GEANT4 Physics Validation using the CMS HCAL Test Beam Experiment

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FNAL PAC Workshop

Outline

- Introduction to the CMS HCAL 2002 test beam experiment (TB02)

- OSCAR2-GEANT4 simulation of TB02

- Pion energy resolution and linearity measurements from TB02 data

- GEANT4 physics validation: impact of MC/data discrepancies on calibration

HB Calorimeter (central)

Sampling calorimeter: brass (passive) & scintillator (active)

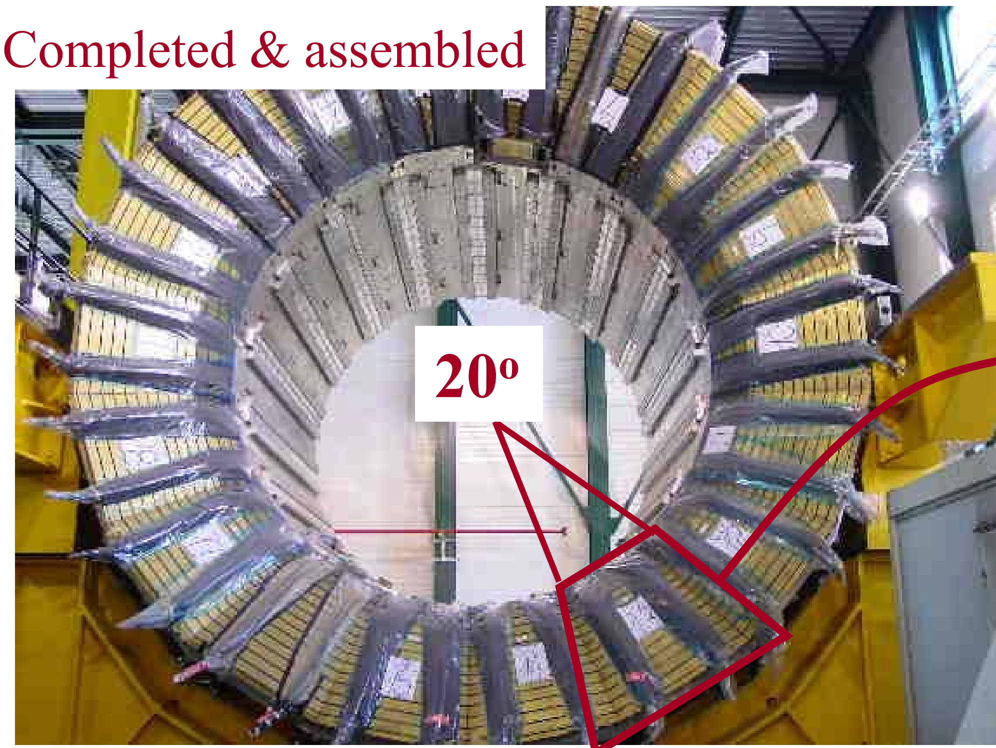
Coverage: $|\eta|<1.3$

Depth: $5.8\ \lambda_{int}$ (at $\eta=0$)

π resolution: $\sim 120\ \%/\sqrt{E}$

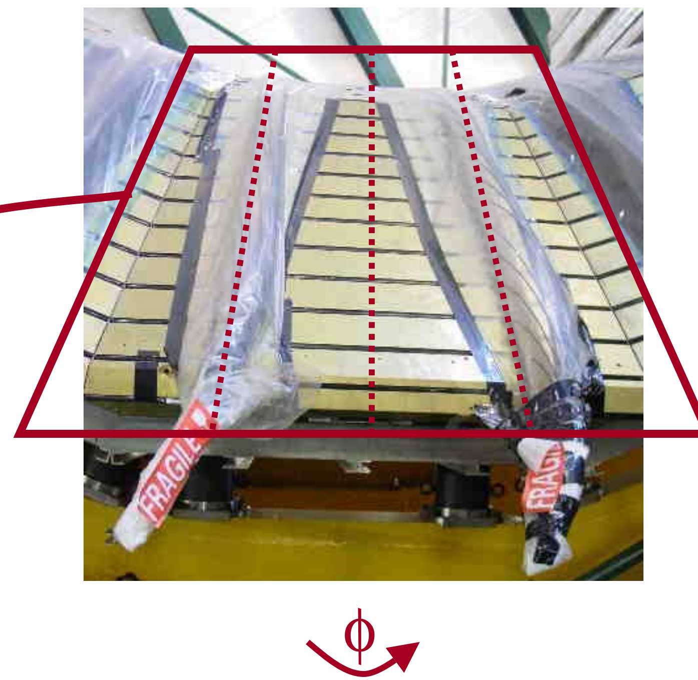
segmentation: $\phi \times \eta =$ 0.087x0.087

Completed & assembled



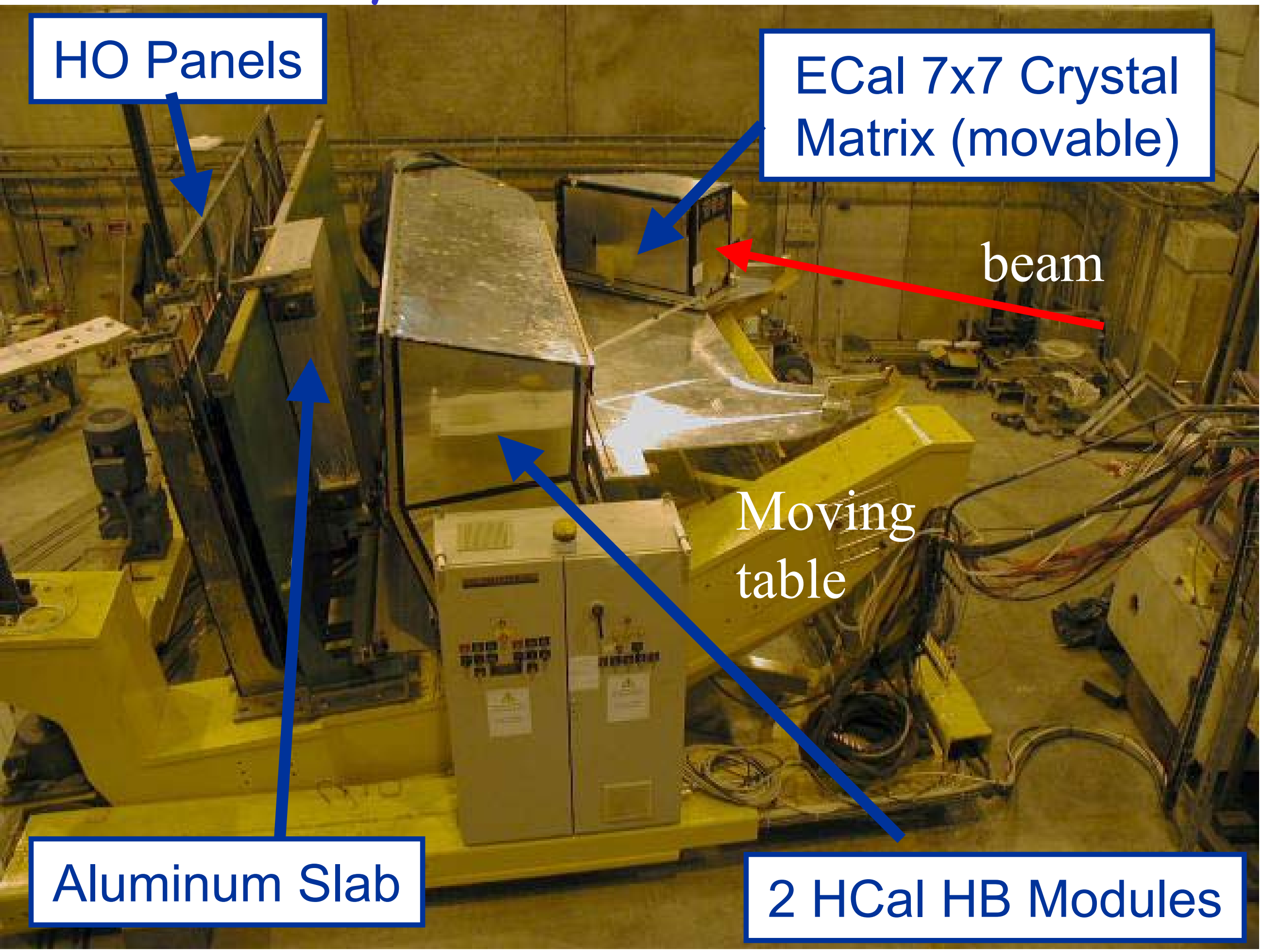
17 layers longitudinally,

$\phi \times \eta = 4 \times 16$ towers



HCAL 2002 Test Beam

Small scale experiment to demonstrate that HCAL works:
49 ECal crystals, 144 HB channels, 16 HO channels.



Over 100 Million Events!

μ^-: 225 GeV
e^-: 20,30,50,100 GeV
π^-: 20, 30, 50, 100, 300 GeV

Read out with a 29.6 ns period

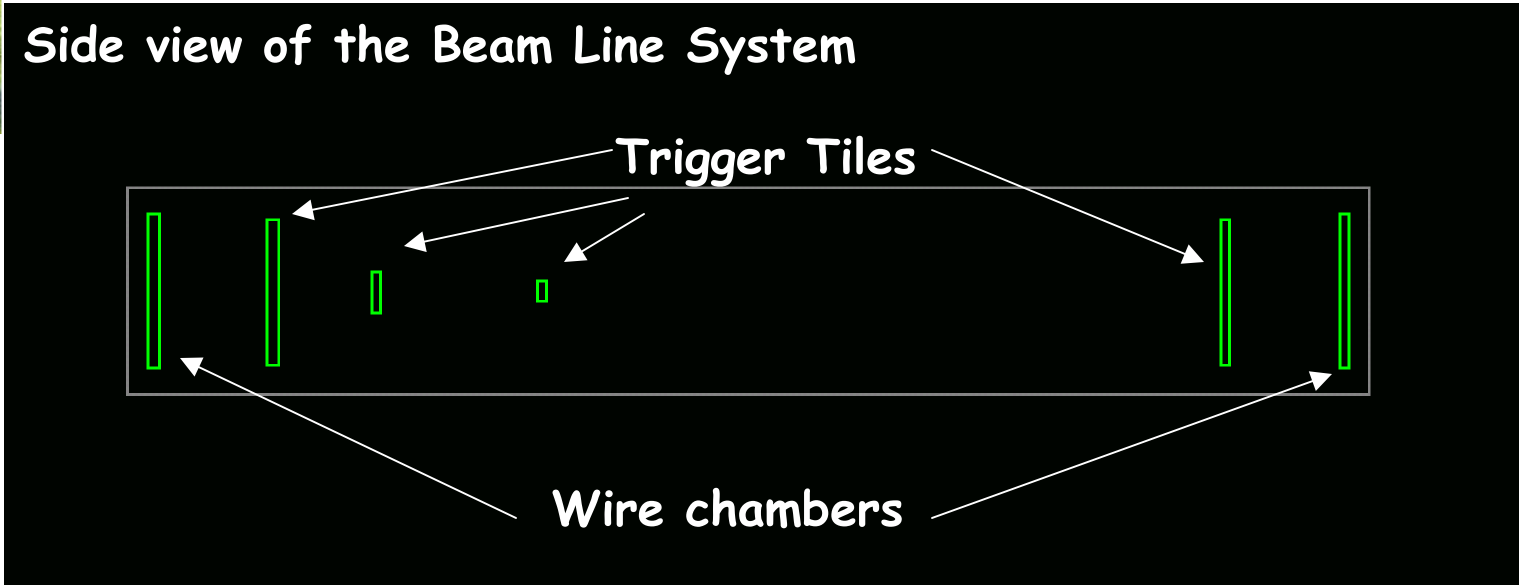
GEANT4 Simulation

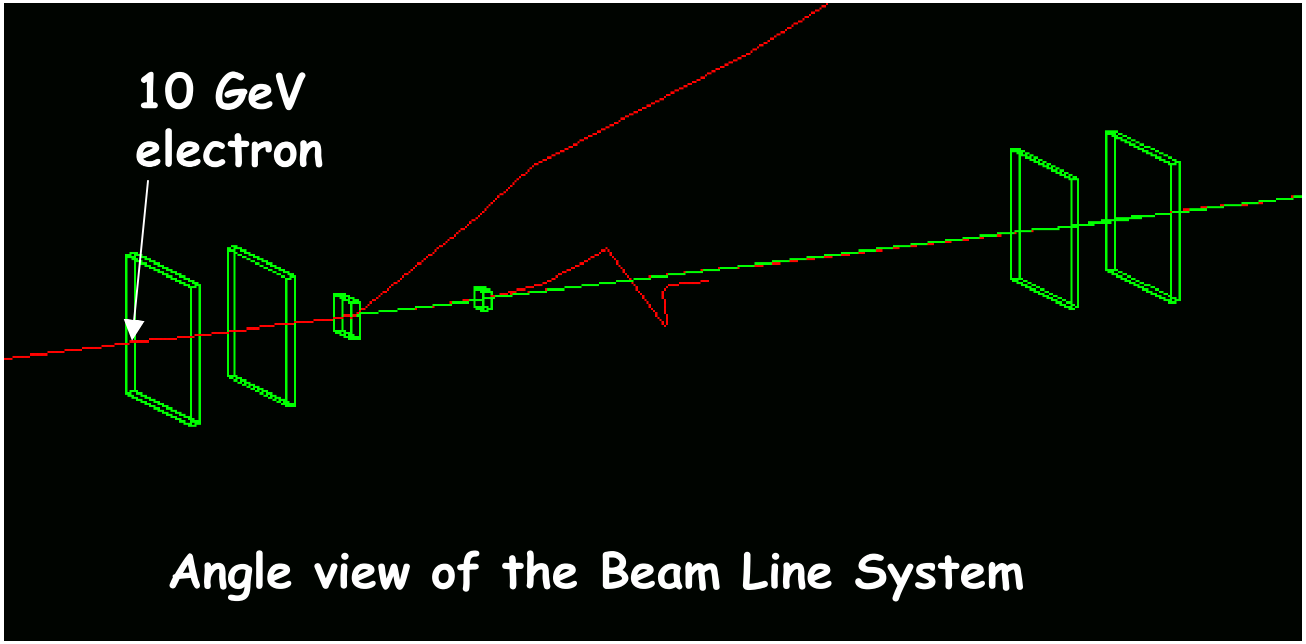
Use OSCAR_2_4_5 (G4.5.2), LHEP-3.6, QGSP-2.7
(HcalTB02 has been released as an OSCAR2 example)

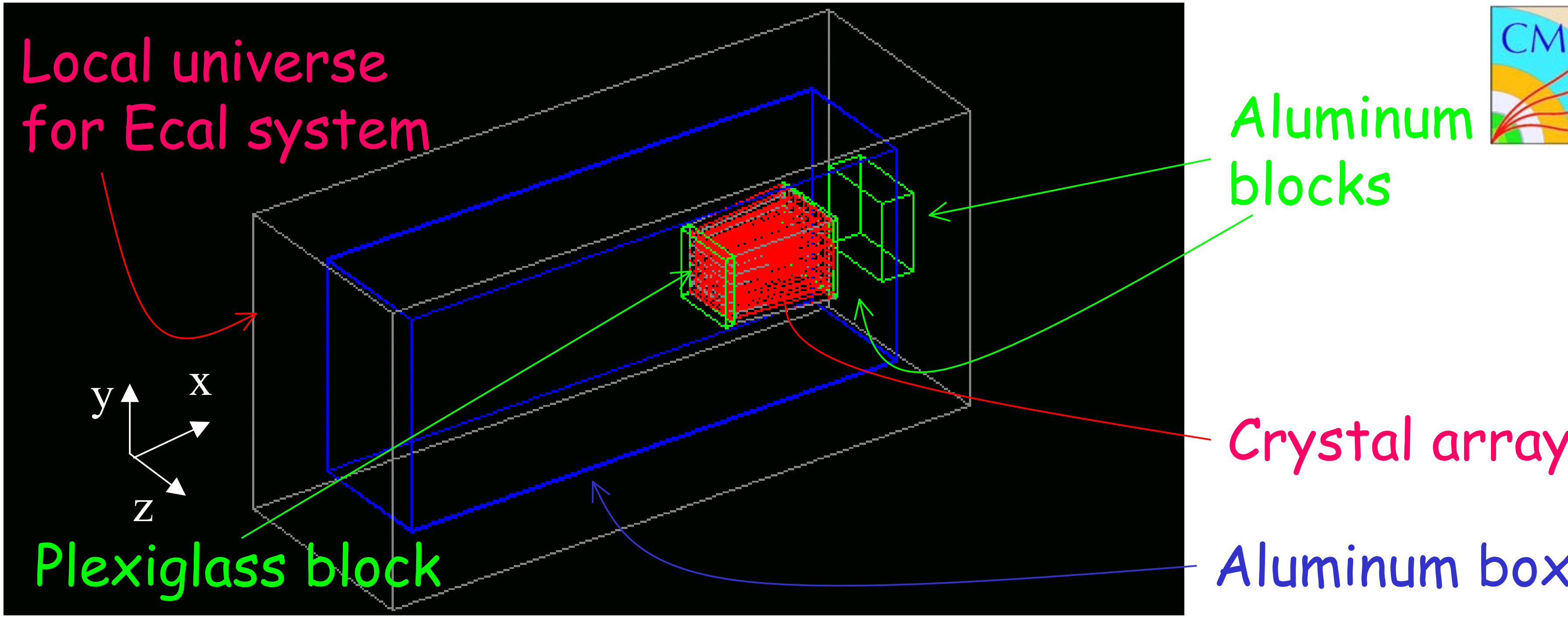
Oscar: CMS simulation framework
GEANT4: is the OO C++ version of the detector simulation tool kit GEANT3
LHEP: GEANT4 physics list constructed from parameterizations of data from experiments.
QGSP: GEANT4 physics list constructed from theoretical models.

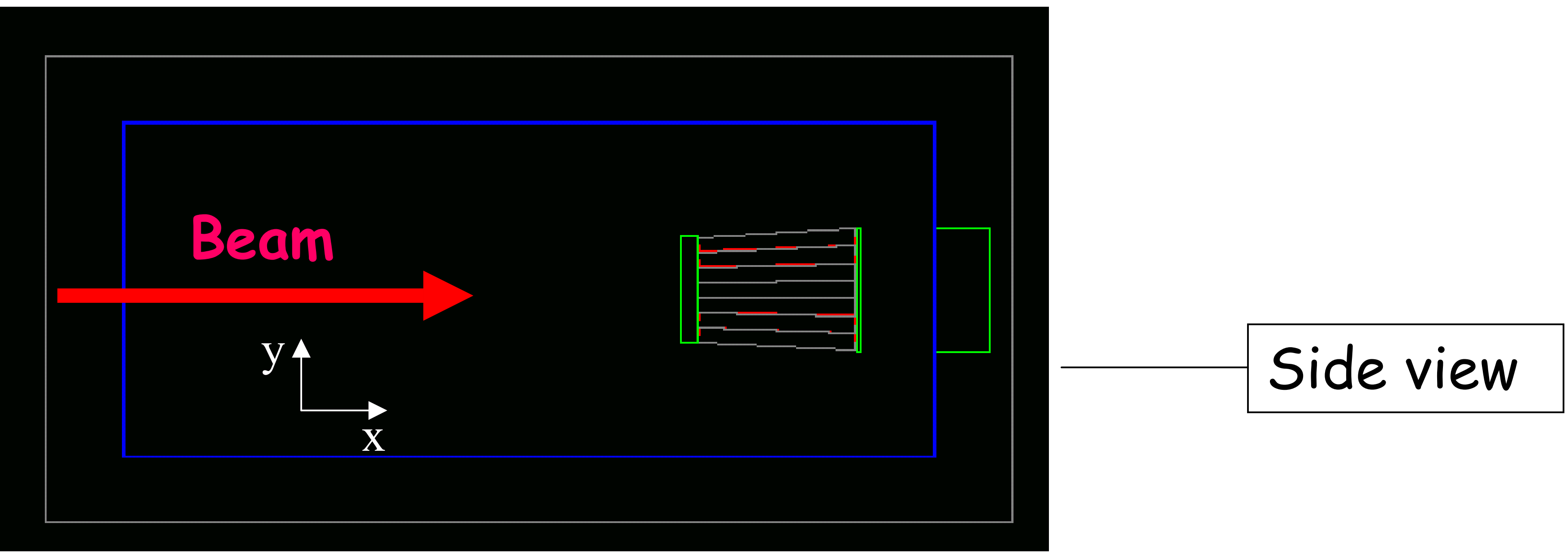
The HcalTB02 simulation consists of:

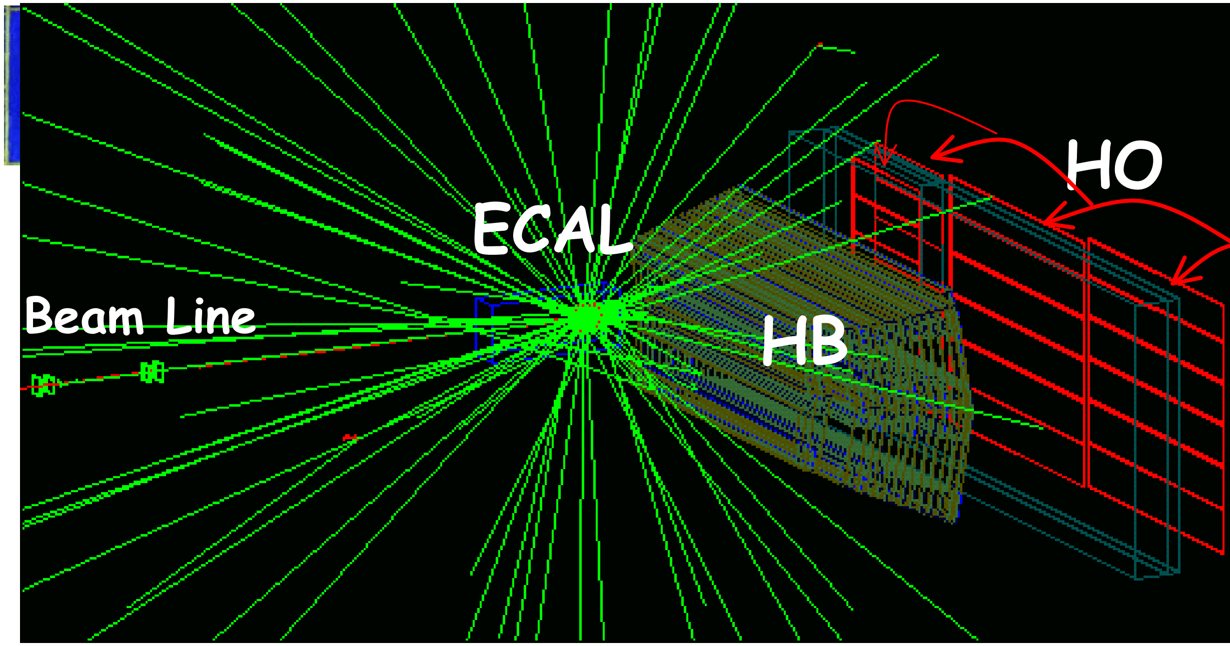
- Beam Line System (trigger tiles & wire chambers)
- ECAL box (Crystal Matrix sub-system)
- HCAL Barrel
- HO
- Allow translation & rotation of both BL & ECAL box
- Root analysis package


Side view of the Beam Line System
Trigger Tiles
Wire chambers


10 GeV
electron
Angle view of the Beam Line System


Local universe
for Ecal system
Aluminum
blocks
Crystal array
Aluminum box
Plexiglass block
y
x
z

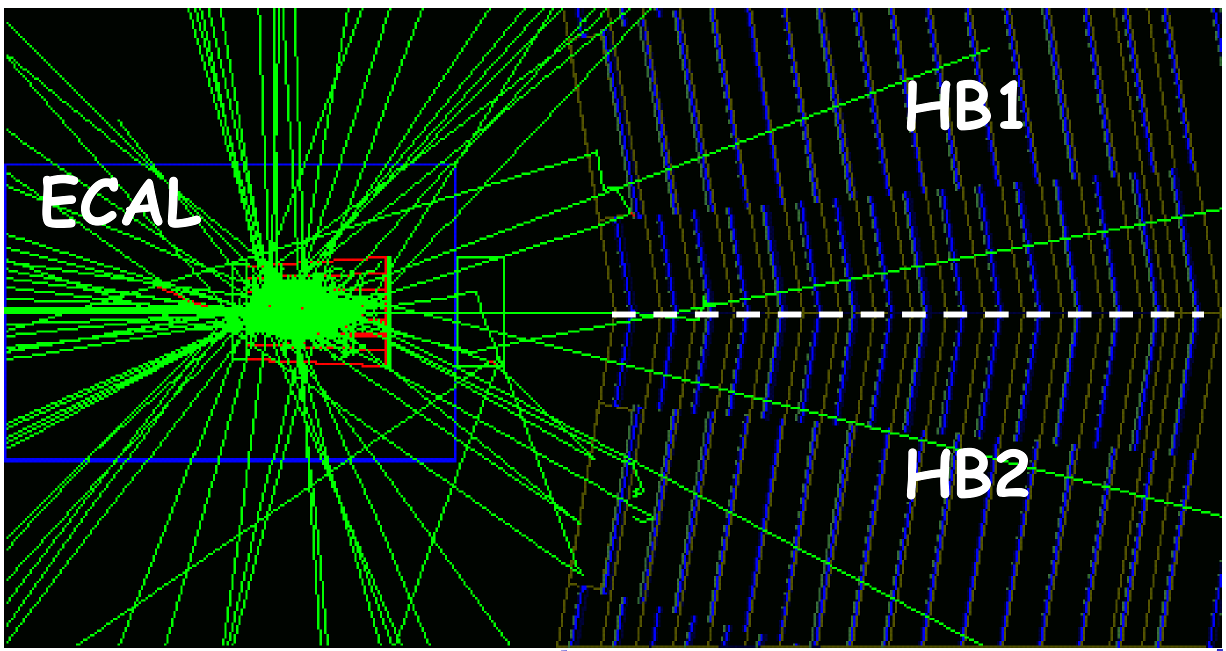

Beam
y
x
Side view



Angle view of the full TB02 detector

10 GeV electron

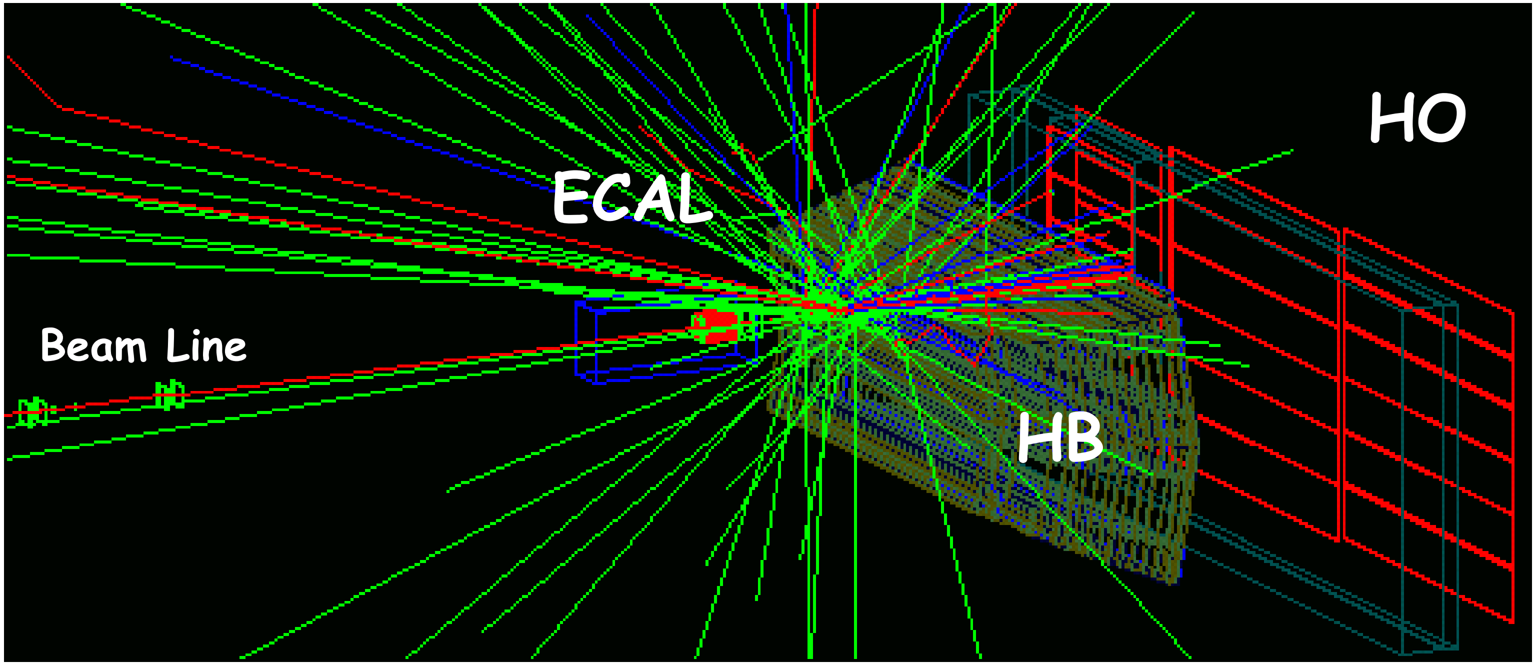
2 (1) layers of scintillator (red)



Side view of the eCal & HB sections of the TB02 detector

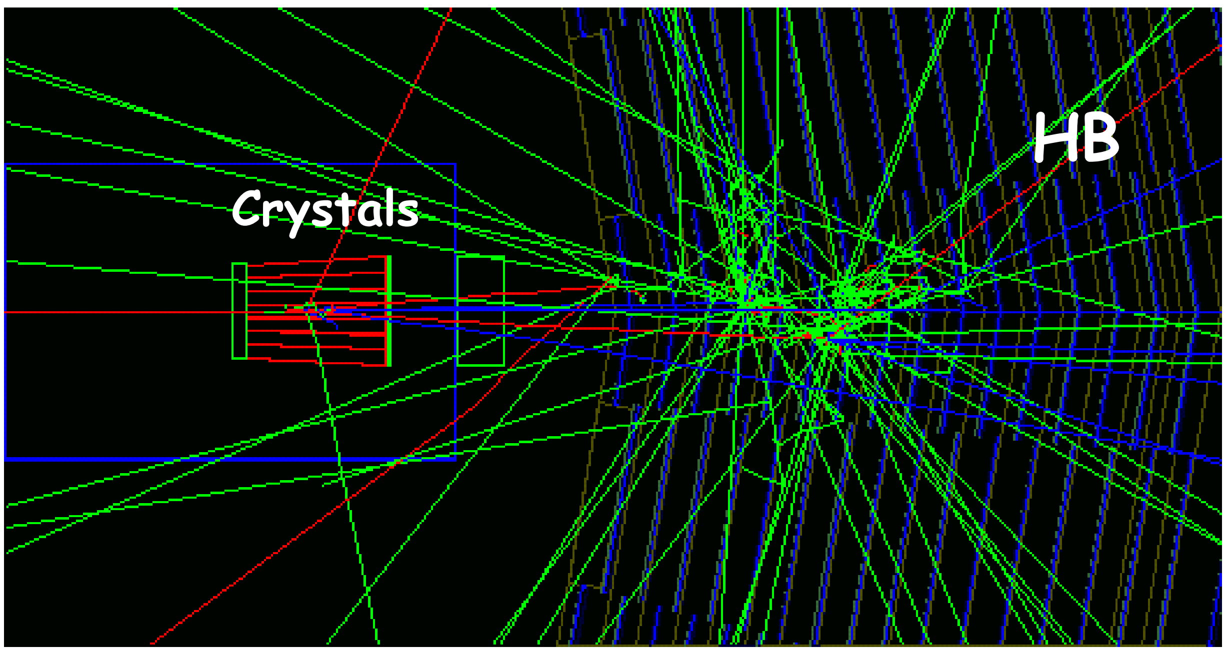
10 GeV electron

17 layers of absorber + scintillator (blue)



Angle view of the full TB02 detector

100 GeV pion

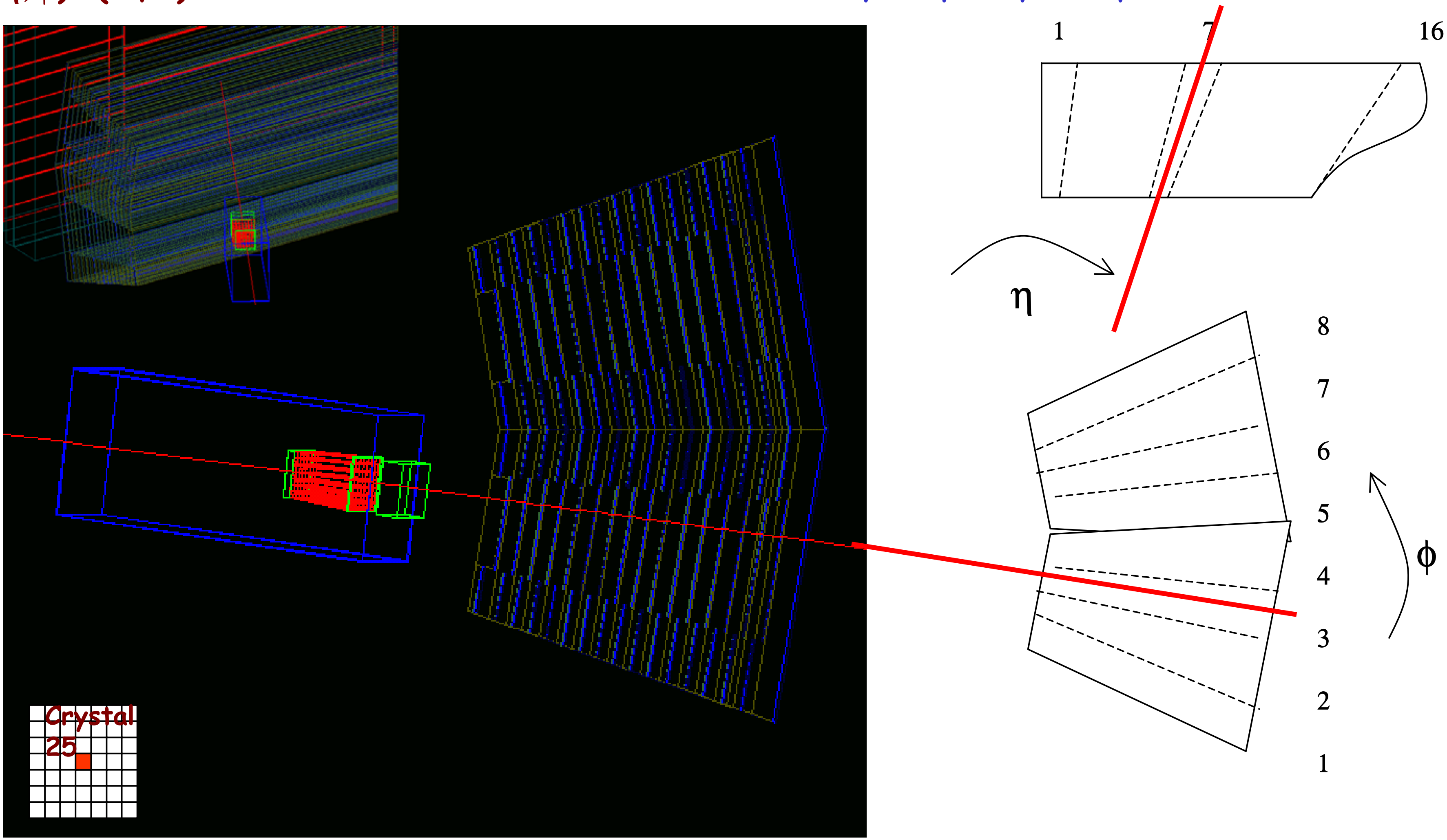


Side view of the ECAL & HB sections of the TB02 detector

100 GeV pion

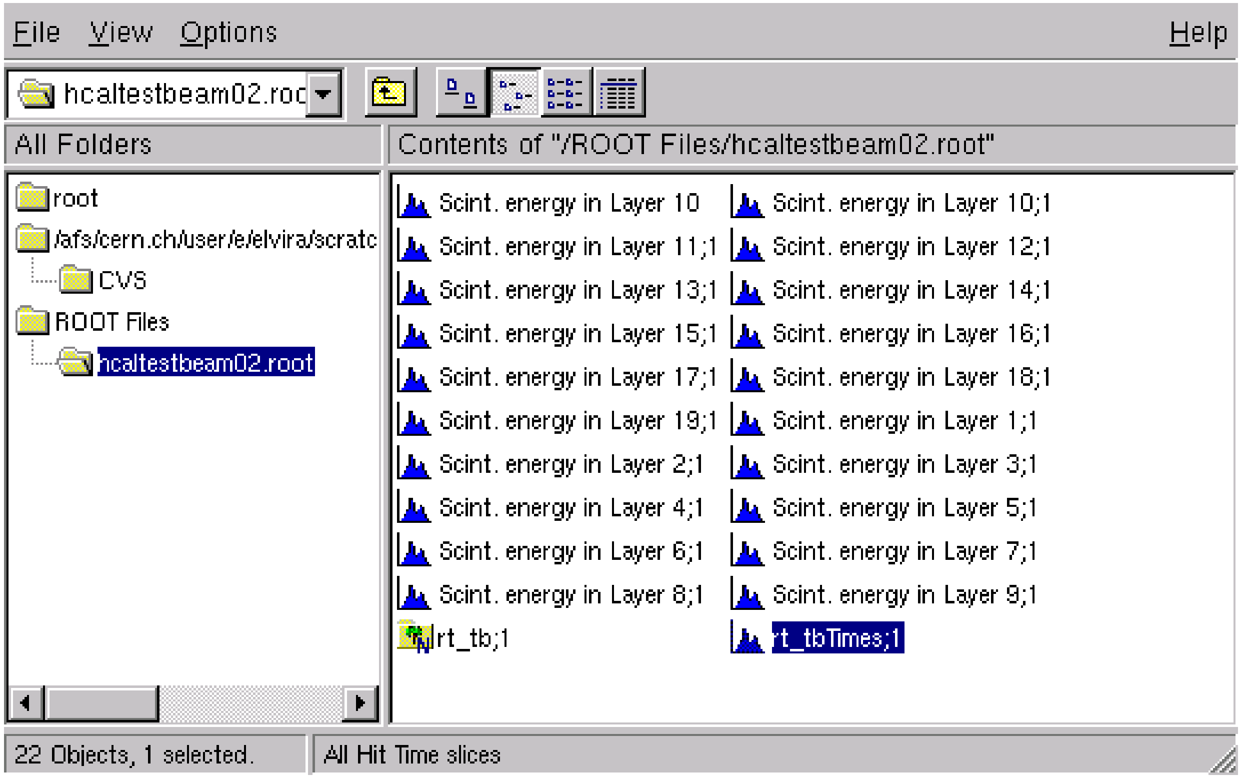
Performance Studies

Based on a beam of π^- events onto crystal 25 (central) and the $(\eta,\phi)=(9,4)$ tower of the HB. Pion beams: 20, 30, 50, 100, 300 GeV.



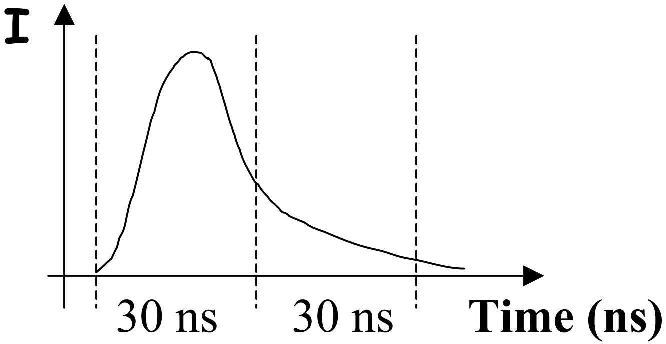
Analysis Package

A ROOT based analysis package is included in the TB02 OSCAR simulation:



Stat. histos (energy per layer), event ntuple with scintillator energy info including energy in 5x5 scint. super-tower, etc.

Readout & Calibration



-In the TB02 experiment there was no longitudinal segmentation (one pulse per tower)

- The signal was integrated over four 30 ns time slices (the whole signal).

Did not simulate the pulse shape

- π Calibration: Add up the scintillator energy in a η×φ=5x5 super-tower (like in the TB experiment). Calibration factor is E_{ini}/E_{5x5} taken from 50 GeV π on tower (η,φ)=(9,4) in an HB only configuration.

  50 GeV pions deposit 425 MeV in a 5x5 HCAL scintillator supertower about the (9,4) central: 0.85%

  Calibration factor is: 117.7

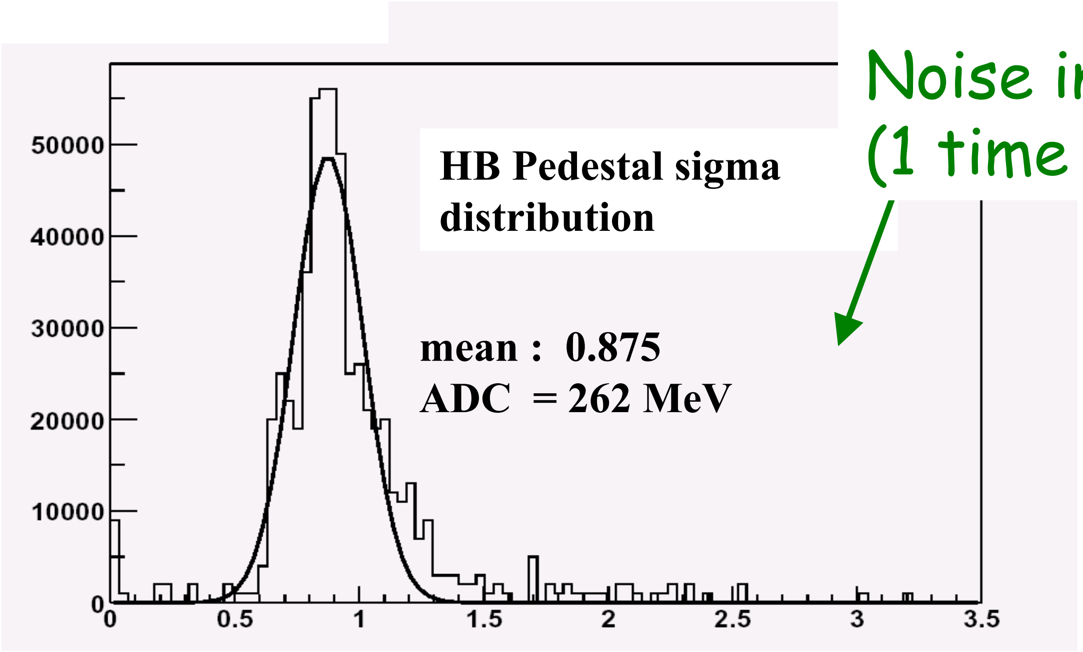
- π Response: with respect to 50 GeV for 20-300 GeV π (linerarity)
- π Resolution: determine energy resolution as the width of the calibrated super-tower energy distribution.

Noise Simulation

$E^{ECal}_{tower} \rightarrow E^{ECal}_{tower} + 115\ MeV * Rand$ ← Elect. Noise, pulse matching to measured electron resolution

$E^{HB}_{scint} \rightarrow E^{HB}_{scint} + 0.1 * E^{HB}_{scint}\ MeV * Rand$ ← Long. Non-uniformity (?)

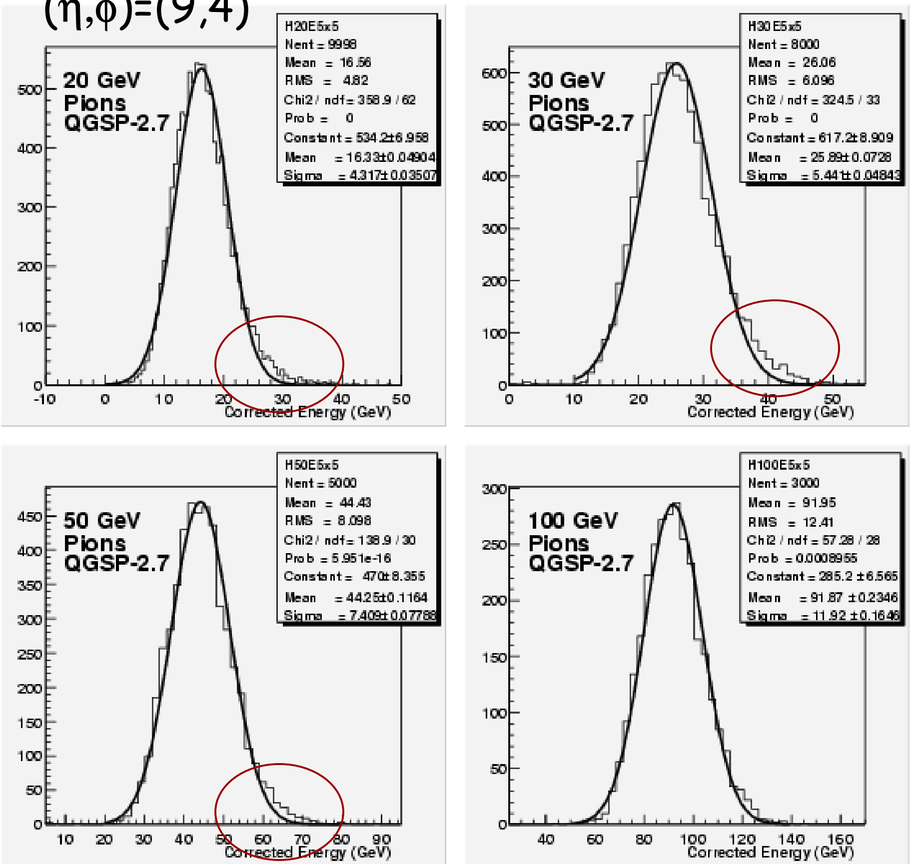
$E^{HB}_{tower} \rightarrow E^{HB}_{tower} + 524\ MeV * Rand$ ← Elect. Noise (4 time slices, *was 2 before*)

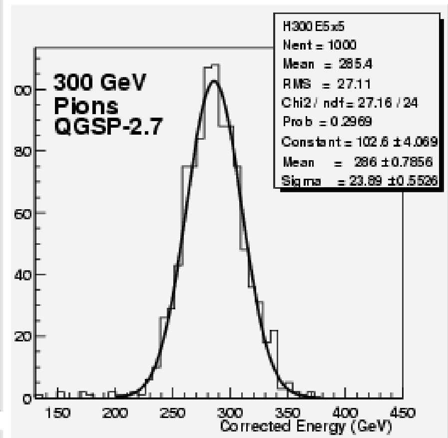


Noise in HB (1 time slice)

Response Functions

(η,φ)=(9,4)





QGSP-2.7

Low energy π: long high energy tail,as expected for a non-compensating calorimeter (non-Gaussian behavior)

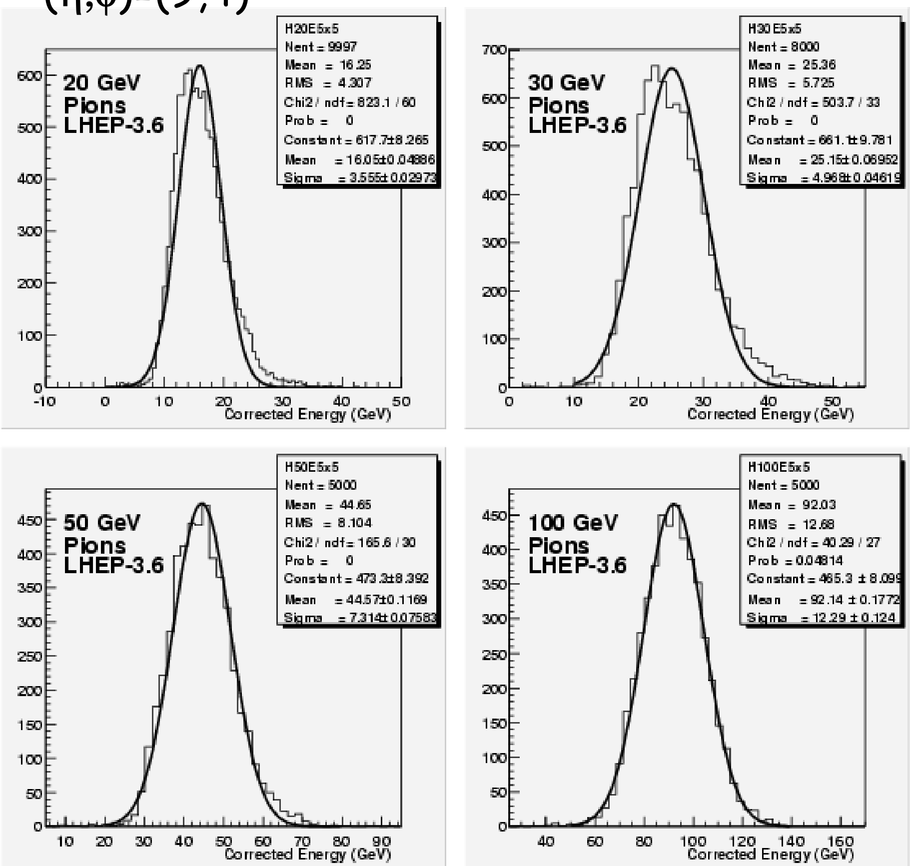
e/h (ECAL) = 1.6

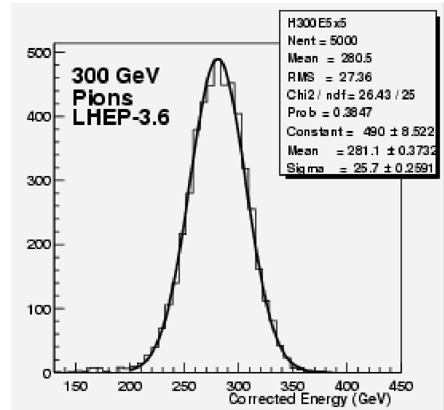
e/h (HCAL) = 1.39

How do I define resolution?
Initially, fit a Gaussian function to the distributions because that's what was done in the data.

Response Functions

(η,φ)=(9,4)





LHEP-3.6

Low energy π: long high energy tail,as expected from a non-compensating calorimeter (non-Gaussian behavior)

e/h (ECAL) = 1.6

e/h (HCAL) = 1.39

Plan to compare both Gaussian and RMS extracted resolutions in data and simulation – have only σ for now

TB02 Data Analysis: Linearity & σ_E/E

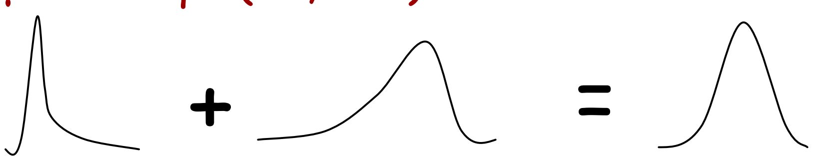
Measure (TB02) energy resolution and linearity for 20, 30, 50, 100, 300 GeV pions. Sources of systematic uncertainties:

- Backgrounds (muons, electrons) - <u>large effect at low energy</u>

  cuts in (E_{HCal},E_{ECal}) space: nominal, high, low.

- HCal calibration from 50 GeV MIP in ECAL – <u>small</u>

  - ECAL/HCAL energy "mix":
  - Background in 50 GeV distribution
  - $\Delta\langle\mu\rangle = \sigma/\mathrm{sqrt}(10{,}000) = \sigma/100$



E_{HB} + E_{ECal} = E_{Tot}

$E_{Tot} = f_{HB} * E_{HB} + f_{ECal} * E_{ECal}$

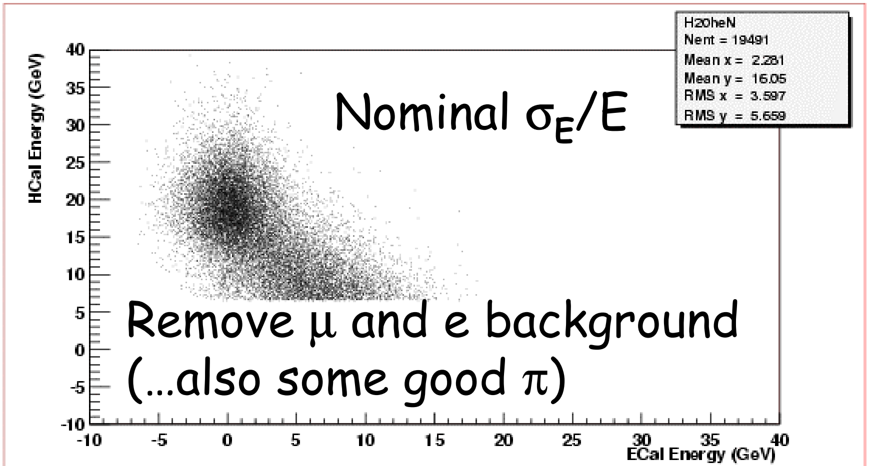
- Choice of HCal calibration point – <u>It's not an uncertainty but part of the calorimeter tuning</u>

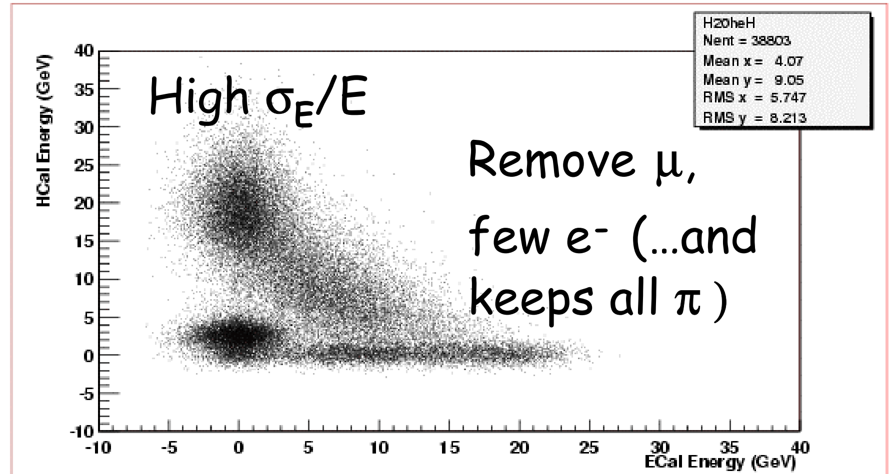
resolution depends on the calibration "point" due to HCal non-linearities

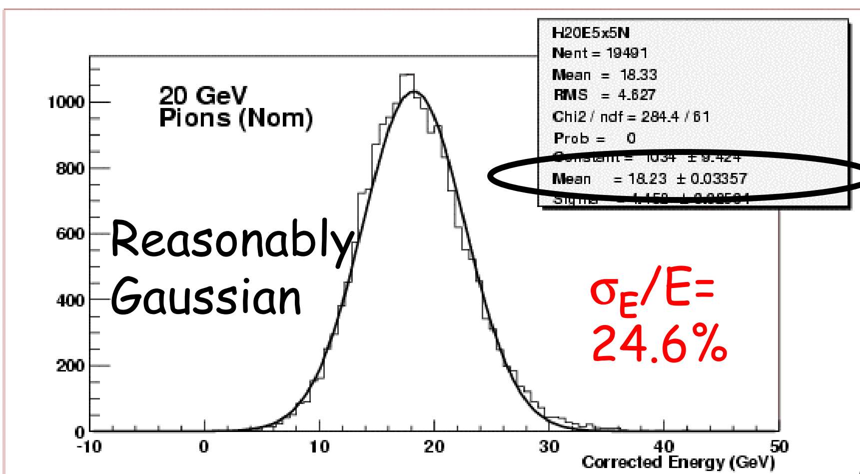
Bkgnd subtraction (20 GeV)

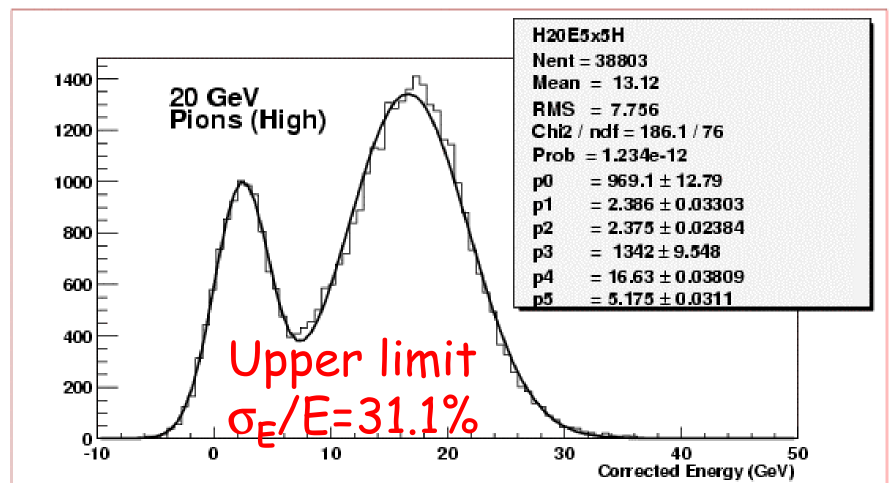
Cut: E_{HB}>6.5 GeV && (E_{HB} > -0.83*E_{em}+ 5.17)

No cuts: double Gaussian gives upper limit)









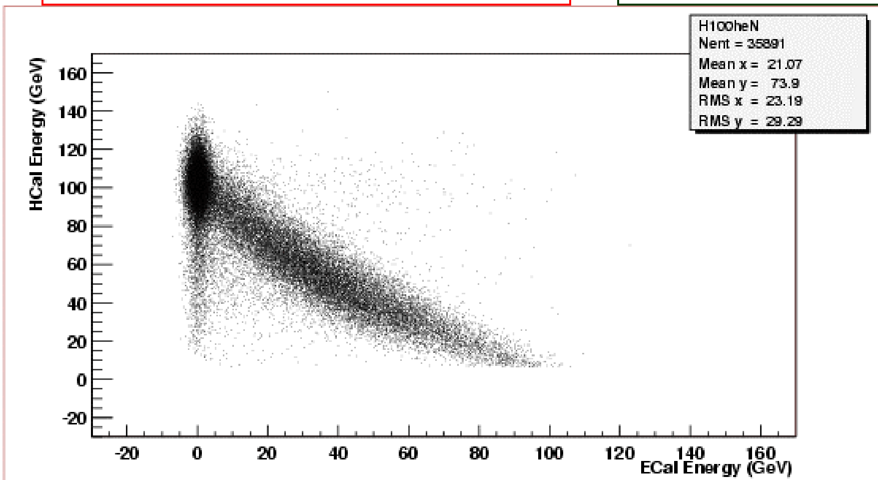
mean~18.2 GeV

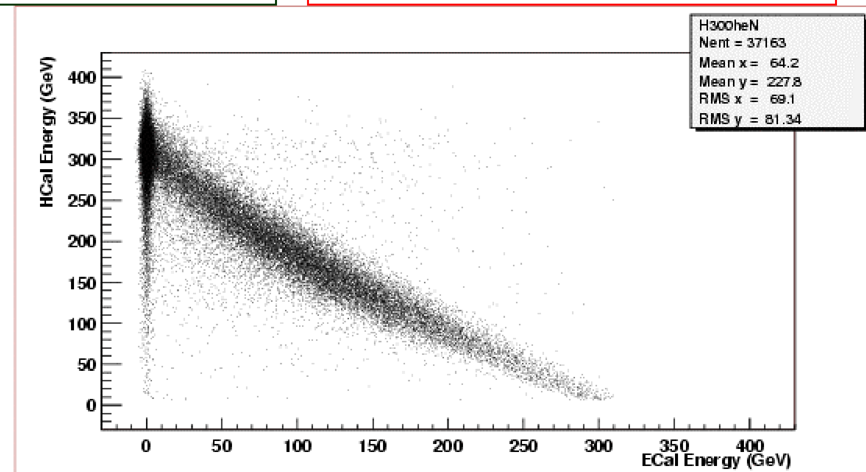
Bkgnd subtraction (100/300 GeV)

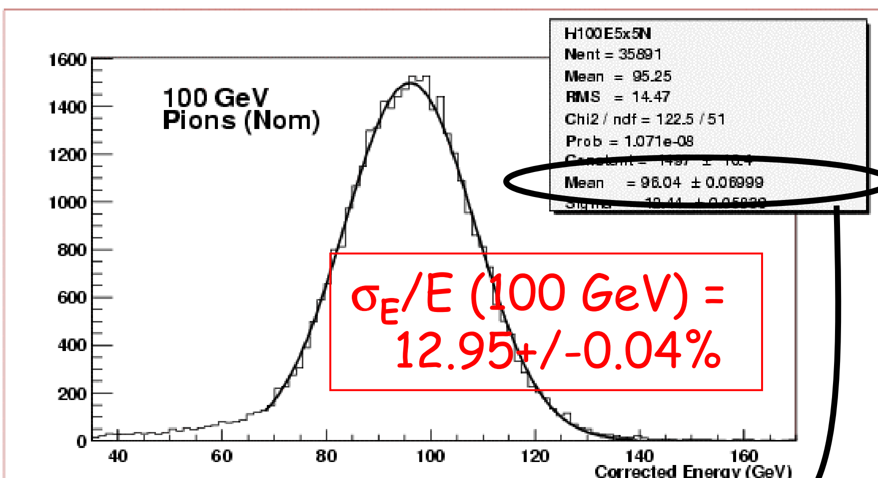
Resp (100 GeV) = 0.9604+/-0.0003

Cut: E_{HB}>6.5 GeV && (E_{HB} > -1.*E_{em}+ 12.7)

Resp (300 GeV) = 0.9823+/-0.0003

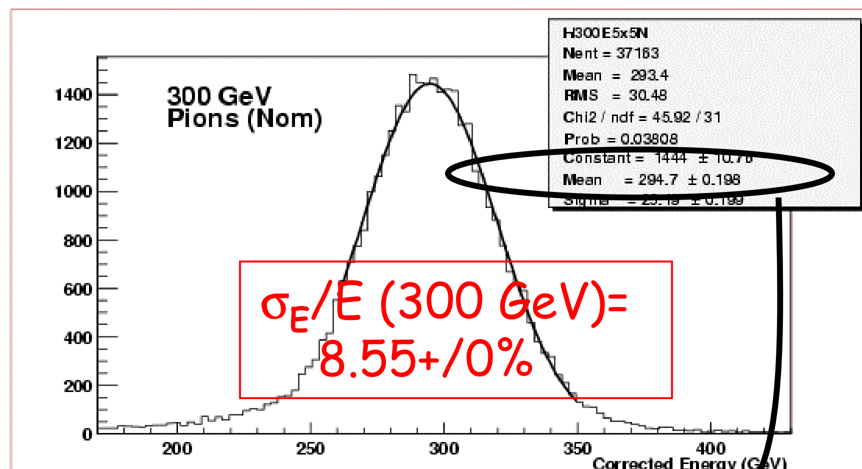






σ_E/E (100 GeV) = 12.95+/-0.04%

mean ~96.04 GeV

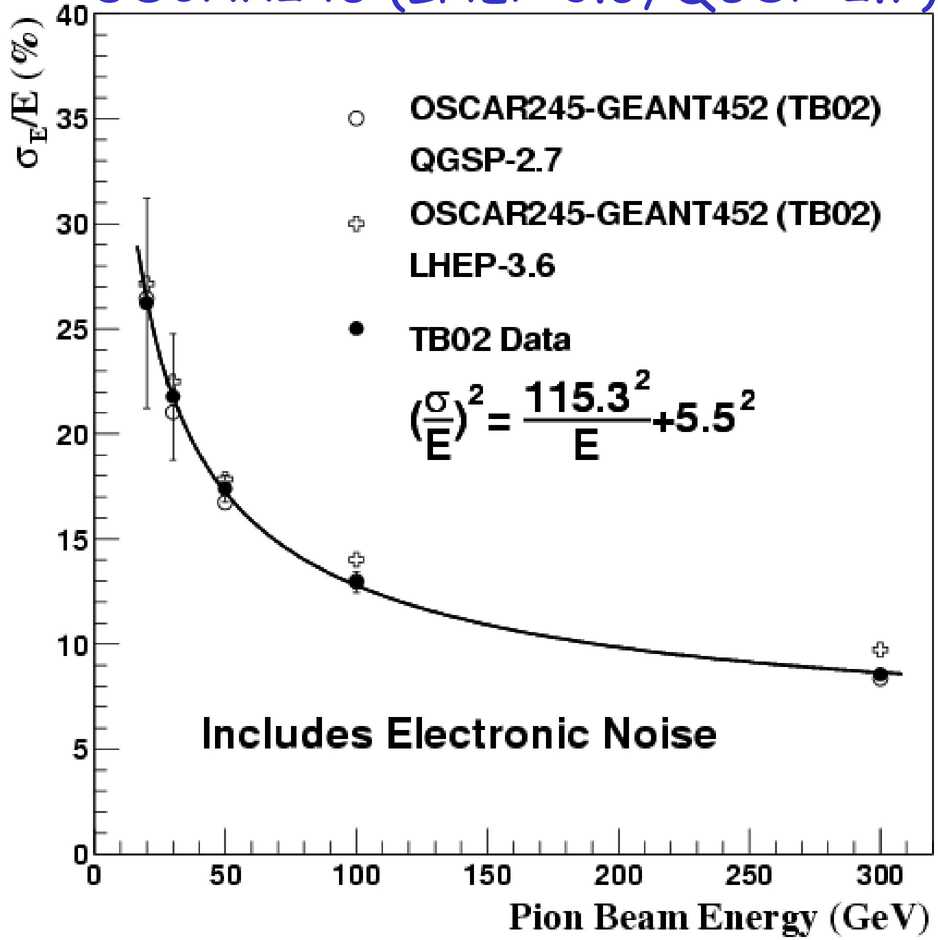


σ_E/E (300 GeV)= 8.55+/0%

mean ~294.7 GeV

Pion Energy Resolution

OSCAR245 (LHEP-3.6, QGSP-2.7)



Data — Syst.

E	σ_E/E(%)	stat	bkgnd	calib
20.	26.22	0.15	5.00	0.1
30.	21.76	0.12	3.00	0.2
50.	17.40	0.10	0.60	0.2
100.	12.95	0.07	0.40	0.3
300.	8.55	0.05	0.00	0.3

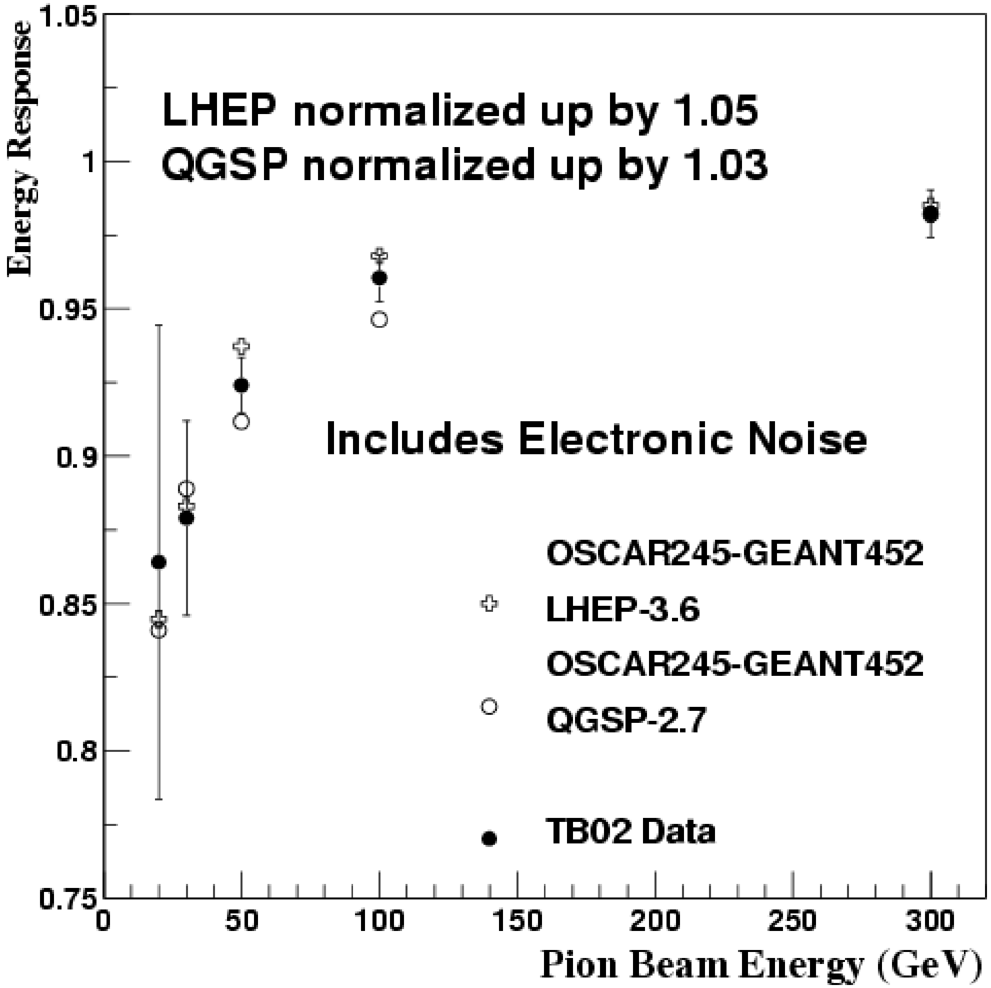
Syst. Errors 100% correlated in Energy, uncorrelated with each other (added in quadrature)

Good agreement in resolution

(LHEP a little higher than data)

Pion Energy Linearity

OSCAR245 (LHEP-3.6, QGSP-2.7)



Syst.

Data

E	σ_E/E	stat	bkgnd	calib
20.	0.8640	0.0015	0.0800	0.008
30.	0.8790	0.0010	0.0320	0.008
50.	0.9240	0.0010	0.0050	0.008
100.	0.9604	0.0007	0.0003	0.008
300.	0.9823	0.0004	0.0003	0.008

Syst. Errors 100% correlated in Energy, uncorrelated with each other (added in quadrature)

Good agreement in linearity

(LHEP/QGSP grows a little faster/slower than data)

Summary on Simulations

- Simulation now runs under OSCAR2, it is part of the official release.
- Data analysis includes systematic uncertainties to allow validation.

Validation studies (resolutions, linearity) using LHEP-3.6 & QGSP-2.7 (TB02-OSCAR245) are completed.

GEAN4 showers shorter than GEANT3 and TB data ?

Longitudinal and transverse profiles will be generated for comparison with the upcoming HCAL TB 2004 experiment (measure longitudinal profiles and pions with E>2 GeV).

Still need to take a look at σ versus RMS resolutions and tune a $\chi 2$ test analysis package (for when we have low energy pions and smaller systematic uncertainties).

Simulation and Calibration (I)

From the D0 experience, what work should we do **NOW** on CMS detector simulations to achieve a high level of accuracy in the Jet Energy Scale (JES) ? 1% for what sample, at what energy & η ?

To first order, JES is derived from collider data at D0:

$$E_{jet}^{ptcl} = \frac{E_{jet}^{meas} - O}{R_{jet} \, S_{cone}}$$

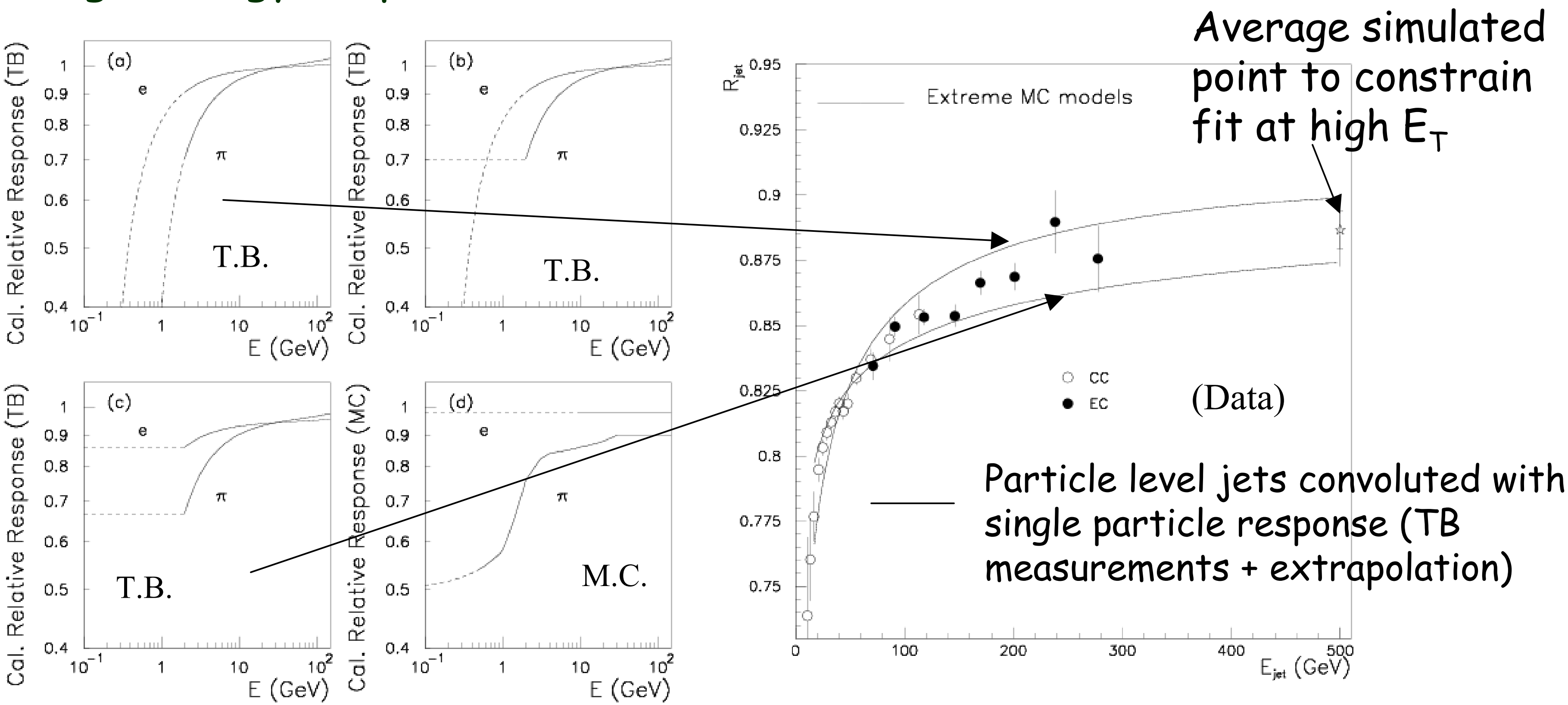
O: offset (u.e., noise, multiple interactions)
R_{jet}: calorimeter response to jets
S_{cone}: out-of-cone showering

Simulations, however, were used directly or indirectly in the derivation of many pieces of the JES correction.

Examples: high energy response, energy leakage, showering correction.

Simulation and Calibration (II)

- High energy response

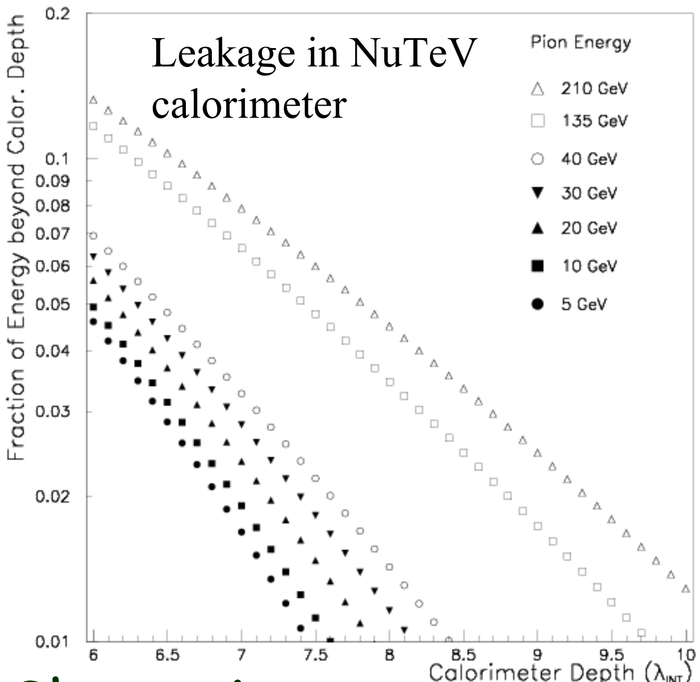


No D0 TB measurement for e and π below 2 GeV. <u>Extrapolations:</u> flat-flat, flat-decreasing, decreasing-decreasing

Look at the different R_{jet} energy dependence from different models! (in the 20-200 GeV region)

Simulation and Calibration (III)

- Energy leakage effect on response



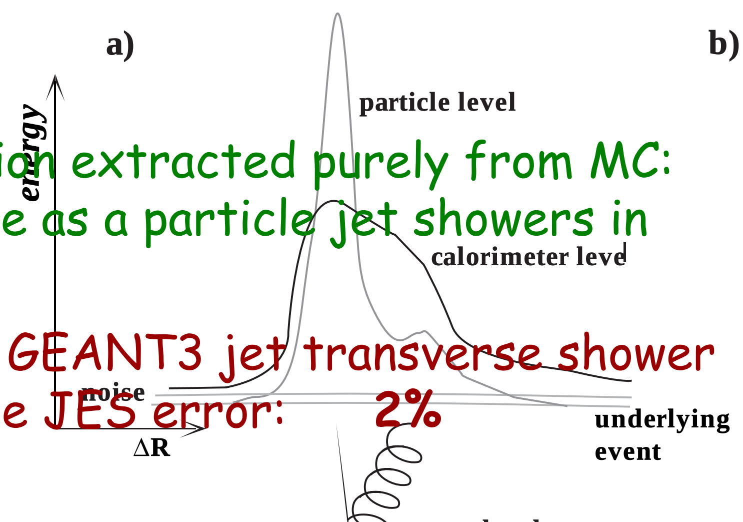
Response at high E_T (>100 GeV) extracted from EC response (γ-jets) normalized to CC measured response (assuming same shape).

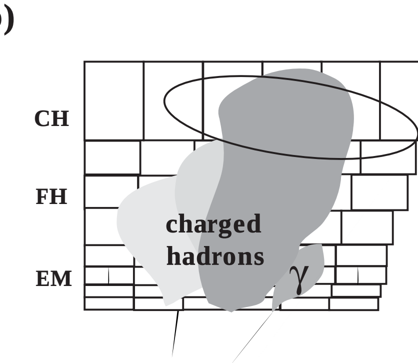
Residual mis-calibration uncertainty due to different leakage in the CC (7.2 λ_I) and the EC (11 λ_I) derived from simulation.

- Showering

Latest Run I showering correction extracted purely from MC: net energy loss through the cone as a particle jet showers in the calorimeter.

Difference between the data & GEANT3 jet transverse shower shape propagated directly to the JES error: **2%**





Conclusion

- Details in the calibration methods are difficult to predict → serious optimization can only occur during first stages of collider run. (We must develop methods with M.C. early on)

- We will have many more handles than D0 or CDF to use data for calibration **but……**

  - It is a certainty that simulations will be needed in interesting M, E_T, η ranges where there are no resonances or other physics handles.
  - We will need calibrations both to the parton (Higgs) and particle levels (QCD).

A detector simulation that mimics the data to a high level of accuracy is critical for achieving the calibration goals (shower shapes, low E linearity & resolution)

Start from physics (JES accuracy needed) ➡ calibration methods (achievable accuracy) ➡ simulation quality (improve accuracy)