Energy-calibration of the ATLAS hadronic and electromagnetic liquid-argon endcap calorimeters

8th ICATPP

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on behalf of the ATLAS LAr Collaboration

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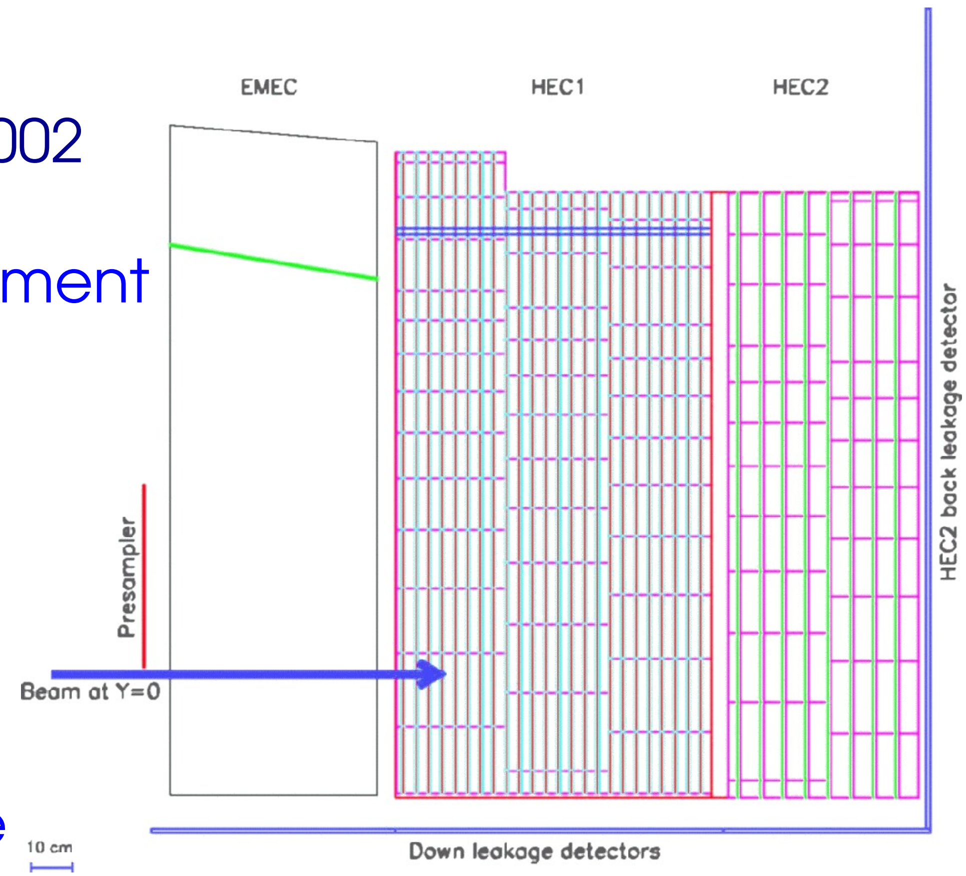
- The ATLAS calorimeters
- EMEC & HEC beam test 2002
  - ▷ Beam test setup
  - ▷ HV corrections & alignment
- Signal reconstruction
  - ▷ Digital filter
  - ▷ Timing
  - ▷ Calibration in nA
- Clustering
- Energy calibration
  - ▷ Electromagnetic scale
  - ▷ Response to pions
  - ▷ Weighting
  - ▷ Road-map to ATLAS



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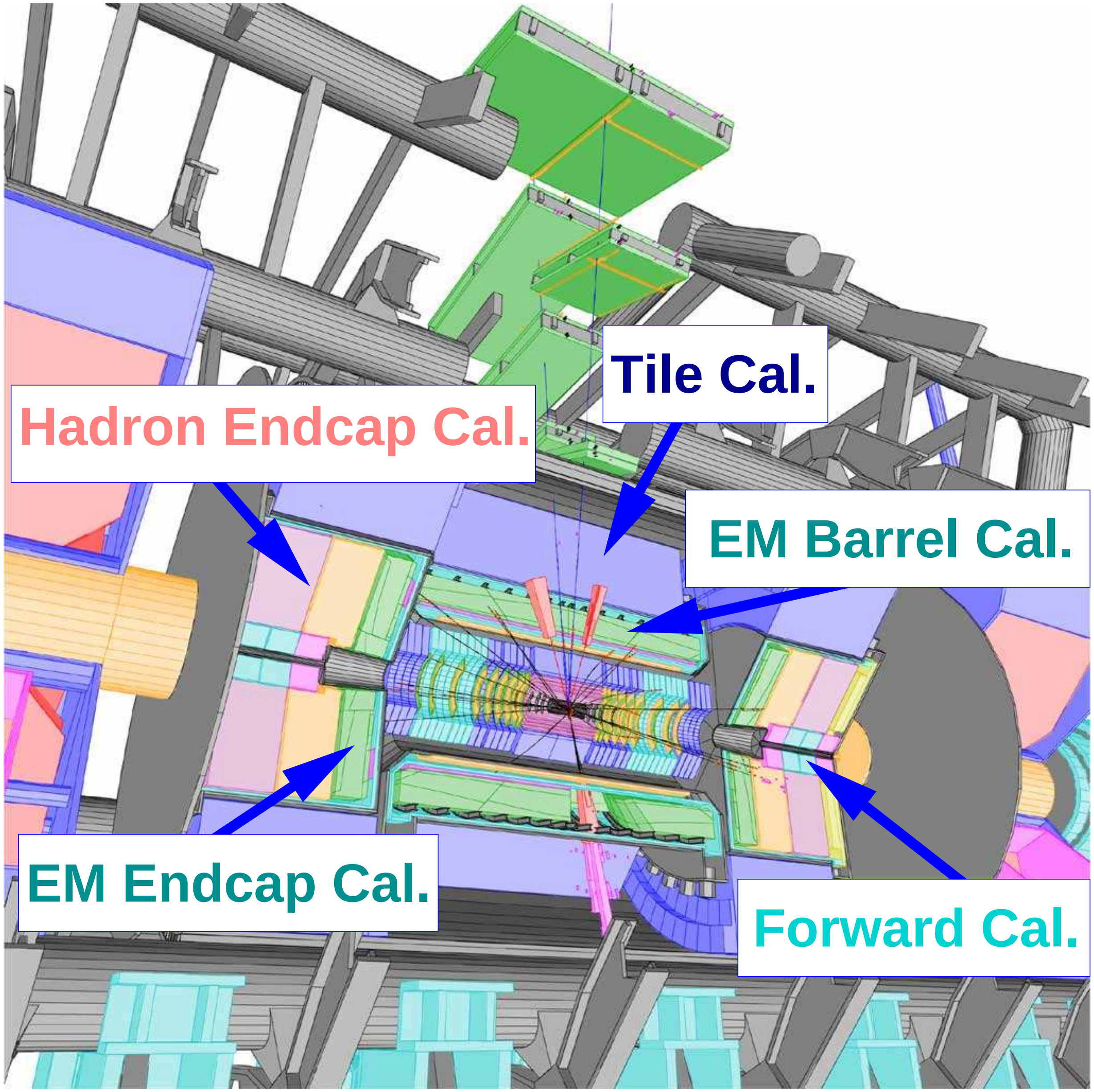
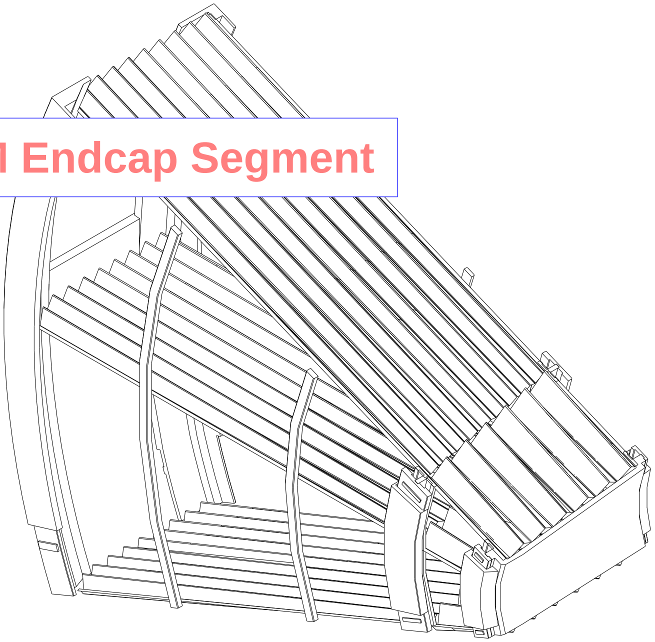
The ATLAS calorimeters

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

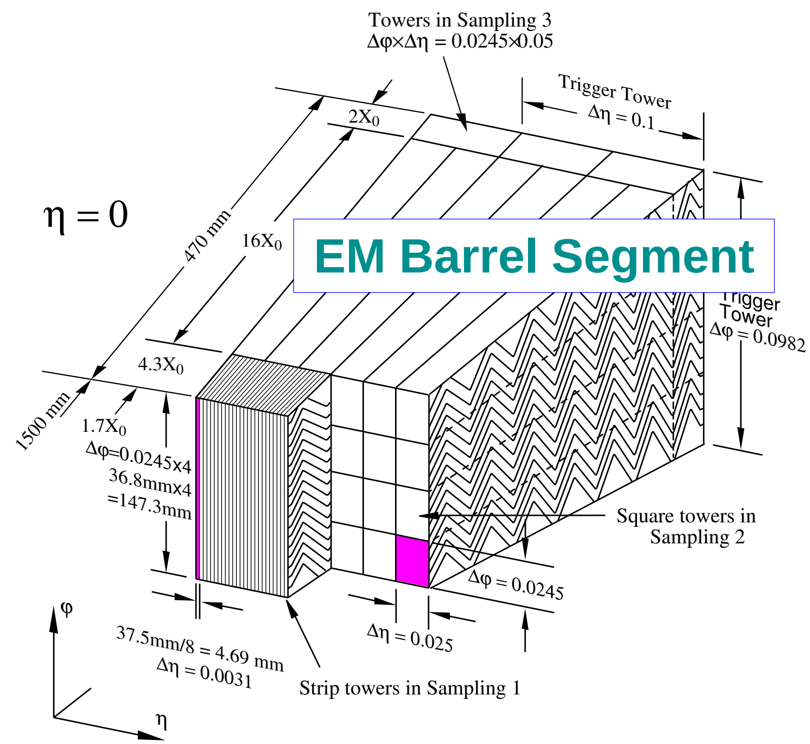


The ATLAS calorimeters > EMEC Accordion Geometry



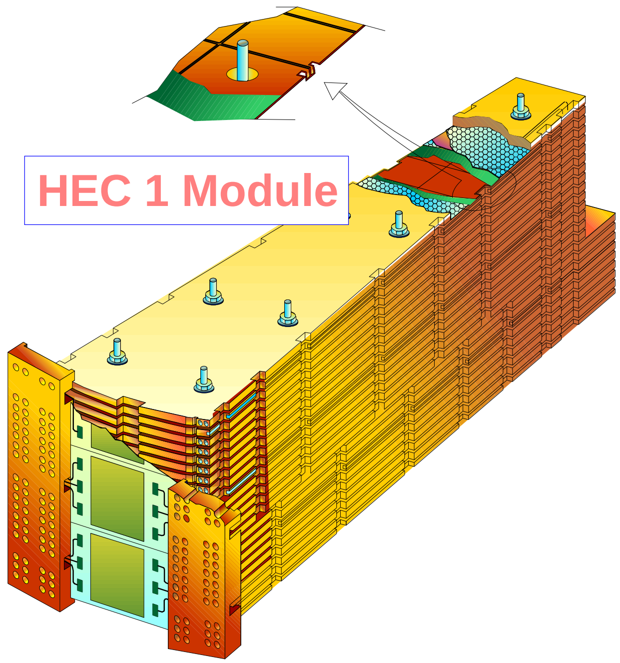
- EMEC absorber structure
  - ▷ Absorbers arranged radially
  - ▷ Folding angle and wave height vary with r
  - ▷ Anodes pointing in η

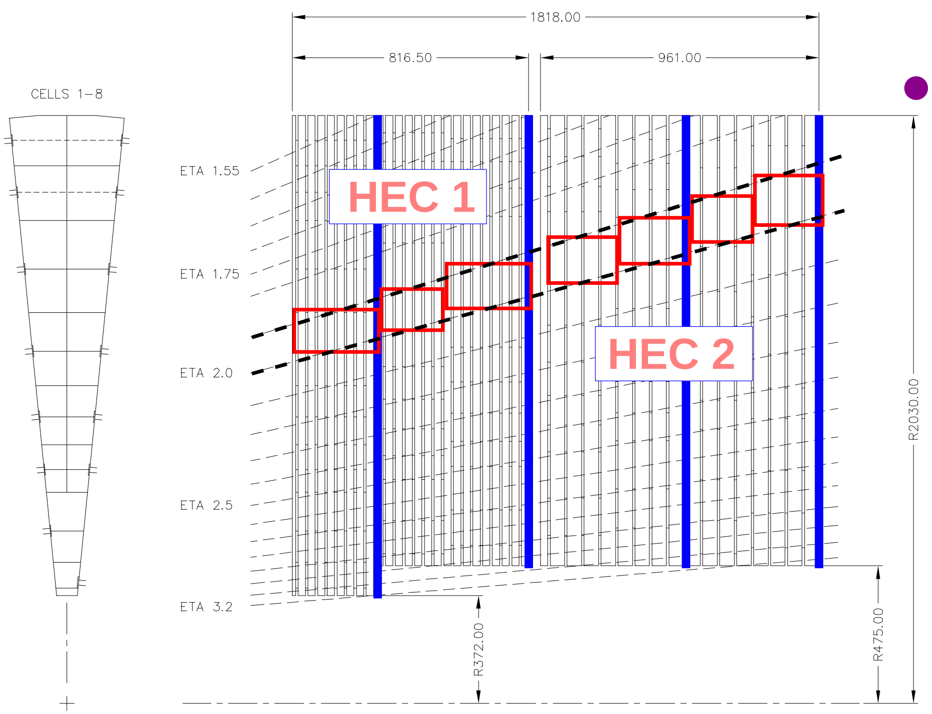
- EMEC readout structure
  - ▷ Layer1 (Front): $\simeq 2-4\,X_0$
    $\delta\eta \times \delta\phi = 0.025/8 \times 0.1$
  - ▷ Layer2 (Middle): $\simeq 16-18\,X_0$
    $\delta\eta \times \delta\phi = 0.025 \times 0.025$
  - ▷ Layer3 (Back): $\simeq 2-4\,X_0$
    $\delta\eta \times \delta\phi = 0.050 \times 0.025$



The ATLAS calorimeters > HEC Geometry

- HEC absorber structure
  - ▷ Absorbers plates parallel to beam axis
  - ▷ 2.5 cm thick Cu plates in HEC 1
  - ▷ 5.0 cm thick Cu plates in HEC 2

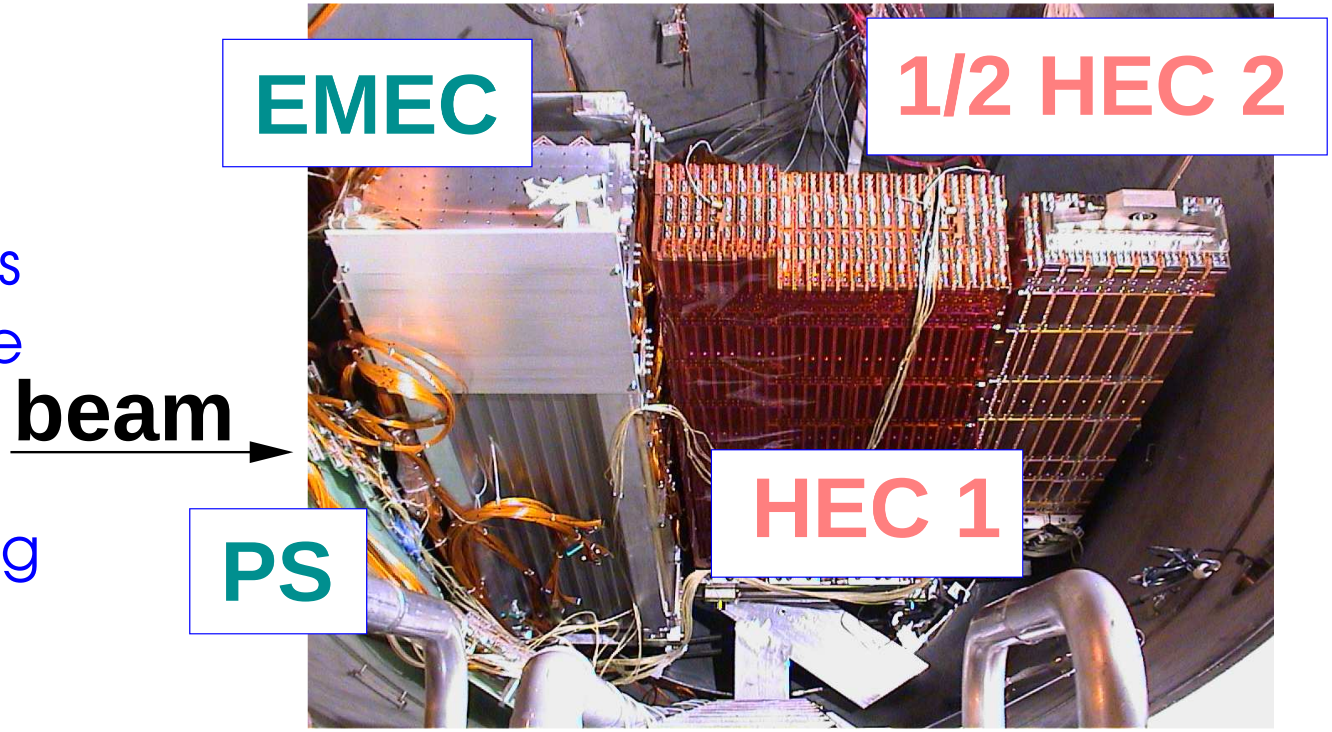




- HEC readout structure
  - ▷ $\delta\eta \times \delta\phi \simeq 0.1(0.2) \times 0.1(0.2)$
  - ▷ Layer1 (HEC1 Front): $\sum 8$ gaps
  - ▷ Layer2 (HEC1 Back): $\sum 16$ gaps summed pseudo pointing in η
  - ▷ Layer3&4 (HEC2 Front&Back): $\sum 8$ gaps summed pseudo pointing in η

EMEC & HEC combined beam test 2002 > Setup

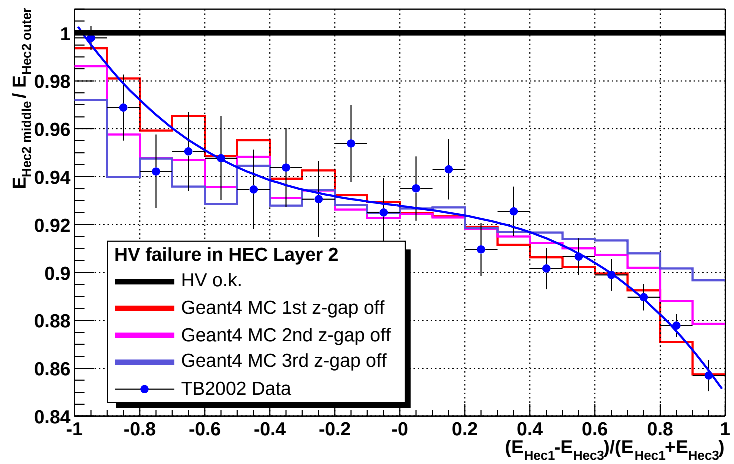
- H6 beam area at the CERN SPS
  - $6 \leq E \leq 200$ GeV $e^{\pm}, \mu^{\pm}, \pi^{\pm}$ beams
  - 90° impact angle (unlike ATLAS)
  - Scintillators for trigger and timing
  - 4 MWPCs with horiz. and vert. layers upstream
  - Optional additional material upstream

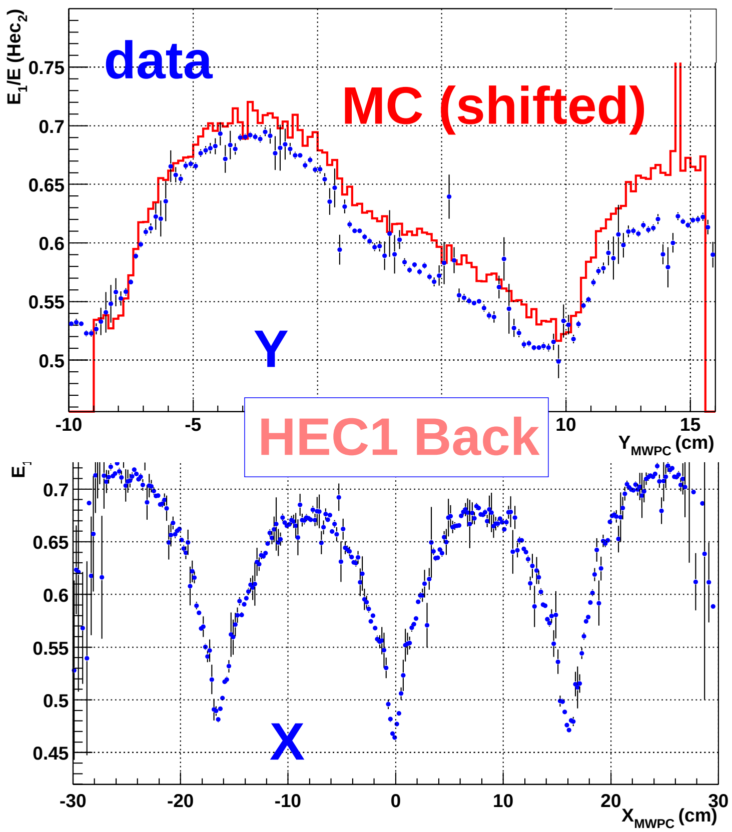


- Main goals for the beam test
  - study the region $\eta \sim 1.8$
  - obtain calibration constants for e and π
  - compare to detailed MC in order to extrapolate to jets
  - test methods for an optimal hadronic energy reconstruction

EMEC & HEC combined beam test 2002 > HV & alignment

- HV failure in HEC Layer 2
  - signal shows dip in one of three ϕ-modules
  - measured over expected signal for 200 GeV pions vs. $(E_1 - E_3)/(E_1 + E_3)$





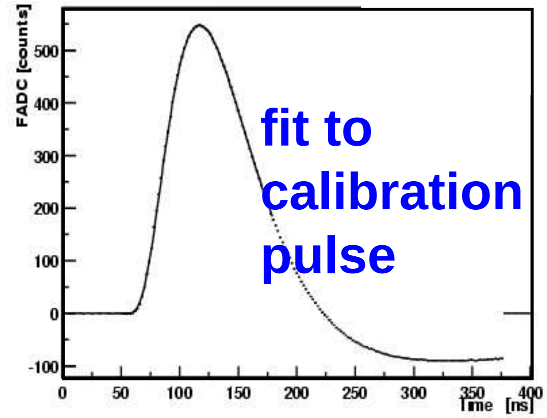
  - Geant4 MC with disconnected 1^{st} z-gap fits data best
  - correction with signal in previous and next sampling

- Alignment
  - E_{max}/E_{tot} vs. $x(y)$
  - use pad/module boundaries for alignment in x (0 cm; PS: +1.3 cm)
  - use comparison with MC for alignment in y (+2.7 cm; PS: +2.5 cm)

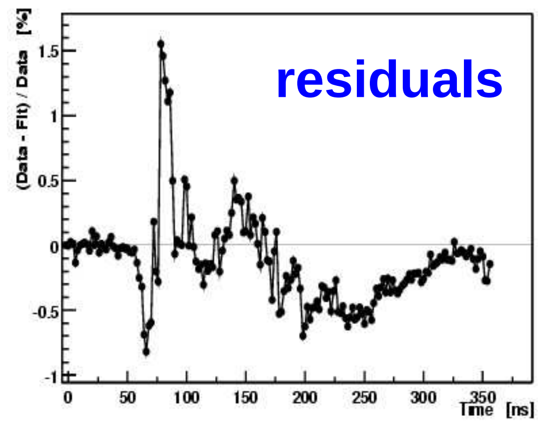
Signal reconstruction > Digital filter

- 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 $< 2\,\%$

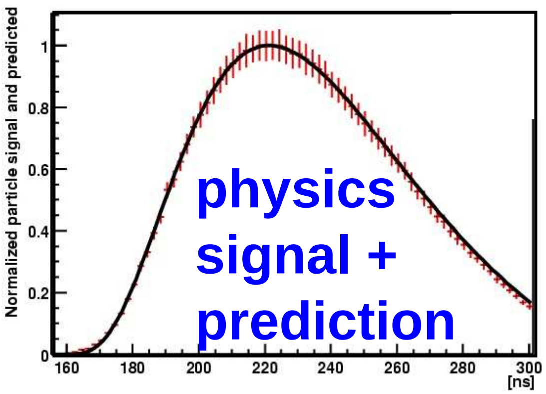
- Calibration pulse fit example
  - ▷ upper plot shows calibration signal and fit for one channel
  - ▷ $\tau_i = 43.2 \pm 0.1\,\text{ns}$ and $\tau_s = 14.20 \pm 0.02\,\text{ns}$ are fitted

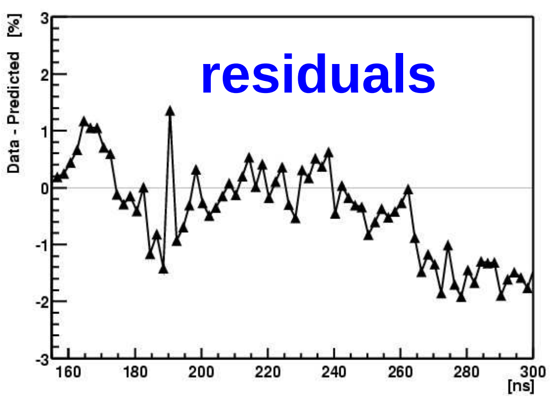


  - ▷ lower plot shows residual deviation from data $< 1.5\,\%$



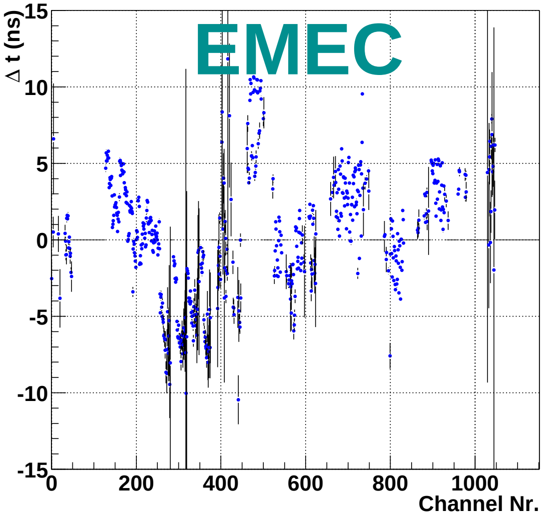
- Physics signal prediction

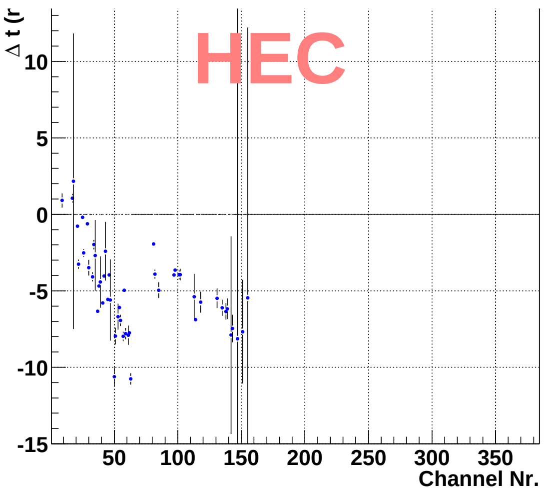




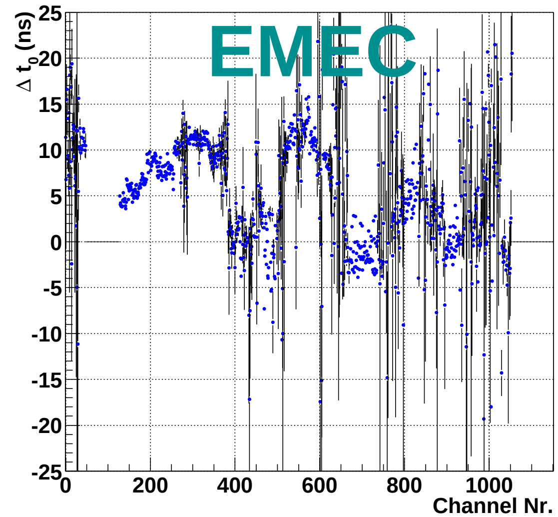
  - ▷ upper plot shows normalized physics signal and prediction for one channel
  - ▷ lower plot shows residual deviation from data $< 1.5\,\%$
  - ▷ noise reduction factor with 5 weights 0.64 (0.72) for HEC (EMEC)

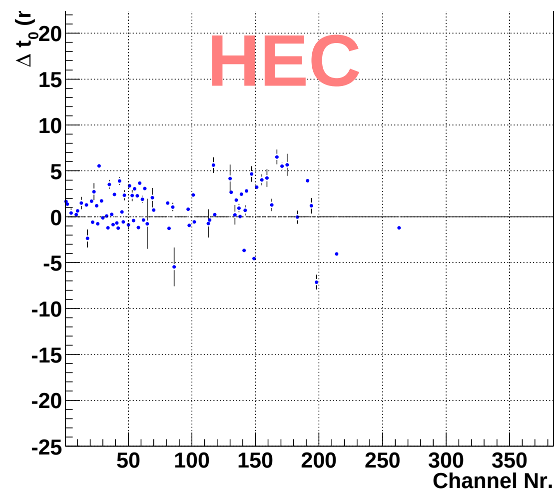
Signal reconstruction > Timing

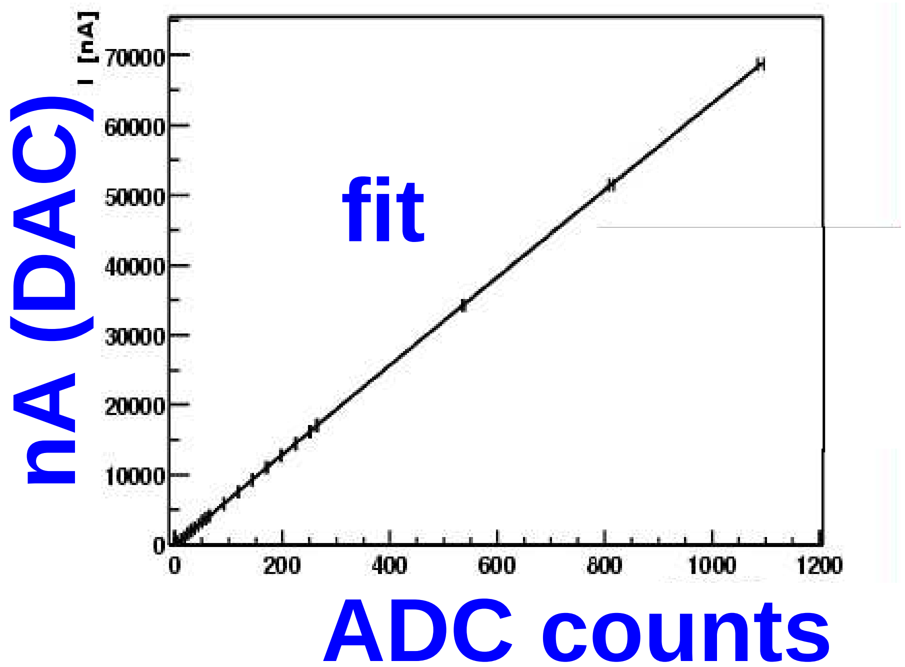


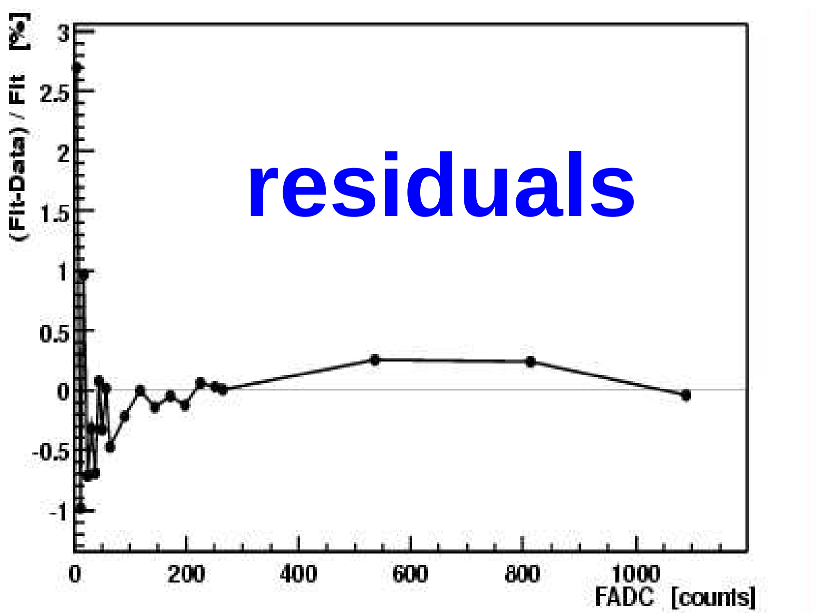


- 2 sets of time constants are needed
- 1st set defines signal peak for each channel relative to the trigger (not needed in ATLAS)
  - ▷ trigger in beam test in a 25 ns window
  - ▷ normally measured by TDC → broken
  - ▷ use polynomial fits to find peak positions
- 2nd set accounts for different cable delays in calibration/physics (also in ATLAS)
  - ▷ use OF weights for time
  - ▷ add time offset
  - ▷ iterate until OF time is 0 ns for each channel on average





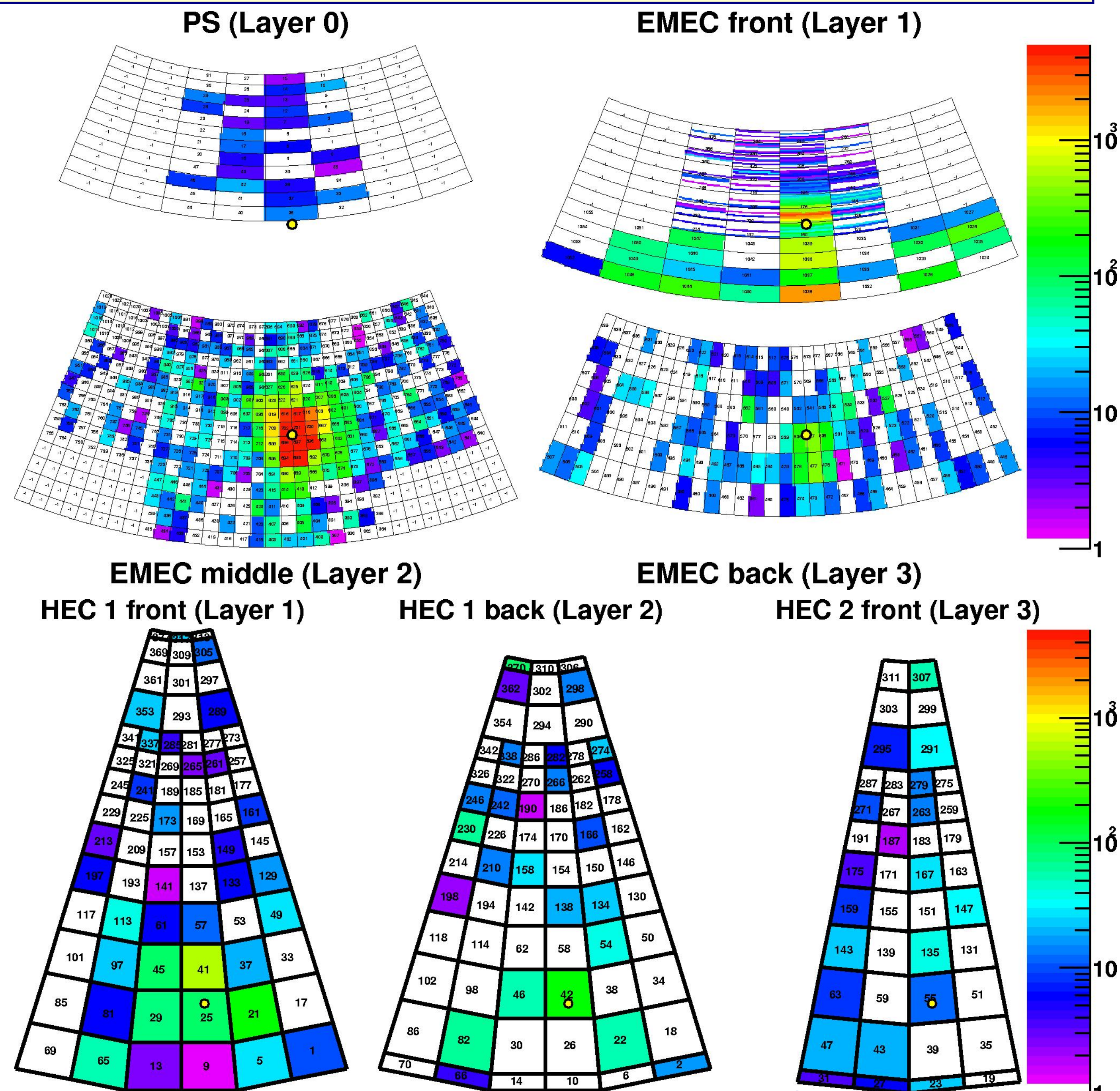




- Calibration from ADC to nA
  - ▷ use the OF weights found before
  - ▷ reconstruct the amplitudes for the calibration DAC level scans
  - ▷ fit the amplitude with a 3rd order polynomial to obtain calibration coefficients ADC $\rightarrow$ nA
  - ▷ accuracy $< 0.5\,\%$

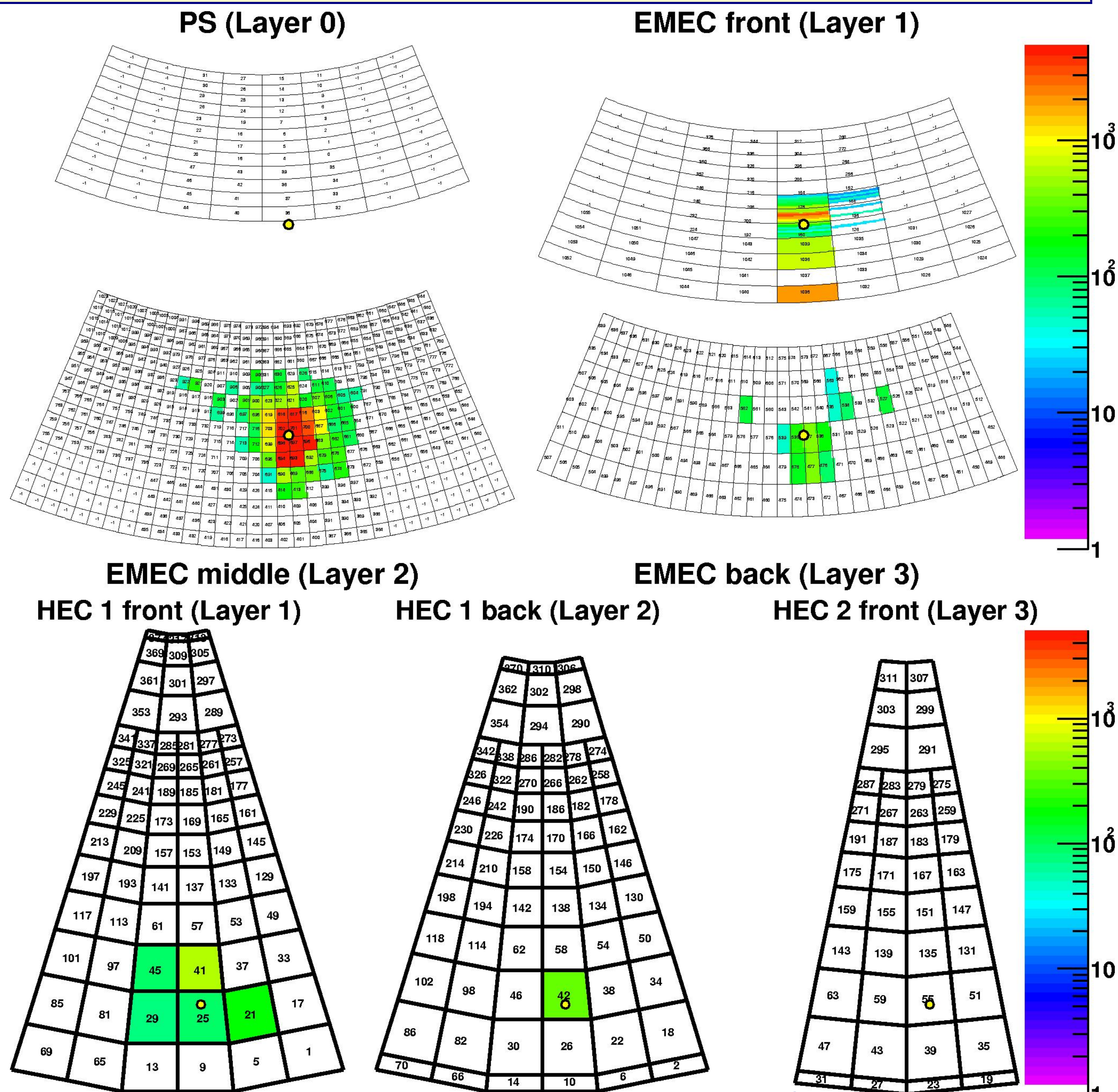
Clustering > Example event

- Event display for a 120 GeV pion in nA
  - 1 PS layer and 3 EMEC layers (1/8 wheel)
  - 2 HEC 1 layers (3/32 wheel)
  - 1 HEC 2 layers (1/16 wheel rotated by $\pi/32$)



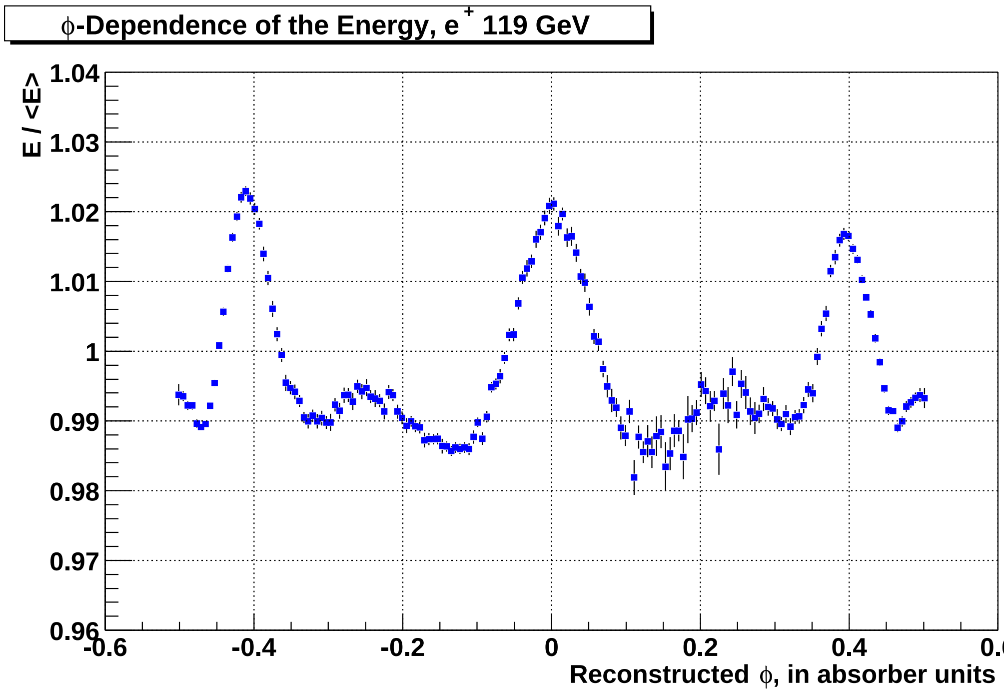
Clustering > Example event > After clustering

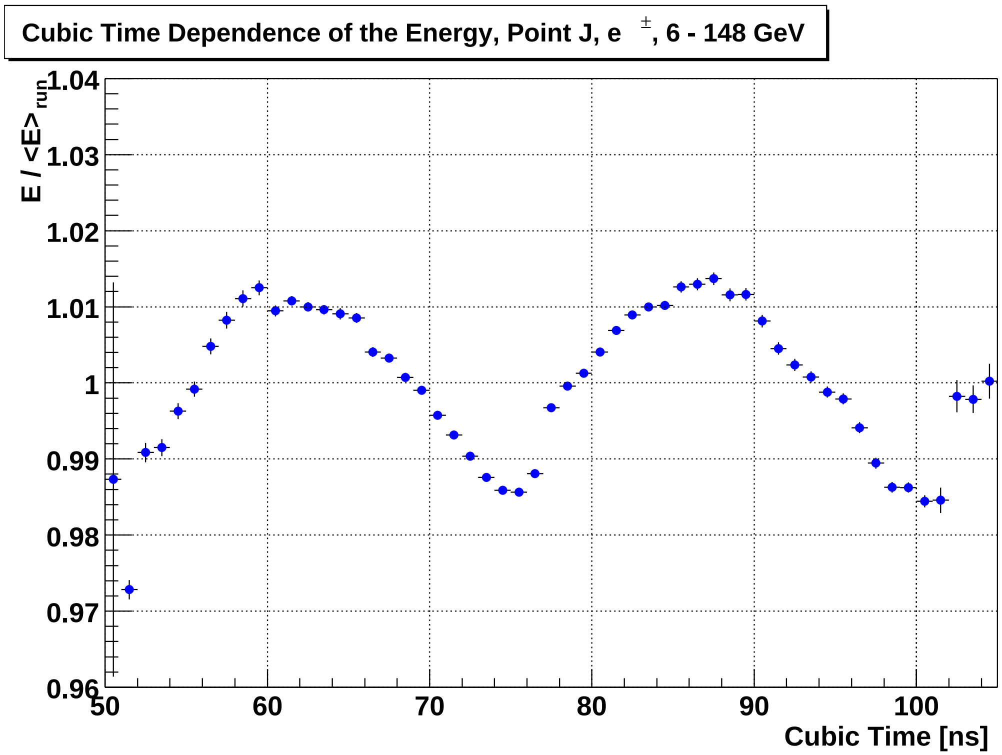
- Cell-based topological nearest neighbor cluster algorithm
  - Clusters are formed in 2D
  - Cell cut $|E/\text{noise}| > 2\sigma$
  - Seed cut $E/\text{noise} > 4\sigma$
  - Include cells neighboring cluster members with $|E/\text{noise}| > 3\sigma$
  - Iterate
- Neighbor means common edge



Energy calibration > Signal Corrections

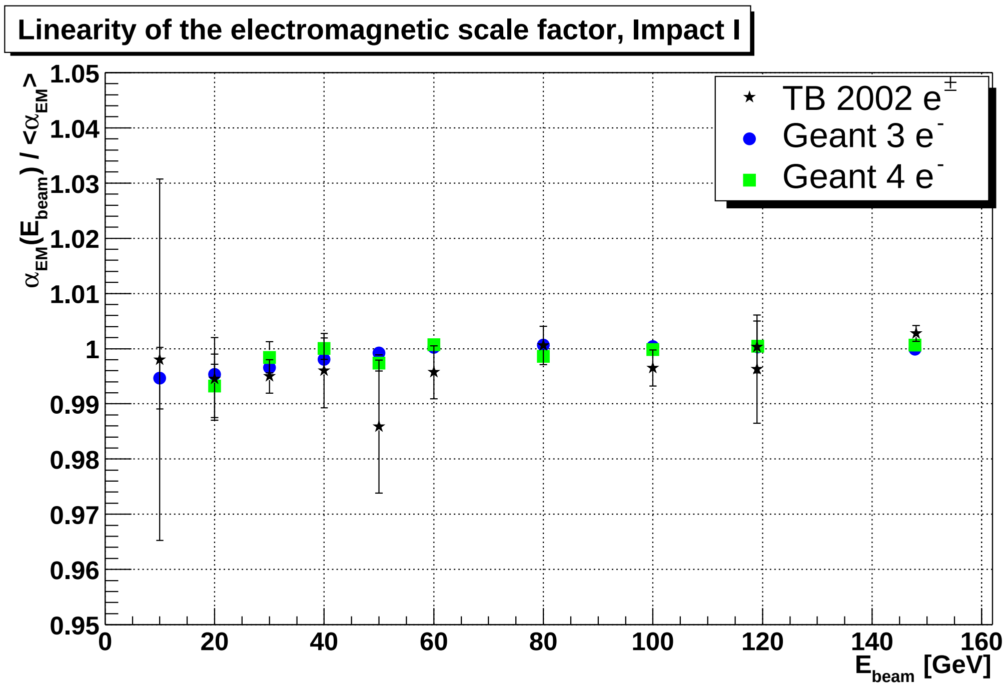
- study EMEC response to electrons first
- predict detector leakage with MC
- apply corrections



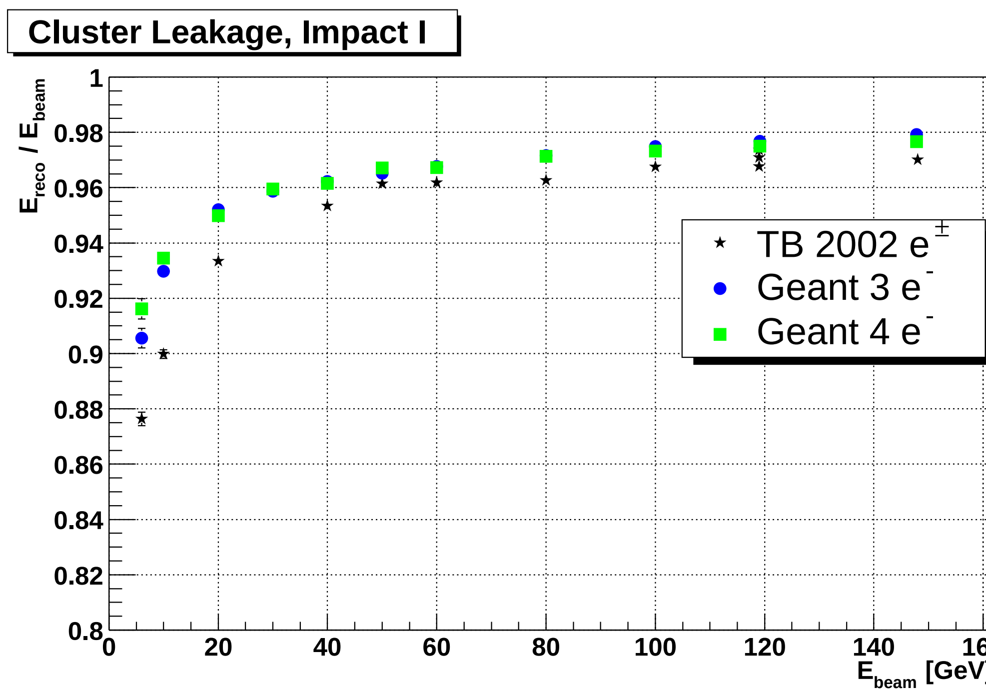


- ϕ correction due to non-uniformity in E-field and sampling variations of $\pm 1.5\,\%$
- correction due to residual variations with the trigger time of $\pm 1\,\%$

Energy calibration > Electromagnetic scale



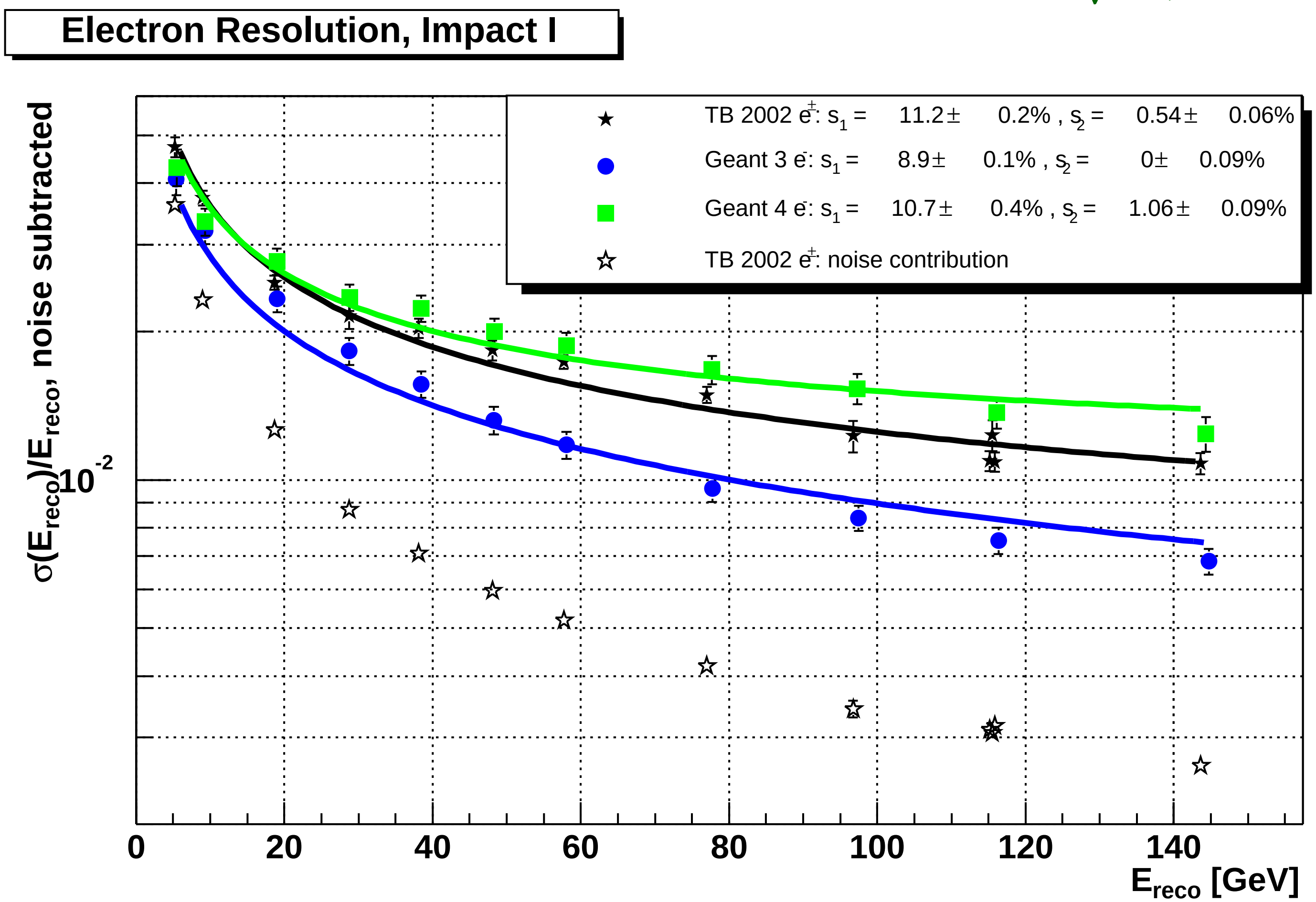
- $\alpha_{em}^{EMEC} = 0.3855 \pm 0.0004\,\mathrm{MeV/nA}$
  - linearity good to $\pm 0.5\,\%$
  - well reproduced by MC
- cluster leakage available in MC and data



- 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 > Resolution for electrons

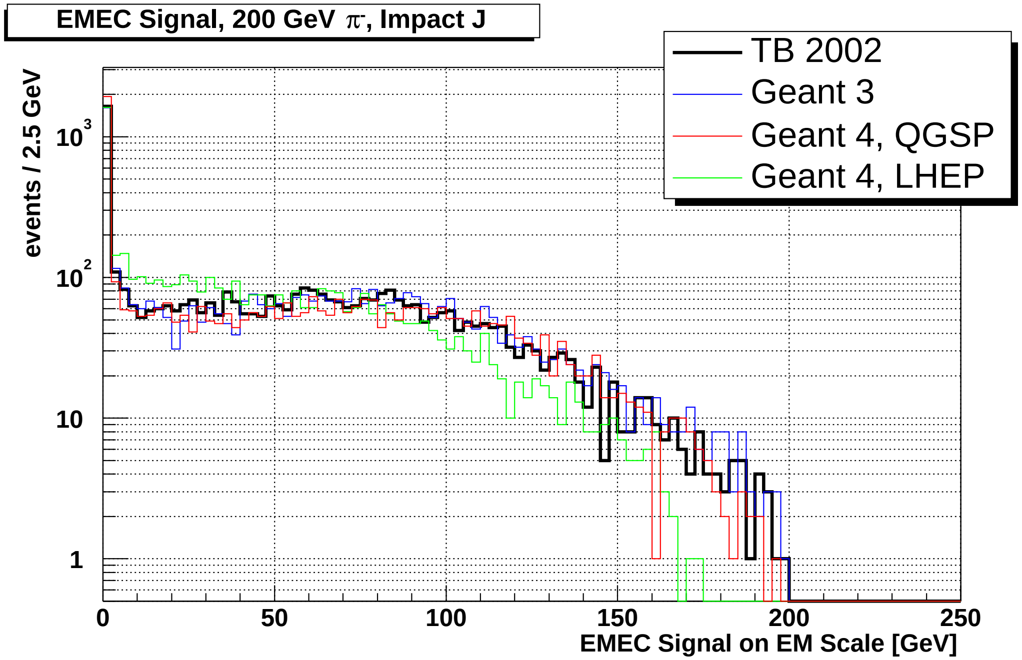
- σ_E/E (%) noise subtracted
  - data: $\frac{11.2 \pm 0.2}{\sqrt{E/\mathrm{GeV}}} \oplus 0.5 \pm 0.1$
  - Geant3: $\frac{8.9 \pm 0.1}{\sqrt{E/\mathrm{GeV}}} \oplus 0.0 \pm 0.1$
  - Geant4: $\frac{10.7 \pm 0.4}{\sqrt{E/\mathrm{GeV}}} \oplus 1.1 \pm 0.1$

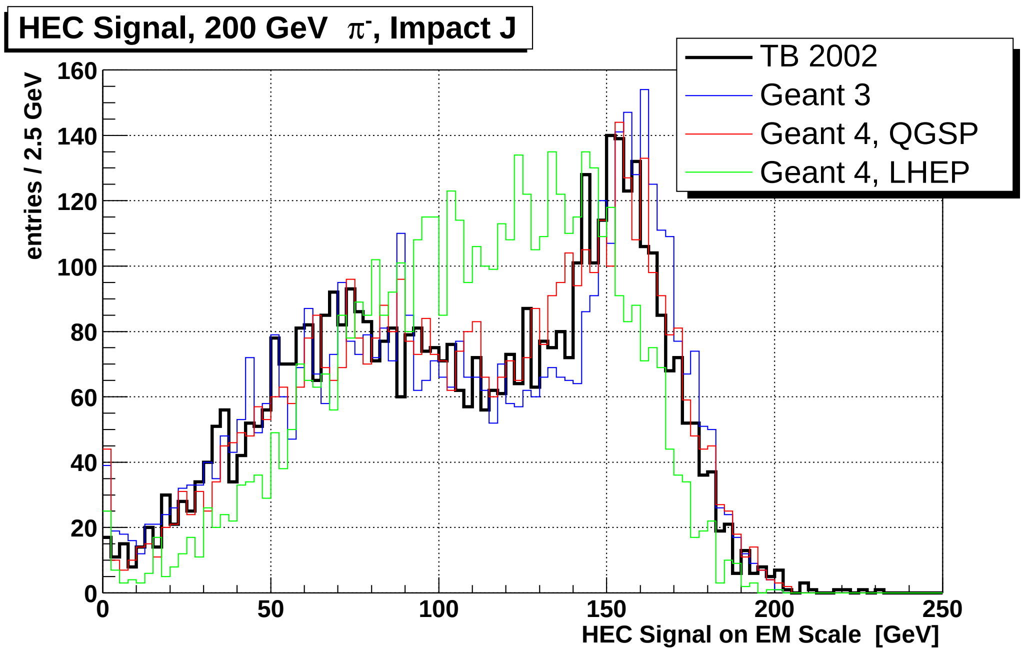


- noise: $\sigma_{\mathrm{noise}}/E \simeq 300\ \mathrm{MeV}/E$

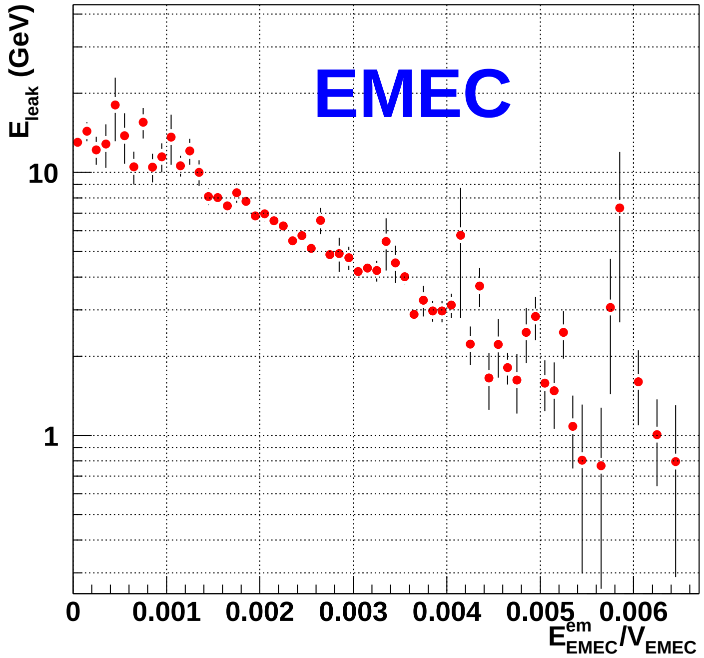
Energy calibration > Response to pions

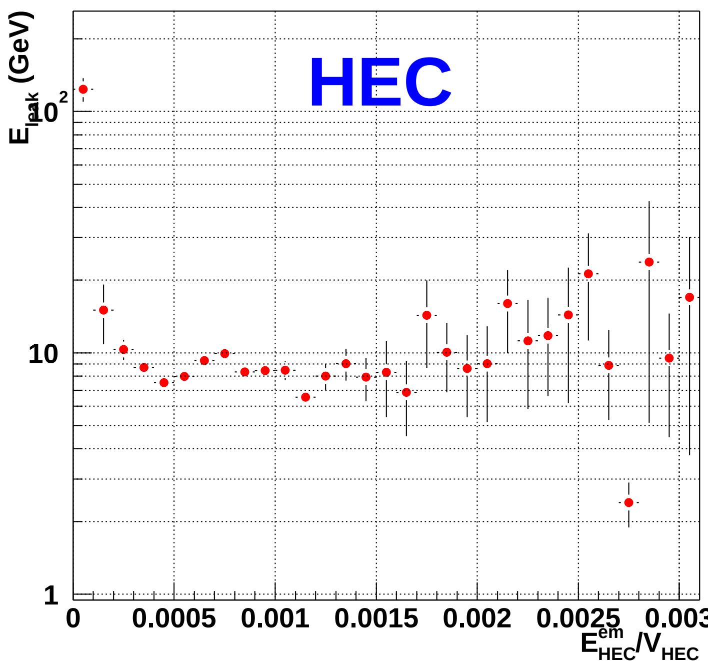
- No electrons in HEC only
  - ▷ Electromagnetic scale from previous HEC stand-alone TB
  - ▷ Modified by new electronics
  - ▷ Calculated value: $\alpha_{em}^{HEC} = 3.266\,\mathrm{MeV/nA}$
- Response to 200 GeV pions in data and MC on em-scale
  - ▷ upper plot shows EMEC
  - ▷ lower plot shows HEC
  - ▷ Geant3 and Geant4 QGSP describe data reasonably well
  - ▷ Geant4 LHEP deviates substantially





Energy calibration > Weighting



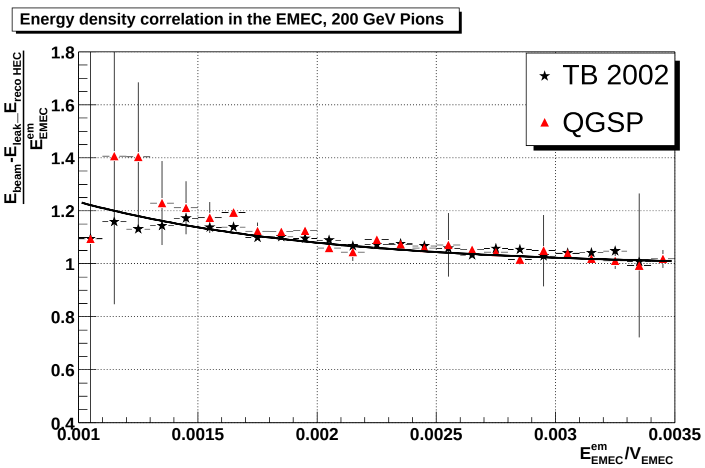


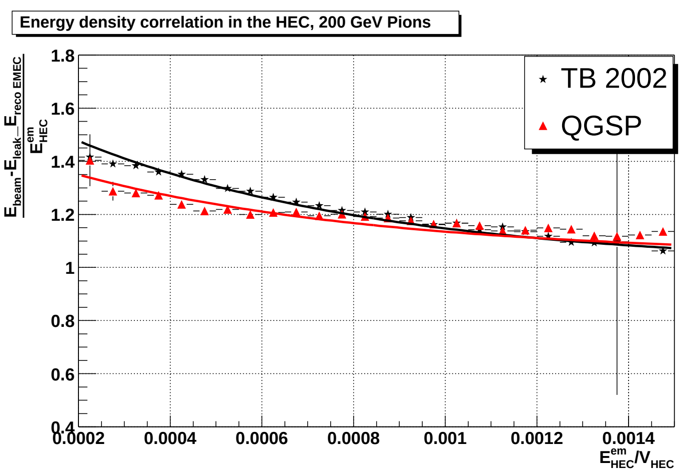
- EMEC and HEC are non compensating
  - ▷ corrections (weights) need to be applied on top of the em-scale constants
  - ▷ various weighting methods are studied
  - ▷ best would be cell-based weights → needs more detailed MC than currently available
  - ▷ cluster based weights as function of energy density E_{clus}/V_{clus} are obtainable now
- needs detector leakage information from simulation as function of E^{HEC}/V^{HEC} and E^{EMEC}/V^{EMEC}
  - ▷ plots show total detector leakage for 200 GeV pions Geant4 QGSP MC

Energy calibration > Weighting > Cluster weights

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

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

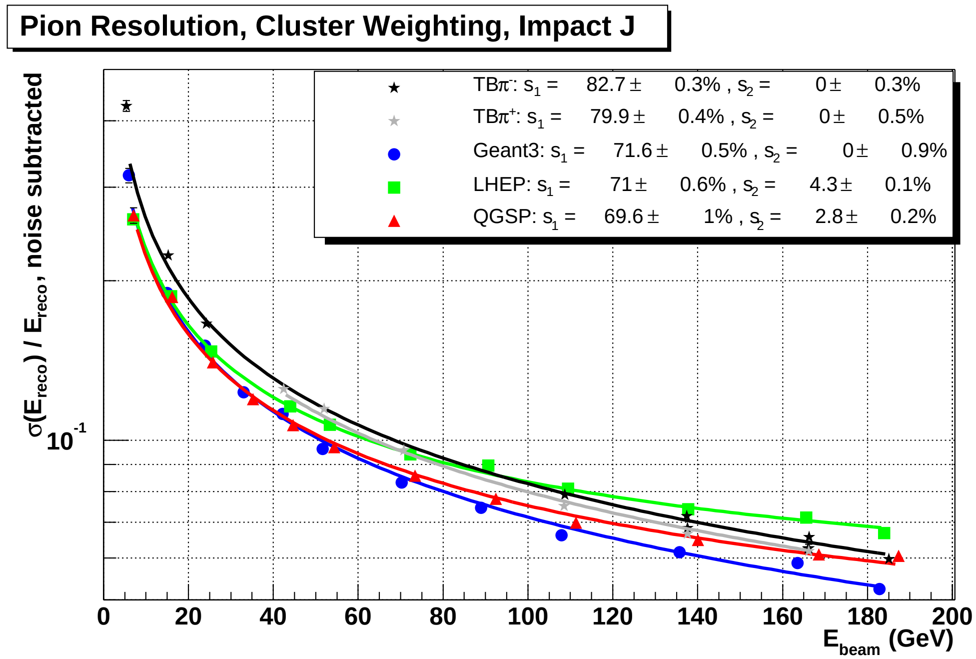


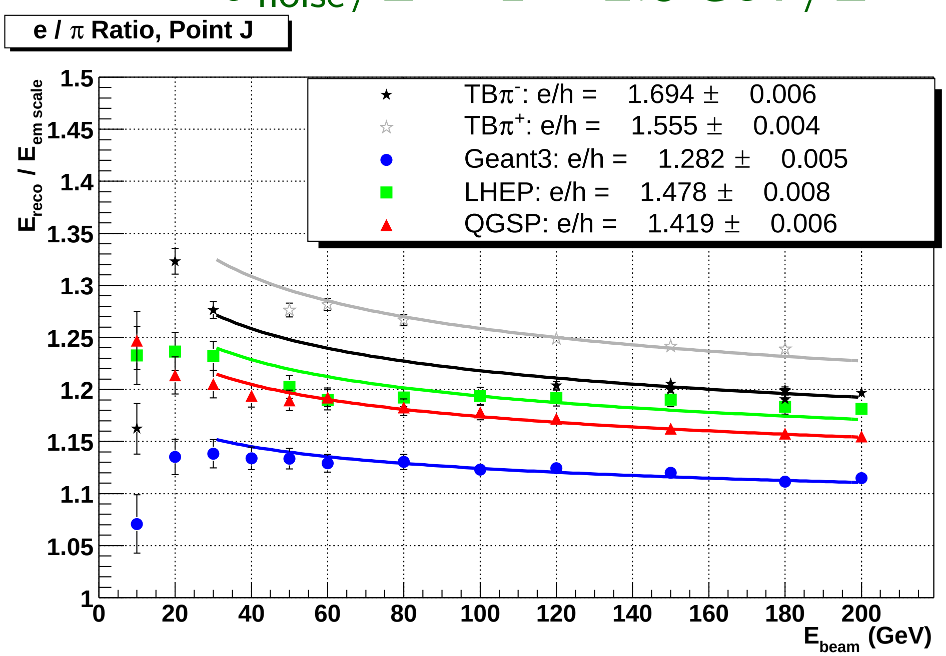


- ▷ $E_{\text{reco}} = E_{\text{em}}\left(c_1 \cdot \exp\left[-c_2 \cdot E_{\text{em}}/V\right] + c_3\right)$ (H1 method)
- ▷ $E_{\text{tot}} = E_{\text{reco}} + E_{\text{em}}^{\text{cluster leak}}$
- ▷ E_{leak} as on previous slide from MC
- ▷ c_2 fixed to $1000\,\text{cm}^3/\text{GeV}$ ($1500\,\text{cm}^3/\text{GeV}$) 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 (π^-): $\frac{82.7 \pm 0.3}{\sqrt{E/\text{GeV}}} \oplus 0.0 \pm 0.3$
  - data (π^+): $\frac{79.9 \pm 0.4}{\sqrt{E/\text{GeV}}} \oplus 0.0 \pm 0.5$
  - noise: $\sigma_{\text{noise}}/E \simeq 1 - 2.5\ \text{GeV}/E$





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

Energy calibration > Road-map to ATLAS

- reusable calibration methods from the beam test
  - ▷ Optimal filter weights
  - ▷ ADC $\rightarrow$ nA calibration constants
  - ▷ Timing constants due to calibration/physics differences
- applicable methods used during beam tests for energy calibration in ATLAS
  - ▷ Clustering (modified cuts for pile-up; 3D instead of 2D)
  - ▷ Cluster and/or cell weighting
- methods untested in beam tests
  - ▷ Jet reconstruction
  - ▷ Particle ID in jets