Jet Reconstruction and Energy Scale Determination in ATLAS

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Outline

ATLAS Calorimeters

Calorimeter signal reconstruction:

- Towers
- Topological clusters

Jet energy calibration techniques:

- Monte Carlo cell energy density and layer weighting
- Data driven in-situ calibration

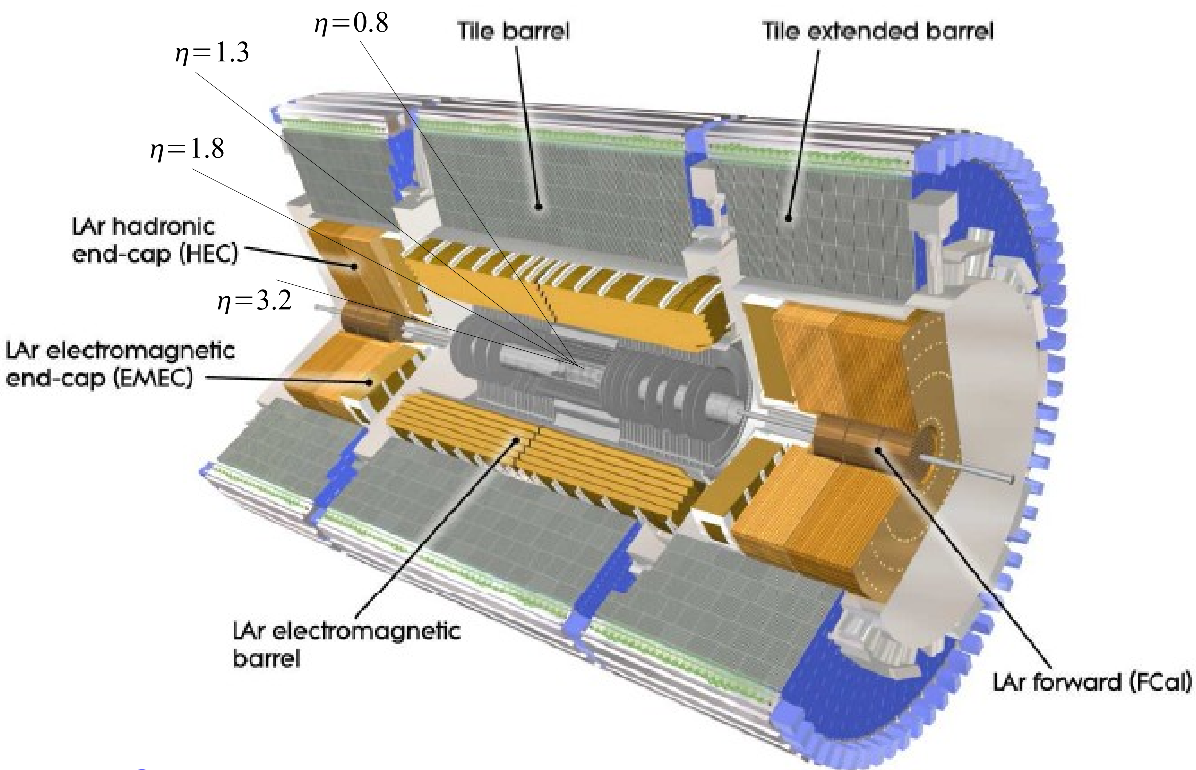
High p_T jet calibration methods

Semi-leptonic b-jet energy scale

Light quark jet calibration using top quark events

Tracking input to jet reconstruction

ATLAS Calorimeters



200,000 channels
$|\eta| < 4.9$

<u>Non-compensating:</u>
e/h ~ 1.4

Hadronic Calorimeter:

Iron/scintillator tiled readout
3 depth segments
$\Delta\eta\Delta\phi \sim (0.1 x 0.1) - (0.2 x 0.1)$
Barrel: $|\eta| < 1.7$
EndCap: Lar/Copper: 4 layers
Forward: Lar/Tungsten: 2 layers
7-9 interaction lengths.

$$\sigma_E / E = 50\% / \sqrt{E} \oplus 3\%$$

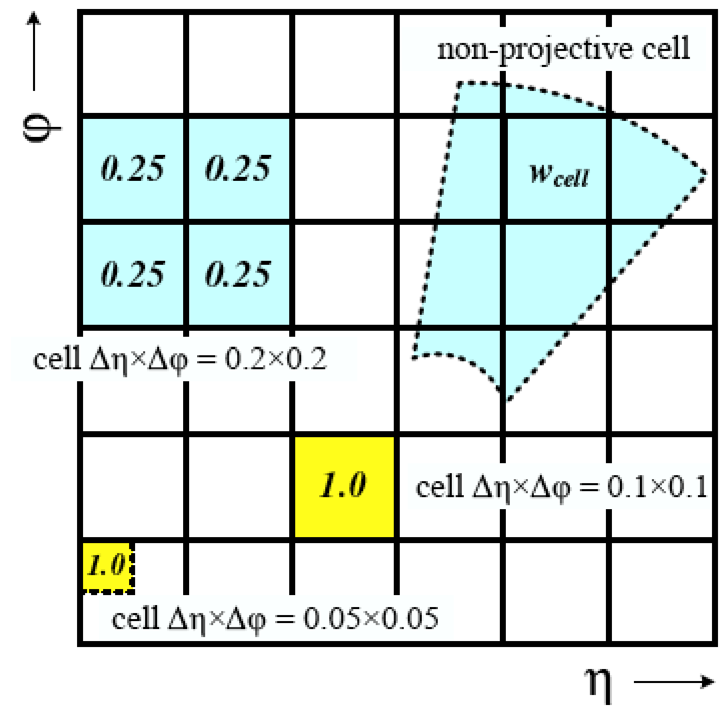
EM Calorimeter:

LAr/Lead, fine granularity:
$\Delta\eta\Delta\phi_{barrel} = (0.003 x 0.1)(0.025 x 0.025)(0.05 x 0.025)$
Central: $|\eta| < 1.4$ (3 layers)
EndCap: $1.375 < |\eta| < 3.2$ (3 layers)
Forward: $3.2 < |\eta| < 4.9$ (1 layer, LAr/Copper)
26-36 radiation lengths.

Calorimeter Signal Reconstruction (I)

Calorimeter Towers:

Cells are projected onto a fixed grid in pseudo-rapidity and azimuth.



Tower bin size: $\Delta\eta\,\Delta\phi = 0.1\,x\,0.1$

All cells are used, weighted by geometric factors.

Noise compensation via re-summation:

Negative signal towers are merged with positive energy neighbor towers within DR<0.35 until the total proto-tower energy is above 0. Isolated negative energy towers are dropped.

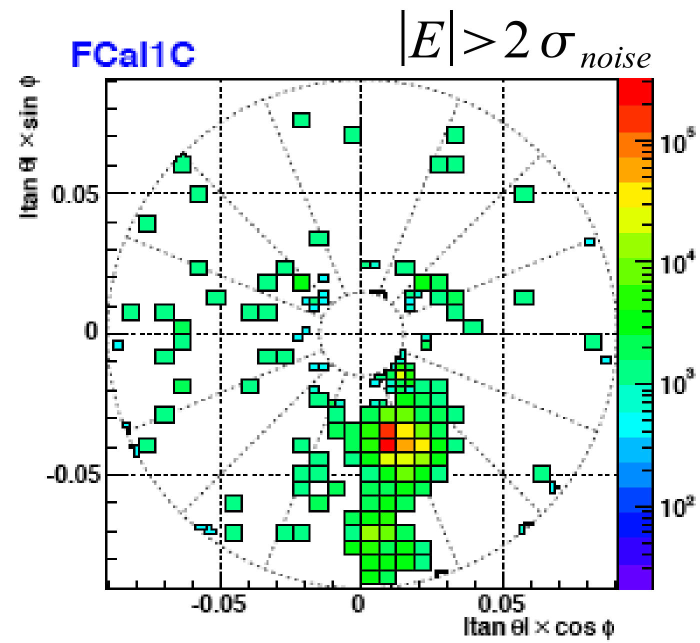
Calorimeter Signal Reconstruction (II)

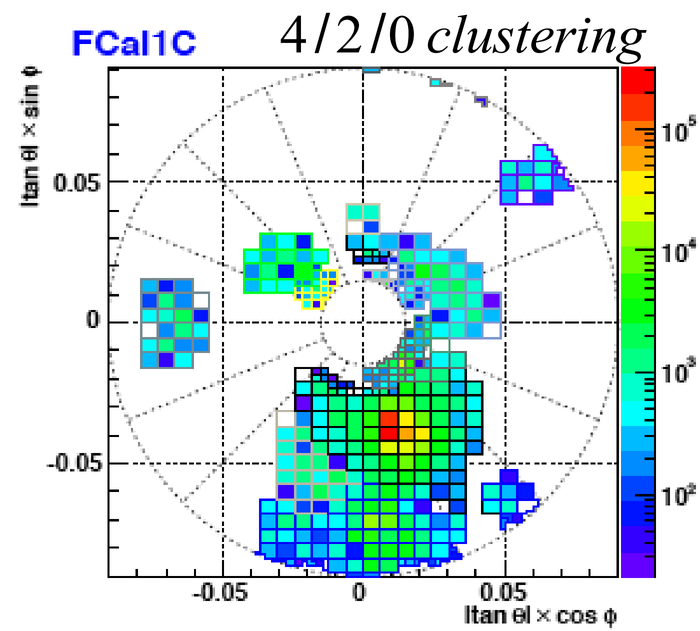
<u>Topological Clusters:</u>

Taking advantage of the fine ATLAS calorimeter granularity, build <u>3-dimensional clusters</u>:

- Find seeds cells with energy significance |S| > 4
- Add all neighboring cells with |S|>2
- Add direct neighbors with |S| > 0
- Split clusters with more than one local maxima.

Topological clusters can serve as input to jet algorithms and also provide alternative noise suppression for towers.





Calorimeter Jet Calibration

Two different approaches:

Global calibration: particle level *jet* energy calibration

Monte Carlo based:

- Calorimeter cell energy density weighting
- Calorimeter layer energy weighting

Data based:

- in-situ calibration using physics processes: minimum bias, photon+jet, di-jets) (similar to DZero approach)
- Light jet energy scale from $W \rightarrow jj$ in Top events.

Local calibration: calibration of calorimeter clusters

Monte Carlo based:

- Attempt to separate EM from HAD clusters and apply individual corrections, *before jet reconstruction*.
- Additional jet-level energy scale correction required.

Cell Energy Density Calibration (I)

Use cell energy density as an estimator of the electromagnetic/ hadronic components of jet showers:

EM showers are characterized by high energy density depositions.
Hadronic showers are broader and less dense.

Cells with low energy density indicate hadronic signals in a non-compensating calorimeter:

Weight low energy density cells by a factor of the order of e/π
High energy density cells receive a weight ~ 1.0

Weights are derived using Monte Carlo QCD events:

cell weights are parametrized and optimized with respect to the truth particle jet energy, accounting for non-compensation and correcting for dead material and out-of-cone.
Additional corrections are needed to restore the jet energy scale.
[Technique inspired by H1]

Cell Energy Density Calibration (II)

Determine a set of cell weights, depending on calorimeter region (cell location) and cell energy density $\rho = E_{cell}/V_{cell}$.

Match reconstructed 0.7 cone jets with their corresponding particle jets and adjust the weights such that the reconstructed jet energy, *on average*, is identical to the particle jet energy and the energy resolution is optimized:

$$\frac{\partial}{\partial w} \sum_{j=1}^{N_{evts}} \left(\left(\sum_{i=1}^{N_{cells}} w(\rho_i, \vec{X}_i) E_i \right) - E_{truth}^{jet} \right)^2 = 0$$

$$\left(E_{reco}^{jet}, \vec{p}_{reco}^{\,jet} \right) = \left(\sum_{i=1}^{N_{cells}} w(\rho_i, \vec{X}_i)(E_i, \vec{p}_i) \right) \times \underbrace{f(\eta_{jet}, p_t^{jet})}_{=1 \text{ for reference jets}}, \text{ with } E_i = |\vec{p}_i|$$

Layer Weighting Technique

Hadronic showers start to develop in the EM calorimeter, and extend to the hadronic layers, whereas EM particles are completely contained within the EM layers.

Introduce longitudinal weighting such that hadronic showers are treated as electromagnetic/hadronic in nature as they develop in the calorimeter.

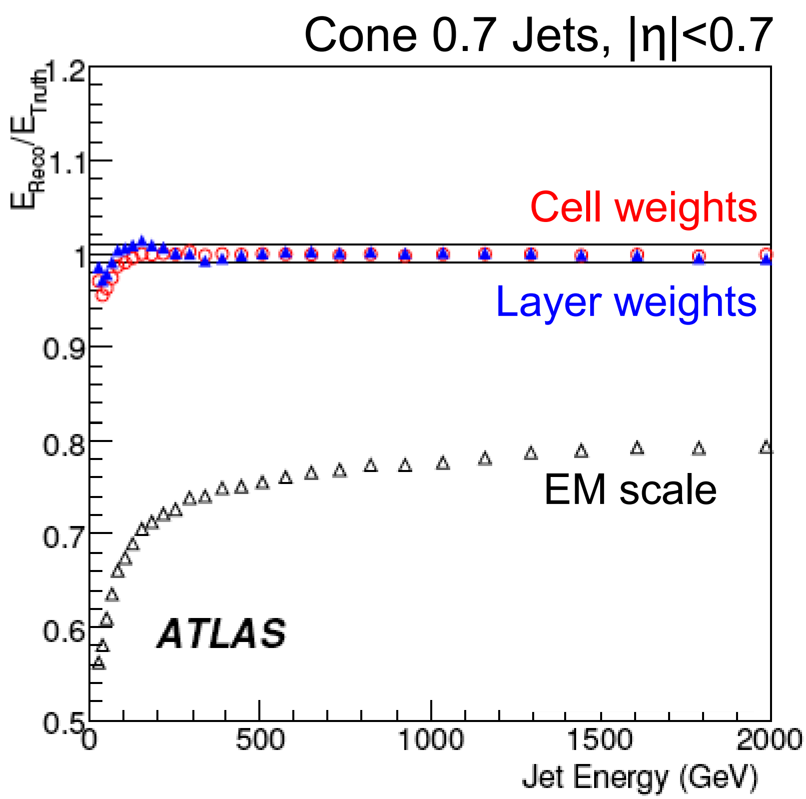
In order to account for the event-by-event fluctuations of the EM content of the hadronic showers, the longitudinal weights are derived in three bins of EM fraction (p_T dependent).

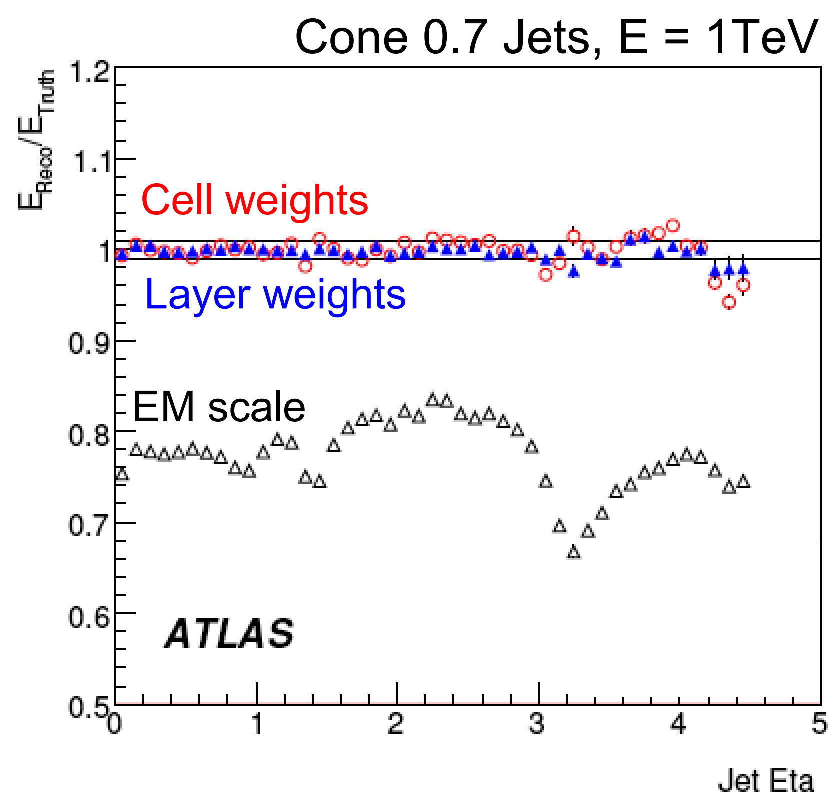
Weights derived from QCD *Monte Carlo* simulations.

$$S = \sum_n \left[\left(E_n^{Ref} - E_n^{Rec}\right)^2 + \lambda \left(E_n^{Ref} - E_n^{Rec}\right) \right]$$

$$E^{Rec} = \sum_i w_i E_i$$

Global Jet Calibration Performance (I)

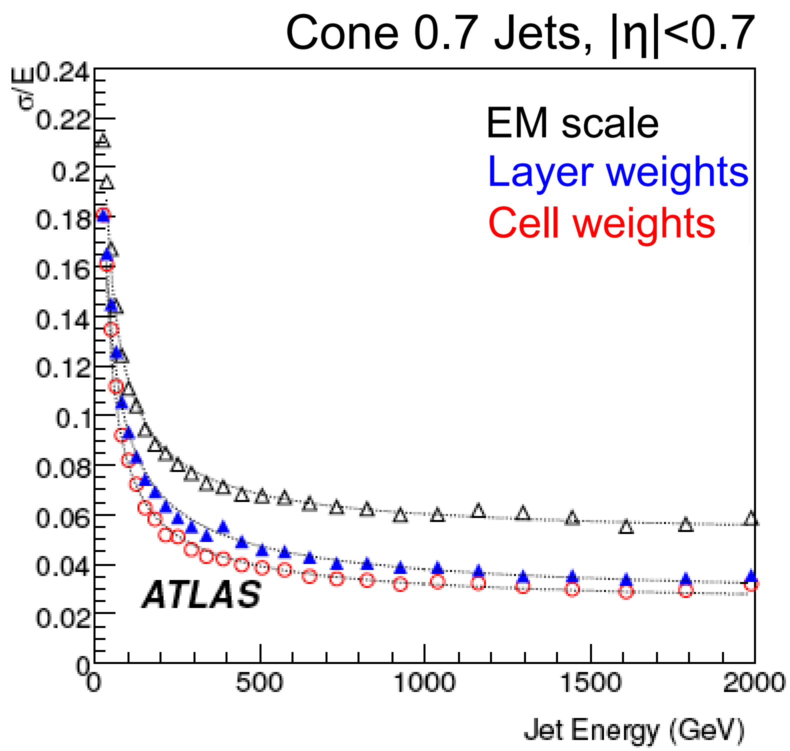


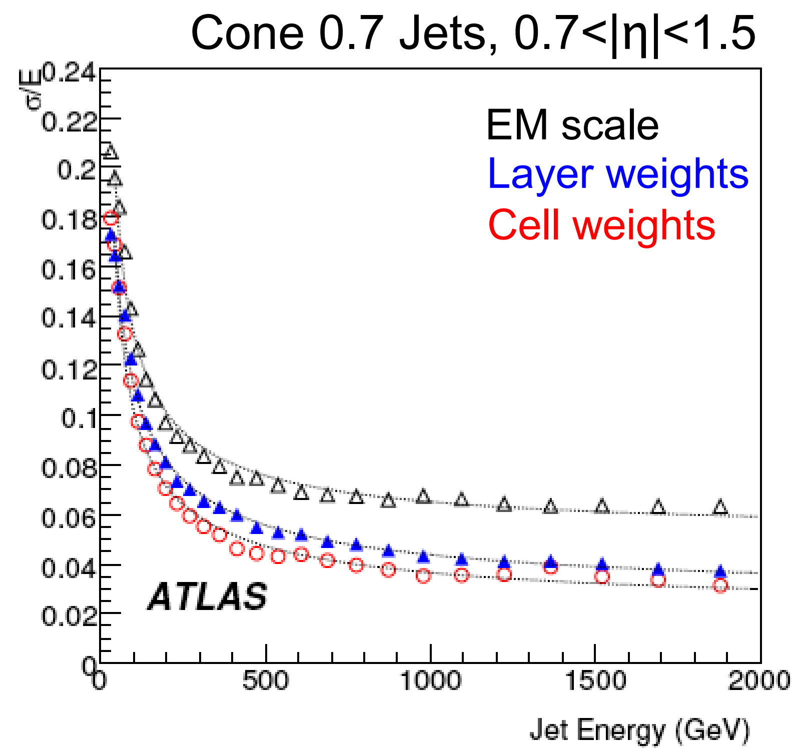


Jet energy response linearity within 2% as a function of jet p_T and Eta.

Weights are derived from Monte Carlo and applied to Monte Carlo: restoration of scale by construction.

Global Jet Calibration Performance (II)





~25% jet energy resolution improvement @ 100 GeV

Cell energy density weighting results in slightly better resolution than layer weighting, but its performance may be more sensitive to pile-up and Monte Carlo modeling of hadronic showers.

Local Hadron Calibration (I)

Calibrate calorimeter cluster signals to the hadronic scale, independently of the jet context. Pure Monte Carlo technique, based on the average response of GEANT 4 single pion simulations.

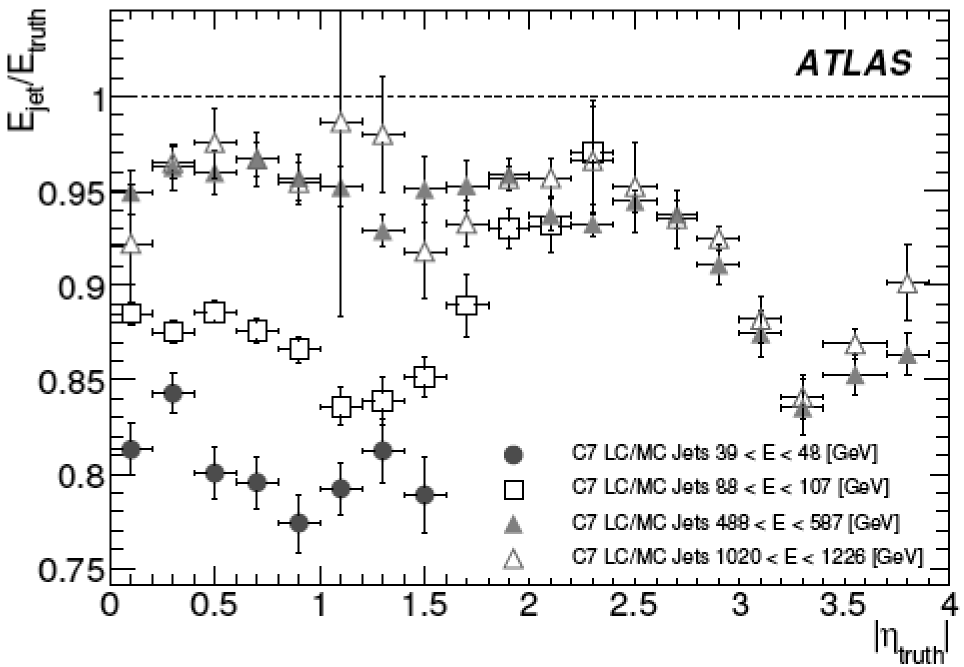
1- Electromagnetic/hadronic cluster classification:
- cluster depth location, energy density, direction, and energy.
- assumes 2/3 of pions are charged.
- 90% (50%) tagging efficiency of charged (neutral) pions @ 5 GeV.

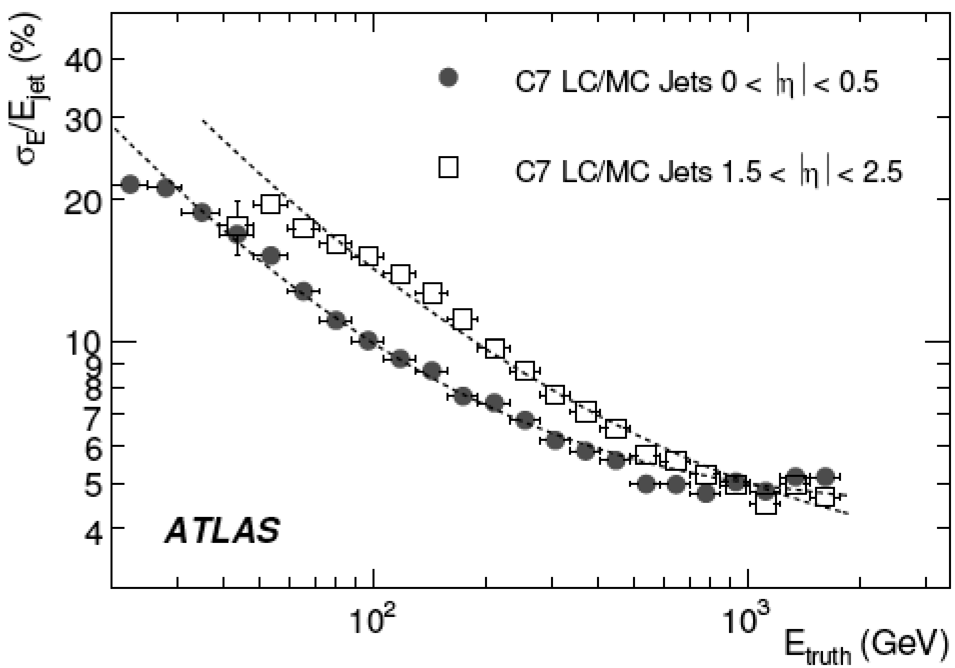
2- Out-of-cluster corrections:
- compensate for energy not deposited inside clusters due to noise suppression thresholds during clustering.

3- Dead material corrections.

4- Jets are built from hadronic calibrated clusters.

Local Hadron Calibration (II)

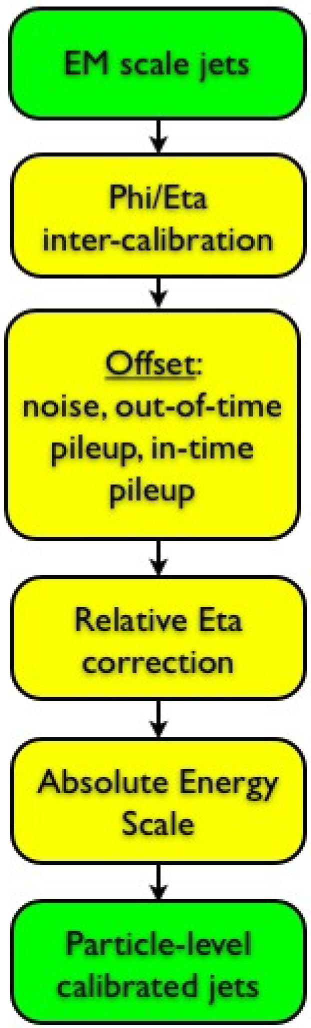




Final jet energy scale correction is needed to account for out-of-cone energy, cluster misclassification, and jet specific effects.

In-situ Jet Energy Calibration (I)

Validation/Corrections of Monte Carlo based calibration methods.
Data driven determination of the jet energy scale (similar to DZero)



Different corrections for tower and cluster jets.

Cell response equalization in phi at fixed eta and layer and normalization of response as a function of Eta.

Average subtraction of the jet energy not originating from the hard scatter interaction.

Jet response normalization in Eta.
(tag and probe di-jet balance)

Absolute hadronic jet energy scale. Z/γ+jet balance, MPF.

In-situ Jet Energy Calibration (II)

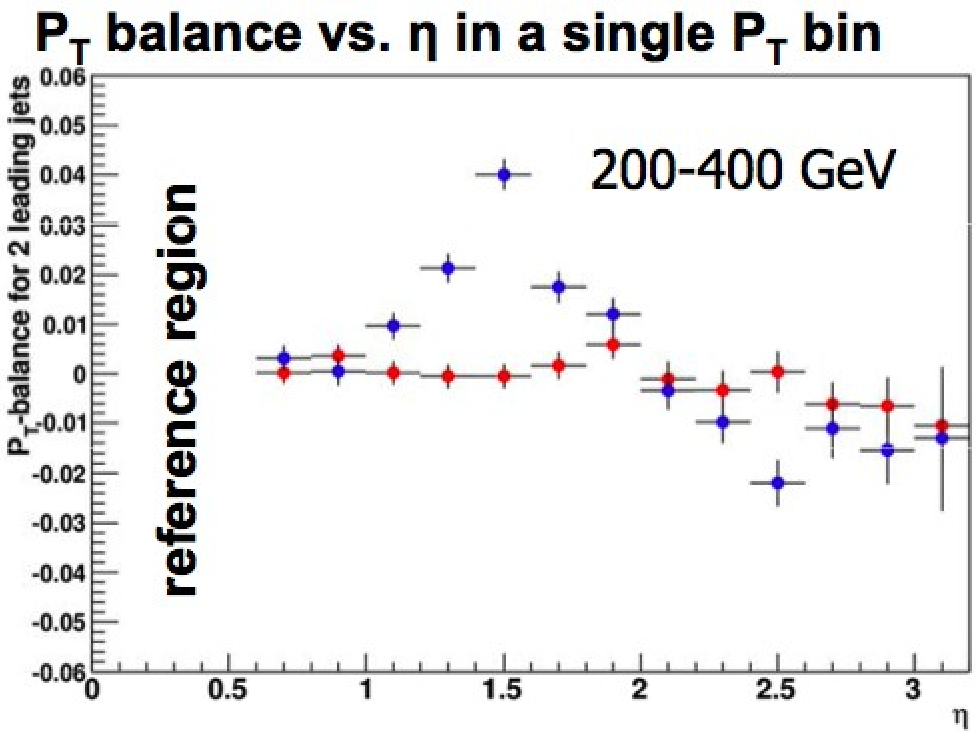
Equalization of the jet energy response in pseudo-rapidity

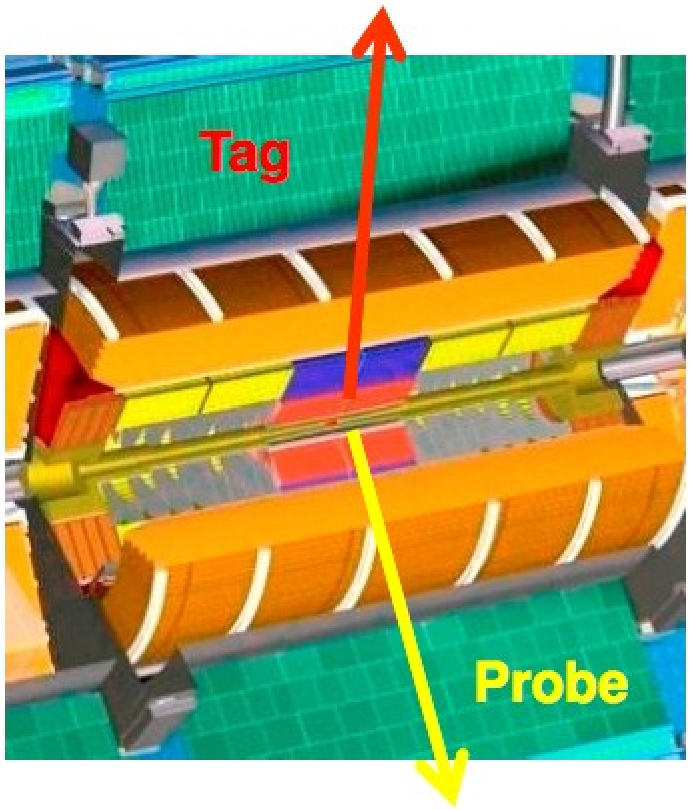
di-jet pT balance:

Tag jet in central calorimeter region

Probe jet back-to-back

$$A = \frac{p_T^{tag} - p_T^{probe}}{(p_T^{tag} + p_T^{probe})/2}$$

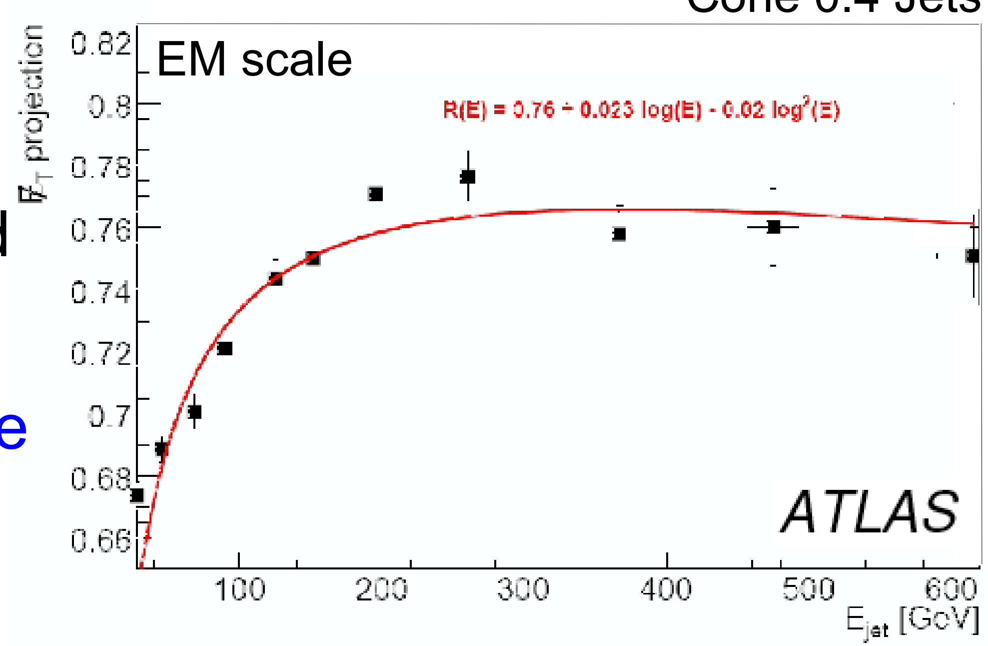




In-situ Jet Energy Calibration (III)

Absolute energy scale determination:

Missing ET Projection Fraction: (DZero approach): balances photon against the hadronic recoil measured by towers.



MPF measures the hadronic response relative to that of the photon:

$$\frac{R_{recoil}}{R_{tag}} = 1 + \frac{MET \, . \, \hat{n}_{tag}}{p_T^{tag}}$$

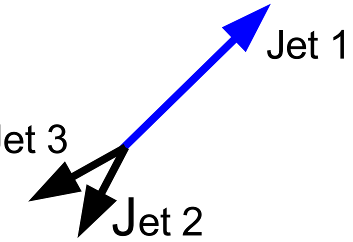
MPF method requires good understanding of missing ET and additional out-of-cone showering correction.

Alternative approach for early data: Z/γ+jet balance:

needs Monte Carlo to correct to particle level.

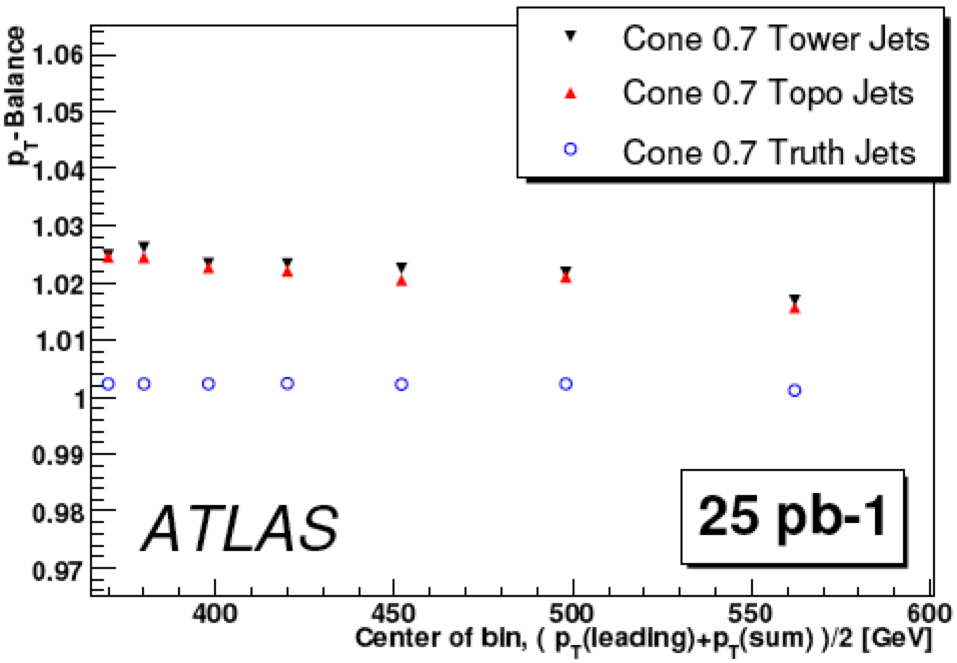
High p_T Jet Calibration

Multi-jet p_T balance:

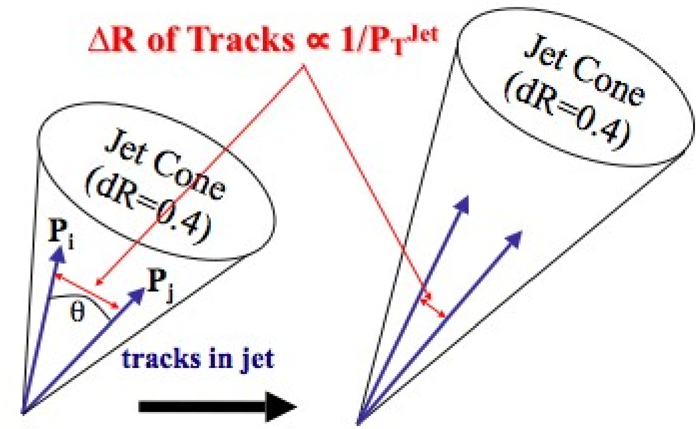


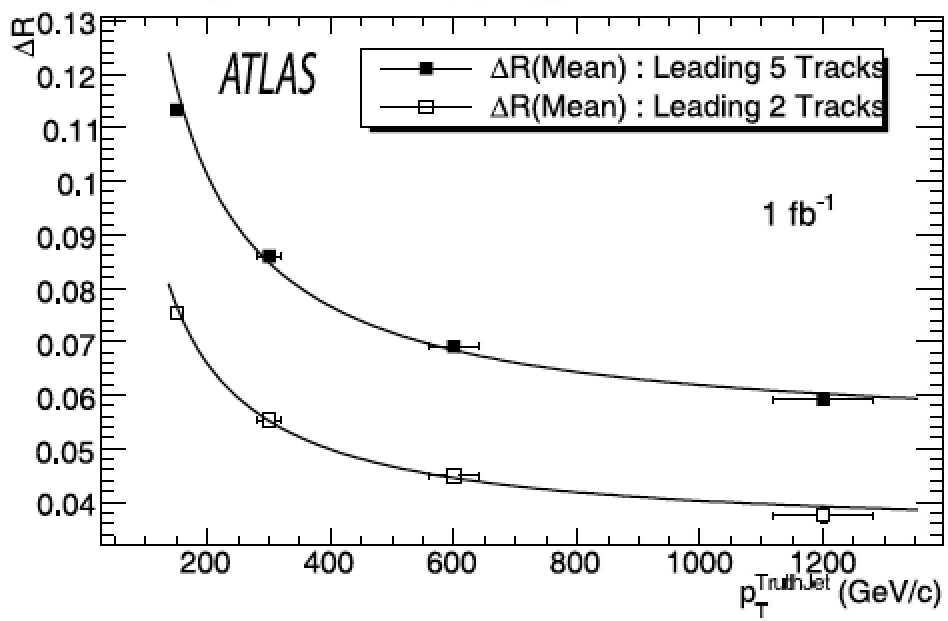
Use low p_T jets to calibrate high p_T jets:

Relative response calibration using calibrated low p_T jets.



Track angle method:
based on the correlation between track ΔR and jet p_T.





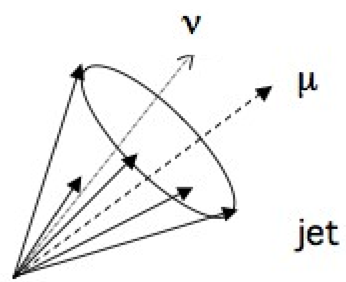
Semi-leptonic b-jet Energy Scale

Monte Carlo based correction for b-jets containing muons.

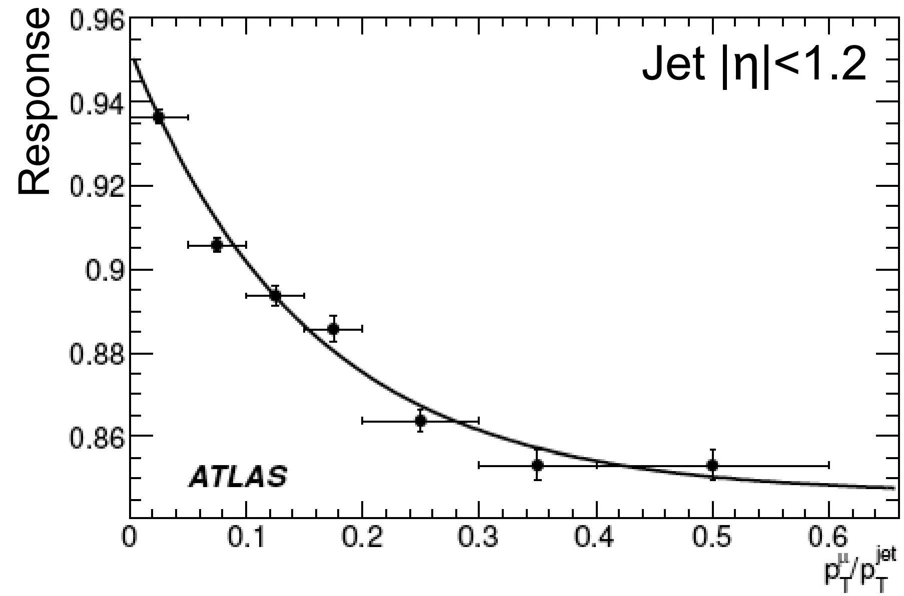
Correction derived after the hadronic jet energy scale, to account for the missing neutrino energy.

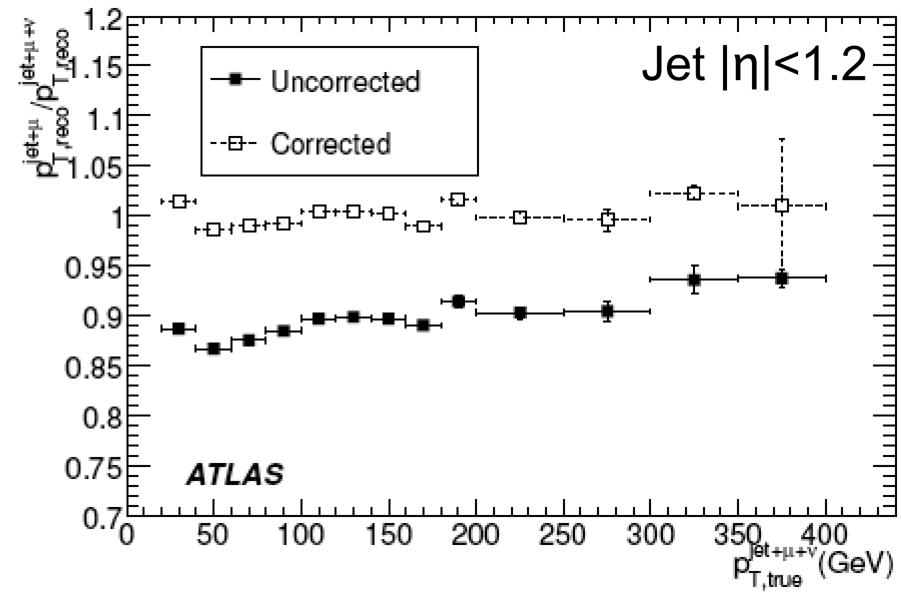
Parametrized as a function of the fraction of transverse momentum carried by the muon:

$$x = \frac{p^{\mu}_{T,reco}}{p^{jet}_{T,reco}}$$



$$p^{jet+\mu}_{T,corr} = [C(x)]^{-1}\, p^{jet+\mu}_{T,reco}$$



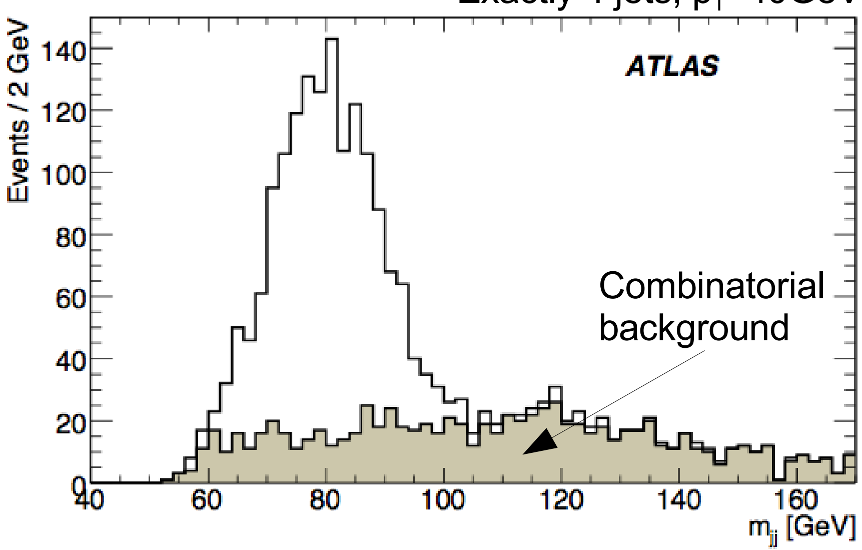


Jet Energy Scale from *W→jj* (I)

Take advantage of the large top quark production cross section at the LHC to calibrate the light quark jet energy scale *in-situ*, from hadronic W decays.

- Select events by requiring high missing ET, one high p_T isolated lepton, and at least four jets, two of them b-tagged.
  - Purity between 65% and 80% depending on the number of jets (2, ≥2) and the minimum jet p_T (20GeV-40GeV)
  - Expect ~7000 (1200) *W→jj* pairs in $1fb^{-1}$ of data with loose (tight) selections.

Exactly 4 jets, p_T>40GeV



Two techniques:

1- Iterative rescaling method:

$$E^{corr} = K(E)\,E$$

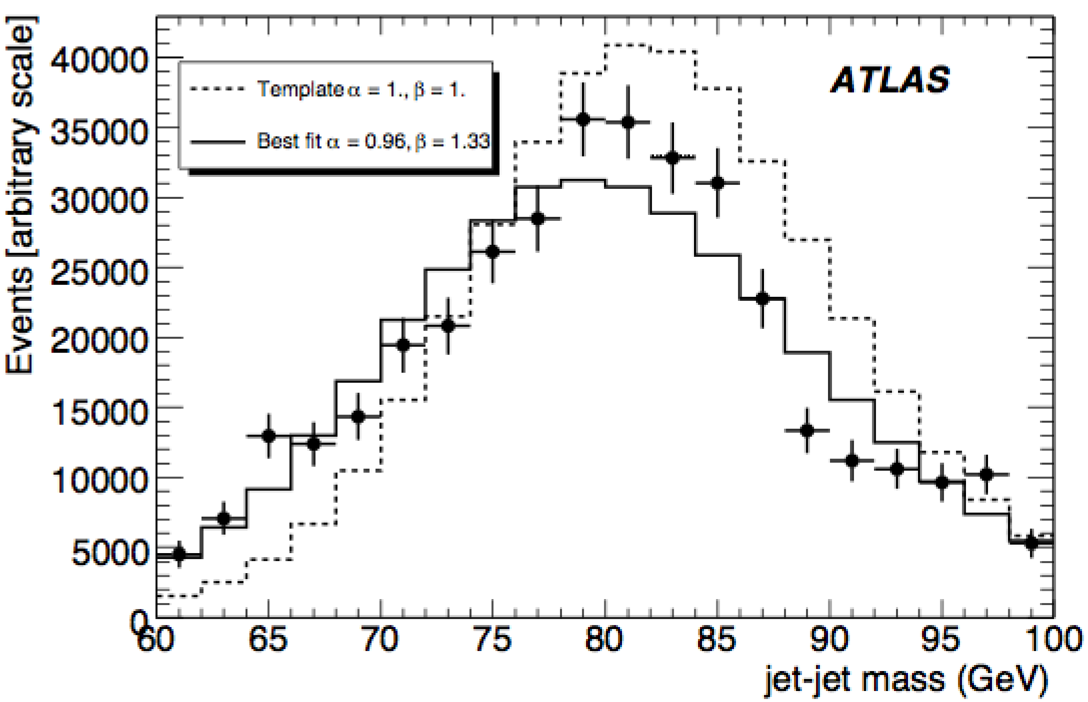
$$M_W^{PDG} = \sqrt{K(E_1)\,K(E_2)}\,M_{jj}$$

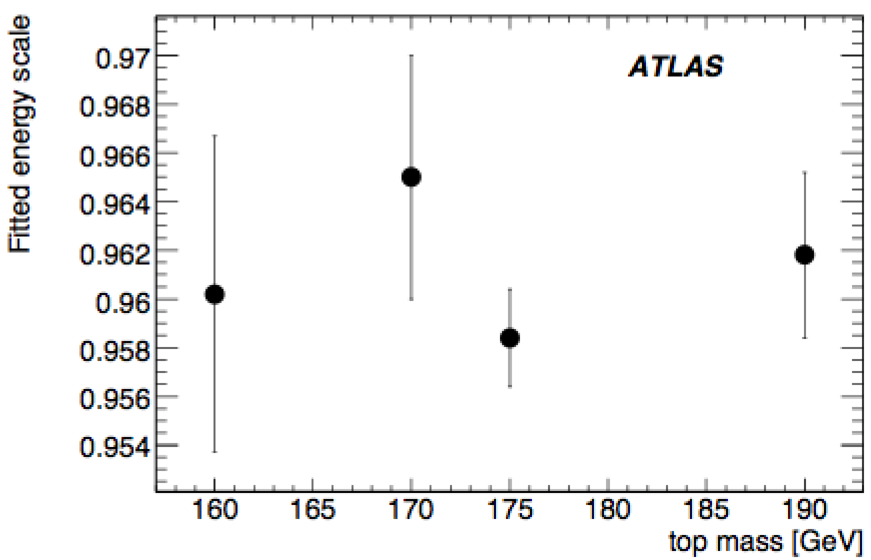
2- Template method

Jet Energy Scale from *W*→*jj* (II)

Template method:

- build di-jet invariant mass templates with two parameters:
  - overall jet energy scale (α)
  - relative jet energy resolution (β)
- fit histograms to data.



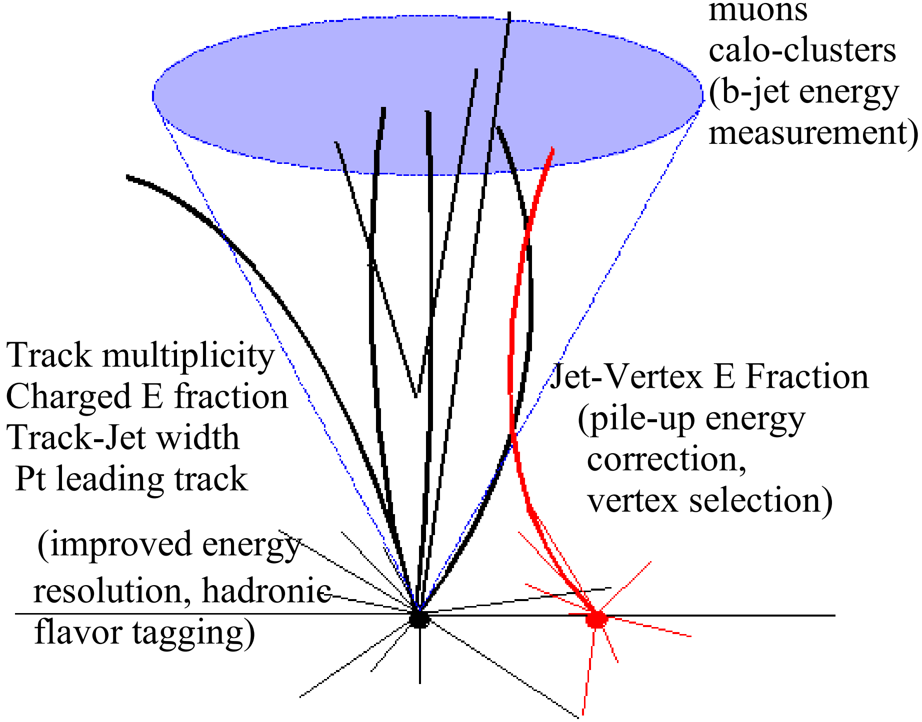


Tracking Input to Jet Reconstruction

Program to use tracking information to improve calorimeter jet energy reconstruction and resolution

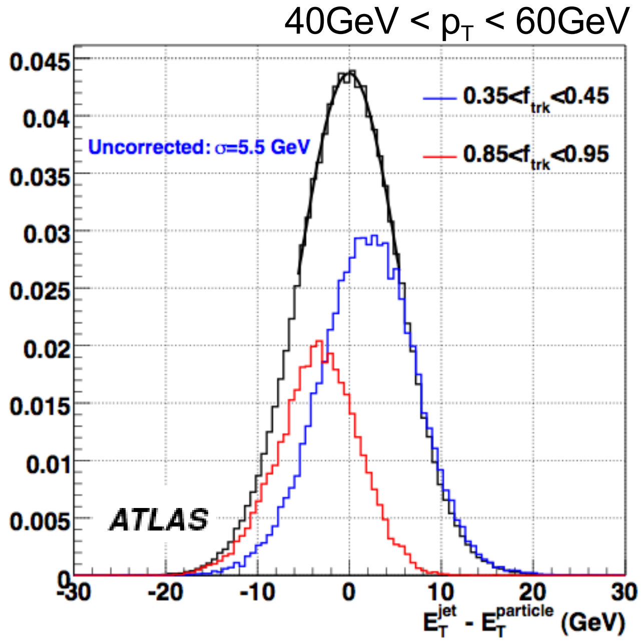
New approach, conceptually different from energy flow techniques:

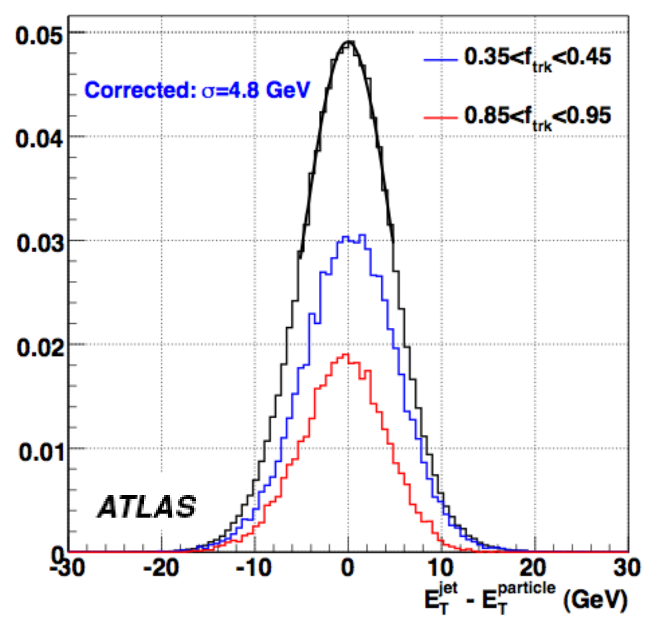
Jet energy resolution of non-compensating calorimeters is driven by the jet-to-jet fluctuations in the EM content of the hadronic shower:



Use tracks to extract information about jet topology and fragmentation, and correct jet response as a function of (track) jet particle composition

Track-based Jet Calibration

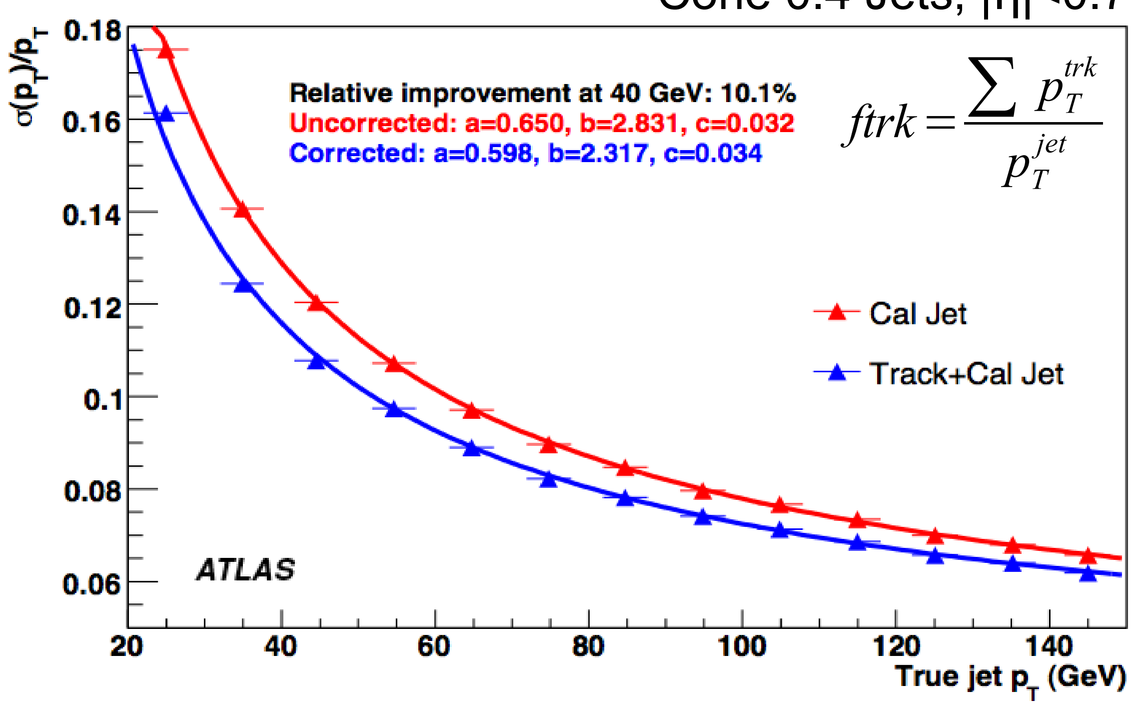




Jet energy scale calibrates the *average* energy response: $\langle R^{jet} \rangle (p_T, \eta) = 1$

Improve jet resolution by accounting for the jet-to-jet response dependence on the ratio of charged to total transverse momentum.

Correction applied after cell weighting calibration



Summary

Several techniques for jet calibration in ATLAS:

In-situ data-driven techniques for initial jet energy scale determination, including $W \rightarrow jj$ from semi-leptonic $t\bar{t}$ events.

Monte Carlo based techniques to improve jet energy resolution:
- Cell energy density weighting
- Layer weighting
- Local hadronic calibration

Track-based corrections to further improve jet energy resolution based on jet-by-jet fragmentation properties.

Experimental program to feedback knowledge on detector back to Monte Carlo to improve jet calibration.