The ATLAS Liquid Argon Hadronic End Cap Calorimeter: Construction and Selected Beam Test Results

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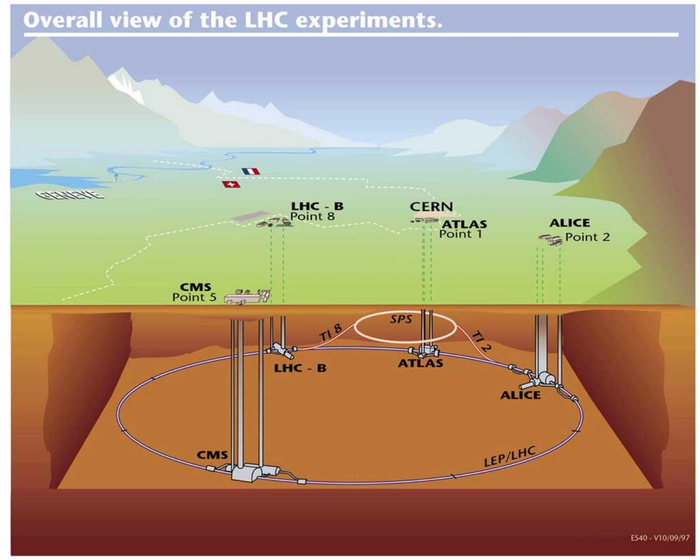
- LHC and ATLAS
- The ATLAS LAr Hadronic End Cap Calorimeter
- HEC Construction Status
- EMEC HEC 2002 Combined Beam Test
- Electron Results
- Pion Results

on behalf of the ATLAS HEC Collaboration:
Canada, China, Germany, Russia, Slovakia

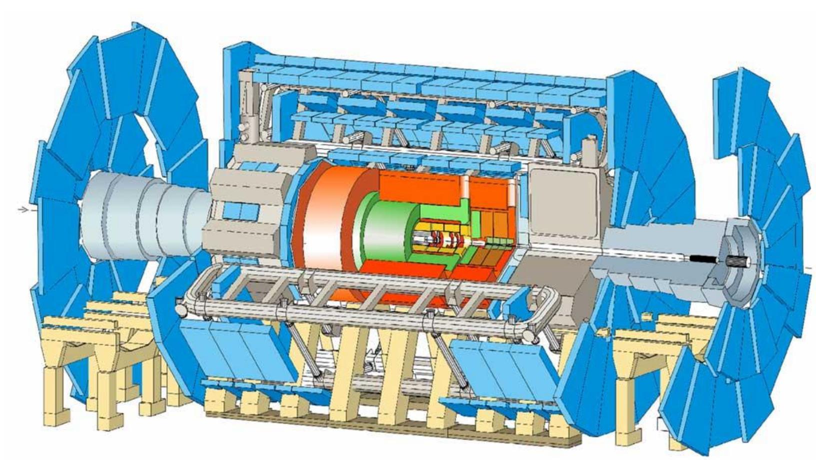
LHC and ATLAS

- The Large Hadron Collider: LHC at CERN
  - 14 TeV pp collisions by 2007
  - 27 km collider in the LEP tunnel

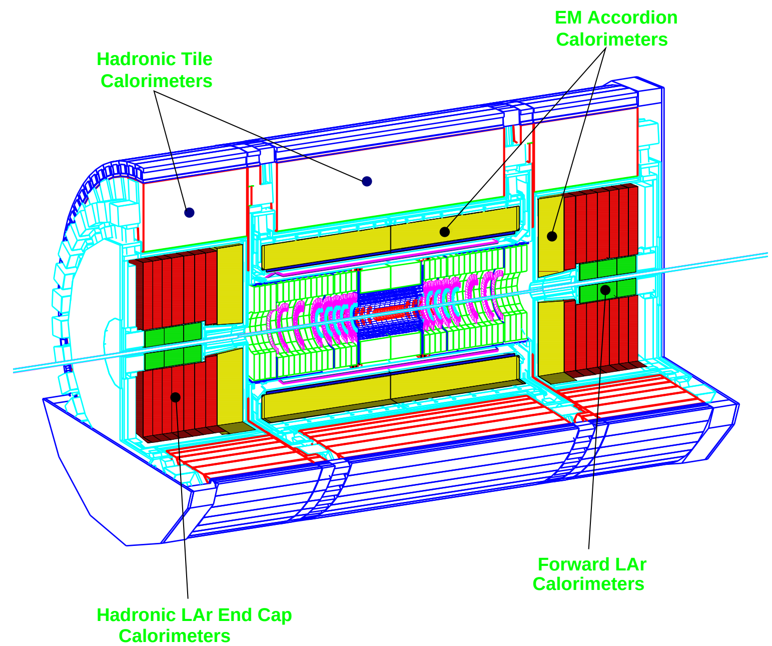


- **ATLAS**: A Toroidal LHC ApparatuS

ATLAS Detector

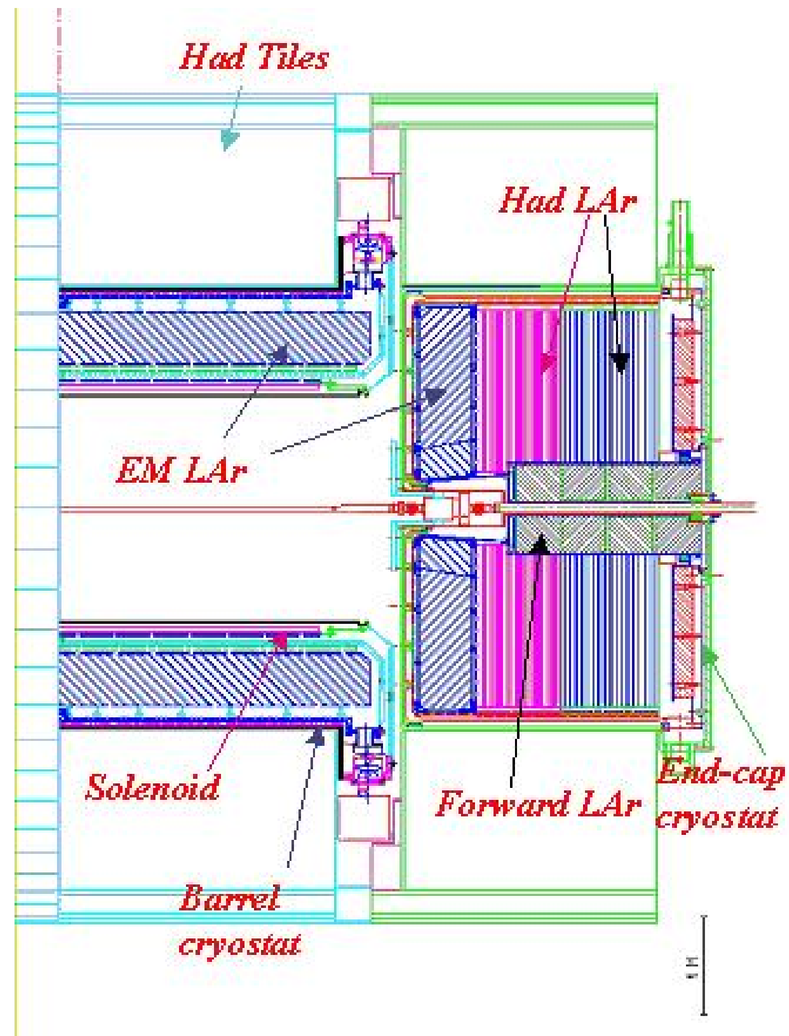


ATLAS Calorimetry (Geant)



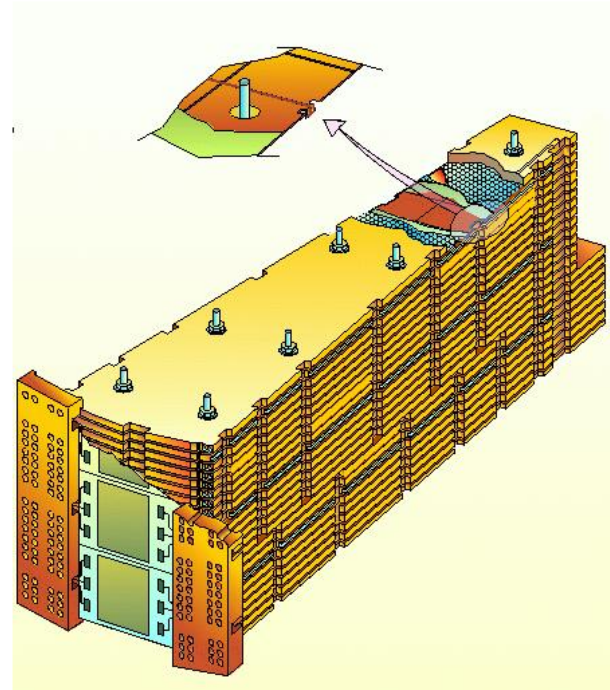
LAr Calorimeter in ATLAS

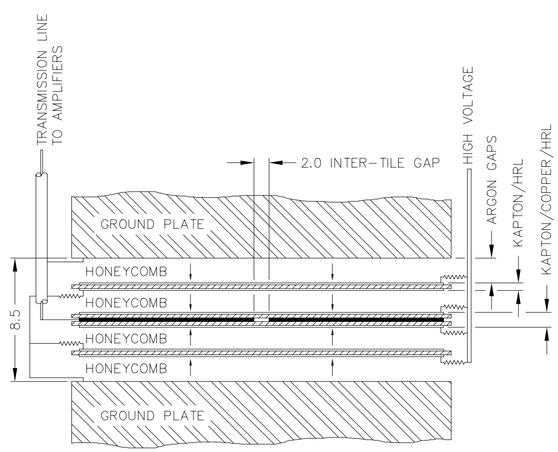
- With the LHC running at high luminosity ($10^{34}cm^{-2}s^{-1}$) the ATLAS calorimeter is designed to trigger on and to provide measurements of e, γ, jets, and missing $E_{\perp}$
- Liquid Argon technique is used for the the hadron end cap calorimeter (HEC) which is the subject of this talk
  - The reconstruction of jets in the forward region and the measurements of the missing $E_{\perp}$ are driving the HEC requested performance parameters
  - A typical $\sigma(E)/E = 50\%/\sqrt{E(GeV)} \oplus 3\%$ is required for jets

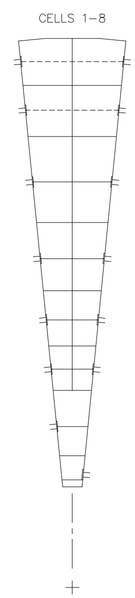


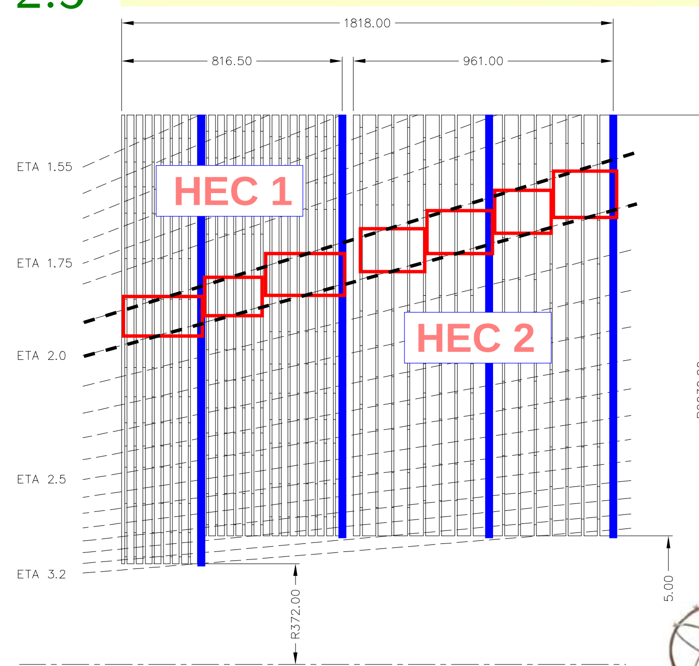
LAr Hadronic End Cap Calorimeter: HEC

- HEC is a LAr sampling calorimeter with CU absorber plates: $1.5 < \eta < 3.2$
- It consists of:
  - 2 end caps: HEC A and HEC C
  - 4 wheels, 2 per end cap
  - 4×32 modules
  - 24 (16) gaps/front (rear) per wheel
  - 4 sub gaps ($1.85\,\mathrm{mm}$) per gap: with electrostatic transformer (EST)
  - 4 longitudinal samplings
  - $\Delta\eta \times \Delta\phi$ of 0.1×0.1 and 0.2×0.2 for $\eta > 2.5$
  - Cold electronics (“active pad”)

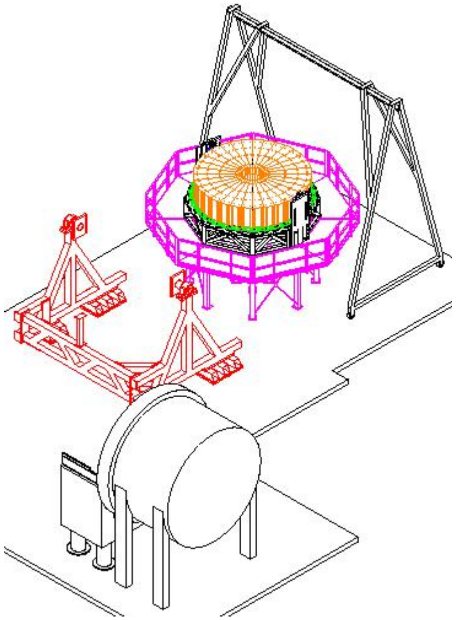


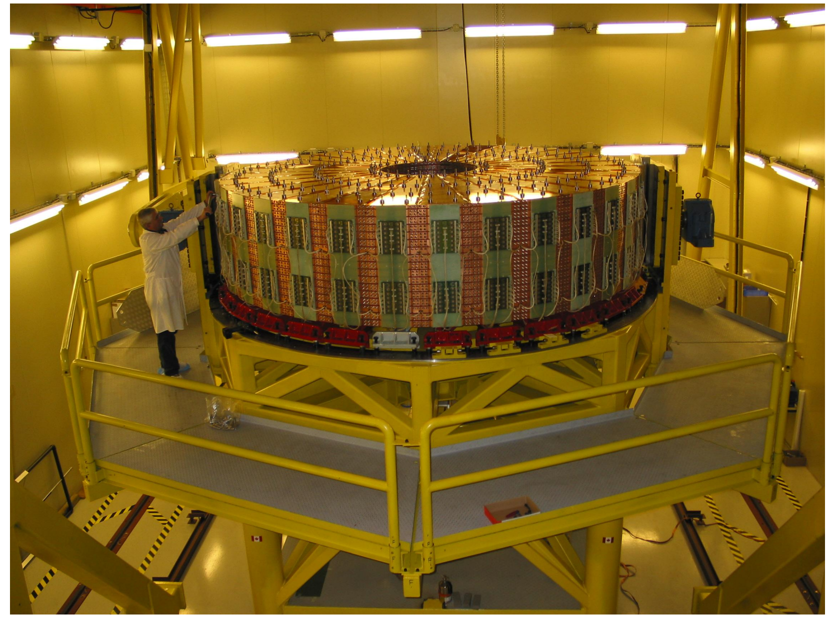


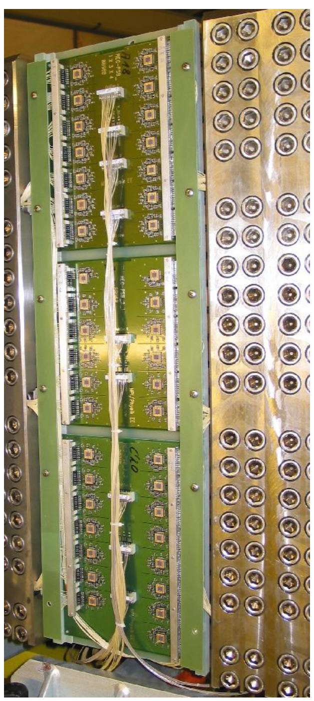


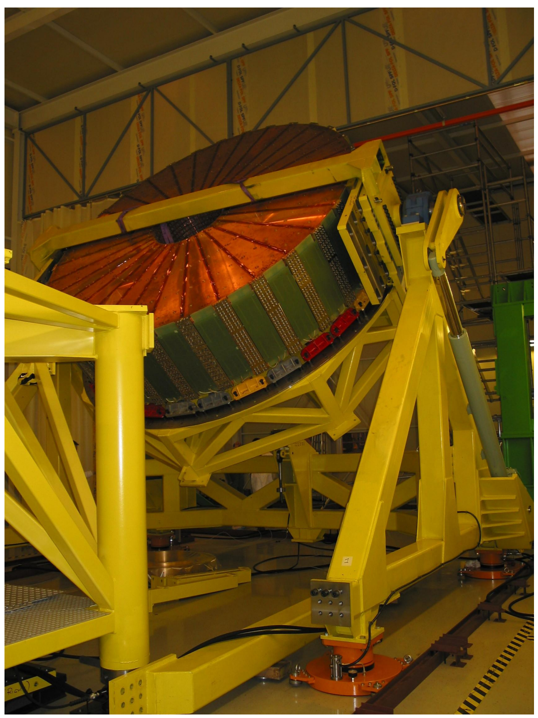


Status of the HEC Assembly at CERN



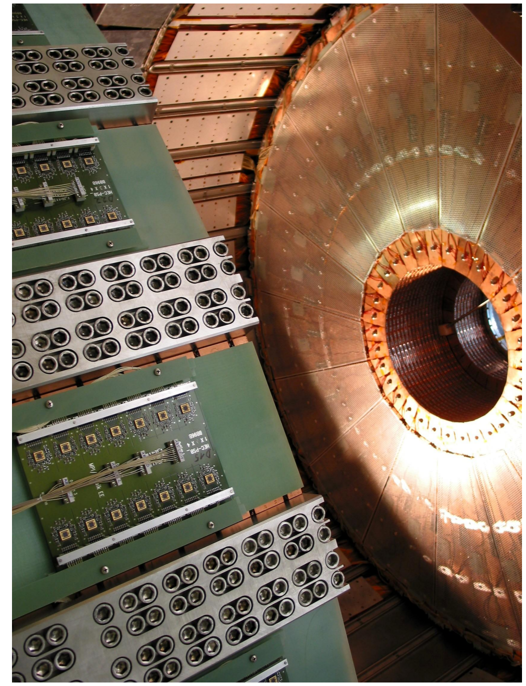


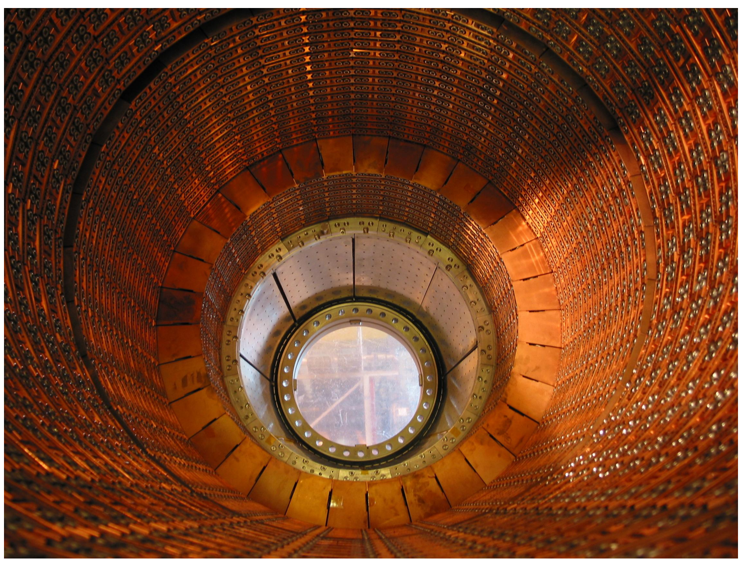




- Assembly of the 4 wheels done
- All modules passed the cold test
- All electronics boards cold tested

End Cap C Integration

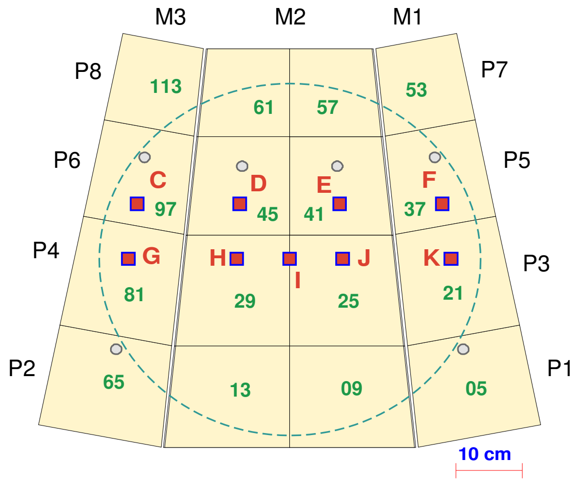




- Integration of HEC C done
  - Wheel deviation $\sim 0.5 - 1.1\,\mathrm{mm}$
  - Out of 5120 only 7 gaps have HV problems
  - Out of 3072 only 1 signal channel is not operational

EMEC & HEC Combined Beam Test 2002

- A full ϕ wedge of the LAr HEC tested at the H6 beam area at the CERN SPS
  - $6 \leq E \leq 200$ GeV with $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$ beams
  - Beam at 90° impact angle, "non-pointing setup" (unlike ATLAS)
  - Beam position chambers
  - Optional additional material upstream, presampler studies



- Main goals for the beam test
  - Study the forward region $1.6 < \eta < 1.8$
  - Obtain calibration constants for e and π
  - Comparison with MC simulation to allow extrapolation to jets
  - Test methods and algorithms for optimal hadronic energy reconstruction in ATLAS

Signal Reconstruction

- Used "Optimal filtering method" (like in ATLAS)
  - "The goal of this method is to reconstruct the amplitude and the time of a signal with a known signal shape from discrete measurements of the signal, minimizing the noise contribution to the amplitude reconstruction"
    - need known physics signal shape: $g(t)$
    - discrete ($\Delta t = 25\,\mathrm{ns}$) signal measurements (signal + noise) $y_i = E\,g_i + b_i$
    - noise autocorrelation matrix (from noise runs) $B_{ij} = \langle b_i b_j \rangle - \langle b_i \rangle \langle b_j \rangle$
    - estimate signal amplitude E with $\tilde{E} = \sum a_i y_i = a^t y$ from minimization of $\chi^2 = (y - E\,g)^t\,B\,(y - E\,g)$
    - solution given by OF weights $a = \frac{B^{-1} g}{g^t B^{-1} g}$

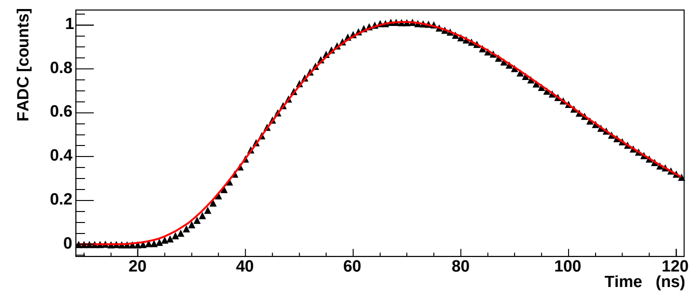
- Big problem is how to get the signal shape $g(t)$
  - obtained directly from data
  - or obtained from calibration pulses and detailed knowledge of difference between signal pulse shape and calibration pulse shape

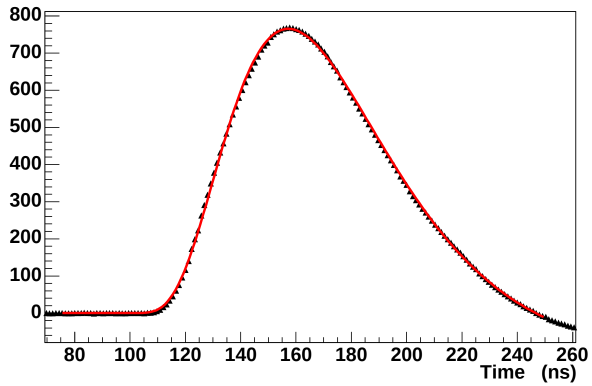
HEC Calibration

- Crucial is to study and understand the difference in pulse height and shape between data and calibration signals
- Need good knowledge of the electronics modeling
- Finally predict signal pulse from calibration pulse
- Precision of the signal reconstruction of real particles: $\pm 1\%$

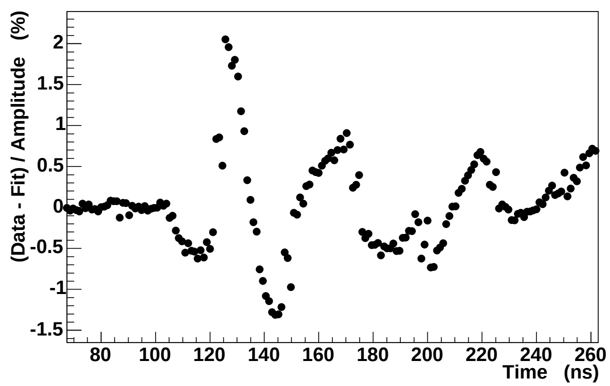
For a typical HEC read-out channel

Particle signal (points) and prediction (line)

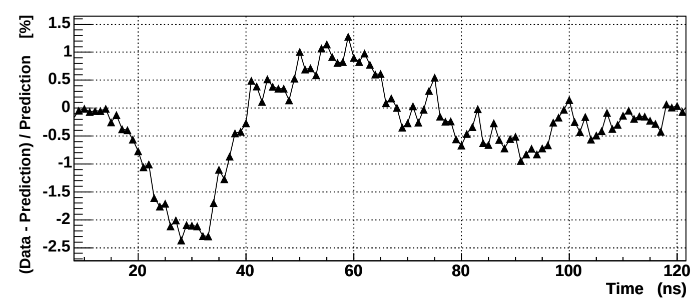




Calibration signal (points)
Fitted electronic function (line)

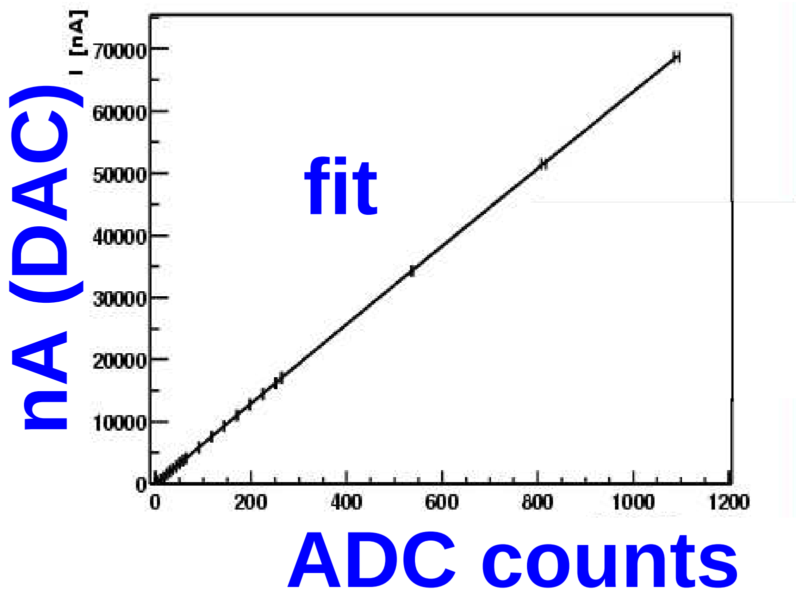


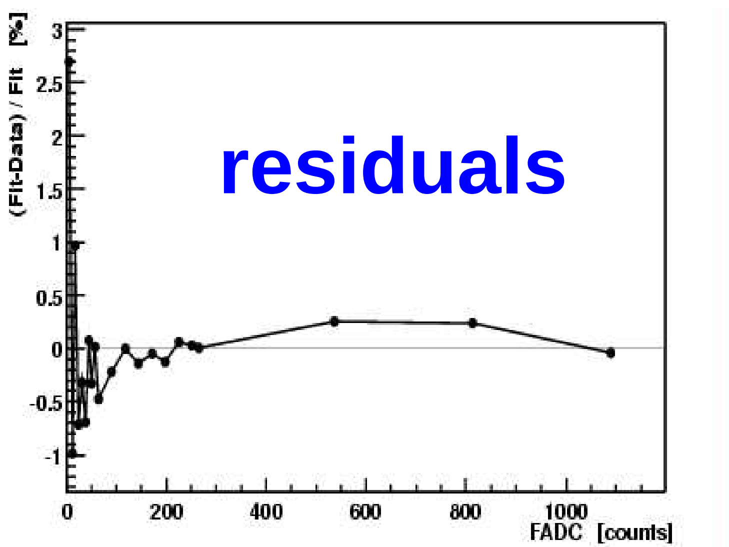
Residua within $\pm 1.5\%$



Residua within $\pm 1.5\%$

Calibration: from ADC to nA



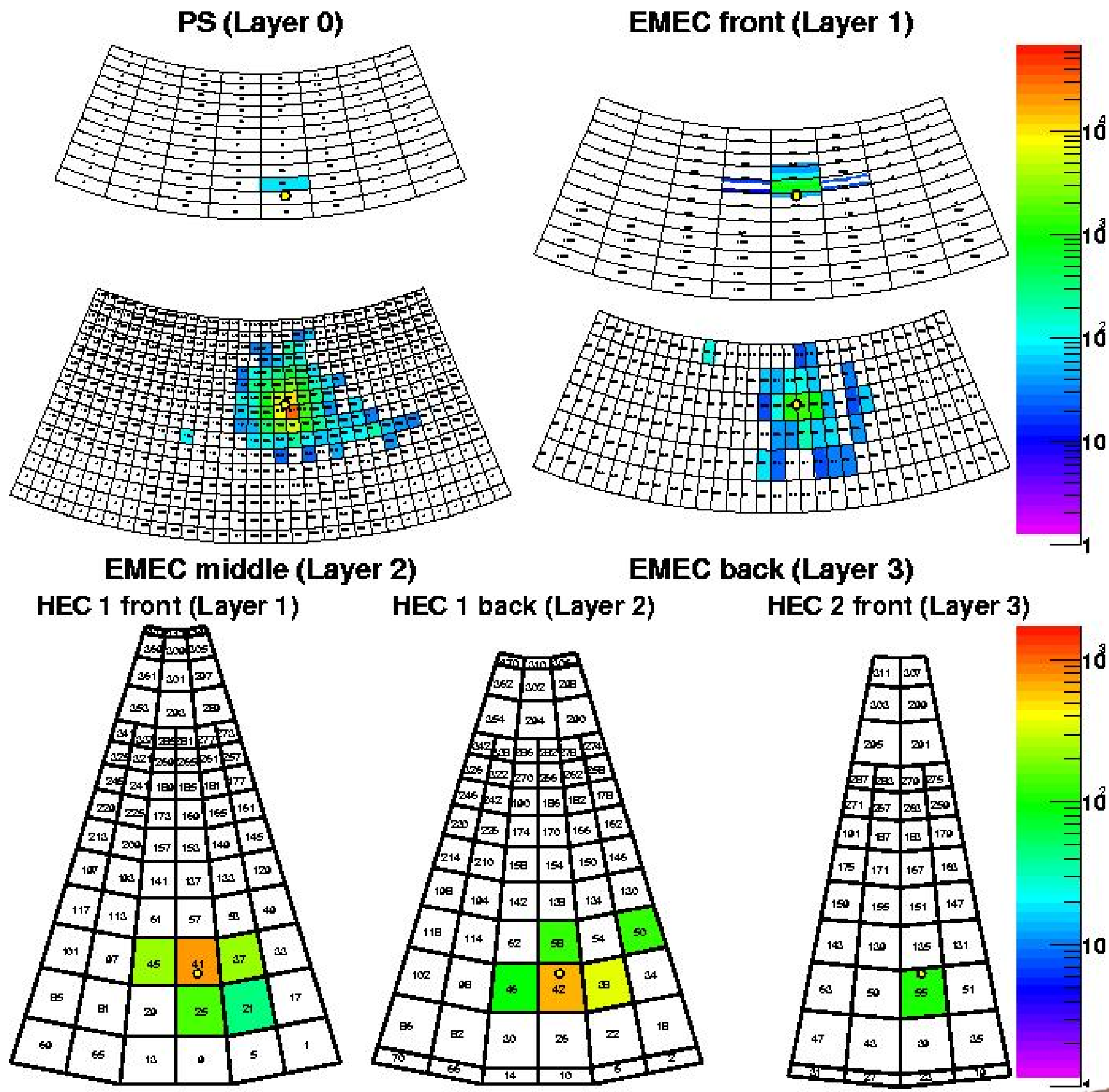


- Calibration from ADC to nA
  - use the OF weights found before
  - reconstruct the amplitudes for the calibration DAC level scans
  - fit the amplitude with a 3rd order polynomial to obtain calibration coefficients ADC $\rightarrow$ nA
  - accuracy $< 0.5\,\%$

Cluster Algorithm

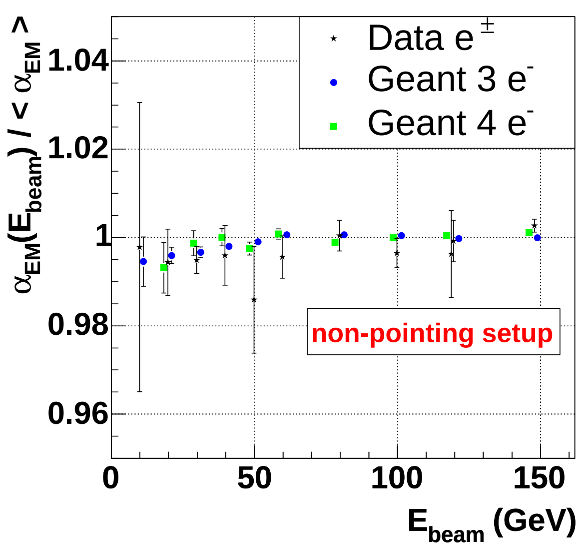
- Cell-based topological nearest neighbour cluster algorithm
- Clusters are formed per layer using neighbours (need to share one common corner)
  - Clusters in 2D
  - Seed cut
    $E_{seed} > 4\sigma_{noise}$
  - Cell cut
    $|E_{cell}| > 2\sigma_{noise}$
  - Expand the cluster with neighbouring cells if:
    $|E_{neighbour}| > 3\sigma_{noise}$

180 GeV π

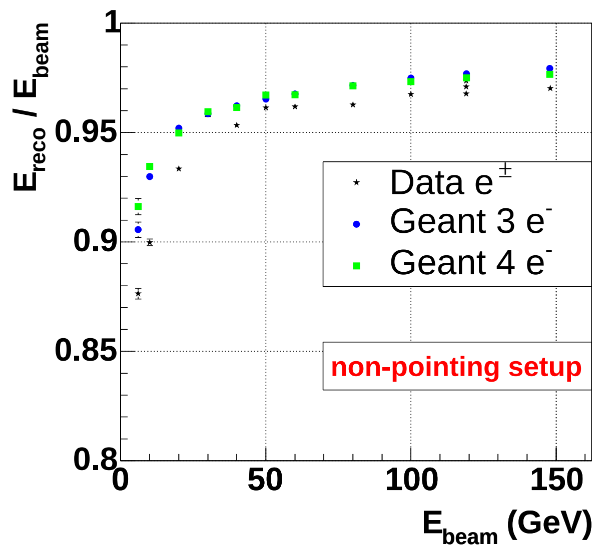


Electron Results: EMEC Electromagnetic Scale

- Needed as reference for hadronic calibration
- α_{em}^{EMEC} obtained after correcting for the energy deposited outside the reconstructed cluster
  - Cluster leakage measurable with both data and MC
  - $E_{beam} = E_{dep} + E_{leak} = \langle E_{reco} \rangle + \langle E_{leak} \rangle$
  - $E_{reco} = \alpha_{em}^{EMEC} I_{vis}^{EMEC}$ and $\alpha_{em}^{EMEC} = \frac{E_{beam} - \langle E_{leak} \rangle}{I_{vis}^{EMEC}}$
- $\alpha_{em}^{EMEC} = 0.430 \pm 0.001 \pm 0.009\,\mathrm{MeV/nA}$
  - Sys. error include signal shape uncertainties and η dependent corrections



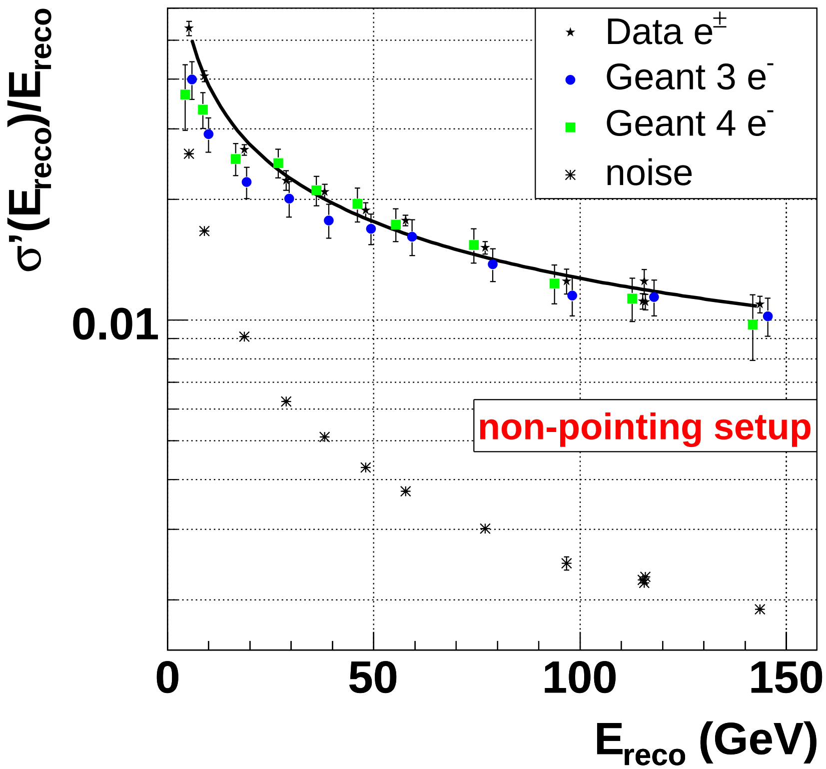
Linearity good to $\pm 0.5\%$
Well reproduced by MC



Electron cluster leakage is $2 - 4\,\%$ at high energies
MC shows smaller ($4 - 10\,\%$) leakage than data ($5 - 12\,\%$) at low energies

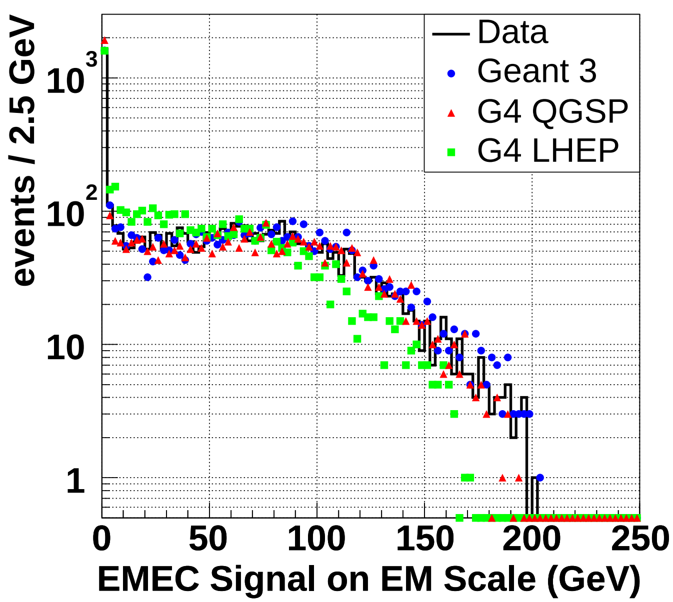
Electron Results: Energy Resolution

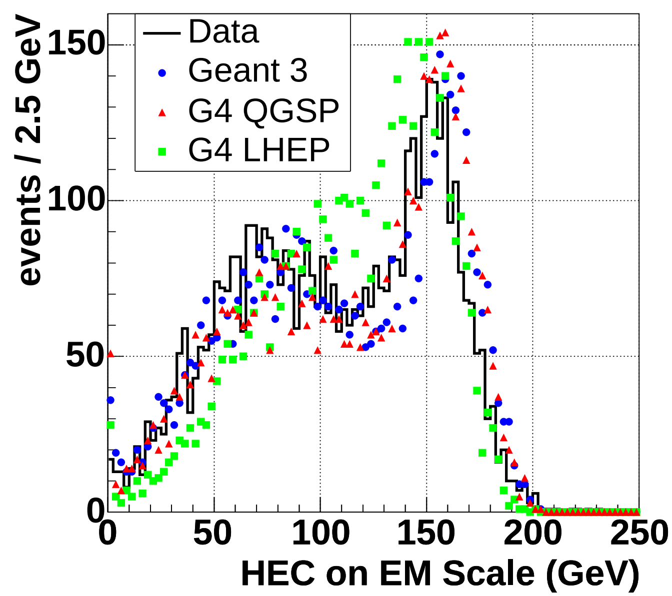
- $\sigma(E_{reco}) = \sigma'(E_{reco}) \oplus \sigma_{noise}$
- $\frac{\sigma'(E_{reco})}{\langle E_{reco} \rangle} = \frac{a}{\sqrt{E_{reco}}} \oplus b$
  - Data with noise subtracted (in %): $\frac{12.1 \pm 0.2}{\sqrt{E/GeV}} \oplus 0.4 \pm 0.1$
  - Geant 3 (in %): $\frac{9.3 \pm 0.6}{\sqrt{E/GeV}} \oplus 0.8 \pm 0.1$
  - Geant 4 (in %): $\frac{10.6 \pm 0.7}{\sqrt{E/GeV}} \oplus 0.7 \pm 0.2$
- Further tuning underway for ATLAS
  - To achieve better agreement between data and MC
- Non-pointing setup: possible some η dependence, due to η variation of sampling fraction and weak η dependence of electric field



Pion Results: Energy Reconstruction on EM Scale

- The energy reconstruction of pions is based on electromagnetic scale
  - For the EMEC value used:
    $\alpha_{em}^{EMEC} = 0.430 \pm 0.001 \pm 0.009\,\mathrm{MeV/nA}$
  - For the HEC used EM scale value from previous stand-alone beam test, modified by new electronics:
    $\alpha_{em}^{HEC} = 0.327 \pm 0.03 \pm 0.03\,\mathrm{MeV/nA}$
- Response to 200 GeV pions in the EMEC and HEC on the EM scale:

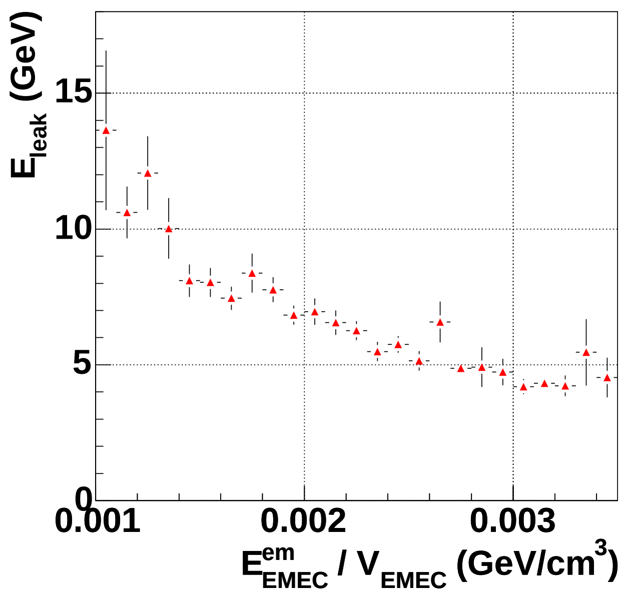


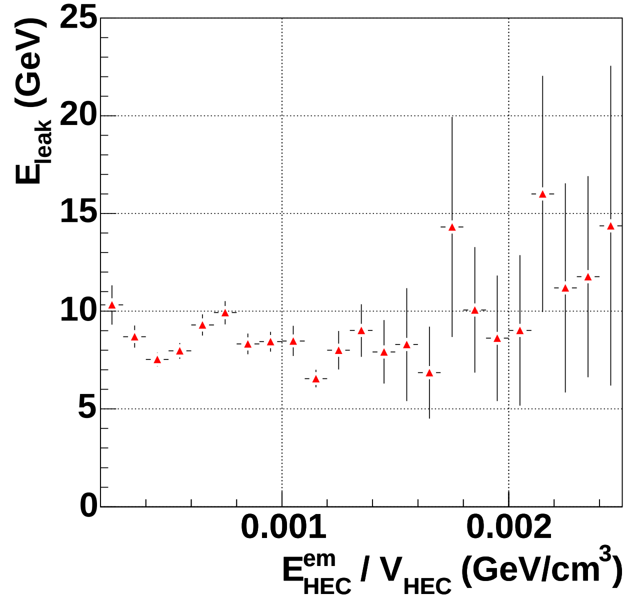


- ▷ GEANT 3 and GEANT 4 QGSP describe the data reasonably well
- ▷ GEANT 4 LHEP simulation deviate substantially from the data

Pion Results: Weighting Approaches

- EMEC and HEC are not compensating calorimeters
  - A calibration coefficient (weight) has to be applied to the signal determined on EM scale
  - Various technique on signal weighting are studied
  - Best would be cell-based weights → needs more detailed MC than available
  - Cluster based weights as function of cluster energy density: E_{clus}/V_{clus}, are available
  - Needs detector leakage information from MC as function of E^{EMEC}/V^{EMEC} and E^{HEC}/V^{HEC} and reconstructed cluster leakage information from data



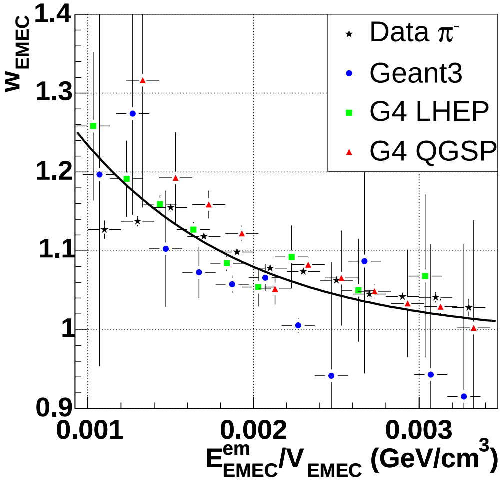


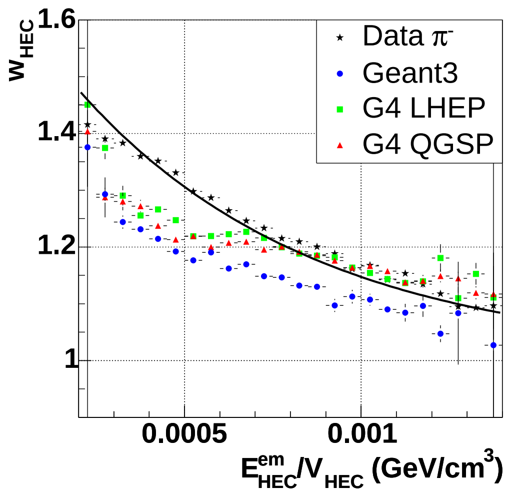
Detector leakage for 200 GeV pions GEANT 4 QGSP MC

Pion Results: Cluster Weighting Approach

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

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

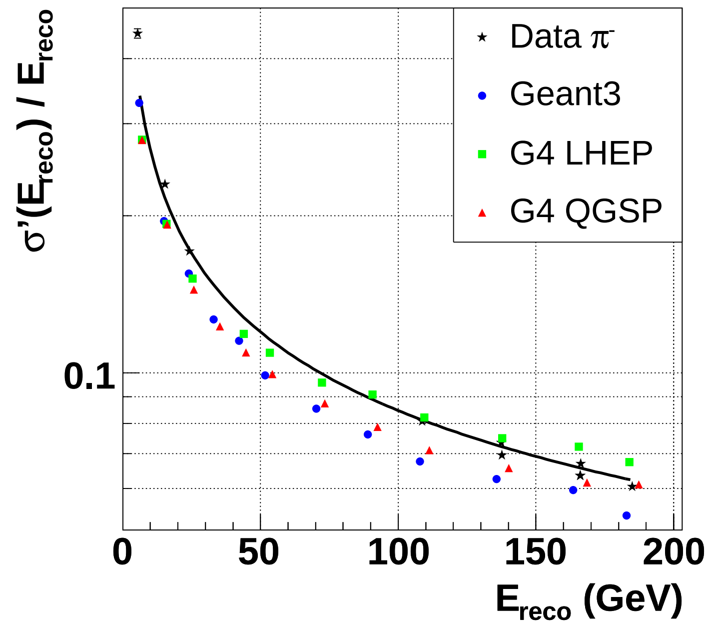


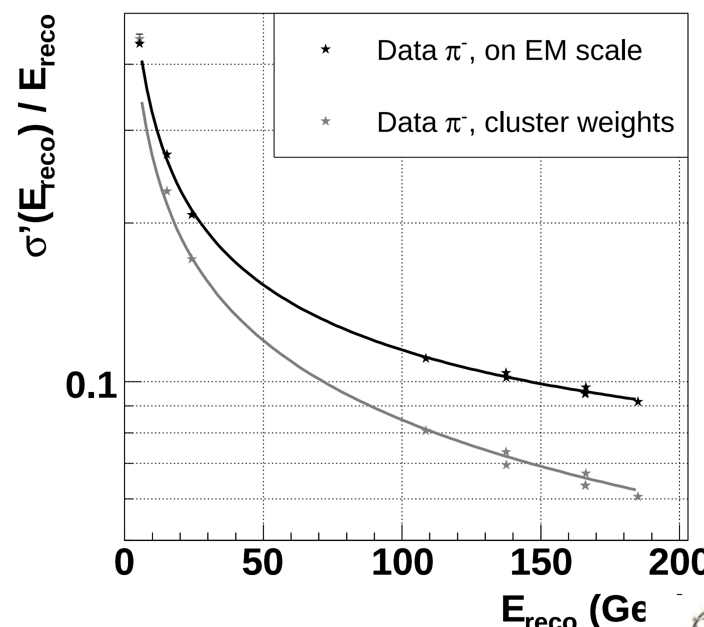


- $E_{\text{reco}} = E_{\text{em}} \left(c_1 \cdot \exp\left[-c_2 \cdot E_{\text{em}}/V\right] + c_3\right)$ (H1 method)
- $E_{\text{tot}} = E_{\text{reco}} + E^{\text{cluster leak}}_{\text{em}}$
- E_{leak} as on previous slide from MC
- c_2 fixed to $1000\,\text{cm}^3/\text{GeV}$ ($1500\,\text{cm}^3/\text{GeV}$) for EMEC (HEC)
- upper (lower) plot shows $E_{\text{reco}}/E_{\text{em}}$ for EMEC (HEC)
- All MC models follow the general trend of the data. GEANT 3 predictions deviate from HEC and EMEC data, no MC models can be preferred

Pion Energy Resolution: Cluster Weighting Approach

- Energy resolution for π^- after noise subtraction: $\frac{\sigma'(E_{reco})}{\langle E_{reco}\rangle} = \frac{a}{\sqrt{E_{reco}}} \oplus b$, constant term compatible with zero
  - Data π^- (in %): $\frac{84.6 \pm 0.3}{\sqrt{E/GeV}}$
  - GEANT 4 models closer to the data than GEANT 3, but neither LHEP and QGSP models give an optimal description
- The cluster weighting approach improve the pions energy resolution compared with the results obtained using just EM scale



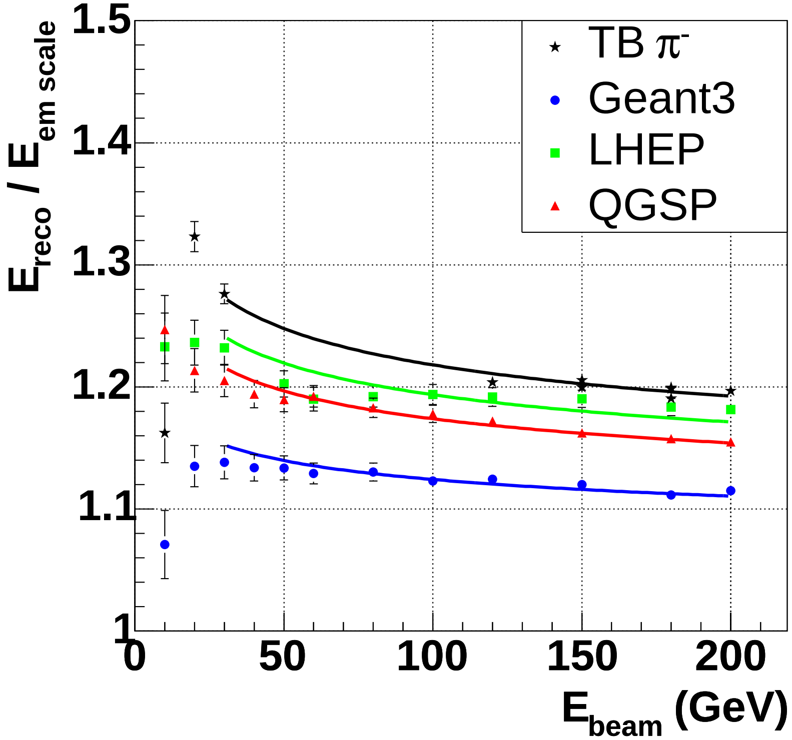


Pion Results: e/π Ratio

- Effective e/π ratio based on cluster weighting scheme:

  $$\frac{e}{\pi} = \langle \frac{E_{reco}}{E_{em}^{EMEC} + E_{em}^{HEC}} \rangle$$

  - e/π ratio indicates the amount of non-compensation
  - MC predictions (π^- only) below the data
  - For combined EMEC and HEC calorimeters the e/h ratios have no direct interpretation



Conclusions

- LAr HEC construction status
  - Module production of HEC finished
  - Integration of one full end cap calorimeter (HEC C) in cryostat done
  - Integration of second end cap calorimeter (HEC A) in cryostat starting middle of 2004 (July 2004)
- LAr EMEC-HEC 2002 beam test results: $1.6 < |\eta| < 1.8$
  - Calibration methods from the beam test reusable in ATLAS
    - Optimal filter weights
    - ADC $\rightarrow$ nA calibration constants
  - Methods used in beam test applicable for hadronic calibration strategy in ATLAS
    - Clustering: from 2D to 3D, also modified cuts for pile-up
    - Cluster and/or cell weighting
  - Methods still to be tested in beam tests
    - Jet reconstruction
    - Particle ID in jets
- Just started EMEC-HEC-FCAL beam test: $2.8 < |\eta| < 3.4$