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

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Outline

- Jet reconstruction, properties, and calibration
  - Inputs to jet finding
  - Jet shapes and internal structure
  - Jet calibration schemes
  - Jet energy scale, uncertainty, and resolution
- Missing ET performance and calibration
- Tau performance and trigger

- *ATLAS Calorimeter and Inner Detector*
  - *P. Pralavorio and A. Limosani*

Inputs to jet reconstruction

Topological clusters:

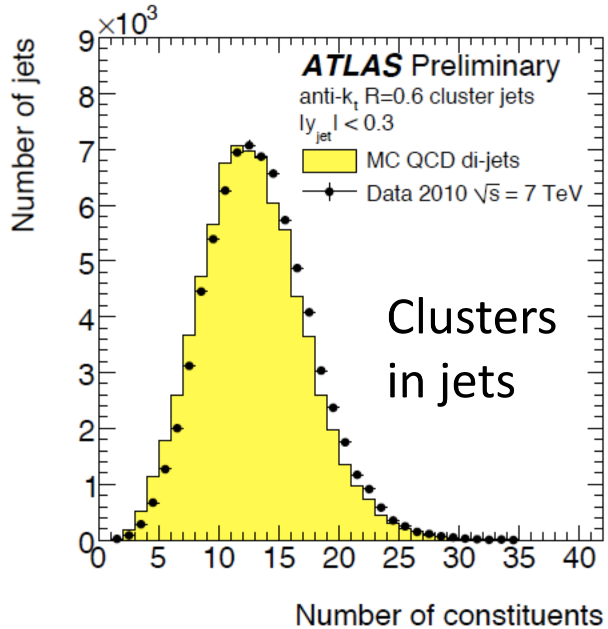
- Dynamically formed three-dimensional objects optimized to follow the shower development

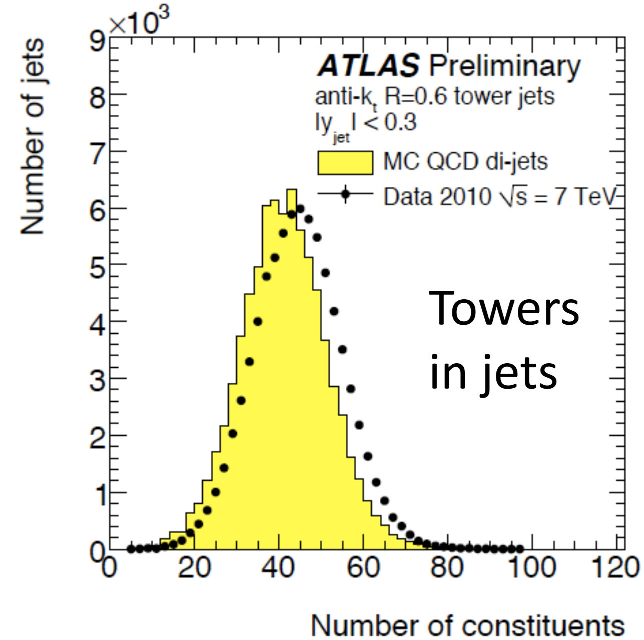
Noise suppressed towers:

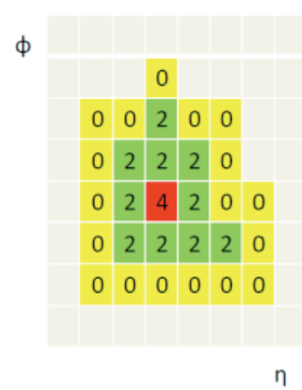
- Fixed geometry grid using cells belonging to topological clusters

Tracks:

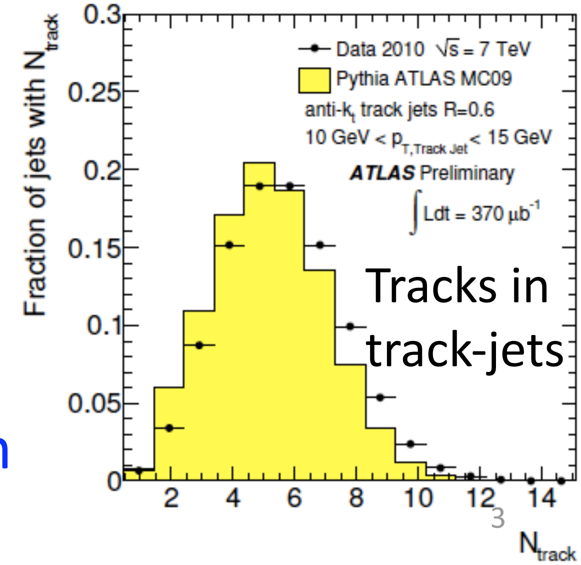
- Independent from calorimeter measurements
- Provide additional z-vertex information (less sensitive to pile-up effects)







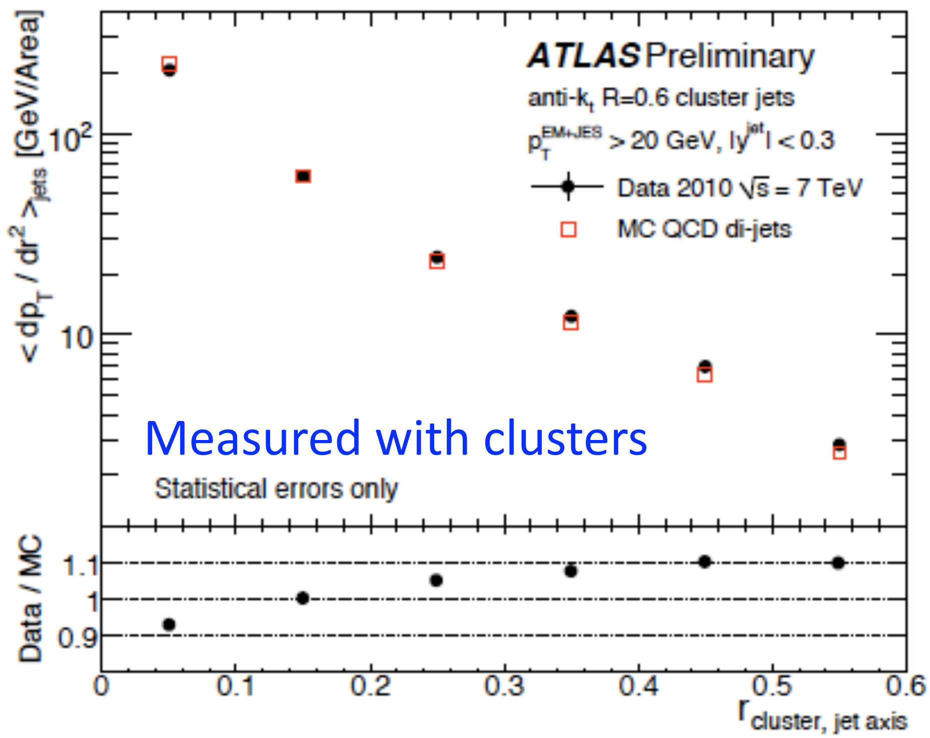
Seed:
$|E_{cell}|>4\sigma$
Neighbors:
$|E_{cell}|>2\sigma$
Nearest neighbors:
$|E_{cell}|>0\sigma$

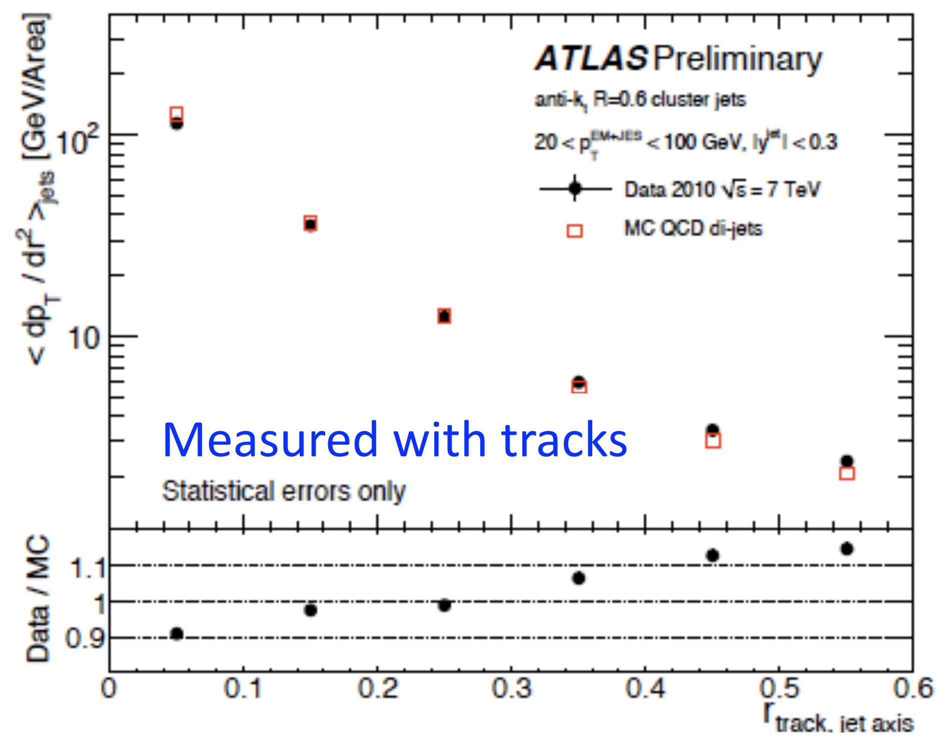


Jets are reconstructed using the anti-k_t algorithm with distance parameter R=0.6

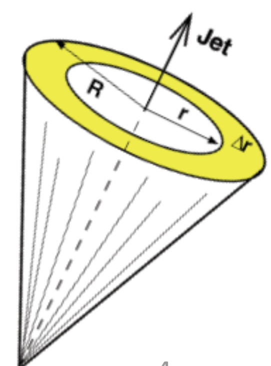
Jet internal structure

EM+JES: energy scale correction, described in page 6





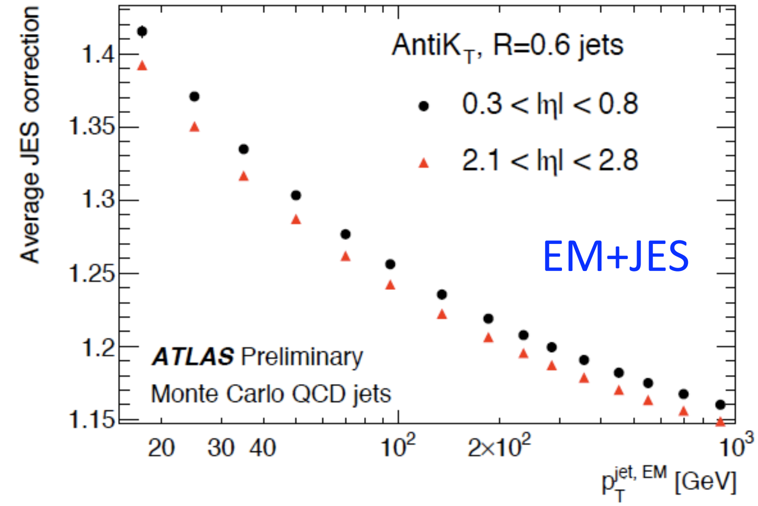
- Measurements of jet shapes and properties are used to test how well the simulation models physics and detector effects
  - Jet fragmentation, detector response to low energy particles, inputs to jet reconstruction, soft underlying event, pile-up
  - Calorimeter and track measurements are independent and can be used to disentangle physics and detector effects
  - Jets are observed to be broader in data than in the simulation



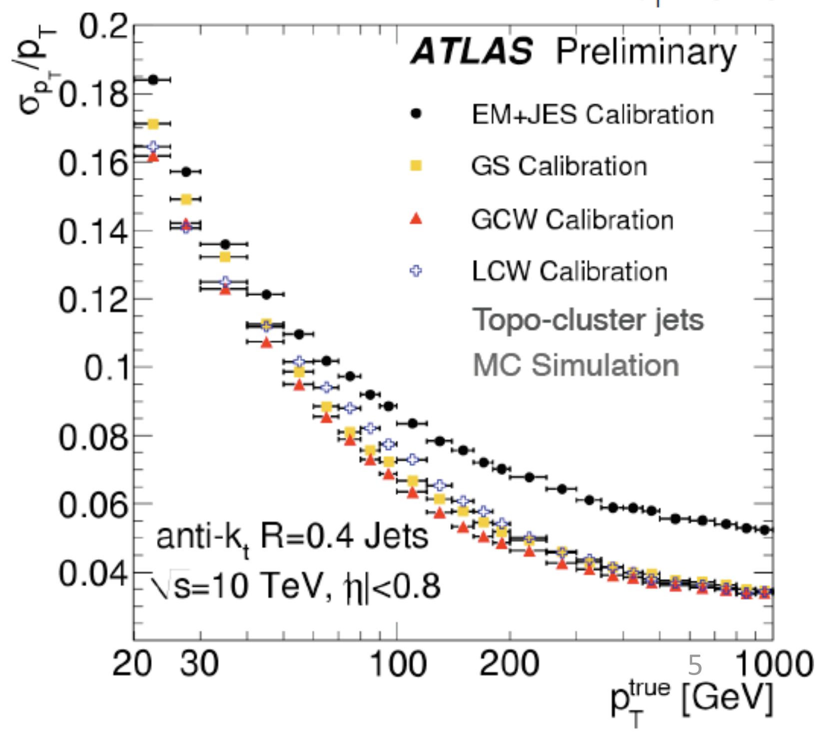
Jet energy calibration

Correct jet energy for calorimeter non-compensation, energy looses in dead material, shower leakage, pile-up

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

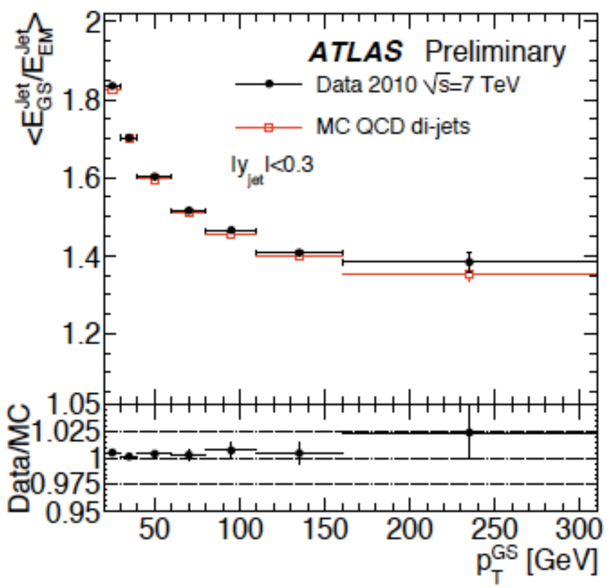


- EM+JES
  - Simple p_T- and η-dependent correction applied to jets measured at the EM scale
- Global sequential calibration (GS):
  - Add jet-by-jet information about the longitudinal and transverse properties of the jet
- Global cell weighting (GCW):
  - Use cell weights based on cell energy density to compensate for the different calorimeter response to hadronic (low E-density) and electromagnetic depositions
- Local cluster weighting (LCW):
  - Use properties of topological clusters to calibrate them individually
  - Cluster calibration derived from Monte Carlo simulations of single charged and neutral pions

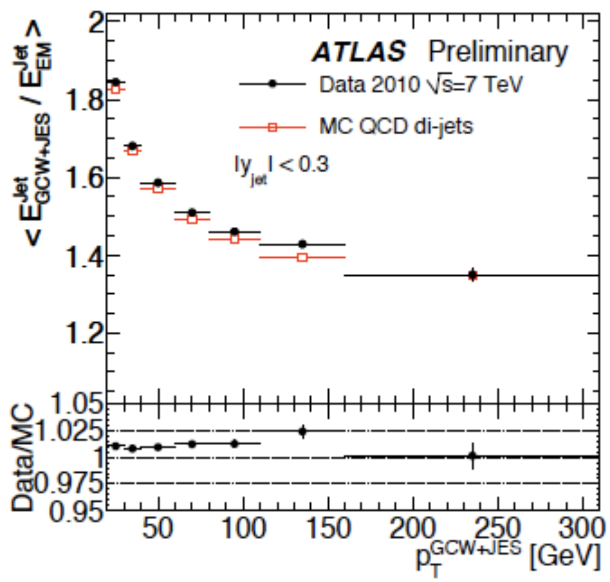


Jet calibration schemes

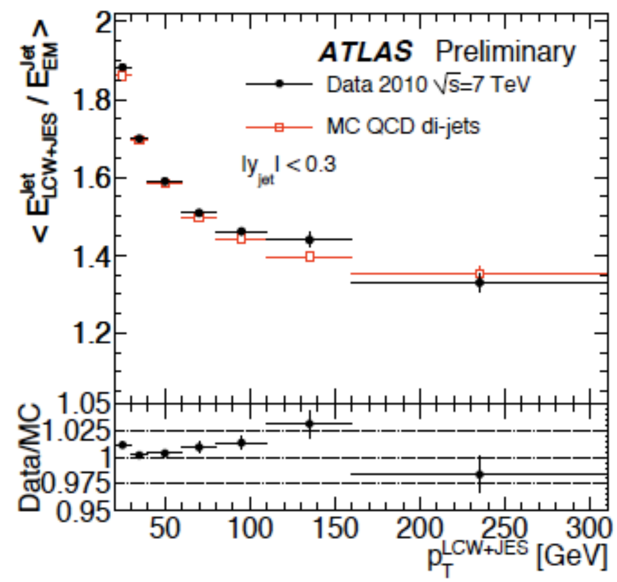
Global Sequential Calibration



Global Cell Weighting



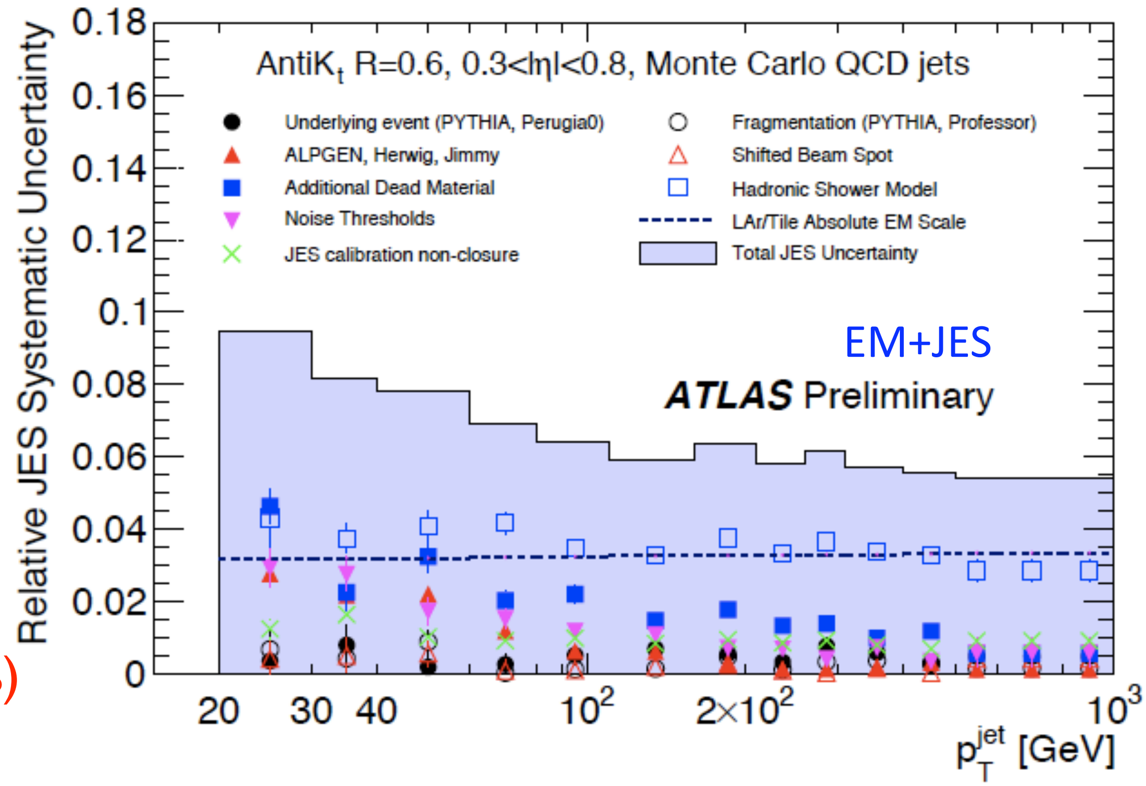
Local Cluster Weighting



- Mean ratio of calibrated over un-calibrated jet energies as a function of calibrated jet p_T:
  - Same average corrections for all three calibration schemes
  - Agreement between the correction factors applied to data and Monte Carlo is better than 2%
  - Similar agreement in the whole rapidity range

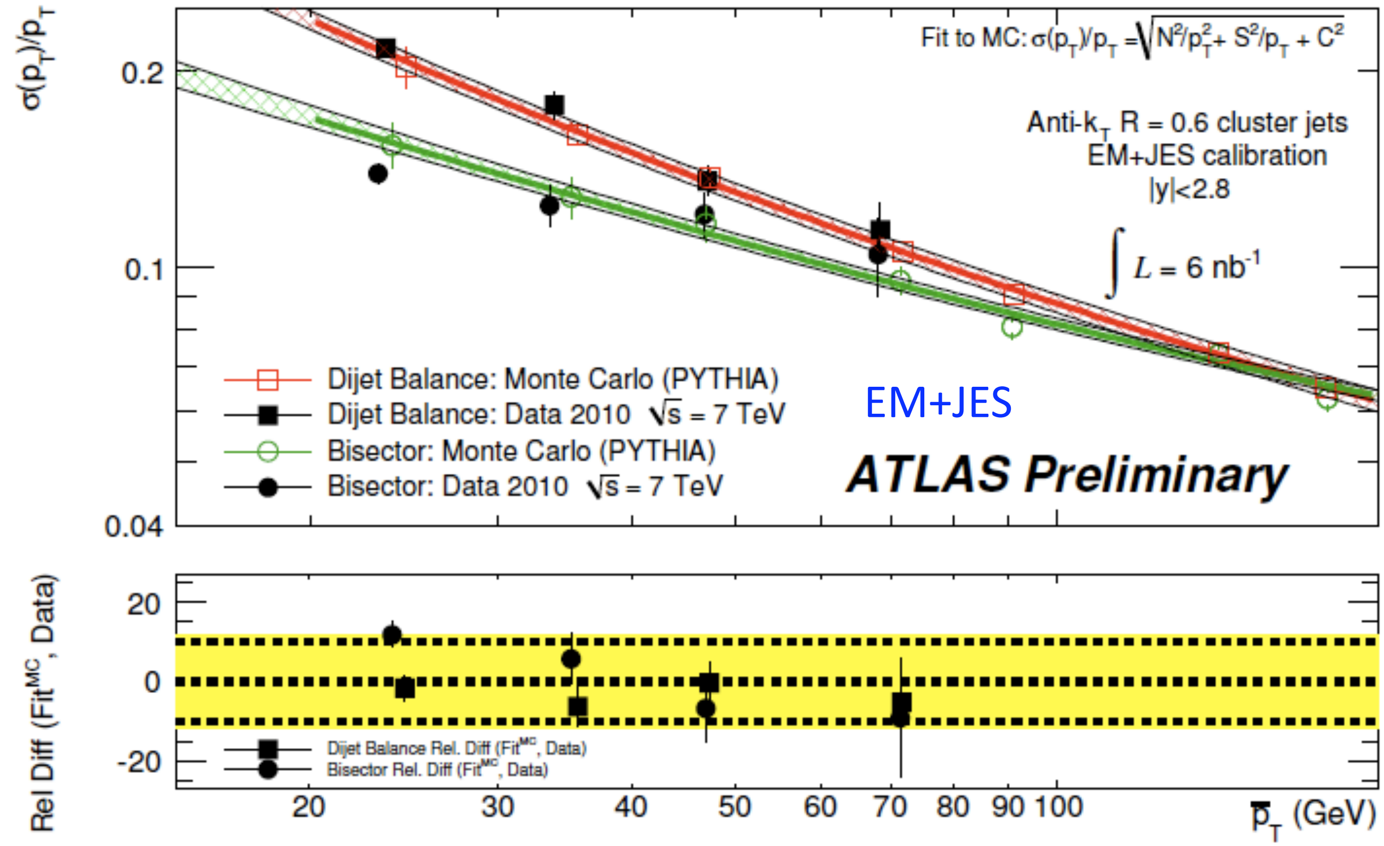
Jet energy scale uncertainty

- JES uncertainty evaluated by comparing Monte Carlo simulations using various detector configurations and hadronic shower 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 than 7% for jets with p_T>100GeV
- Expect reduction of the systematic uncertainty in the near future by propagating single particle response measurements in data to jets

Jet energy resolution



- 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 p_T between 20 and 80 GeV and |y|<2.8

Missing transverse energy

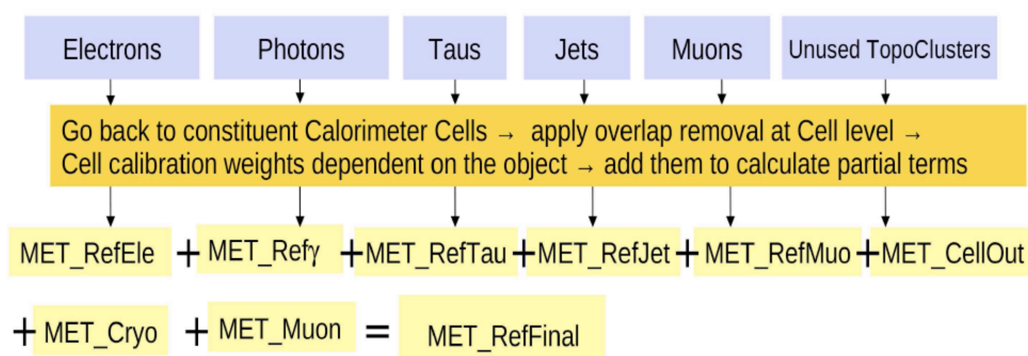
- Missing ET reconstructed from cells belonging to topological clusters and from reconstructed muons:

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

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

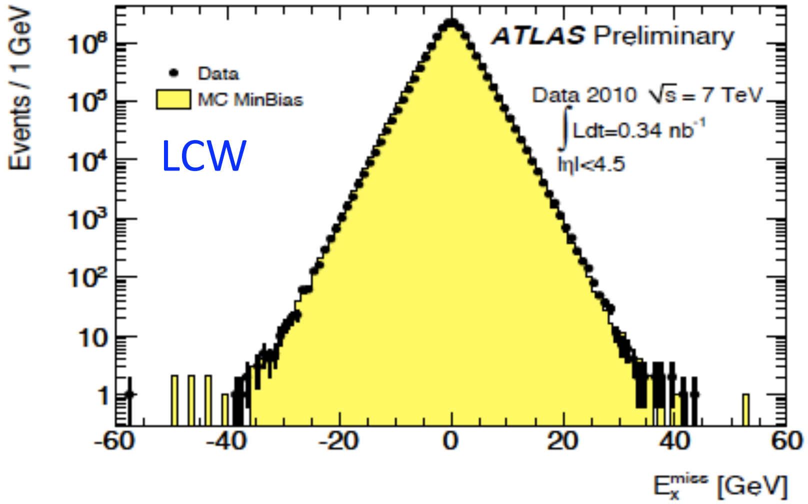
$$E_{\text{T}}^{\text{miss,calo}} = \sqrt{\left(E_x^{\text{miss,calo}}\right)^2 + \left(E_y^{\text{miss,calo}}\right)^2}$$

- Missing ET calibration:
  - Cell energy density or local cluster weighting to correct for non-compensation and energy losses in inactive material
  - Refined calibration based on energy corrections of physics objects

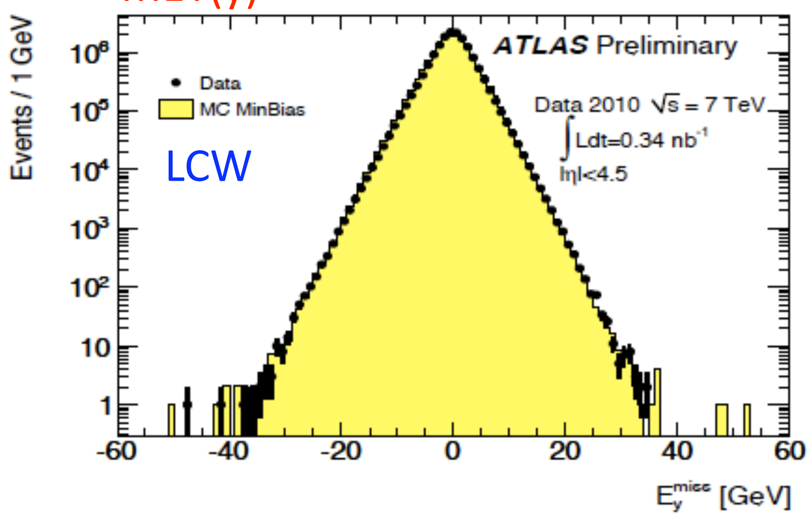


Missing ET performance

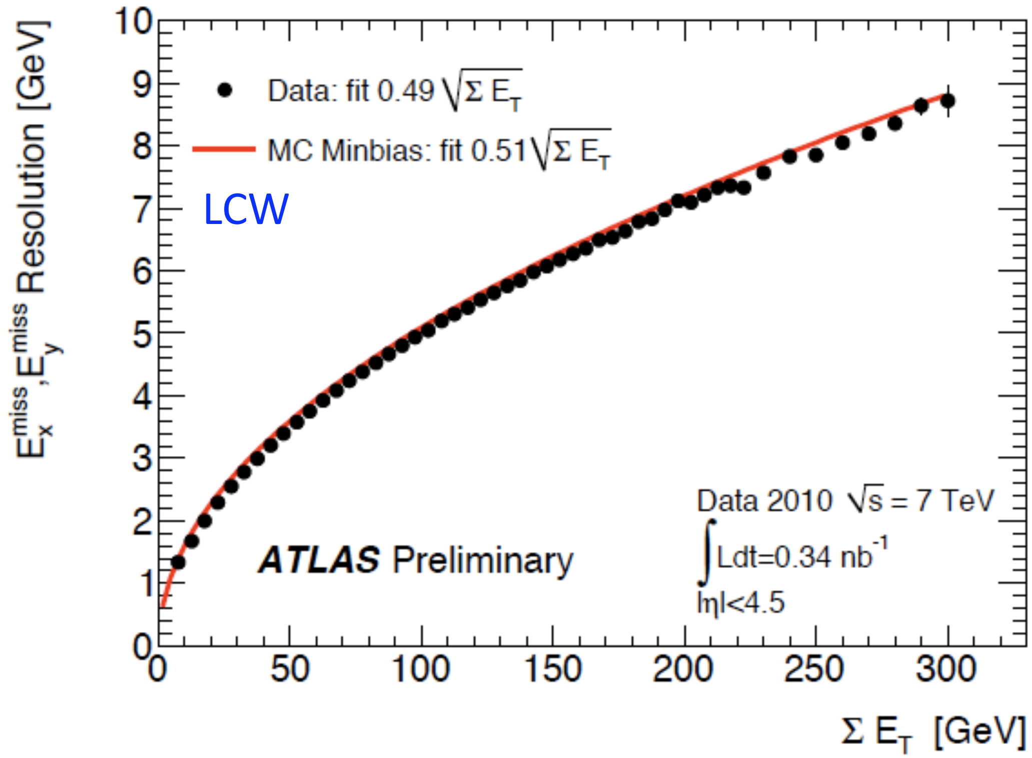
MET(x)



MET(y)



Local Cluster Weighting



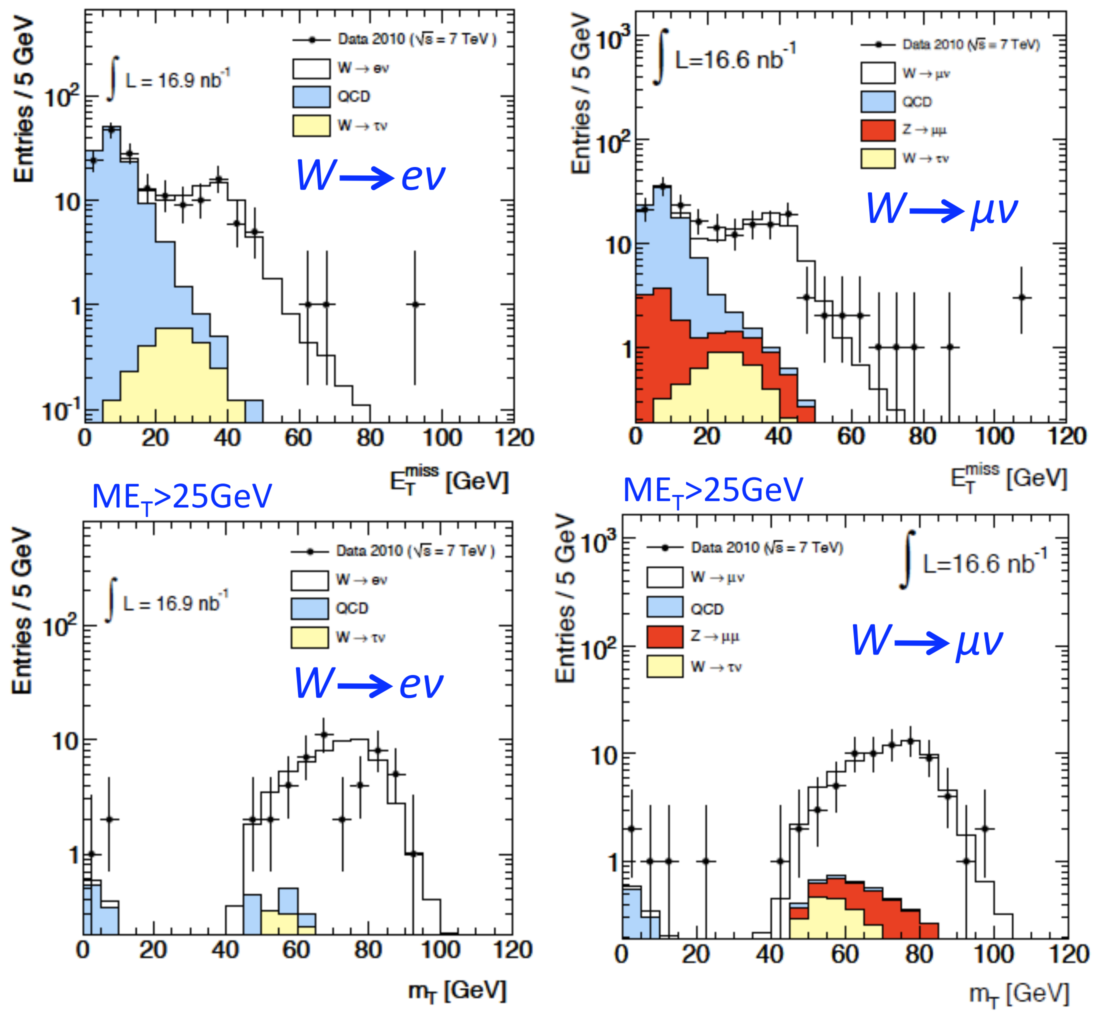
- Calibrated missing ET distributions and tails in minimum bias events are well described by the simulation
- Missing ET resolution in the data in good agreement with the simulation before and after cluster and cell level calibrations

Missing ET in W→lν events

- Require tight isolated electron and muons

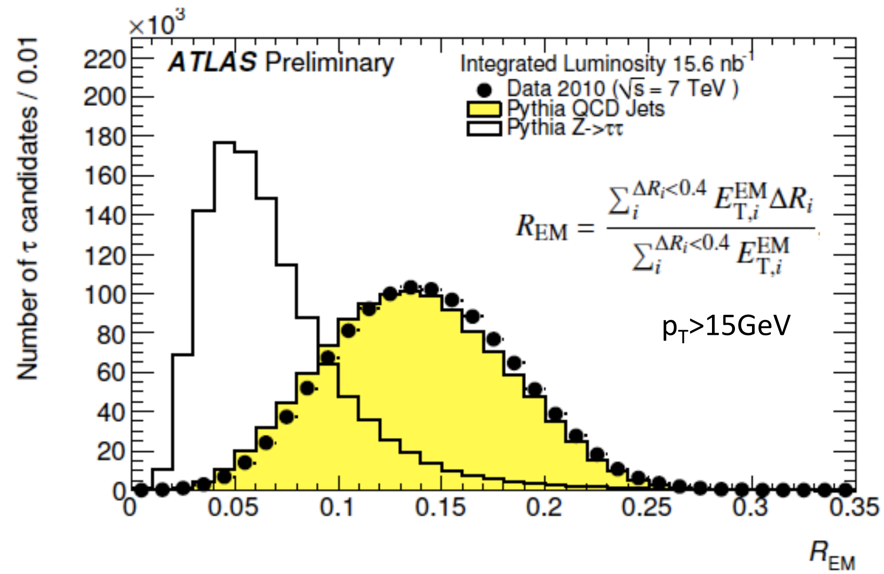
$$p_T^{e,\mu} > 20GeV$$
$$|\eta^e| < 2.47$$
$$|\eta^\mu| < 2.4$$

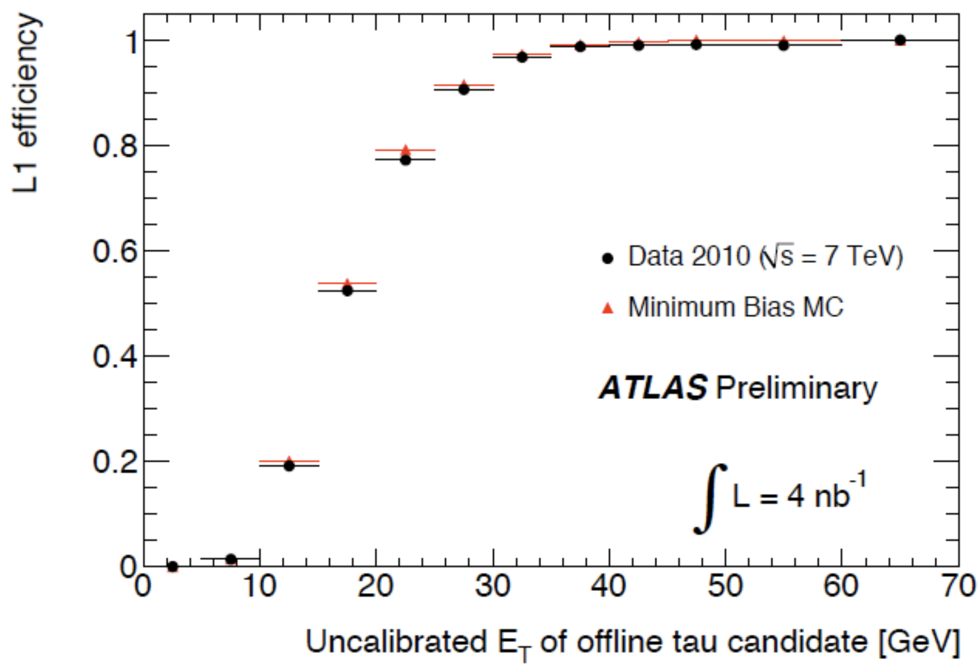
- Missing ET measures the neutrino

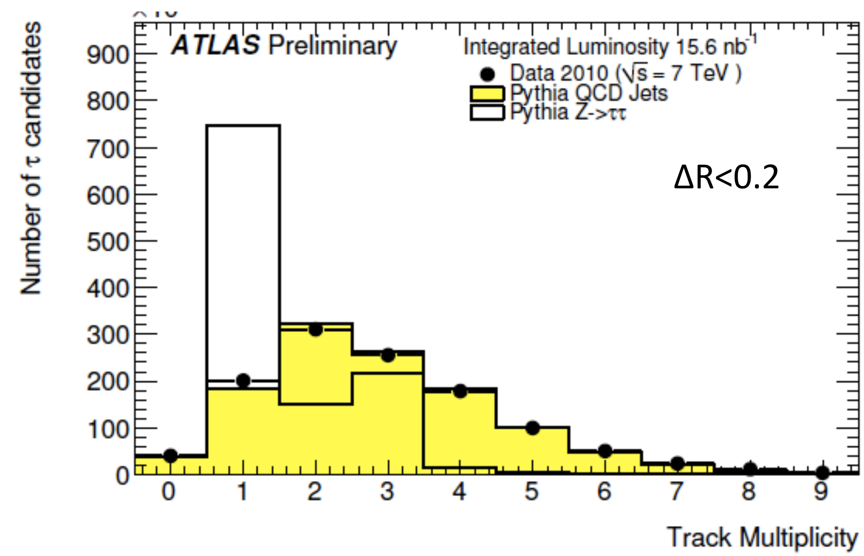


Tau performance and trigger

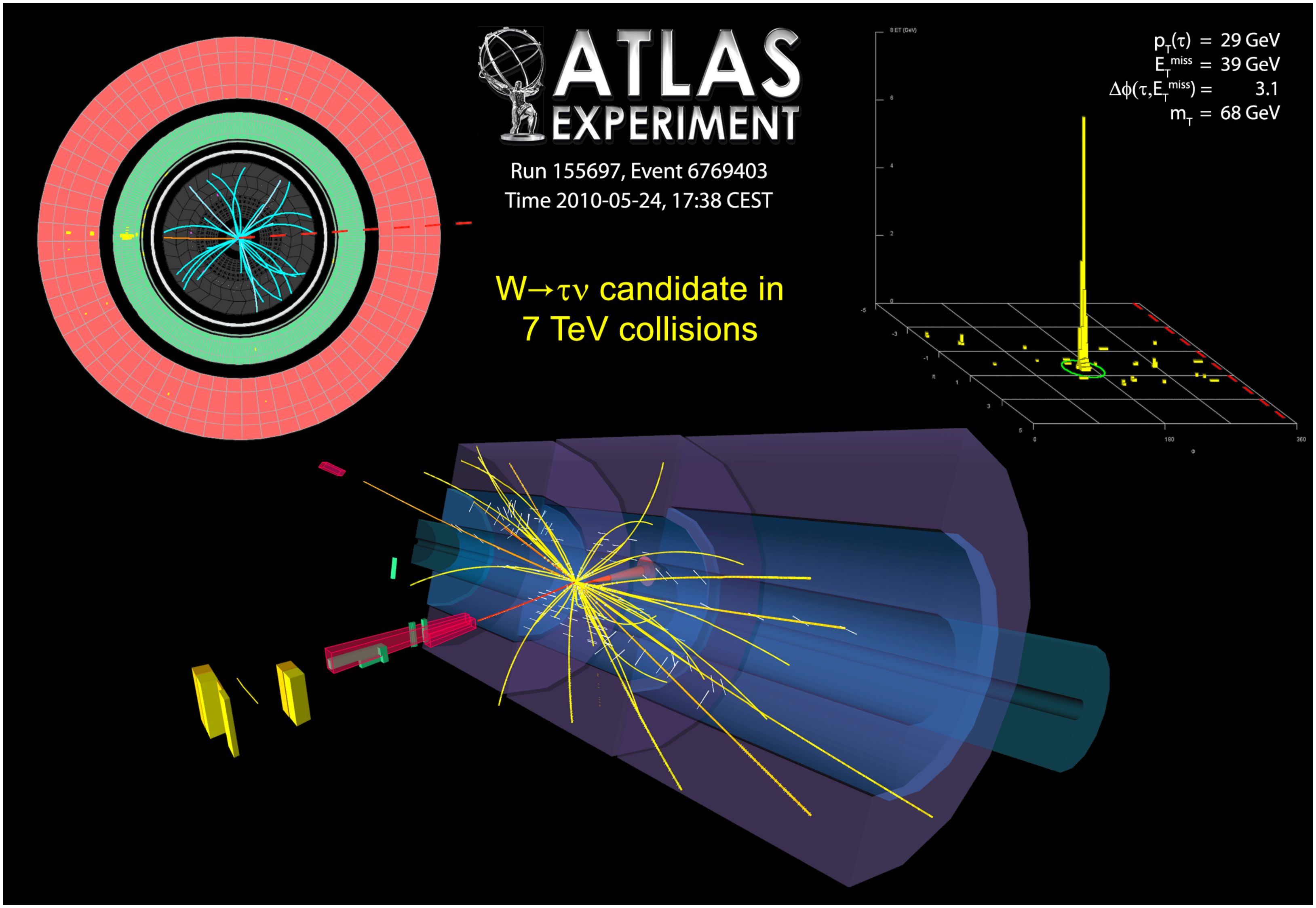
- Hadronic taus are reconstructed using a combination of calorimeter and tracking information:
  - match narrow calorimeter clusters with small number of tracks
  - shower shape information and isolation variables
- Validate the inputs to tau identification and trigger using QCD di-jet data







W→τν Candidate

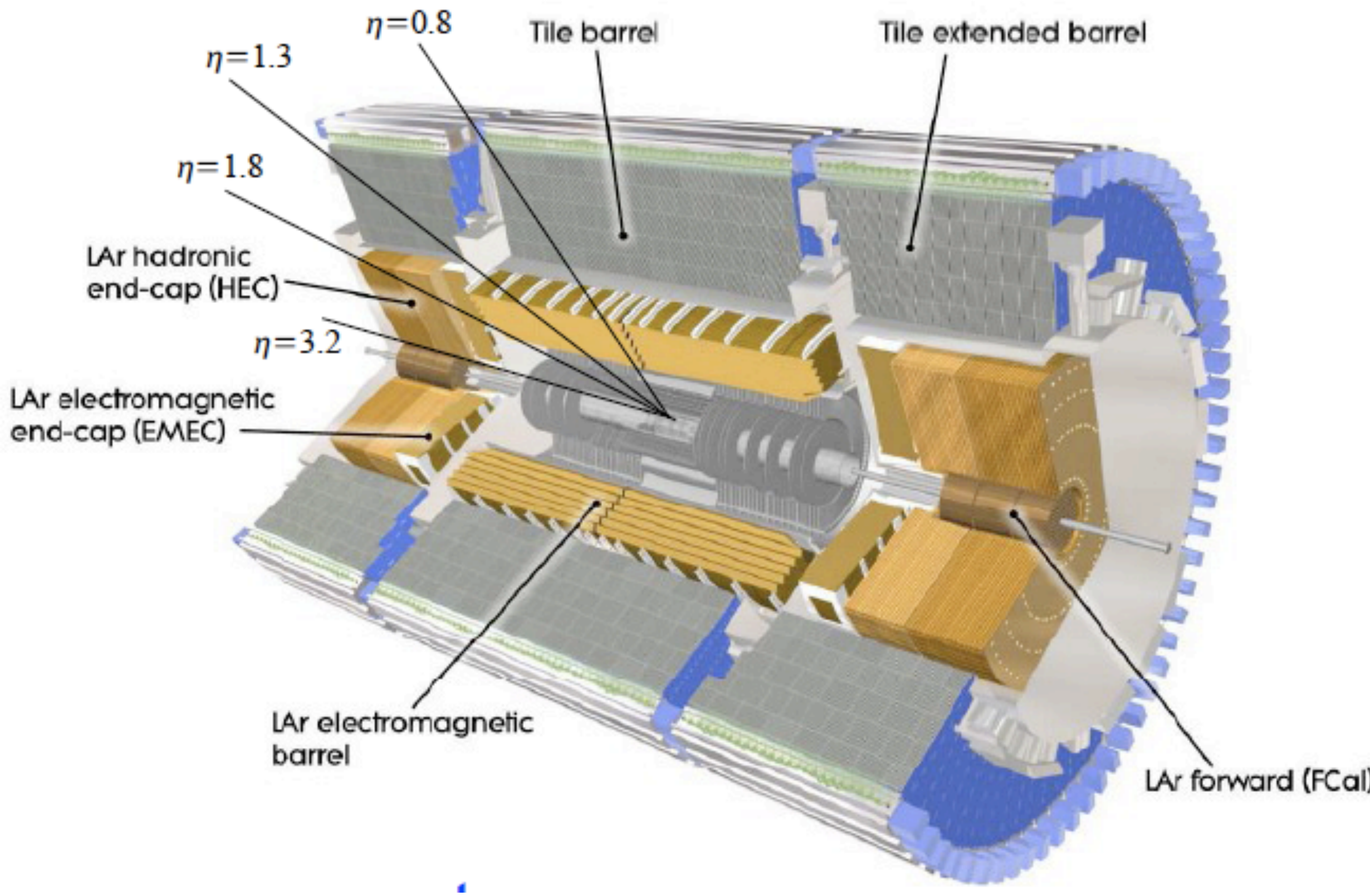


Summary

- ATLAS has developed several jet, tau, and missing ET reconstruction and calibration schemes, with different levels of complexity and sensitivity to systematic effects:
  - Inputs to jet, tau, and missing ET reconstruction and calibration are well described by the simulation within 10%
    - Slightly higher soft activity is found around jets in the data
  - The first ATLAS jet energy scale has been determined with an uncertainty smaller than 7% for jets with p_T>100GeV
  - The Monte Carlo simulation describes the jet energy resolution within 14% for jets with 20GeV< p_T< 80GeV
  - Expect improvements in jet and missing ET performance from the use of the more complex ATLAS calibration schemes, tracks, and single particle response measurements to set the jet energy scale

BACKUP

The ATLAS calorimeter system



|η|<4.9

Sampling EM calorimeter:
- LAr/lead, 3 layers
- high granularity (173K cells)

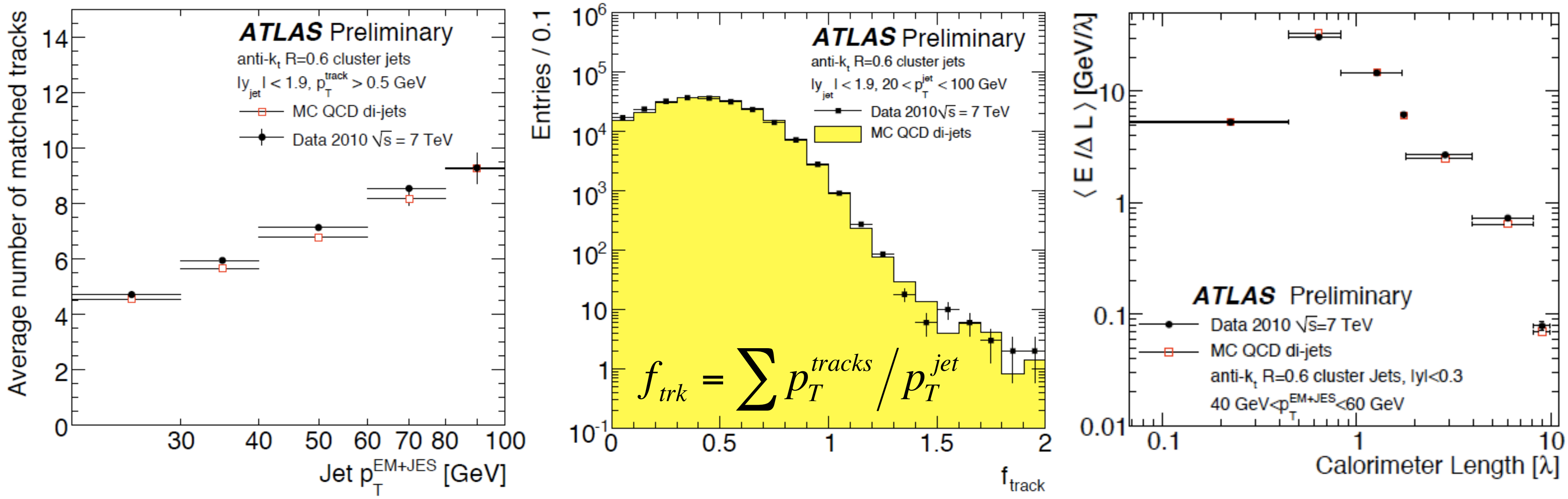
$\Delta\eta\,\Delta\phi_{barrel} = (0.003\,x\,0.1)(0.025\,x\,0.025)(0.05\,x\,0.025)$

Sampling Hadronic calorimeter:
- Steel + tile scintillators (Tile)
- LAr/copper (HEC)
- LAr/copper/tugnstate (FCal)

Jet data quality

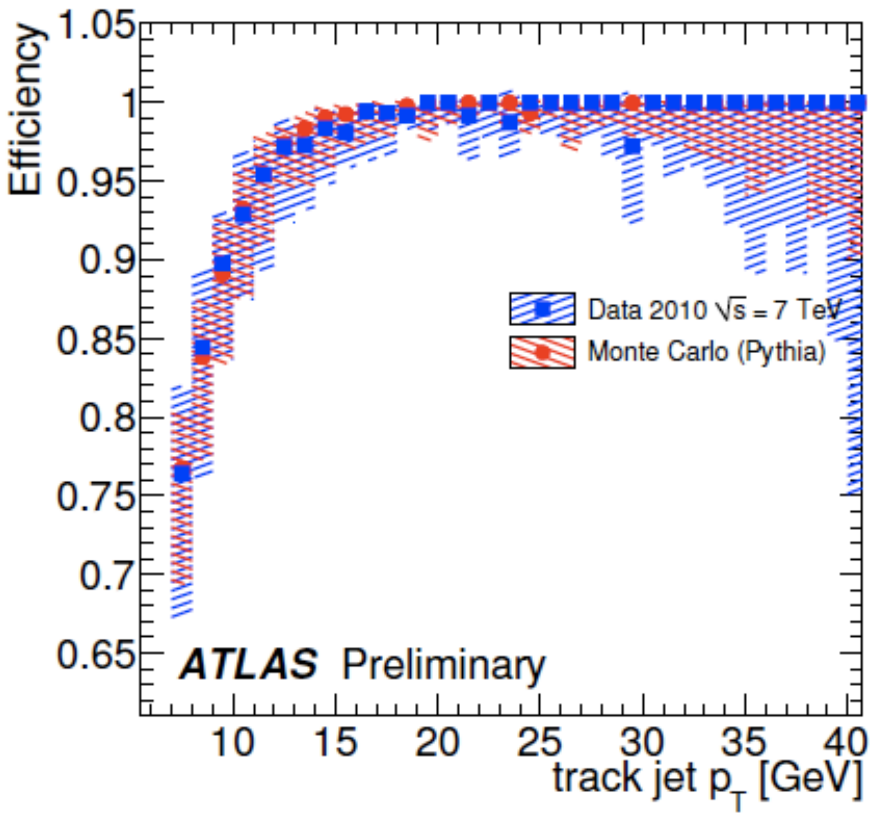
- Minimum number of cells containing 90% of the energy (n_{90}) of the jet must be larger than 5 for jets which deposit more than 80% of their energy in the HEC ($f_{HEC}>0.8$)
- Cell signal quality factor, representing the fraction of cells with poor signal quality defined by the pulse shape must be smaller than 0.8 for jest which deposit at least 95% of their energy in the EM calorimeter
- Energy-squared-weighted cell time of $\Delta t<50$ns with respect to the triggered event

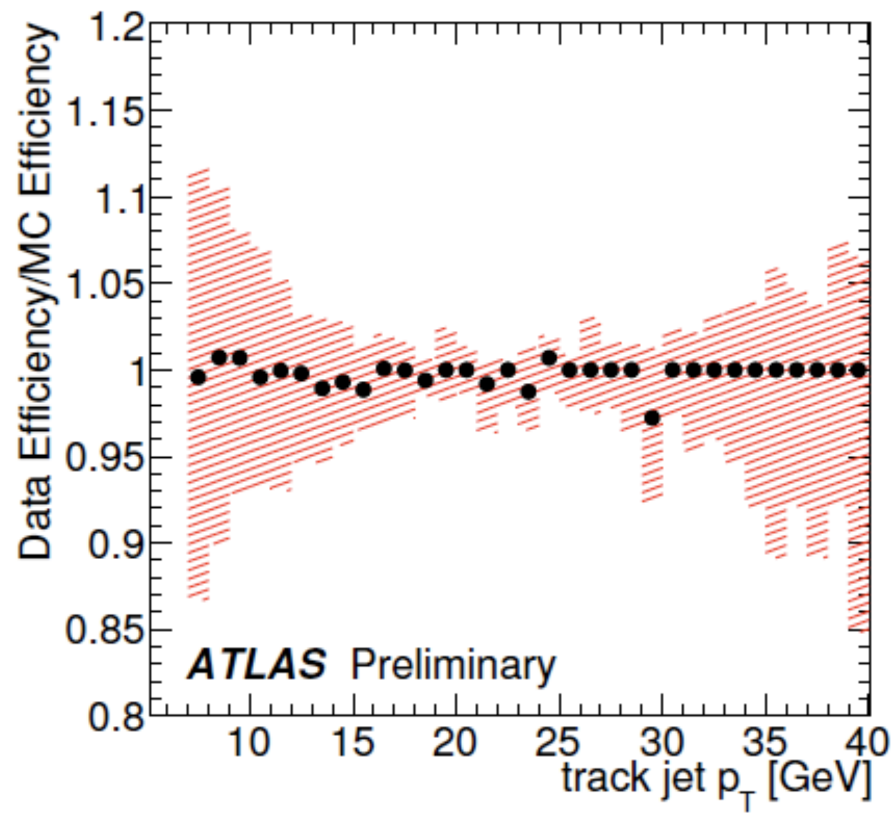
Jet internal structure (II)



- Slightly more low p_T (<1GeV) tracks in jets in the data than in the simulation (PYTHIA LO MC + PS)
- Charged particle fraction (f_{trk}) well described by the simulation. Small discrepancies (<4%) for low p_T jets in the forward region
- Good Monte Carlo description of the longitudinal profile. Small discrepancies in the gap scintillators and end-cap pre-sampler

Jet reconstruction efficiency





- Calorimeter jet reconstruction and identification efficiency relative to track-jets
  - Tag and probe method

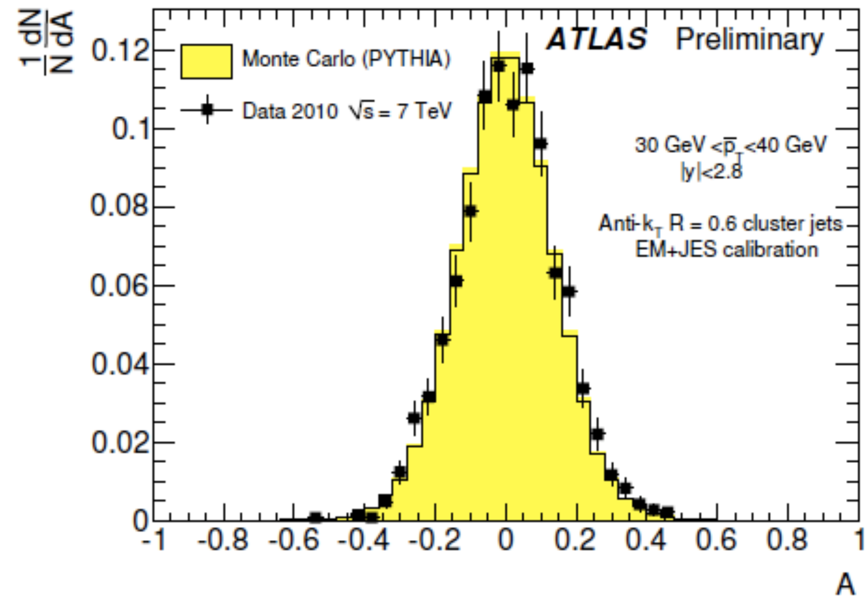
Jet energy resolution (di-jet balance)

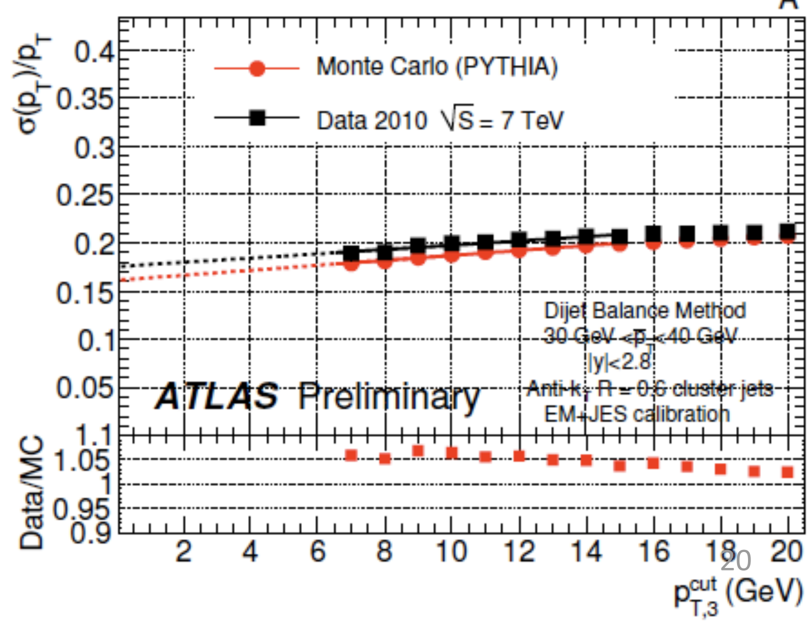
- p_T asymmetry measured in back-to-back di-jet events as a function of $p_{T,3}$ threshold values
- Fractional jet energy resolution obtained from the different $p_{T,3}$ thresholds is fitted and extrapolated to $p_{T,3} = 0$ for each p_T bin

$$A \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \longrightarrow \frac{\sigma_{p_T}}{p_T} = \sqrt{2}\sigma_A$$

$$K_{soft}(p_{\mathrm{T}}) = \frac{\left(\frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T}}}\right)_{p_{\mathrm{T},3} \longrightarrow 0}}{\left(\frac{\sigma_{p_{\mathrm{T}}}}{p_{\mathrm{T}}}\right)_{p_{\mathrm{T},3} < 10 \text{ GeV}}}$$

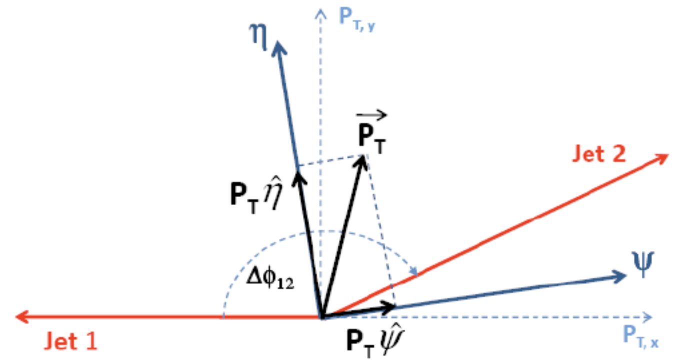
$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{corrected} = K(p_T) \times \left(\frac{\sigma_{p_T}}{p_T}\right)_{p_{T,3} < 10 GeV}$$





Jet energy resolution (bisector)

- The imbalance transverse momentum $\vec{p}_T = \vec{p}_T^{\,1} + \vec{p}_T^{\,2}$ is projected along an orthogonal coordinate system in the transverse plane:
  - η-axis is chosen in the direction that bisects the two leading jets



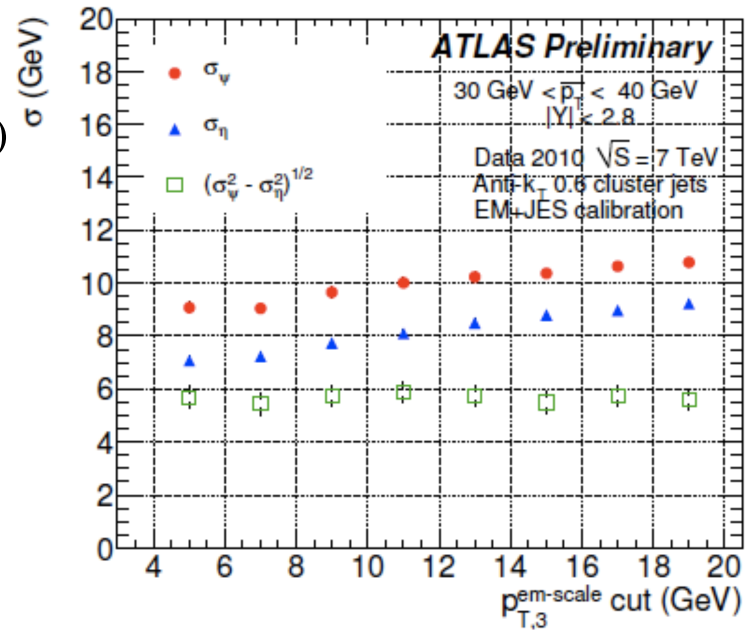
- It can be shown that the variances of $p_{T,\Psi}$ and $p_{T,\eta}$ are given by:

$$\sigma_\Psi^{2\,calo} = Var(p_{T_\Psi}^{calo}) = Var(p_{T,1_\Psi}^{part} + p_{T,2_\Psi}^{part}) + 2\sigma^2(p_T)\sin^2(\Delta\phi/2)$$

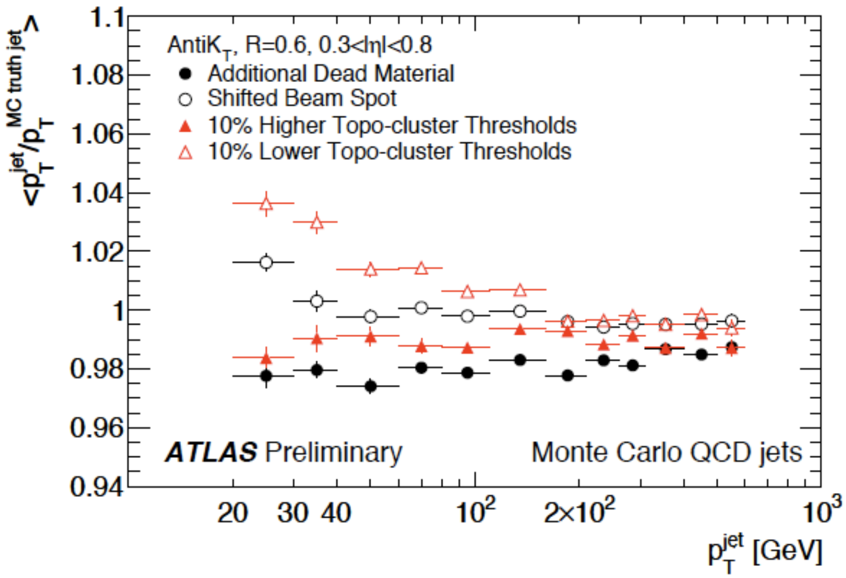
$$\sigma_\eta^{2\,calo} = Var(p_{T_\eta}^{calo}) = Var(p_{T,1_\eta}^{part} + p_{T,2_\eta}^{part}) + 2\sigma^2(p_T)\cos^2(\Delta\phi/2)$$

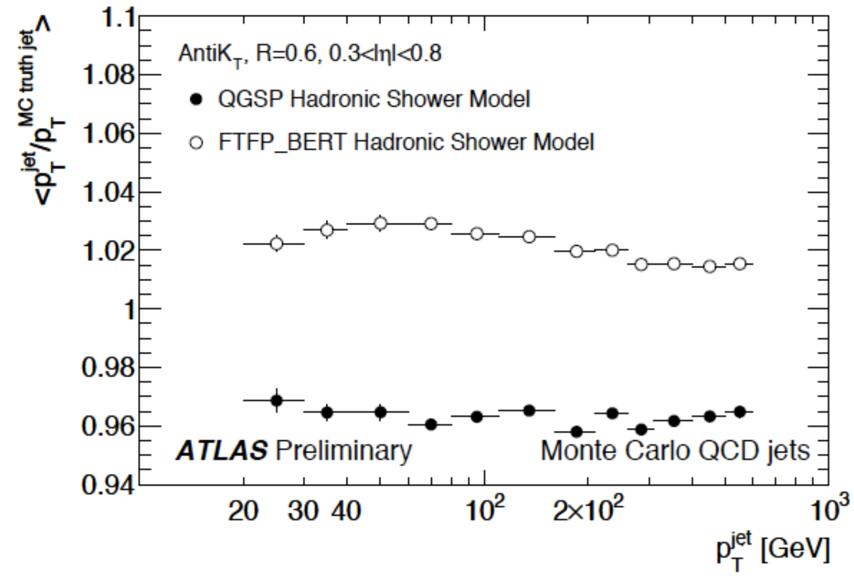
- If $\sigma^2_\Psi = \sigma^2_\eta$ at particle level (basic assumption of the method):

$$\frac{\sigma(p_T)}{< p_T >} = \frac{\sqrt{\sigma_\Psi^{2\,calo} - \sigma_\eta^{2\,calo}}}{\sqrt{2} < p_T > |\cos(\Delta\phi)|}$$



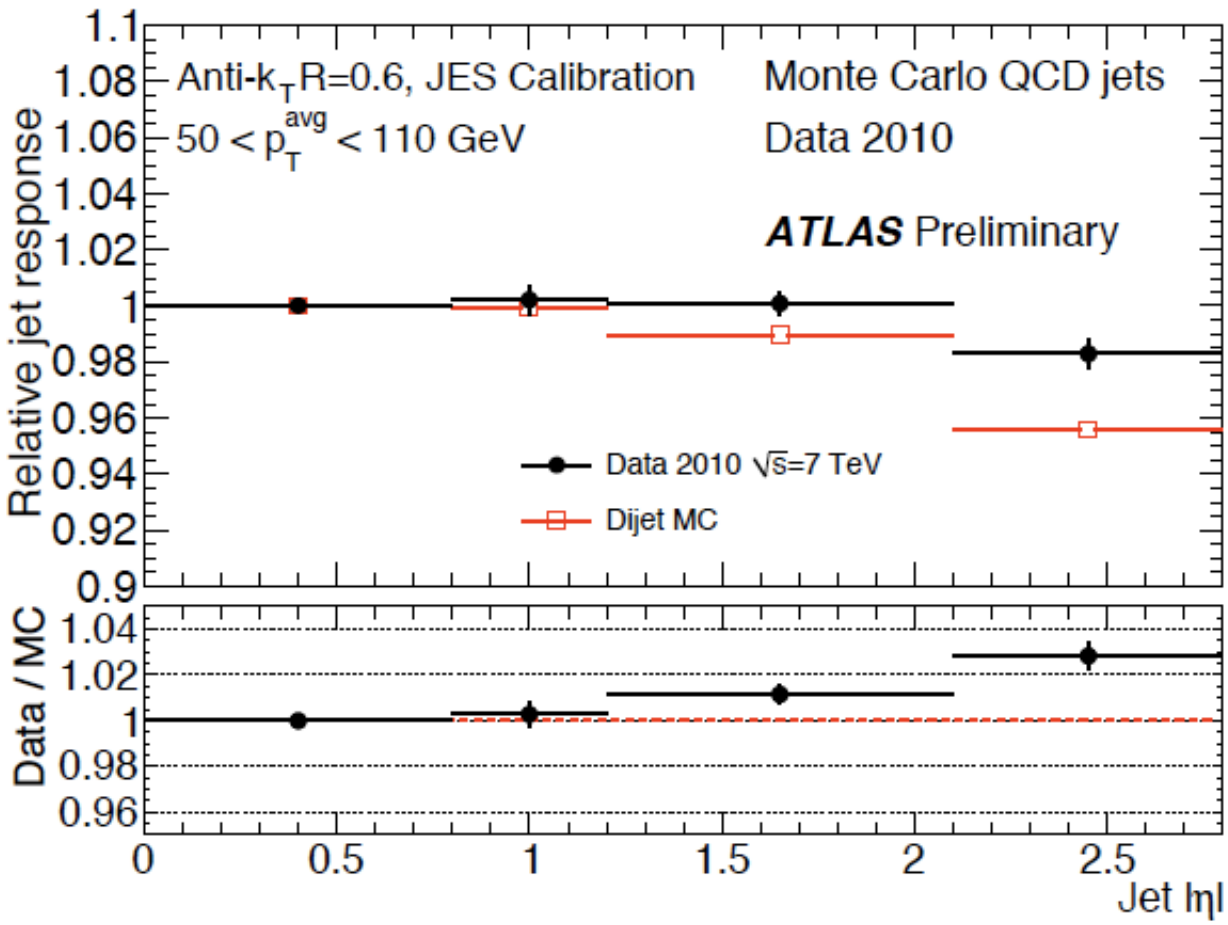
Jet energy scale uncertainty





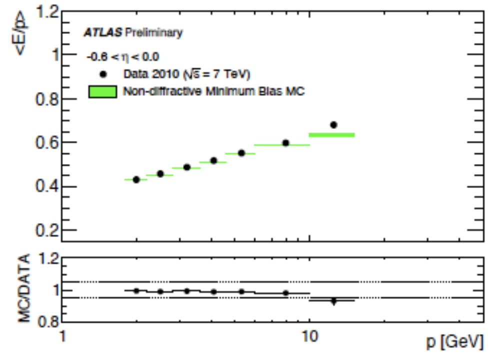
- Uncertainties due to detector description, experimental conditions and JES calibration:
  - Material budget and distorted geometry
  - Topological cluster noise thresholds:
    - 10% noise threshold uncertainty from the stability of the noise spread in dedicated noise runs and the comparison of the noise distribution in data and MC
  - Shifted beam spot
  - Hadronic shower model
    - Test beam single pion response measurements lie within QGSP and FTFP_BERT models (QGSP_BERT nominal hadronic shower model)

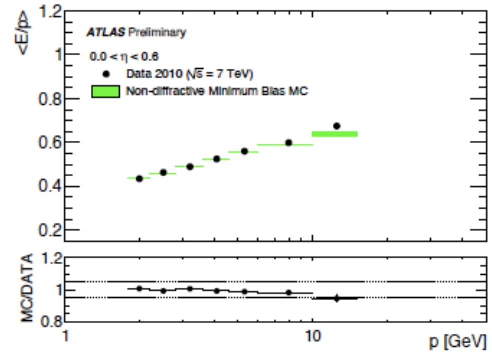
Jet eta inter-calibration

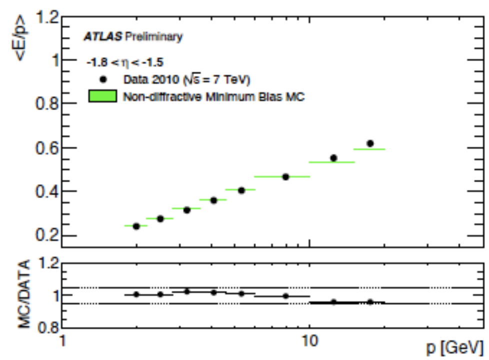


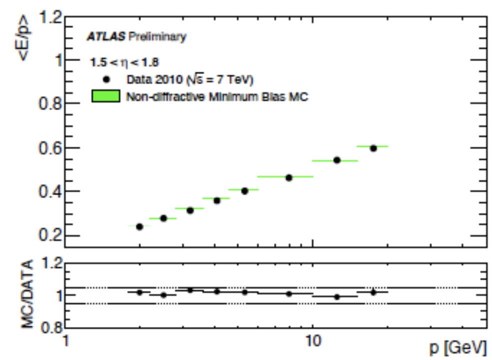
- Relative jet response as a function of jet eta
- Set additional JES uncertainty for the endcap region:
  - 2.4% difference between data and Monte Carlo response
  - 2% difference from one of the relative energy scale in the data

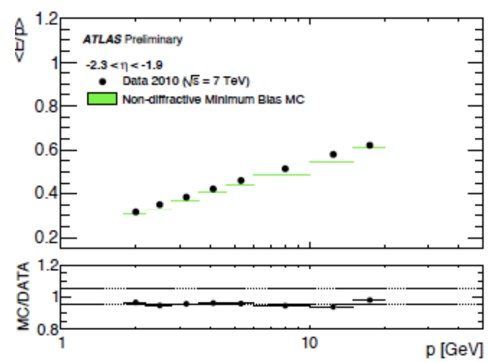
Single particle response

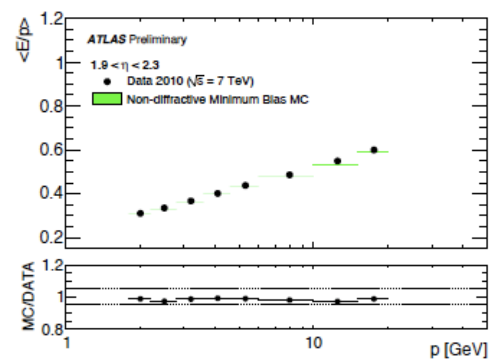






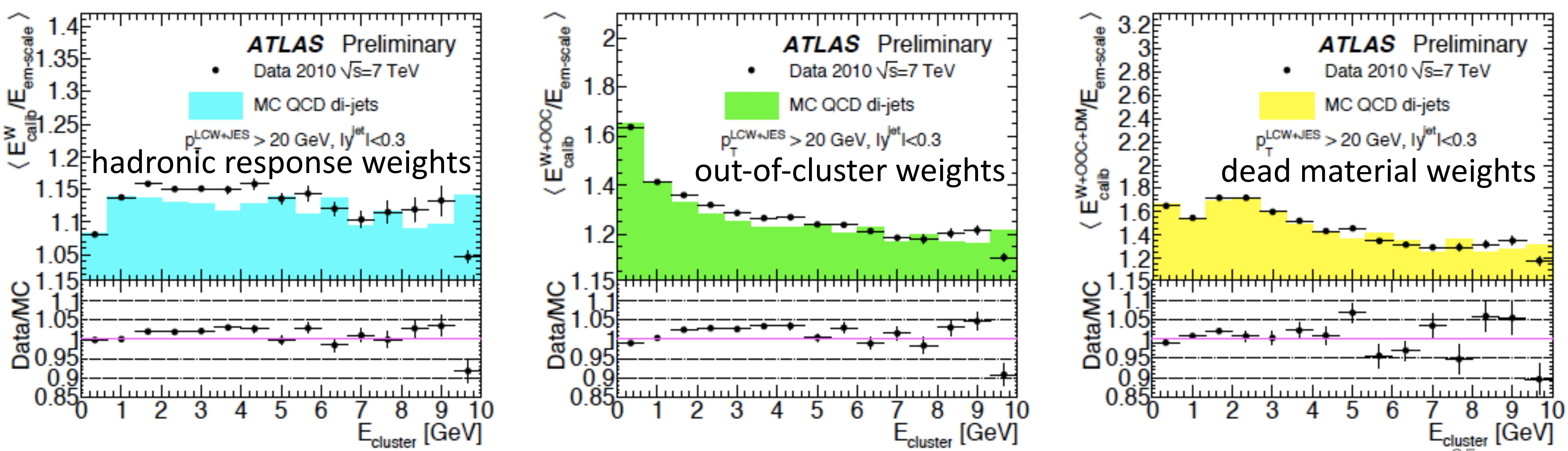




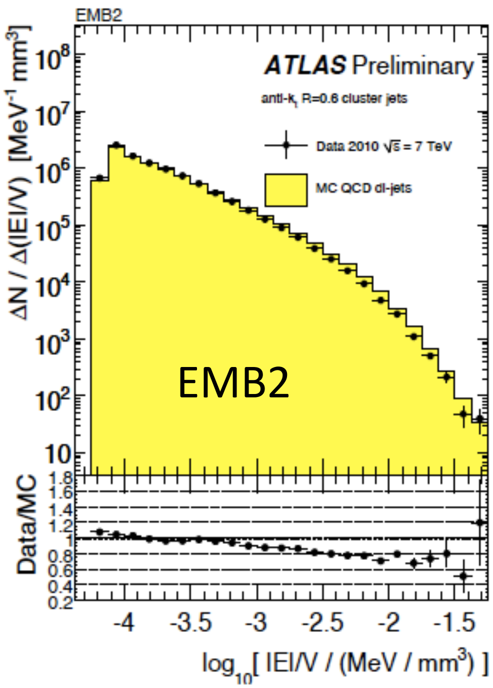


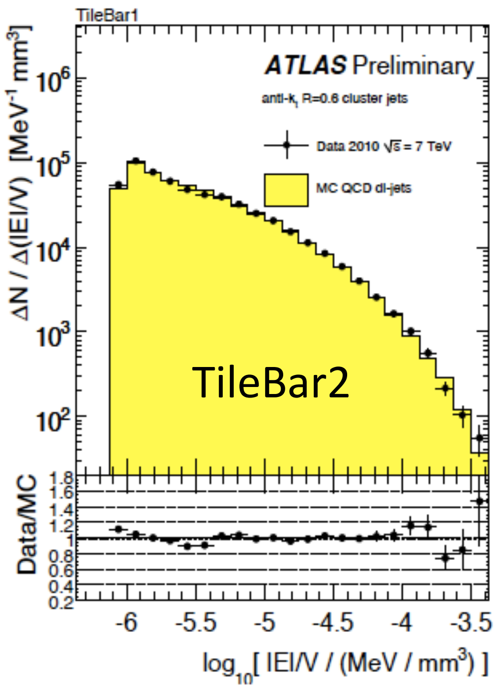
Local cluster weighting calibration

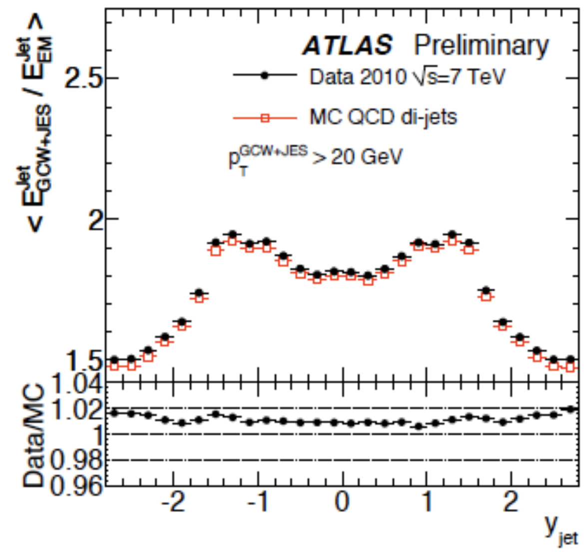
- LCW calibration scheme allows to improve the jet energy resolution by calibrating clusters individually *prior* to jet reconstruction
  - Discriminant to classify clusters as EM/HAD (cluster η, depth, cell E-density)
  - Cluster weights:
    - Hadronic response (cell E-density and cluster energy)
    - Out-of-cluster (cluster depth and energy around the cluster)
    - Dead material (fractional energy deposited in each calorimeter layer and cluster energy)
- 2% agreement between data and Monte Carlo simulation for the ratio of calibrated cluster energy over the un-calibrated cluster energy after each calibration step. Very good agreement between data and simulation for all inputs to LCW.



Global cell energy-density weighting



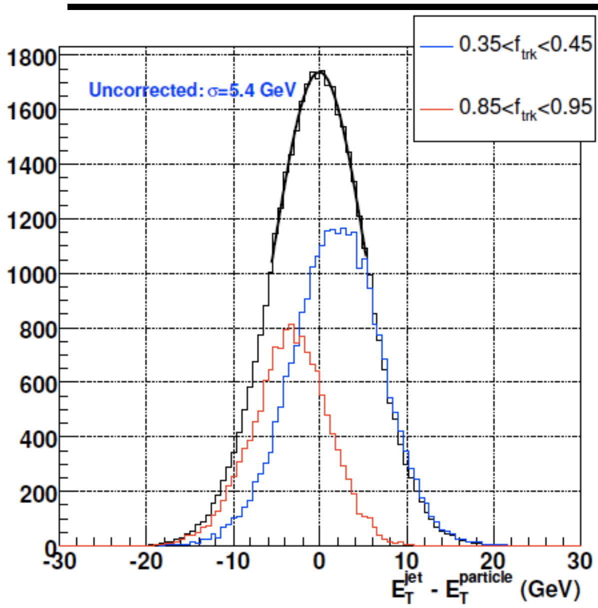


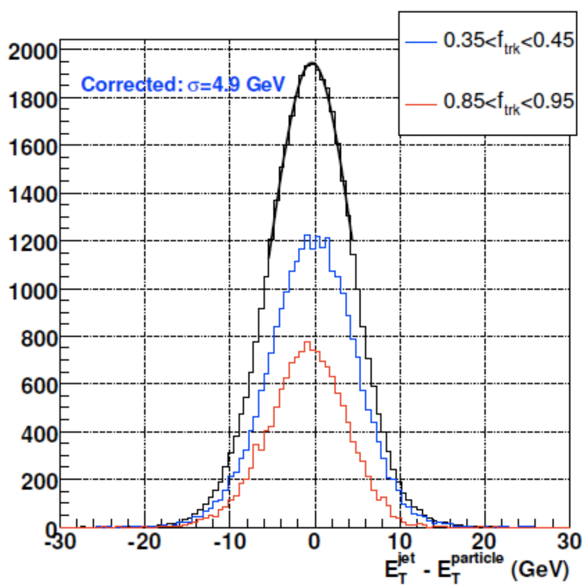


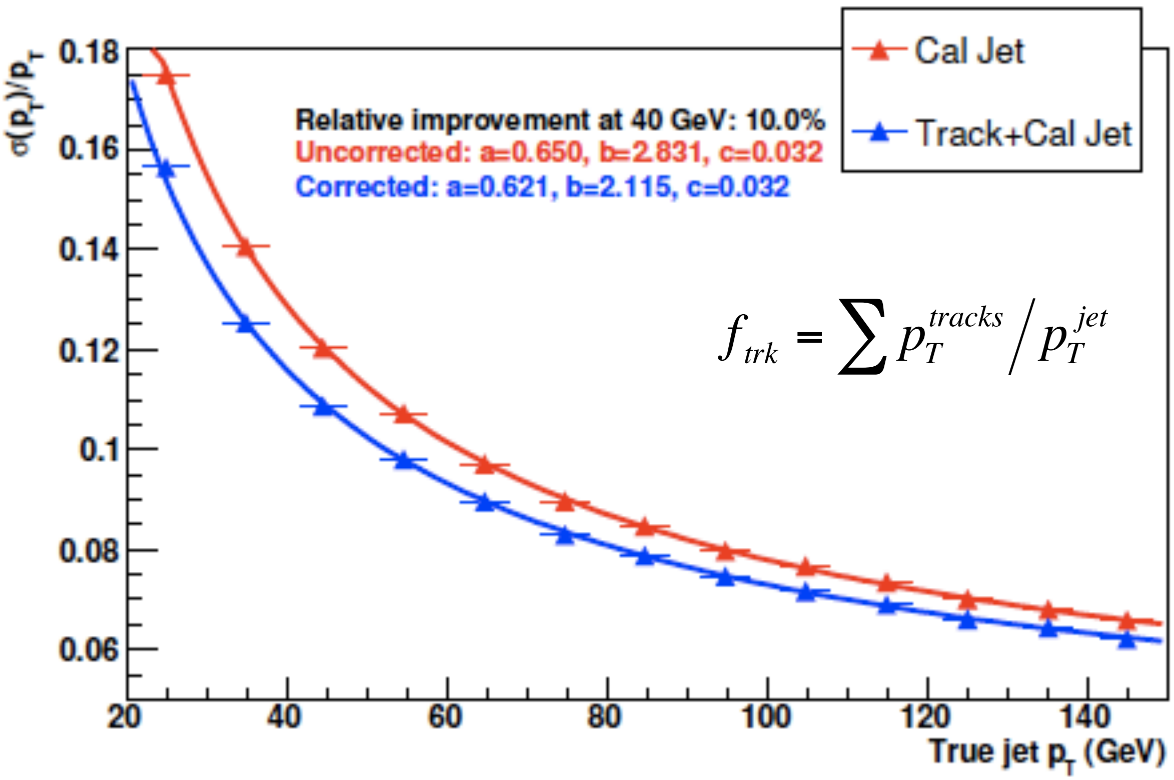
- Less cells with high energy density in data than predicted by the simulation in the EM calorimeter
- Good agreement between data and simulation for the cell energy density in the hadronic calorimeter
- Jet energy scale correction in data and simulation agrees within 2%

- Apply cell weights according to cell's energy density. Compensate for:
  - Lower calorimeter response to hadrons
  - Energy losses in dead material

Track-based jet corrections



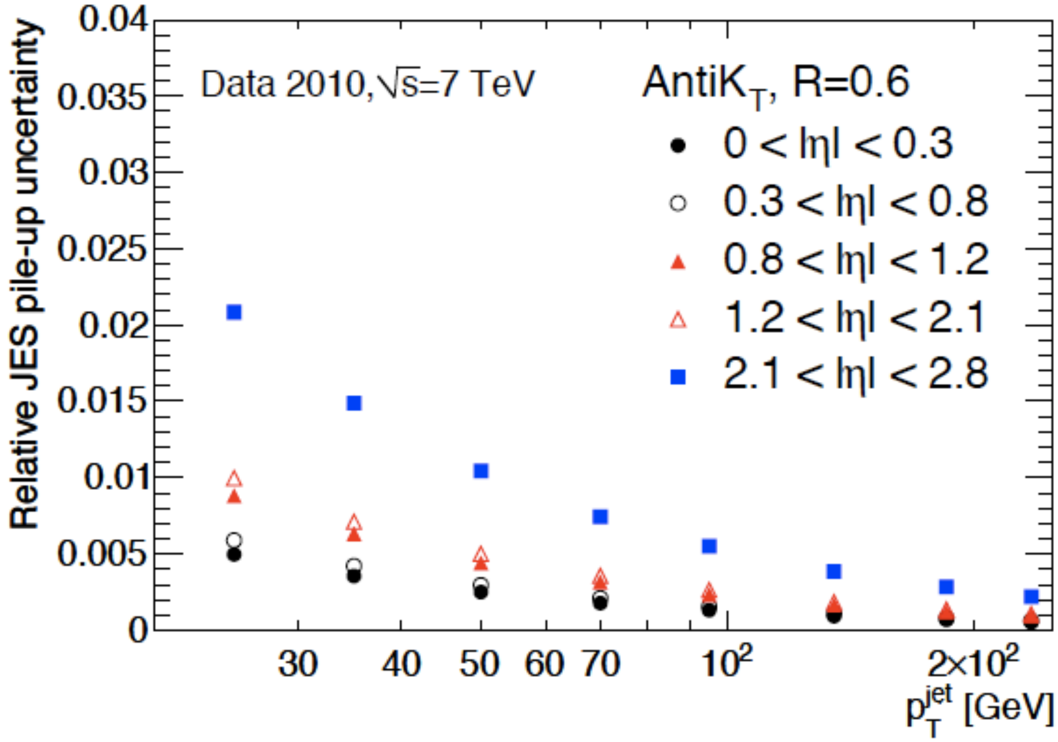




$$f_{trk} = \sum p_T^{tracks} \Big/ p_T^{jet}$$

- Improve the jet energy resolution by accounting for the jet-to-jet response dependence on track-jet properties *after* jet energy scale corrections

Pile-up jet offset

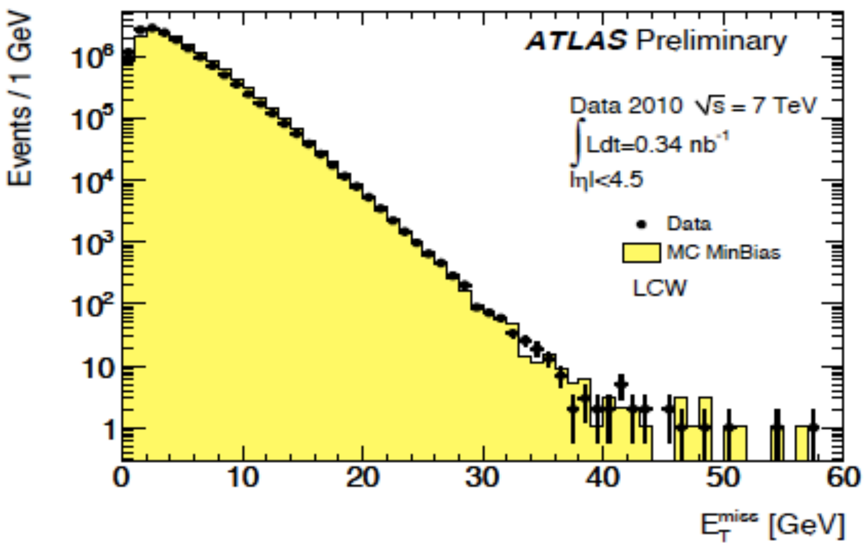


$$\Delta p_T(\eta, \langle N^{\text{pile-up}} \rangle) = \frac{\Delta E_T}{A \cdot N_{vtx}}(\eta) \cdot A(\eta) \cdot \langle N^{pile-up} \rangle$$

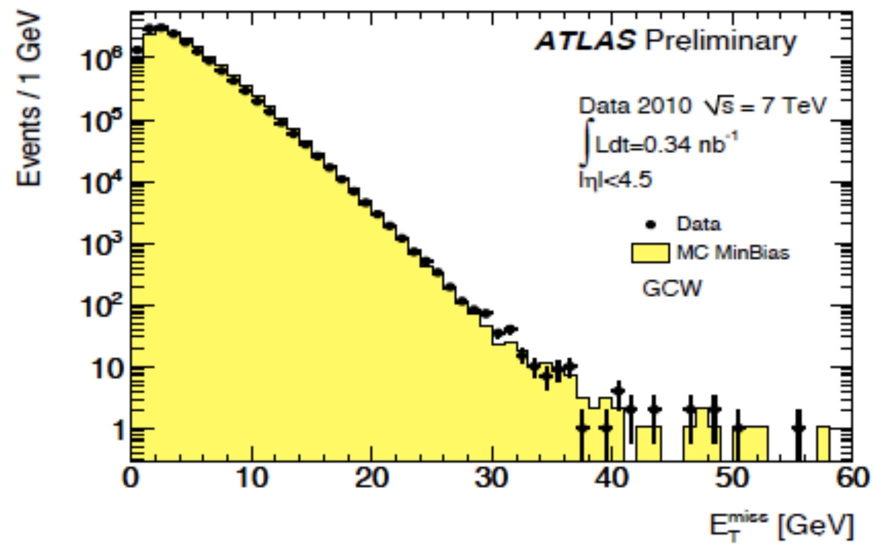
η region	$\langle N_{tower} \rangle$	ΔE_T/tower/vertex
$0.0 < \|\eta\| < 1.0$	47	10 MeV
$1.0 < \|\eta\| < 2.0$	59	15 MeV
$2.0 < \|\eta\| < 3.0$	88	30 MeV

- Measure the mean tower energy as a function of eta and 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 N_{PV}=1from the average tower energy for events with N interactions
- Estimate the average number of towers in jets as a function of eta
- $\langle N^{pile\text{-}up} \rangle = \langle N_{PV}-1 \rangle + RMS(N_{PV}-1)$

Missing ET



ATLAS Preliminary
Data 2010 √s = 7 TeV
∫Ldt=0.34 nb⁻¹
|η|<4.5
Data
MC MinBias
LCW
Events / 1 GeV
E_T^miss [GeV]



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