What have we learnt so far from CALICE?

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- Overview of the CALICE program and prototypes
- Review of results from test beams, with some emphasis on validation of Monte Carlo tools
- Forward look

CALICE

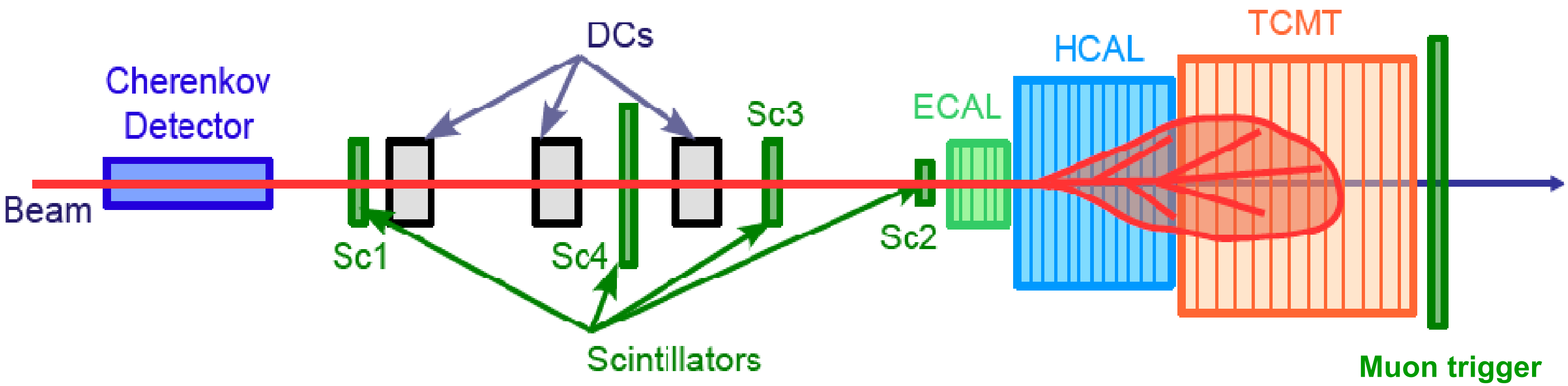
- Large (> 200 physicist) collaboration pursuing R&D into high granularity particle flow calorimeters.
- Several technologies.
- Two main phases of activity:

- "Physics Prototypes"
  - Small prototypes. Proof of principle of technologies.
  - Two types of ECAL - Si-W (1x1x0.0525 cm^3 pads) and Scintillator-W (1x4.5x0.3 cm^3 short strips).
  - Two types of HCAL – Fe-Scintillator (3x3 cm^2 tiles with SiPM readout) and Fe-RPC/GEM (1x1 cm^2 pads; digital readout).
  - Tail Catcher / Muon Tracker (TCMT) – Fe-Scintillator strips. Sample tails of showers; possible muon detector technology.
- "Technical Prototypes"
  - Second generation. Testing more realistic hardware designs which could be scaled up to full detector.
  - Mainly under the aegis of EUDET.

CALICE

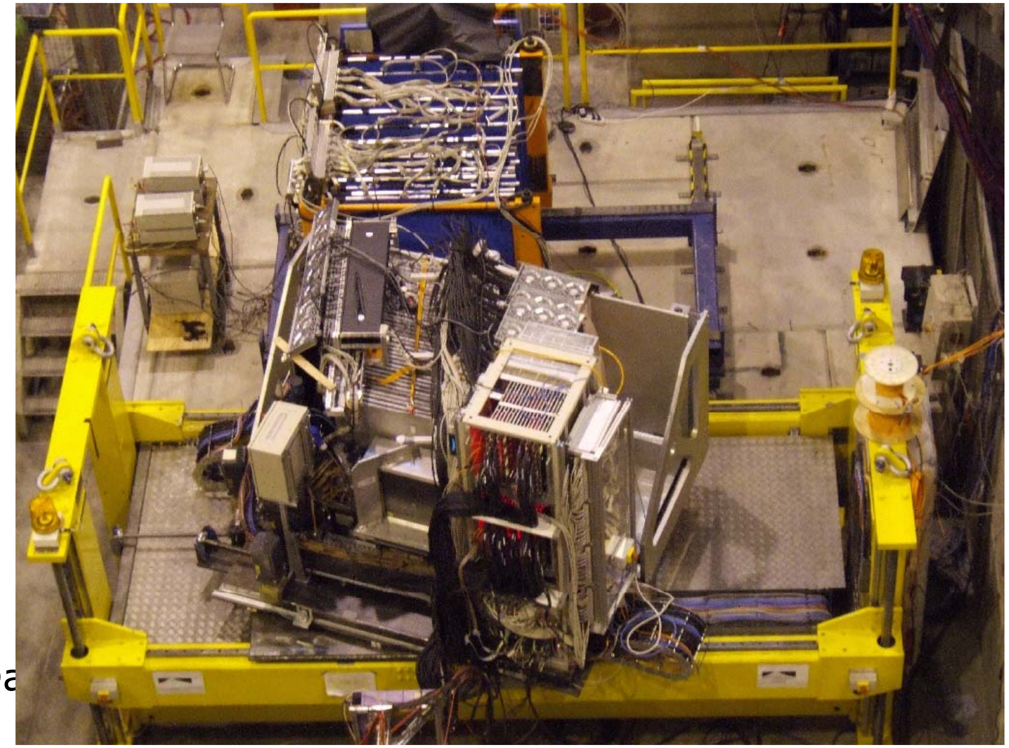
- We have been performing combined tests of ECAL/HCAL/TCMT "physics prototypes" in test beams at DESY/CERN/Fermilab since 2006.
- Also some standalone tests.
- Aims are twofold:
  - R&D – tests of hardware concepts, electronics etc. Establish viability of the various options.
  - Validate Monte Carlo tools. This can impact on ILD work. Specific examples:
    - Simulate prototypes using Mokka-GEANT4, i.e. the same package as used for ILD simulations.
    - Test adequacy of geometrical representation.
    - Test physics models, especially hadronic physics lists. Identify the "best"? Or characterise systematic errors.
    - Understand the importance of digitisation effects (noise, crosstalk, saturation effects, alignment etc.) and their impact on detector response.

Test beam – typical layout

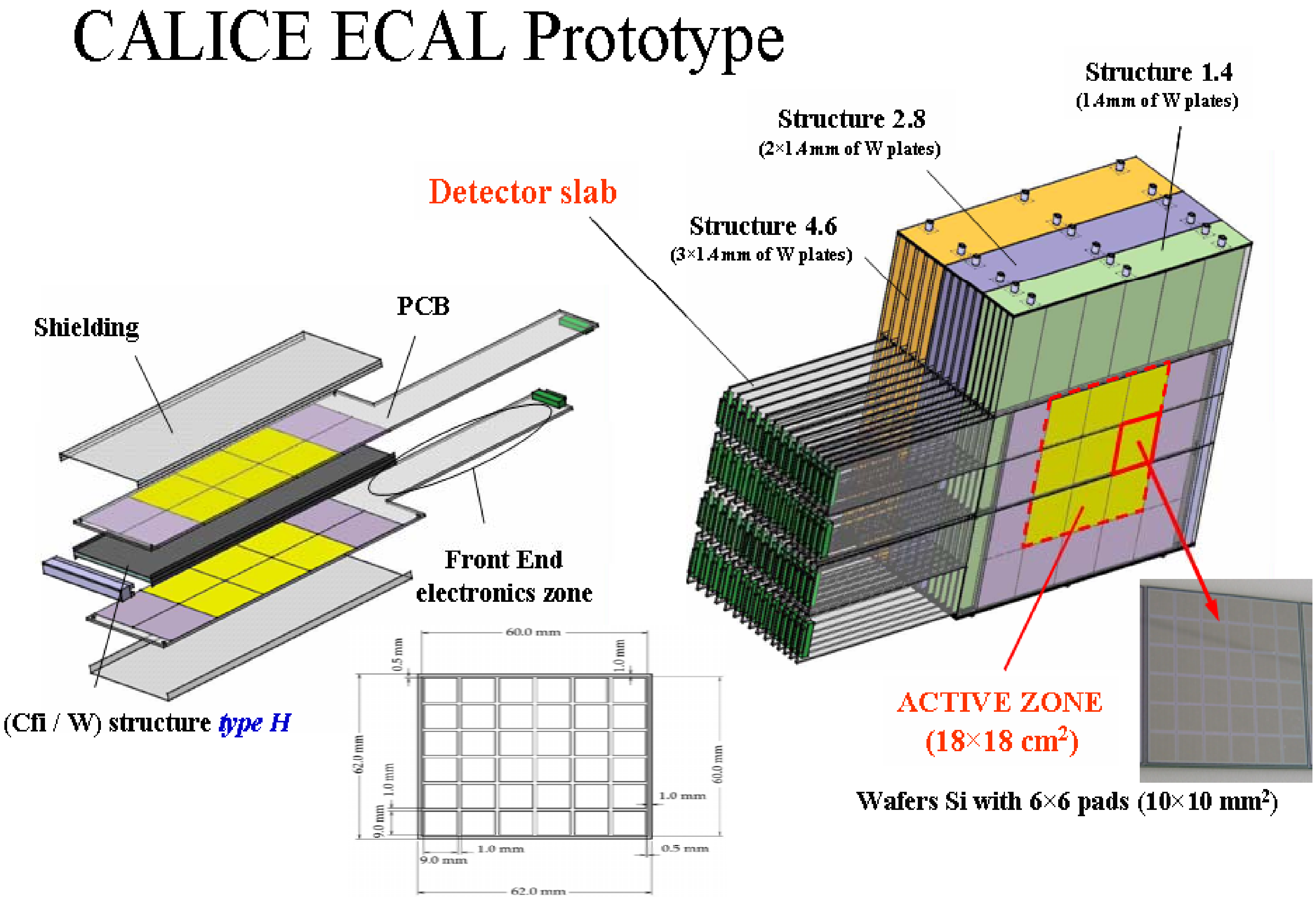


Data recorded:

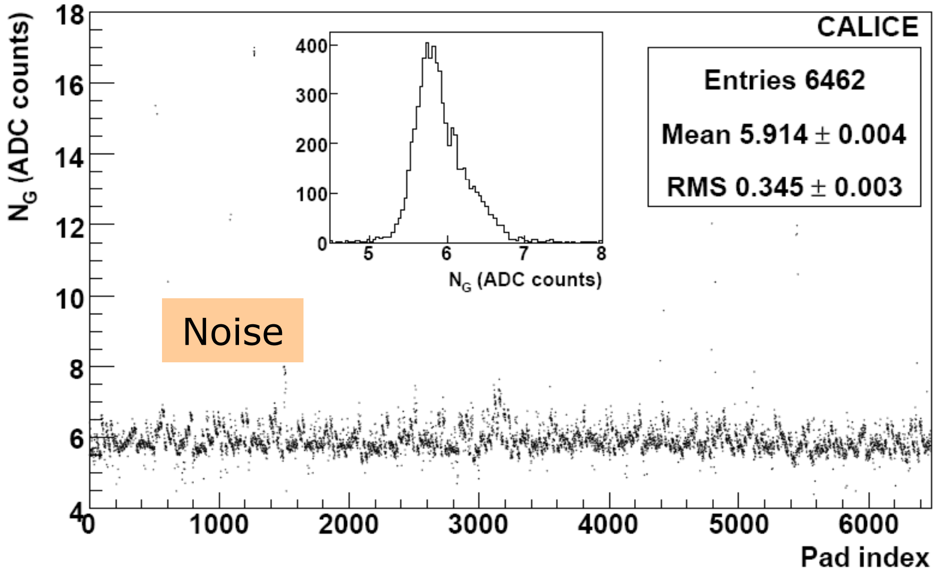
- 2006 – DESY/CERN
- 2007 - CERN
- 2008 – Fermilab MTBF
- Si-W ECAL, HCAL, TCMT
- $e^{\pm}$ 1-50 GeV
- $\mu^{\pm}$ (mainly for calibration)
- $\pi^{\pm}$ 2-180 GeV
- Various impact points
- Angles of incidence 0°, 20°, 30°, 45°
- Typically ~200K events per configuration.

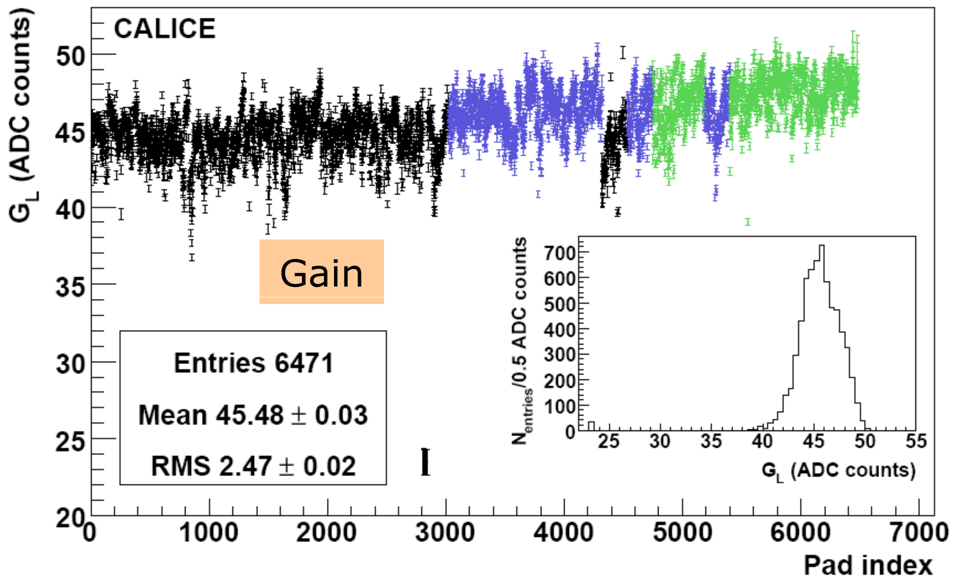


Si-W Ecal prototype



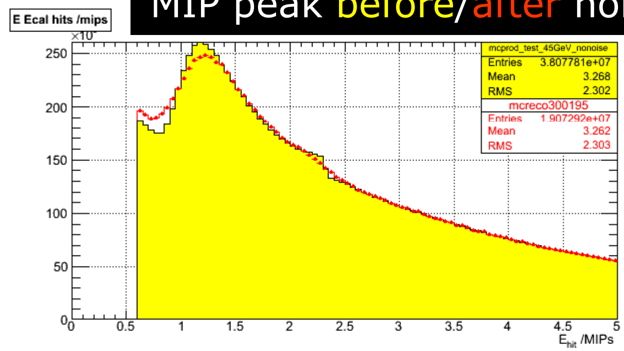
ECAL – noise and gain

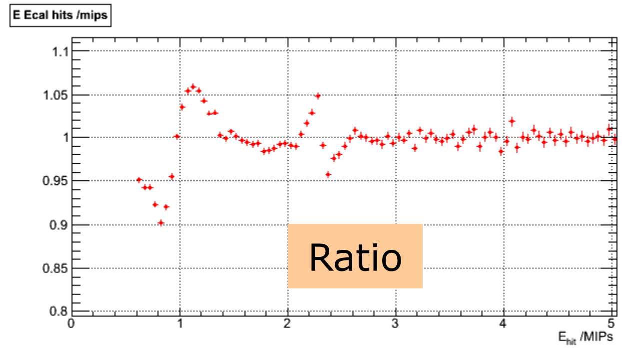




- Gain calibrated with muons. Rather uniform channel to channel.
- Average noise ~6 MIPs. Signal/Noise ~8.
- With a typical threshold cut for analysis of ~0.6 MIP, the effect of noise on the MIP peak is small. We include in simulation, but the effect is minimal for most purposes.

MIP peak before/after noise sim.

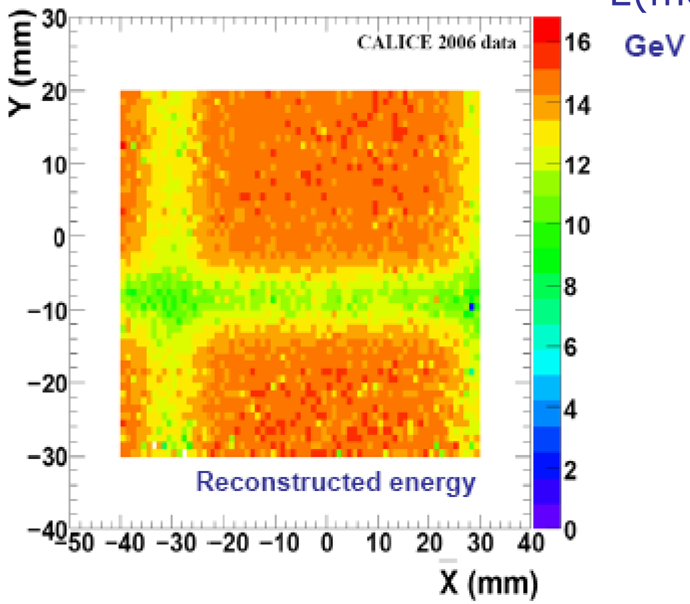


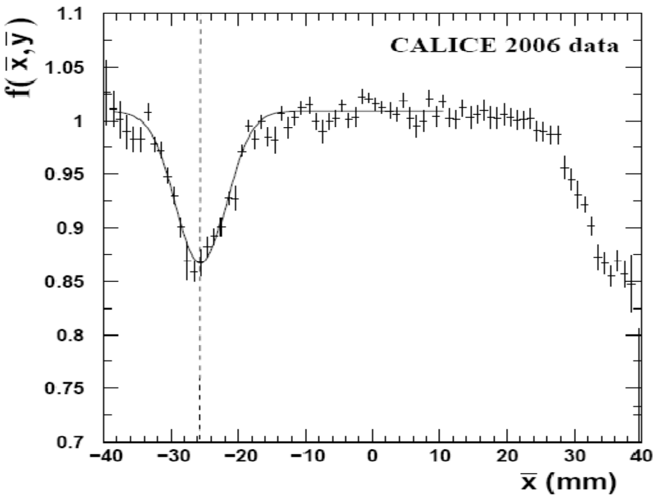


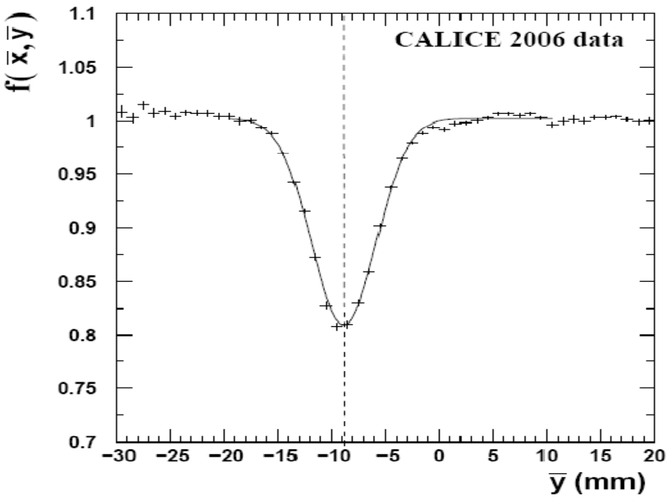
Effect of guard rings

15 GeV
e^- beam
E(meas)

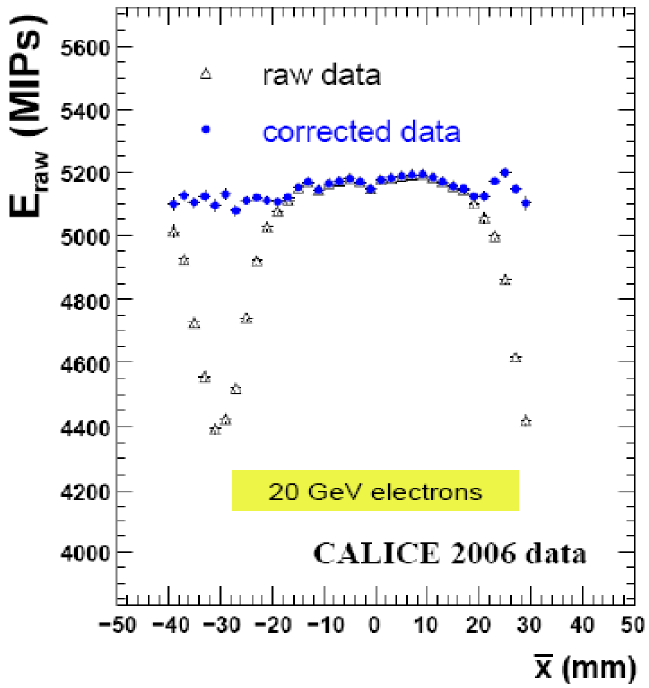
- 1mm guard rings around wafers $\rightarrow$ 2 mm dead zone between wafers (7% of area).
- See as a drop in response as scan across the calorimeter.
- Deeper in y than x because wafers aligned in y, staggered in x.
- n.b. larger gaps at alveolar boundaries.

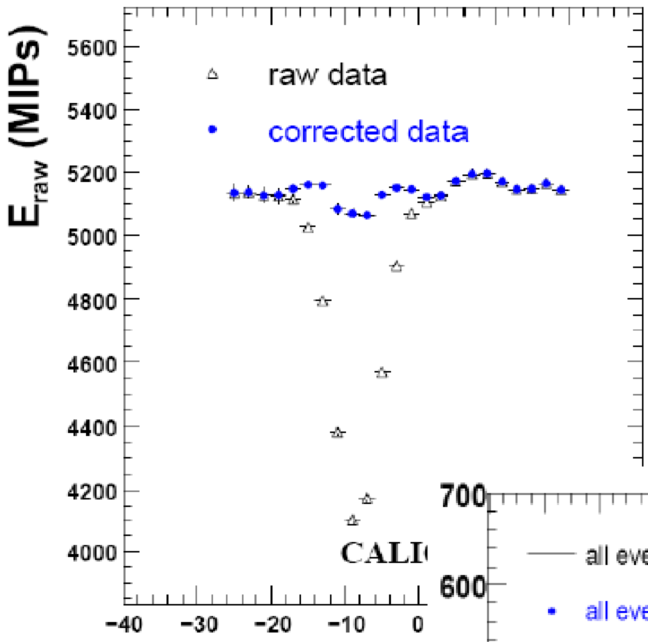


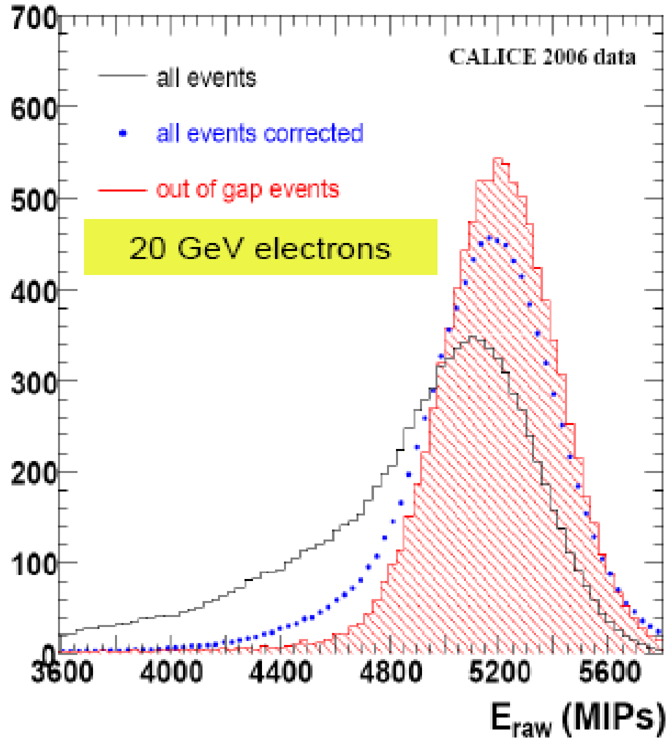




Guard ring correction

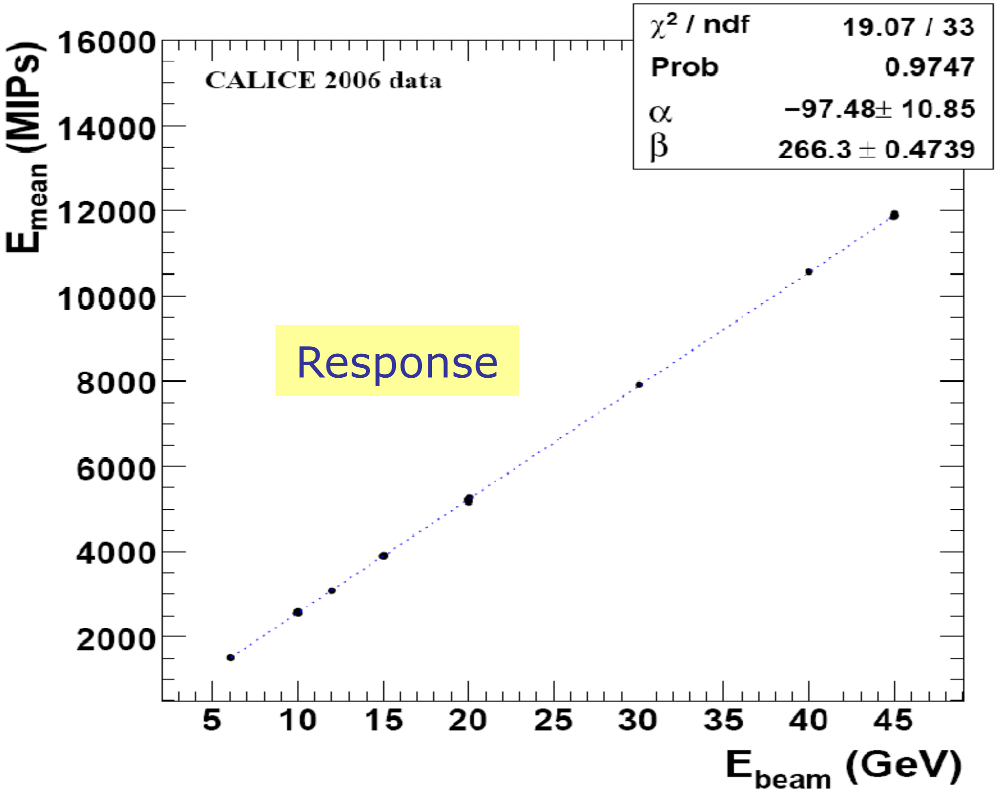


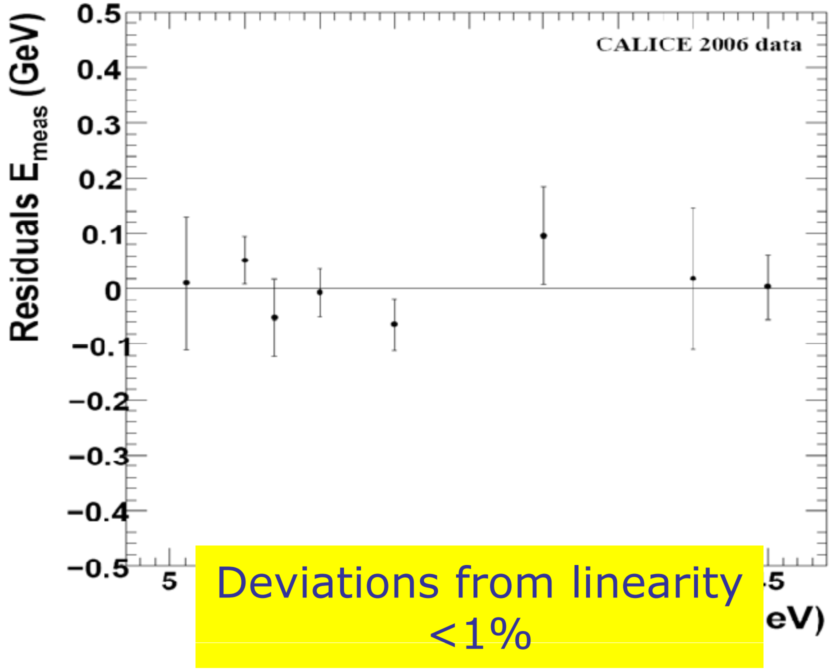




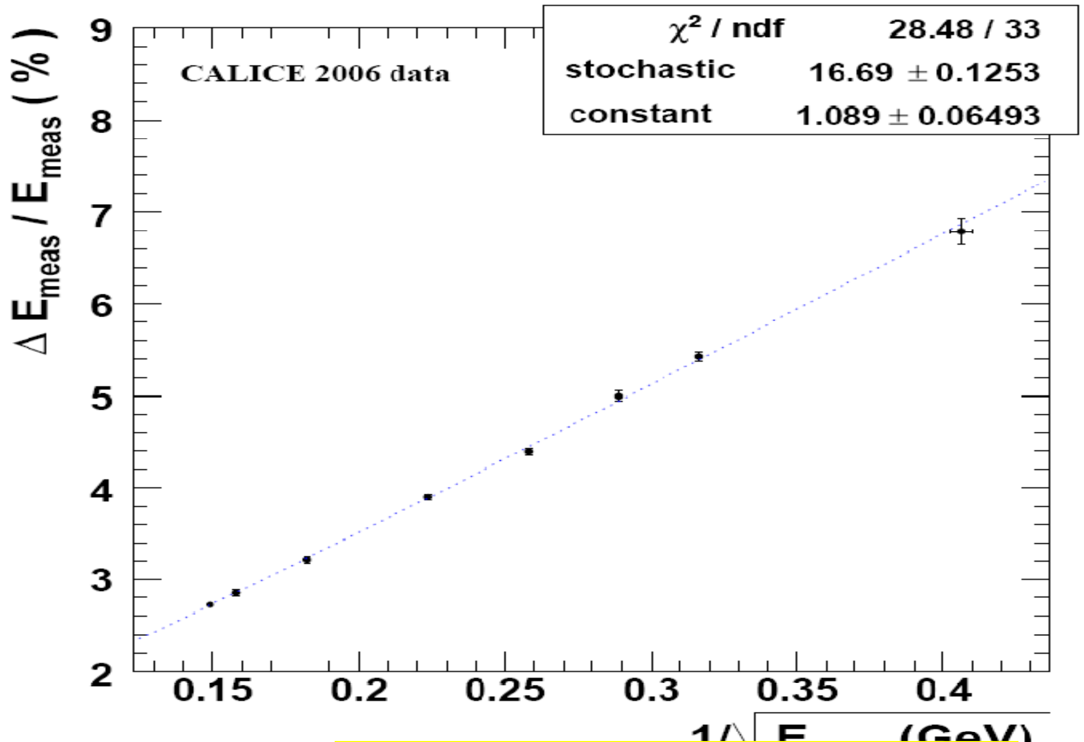
- Gaussian parametrisation of energy loss
- Permits a reasonable uniformity vs (x,y)
- Reduces low tail in measured energy
- But inevitable penalty in resolution.

ECAL energy response for e^-





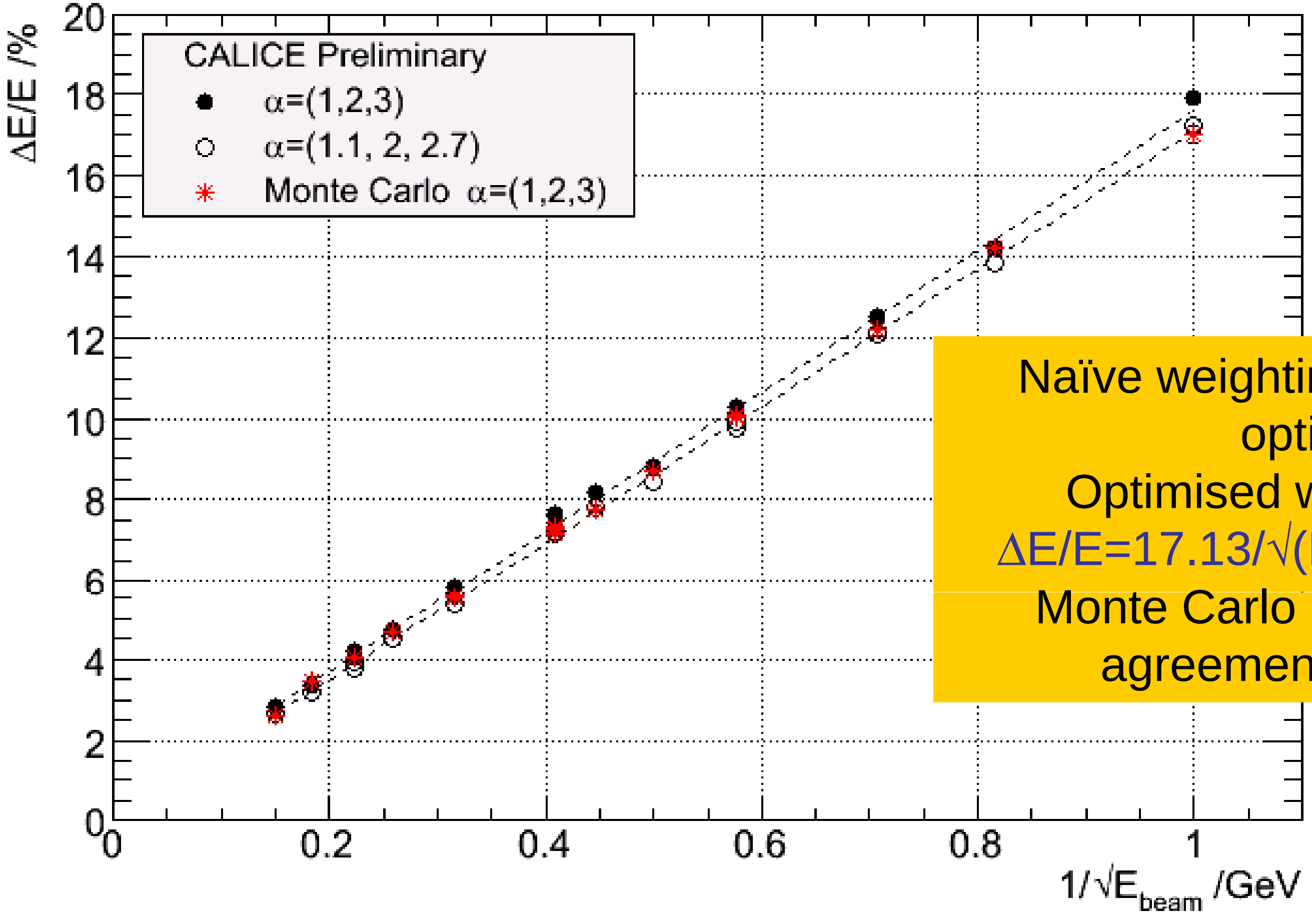
ECAL energy resolution for e^-



$\Delta E/E = 16.69\%/\sqrt{E} \oplus 1.09\%$

ECAL Resolution (CERN+DESY)

Older version of the analysis, but shows that data and MC are in good agreement



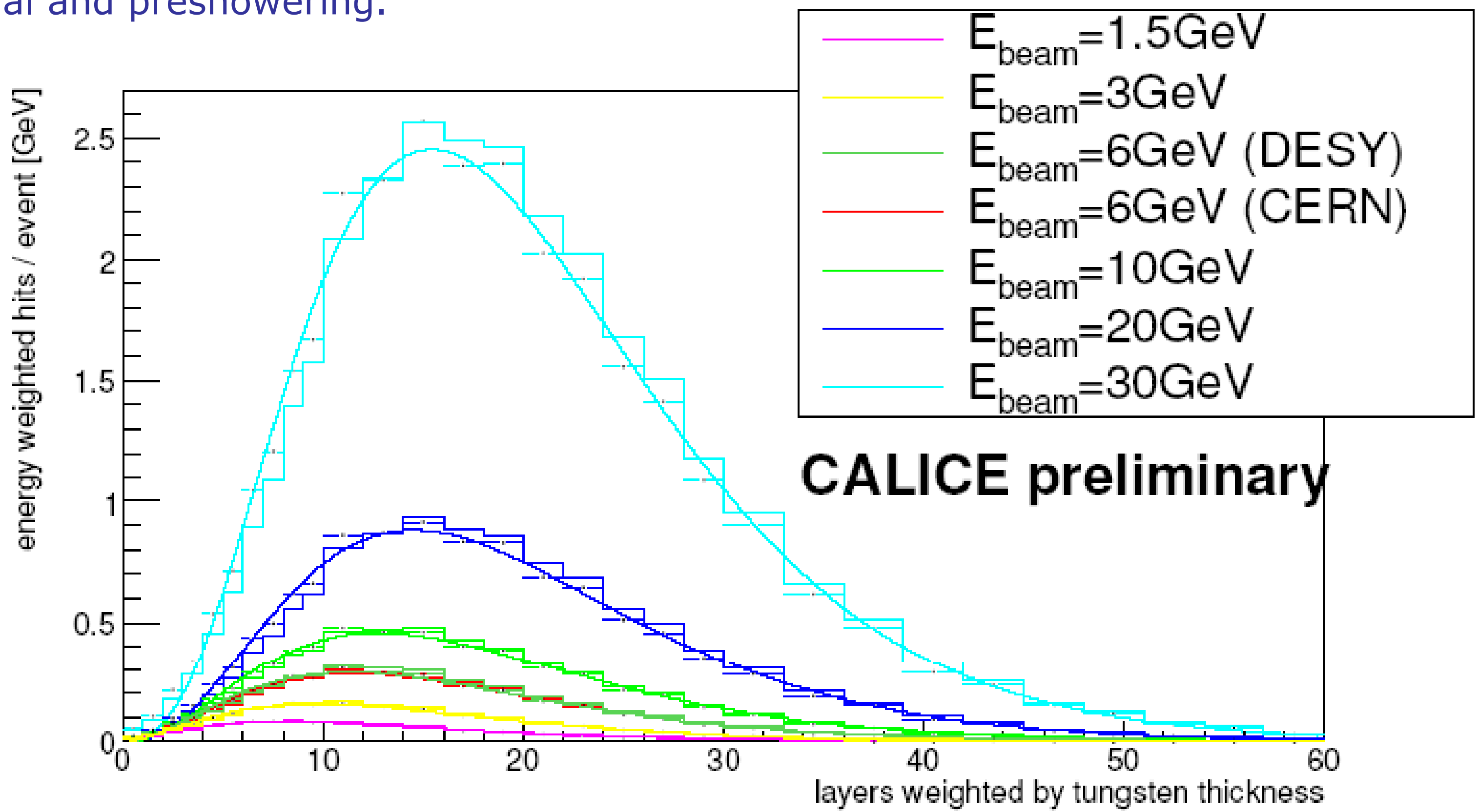
Naïve weighting not far from optimal

Optimised weights yield $\Delta E/E = 17.13/\sqrt{(E/\text{GeV})} \oplus 0.54\%$

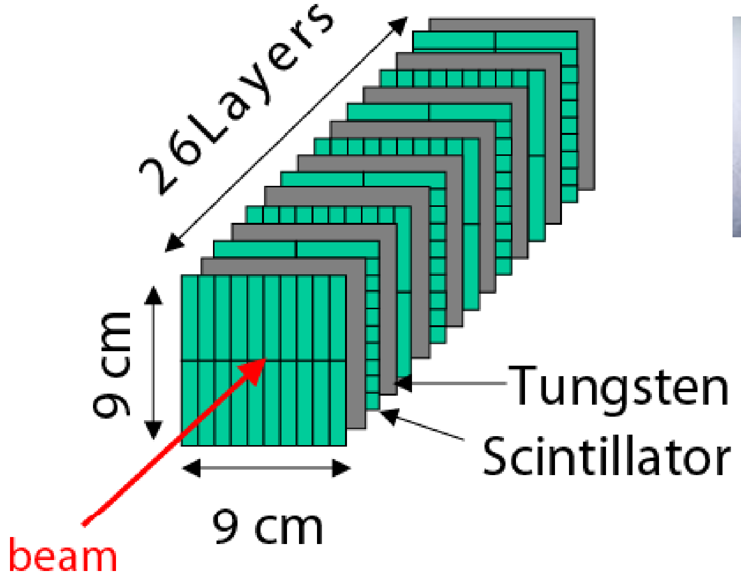
Monte Carlo in pretty good agreement with data

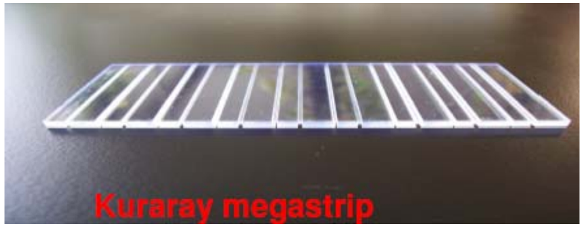
ECAL longitudinal shower profile for e^-

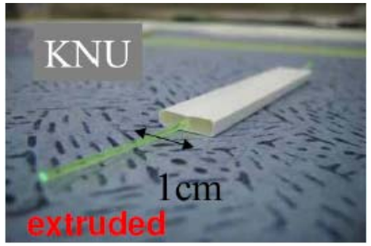
- Data (dashed) agree quite well with Monte Carlo expectation (solid).
- Some shift – likely associated with upstream material and preshowering.



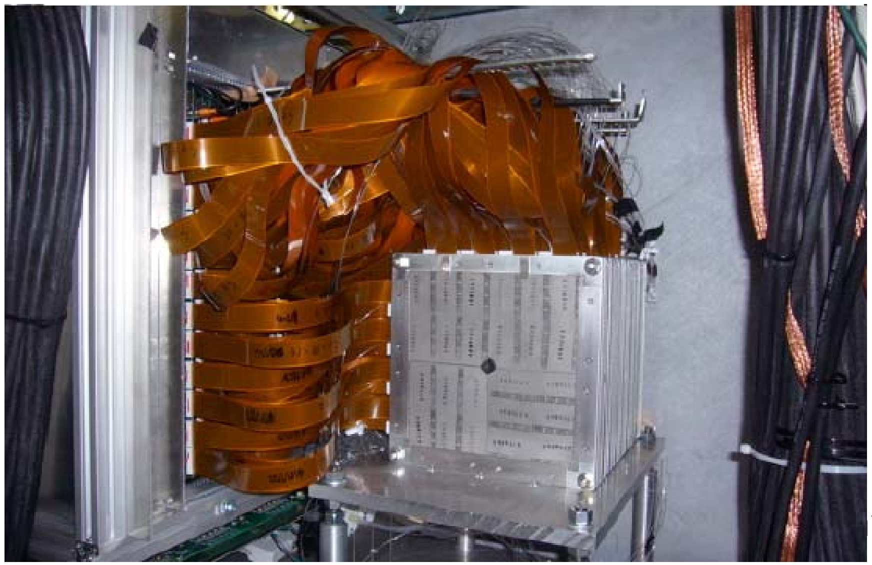
Scintillator-Tungsten ECAL





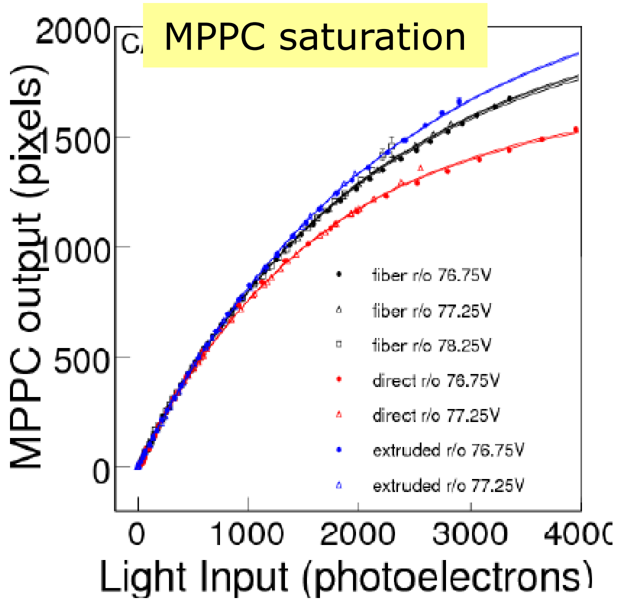


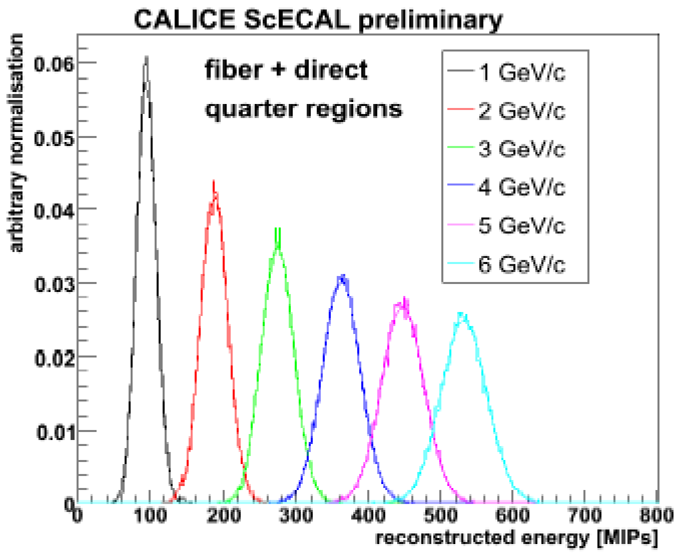
- ¼-size prototype tested at DESY in 2007.
- Strips 4.5x1 cm scintillator; 3 mm thick.
- MPPC readout
- Three options tested
  - Megastrip; WLS fibre readout
  - Megastrip; direct readout
  - Extruded strips, WLS fibre

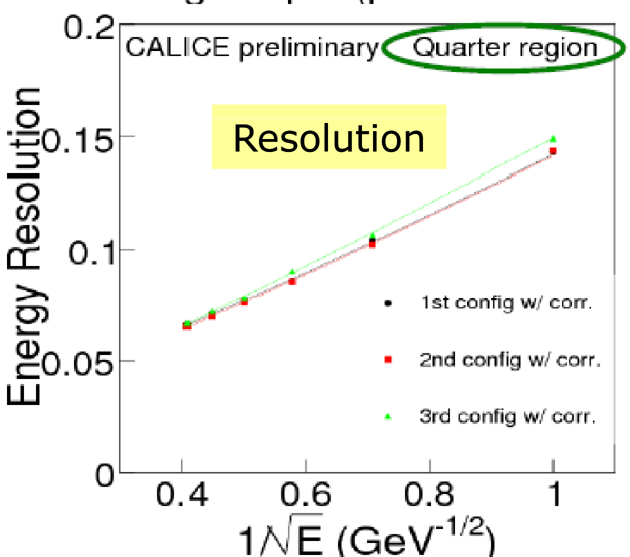


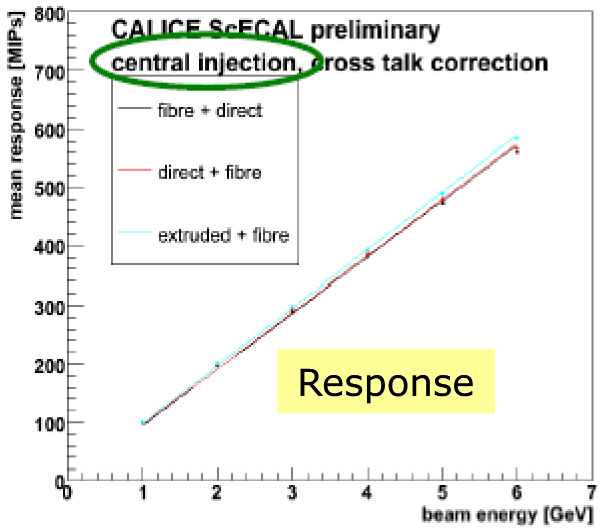
- "Full size prototype" (18x18 cm)
- Extruded strip technology
- Just entered MTBT test beam at FNAL in September 2008
- Mounted on AHCAL for π and electron tests

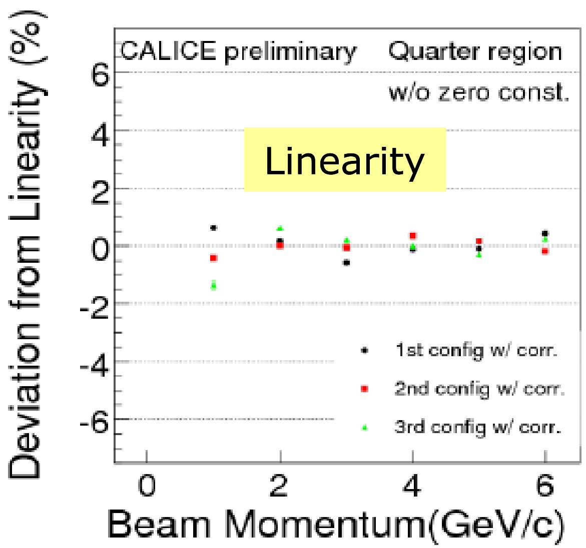
ScECAL – results from DESY test





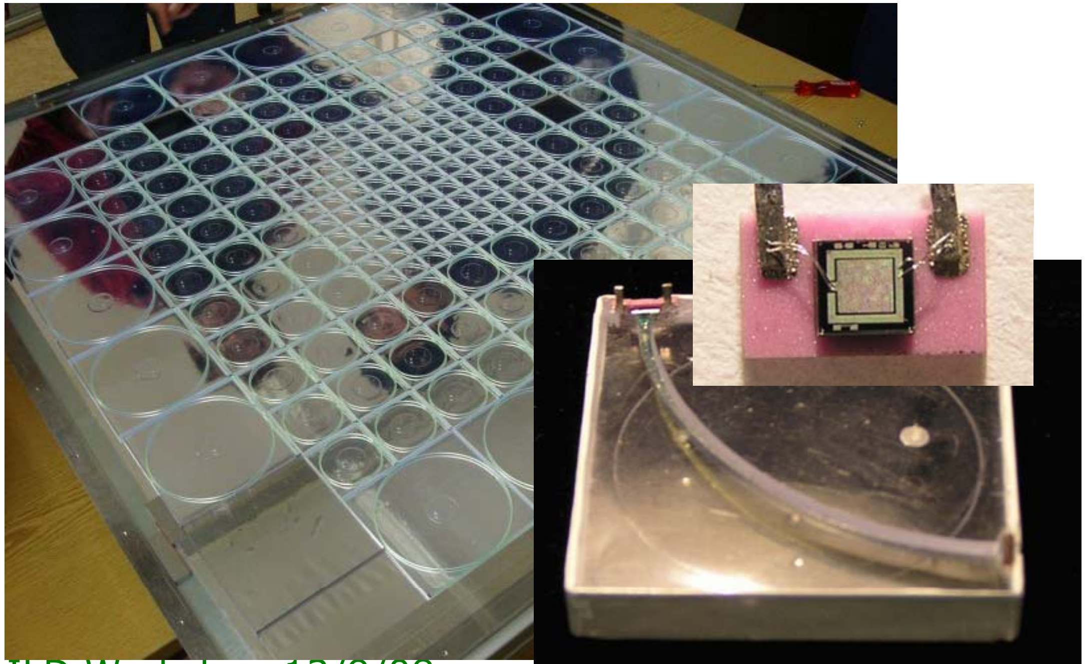


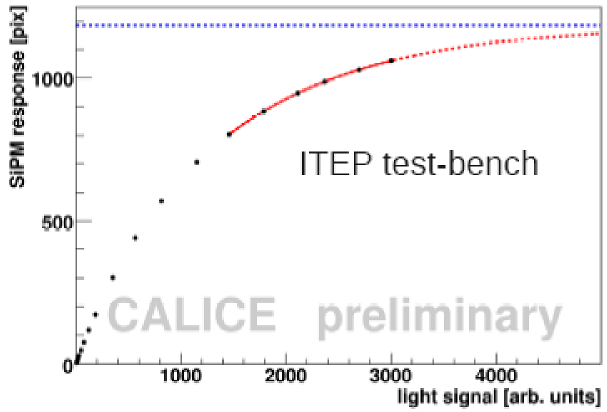


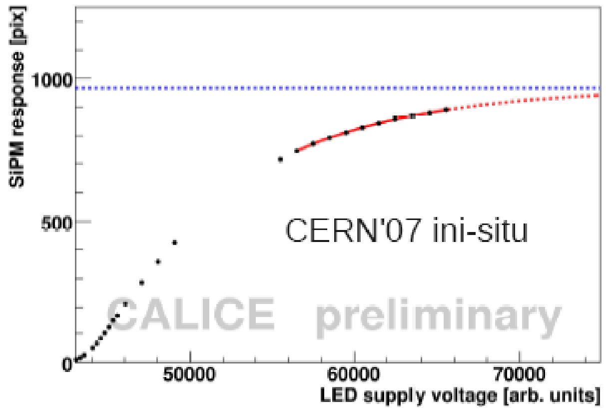


Fe-Scintillator analogue HCAL (AHCAL)

- ❖38 Layers of scintillator tiles
- ❖Cross-section 1x1 m^2
- ❖3x3, 6x6, 12x12 cm^2 tiles; 5 mm thick.
- ❖Read out by WLS fibres, SiPM photodetectors
- ❖Iron absorber plates 20 mm thick

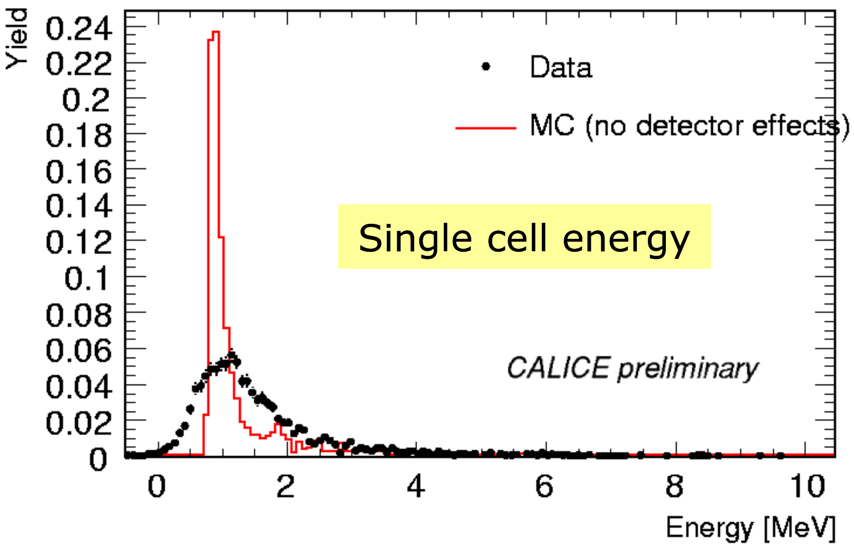




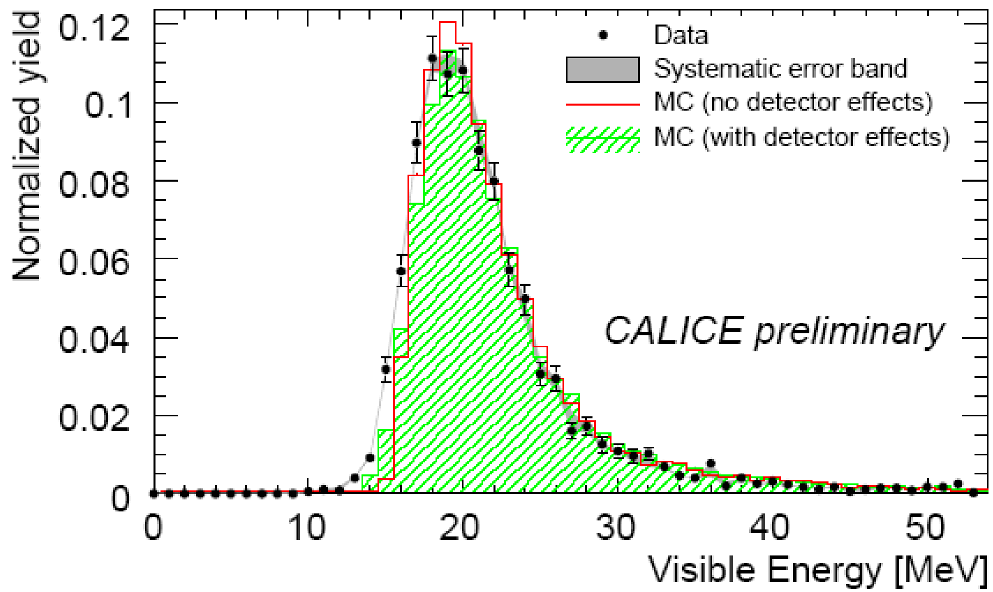


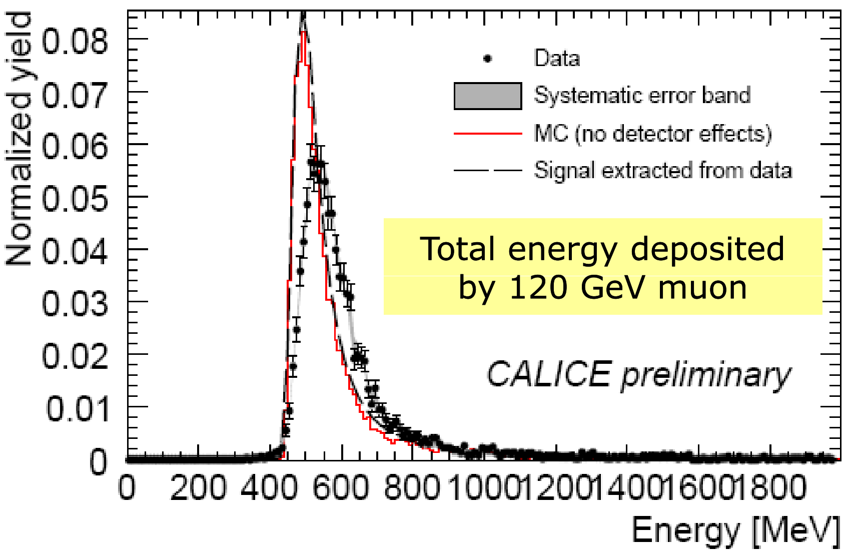
- •Saturation curves for SiPMs.
- •Important correction, especially in high energy electron showers.
- •Also temperature control/corrections important.

Muon response of AHCAL



Total energy in 3x3 cm^2 tube

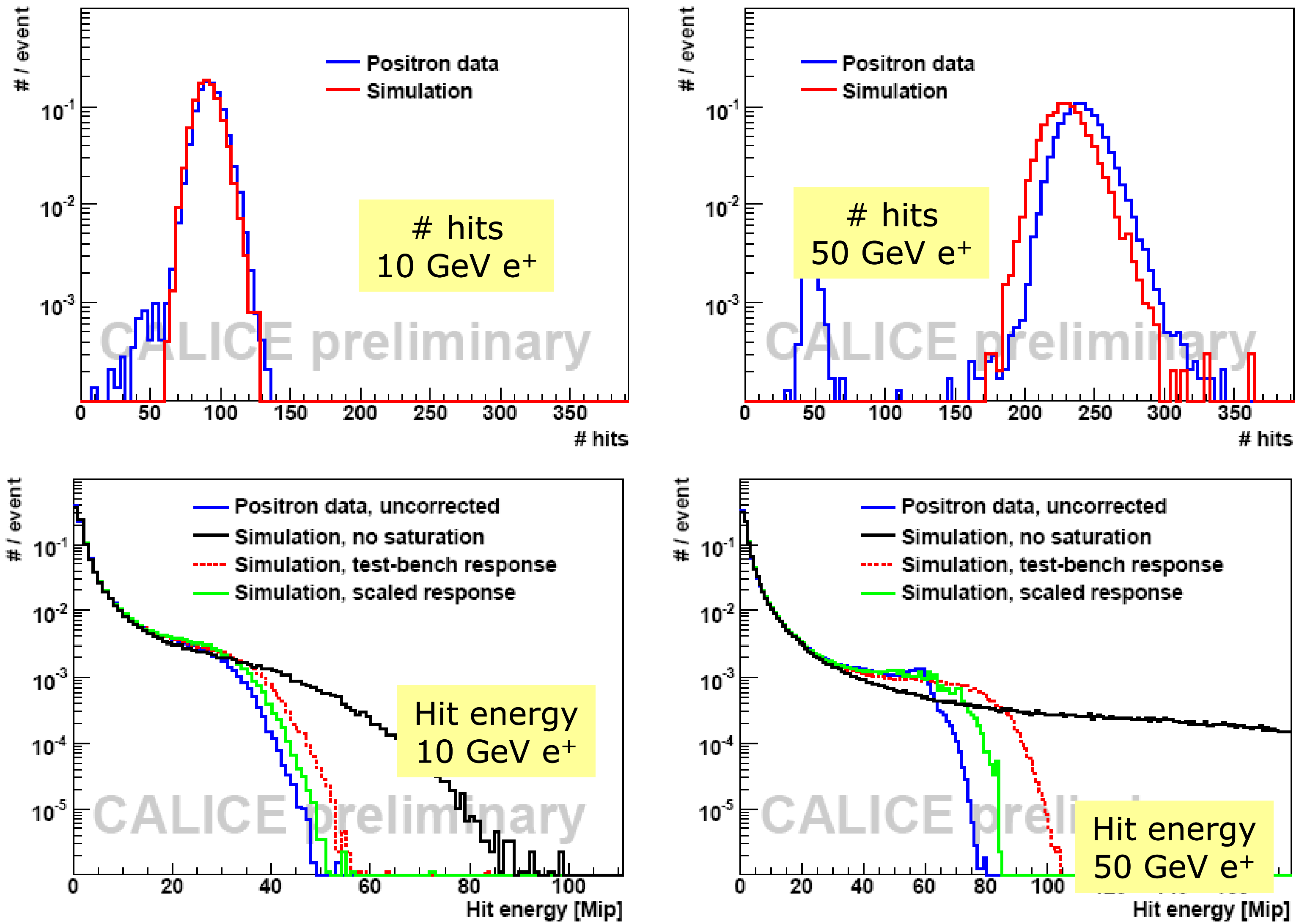




Considered in MC digitisation:
- Signal leakage to neighbours (global factor only)
- Non-linear response (response curves and calib constants)
- Pixel statistics
- Energy scale (calib constants)
- Dead/uncalibrated channels

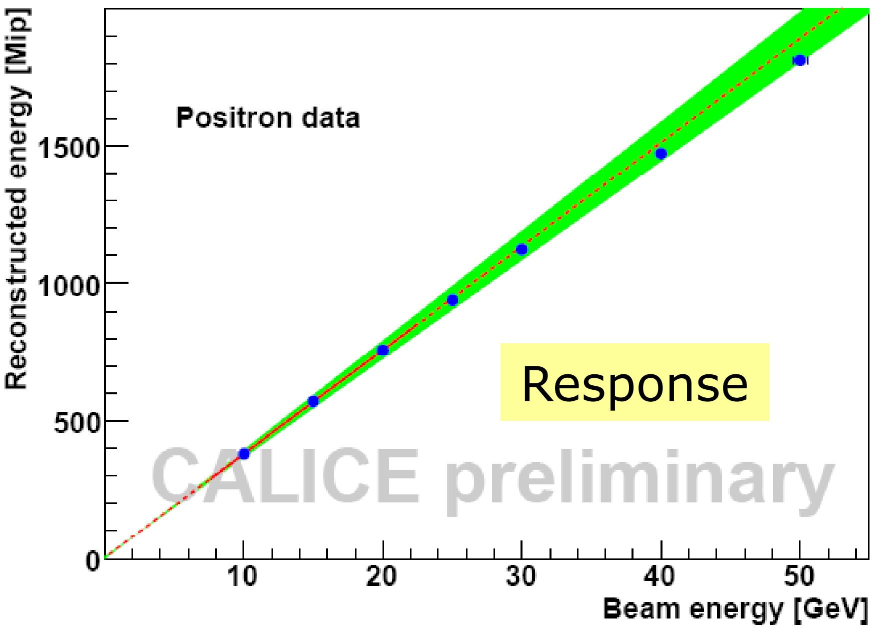
Not (yet) considered, but likely to be significant:
- Birks' law in simulation
- Tile non-uniformity (edge effects)

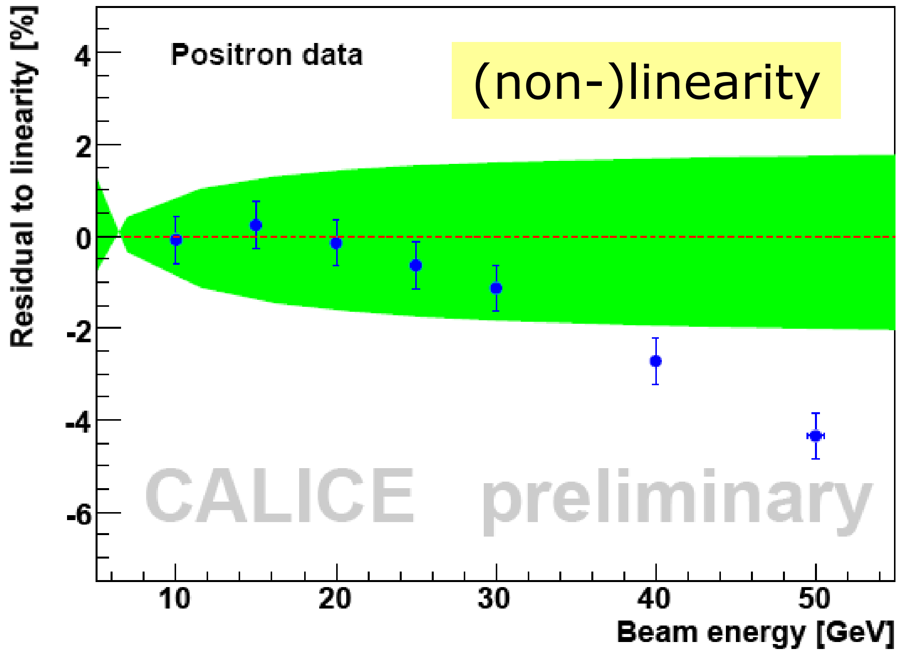
Positron response of AHCAL

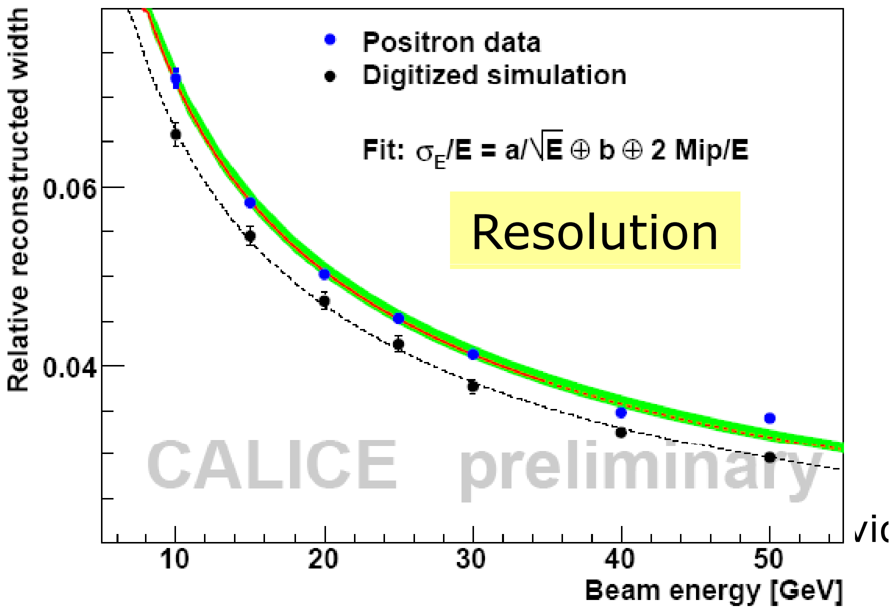


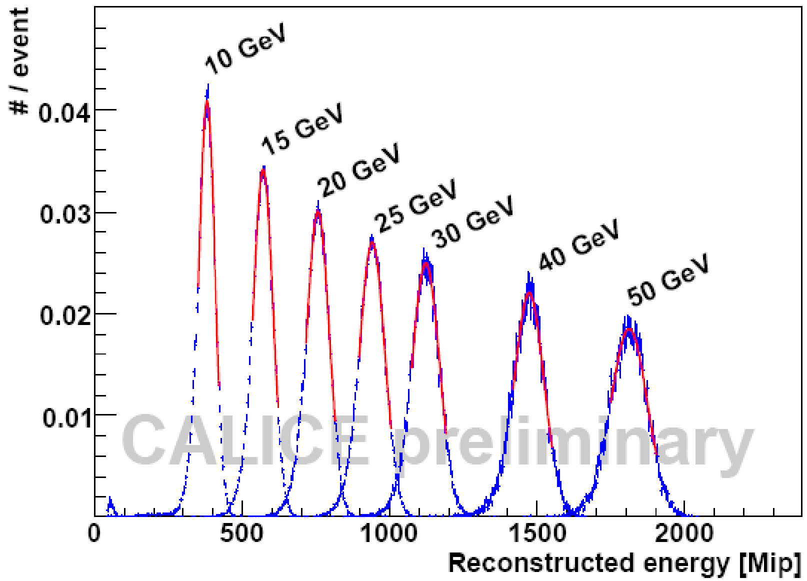
Still some discrepancies between data and MC, especially at higher energies.

Positron response of AHCAL

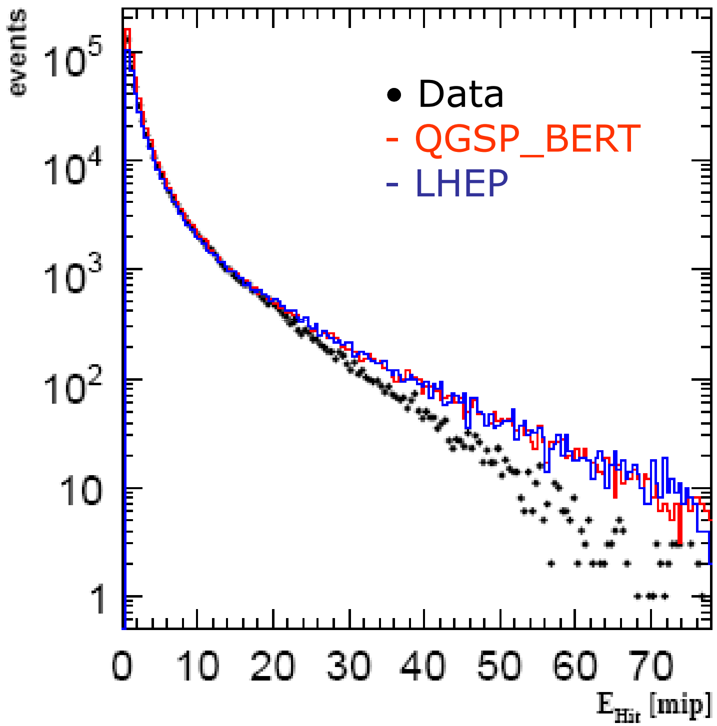


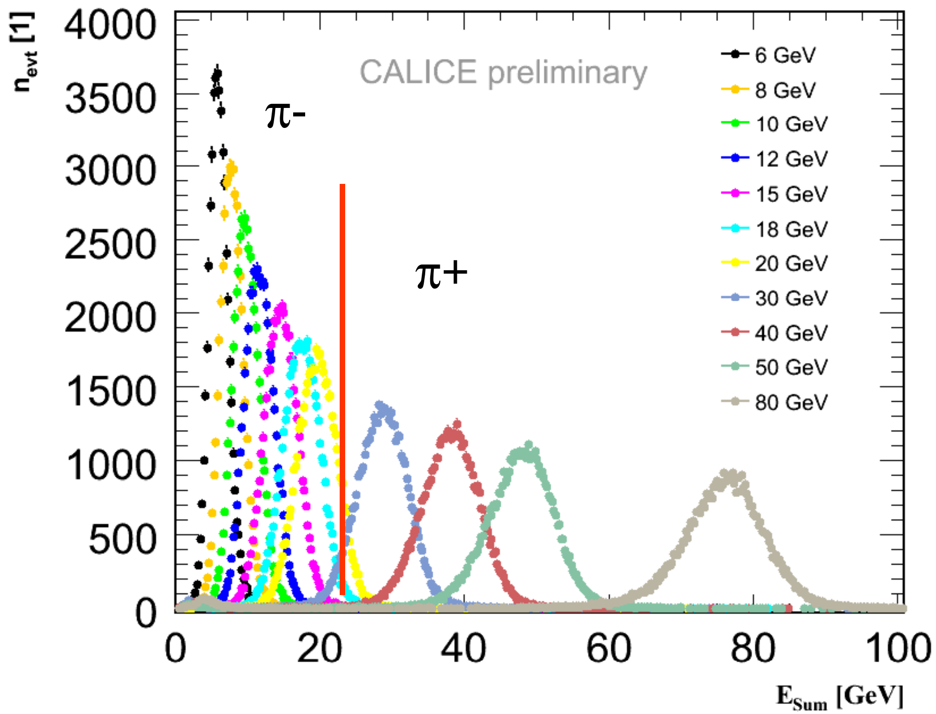






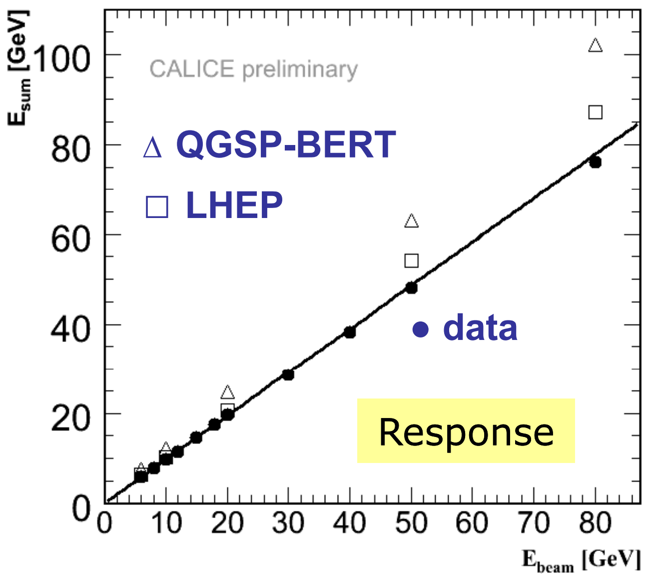
Pion response of AHCAL

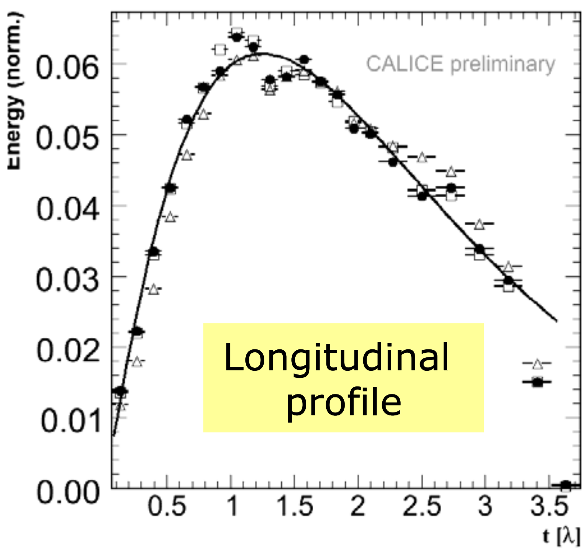


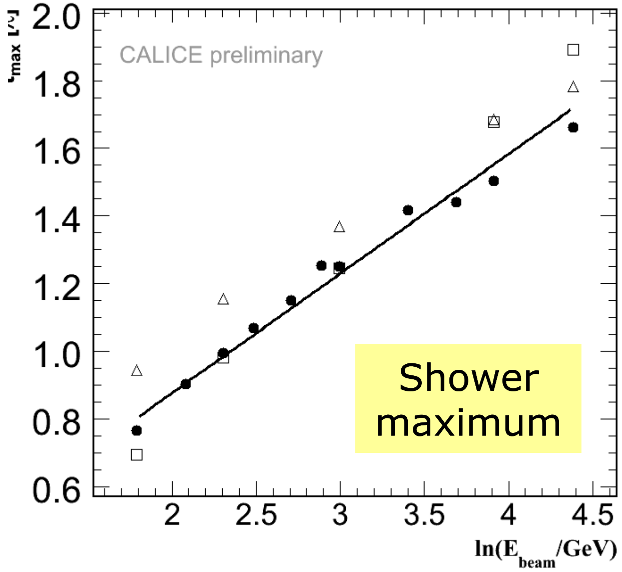


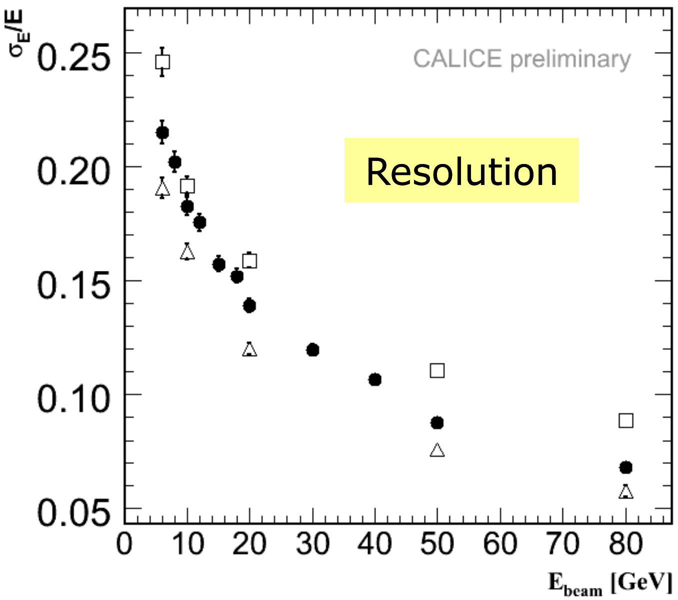
- Hit energies typically much lower than in e^+ showers
- Hence saturation corrections less critical, but simulation of data still imperfect.
- Comparisons with MC models should be regarded as provisional.

AHCAL – pion response, c.f. MC





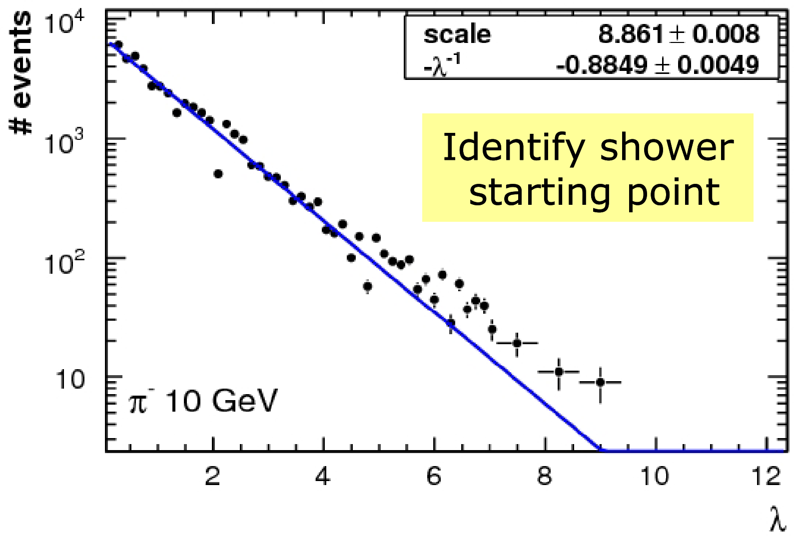


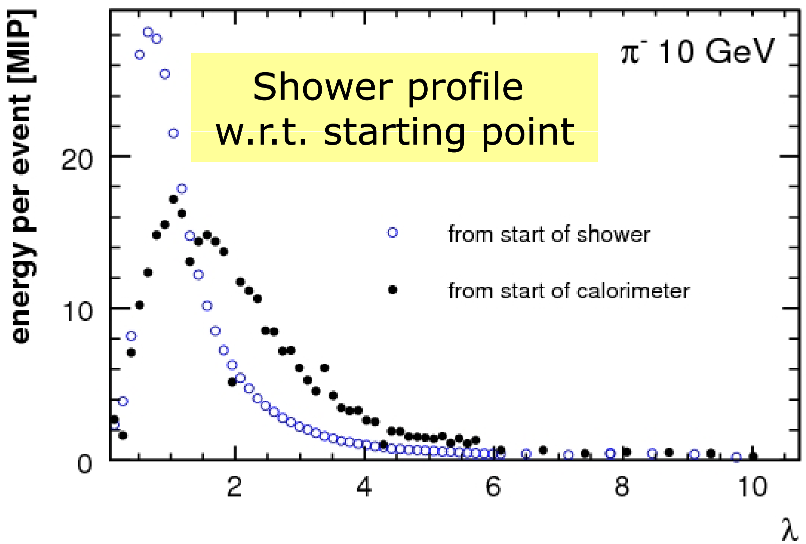


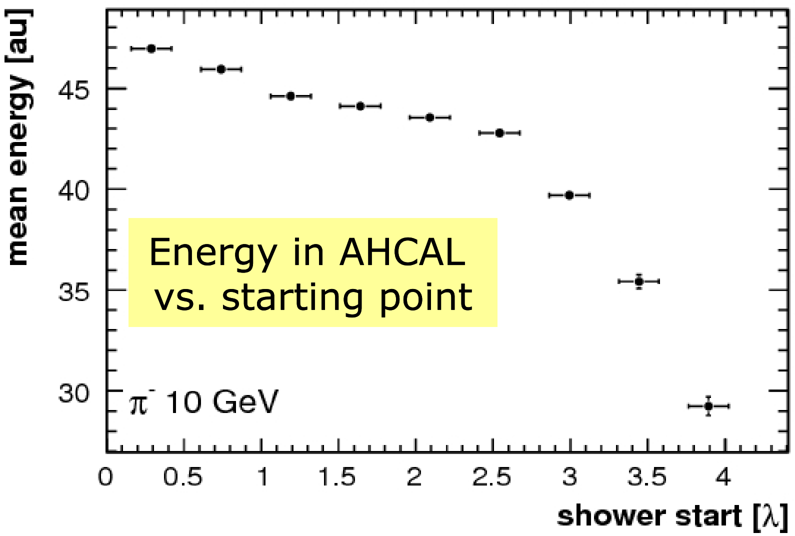
Compare two (extreme?) models with data

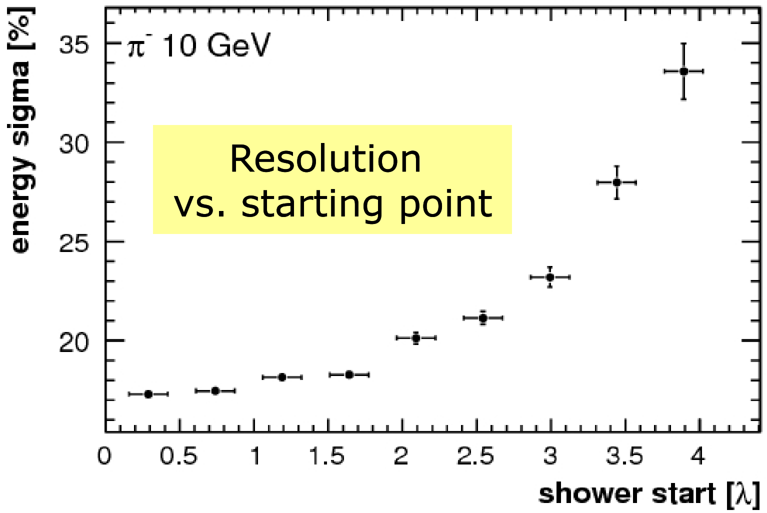
- Both models give reasonable trends.
- On this basis, probably LHEP seems slightly favoured over QGSP_BERT (≈ LCPhys)
- But both (or the data) have deficiencies.
- Too early to draw firm conclusions

HCAL shower leakage study

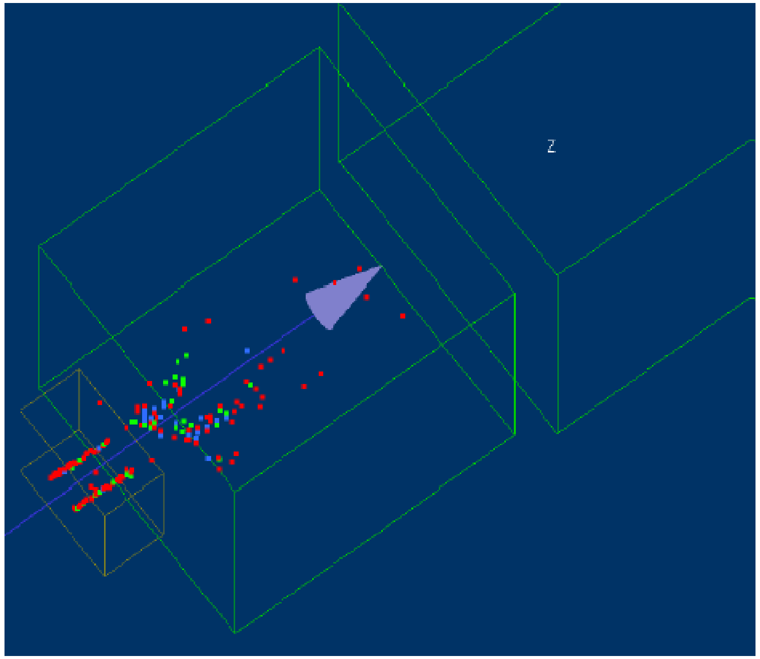


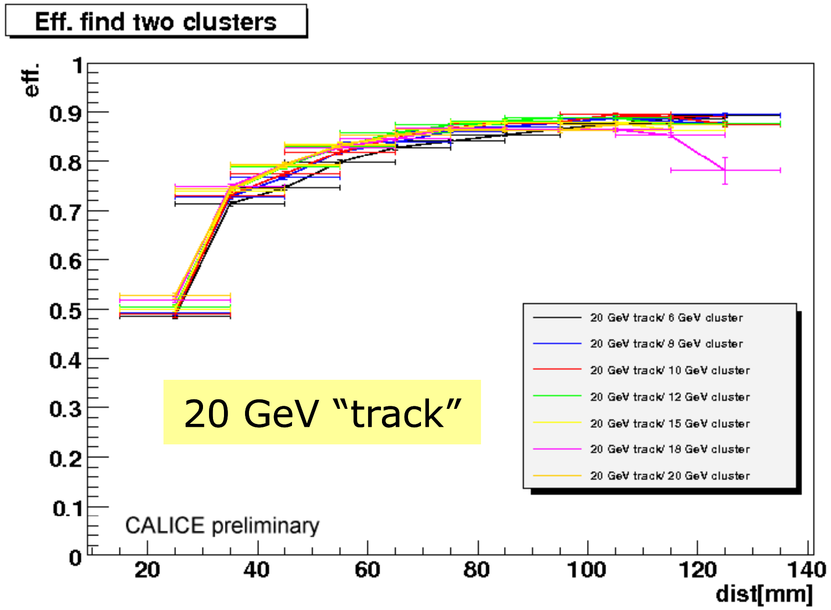


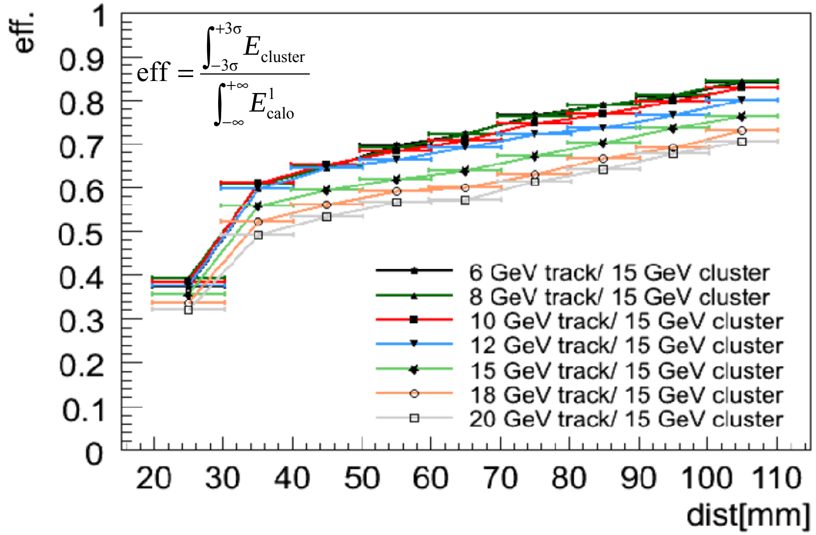




Two shower separation



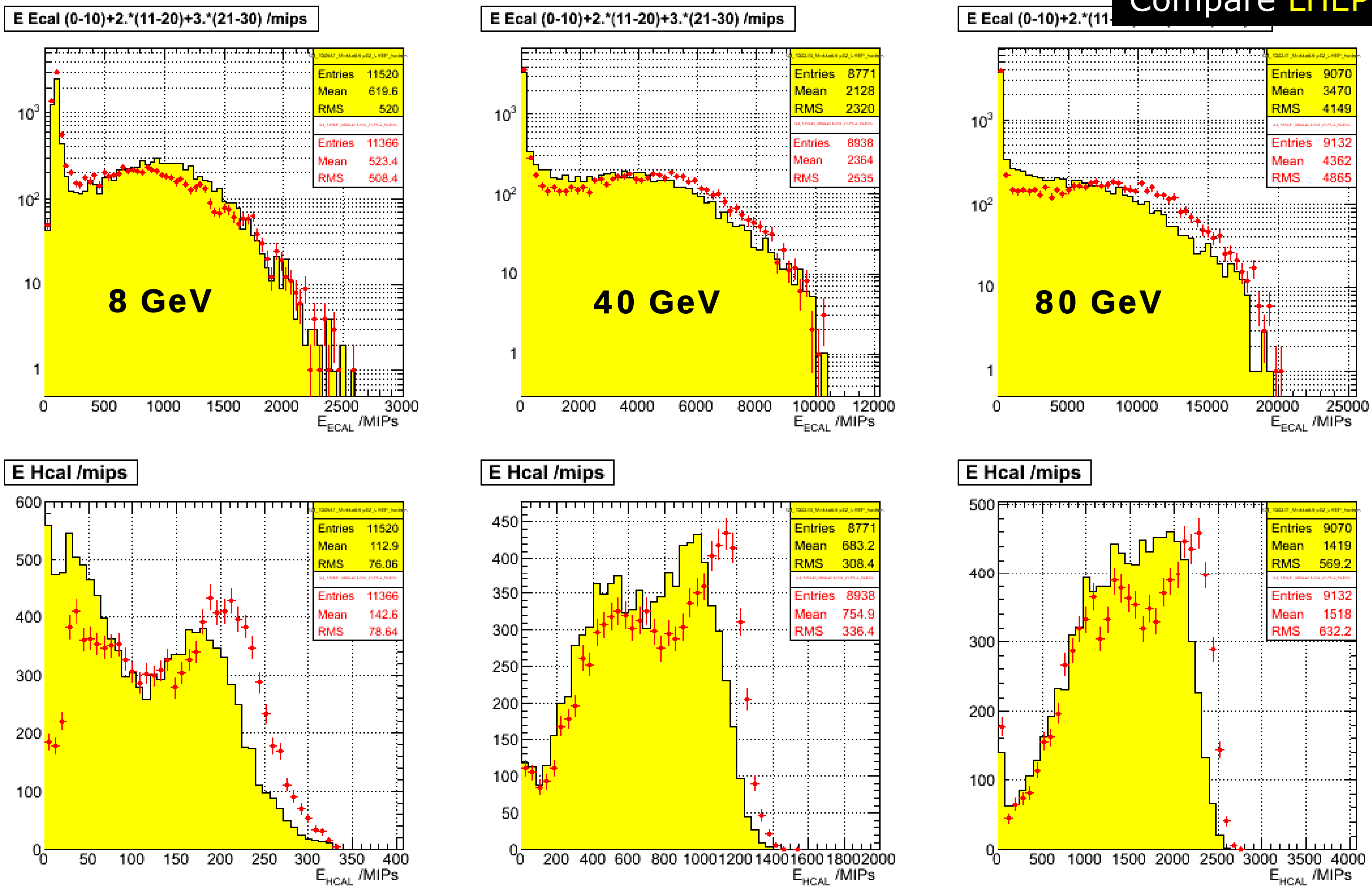




- Superimpose pairs of data pion events; up to 10 cm separation.
- Pretend one is charged, one neutral.
- Apply track-like particle flow.
- Look at separation between particles' energy.
- Much more can and will be done along these lines…

Pion showers in ECAL (MC only)

Compare LHEP with LCPhys



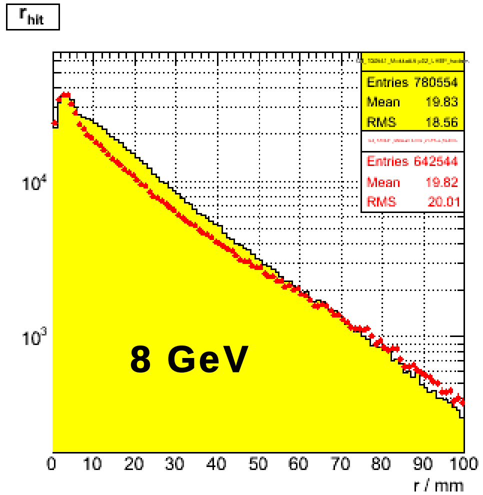
ECAL energy

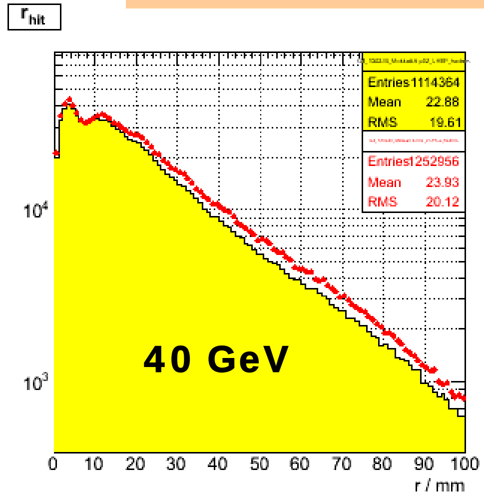
HCAL energy

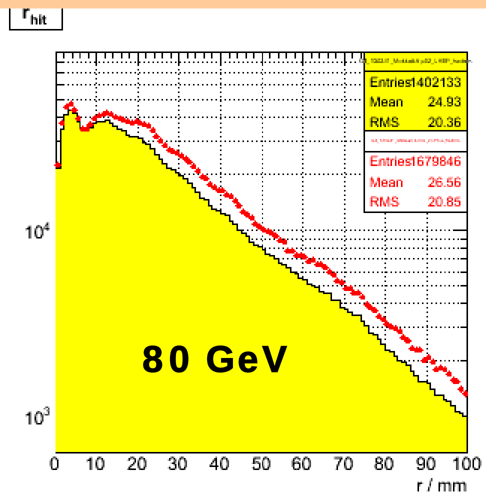
Pion showers in ECAL

Compare LHEP with LCPhys

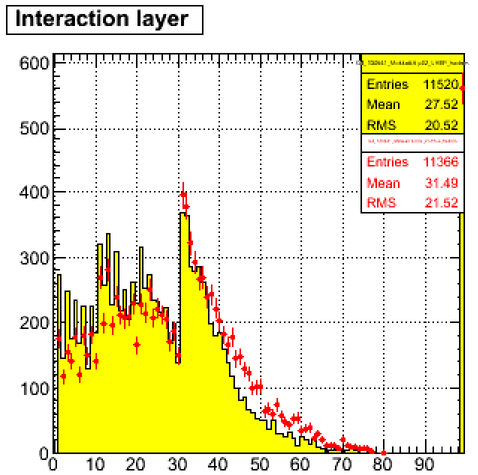
Even ECAL alone has sensitivity to shower models
Also correlations between ECAL and HCAL are interesting

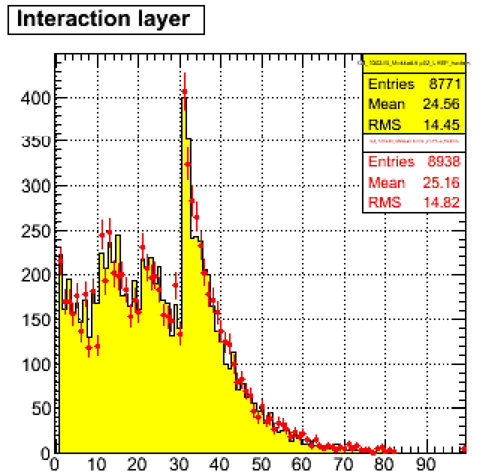


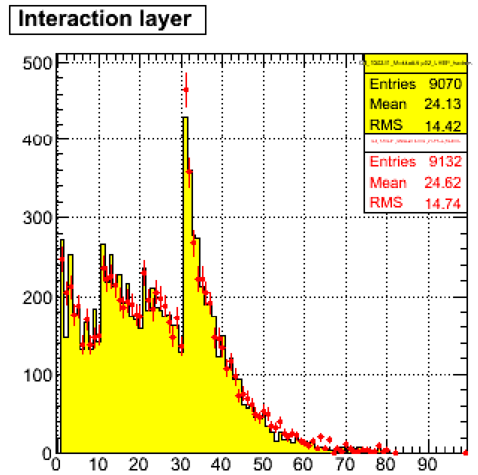




Radial distribution of hits



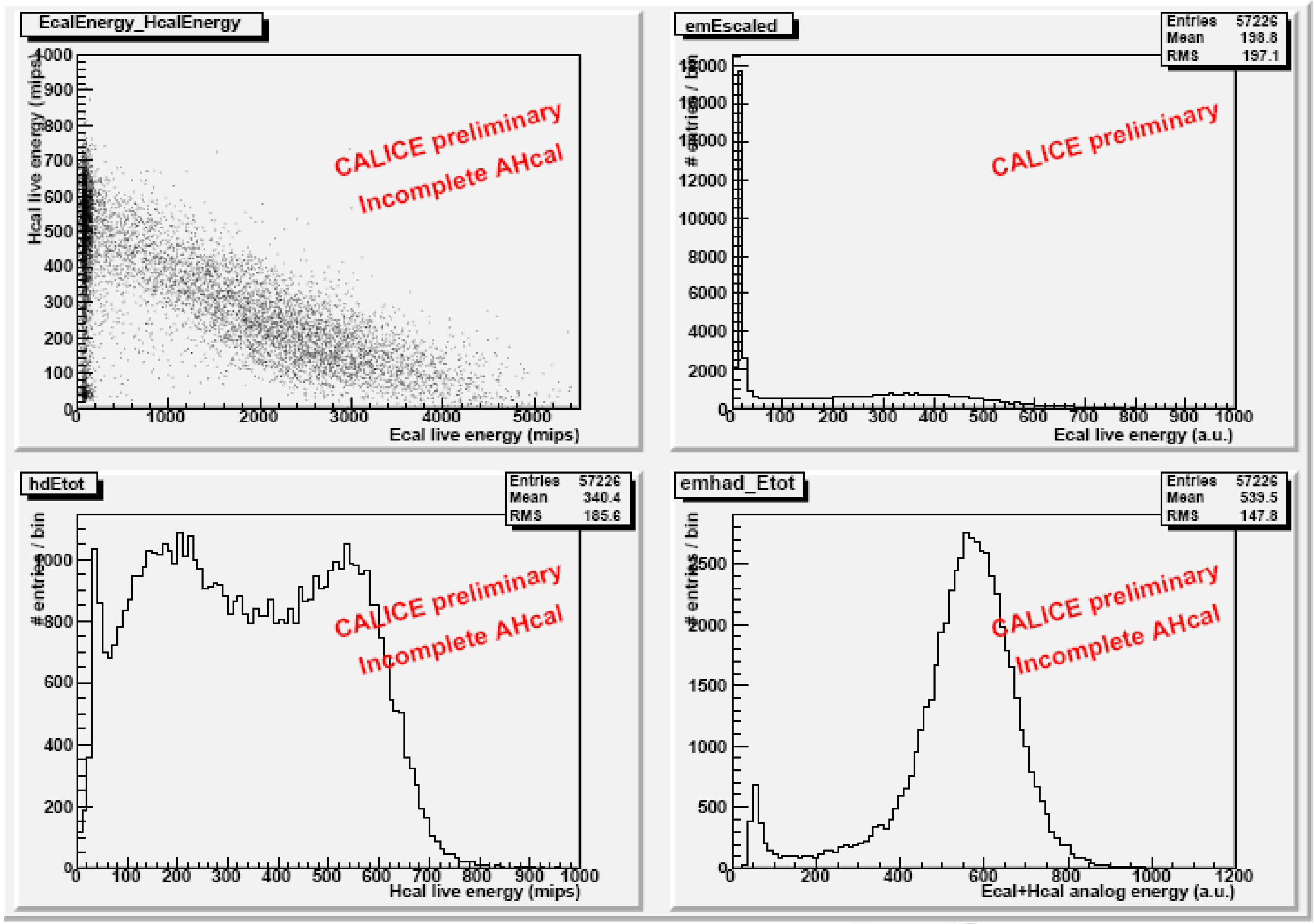




First interaction layer

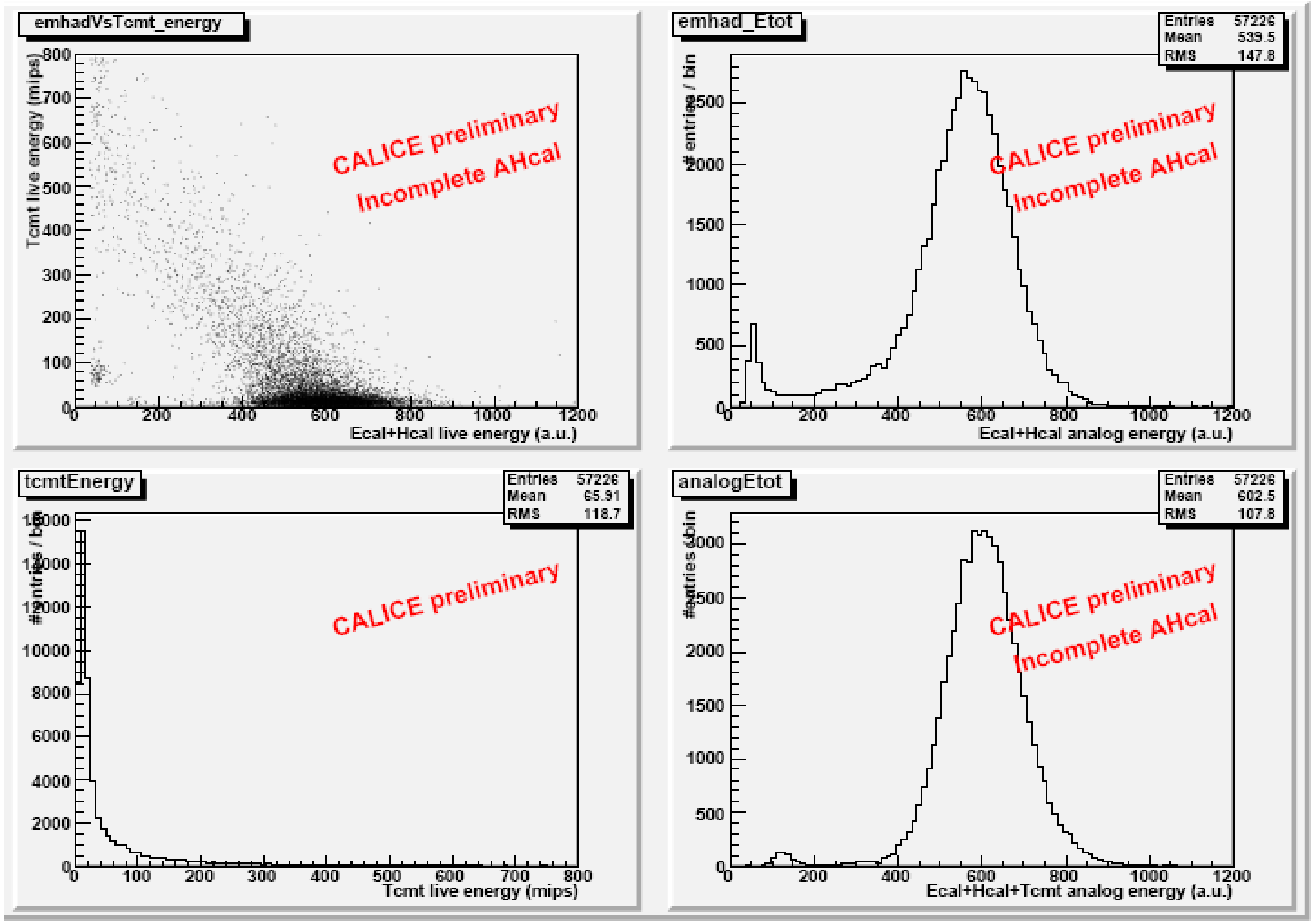
Combined ECAL/AHCAL/TCMT analysis

Correlate ECAL and AHCAL energies. 20 GeV π^-



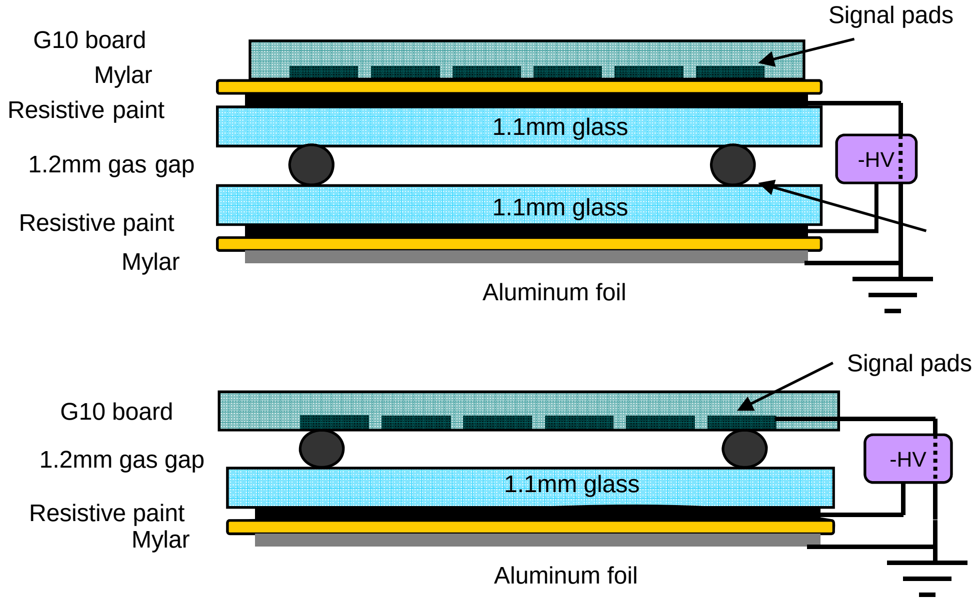
Combined ECAL/AHCAL/TCMT analysis

Now correlate ECAL+AHCAL energy with TCMT 20 GeV π^-



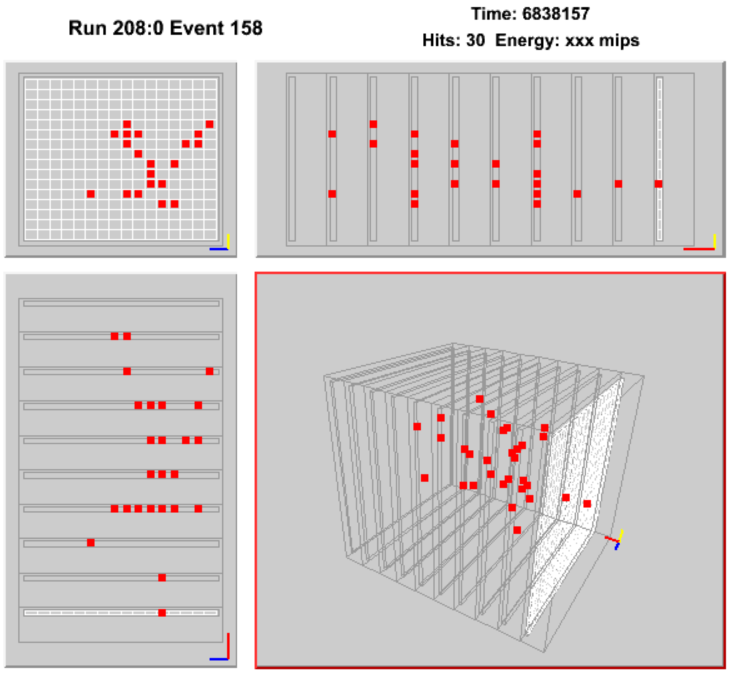
DHCAL

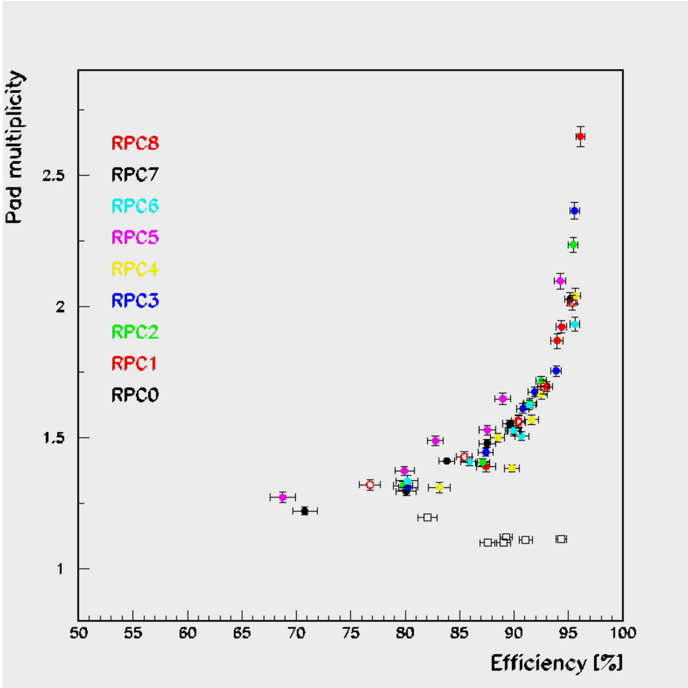
- Digital HCAL
- Basic idea – Fe-RPC stack
- RPCs - digital readout with 1x1 cm^2 pads
- Alternative technologies also being developed – GEMs or MicroMegas



- Small test stack tested at FNAL in 2007
- 9 layers, two designs of RPC, 16x16 cm^2 active area
- Now working towards a 1 m^3 stack, using same iron structure as the tile AHCAL
- Plans for test in 2009, along with ECAL, TCMT as usual.

DHCAL results





A pion shower

Muon beam – pad multiplicity vs efficiency

Noise measurements – observed especially around the fishing line spacers. At the default setting the rate measured ~ 0.1 Hz/cm^2

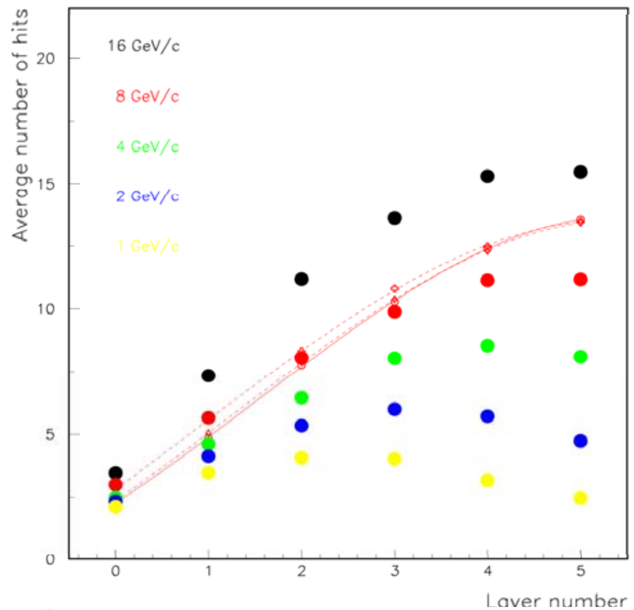
DHCAL – electron showers

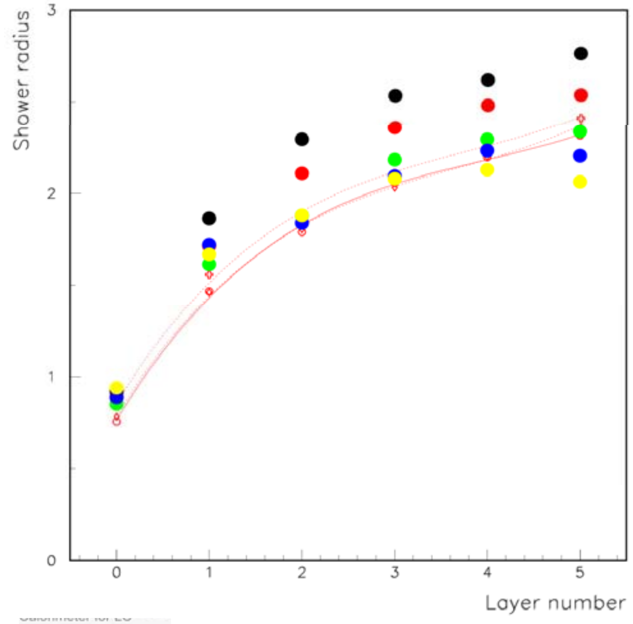
•Calorimeter ~9 X_0 : showers not confined.
•Can still compare with simulation.

•**MC simulation**:

- •Get (x,y,z) of each energy deposit in the active RPC gaps
- •Generate charge from *measured* charge distribution
- •Introduce cutoff to filter close-by energy deposity
- •Noise hits are ignored
- •Distribute charge according to exponential distribution
- •Tune parameters on muon data; tweak two-particle cutoff using positrons.
- •Apply threshold to pad energies → digital hits.

•Compare data with simulation at 8 GeV
•PRELIMINARY
•Longitudinal shower shape reasonably OK? Some indication of upstream material.
• r.m.s. shower radius – still some discrepancy at present.





Future prospects

- A lot of the work so far on electron/muon data, to understand detector performance and its relaitionship to Monte Carlo in a clean environment
- In the future - much more on hadronic showers; detailed substructure of showers.
- Fermilab 2008 run has taken lots of low energy hadron (and electron) data.
- Many more comparisons with various physics lists in GEANT4
  - Possibly working towards creating new physics lists to better represent the CALICE data
- Correlation between ECAL/HCAL/TCMT and combination to optimise performance
- Results from ScECAL and comparison wth Si-W.
- Combined tests of $1m^3$ DHCAL prototype.
  - Validate ideas of digital calorimetry.
- Test PFAs on text beam data; simulate double shower environments by combining pairs of events, etc.