FoCal – a high-granularity electromagnetic calorimeter for forward direct photon measurements

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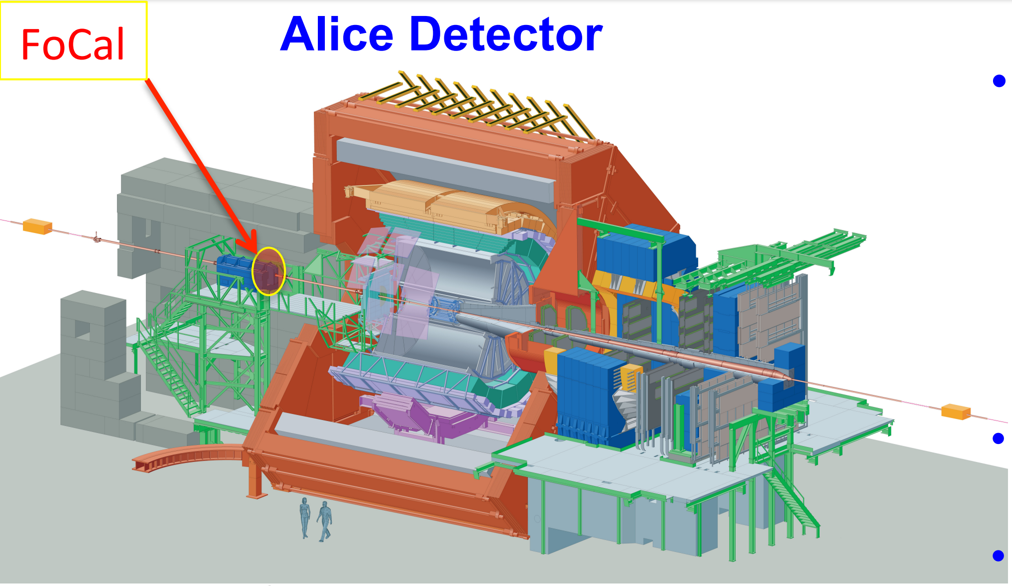
The FoCal Project



- **What is the FoCal?**

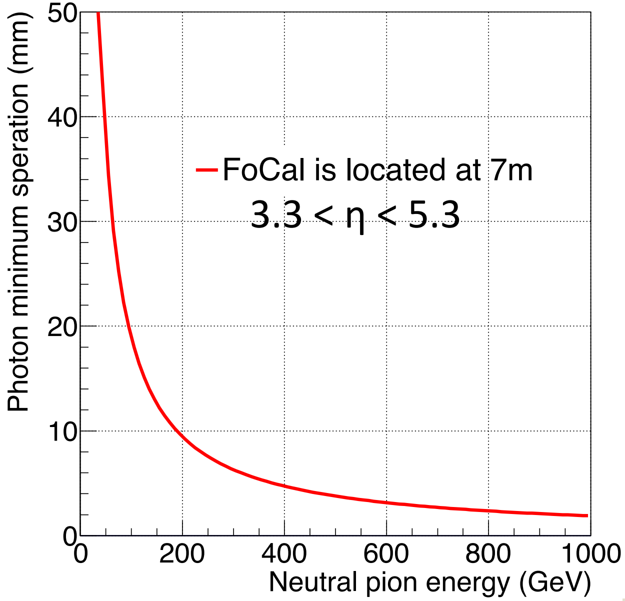
  FoCal = FoCal-E + FoCal-H

  A Forward Calorimeter for measurement of forward direct photons at the LHC, upgrade proposal in ALICE.
- **Main goal**: decisive probe of gluon-density saturation at small Bjorken-x.
- **Golden measurement**: direct photon p_T distributions in pp and p-Pb, probe Bjorken-x down to ~10^{-5}
- **Requires high-granularity detector**

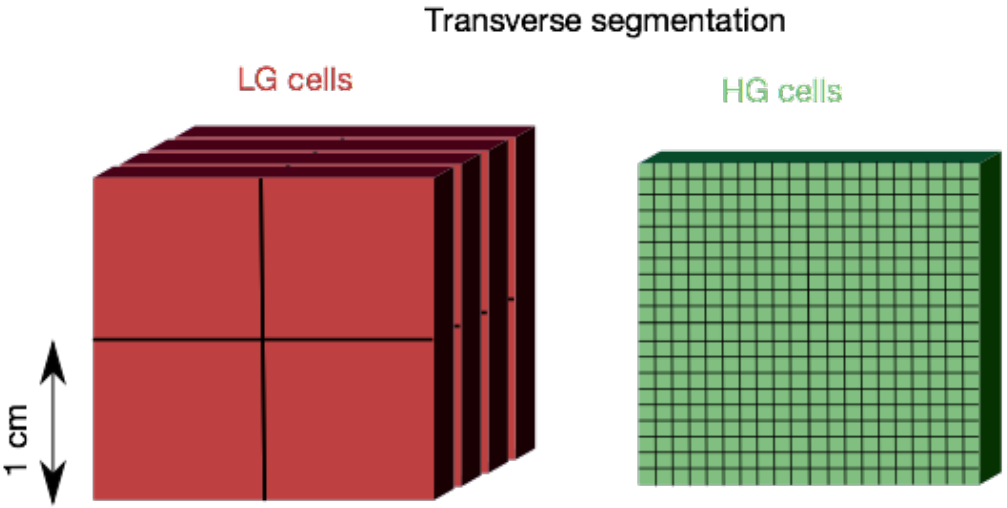
– Discrimination between direct photons and photons from π^0 decay at high energy, small opening angle from π^0 decay.

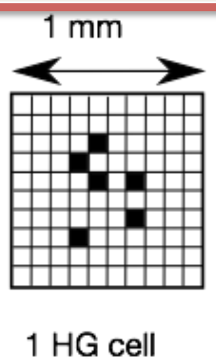
Should also allow:

– 3D shower shape analysis, particle flow.



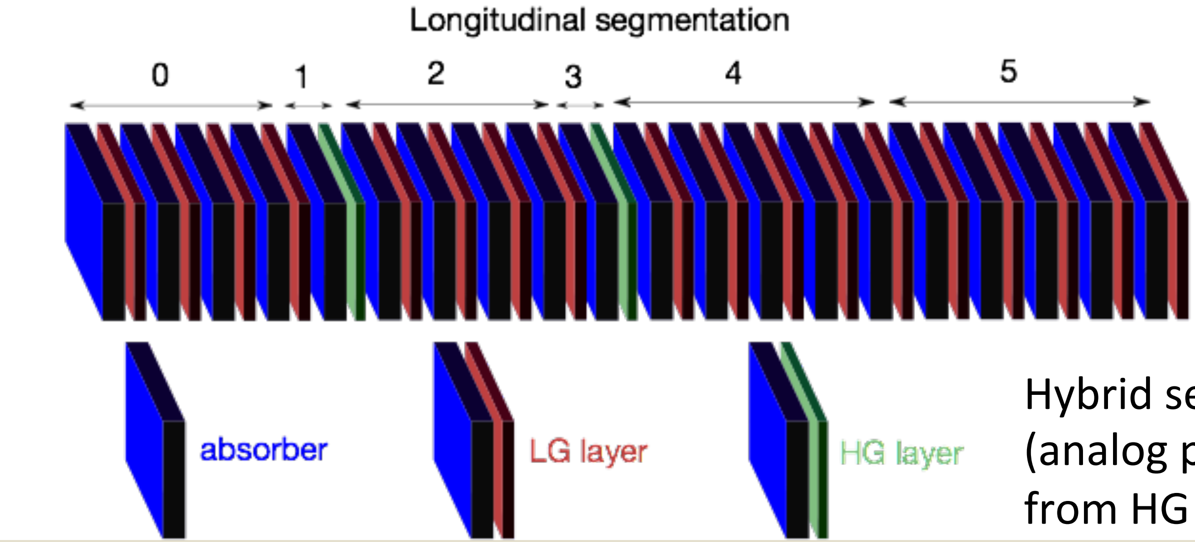
Conceptual design of FoCal upgrade





LG → Pad readout **1cm×1cm**

HG → MAPS **30μm×30μm**



Prototype model test:
Physics performance simulations have been performed and with this configuration the measurement is OK

Hybrid setup: energy measurement in LG (analog pad) layers, two-shower separation from HG (digital pixel) layers

Existing EM-calorimeters vs FoCal

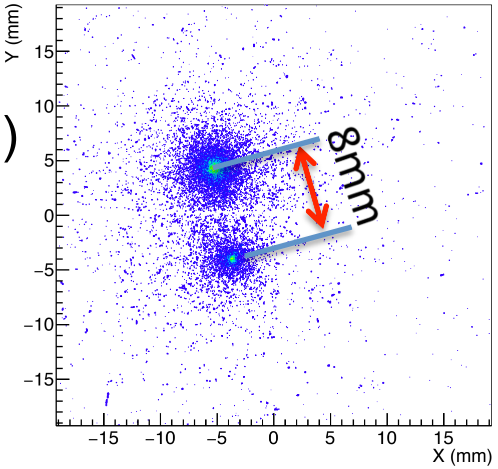
	ATLAS	**ALICE**	**LHCb**	**CMS**	**Future FoCal**	**FoCal prototype**
Absorber + sampler	Pb+LAr	Pb+sc	Pb+sc	$PbWO_4$	**W+Si**	**W+Si**
Finest Granularity (mm^2)	4.7×147	60×60	40×40	22×22	**≈1**	**0.03×0.03**
Moliere Radius(mm)	48	32	35	21.9	**<15**	**~11**

Besides the energy measurement, the proposed FoCal should enable：

1. High granularity ➔ very fine shower shape (lateral profile)
2. Small Molière Radius (90% energy deposition) ➔ small shower size

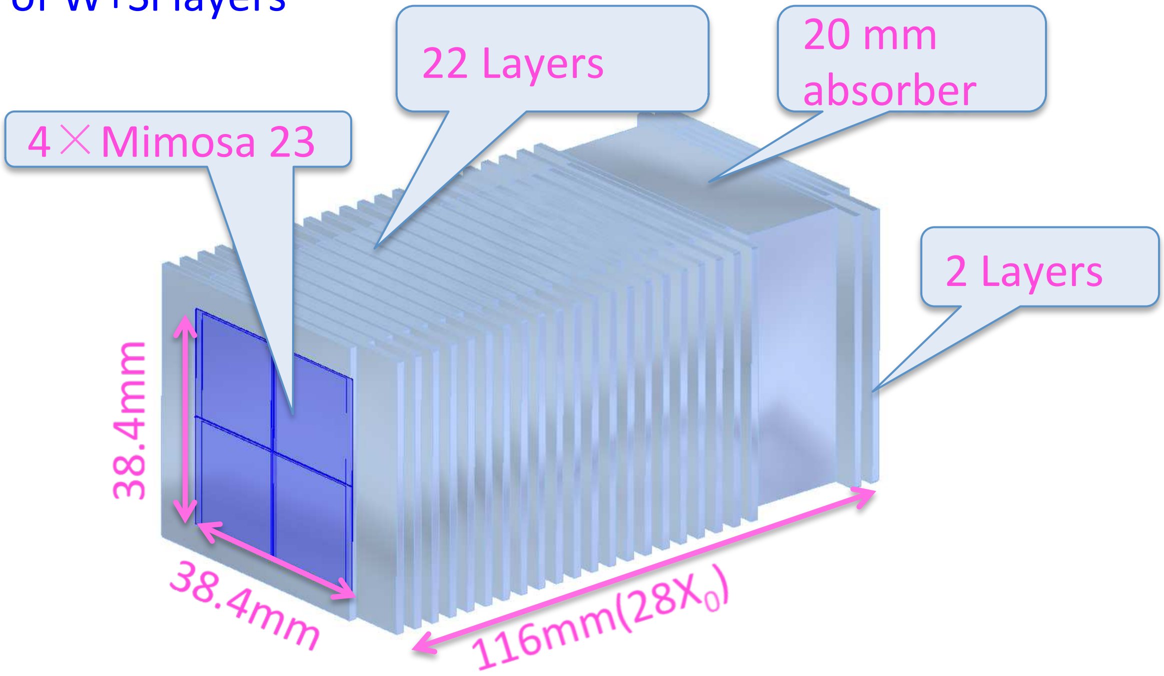
The two features are crucial for two-shower separation.

Single event measurement of two showers in prototype detector



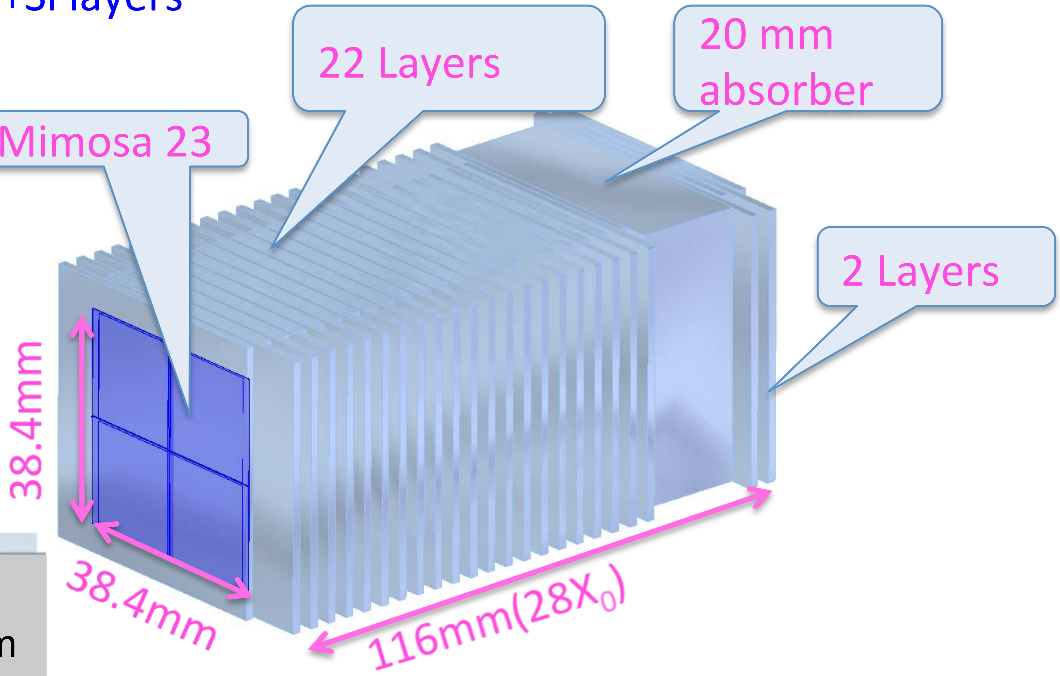
FoCal prototype

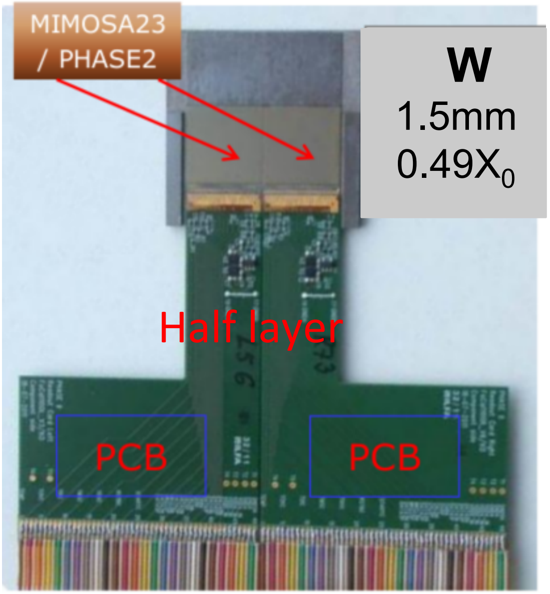
Stack of W+Si layers



FoCal prototype

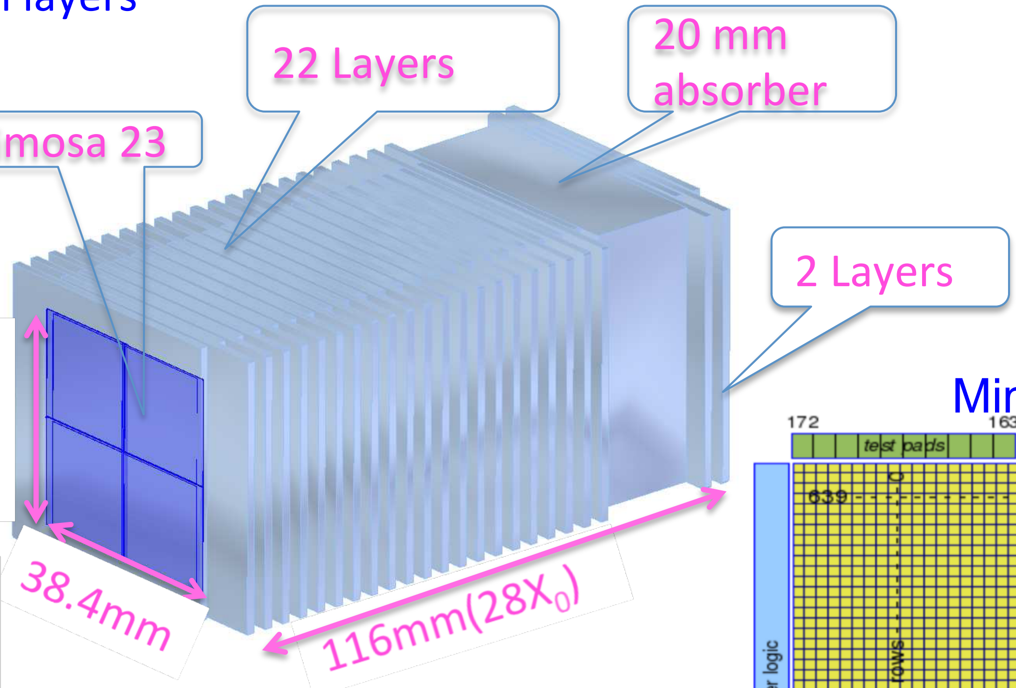
Stack of W+Si layers

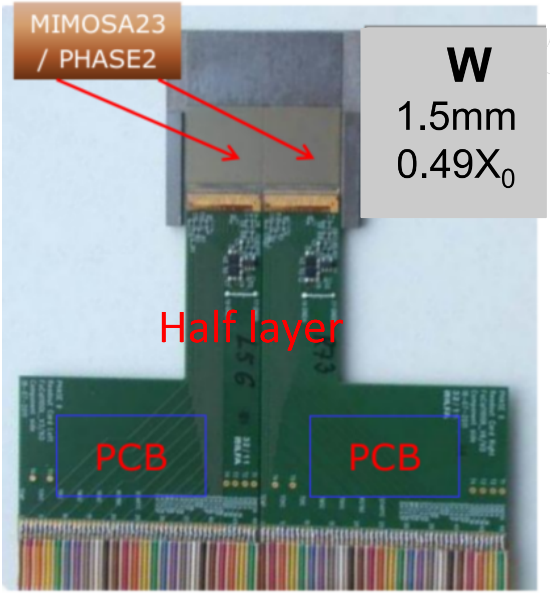




FoCal prototype

Stack of W+Si layers

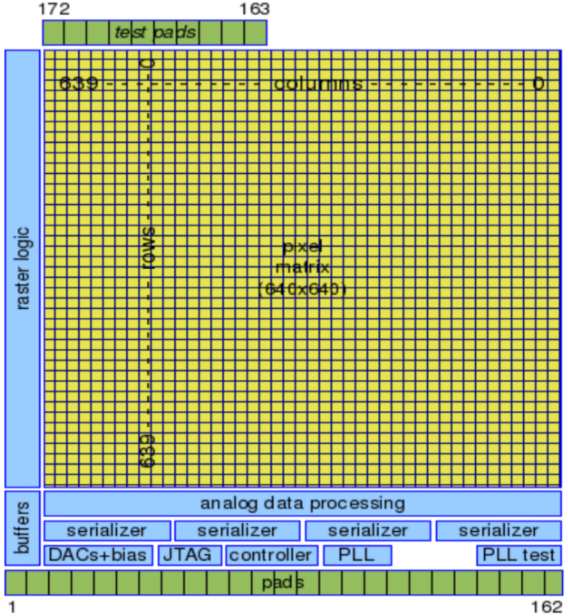




Mimosa 23 – a type of MAPS (Monolithic Active Pixel Sensor)

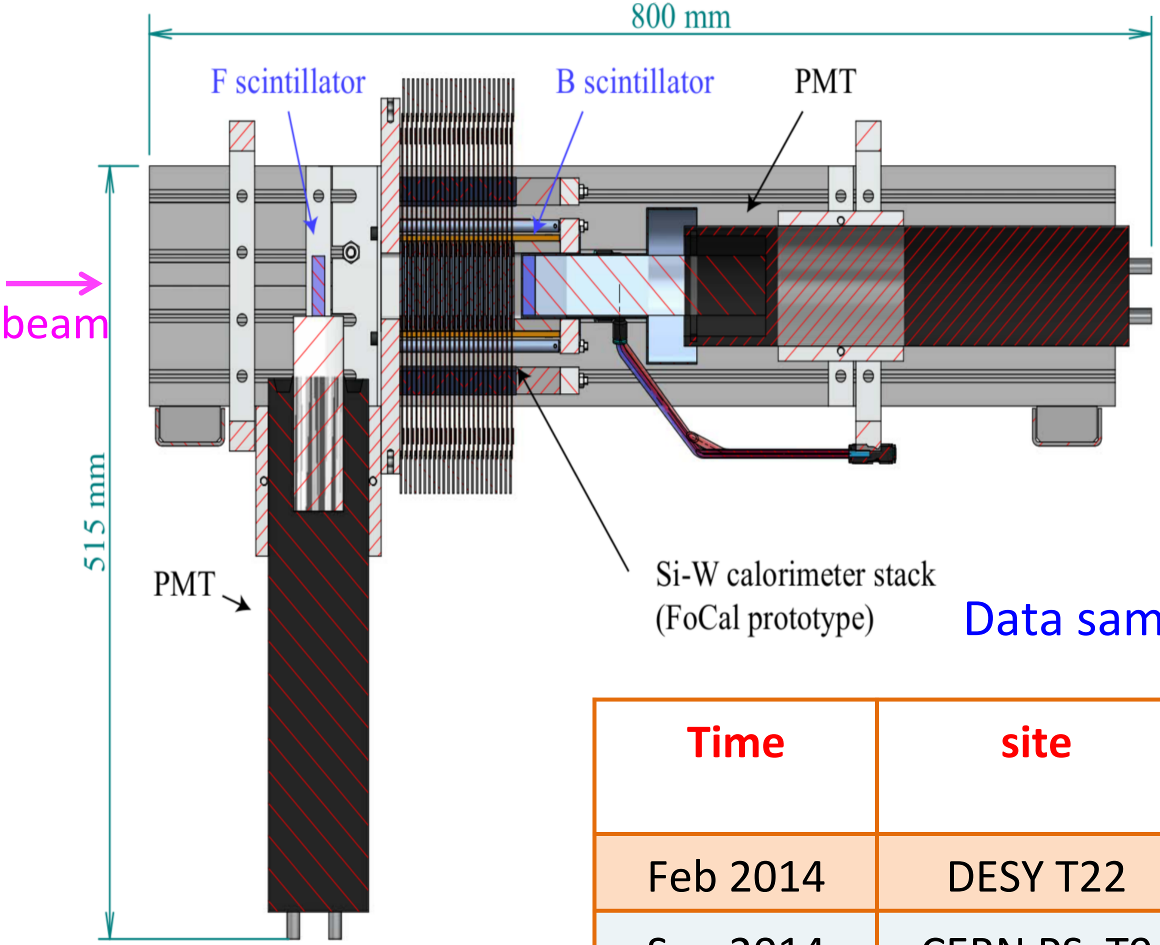
- Rolling shutter
- 640×640 pixels
- 640μs/frame
- ~39M pixels in total

Mimosa 23



on-chip discriminators: digital output → particle counting

Test beam setup



Data samples collected in test beam

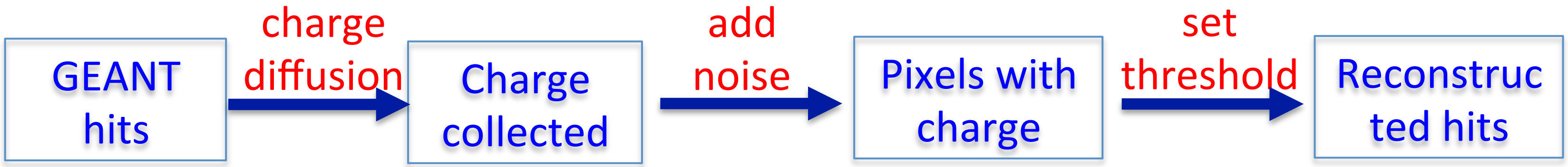
Time	site	Particle type	Energy (GeV)
Feb 2014	DESY T22	e^+	2, 3, 4, 5.4
Sep 2014	CERN PS T9	e^-, $\pi^\pm$, p	2, 3, 4, 5, 6, 8, 10
Nov 2014	CERN SPS T8	e^-, $\pi^\pm$	30, 50, 100,244
2013-2016	Utrecht lab	cosmic	-

Monte-Carlo Simulation

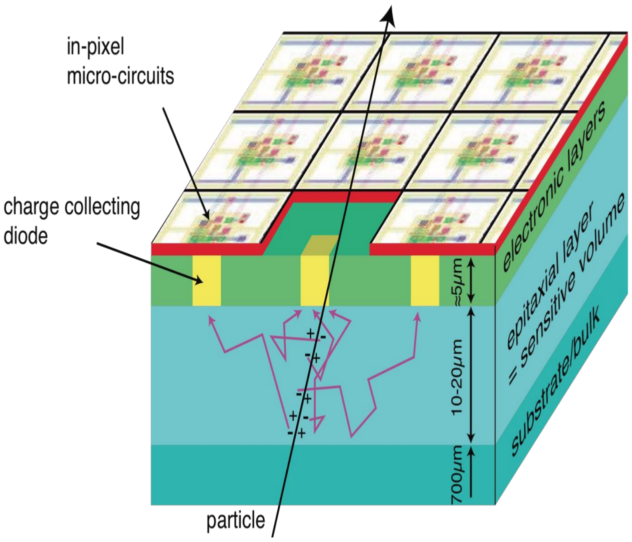
◆ build-up a "real" detector (misalignment, inclination and excluded pixels are taken into account)

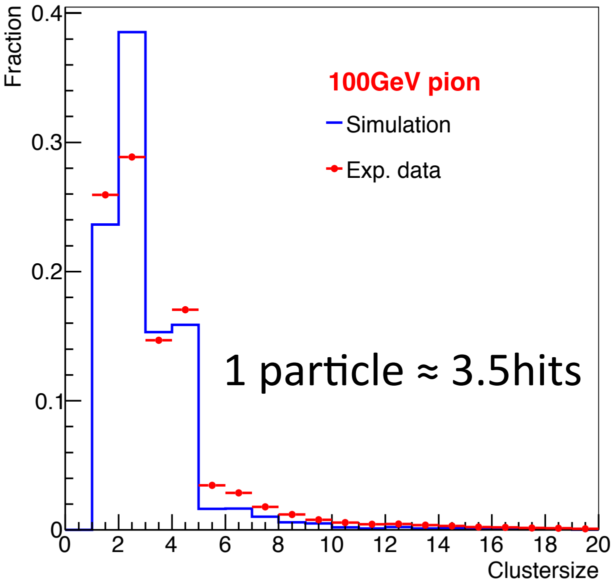
◆ modeling of charge diffusion ~ **isotropic diffusion** + **attenuation**

◆ noise is added ~ Poisson(3.55)



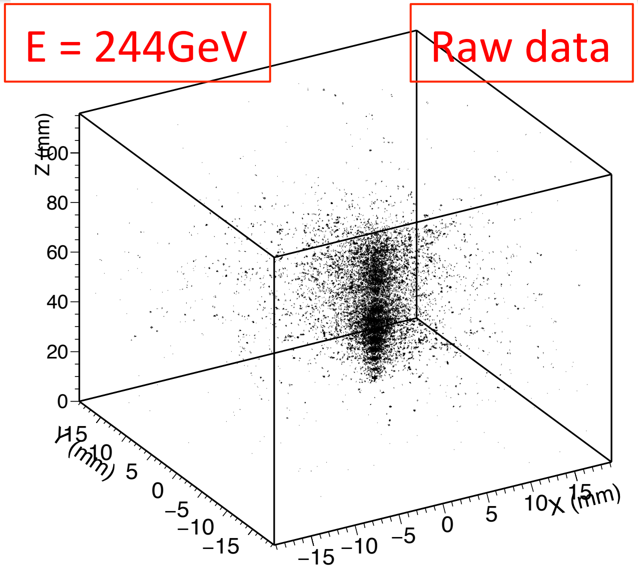
GEANT hits → charge diffusion → Charge collected → add noise → Pixels with charge → set threshold → Reconstructed hits



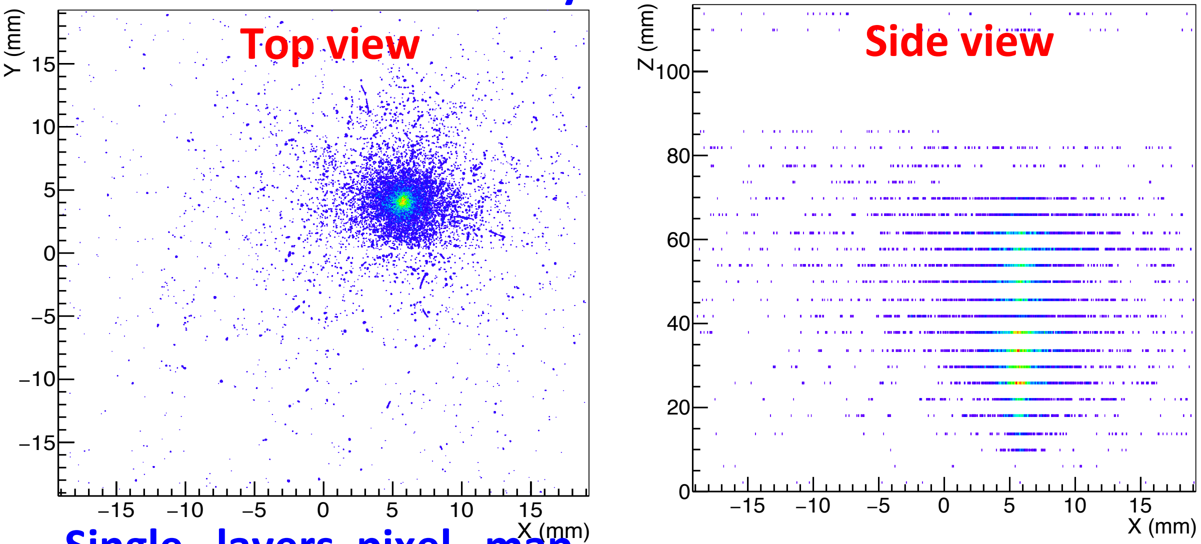


1 particle ≈ 3.5hits

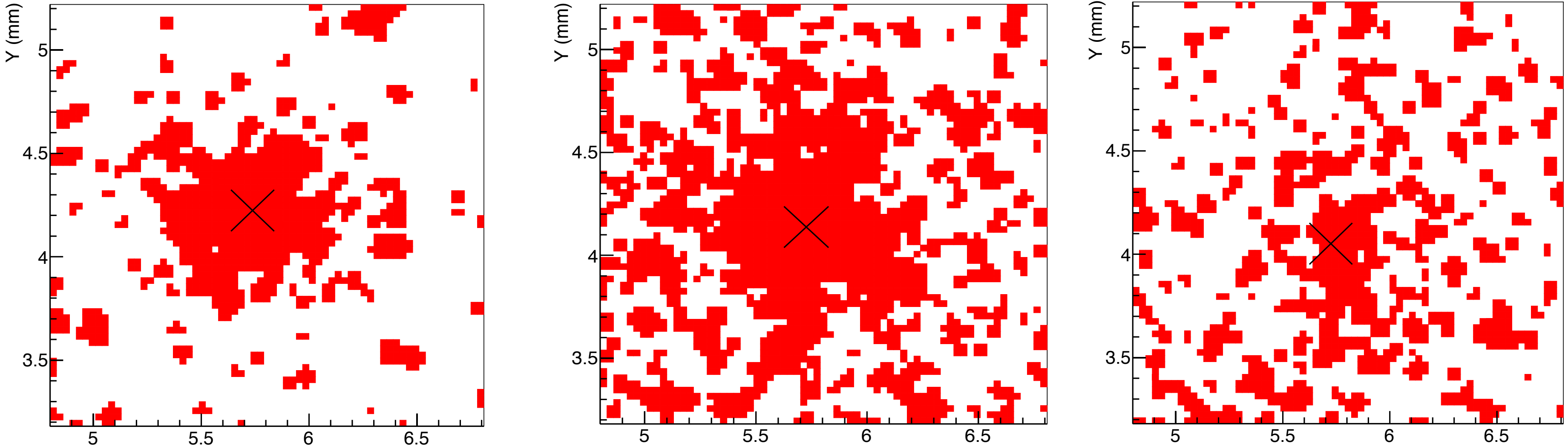
Example of single EM shower



Hit density distributions



Single layers pixel map

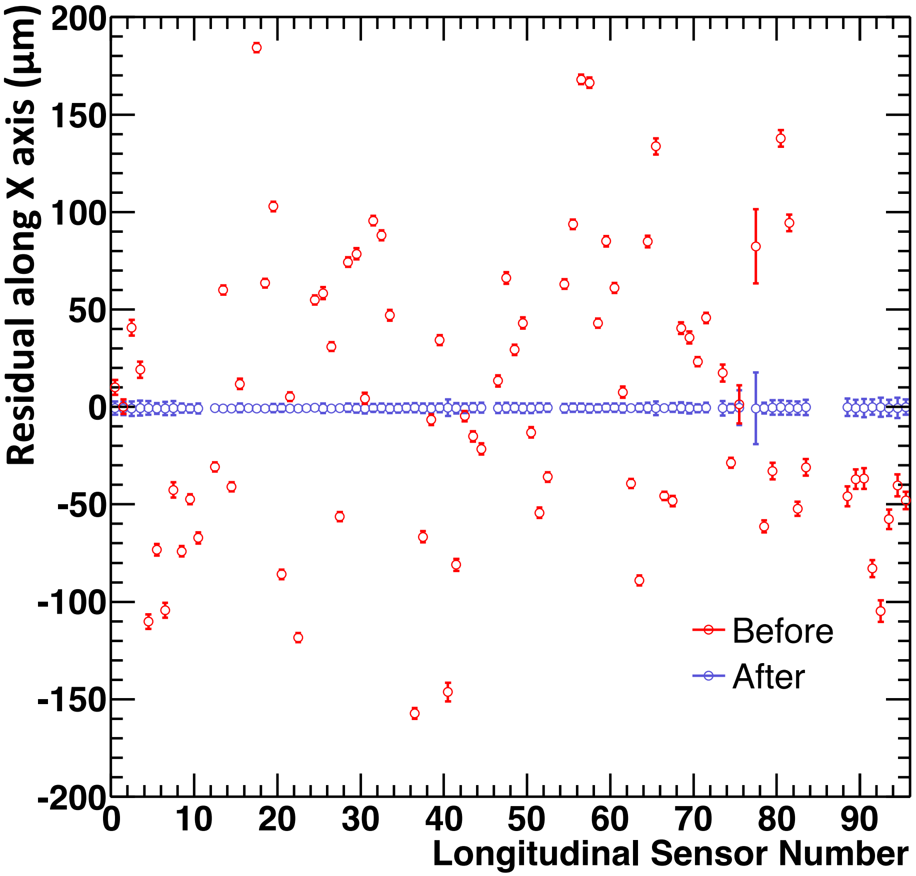


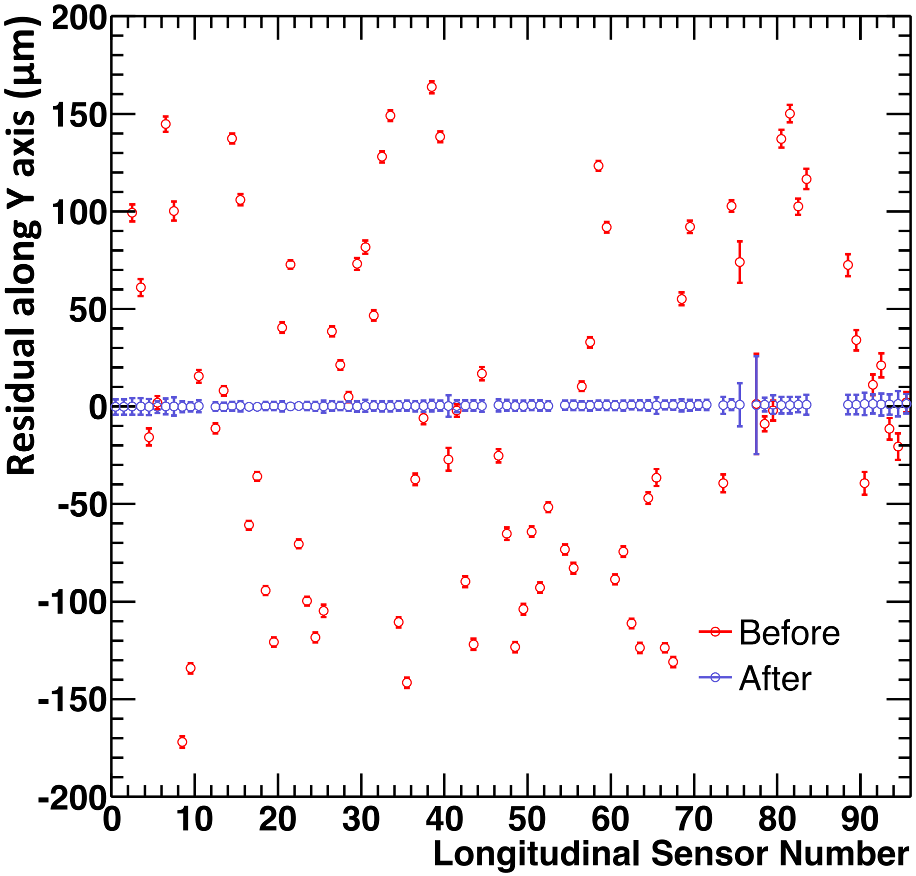
Layer 4

Layer 8

Layer 12

Alignment





After alignment, new coordinate becomes:

$$X_{new} = X_{old} \cos\theta + Y_{old} \sin\theta + \Delta X$$

$$Y_{new} = Y_{old} \cos\theta - X_{old} \sin\theta + \Delta Y$$

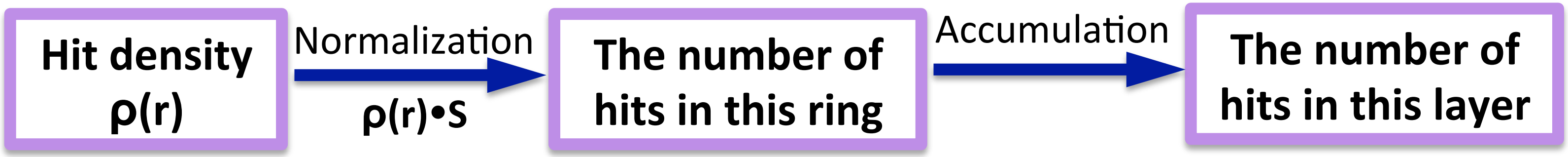
Track residuals:

- **residual < 5μm**
- **width ~11μm**

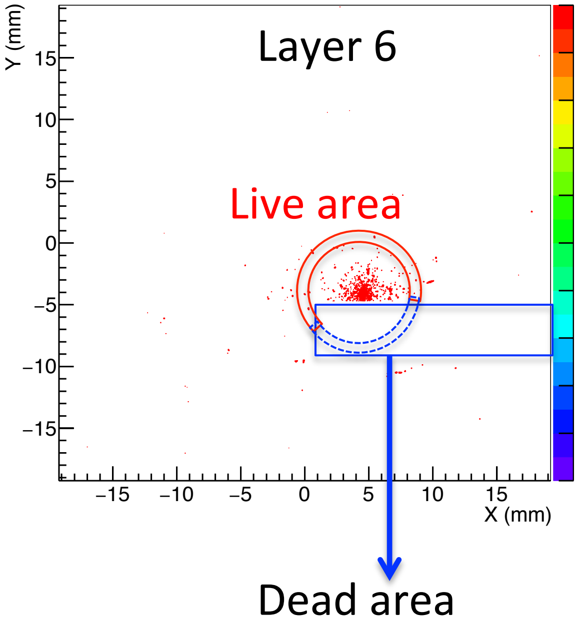
Calibration (I)

No signal available from part of the sensors (dead, noisy, …):

compensation for dead area (16.7% of total pixels)



Hit density ρ(r) → Normalization ρ(r)•S → **The number of hits in this ring** → Accumulation → **The number of hits in this layer**



ρ(r) **is the hit density at distance to the shower axis r.**

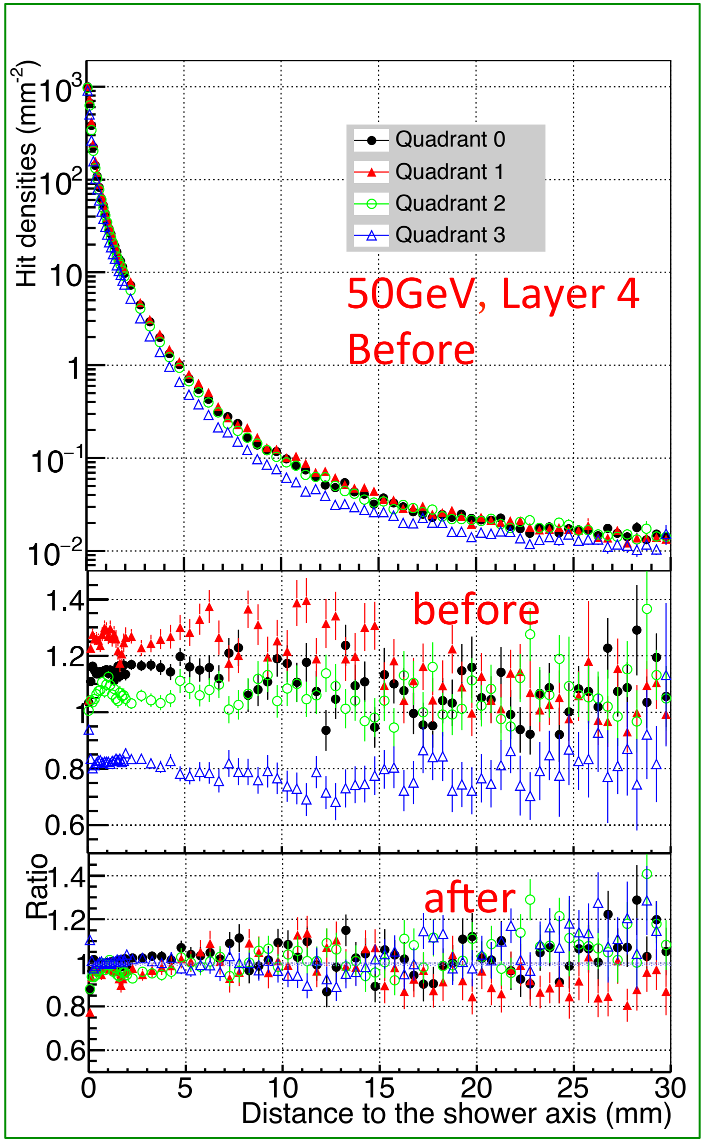
$$\rho(r)=\sum_{i=0}^{3}\frac{c_i dN_i}{dS_{live}}$$

c_i is the calibration factor for sensor sensitivity (next slide)

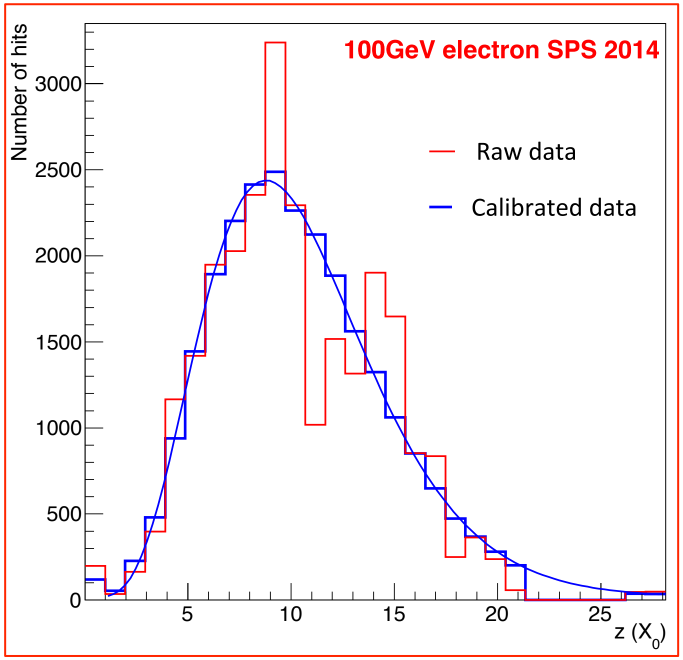
The above procedure can be described as:

$$N_{total}=\int 2\pi r\rho(r)dr$$

Calibration (II)



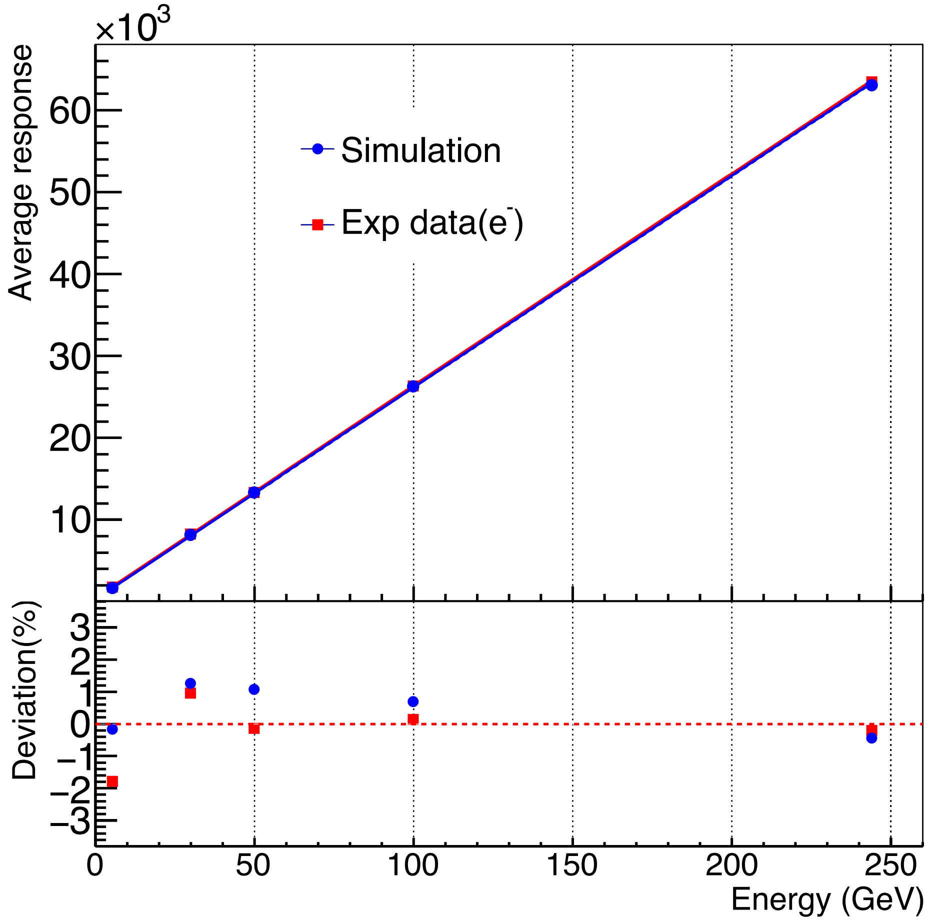
- Relative calibration of different sensors in one layer from lateral profile.



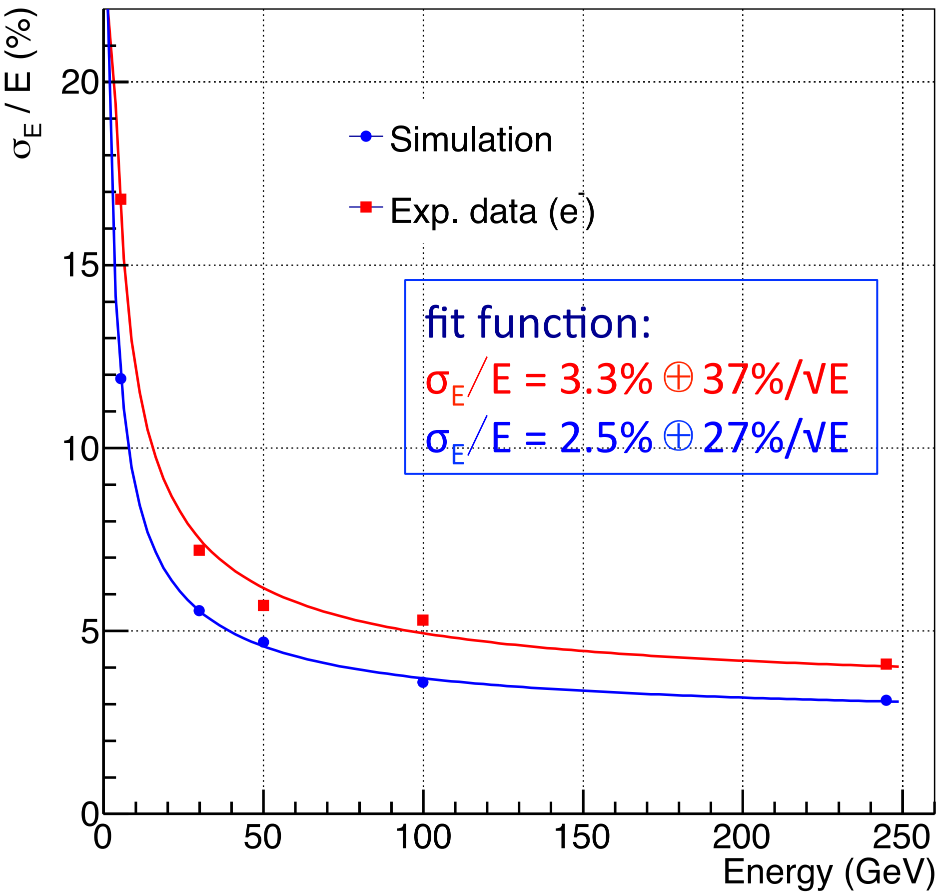
- Relative calibration of different layers from longitudinal profile which should be fitted well by a Gamma function.

Results

Linearity and energy resolution



Good linearity



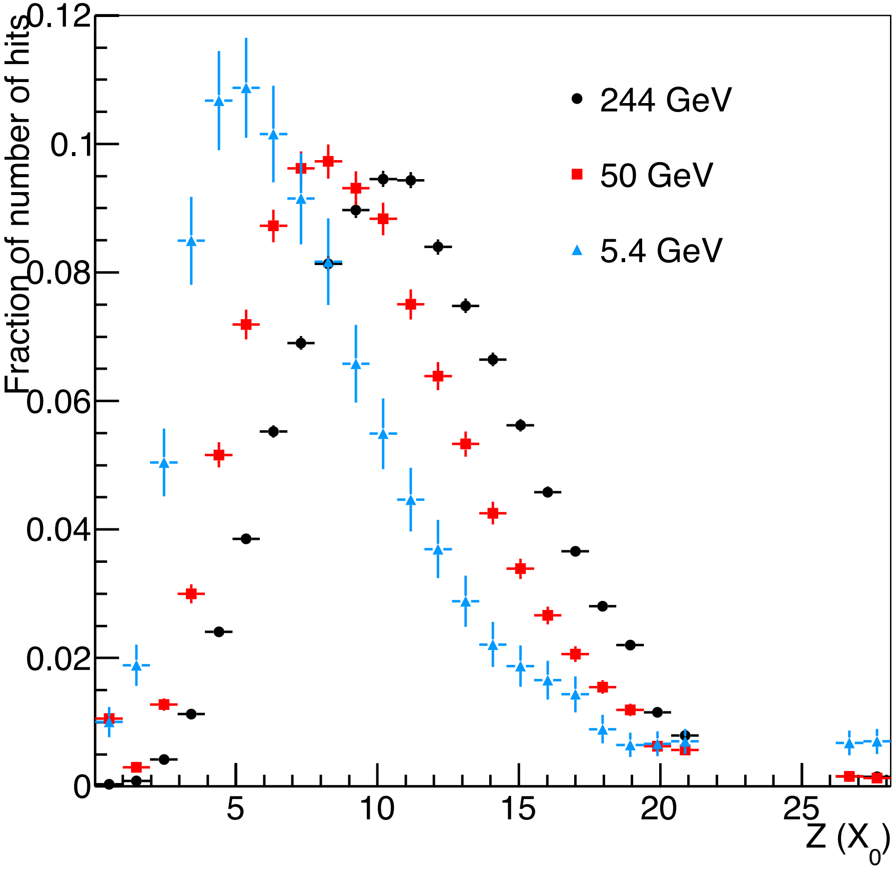
Satisfactory energy resolution

Beam with energy spread 1.3%.

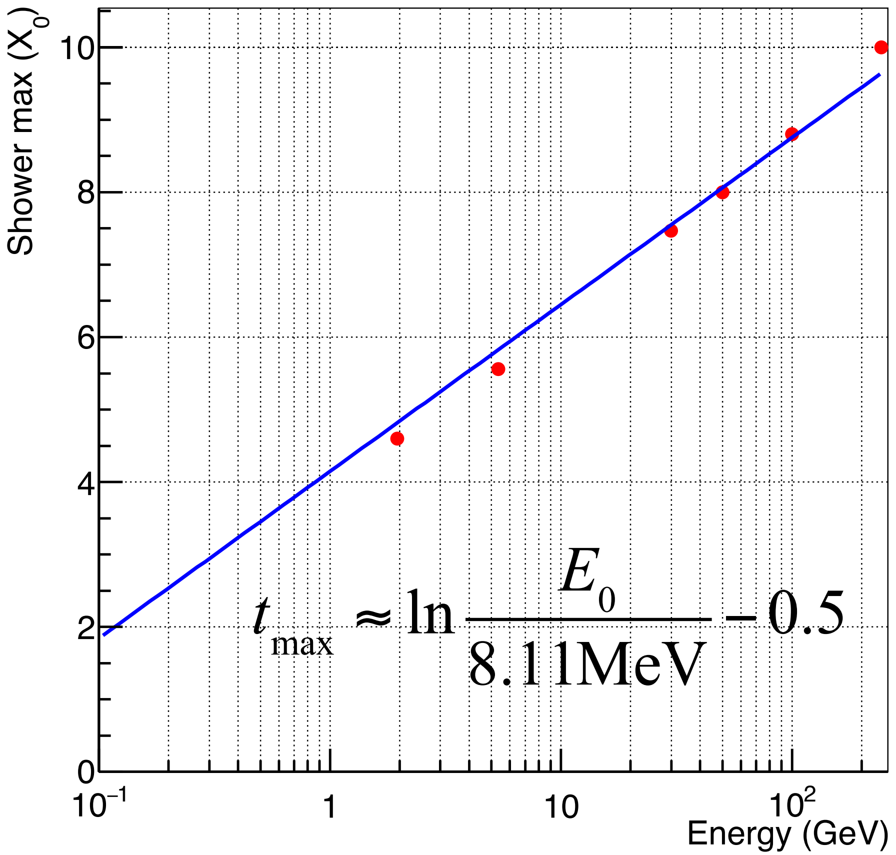
Results

Longitudinal Profile

Normalized longitudinal shower profile

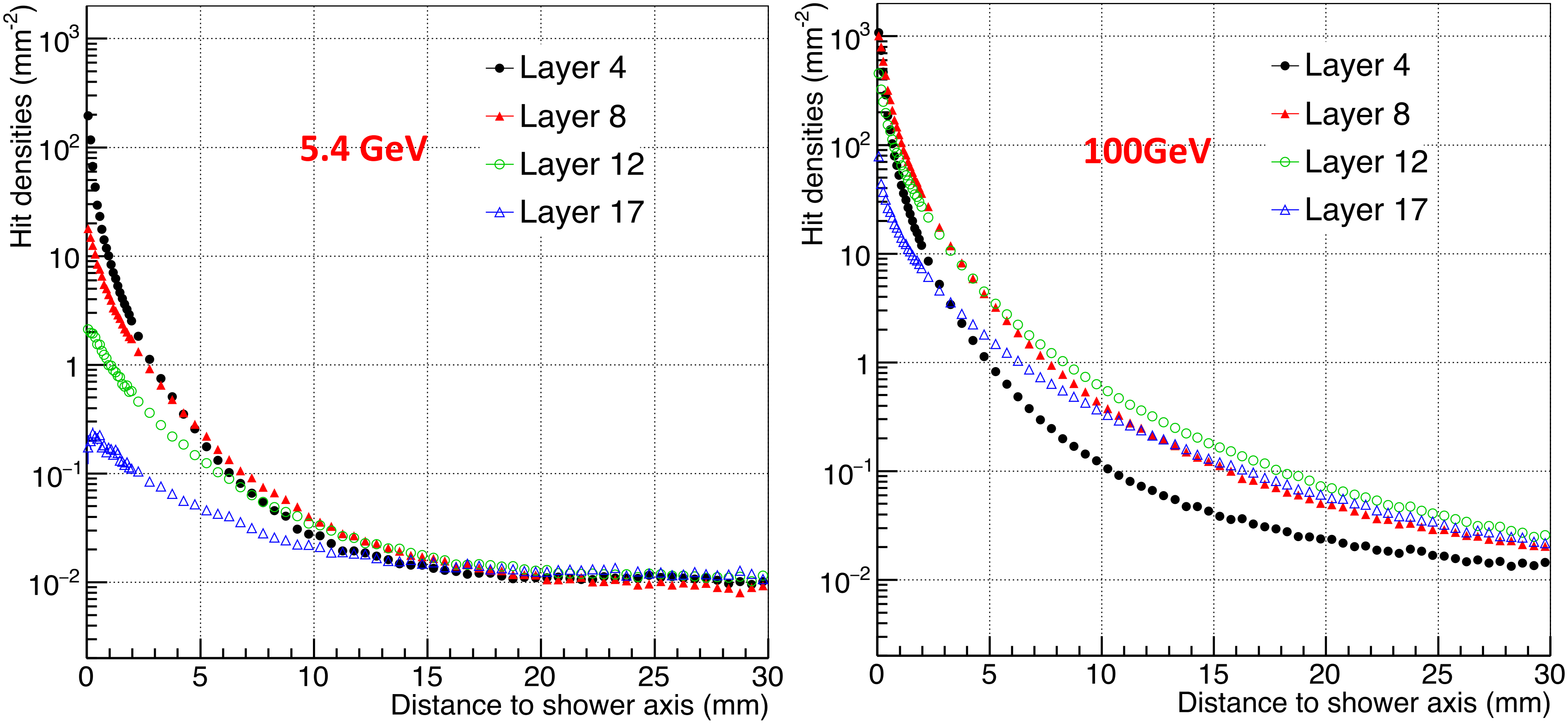


Position of the shower maximum



Results

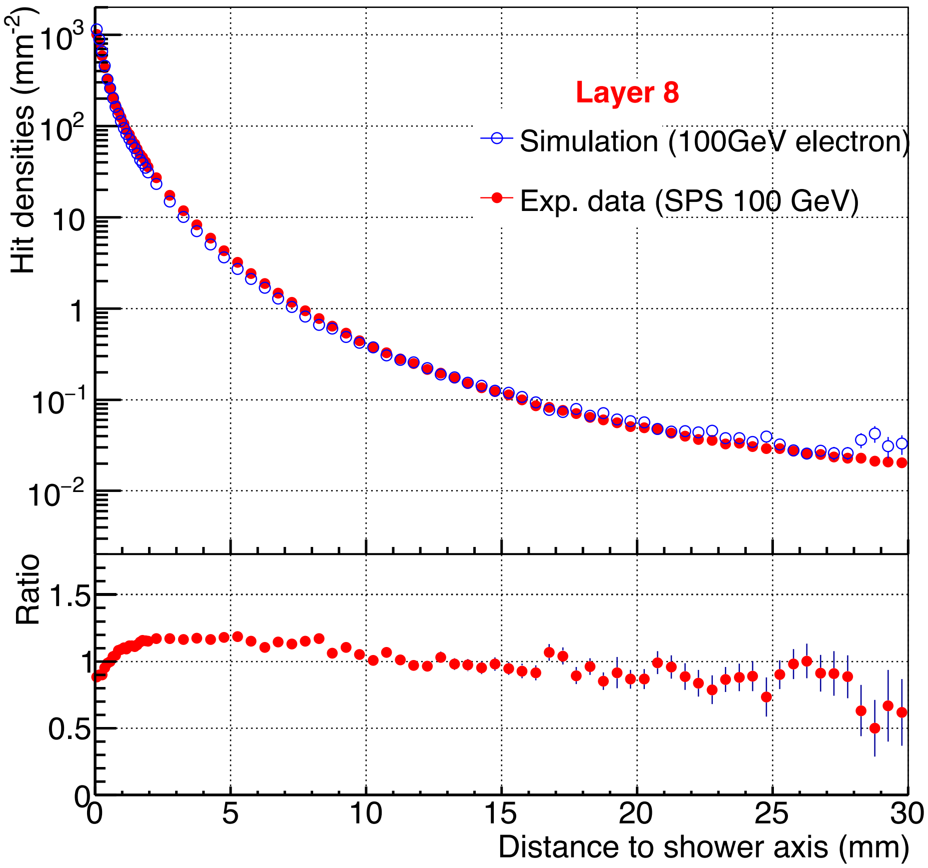
Typical lateral profile

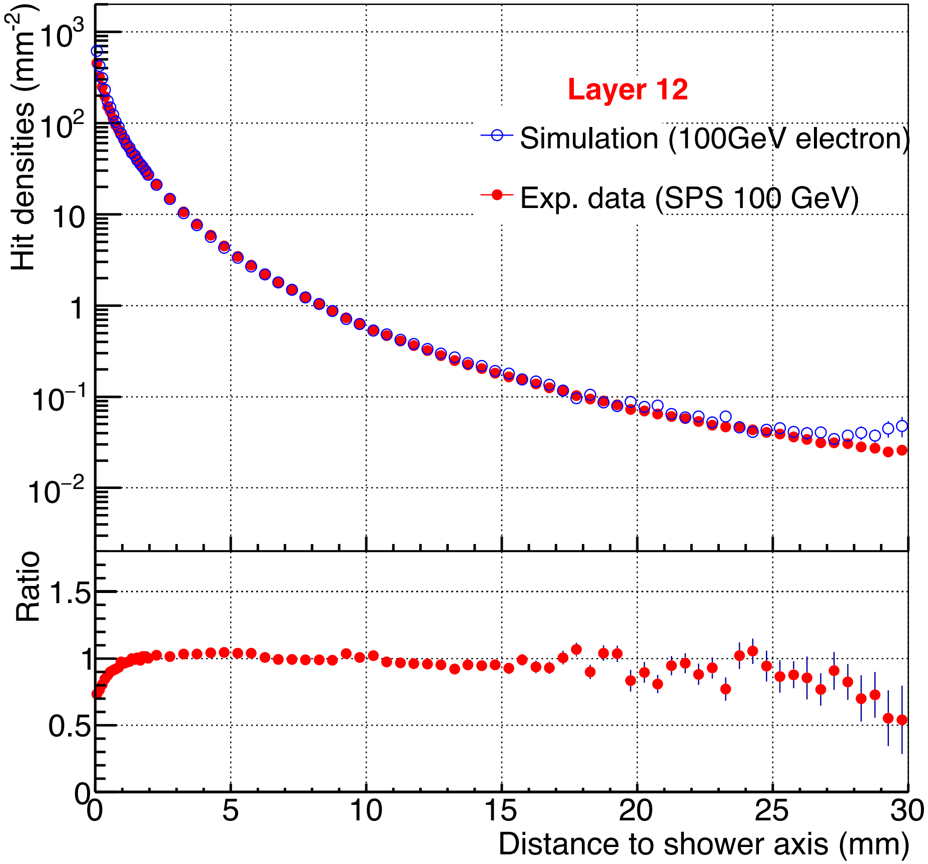


Unique measurement of hit densities as a function of distance to the shower axis.

Results

Comparison between simulation and experiment

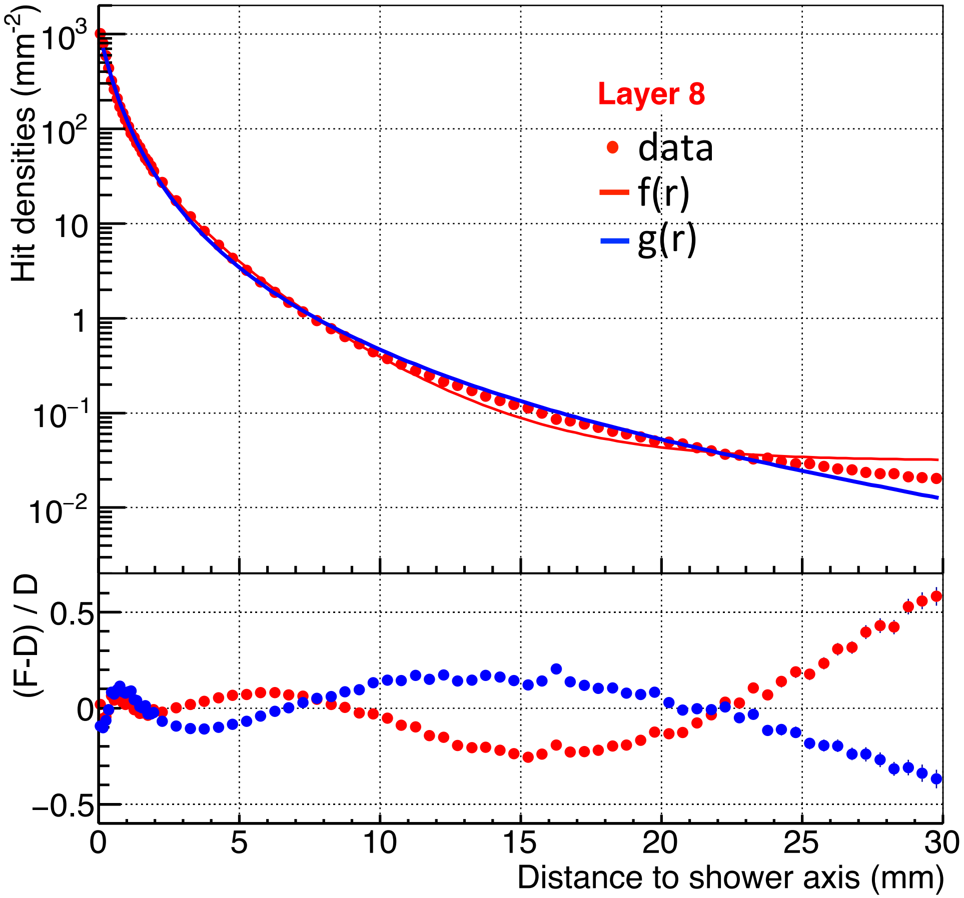




Good agreement between experiment and simulation

Results

Fit of lateral profile



Fit function:

(0) $F(r) = N[\exp(-r/\lambda_1) + C_{12}\exp(-r/\lambda_2)]$ ✘

(1) $f(r) = N[\exp(-\sqrt{r/\lambda_1}) + C_{12}\exp(-r/\lambda_2)]$ [1]

(2) $g(r) = p0(1 + \frac{r}{p1 \bullet p2})^{-p1}$ [2]

Exploring analytical parameterizations of shower profile:
Agreement within ~20% for r < 25 mm.

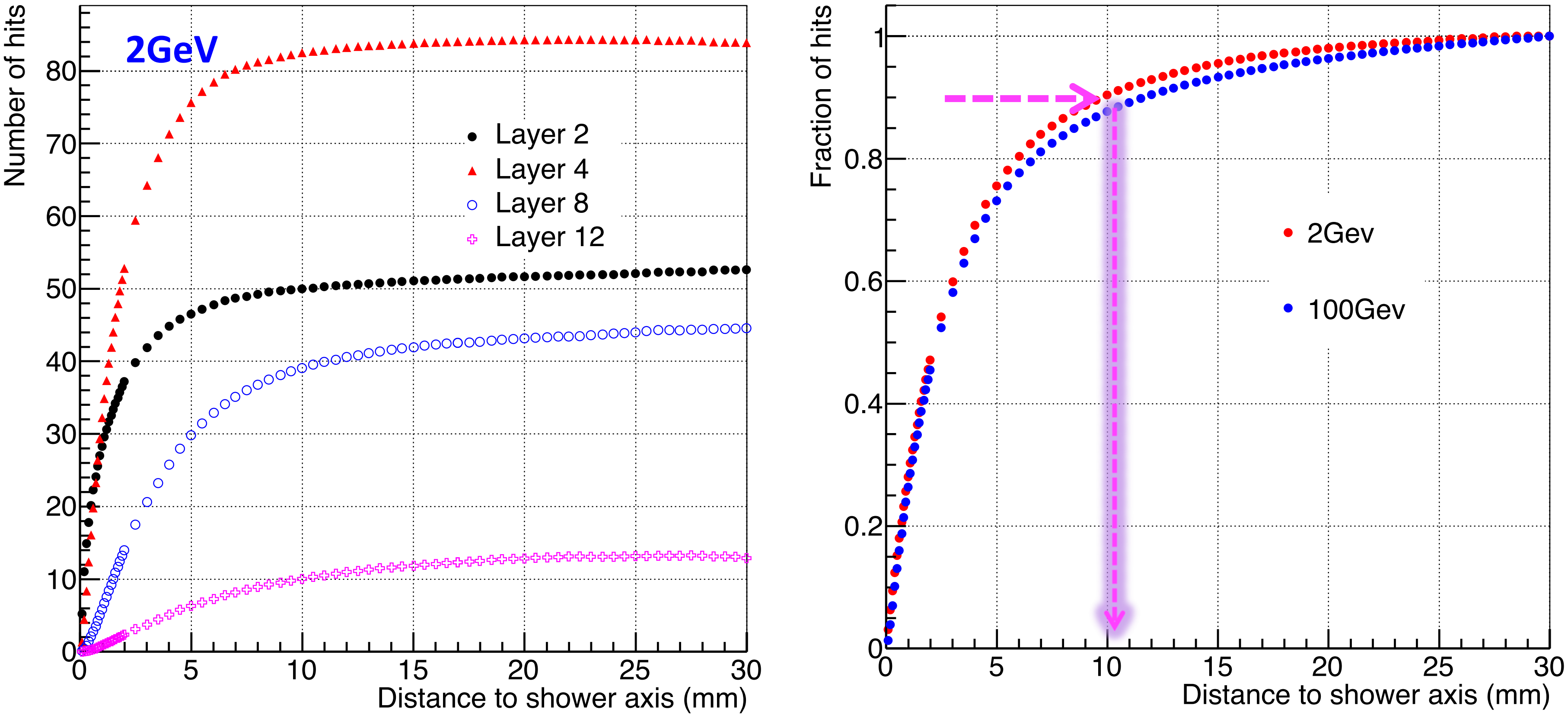
[1] G. Ferri *et al.* , Nucl. Inst. Meth. A273(1988)123
[2] R. Hagedorn, Riv. Nuovo Cim. 6(1983)1

Results

Integrated lateral profiles

Single layers

Sum of all layers

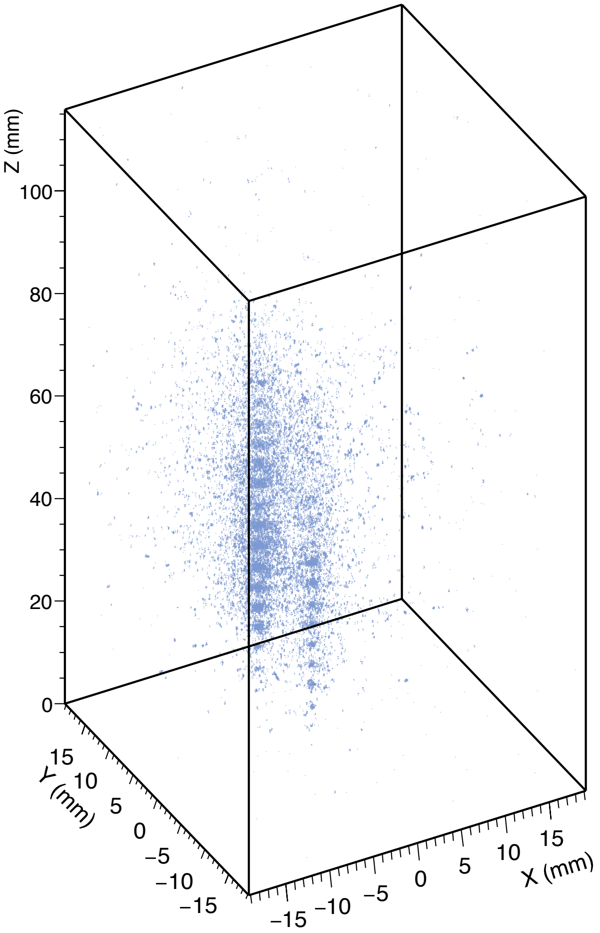


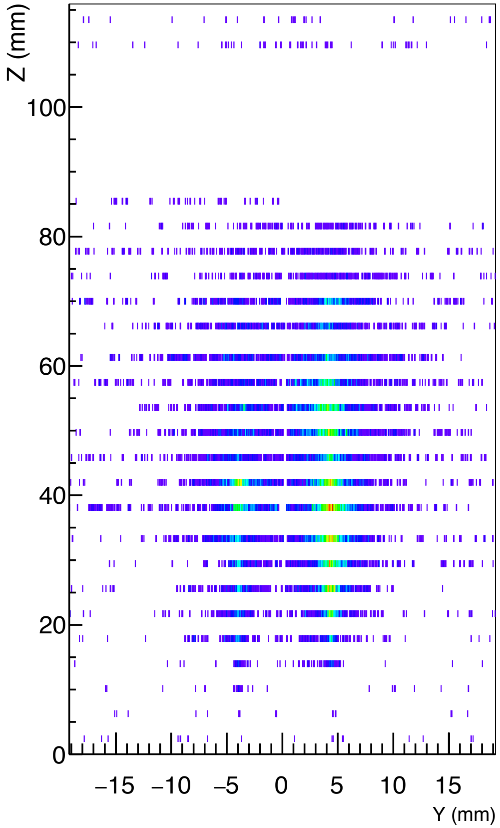
Integrated lateral profile as a function of distance to the shower axis.

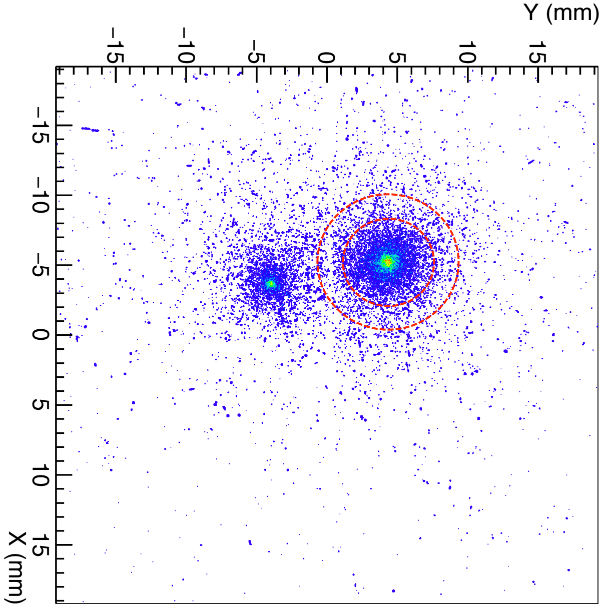
Estimated Moliere radius $R_M \sim$ 11mm

Results

Two shower separation







Core energy:

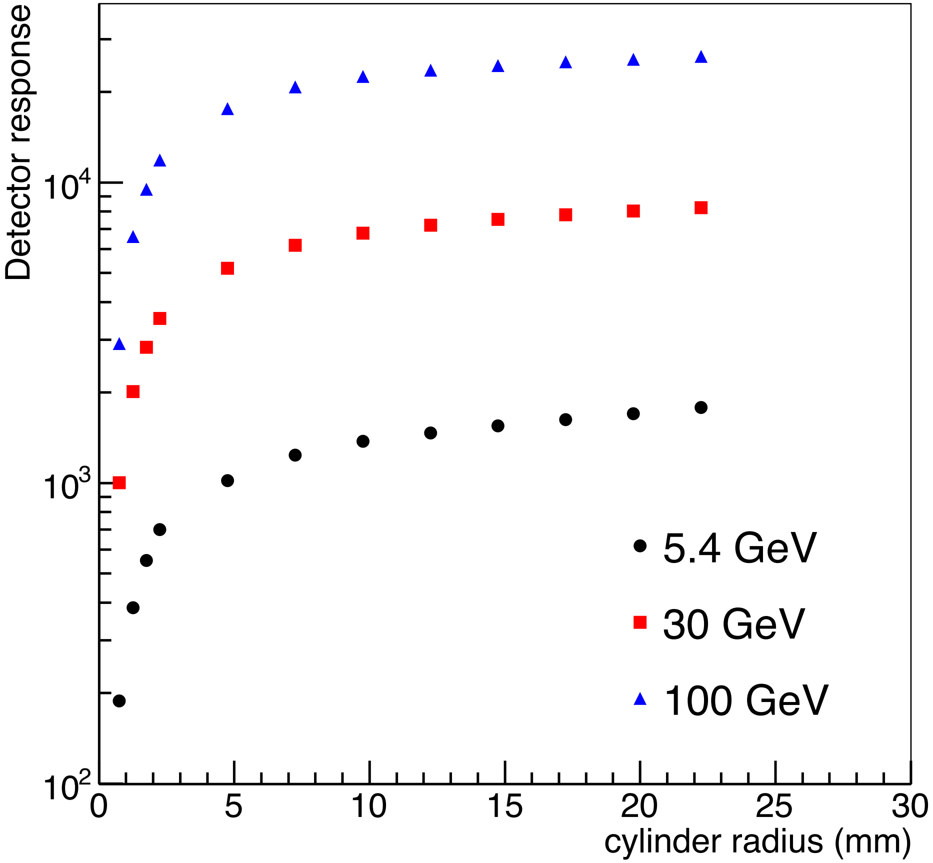
- Calculate total energy in cylinder of finite radius around shower centre.
- Study as a function of radius.

Results

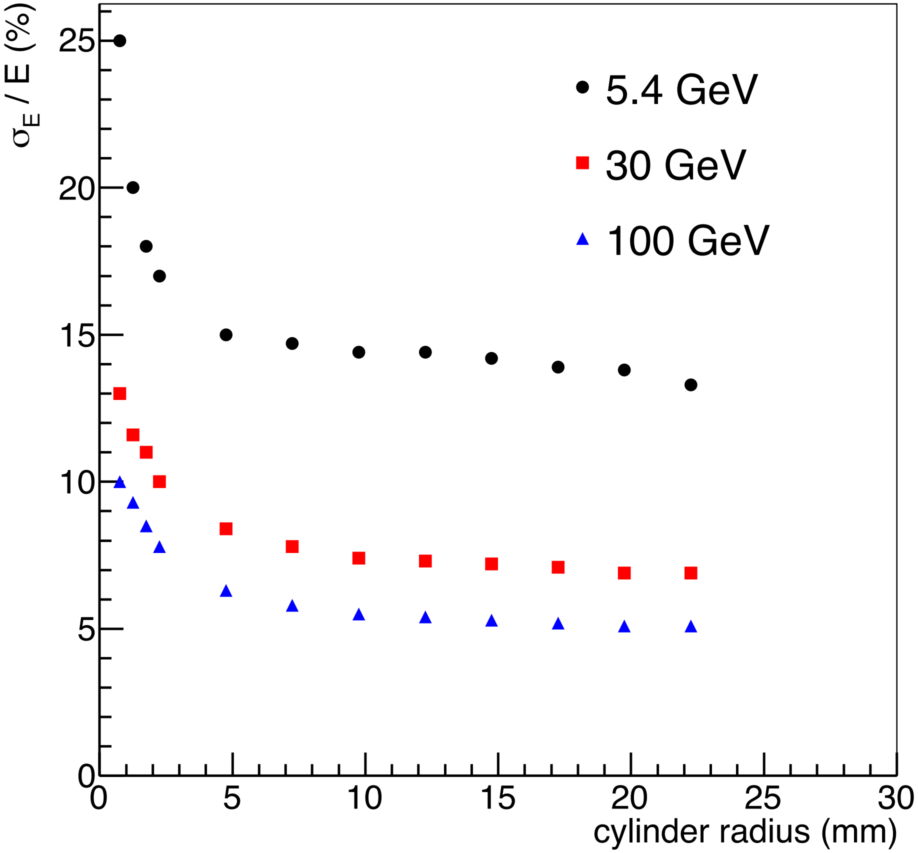
Core energy

Evolution with radius

Detector response



Energy resolution



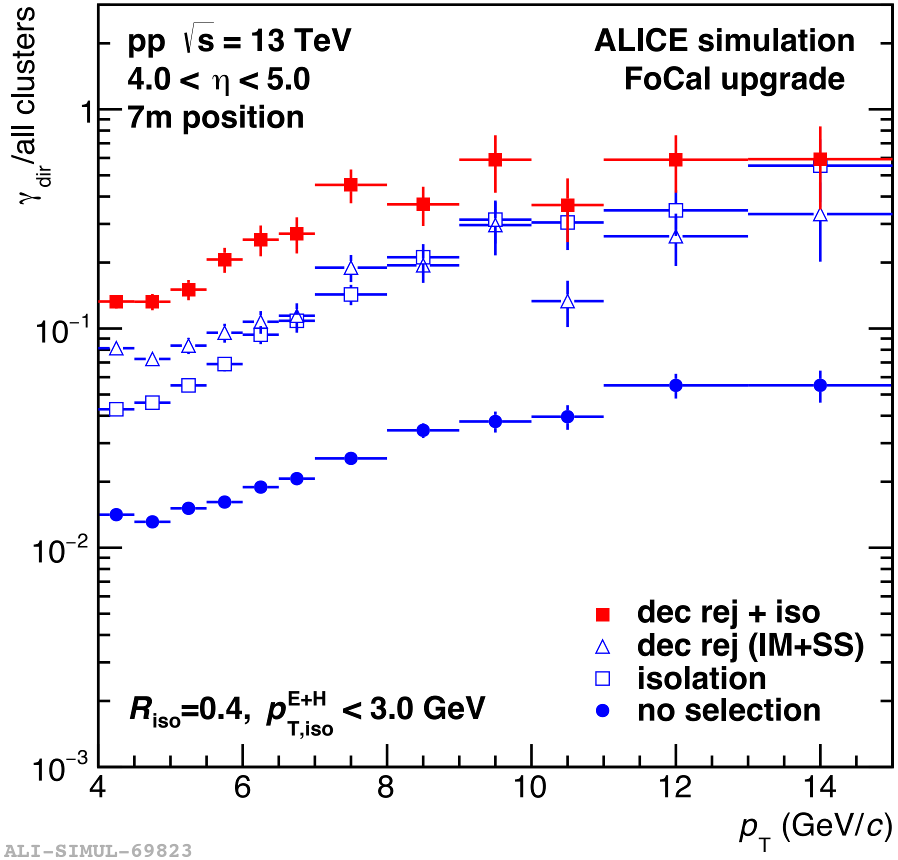
Down to 5 mm (~$R_M/2$) the resolution is hardly affected.

Conclusions

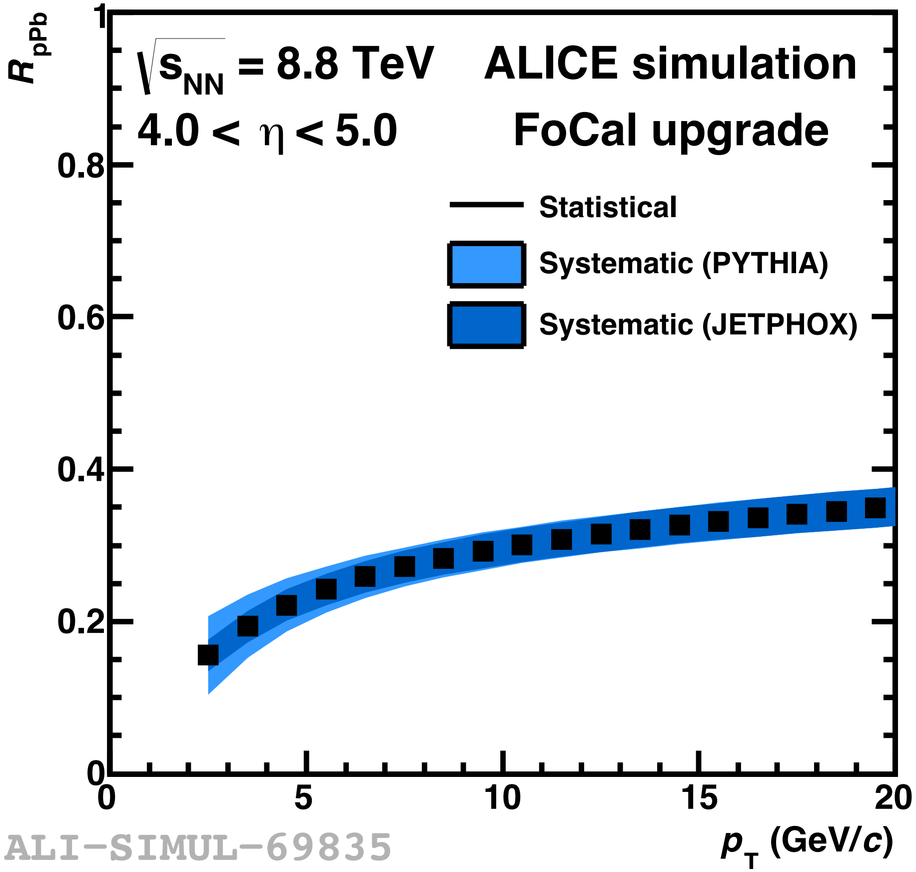
- **Successful Proof of Principle of Particle Counting Calorimetry.**
  - A high granularity digital Si-W calorimeter prototype for FoCal has been built and tested.
  - Good linearity has been achieved.
  - General performance agrees well with the simulation.
- **Spatial granularity allows unique measurements**
  - High resolution lateral shower profiles have been obtained.
  - Very efficient two-shower separation should be possible.

Thanks for your attention

Physics performance in simulation



ALI-SIMUL-69823



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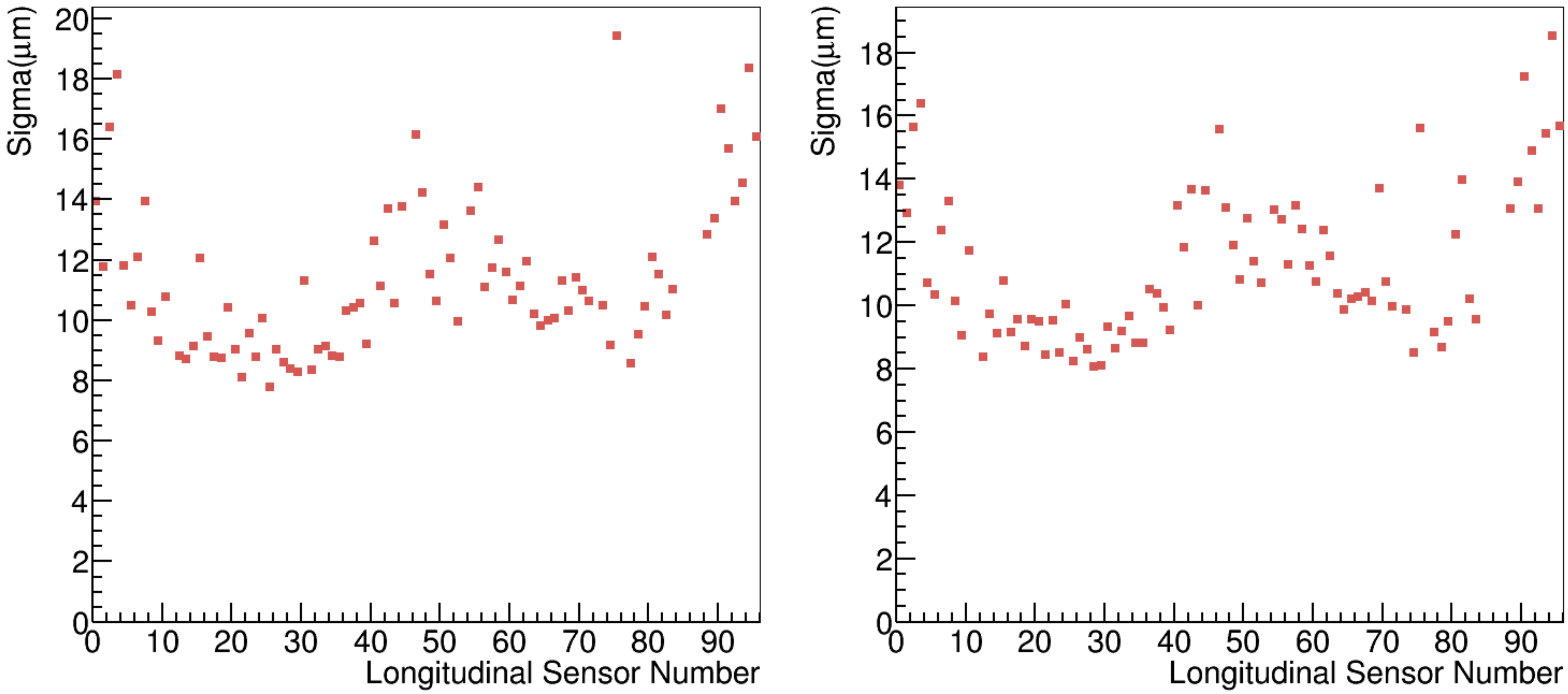
High granularity layers in FoCal-E strongly improve rejection power for pion decay photons and lead to an acceptable direct photon signal fraction.

Detector performance should allow a discrimination of competing physics scenarios.

Alignment



Average sigma of Gaussian fit : ~11μm