Detailed Measurements of Shower Properties in a High Granularity Digital Electromagnetic Calorimeter

Naomi van der Kolk
for the ALICE-FoCal Collaboration

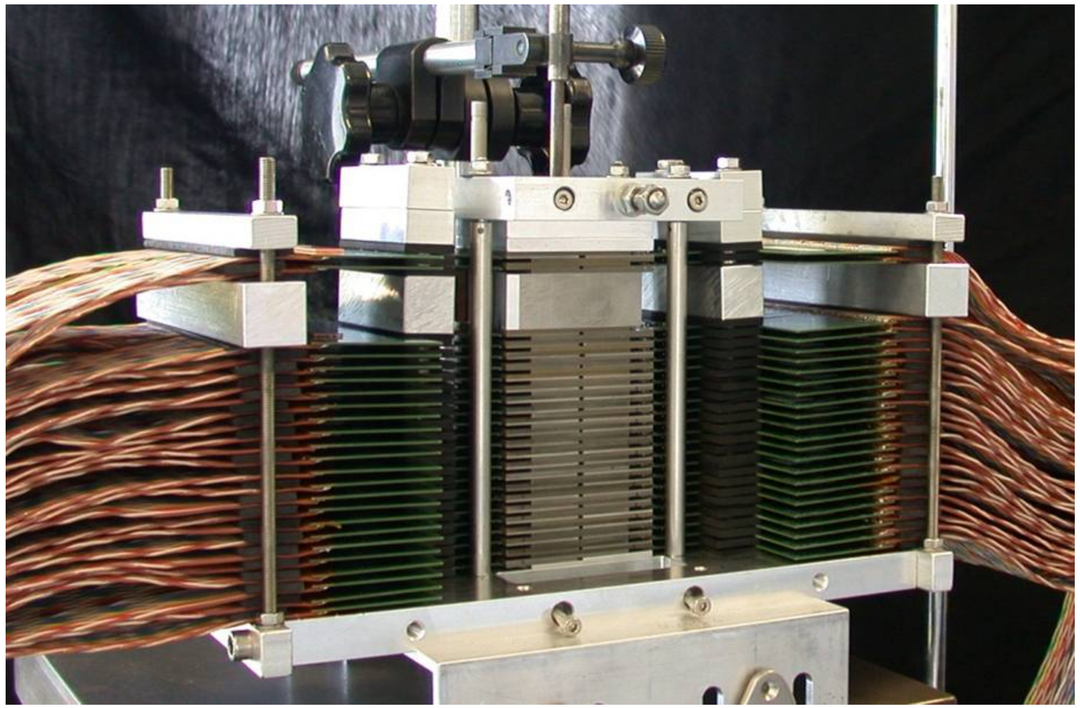
Nikhef

NWO Netherlands Organisation for Scientific Research

Physics Utrecht EMMEΦ

FoCal prototype

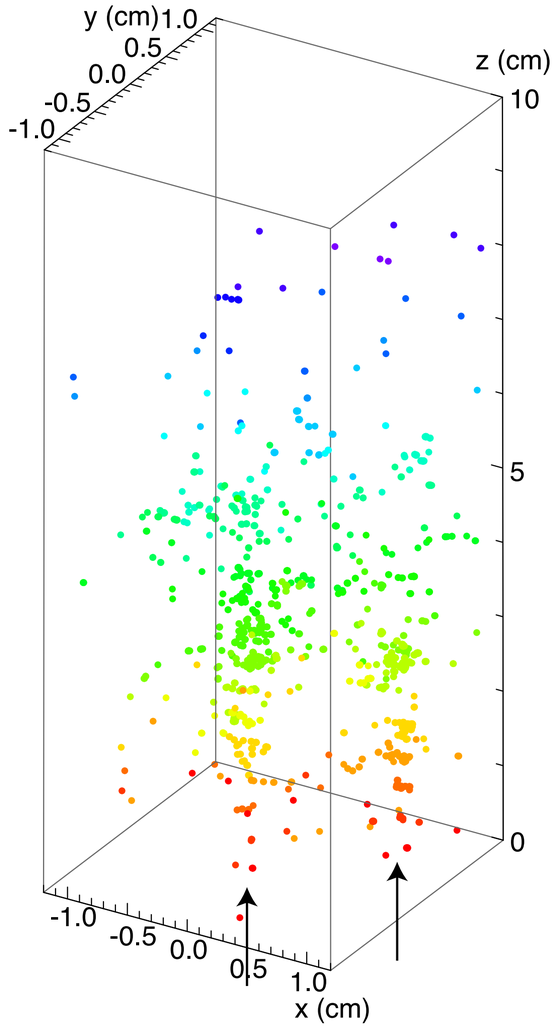
- **Si-W ECAL** using Monolithic Active Pixel Sensors (MAPS) PHASE2/MIMOSA23 produced at IPHC
- **Digital ECAL**: count the number of pixels above threshold
- Average pixel occupancy should be <<1
- For particle densities of $10^3/mm^2$ in the shower core need pixels of the order 50 - 100 μm
- 24 layers of 0.97 X_0 (3 mm W, 1 mm sensor) with active area of 4x4 cm^2, with pixel size 30 μm: 39 M pixels total
- Moliere radius ~ 11 mm
- **Demonstrate digital calorimetry**
- **Test MAPS for calorimeter application**
- **Ideal for testing particle showers in detail (electromagnetic and hadronic)**



The FoCal in ALICE

- **Direct photon production** in p-Pb collisions at forward rapidities offer a clean probe for parton distribution functions and gluon saturation
- In order to detect direct photons, they must be separated from **decay photons** from (mostly) π^0
- At high energies and high rapidities **particle densities** will be very high
- Decay photons from high energy π^0 will have a small separation angle
- In order to separate such photon showers in an ECAL a **very high granularity** is needed
- R&D prototype for a **proposed upgrade** of the ALICE forward calorimeter; **FoCal**
- Recently submitted arXiv:1708.05164

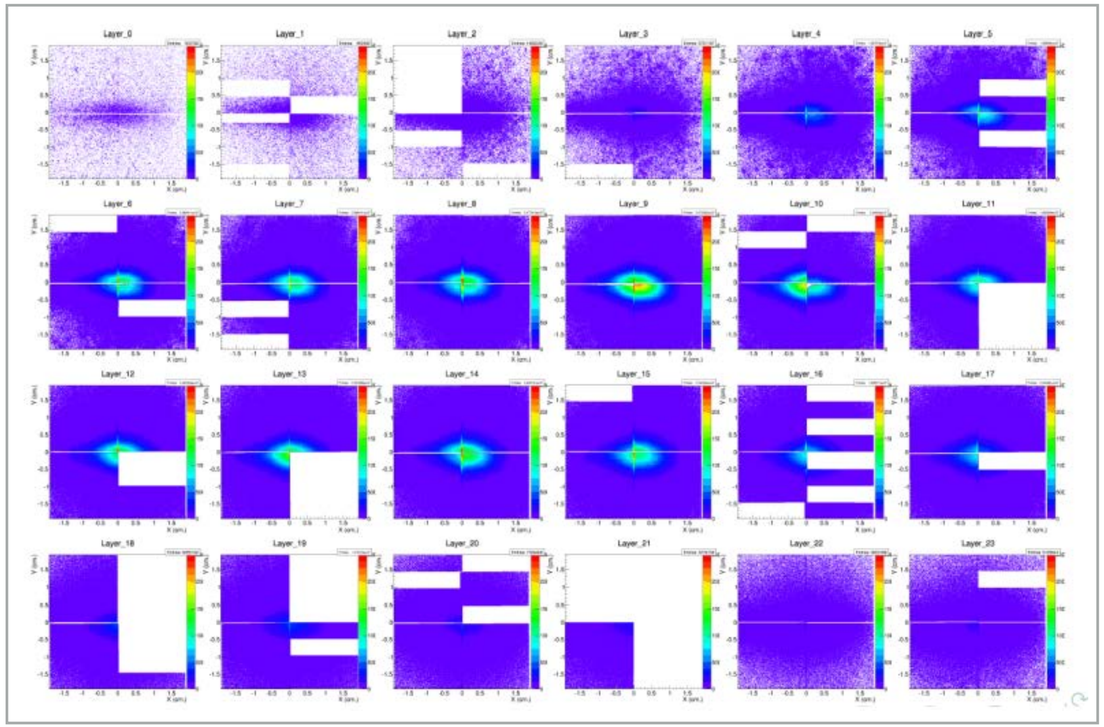
More details in the talk by Thomas Peitzmann at 16:50 today



Test beam results (2014)

Site	Particle type	E (GeV)	N_{evts}
DESY T22	e^+	2, 3, 4, 5.4	9.5 k
CERN SPS T8	e^+, π^+	30, 50, 100	30 k, 30 k, 80 k
CERN SPS T8	e^-, π^-	244	16 k

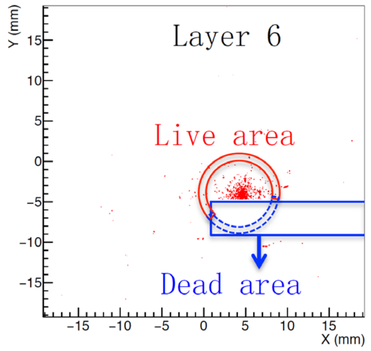
17% dead area

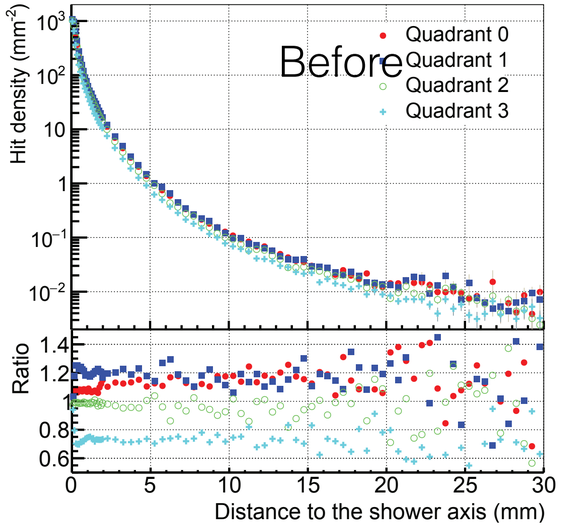


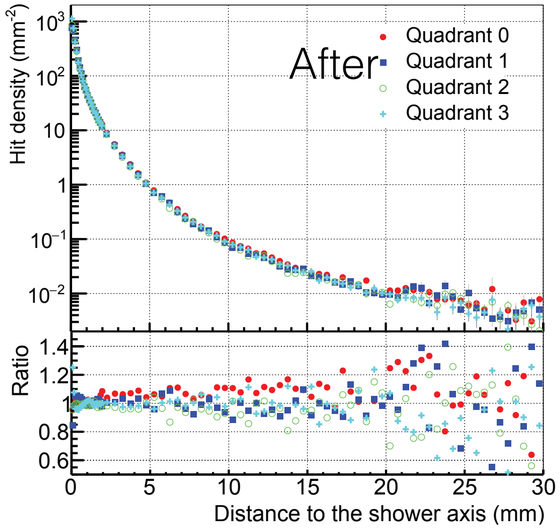
Average noise rate 10^{-5}/pixel

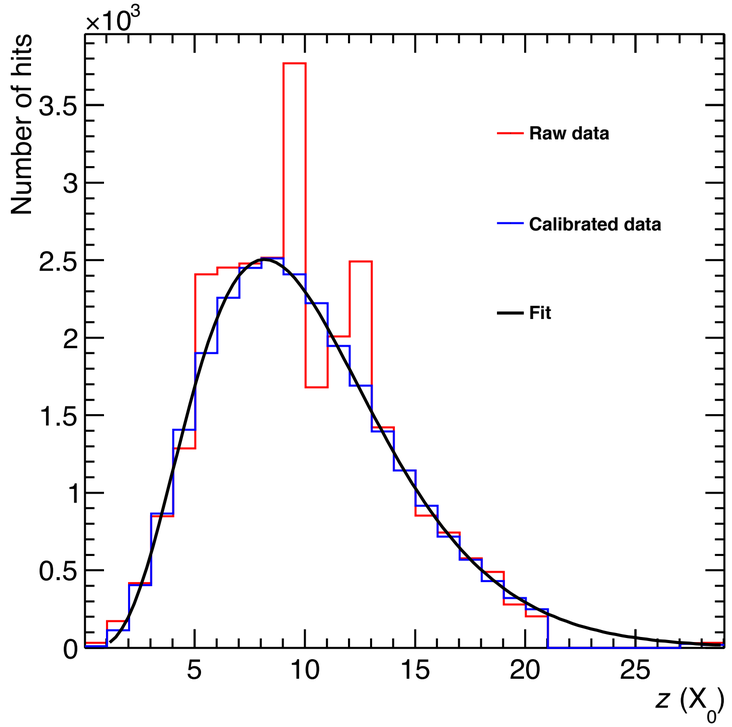
Calibration

- Use e.m. shower shapes to calibrate and correct for dead areas and sensor sensitivity
- Calculate hit density in rings around the shower centre
- Equalise sensitivity of the 4 sensors within each layer
- Equalise layers with Gamma function fit $N(t) = N_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)} (t = x/X_0)$



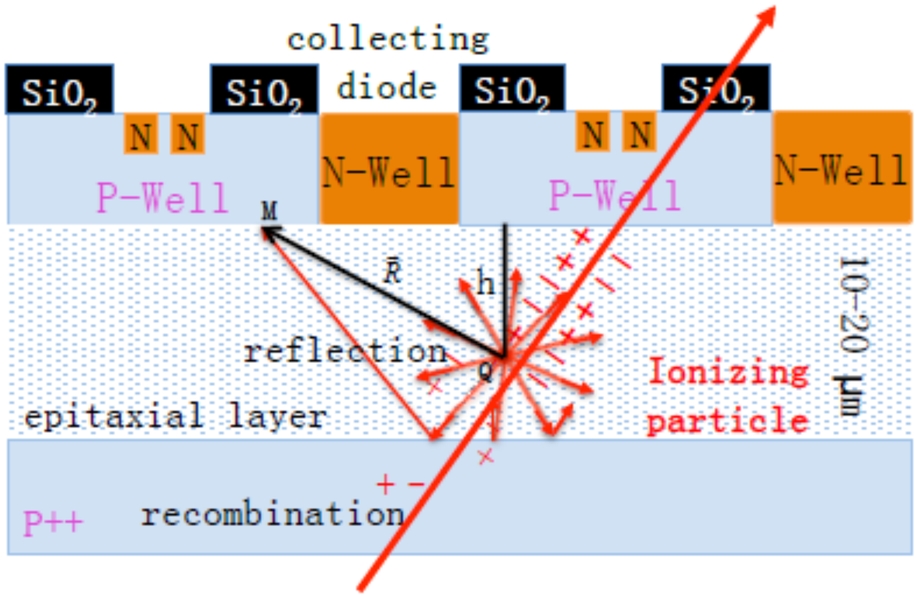






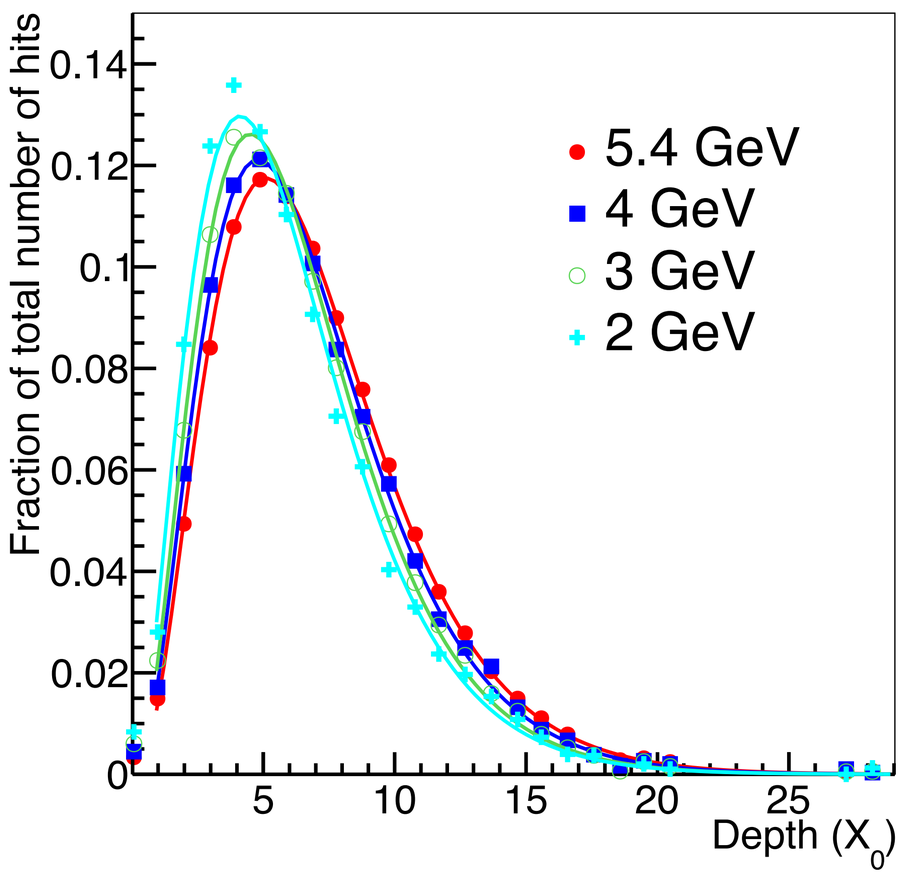
Geant4 simulation

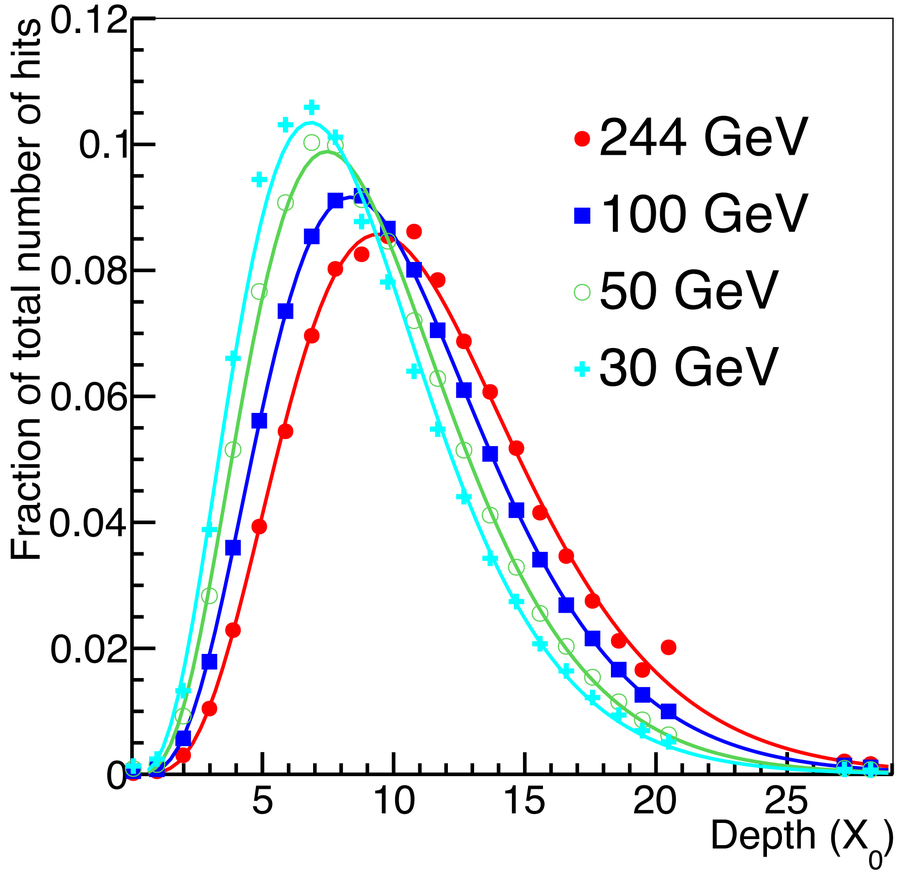
- Prototype has been implemented in Geant4, ideal and real detector
- Simple charge diffusion model implemented
  - Recombination modelled by attenuation length
  - Charge threshold for pixels
- Threshold and attenuation length tuned to data (not very sensitive)



Longitudinal Profiles

- Based on the integral of the hit density
- Normalised distributions
- Deeper showers at higher energies



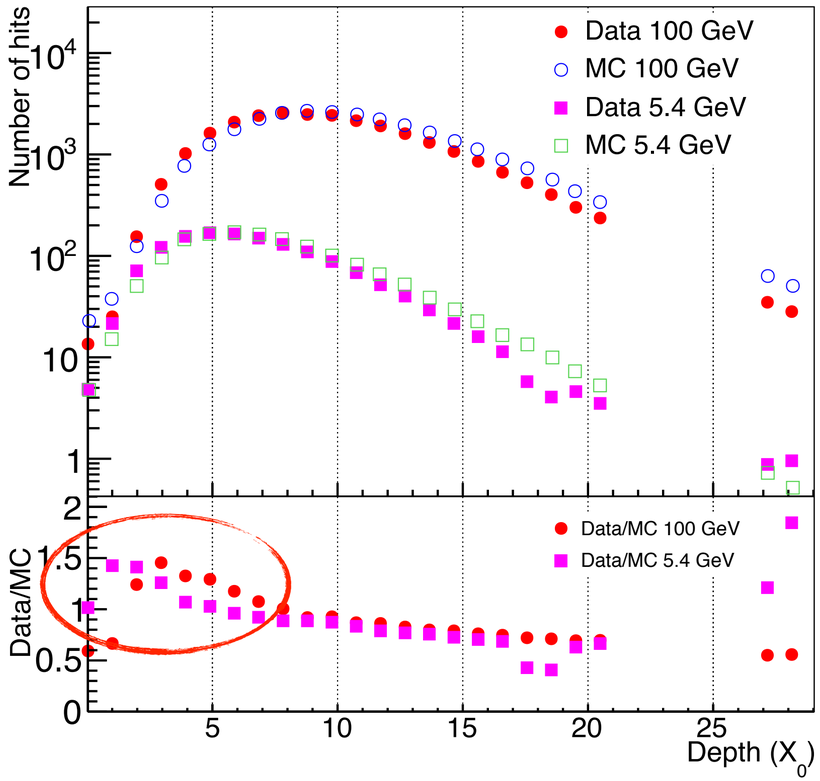


Comparison to Geant4

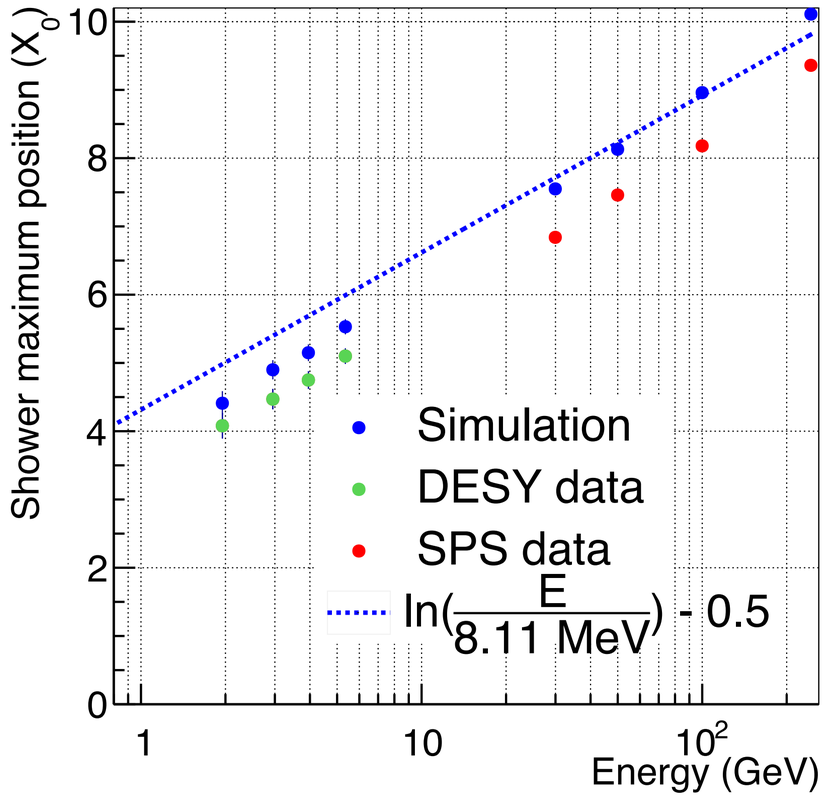
Geant4 10.0.1

- Larger number of hits in data in the first few radiation lengths
- Shower maximum reached earlier in data compared to MC

Longitudinal Profile

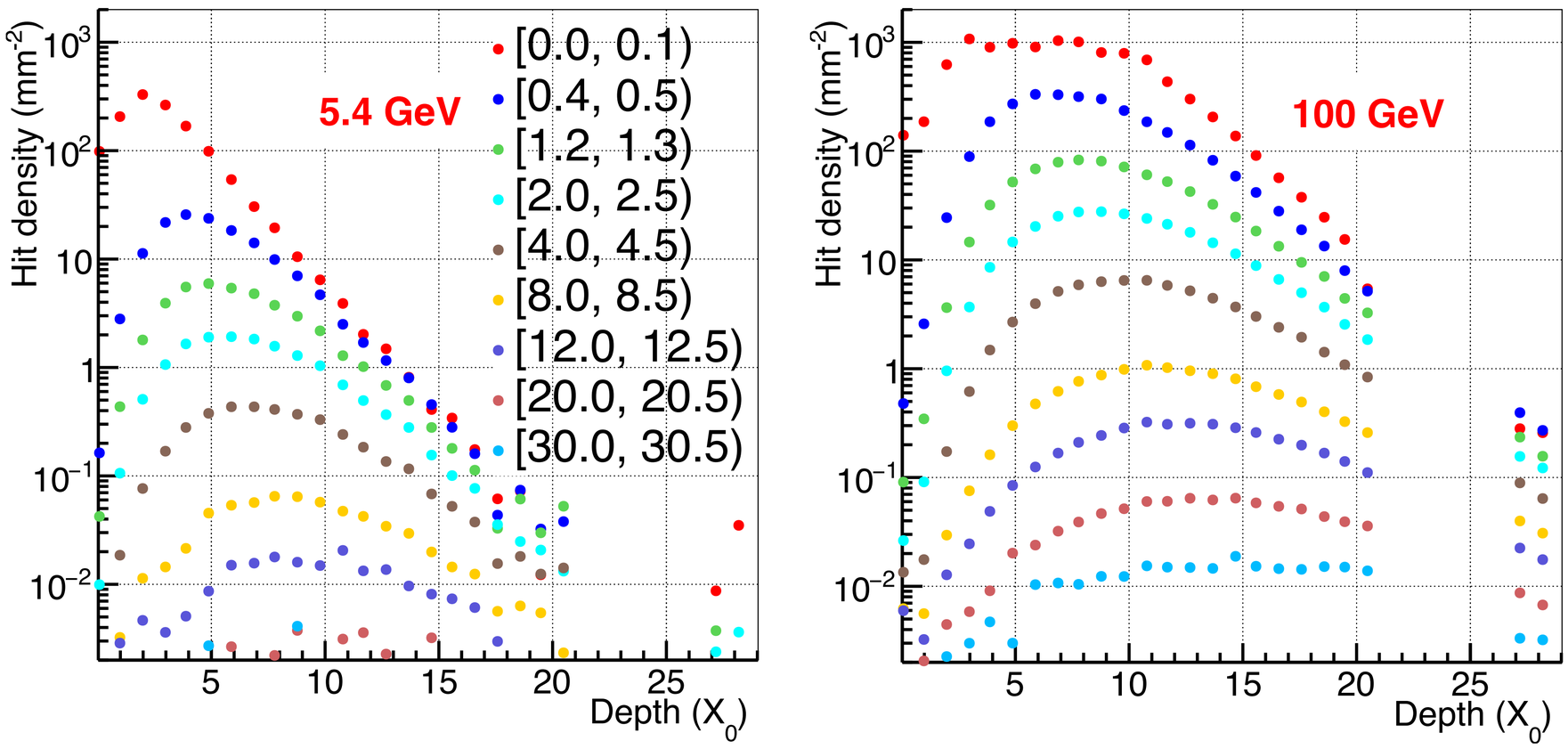


Shower Maximum



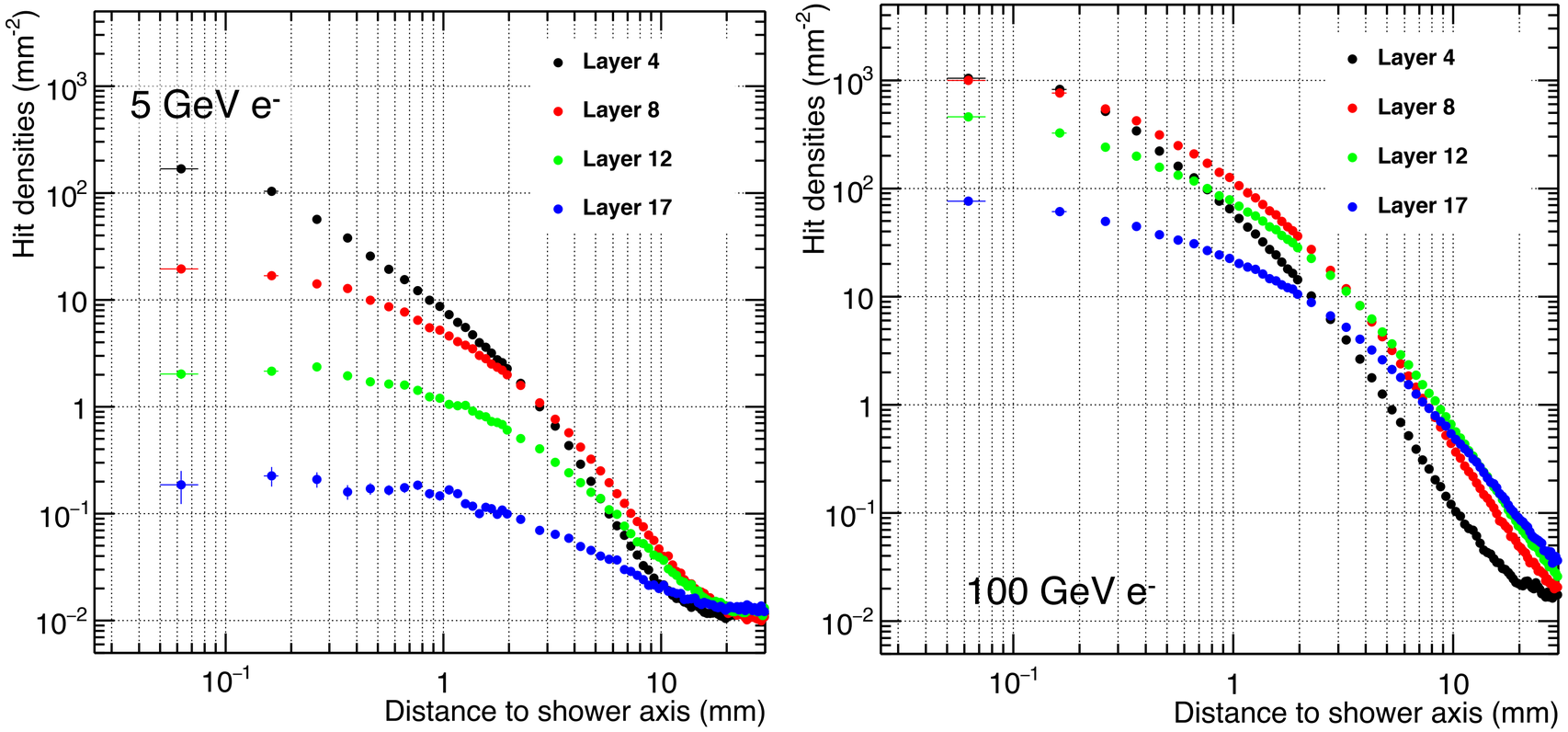
Longitudinal Profiles

- Average hit density as a function of depth for different radial positions
- Maximum hit density deeper for increasing ring radius
- Saturation in shower core (< 0.1 mm) at high energies



Radial Profiles

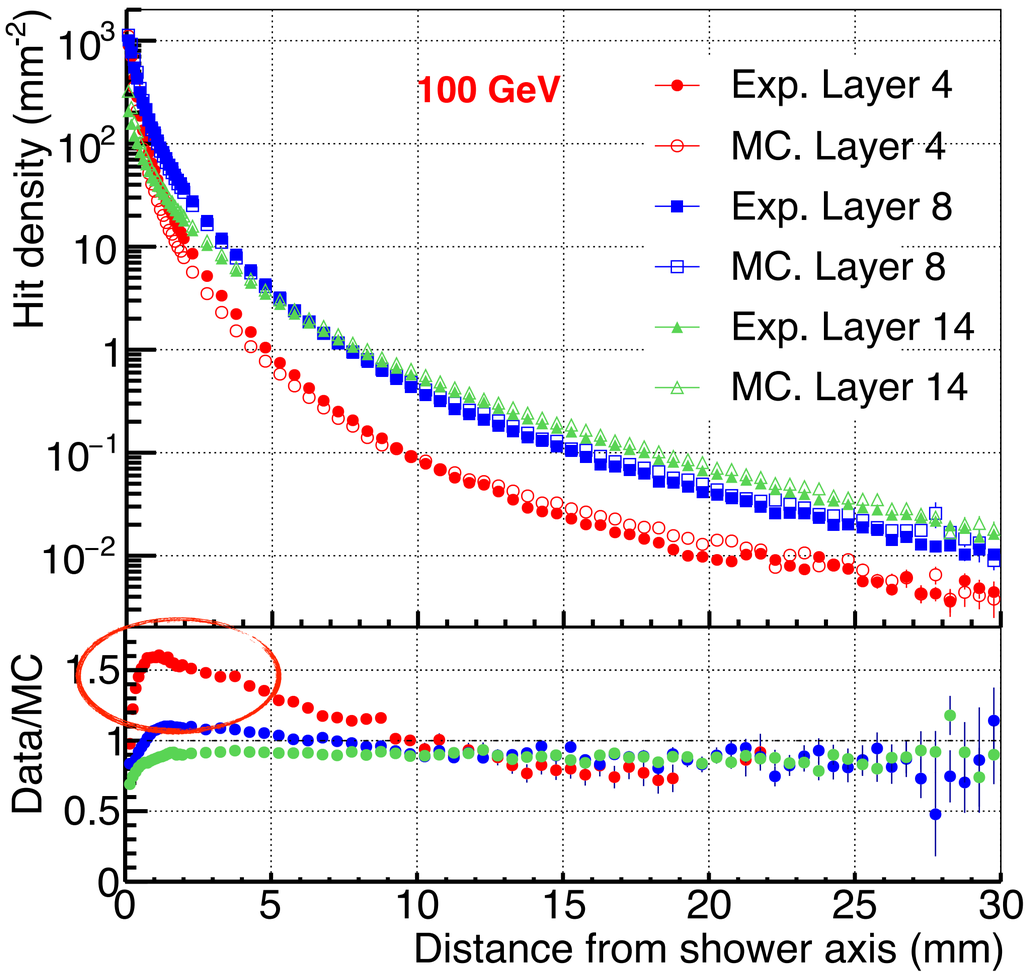
- Average hit density as a function of radius for different layers
- Profiles broaden with depth
- Increase up to shower maximum and then decay



Comparison to Geant4

Geant4 10.0.1

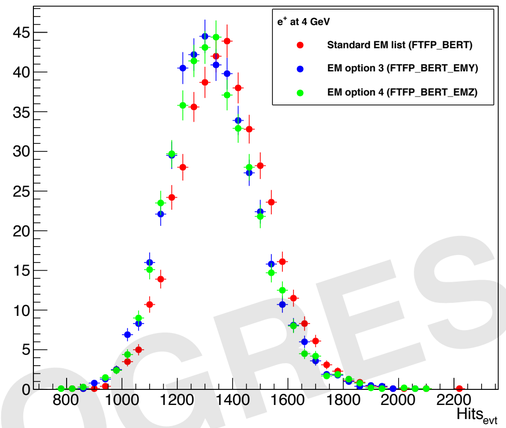
- In data a larger hit density in the shower core is seen in the first few layers
- In the MC the profiles are narrower compared to data
  - Does the MC produce a too low hit density in the core?
  - Caused by the imperfect charge sharing implementation in the simulation?

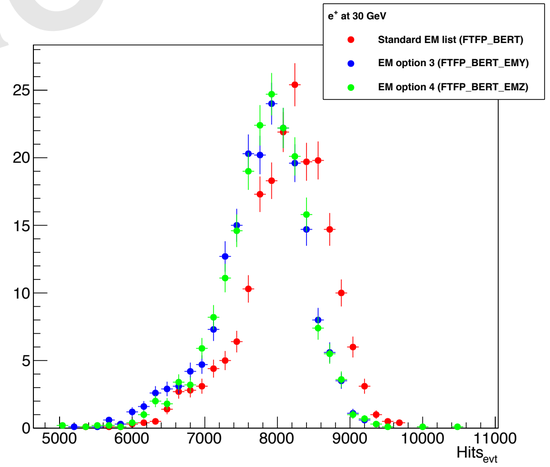


Different Geant4 EM model implementations

Geant4 10.0.1

- For the CALICE DHCAL _EMY physics list showed better performance
- Investigate the difference of several EM implementations on the showers in FoCal: standard, _EMY (option 3) and _EMZ (option 4)
- Very small differences:
  _EMY and _EMZ 3% (4 GeV) - 4% (30 GeV) less total hits
  In longitudinal profile over large range
  In lateral profile in shower core (<1 mm) and periphery
- Qualitative differences in same area as the differences with data





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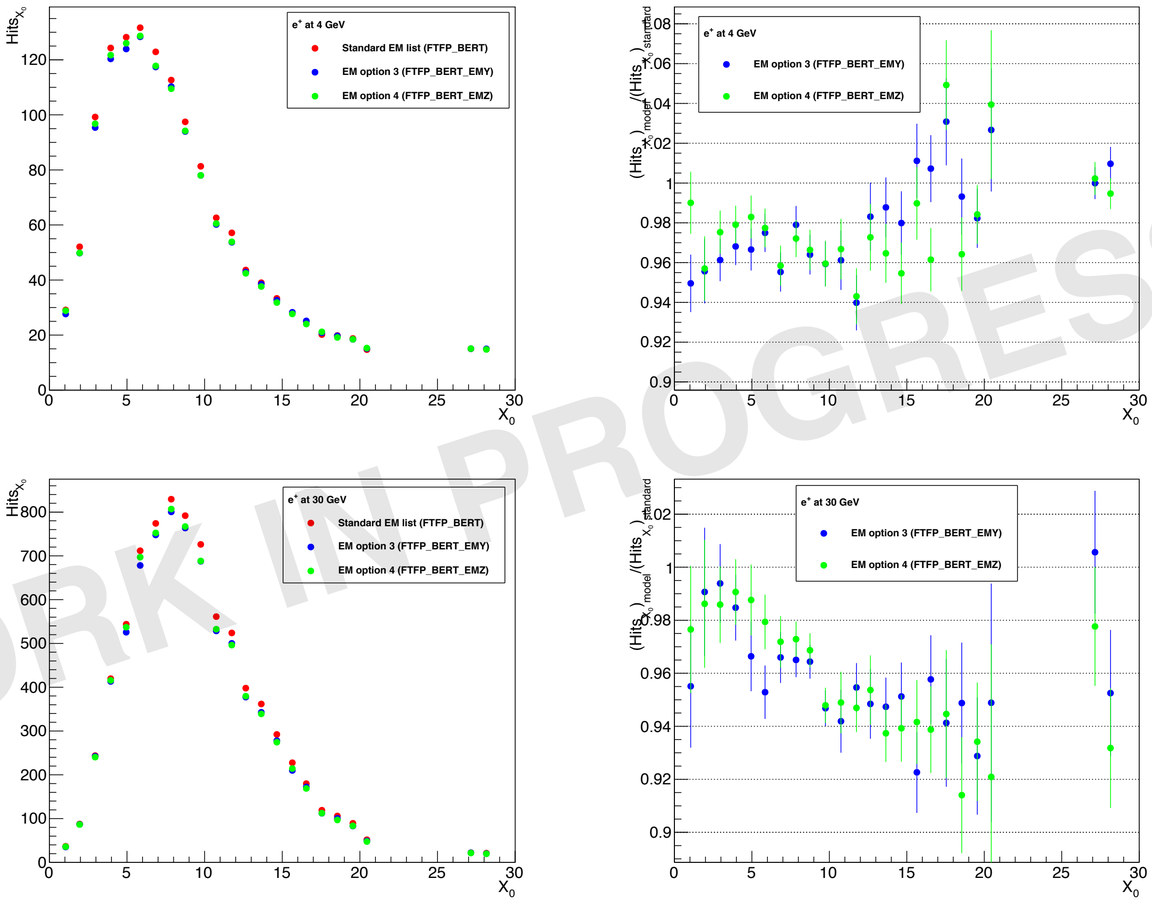

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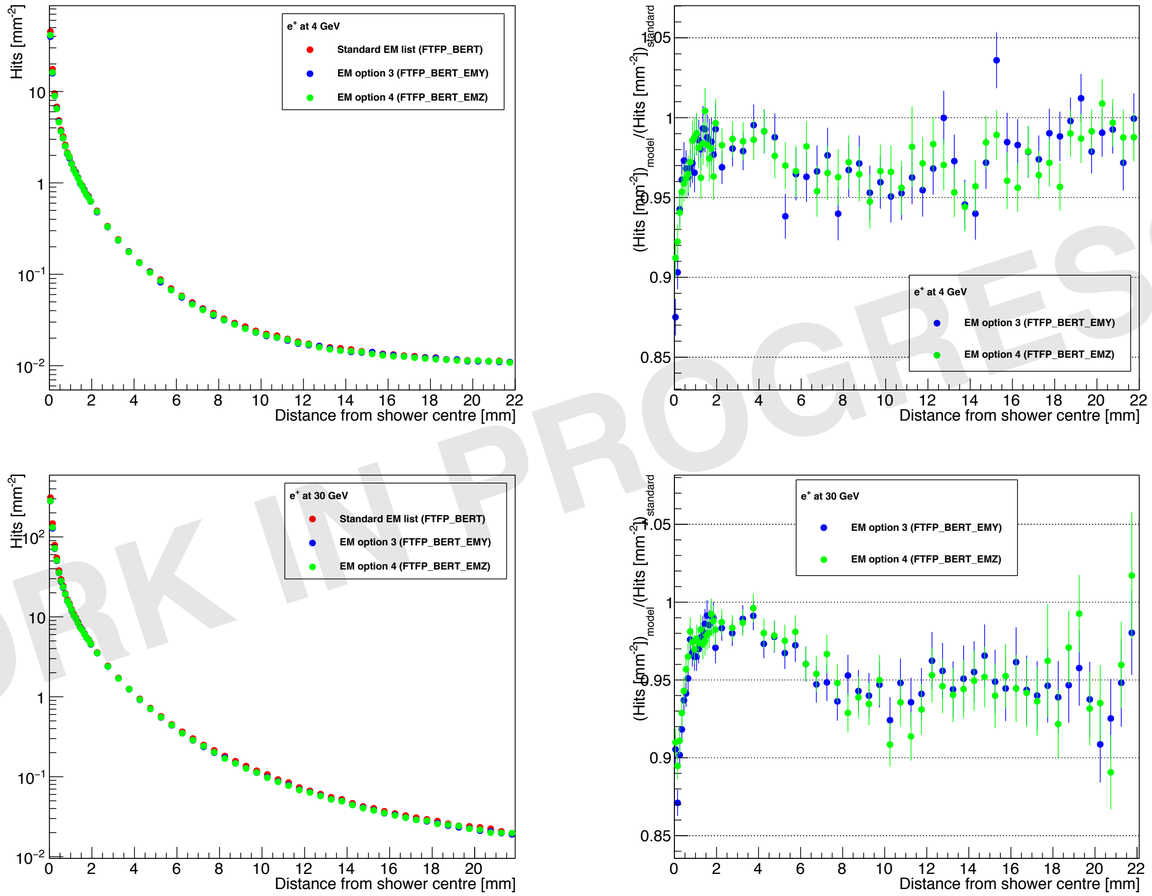
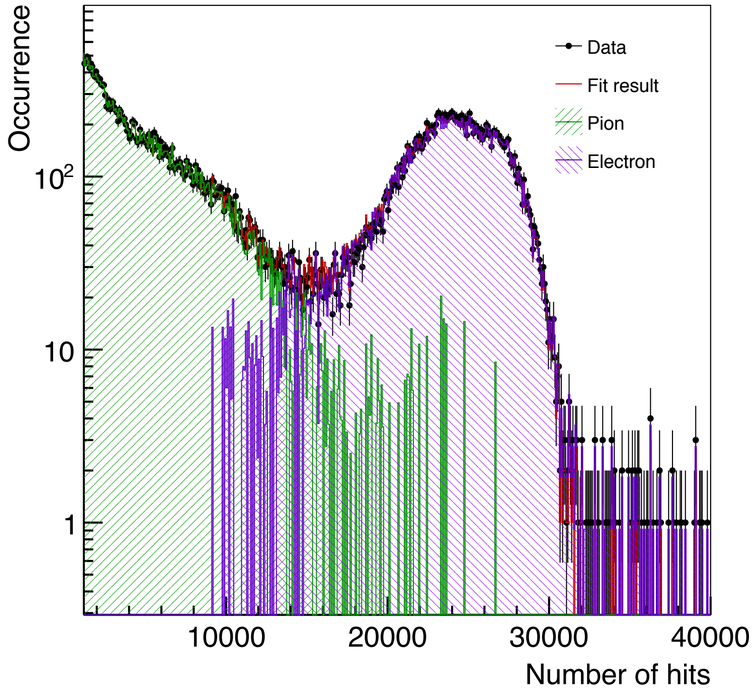
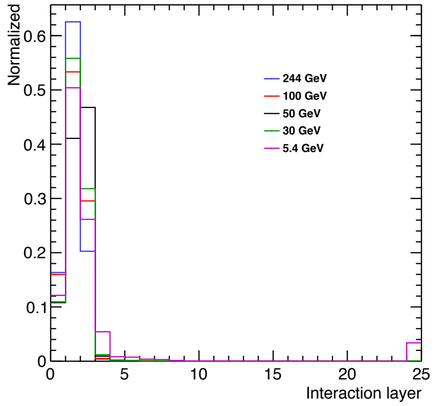


Particle identification

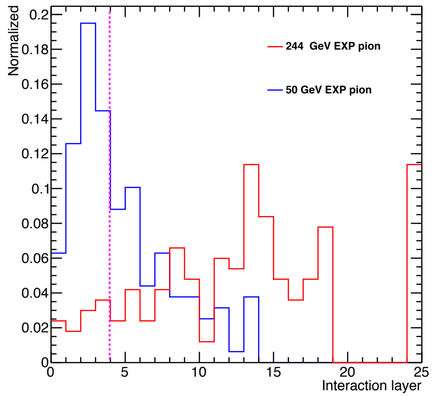
- Good selection of electrons vs pions possible in test beam data based on the number of hits
- Higher energy pions can generate the same number of hits as lower energy electrons
- Investigate other selection criteria applicable in a real experiment:
  Interaction layer
  Hit density in shower core
  3D shower shape (Master thesis just started)



100 GeV mixed (electron + pion) data. The fraction of electrons and pions is determined from a template fit based on MC simulations



Interaction layer of electrons at different energies, mostly before 5th layer

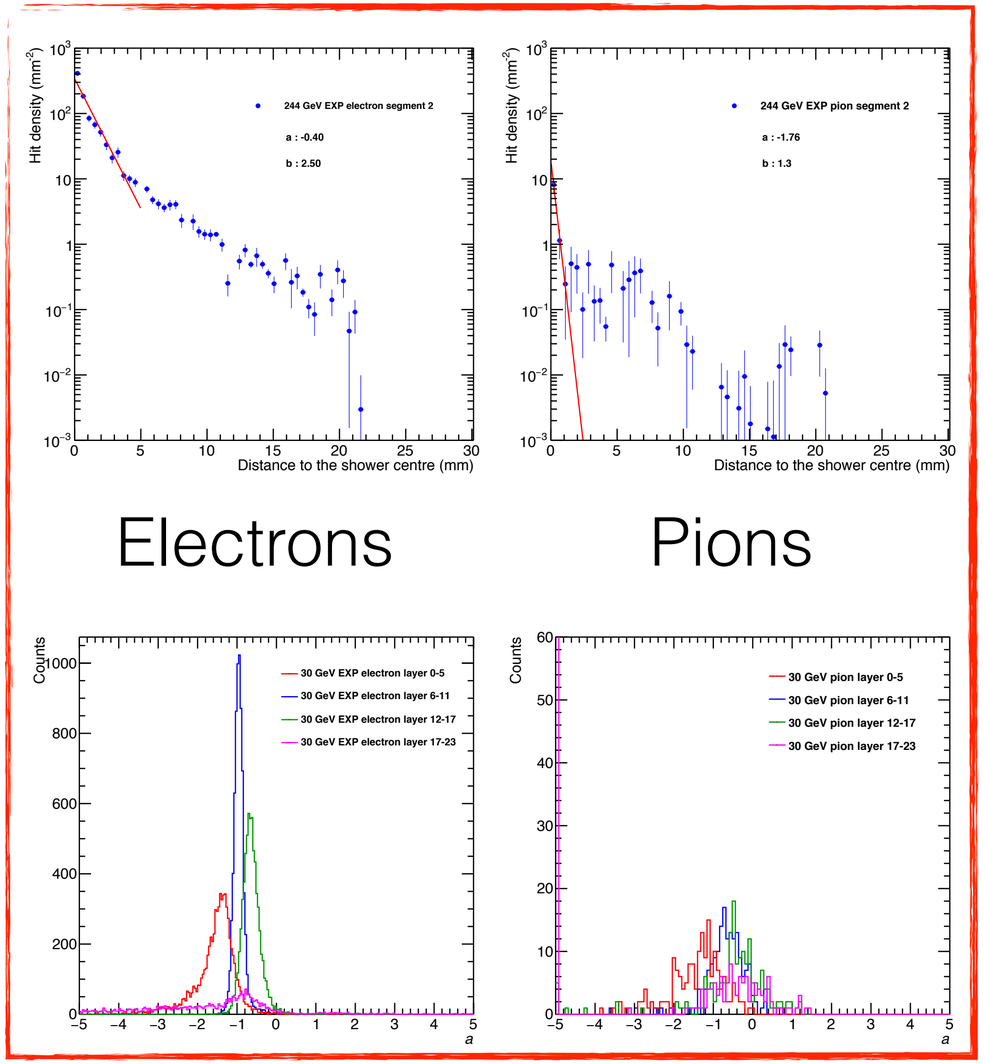


Interaction layer of pions with a similar number of hits as 30 GeV electrons

Interaction layer l is defined as:
N_{hits} > 30 for 3 layers or 2 consecutive layers in the range [layer l, layer (l+4)]

Fit to central radial hit density

- Fit a linear function to the log of the radial hit density in the first 5 mm from the centre
- Compare fit parameters a (slope) and b (constant) between electrons and pions
- Distribution for pions much more spread out



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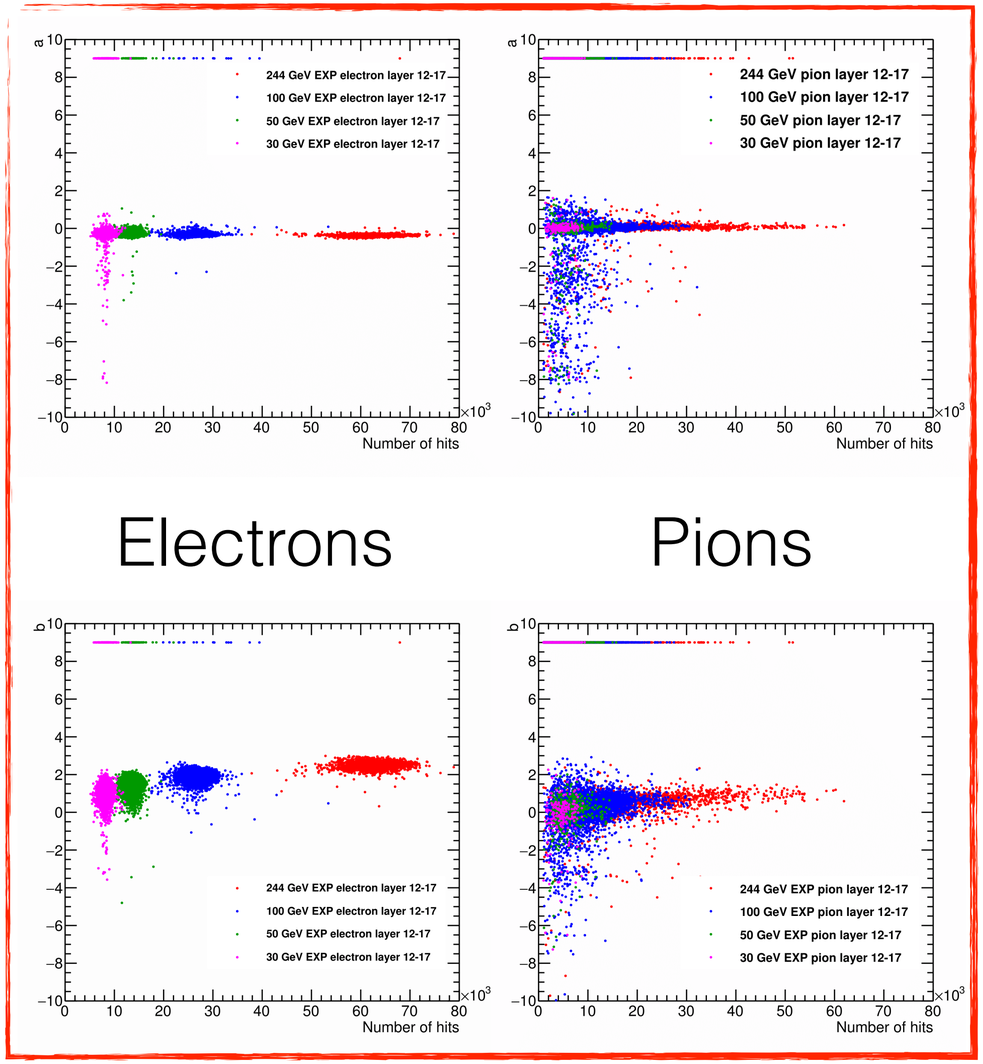


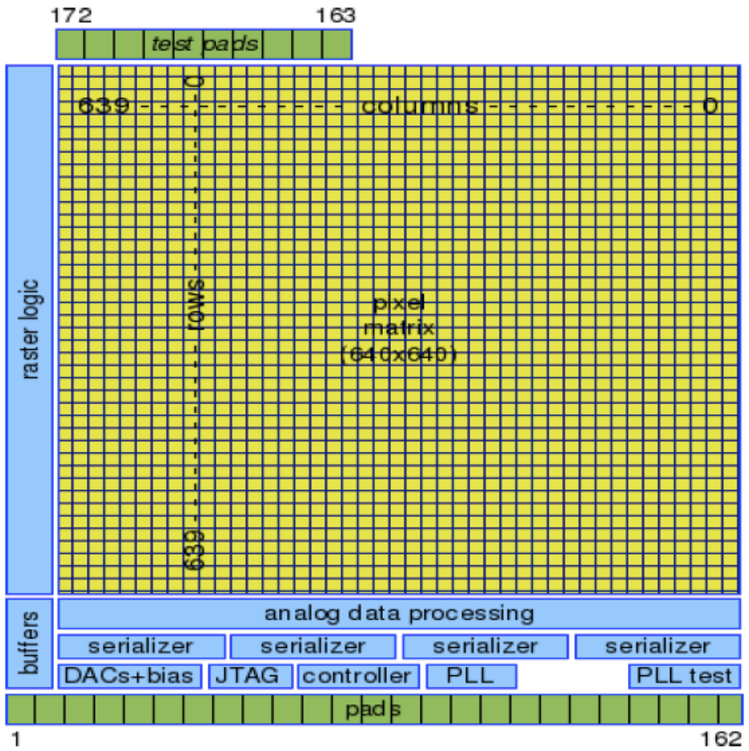
Conclusion

- Successful test of the MAPS prototype
  - proof of principle of a digital pixel calorimeter
  - new prototype based on ALPIDE chip underway
- Unprecedented detail of spatial distribution of e.m. showers
  - Ideal for testing MC models in detail; electromagnetic but also hadronic models (ongoing)
  - Identify particle type based on shower observables (ongoing)

Thanks for your attention

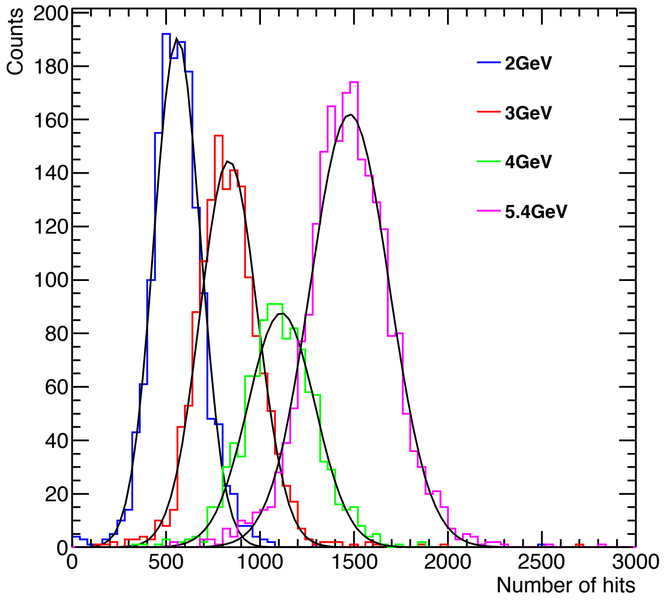
MIMOSA23 chip

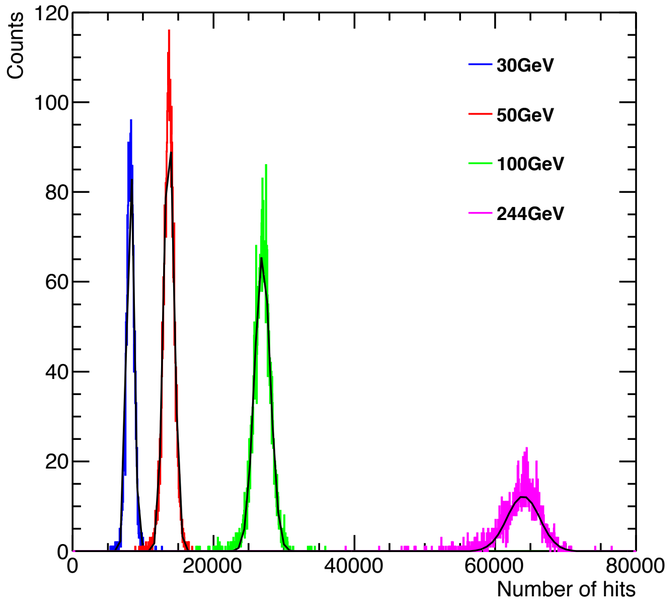
- Monolithic Active Pixel Sensor
- Chip size: 19.52 mm x 20.93 mm
- Active area: 19.2 mm x 19.2 mm
- Pixel pitch: 30 μm, 640 x 640 pixels (=409600/chip)
- Readout frequency: 160 MHz
- 1 MHz rolling shutter, 640 μs integration time

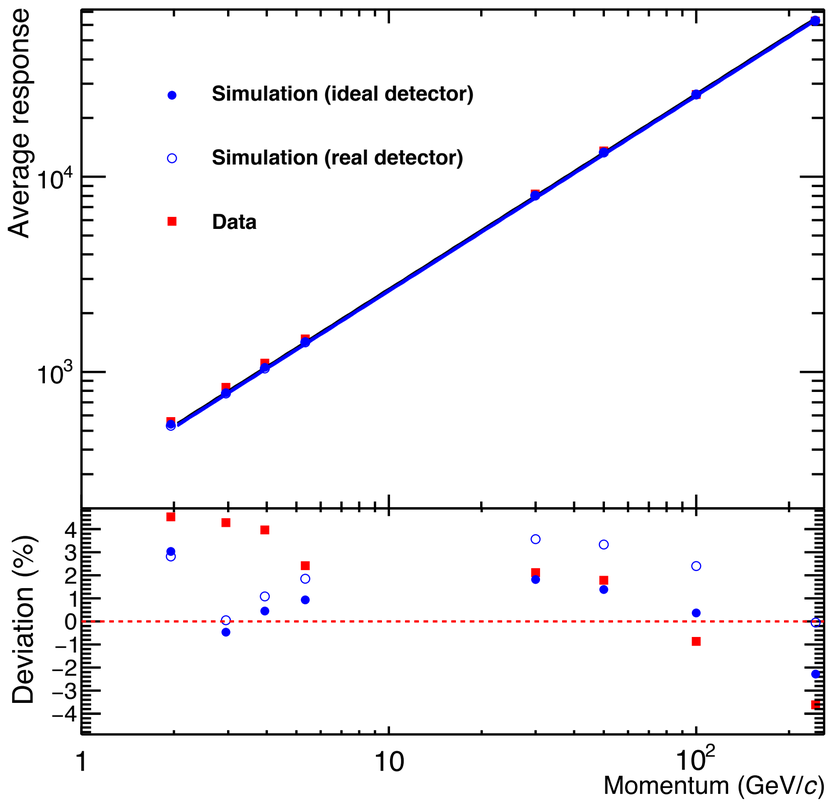


Response

- Response calculated via integration of calibrated radial hit density
- Good linearity





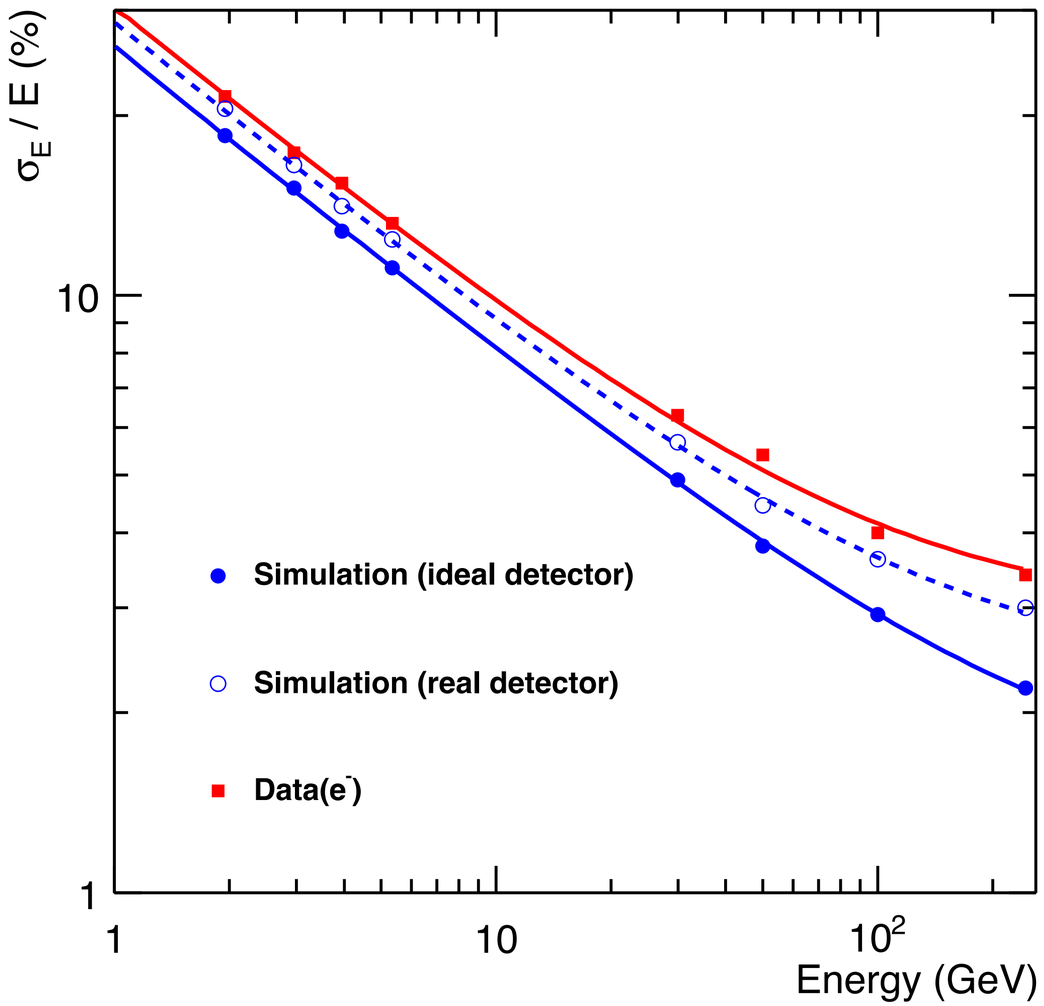


Energy resolution

- Good energy resolution

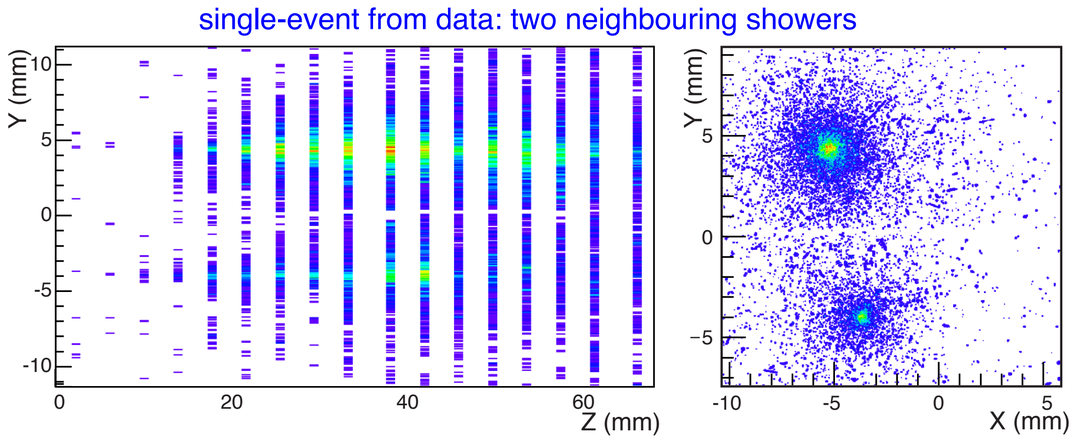
$$\frac{\sigma}{E} = \frac{30}{\sqrt{E(GeV)}} + \frac{6.3}{E(GeV)} + 2.8$$

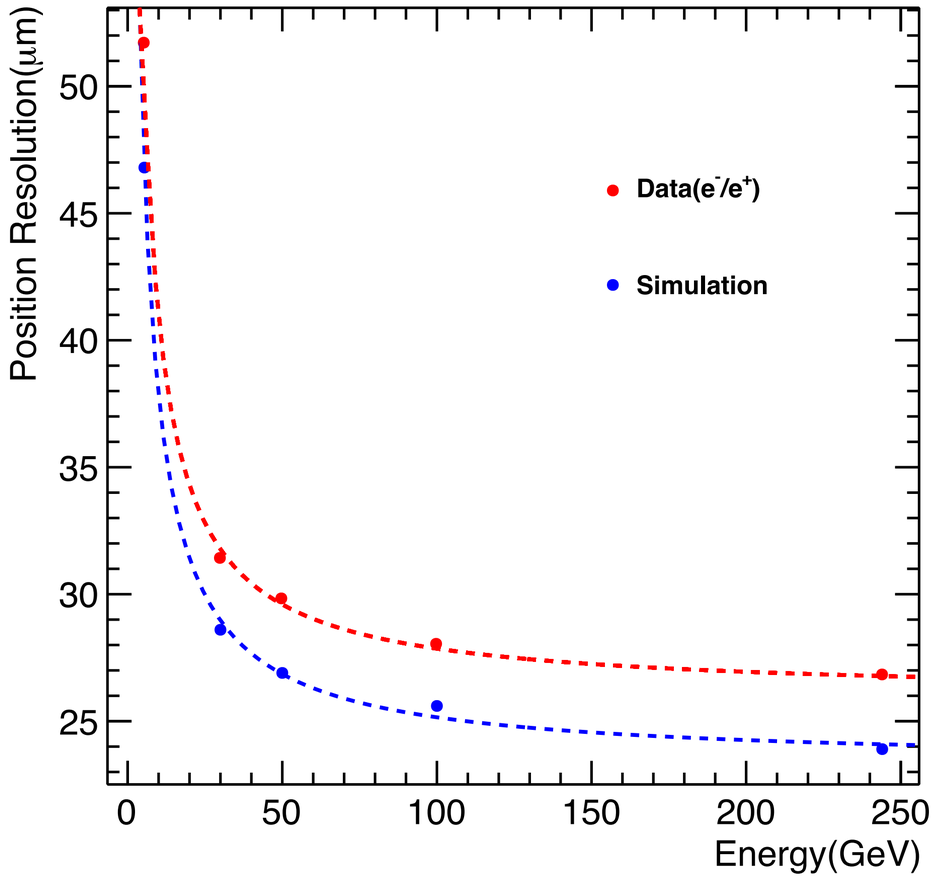
- Proof of principle of digital calorimeter



Position resolution

- Position resolution determined from the spread in the residuals of the centre of gravity (layers 1 - 23) compared to the first layer (layer 0)
- Resolution reached smaller than pixel size
- Excellent 2 shower separation possible





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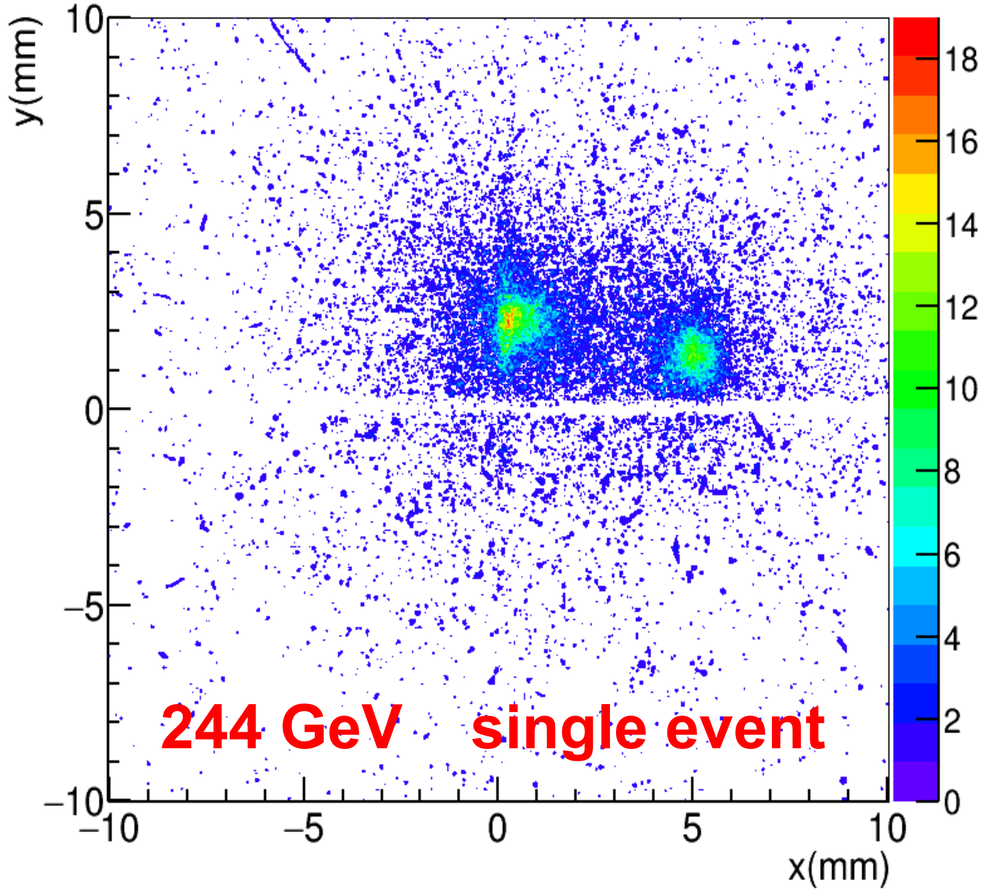

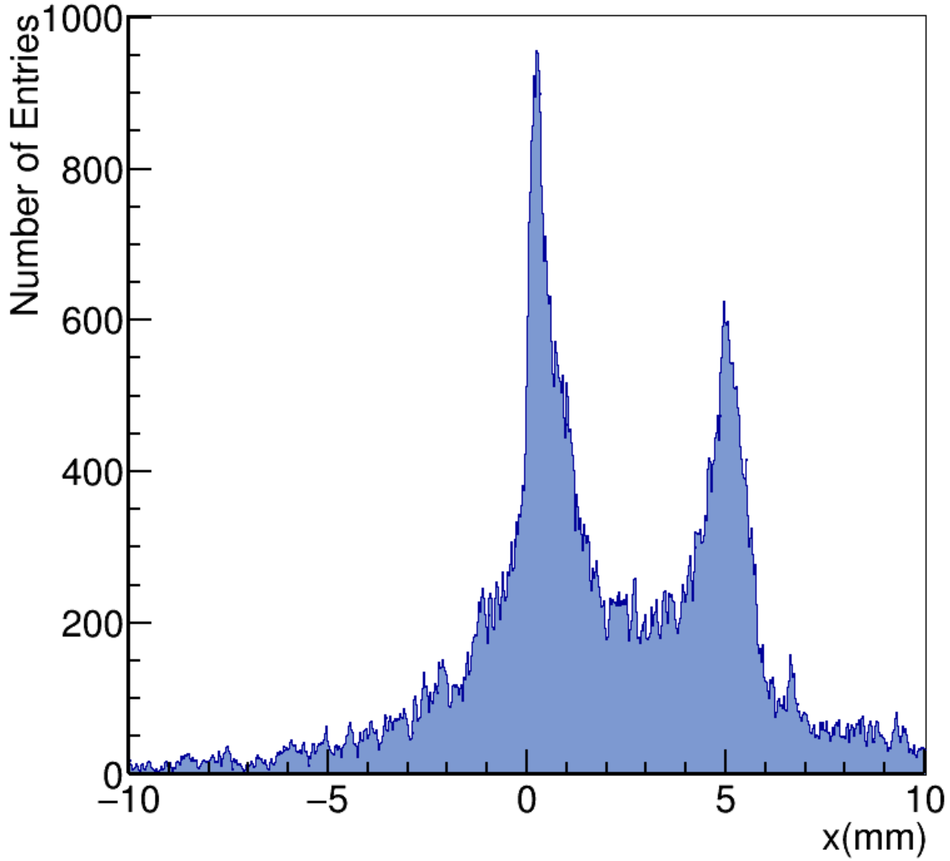

- Shower separation down to ~5 mm possible

Shower core

- Response and energy resolution possible from the shower core only (r = 5 mm)
  Integral in cylinder around the shower centre

- Separation power to ~0.5 R_M possible