Jet Energy Calibration

Workshop on non-perturbative QCD of jets

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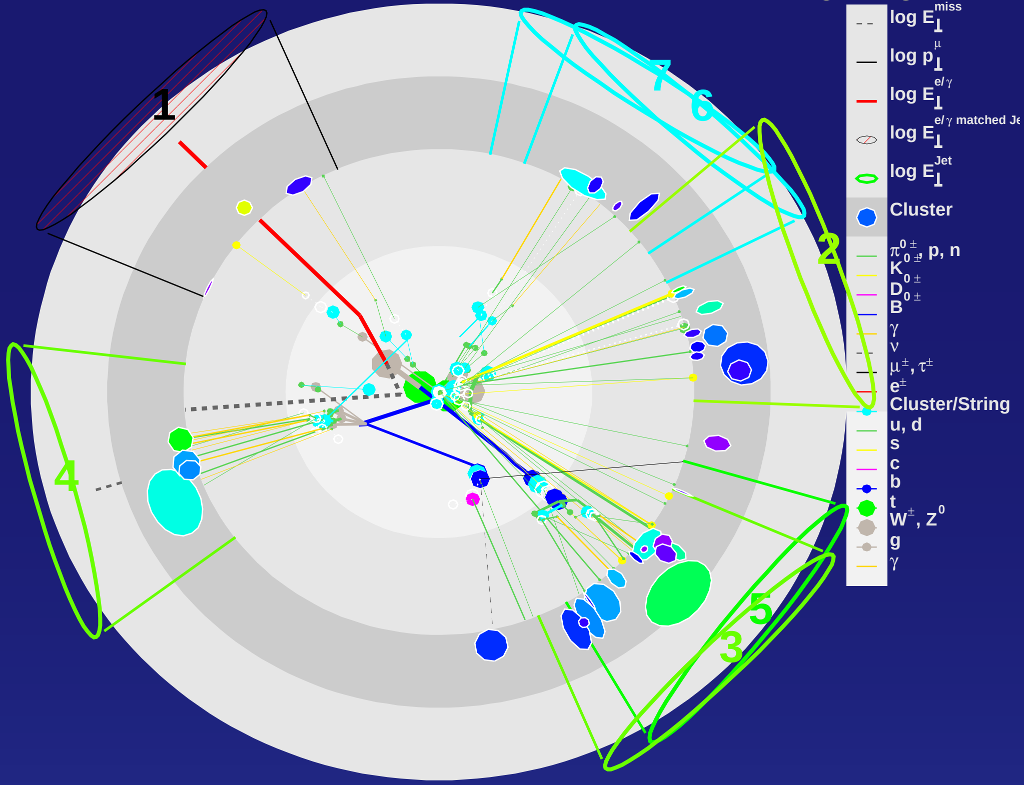
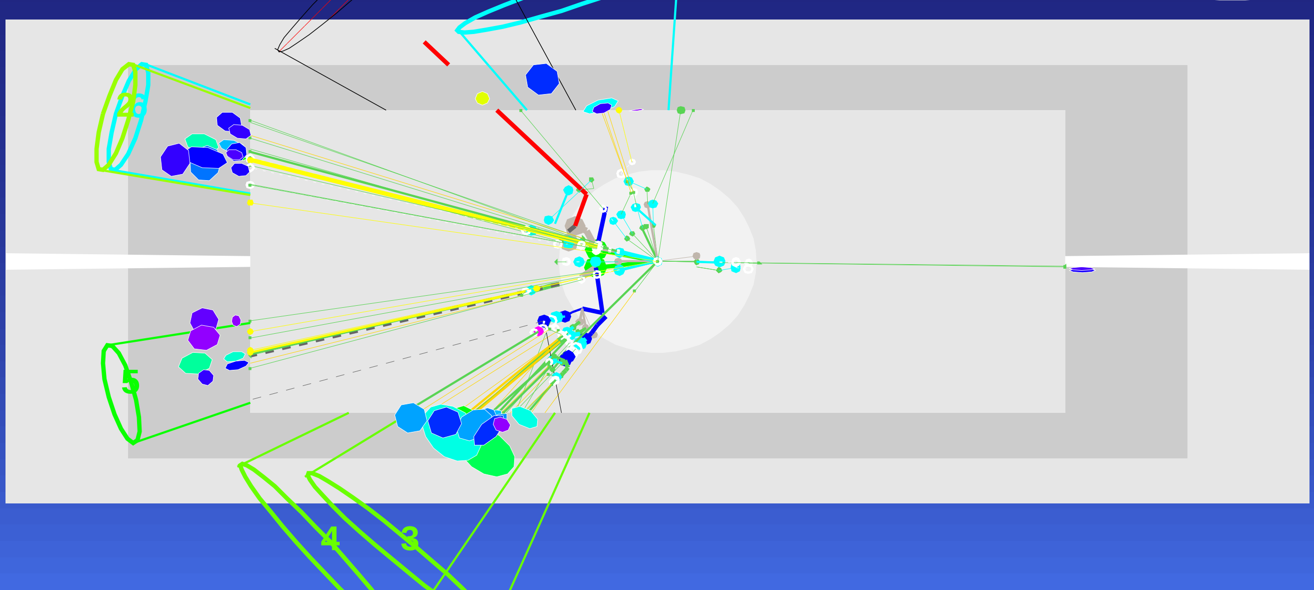
8. Jan 2007, Schloß Ringberg

- Introduction
- Clusters
- Jets
- Calibration Approaches
- Calorimeter Calibration
- In Situ Calibration
- Conclusions

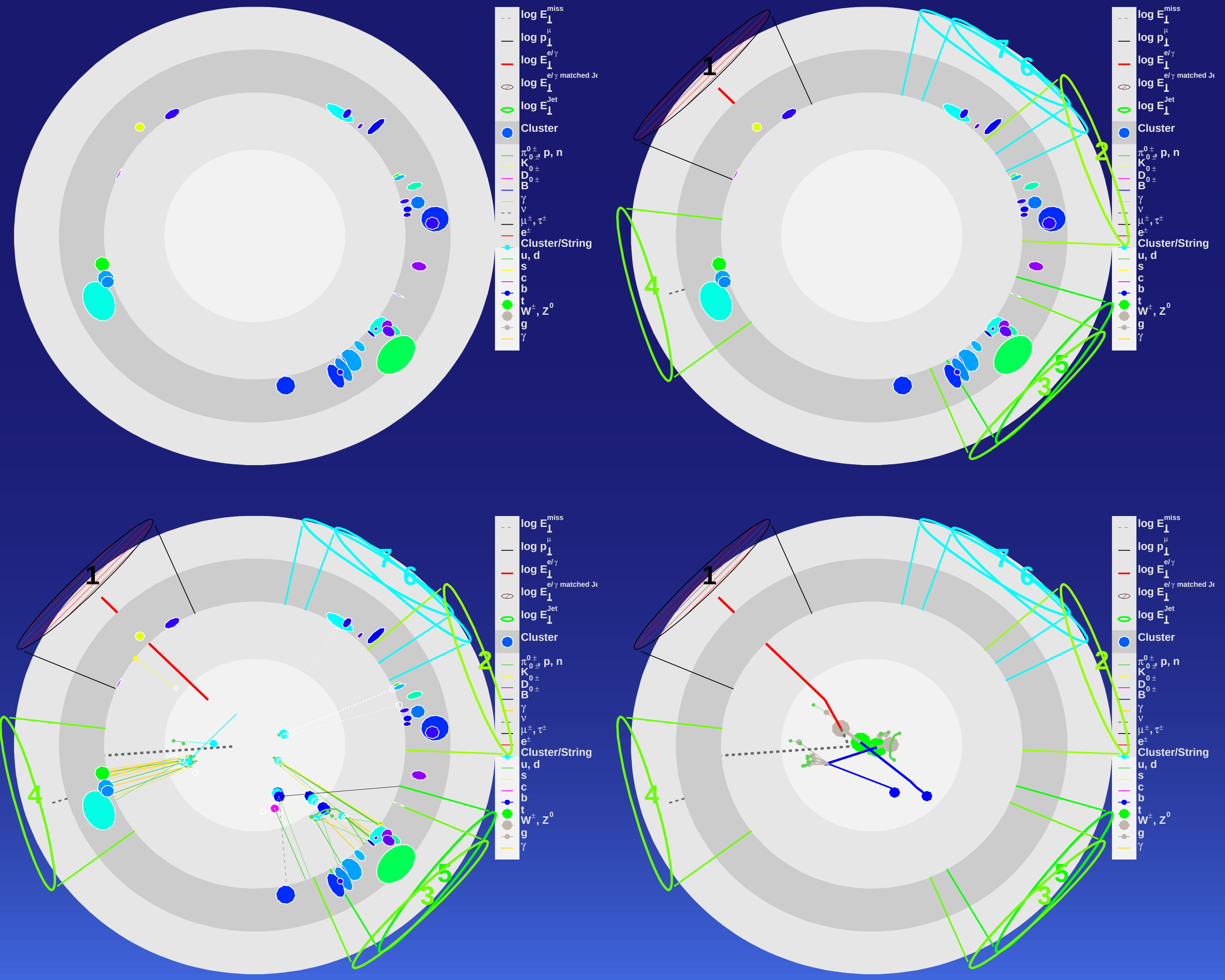




Introduction

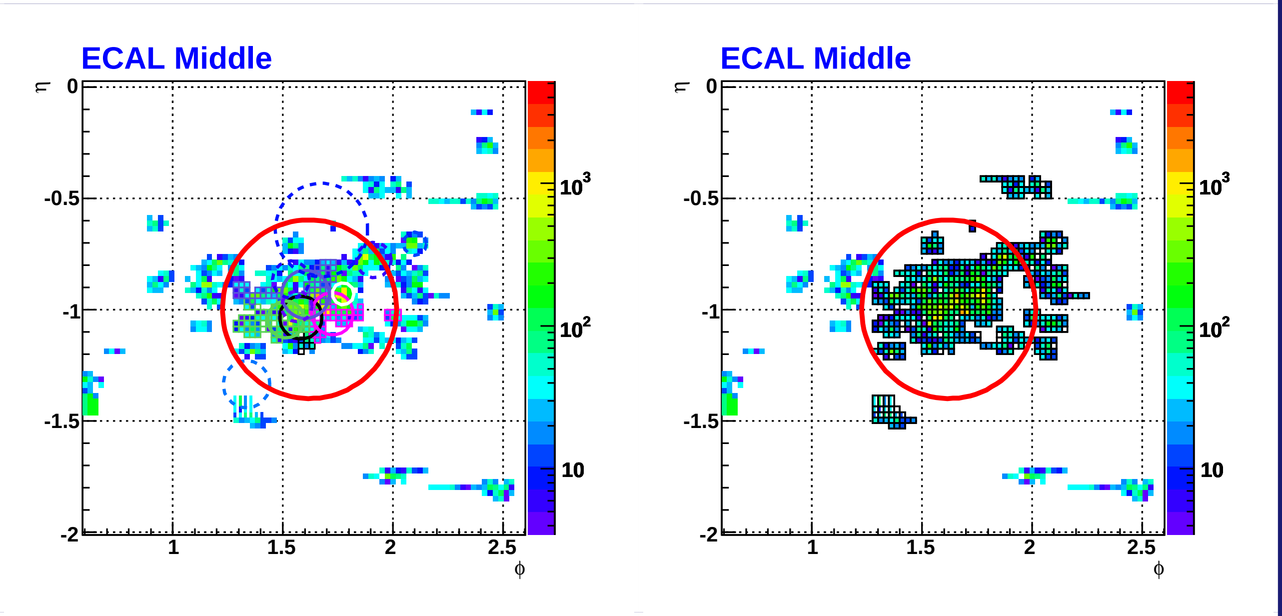
- Jet energy calibration can be divided in 4 steps

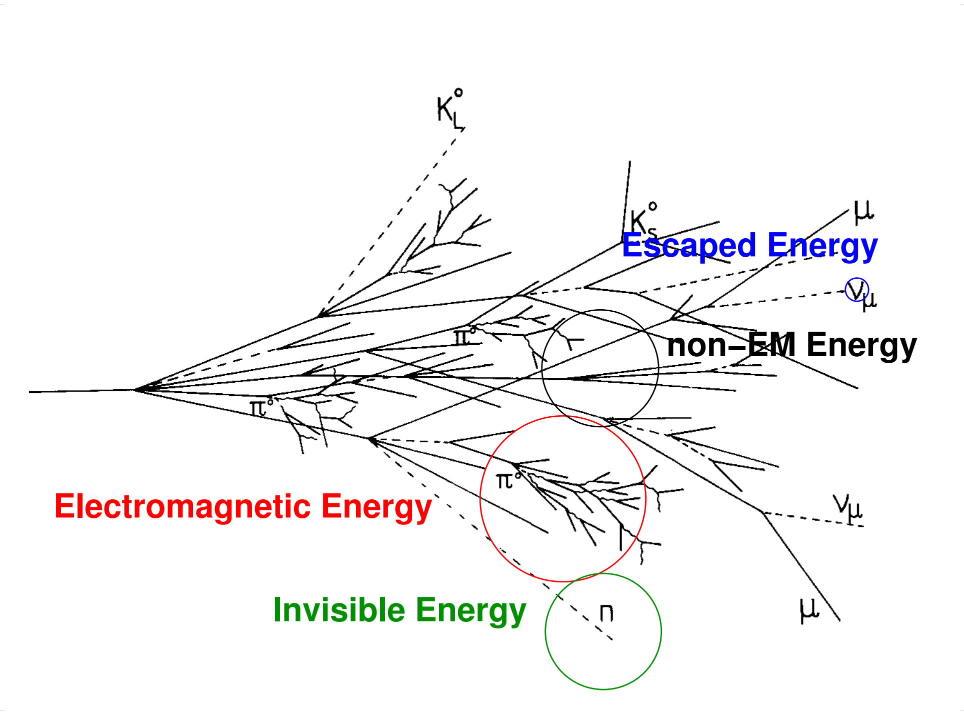
1. calorimeter tower/cluster reconstruction
2. jet making
3. jet calibration from calorimeter to particle scale
4. jet calibration from particle scale to the parton scale



Experimental Challenges

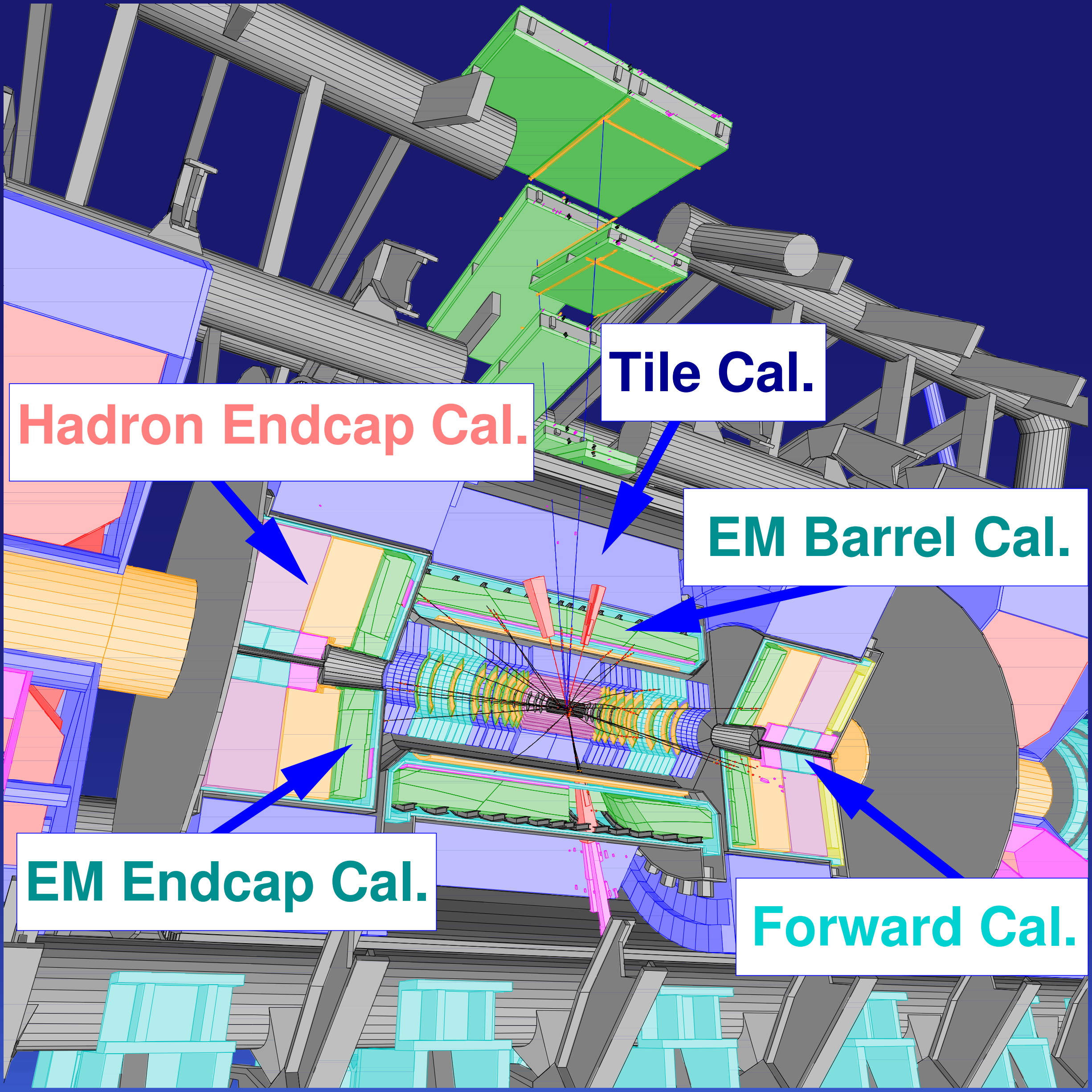
- Calorimeter Cluster Reconstruction
  - shower containment
  - particle separation and identification
  - electronics noise
  - pile-up
- Jet Making
  - choice of algorithm (cone, $K_\perp$, . . .)
  - jet size
  - overlap with electrons
- Jet Calibration to Particle Level
  - e/h compensation
  - dead material corrections
  - out-of-cluster corrections
  - out-of-jet corrections
- Jet Calibration to Parton Level
  - match to parton jet
  - differences for light-quark, b-quark, gluon-jets
  - MC dependencies



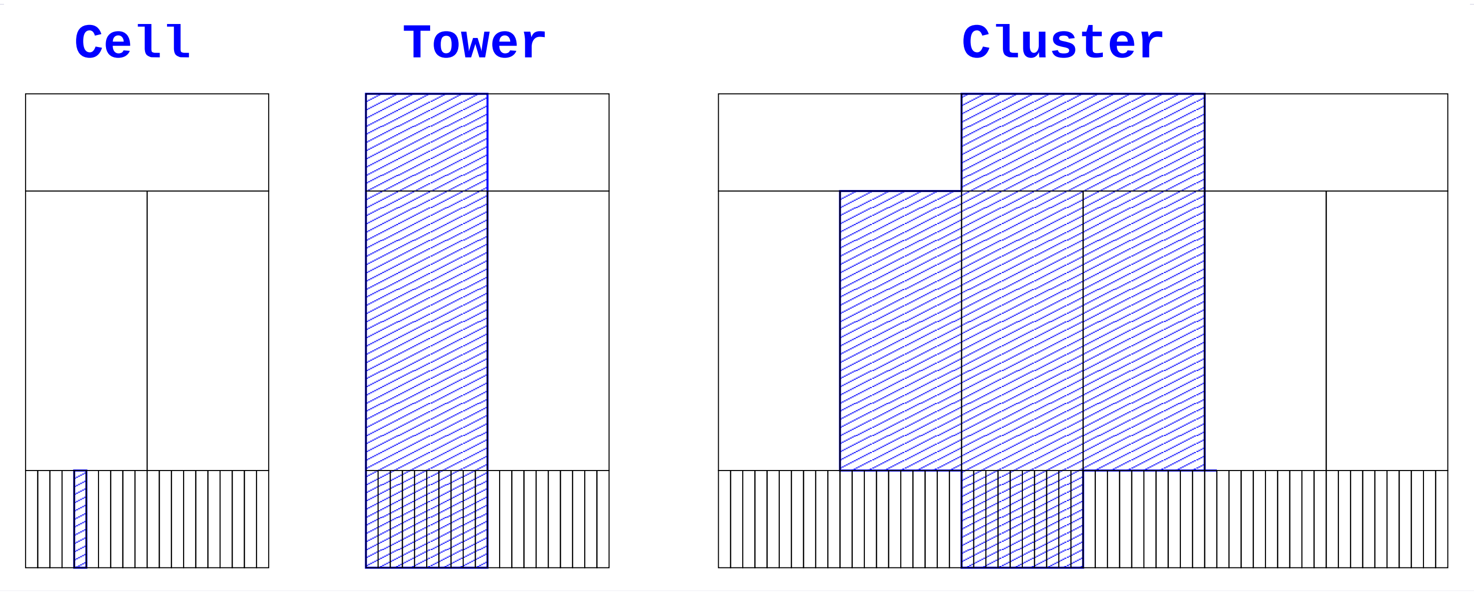


Example: The ATLAS Calorimeters

- Layout of the ATLAS Calorimeters
- EM LAr-Pb accordion calorimeter
  - Barrel (EMB): $|\eta| < 1.4$
  - End-cap (EMEC): $1.375 < |\eta| < 3.2$
- Hadron calorimeters
  - Barrel (Tile): Scint.-Steel $|\eta| < 1.7$
  - End-cap (HEC): LAr-Cu $1.5 < |\eta| < 3.2$
- Forward calorimeter (FCal) $3.2 < |\eta| < 4.9$
  - FCal1: LAr-Cu
  - FCal2&3: LAr-W



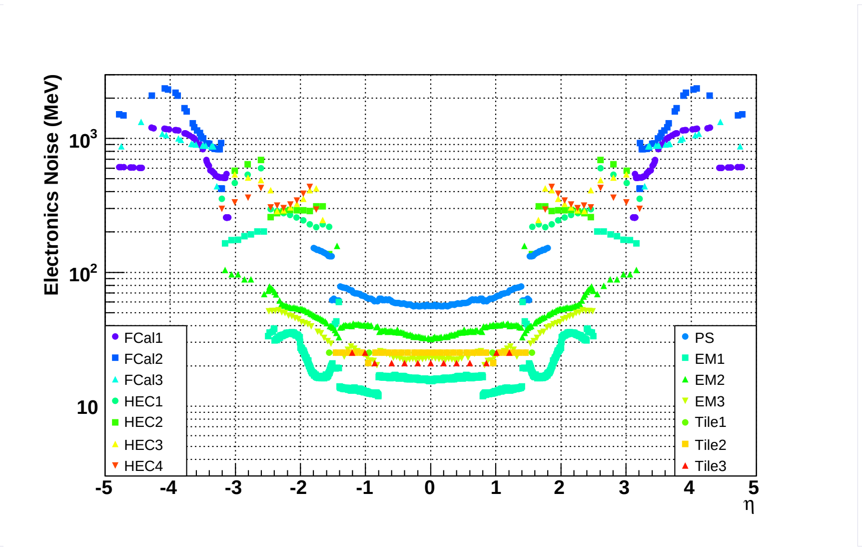
Reconstruction Objects in Calorimetry

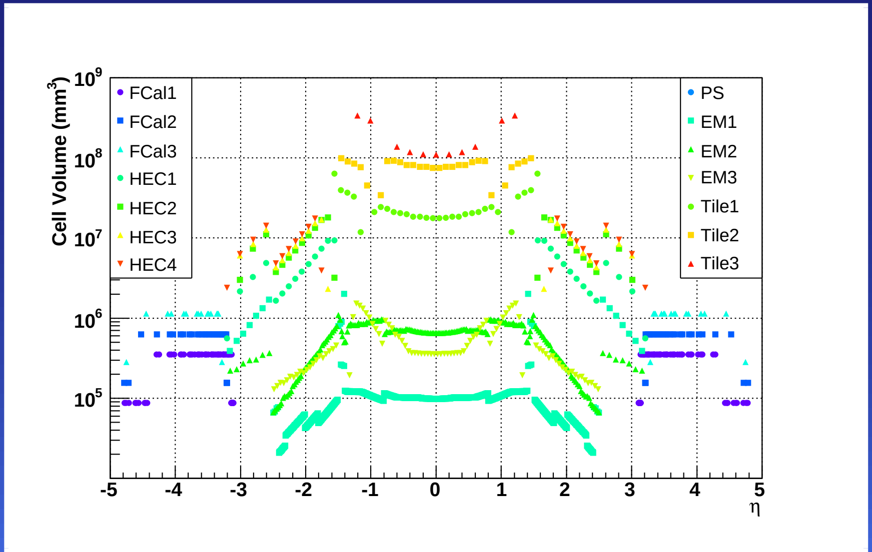


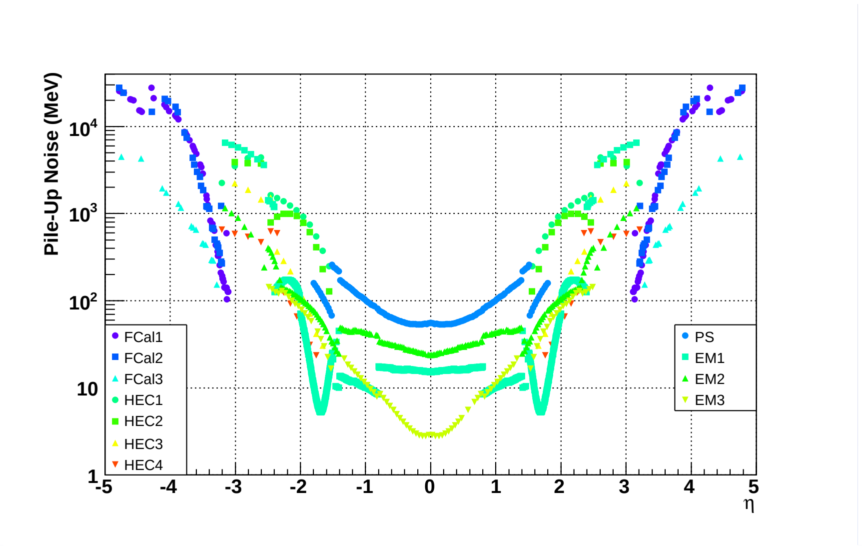
- The cell is the smallest reco object
  - all ATLAS calorimeters together provide 187652 cells
  - each cell provides mainly the raw reconstructed energy in MeV
- A tower is a group of cells (or even a group of fractions of cells) in a fixed $\Delta\eta \times \Delta\phi$ grid over some or all samplings
  - contains the sum of cell (fraction) energies and the center of the grid square (η and ϕ) as members
  - in use in ATLAS are 65536 LAr EM only `LArTower`s with $\Delta\eta \times \Delta\phi = 0.025 \times 2\pi/256$
  - and 6400 `CaloTower`s including all calorimeters with with $\Delta\eta \times \Delta\phi = 0.1 \times 2\pi/64$
- A cluster is a group of cells (or even fraction of cells) formed around a seed cell
  - is the main reco object for calorimetry
  - with either a fixed size in $\Delta\eta \times \Delta\phi$ (sliding window)
  - or variable borders based on the significance of the cells (topo cluster)
  - contains lots of data members based on weighted cell members for energy, position and shape

Clusters

- Cluster algorithms need to serve multiple purposes
  - suppress noise (electronics noise and pile-up)
  - keep electromagnetic showers in one cluster
  - separate multiple signals which are close by
  - work on very different sub-systems
- Plots on the right and below show large variations in η for
  - electronics noise at high luminosity ($L = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-2}$) ($\sim 1.5 \cdot 10^{1} - 2 \cdot 10^{3}$ MeV)
  - pile-up noise at high luminosity ($\sim 3 \cdot 10^{0} - 3 \cdot 10^{4}$ MeV)
  - cell volume ($\sim 2 \cdot 10^{4} - 3 \cdot 10^{8}$, mm^3)







Topological Clusters (ATLAS)

Cluster Making

- form clusters around seed cells with $|E_{\text{seed}}| > 4(\sigma_{\text{elec-noise}} \oplus \sigma_{\text{ pile-up-noise}})$
- expand clusters around neighbor cells with $|E_{\text{neigh}}| > 2\sigma$
- include perimeter cells with $|E_{\text{cell}}| > 0\sigma$
- merge clusters if they share a neighbor cell
- expansion is driven by neighbors in $3D$:
  usually 8 neighbors in the same layer ($2D$) plus cells overlapping in η and ϕ with central cell in next and previous layer (just 2 if granularity would be the same)

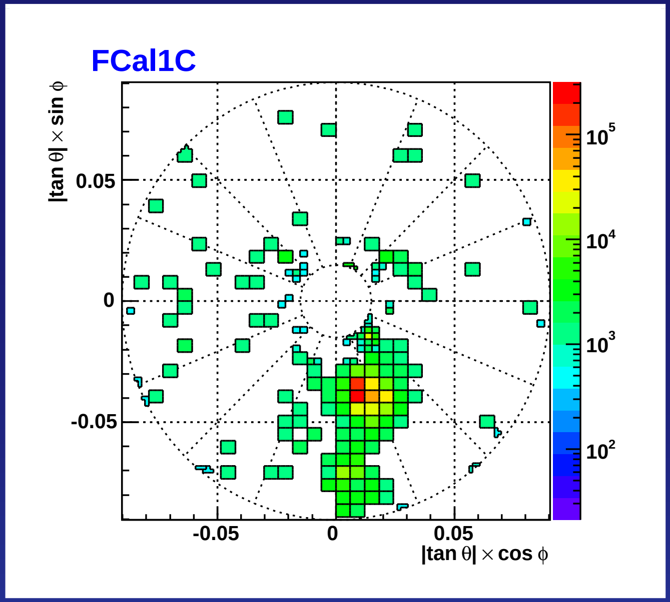
Cluster Splitting

- search for local maxima in cell energy with $E_{seed} > 500\,\text{MeV}$ in all clustered cells in EM-samplings (HAD-samplings secondary)
- re-cluster around local maxima with same neighbor driven algorithm but no thresholds and no merging
- cells at cluster borders are shared with energy and distance dependent weights

Topological Clusters (ATLAS) ► Example

- look at di-jet MC sample including electronics noise with activity in the forward region
- plots show $|E_{\text{cell}}|$ on a color coded log-scale in MeV in the first (EM) FCal sampling for one event

$|E| > 2\,\sigma_{\text{noise}}$



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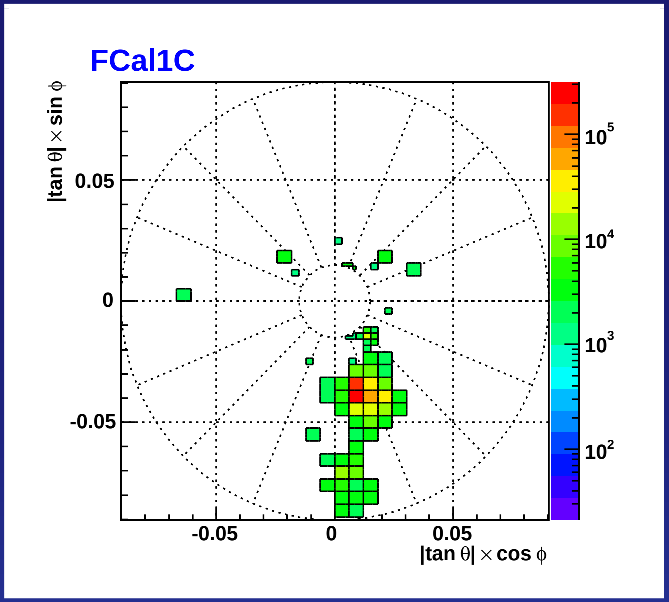
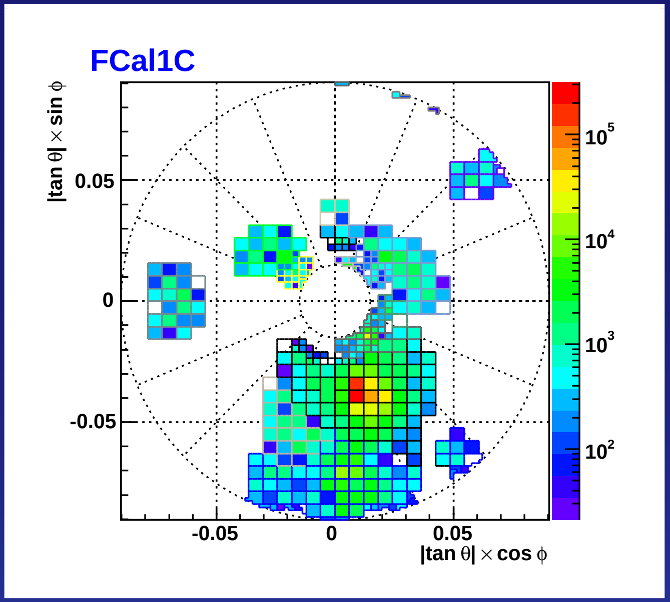


$4/2/0$ topological clusters



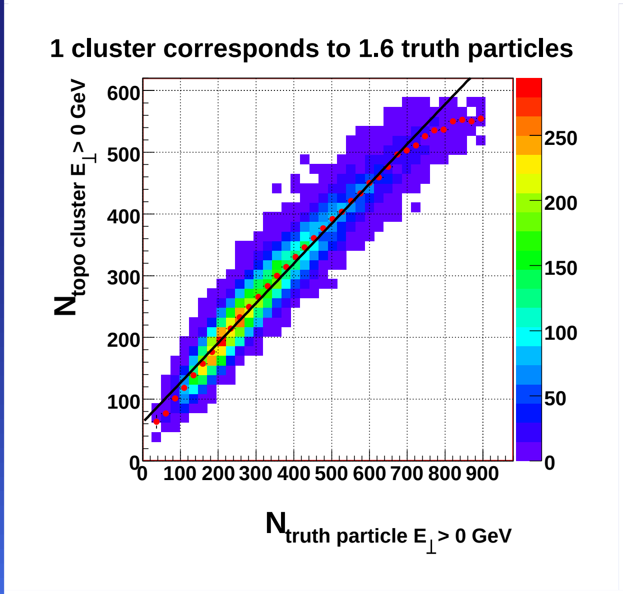
- $2\,\sigma$ cut is removing cells from the signal region
- $4\,\sigma$ cut shows seeds for the cluster maker
- after clustering all cells in the signal regions are kept
- cluster splitter finds hot spots

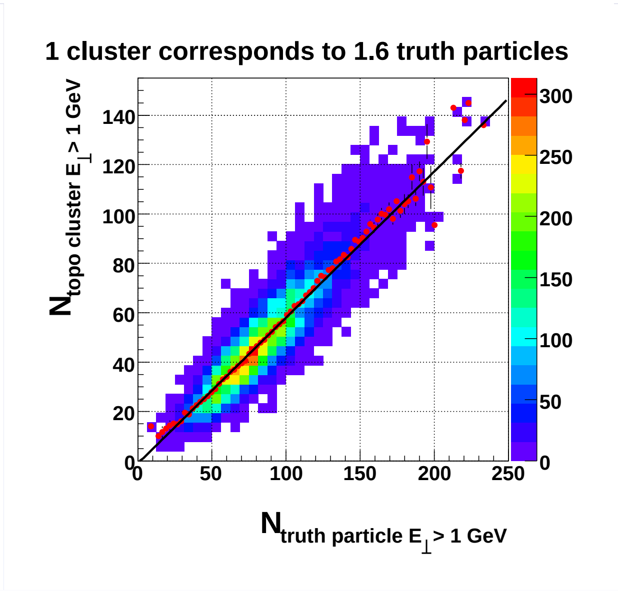
Jets

- Jets are
  - a collection of 4-vectors based on tracks and/or calorimeter objects (cells or towers or clusters)
  - defined by a metric on 4-vector level
  - the easiest reference level to base particle level calibration or monitoring of calibration on although in most cases the constituents are the objects being calibrated
  - receiving the final parton level calibration
  - used for physics studies
- ATLAS uses
  - a seeded cone algorithm with split and merge and towers or topo clusters as input for $R = 0.4$ and 0.7 with seed cuts of typically 1 or $2\,\mathrm{GeV}$ in $E_\perp$
  - the $\mathrm{K}_\perp$ algorithm (FastKt) with towers or topo clusters as input (no pre-clustering) for $R = 0.4$ and 0.6
  - typically an $E_\perp$ cut of 7 or $10\,\mathrm{GeV}$ on the final jets

Jet Input

- Pro’s & Con’s of towers and topo clusters as jet input
- Towers
  - $+$ have always the same fixed size $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
  - $+$ have no seed – all cells end up in towers
  - $-$ do not provide noise or pile-up suppression
  - $-$ do not contain showers
- Topo Clusters
  - $+$ provide efficient noise and pile-up suppression
  - $+$ correspond to individual hadrons
  - $-$ typically have detector region dependent size $r \sim 0.1 - 0.2$


1 cluster corresponds to 1.6 truth particles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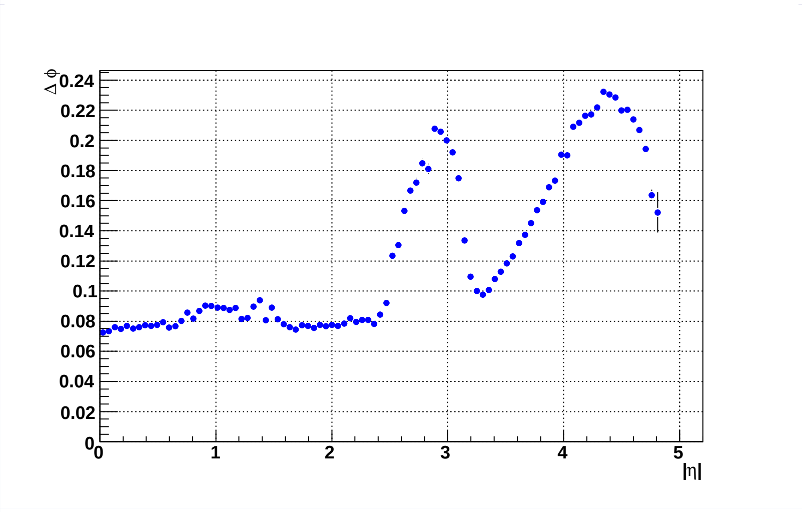


Calibration Approaches

- Jet Calibration
  - use towers or topo clusters on EM-scale as input to jets
  - match a truth particle jet with each reco jet
  - fit a cell-level calibration function based on energy density to all matched jet pairs
- Local Hadron Calibration
  - calibrate topo clusters independent of any jet algorithm to hadronic scale
  - make jets out of calibrated topo clusters
- In-situ check of hadronic scale
  - can use single isolated hadrons from minimum bias and from τ decays to check hadronic scale (E/p-ratio)
- Final In-situ Calibration
  - both approaches above need the final step from hadron to parton level
  - with W-mass in $\mathrm{t}\bar{\mathrm{t}} \rightarrow \mathrm{Wb\,Wb} \rightarrow \mathrm{l}\nu j_{\mathrm{b}}\, jjj_{\mathrm{b}}$
  - with $p_{\perp}$ balance in $\mathrm{Z}/\gamma + j$

Calorimeter Calibration ► Jet-Level Calibrations

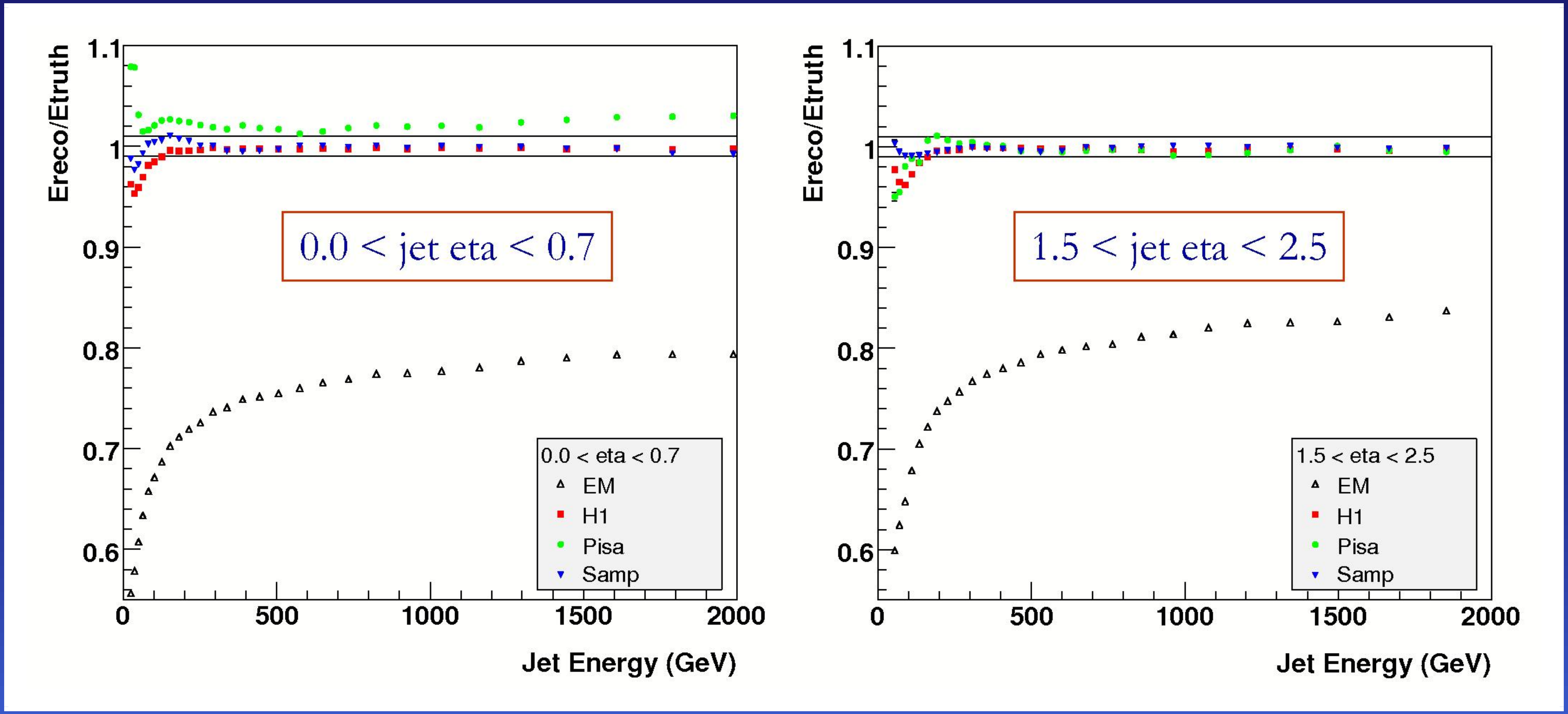
- Three different weighting schemes are currently in use

1. Jet Sampling Calibration — F. Merrit, J. Proudfout, A. Gupta, et al.
    - apply weight to all cells in same sampling
    - layer weights: $w_i = f(E_{\text{jet}}, \eta)$
    - $\sim$ 8 parameters per energy and eta region
2. Jet H1 Cell Weights (BNL) — F. Paige et al.
    - two step procedure
    - 1^{st} cell weights: $w_i = f(E_{\text{cell}}/V_{\text{cell}})$
    - 2^{nd} jet weight $w_j = f(E_{\text{jet}}, \eta)$
3. Jet H1 Cell Weights (Pisa) — C. Roda, I. Vivarelli, A. Dotti, et al.
    - cell weights: $w_i = f(E_{\text{cell}}/V_{\text{cell}}, E_{\text{jet}})$
    - similar to BNL method, but with extra info of E_{jet} in cell weights

- all three methods use matched truth jet with same jet-algorithm to determine the true energy

Jet-Level Calibrations ► Linearity

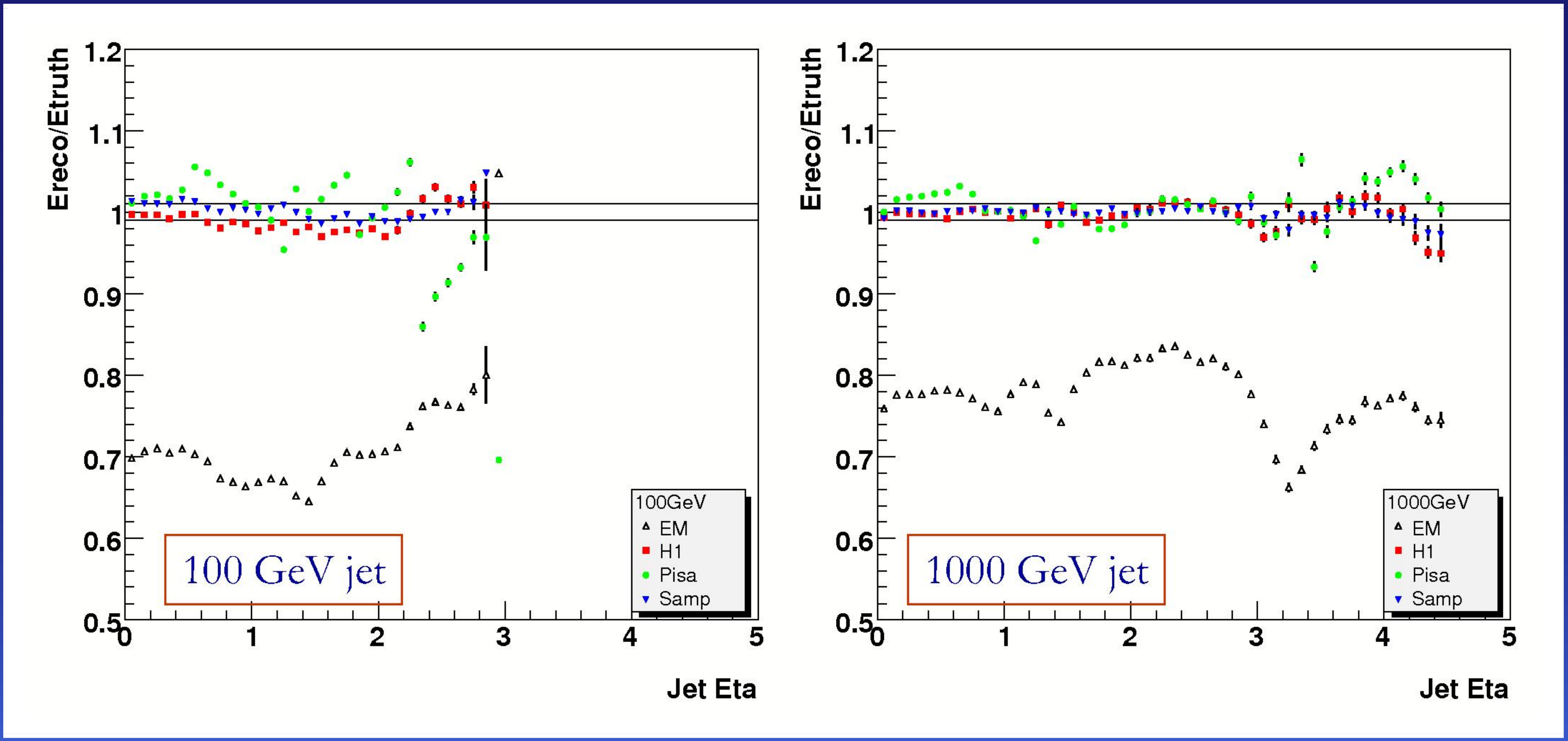
- Compare the three schemes with common setup
- Use isolated jets from Pythia/Geant4 simulated di-jet events from $2\,\mathrm{GeV} < E_{\mathrm{jet}} < 2\,\mathrm{TeV}$
- above $100\,\mathrm{GeV}$ Sampling and BNL method reach linearity on 1%-level
- some deviations beyond 1% for Pisa



A. Gupta et al.

Jet-Level Calibrations ► Linearity in η

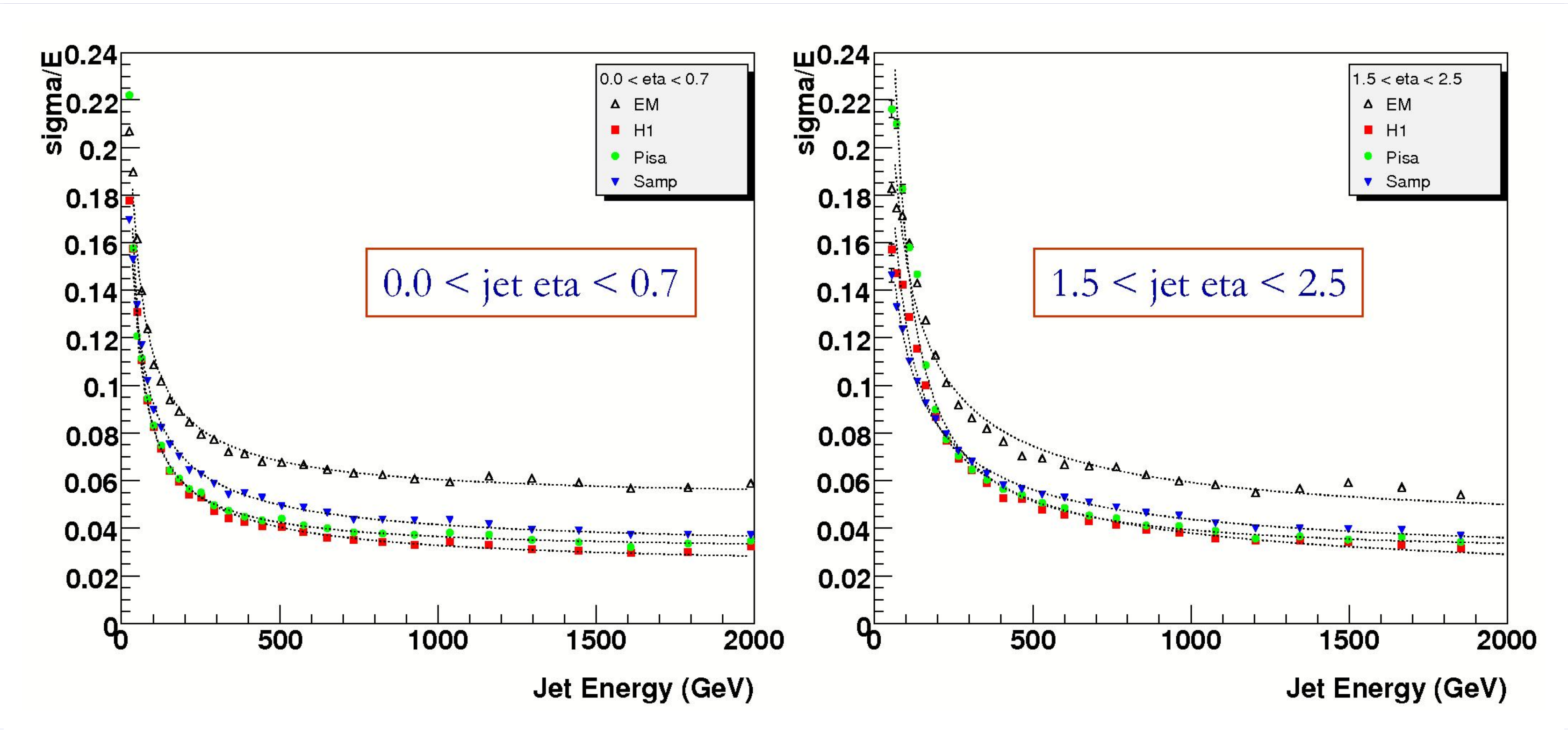
- Linearity more complicated in η due to changes in calorimeter systems, dead material, and cracks
- above 100 GeV Sampling and BNL method reach linearity on 2%-level
- again larger deviations for Pisa at low energies
  - no jet-level fudge factor applied plus some SW problems



A. Gupta et al.

Jet-Level Calibrations ► Resolution

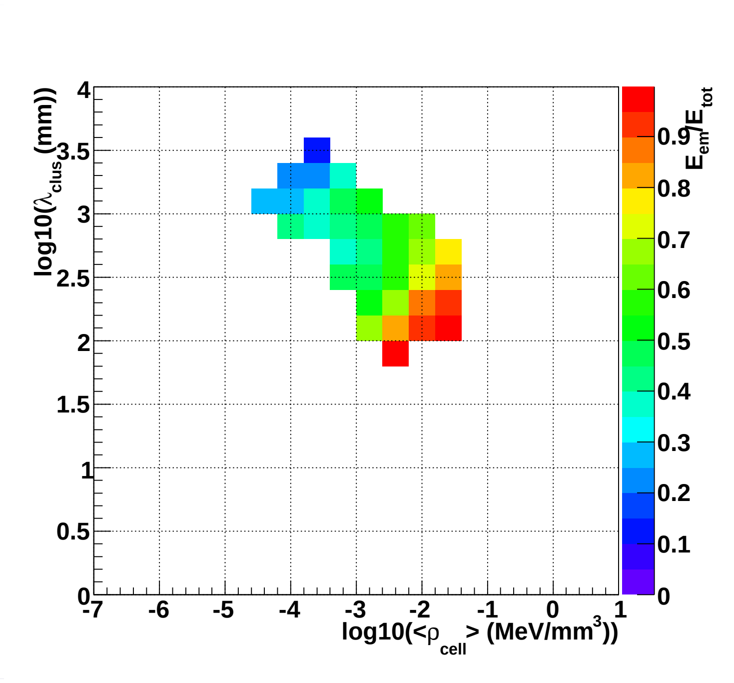
- sampling calibration slightly better at lowest energies
- cell energy density calibrations better at medium and high energies
- differences shrink at highest energies
- BNL method gives $\frac{\sigma_E}{E} = \frac{0.74}{\sqrt{E(\text{GeV})}} \oplus 0.02 \oplus \frac{2.9}{E(\text{GeV})}$ in central barrel region



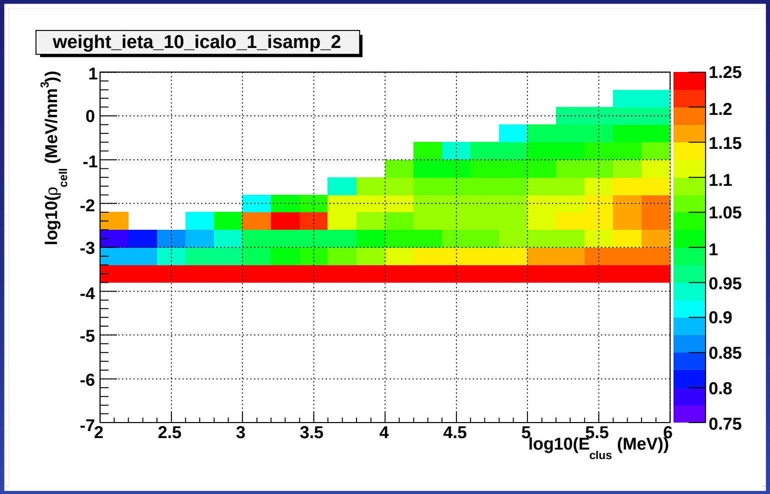
A. Gupta et al.

Calo Calibration ► Local Hadron Calibration

S. M., G. Pospelov et al.



- ► Classify and calibrate topo clusters to hadron-level
- ► Classification
  - use shower shape variables (cluster moments) like shower depth and (weighted) energy density of the cell constituents
  - em showers are less deep and have higher average energy density than had showers
  - make a cut on expected em fraction for given bin derived from single pion simulations (right plot)

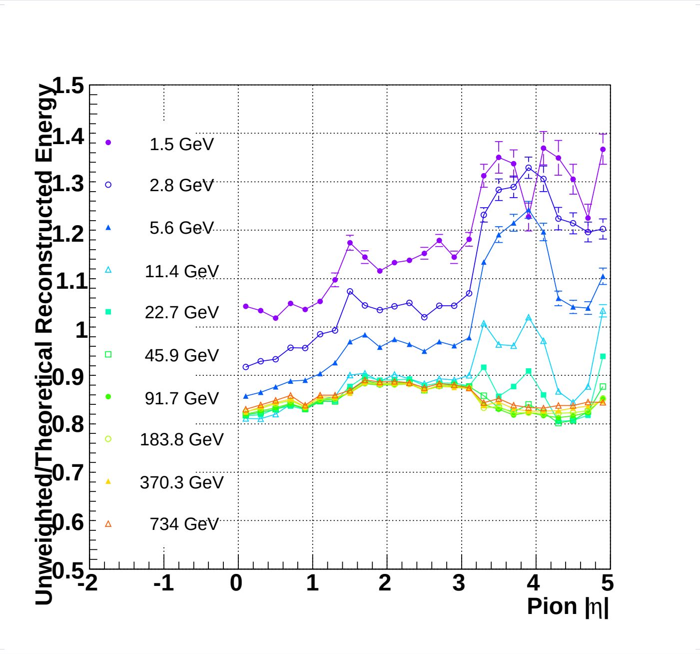


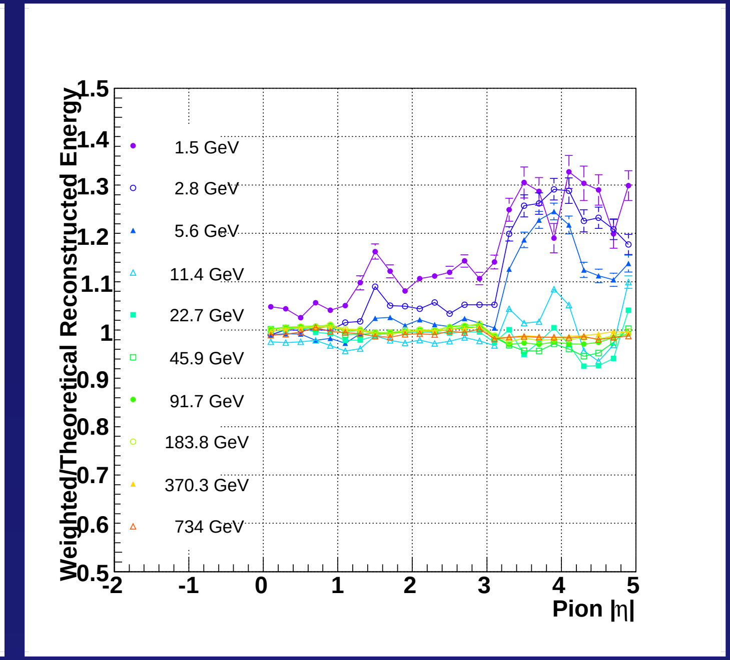
- ► Calibration
  - treat only clusters classified as hadronic

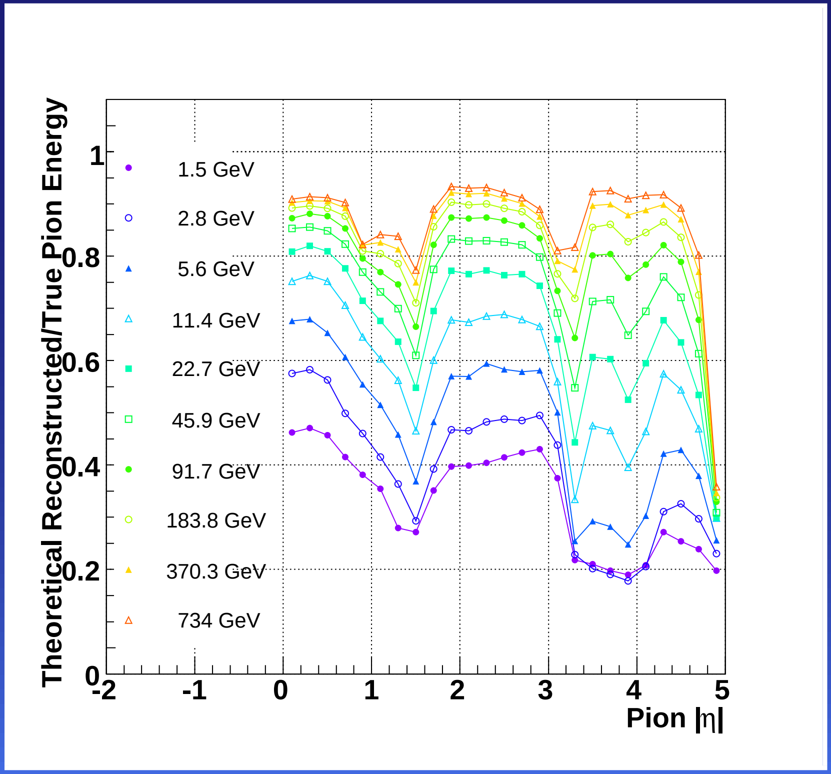
    ► dead material corrections for em clusters are beeing worked on
  - derive cell weights from Geant4 true energy (calibration hits) including invisible energy and absorber deposits and reconstructed cell energy for each η region and layer: $w_i = \langle E_{\text{true}} / E_{\text{reco}} \rangle,\ i = \text{bin\#}(E_{\text{cluster}}, E_{\text{cell}} / V_{\text{cell}})$
  - example weights in main sampling of EM calorimeter for $2.0 < |\eta| < 2.2$
- ► Correct for dead material and out-of-cluster deposits

Local Hadron Calibration ► Energy Corrections

- Cell weights
  - account for the non-compensation of the calorimeters
  - left (right) plot shows ratio of reco cluster on em-scale (calibrated scale) over true calibration hit contents

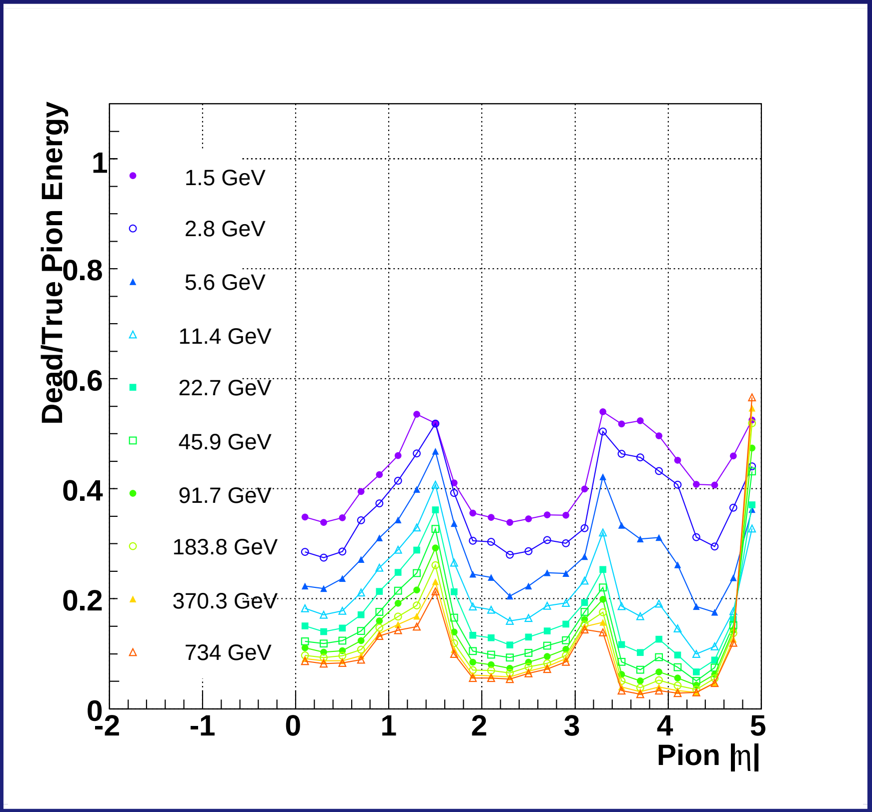


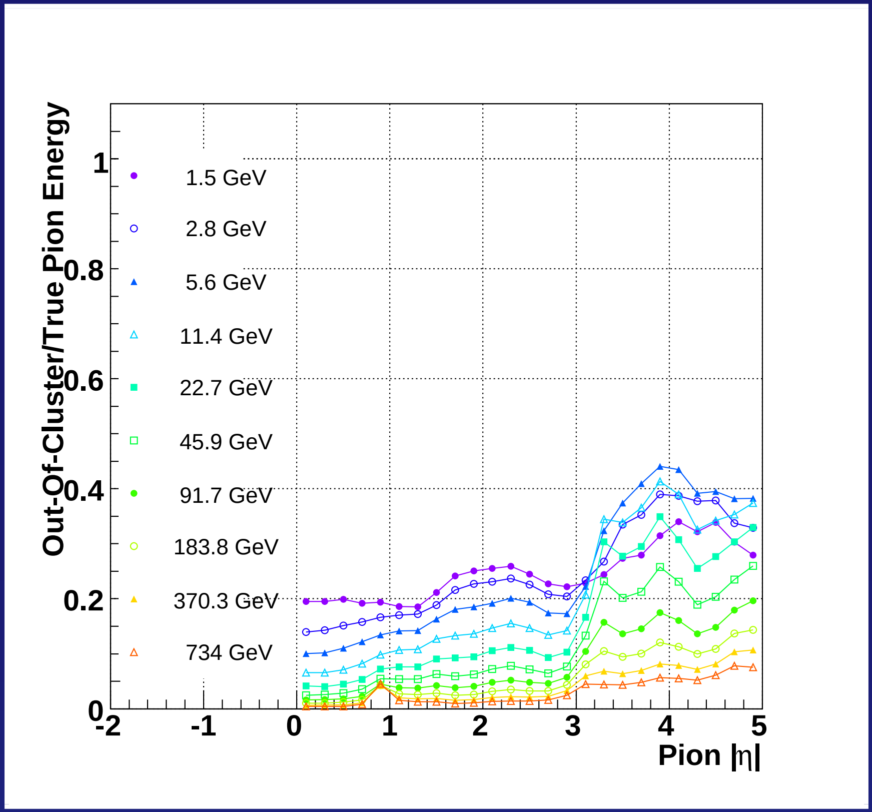




- After cell weighting
  - the cluster is not yet fully calibrated
  - plot shows ratio of calibration hit truth over pion energy
  - still need corrections for:
    - ► energy deposits outside the calorimeters (dead material)
    - ► and inside the calorimeters but not in reconstructed clusters (out-of-cluster)

Local Hadron Calibration ► Dead Material & Out-Of-Cluster Corrections

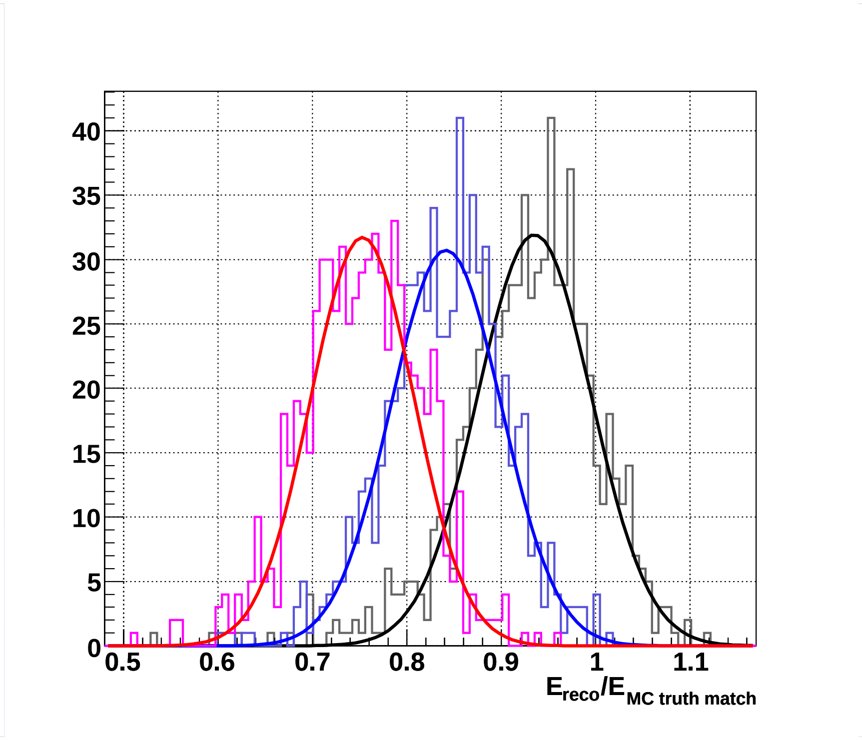




- Dead material corrections
  - account for deposits in material in front and between calorimeter systems overlapping in $\eta \times \phi$ with cells from the cluster (left plot)
- Out-Of-Cluster corrections (not yet done)
  - account for all the rest (right)
  - mainly deposits in calorimeter cells left out by the cluster algorithm

Local Hadron Calibration ► Performance

- Use two leading jets ($K_\perp$ with $R = 0.6$) in di-jet MC samples in the region $0.2 < |\eta| < 0.4$
- Energy of the leading jets in this sample and region is about 150 ± 40 GeV
- plot shows the ratio of total energy of the reconstructed jet over the energy of a matched truth jet (also $K_\perp$ with $R = 0.6$) with $\Delta R < 0.05$ for EM-scale (red); weighted (blue); weighted with DM corrections (black)

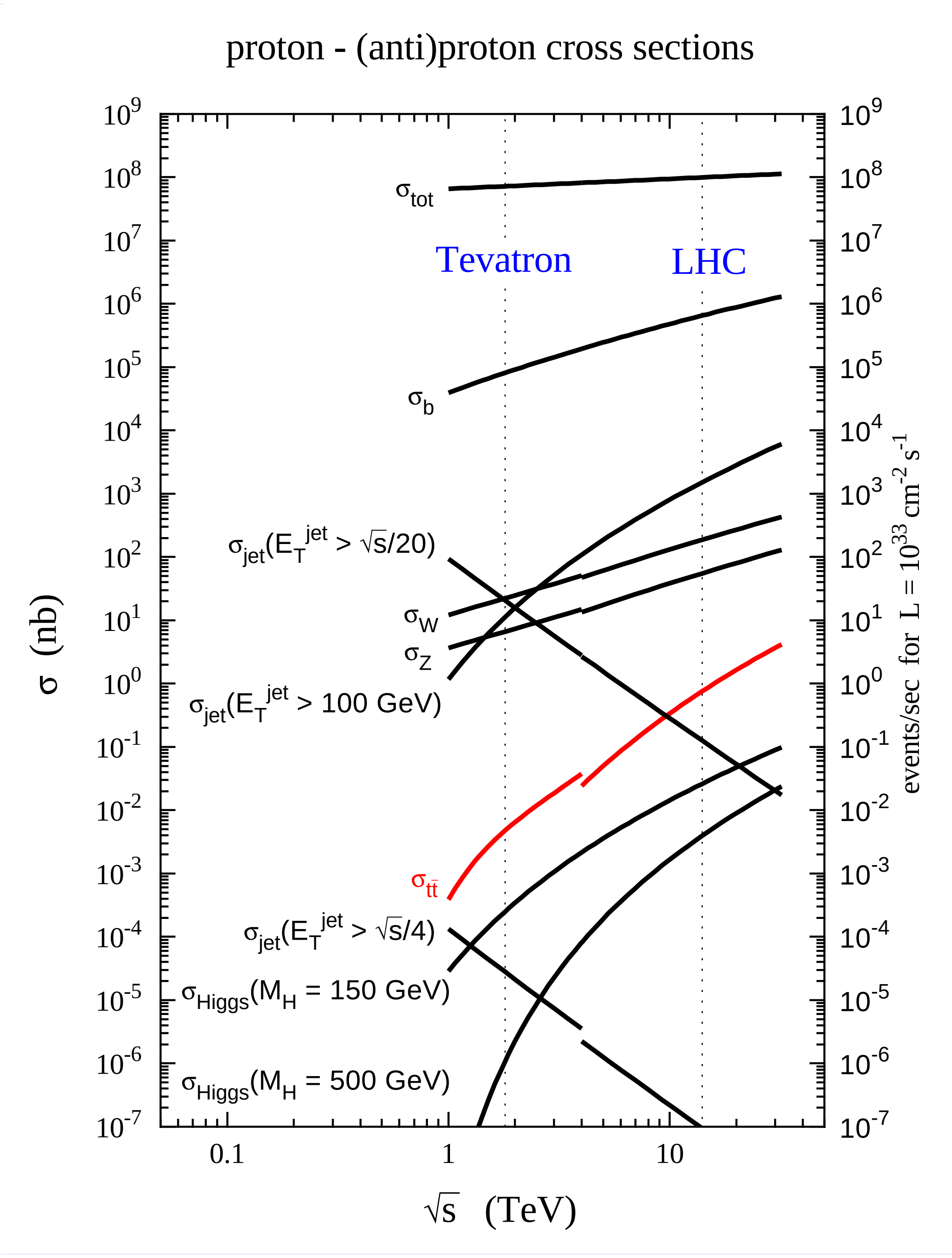


	EM-scale	Weighted	Weighted+DM
mean (%)	75.3	84.1	93.5
σ (%)	5.5	5.8	6.0
$\sigma\,/$mean (%)	7.3	6.9	6.5

- mean and relative resolution improve in every step
- final deviation from truth jet energy is only 6.5 % consistent with expected out-of-jet corrections

In Situ Calibration ► W $\longrightarrow jj$ from $t\bar{t}$

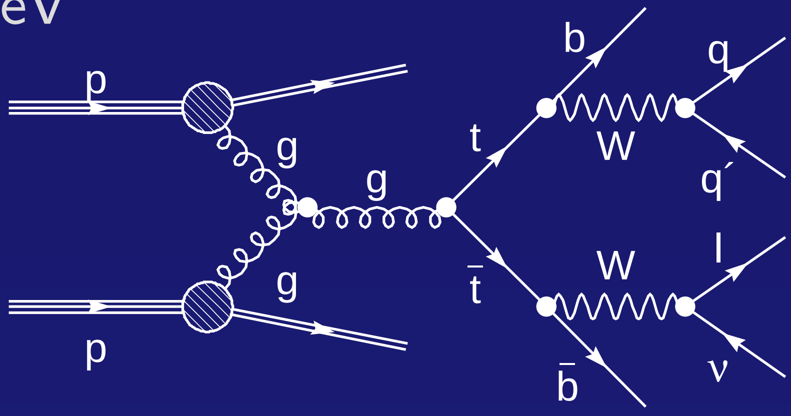
- total cross section for $t\bar{t}$-production is about a factor of 100 larger at LHC as compared to Tevatron
- $\sigma_{t\bar{t}}(14.0\,\mathrm{TeV}) = 800\,\mathrm{pb}$
- LHC will be a top factory with more than $8 \cdot 10^6$ $t\bar{t}$-pairs at low luminosity ($L = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-2}$)
- in the lepton+jets channel the trigger conditions should be ideal
- $m_{jj} = m_\mathrm{W}$ provides a direct constraint on the parton level
- applicable to light jets only up to $\sim 200\,\mathrm{GeV}$
- jets from W are very close
  ► can use only small jet cones ($R \sim 0.5$)

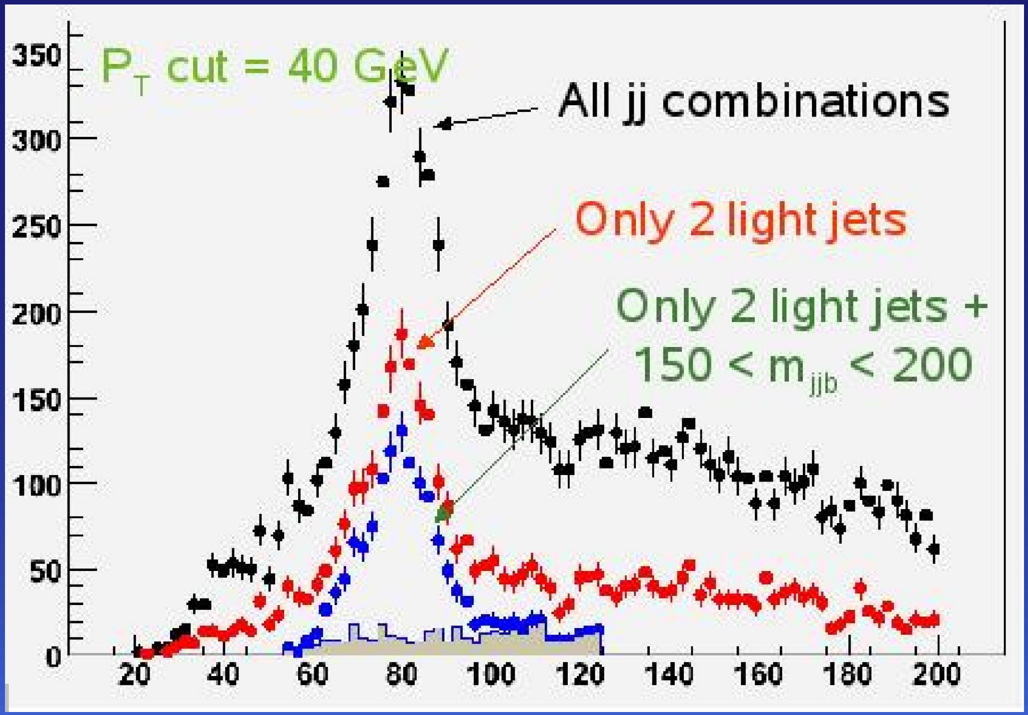


W.J. Stirling, 1998

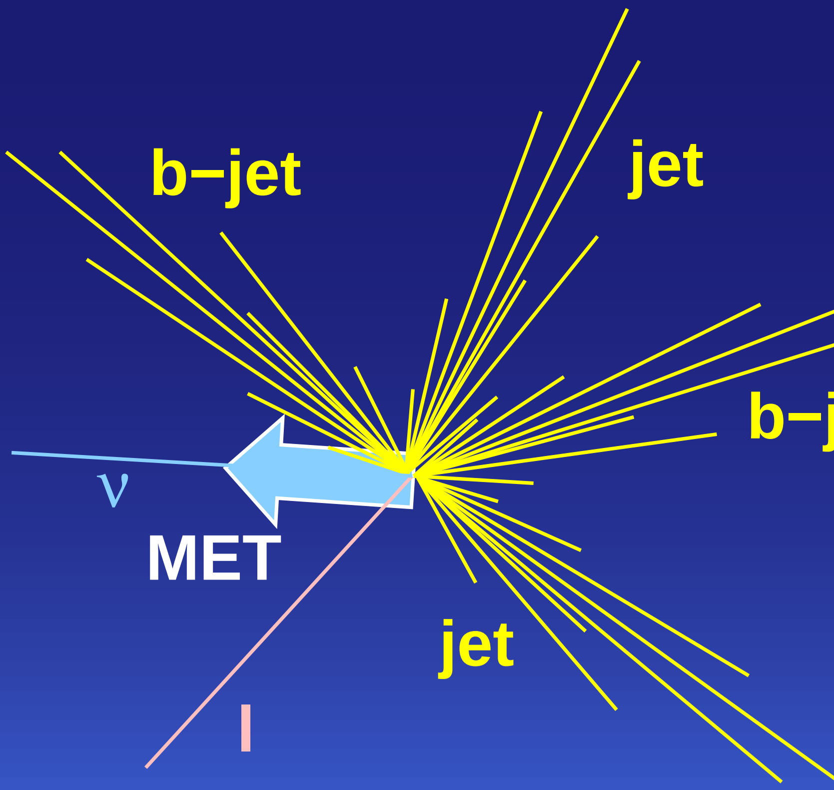
W $\rightarrow jj$ from $t\bar{t}$ ► Event Selection

- usual $t\bar{t} \rightarrow l\nu j_b\, jjj_b$ selection
  - 1 isolated lepton (e or μ) with $p_\perp > 20\,\text{GeV}$
  - $\not{E}_\perp > 20\,\text{GeV}$
  - at least 4 jets with $p_\perp > 40\,\text{GeV}$
  - 2 light jets
  - 1 or 2 jets with b-tag
- additional cut to improve the W $\rightarrow jj$ purity
  - $150\,\text{GeV} < m_{jjj_b} < 200\,\text{GeV}$

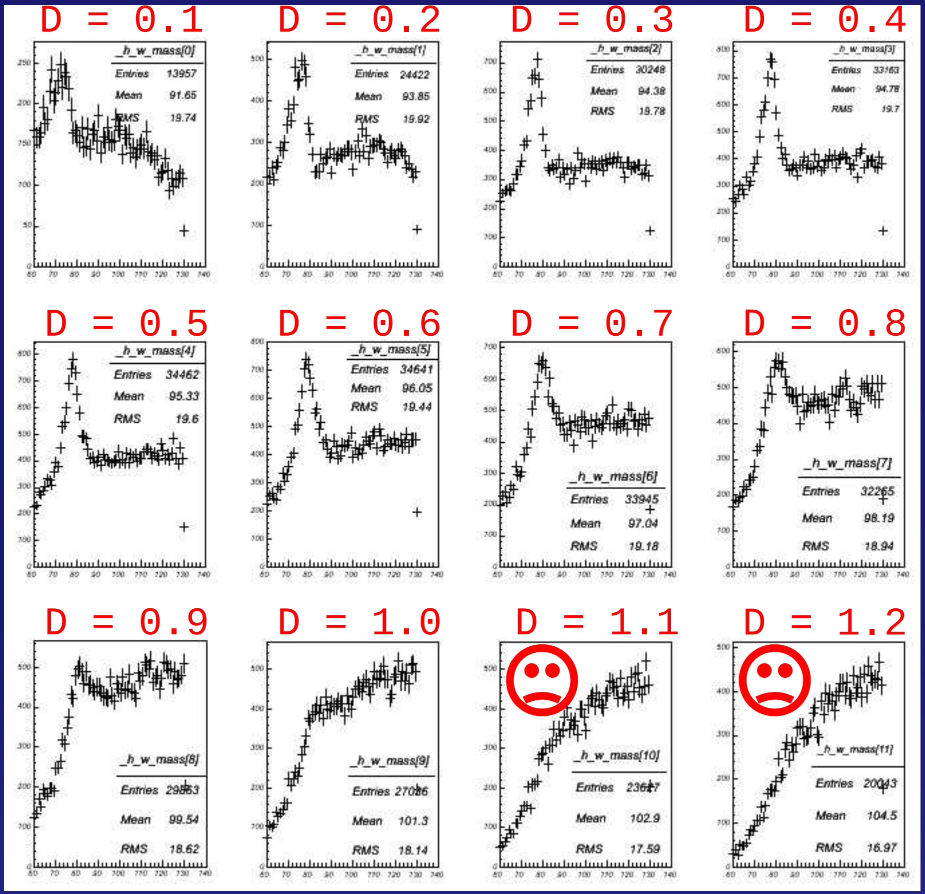




J. Schwindling

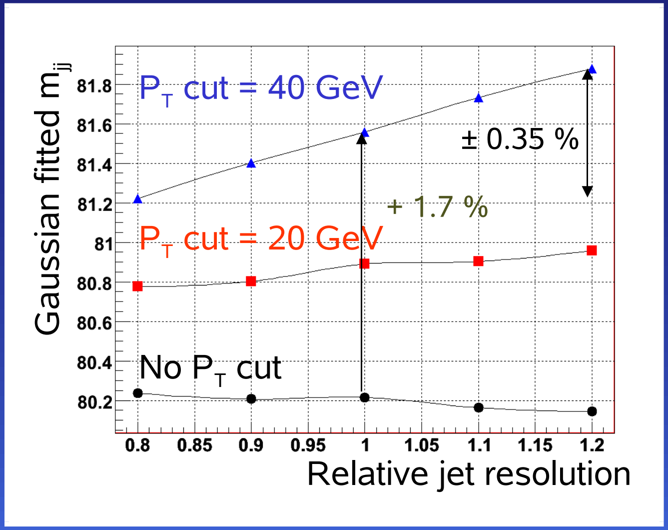


W $\rightarrow jj$ from $t\bar{t}$ ► Jet Systematics



N. Ghodbane

- jet size, resolution, and selection cuts on $p_\perp$ bias the W-mass peak
- jet size for $K_\perp$ jets
  - below $R = 0.3$ jets too small to contain hadronic shower
    - mass-resolution worsens
  - beyond $R = 0.7$ chance for merged jets from W-decay increases
    - method does not work anymore
  - optimal region $R = 0.4 - 0.6$



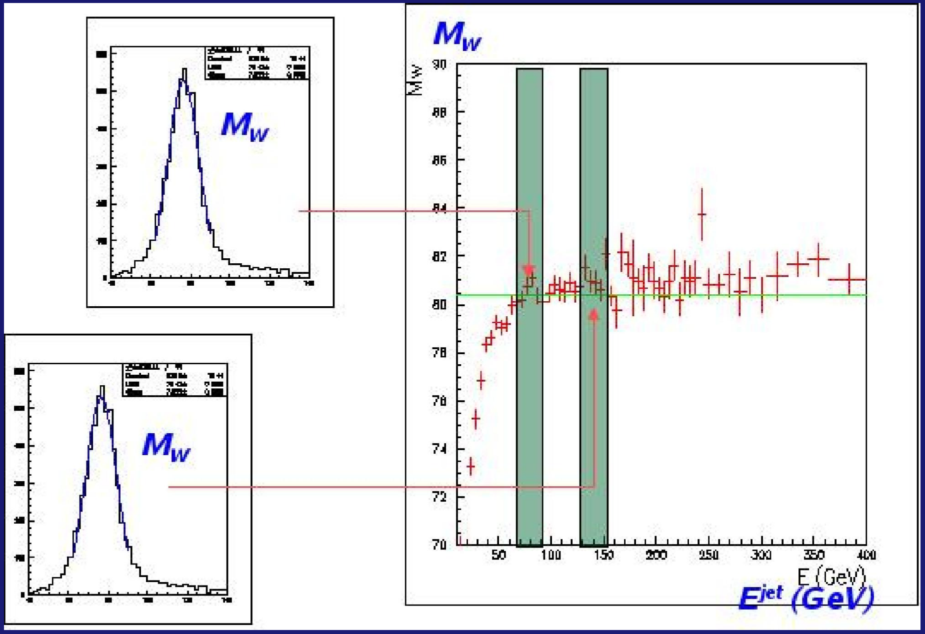
J. Schwindling

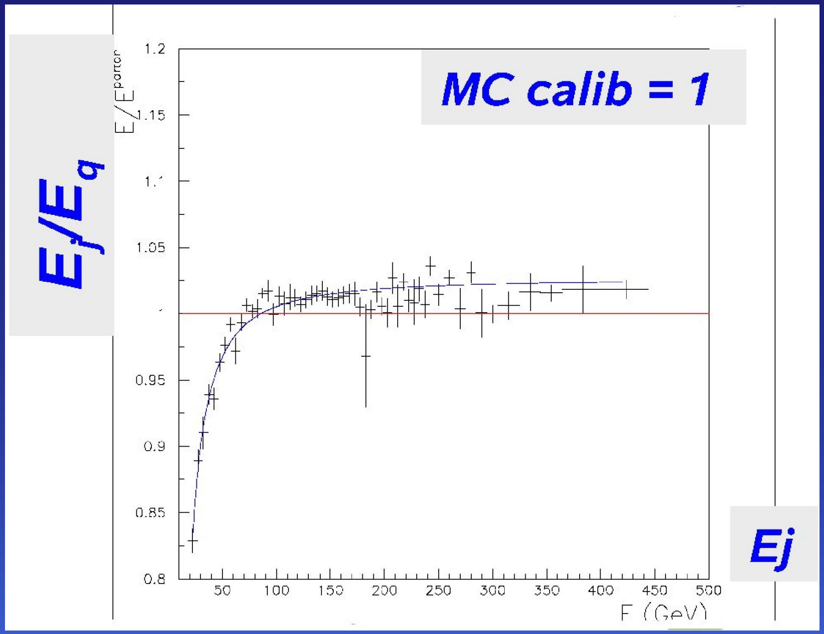
- jet resolution and $p_\perp$-cut
  - for a given relative jet resolution the fitted W-mass depends on the $p_\perp$ cut
  - for a given $p_\perp$-cut the fitted mass depends on the jet resolution
    - need to account for this bias in the calibration procedure

$\mathrm{W} \longrightarrow jj$ from $\mathrm{t\bar{t}}$ ► Rescaling Method

D. Pallin et al.

- assume $\frac{E^{\text{parton}}}{E^{\text{jet}}} = \alpha(E^{\text{jet}})$
  - ignore any dependency on ϕ, η and E_{W}
- extract m_{W} from Gaussian fits to di-jet mass-distribution in bins of E^{jet}
  - every jet-jet pair appears twice in the histograms (right plot(s))
- use mass constraint $m_{\mathrm{W}} = m_{\mathrm{W}}^{\mathrm{PDG}}$ for mean values of fitted Gaussians
  - $m_i = \sqrt{\alpha_{j_1}\alpha_{j_2}}\, m_{j_1 j_2}$, with E_{j_1} in energy bin i



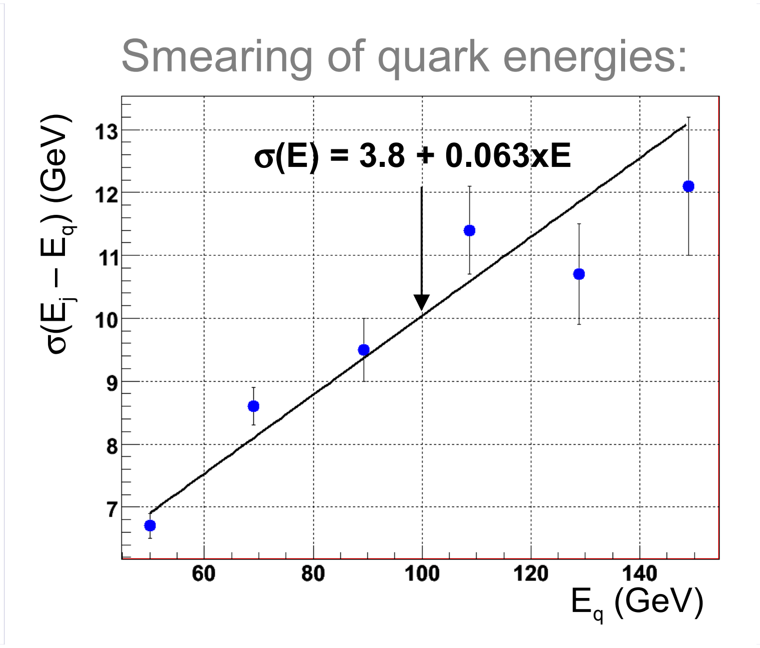


- extract α_i by either
- χ^2-fit
  - minimizing $\chi^2 = \sum \frac{\left(\sqrt{\alpha_{j_1}\alpha_{j_2}}\, m_{j_1 j_2} - m_{\mathrm{W}}^{\mathrm{PDG}}\right)^2}{\sigma^2}$
- iterative procedure (left plot)
  - $\alpha_i^k = \alpha_i^{k-1} \frac{m_{\mathrm{W}}^{\mathrm{PDG}}}{m_i^{k-1}}$
- template method
  - smeared MC parton distributions with energy scale α and relative resolution β

W $\longrightarrow jj$ from $t\bar{t}$ ► Template Method

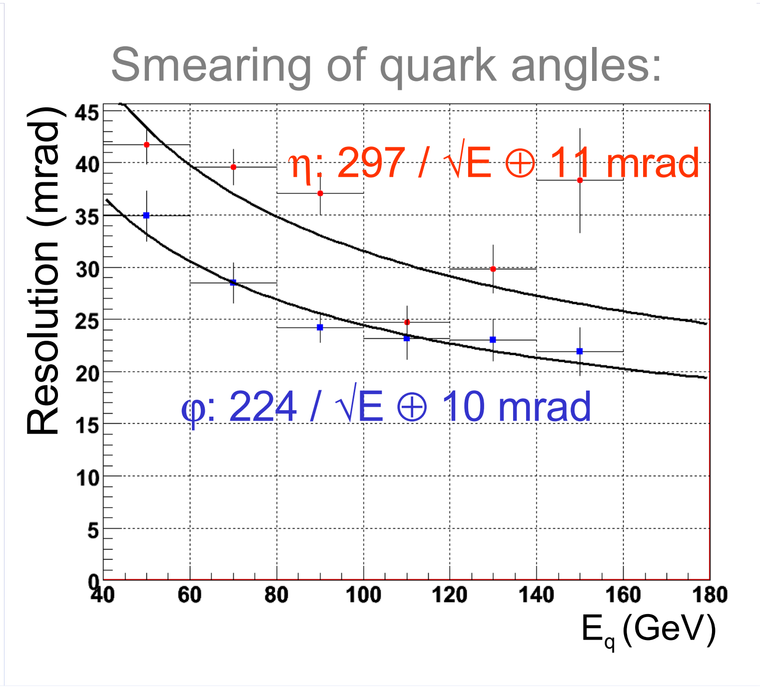
N. Besson, J. Schwindling et al.

- method from CDF recently ported to ATLAS
- generate smeared W $\longrightarrow qq$ (template) distributions from $t\bar{t}$ events
- α smears the energy scale
- β the relative resolution
- Smearing: $E_{\text{jet}} = \alpha \times \text{gauss}(E_q, \beta \times (3.8\,\text{GeV} + 0.063 E_q))$
- smear angular resolution too:
  - $\sigma_\eta = (297/\sqrt{E_q(\text{GeV})} \oplus 11)\,\text{mrad}$
  - $\sigma_\phi = (224/\sqrt{E_q(\text{GeV})} \oplus 10)\,\text{mrad}$
- and smear energy correlated between jets ($\rho \sim 0.4$ due to overlapping jets, UE, …?)



Smearing of quark energies:

σ(E) = 3.8 + 0.063xE



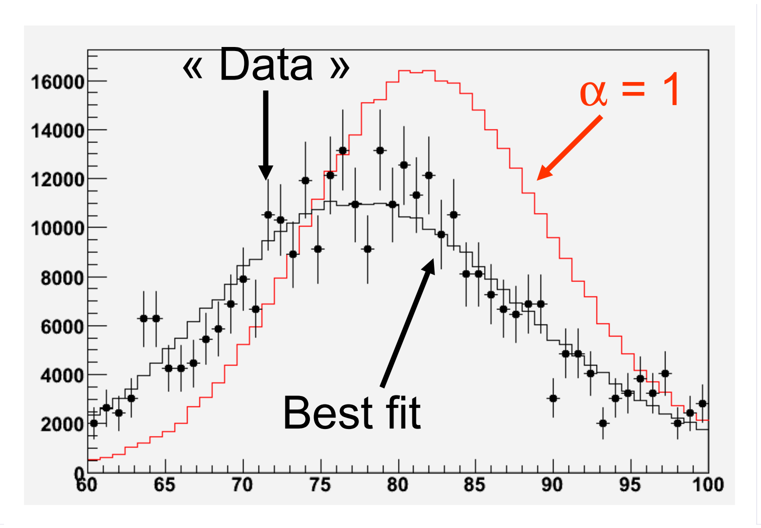
Smearing of quark angles:

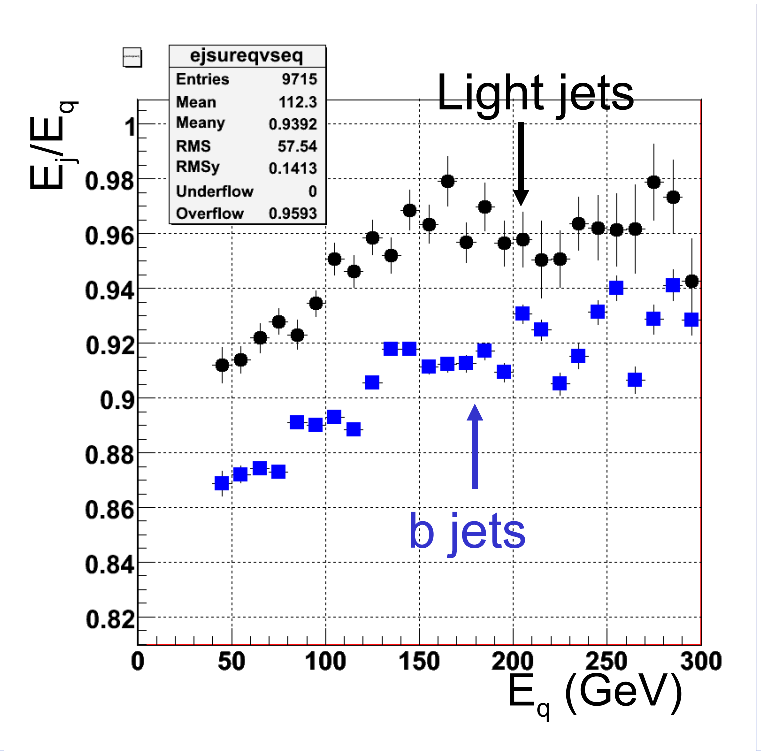
η: 297 / √E ⊕ 11 mrad

φ: 224 / √E ⊕ 10 mrad

W $\longrightarrow jj$ from $t\bar{t}$ ► Template Method

- fit “data” to templates (top plot)
- take α and β from best χ^2
- $\alpha \simeq 0.94$ comes out as expected (bottom plot)
- but typically $\beta > 1$
  - need to study impact of UE, $n(n-1)/2$ sets of templates for n bins of jet energy, . . .
- also b-jet scale typically 0.95 of light jet scale
  - need to study $Z \longrightarrow b\bar{b}$





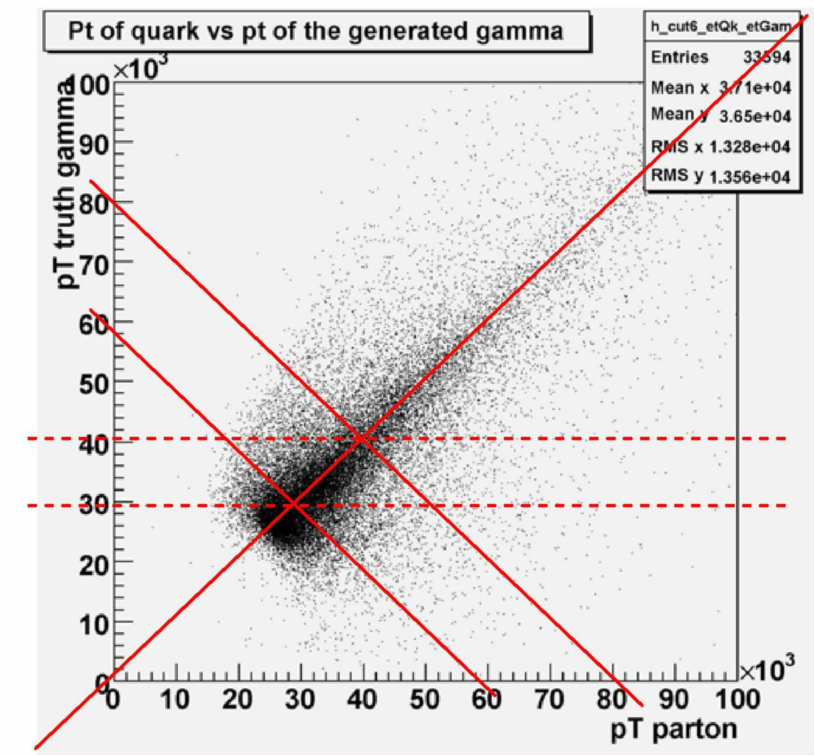
In Situ Calibration ► $p_\perp$-balance in $Z/\gamma + j$

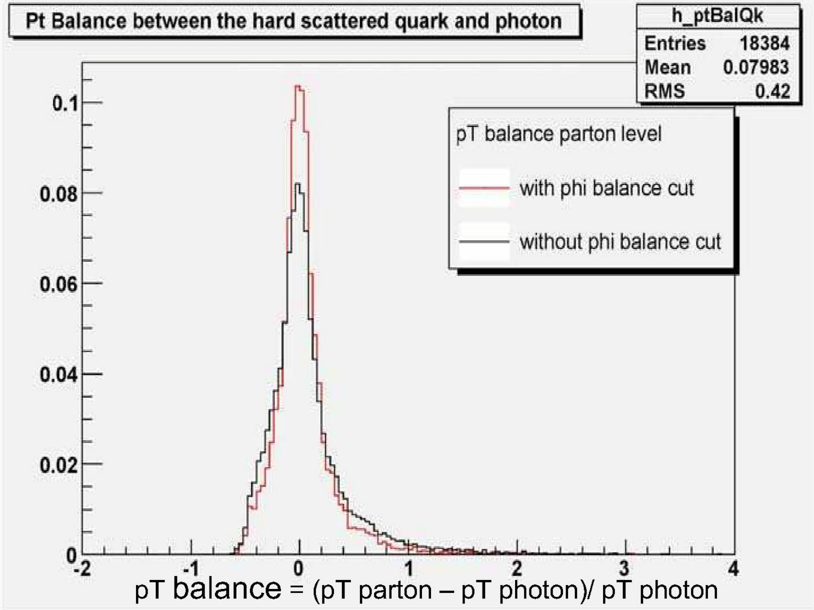
- large statistics expected at $L = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-2}$
  - for $20\,\mathrm{GeV} < p_\perp < 60\,\mathrm{GeV}$
    - $\sim 2\,\mathrm{Hz}$ for $Z^0(\to ll) + j$
    - $\sim 0.1\,\mathrm{Hz}$ for $\gamma + j$
  - for $60\,\mathrm{GeV} < p_\perp$
    - $\sim 0.1\,\mathrm{Hz}$ for $Z^0(\to ll) + j$
    - $\sim 2\,\mathrm{Hz}$ for $\gamma + j$
- γ and $Z^0 \to ll$ are well calibrated EM objects
- two complementary methods are studied
  1. $p_\perp$ balance
     - recoil against leading jet $\Delta\phi > 175°$
     - sensitive to out-of-jet effects
  2. missing $E_\perp$ projection
     - vector sum of entire calorimeter response
     - recoil of complete hadronic system against Z/γ
     - no jet-algorithm dependence

$p_\perp$-balance in $\gamma + j$ ► Event Selection

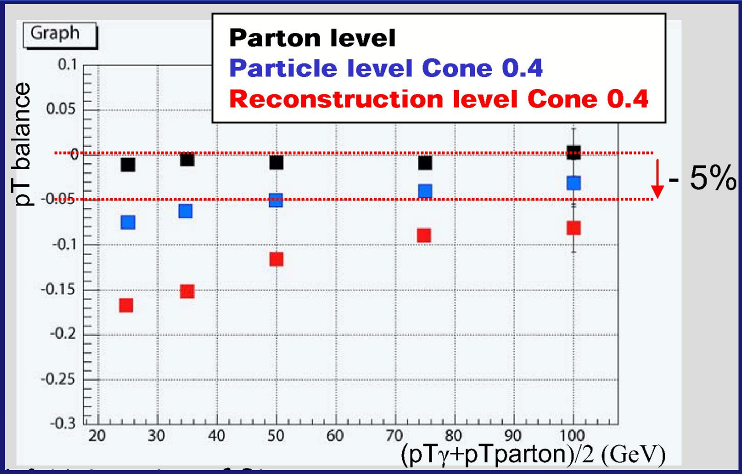
$\gamma +$ jet analysis: S. Jorgensen et al.

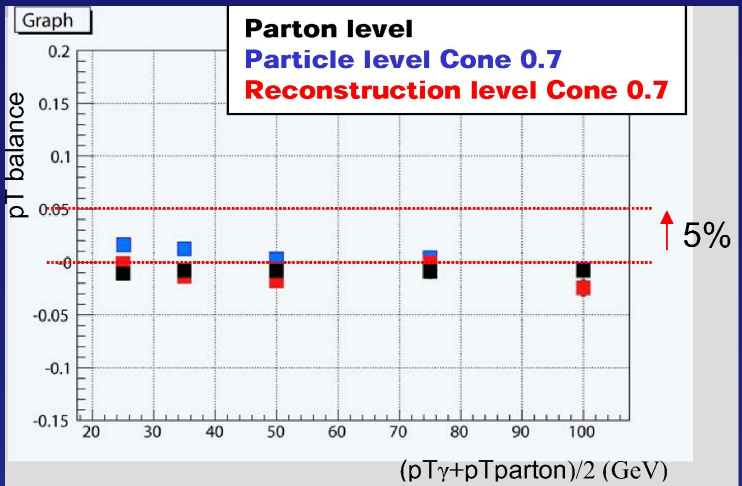
- select isolated γ
- select highest $p_\perp$ jet
- apply ϕ back-to-back cut
  $\Delta\phi > 175°$
- use average $p_\perp$ of γ and jet for analysis
- $p_\perp$-balance $= \frac{p_\perp^{\text{jet}} - p_\perp^\gamma}{p_\perp^\gamma}$
- iterate Gaussian fits within $\pm 1\sigma$ around mean to reduce sensitivity to tails

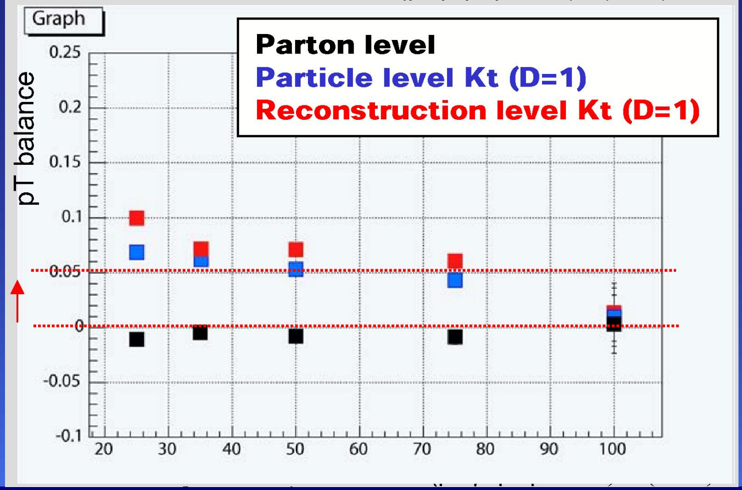




$p_\perp$-balance in $\gamma + j$ ► Tower jets



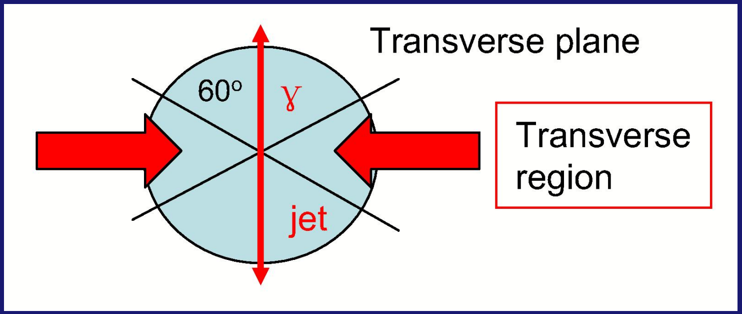


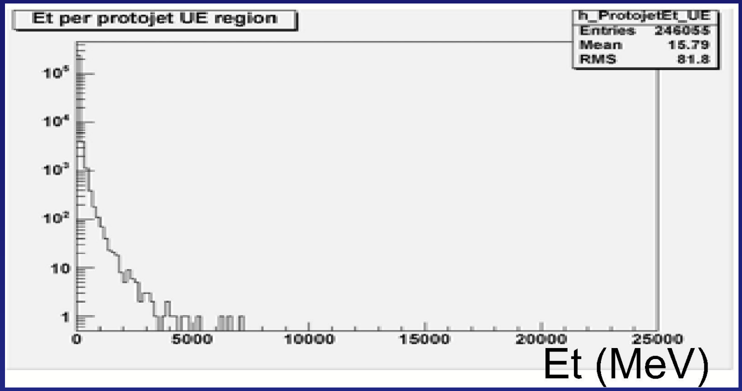


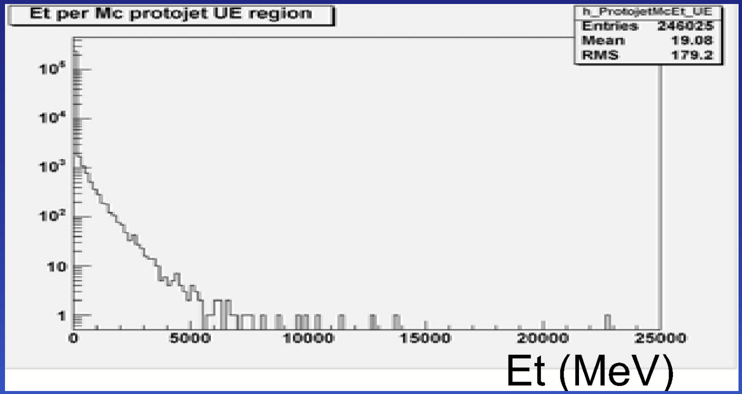
- compare cone with $R = 0.4$ (top) and $R = 0.7$ (middle) with $K_\perp$ with $R = 1$ (bottom)
- on parton- (black), hadron- (blue), and jet-level (red)
- the jet- and hadron-level differences are mainly due to the jet-style H1 cell calibration which was obtained from cone jets with $R = 0.7$
- particle level shows cone jet with $R = 0.4$ too small
- $K_\perp$ with $R = 1$ too large by similar amount on particle level (underlying event and noise)

$p_\perp$-balance in $\gamma + j$ ► Underlying Event

- check jet constituents normalized to tower size ($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$) in transverse ϕ-direction of $\gamma -$ jet-axis
- outside $\Delta\phi = 60^\circ$ from $\gamma -$ jet-axis
- direct test of underlying event in the signal sample



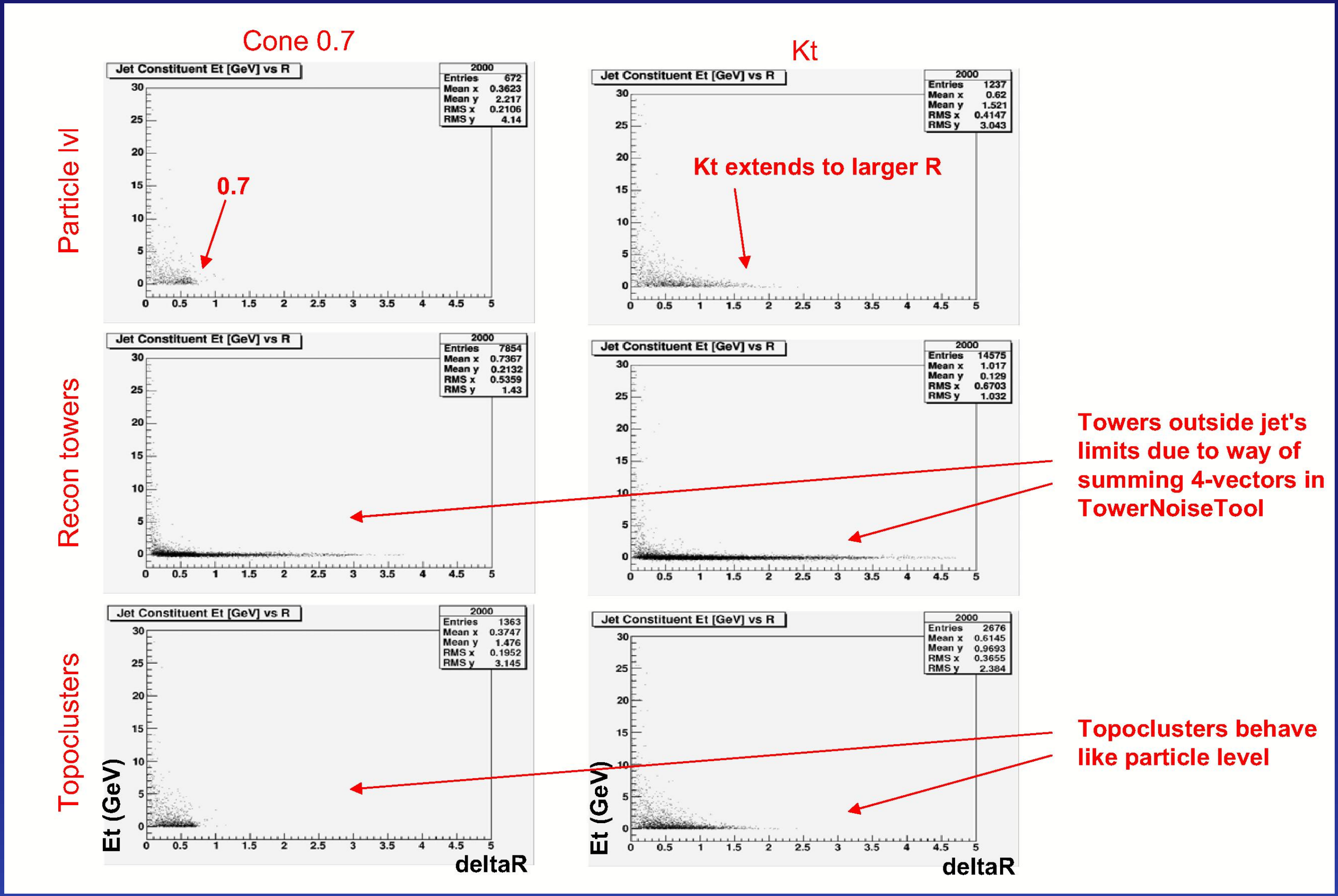




- tower protojets (upper plot) contain $15.8\,\mathrm{MeV}$ on average (EM-scale) in transverse direction per tower area
- particle protojets (lower plot) contain $19.1\,\mathrm{MeV}$ on average in transverse direction per tower area
- leads to moderate estimates for average underlying event transverse energy in signal jets of ($3\,\mathrm{GeV}$ for $R = 0.7$ cone jets)
- but spread is much larger (factor $5 - 10$)

$p_\perp$-balance in $\gamma + j$ ► Radial Jet Profiles

- look at jet constituents $E_\perp$ versus distance from jet axis ΔR (one entry per constituent)
  - pretty sharp cut at cone radius for particle-jets and topo-cluster-jets
    - entries beyond the cone radius are due to split & merge procedure
  - for tower-jets lots of entries beyond nominal radius
    - due to recombination of negative towers with close by positive towers



0.7

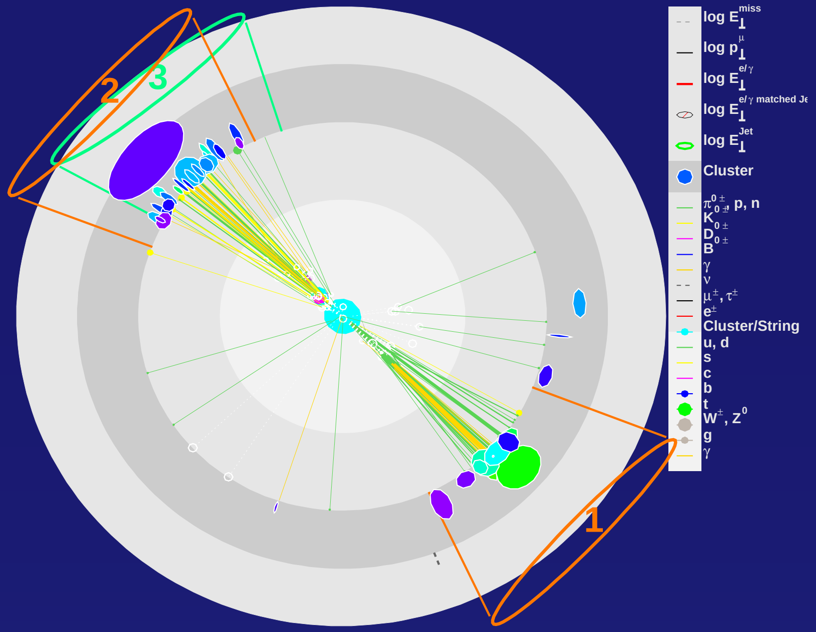
Kt extends to larger R

Towers outside jet's limits due to way of summing 4-vectors in TowerNoiseTool

Topoclusters behave like particle level

- topo-cluster-jets behave like particle-jets

Conclusions



- Jet Energy Calibration is a complex task
- Choice of Constituents
  - towers or clusters?
- Choice of Jet Algorithm and Size
  - cone or $K_\perp$?
  - $R = 0.4, 0.6, 0.7, 1$?
- Choice of Calibration Method/Process
  - jet-level or cluster-level?
  - with or without final jet correction?
  - di-jet, top-pairs, $Z/\gamma +$ jet(s)?
- Impact of Noise, Underlying Event, and Pile-Up
  - treat already on cluster level or subtract later from jets?
- Will keep all options open for the start of LHC since only data can tell which way is best