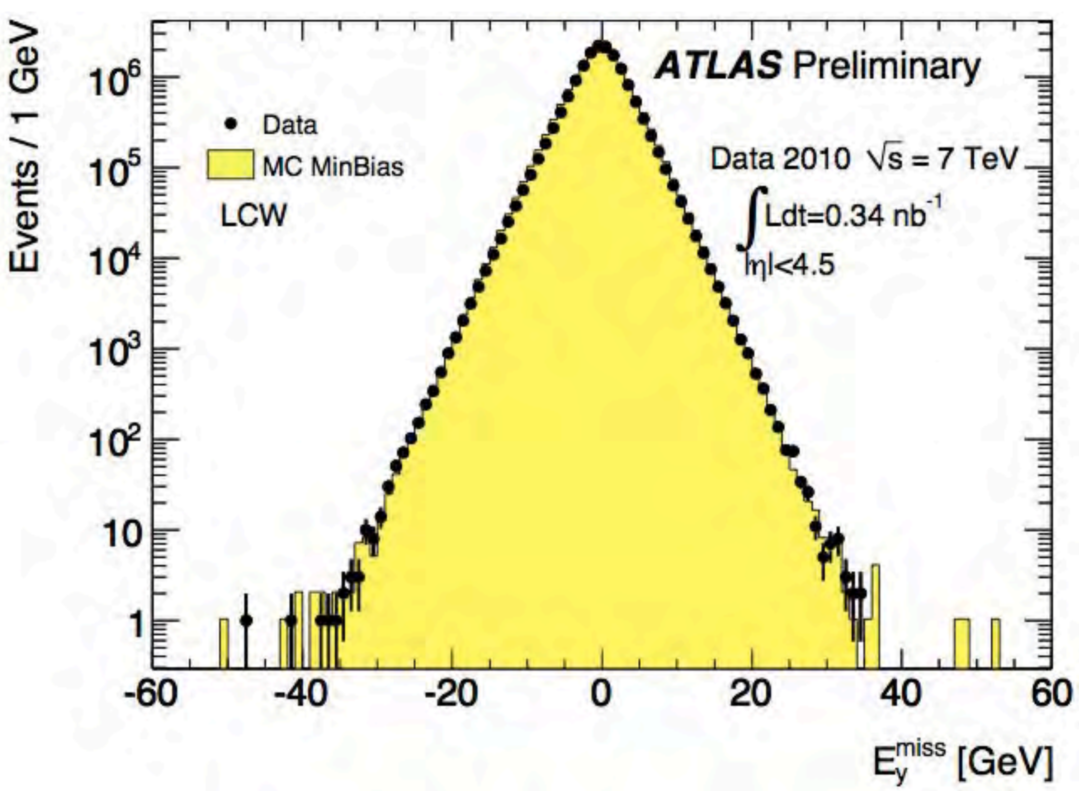
Missing E_T: Calorimeter Term

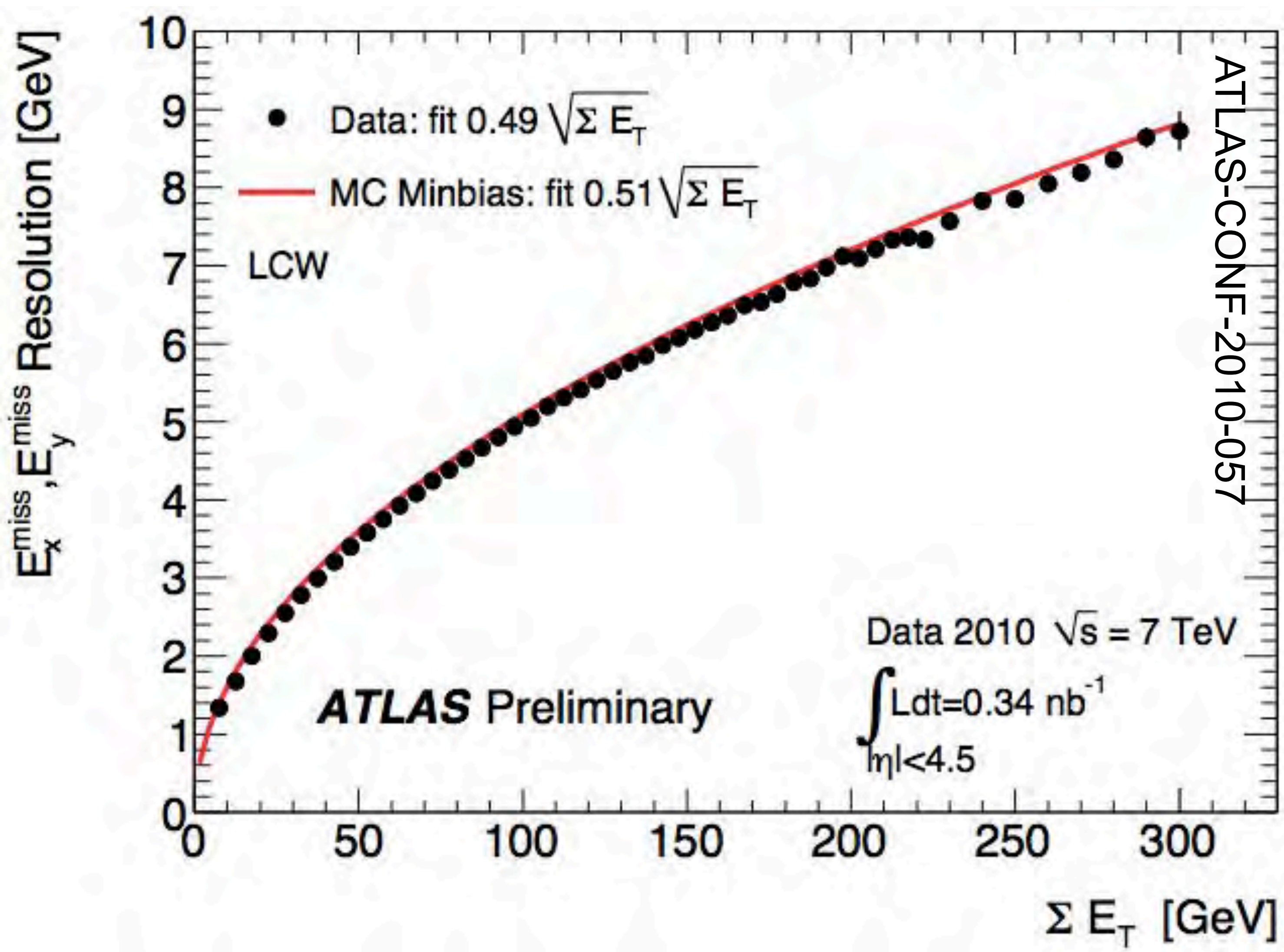
- Cells used can either be
  - at EM scale (no compensation!)
  - calibrated with GCW
  - calibrated with LCW (which includes dead material corrections)
- The calorimeter term can be further improved using energy corrections of physics objects
  - apply overlap removal between objects at cell level
  - objects calibrated independently, then use cells from objects



Missing E_T Performance



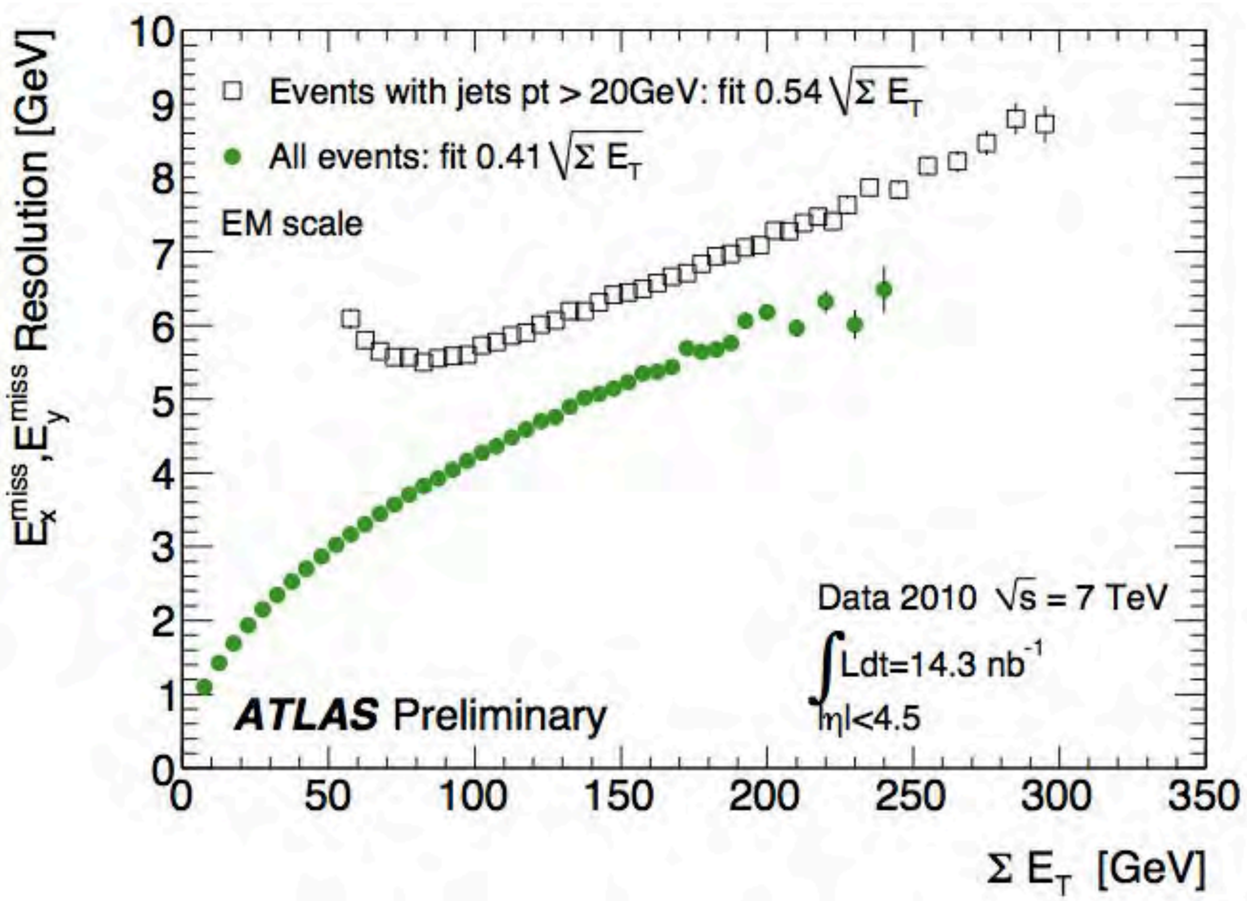


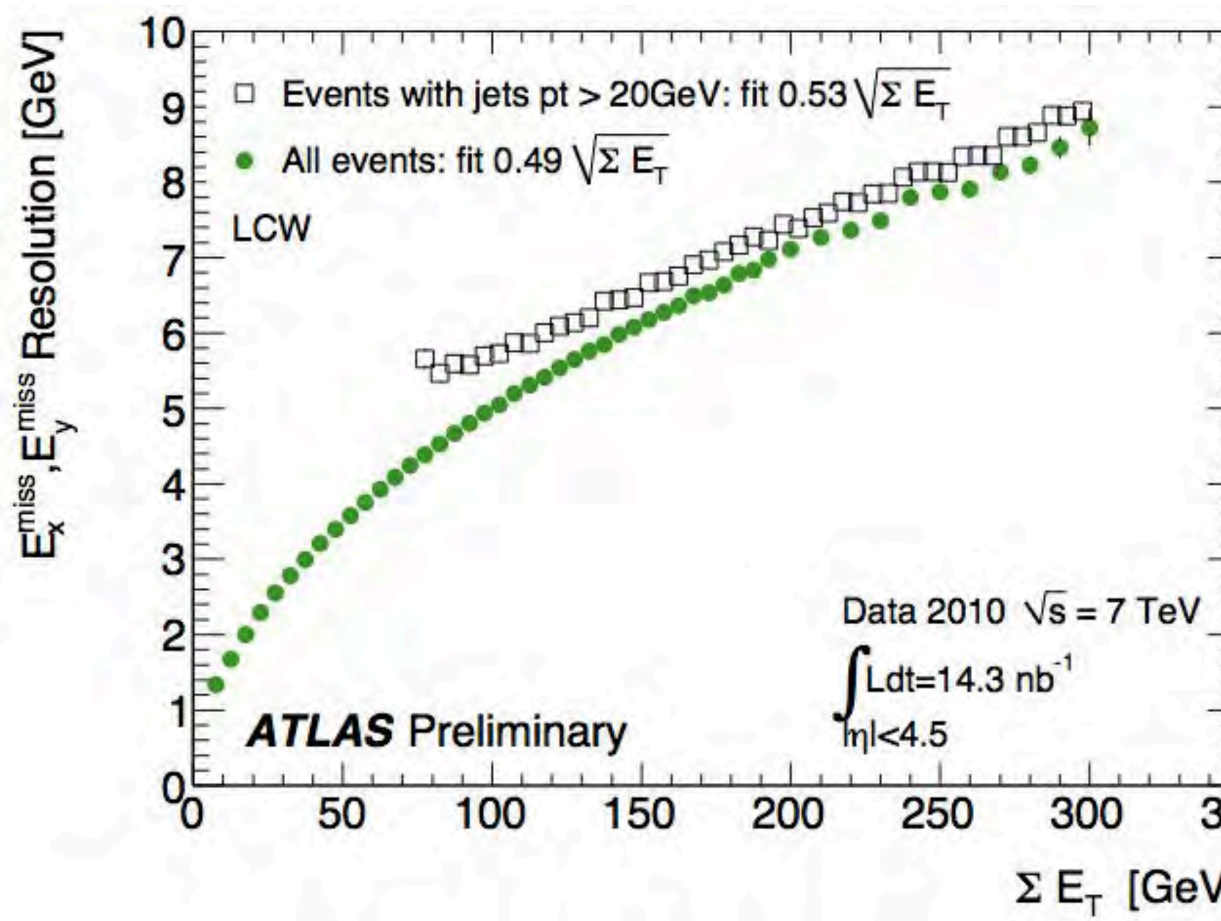


- Calibrated missing E_T distributions and tails in minimum bias events are well described by the simulation
- Missing E_T resolution in the data in good agreement with the simulation before and after cluster and cell level calibrations

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





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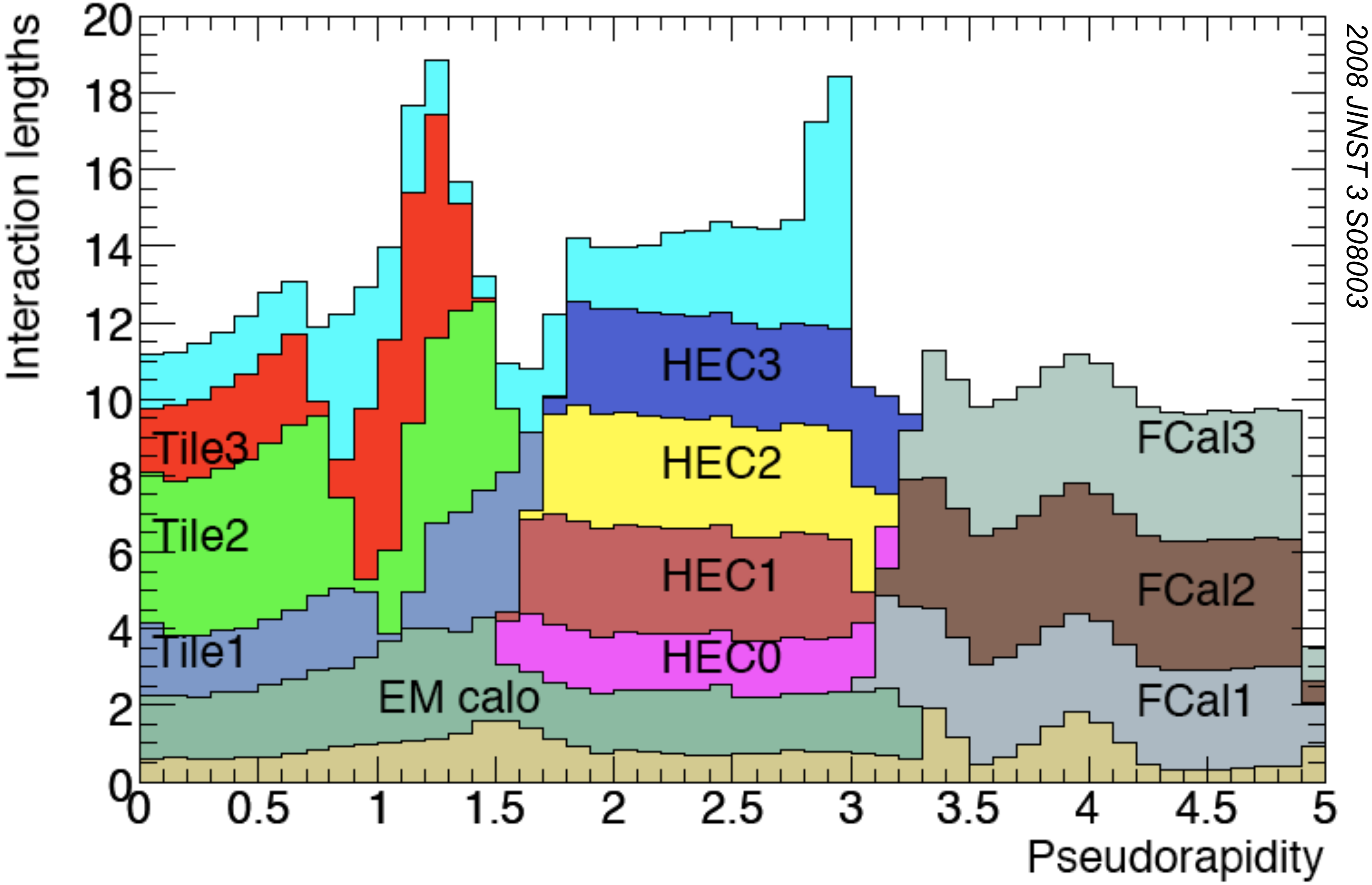
Conclusions and Outlook

- 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 that 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

Extra Slides

Material Budget



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:

$$d_{ij} = min\left(\frac{1}{p_{T_i}^2}, \frac{1}{p_{T_j}^2}\right)\frac{\Delta_{ij}^2}{R^2} \quad (1)$$

$$d_{ii} = \frac{1}{p_{T_i}^2} \quad (2)$$

where:

- $\Delta_{ij} = (\phi_i - \phi_j)^2 + (y_i - y_j)^2$
- p_{T_i}, y_i, and ϕ_i 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}:

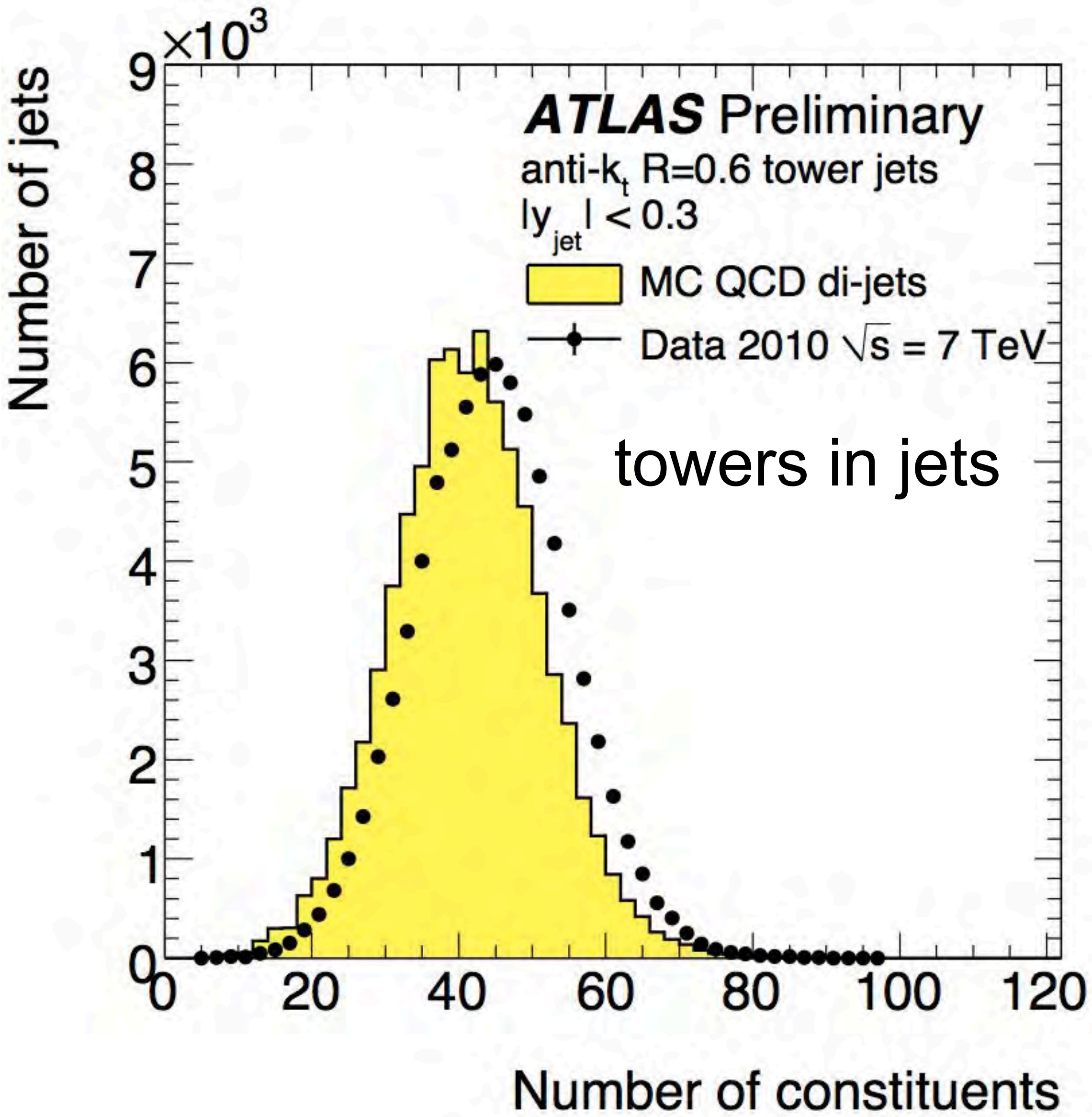
$i \neq j$ Remove proto-jet i and j and add 4-vector sum as new proto-jet
$i = j$ Remove proto-jet i and call it a final jet

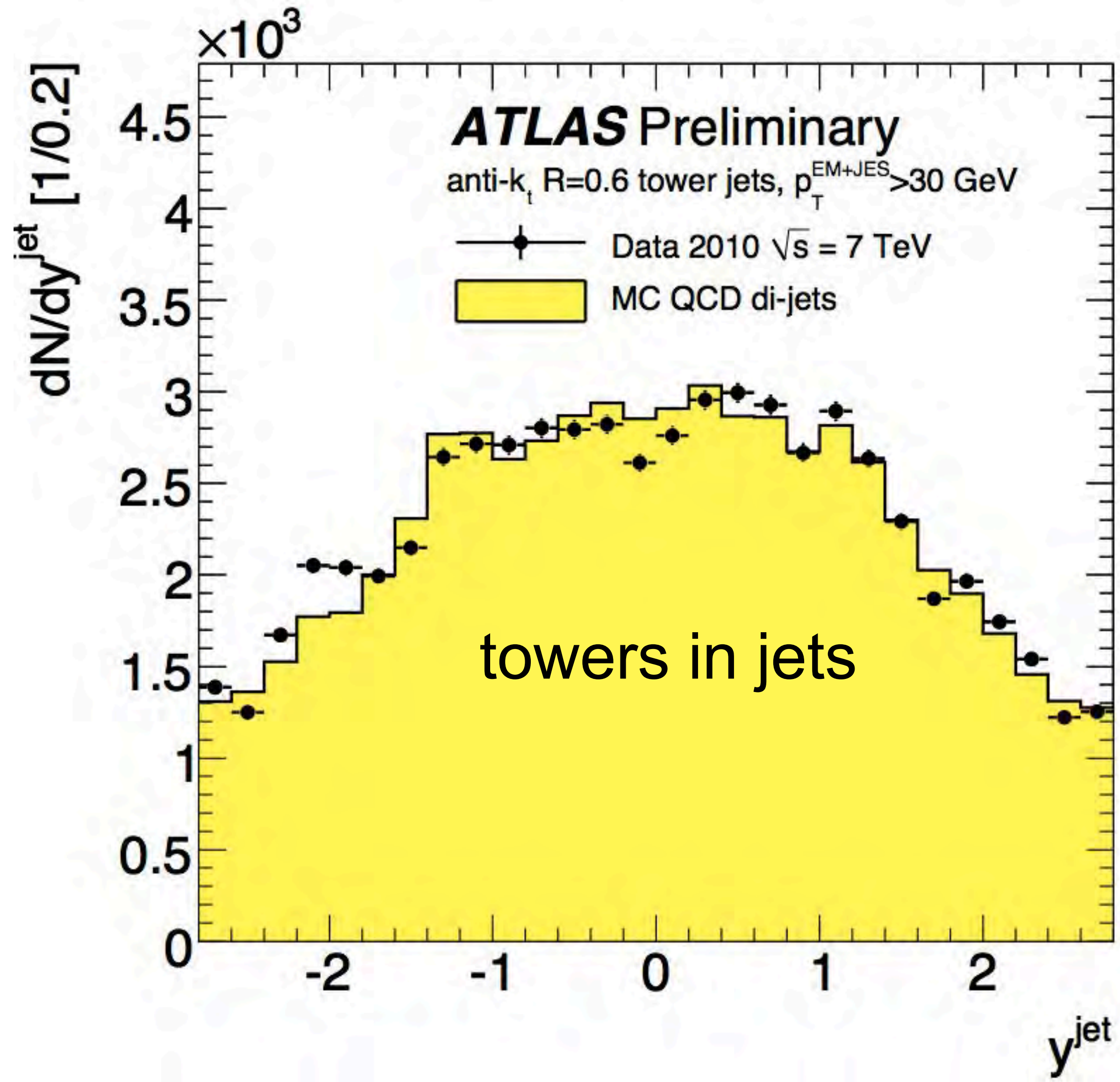
[1] M. Cacciari and G. P. Salam, Phys. Lett. B 641, 57 (2006)

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 $p_T^{track} > 150$ MeV
    - $|z_{vertex}| < 100$ mm
- Monte Carlo Simulation
  - non-diffractive pp collisions describing hard 2->2 processes using a matrix-element plus parton-shower modelin 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





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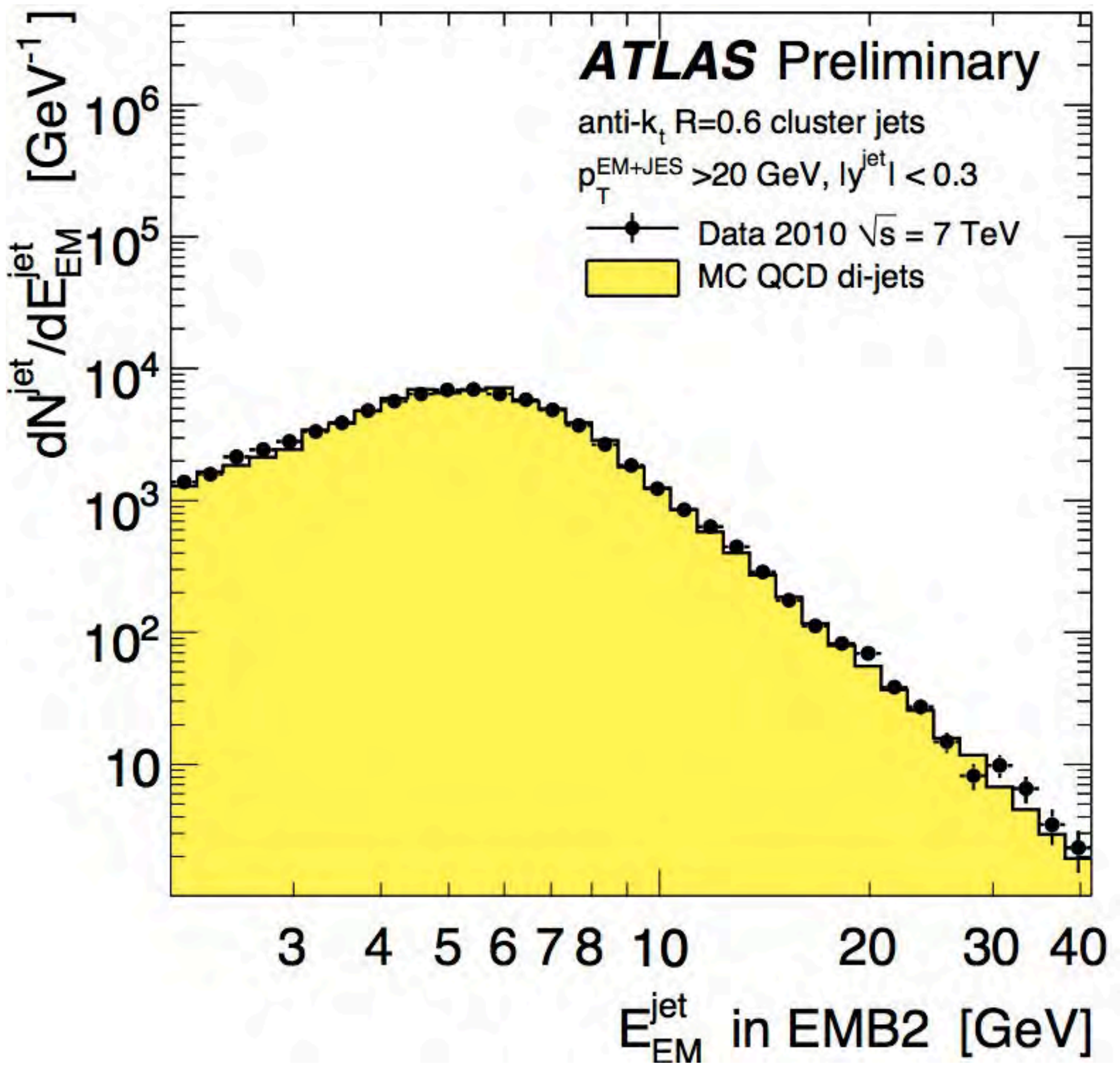
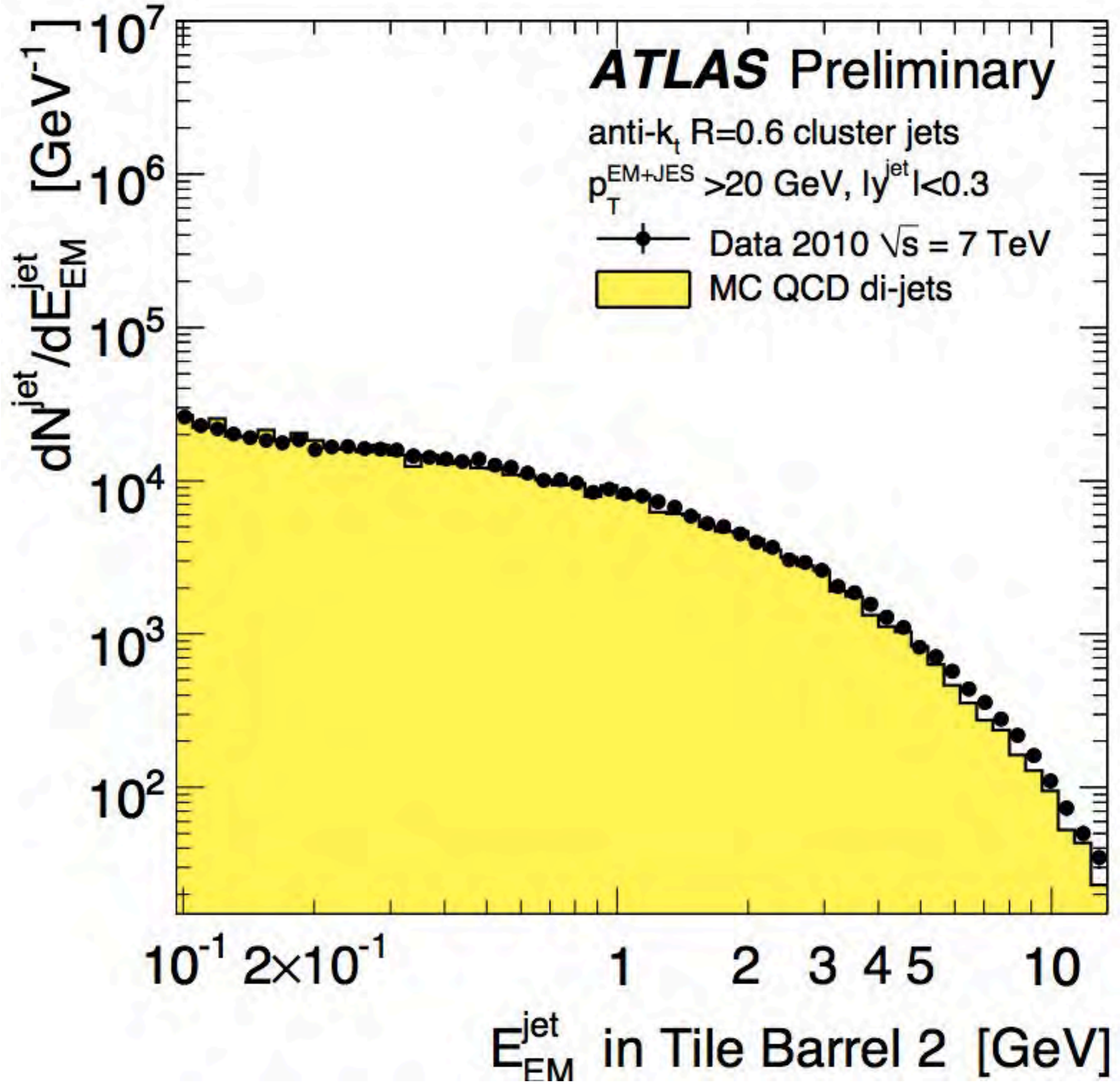
- Difference between MC and data probably connected to deficiencies in the physics description in the MC

Jet Longitudinal Profile





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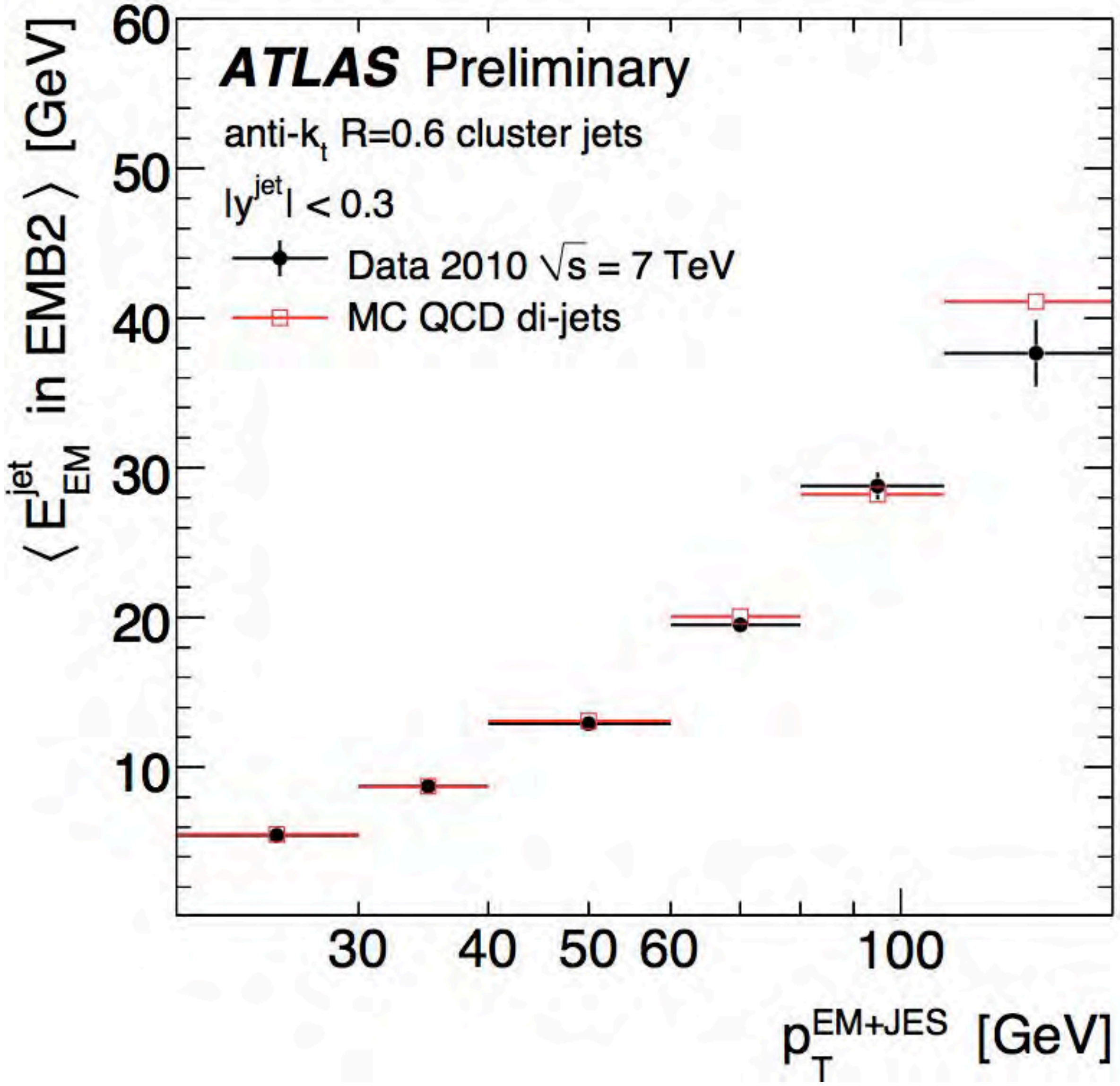
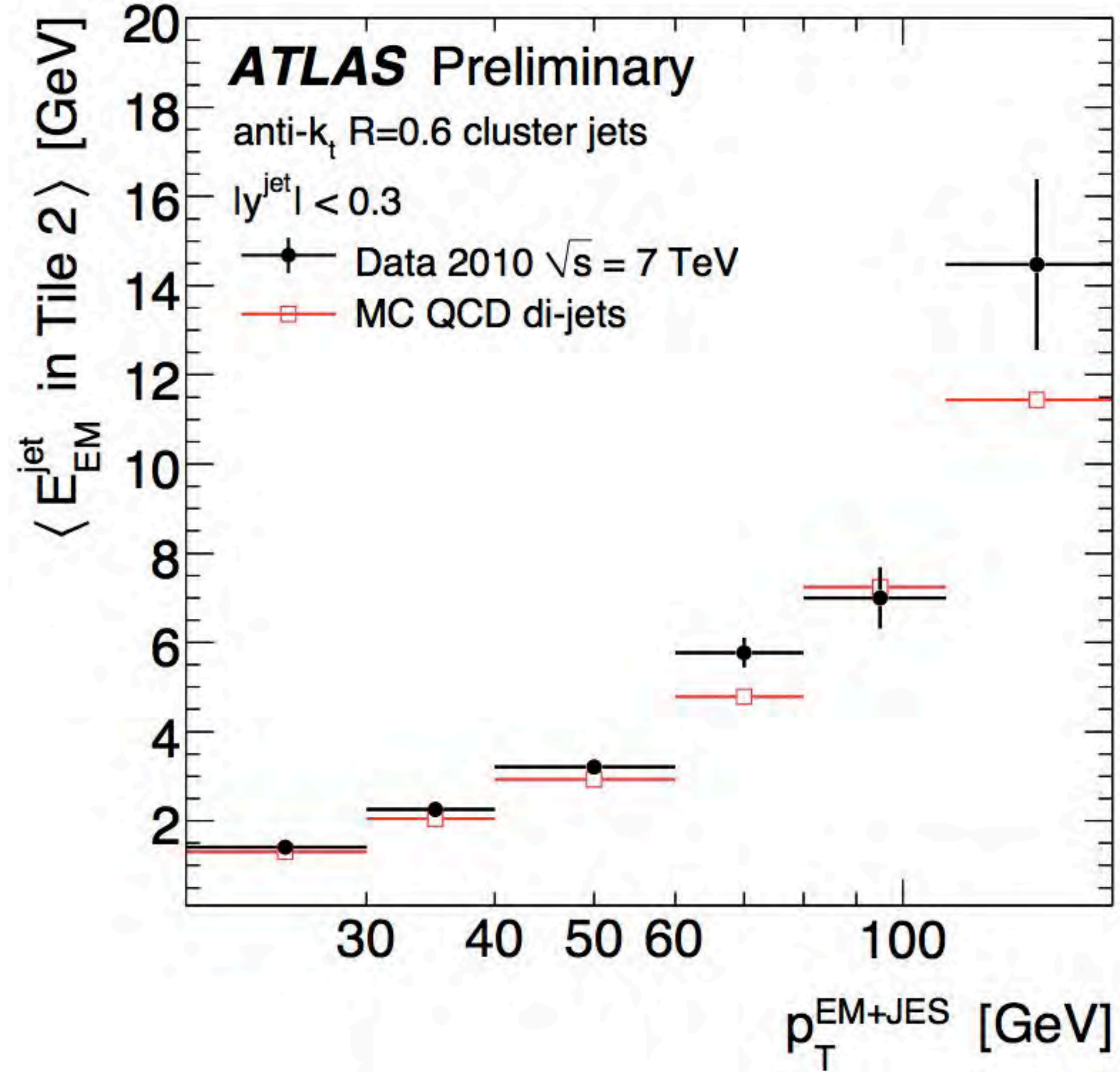
- Distribution of energy deposited longitudinally in cluster jets
- Good agreement with MC observed in the barrel and in the endcap region, and over the whole p_T range probed

Jet Longitudinal Profile





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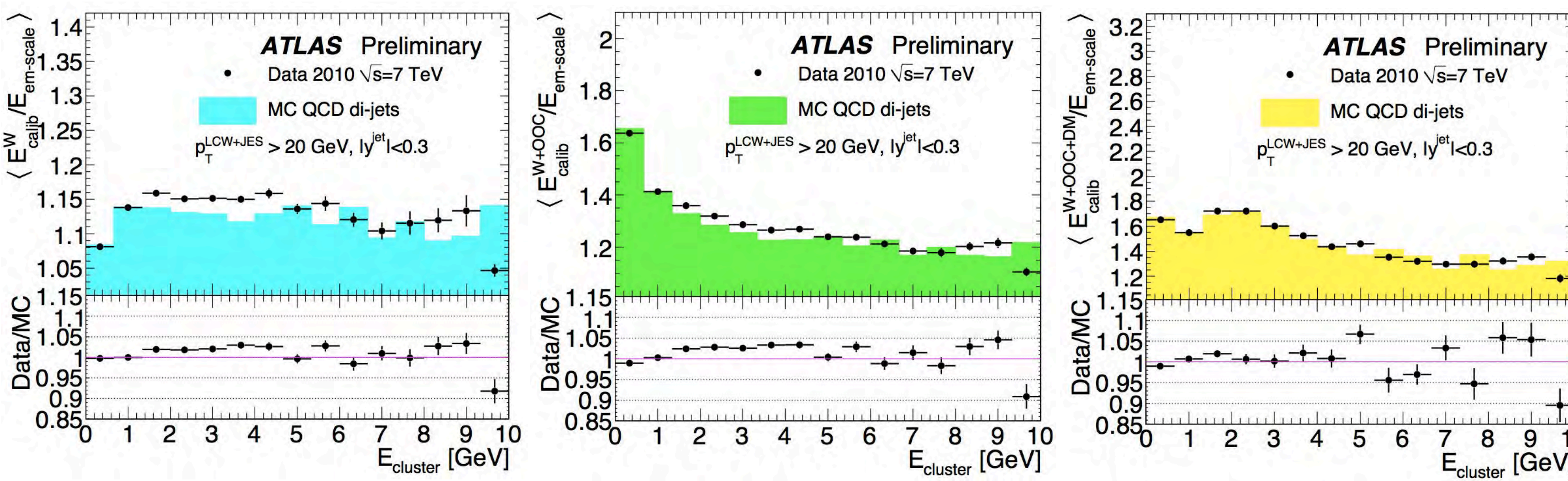
- Mean energy deposited longitudinally in cluster jets as a function of p_T^{jet}
- With other measurements, this seems to indicate that, in the barrel region, hadronic showers are deeper in data compared to MC simulation

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 η, 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



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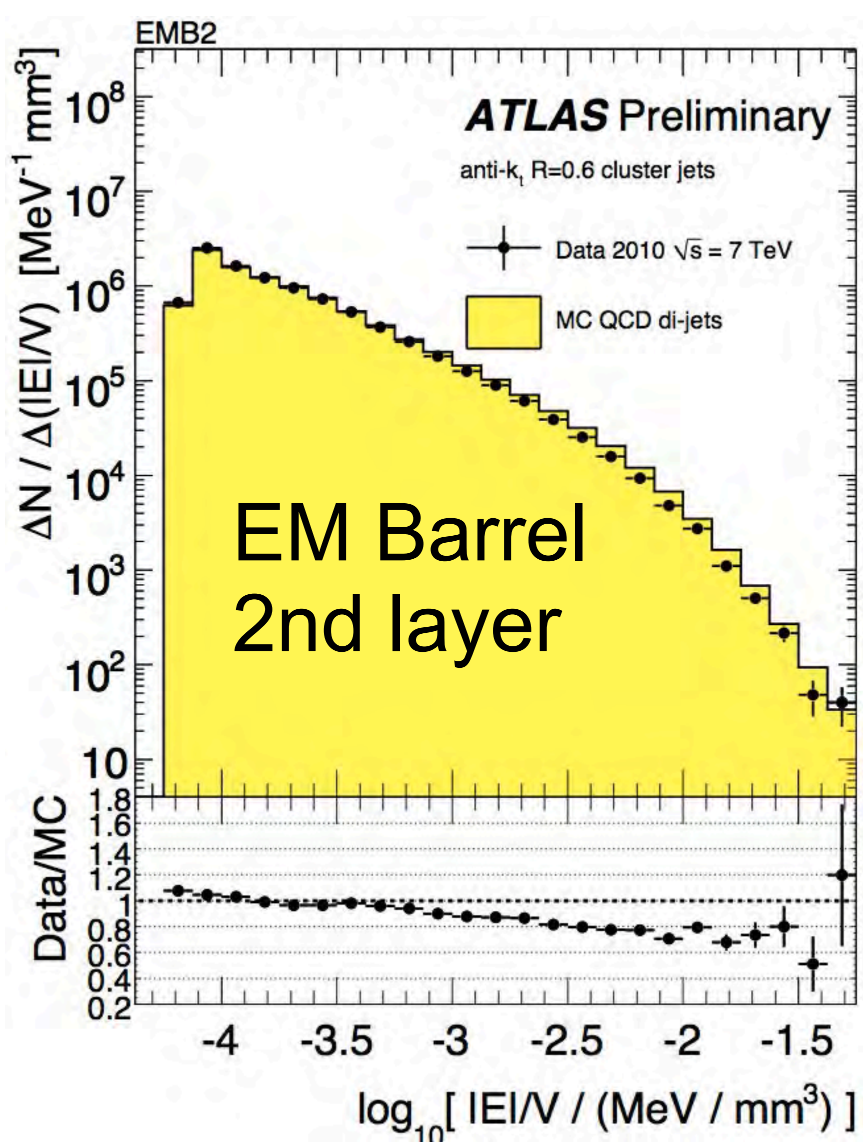
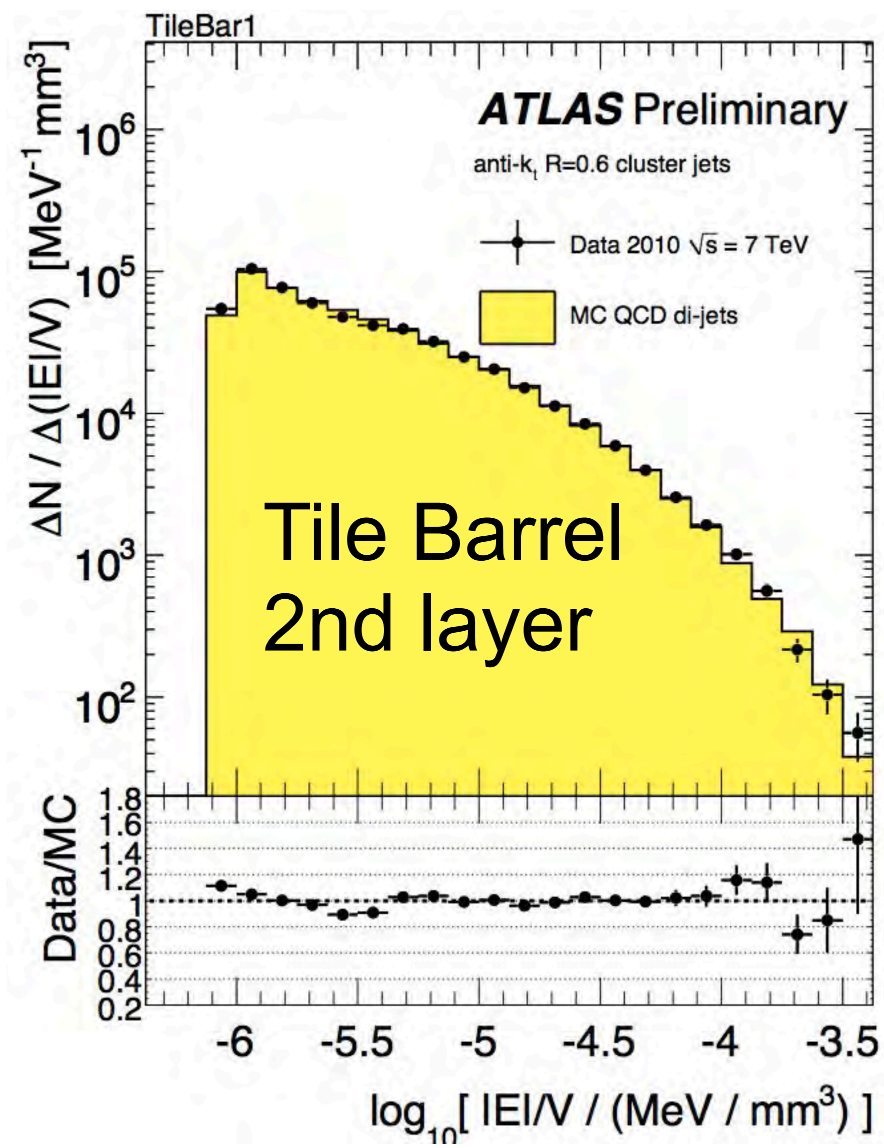
Global Cell Weighting

- 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





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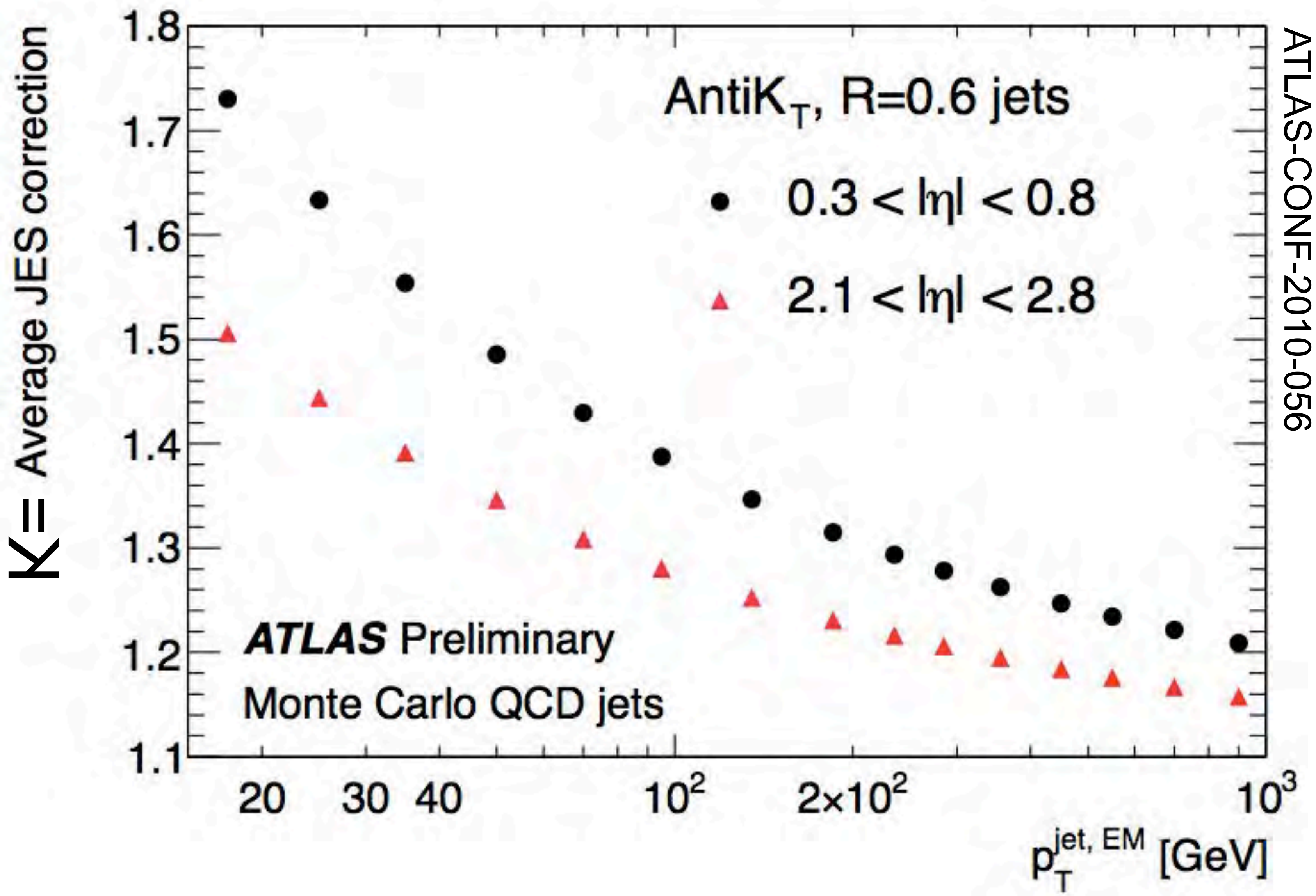
Jet Energy Scale Correction

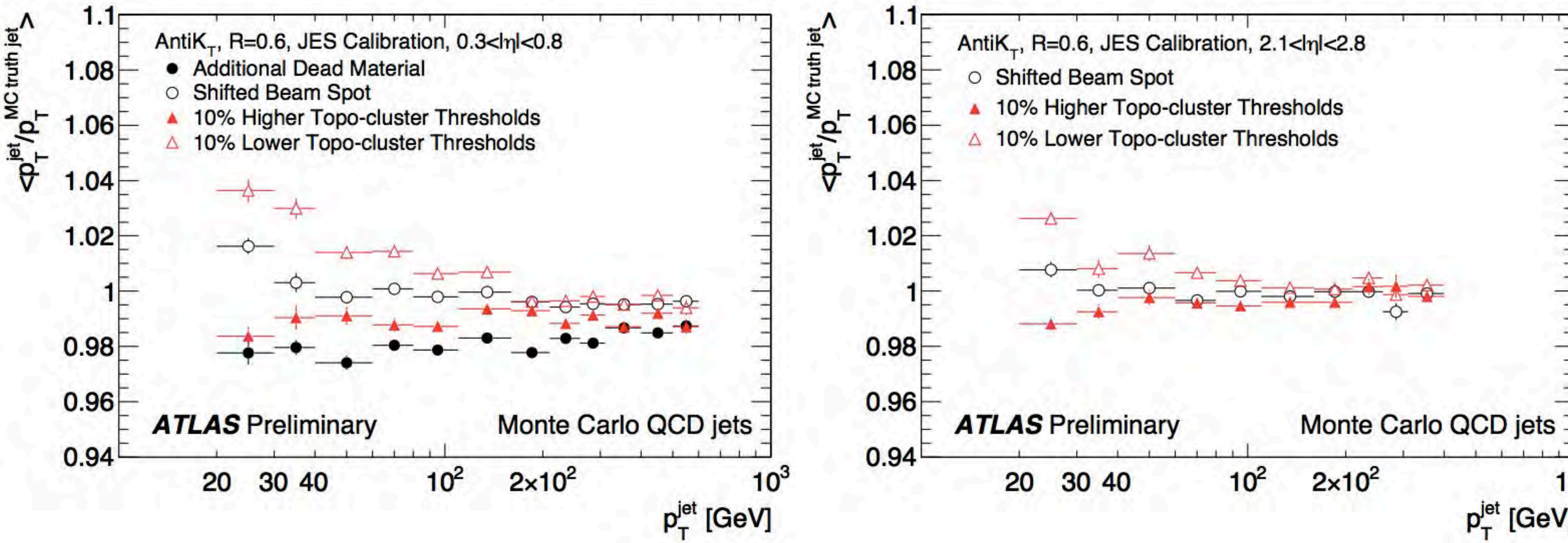
$$p_T^{\text{jet}} = K p_T^{\text{jet,EM}}$$

EM+JES



Increased in electromagnetic content in jets of higher energies

Jet Energy Scale Uncertainty



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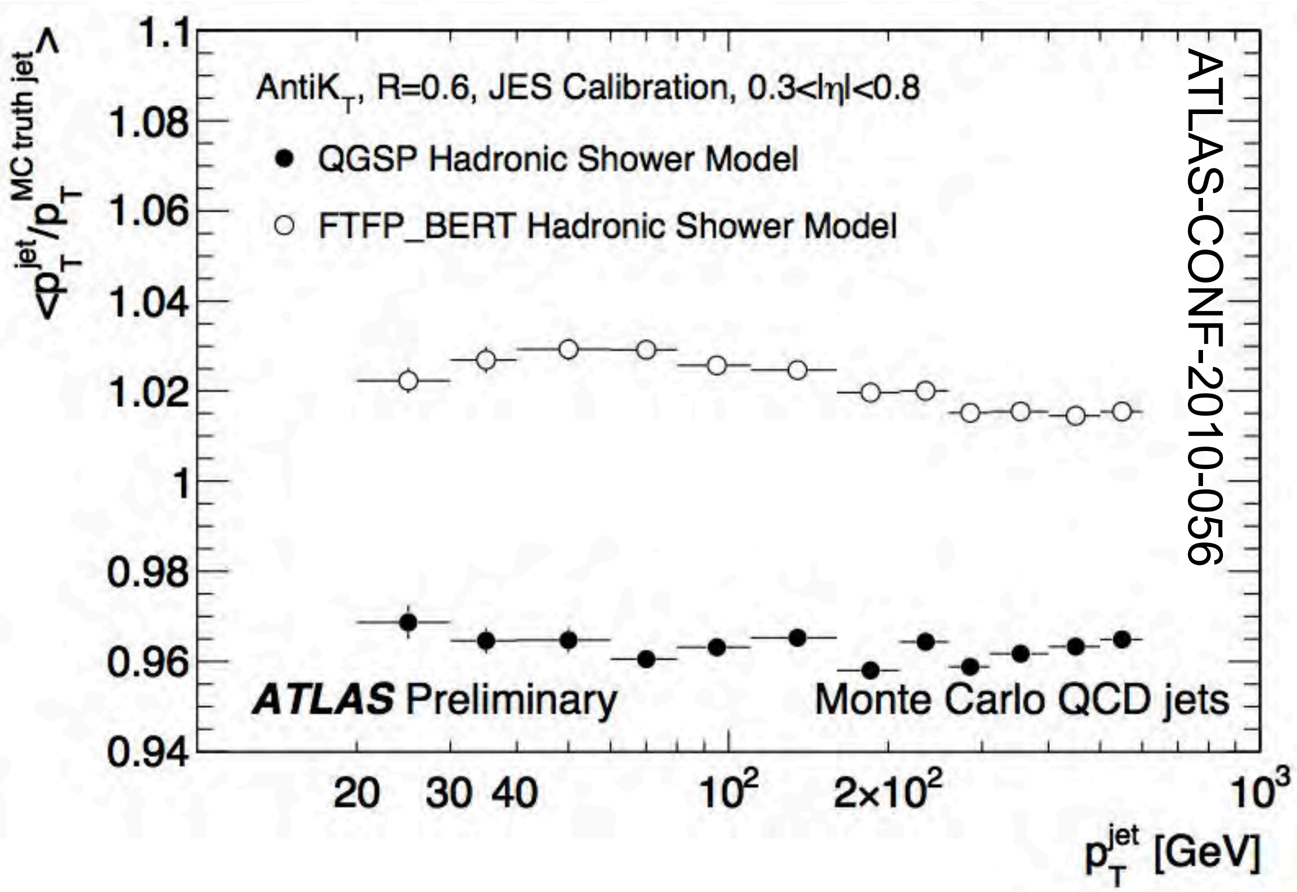
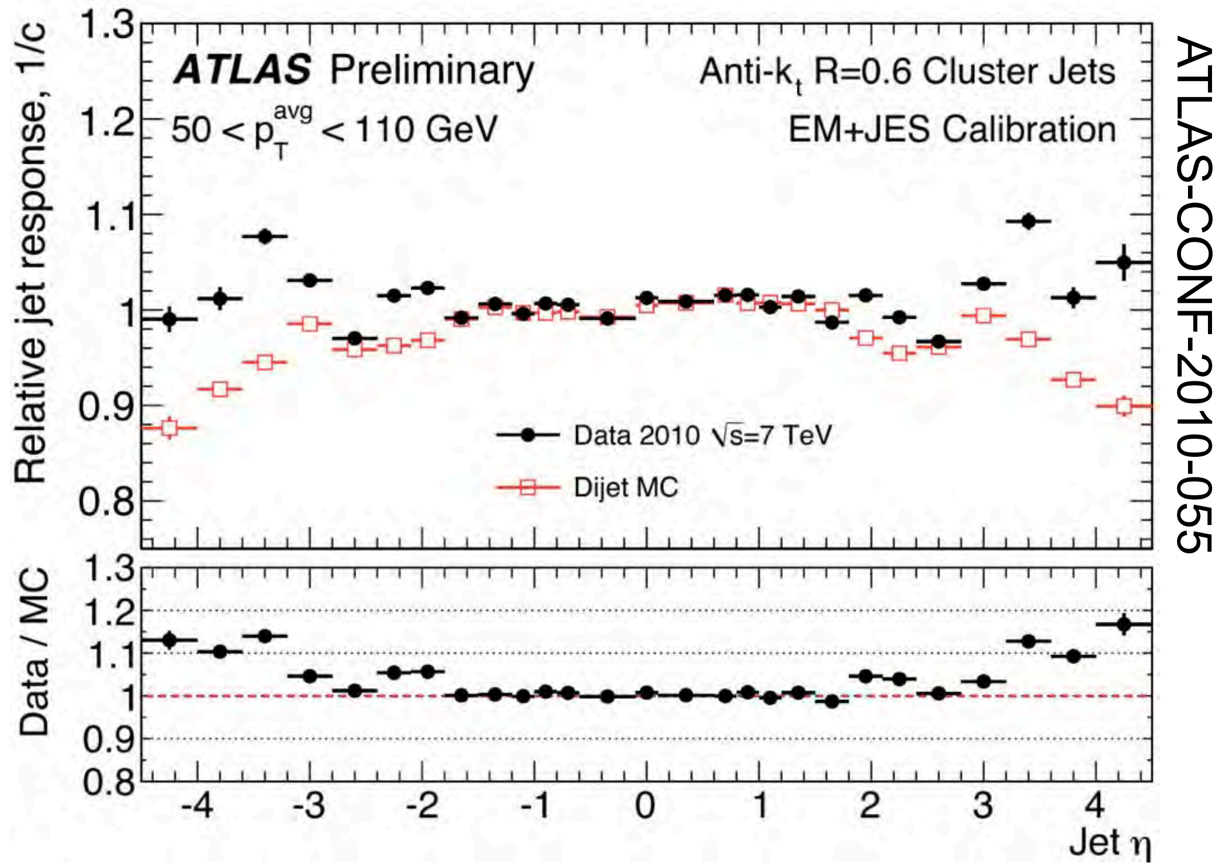
- Uncertainties due to material description and experimental conditions
  - material budget and distorted geometry
  - topological cluster noise thresholds
    - 10% noise threshold uncertainty from the stability of the noise spread in dedicated noise runs and the comparison of the noise distribution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

Jet Energy Scale Uncertainty

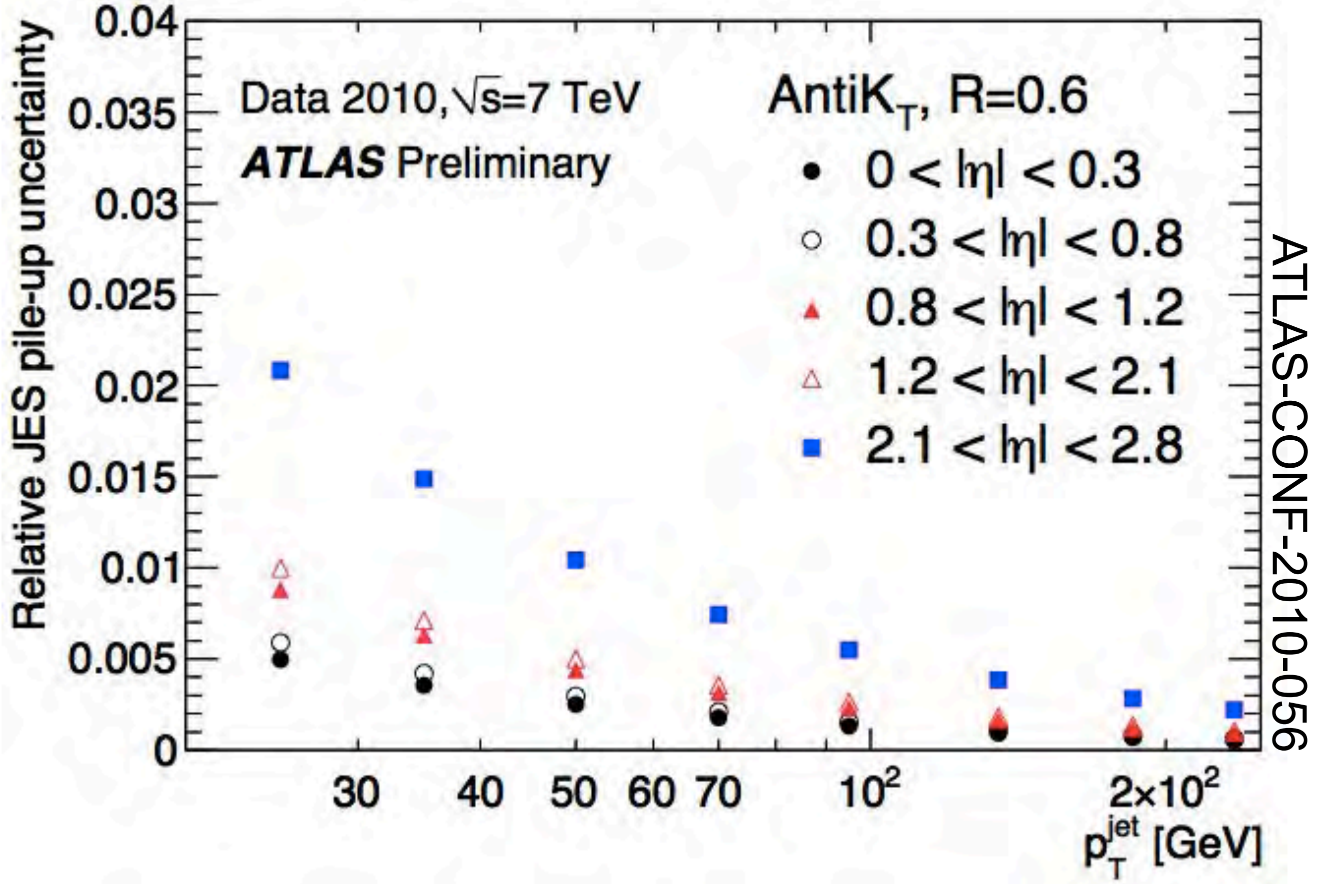




- Other jet energy scale uncertainties
  - hadronic shower model
    - beam test single pion response measurement lie within QGSP and FTFP_BERT model (nominal hadronic shower model is QGSP_BERT)
  - uncertainty assessed to |η| < 4.5 using in-situ di-jet balance measurements
    - in |η| < 1.8, MC and data agree to better than 2%
    - in 1.8 < |η| < 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



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

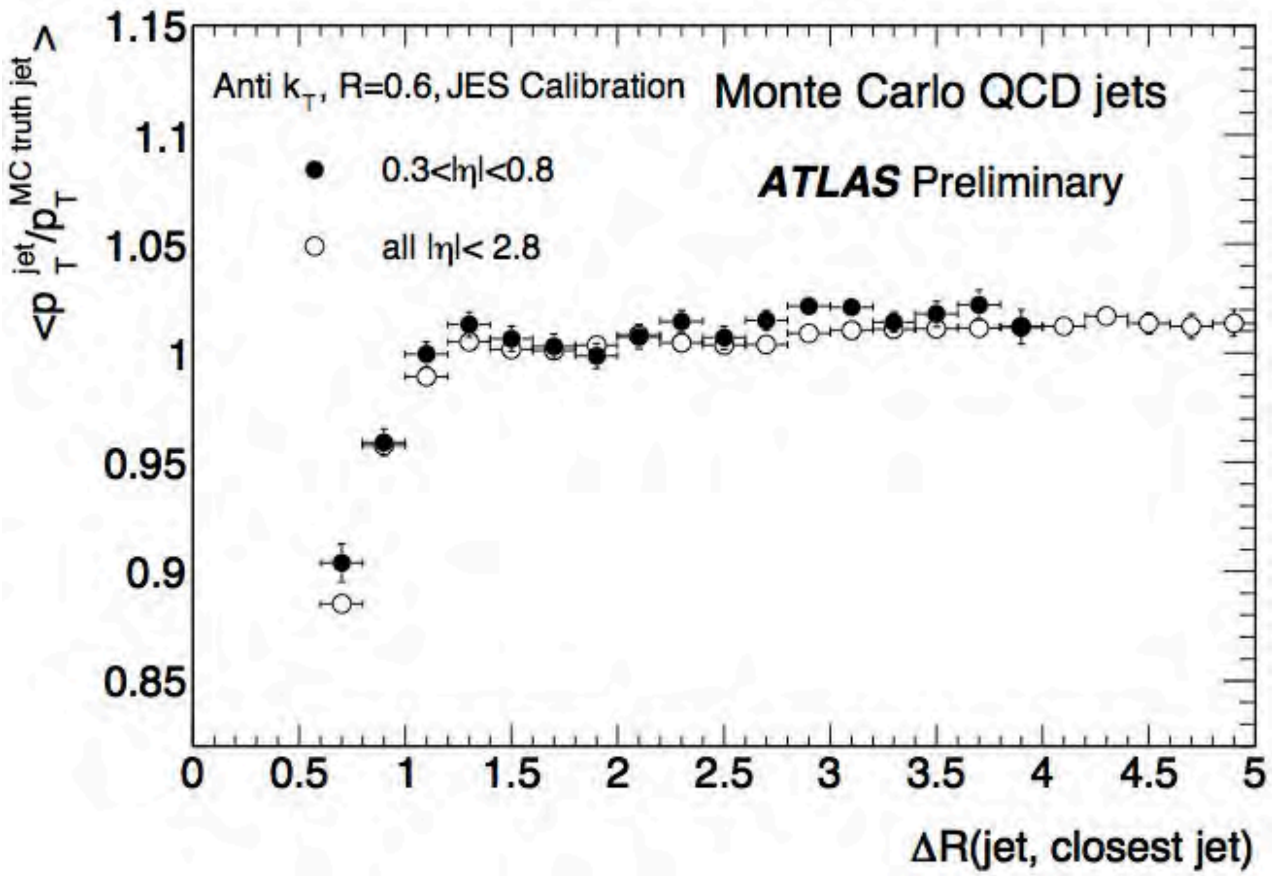
- measure the mean tower energy as a function of η and of the number of primary vertices
- estimate the additional tower energy as a function of the number of interactions by subtracting the average tower energy for events with one vertex from the average tower energy for events with N additional interactions
- estimate the average number of towers in jets as a function of η
- estimate the average number of additional interactions as

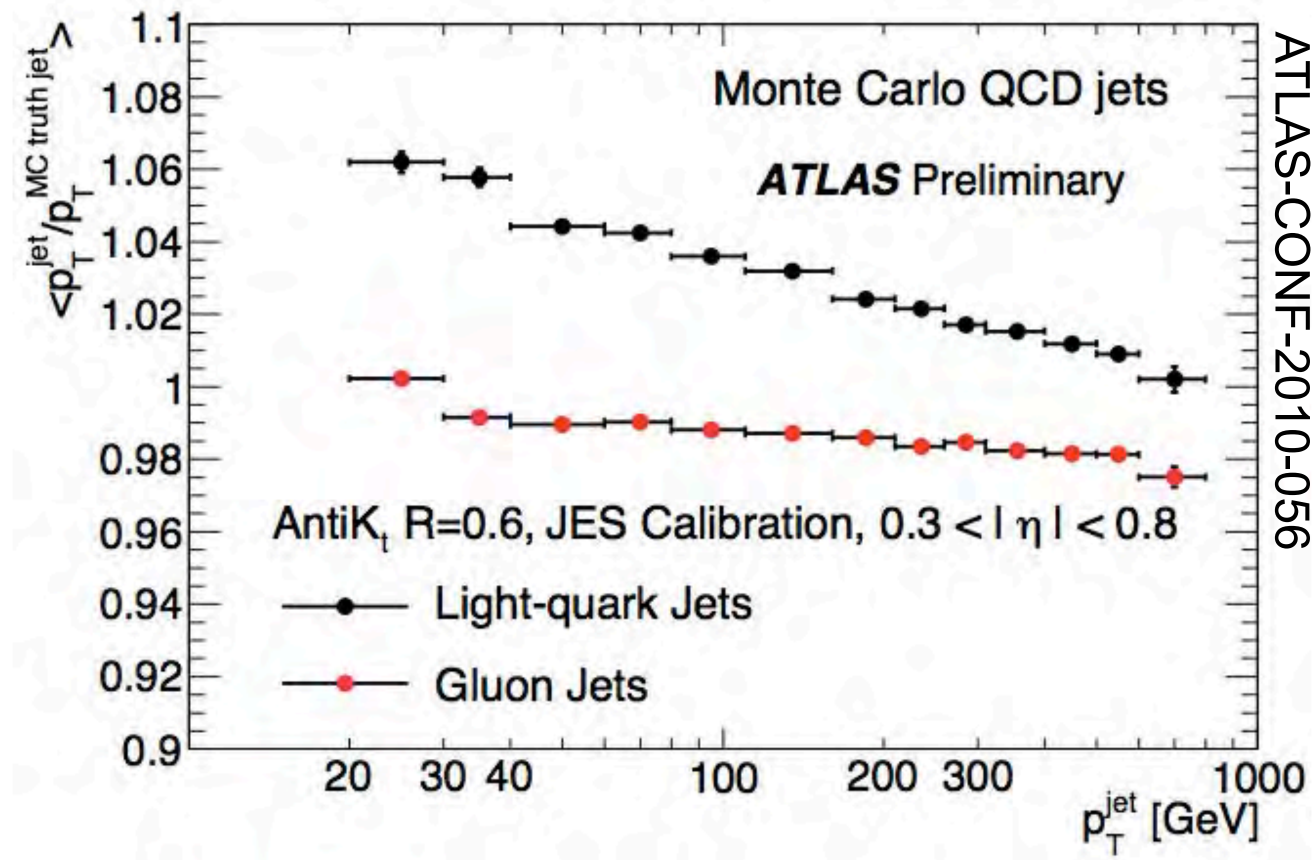
$$\langle N^{\text{pile-up}} \rangle = \langle N \rangle + \sigma_N$$

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

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





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- the response of non-isolated jets in lower than that of isolated jets; all η 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

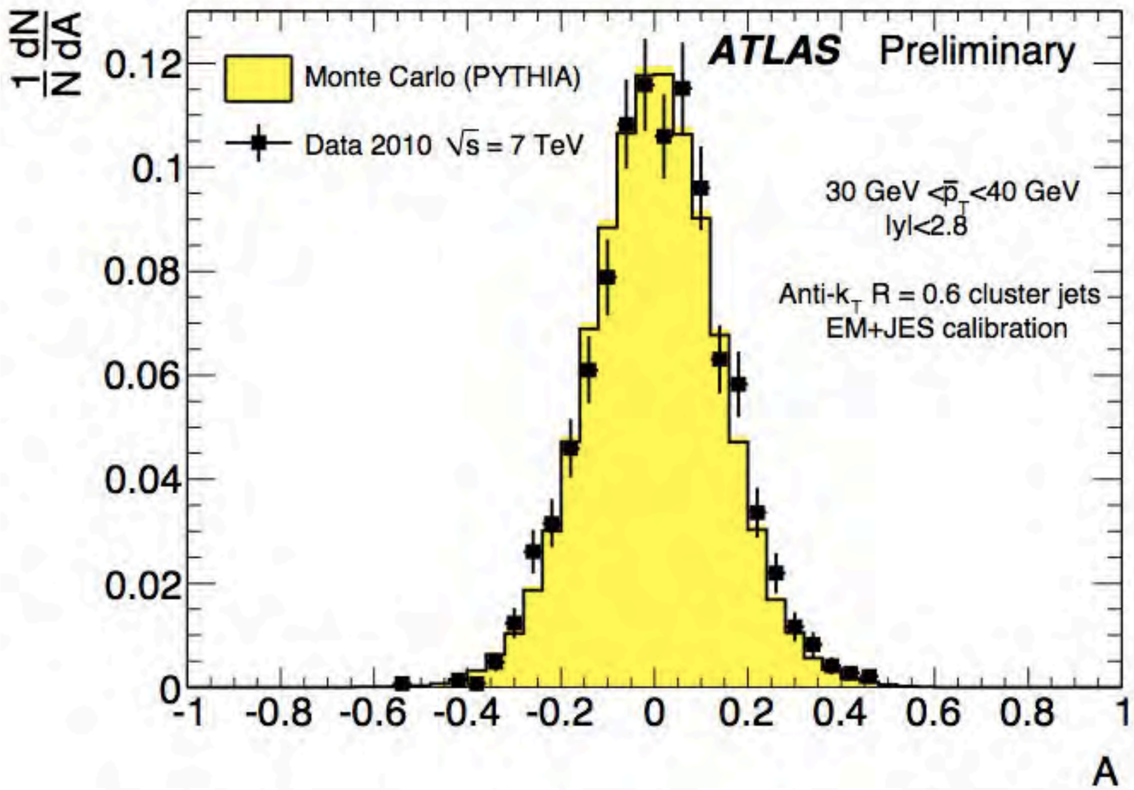
Jet Energy Resolution (di-jet balance)

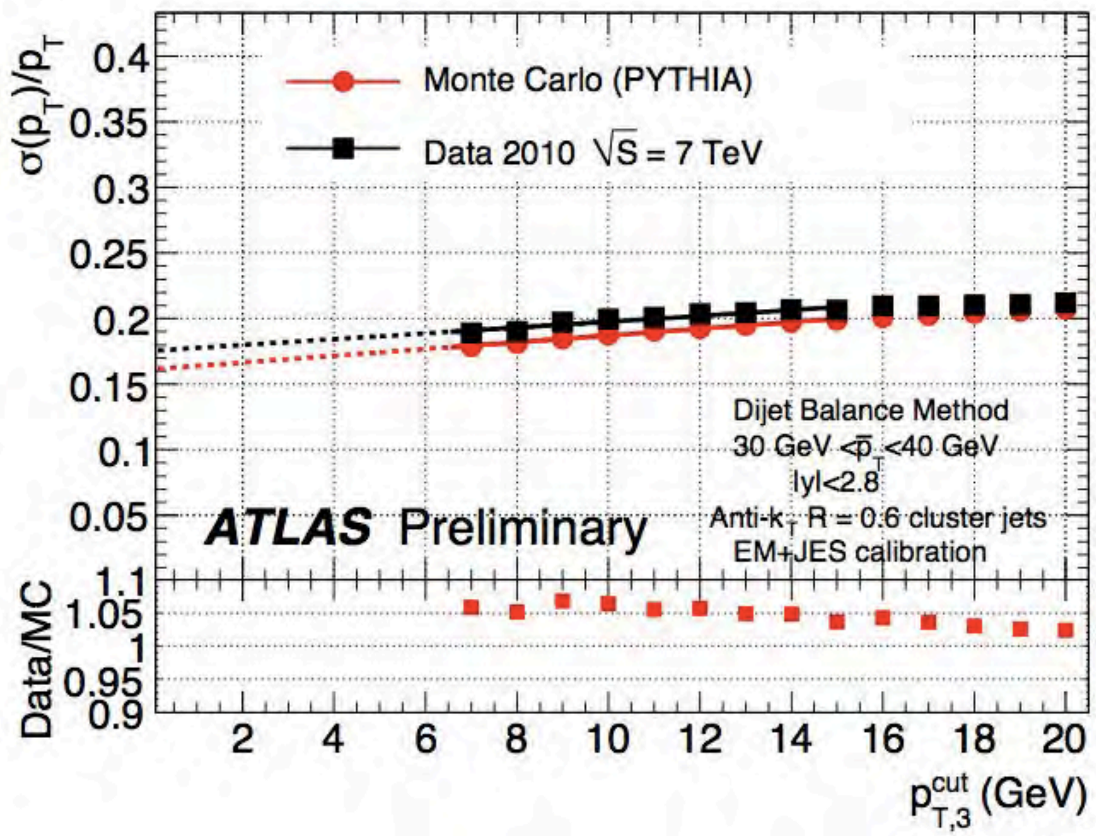
- p_T asymmetry measured in back-to-back di-jet events as a function of the third jet p_T threshold values p_{T3}^{cut}
- Resolution obtained from different p_{T3}^{cut} is fitted and extrapolated to p_{T3}=0 for each p_T bin

$$A \equiv \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}} \qquad \frac{\sigma_{p_T}}{p_T} = \sqrt{2}\,\sigma_A$$

$$K(p_T) = \frac{\left(\frac{\sigma_{p_T}}{p_T}\right)_{p_{T3}\to 0}}{\left(\frac{\sigma_{p_T}}{p_T}\right)_{p_{T3}<10\ \mathrm{GeV}}}$$

$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{\mathrm{corrected}} = K(p_T) \times \left(\frac{\sigma_{p_T}}{p_T}\right)_{p_{T3}<10\ \mathrm{GeV}}$$





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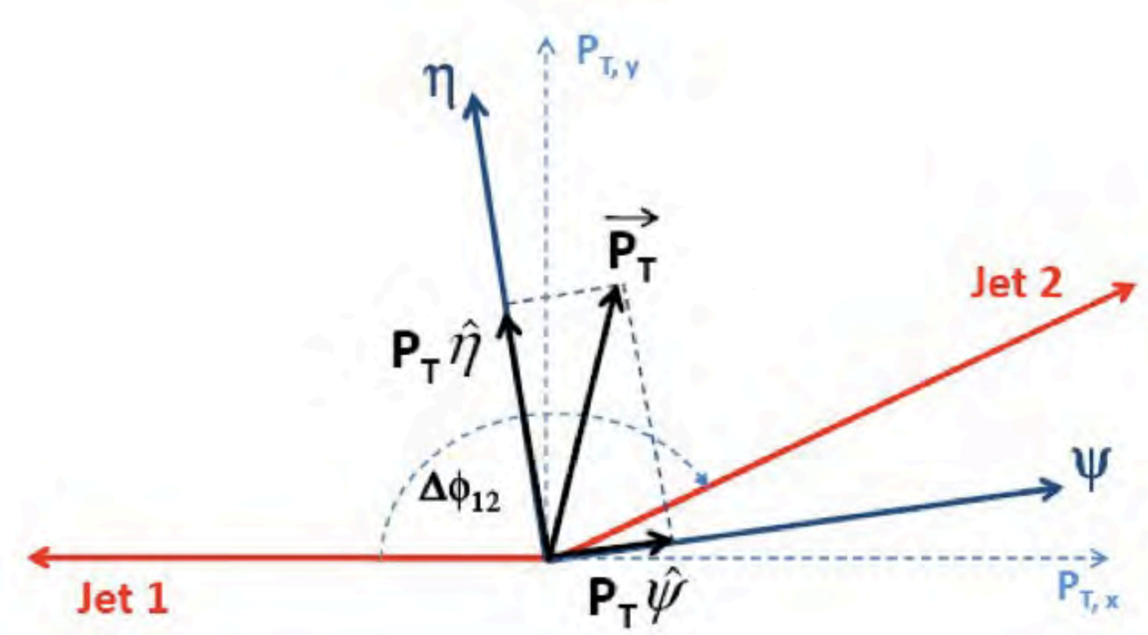
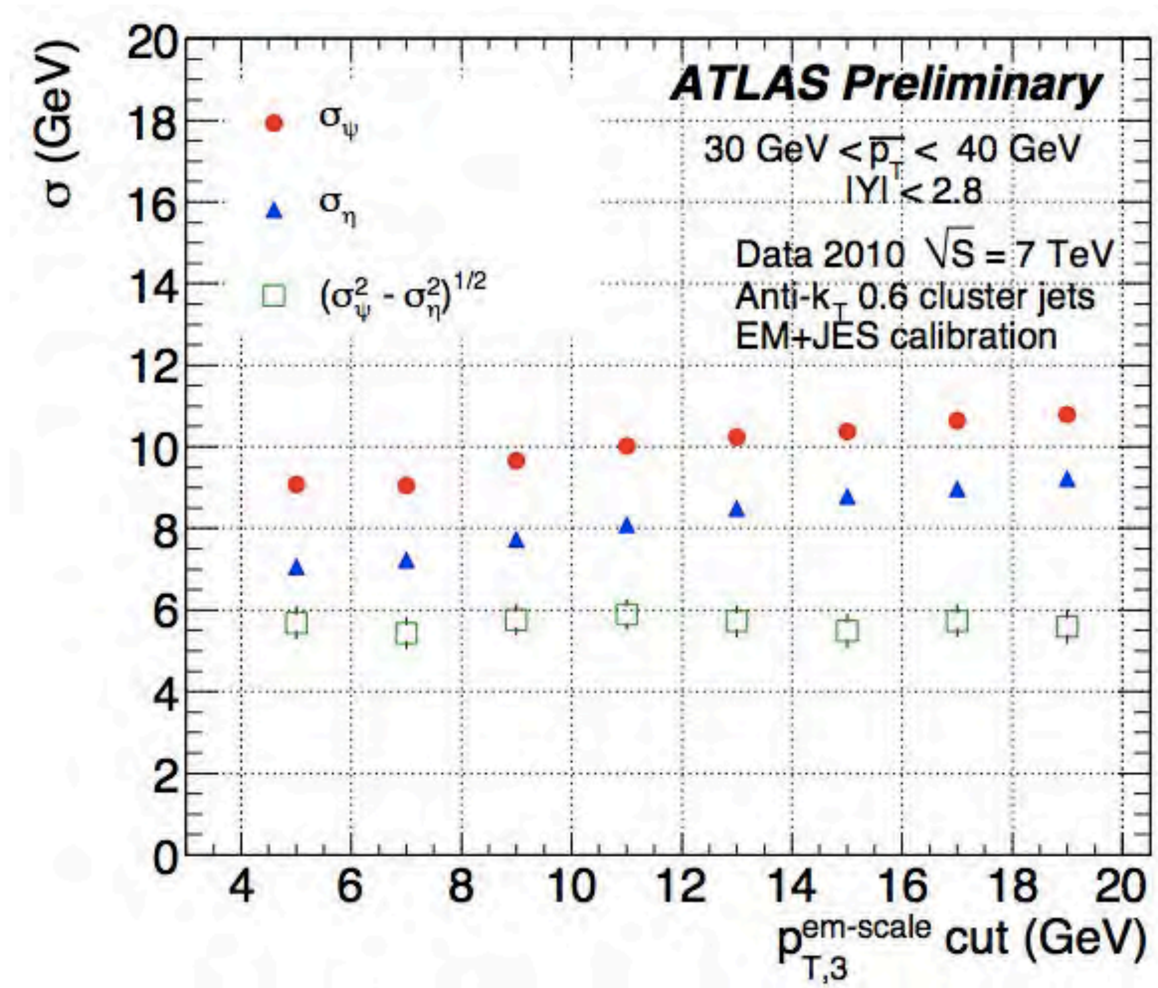
Jet Energy Resolution (bisector)

$$\vec{p}_T = \vec{p}_{T1} + \vec{p}_{T2}$$

- The imbalance transverse momentum vector is projected along an orthogonal coordinate system in the transverse plane
  - the η-axis is chosen to bisect the two leading jet directions
- Basic asumption 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

$$\sigma_{p_T}^2 = \frac{\sigma_\psi^2 - \sigma_\eta^2}{-2\cos(\Delta\phi)}$$





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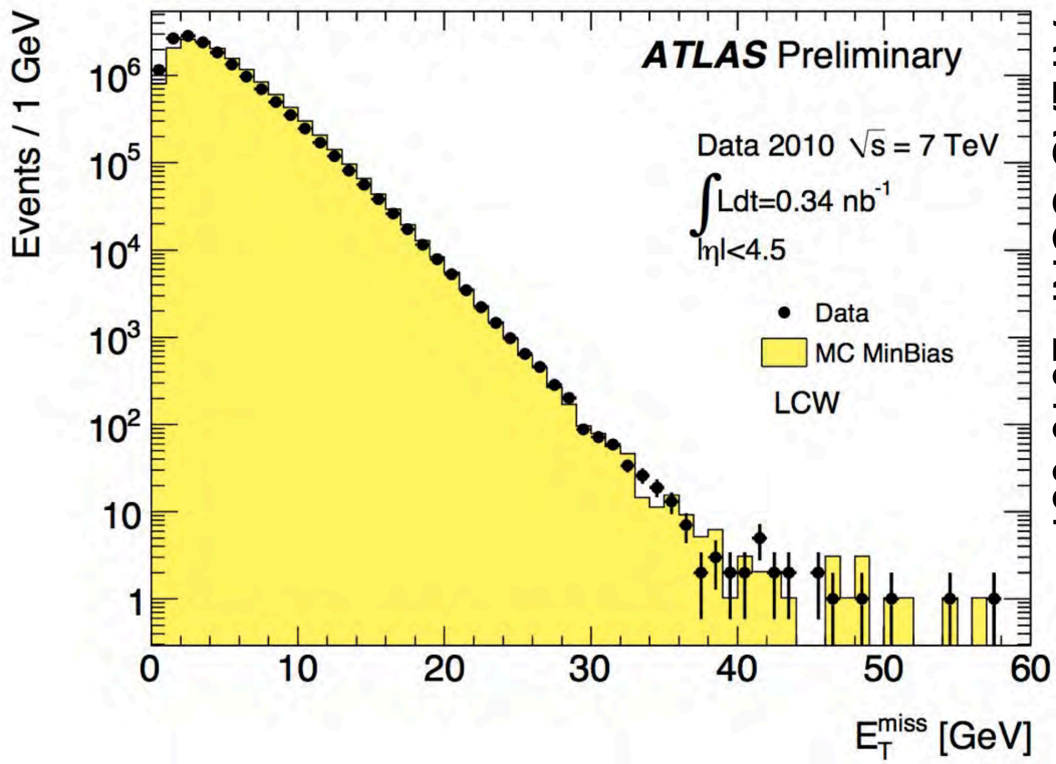
Missing E_T Performance



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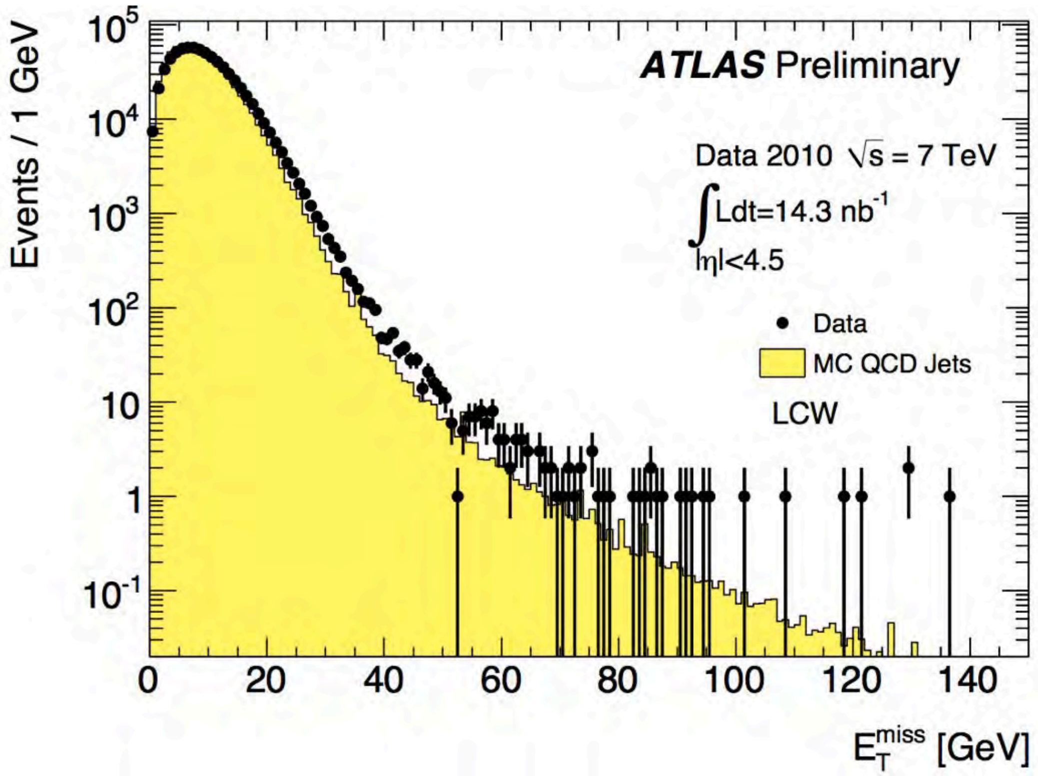
- Minimum bias events
  - cells in clusters used
  - LCW calibration used



- A sample enriched in high p_T jets (anti-k_T R=0.4) contains outlier, 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