Hadronic Energy Calibration in ATLAS

ATLAS Seminar — Sven Menke, MPI München — 22. December 2004, MPI München

with many thanks to the Hadronic Calibration Group:

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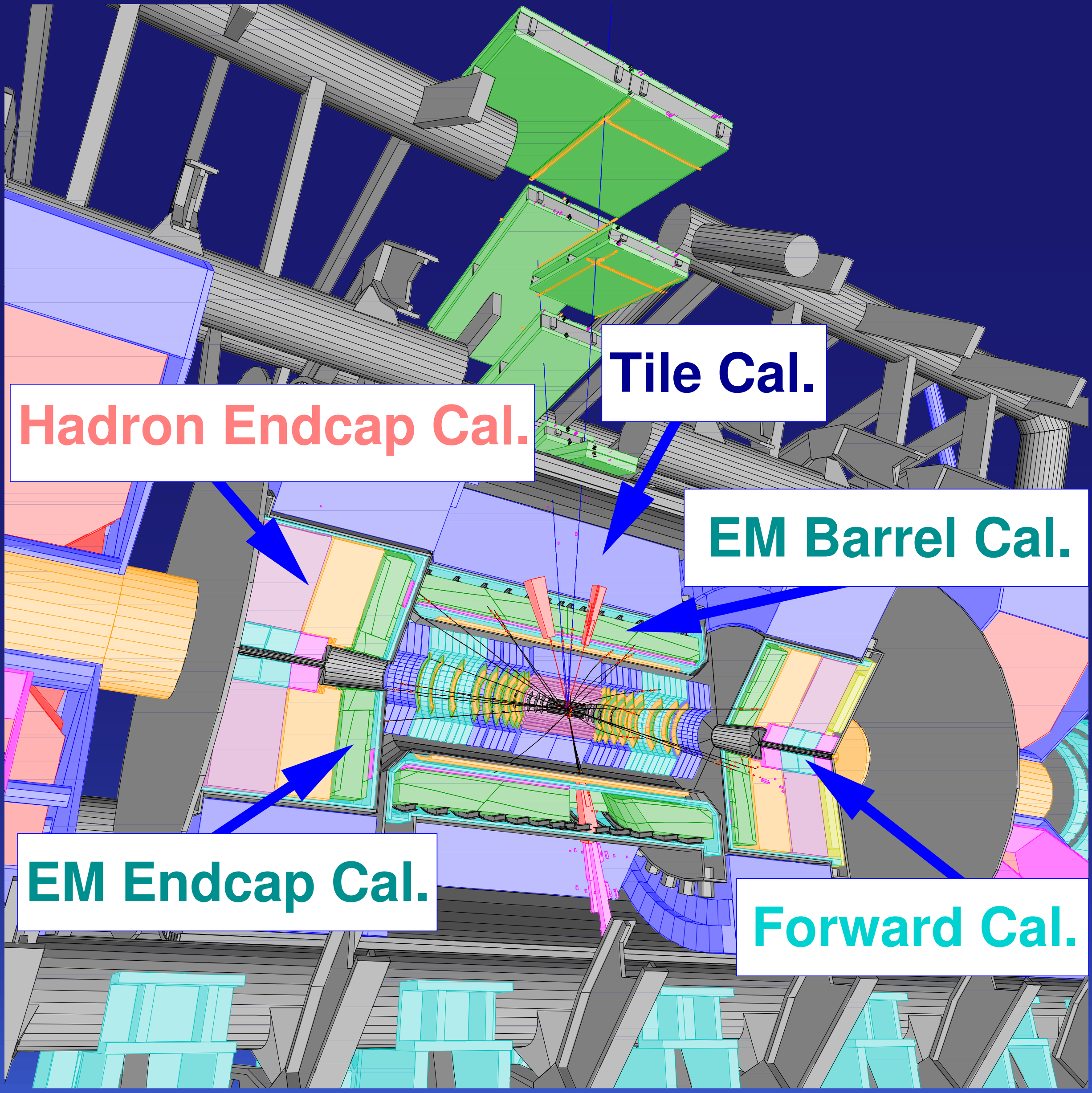
- Hadron Calorimetry in ATLAS
- The H1 Weighting Method
  - Cluster–Level method
  - Cell–Level method
  - Cell–Level method with detailed Simulation
- Jets and Clusters
- Testbeam
  - Signal Reconstruction
  - Electromagnetic Scale
  - Response to Pions
  - Cell–Level method applied to Testbeam data
- Roadmap to ATLAS
- Conclusions

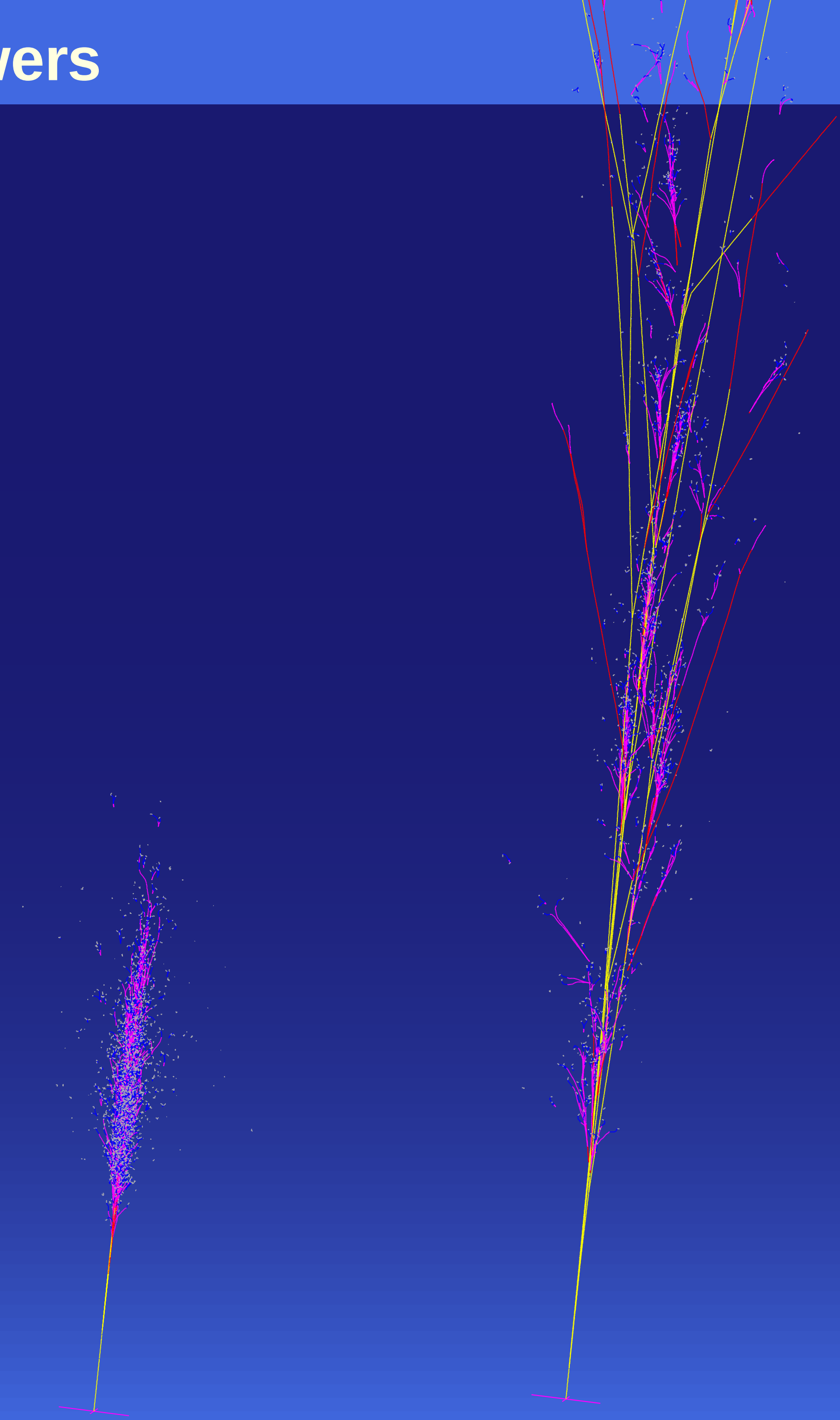
ATLAS Calorimeters

- 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



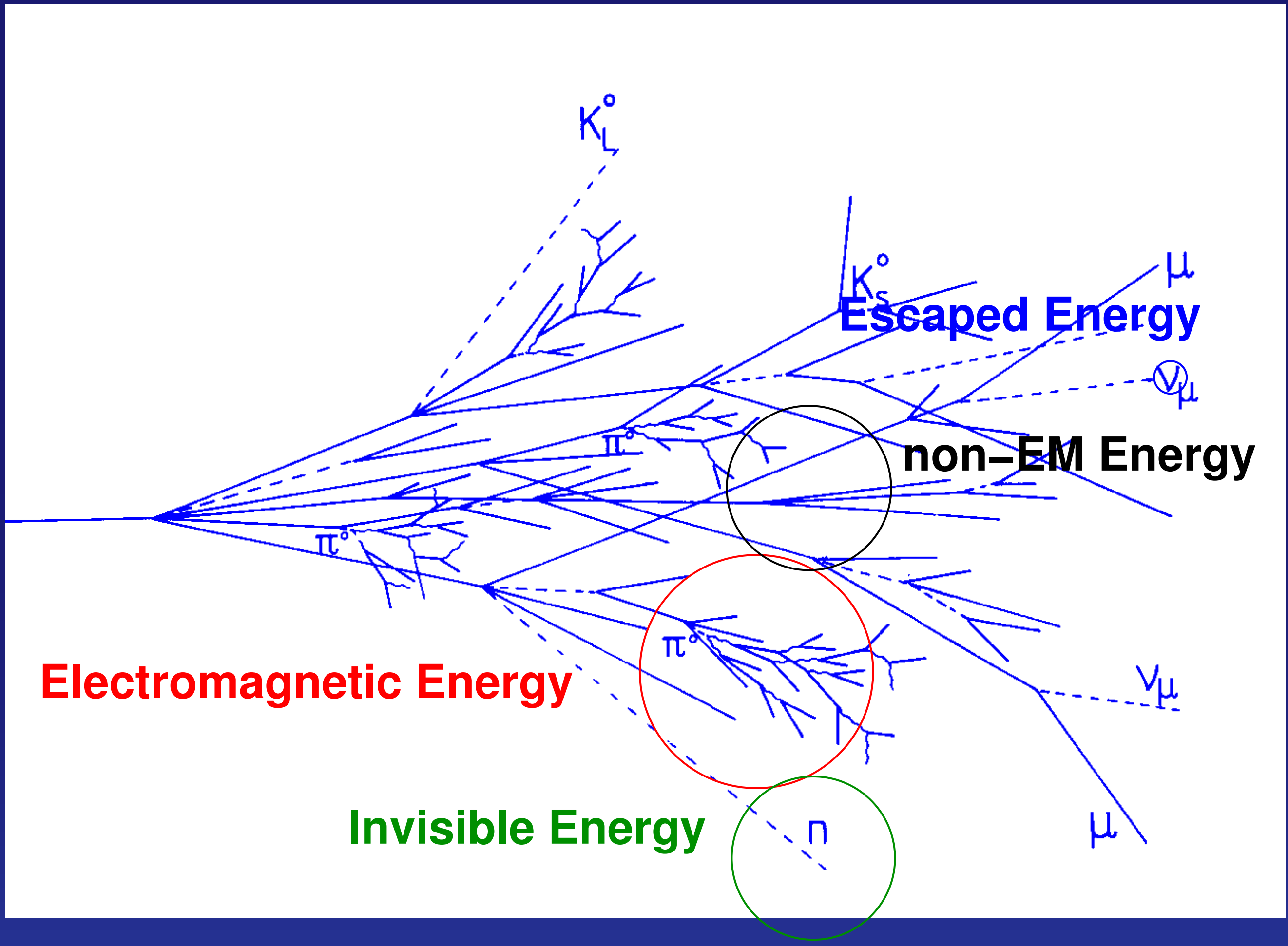
Electromagnetic vs. Hadronic Showers

- An electromagnetic shower
  - consists of visible EM energy only
  - is very compact ($X_0 \simeq 2\,\mathrm{cm}$)
  - can be simulated with high precision since mostly electromagentic processes need to be calculated
  - allows high accuracy calibration (mostly for detector non-uniformities, electronics non-linearities, leakage)
- A hadronic shower
  - consists of EM and hadronic energy (some invisible)
  - is very large ($\lambda_0 \simeq 20\,\mathrm{cm}$)
  - is difficult to simulate since it involves many QCD processes
  - limits the accuracy for calibration (mostly due to large fluctuations)
- The examples show $50\,\mathrm{GeV}$ showers of an electron (left) and a pion (right) in iron



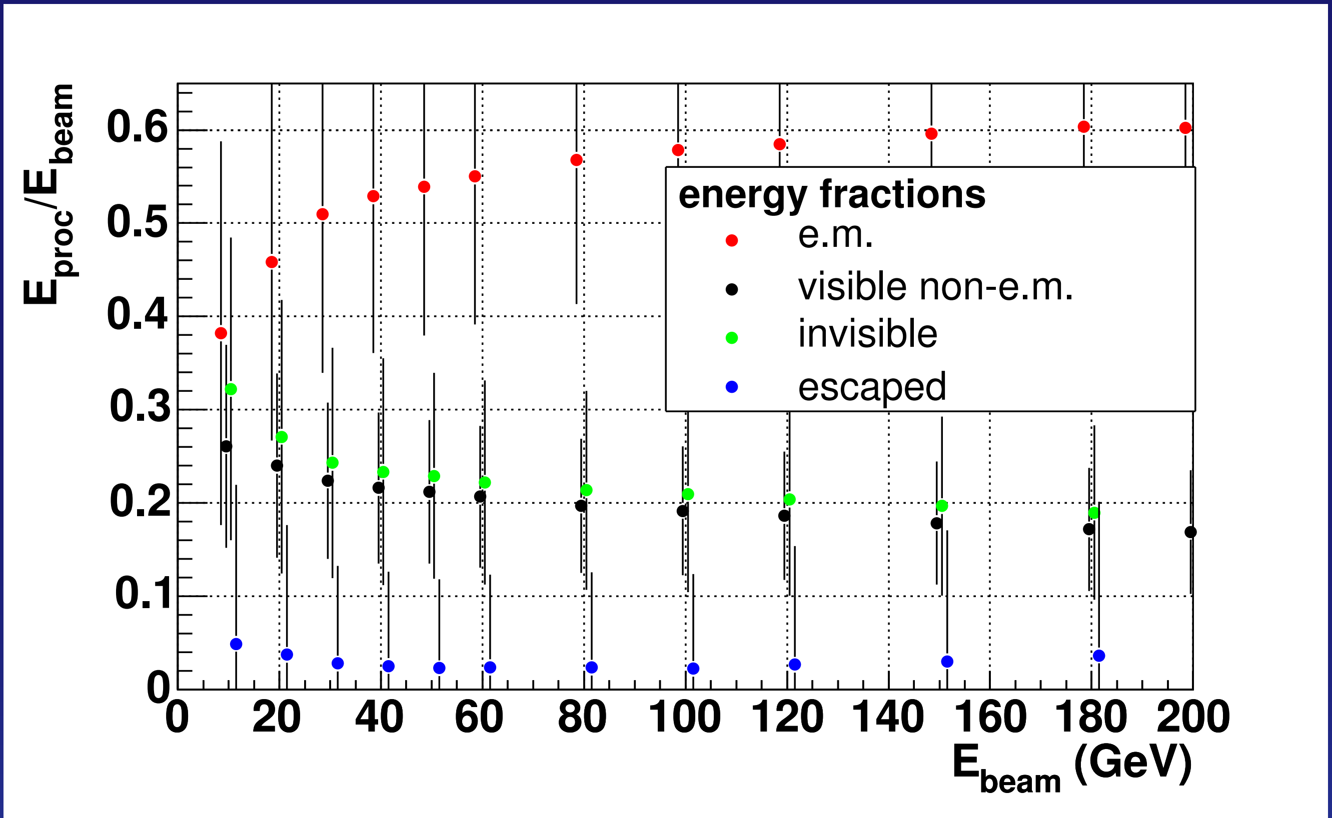
Hadron Calorimetry in ATLAS

- A hadronic shower consists of
  - EM energy (e.g. $\pi^0 \rightarrow \gamma\gamma$) $\mathcal{O}(50\,\%)$
  - visible non-EM energy (e.g. dE/dx from $\pi^{\pm}$,$\mu^{\pm}$, etc.) $\mathcal{O}(25\,\%)$
  - invisible energy (e.g. breakup of nuclei and nuclear excitation) $\mathcal{O}(25\,\%)$
  - escaped energy (e.g. ν) $\mathcal{O}(2\,\%)$
- each fraction is energy dependent and subject to large fluctuations



- invisible energy is the main source of the non-compensating nature of hadron calorimeters
- hadronic calibration has to account for the invisible and escaped energy

- From a Geant4 simulation of EMEC and HEC:

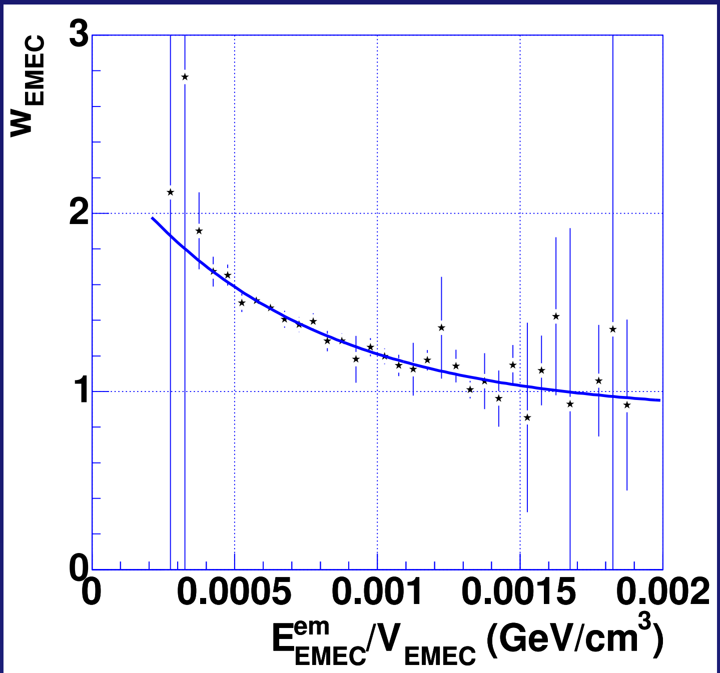


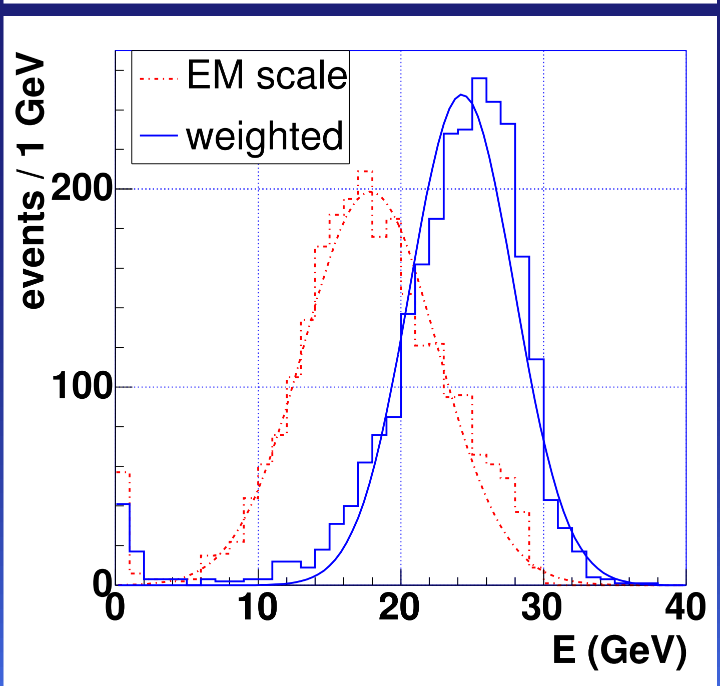
- EM energy strongly anti-correlated with visible non-EM energy
- visible non-EM energy strongly correlated with invisible energy

- need to separate EM part of the shower from the non-EM part
- apply a weight to the non-EM part to compensate invisible energy

- How to separate EM fraction from non-EM fraction?
  - $X_0 \ll \lambda \simeq 20\,\mathrm{cm}$
  - high energy density in a cell denotes high EM activity
  - low energy density in a cell corresponds to hadronic activity
  - apply weights as function of energy density

H1 Weighting Method





$$E' = w\,E$$
$$w = \left[c_1 \exp\left(-c_2\,E/V\right) + c_3\right]$$

- $w \to 1$ for large E/V:
  - $c_3 \approx 1$
  - weighting does not change electromagnetic clusters
- small energy density dominated by hadronic activity: $w > 1$:
  - $c_{1,2} > 0$
  - exact values depend on total cluster energy, choice of weighted unit (cell or cluster), . . .
- plot shows 30 GeV pions from 2002 EMEC–HEC test beam as a simple cluster weight example
  - restrict sample to pions fully contained in the EMEC
  - plot E_{beam}/E vs. E/V with E, V: cluster energy and volume, respectively
  - extract weight function
  - compare resolution for weighted and unweighted sample

$$
\begin{aligned}
E'_{\text{sub-calo}} &= w\, E_{\text{sub-calo}} \\
w &= \left[c_1 \exp\left(-c_2\, E_{\text{sub-calo}} / V_{\text{sub-calo}}\right) + c_3\right]
\end{aligned}
$$

- reconstruct "3D"-cluster
  - cluster definition follows in a couple of slides
- split the cluster in sub-calorimeter parts (e.g. EMEC/HEC)
  - because weights depend on intrinsic calorimeter properties
- apply cluster-energy dependent weights found in test beam as function of $E_{\text{sub-calo}} / V_{\text{sub-calo}}$
- tested on single particle test beam data and MC only
  - no straightforward extension to jets :-(
  - serves as a simple test case for H1 weighting
  - does not need any MC as input :-)

$$E'_{\text{cell}} = w\,E_{\text{cell}}$$
$$w = \left[c_1 \exp\left(-c_2\,E_{\text{cell}}/V_{\text{cell}}\right) + c_3\right]$$

- reconstruct “3D”-cluster
- split the cluster around cells with high energy density
  - to separate electromagnetic from purely hadronic deposits
- apply cluster-energy and region (granularity, sub-calorimeter) dependent weights found in test beam as function of $E_{\text{cell}}/V_{\text{cell}}$
- tested (so far) on single particle test beam data and MC only
  - should be possible to extend the method to jets
  - drives the need for cluster classification of the split clusters

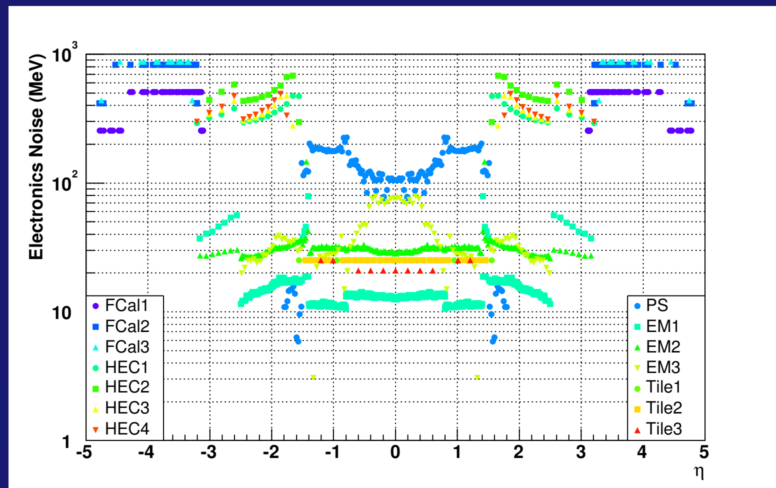
$$E'_{\text{cell}} = w\,E_{\text{cell}}$$
$$w = \left(E^{\text{em}}_{\text{cell}} + E^{\text{non-em vis}}_{\text{cell}} + E^{\text{non-em invis}}_{\text{cell}} + E^{\text{escaped}}_{\text{cell}}\right) / \left(E^{\text{em}}_{\text{cell}} + E^{\text{non-em vis}}_{\text{cell}}\right)$$

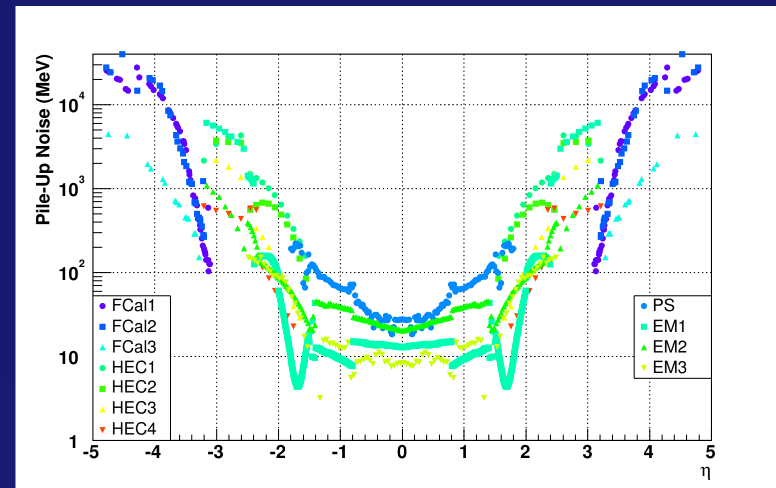
- start again with “3D”-clustering and splitting to define cluster-level quantities the weights might depend on
  - energy and energy density
  - cluster shape
  - distance of the cell from shower axis, . . .
- production of detailed Geant4 simulations for the EMEC+HEC combined test beam 2002 has just started
- contains “calibration hits” in the 4 energy categories for
  - active material
  - absorber material
  - dead material
- some of the problems to solve for the weight definition:
  - active cells tend to be smaller in $\Delta\eta \times \Delta\phi$ than corresponding absorber cells
  - absorber not covered by read-out area is called dead material
  - need to find out which dead material area should be included in which read-out cell

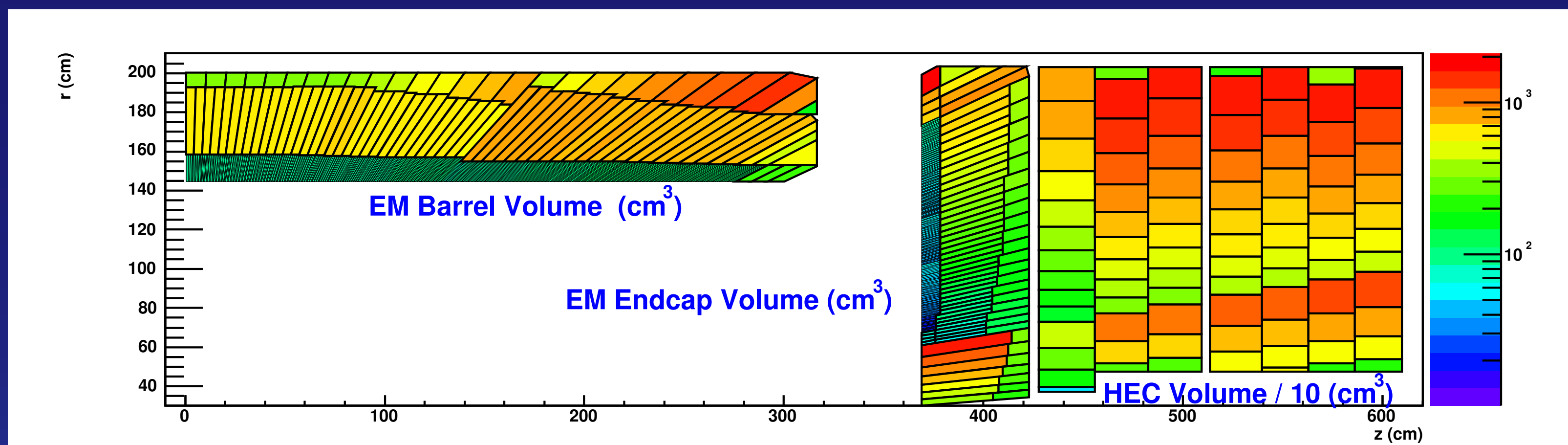
Jets and Clusters

- Clusters
  - a group of calorimeter cells which are topologically connected
  - often grouped around a seed cell with some large energy
  - either fixed in size: `SlidingWindow`
  - or dynamic: `CaloTopoCluster`
  - should be the base for hadronic calibration
- Jets
  - a collection of 4-vectors based on tracks and/or calorimeter objects (`CaloCell`s or `CaloTower`s or `CaloCluster`s)
  - defined by a metric on 4-vector level
  - should only need calibration against double counting although hadronic calibration on jet level is still possible
  - used for physics studies
- Hadronic Calibration Group
  - decided to base hadronic calibration on `CaloTopoCluster`

- Clustering needs to cope with large cell-to-cell variations of
  - electronics noise
  - pile-up noise
  - granularity







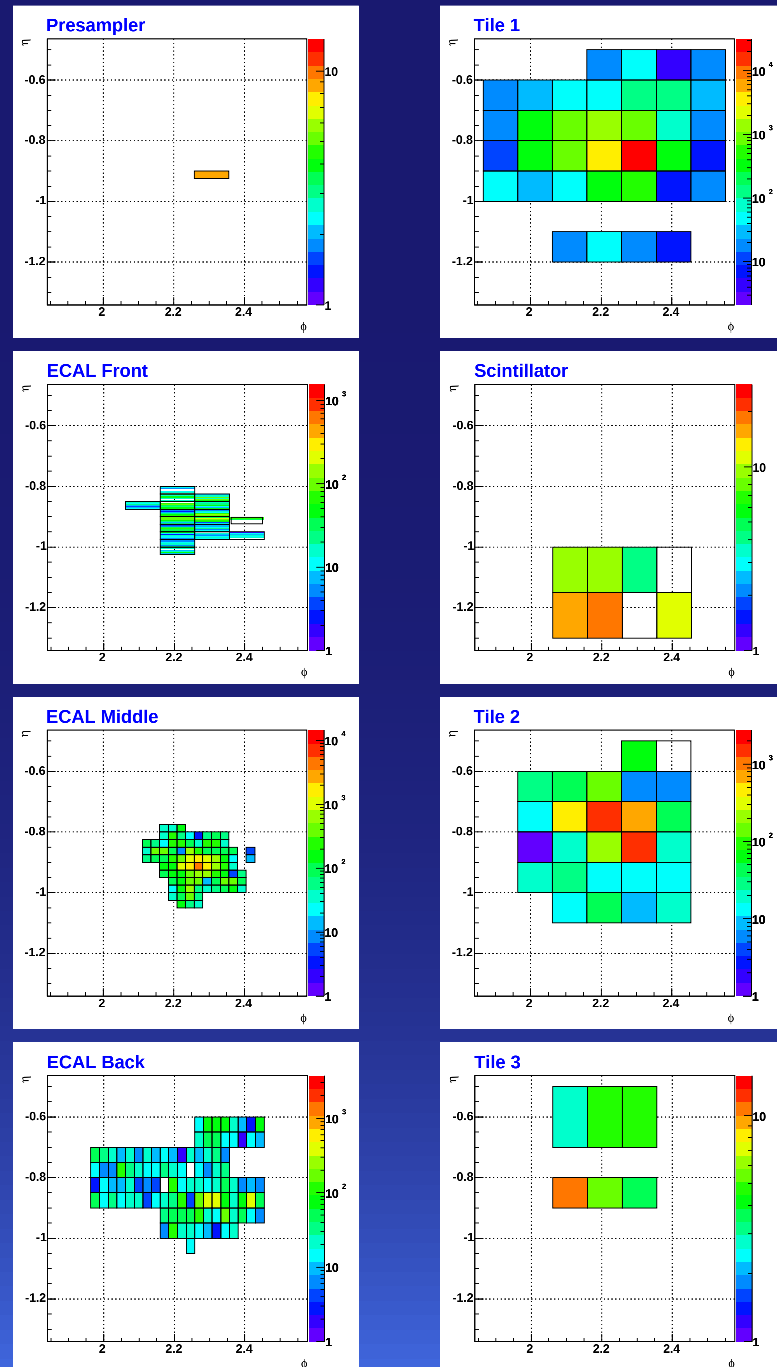
- use conditions database to obtain
  - $\sigma_{noise} = \sigma_{elec-noise} \oplus \sigma_{pile-up}$ for every channel in every event
  - use E/σ_{noise} for discrimination in topological clustering
  - use $\rho_{\perp} = E_{\perp}/V$ for definition of hot spots and topological re-clustering of previously found clusters

- `CaloTopoClusterMaker` makes `CaloCluster`s from `CaloCell`s in all Calorimeters
  - by grouping cells which are topological neighbors, where neighbors (defined in `CaloIdentifier`) can be
    - all2D: in the same layer and calorimeter
    - all3D: in the same calorimeter
    - super3D: anywhere across all calorimeters
  - with three Signal over Noise thresholds
    - CellThreshold: $|E/\sigma_{\text{noise}}| > T_{\text{cell}}$ (default $T_{\text{cell}} = 0$); only cells above this threshold are used
    - NeighborThreshold: $|E/\sigma_{\text{noise}}| > T_{\text{neighbor}}$ (default $T_{\text{neighbor}} = 3$); only cells above this threshold are asked for their neighbors
    - SeedThreshold: $E/\sigma_{\text{noise}} > T_{\text{seed}}$ (default $T_{\text{seed}} = 6$); only cells above this threshold initiate a cluster
  - with σ_{noise} being either
    - fixed; only useful for testing ...
    - elec-noise from `CaloNoiseTool` (default)
    - elec-noise $\oplus$ pile-up-noise from `CaloNoiseTool`

- `CaloTopoClusterMaker` since athena `8.2.0` is a `CaloClusterMakerTool` which is used by the generic `CaloClusterMaker` top algorithm

1. loop over all `CaloCells` in the given `CaloCellContainer`(s)
   a) make a vector of cells above cell threshold with `IdentifierHash` as index
   b) create a proto-cluster for each cell above neighbor threshold
   c) create a list (`mySeedCells`) for each cell above seed threshold and mark them used
2. sort initial `mySeedCells` in E/σ_{noise} in descending order
3. loop over `mySeedCells`
   a) loop over the neighbors of the current cell
      i. for neighbors above neighbor threshold merge proto-clusters; if not marked used do so and add to `myNextCells`
      ii. neighbors below neighbor threshold not belonging to any proto-cluster are included in parent proto-cluster
4. set `mySeedCells = myNextCells`
5. return to 3. if `mySeedCells` is not empty
6. keep proto-clusters with at least one cell above seed threshold

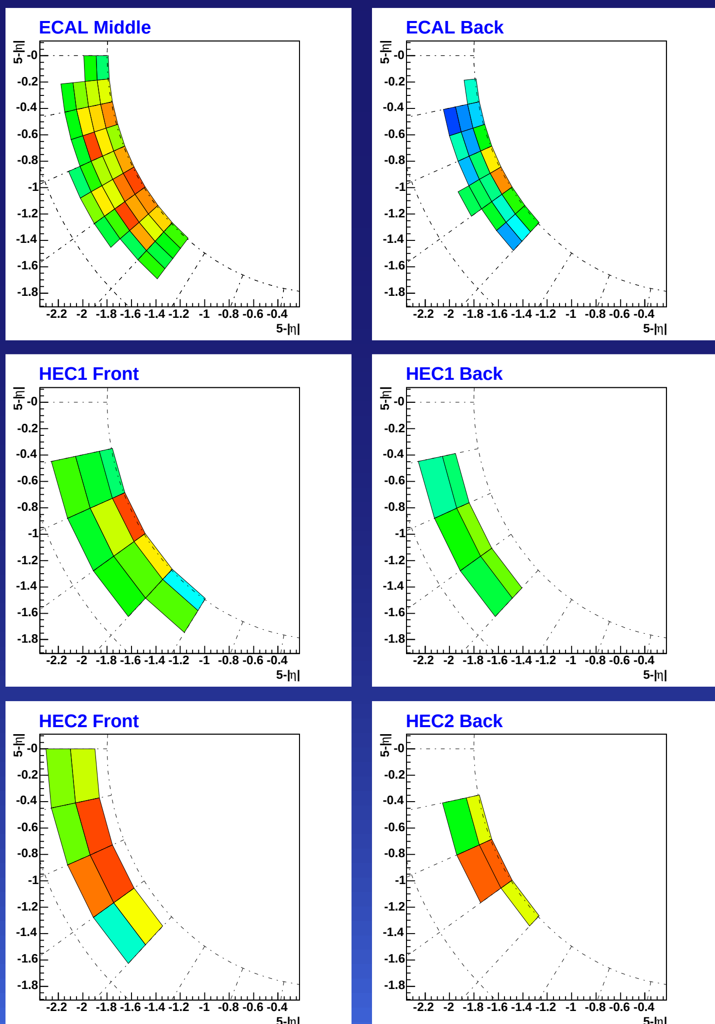
- Jet with $p_\perp > 70\,\mathrm{GeV}$, $|\eta| < 5$ in EM barrel, Tile Barrel, Gap, & Extended Barrel
  - all plots show same $\Delta\eta \times \Delta\phi$ region
  - the color boxes denote the energy per cell in MeV on a log-scale (different scale for each plot)
  - 4 EM Barrel Layers
  - 3 Tile Barrel Layers
  - Tile Gap Scintillators
  - 3 Tile Extended Barrel Layers
  - all in one cluster

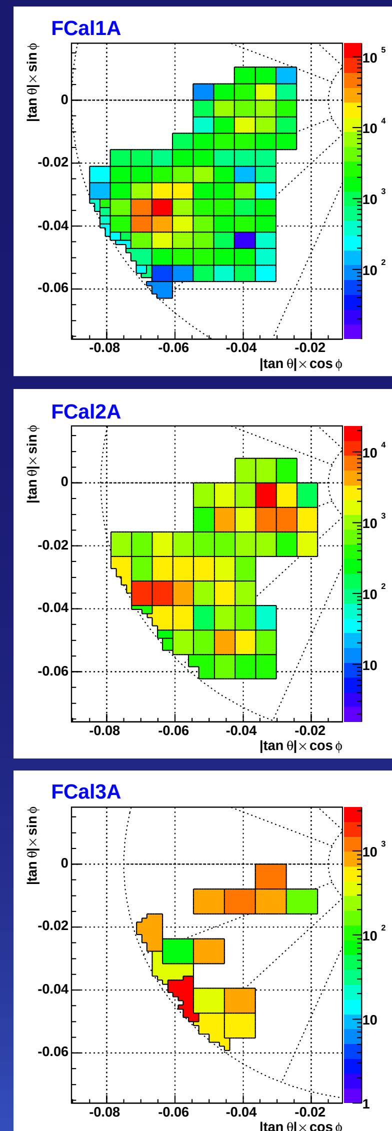


- `CaloTopoClusterMaker` makes clusters across all Calorimeters (`LArNeighbourOption::super3D`)
  - based on Signal over Noise thresholds
  - and topological neighbors
- Classification requires identification of “Hot-Spots”
  - need to split clusters around local maxima in real physical observable
  - transverse cell energy density $\rho_\perp = E_\perp / V$ seems best
- `CaloTopoClusterSplitter` re-clusters each existing cluster into one or more clusters
  - around the local maxima above a seed threshold
  - with same (or different) topological neighbors
  - without cell or neighbor thresholds
  - keeping local maxima in separate clusters
  - with $\rho_\perp$ ordered seeds in every iteration

- present in offline releases since athena `8.2.0`
- `CaloTopoClusterSplitter` is a `CaloClusterMakerTool` like `CaloTopoClusterMaker`
  1. loop over all `CaloCell` members of all previously made `CaloCluster`s
     a) store all cells as potential neighbor cells for topological clustering; the parent cluster is kept as a reference such that only cells within the same parent cluster can be re-clustered together
     b) create a proto-cluster for each cell
     c) keep as seed cells those which are a local max ($\rho_\perp > 500\,\text{MeV}/(600000\,\text{mm}^3)$, $\rho_\perp > \max\{\rho_{\perp,\text{neighbors}}\}$, $N_\text{neighbors} \geq 4$)
  2. sort current seed cells in descending order in $\rho_\perp$ and mark them used
  3. loop over the current seed cells
     a) loop over the neighbors of the current seed cell
        i. include the neighbor cell in current proto-cluster if it is not a local max itself, does not belong to a proto-cluster of size > 1, and does belong to the same parent cluster
        ii. add the neighbor cell to the list of next seed cells if it is not marked used and mark it used
  4. copy the list of next seed cells to the current list
  5. iterate (starting at step 2) until list of current seed cells is empty
  6. copy all cells of parent clusters not re-clustered in separate clusters (one per parent cluster)
  7. remove all original `CaloCluster`s and create new `CaloCluster`s from the local max proto-clusters and the rest proto-clusters
- switched on by default as specified in `CaloRec/CaloTopoCluster_jobOptions.py`

- Jet with $p_\perp > 70\,\mathrm{GeV}$, $|\eta| < 5$ in EM, HEC, FCal
- Parent Cluster before splitting

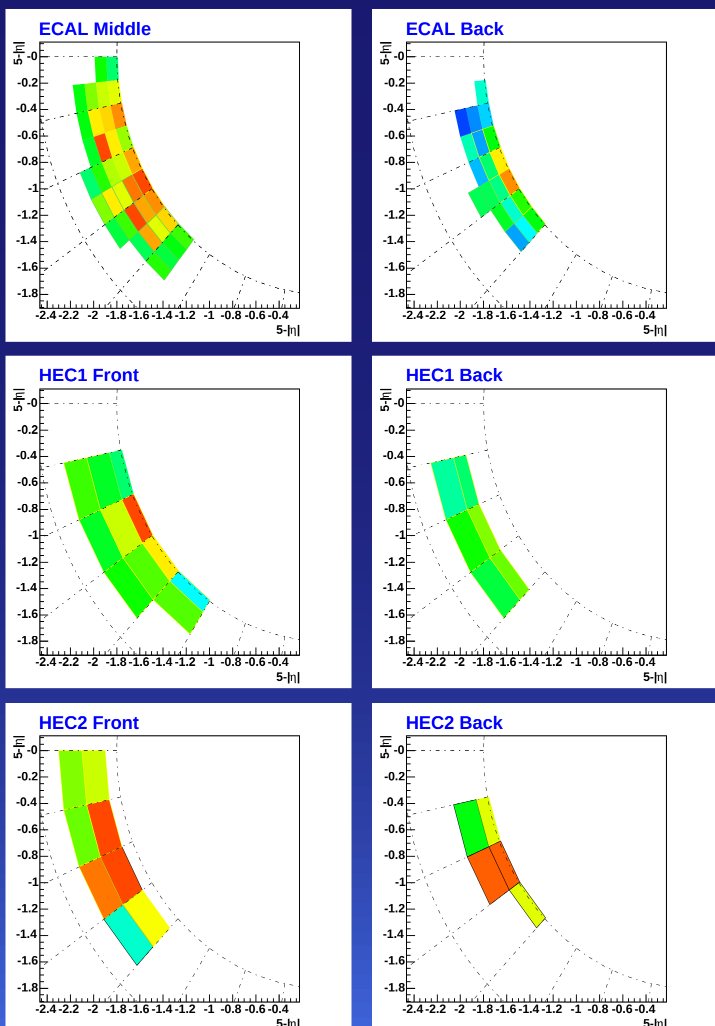


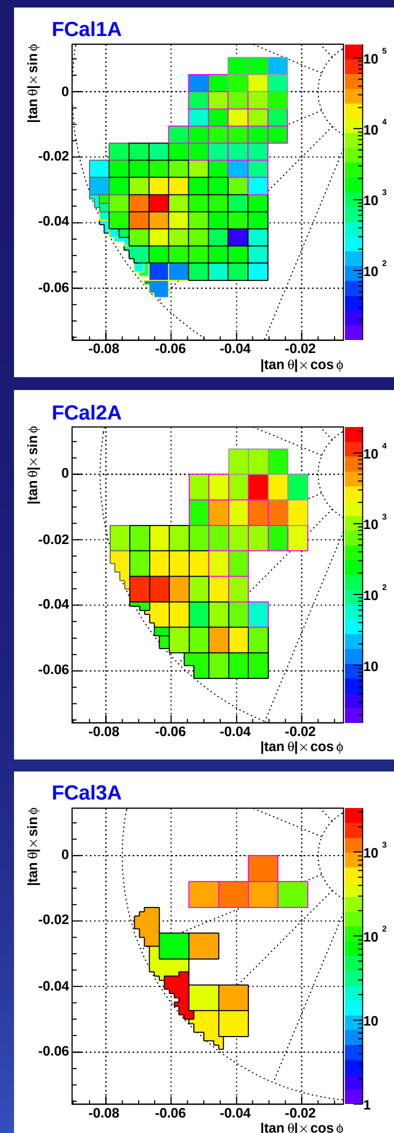


- EMEC has only 2 layers in this region
- EMEC3 neighbors HEC1
- HEC1 overlaps with the front of FCal1
- rear faces of FCal1 and 2 neighbor HEC3 and 4
- all 9 layers belong to the same cluster
- at least 4 potential local maxima visible

Topological Cluster Splitter ► Example Event ► after Splitting

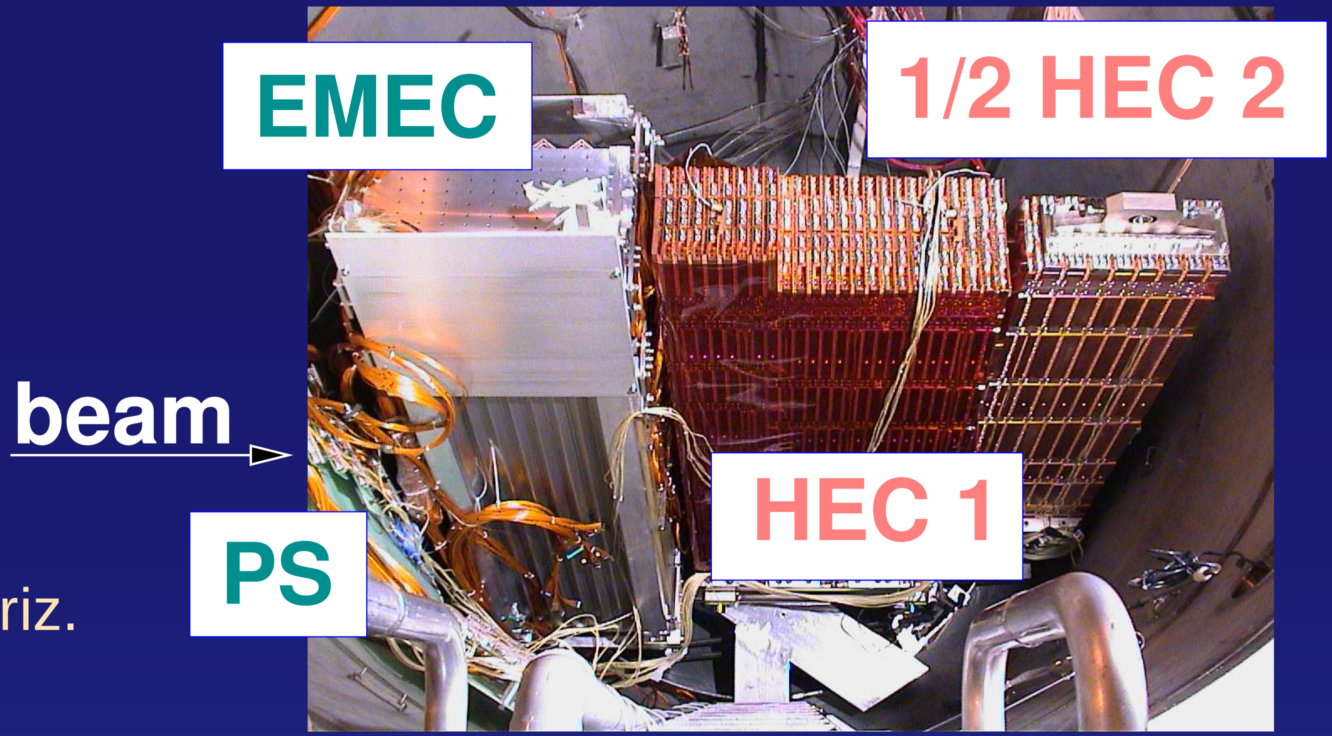
- same Cluster after splitting





- different sub-clusters denoted by different box colors
- 7 local maxima were found in the parent cluster
- sub-clusters are also crossing system boundaries
- single γ clusters remain un-split

- H6 beam area at the CERN SPS
  - $6 \leq E \leq 200$ GeV $e^{\pm}, \mu^{\pm}, \pi^{\pm}$ beams
  - 90° impact angle (unlike ATLAS)
  - Scintillators for trigger and timing
  - 4 MWPCs with horiz. and vert. layers upstream
  - Optional additional material upstream

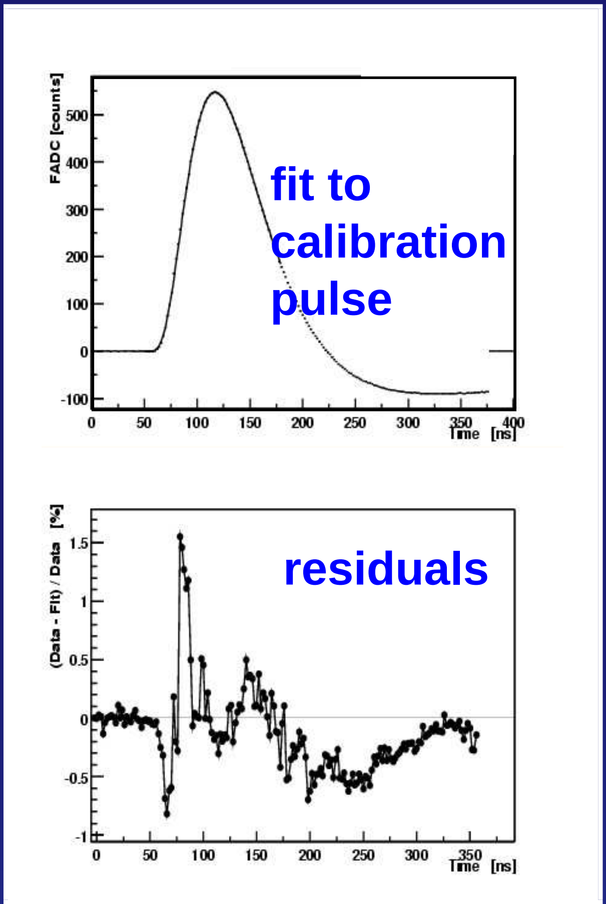


- Main goals for the beam test
  - study the region $\eta \sim 1.8$
  - obtain calibration constants for e and π
  - compare to detailed MC in order to extrapolate to jets
  - test methods for an optimal hadronic energy reconstruction

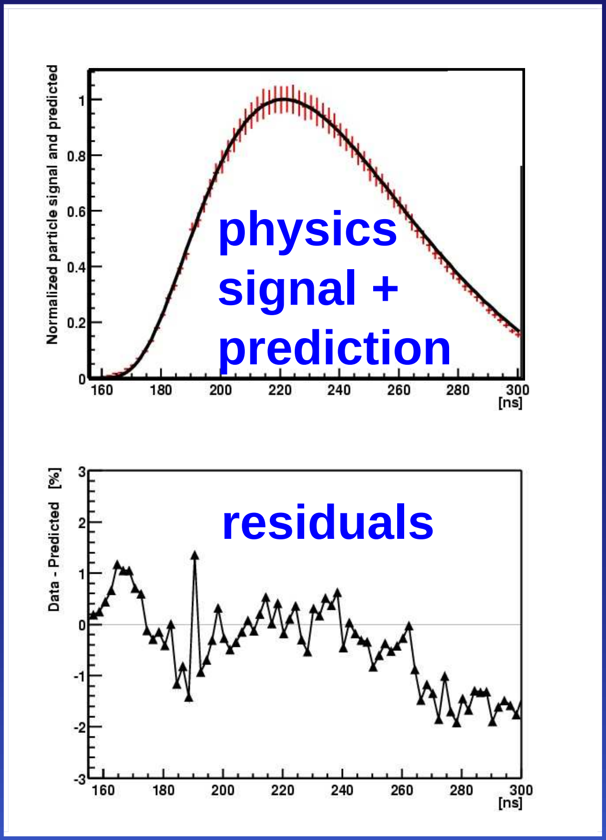
- Optimal filtering principle:
  - need known physics signal shape $g(t)$
  - discrete measurements (signal plus noise): $y_i = Eg_i + b_i$
  - and autocorrelation matrix from noise runs: $B_{ij} = \langle b_i b_j \rangle - \langle b_i \rangle \langle b_j \rangle$
  - estimate amplitude E with $\tilde{E} = a^t y$ from minimization of $\chi^2(E) = (y - Eg)^t B^{-1} (y - Eg)$
  - solution is given by OF weights $a = \frac{B^{-1} g}{g^t B^{-1} g}$
- Biggest problem: how to get $g(t)$?
- HEC:
  - measure or fit all parameters of the electronics chain
  - convolution with calibration pulse gives shaping times
  - convolution with predicted physics shape has only one free parameter (drift time)
  - accuracy $\pm 1.5\,\%$
- EMEC:
  - electronics chain too complicated (incomplete)
  - HEC procedure would give only $\pm 4\,\%$ accuracy
  - treat transfer function as completely unknown
  - measured calibration output in freq. domain plus known physics- and calibration-pulse transforms are enough to predict the physics output
  - accuracy $< 2\,\%$

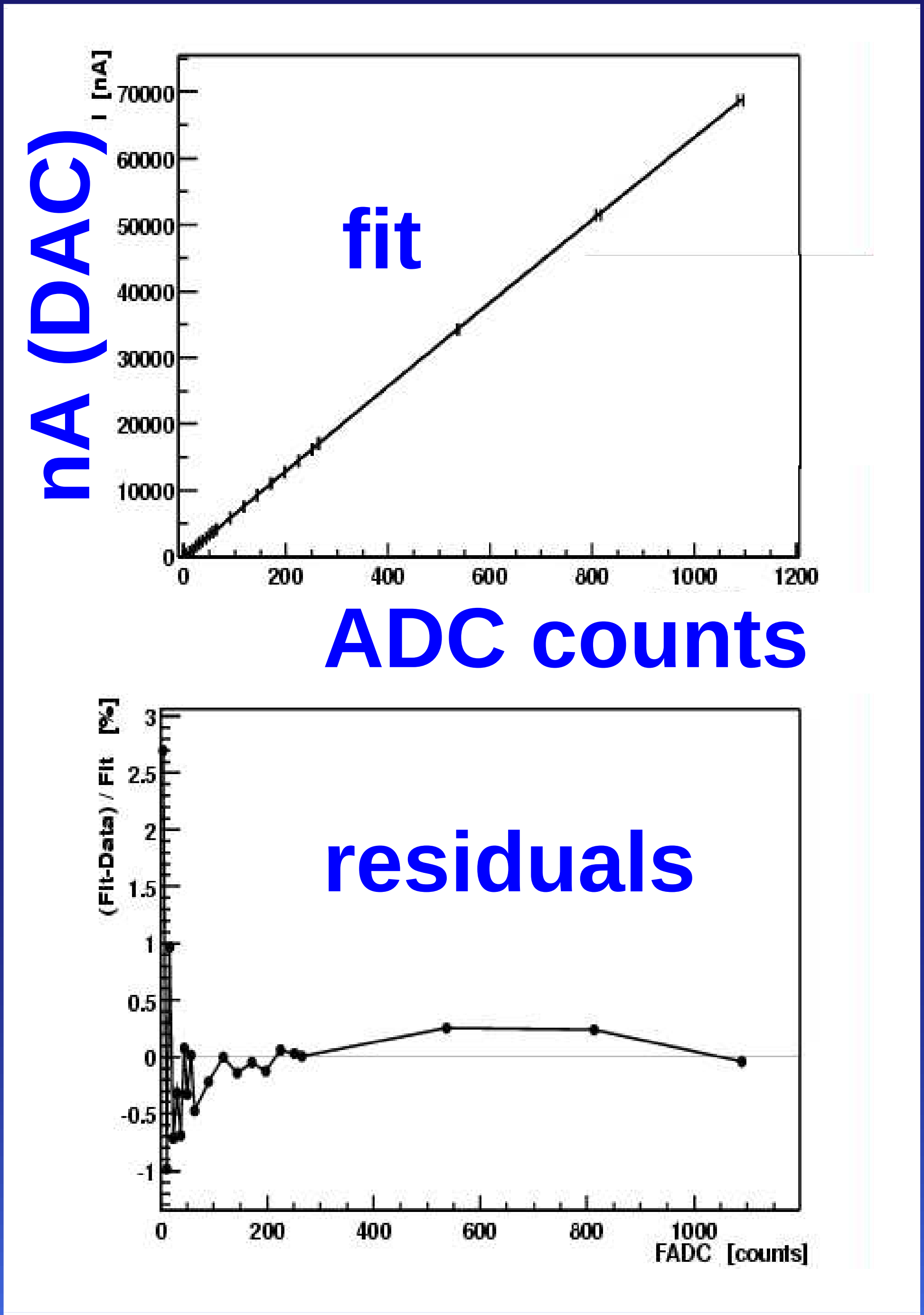
Signal reconstruction ► Digital filter ► HEC

- Calibration pulse fit example
  - upper plot shows calibration signal and fit for one channel
  - $\tau_i = 43.2 \pm 0.1\,\mathrm{ns}$ and $\tau_s = 14.20 \pm 0.02\,\mathrm{ns}$ are fitted
  - lower plot shows residual deviation from data $< 1.5\,\%$



- Physics signal prediction
  - upper plot shows normalized physics signal and prediction for one channel
  - lower plot shows residual deviation from data $< 1.5\,\%$
  - noise reduction factor with 5 weights 0.64 (0.72) for HEC (EMEC)

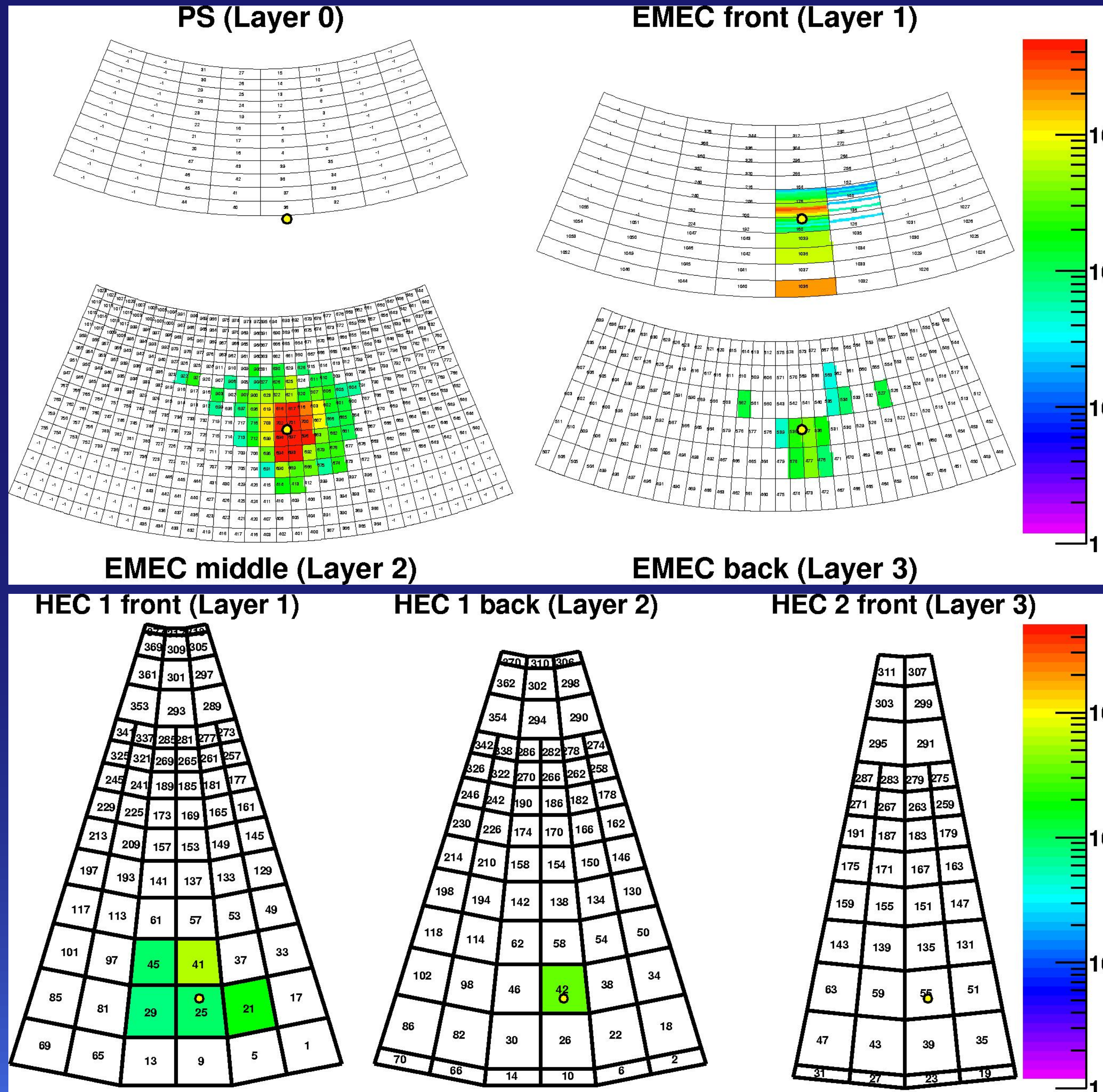


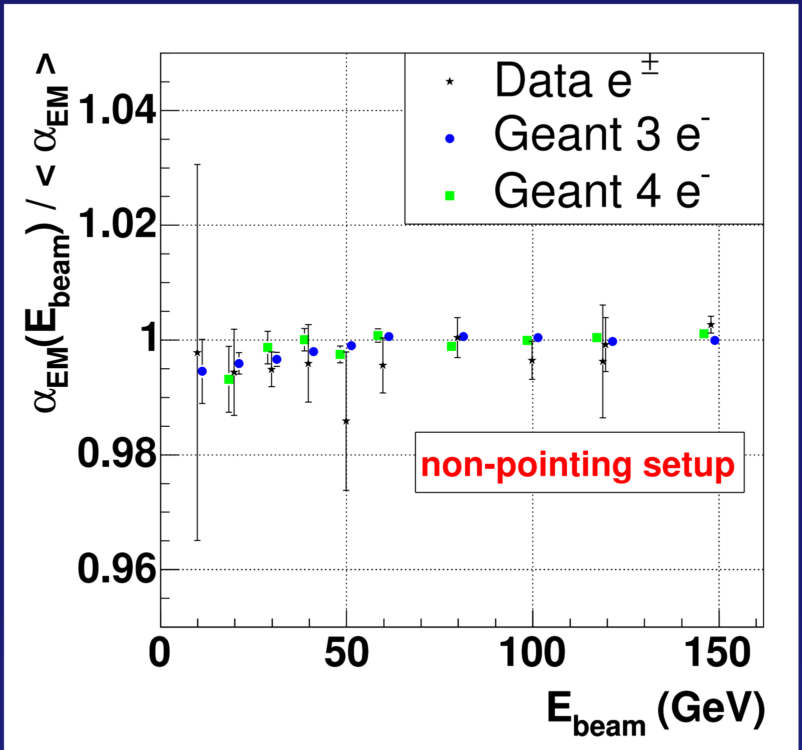


- Calibration from ADC to nA
  - use the OF weights found before
  - reconstruct the amplitudes for the calibration DAC level scans
  - fit the amplitude with a 3rd order polynomial to obtain calibration coefficients ADC $\rightarrow$ nA
  - accuracy $< 0.5\,\%$

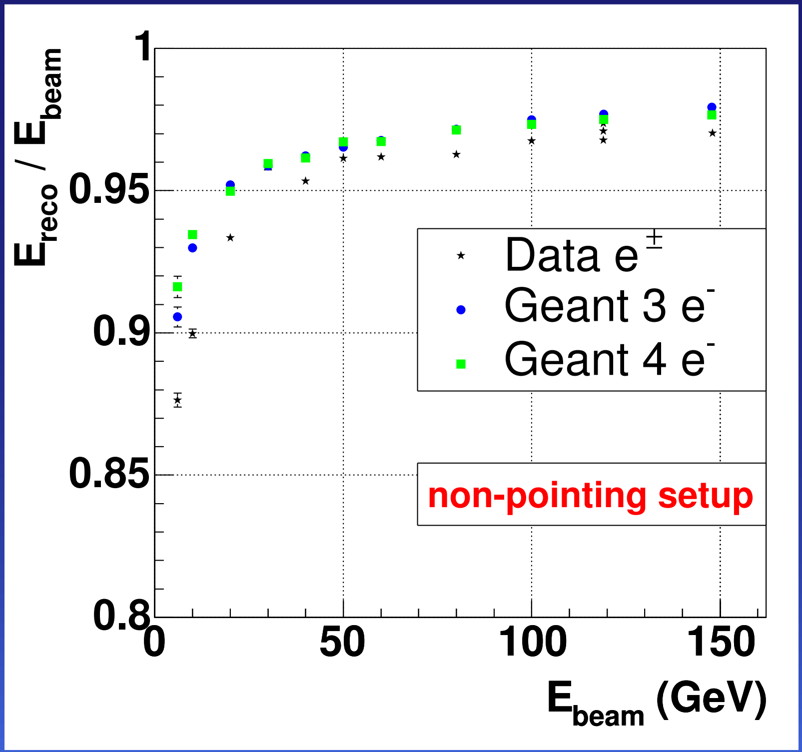
EMEC & HEC combined beam test 2002 ► Topological Clustering

- Event display for a 120 GeV pion in nA
- Cell-based topological nearest neighbor cluster algorithm
  - Clusters are formed in 2D
  - Seed cut $E/\sigma_{\text{noise}} > 4$
  - Include cells neighboring cluster members with $|E/\sigma_{\text{noise}}| > 3$
  - Cell cut $|E/\sigma_{\text{noise}}| > 2$
  - Iterate
- Neighbor means common edge





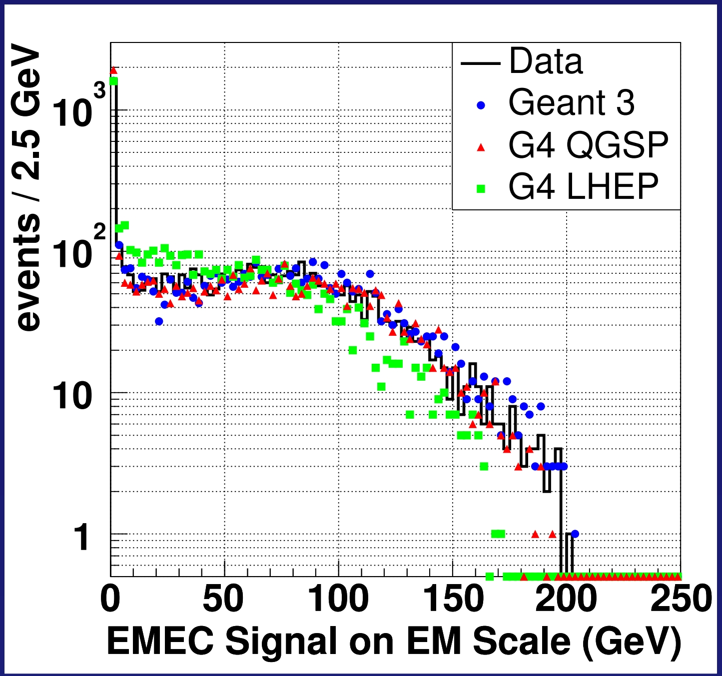
- $\alpha_{em}^{EMEC} = 0.430 \pm 0.001\,\mathrm{MeV/nA}$
  - linearity good to $\pm 0.5\,\%$
  - well reproduced by MC
- cluster leakage available in MC and data

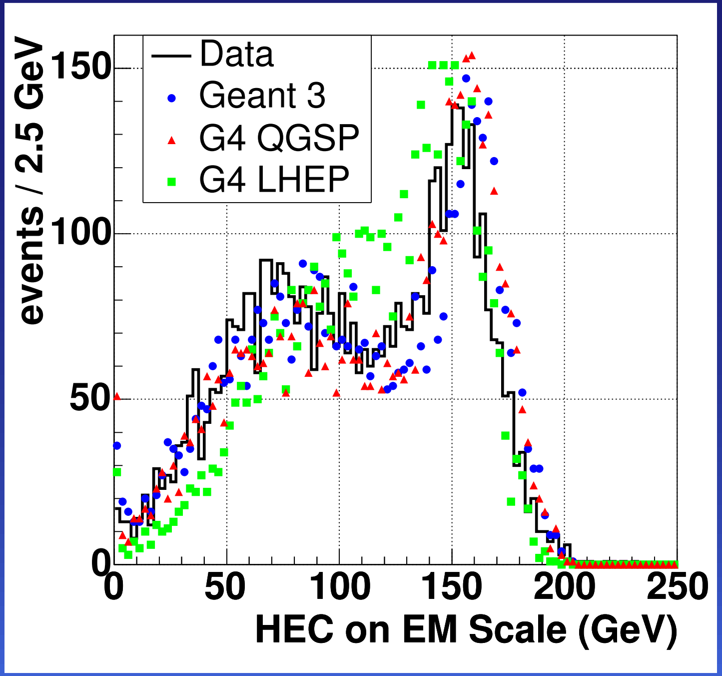


- plot shows data, Geant3 and Geant4
- well modeled by the MC ($2 - 4\,\%$ leakage at high energies)
- MC shows smaller ($4 - 10\,\%$) leakage than data ($5 - 12\,\%$) at low energies

Energy calibration ► Response to pions

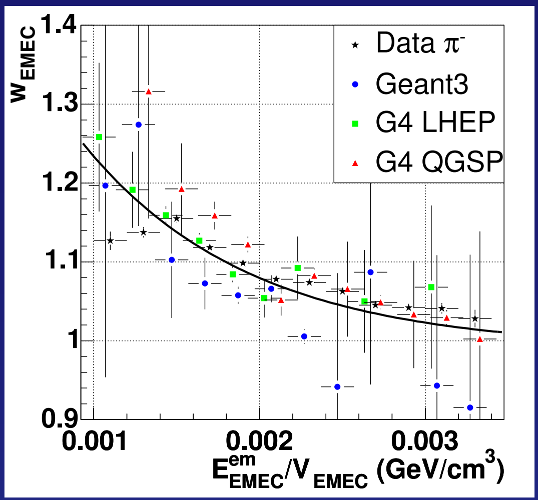
- No electrons in HEC only
  - Electromagnetic scale from previous HEC stand-alone TB
  - Modified by new electronics
  - Calculated value: $\alpha_{\mathrm{em}}^{\mathrm{HEC}} = 3.27\,\mathrm{MeV/nA}$
- Response to 200 GeV pions in data and MC on em-scale
  - upper plot shows EMEC
  - lower plot shows HEC
  - Geant3 and Geant4 QGSP describe data reasonably well
  - Geant4 LHEP deviates substantially

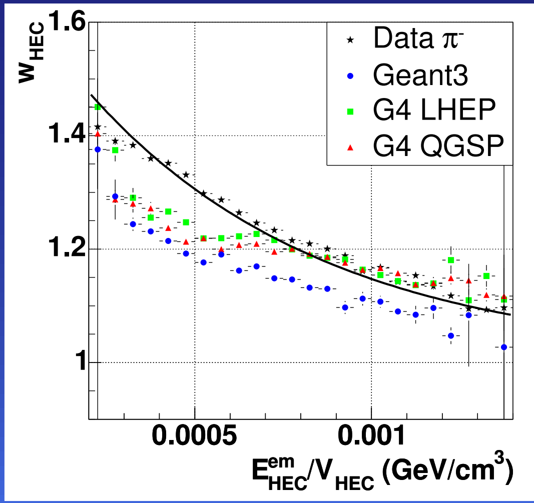




- Cluster weights are found by minimizing: $\chi^2 =$

$$\sum_{\text{events}} \frac{\left(E_{\text{beam}} - E_{\text{leak}}^{\text{HEC}} - E_{\text{tot}}^{\text{EMEC}} - E_{\text{reco}}^{\text{HEC}}\right)^2}{\sigma^2} + \frac{\left(E_{\text{beam}} - E_{\text{leak}}^{\text{EMEC}} - E_{\text{tot}}^{\text{HEC}} - E_{\text{reco}}^{\text{EMEC}}\right)^2}{\sigma^2}$$

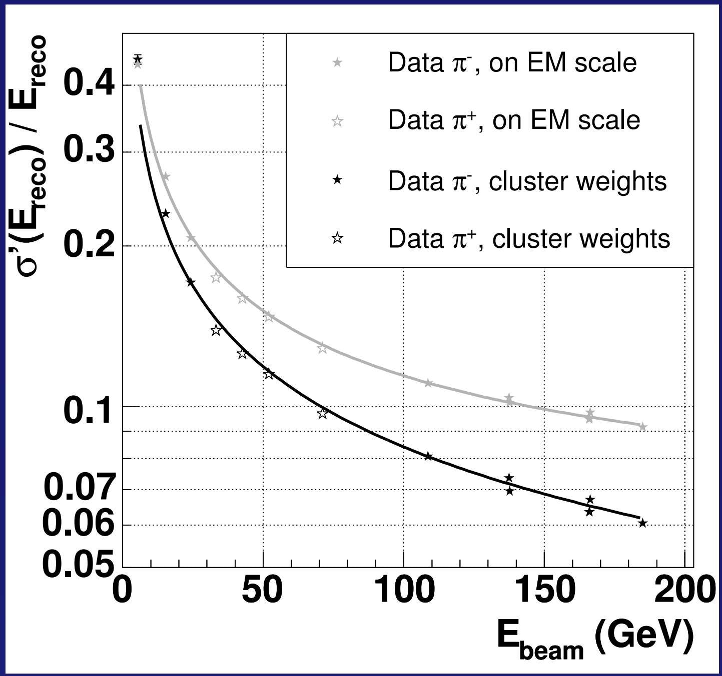


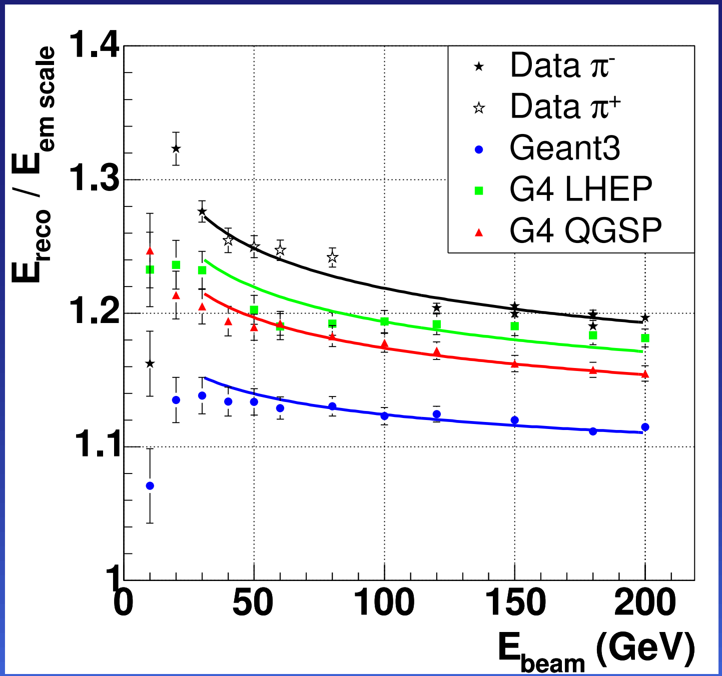


- $E_{\text{reco}} = E_{\text{em}} \left(c_1 \cdot \exp\left[-c_2 \cdot E_{\text{em}}/V\right] + c_3\right)$ (H1 method)
- $E_{\text{tot}} = E_{\text{reco}} + E_{\text{em}}^{\text{cluster leak}}$
- $E_{\text{leak}}^{\text{EMEC (HEC)}}\left(E_{\text{em}}^{\text{EMEC (HEC)}}/V^{\text{EMEC(HEC)}}\right)$ from MC
- c_2 fixed to $1000\,\text{cm}^3/\text{GeV}$ ($1500\,\text{cm}^3/\text{GeV}$) for EMEC (HEC)
- upper (lower) plot shows $E_{\text{reco}}/E_{\text{em}}$ for EMEC (HEC)

Energy calibration ► Resolution for pions

- σ_E/E (%) noise subtracted
  - data: $\frac{84.1 \pm 0.3}{\sqrt{E/\mathrm{GeV}}} \oplus 0.0 \pm 0.3$
  - noise: $\sigma_{\mathrm{noise}}/E \simeq 1 - 1.5\,\mathrm{GeV}/E$





- Geant3 and all Geant4 models give similar results
- combined e/π ratio
  - shows total $E_{\mathrm{reco}}/E_{\mathrm{em}}$
  - indicates the amount of non-compensation
  - fitted e/h-ratios for combined HEC and EMEC have no direct interpretation

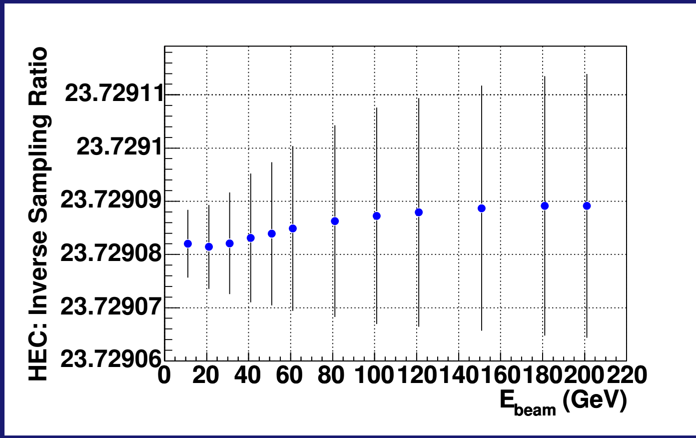
Energy calibration ► Cell Weighting with MC

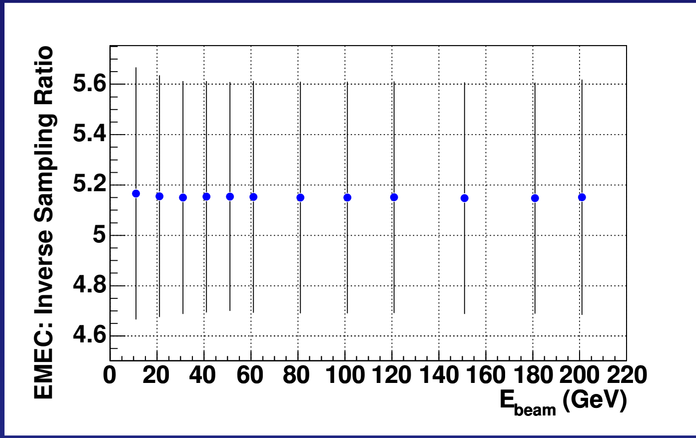
$$E'_{\text{cell}} = w\,E_{\text{cell}}$$
$$w = \left(E^{\text{em}}_{\text{LAr+Abs}} + E^{\text{non-em vis}}_{\text{LAr+Abs}} + E^{\text{non-em invis}}_{\text{LAr+Abs}} + E^{\text{escaped}}_{\text{LAr+Abs}}\right) / \left(E^{\text{em}}_{\text{LAr}} + E^{\text{non-em vis}}_{\text{LAr}}\right)$$

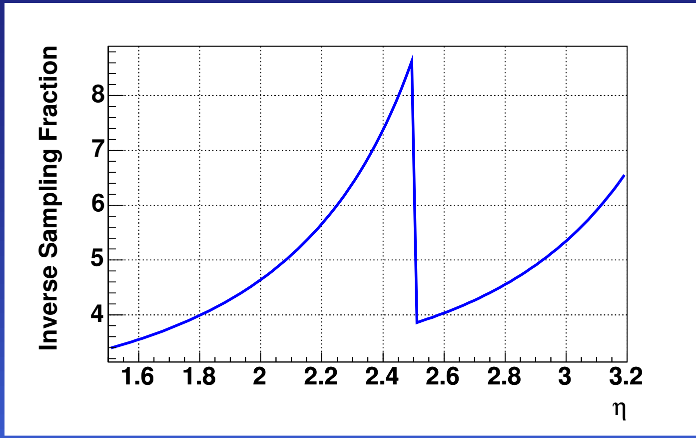
- start with “3D”-clustering and splitting to define cluster-level quantities the weights might depend on
  - energy and energy density
  - cluster shape
  - distance of the cell from shower axis, . . .
- for test beam data use sum of “2D”-clusters “3D”-cluster
- take cluster energy on EM scale as start value
- interpolate weights from MC according to cluster energy
- apply cell weights and re-calculate cluster energy
- iterate

Cell Weighting with MC ► Choice of Variables

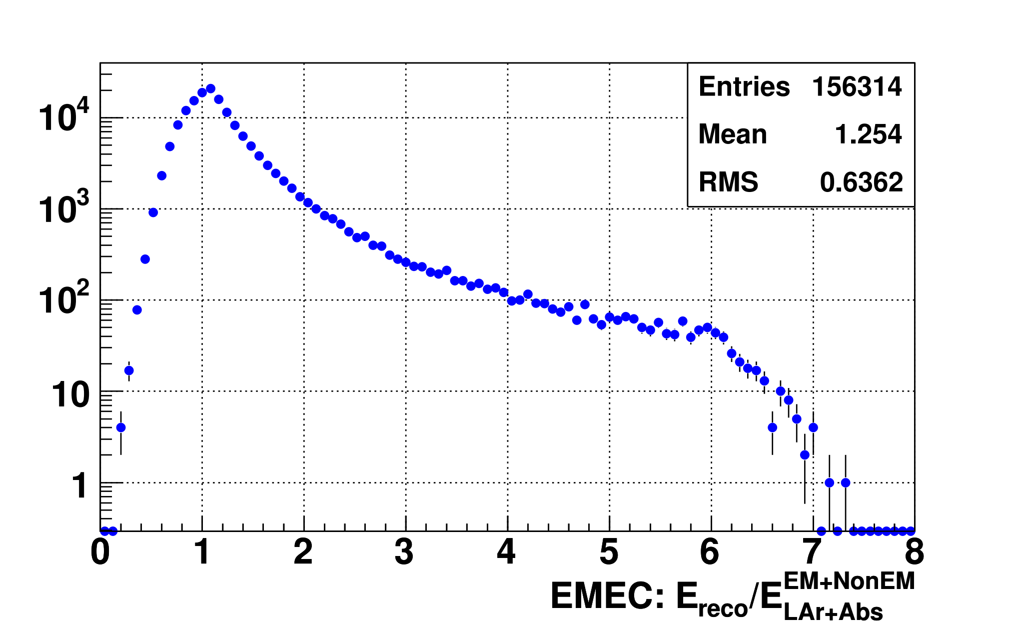
- the choices for the denominator in the weight basically are:
  1. include the absorber in the denominator: $w \sim 1/E^{\text{em + non-em}}_{\text{LAr+Abs}}$
  2. use only the liquid argon part: $w \sim 1/E^{\text{em + non-em}}_{\text{LAr}}$
  3. use the "reconstructed" liquid argon part: $w \sim 1/E_{\text{rec}}$
- for the HEC alone choice 2 and 3 are equivalent and differ by the constant sampling ratio only
- for the EMEC choice 2 is not possible because the sampling ratio varies with η
- we tried choice 1
  - theoretical electron weights are 1 :-)
  - no dependency on sampling ratios :-)
  - gives biased results due to mismatch with reconstructible energy :-(
- this leaves us with choice number 3

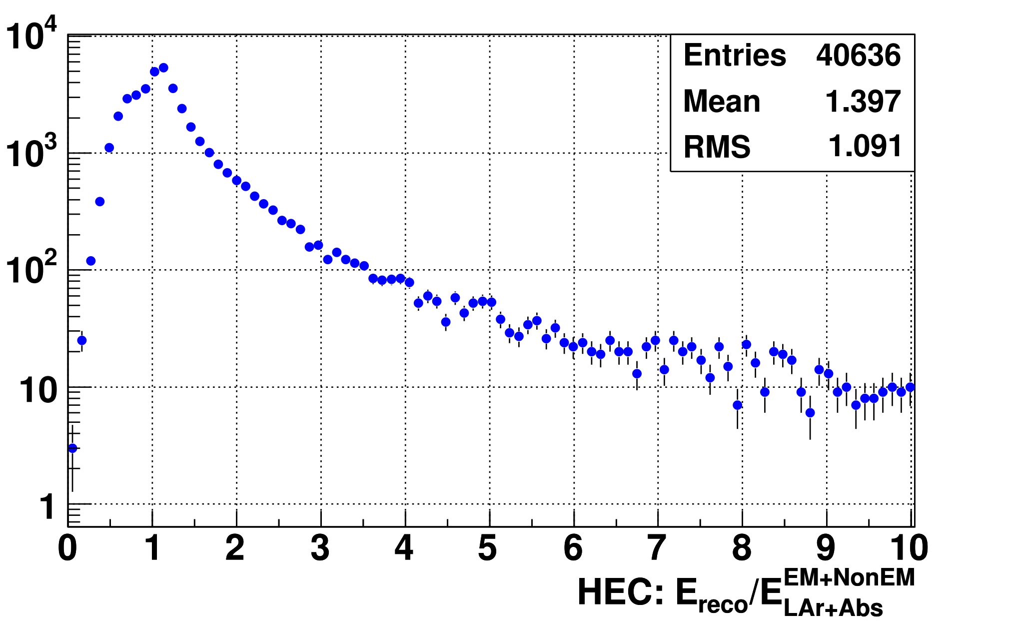






Cell Weighting with MC ► Avoiding Bias

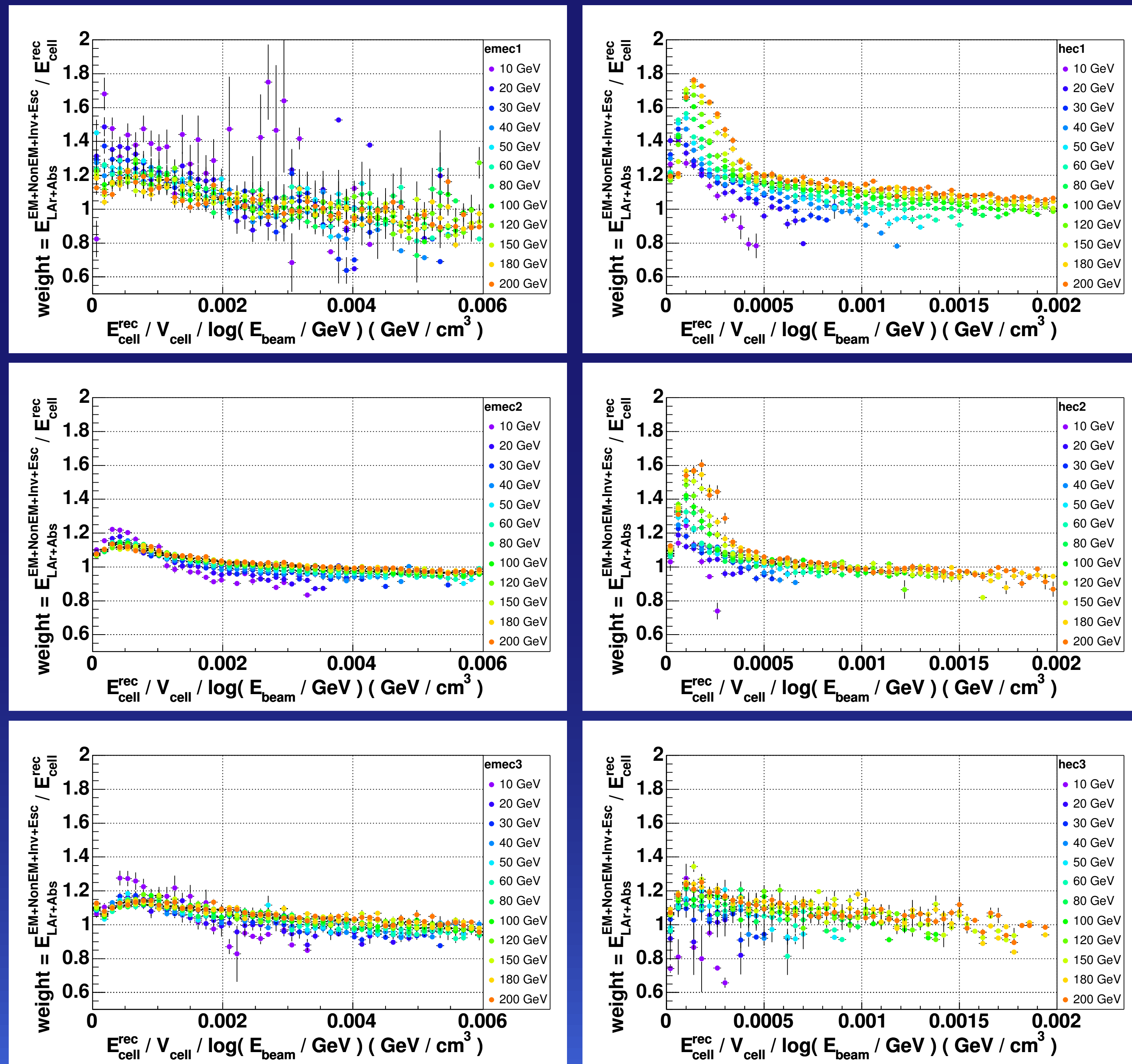




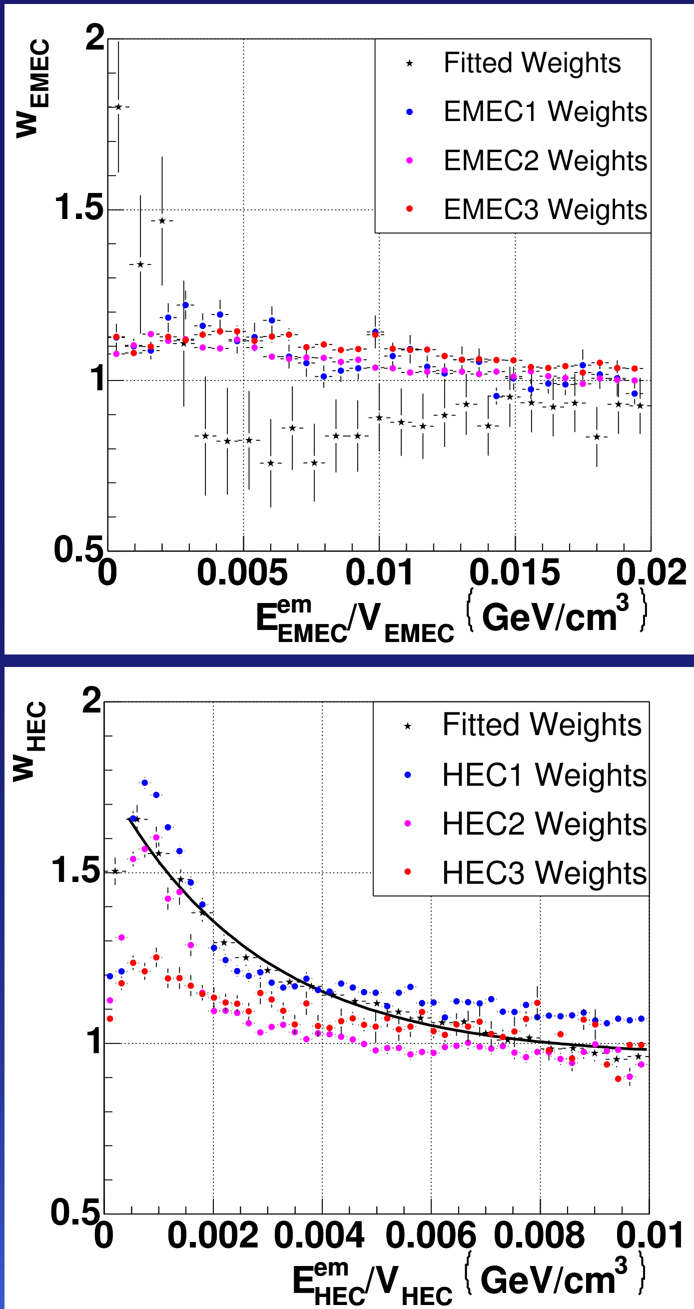
- compare the reconstructed cell energy with total visible cell energy (LAr+Abs) for 200 GeV pions
- shows the variation in the sampling ratio (this quantity is constant for dE/dx only)
- most probable value is 1 but large positive tails shift mean to higher values
- results in over-weighting when cell weights are calculated from total visible cell energy
- upper plot shows EMEC
- lower plot shows HEC

Cell Weighting with MC ► Choice of x-Axis

- We tried many choices for the x-axis
  - function of $E_{\text{cell}}^{\text{w/wo noise}}/V_{\text{cell}}$ for every layer
  - scaled by $1/E_{\text{beam}}$ or $1/\log E_{\text{beam}}$ for better interpolation
  - modified by (optional) non-linear terms
  - plots show weights vs. $1/\log E_{\text{beam}}$-scaled energy density without noise for the three EMEC layers (left) and the three HEC layers (right) at point J



Cell Weighting with MC ► Compare to NIM paper weights



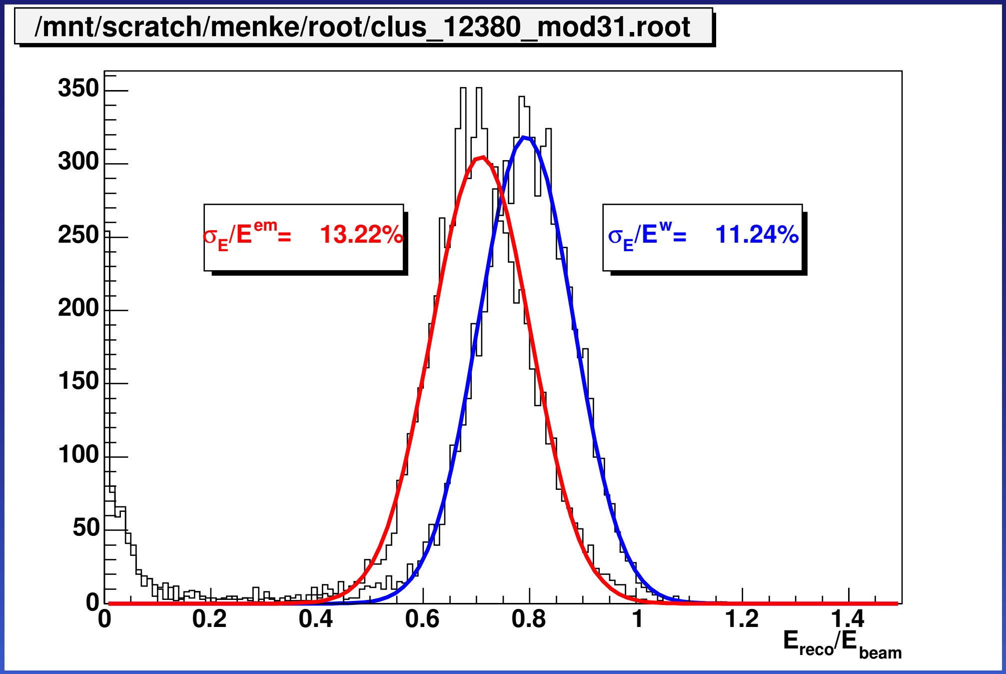
- For the NIM paper we fitted cell weights for EMEC and HEC by minimizing

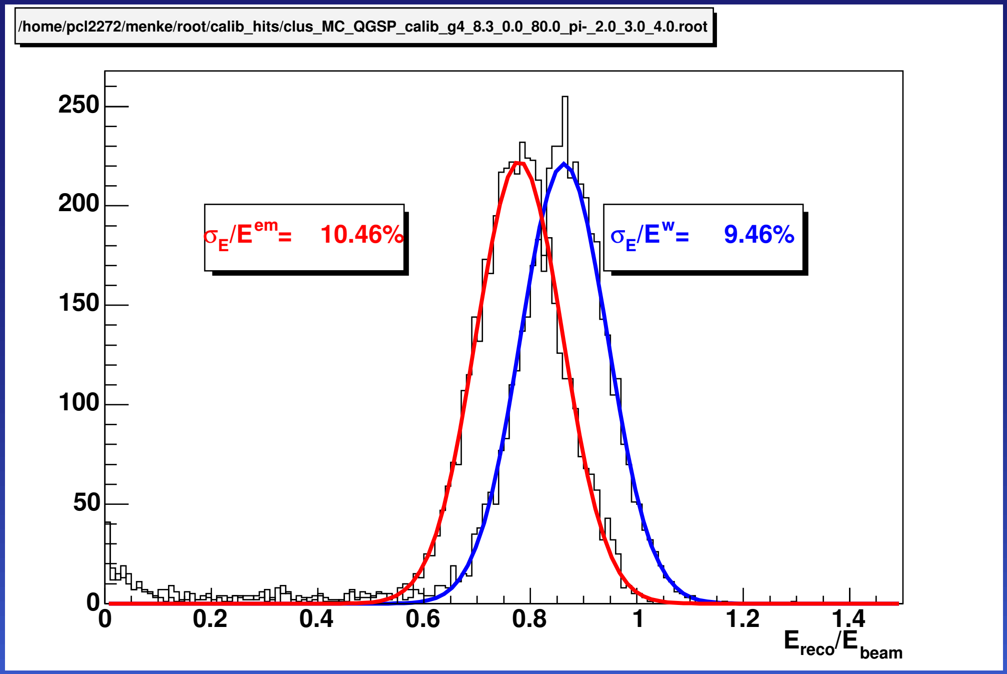
$$\chi^2 = \sum_{\text{events}} \frac{(E_{\text{beam}} - E_{\text{leak}} - E_{\text{reco}})^2}{\sigma^2_{\text{noise}} + \sigma^2_{\text{leak}}}$$

  - with $E_{\text{reco}} = \sum_{i=1}^{N_{\text{weights}}} w_i \sum_{\substack{\text{cells with} \\ \rho_i \leq \rho < \rho_{i+1}}} E_{\text{cell}}$
  - 25 weights for HEC per energy point
  - 25 weights for EMEC per energy point
- fit was performed for every beam energy separately
- σ_{noise} was not weighted
- comparison plots show weights for 200 GeV pions
  - NIM paper weights are in black
  - upper plot shows EMEC weights
  - lower plot shows HEC weights

Application of the Weights to Data and MC ► π^-

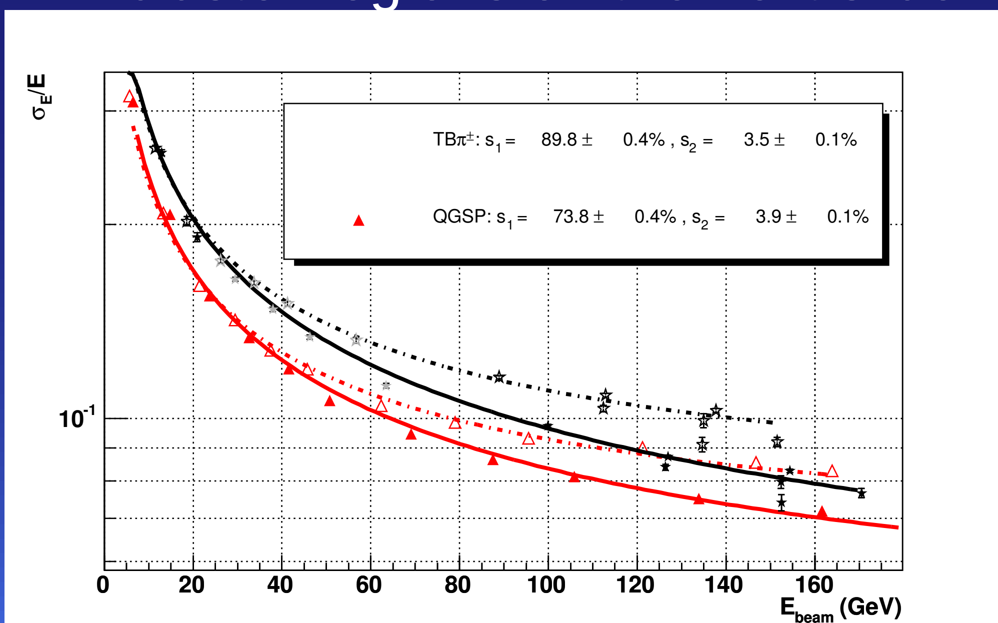
- the following plots are for $x = E_{\text{cell}}^{\text{with noise}} / V_{\text{cell}} \times 1/\log E_{\text{clus}}$
- examples show (normalized) cluster energies for $80\,\text{GeV}\ \pi^-$ before and after the weighting iteration
  - in red before the iteration (em)
  - in blue after the iteration (w)
  - usually 2 iterations are enough

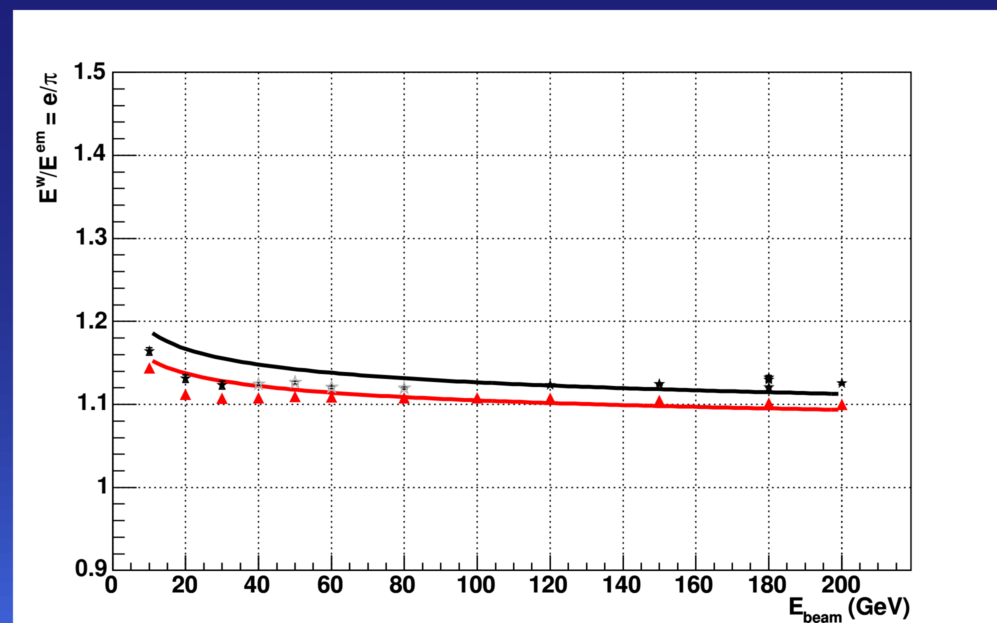




Application of the Weights to Data and MC ► π^- ► Resolution

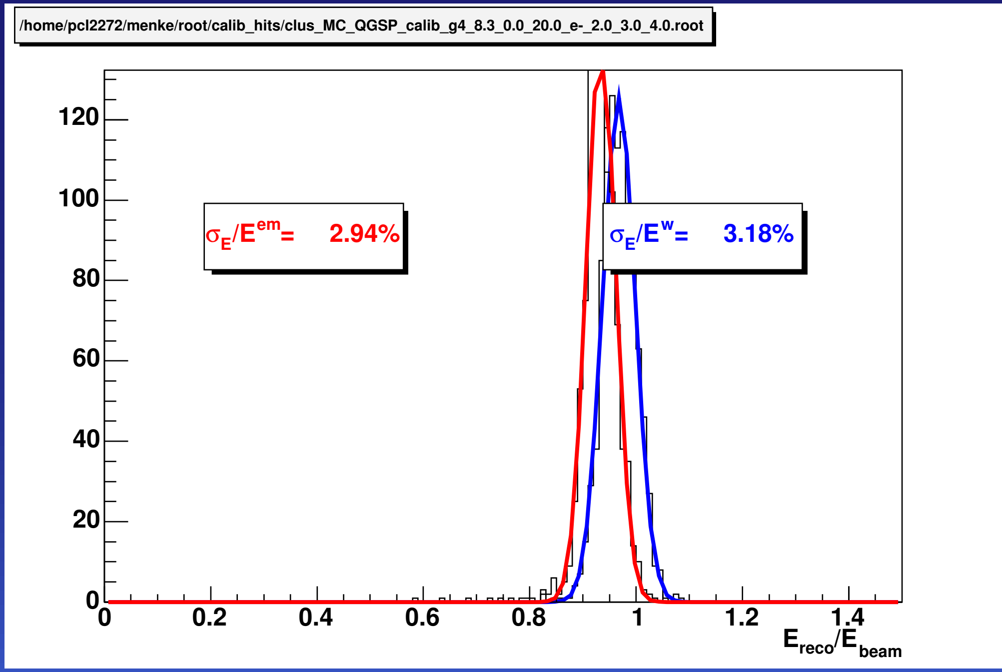
- Iterative procedure at point J including noise yields:
  - data: $\sigma_E/E = 89.8\,\%/\sqrt{E\ (\mathrm{GeV})} \oplus 3.5\,\%$
  - MC: $\sigma_E/E = 73.8\,\%/\sqrt{E\ (\mathrm{GeV})} \oplus 3.9\,\%$
- weighted energy matches true total deposited energy in the cluster for MC (plot not shown) :-)
- beyond 40 GeV improved resolution after weighting :-)
- below 40 GeV weighting corrects the scale only
- have a look at electrons to estimate influence on pure electromagnetic cluster regions on the next slide

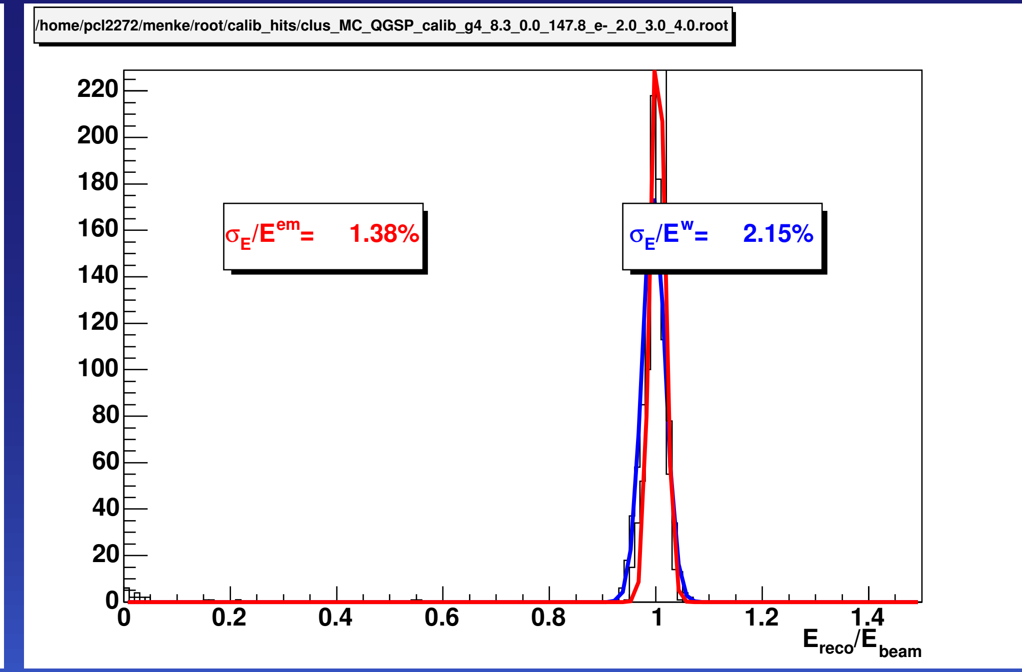




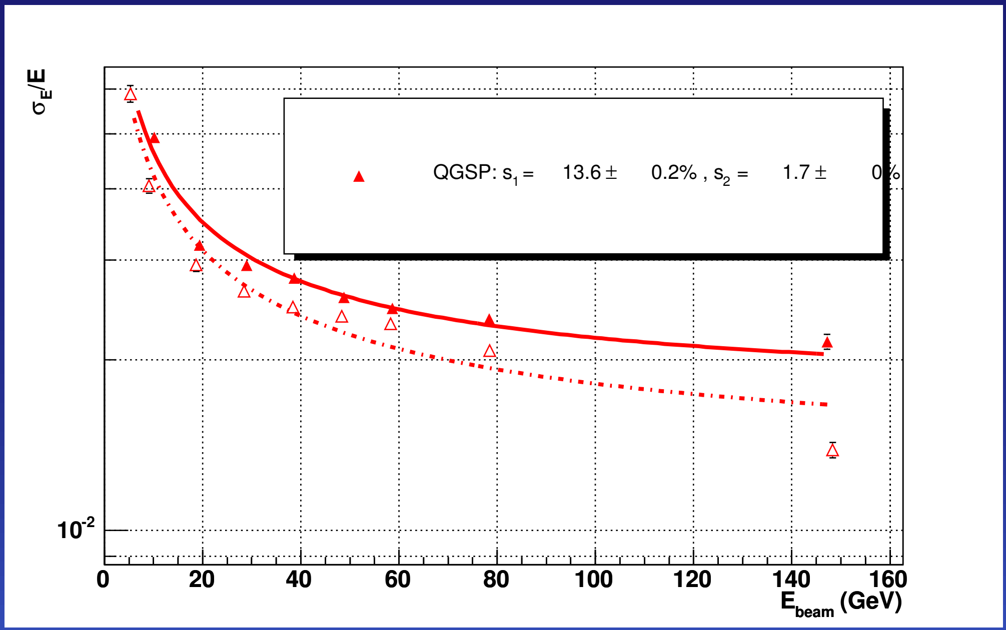
Application of the Weights to Data and MC ► e^-

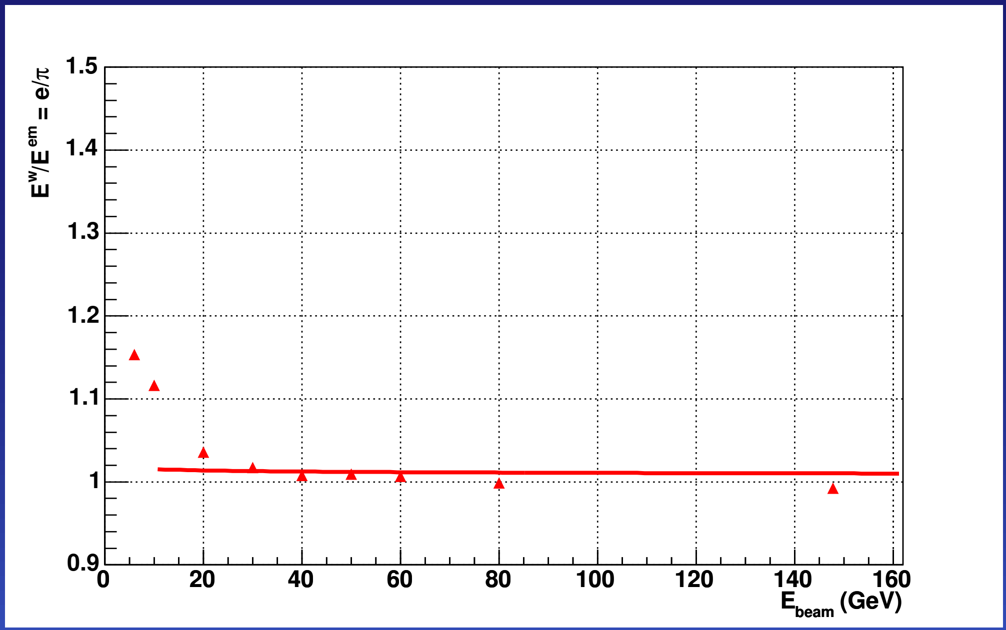
- apply same procedure to (MC) electrons
- this will show how large the bias is for pure electromagnetic showers
  - resolution gets worse
  - scale is off for low energies but o.k. for high energies
  - example shows 20 GeV and 148 GeV electrons





- **resolution**
  - worse after weighting as expected
  - probably tolerable since we've to be concerned about electromagnetic parts of hadronic showers only
- **bias**
  - as high as 15 % for 10 GeV
  - vanishes beyond 40 GeV





Roadmap to ATLAS

- Calibration Hits from Geant4 MC will give the calibration constants for hadronic calibration
  - compare MC with EMEC/HEC/FCAL and EMB/Tile 2004 combined test-beams
  - extend method to full ATLAS simulation
- port single particle calibration to jets
  - requires cluster splitting and identification
  - should not require new constants if previous step is successful
- cross-check with $p_\perp$-balance
  - form all cells in one η-region (similar to total missing $E_\perp$ studies)
  - form $Z^0 \rightarrow e^+e^-/\gamma + \text{jet}$ events
  - possibly introduces bias from trigger/ID performance

Conclusions

- Hadron calorimetry in ATLAS requires
  - topological clustering to identify “hot spots” and set the energy scale
  - H1 type weighting
  - works on cluster- and cell-level in test beam
- Detailed new Geant4 MC with “calibration hits”
  - first look at MC looks promising
  - will be used for cell-level H1 weighting
- Hadronic Calibration is cross-checked in situ
  - with $p_\perp$-balance for entire η-rings form minimum bias events
  - with $p_\perp$-balance of $\mathrm{Z}^0/\gamma + \mathrm{jet}$ events