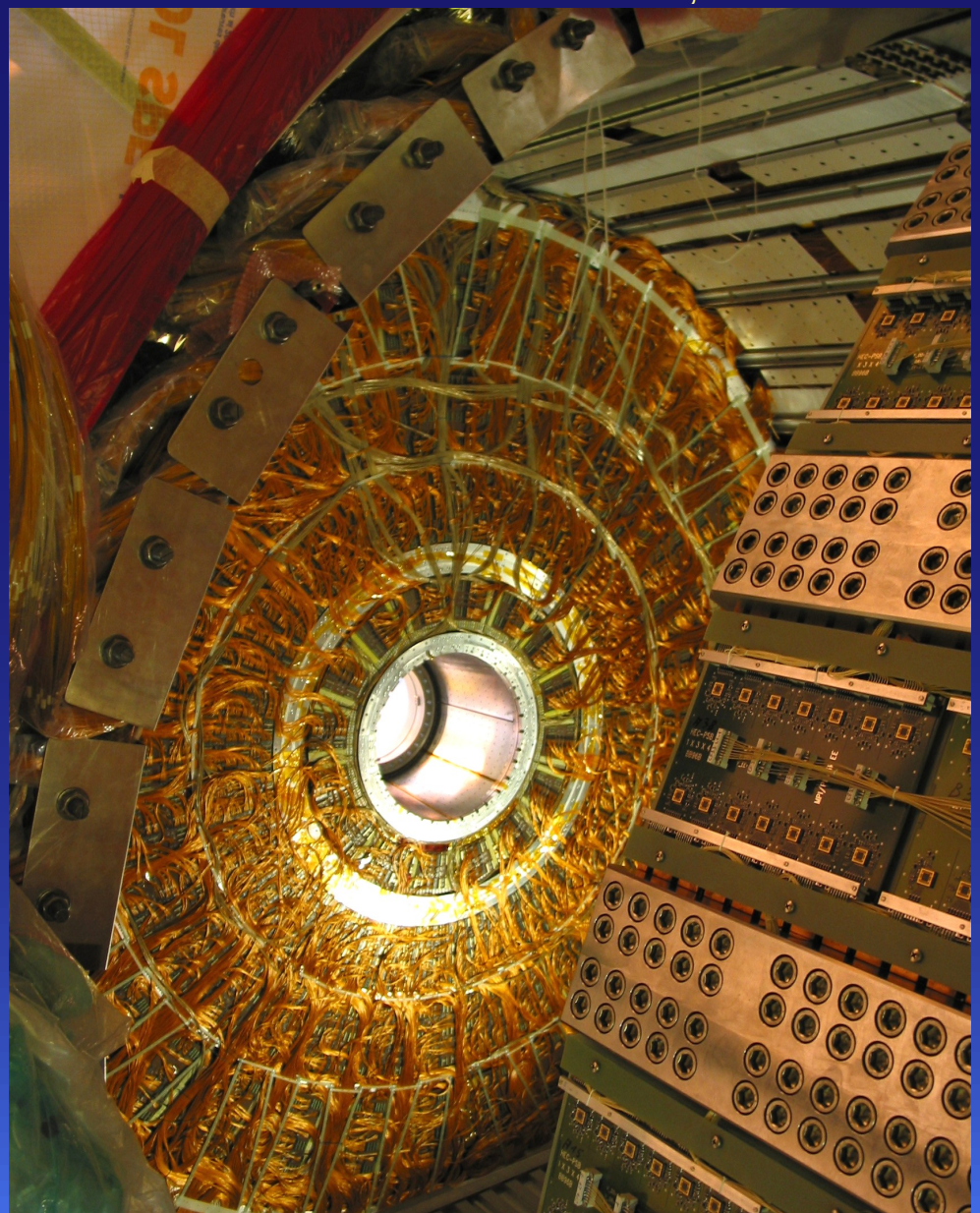
Status and Performance of the ATLAS Calorimeters

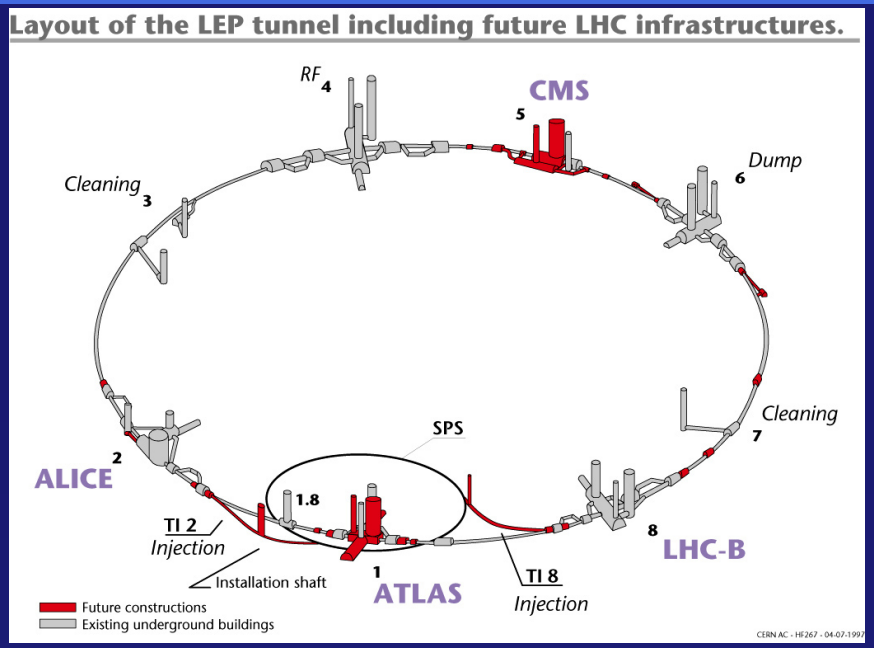
HEP Seminar Sven Menke, MPI München 24. June 2004, Uni Bonn

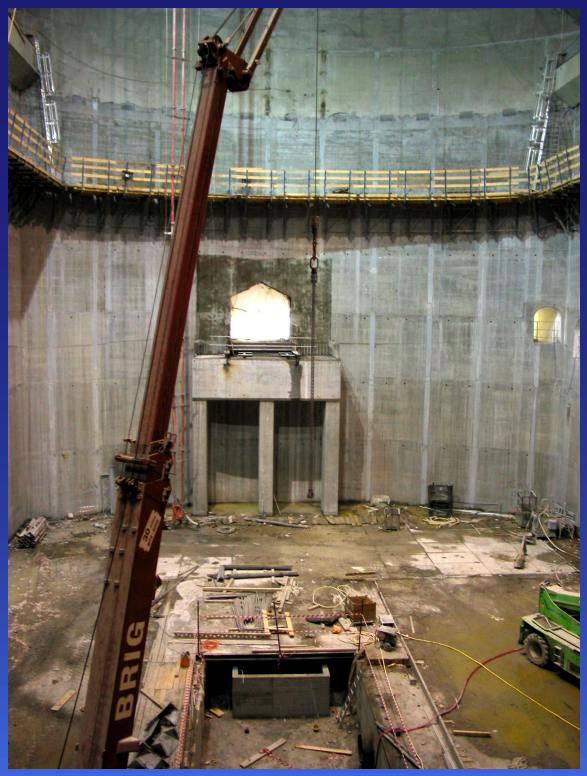
- LHC and ATLAS
- The ATLAS Calorimeters
  - Electromagnetic Calorimeter – EM
  - Hadronic Barrel Tile Calorimeter – Tile
  - Hadronic End-cap Calorimeter – HEC
  - Forward Calorimeter – FCal
- Construction/Installation Status
- Performance studies in beam tests
  - Signal Reconstruction
  - Clustering
  - Energy Calibration
- Roadmap to ATLAS
- Conclusions

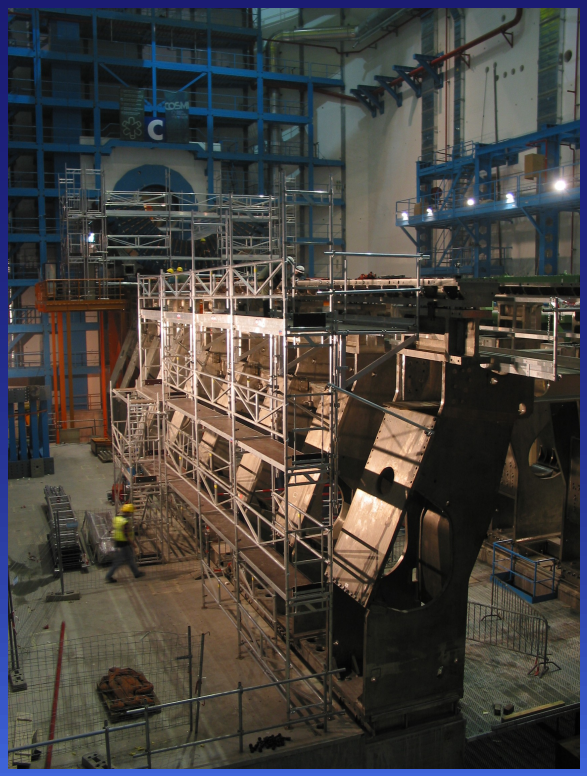


LHC and ATLAS

- The Large Hadron Collider LHC @ CERN
  - 14 TeV pp collisions by 2007
  - 27 km collider in the LEP tunnel @ CERN
- Progress in the ATLAS Pit from March 2003 (left, middle) to April 2004 (right)







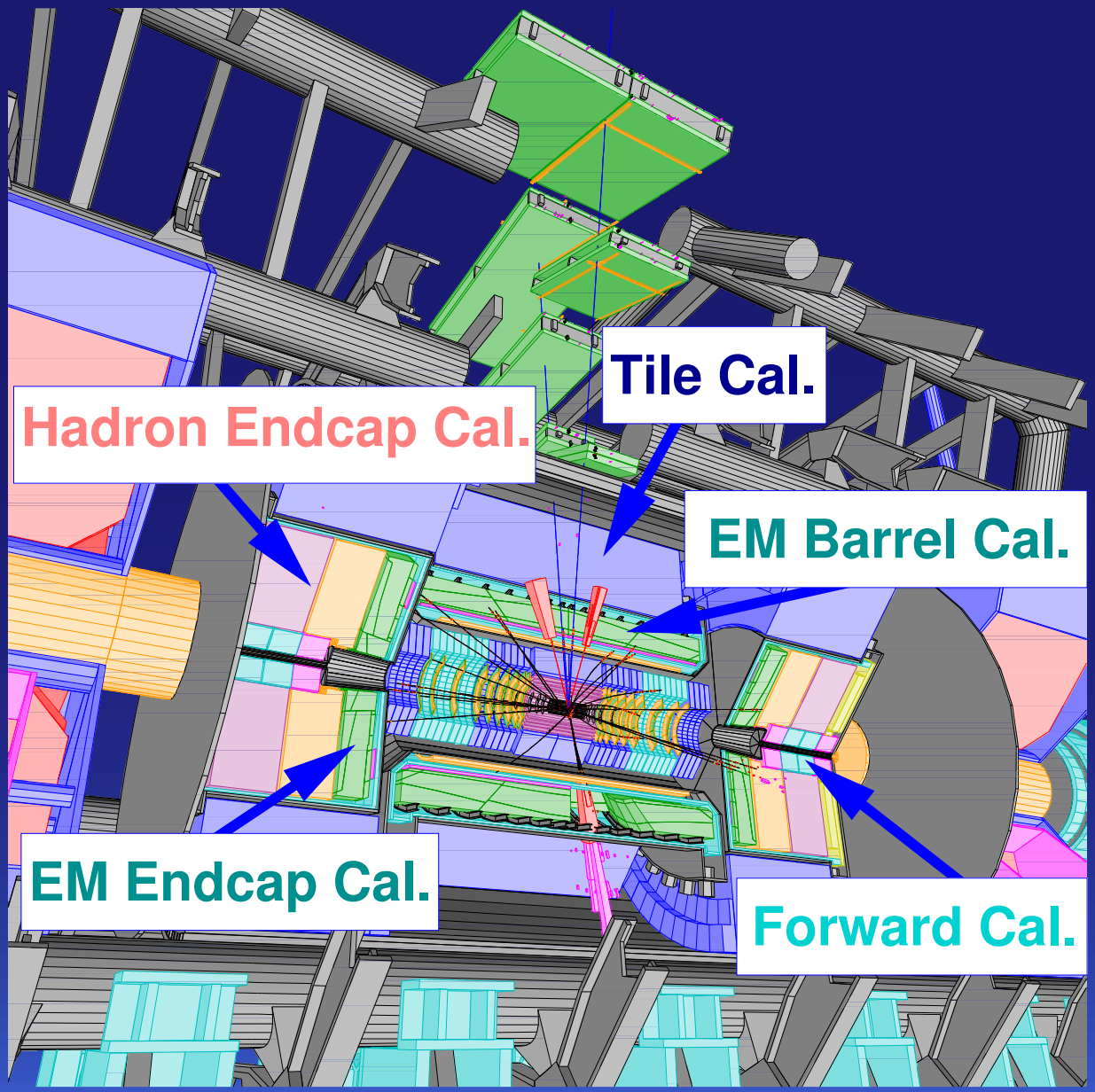
LHC and ATLAS ► Construction Web-Cam

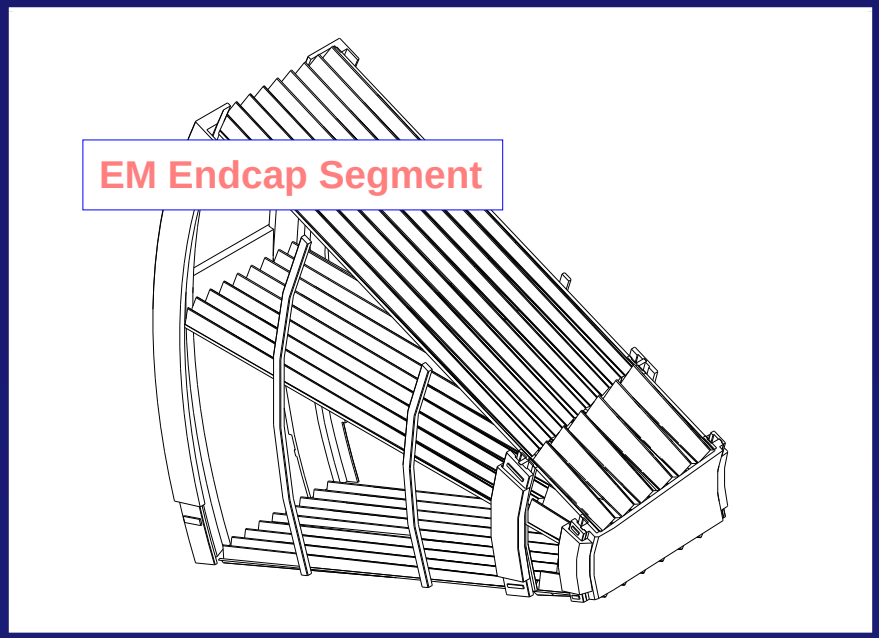
- Two Web-Cams are installed since May 2003 in the ATLAS Cavern

  http://atlaseye-webpub.web.cern.ch/atlaseye-webpub/web-sites/pages/UX15_webcams.htm
- Video (click on the picture) made of the individual jpeg frames:
  - 31. October 2003 – 16. June 2004
  - One picture taken every 30 minutes during working hours
  - Video shows every 2nd picture – 4.5 days per second

The ATLAS Calorimeters

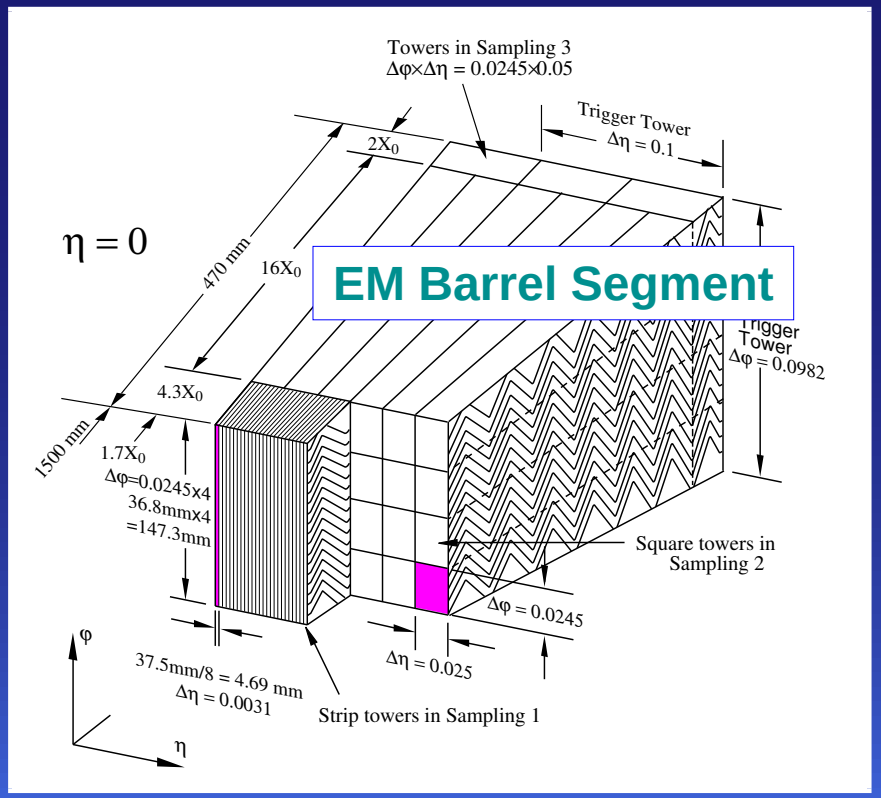
- Layout of the ATLAS Calorimeters
- EM LAr-Pb accordion calorimeter
  - Barrel (EMB): $|\eta| < 1.4$
  - End-cap (EMEC): $1.375 < |\eta| < 3.2$
- Hadron calorimeters
  - Barrel (Tile): Scint.-Steel $|\eta| < 1.7$
  - End-cap (HEC): LAr-Cu $1.5 < |\eta| < 3.2$
- Forward calorimeter (FCal) $3.2 < |\eta|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





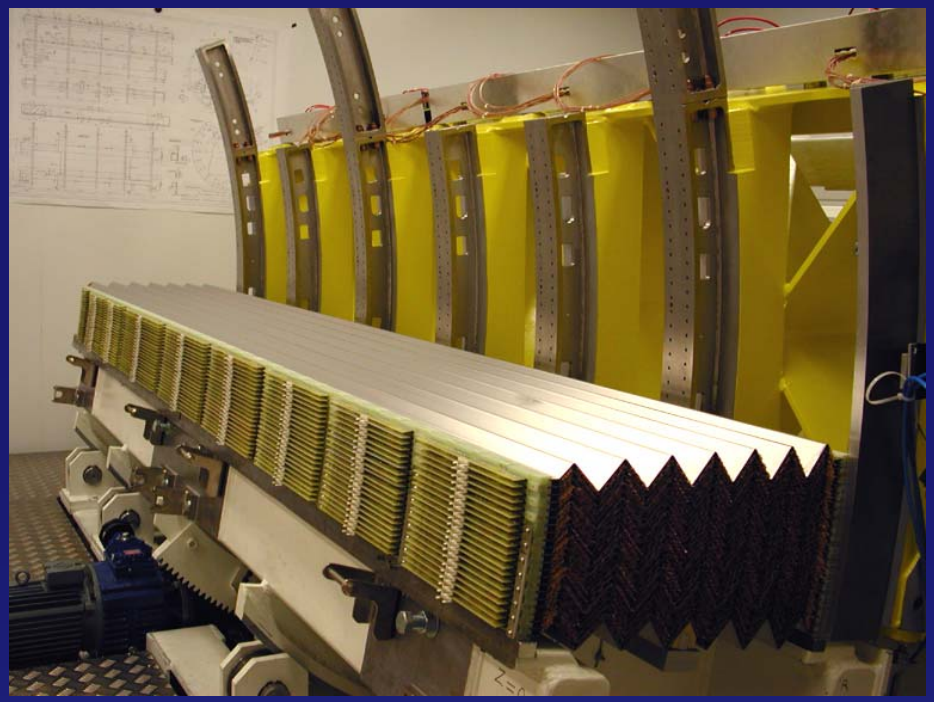
- EM absorber structure
  - Pb-Absorbers (1.5, 1.1, 1.7, 2.2 mm) arranged radially
  - Folding angle and wave height vary with r (End-cap)
  - Anodes pointing in η

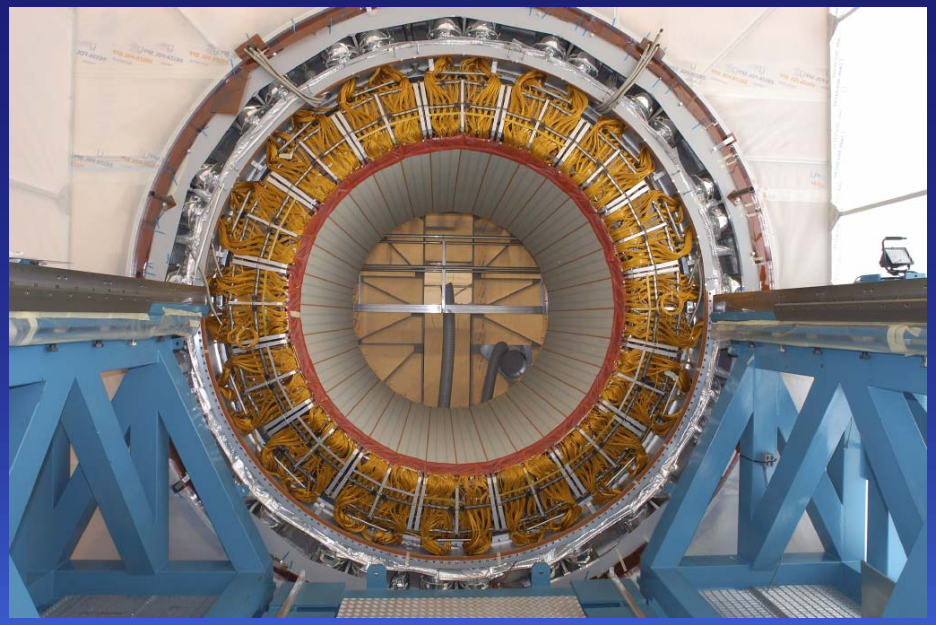
- EM readout structure
  - Layer1 (Front): $\simeq 2 - 4\,X_0$
    $\delta\eta \times \delta\phi = 0.025/8 \times 0.1$
  - Layer2 (Middle): $\simeq 16 - 18\,X_0$
    $\delta\eta \times \delta\phi = 0.025 \times 0.025$
  - Layer3 (Back): $\simeq 2 - 4\,X_0$
    $\delta\eta \times \delta\phi = 0.050 \times 0.025$
  - 173312 readout channels incl. PS



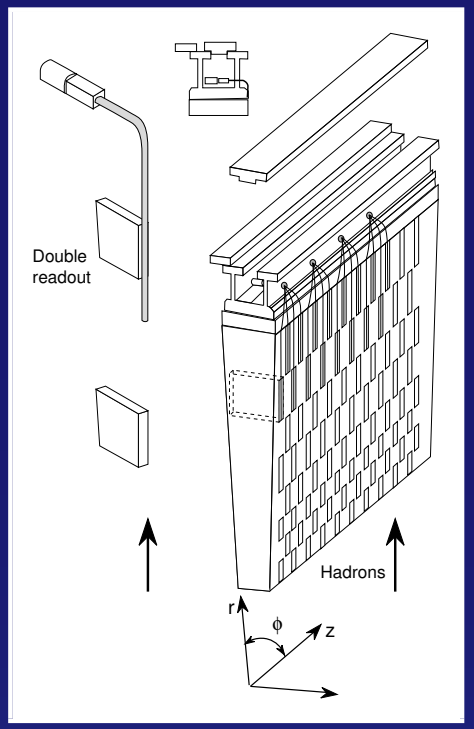
- both EM Barrel wheels and both EM End-cap wheel completed (June 2004)
- EM Barrel status
  - cooling and HV tests following the insertion and welding of the cryostat
  - slow cooling (down to 89 K in 40 days) is crucial due to Accordion structure
  - cooling done; HV tests still ongoing
- EM End-cap status
  - EMEC C completed September 2003; EMEC A completed June 2004
  - EMEC C inserted in cryostat October 2003
  - Endcap A insertion expected July 2004
- participating in Combined Barrel/End-cap Test-beams Summer 2004 (H6 & H8)

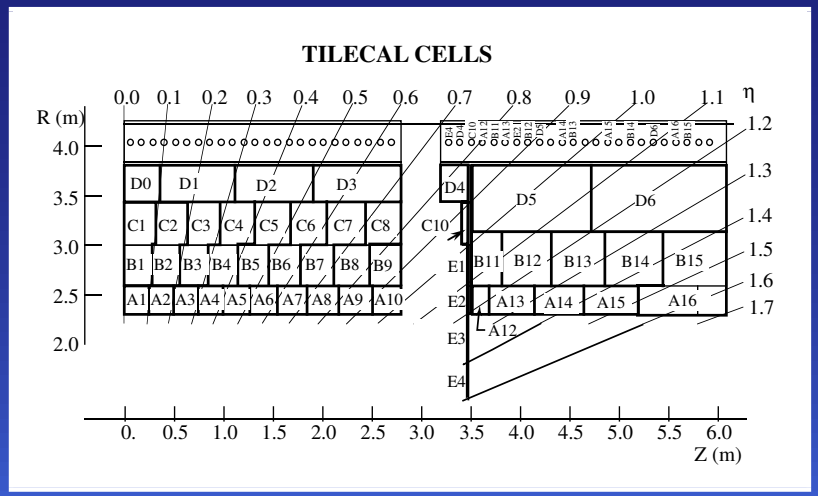
The ATLAS Calorimeters ► EM Construction Pictures





- Tile absorber structure
  - laminate of 4 – 5 mm thick steel plates (absorbers and spacers) stacked to 293.2 mm thick sub-modules
  - scintillating tiles are inserted in the holes left by the spacer plates
  - high periodicity makes absorber structure independent from optical instrumentation
  - 19 (9) sub-modules make one barrel (extended barrel) module
  - 64 identical modules in ϕ

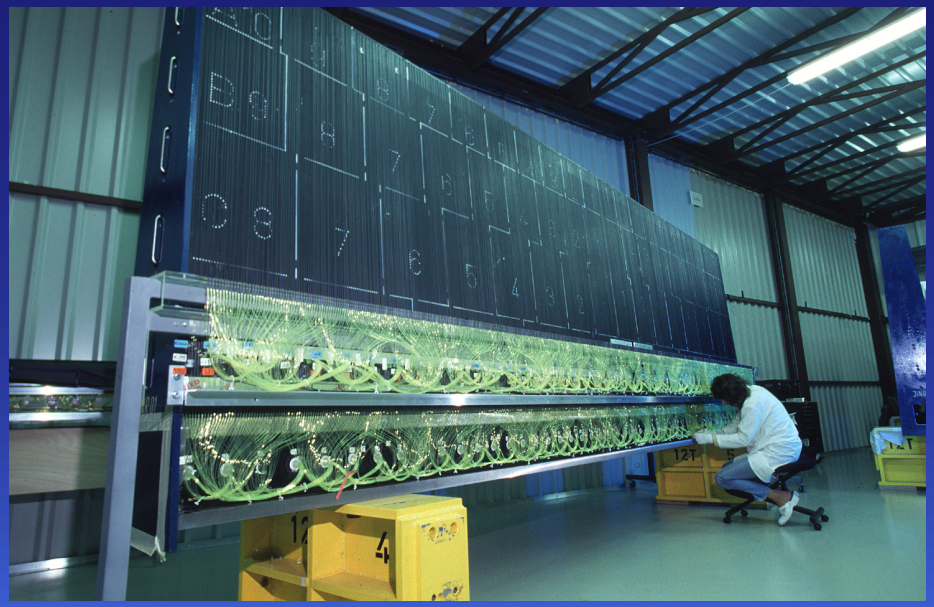




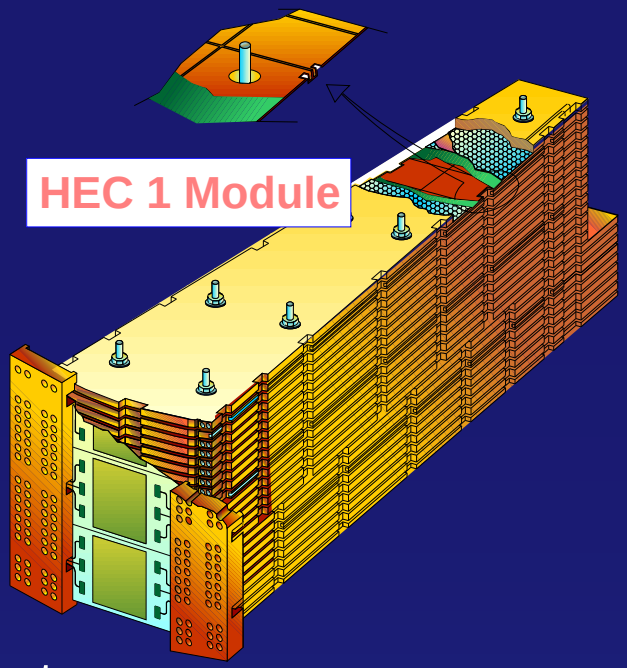
- Tile readout structure
  - tiles are grouped to readout cells in 3 longitudinal layers (B and C are readout together)
  - $\delta\eta \times \delta\phi \simeq 0.1 \times 0.1$ (0.2×0.1)
  - gap scintillators provide calorimetric information between TileB and TileEB and between EMB and EMEC
  - 5248 readout channels

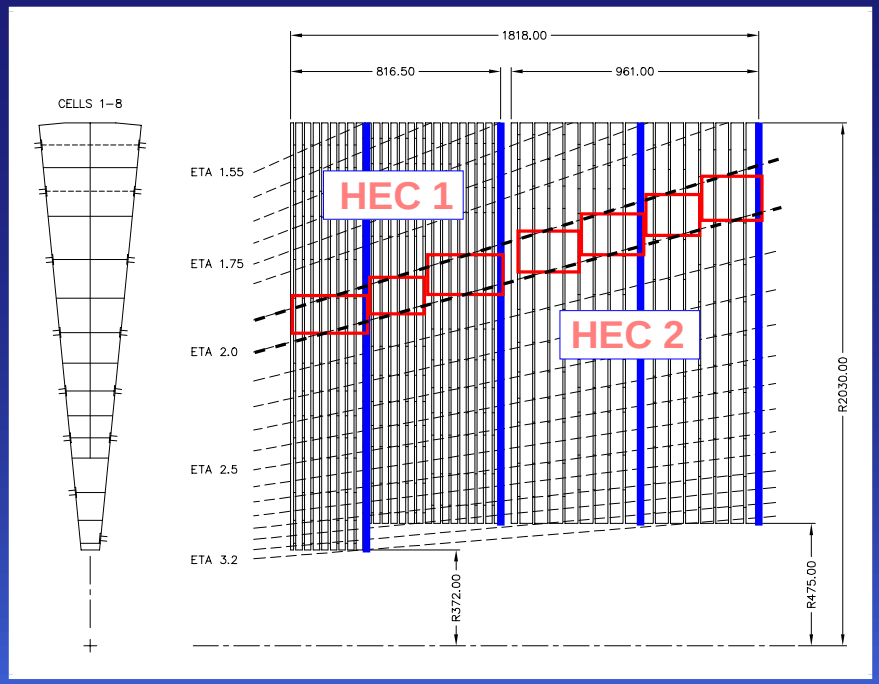
- Tile Barrel
  - pre-assembly and disassembly done Feb 2004
  - Spring 2004 bottom half assembly in Pit. The first piece of the ATLAS detector are in the Pit!
  - Fall 2004 top half assembly after LAr Barrel cryostat insertion
- Tile Extended Barrel
  - C side pre-assembly done June 2003
  - assembly in the Pit October 2004 to February 2005
  - A side pre-assembly started May 2004
  - A side assembly in the Pit May 2005 to September 2005
- participating in Combined Barrel Test-beam Summer 2004 (H8)

The ATLAS Calorimeters ► Tile Construction Pictures



- 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

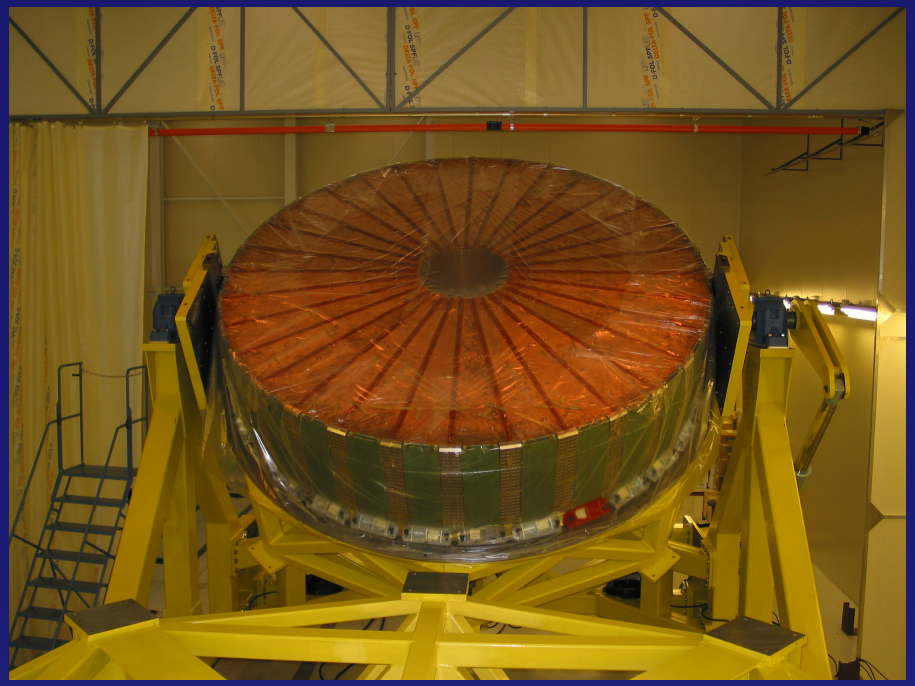


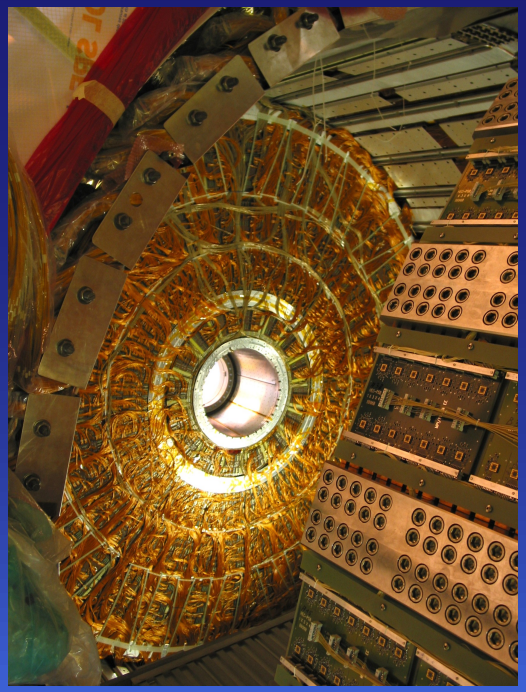


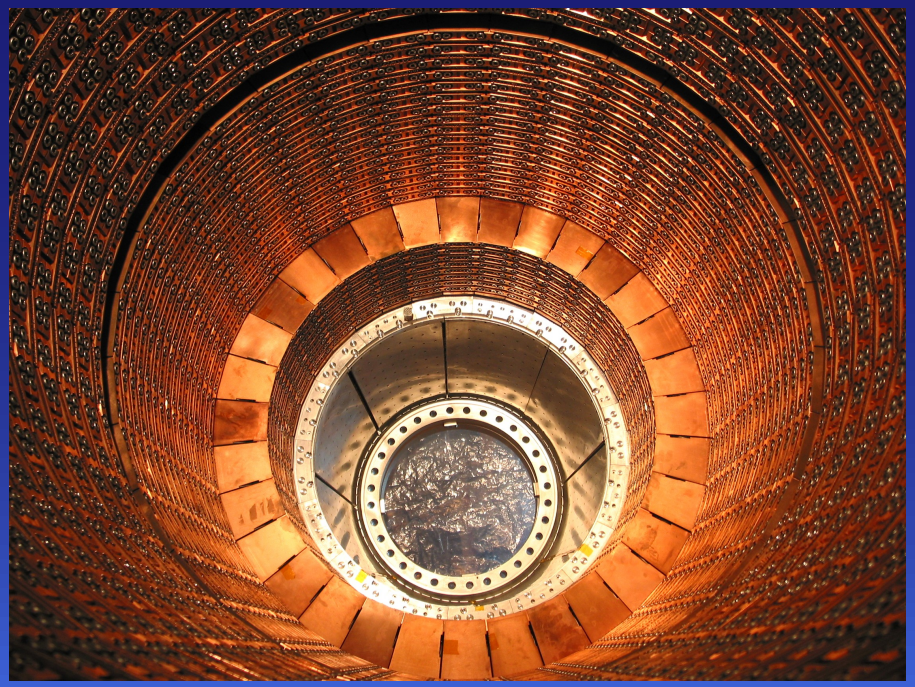
- HEC readout structure
  - $\delta\eta \times \delta\phi \simeq 0.1(0.2) \times 0.1(0.2)$
  - Layer1 (HEC1 Front): $\sum 8$ gaps
  - Layer2 (HEC1 Back): $\sum 16$ gaps summed pseudo pointing in η
  - Layer3&4 (HEC2 Front&Back): $\sum 8$ gaps summed pseudo pointing in η
  - 5632 readout channels

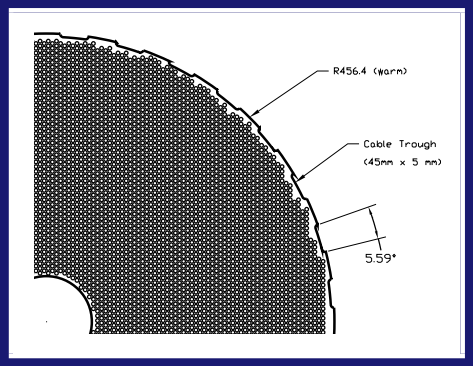
- All 4 HEC wheels (A & C) are ready and assembled
- HEC C installed in End-cap cryostat since October 2003
- HEC A status
  - HEC1A assembled March 2003, ready for insertion since November 2003
  - HEC2A assembled January 2004
  - wait for EMECA completion for cryostat insertion
- participating in Combined End-cap Test-beam Summer 2004 (H6)

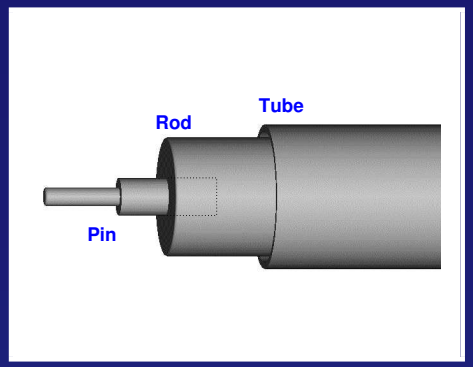
The ATLAS Calorimeters ► HEC Construction Pictures





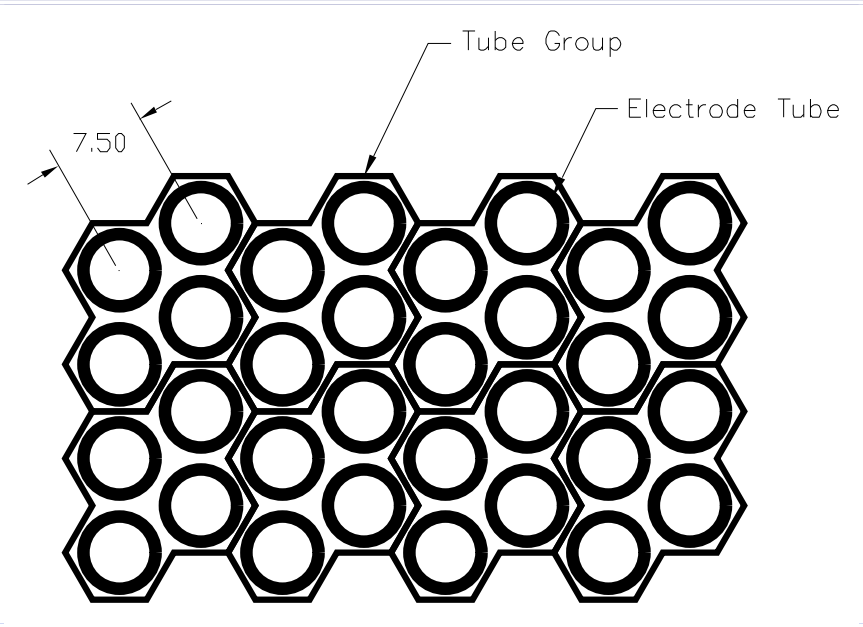






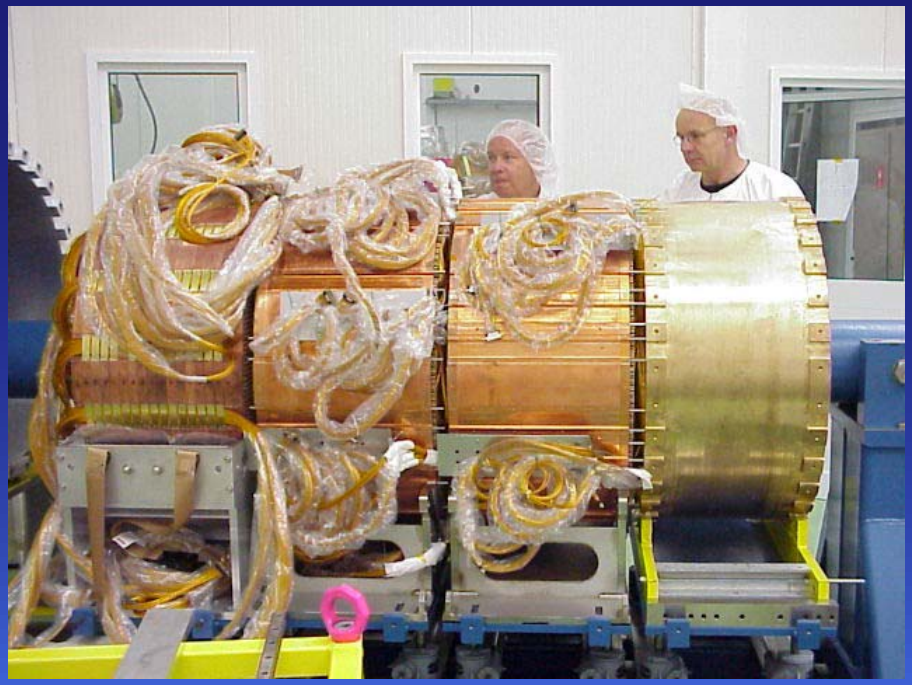
- FCal absorber structure
  - 3 modules made of 45 cm thick Cu (FCal1) or W (FCal2, FCal3)
  - 12260 (10200, 8224) holes in FCal1 (FCal2, FCal3) filled with electrodes consisting of an outer Cu tube and an inner Cu rod with 250 μm LAr gap between them
  - rods are centered inside the tubes by quartz fibres wound around the rods

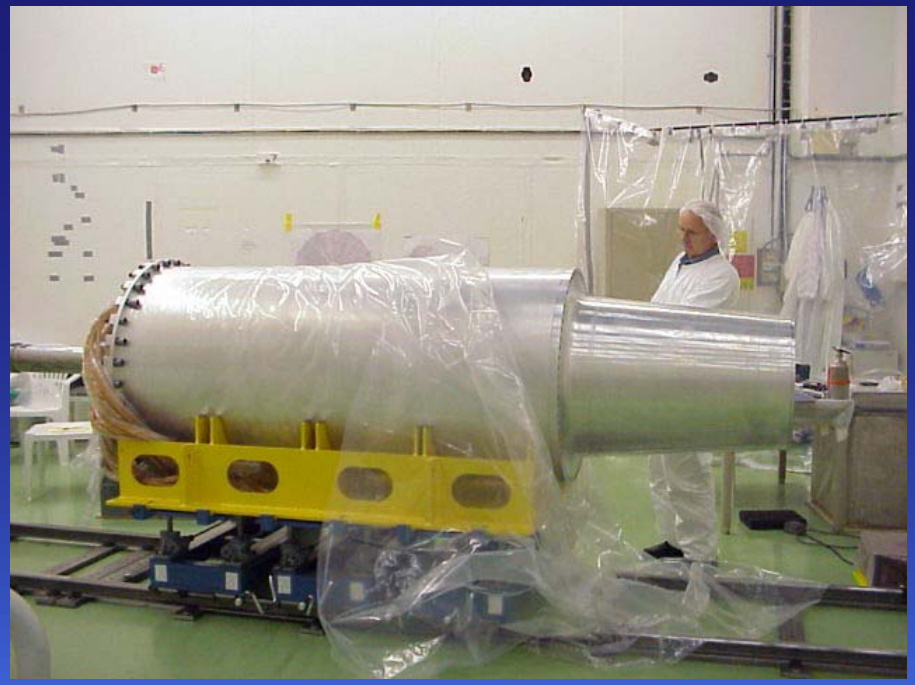
- FCal readout groups
  - 2×2 (2×3, 3×3) tubes form one readout group
  - 1 (inner and outer border) or 2×2 (main part) readout group(s) form one readout channel
  - 3524 readout channels



- All 6 FCal modules (A and C) are assembled
- FCal C status
  - final assembly took place in 2003
  - cold tested in September 2003
  - dead channels 0.03, 0.2, 0.5 % — repaired
  - inserted in support tube November 2003
  - ready for insertion in cryostat starting July 2004
- FCal A status
  - cold tested in February 2004
  - dead channels 0.3, 0.6, 0.3 % — repaired
  - ready for insertion in support tube starting September 2004
- participating in Combined End-cap Test-beam Summer 2004 (H6)

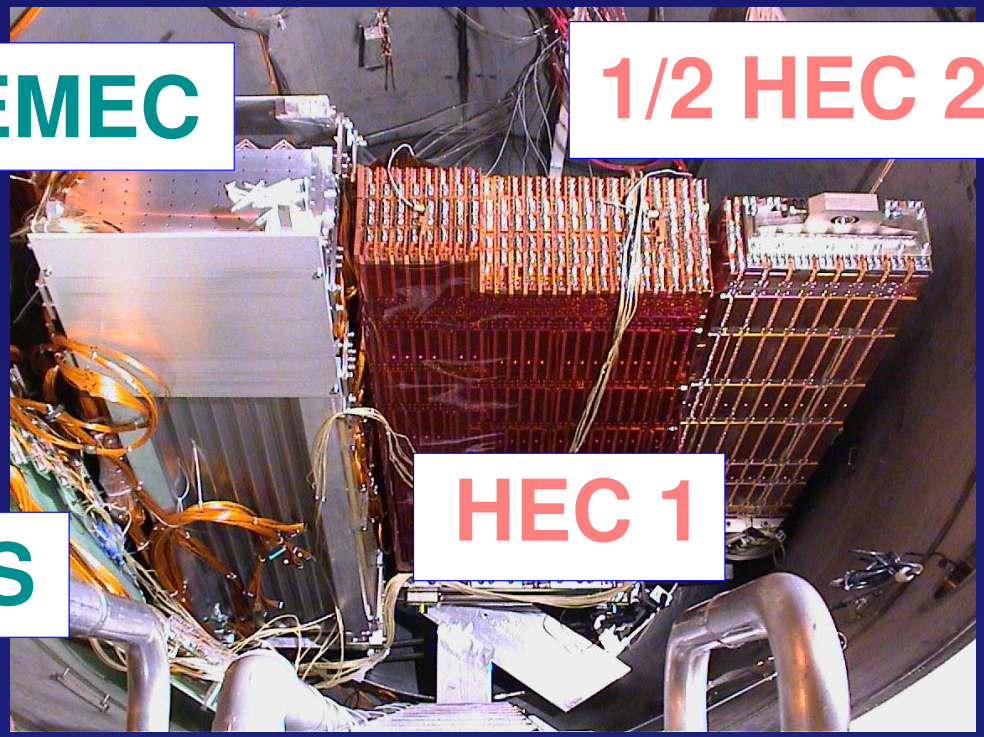
The ATLAS Calorimeters ► FCal Construction Pictures





EMEC & HEC combined beam test 2002 ► Setup

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



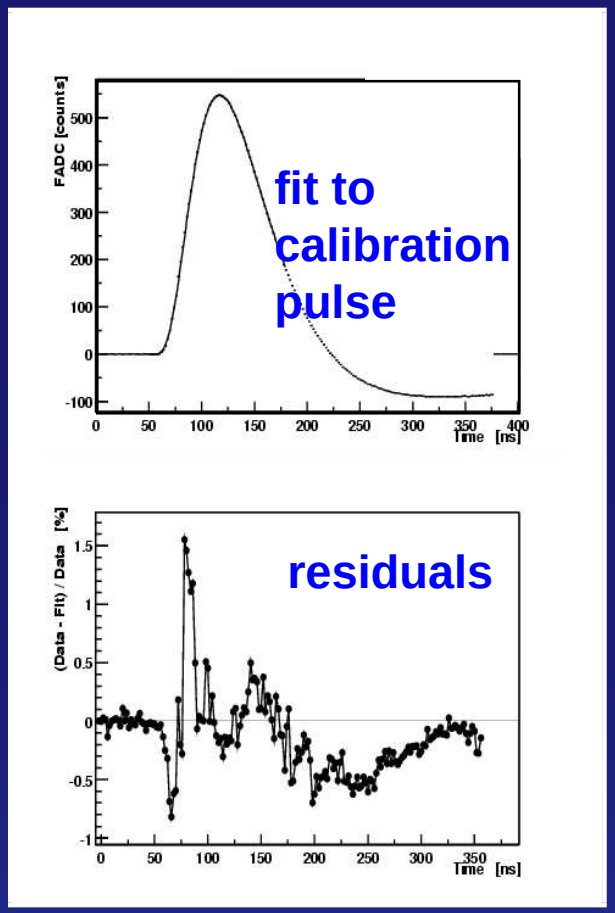
- Main goals for the beam test
  - study the region $\eta \sim 1.8$
  - obtain calibration constants for e and π
  - compare to detailed MC in order to extrapolate to jets
  - test methods for an optimal hadronic energy reconstruction

Signal reconstruction ► Digital filter

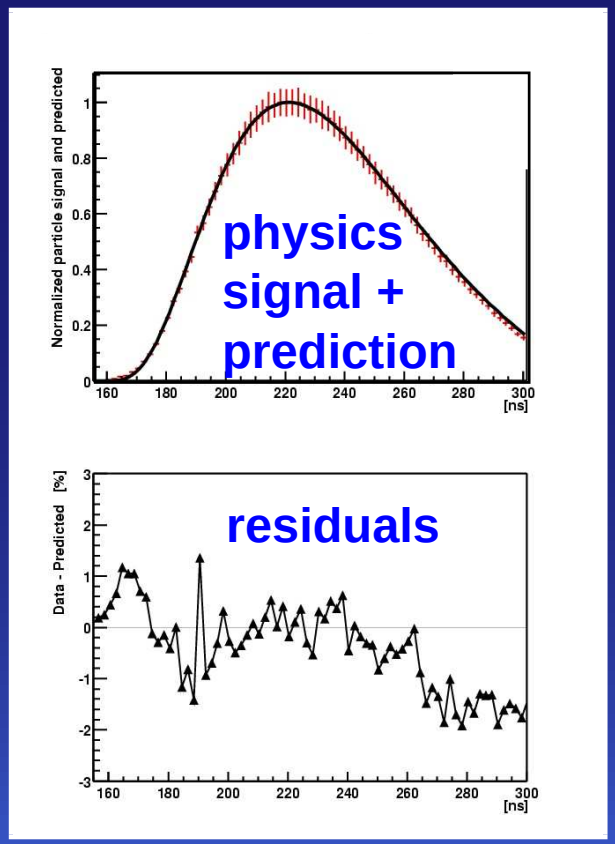
- Optimal filtering principle:
  - need known physics signal shape $g(t)$
  - discrete measurements (signal plus noise): $y_i = Eg_i + b_i$
  - and autocorrelation matrix from noise runs: $B_{ij} = \langle b_i b_j \rangle - \langle b_i \rangle \langle b_j \rangle$
  - estimate amplitude E with $\tilde{E} = a^t y$ 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 $< 2\,\%$

Signal reconstruction ► Digital filter ► HEC

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

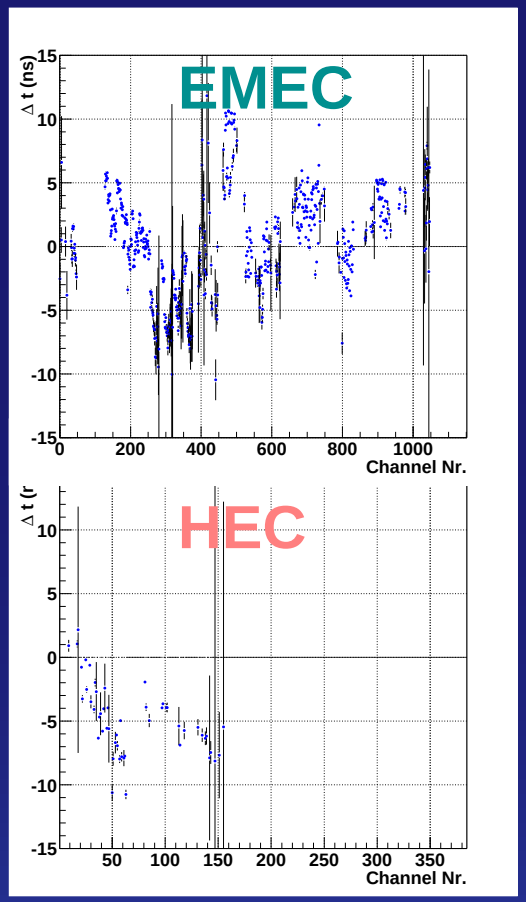


  - lower plot shows residual deviation from data $< 1.5\,\%$

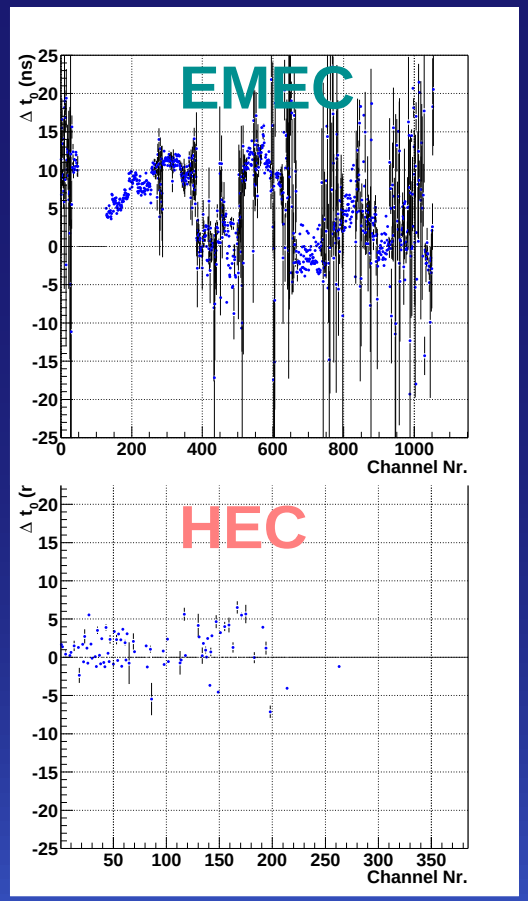


- Physics signal prediction
  - upper plot shows normalized physics signal and prediction for one channel
  - lower plot shows residual deviation from data $< 1.5\,\%$
  - noise reduction factor with 5 weights 0.64 (0.72) for HEC (EMEC)

Signal reconstruction ► Timing

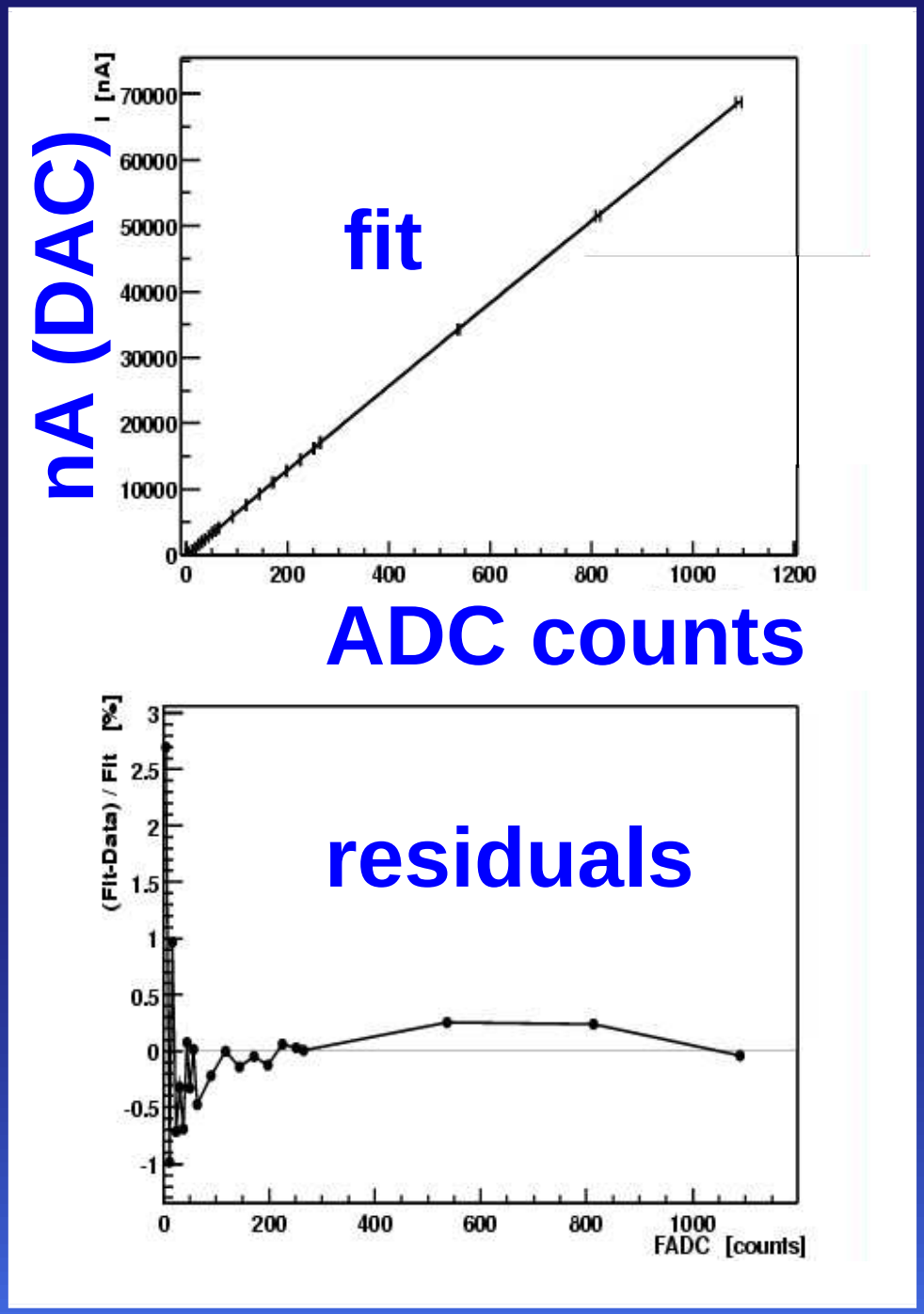


- 2 sets of time constants are needed
- 1st set defines signal peak for each channel relative to the trigger (not needed in ATLAS)
  - trigger in beam test in a 25 ns window
  - normally measured by TDC → broken
  - use polynomial fits to find peak positions
- 2nd set accounts for different cable delays 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

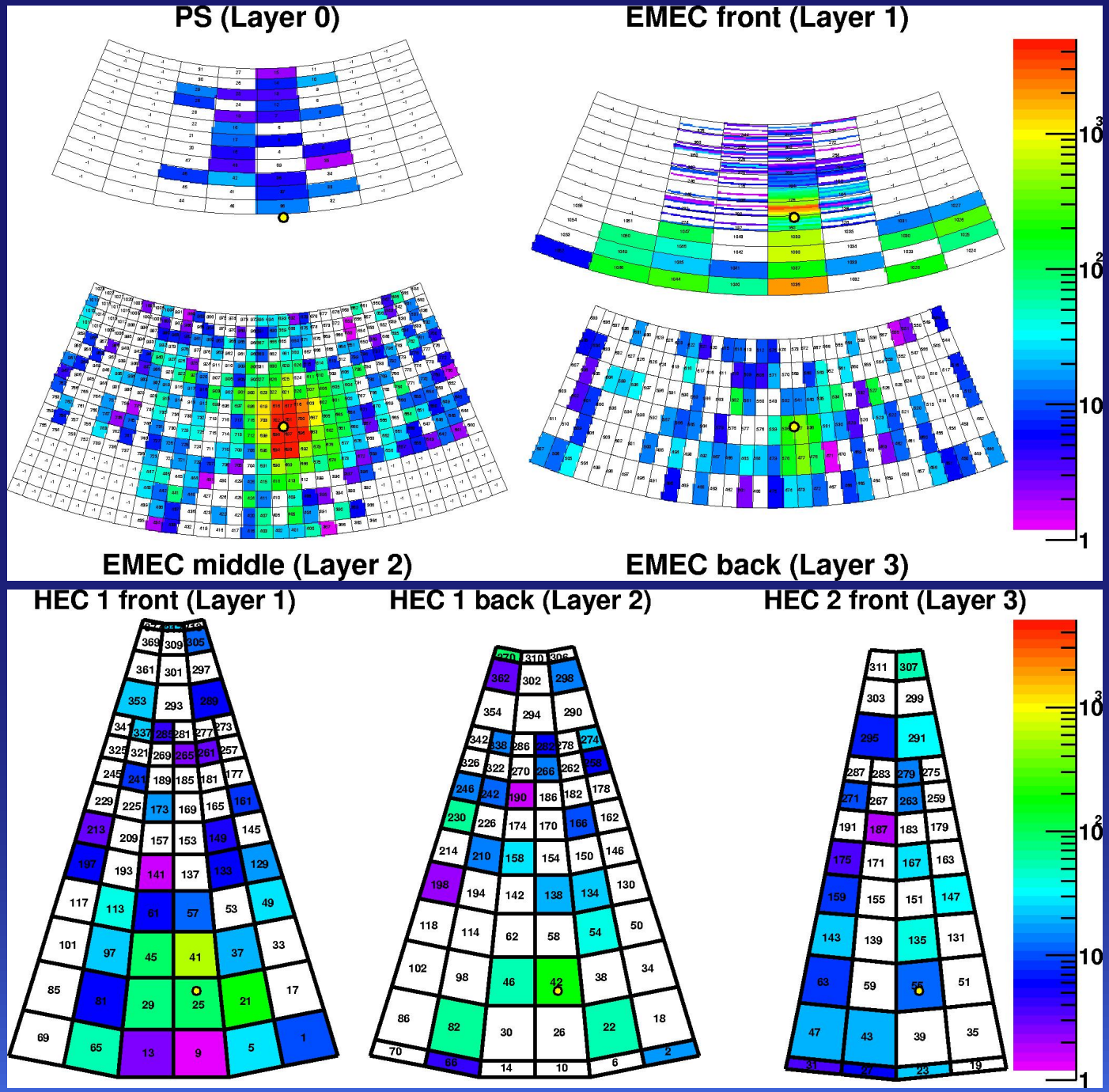
Signal reconstruction ► Calibration in nA



- 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 $< 0.5\,\%$

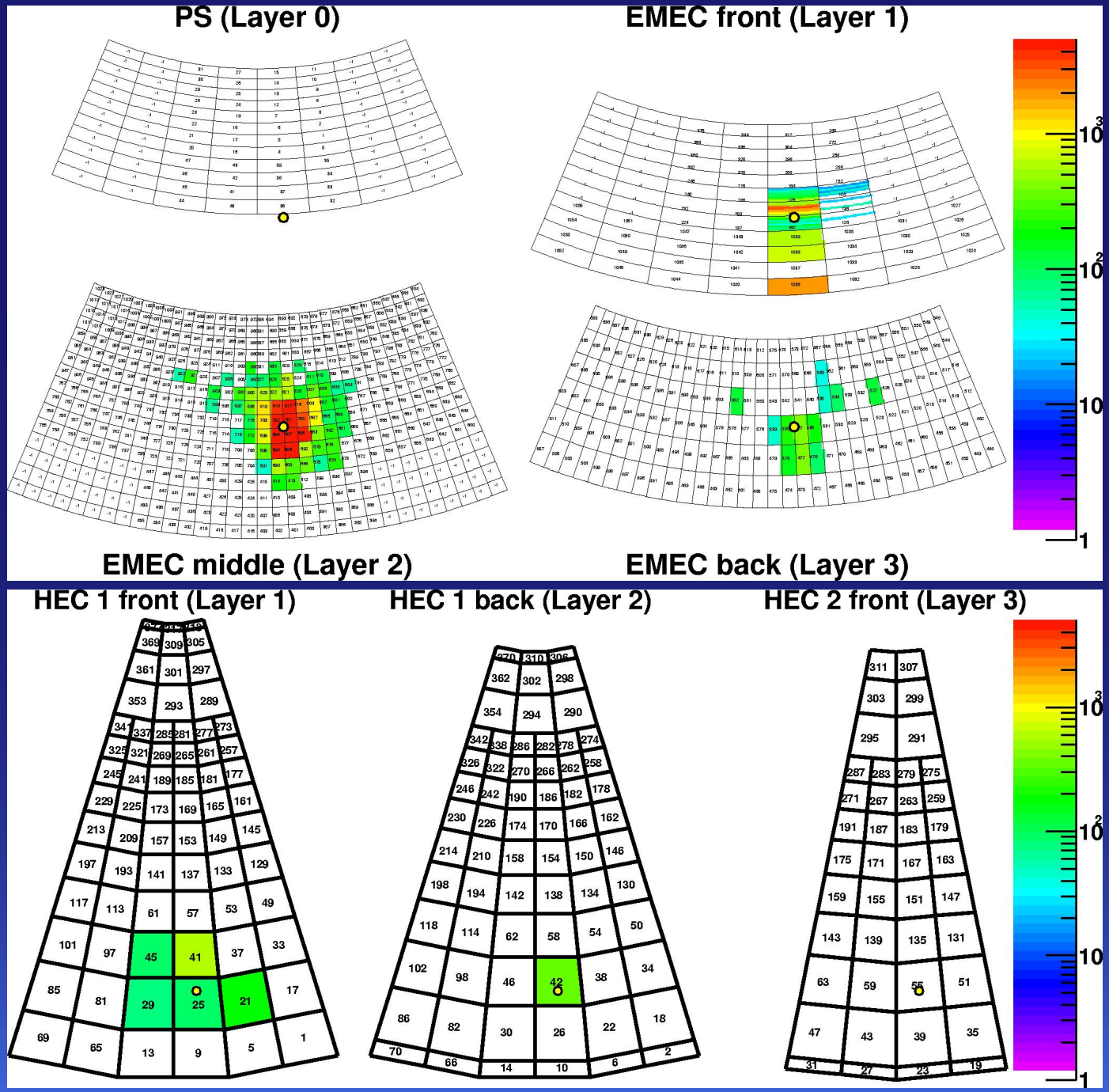
Clustering ► Example event

- 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 $\pi/32$)



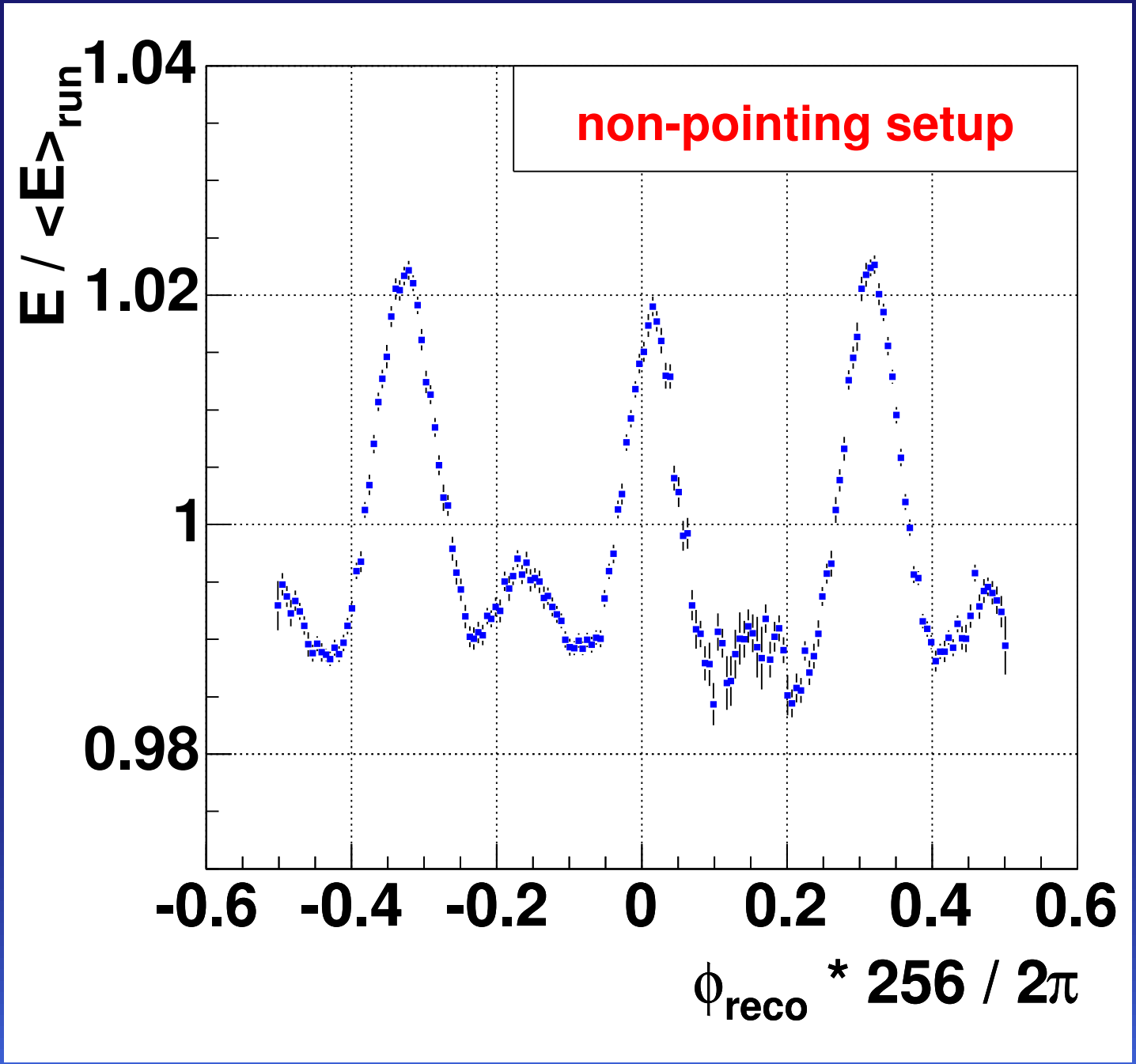
Clustering ► Example event ► After clustering

- Cell-based topological nearest neighbor cluster algorithm
  - Clusters are formed in 2D
  - 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

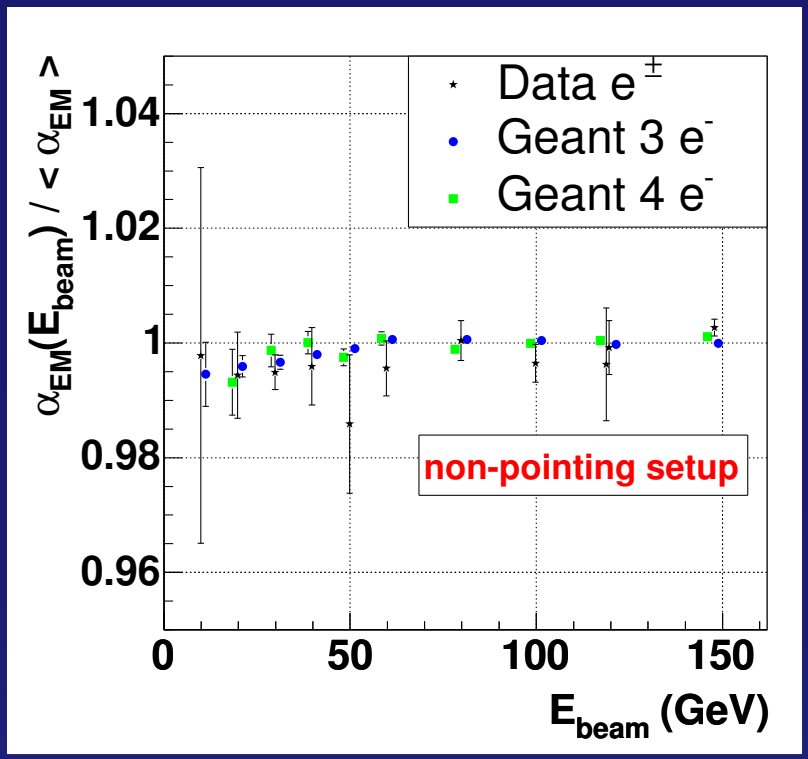


Energy calibration ► Signal Corrections

- 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 $\pm 1.5\,\%$

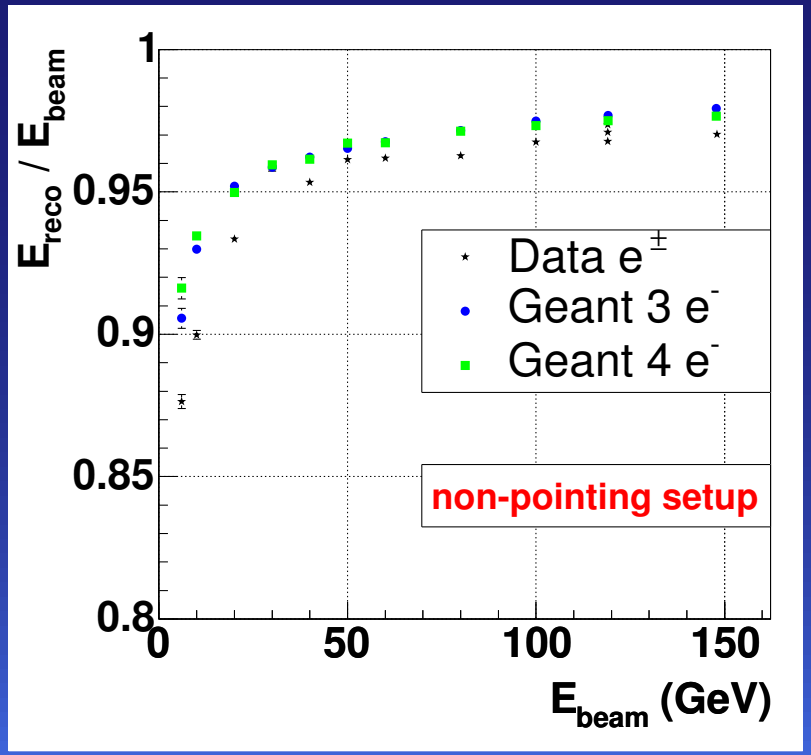


Energy calibration ► Electromagnetic scale



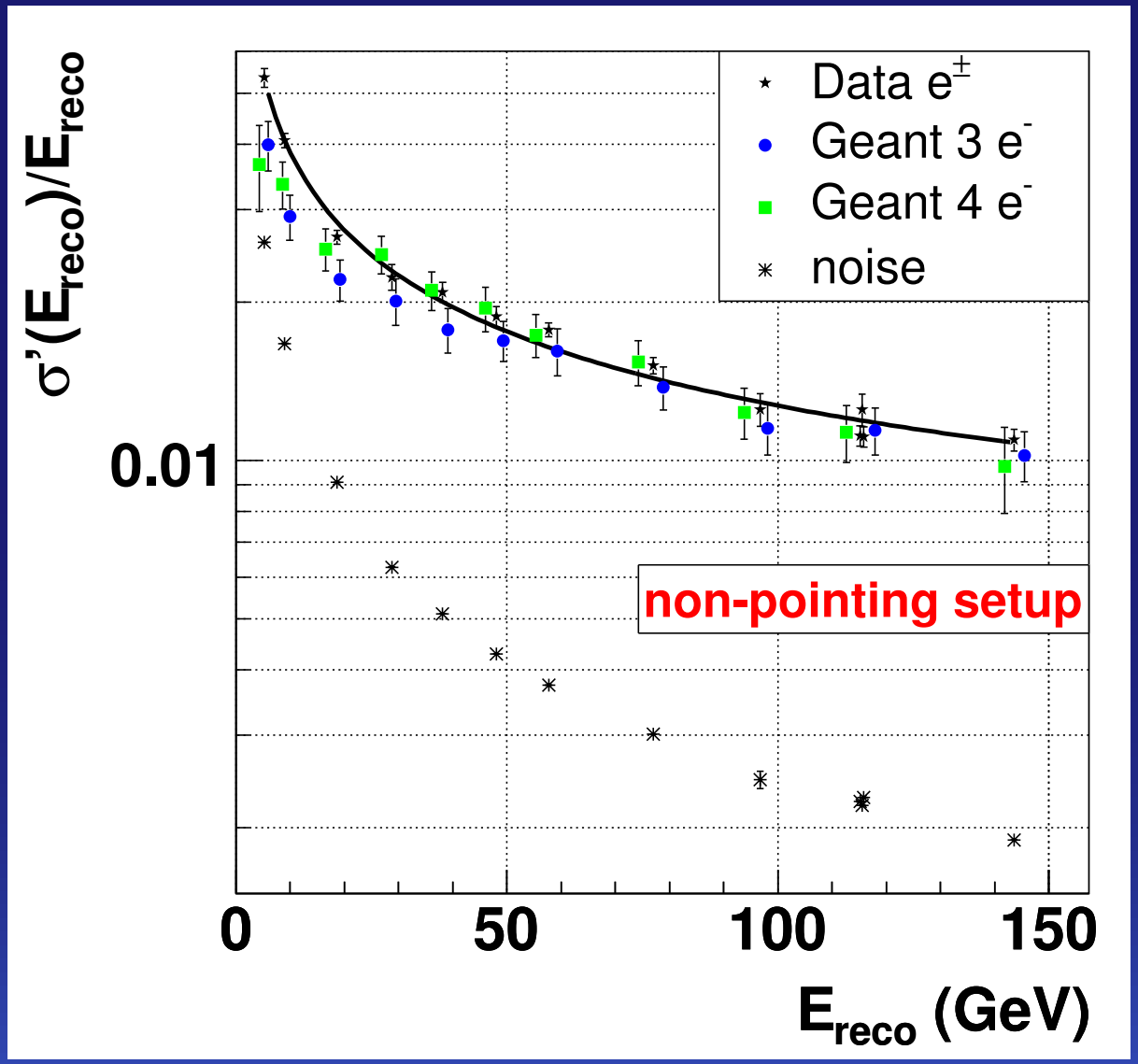
- $\alpha_{em}^{EMEC} = 0.430 \pm 0.001\,\mathrm{MeV/nA}$
  - linearity good to $\pm 0.5\,\%$
  - well reproduced by MC
- cluster leakage available in MC and data

- 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



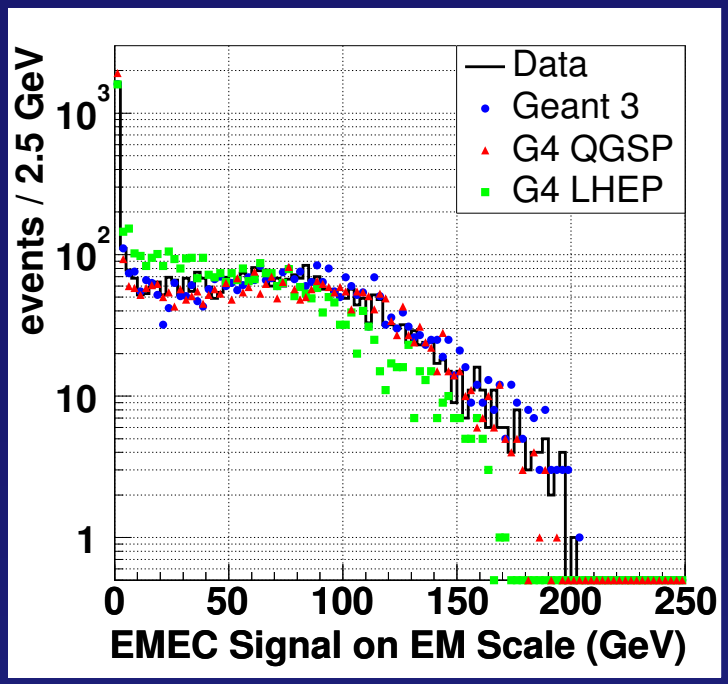
Energy calibration ► Resolution for electrons

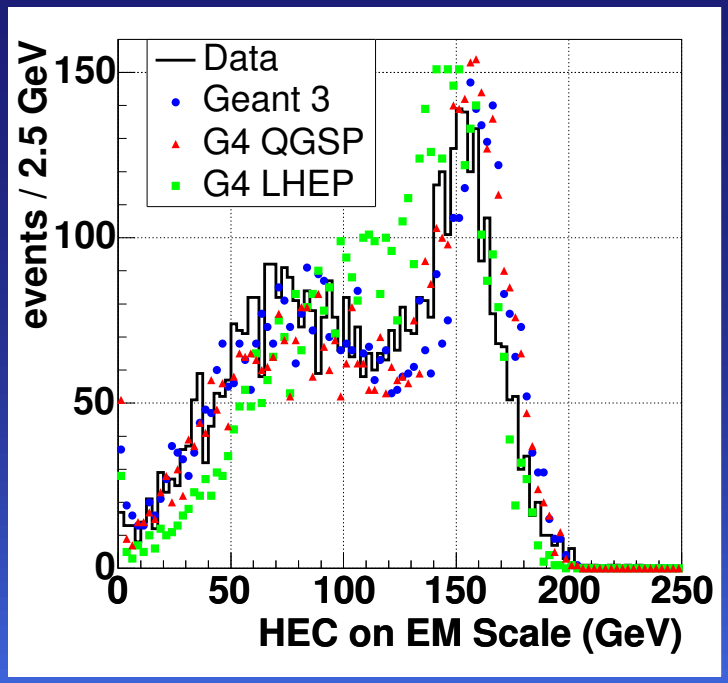
- σ_E/E (%) noise subtracted
  - data: $\frac{12.1 \pm 0.2}{\sqrt{E/\mathrm{GeV}}} \oplus 0.4 \pm 0.1$
  - slightly worse than stand-alone beam test with pointing geometry
  - Geant3: $\frac{9.3 \pm 0.6}{\sqrt{E/\mathrm{GeV}}} \oplus 0.8 \pm 0.1$
  - Geant4: $\frac{10.6 \pm 0.7}{\sqrt{E/\mathrm{GeV}}} \oplus 0.7 \pm 0.2$
- noise: $\sigma_{\mathrm{noise}}/E \simeq 250\,\mathrm{MeV}/E$



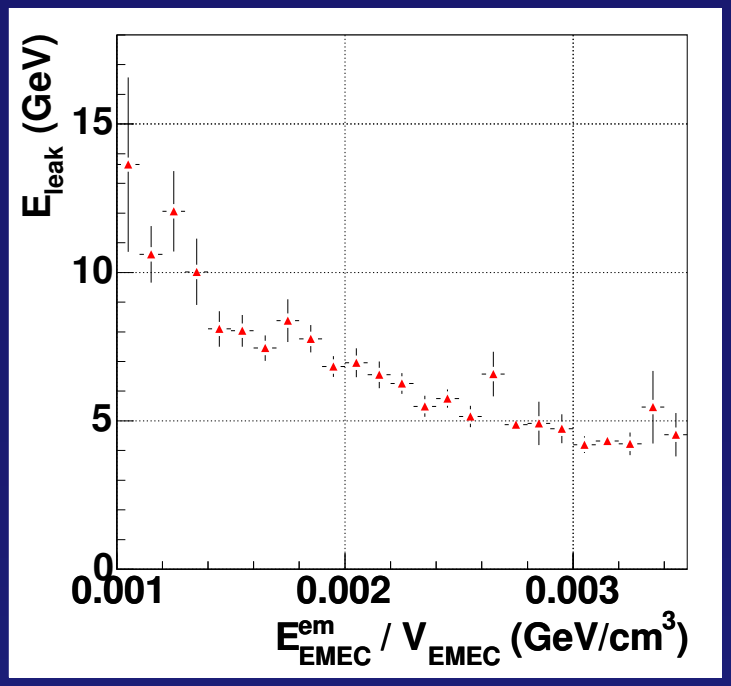
Energy calibration ► Response to pions

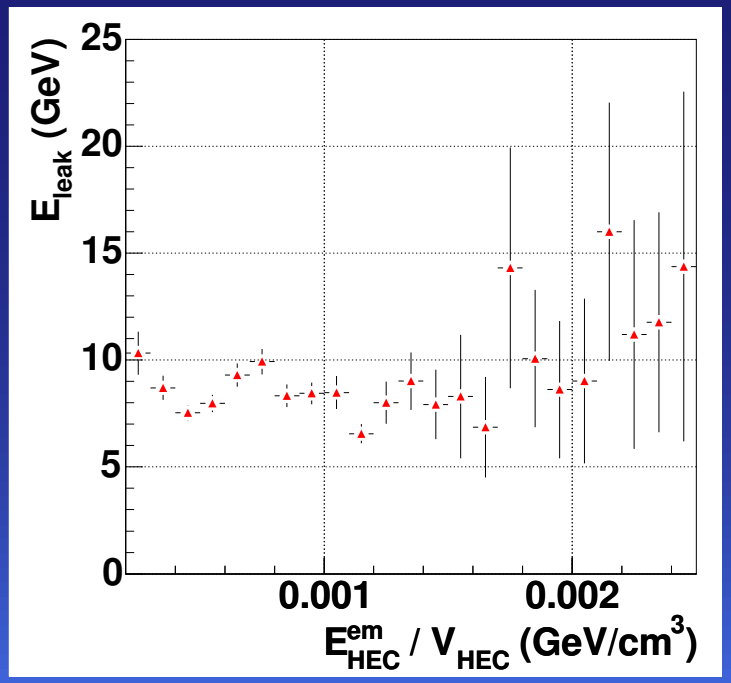
- No electrons in HEC only
  - Electromagnetic scale from previous HEC stand-alone TB
  - Modified by new electronics
  - Calculated value: $\alpha_{\mathrm{em}}^{\mathrm{HEC}} = 3.27\,\mathrm{MeV/nA}$
- Response to 200 GeV pions in data and MC on em-scale
  - upper plot shows EMEC
  - lower plot shows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





Energy calibration ► Weighting



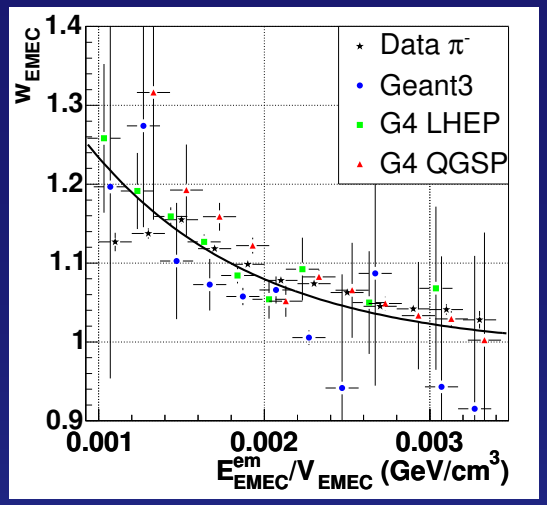


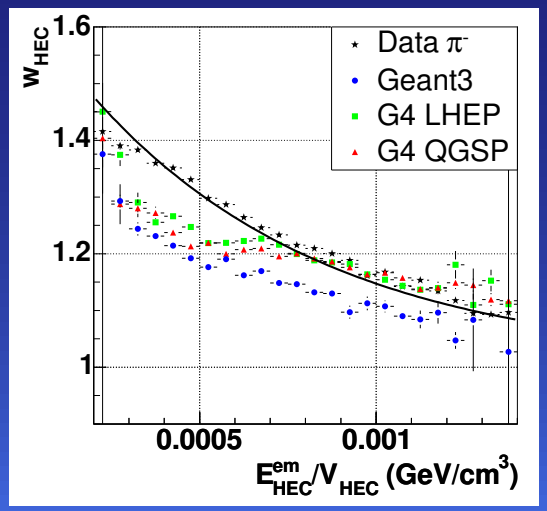
- EMEC and HEC are non compensating
  - corrections (weights) need to be applied on top of the em-scale constants
  - various weighting methods are studied
  - best would be cell-based weights $\longrightarrow$ needs more detailed MC than currently available
  - cluster based weights as function of energy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

Energy calibration ► Weighting ► Cluster weights

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

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

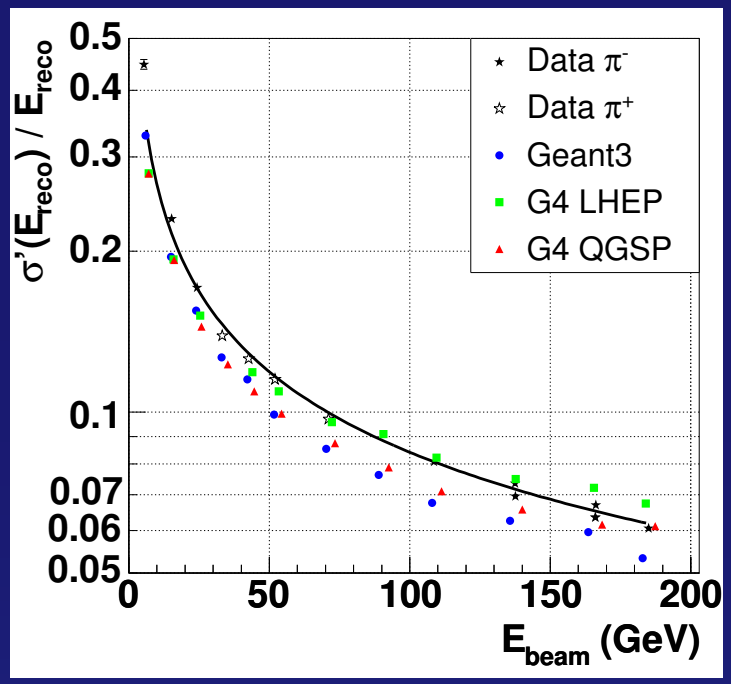


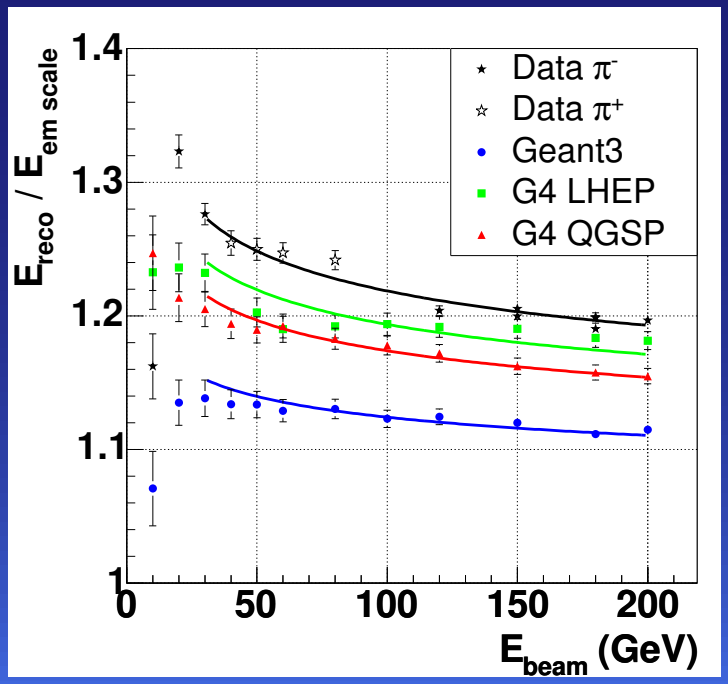


- $E_{\text{reco}} = E_{\text{em}} \left(c_1 \cdot \exp\left[-c_2 \cdot E_{\text{em}}/V\right] + c_3\right)$ (H1 method)
- $E_{\text{tot}} = E_{\text{reco}} + E_{\text{em}}^{\text{cluster leak}}$
- E_{leak} as on previous slide from MC
- c_2 fixed to $1000\,\text{cm}^3/\text{GeV}$ ($1500\,\text{cm}^3/\text{GeV}$) 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:
    $$\frac{84.1 \pm 0.3}{\sqrt{E/\mathrm{GeV}}} \oplus 0.0 \pm 0.3$$
  - noise:
    $\sigma_{\mathrm{noise}}/E \simeq 1 - 1.5\,\mathrm{GeV}/E$





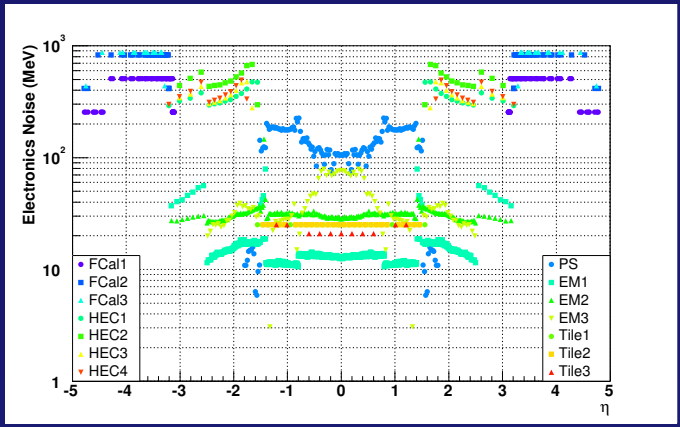
- Geant3 and all Geant4 models give similar results
- combined e/π ratio
  - shows total $E_{\mathrm{reco}}/E_{\mathrm{em}}$
  - indicates the amount of non-compensation
  - fitted e/h-ratios for combined HEC and EMEC have no direct interpretation

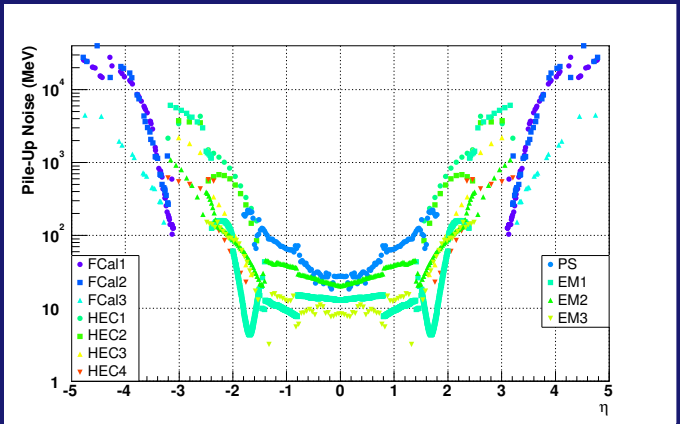
Roadmap to ATLAS

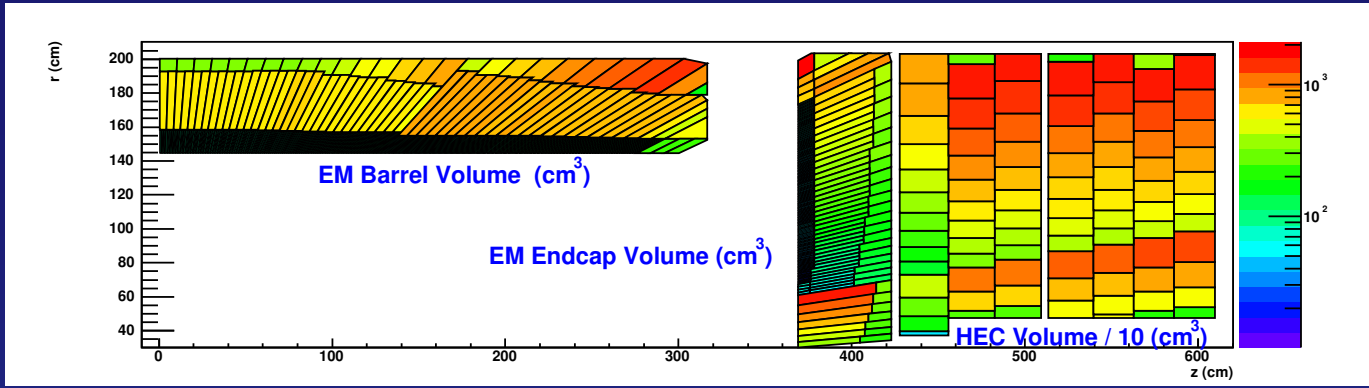
- more combined beam tests this summer (H6 and H8)
  - EMEC/HEC/FCAL in H6
  - EMB/TileB in H8
  - with official ATLAS readout hardware/software
- new Geant4 simulation with calibration hits
  - reports electromagnetic, non-electromagnetic, invisble and escaped energy in active cells and “dead” material
  - hadronic physics lists need input from beam tests
- prepare reconstruction software for full ATLAS
  - clustering in presence of Pile-Up

Roadmap to ATLAS ► Topological Clustering

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

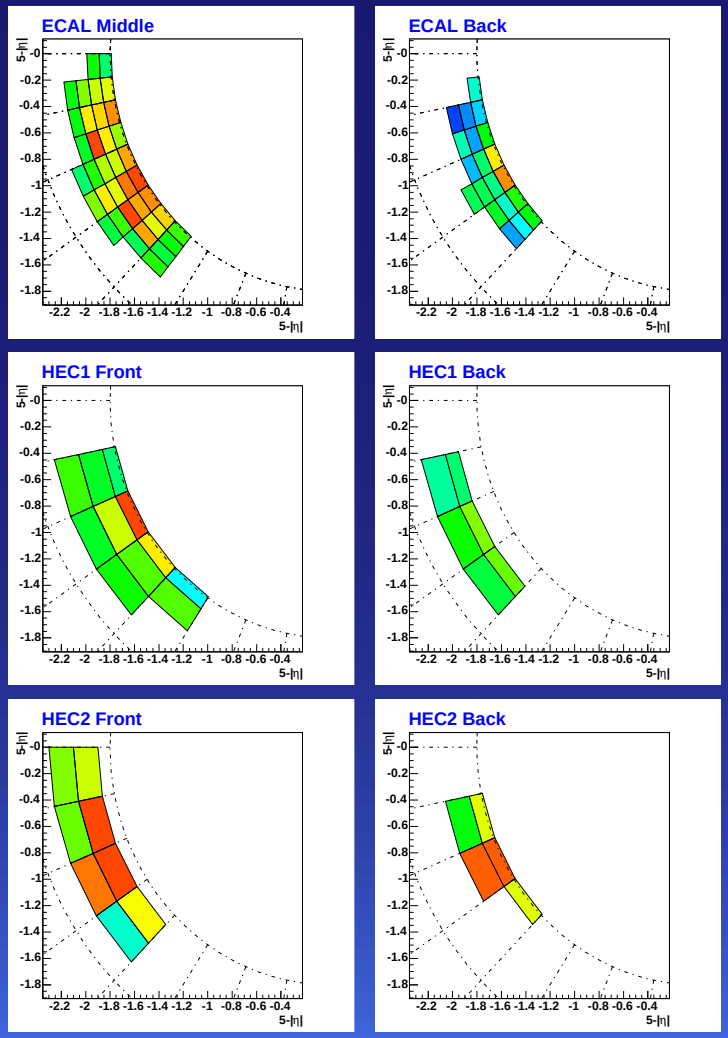


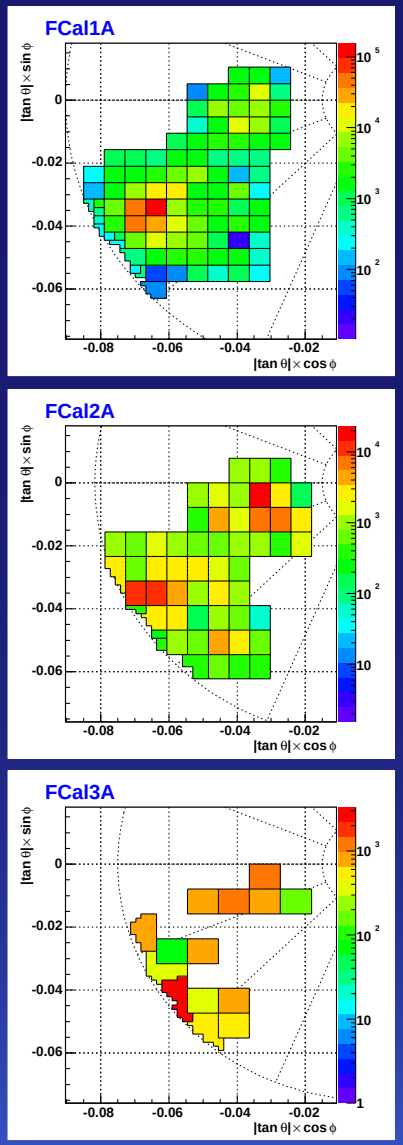




- use conditions database to obtain
  - $\sigma_{\text{noise}} = \sigma_{\text{elec-noise}} \oplus \sigma_{\text{pile-up}}$ for every channel in every event
  - use E/σ_{noise} for discrimination in topological clustering
  - use $\rho_{\perp} = E_{\perp}/V$ for definition of hot spots and topological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

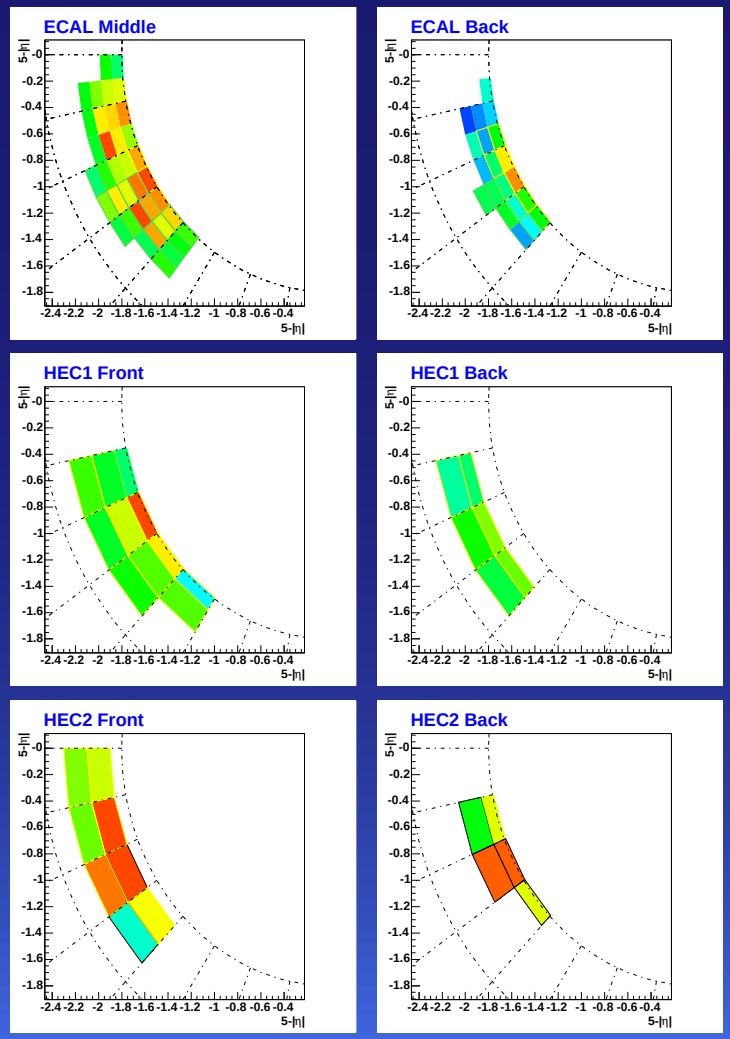
- Jet with $p_\perp > 70\,\mathrm{GeV}$, $|\eta| < 5$ in EM, HEC, FCal
- Parent Cluster before splitting

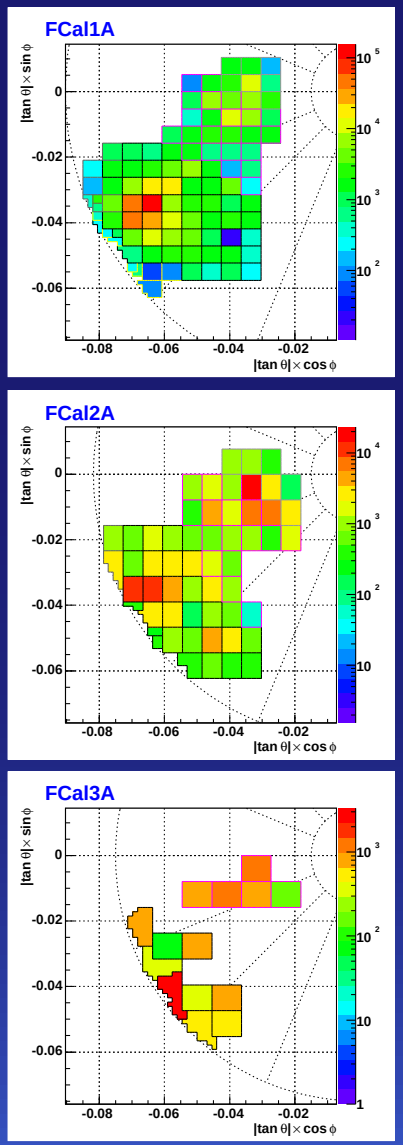




- EMEC has only 2 layers in this region
- EMEC3 neighbors HEC1
- HEC1 overlaps with the front of FCal1
- rear faces of FCal1 and 2 neighbor HEC3 and 4
- all 9 layers belong to the same cluster
- at least 4 potential local maxima visible

- 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-splitted

Conclusions

- All ATLAS Calorimeter module are built and tested
  - construction went as planned
  - filled cryostats are being tested
  - first half of the Tile Barrel is installed in the Pit
- Combined beam test 2002
  - first of this kind was the 2002 combined test of EMEC and HEC
  - performance as expected
  - triggered new developments for Geant4 simulation (calibration hits)
- Combined beam tests 2004
  - H6 (End-cap) and H8 (Barrel) combined tests started this month
  - first test of complete ATLAS like setup (HW and SW)
  - will be the last tests prior to real ATLAS data taking