H6 Beam Tests Analysis Studies

1st North American ATLAS Physics Workshop
19-21 December 2004, Tucson, Arizona

- H6 LAr calorimetry beam tests
- Signal reconstruction
- Response to electrons
  - Electromagnetic Scale
- Response to pions
  - weighting schemes
- Simulation
- Conclusion and outlook

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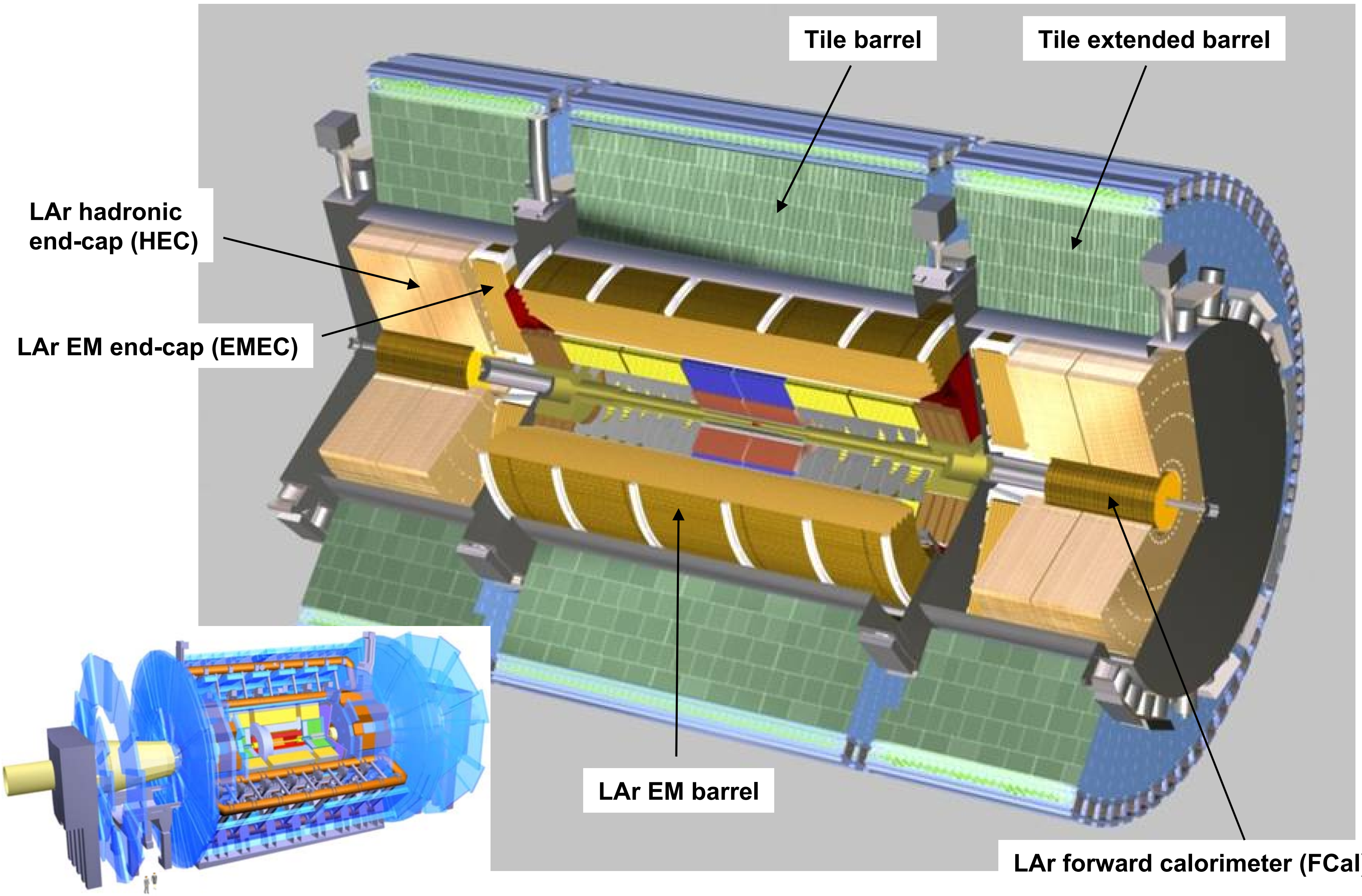
ATLAS LAr and Tile Calorimeters



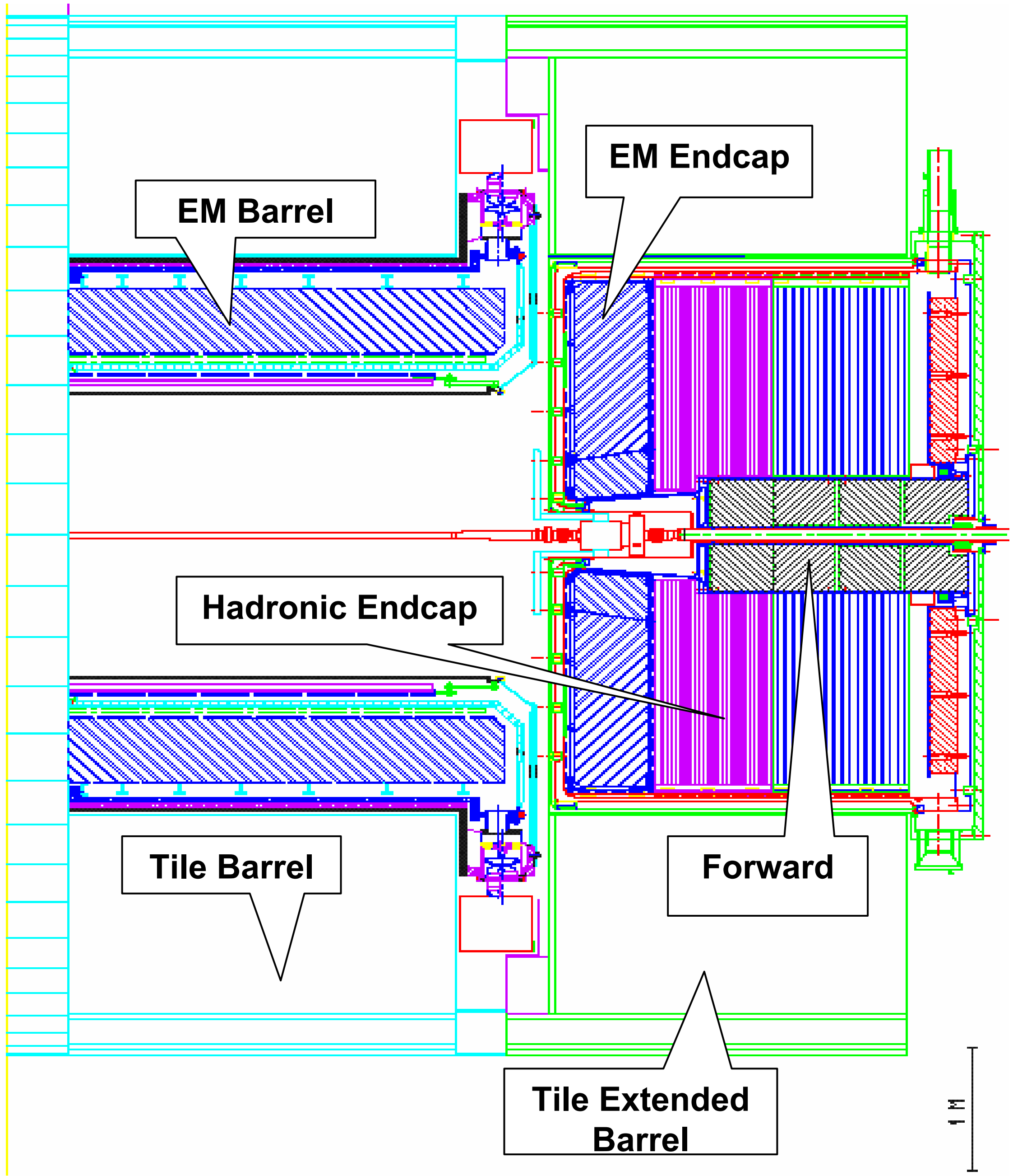
Design Physics Requirements

EM Calorimeters

- Benchmark channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow eeee$ require high resolution at ≈ 100 GeV and coverage to low E_T
- b-physics: e reconstruction down to GeV range
- Dynamic range: MIP to $Z' \rightarrow ee$ at a few TeV
- Design goals for $|\eta| < 2.5$
  - $\sigma(E)/E = 8\text{-}11\ \%/\sqrt{E} \oplus 0.2\text{-}0.4/E \oplus 0.7\%$
  - Linearity better that 0.1%

Hadron and Forward Calorimeters

- Benchmark channels $H \rightarrow WW \rightarrow$ jet jet X and Z/W/t require good jet-jet mass resolution
- Higgs fusion → good forward jet tagging
- $E_{Tmiss} \rightarrow$ jet resolution and linearity
- Design goals
  - $\sigma(E)/E = 50\%/\sqrt{E} \oplus 3\%$ for $|\eta| < 3$
  - $\sigma(E)/E = 50\%/\sqrt{E} \oplus 10\%$ for $3 < |\eta| < 5$



LAr Calorimeters

- EM Barrel
  - $|\eta| < 1.5$
- EMEC
  - $1.4 < |\eta| < 3.2$
- HEC
  - $1.5 < |\eta| < 3.2$
- FCal
  - $3.1 < |\eta| < 4.9$

Electromagnetic Endcap Calorimeter

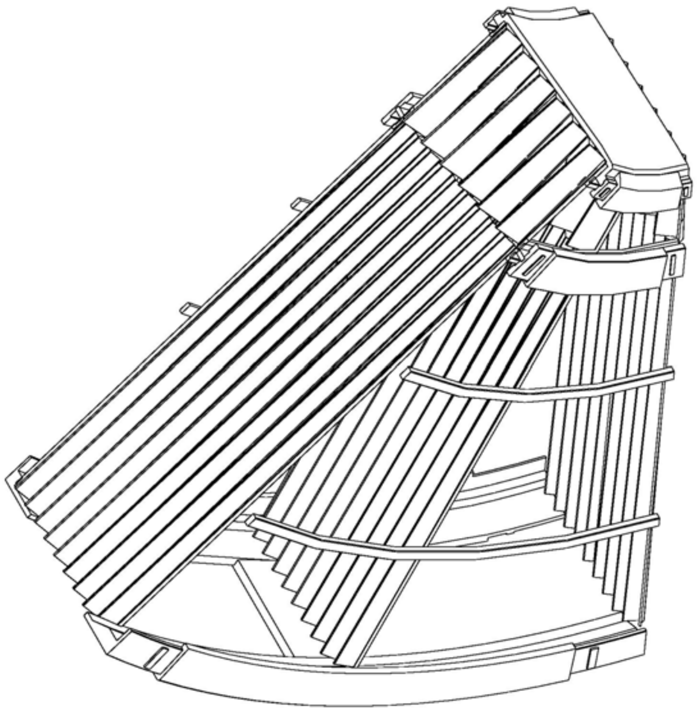
- EMEC absorber structure
  - Pb absorbers arranged radially, no azimuthal cracks
  - folding angle and wave amplitude vary with radius
  - inner and outer wheels
- EMEC readout structure
  - layer 0 (presampler)

    $\Delta\eta \times \Delta\varphi = 0.025 \times 0.1$
  - layer 1 (front): $\approx$ 2 to 4 X_o

    $\Delta\eta \times \Delta\varphi = 0.025/8 \times 0.1$
  - layer 2 (middle): $\approx$ 16 to 18 X_o

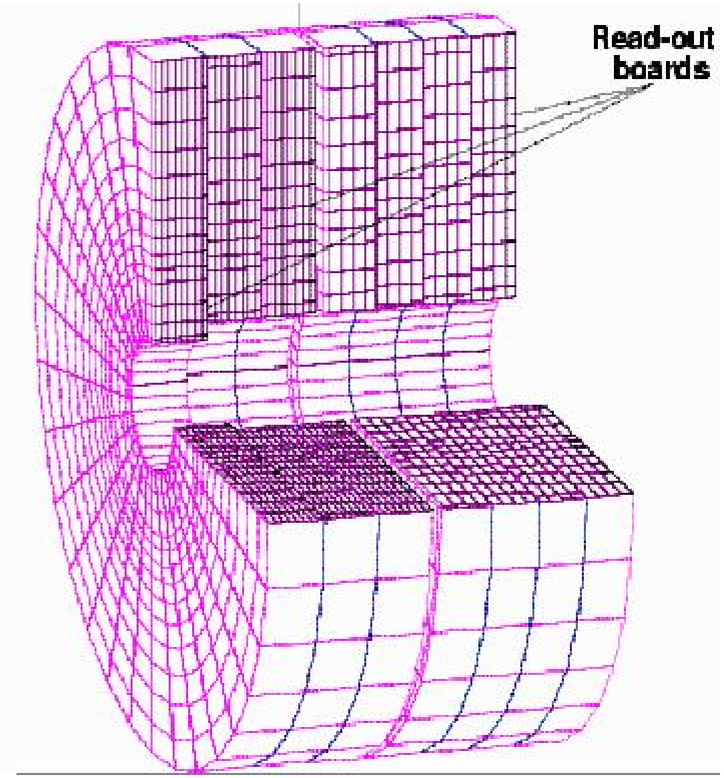
    $\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$
  - layer 3 (back): $\approx$ 2 to 4 X_o

    $\Delta\eta \times \Delta\varphi = 0.050 \times 0.025$



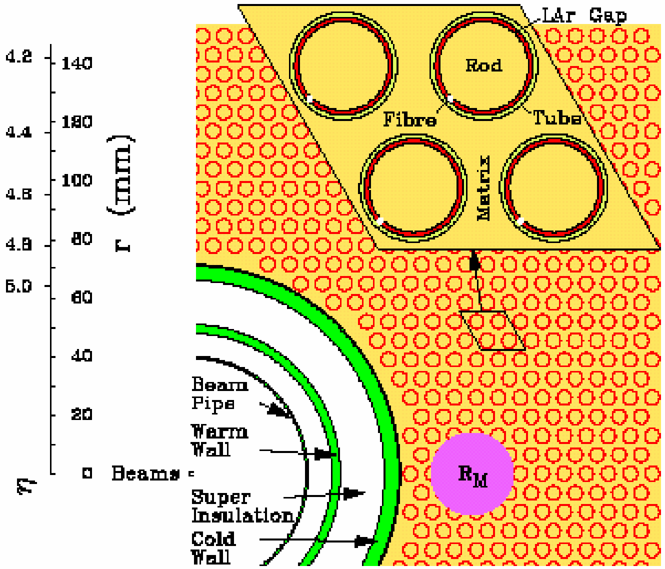
Hadronic Endcap Calorimeter

- HEC absorber structure
  - Cu absorbers in the transverse plane
  - front and back wheels, 2 samplings each
  - EST readout structure
- HEC readout structure
  - $1.5 < |\eta| < 2.5 \Rightarrow \Delta\varphi = 0.1 \times 0.1$
  - $2.5 < |\eta| < 3.3 \Rightarrow \Delta\varphi = 0.2 \times 0.2$



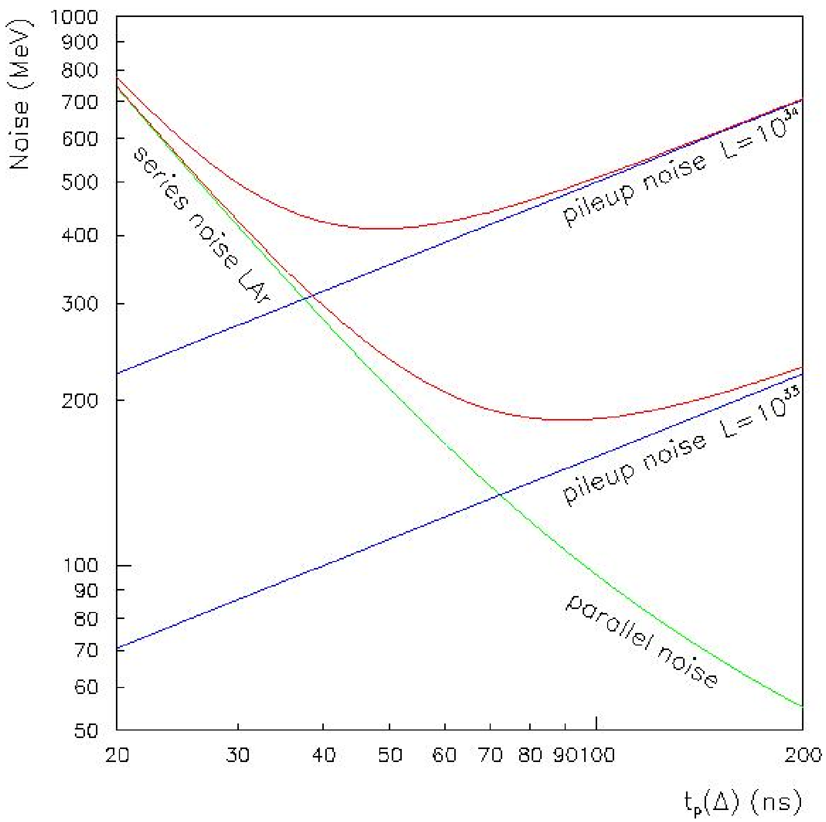
Forward Calorimeter

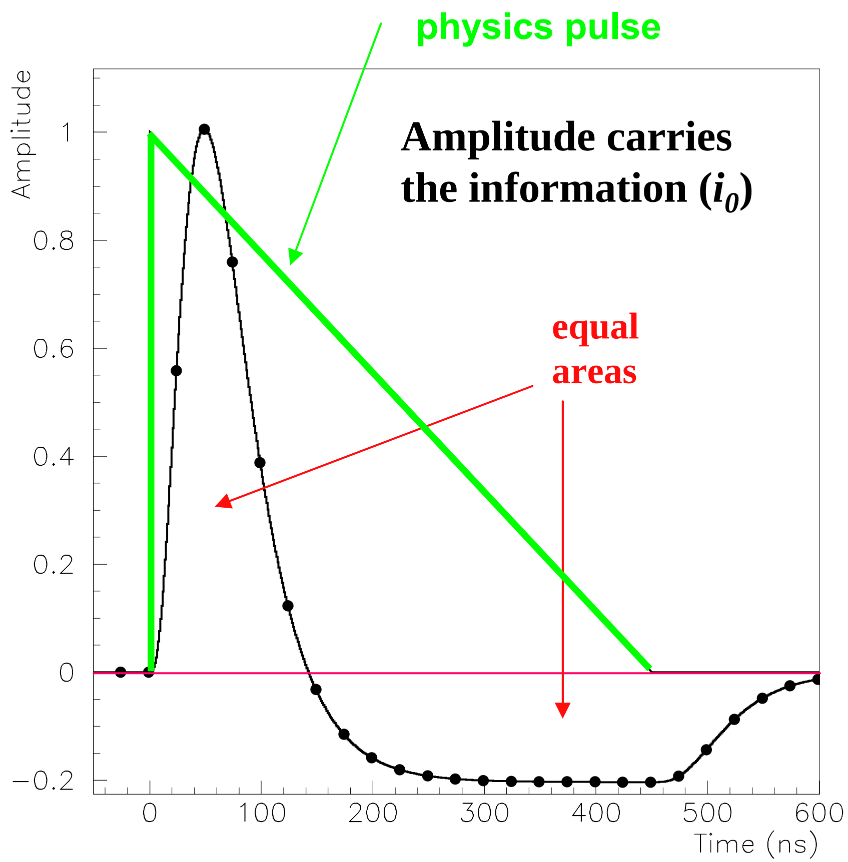
- **FCal absorber structure**
  - Cu (FCal1) and W (FCal2/3) absorber with cylindrical ionization chambers parallel to the beam line
- **FCal readout structure**
  - Principal coverage is $3.1 < |\eta| < 4.9$ and $\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.2$
  - Non-projective!



	Type	Absorber	Gap (μm)	Number of Electrodes
FCal1	EM	copper	250	12000
FCal2	HAD	tungsten	375	10000
FCal3	HAD	tungsten	500	8000

LAr Bipolar Signal Pulse Shaping





Optimal shaping time is an optimization problem between electronics noise and pileup noise

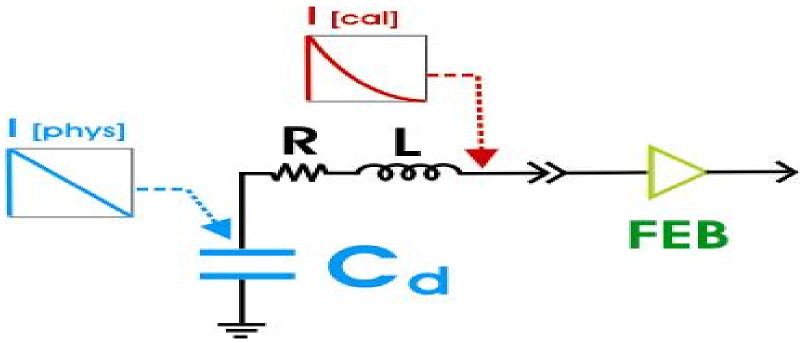
Pulse shape sampled every 25 ns

Optimal Filtering Signal Reconstruction

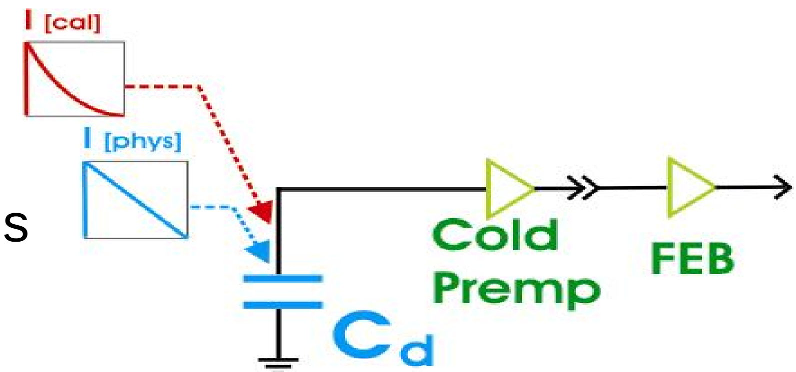
- Optimal filtering
  - need known physics signal shape $g(t)$
  - discrete (Δt = 25 ns) measurements (signal + noise): $y_i = Sg_i + b_i$
  - relies on timing from ATLAS TTC
  - autocorrelation matrix from noise runs: $B_{ij} = \langle b_i b_j \rangle - \langle b_i \rangle \langle b_j \rangle$
  - estimate signal amplitude S with $\tilde{S} = \sum a_i y_i = \mathbf{a}^{\mathrm{T}} \mathbf{y}$
  - minimize $\chi^2(\tilde{S}) = (\mathbf{y} - S\mathbf{g})^{\mathrm{T}} \mathbf{B}^{-1} (\mathbf{y} - S\mathbf{g})$
  - solution is given by the optimal filtering coeffs (OFC) $\mathbf{a} = \dfrac{\mathbf{B}^{-1}\mathbf{g}}{\mathbf{g}^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{g}}$
- Signal shape
  - obtained directly from data (cross talk needs careful consideration)
  - or obtained from calibration pulses and detailed knowledge of difference between signal pulse shape and calibration pulse shape

All LAr detectors have calibration pulser system

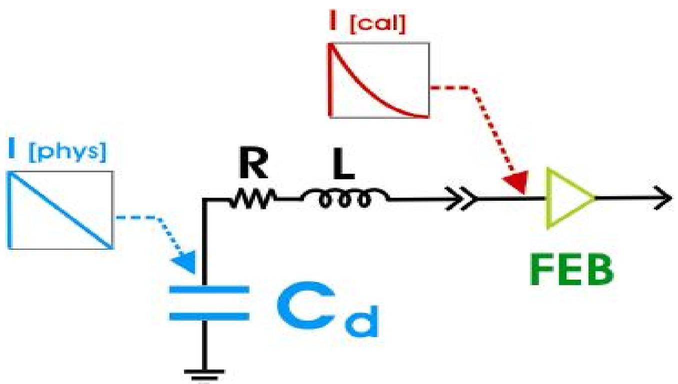
- EM
  - Inject on summing boards



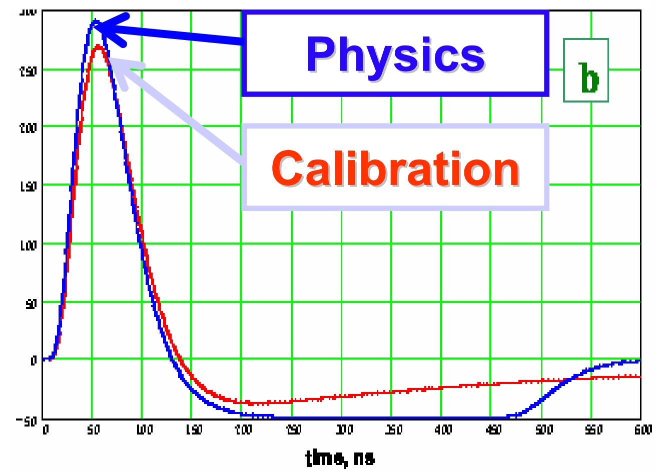
- HEC
  - Inject at calo pads



- FCal
  - Inject on FEB backplane



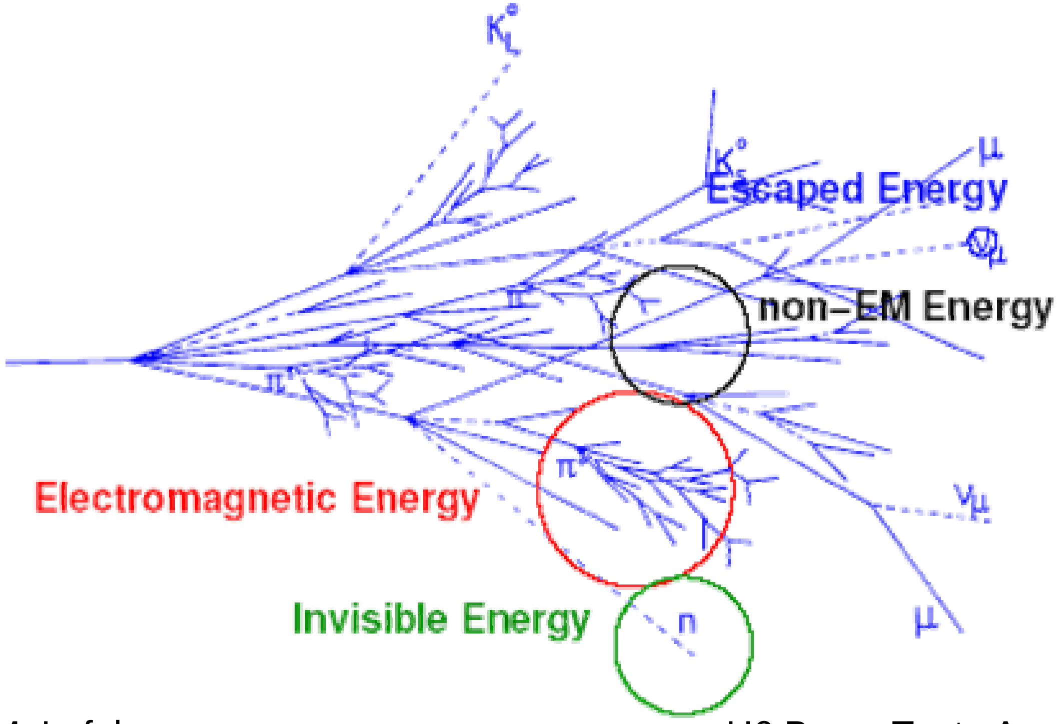
Same I_0



- To use calibration system:
  - Understanding ADC[phys]/ADC[cal] for fixed I_0 is key

Hadronic Energy Reconstruction

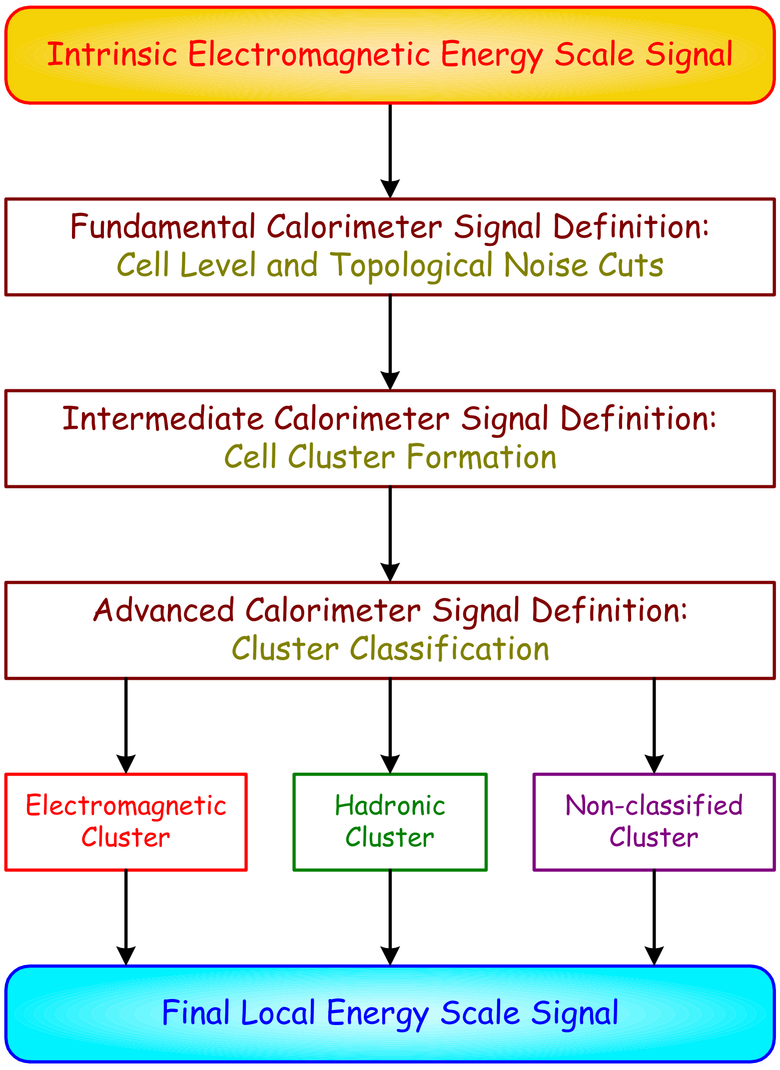
- Hadronic shower consists of
  - EM energy (eg $\pi^0 \rightarrow \gamma\gamma$) : O(50%)
  - Visible non-EM energy (eg dE/dX) : O(25%)
  - Invisible non-EM energy (eg nuclear breakup) : O(25%)
  - Escaped energy (eg ν) : O(2%)



- Goal:
  - Event-by-event offline compensation of hadronic energy deposition
  - Improve linearity and resolution

Model II: Local Calorimeter Calibration Algorithm Flow

P. Loch



Electronic and readout effects unfolded (nA->GeV calibration)

Detector noise suppression algorithms (optional, can be absorbed into cluster formation algorithm)

Cluster formation in calorimeter regions (2D->3D->spanning regions)

Simple cluster shape analysis -> classification

Apply cluster type specific calibration functions, dead material and crack corrections

Best estimate for general energy flow in event -> re-calibrate smallest readout units (cells)!

Cluster/cell weighting formalism

- Cluster (or cell) weights are used for energy reco

$$E_{\text{reco}}(C_j) = \sum_{\substack{\text{cells or} \\ \text{clusters}}} w(C_j, A_k) E_{\text{em}}$$

  - weights depends on some parameters C_j and some observables A_k

- Parameters should be obtained from (validated!) MC
- First look at parameters can be obtained from TB data through the minimization of

$$\chi^2 = \sum_{\text{events}} \frac{\left[E_{\text{beam}} - E_{\text{leak}} - E_{\text{reco}}(C_j)\right]^2}{\left(\sigma^2_{\text{leak}} + \sigma^2_{\text{reco}}\right)}$$

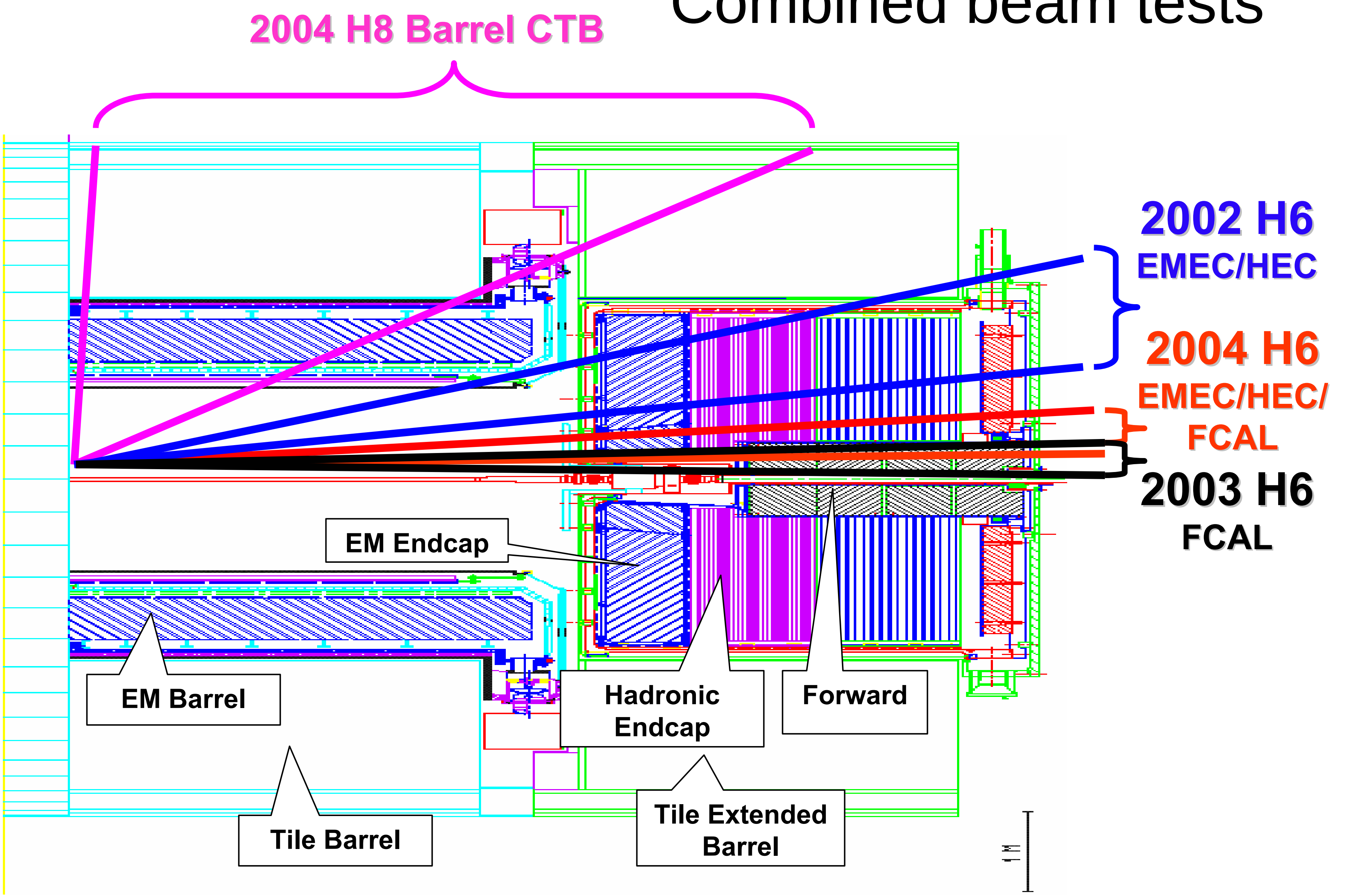
  - leakage outside the cluster/cell (but in the calorimeter) can be parameterized from the data
  - leakage outside the detector must be parameterized from MC

H6 beam tests

HEC standalone (1998-2001)	EM scale
EMEC standalone (1999)	EM scale, presampler
EMEC-HEC (2002)	combined pion response
FCal standalone (2003)	Fcal calibration
EMEC-HEC-FCAL (2004)	combined forward response

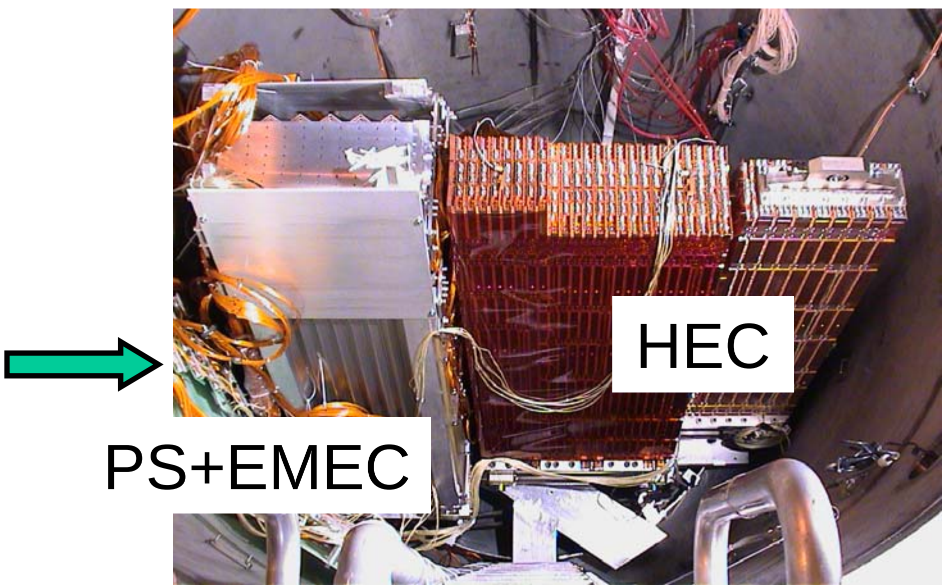
- The tests serve multiple purposes, including
  - QA/QC during detector construction
  - EM scale calibration
  - Investigate hadronic shower reconstruction scheme
  - Study detector interface regions
  - Exercise ATLAS electronics chain
  - Tests of online/offline monitoring/reconstruction software

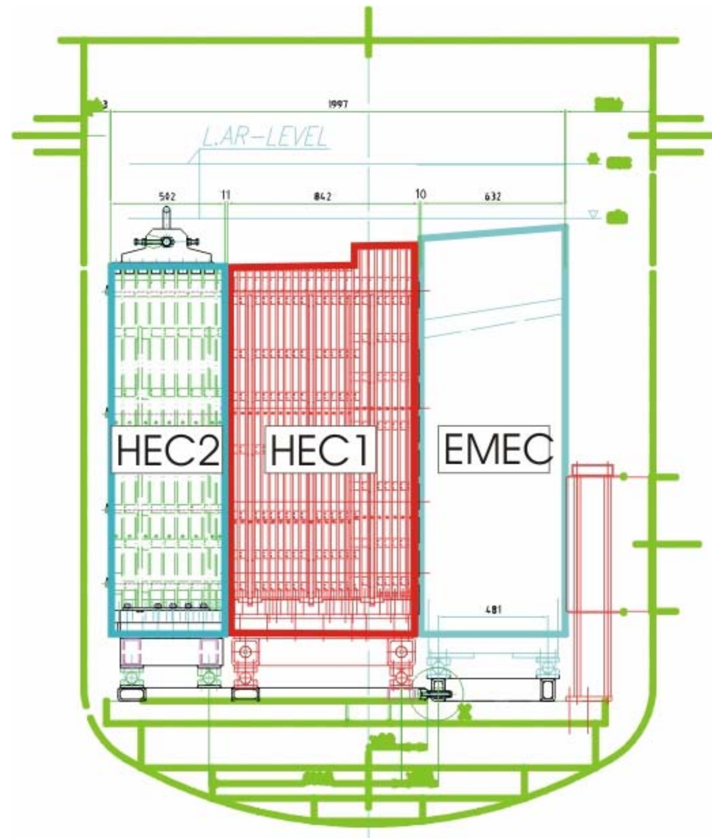
Combined beam tests



HEC-EMEC: beam test configuration

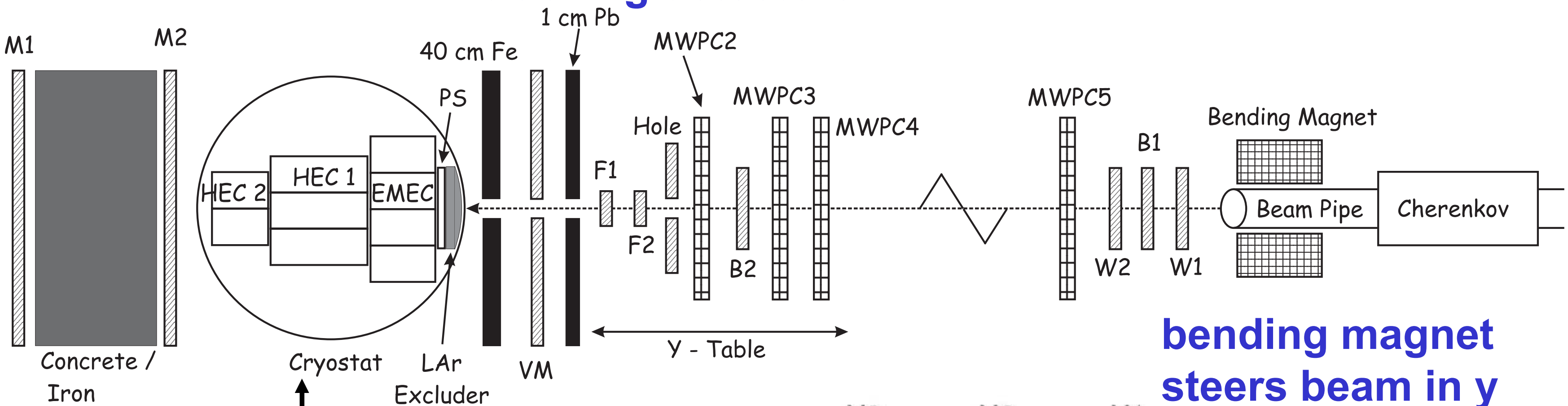
- H6 beam area at the CERN SPS
  - $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$ beams with 6 GeV $\leq$ E $\leq$ 200 GeV
  - 90^{o} impact angle: non-pointing setup (not like ATLAS)
  - beam position chambers
  - optional additional material upstream (presampler studies)





EMEC-HEC: H6 beamline

beamline trigger scintillators and tracking detectors

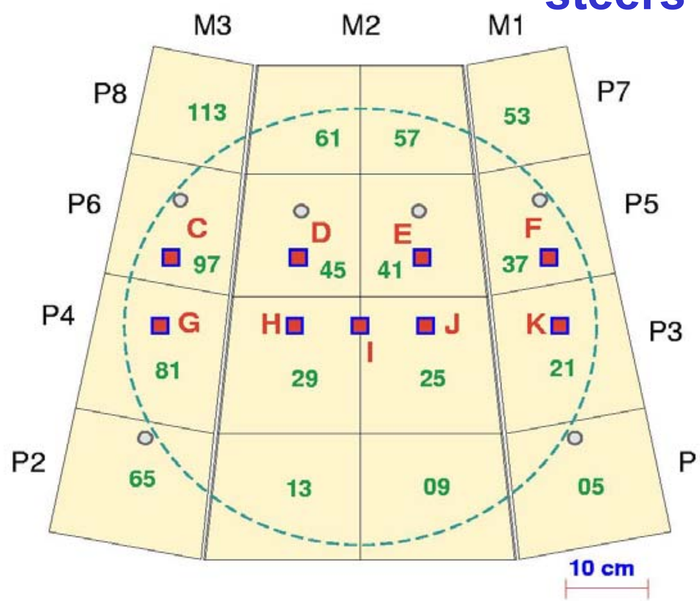


bending magnet steers beam in y

μ detector

cryostat moves laterally ± 30 cm

front face of HEC seen through the EMEC



EMEC and HEC Signal Reconstruction Steps

- Relate calibration pulse shape with physics pulse shape
  - use electronics model (from simple model to full simulation)
  - extract model parameters (various techniques)
- Use predicted physics pulse shape and noise autocorrelation matrix to obtain OFC
  - physics pulse shape not available for all channels!
- Use calibration (ramp) runs to calibrate current
  - DAC $\rightarrow$ R $\rightarrow$ nA
  - DAC $\rightarrow$ ADC[cal] $\rightarrow$ ADC[phys]
- Obtain EM scale from beam test or simulation
  - nA $\rightarrow$ MeV
- Accuracy and channel uniformity goals
  - EM: $\approx$ 0.5% and HEC: $\approx$ 1%

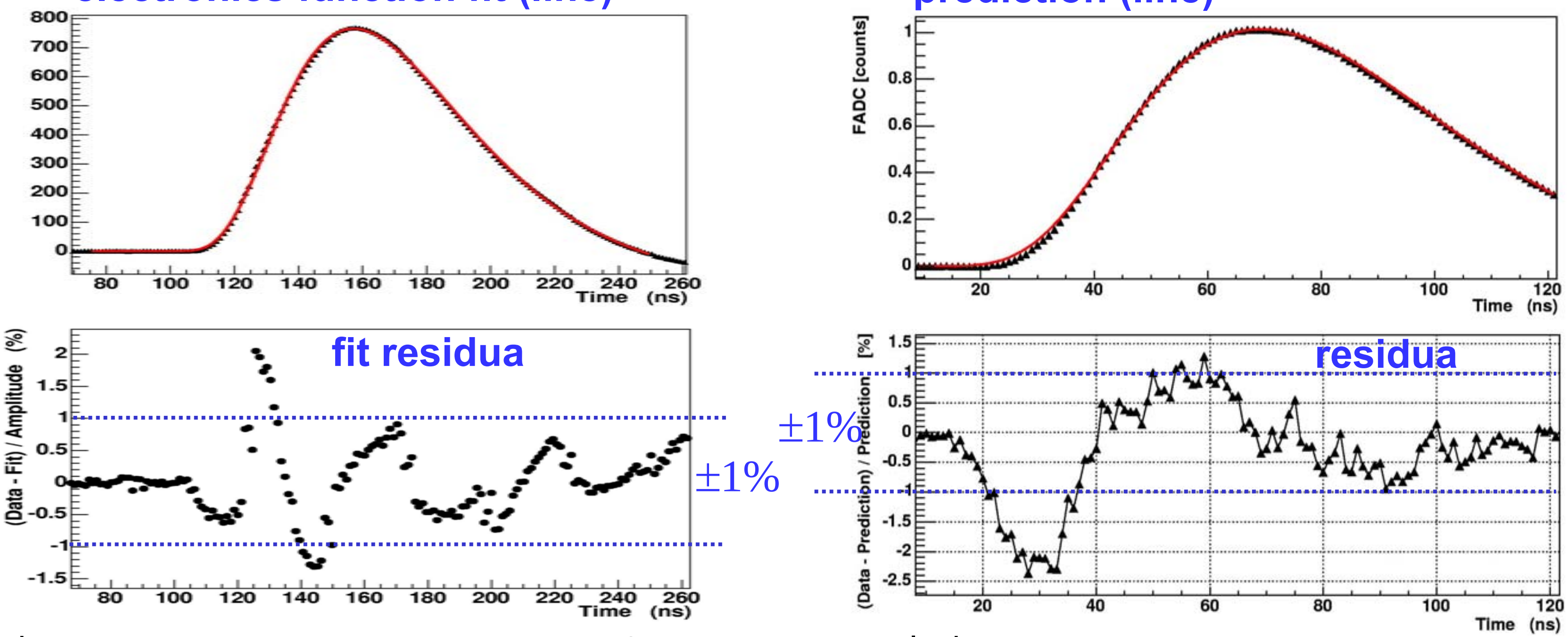
Example: HEC calibration ADC to nA

Calibration pulse height

- crucial to understand the channel-by-channel variation in the difference in pulse height and shape between data and calibration signals
- electronics modeling
- predict signal pulse from calibration pulse to about 1%

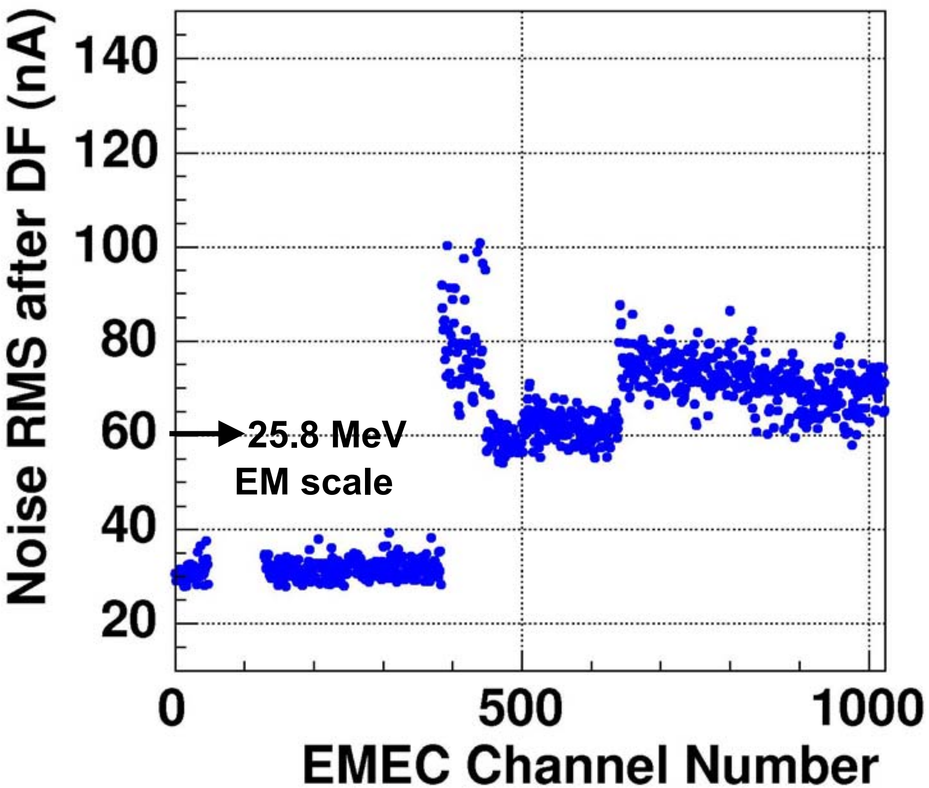
calibration signal (points)
electronics function fit (line)

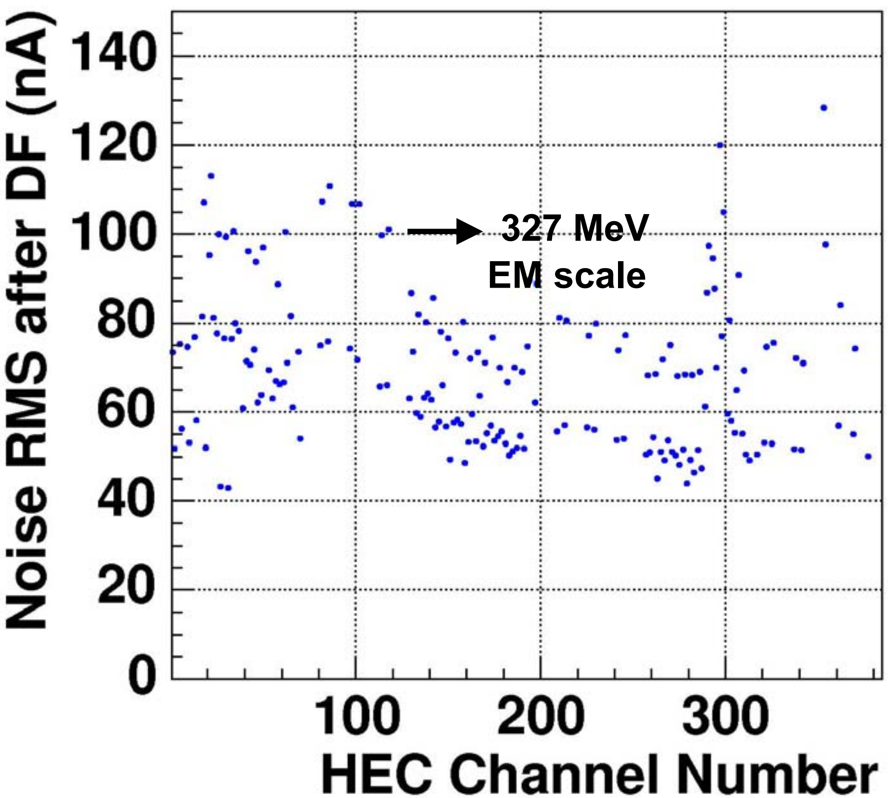
data signal (points)
prediction (line)



EMEC-HEC: electronic noise

- Electronic noise obtained directly from data
  - EMEC: use muon data and remove hit cells
  - HEC: use first 5 time samples (which are out of signal region)

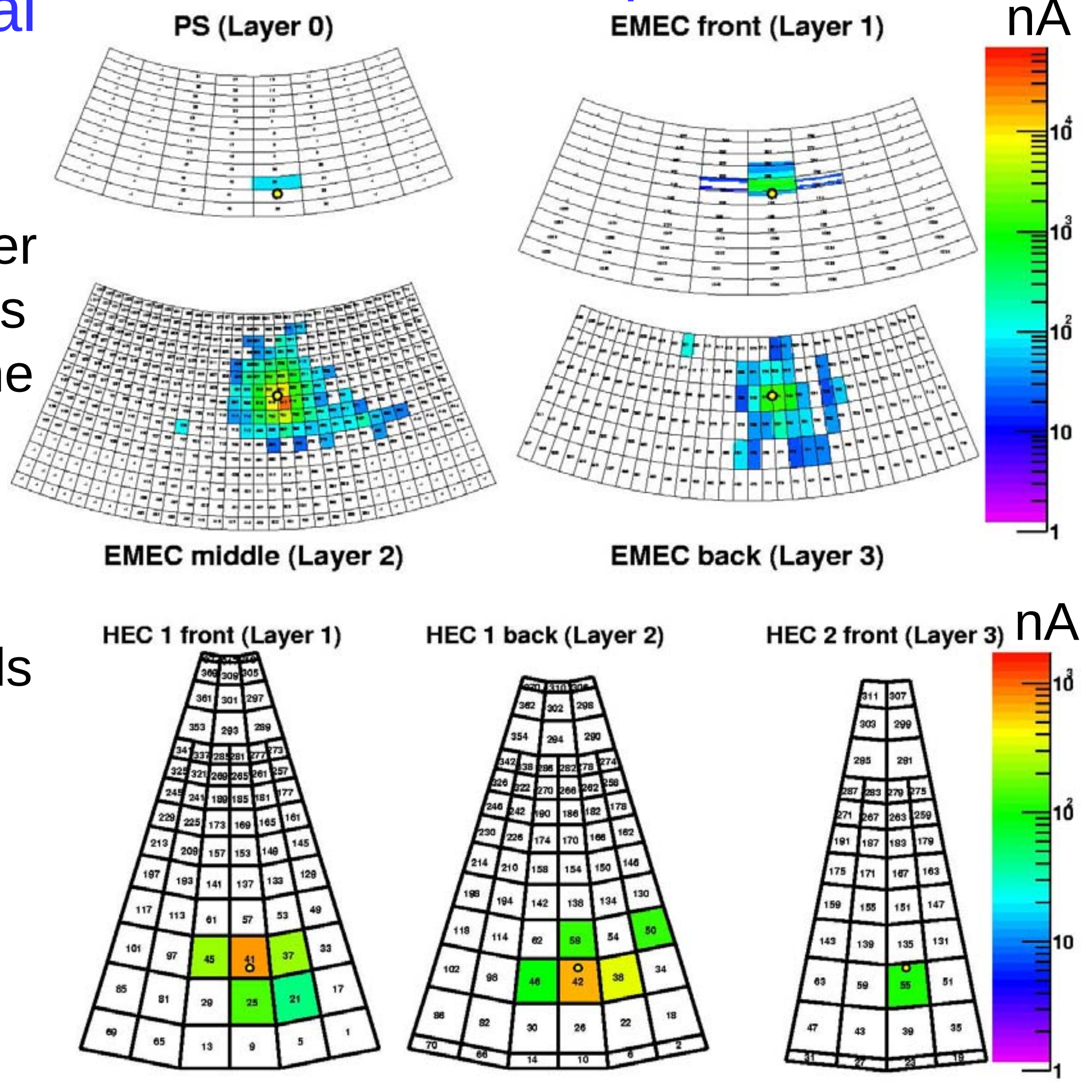




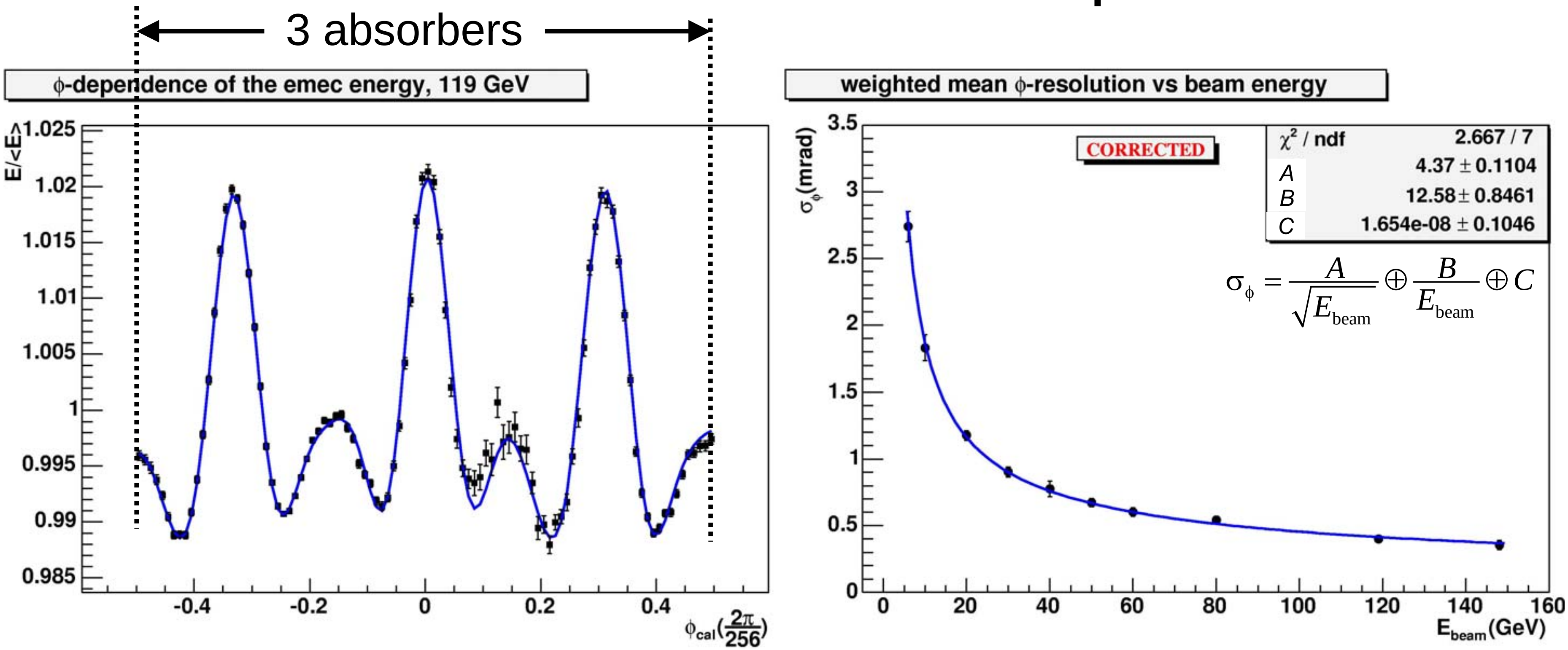
EMEC-HEC: Clustering

- Cell-based topological nearest neighbor cluster algorithm
  - clusters are formed per layer using neighbours (that share at least one corner)
  - $E_{seed} > 4\sigma_{noise}$
  - $|E_{cell}| > 2\sigma_{noise}$
  - include neighbour cells with $|E_{cell}| > 3\sigma_{noise}$

180 GeV pion



EMEC-HEC: electron response



- phi-modulation correction, and resulting phi-resolution
  - electric field and sampling fraction non-uniformities
  - non-pointing setup
  - well understood

EMEC-HEC: electromagnetic scale

- Needed as reference for hadronic calibration
- Obtained from beam test data

$$E_{\text{beam}} = E_{\text{dep}} + E_{\text{leak}} = \langle E_{\text{reco}} \rangle + \langle E_{\text{leak}} \rangle$$

Include ≈ 2% φ-dependent geometrical response corrections

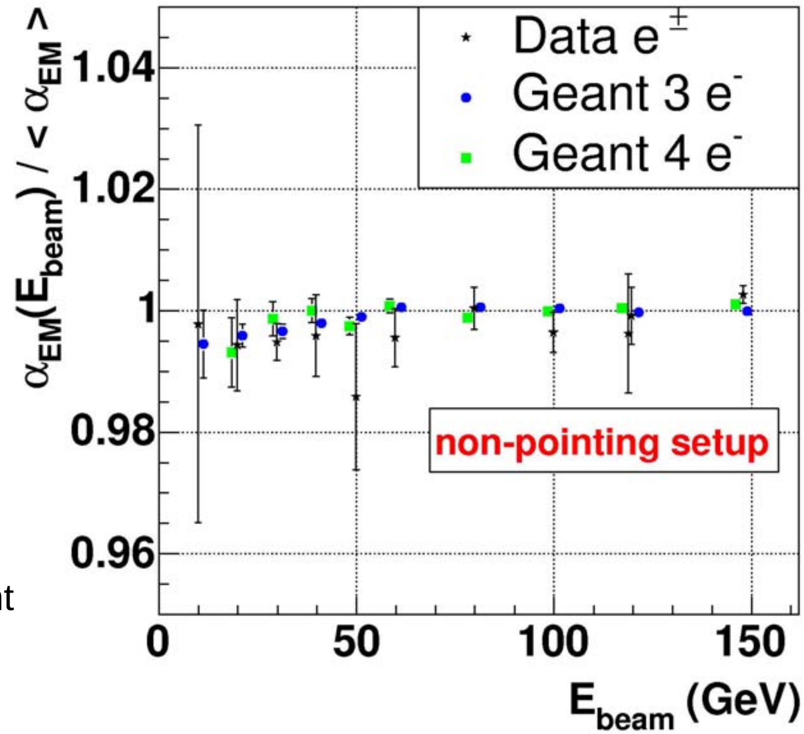
where $E_{\text{reco}} = E_{\text{em}}^{\text{EMEC}} \equiv \alpha_{\text{em}}^{\text{EMEC}} I_{\text{vis}}^{\text{EMEC}}$

The leakage is only outside the cluster, hence measurable. It is < 3% for E_{beam} > 30 GeV

$$\alpha_{\text{em}}^{\text{EMEC}} = \frac{E_{\text{beam}} - \langle E_{\text{leak}} \rangle}{\langle I_{\text{vis}}^{\text{EMEC}} \rangle}$$

$$= (0.430 \pm 0.001 \pm 0.009) \text{ MeV/nA}$$

signal shape uncertainties and η dependent corrections which have not been applied



Linearity better than ±0.5%

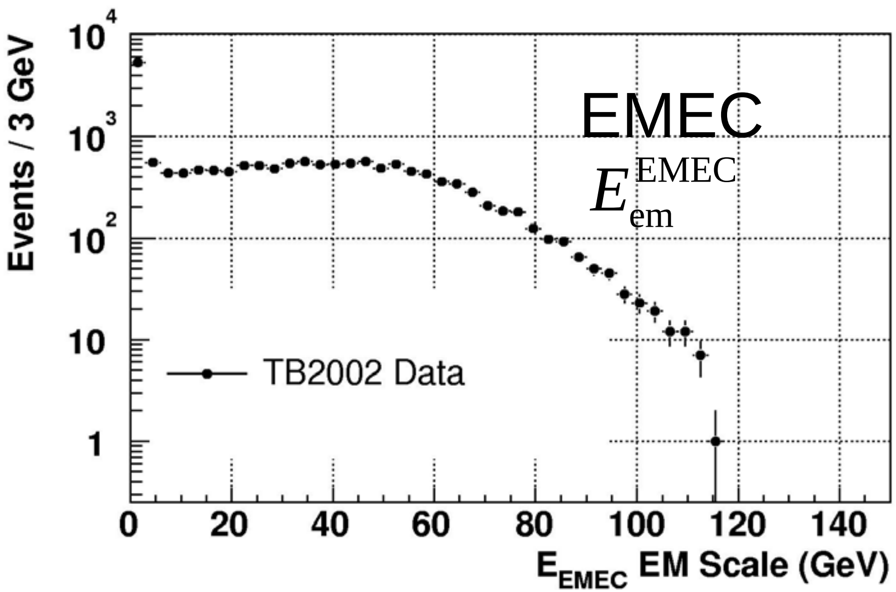
EMEC-HEC: pions response

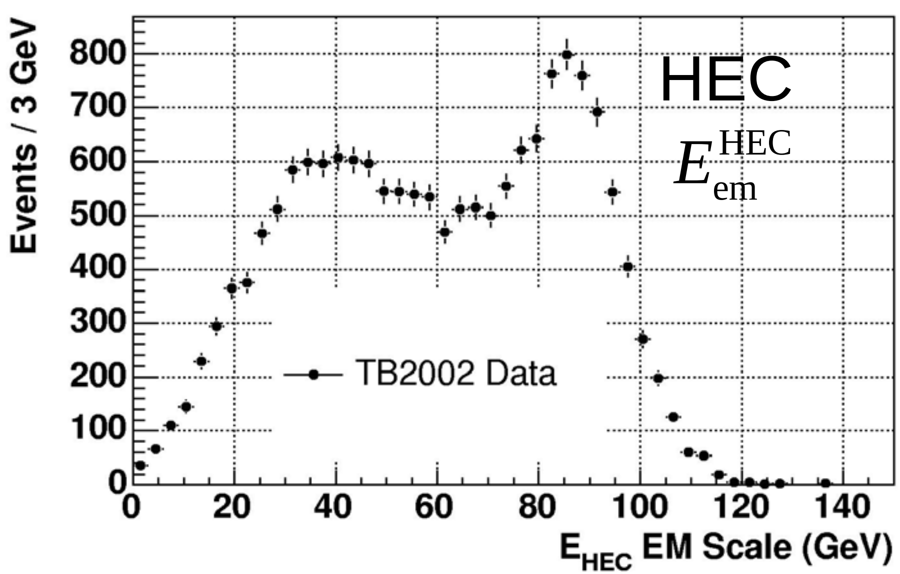
- Use HEC EM scale from previous TB, modified by new electronics, and EMEC EM scale obtained here

$$\alpha_{em}^{EMEC} = (0.430 \pm 0.001 \pm 0.009) \ \text{MeV/nA} \qquad E_{em}^{EMEC} \equiv \alpha_{em}^{EMEC} I_{vis}^{EMEC}$$

$$\alpha_{em}^{HEC} = (3.27 \pm 0.03 \pm 0.03) \ \text{MeV/nA} \qquad E_{em}^{HEC} \equiv \alpha_{em}^{HEC} I_{vis}^{HEC}$$

- Example: 120 GeV pions in EM scale





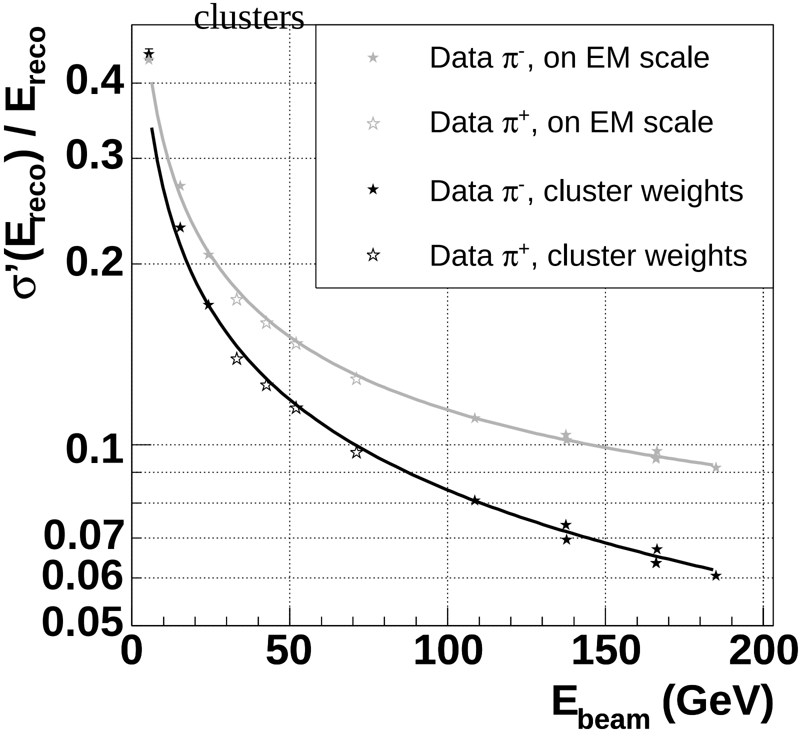
EMEC-HEC: beam energy dependent cluster weights

- Consider 3D topological clusters
- Use cluster energy density as observable
- Use simple weight function, à la H1

$$E_{\mathrm{reco}}\left(C_j^{\mathrm{E}}, C_j^{\mathrm{H}}\right) = \sum_{\substack{\text{EMEC}\\ \text{clusters}}} w^{\mathrm{E}}\left(C_j^{\mathrm{E}}, \rho\right) E_{\mathrm{em}}^{\mathrm{EMEC}} + \sum_{\substack{\text{HEC}\\ \text{clusters}}} w^{\mathrm{H}}\left(C_j^{\mathrm{H}}, \rho\right) E_{\mathrm{em}}^{\mathrm{HEC}}$$

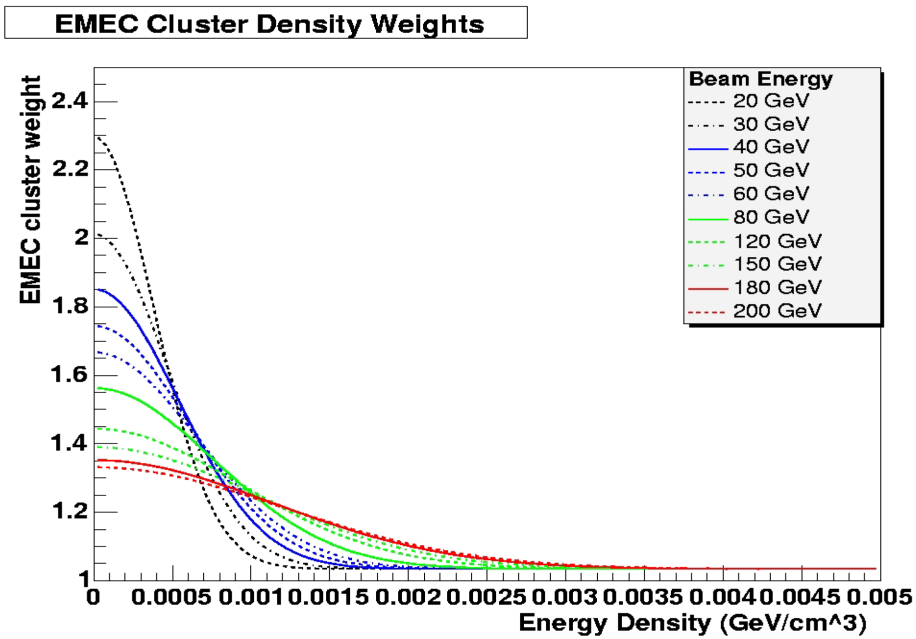
$$w\left(C_j, \rho\right) = C_1 \exp\left(-C_2 \rho\right) + C_3$$

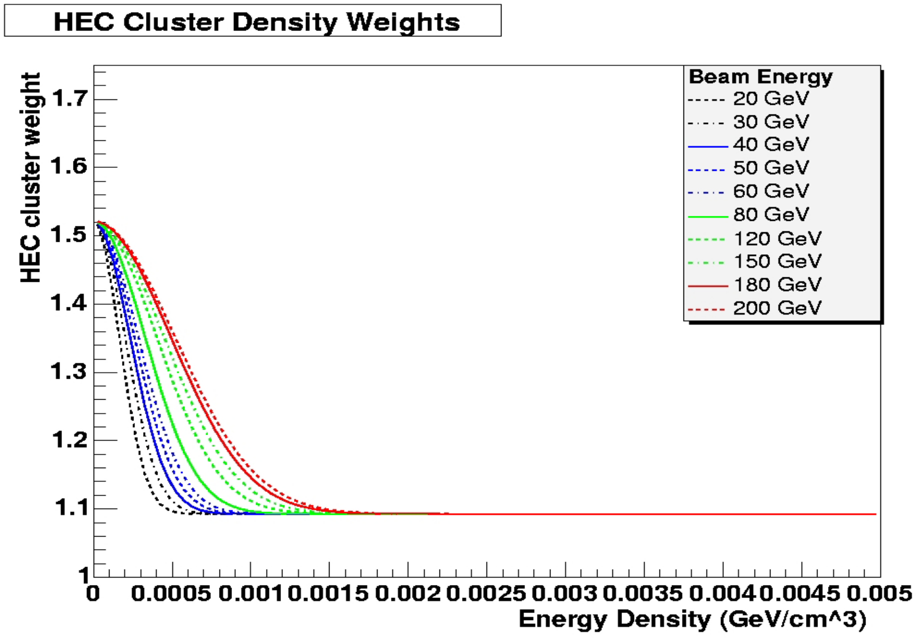
- Significant improvement of energy resolution
  - Results published [NIM A531 (2004) 481-514] uses fixed C2 values
  - Electronics noise subtracted in quadrature



EMEC-HEC beam energy independent cluster weight

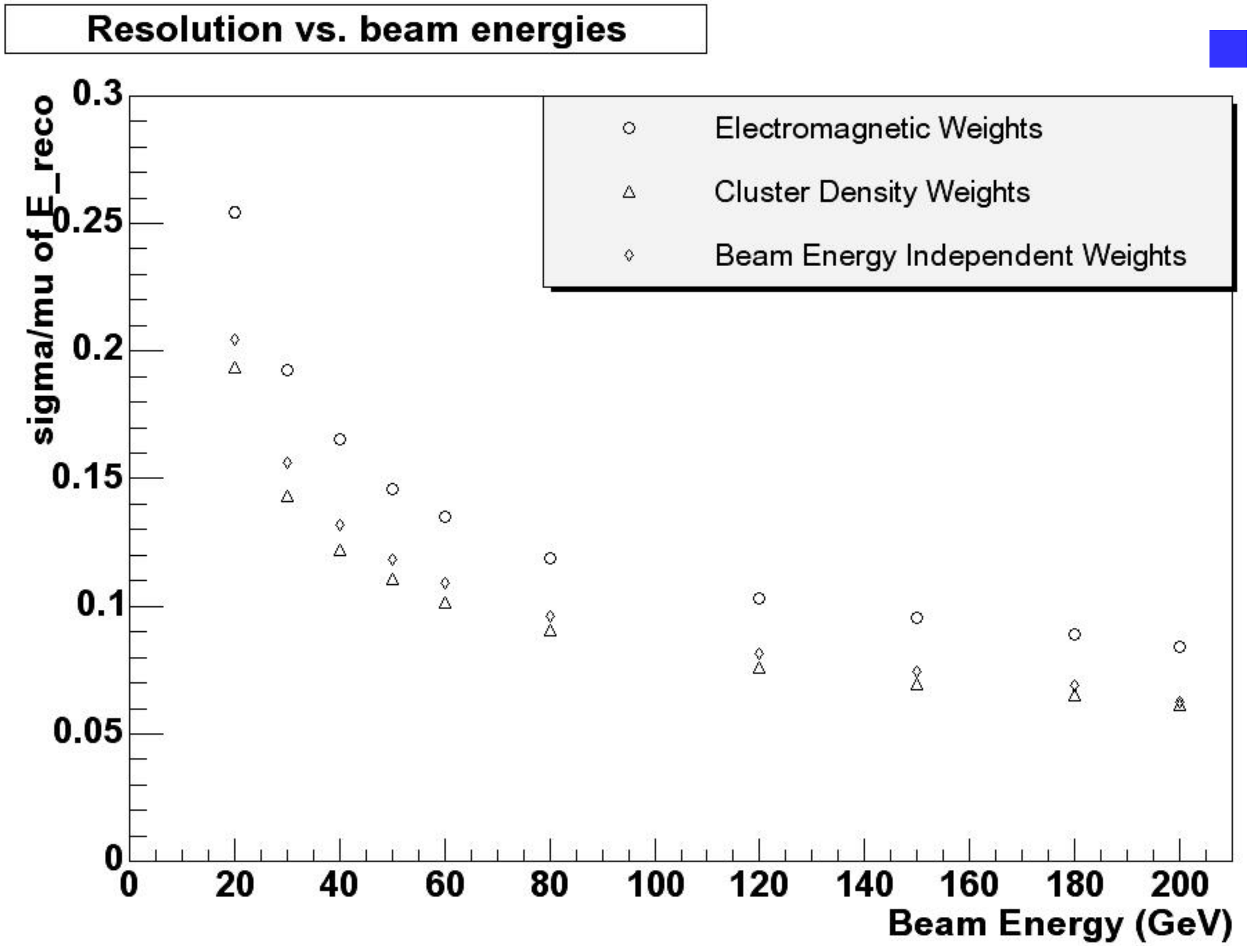
- The knowledge of the beam energy must be taken out!
- First look at beam energy independent cluster weights
  - Use beam energy to produce weight parameterization
  - Estimate beam energy using cluster energy
  - In general one pion corresponds to many clusters
  - Use $w\left(C_j,\rho\right)=C_1\exp\left(-C_2\rho^2\right)+C_3$





EMEC-HEC beam energy independent cluster weight

- As expected the energy resolution is degraded somewhat, especially at low energy



- Linearity of response is not affected by the removal of the knowledge of the beam energy

Cell weights

- Weights can also be applied at cell level
  - thought to be more flexible and more adapted to ATLAS
- cell weights can depend on cluster observables
  - energy and energy density
  - cluster shape
  - distance of cell from shower axis, etc.
- Initial attempts (EMEC-HEC NIM) only used energy density
  - weights obtained from data
  - results comparable to cluster weights
- Recent attempts includes more observables and MC

$$E_{\text{cell}}^{\text{reco}} = wE_{\text{cell}}$$

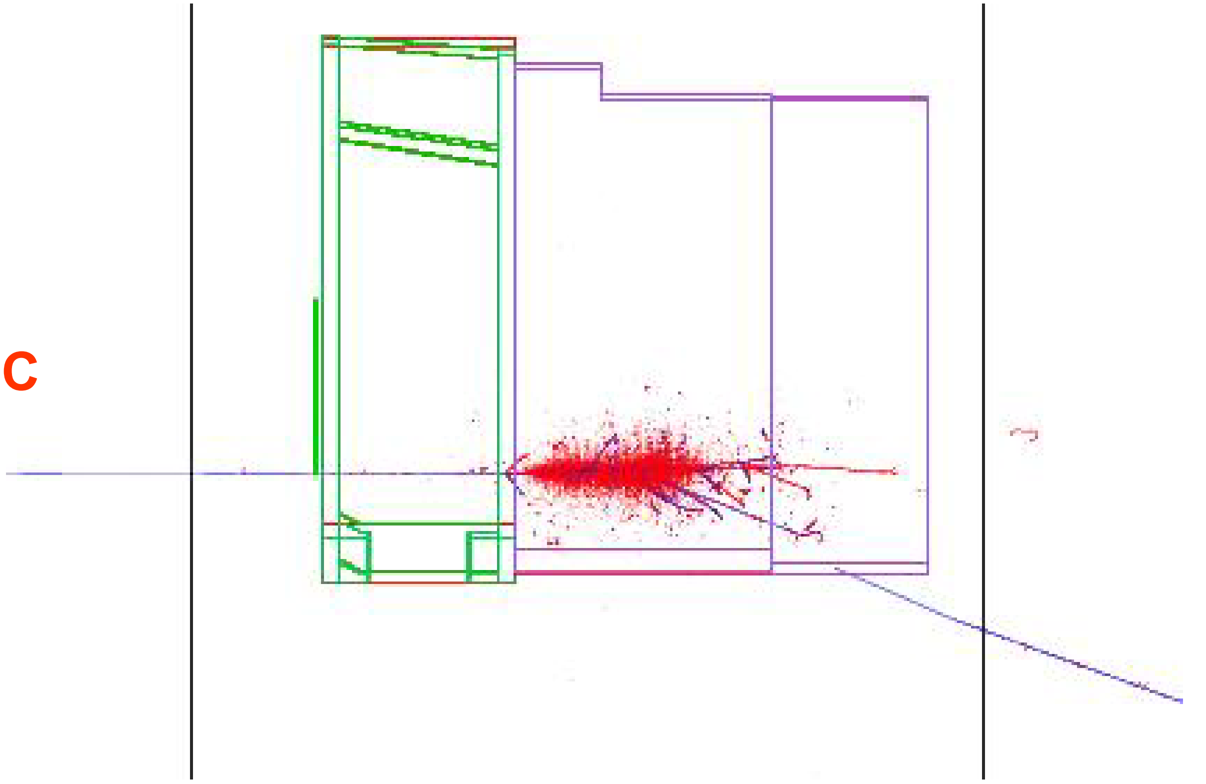
$$w = \frac{E_{\text{cell}}^{\text{em}} + E_{\text{cell}}^{\text{non-em vis}} + E_{\text{cell}}^{\text{non-em invis}} + E_{\text{cell}}^{\text{escaped}}}{E_{\text{cell}}^{\text{em}} + E_{\text{cell}}^{\text{non-em vis}}}$$

EMEC-HEC: simulation

- Large effort on the MC front
  - implementing access to MC truth within the Athena framework
- TB MC in Athena will very shortly allow direct comparison (≈same code!) of data and MC

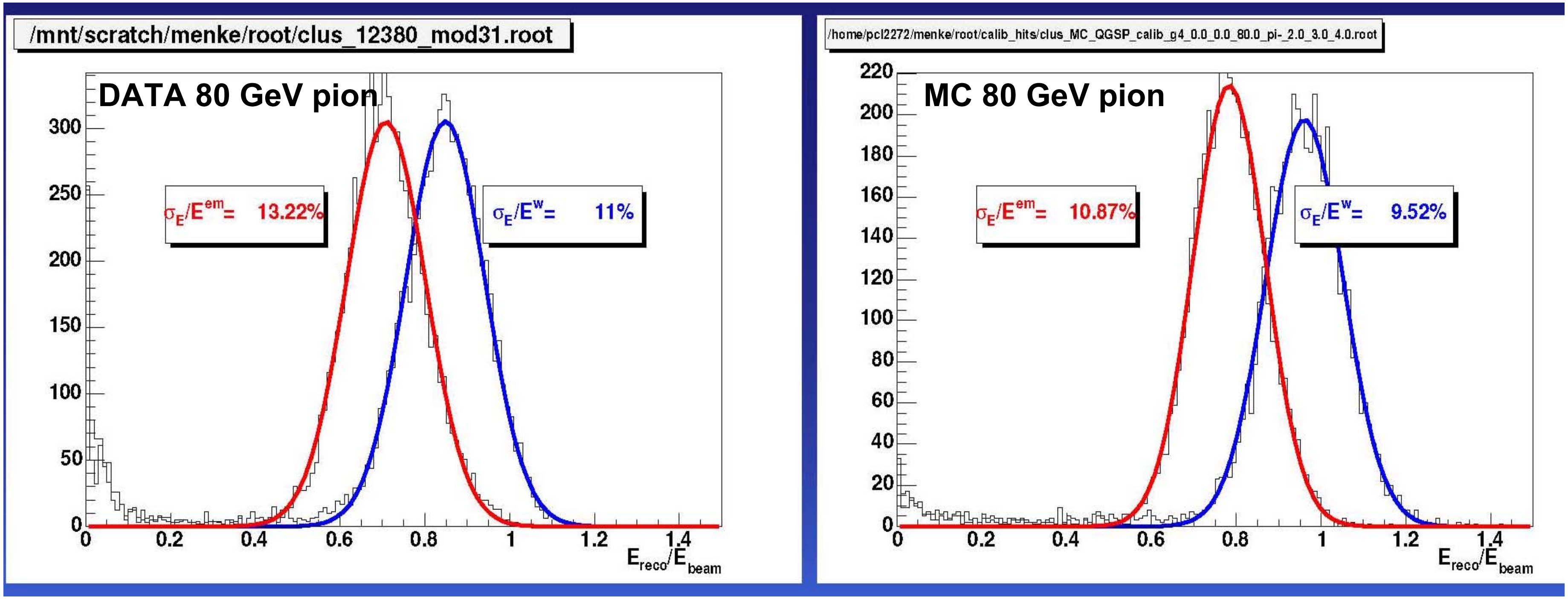
100 GeV pion (charged tracks) in the 2002 EMEC-HEC beam test setup

GEANT4 in Athena



EMEC-HEC: cell weights

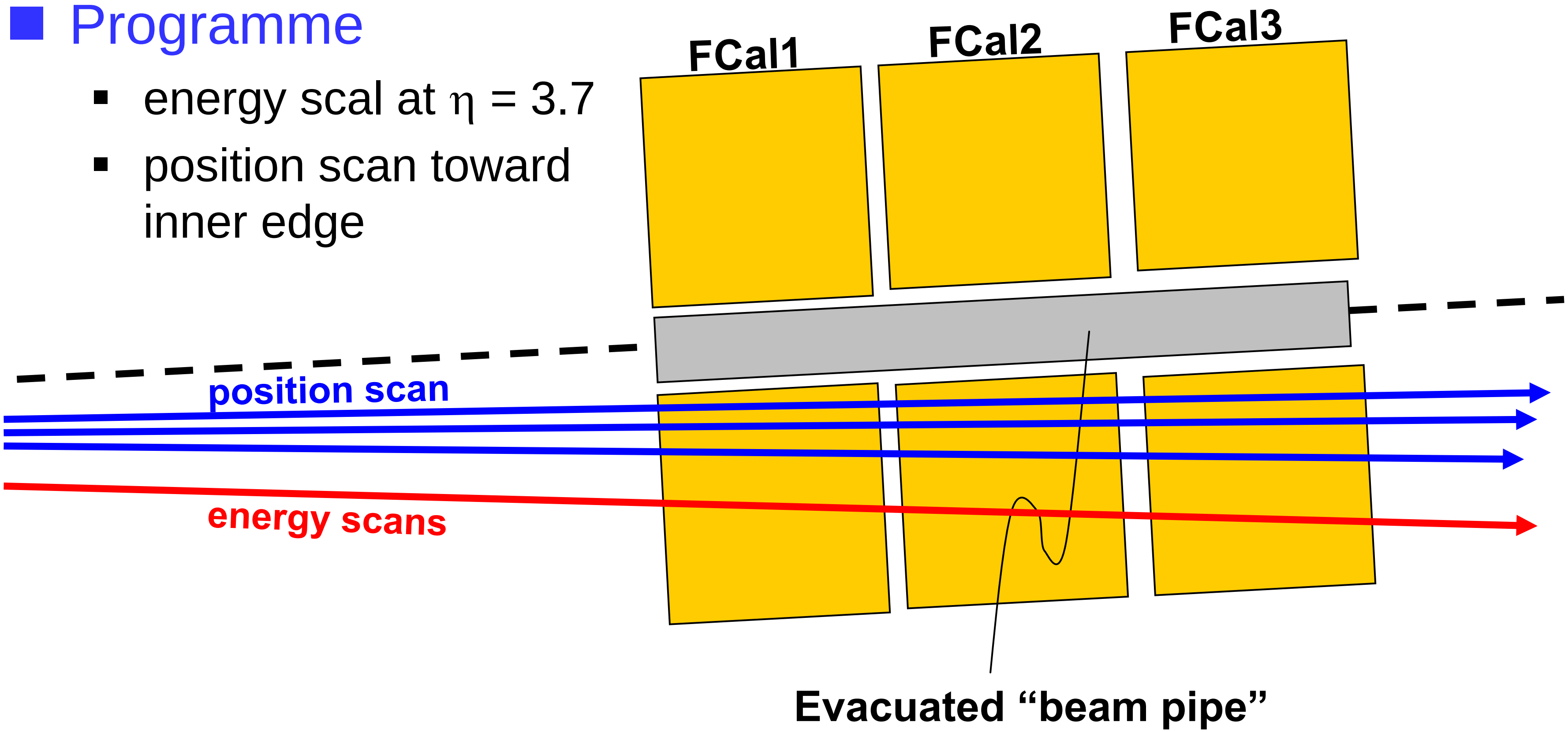
- Initial work on cell weighting promising...
  - weights obtained from MC only



- ... but still work in progress
  - understand data/MC differences
  - understand bias in reconstructing EM showers
  - energy linearity

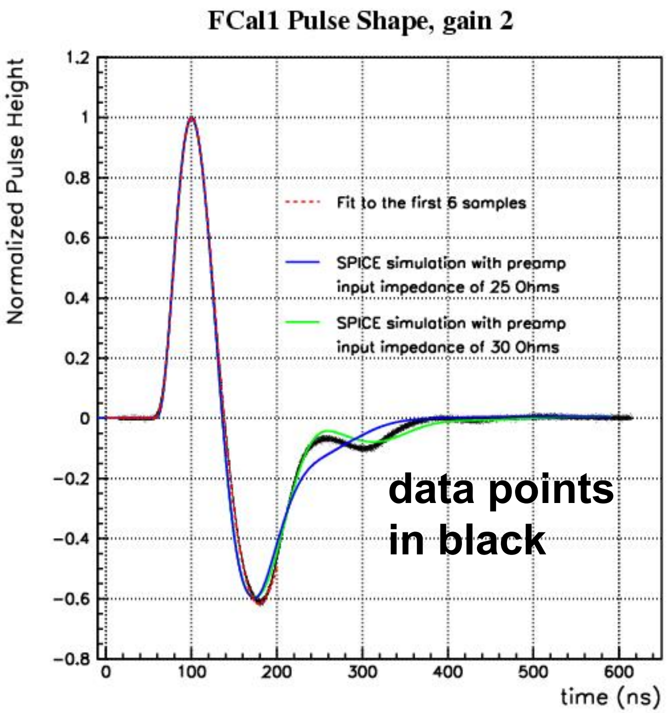
FCal 2003 beam test configuration

- H6 beam area at the CERN SPS
  - use π beams with 10 GeV $\leq$ E $\leq$ 200 GeV
  - use e beams with 5 GeV $\leq$ E $\leq$ 200 GeV
- Programme
  - energy scal at η = 3.7
  - position scan toward inner edge

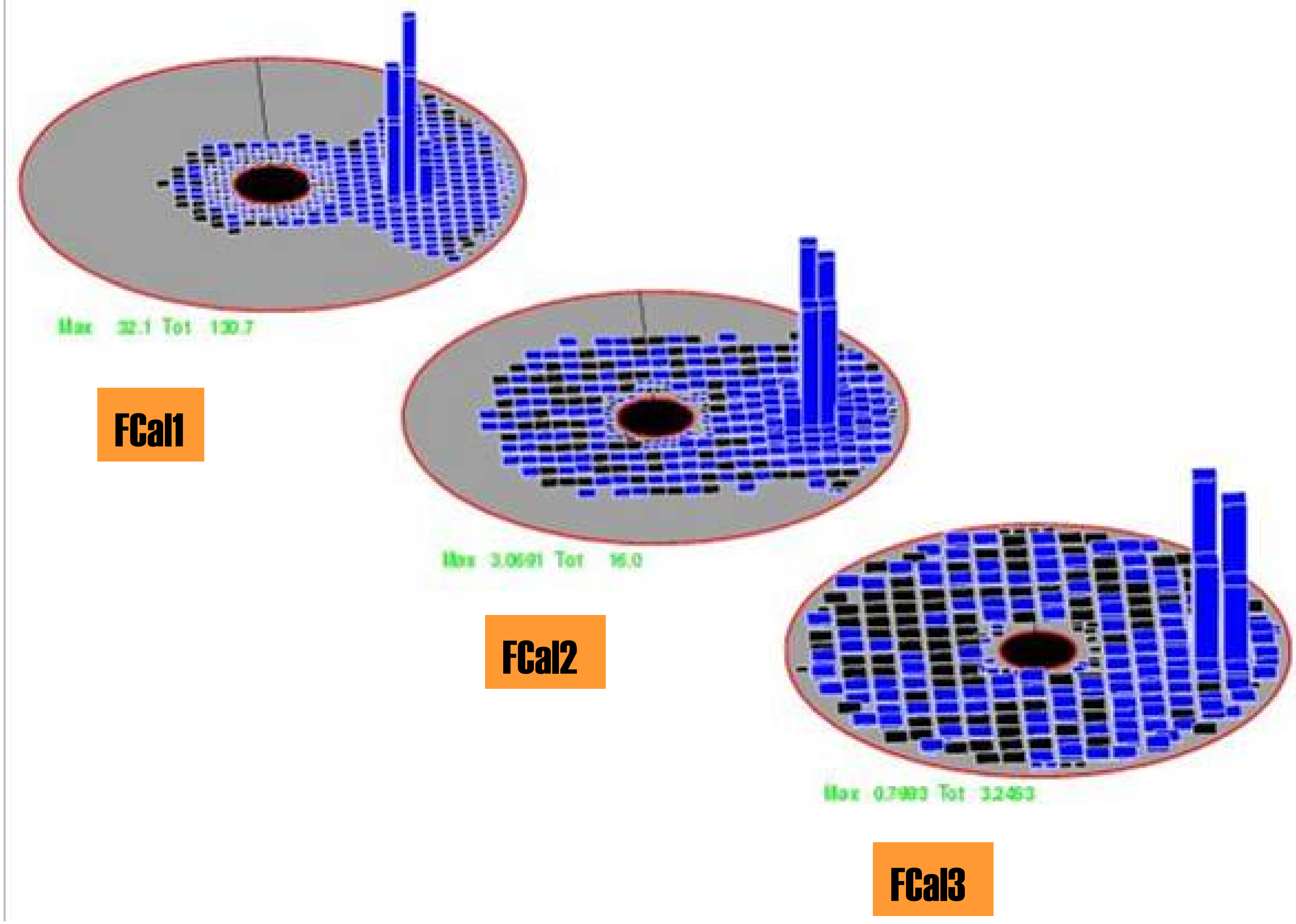


FCal Signal Reconstruction Steps

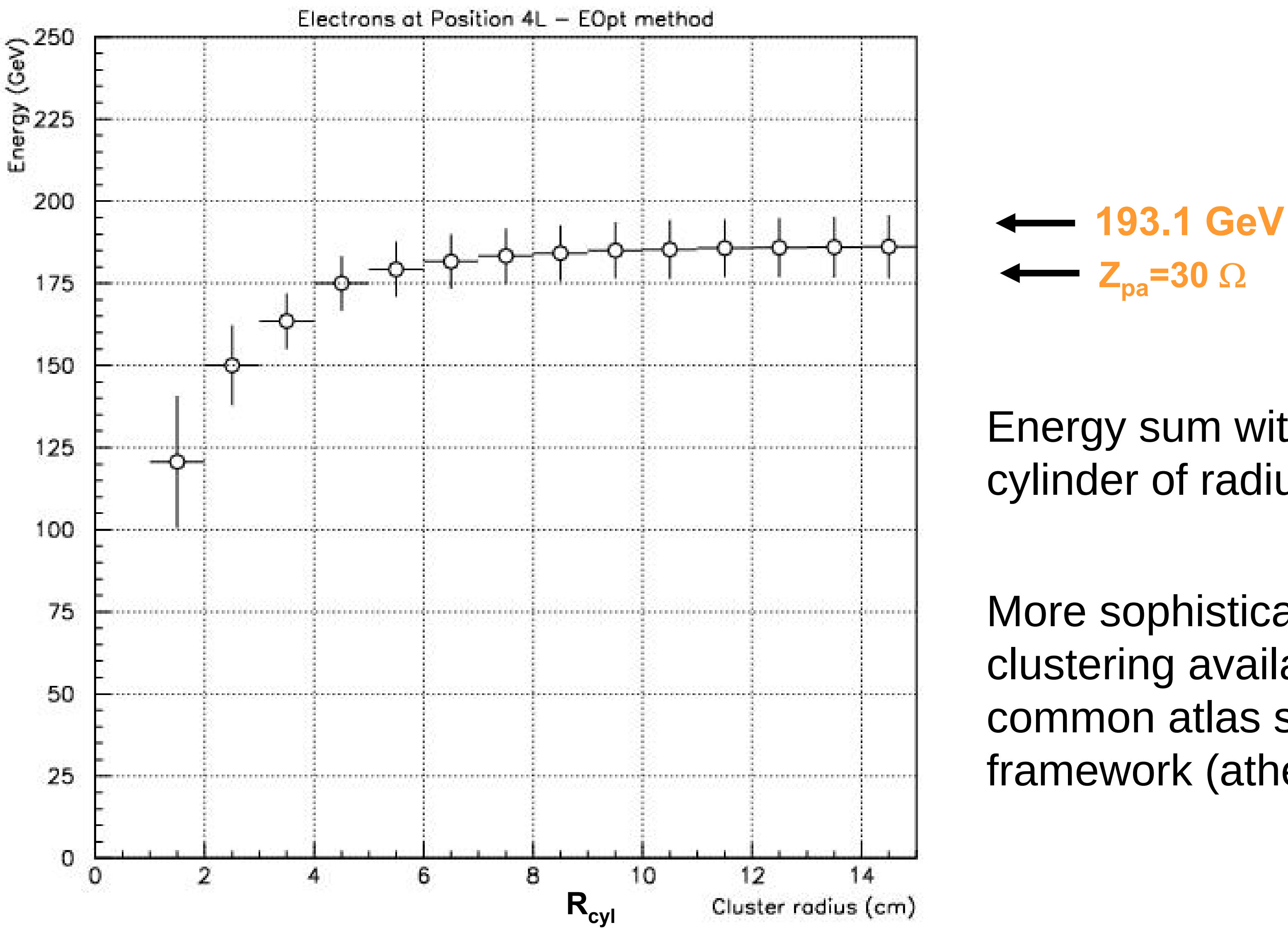
- Use direct physics pulse shape accumulation from beam test to obtain OFC
- Use beam test and/or MC to normalize the energy scale
  - ADC[phys] $\rightarrow$ MeV
  - That is, calibration system is not yet used directly
- Accuracy and channel uniformity
  - FCal: $\approx$ a few %
- Calibration system used for FEB stability monitoring
  - Investigations in progress about use of reflection pulse



FCAL energy deposits from 200 GeV π's (accumulated)



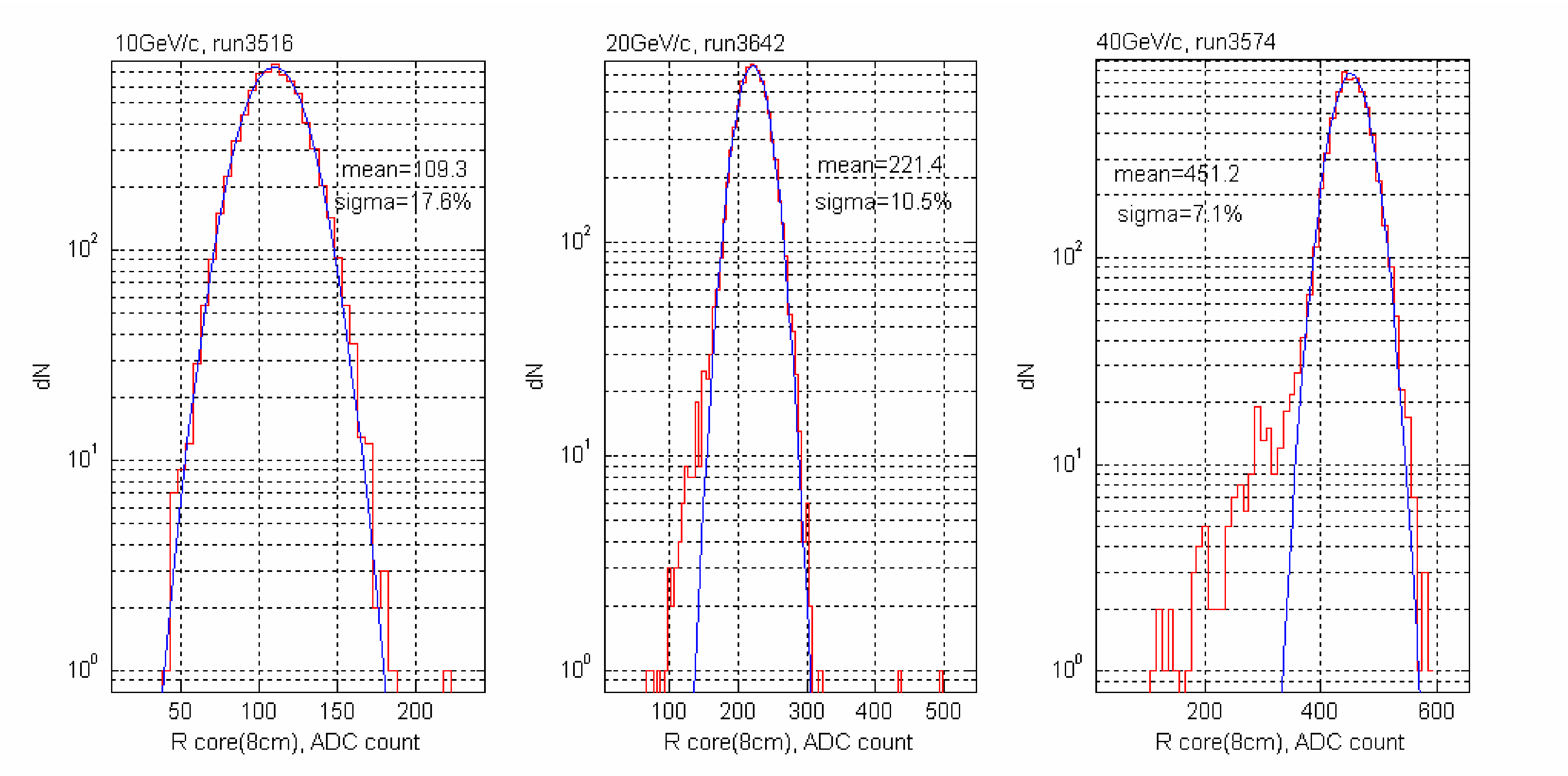
FCAL energy reconstruction for electrons



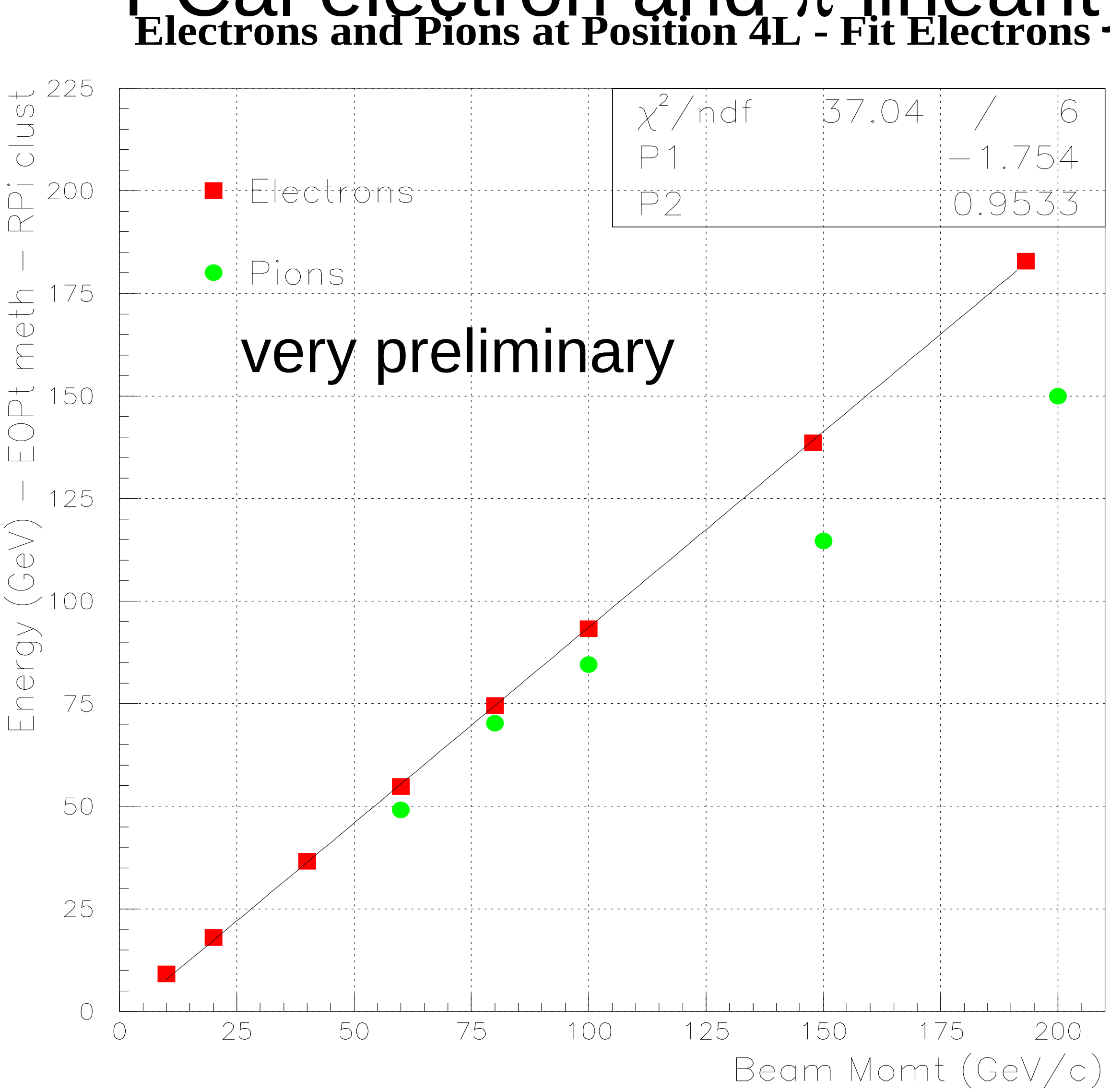
Energy sum within a cylinder of radius R_{cyl}

More sophisticated clustering available in common atlas software framework (athena)

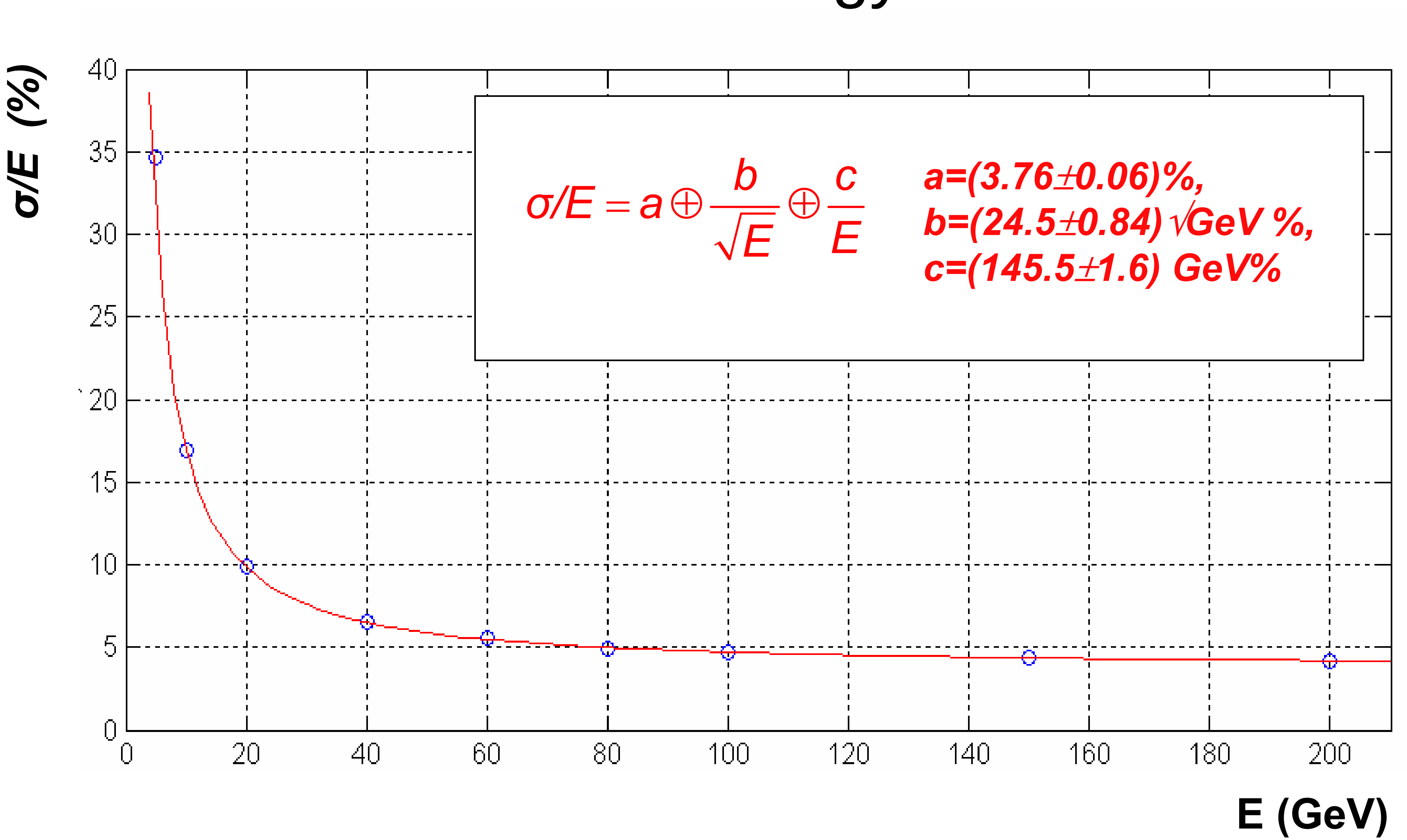
FCal electron response 10, 20 and 40 GeV



FCal electron and π linearity



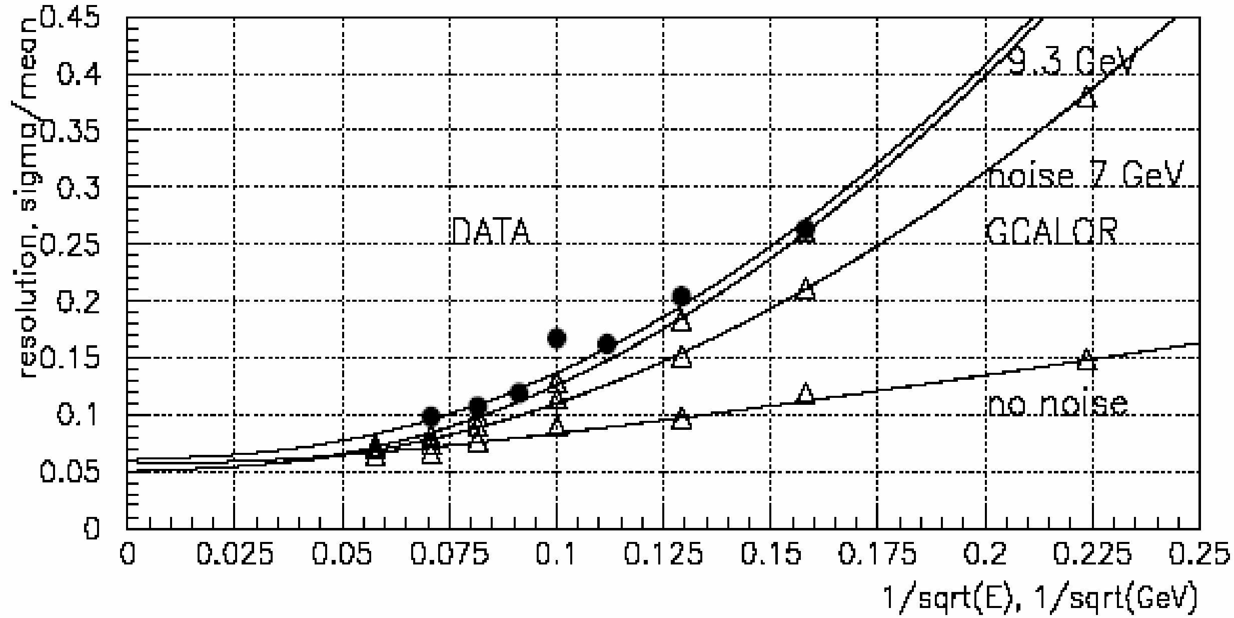
FCal electron energy resolution



FCal pion energy resolution

Current pion results involve rather simple analysis:

Reconstruction using EM scale with relative sampling fractions from MC



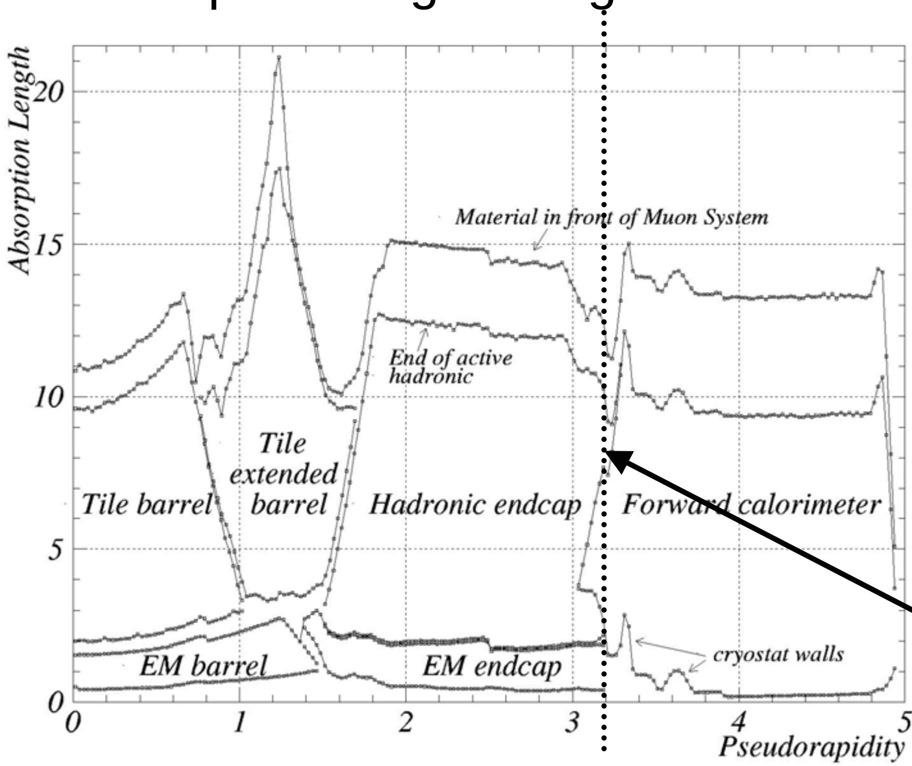
$$\frac{\sigma(E)}{E} = \frac{(80 \pm 10)\%}{\sqrt{E(\mathrm{GeV})}} \oplus (6.1 \pm 0.6)\% \oplus \frac{(930 \pm 4)\%}{E(\mathrm{GeV})}$$

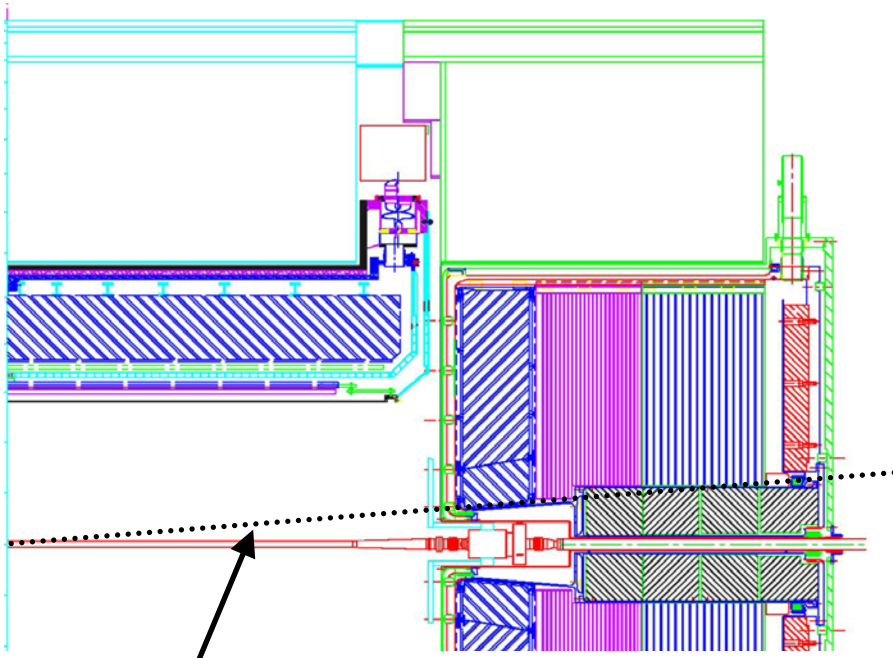
Fitted noise term slightly larger than measured noise

EMEC-HEC-FCAL 2004 beam test

- Focus on energy reconstruction in the 2.8 < |η| < 3.2 region
- Address the challenging |η| ≈ 3.2 interface region

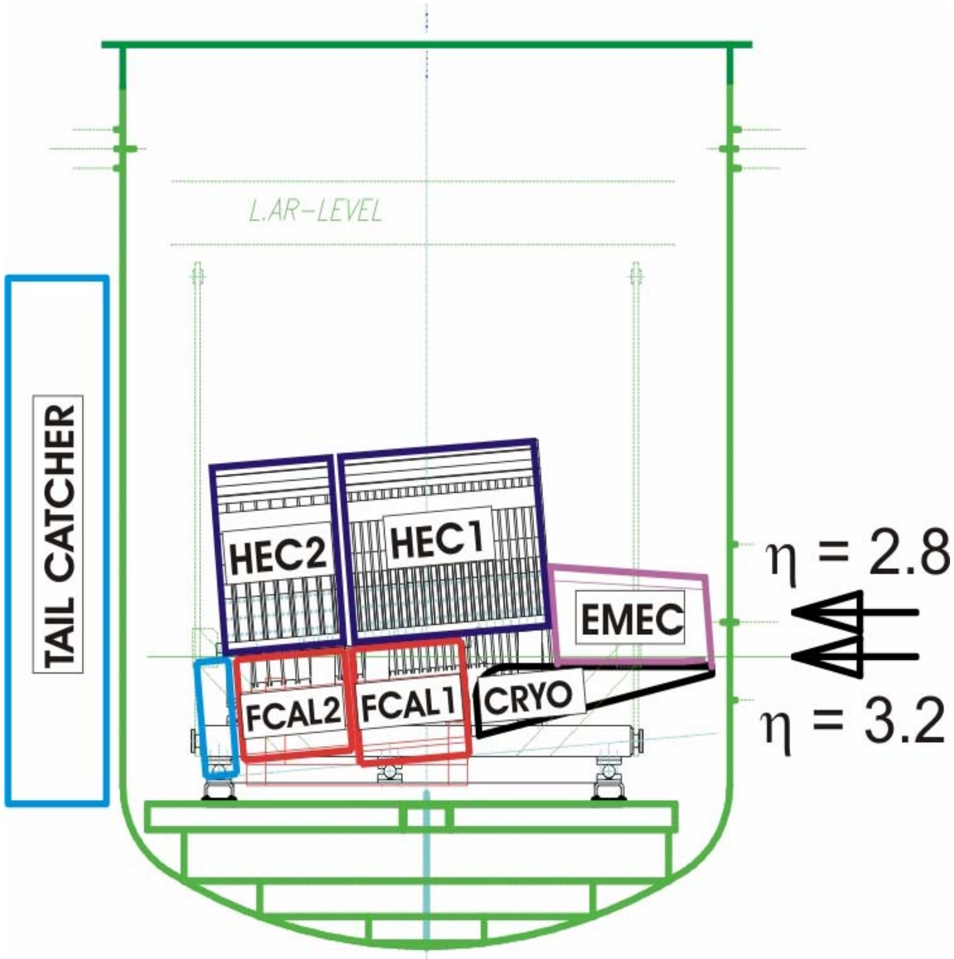
absorption length budget





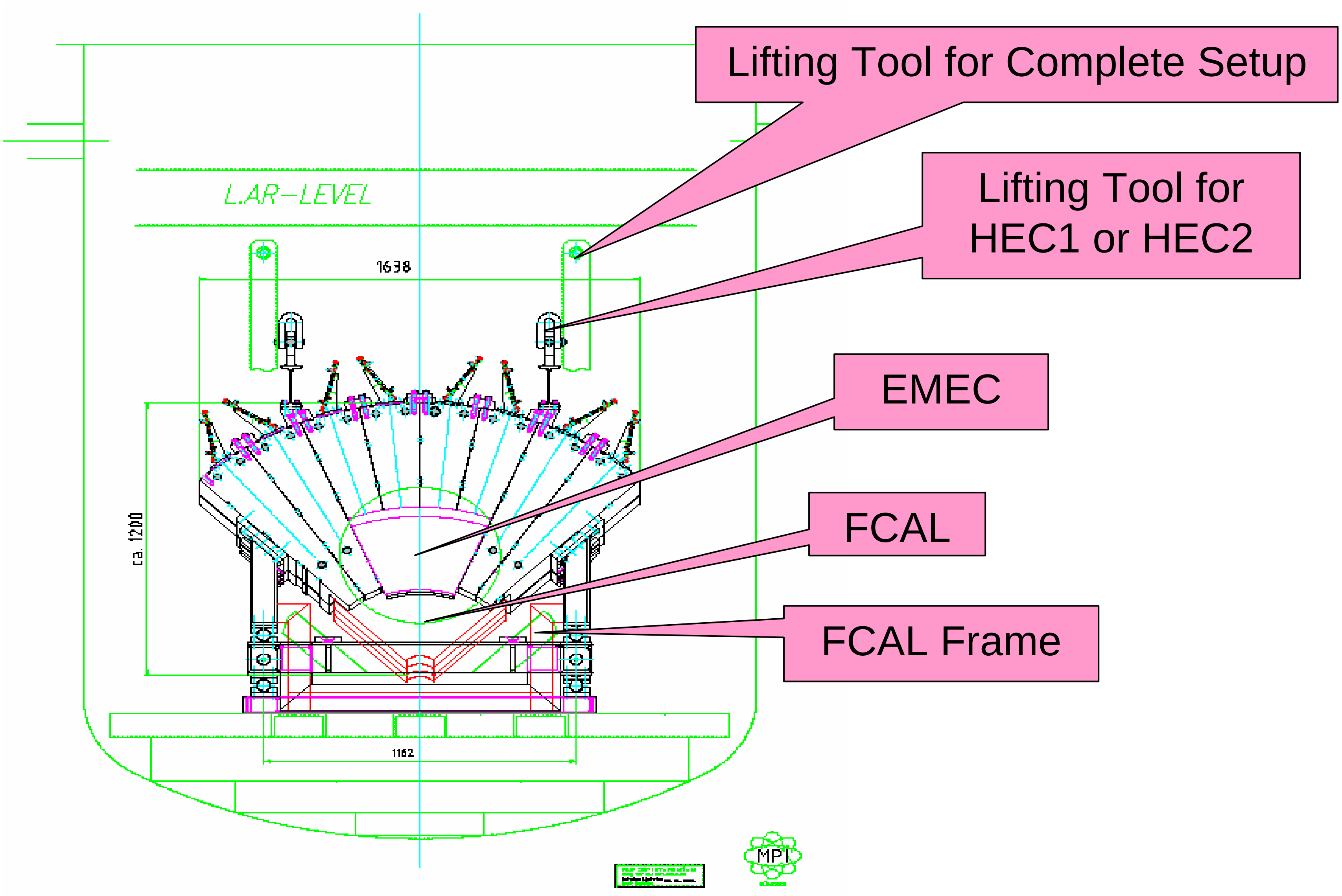
interface around |η| ≈ 3.2

EMEC-HEC-FCAL 2004 beam test

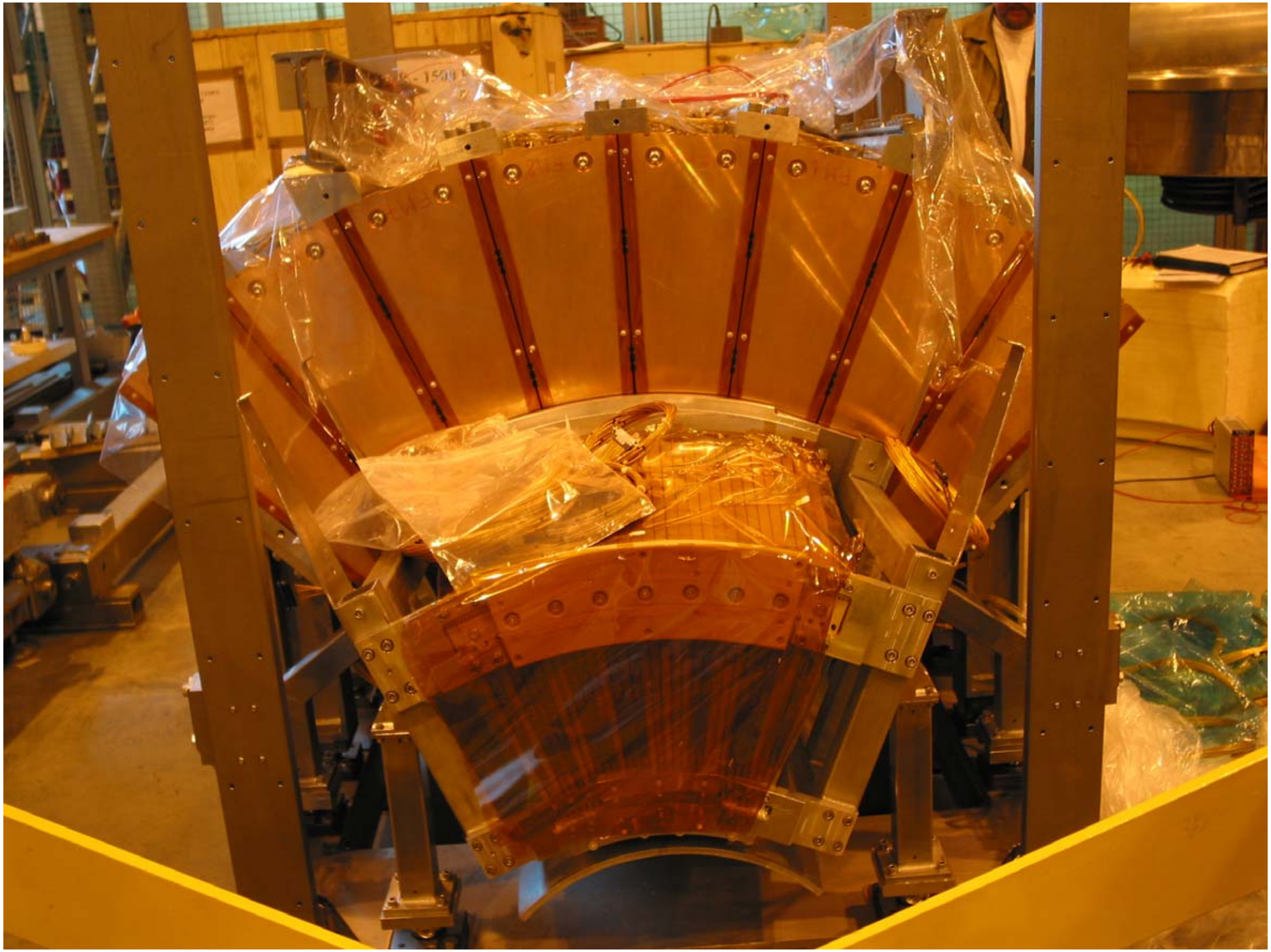


- Space constraints in cryostat
  - EMEC module0 (refurbished)
  - HEC mini-modules (space constraints in H1 cryostat)
  - FCal1 module0 (refurbished in Arizona)
  - FCal2 module0 (refurbished in Toronto)
  - Cold Tailcatcher (Cu-LAr parallel plate technology) instead of FCal3
  - New warm tailcatcher behind cryostat
  - Mockup of cryostat forward cone and FCal cold tube

EMEC-HEC-FCAL: beam test setup



EMEC-HEC-FCAL: beam test setup



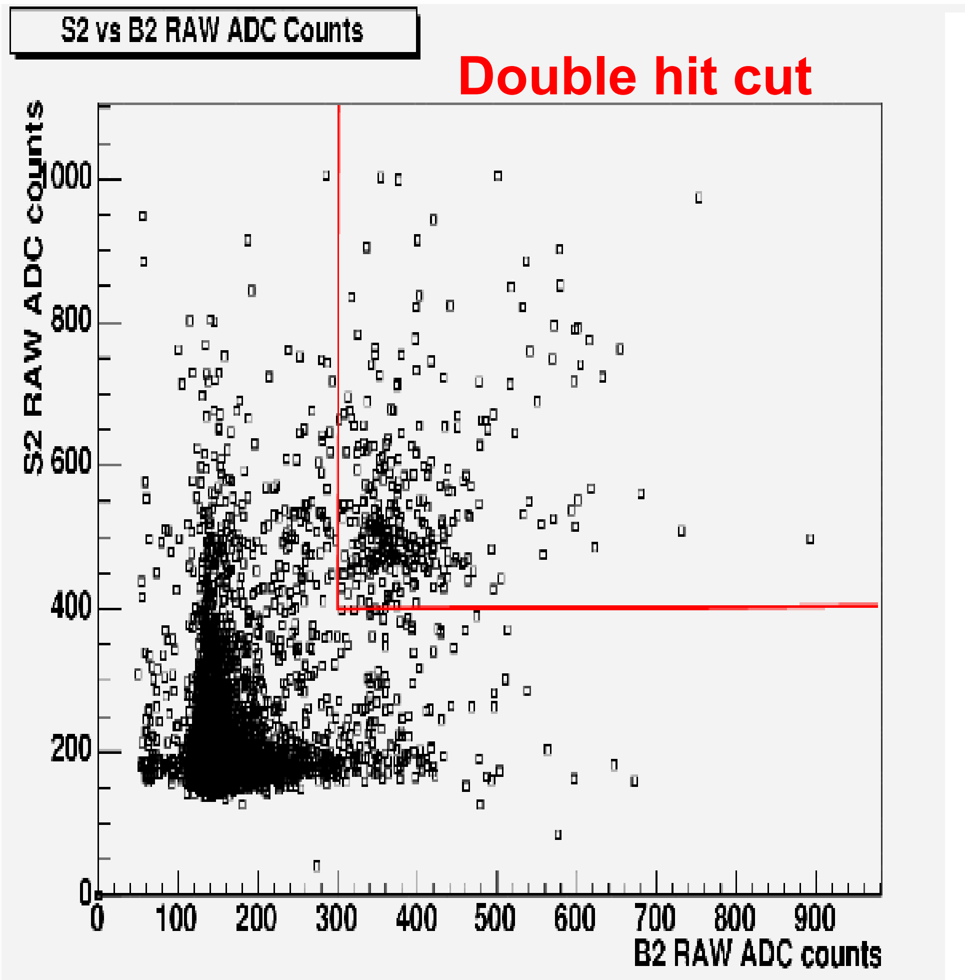
EMEC-HEC-FCAL: data taking

- Two run periods:
  - Run I May - July
  - Run II Aug – October
  - Some changes to setup between runs
- Energy scans at selected points
- Vertical scans at multiple energies
- Horizontal scans at various heights (all detectors)
- Pion data from 40-200 GeV
- ~ 10^7 events, 1TB of physics data

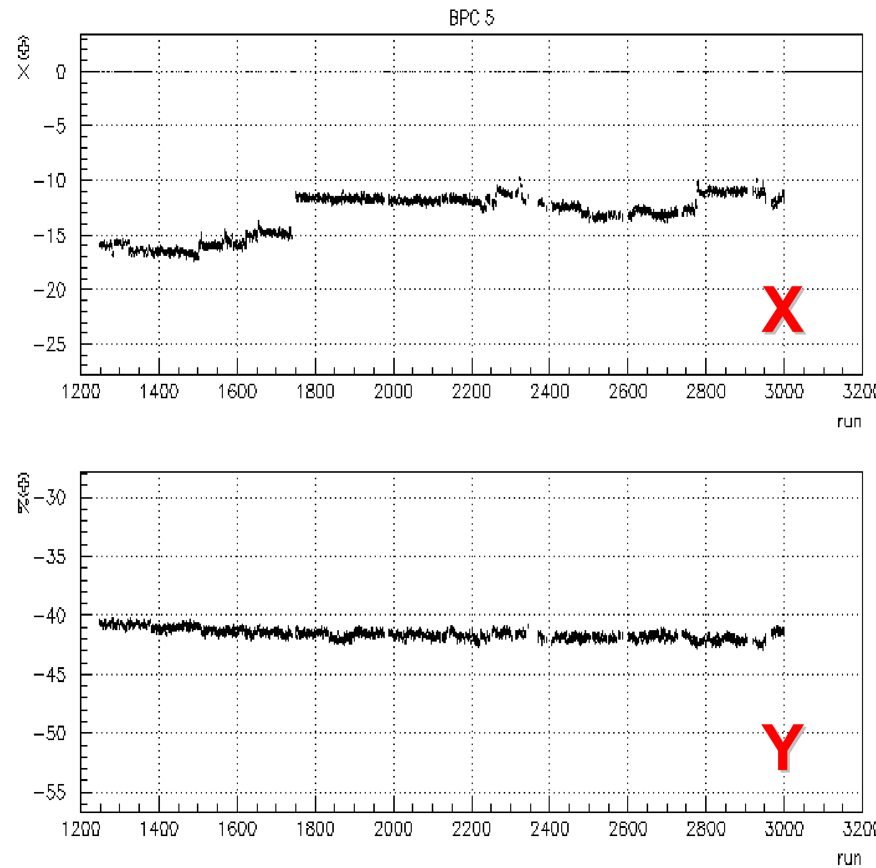
EMEC-HEC-FCAL studies underway

- Continued offline software reconstruction coordination
- Testbeam beam elements fully supported in Athena
- Studies of scintillator pedestals
- Studies of beam selection criteria
- BPC Calibration
- BPC Alignment
- Autocorrelation matrix – in database for Run II
- Pulse Shape Studies
- Calorimeter Noise studies
- OFC determination (awaiting pulse shape from physics data)
- Monte Carlo simulation

EMEC-HEC-FCAL: beam studies



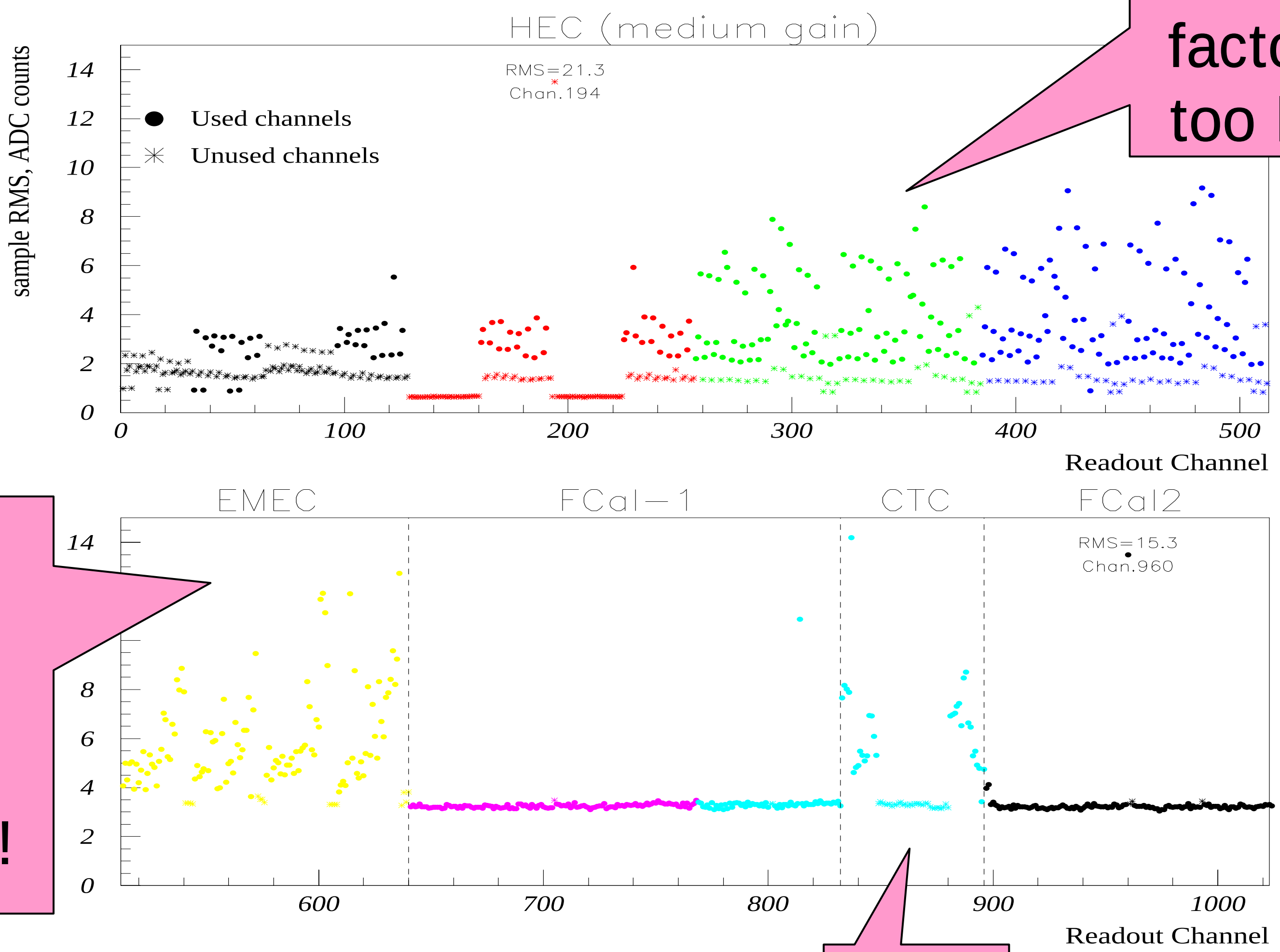
BPC5 time drift during run



Relatively small effect (order 100 μm).
Correction in progress

2004 EMEC/HEC/FCAL: Noise

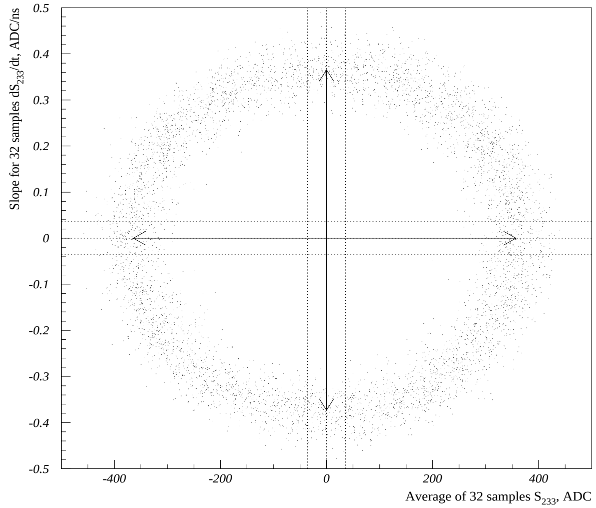
HEC noise: factor 2-3 too large!

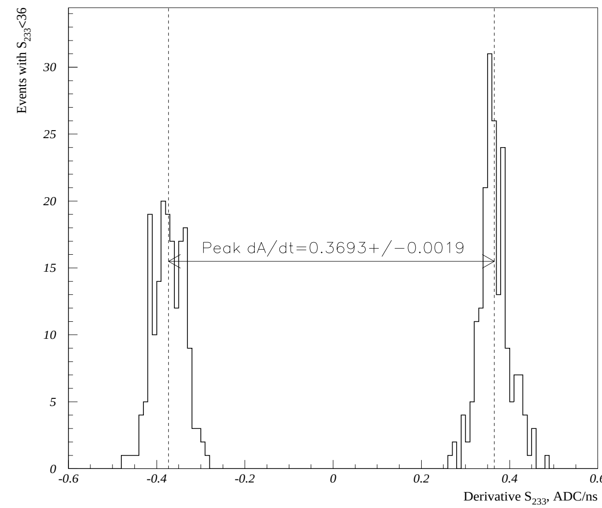


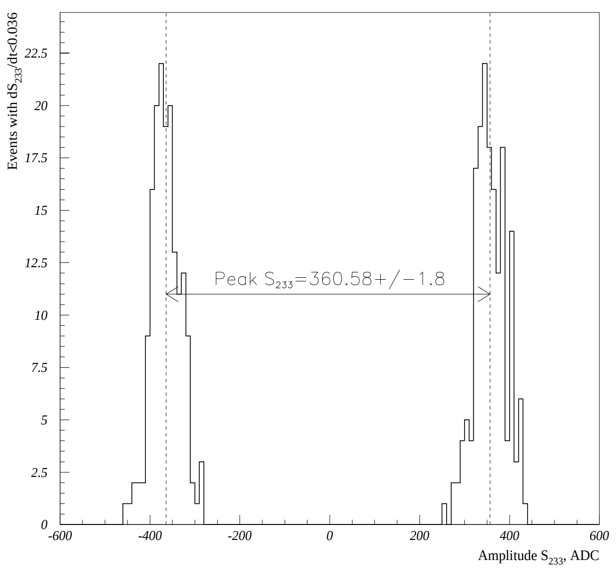
EMEC noise: typically factor 5 too large!

CTC

EMEC-HEC-FCAL: HEC noise from amplitude and slope







$$\left.\begin{aligned} A &= A_0 \sin(\omega t) \\ \frac{dA}{dT} &= A_0 \omega \cos(\omega t) \end{aligned}\right\} \Rightarrow \omega = \frac{\max(\frac{dA}{dT}) - \min(\frac{dA}{dT})}{\max(A) - \min(A)}$$

$$A_0 = 360.6 \pm 1.8 ADC$$

$$f = \frac{\omega}{2\pi} = 163.0 \pm 1.2 kHz$$

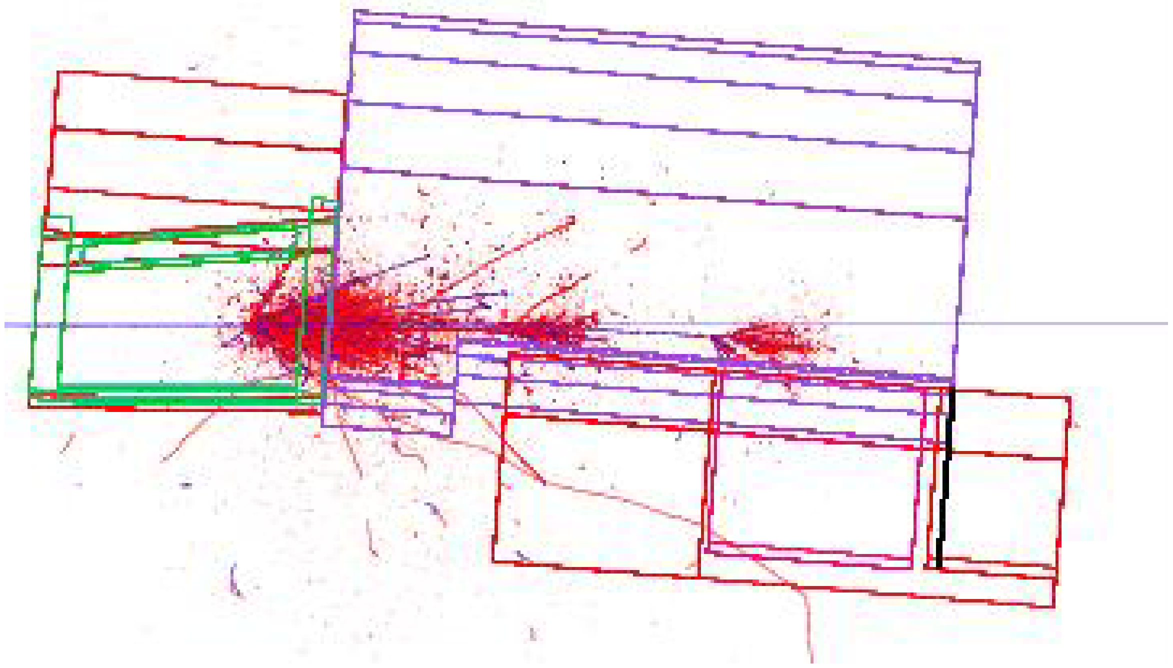
Hope: was “one-off” DC-DC converter used only in this TB

Fix for TB : Either measure noise phase or do event-by-event ped fit

EMEC-HEC-FCAL TB Monte Carlo

- Very first (2004/12/08) visualization of 2004 EMEC-HEC-FCAL TB MC using Athena!

100 GeV pion (charged tracks) in the 2004 EMEC-HEC-FCAL beam test setup



Conclusions

- Extensive H6 beam test programme
  - a lot of data collected
- Test of electronics calibration method and signal reco
  - optimal filter weights
  - detailed electronic calibration procedure for ADC to nA
  - development of the related software tools
- Hopefully robust EM scale established
- Test of first steps toward an hadronic calibration strategy
  - cluster and/or cell weighting
- GEANT4 simulation of beam test setups recently available in Athena

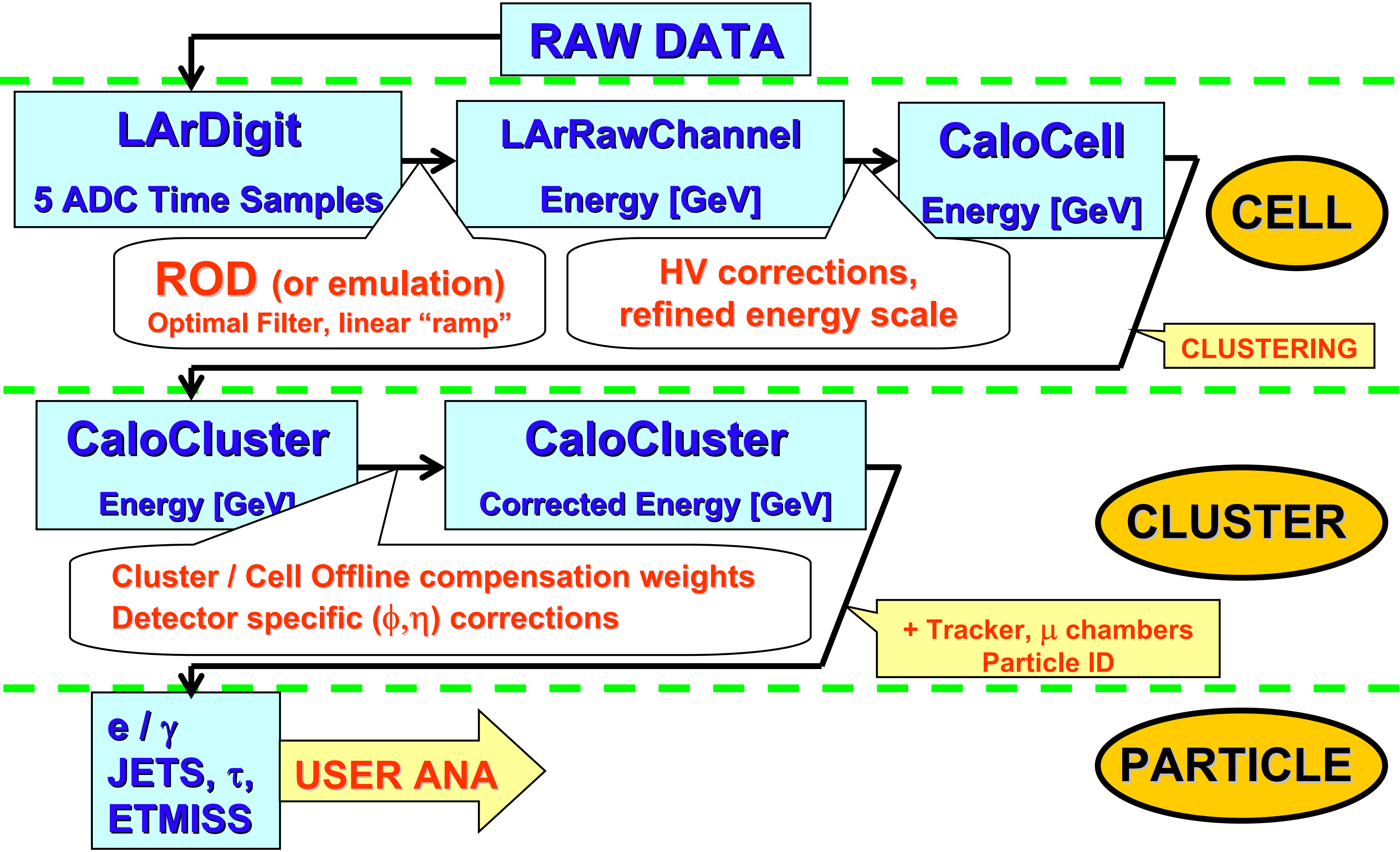
Critical tasks

- Persistify 2002 EMEC-HEC data
  - fill database with noise and autocorrelations for each cell
- Consolidate the pulse shape analysis software
  - need a robust OFC producing suite of software
  - demonstrate the usage of the FCal current calibration system
- Further develop the reconstruction of “final local energy scale signal”
  - use Athena tools, like cluster split/merge tools
  - produce cell level weights depending on cluster quantities
  - validate with beam test EM clusters and simulation
  - use GEANT4 in Athena; minimize code difference between data and simulation analyses
- Combine effort across all beam tests

Critical tasks

- Address the challenging detector overlap regions
  - will require specialized techniques for signal reconstruction
- Develop strategies against hardware failures
  - simulation of HV problems, dead cells, etc.
  - use beam test data and simulation
  - develop the related softare
  - asses impact on performace

Data and Corrections Flow



Hadronic Calibration Models

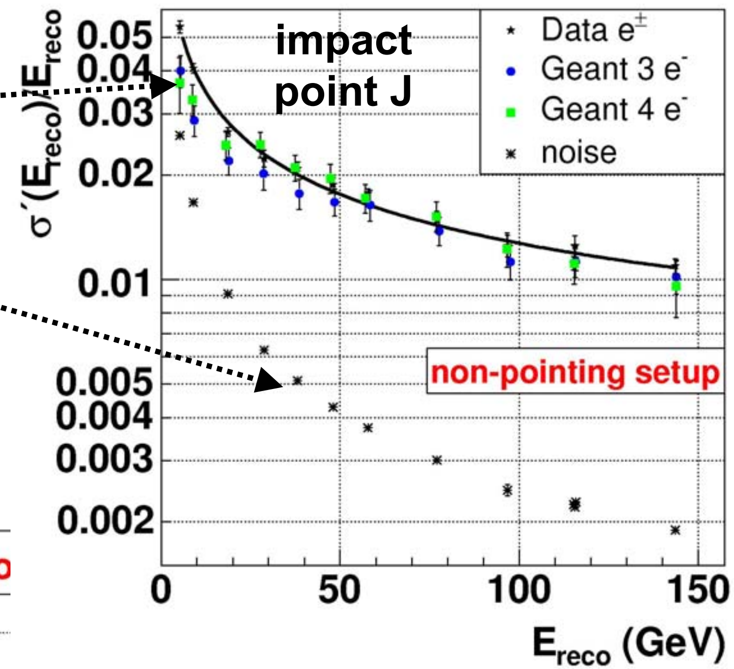
- Model I : Physics object based:
  - first reconstruct hadronic final state physics objects (jets, missing Et) using calorimeter signals on a fixed (electromagnetic) energy scale (accepting the fact that these are ~30% too low, typically);
  - then calibrate the jets in situ using physics events
  - a priori using “MC Truth” in simulations for normalization (presently studied approach in ATLAS)
    - Model I is currently the most common approach in ATLAS physics studies. It is somewhat fragile, sensitive to fragmentation modeling, jet finding, etc.
- Model II : Detector-based objects
  - reconstruct calorimeter final state objects (clusters) first and calibrate those using a “local” normalization (reference local deposited energy in calorimeter)
  - reconstruct physics objects in this space of calibrated calorimeter signals
  - apply higher level corrections for algorithm inefficiencies determined in situ or a priori, as above
    - Model II has been the focus of our testbeam analysis, and we are studying it’s applicability to ATLAS

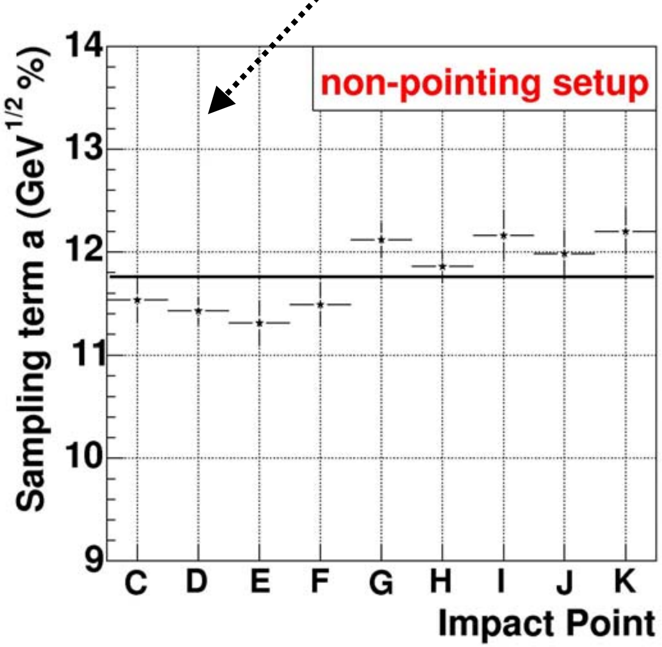
EMEC-HEC: electrons energy resolution

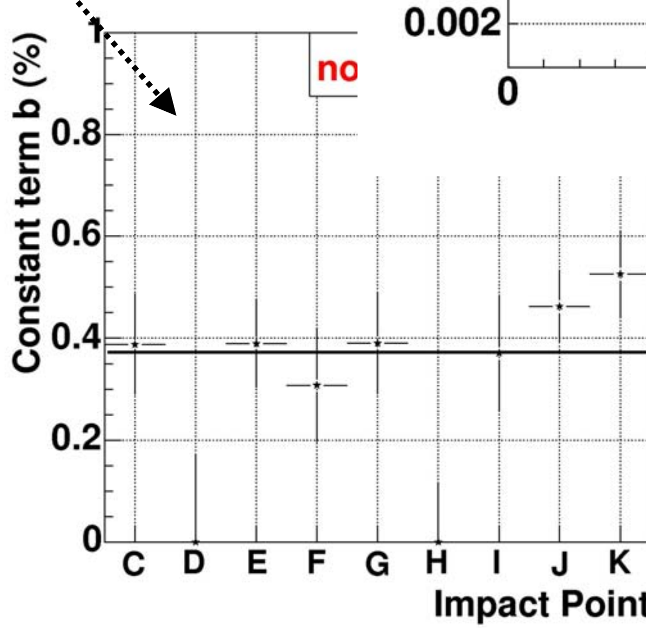
$$E_{\text{reco}} = E_{\text{em}}^{\text{EMEC}} = \alpha_{\text{em}}^{\text{EMEC}} I_{\text{vis}}^{\text{EMEC}}$$

$$\sigma(E_{\text{reco}}) = \sigma'(E_{\text{reco}}) \oplus \sigma_{\text{noise}}$$

$$\frac{\sigma'(E_{\text{reco}})}{\langle E_{\text{reco}} \rangle} = \frac{a}{\sqrt{E_{\text{reco}}}} \oplus b$$



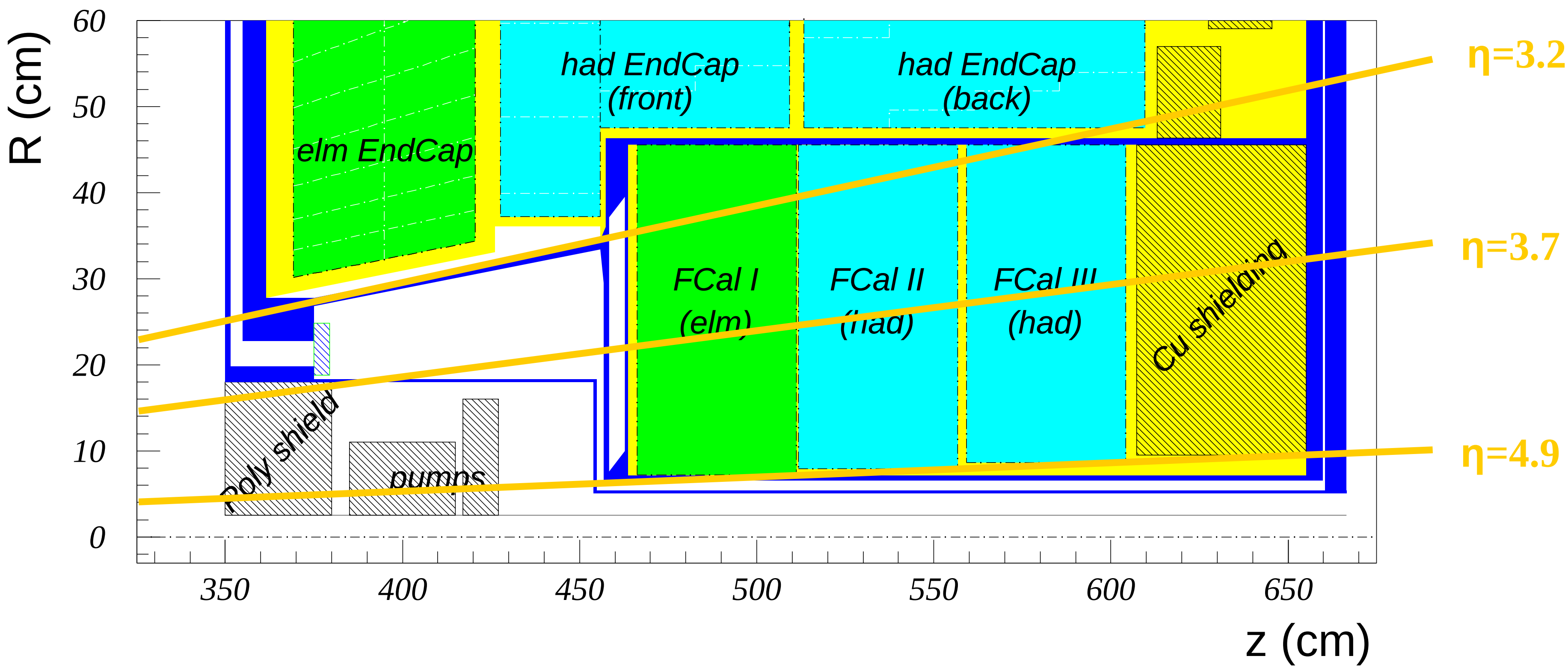




Note: non-pointing setup!!

possibly some η dependence, due to η variation of sampling fraction and weak η dependence of electric field

Dead material in front of the FCal

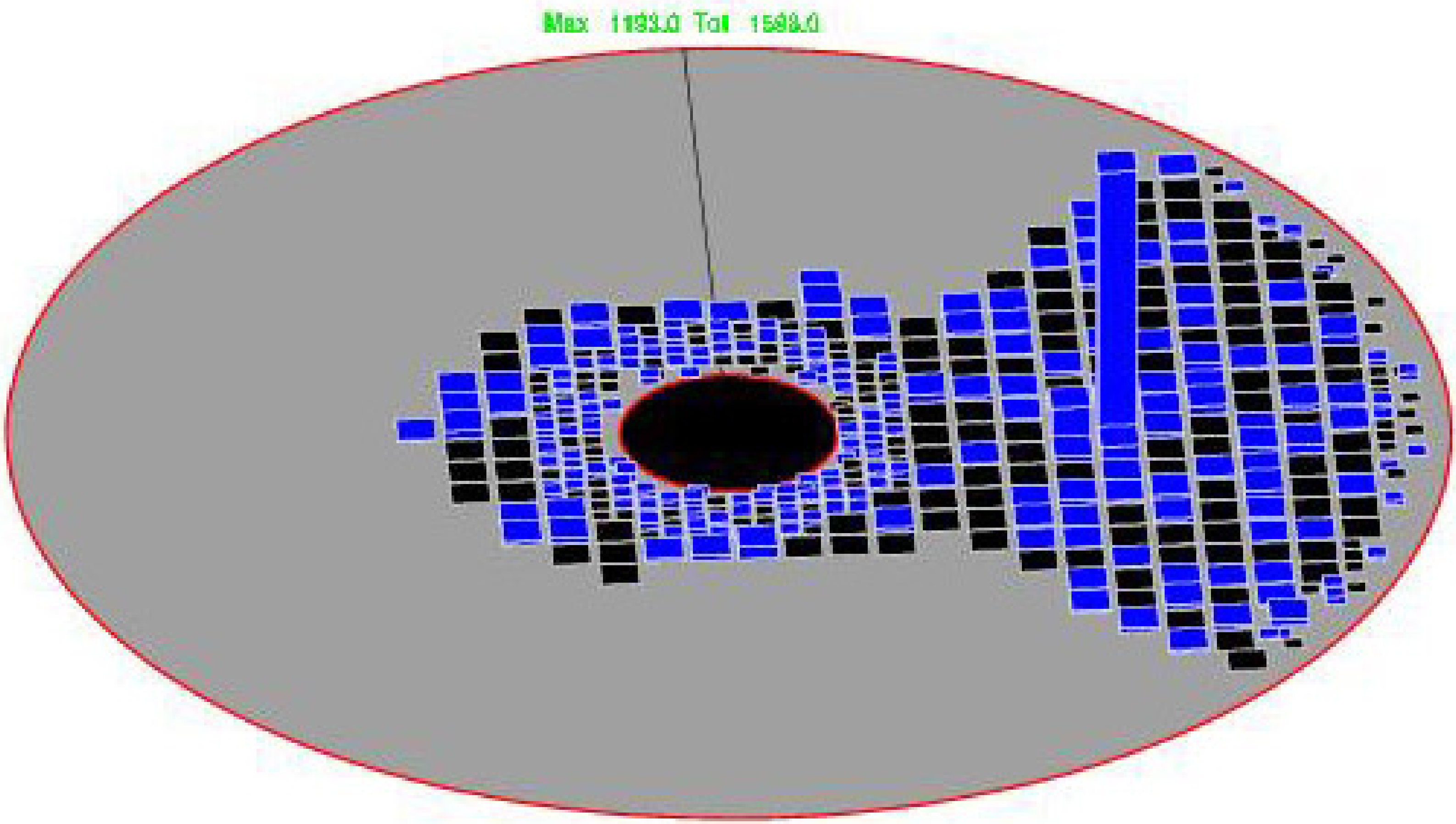


Want to measure calorimeter resolution with and without "simulated" upstream material: cryostat bulkhead, poly shielding, pumps

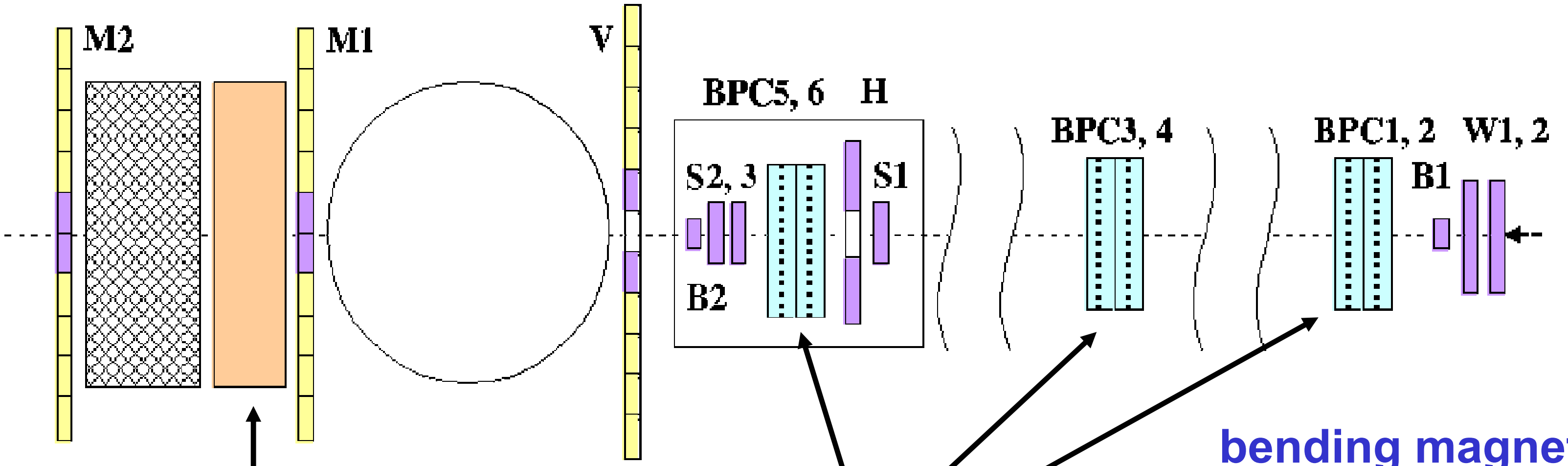
Testbeam calibration of FCal particularly important as in-situ calibration very difficult. No tracking in front of the FCal

FCAL electron event display

FCal1 Single electron 200 GeV/c



H6 beamline for 2003 and 2004 beam tests



bending magnet steers beam in y

ITEP BPCs (150 μm resolution)

tail catcher