Geant4 Standalone Simulation Setup for HGCAL

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for the HGCAL software group

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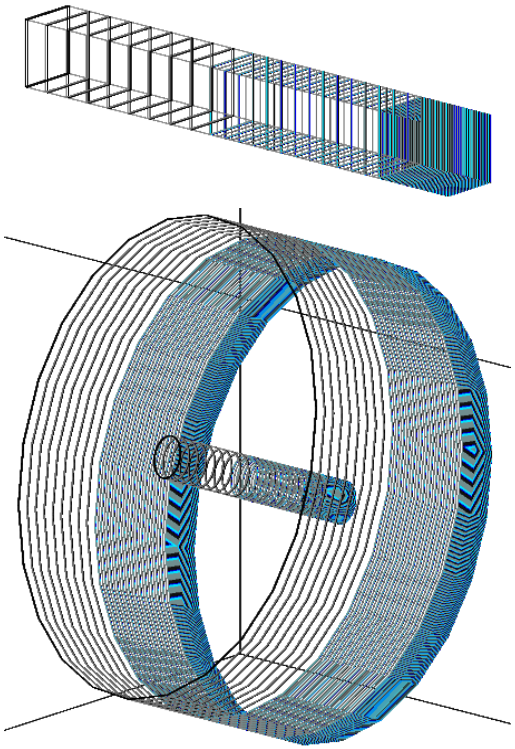
Introduction

- Standalone: Geant4 implementation external to CMSSW.
- Documentation in progress: CMS twiki HGCalPerformanceStudiesWithG4.
- Coordinate system of CMS: z along beam, y vertical.
- Several geometries now implemented:
  - Simple square front-face, 20×20 cm^2, 50×50 cm^2 and 1×1 m^2: (0,0,0) in middle of the detector
  - Full endcap: (0,0,0) of CMS, i.e. ECAL front-face at +3170 mm in z.
  - $15\,\text{cm} < \text{radius} < 170\,\text{cm} \Rightarrow 1.4 < \eta < 3.7$.



The standalone setup

- Code in git: `https://github.com/pfs/PFCal/tree/master/PFCalEE`.
- Steering parameters to easily study different designs:
  - Detector version: ECAL, ECAL+HCAL, HCAL-only, ECAL-CALICE etc...
  - Detector model: square or full endcap
- Based on "sampling sections": very easy to vary material, absorber width etc...
- Easy to setup, easy to modify, easy to run....
- Output written in simple TTree, with collection of "HGCSSSimHits" $\Rightarrow$ easy to analyse.
- Digitisation also implemented as second step: output "HGCSSRecoHits" (and optionally calojets "HGCSSRecoJets", work in progress...)
- Both steps run with single python config: one-line command to send many samples in the batch system, output written to EOS.
- Inputs: particle gun (with square geometry), or HEPMC files (with full endcap).

Objectives

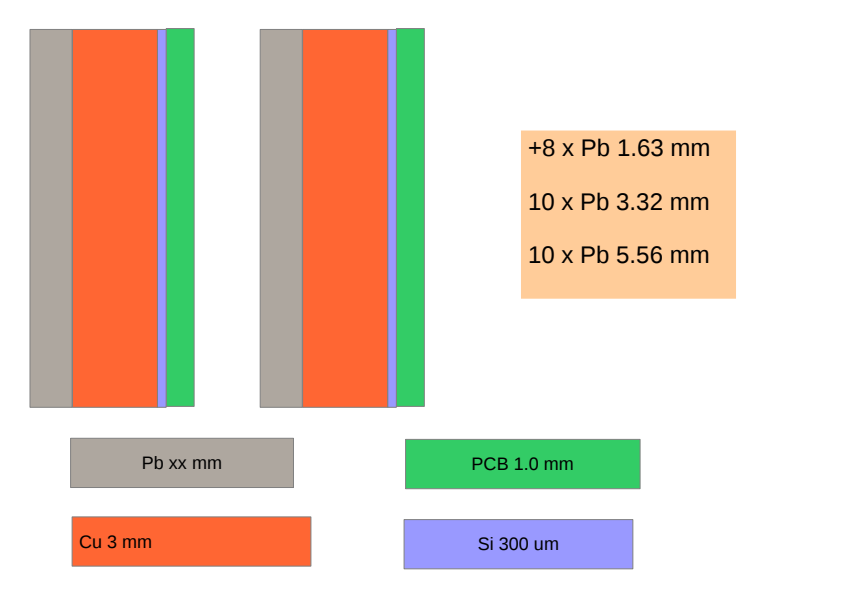
- Flexibility: benchmarked against CALICE results, simulation of beam test setups
- Independent cross-check: debugging tool for CMSSW implementation.
- Lightweight: for design optimisation.

Results discussed Today

- Performance of the ECAL: energy resoluton and shower profile.
- Pion resolution: Calice benchmark.
- Pion resolution with global software compensation.

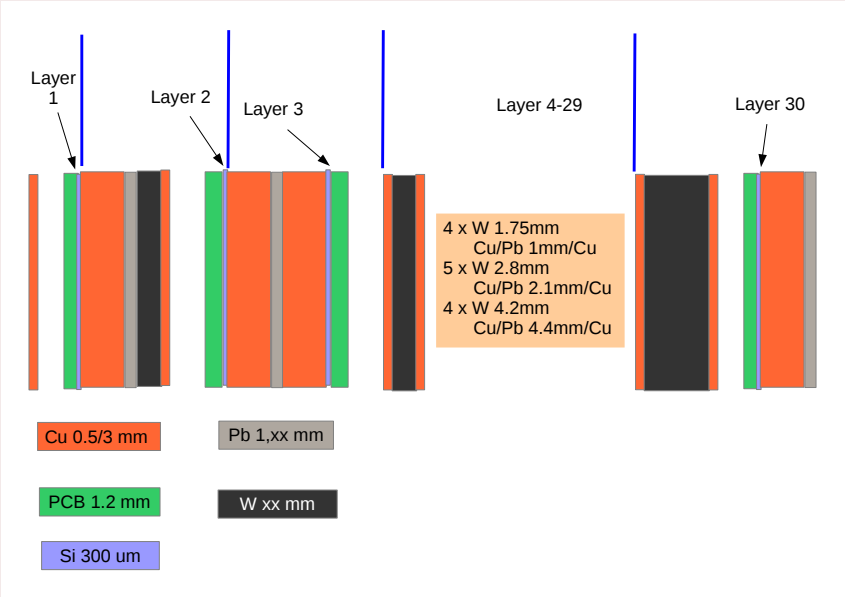
ECAL geometries implemented

≃v4 - simple - "version 8"



- Versions 0-11
- Varied Si thickness, air gap
- Varied absorber material/width
- Varied longitudinal sampling

v5 - drawer structure - "version 12"

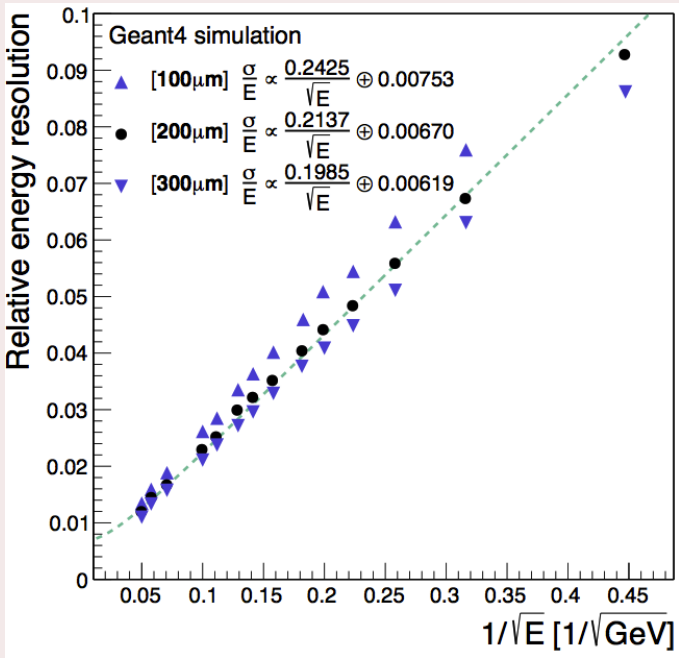


- Air gap 2 mm (version 12) and 4 mm (version 13).

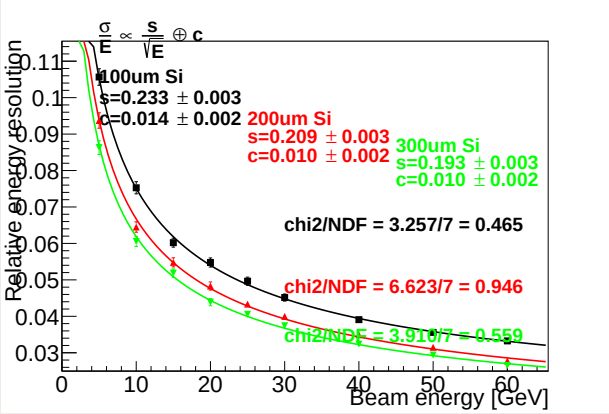
Energy resolution for electrons in the ECAL

- Ideal conditions: simhits from G4, no digitisation.
- Sum the total energy deposited in the Si weighted by absorber thickness in units of X_0.
- Optimisation of the weights ⇒ marginal improvement.
- Linearity within 2%.
- Resolution studied as a function of the silicon thickness.

Geometry v4



Geometry v5



e/γ profile in the transverse plane

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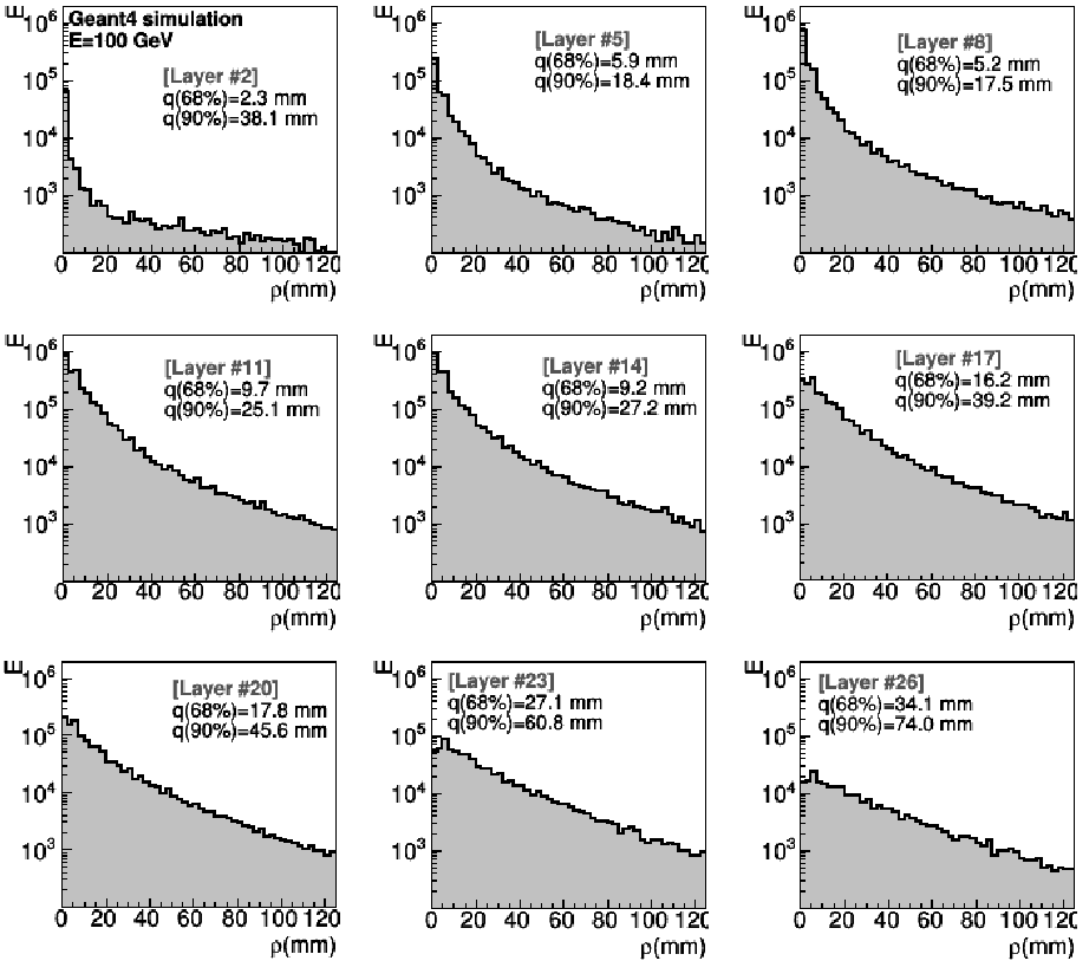
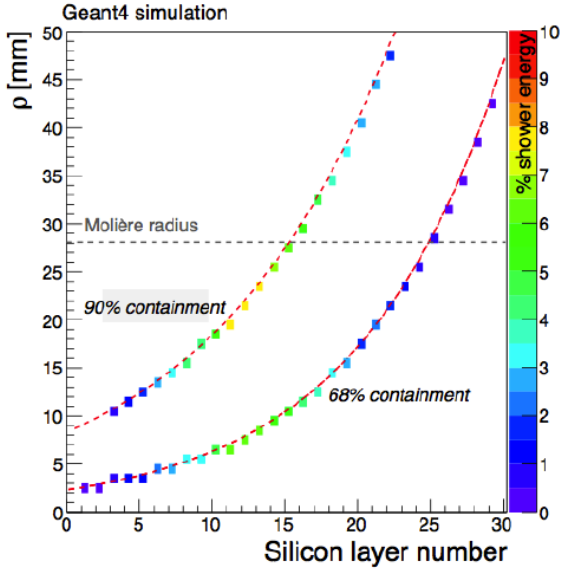




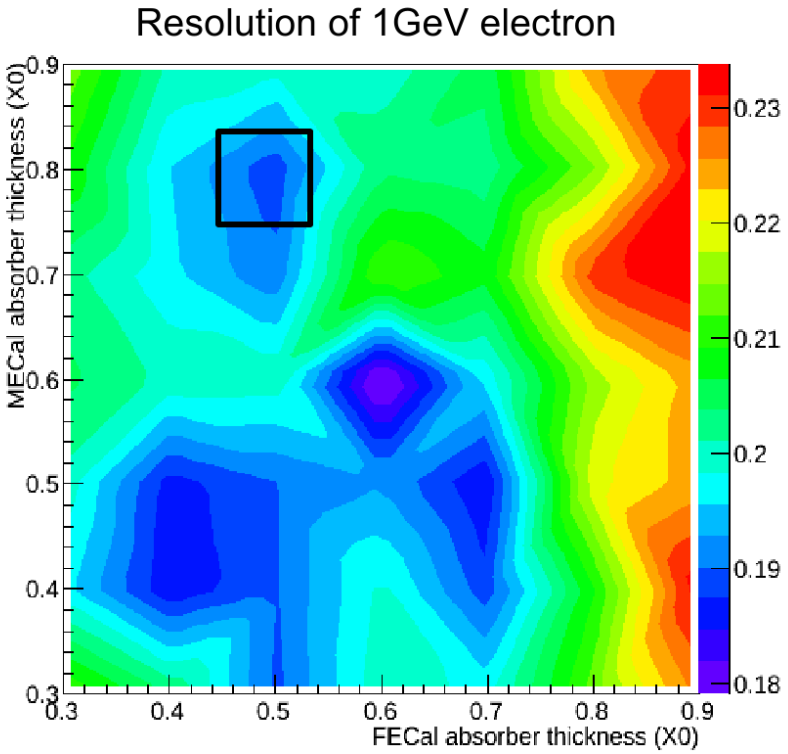
- EM showers considerably narrower than R_M before shower max
- After shower max dominated by beam halo (diffuse energy deposits)

Optimisation of the longitudinal segmentation

- Fix total thickness to 25 X_0, fix 3 blocks of 10 layers.
- Scan thickness in 1st and 2nd blocks.
- Plot resolution for 1 GeV electrons.

Menglei Sun (CMU)

Pb



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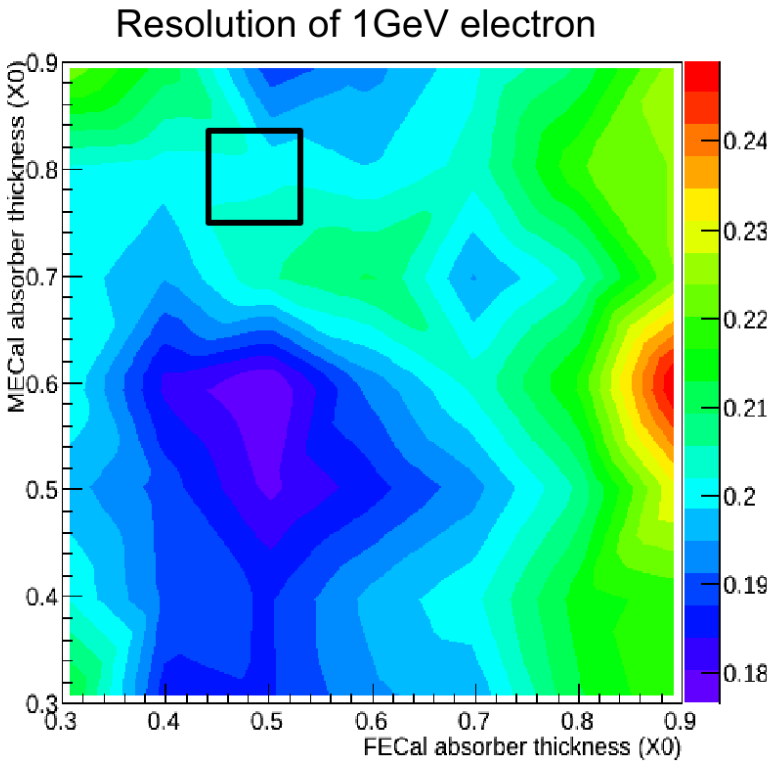
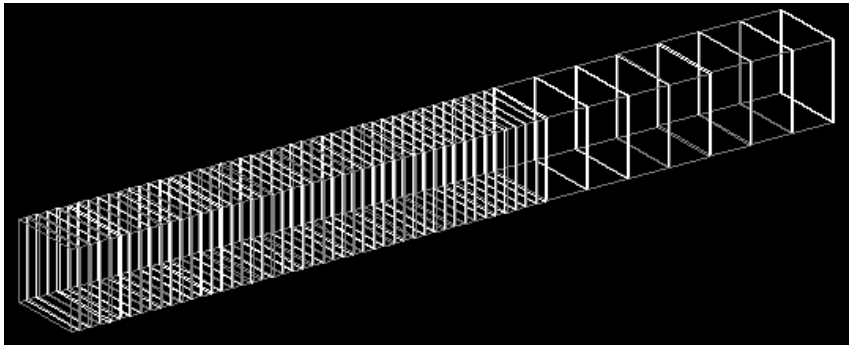


Pion resolution: reproducing Calice geometry

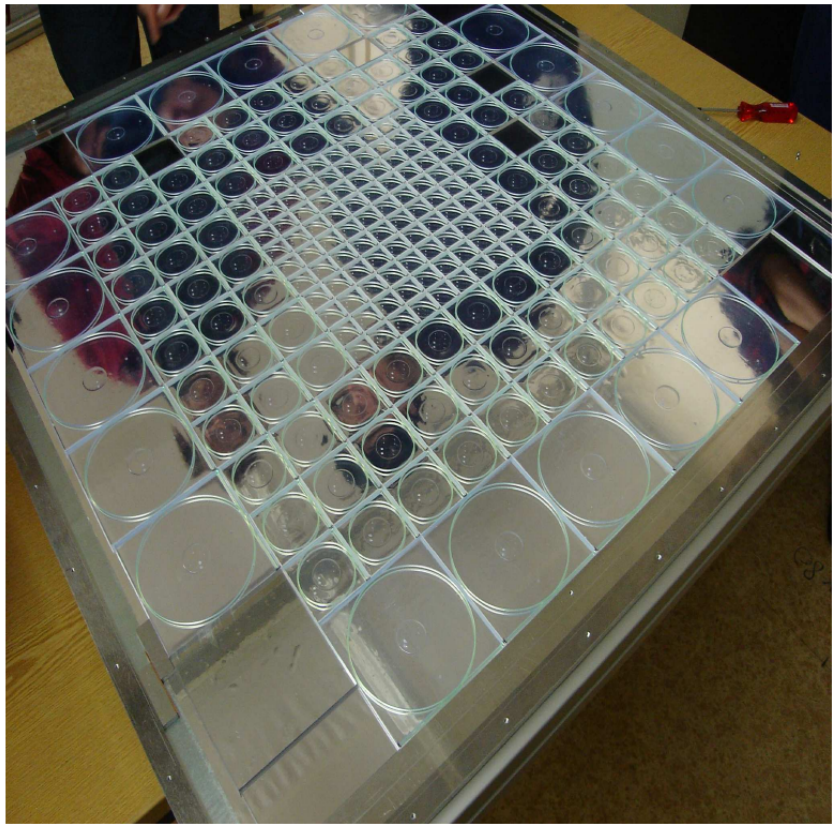
- Standalone simulation "version 23": Calice-like HCAL only.
- Absorber: Fe, 21 mm per layer for 38 layers.
- Followed by tail catcher (TCMT): 9 21-mm + 7 104-mm layers.
- Sensitive material: scintillator (Polystyrene) 5-mm thick.
- Lateral size: 1×1 m^2.
- Using Geant4 v9.3.p04, QGSP_BERT physics list.
- Following method described in JINST 7(2012) P09017.
- Same energy range: pions from 10 to 80 GeV.
- Same digitisation procedure.

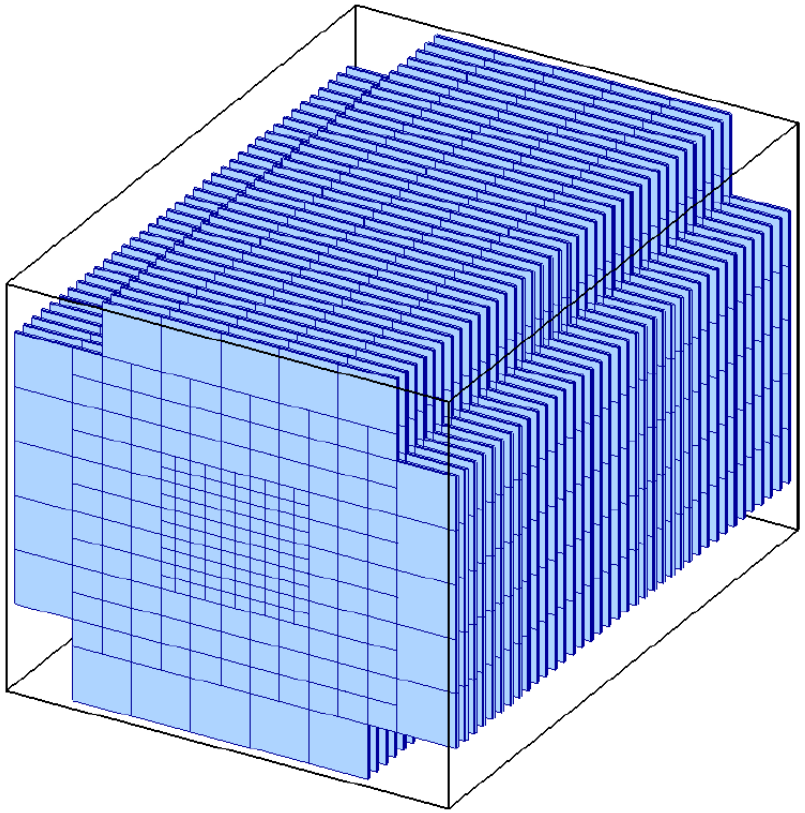
- "AS IMPLEMENTED IN MOKKA" `https://twiki.cern.ch/twiki/pub/CALICE/SoftwareMain/hcalTBeam.pdf`



- Thanks to Marina Chadeeva (ITEP) and Frank Simon (MPI) for lots of help.

Transverse granularity





Digitisation procedure

Timing cut of 150 ns

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MC digitization procedure

Conversion of MC signal from MeV to MIP $\rightarrow e_{MIP}$

$\Downarrow$

Generation of random number of photoelectrons n_{pe}
from Poisson distribution with $\langle n_{pe} \rangle = e_{MIP} \cdot N_{pe}$ $(N_{pe} = 11)$

$\Downarrow$

Calculation of number of pixels n_{pixel} taking in account saturation and cross talk C:
$n_{pixel} = N_{total} \cdot \frac{(1-x)}{(1-C \cdot x)}$ where $x = \exp(-n_{pe}/N_{total})$, $C = 0.25$, $N_{total} = 1156$

$\Downarrow$

Generation of random signal n^{new}_{pixel} from Gaussian distribution $Gaus(\langle n_{pixel} \rangle, \sigma_G)$
where $\sigma_G = 3$ pixels (≈ 0.2 MIP)

$\Downarrow$

Recalculation from pixel to MIP: $e^{new}_{MIP} = \frac{N_{total}}{N_{pe}} \cdot \ln(\frac{N_{total} - C \cdot n^{new}_{pixel}}{N_{total} - n^{new}_{pixel}})$

$\Downarrow$

~~Adding noise hits from random event of pedestal run cell to cell~~

Adding 0.12 MIP gaussian noise everywhere

Adding 2.5% cross-talk / 3-cm edge

Implementing exact granularity

choose 2% dead cells randomly in 1st event

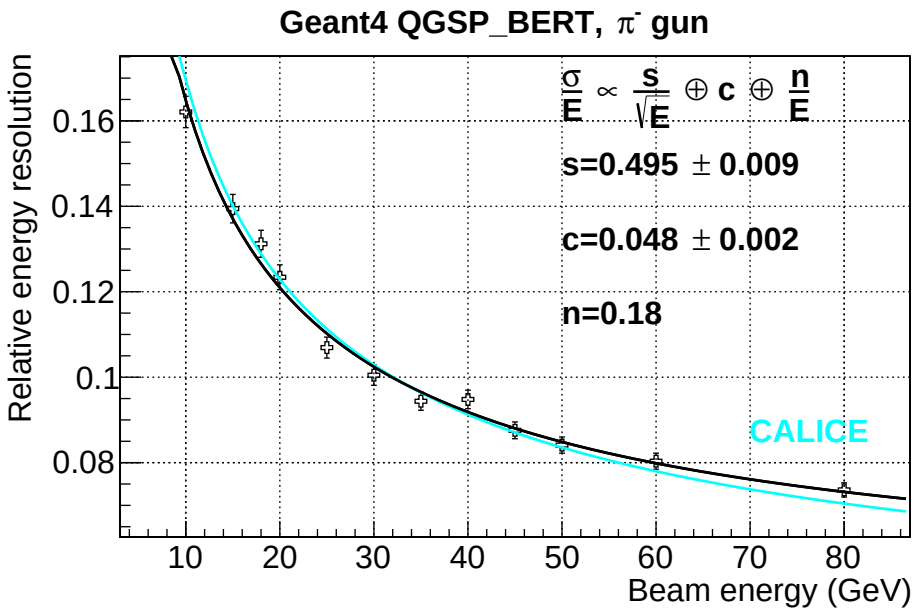
Marina Chadeeva, ITEP ... ek at IPN Lyon, September 2009

Uncorrected resolution for 10-80 GeV charged pions

- Electron response consistent with Calice.
- Calice publication for QGSP_BERT, uncorrected (arXiv:1207.4210)

Remaining differences wrt Calice papers

- No ECAL in front
- SiPM saturation and noise **not** from data



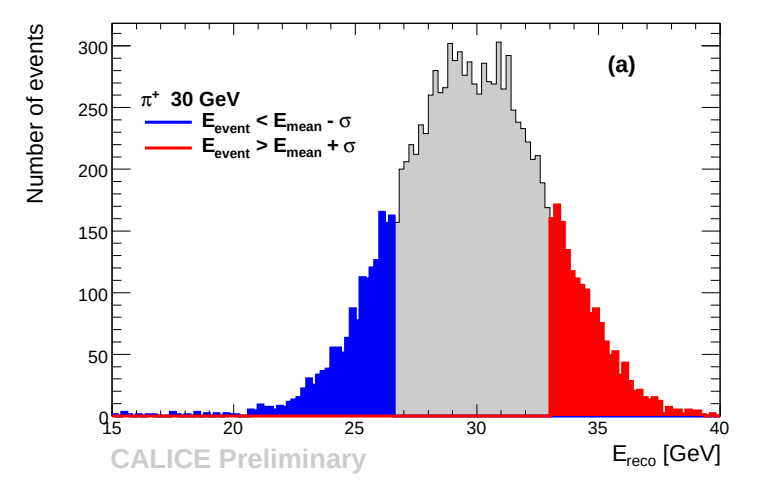
⇒ **Calice benchmark reproduced.**

Global software compensation method (I)

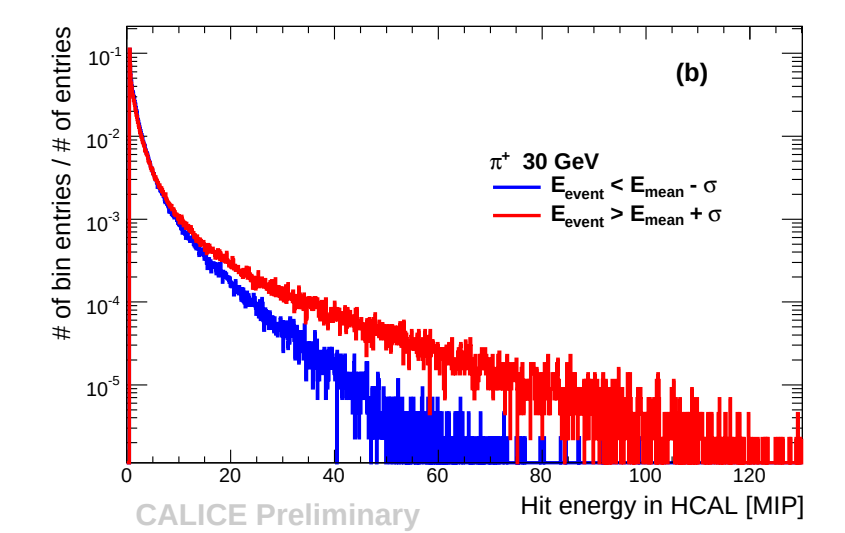
- See Calice CAN-028: `https://twiki.cern.ch/twiki/bin/view/CALICE/CaliceAnalysisNotes`
- Main idea: identify event-by-event EM content and correct accordingly.
- $e/\pi \simeq 1.2 \Rightarrow$ higher energy $=$ higher EM content.

- Global method: different EM content = different hit spectra.
- High-end tail = red population = higher EM content = higher mean energy per hit.
- Low-end tail = blue population = lower EM content = lower mean energy per hit.

Total energy

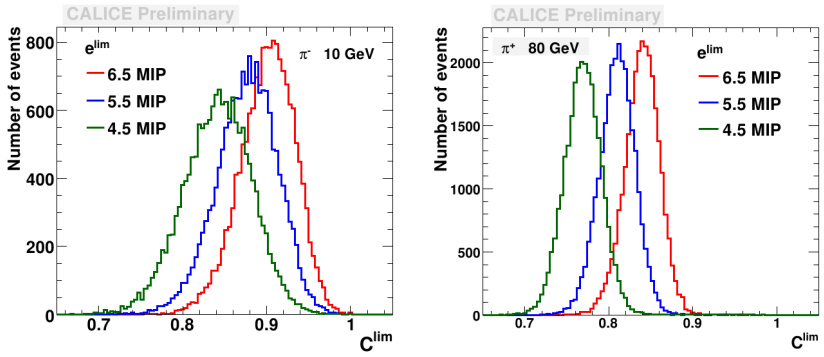


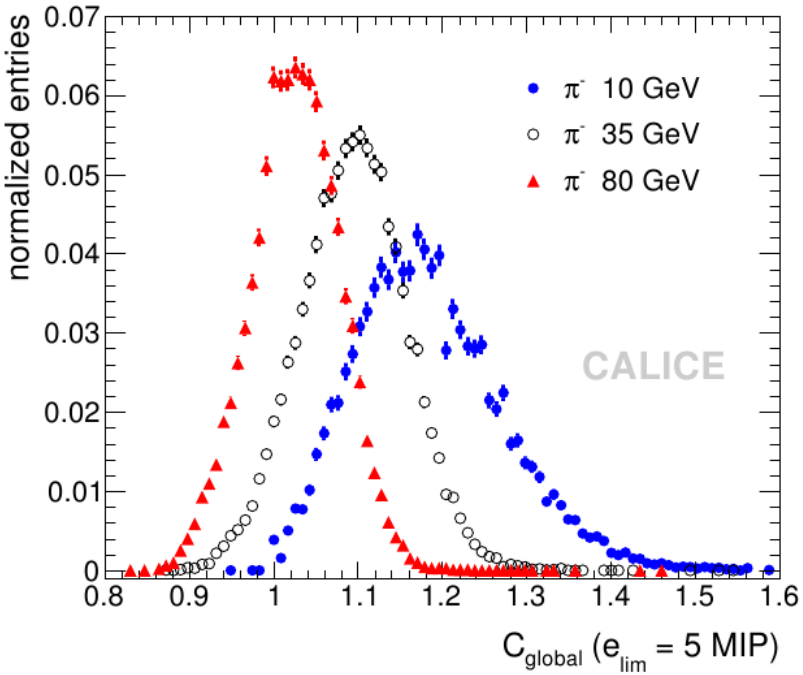
Hit spectra



Global software compensation method (II)

- Define $C_{global} = \frac{N_i(e \leq e_{lim})}{N_i(e \leq e_{av})}$
- N_i: number of hits in a given event
- $e_{lim} = 5MIPs$, free parameter tuned to work for all energies.
- e_{av} mean energy of the event hit spectrum in MIPs.

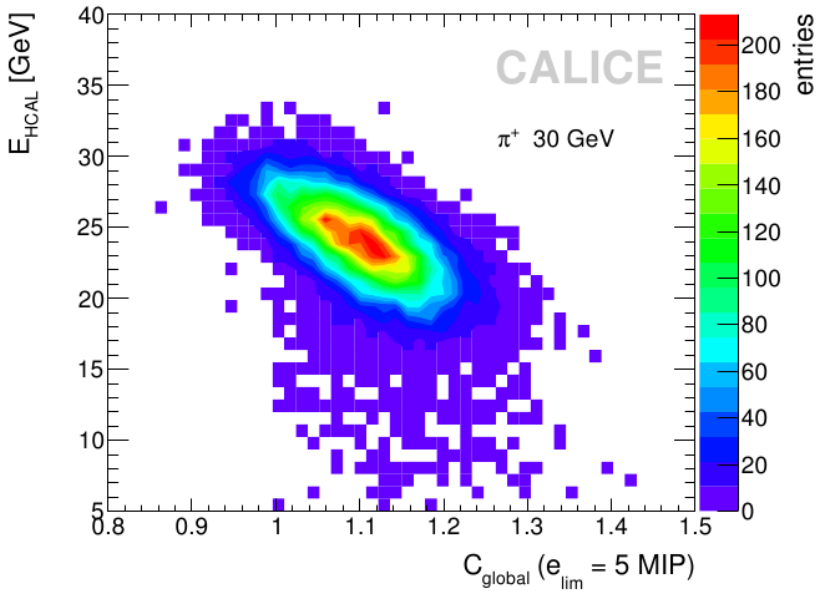




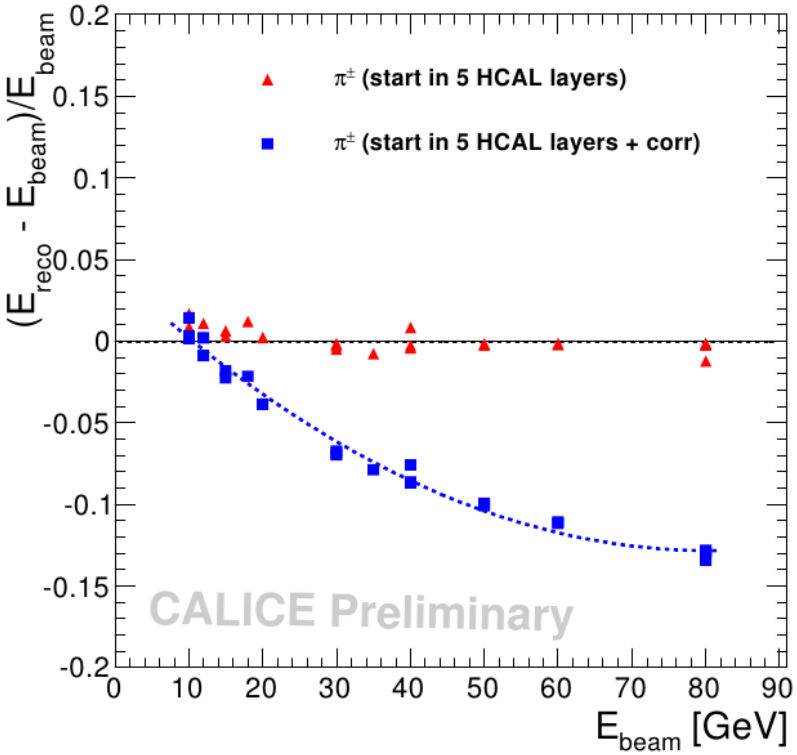
- As expected: EM fraction increases with particle energy $\Rightarrow$ C_{global} decreases.

Global software compensation method (III)

- Use anti-correlation between total energy and C_{global} to correct on an event-by-event basis.
- $E_{shower} = E_{uncor} \times C_{global}$



- Ad'hoc correction to recover the linearity using second-order polynom.



Calice Results

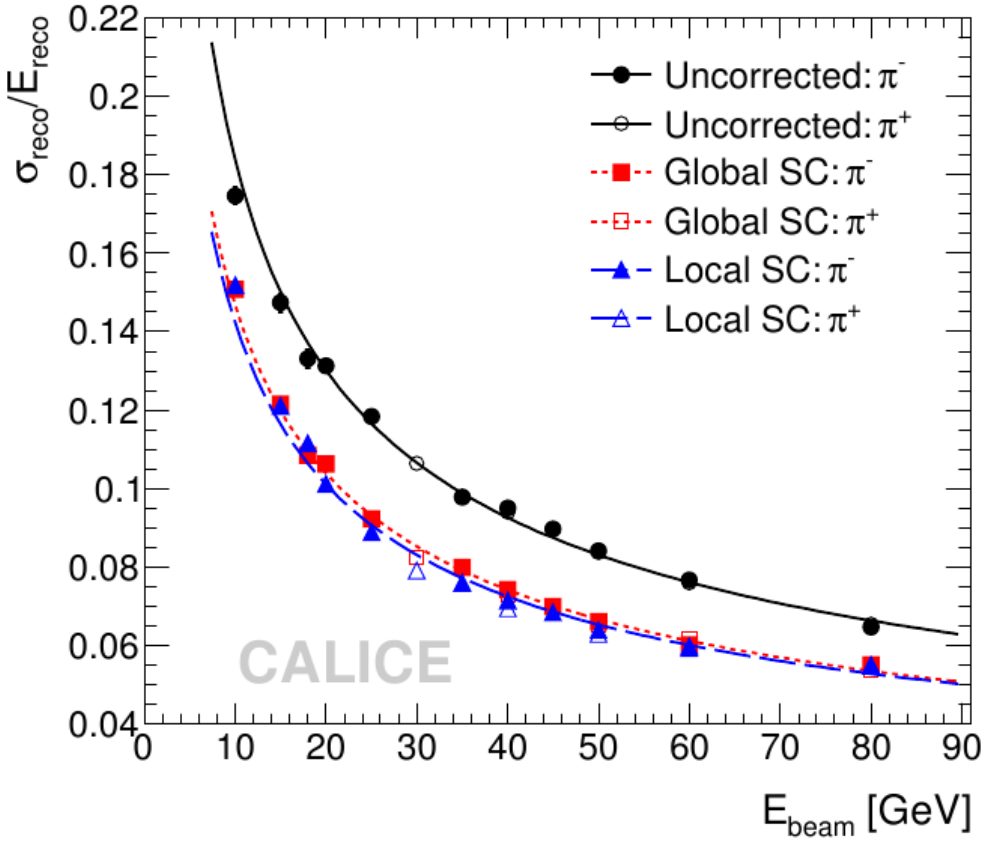
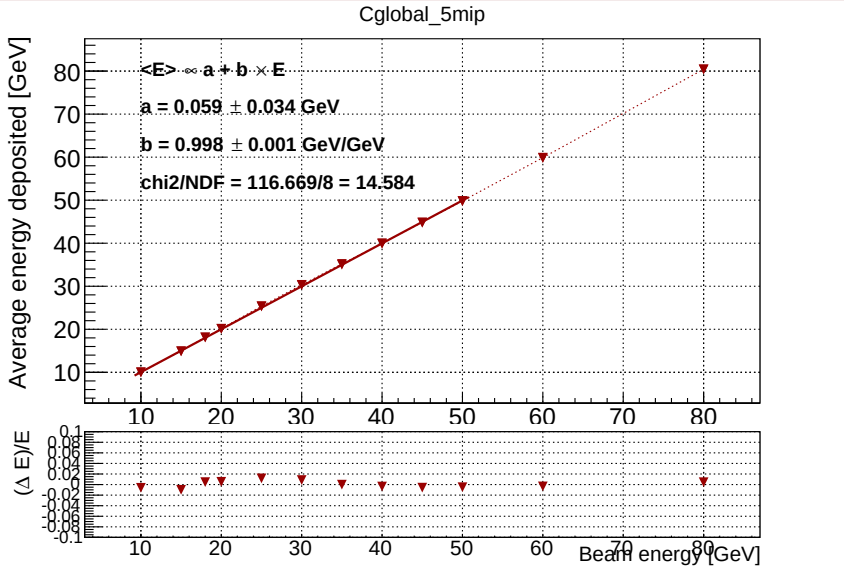


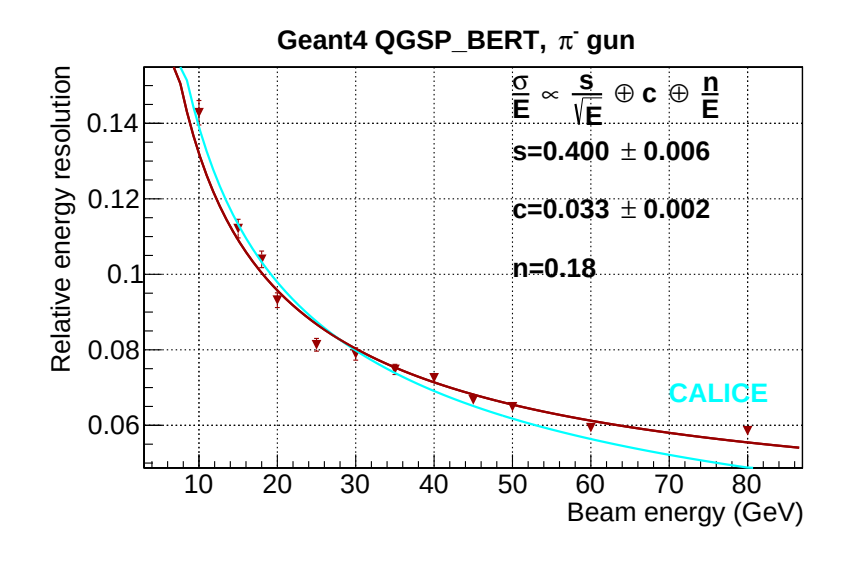
Figure 4. Energy resolution versus beam energy without compensation and after local and global software compensation. The curves show fits using Equation 2.2, with the black solid line showing the fit to the uncorrected resolution, the red dotted line to the global software compensation and the blue dashed line to the local software compensation. The stochastic term is $(57.6 \pm 0.4)\%$, $(45.8 \pm 0.3)\%$ and $(44.3 \pm 0.3)\%$, with constant terms of $(1.6 \pm 0.3)\%$, $(1.6 \pm 0.2)\%$ and $(1.8 \pm 0.3)\%$ for the uncorrected resolution, global software compensation and local software compensation, respectively.

Results

Linearity



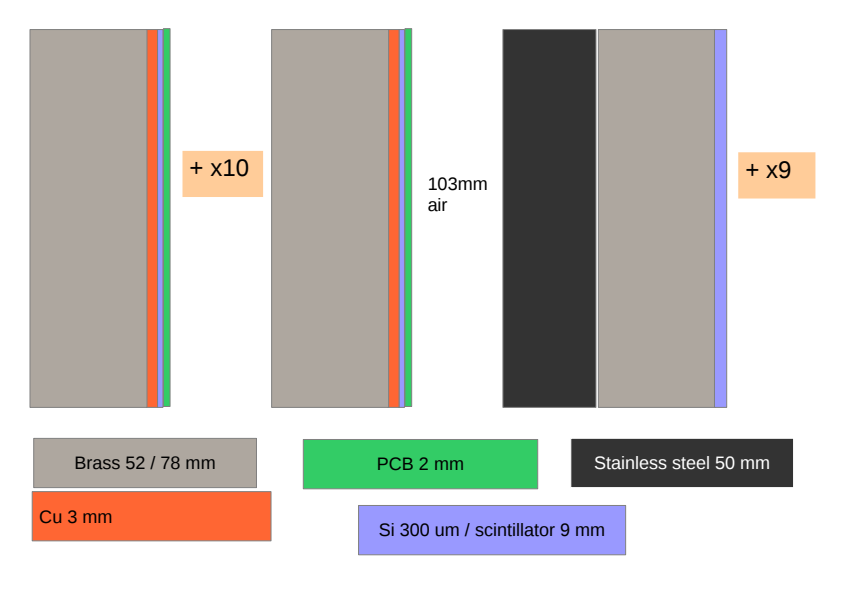
Resolution



Moving on to our design

Geometry implemented

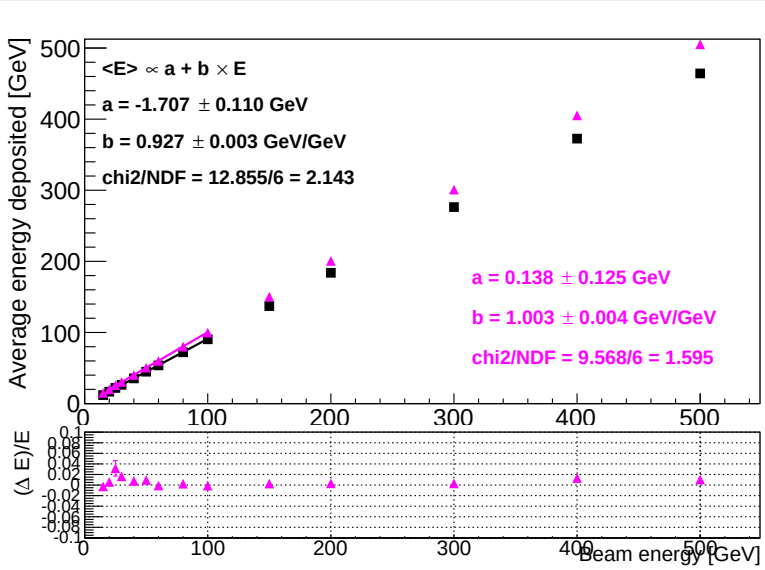
- FHCAL: 50 mm stainless steel + 12 layers with 52 mm Brass + 3 mm Cu + 300 μm Si + 2 mm PCB + 2 mm air
- BHCAL: 10 layers with 78 mm Brass + 9 mm scintillator.

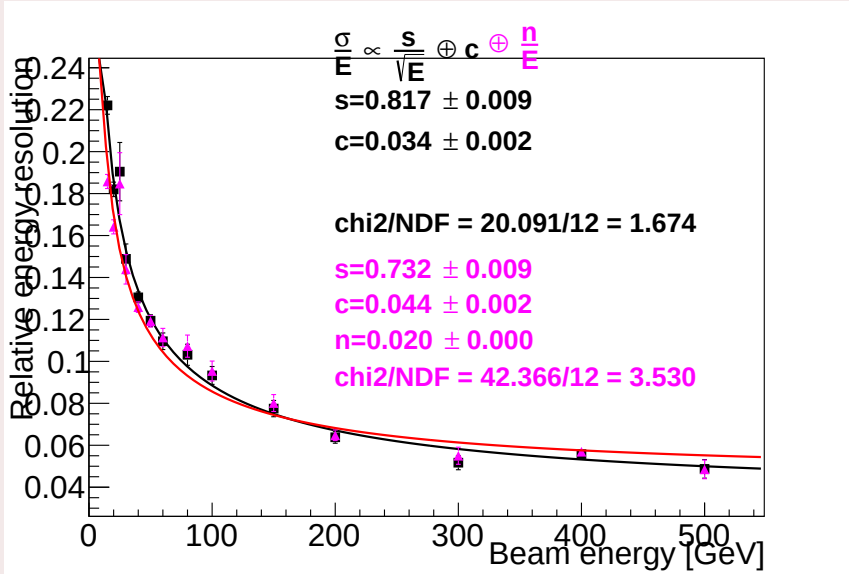


Procedure

- 1 MIP = 4 ADC counts, timing cut kept at 150 ns.
- Calibrate FHCAL to EM scale: $E_{MIP} = -209 + 118 \times E_{GeV}$
- Calibrate BHCAL to EM scale: $E_{MIP} = -5.1 + 9.92 \times E_{GeV}$
- Calibrate BHCAL to FHCAL: slope = 2.7 ± 0.1 (stat)
- Slope before digitisation: 0.23 ± 0.01 (stat)
- For pions, apply e/π=1.09.
- Sum hits with energy above 0.5 MIP cut.

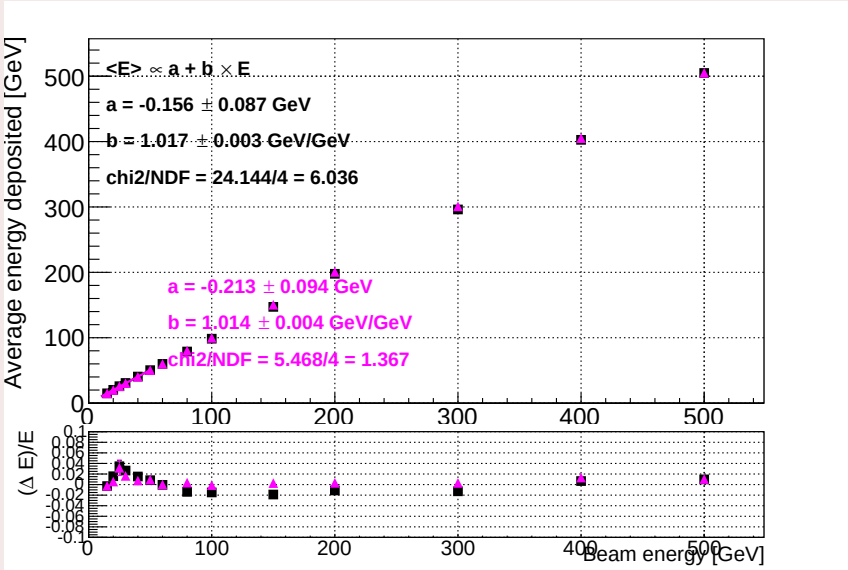
HGCAL response to pions



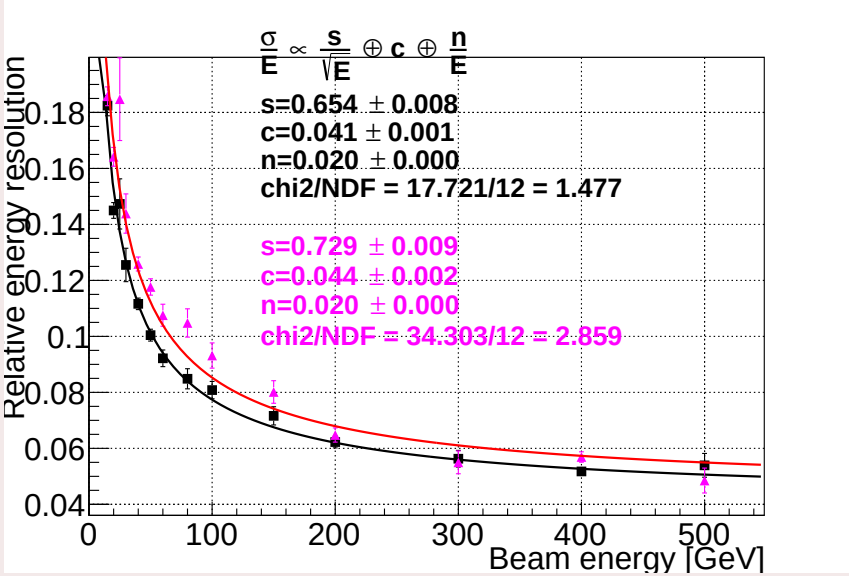


HGCAL response after global software compensation

Linearity



Resolution



- Larger gain at lower energies.
- Not as much gain as in Calice case, but no real optimisation done, and much larger energy range covered...

Conclusion

Lots of progress on the ECAL side

- Good overall picture of the performance, optimisation started.
- Standalone has already proven very useful to cross-check CMSSW implementation.
- Optimisation started.

And also on the HCAL side

- Reproduced the Calice results, using implementation of the AHCAL physics prototype.
- Implemented software compensation method.

You're welcome to join!

- Excellent time to join the group!
- Many tasks are open and manpower is needed
- `https://twiki.cern.ch/twiki/bin/view/CMS/PFForwardCalorimeterStudies`

Backups

BACKUPS

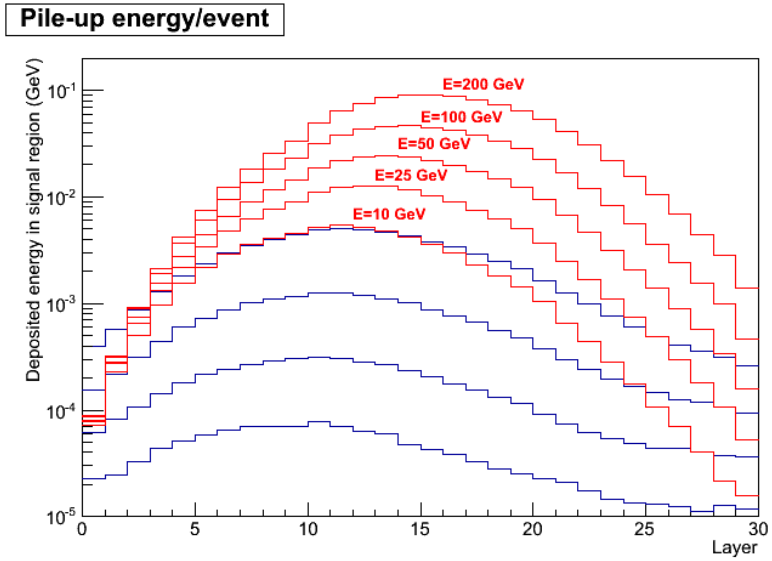
Simulation and analysis

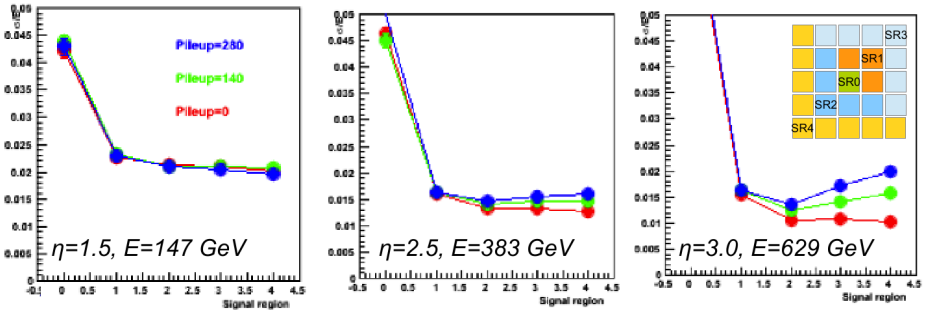
- Simulation
  - Standalone: 15-170cm radius ECAL; $10\times0.5X_0+10\times0.8X_0+10\times1.2X_0$
  - Pile-up: Pythia (from Pedro) 0, 140, 280 interactions/event
  - Signal: $H\rightarrow\gamma\gamma$ with Higgs exactly along z and photons symmetric; choose Higgs momentum to give photons at η=1.5, 2.0, 2.5, 2.8, 3.0; E_T=67.5 GeV
  - Cells: $1\times1cm^2$; uses only SimHits, not Digis
- Analysis
  - Find initial direction using peaks in $\eta-\phi$ plot
  - Find 5×5 cell array in each layer centred on projected initial direction
  - Construct position in x-y per layer
  - Project truth photon into array to find residuals and error matrix
  - Fit positions in all layers for overall shower position and direction
  - Find 5×5 cell array in each layer centred on projected fitted direction
  - Do energy reconstruction using signal regions within 5×5 array
  - Combine the two photons to give a Higgs mass

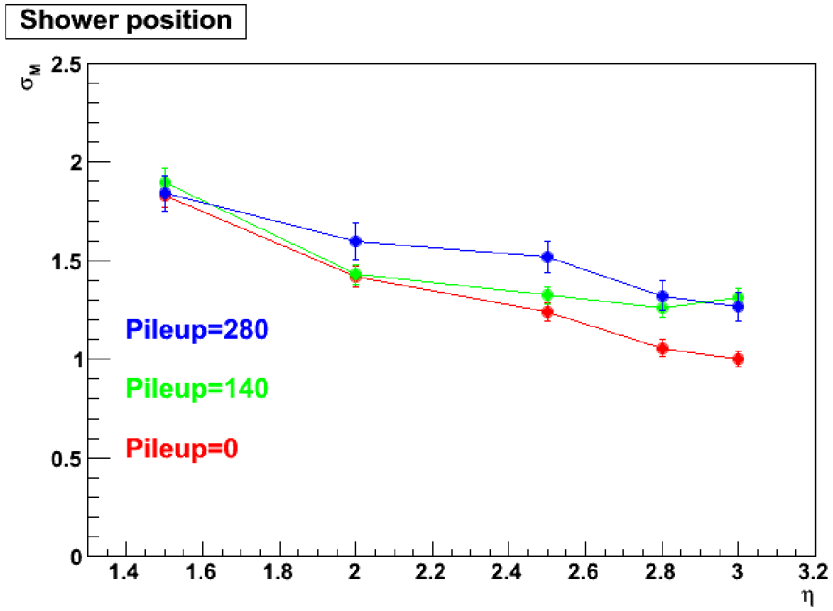
18 Mar 2014 Paul Dauncey

Application: Higgs to gamma gamma mass resolution

- Generated minbias Poisson(X) events, overlayed to signal hits.
- Energy from PU: dominated by π^0 photons.
- Small continuum from $\pi^{\pm}$ MIP-like tracks.



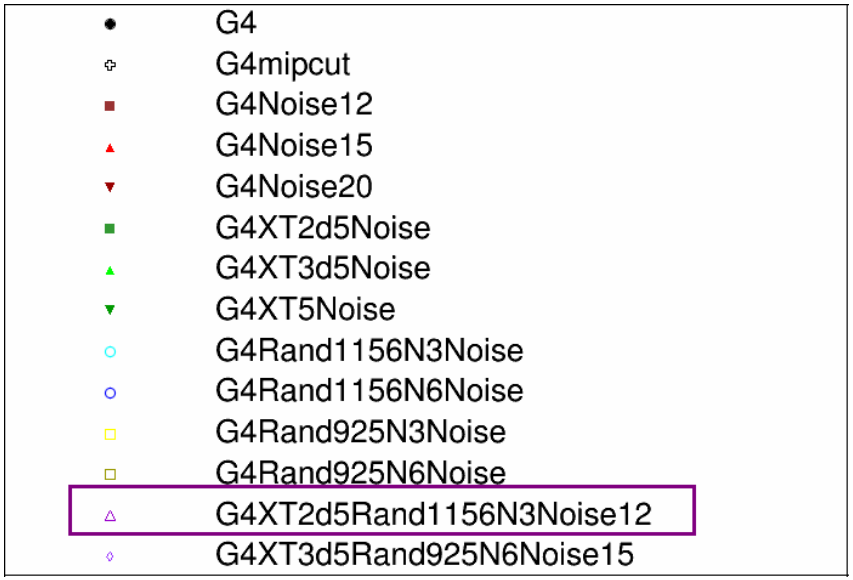




- Study impact of PU on resolution, integrating over different signal regions.
- Extract final impact on $M_{\gamma\gamma}$ resolution, with different scenarios for finding vertex position.

Pion resolution: Procedure

1. For pions: select events that have a first nuclear interaction within the first 5 layers ($\simeq 0.7\lambda_I$)
2. Weight back TCMT layers by ratio of absorber thicknesses: 104/21.
3. Sum total energy in 1×1 m^2, for hits above 0.5 MIP.
4. Correct to the EM scale:
   - HCAL response to electrons
   - Extract slope and offset
5. Add fixed factor 1.19 for pions. Neglect offset.
6. Add one-by-one (and vary) digitisation parameters.

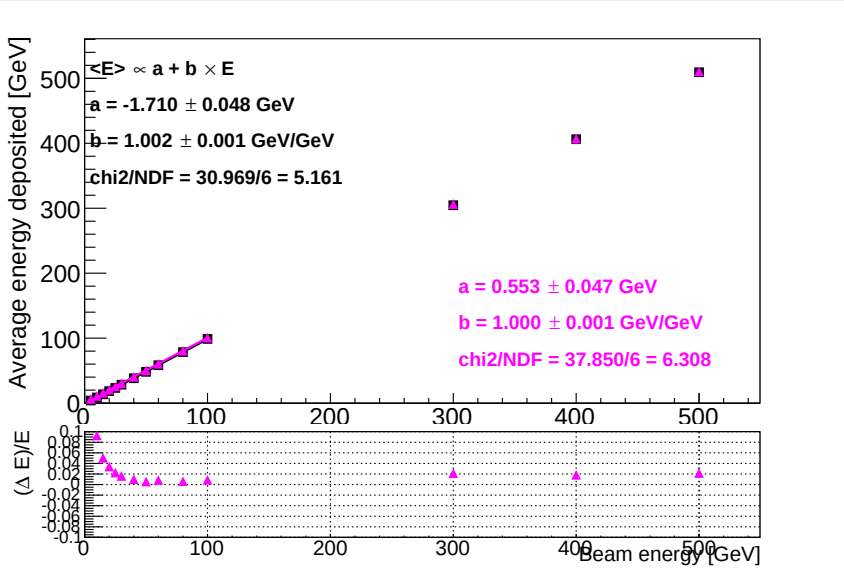


Remaining differences with Calice papers

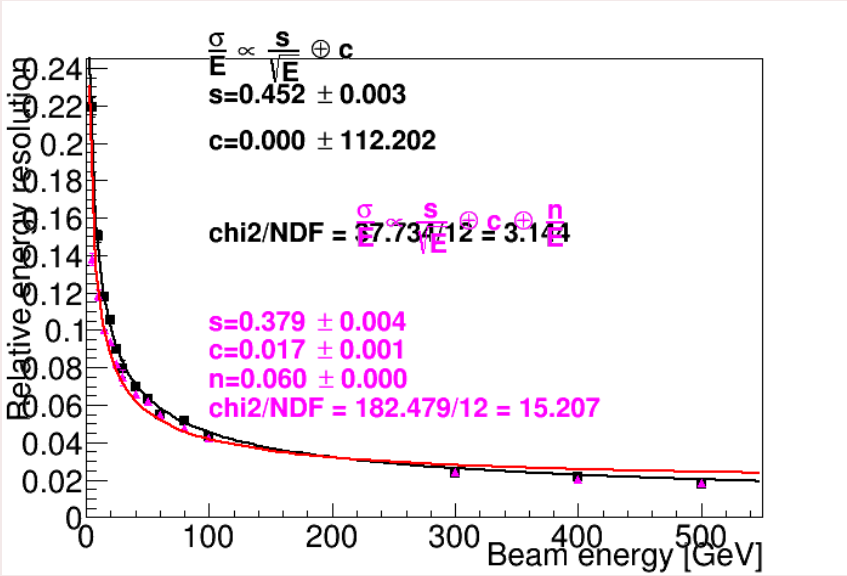
- No ECAL in front
- SiPM saturation and noise **not** from data

FHCAL response to electrons

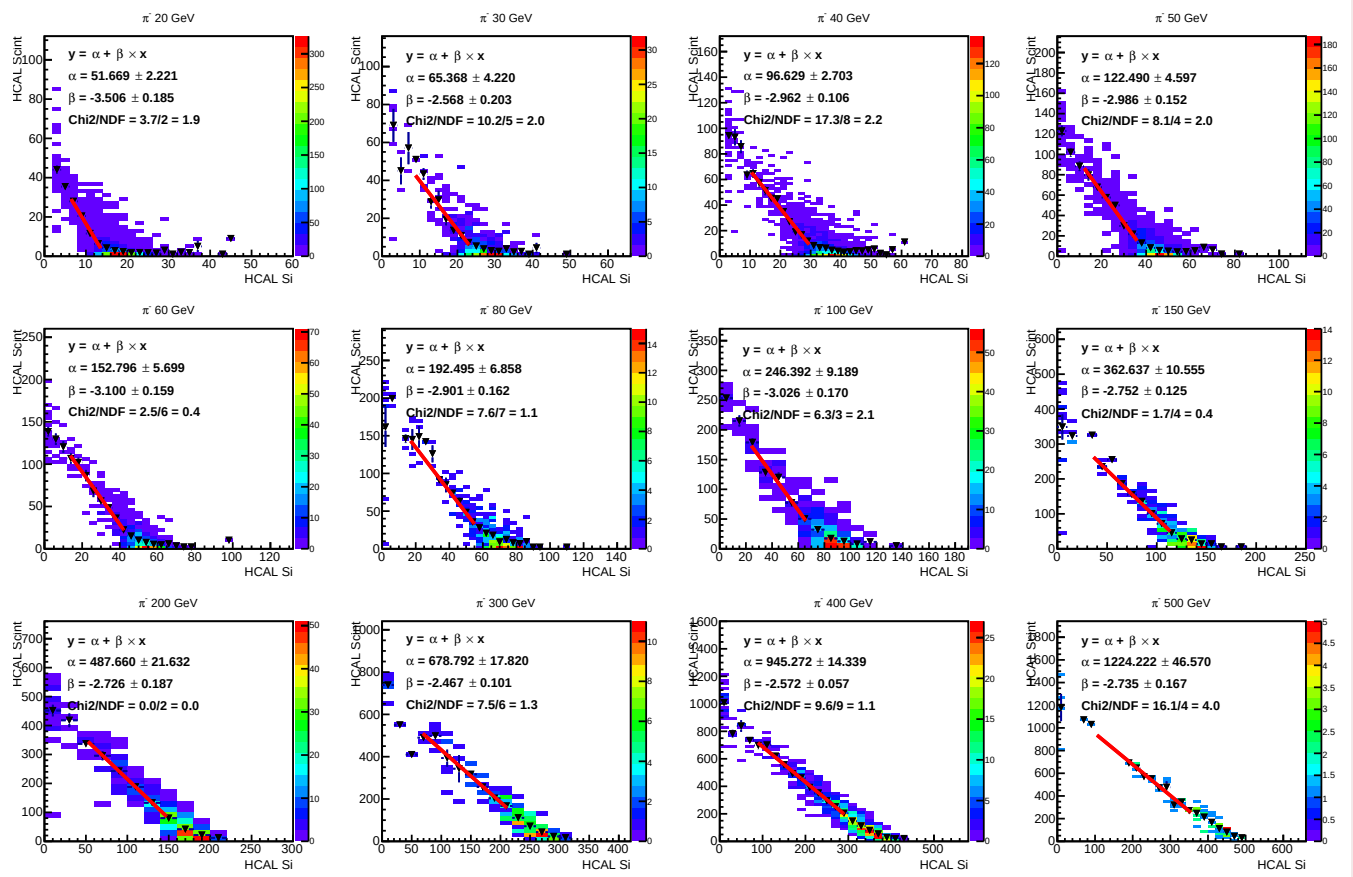
Linearity

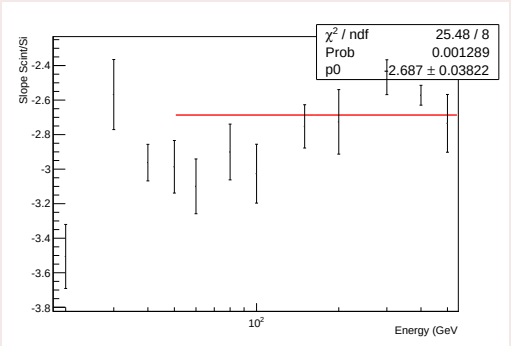
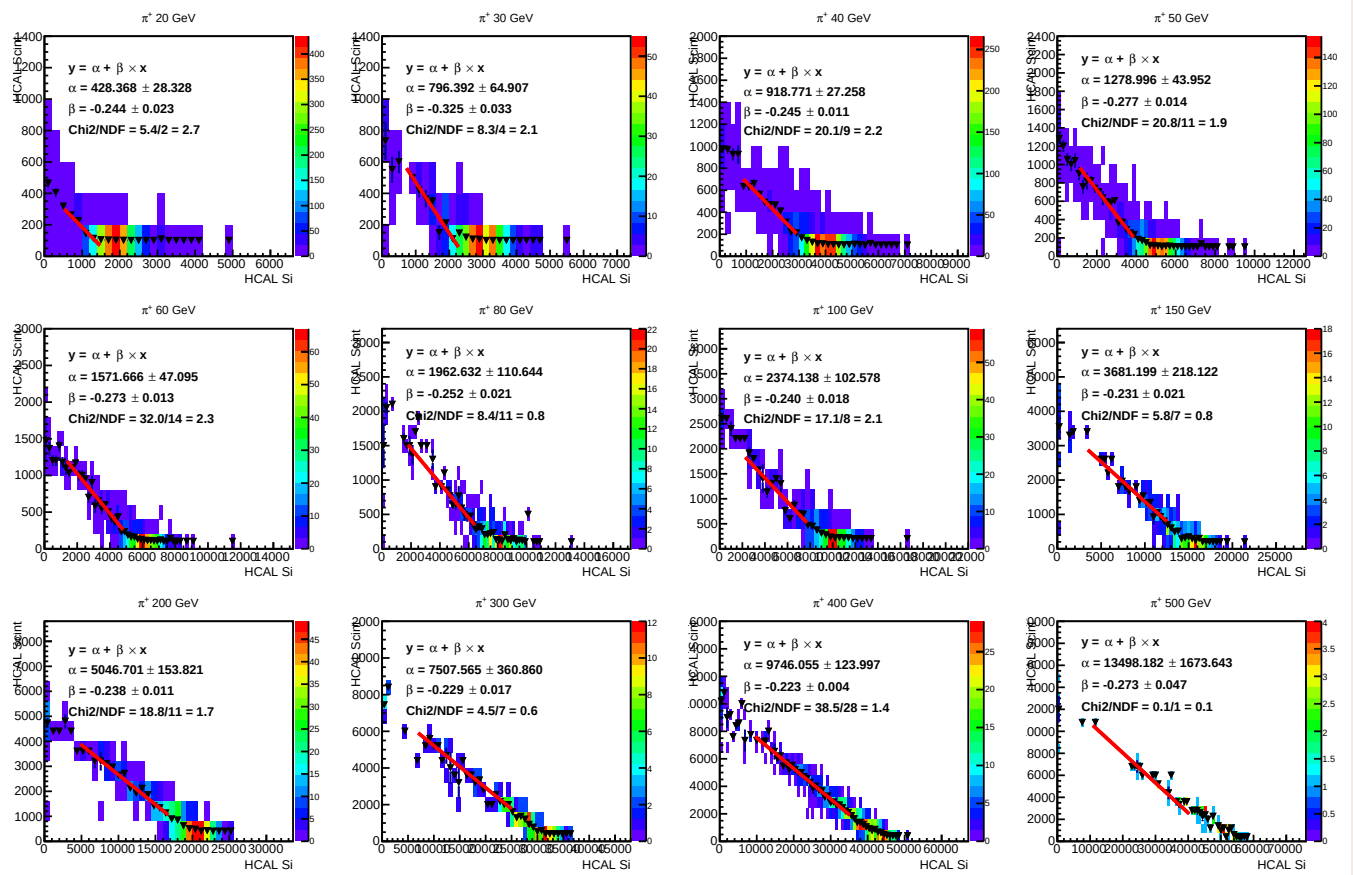
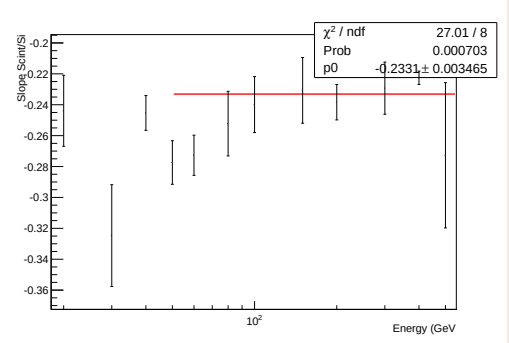


Resolution



BHCAL vs FHCAL after digitisation





BHCAL vs FHCAL before digitisation