Jet Reconstruction in the ATLAS Calorimeters

Michiru Kaneda
(University of Tokyo)
On behalf of the ATLAS collaboration
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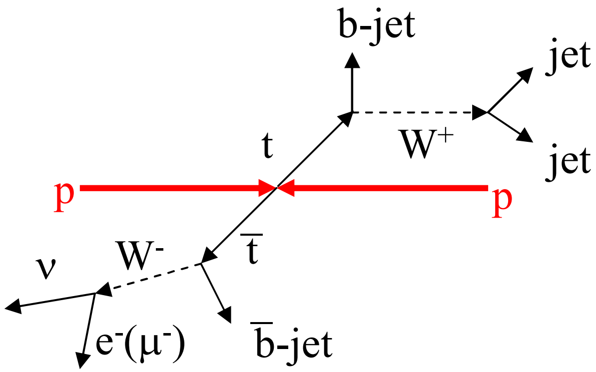
Outline

- Introduction
- ATLAS Calorimeters
- Reconstruction and Calibration Scheme
  - Clustering
  - Jet Reconstruction Algorithms
  - Jet Energy Calibration
    - Global and local approach
  - In situ Calibration
- Summary

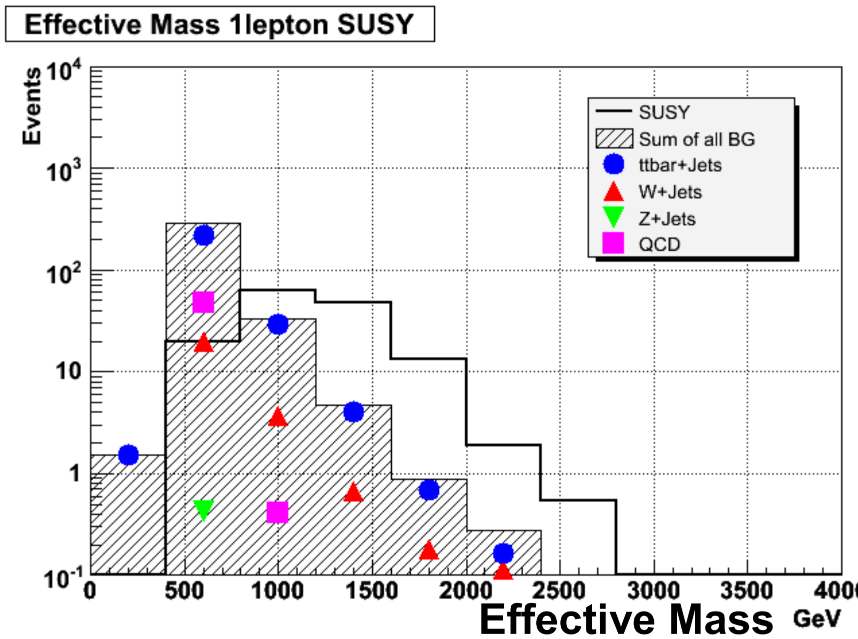
Introduction

- We want to calibrate Jet Energy Scale within ~1% for precise Top Mass measurement, SUSY search and so on…



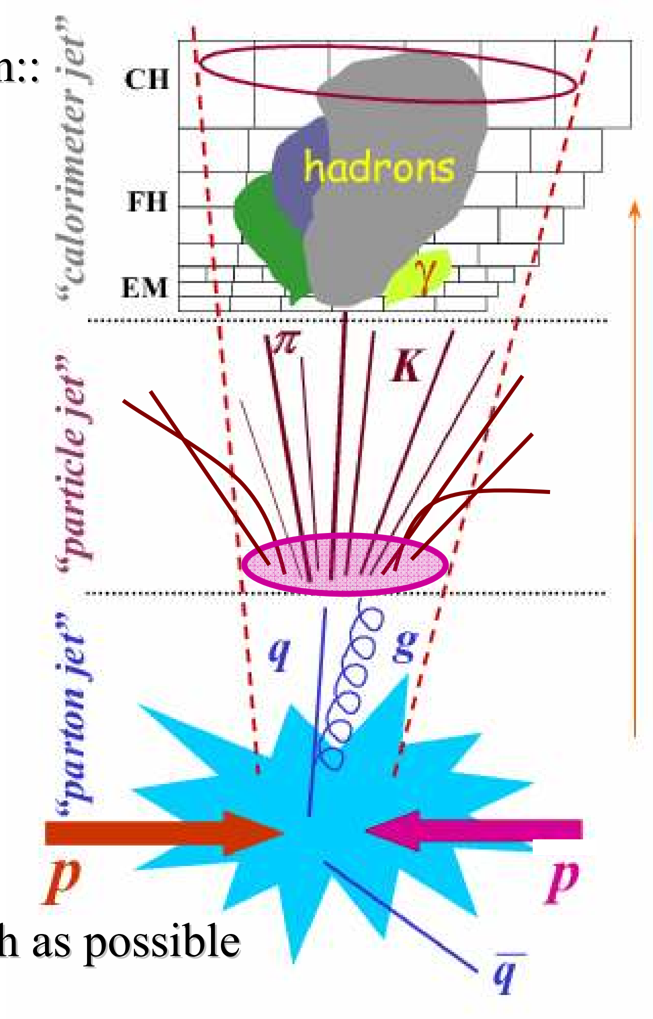
LHC produce large amount of ttbar events
More than 8 million ttbar produced
per year at low luminosity ($10^{33}cm^{-2}s^{-1}$)
->For top mass measurement, systematic error become dominant and a dominant error is Jet Energy Scale Uncertainty::
b quark energy 1% uncertainty -> δM_{top} ~ 0.7GeV
light quark energy 1% uncertainty -> δM_{top} ~ 0.3GeV

Effective Mass = MissEt + Σ_i(P_T of i th Jet) (i=1~4) is used for SUSY search

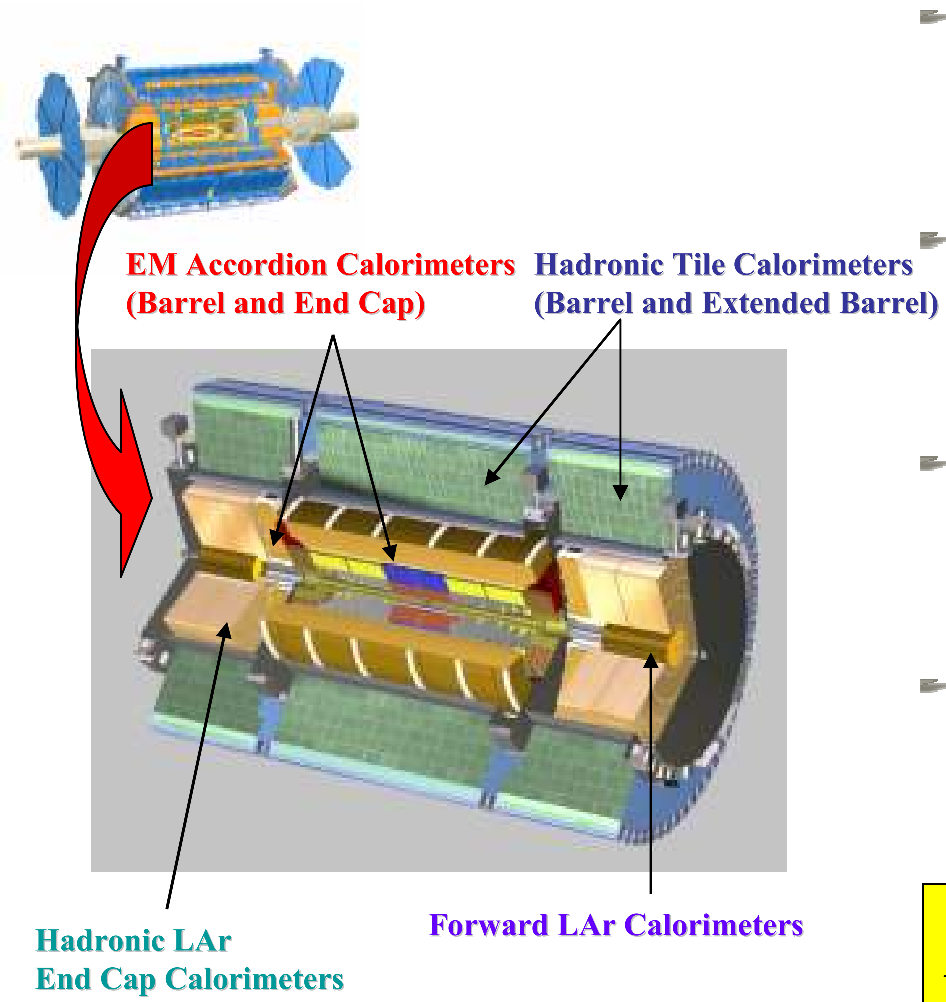


Introduction

- There are many effect to consider in Jet Reconstruction::
  - Detector effects
    - Non compensation
    - Dead material
    - Electric noise
    - Energy leakage
    - Non uniformities
    - Magnetic field effects
  - Jet reconstruction Algorithm effects
    - Cone, K_T
    - Out of Cone energy losses
  - Physics effects
    - Jet types (light quarks, gluons, b-jet or τ-jet)
    - Parton shower and fragmentation
    - Underlying events
    - Initial state radiation and final state radiation
    - Pileup from minimum bias events
- We must apply the corrections for these effect as much as possible



ATLAS Calorimeters



- EM Accordion::|η|<3.2
  - Pb/LAr 24-26 X_0
  - 3 longitudinal sections 1.2λ
  - $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
- Central Hadronic::|η| < 1.7
  - Fe/Scintillator 3 longitudinal sections 7.2λ
  - $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (sampling 1 and 2)
  - $= 0.2 \times 0.2$ (sampling 3)
- Hadronic End Cap::1.5< |η|<3.2
  - Cu/LAr 4 longitudinal sections
  - $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ ($1.5 < |\eta| < 2.5$)
  - $= 0.2 \times 0.2$ ($2.5 < |\eta| < 3.2$)
- Forward Calorimeter::3< |η|<4.9
  - EM Cu/LAr and HAD W/LAr
  - 3 longitudinal sections
  - $\Delta\eta \times \Delta\phi = \sim 0.2 \times 0.2$

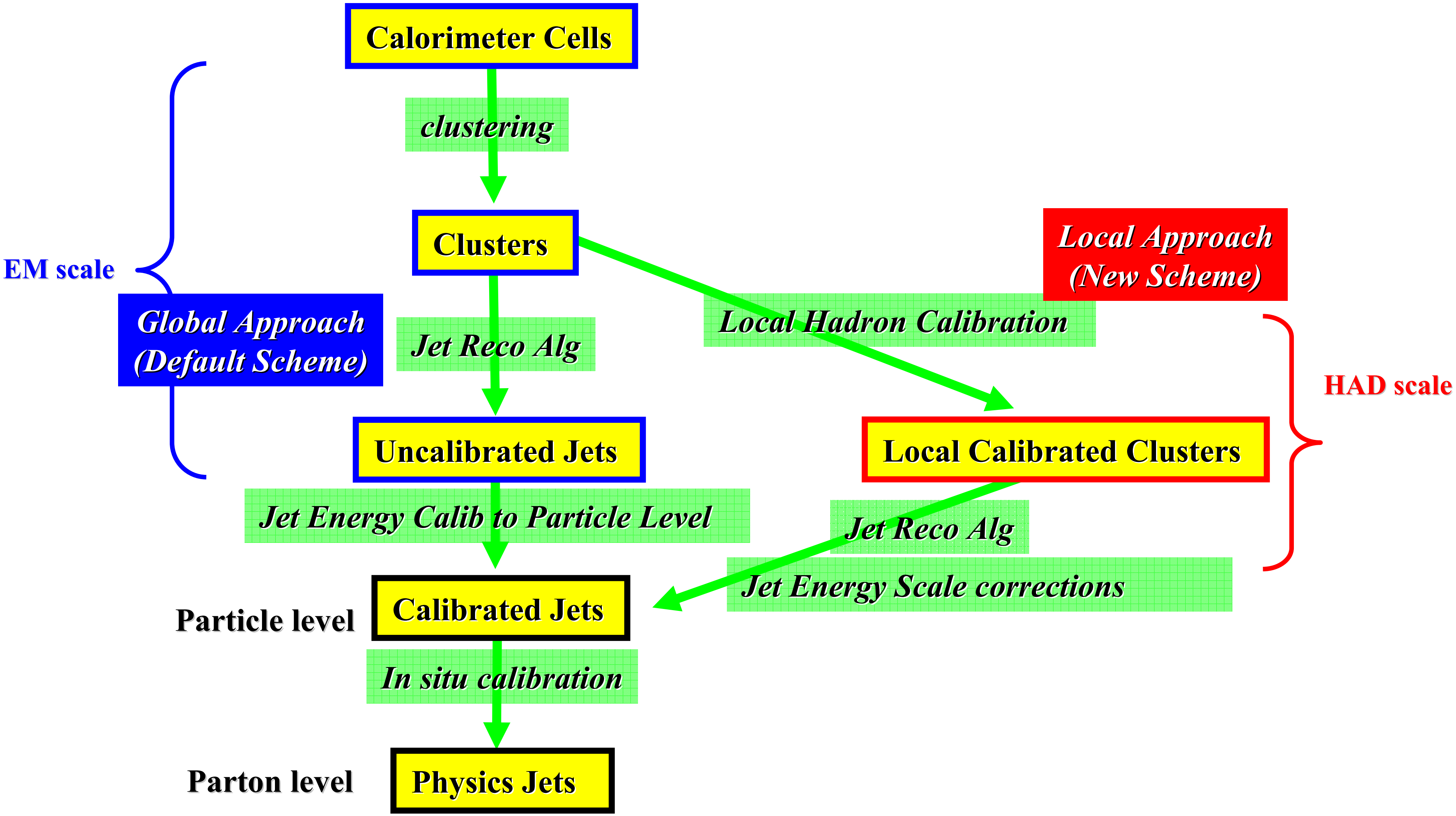
EM LAr + TileCal resolution and Linearity

$$\frac{\sigma}{E} = \left(\frac{41.9\%}{\sqrt{E}} + 1.8\%\right) \oplus \frac{1.8}{E}$$

linearity < 2% 10-300 GeV

obtained at 1996 Combined TestBeam , η= 0.35
(ref. NIM449(2000) 461-447)

Reconstruction and Calibration Scheme

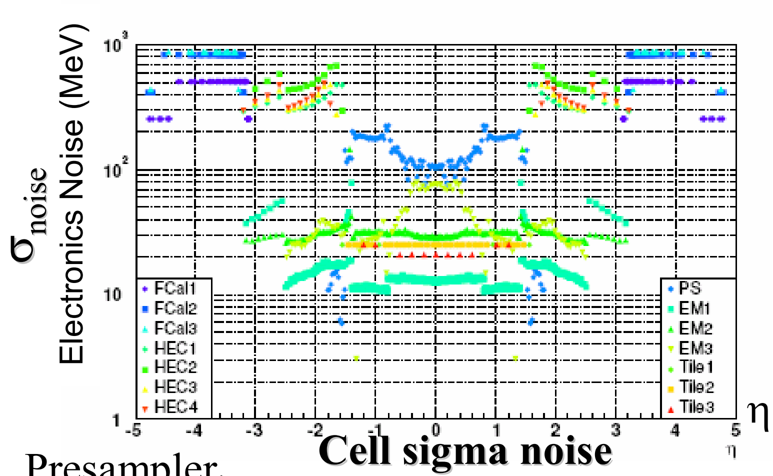


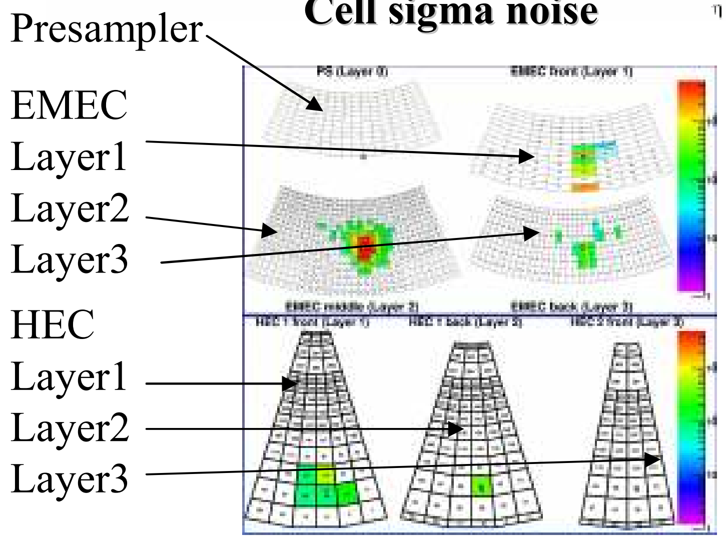
Clustering

There are two methods

- Calorimeter Towers (2D method)
  - Tower of dimension $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
  - Compensate towers with negative energy with its positive neighbors.

- 3D Cell Clusters (3D method)
  - Seed Cell::$|E/\sigma_{noise}|>T_{seed}$
  - Neighboring Cell to expand::$|E/\sigma_{noise}|>T_{neigh}$
  - Cells to expand::$|E/\sigma_{noise}|>T_{used}$
  - Default $\{T_{seed},T_{neigh},T_{used}\}=\{4,2,0\}$
  - can suppress noises better



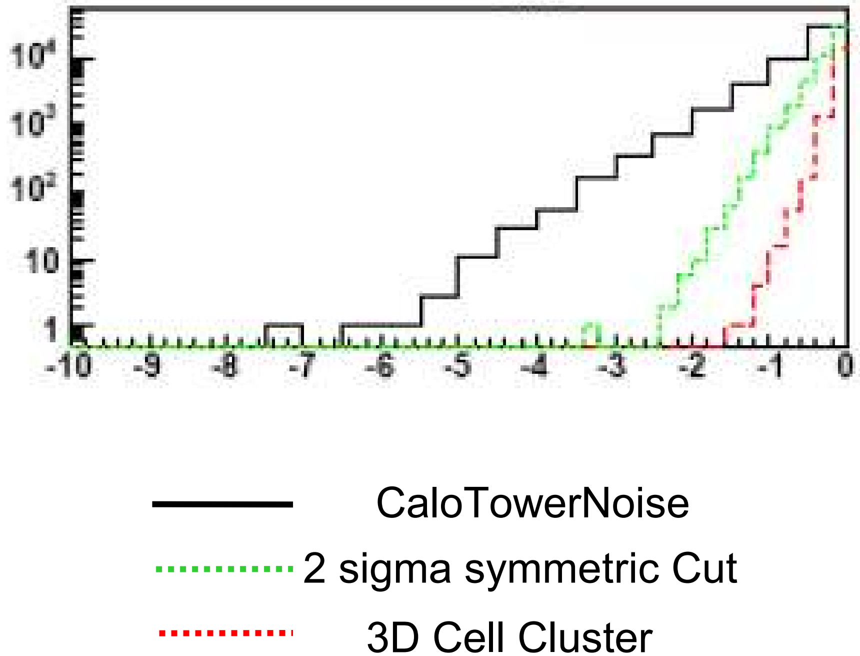


3D Cell Cluster for 120GeV pion in EMEC and HEC (2002 Test Beam Data)

Noise Suppression Performance

- This plot shows the energy left in the EMEC calorimeter
- 2 sigma symmetric Cut means::
  - Remove all cells with $|E|<2\sigma_{noise}$
- 3D Cell Clusters show better noise suppression

EMEC



Jet Reconstruction Algorithms

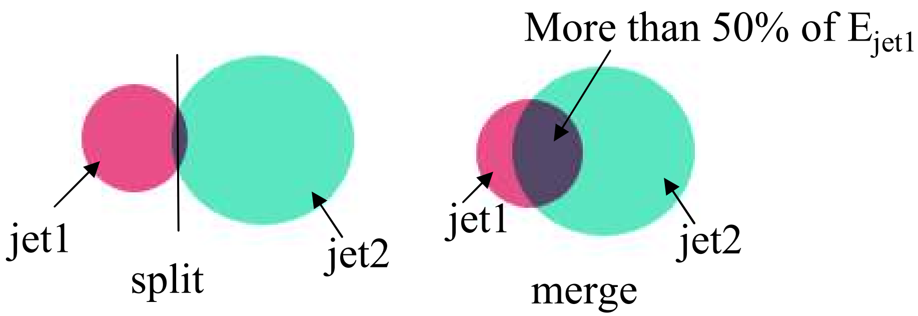
- Two algorithms, Cone and K_T are being used in ATLAS

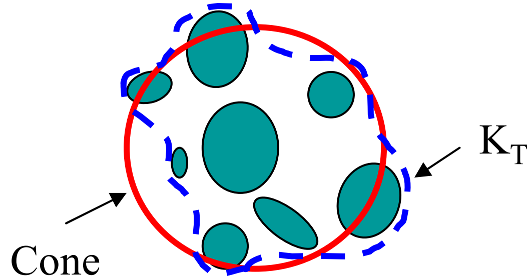
Cone Algorithm (Seeded Algorithm)

- E_T Seed::2GeV
- Collect neighbors around a seed in $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)}$
  - $\Delta R=0.7$::To avoid fragmentation loss for low Pt jets
  - $\Delta R=0.4$::Necessary at high luminosity and to separate overlapping jets
- Split and Merge
  - Merge two jets if overlapping energy is more than 50% of the least energetic jet energy.

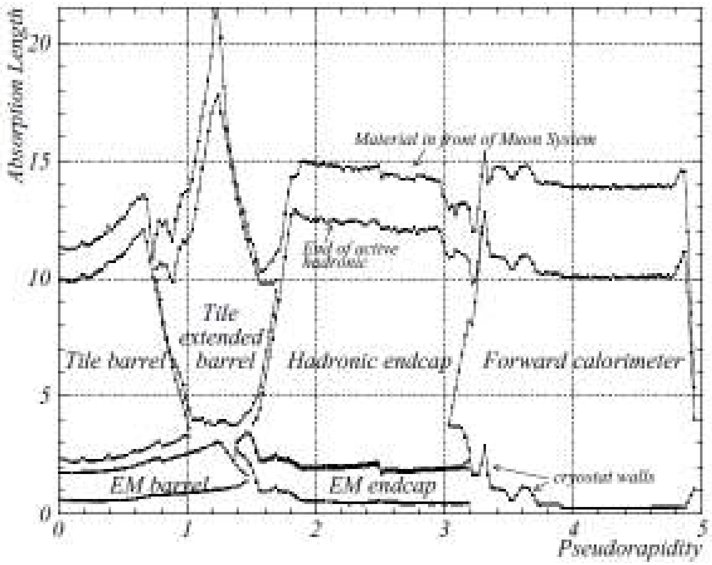
K_T Algorithm

- For each cluster i:
  - Define $d_{ii}=p_{Ti}^2$,
    $d_{ij}=\min(p_{Ti}^2,p_{Tj}^2) \times \Delta R_{ij}^2/D^2$
  - Then find d_{min}
    (=the smallest member of $\{d_{ii},d_{ij}\}$)
  - If $d_{min} = d_{ii}$ -> jet
  - If $d_{min} = d_{ij}$ -> merge i and j
- D::paremeter “Jet Size” = 1
- The shape of the jet is not fixed a priori





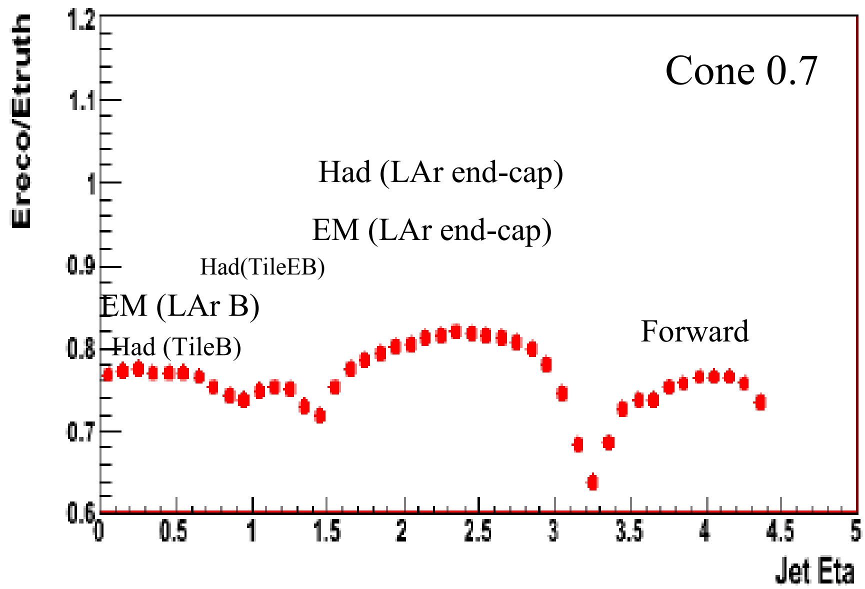
Jet Response Uniformity



Total thickness in labs of the ATLAS calorimetry as a function of pseudrapidity

The total thickness of the active calorimeters is close to or larger than 10λ over the full coverage up to |η| =4.9

There are the amount of the dead material in front of the calorimeters and in the regions between the Tile and EM Calorimeters



Jet energy calibrated at EM scale /normalized to MC truth energy

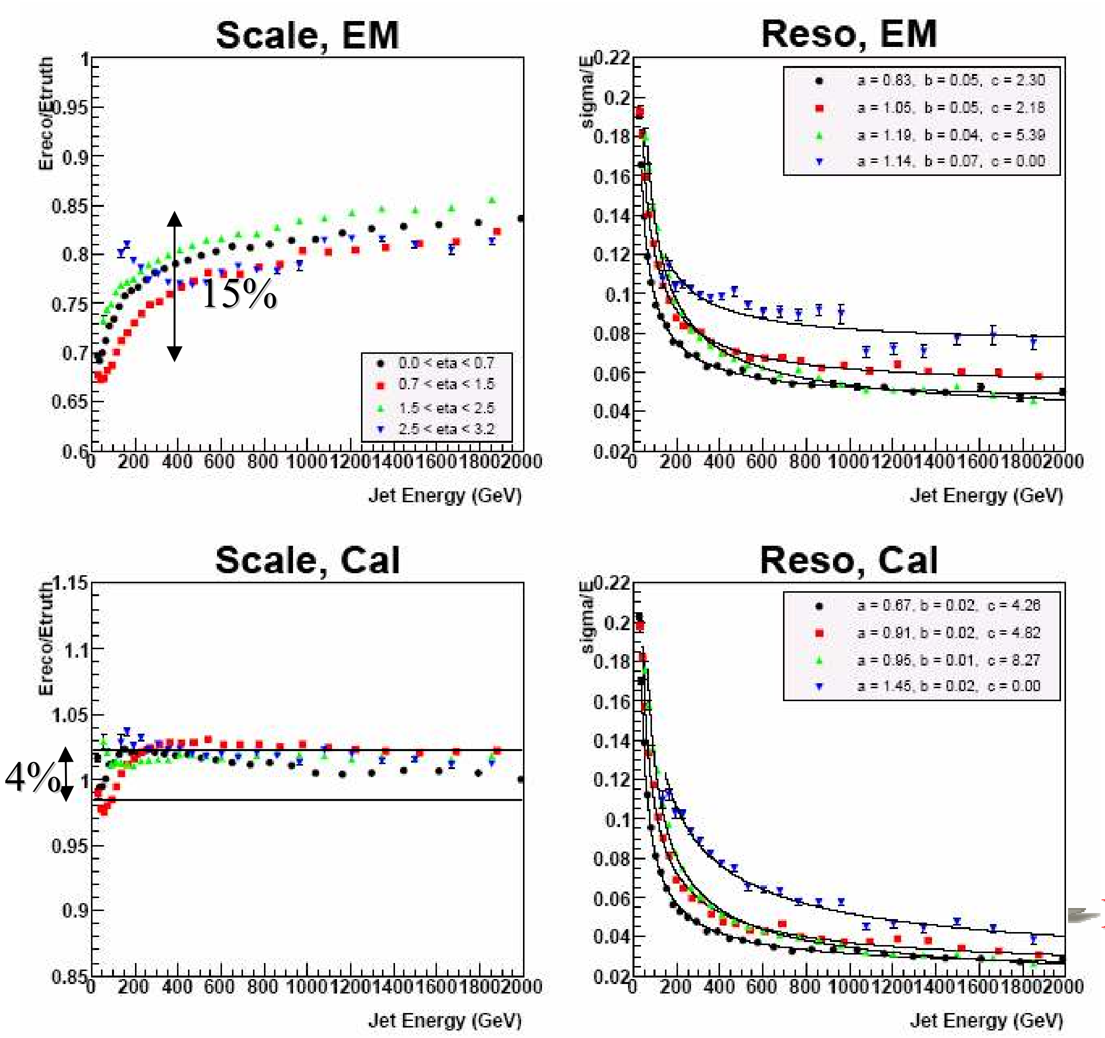
Calorimeter response depends on:

- dead material and gaps
- level of non-compensation

Jet Energy Calibration to Particle Level (Global approach)

- This Calibration is for::
  - Correction for detector effects such as dead material and non compensation
- The calibration applies weights to the cells::
  - $E_J^{rec} = \Sigma_i w_i Ecell_i$
- w_i is obtained by minimizing the energy resolution(χ^2) to the MC truth (MC particle jet)::
  - minimize $\chi^2=\Sigma_i\{(E_J^{rec}{}_i-E_J^{MC}{}_i)^2/E_J^{MC}{}_i^2\}$
- Same weights are used for different algorithms.
- A factor $R(E_T,\eta)=E_T rec/E_T MC$ is applied to correct for residual non linearities and for algorithm effects

Jet energy resolution (Global approach)



- Cone 0.7
- For $|\eta| < 0.7$ (Black Point in the left plots)

Before calibration

$$\frac{\sigma(E)}{\mathrm{E}} = \frac{0.83}{\sqrt{E(GeV)}} \oplus 0.05 \oplus \frac{2.4}{E(GeV)}$$

After calibration

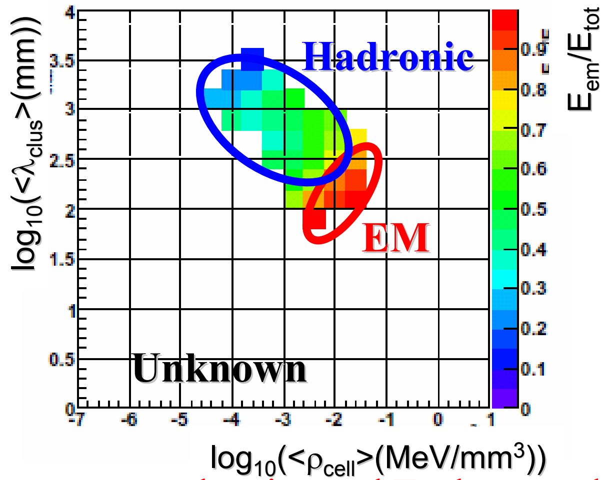
$$\frac{\sigma(E)}{\mathrm{E}} = \frac{0.67}{\sqrt{E(GeV)}} \oplus 0.02 \oplus \frac{4.3}{E(GeV)}$$

- Linearity ± 2% in energy region 50-2000GeV

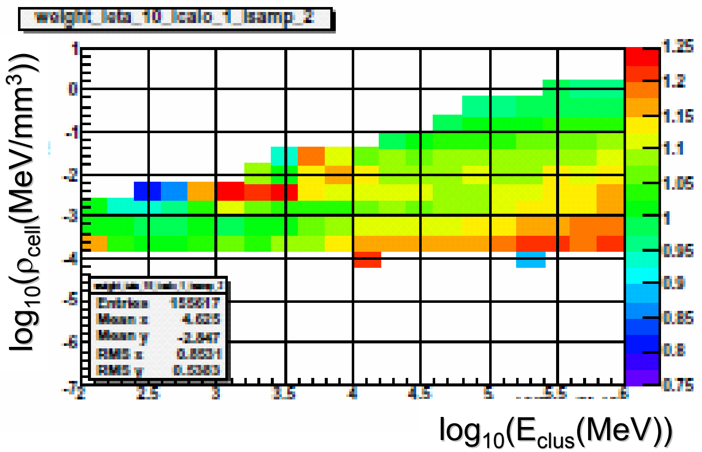
Local Hadron Calibration

- Local Hadron Calibration::
  - Calibrate 3D Cell Clusters before reconstructing the jets
    - Not depend on Jet Reco Algorithms
  - Based on MC information: for each cell EM energy, Escaped energy, Invisible energy, Non EM energy

- Classify the clusters to EM, Hadronic and Unknown by shower depth (λ_{clus}) and the energy weighted average over the cell density ($<\rho_{cell}>$)
- Apply weights to "Hadronic" clusters (as function of the cluster energy E_{clus} and the cell energy density ρ_{cell})
- Apply Dead Material Correction, too



Larger energy density and Early part shower =>EM

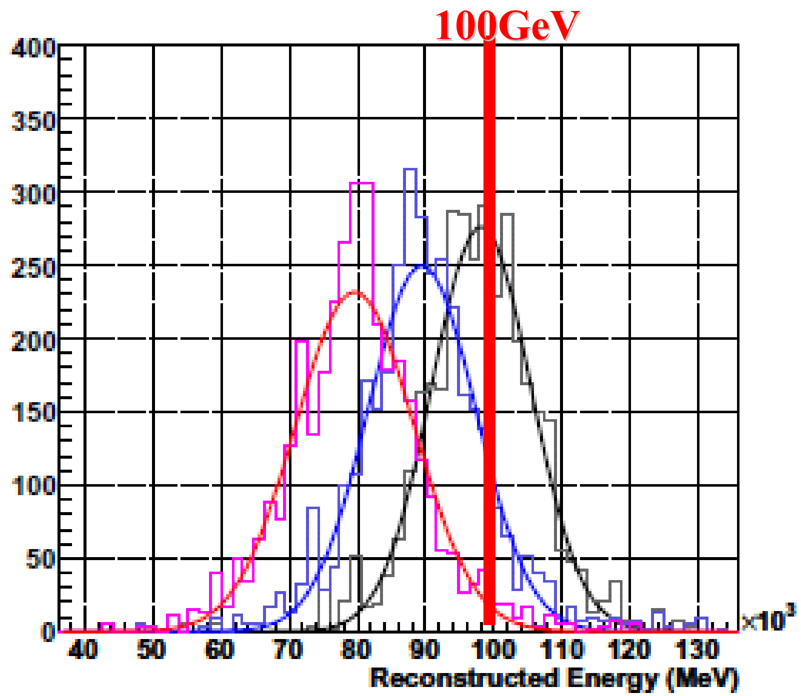


Weights for EMEC

Local Hadron Calibration cont.

- Right histograms shows example of Local Hadron Calibration for 100GeV Pion.
  - Red line:: EM scale
  - Blue line:: Weighted
  - Black line:: Weighted with DM corrections

	EM scale	Weighted	Weighted+DM
Mean(%)	79.9	89.5	98.2
σ(%)	8.7	7.9	7.3
σ/Mean(%)	10.9	8.8	7.4



The ration of total energy reconstructed in clusters in a cone with $\Delta R < 1$ around the true pion direction over the true pion energy on each steps (100GeV Single Pion, $0.2 < |\eta| < 0.4$)

- Mean and resolution improve in every step
- Final deviation from beam energy only 1.8% consistent with expected out-of-cluster corrections

In situ Calibration

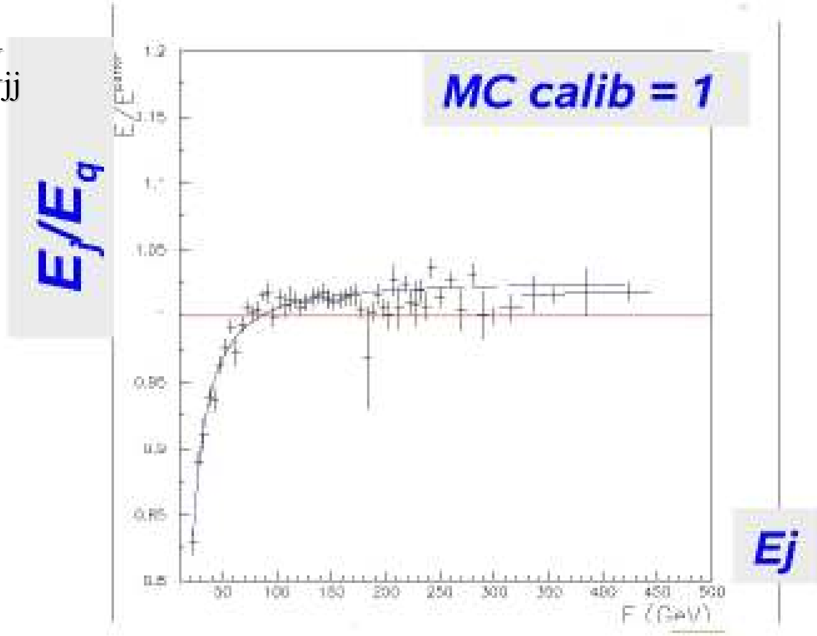
- This Calibration is for::
  - Correction for energy losses out of jet clustering
  - Correction for energy of physics effect such as underlying event, ISR and FSR
- Some methods are studied::
  - W->jj : use W produced by the top decay in the ttbar events
    - Very large statistics (More than 8 million ttbar produced per year at low luminosity ($10^{33}cm^{-2}s^{-1}$)), ~200GeV
  - Z(->ee or μμ)+j : P_T balance or ETmiss projection method
    - It will also provide constraints on the b-jet energy scale, ~40-400GeV
  - γ+j : P_T balance or $E_T$miss projection method
    - Higher statistics but high QCD background
  - Multi Jets : use balance one high P_T jet with two or more lower P_T jets
    - uniformity check especially for very high energy jets

W->jj (in the ttbar events)

- Use ttbar events in which one W decays leptonicaly and another W decays hadronically (tt->WWbb->(lν)(jj)bb)
  - Clean trigger from the isolated lepton
- σ_{ttbar} (14.0TeV) = 800 pb (about factor 100 larger at LHC than at Tevatron)
- Use Cone 0.4 (because ttbar events are busy)
- Calibration constants $\alpha_i(E_i) = E_i^{part}/E_i^{jet}$:
  - Obtained by constraint :: $M_W^{PDG} = \sqrt{(\alpha_1\alpha_2)}M_{jj}$
- Right plot shows :

  E_{jet}(calibrated)/E_{part} VS E_{jet}

  with MC calib = 1
- Bias is within 1% (E_{jet}>40GeV)
- Huge effect below 40GeV
- Manage to retrieve α(E) to 1% with 1fb^{-1}

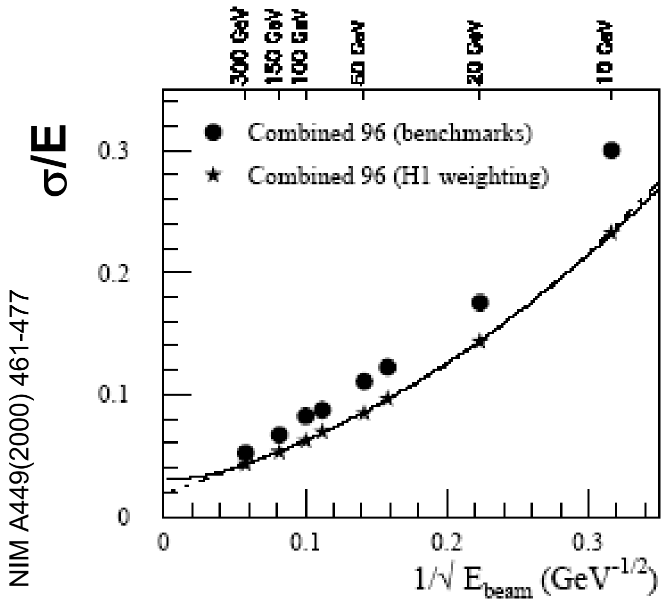


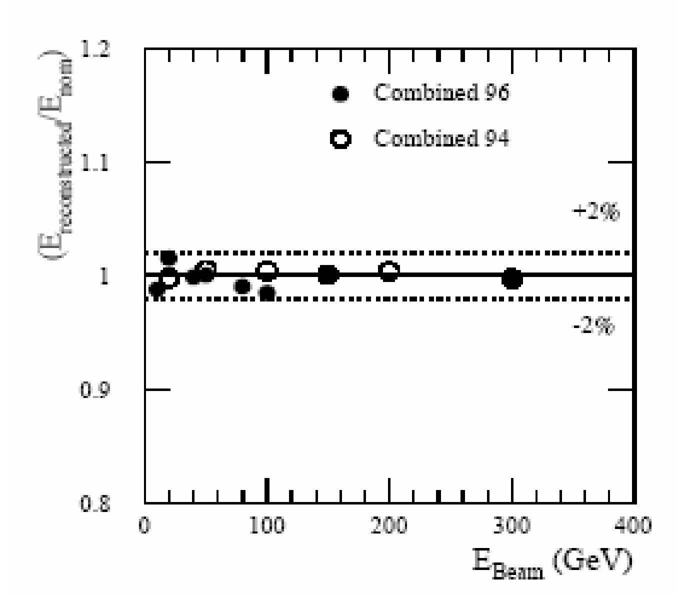
Summary

- Some different methods and algorithm for jet energy calibration and reconstruction are being studied.
- 3D Cell Clusters show a good noise suppression.
- Calibration algorithms (default) to correct for detector effects give linearity with in 2% for E = 50GeV-2000GeV
- Local Hadron Calibration shows very promising results.
- In situ calibration strategies are being developed: W->jj can calibrate to parton level within 1% for E_{Jet}>40GeV.

Back Up Slides

Combined TestBeam (Central region)





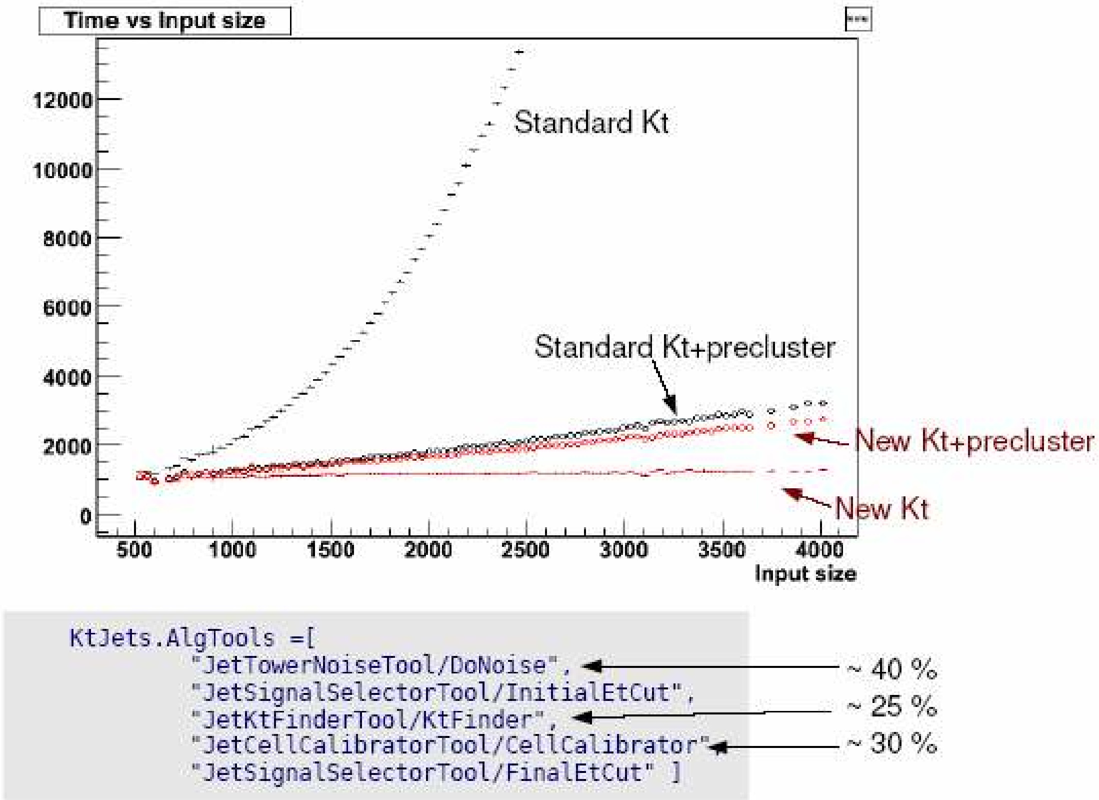
EM LAr + TileCal resolution
obtained at 1996 Combined TestBeam, η= 0.35
(ref. NIM449(2000) 461-447)

$$\frac{\sigma}{E} = \left(\frac{41.9\%}{\sqrt{E}} + 1.8\% \right) \oplus \frac{1.8}{E}$$

linearity < 2% 10-300 GeV

Fast K_T

- K_T algorithms are typically slow since speed scales with $O(N^3)$
- It has been shown that they can be made faster by using nearest neighbour information (Cacciari, Salam hep-ph/0512210)
- FastK_T has been implemented in ATLAS and it also allows to skip the preclustering phase.



Jet Reconstruction Algorithm (Midpoint Algorithm)

Midpoint Algorithm
(Implementation based on CDF approach)

- E_T Seed::2GeV
- Cone precluster with radius 0.5 x ΔR
- Add midpoints if preclusters i, j are separated < 2 x ΔR
- Cone jets of radius ΔR are searched
- Merge if > 50% of P_T of lowest jet is shared, else split

Weighting Schemes

- Method based on longitudinal energy deposit

1. Sampling Calibration

   - Weights calorimeter layers (w_i) = f(Jet energy, eta)

   - 8 or less parameters per fit depending on eta and energy.

- Methods based density – Uses detailed on energy cell information -> more parameters in the fit

1. H1-Style – two steps procedure

   - Cell weights (w_i) = f(Cell energy density)

   - Apply extra correction factor function of Ejet and eta to improve linearity and uniformity.

2. Pisa Calibration

   - Cell weights (w_i) = f(Cell energy density, Jet energy)

   - Similar idea as above, use extra info of jet energy.

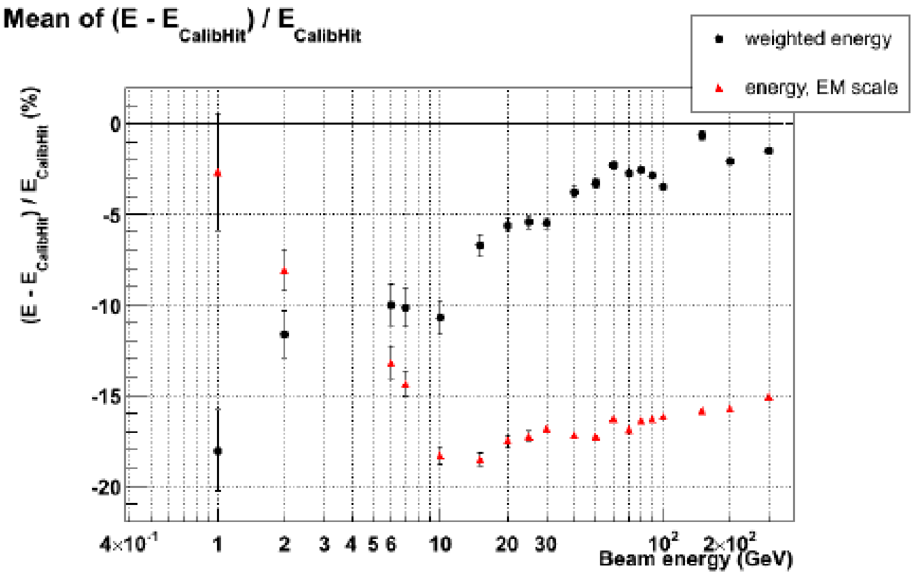
3. Psuedo H1

   - Similar as H1-style. Not yet ready to provide jet energy scale.

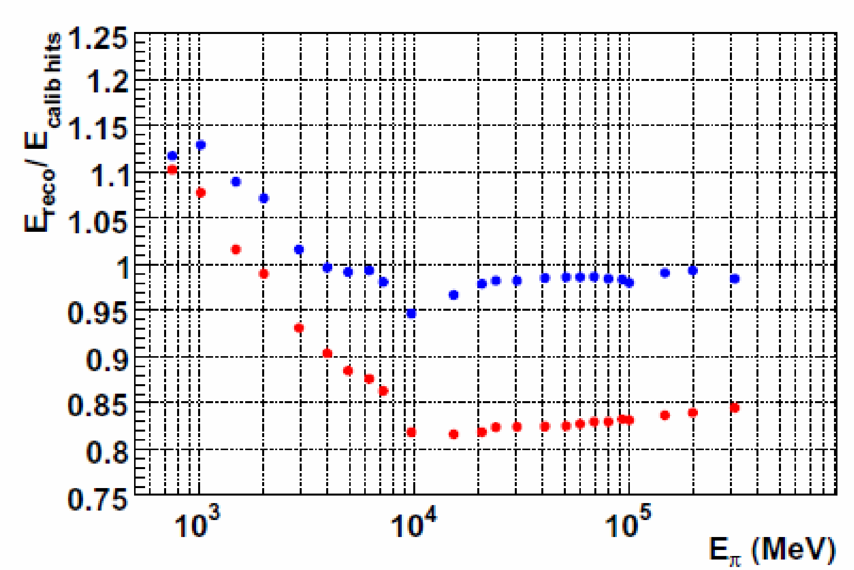
Local Hadron Calibration::performance on CTB Monte Carlo (Linearity)

- Left plot::local hadron calibration (red::EM scale, black::weighted, mean from a Gaussan fit)
- Right plot::default method (red::EM scale, blue::weighted, mean of the distribution)
- Local Hadron Calibration shows 0.5-1% worse but this might be due to different definitions of the mean

Local Hadron Calibration



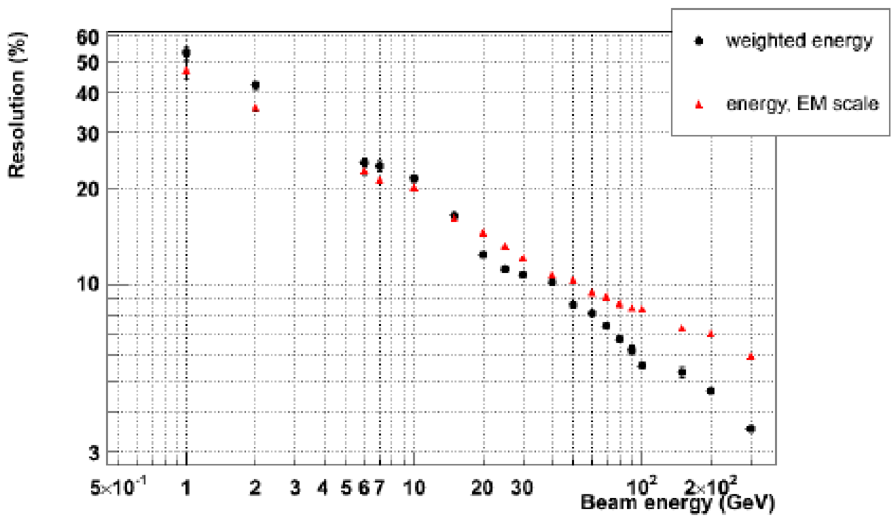
Default method



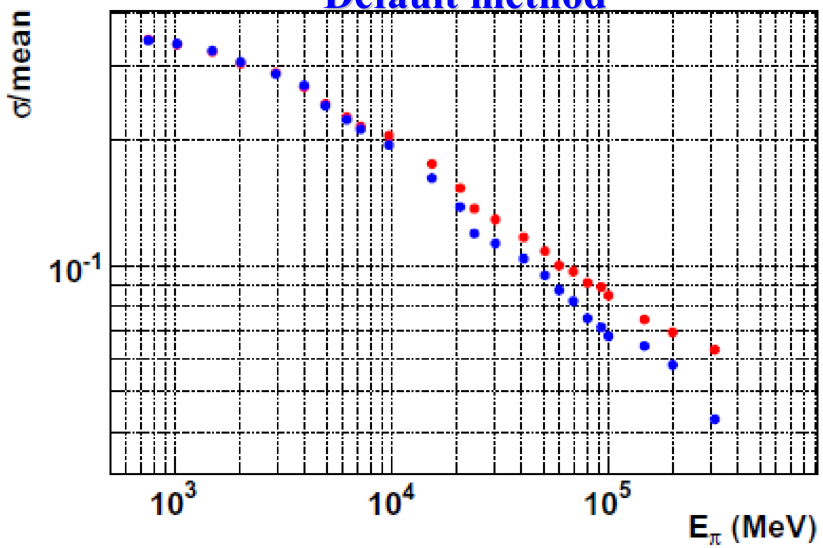
Local Hadron Calibration::performance on CTB Monte Carlo (Resolution)

- Left plot::local hadronic calibration (red::EM scale, black::weighted, relatice sigma from the Gaussian fit)
- Right plot::default method (red::EM scale, blue::weighted, RMS of the distribution divided by its mean)
- Both plots show improved resolution above 10GeV
- Numerical differences stem again mainly from different definitions (sigma vs. RMS)- default method is maybe a bit worse in resolution at high energies

Local Hadron Calibration



Default method

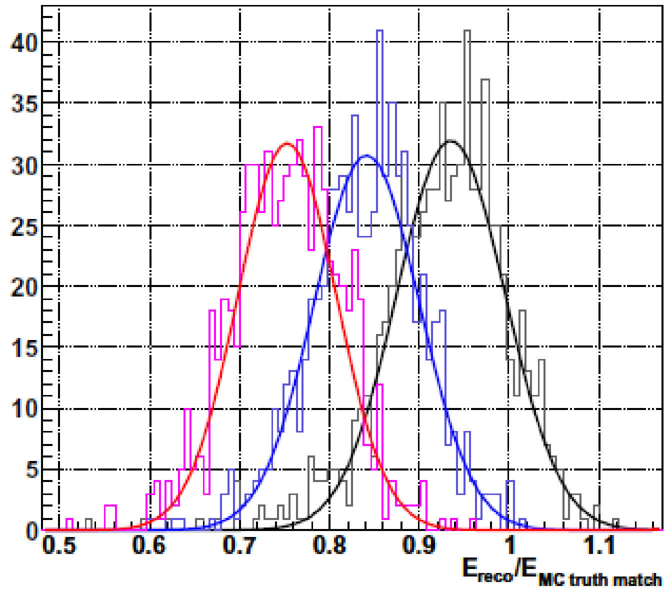


Local Hadron Calibration(di-jet)

- Right histograms shows example of Local Hadron Calibration for di-jet sample.
- Using tow leading jets (K_T with D=0.6), $0.2<|\eta|<0.4$, and energy of the leading jets in the sample and region is about 150±40GeV
  - Red line:: EM scale
  - Blue line:: Weighted
  - Black line:: Weighted with DM corrections

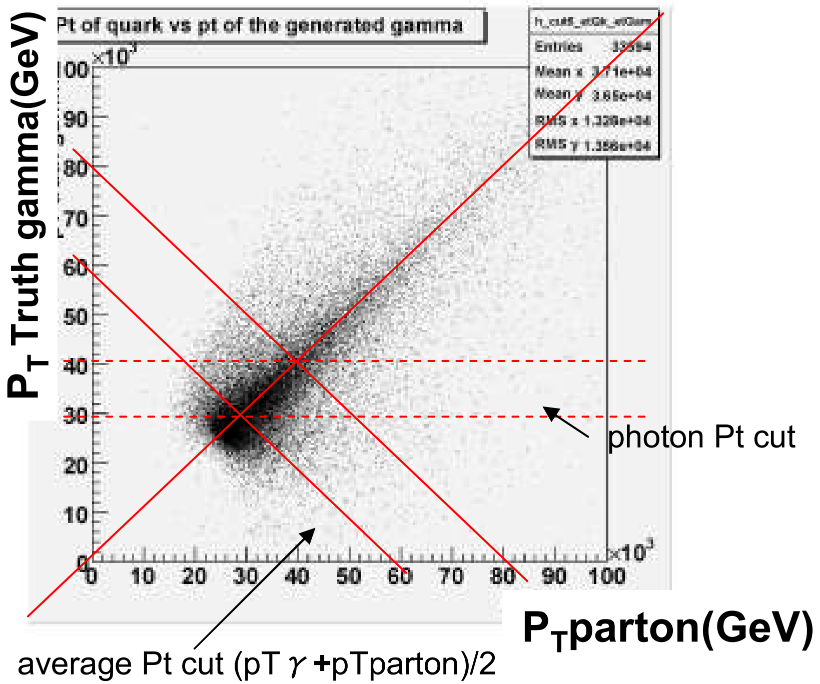
	EM scale	Weighted	Weighted+DM
Mean(%)	75.3	84.1	93.5
σ(%)	5.5	5.8	6.0
σ/Mean(%)	7.3	6.9	6.5

- Mean and resolution improve in every step
- Final deviation from beam energy only 6.5% consistent with expected out-of-jet corrections



The ration of total energy reconstructed jet over the energy matched truth (also K_T with D=0.6) with $\Delta\eta<0.05$, $\Delta\phi<0.05$

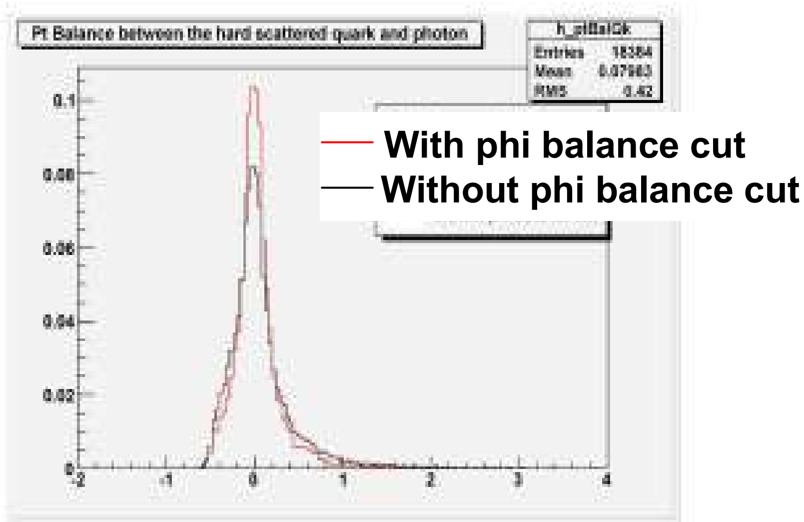
γ+jet



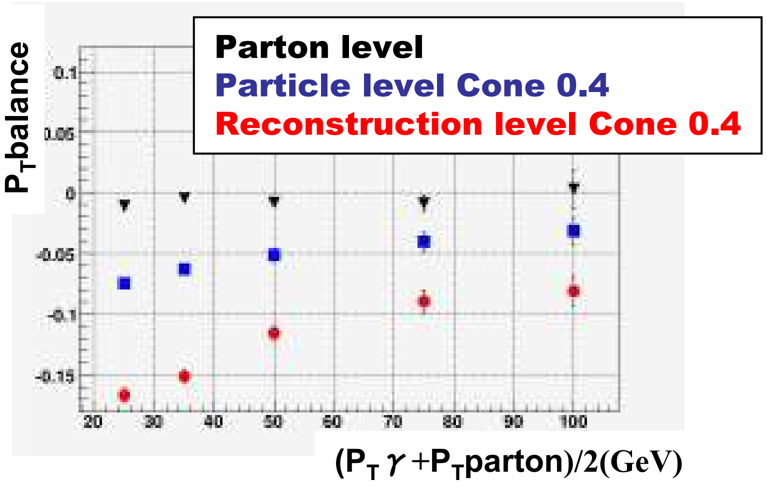
- Select isolated gamma
- Select Highest P_T jet
- Apply phi back-to-back cut

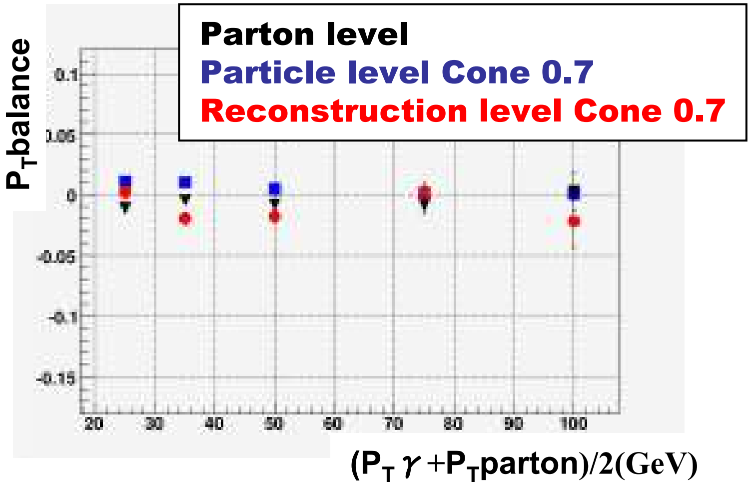
$P_T$balance =
($P_T$jet – $P_T$photon)/$P_T$photon

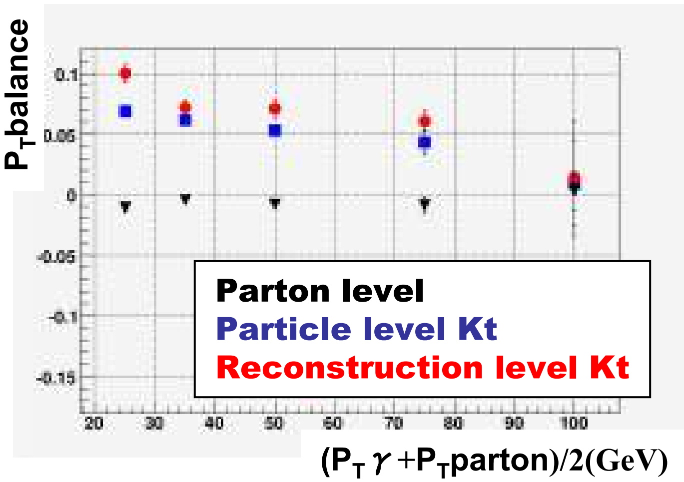
To fit MOP with little sensitivity to tails: iterate a gaussian fit between ± σ around the most probable value



γ+jet cont.







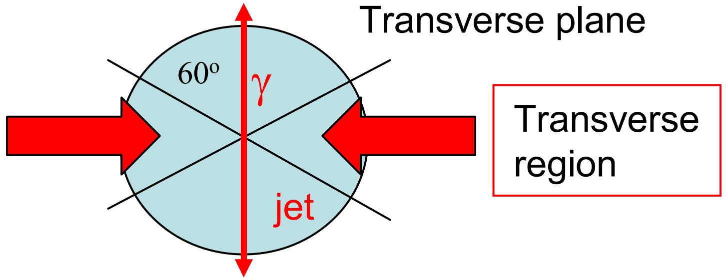
Biases on P_T balance MOP for the different jet algorithms

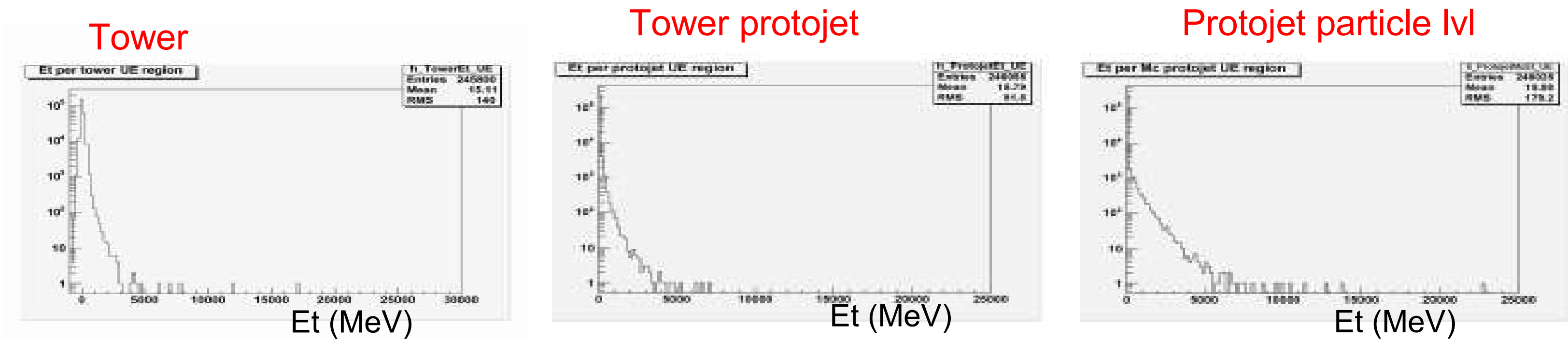
Algorithms	Cone 0.7	Cone 0.4	Kt (D=1)
Parton level	-1 - 0%	-1 - 0%	-1 - 0%
Particle level	1 - 0%	-6 - -3%	6 - 1%
Recon level	-2 - 0%	-15 - -7%	7 - 2%

- Selection gives < 1% bias
- To estimate the mean E_T of UE, a study which use transverse interaction region is in progress.

γ+jet: Underlying Event

- Try to estimate the mean ET of UE from the event sample
- Select the "transverse region" of the event: avoiding 60 degrees in Phi around both photon and the jet (suggested by the SM group)





Mean transverse energy per η x ϕ = 0.1 x 0.1 :

Tower (RMS of el.noise ~140 MeV)	16.17 ± 0.03 MeV
Recon tower protojet (tower preclusters after noise treatment)	16.84 ± 0.03 MeV
Recon topocluster protojet (topoclusters)	12.52 ± 0.02 MeV
Particle protojet (Σ particles per tower)	19.91 ± 0.02 MeV

EM scale (Tower, Recon tower protojet, Recon topocluster protojet)

3 GeV in cone 0.7 (Particle protojet)

- Average UE level ~10% RMS of el.noise (very sensitive to noise suppression)