Calorimeter for ILC

First SDHCAL results from 1 m³ test beam data

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in behalf of CALICE-SDHCAL group

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FOREWORDS

- Preliminary results from August and May runs
- Raw performances of the Semi-Digital HCAL,
  1 m^3 based on 1×1 cm^2 GRPC
  - response to single beam particles
  - Uncalibrated (cell-wise) calorimeter
  - no use the Ebeam knowledge
  - Not a Particle Flow performances estimation
- Data driven analysis
  - MC needs tuning to data (tbd)
  - esp. particle ID.
- Mainly results from 1 integrated analysis
  - merging techniques from complementary analysis (not presented here)
  - rush effort of the SDHCAL group and CALICE referee's to validate results
    → CALICE preliminary tag

Semi-Digital HCAL Concept

Ultra-granular HCAL can provide a powerful tool for the **PFA** leading to an excellent Jet energy resolution.

It is based on two points:

1- Gaseous Detector

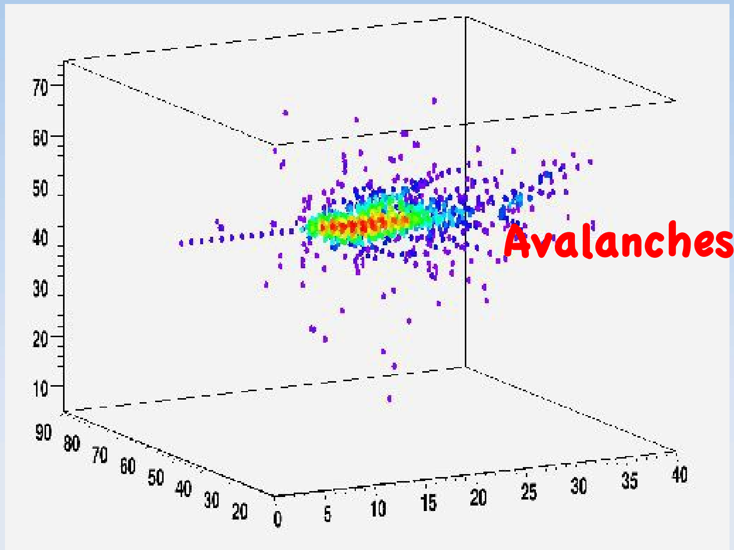
Gaseous detectors like **GRPC** are homogenous, cost-effective, and allow high longitudinal and transverse segmentation.

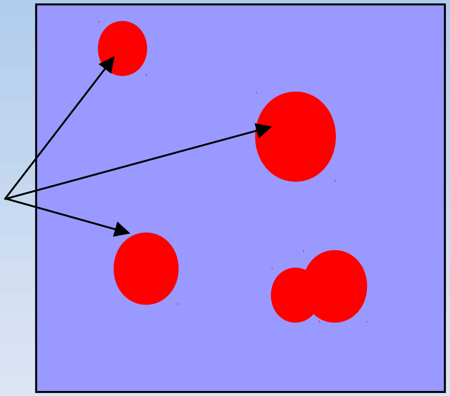
2- Embedded electronics Readout

A simple binary readout leads to a very good energy resolution

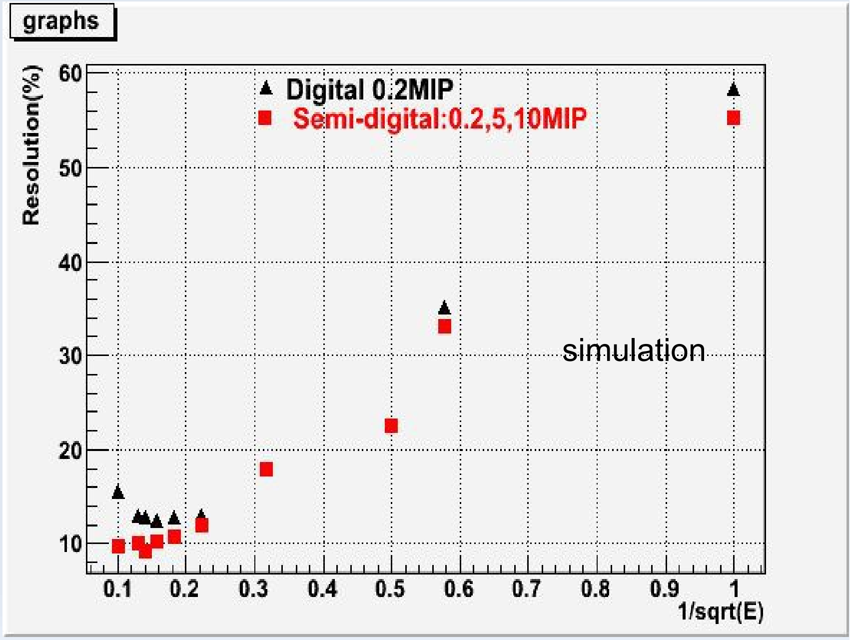
However, at high energy the shower core is very dense and saturation shows up

2-bit readout improves on energy resolution at energies> 30 GeV

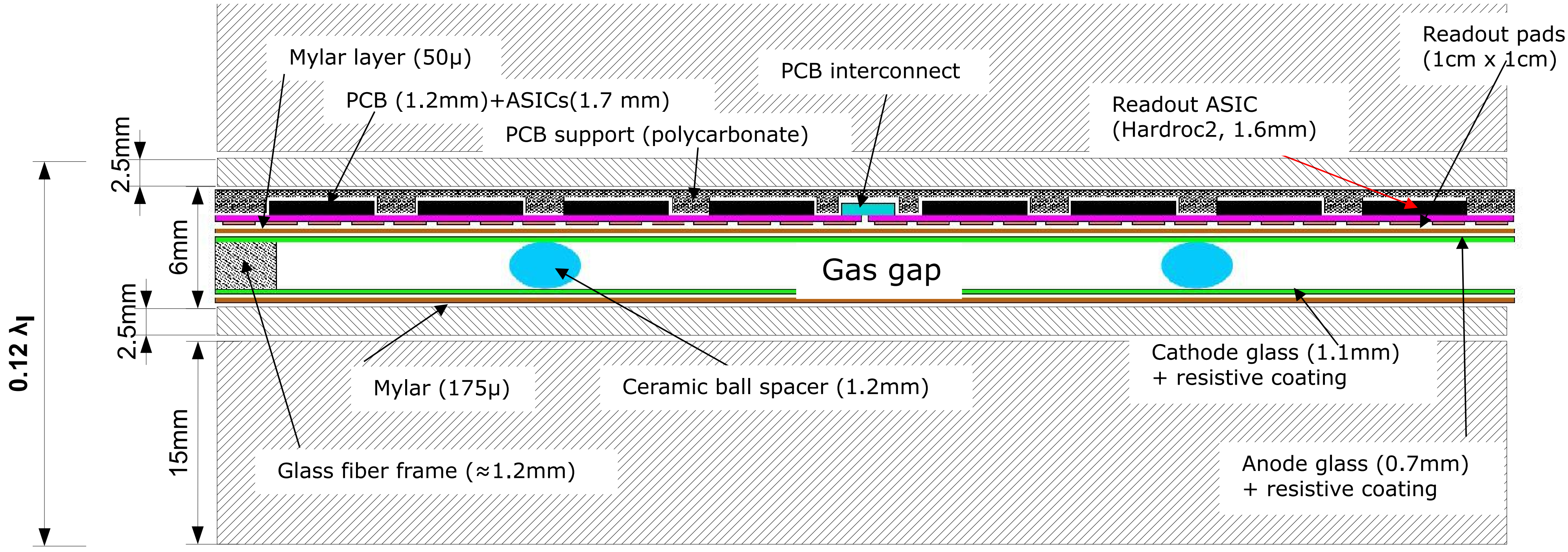




1 cm² pad



Structure of an active layer of the SDHCAL



48 layers of 0.12 λ_I = 5.76 λ_I

Beam conditions

- Beams of pions, electrons and muons at CERN
  - 2 weeks in May 2012 @ SPS H2
    - π+: 20, 30, 40, 50, 60, 70, 80 GeV
    - e- :10, 20, 30, 40, 50, 60 GeV
    - μ dedicated runs...
  - 2 weeks in August (& September) 2012 @ SPS H6
    - π+: 5, 7.5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100 GeV
    - + few μ dedicated runs
- Beam composition:
  - all runs contain μ's (esp. e-) and cosmics
  - π's runs filtered by 4mm Pb to remove e- (esp. for E≥20 GeV)
  - proton component in HE π's runs (@ E≥20 GeV)
  - $\delta E_{beam}/E \sim 1\ \%$
- Large beam profile
  - low rates (ε ↘ at ƒ ≥ 100 Hz)
  - Rate monitored online by μ tracks and π tracks segments
    - Only run with ƒ≤1000 part/spill ⇔ φ ≤ 100 Hz/cm²

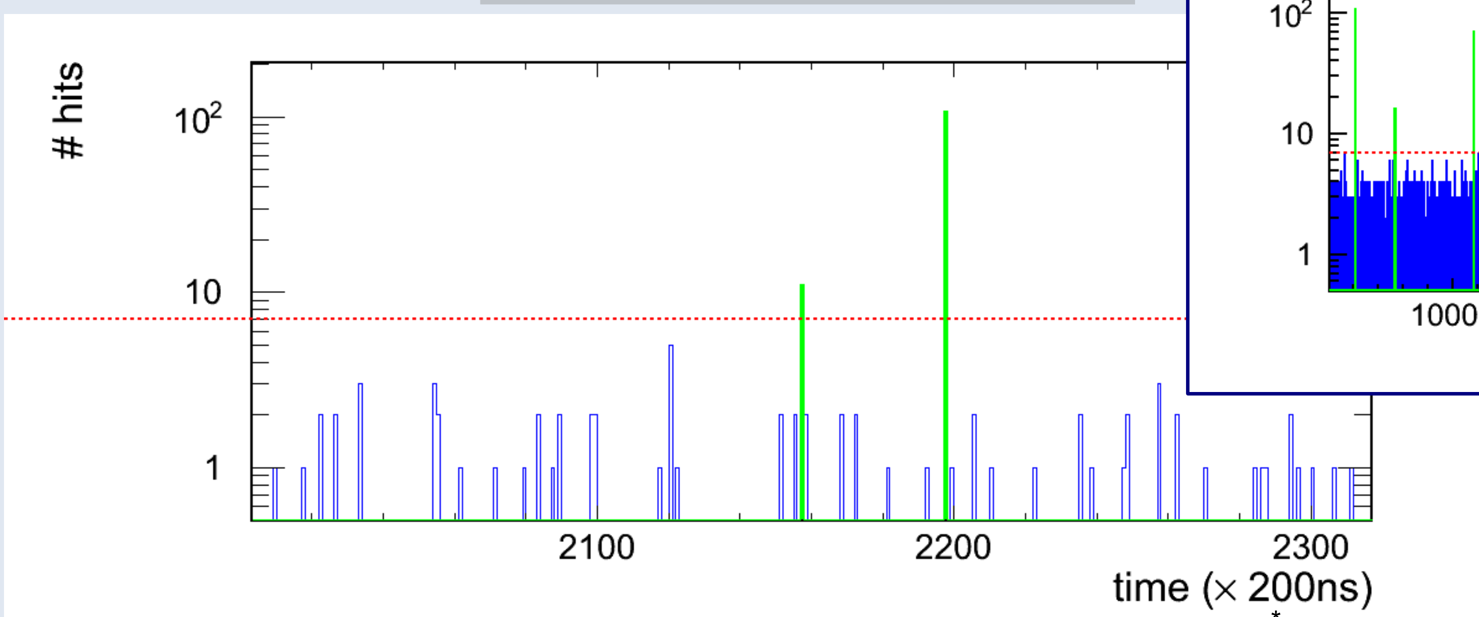
Configuration:

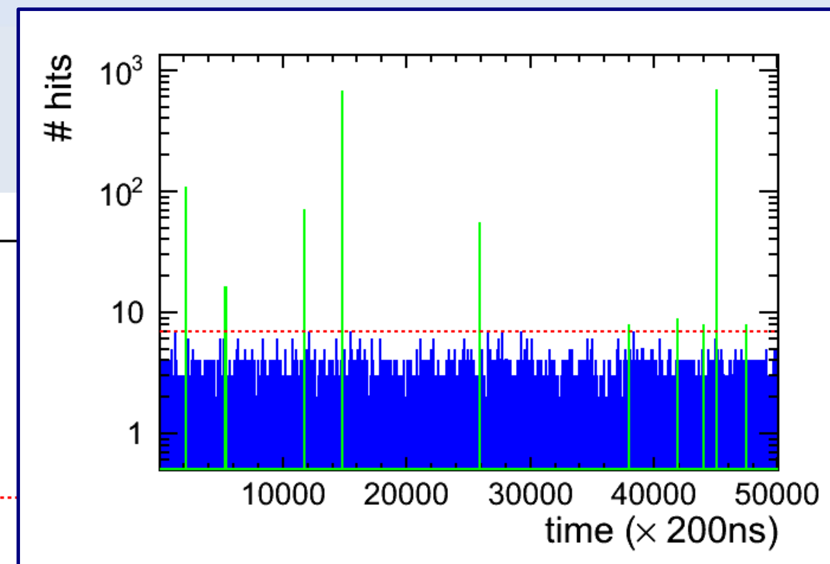
- GRPC set-up & response
  - gas: TFE 93%, CO_2 5%, SF_6 2%
  - HV = 6.9 kV
  - the average MIP induced charge being around 1.2 pC
  - Thresholds set at 114 fC, 5 pC and 15 pC (0.1; 4; 12.5 mip)
- Dead zones:
  - 1/3 slab of plane # 46 dead in May ; repaired for August runs
  - 1^{st} 47 planes available during 1st week fo August.
  - 7 ASIC switched off (and not replaced) ↔ 1 ‰ dead zone.
- Gains
  - All set to 1 (no gain corr.) during this data taking
    - (will be done for next period)

Data taking

- Triggerless mode : record events until memory is full, then data transfer and restart.
- Power-Pulsed mode : According to the time spill structure
  - (N×400 ms (PS)*, 10s (SPS) every 45 s)
- Physics events are built as follows: 3 consecutive BC (200ns)
  - Based on cosmic studies

Hits left by charged particles





* N is often 1 and sometimes 2-3 spills/cycle

Selection

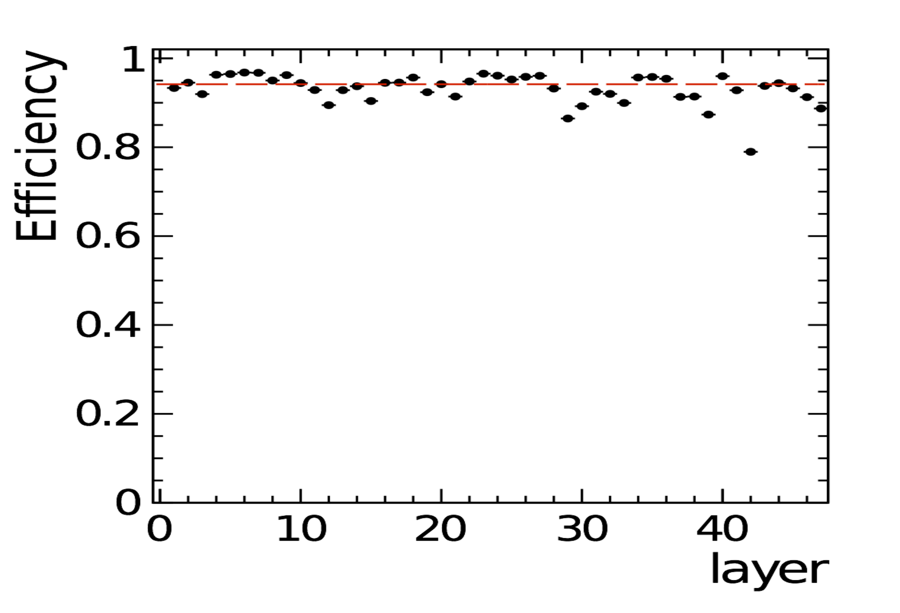
μ track selection (monitoring)

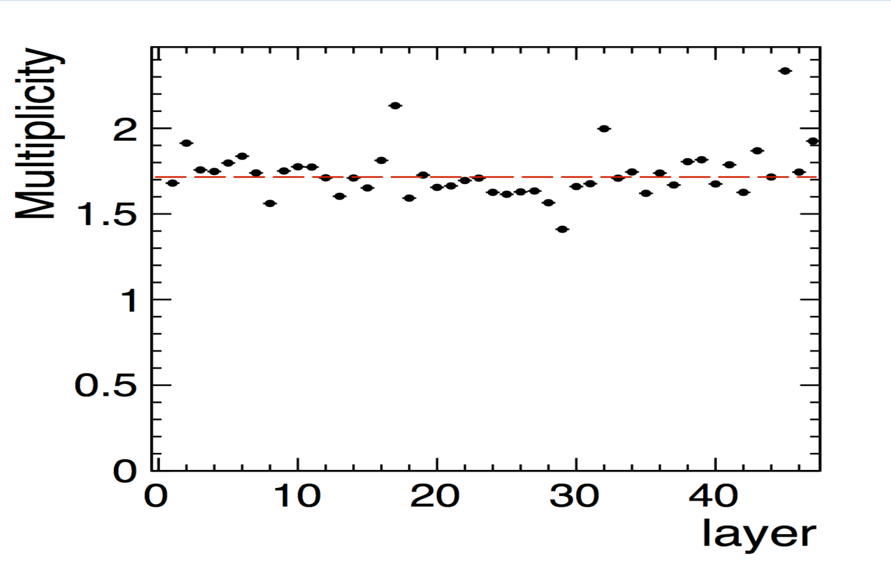
- ε, μ estimated from tracks reconstructed from other layers
  - hits are grouped in clusters if sharing an edge
  - isolated clusters ($\Delta r_{\text{in layer}} > 12$ cm) dropped
  - Tracks reconstructed if remaining $N_{\text{layers}} > 7$,
    - with at least 1 layer on each side of investigated one (except 1st and last layer)
  - χ^2 with $\Delta x,y$ = Span(cm) in (x,y) / $\sqrt{12}$
- Efficiency

$$\frac{Nb\ tracks\ with \geq 1\ hit\ \delta r \leq 3\,cm\ from\ track\ impact\ in\ plane}{Nb\ of\ tracks}$$

- Multiplicity =

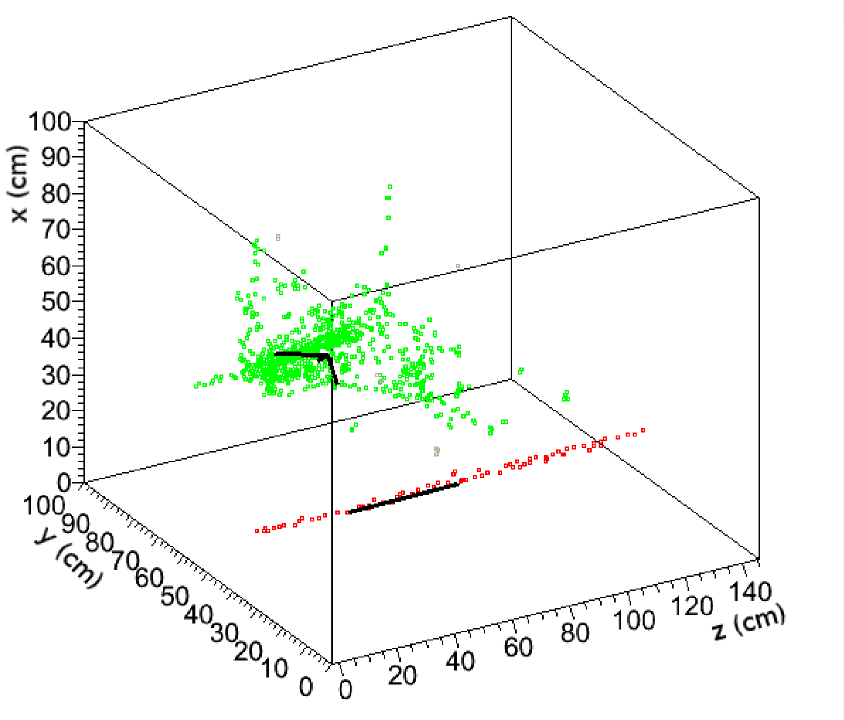
$$\langle Nb\ hit\ in\ cluster\ closest\ to\ tracks,\ if\ any \rangle$$





Particle ID

- Topological:
  - Principal Component Analysis (PCA) on all hits or clusters
  - 3 main ⊥ axis eigenvalues $\lambda_1, \lambda_2, \lambda_3$ with $\lambda_1 < \lambda_2 < \lambda_3$
    $\lambda_i \equiv \sigma$ (hits) on axis
    - λ_3 = longitudinal comp.
  - Transverse Ratio $(\lambda_1 \oplus \lambda_2) / \lambda_3$ → muons vs e, π
- Shower start
  - λ_{1p}, λ_{2p} idem to λ_1, λ_2 restricted to 1 plane
  - *1st interaction plane (FIP) ≡*
    - $\lambda_{1p} \oplus \lambda_{2p} > 1.5cm$
    - $N_{hit}^{plane} > 5$



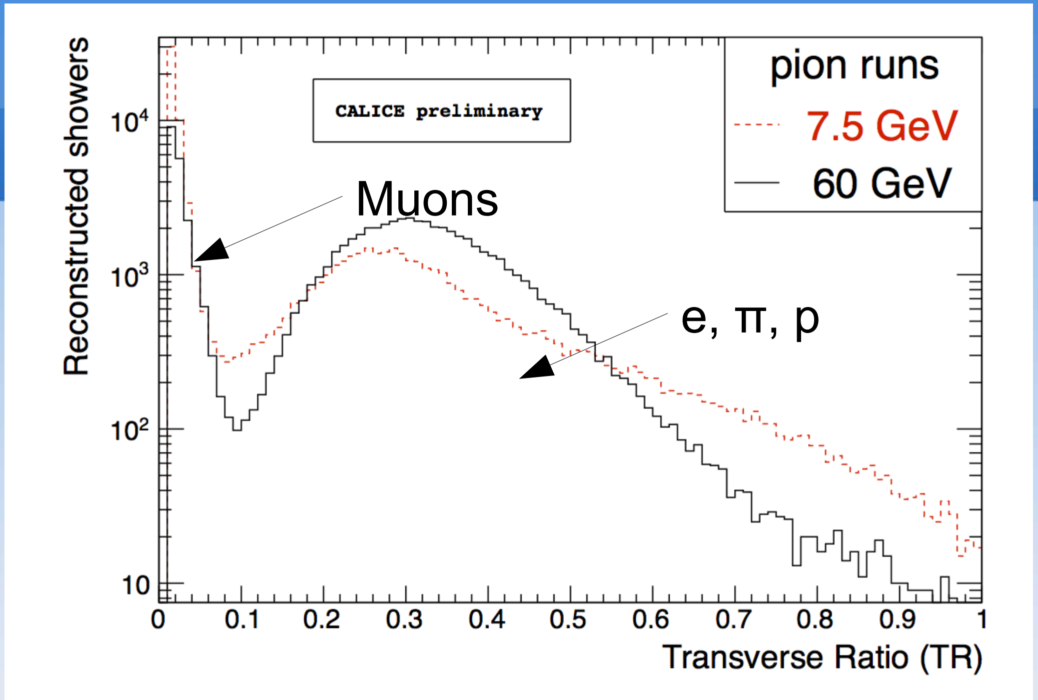
Particle ID (cont'd)

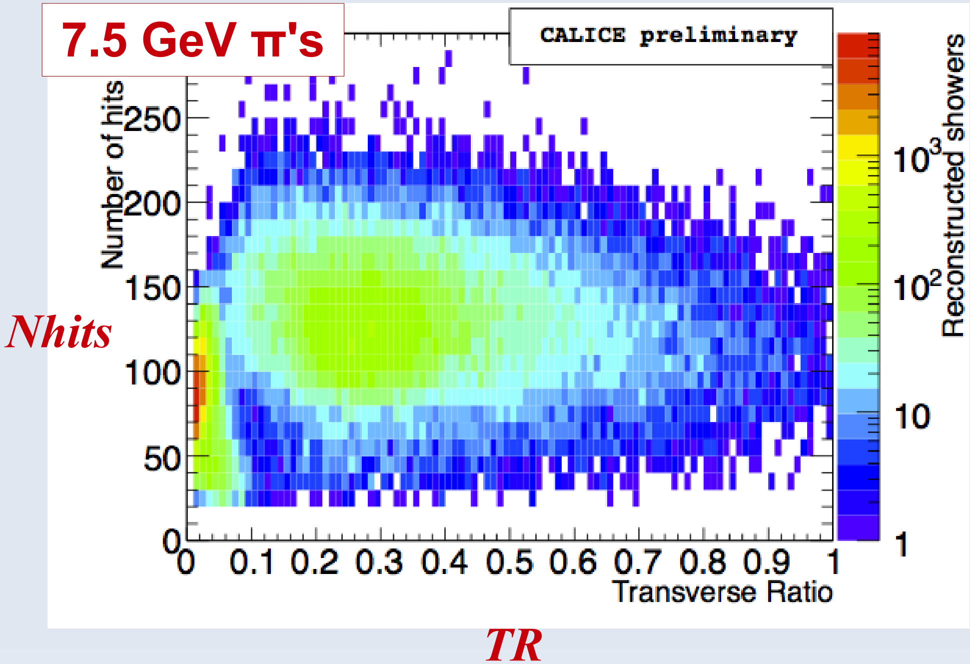
- Density
  - $V_1 = (\sum_{layers} N_{25}^{layer}) / N_{hits}$
    - $N_{25}^{layer} = N_{hits}$ in 5×5 around barycenter in 1 layer
  - $V_2 = FD_{3D} / \ln(N_{hits})$
    - Fractal dimension: $$\mathrm{FD}_{3\mathrm{D}} = \frac{1}{|I|}\sum_{n\in I}\frac{\ln(N_{\mathrm{hit}}/N_{\mathrm{cube}}(n))}{\ln(n)}$$

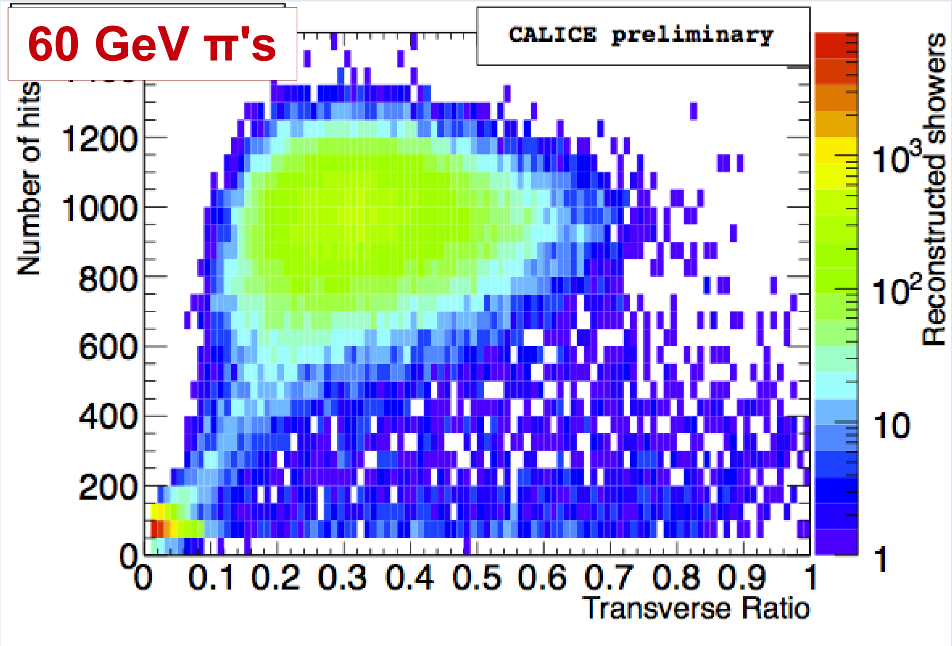
    $N_{cube}(n)$ ≡ number of cube in I={2,3,4,6,8,12,16}
- *Clustering :*
  - removal of isolated hits and tagging of overlapping events
  - MST à la charm-II using $$D_{\alpha,\beta} = \left|\mathrm{plane}_\alpha - \mathrm{plane}_\beta\right| + 2\times\left(\left|I_\alpha - I_\beta\right| + \left|J_\alpha - J_\beta\right|\right)$$
    - $N_{hits} > 25$; $\lambda_3 > 4.5$ cm; $\lambda_2 / \lambda_3 > 0.01$.

Event selection

- μ rejection:
  - Transverse ratio
    TR ≥ 0.1 → 98% of μ's

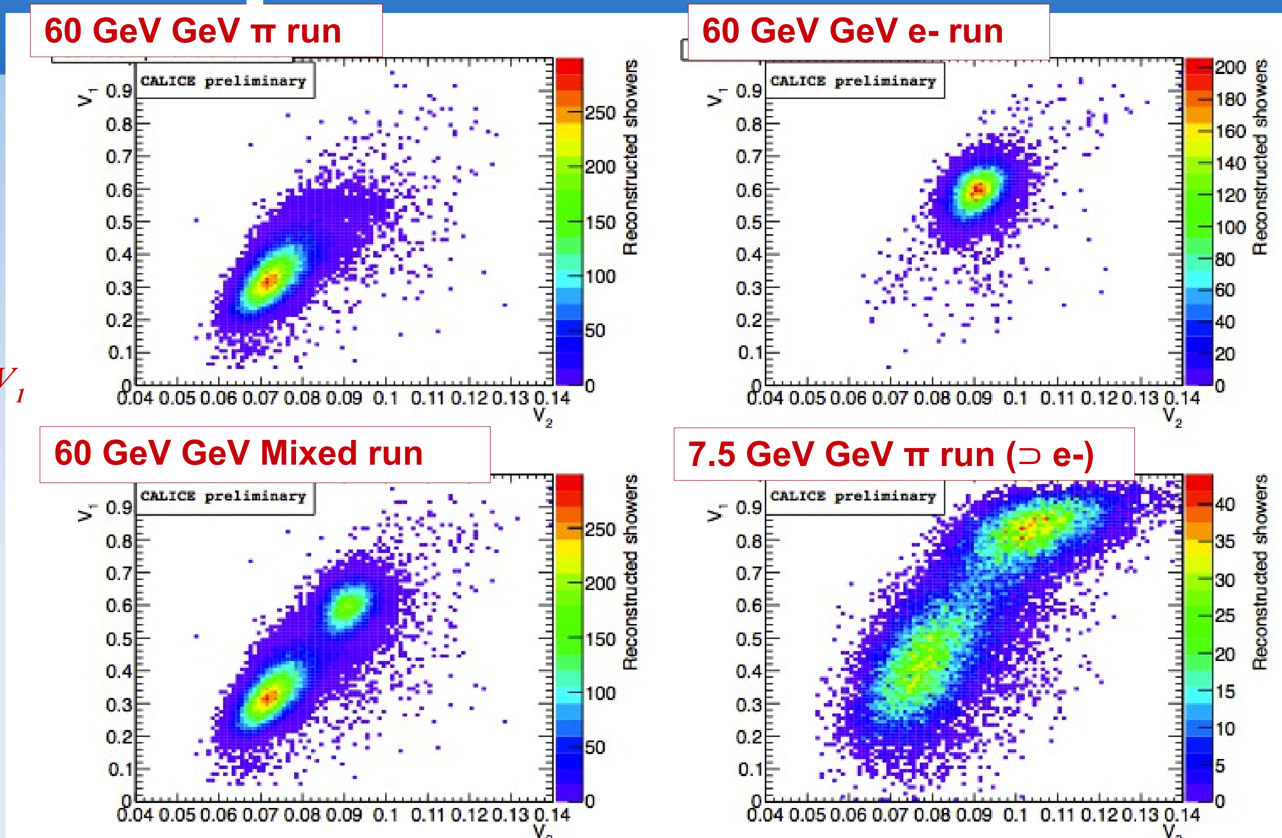






e/π separation

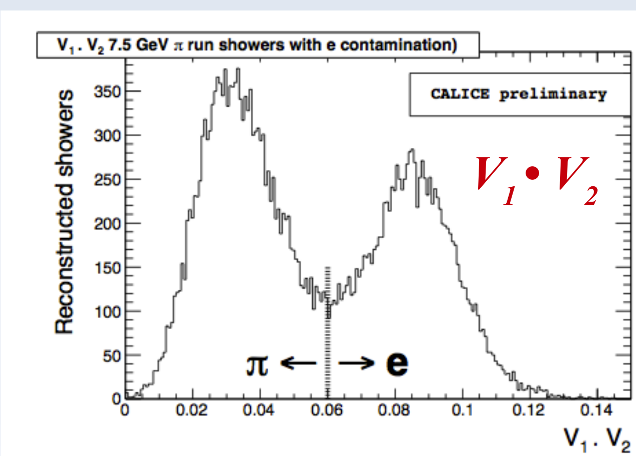
lateral density V_1

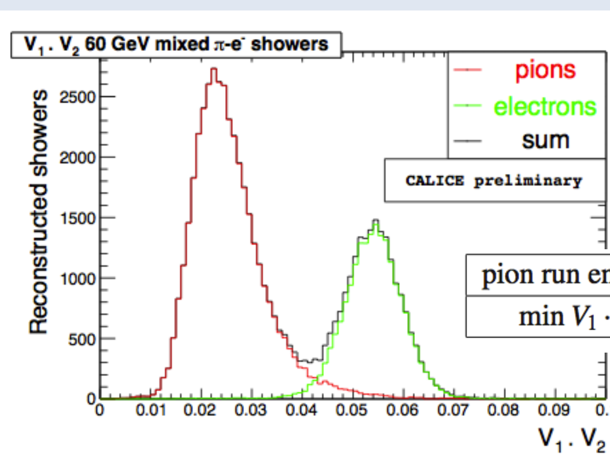


Fractal Dimension V_2

- Operation on clusters
- Negligeable loss of π's @ HE
- few % e- residual contamination @ LE

10% variation of cut ⇒ Systematics





Variation of cut with E_{beam}

pion run energy (GeV)	5	7.5-15	20	30-40	50-60	70-80
min $V_1 \cdot V_2$ value	0.065	0.06	0.055	0.05	0.045	0.04

Leakage reduction

- FP # ≤ 4.
  - removes cosmics (lateral entrance)
- First Interaction Plane (FIP) # < 15
  - removal of late interacting hadrons.

OR
- The last shower plane (LP) # < 42
- or Nhit(last 7 planes) / Nhit(first 30 planes) < 0.15

- The first (last) plane (FP, LP) of the reconstructed shower
  - containing a hit:
  - could be ≠ from interaction plane

After all Selection

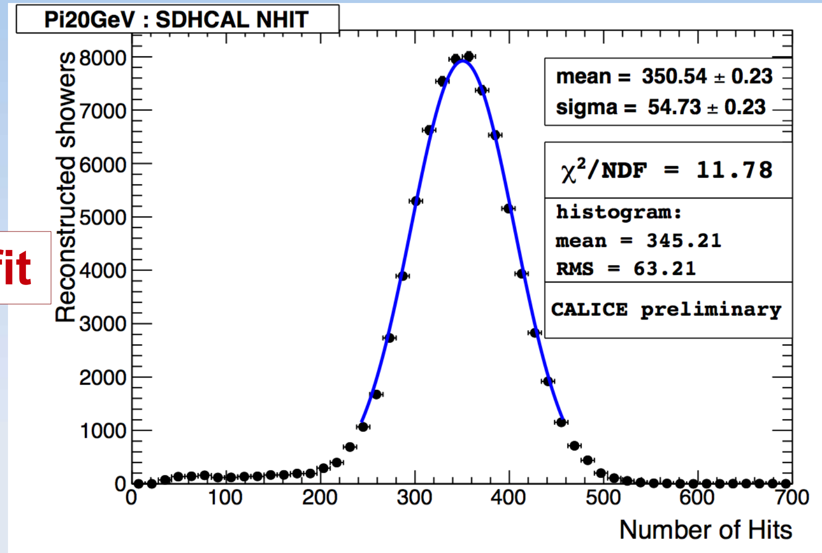
Energy [GeV]	Number of π's events
5	9504
7.5	15074
10	20406
15	33405
20	78391
25	59495
30	53179
40	48720
50	76566
60	38917
70	30893
80	32964

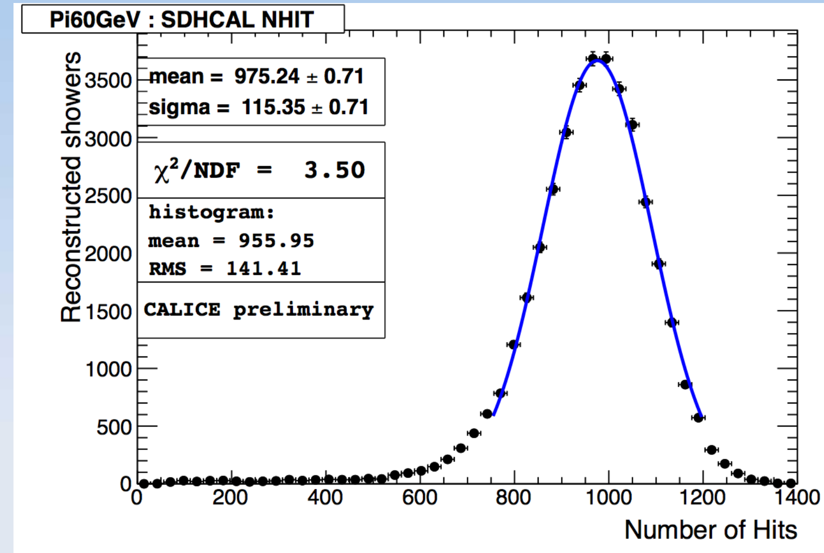
Results

Raw number of hits (binary HCAL)

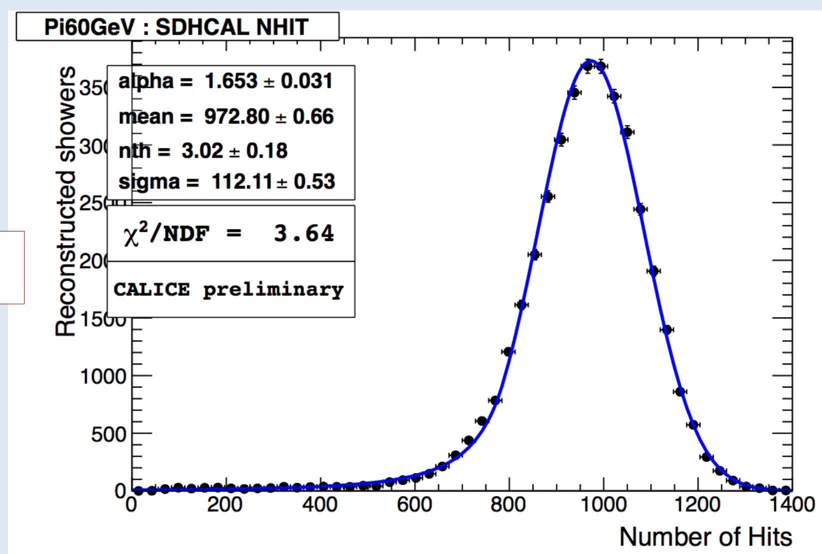
20 GeV π's | **60 GeV π's**

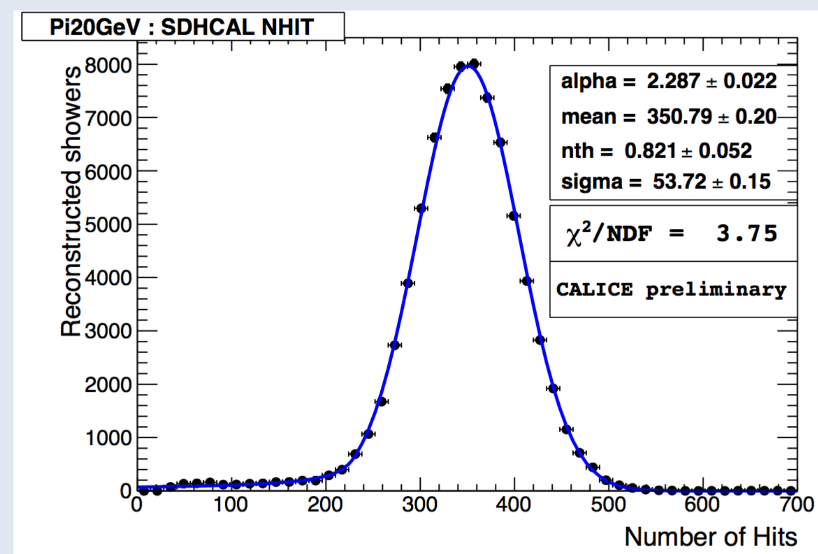
±2σ Gaussian fit



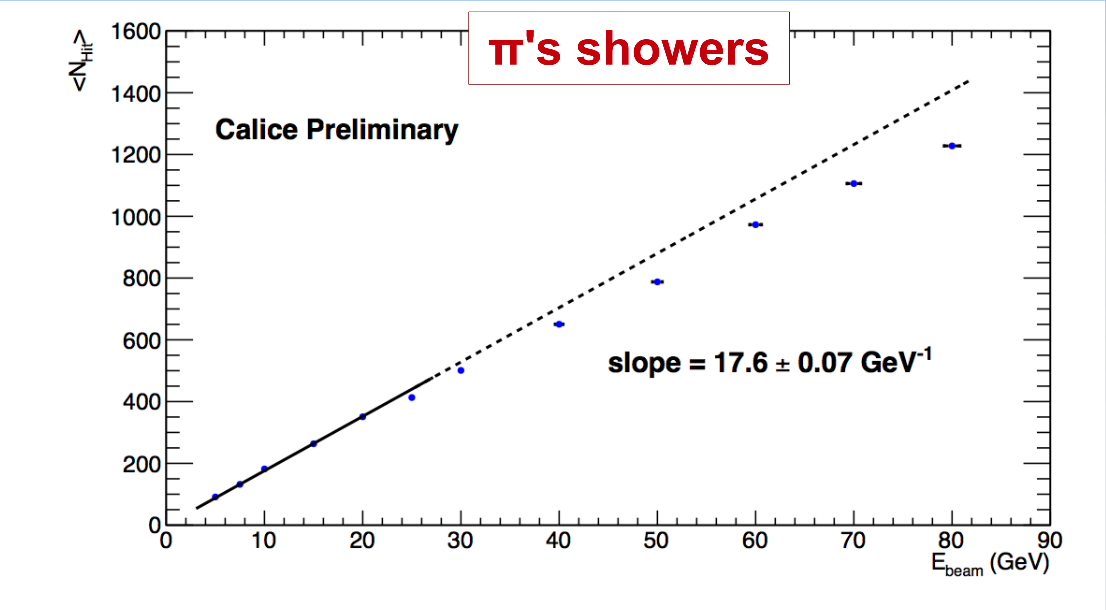


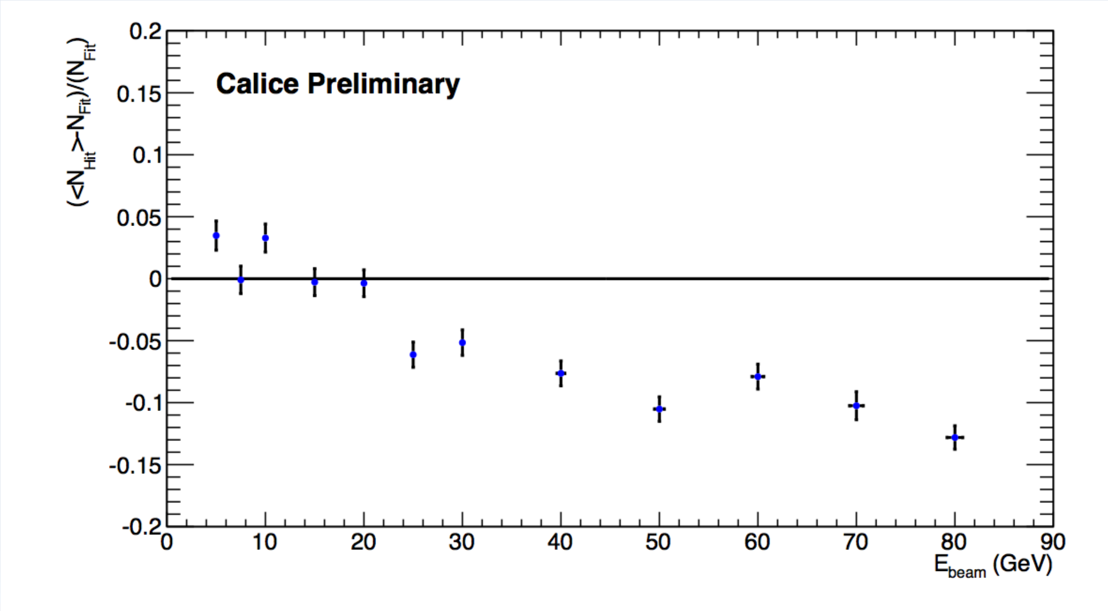
Crystal Ball fit





Nhit response (binary HCAL)





- Saturation observed for $E_{beam} \geq 30$ GeV
- Offset (~4 hits) compatible with noise over 3 clock cycles
- Fit by quadratic function:

  E = (C+ D • Nhit) Nhit

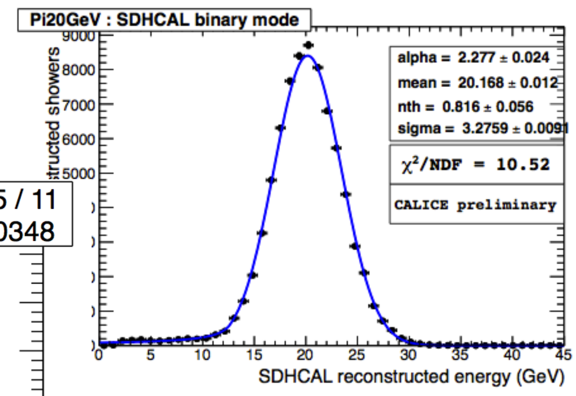
  yields:

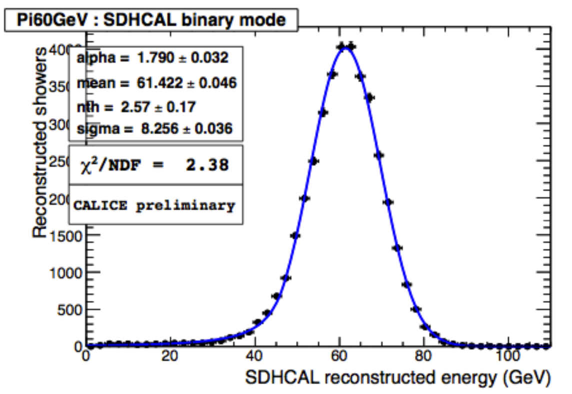
  C = 54.3 MeV

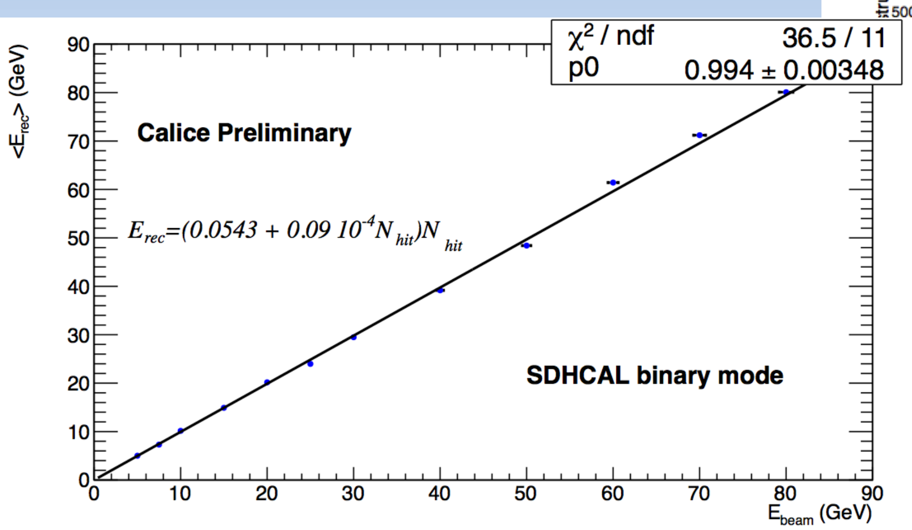
  D = 0.009 MeV

Linearised response (event by event)

Crystal Ball fit

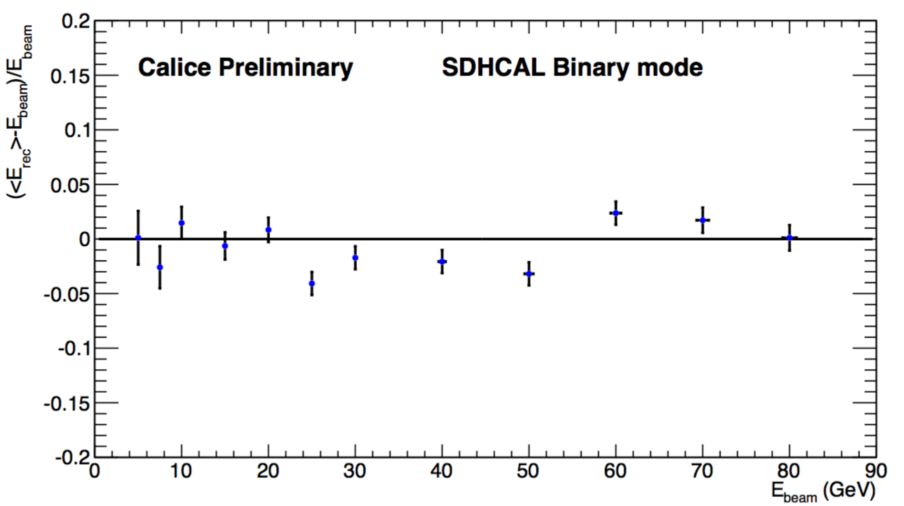


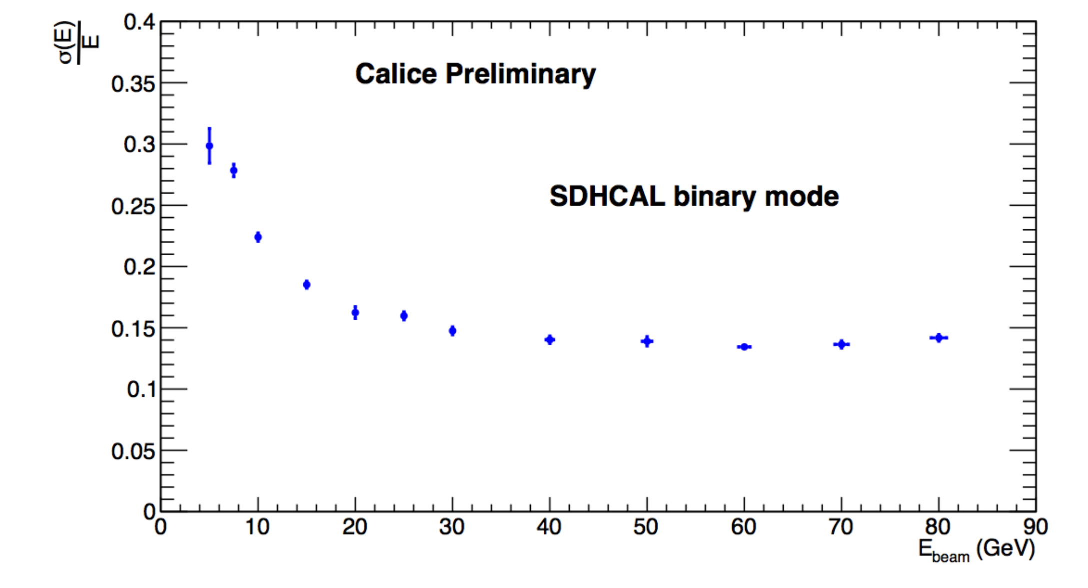




Width (Gauss, CB) → σ(E)/E

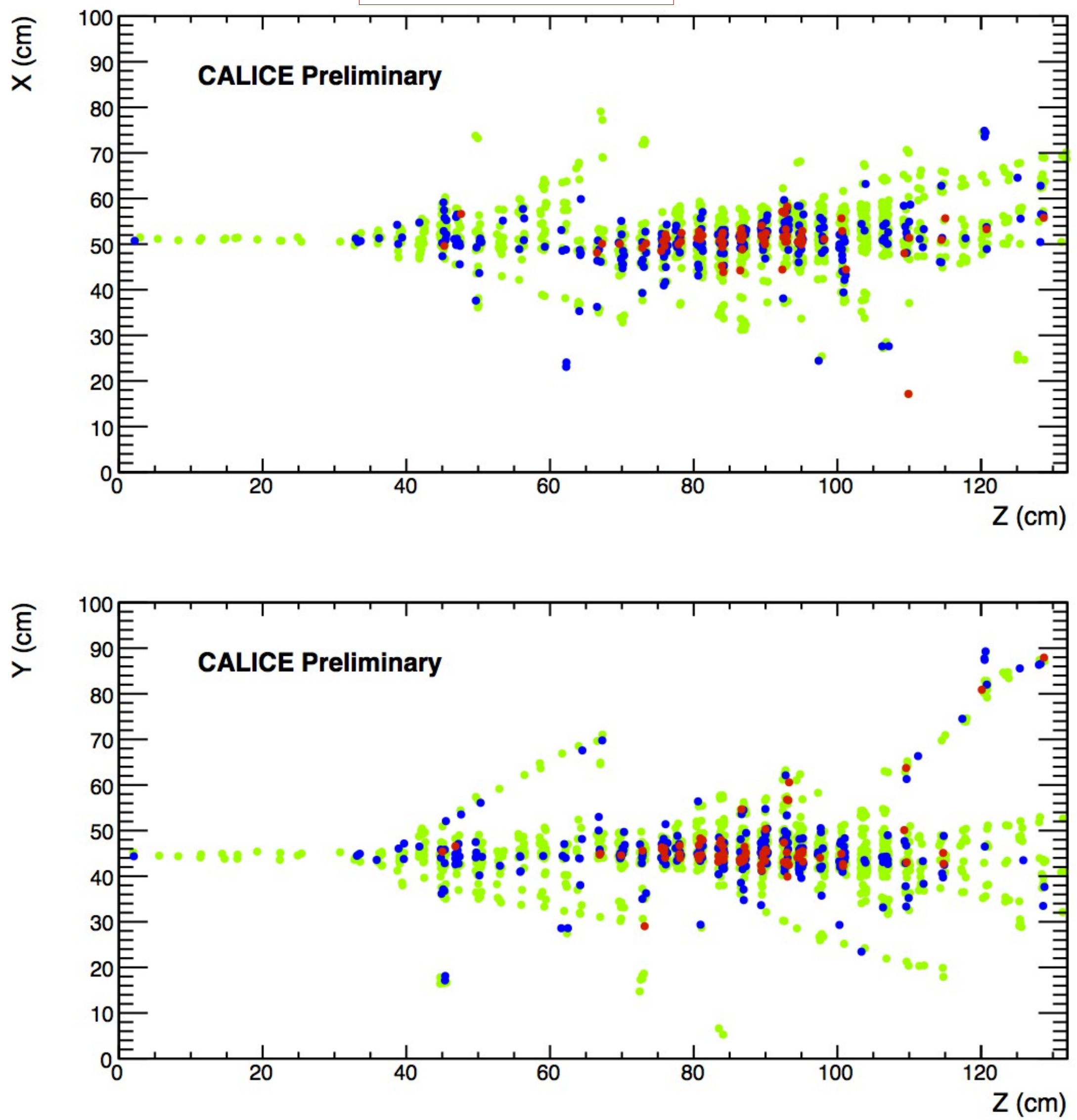
- Err = Stat ⊕ δ(Gauss, CB fit) ⊕ cut var ±10%





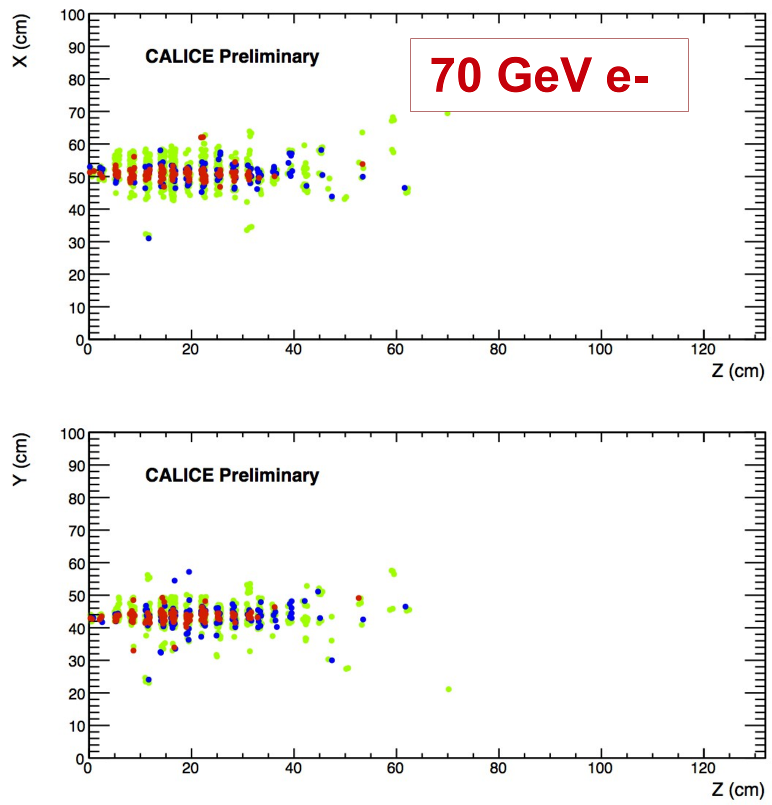
SDHCAL response (multi-thr.)

80 GeV Pion

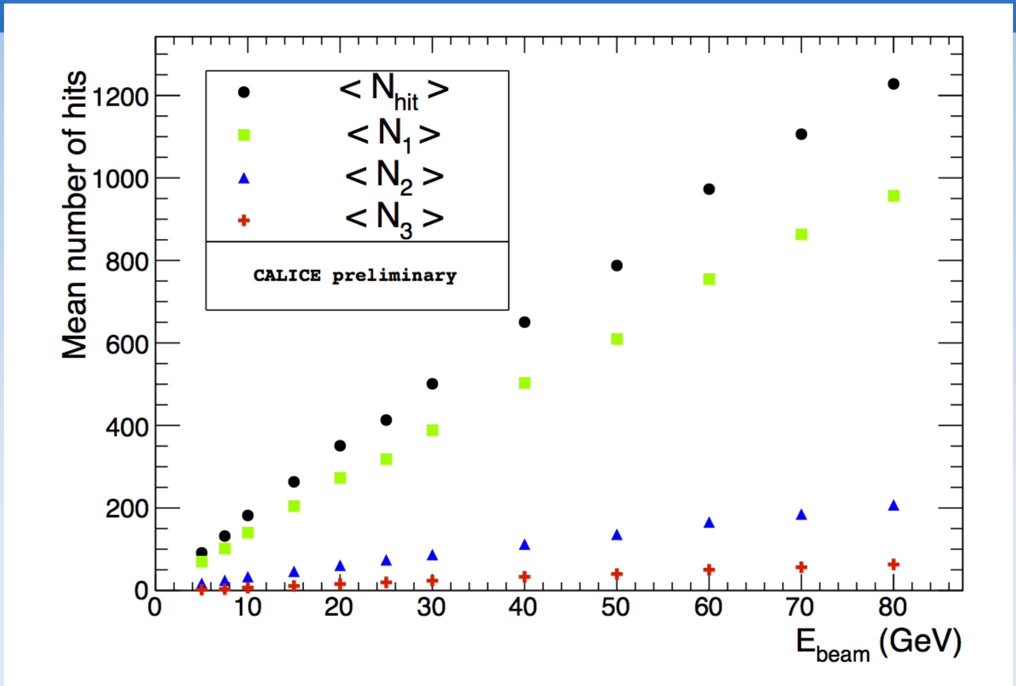


Thresholds set at
114 fC, 5 pC and 15 pC
(~ 0.1; 4; 12.5 mip)

- Additional information on shower structure



SDHCAL response (multi-thr.); Nhits



- N1 = # of Hits ≥ thr1, <thr2
- N2 = # hits ≥ thr 2, <thr3
- N3 = # hits ≥ thr3

Nhit = N1+N2+N3

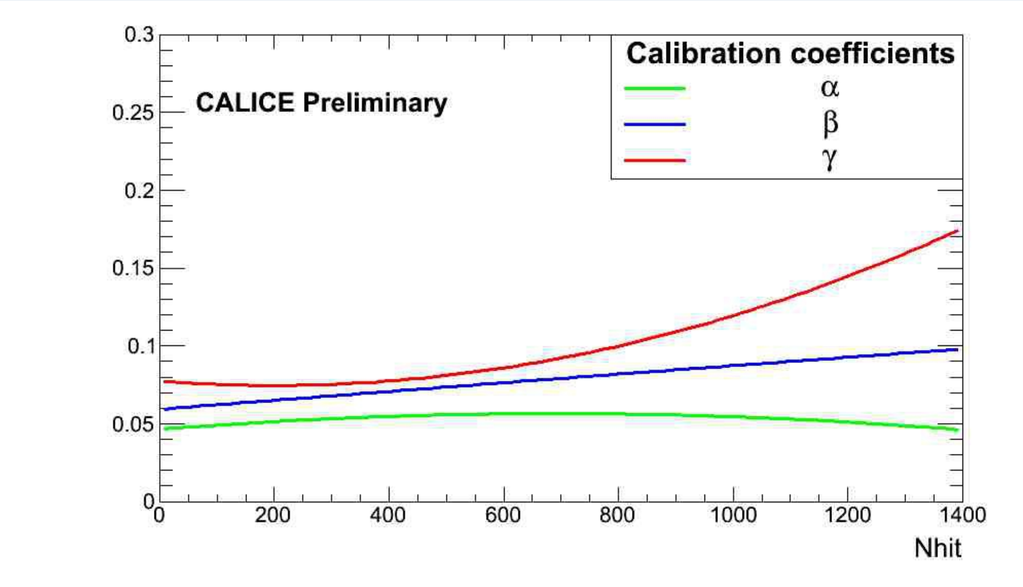
E_{rec} = α N1 + ß N2 + γ N3.
α,ß,γ = ƒ(Nhit)

- Min of χ^2 with

$$\chi^2 = \sum_i^N \frac{\left(E^i_{true} - E^i_{rec}\right)^2}{E^i_{true}}$$

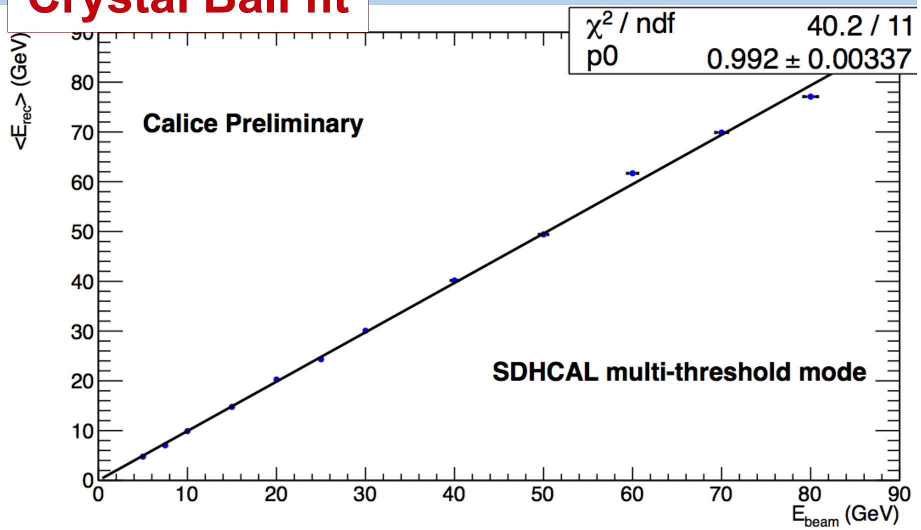
over 10, 20, 30, 40, 50 and 60 GeV samples (1/3 of stat.)

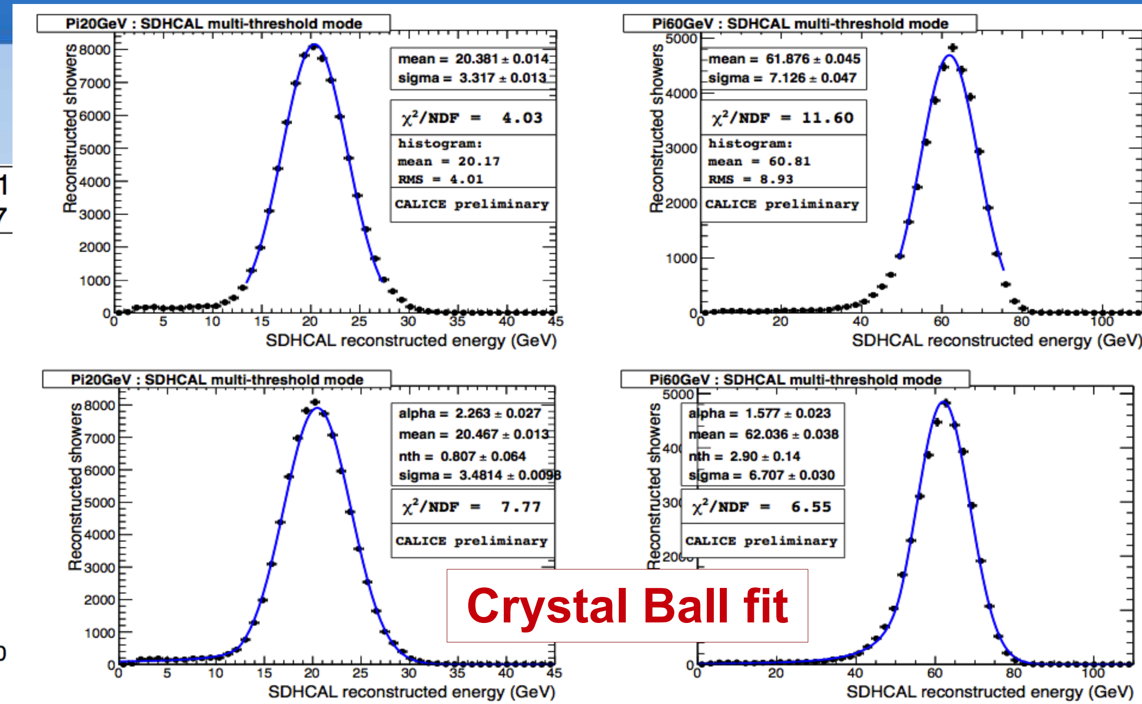
- Parametrised as quartic function of Nhit
- Valid for *single – known – particle...*

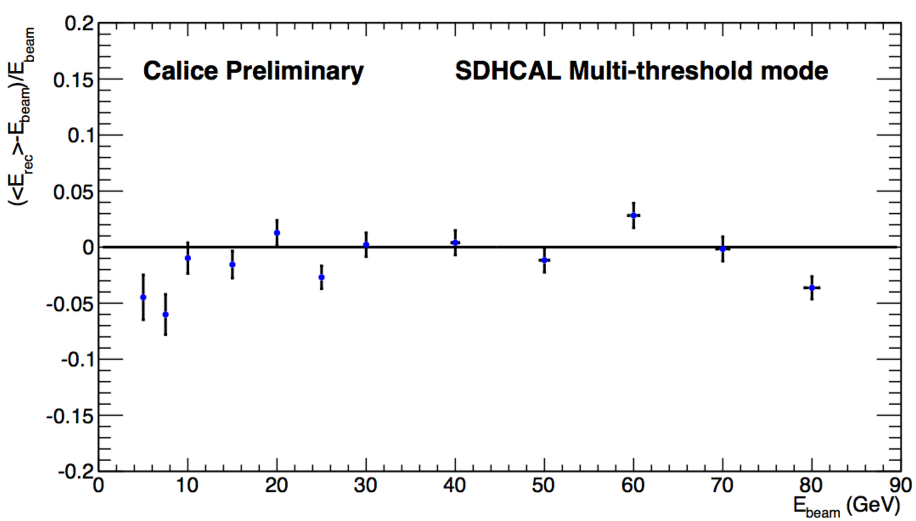


SDHCAL response

Crystal Ball fit

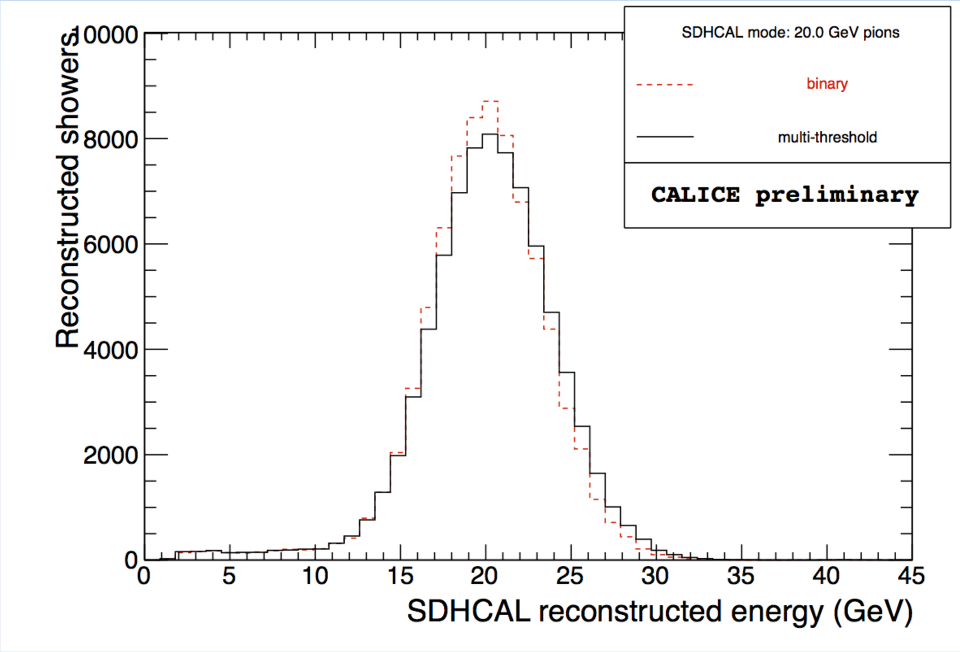


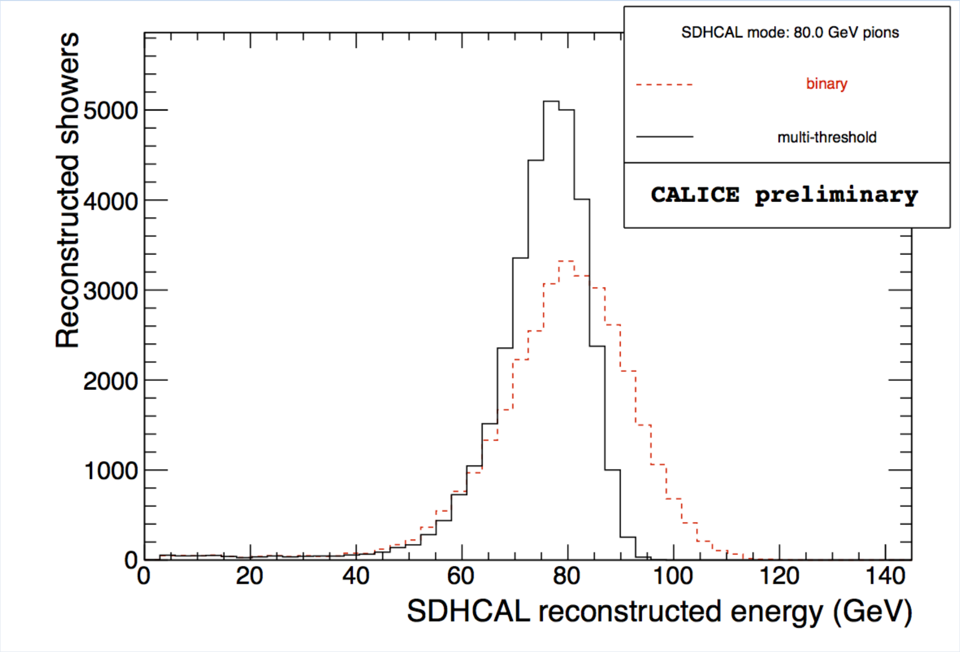




- Linearity ≤ 5% over full range
  - Tuning done for $E_{beam} \geq 10$ GeV
  - e- contamination @ low E.

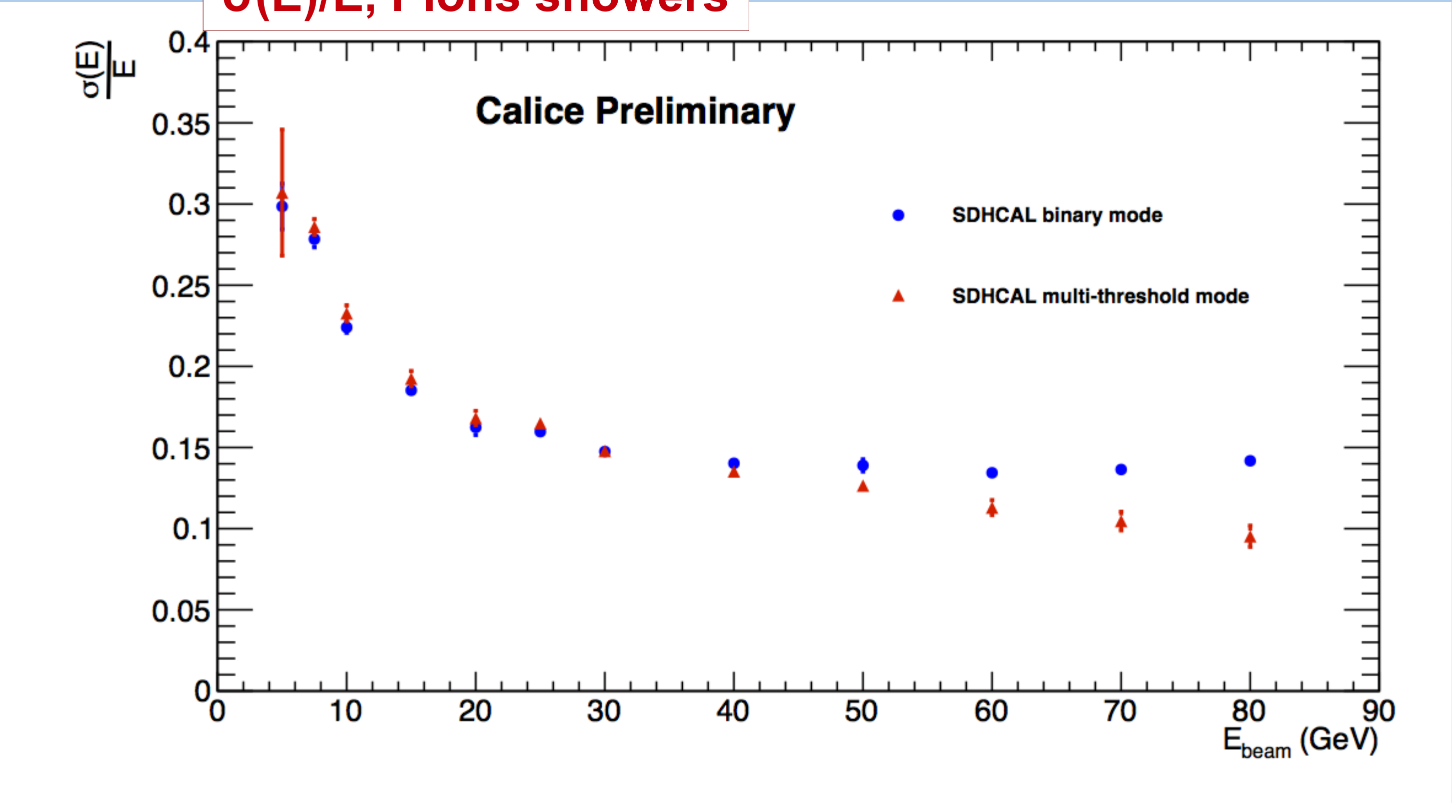
SDHCAL: binary vs multi-thr.





SDHCAL binary & multi-thr modes

σ(E)/E, Pions showers

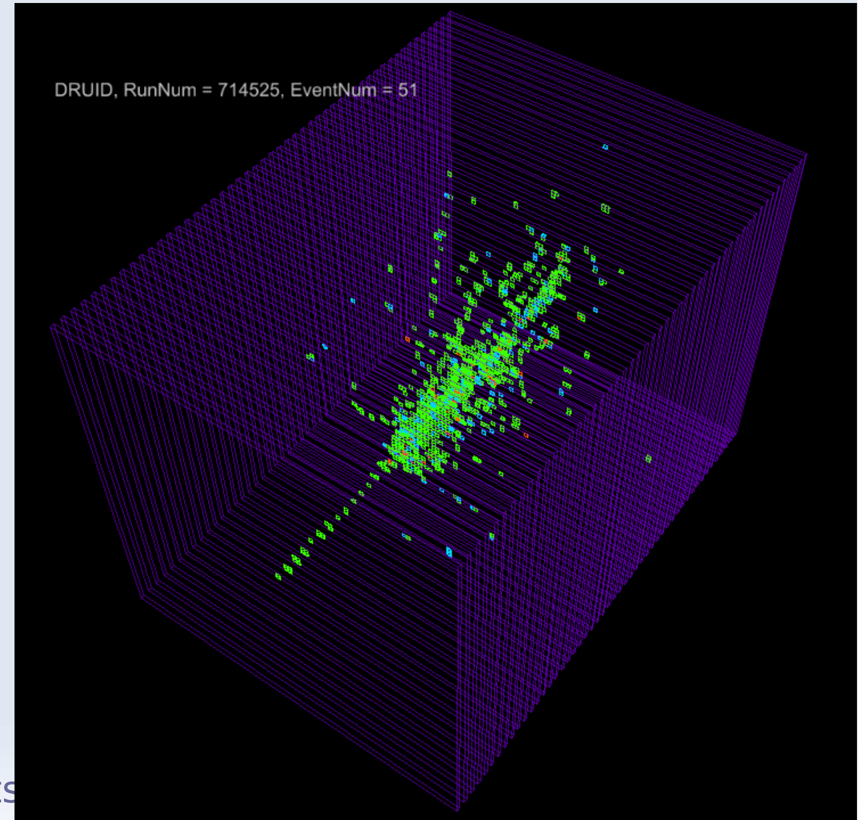


- Raw resolution of **untuned** calorimeter
  - SDHCAL
  - DHCAL
- Single pions, filtered for leakage
- Err = Stat ⊕ δ(Gauss, CB fit)
  ⊕ cut var ±10%SHCAL

- Visible improvement of resolution for $E_\pi \geq 50$ GeV
  - ≤10% at 80 GeV.
- Raw performances
  (no pattern recognition, PFA, ...)

Conclusion & prospects

- The CALICE technological SDHCAL-GRPC prototype was successfully tested with its 48 layers and its 6 λ_I in different places (SPS, PS)
  - Power-Pulsing allows optimal conditions (temperature, noise) and it was the running mode during this year different TB.
  - Excellent data quality was obtained in TB (especially in August with gas installation under our own control) with smooth running conditions (no intervention for the 2-week TB period).
- Preliminary results without data treatment (no gain correction, no local calibration, ...) indicate an excellent single particle energy resolution on pions
- Multi-threshold mode brings significant improvement at $E_\pi \geq 50$ GeV.
- Comparison with simulation is ongoing and will bring rich information to better understand the hadronic showers.



Back up

Crystal Ball function

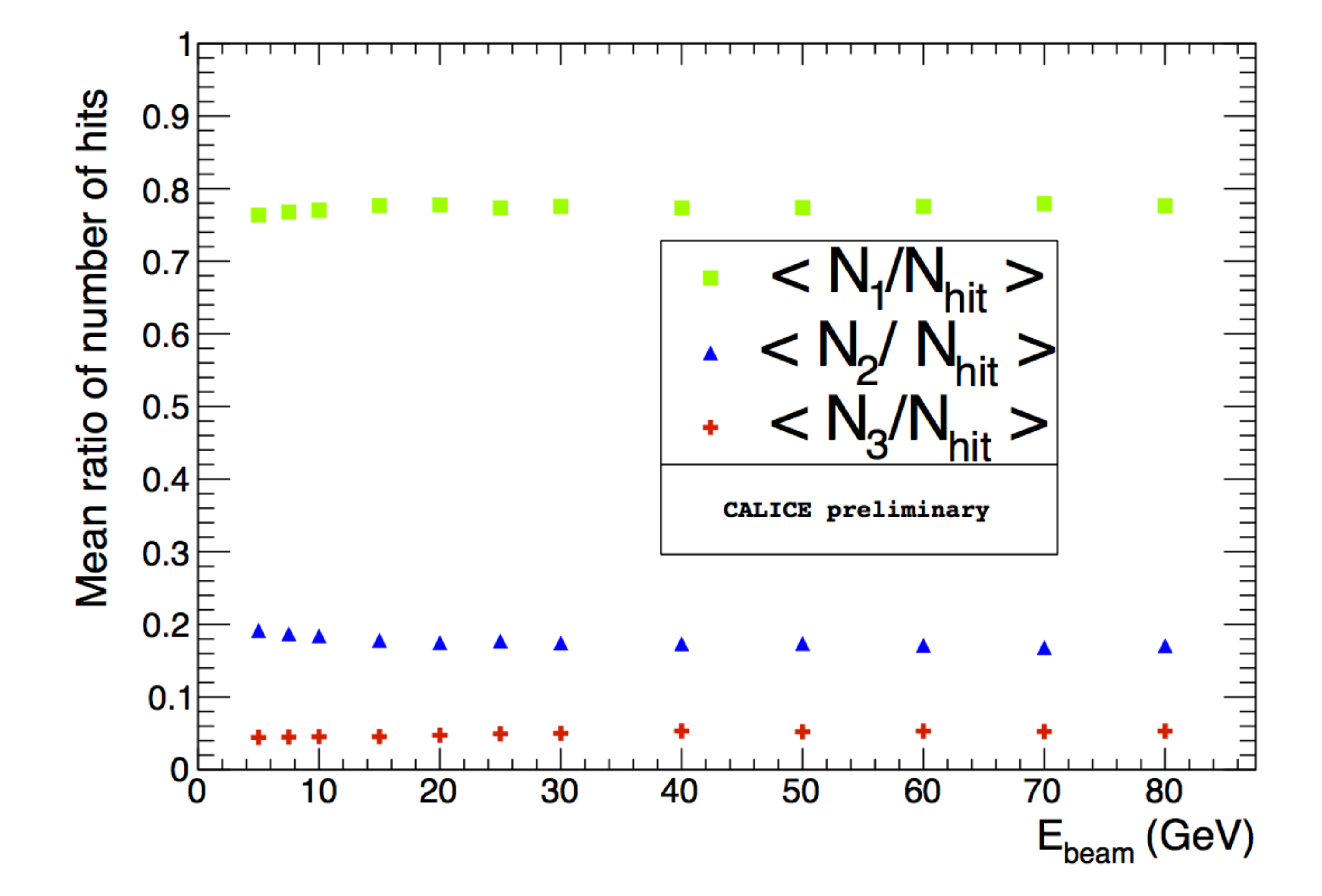
$$f(x;\alpha,nth,\bar{x},\sigma) = N \cdot \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}) & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-nth} & \text{for } \frac{x-\bar{x}}{\sigma} \leq -\alpha \end{cases}$$

where:

$$A = \left(\frac{nth}{|\alpha|}\right)^{nth} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right)$$

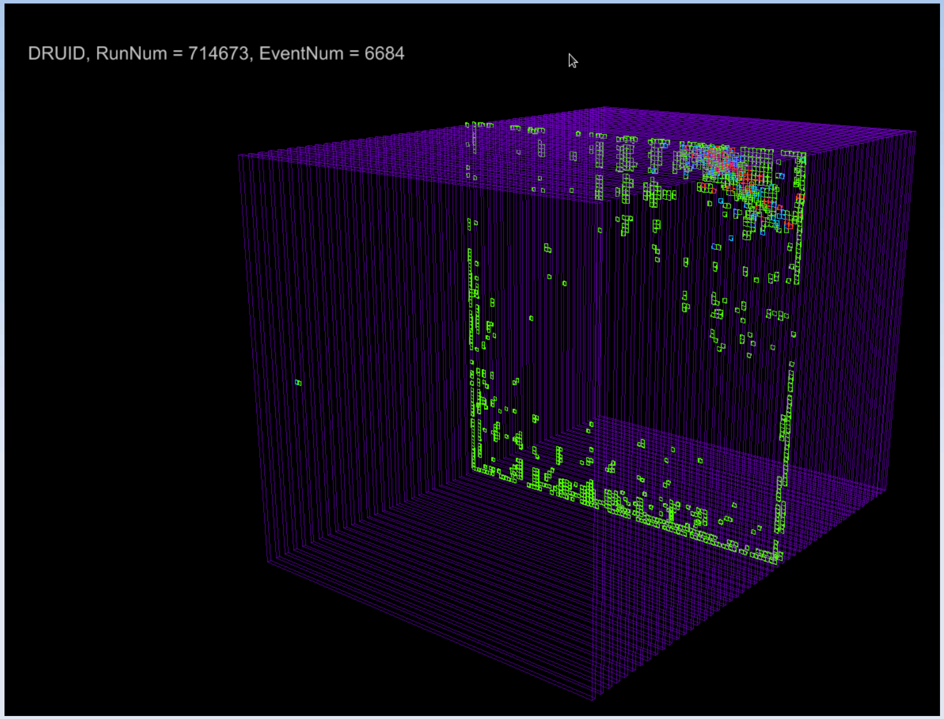
$$B = \frac{nth}{|\alpha|} - |\alpha|$$

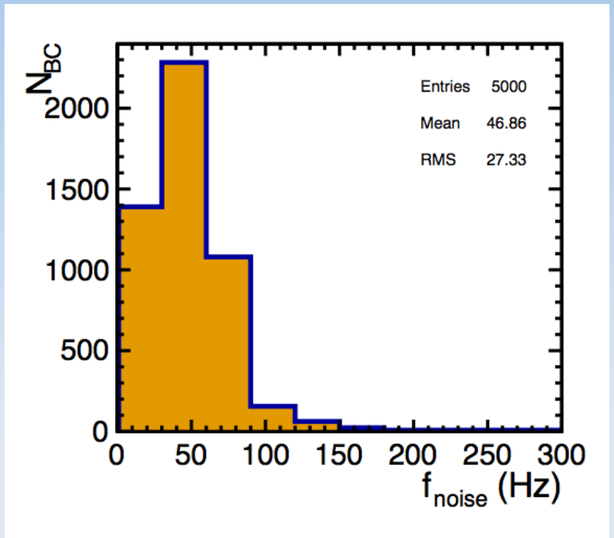
N is a normalization factor.

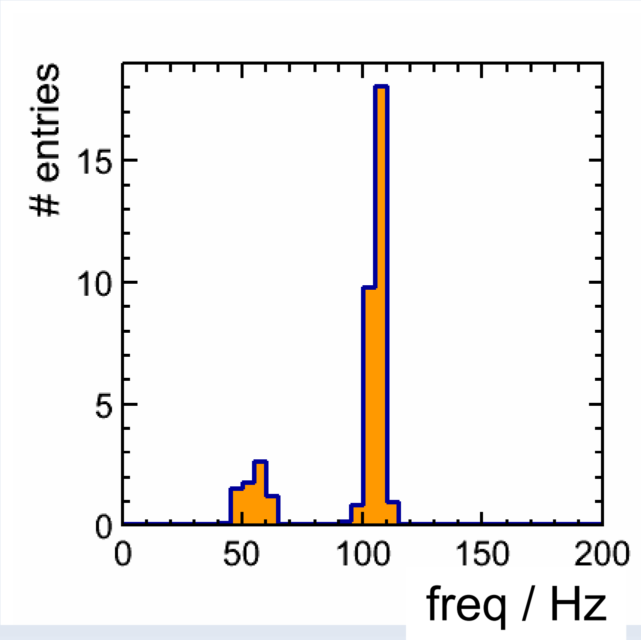


Mean ratio of number of hits
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
80
E_{beam} (GeV)
$< N_1/N_{hit} >$
$< N_2/ N_{hit} >$
$< N_3/N_{hit} >$
CALICE preliminary

Coherent noise



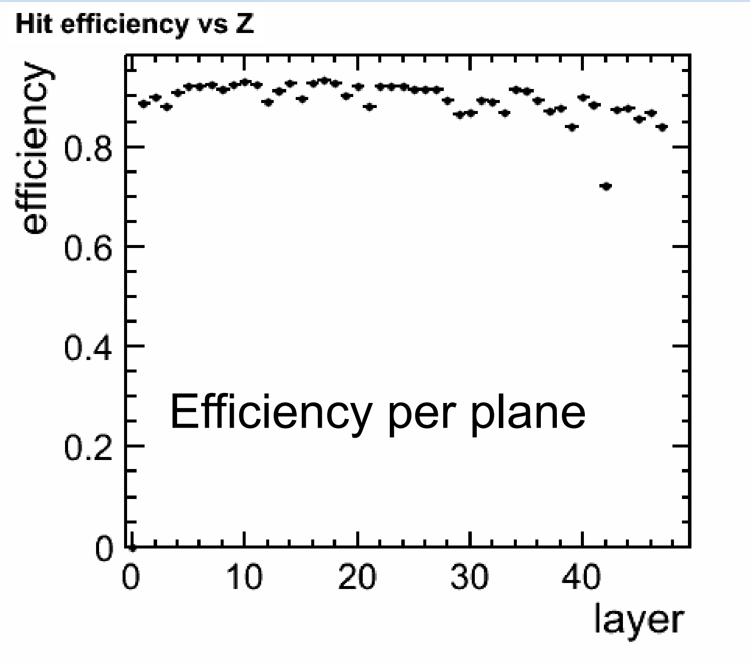


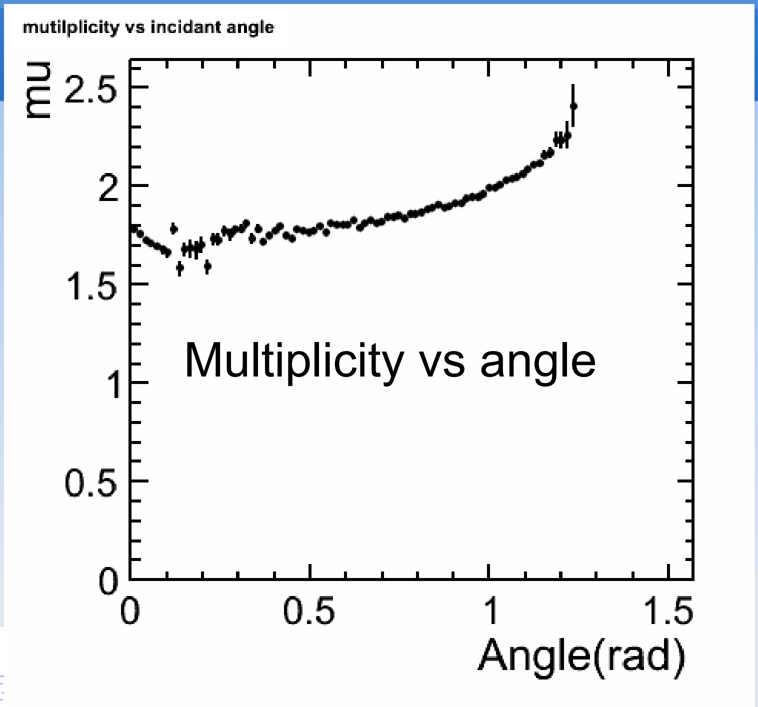


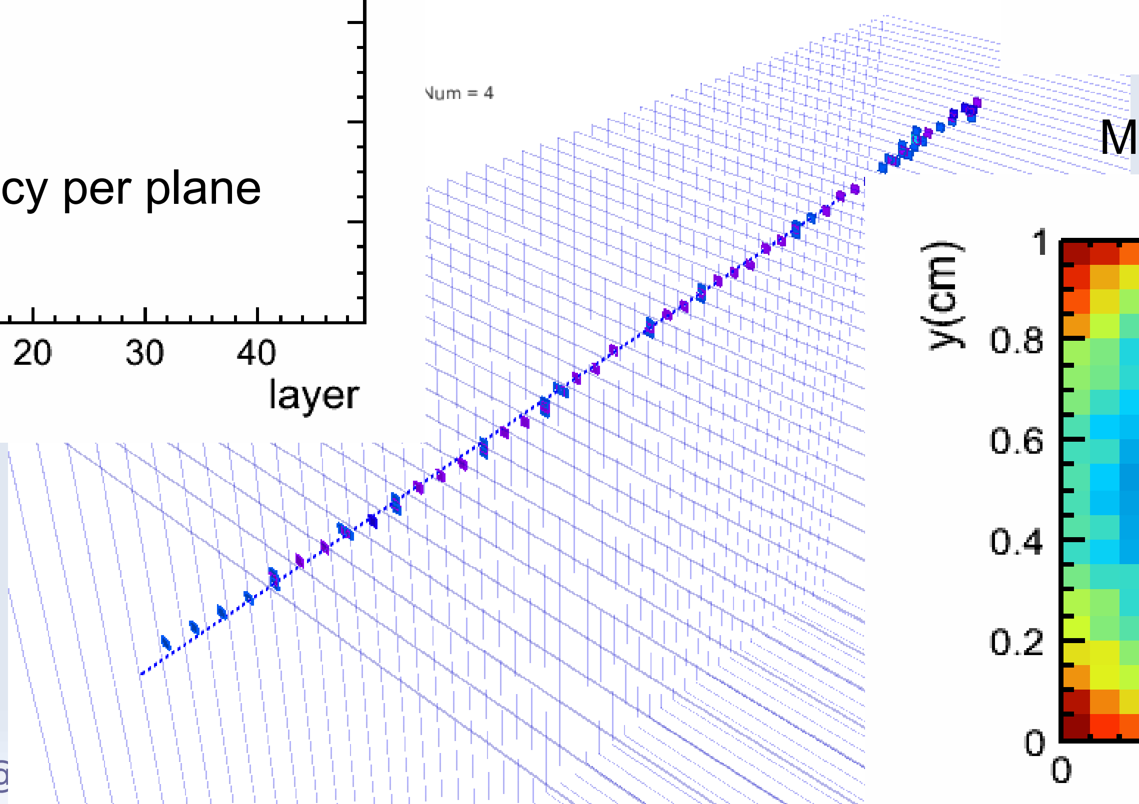
Micro structure of segmented GRPC response...

With muons (beam + cosmics), one can derive efficiencies and multiplicities per plane, per ASIC, per channel or per area smaller than a cell.

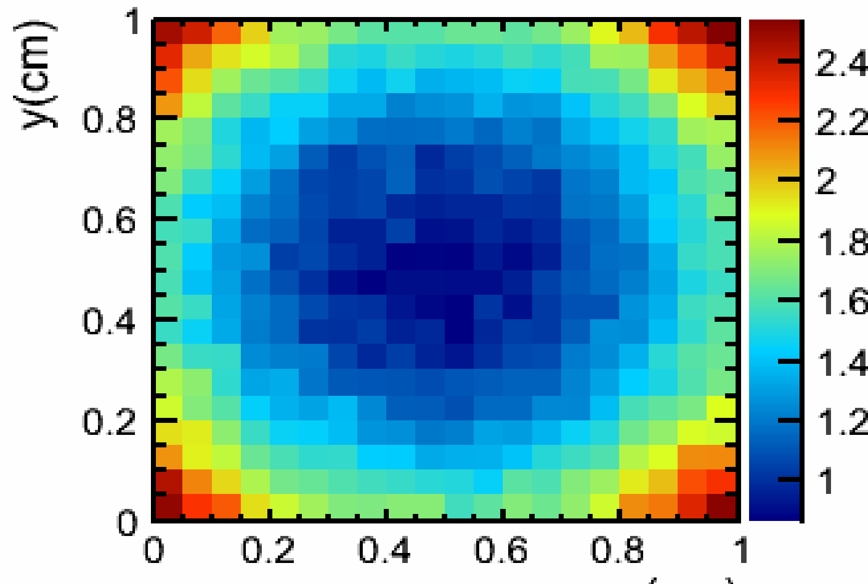
Muons recorded during august test beam.



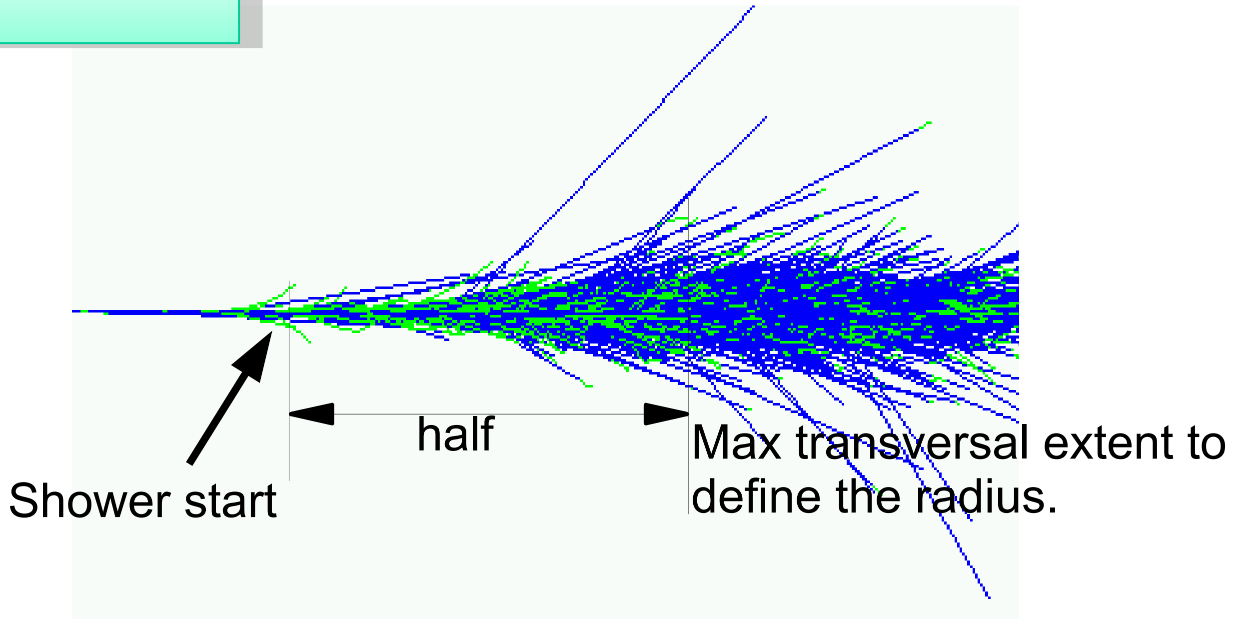




Multiplicity in a cell



Shower shape variables



Shower start = layer for which a hit has at least 8 3D-Nearest Neighbours if layer+3 has at least 12 Nearest Neighbours.

Then for each layer, clusterise the hits, removing hits which are at more than 3 rms (spatial distribution) from the center of gravity.

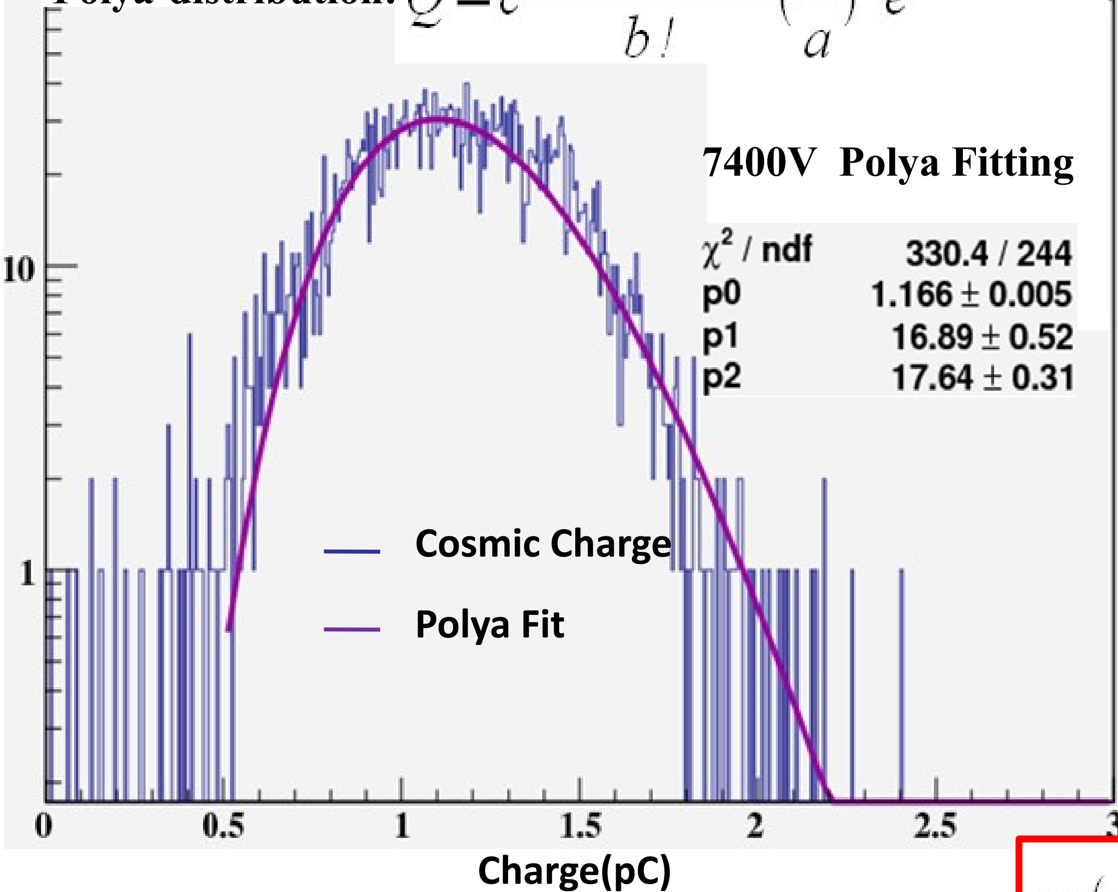
Find the layer which has the biggest spatial rms of the hit distribution. That rms is the radius.

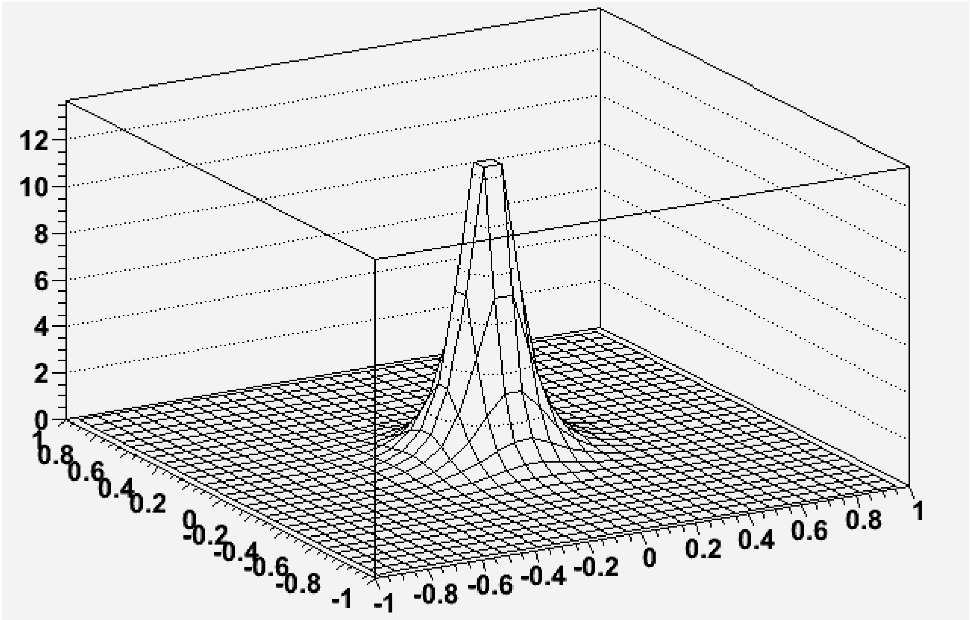
Half is the distance between the shower start layer and the layer that has the biggest spatial rms.

Comparison with simulation (I)

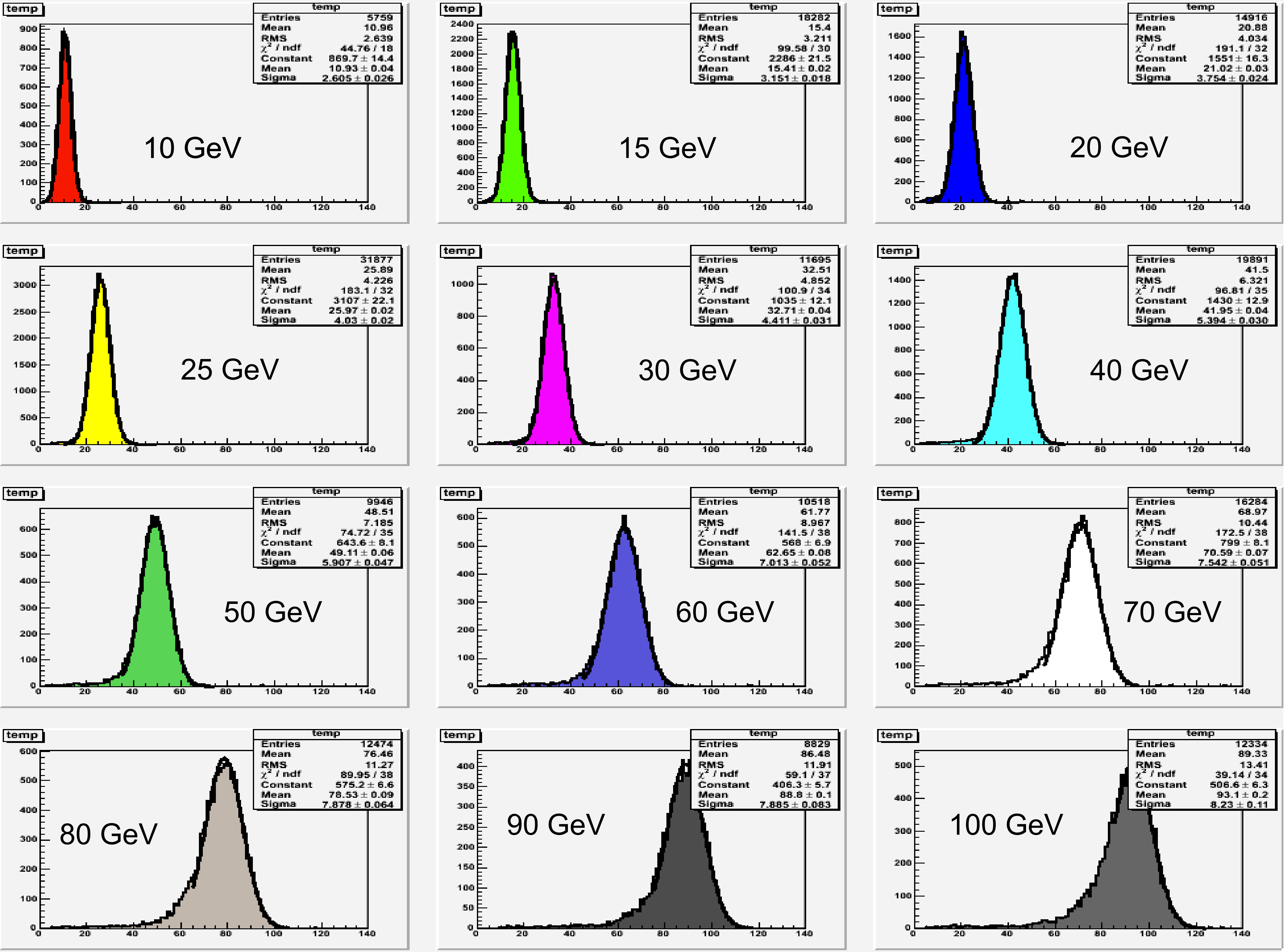
- Use standalone GEANT4 application to simulate the prototype.
- Digitisation included in the prototype

Polya-distribution: $Q = c \frac{(b+1)^{(b+1)}}{b!} \left(\frac{x}{a}\right)^{b} e^{\left(-(b+1)\frac{x}{a}\right)}$





$$\sigma(x,y) = c\,\frac{-q}{2a}\,\frac{1}{\cosh\left(\pi\frac{\sqrt{(x-x_0)^2+(y-y_0)^2}}{a}\right)}$$


10 GeV
temp
Entries 5759
Mean 10.96
RMS 2.639
χ² / ndf 44.76 / 18
Constant 869.7 ± 14.4
Mean 10.93 ± 0.04
Sigma 2.605 ± 0.026
15 GeV
temp
Entries 18282
Mean 15.4
RMS 3.211
χ² / ndf 99.58 / 30
Constant 2286 ± 21.5
Mean 15.41 ± 0.02
Sigma 3.151 ± 0.018
20 GeV
temp
Entries 14916
Mean 20.88
RMS 4.034
χ² / ndf 191.1 / 32
Constant 1551 ± 16.3
Mean 21.02 ± 0.03
Sigma 3.754 ± 0.024
25 GeV
temp
Entries 31877
Mean 25.89
RMS 4.226
χ² / ndf 183.1 / 32
Constant 3107 ± 22.1
Mean 25.97 ± 0.02
Sigma 4.03 ± 0.02
30 GeV
temp
Entries 11695
Mean 32.51
RMS 4.852
χ² / ndf 100.9 / 34
Constant 1035 ± 12.1
Mean 32.71 ± 0.04
Sigma 4.411 ± 0.031
40 GeV
temp
Entries 19891
Mean 41.5
RMS 6.321
χ² / ndf 96.81 / 35
Constant 1430 ± 12.9
Mean 41.95 ± 0.04
Sigma 5.394 ± 0.030
50 GeV
temp
Entries 9946
Mean 48.51
RMS 7.185
χ² / ndf 74.72 / 35
Constant 643.6 ± 8.1
Mean 49.11 ± 0.06
Sigma 5.907 ± 0.047
60 GeV
temp
Entries 10518
Mean 61.77
RMS 8.967
χ² / ndf 141.5 / 38
Constant 568 ± 6.9
Mean 62.65 ± 0.08
Sigma 7.013 ± 0.052
70 GeV
temp
Entries 16284
Mean 68.97
RMS 10.44
χ² / ndf 172.5 / 38
Constant 799 ± 8.1
Mean 70.59 ± 0.07
Sigma 7.542 ± 0.051
80 GeV
temp
Entries 12474
Mean 76.46
RMS 11.27
χ² / ndf 89.95 / 38
Constant 575.2 ± 6.6
Mean 78.53 ± 0.09
Sigma 7.878 ± 0.064
90 GeV
temp
Entries 8829
Mean 86.48
RMS 11.91
χ² / ndf 59.1 / 37
Constant 406.3 ± 5.7
Mean 88.8 ± 0.1
Sigma 7.885 ± 0.083
100 GeV
temp
Entries 12334
Mean 89.33
RMS 13.41
χ² / ndf 39.14 / 34
Constant 506.6 ± 6.3
Mean 93.1 ± 0.2
Sigma 8.23 ± 0.11

Note