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Towards ultra-high granularity calorimetry

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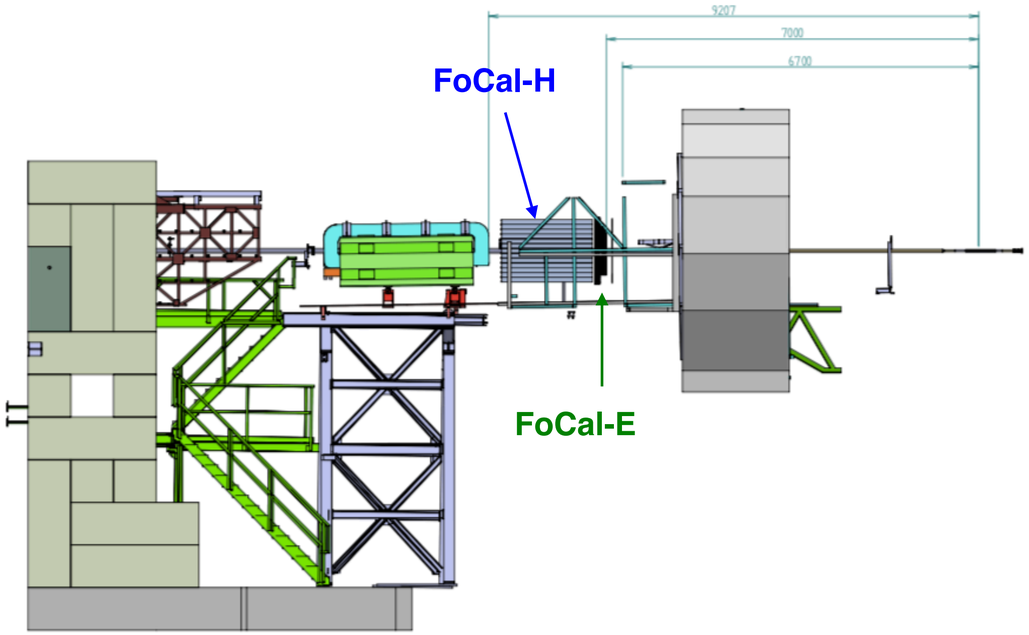
for the EPICAL and FoCal Collaborations

CPAD Instrumentation Frontier Workshop 2021

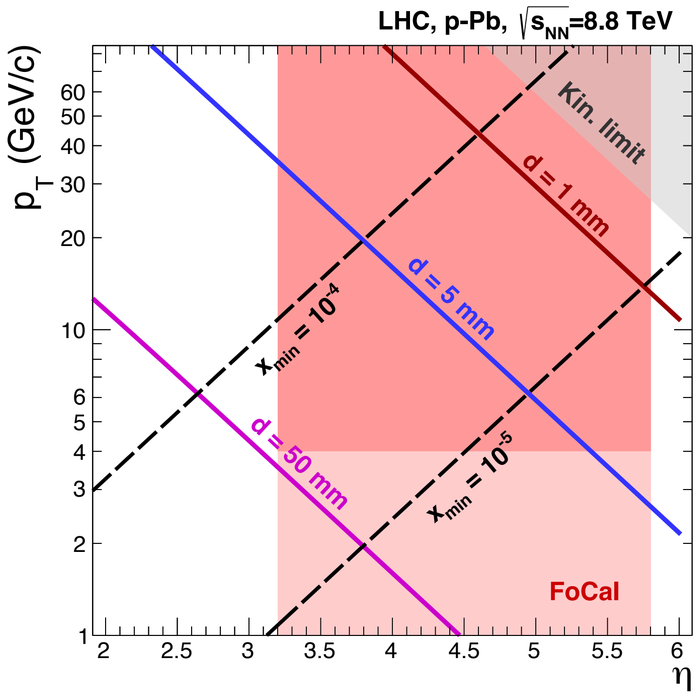
Digital Pixel Calorimeter Basics

- Calorimeter signal (deposited energy): total track length of charged shower particles
  - traditional (analog): e.g. scintillation light or ionisation (total or sampled)
- Digital: sample number of shower particles
  - ideally: high-efficiency single-bit signal per particle (hits)
  - high granularity required due to high particle density
  - have to account for intrinsic spatial spread of particle signal
- Technology of choice: silicon pixel sensors
  - charge sharing produces cluster of hits
  - spatially differential signal: hit/cluster density
- High granularity
  - required for good linearity and resolution (avoid saturation)
  - spatial information is additional benefit: advantage for two-shower separation

FoCal in ALICE



- main challenge:
  - separate γ/π^0 at high energy
    - resolve photon pairs with separation < 5 mm
    - need small lateral shower width, high-granularity read-out:
  - Si-W calorimeter

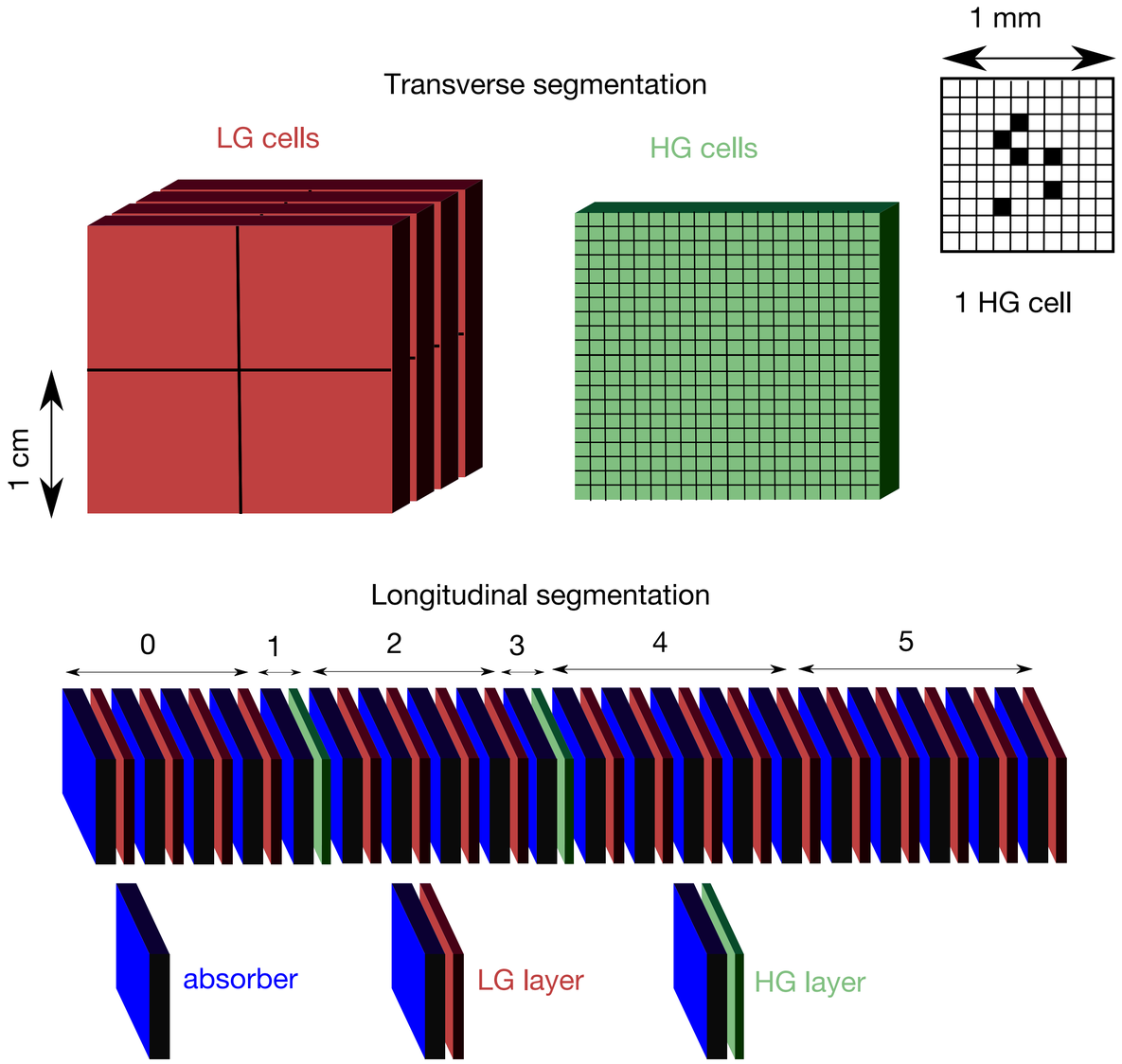


FoCal-E: high granularity electromagnetic calorimeter for γ and π^0 measurement
FoCal-H: conventional hadronic calorimeter for isolation and jets

positioned at $z \approx 7$m: $3.2 < \eta < 5.8$

Letter of Intent: http://cds.cern.ch/record/2719928

FoCal-E – Design Principle



studied in performance simulations:

20 layers:
W (3.5mm ≈ 1 X_0) + Si-sensors

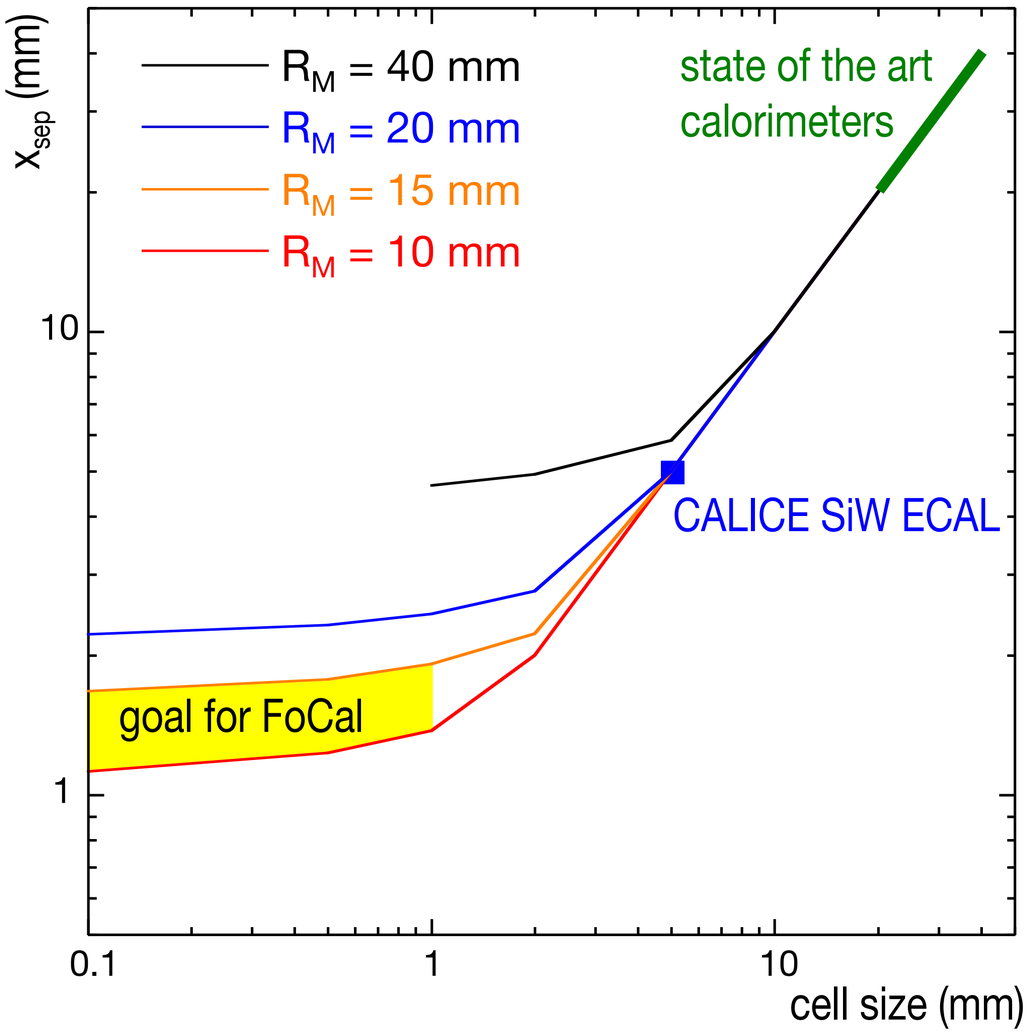
hybrid design (2 types of sensors)

- **Si-pads** (≈ 1 cm^2):
  energy measurement, pileup rejection
- **CMOS pixels** (≈ 30x30 μm^2):
  two-shower separation, position resolution

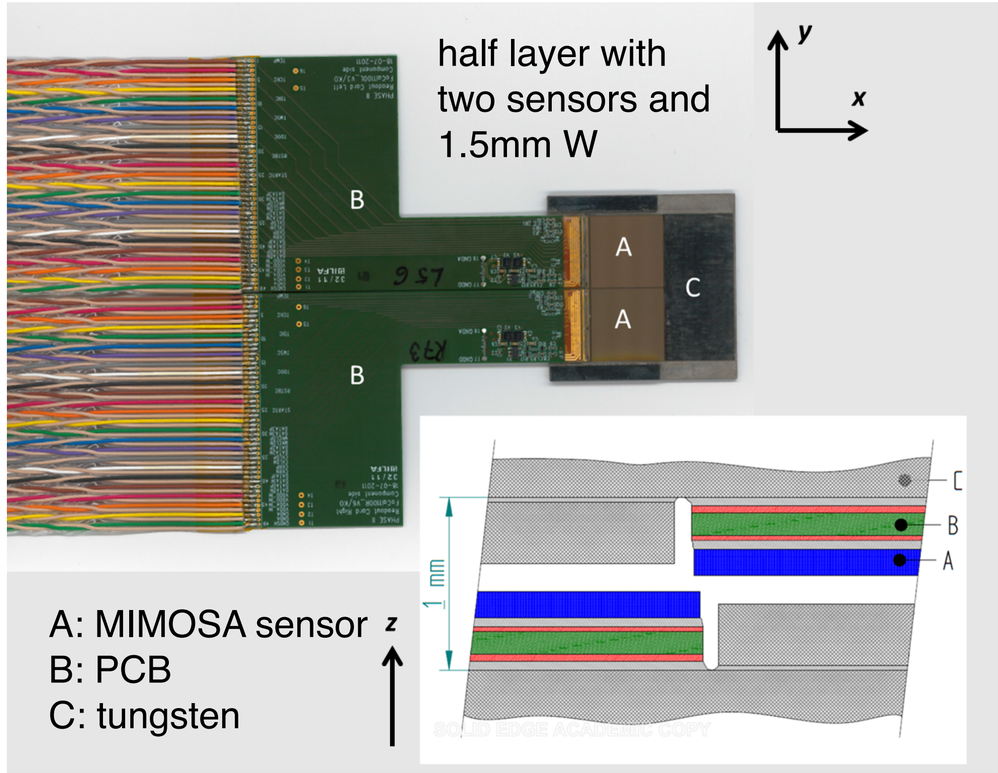
final optimization to be done:
e.g. location (and number?) of pixel layers

Motivation of Pixel Layers

- rejection of decay photons
  - two-shower separation
  - shower shape measurement
- choose pixel sensors ≈ 30μm
  - granularity ≈ 1 mm important for separation
  - 1 mm pixels would suffer extremely from multiple hits
    - hit density > $10^3/mm^2$ in shower core
- digital pixels: need finer granularity to measure hit density in shower
  - number of hits/clusters as signal
  - equivalent to deposited energy
- also allows precision shape measurement



The First Full Digital Si-W Pixel Calorimeter: EPICAL-1



calorimeter stack of 24x2 half layers equipped with MIMOSA CMOS pixel sensors – 30x30 μm^2 pixels

two half layers mounted together with opposite orientation to minimise dead areas

total layer thickness ≈ 1 X_0, active cross section 4x4 cm^2

full active layer with readout boards within 1mm

extremely compact design
- allows for high pixel density and small Molière radius

beam tests performed at DESY (e^-, 2-5.4 GeV), SPS (mixed, 30-244 GeV)

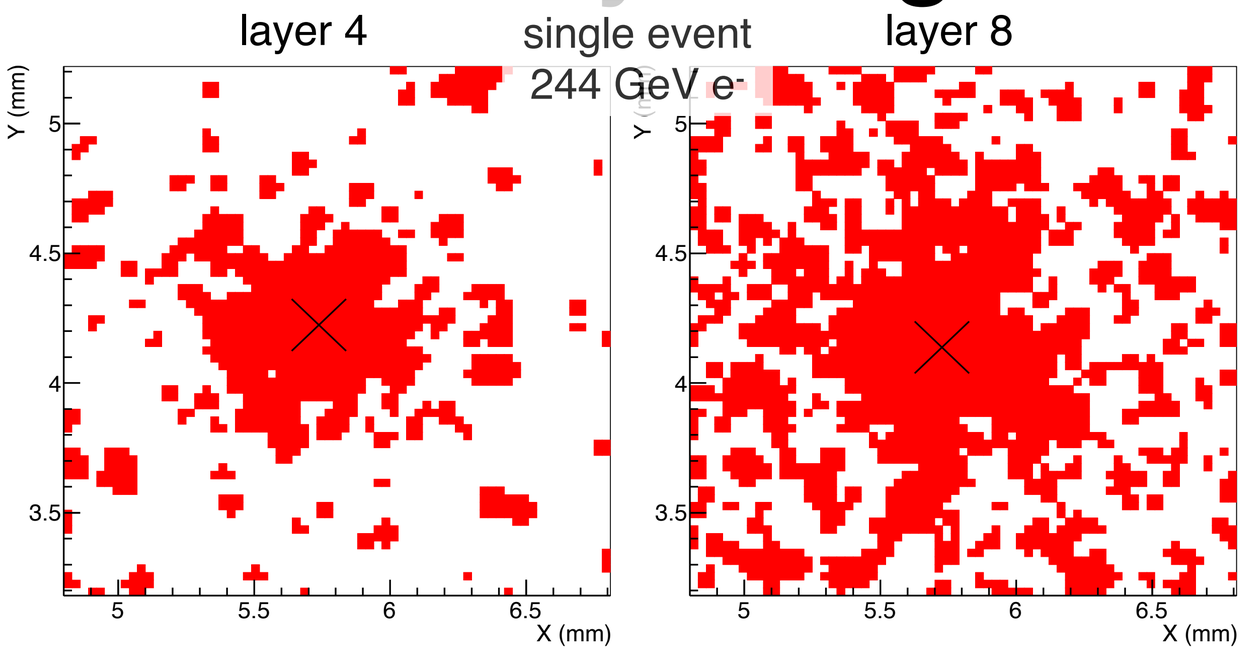
limitations: very slow readout, significant number of dead channels

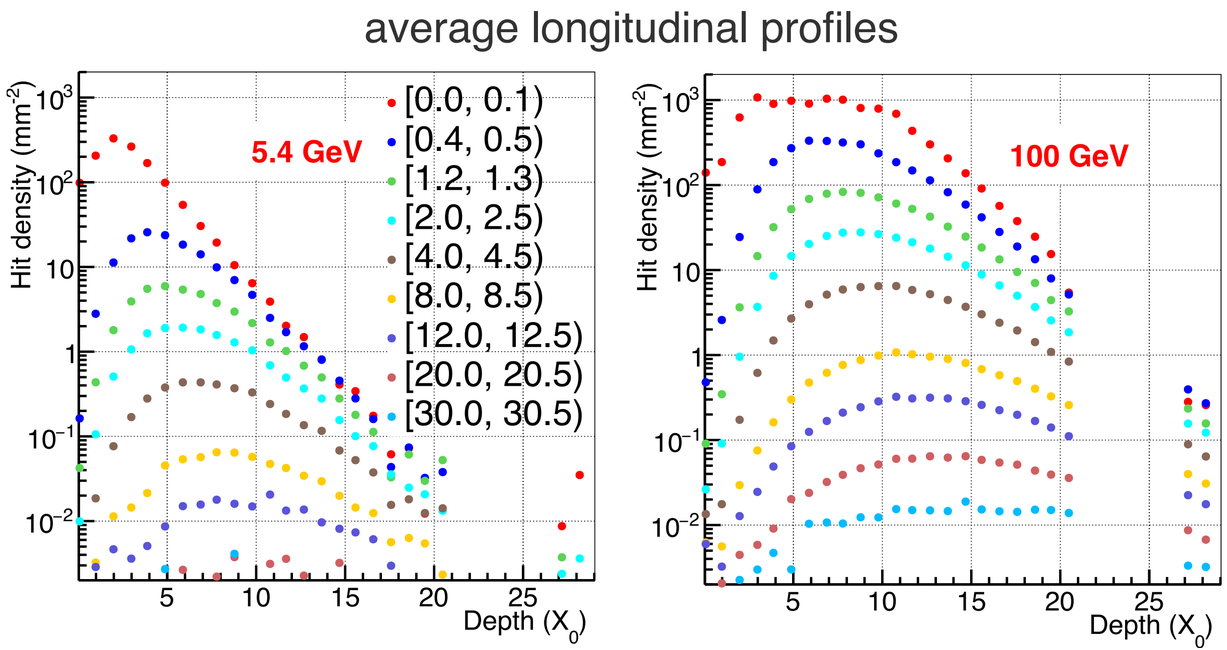
successful proof of principle of a digital calorimeter
key to understanding a new detector technology

First results published in JINST 13 (2018) P01014

Hit Density in High-Energy Shower

EPICAL-1





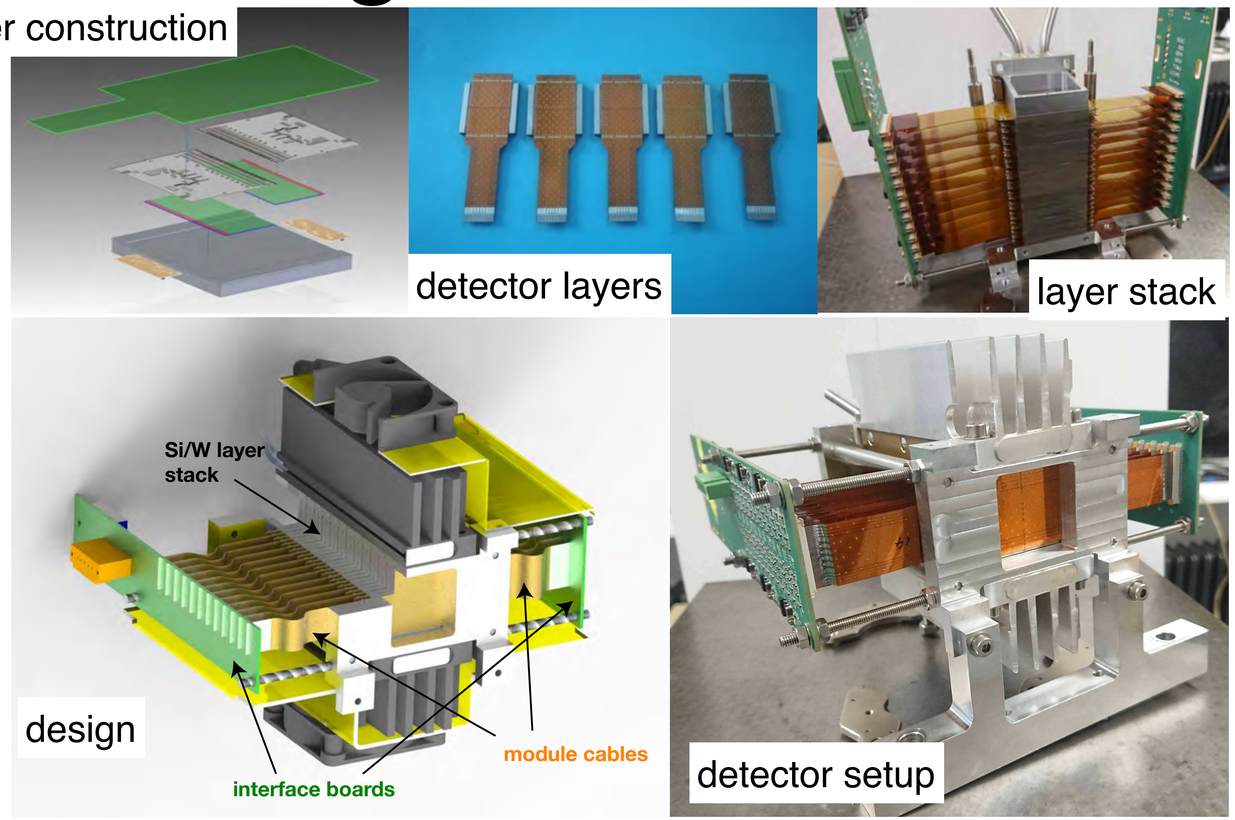
digital measurement provides high effective dynamic range

- full occupancy at ≈ 10^3/mm^2 hit density

very high hit density in shower core

- saturation (overlap of clusters) likely for very high energy
- observable in innermost shower core
- no issue here
  - leads to few % non-linearity
  - correction possible

New Digital Calorimeter Prototype – EPICAL-2



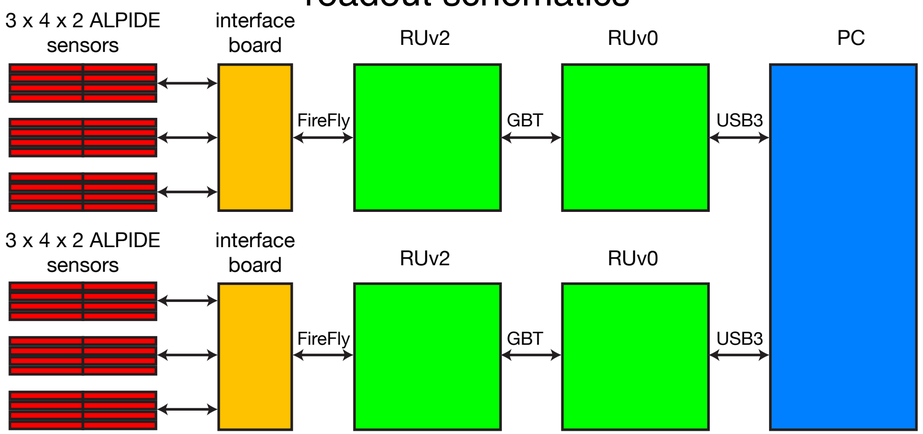
24 layers with each
- 3mm W absorber
- 2 ALPIDE CMOS sensors
- ultra-thin flex cables (LTU Kharkov)

30x30 μm^2 pixel size
active cross section 3x3 cm^2

again compact design
expect $R_M \approx 11$mm

water or air cooling available

readout schematics

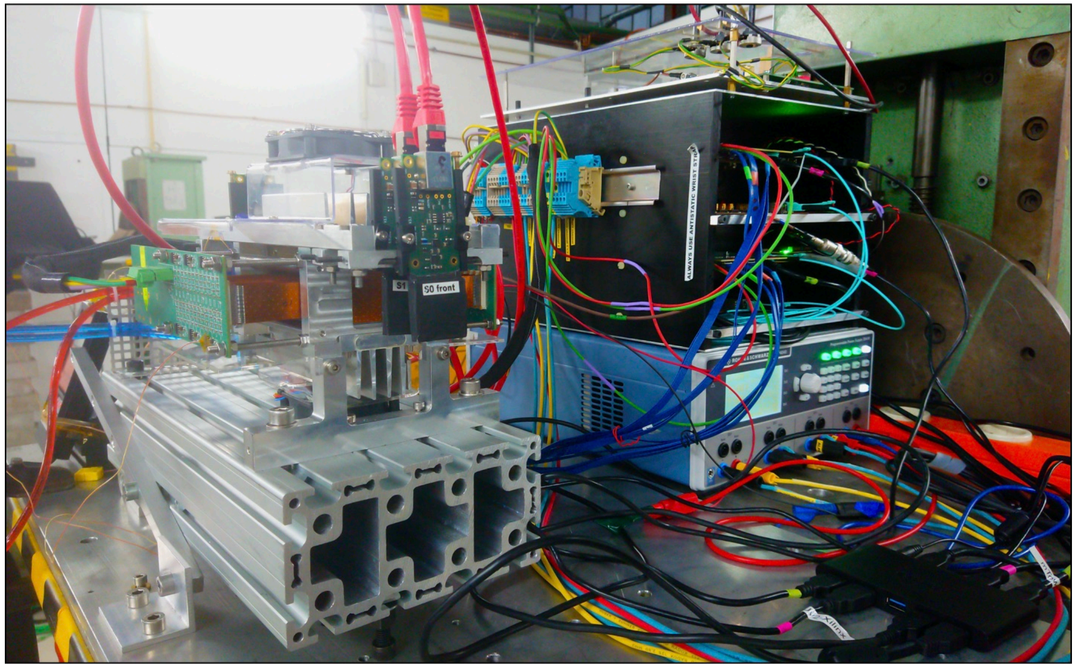


ALPIDE output via 1.2 Gb/s serial line

readout via 2 levels of FPGA
preliminary connection to DAQ PC
via USB (rate limitation)
to be replaced with ALICE CRU

Measurements

- electron/positron test beam
  - DESY TB22, February 2020
  - beam energies 1.0, 2.0, 3.0, 4.0, 5.0, 5.8 GeV
  - various angles of incidence, detector positions
  - different detector temperatures
  - total ≈ 44 million events
- cosmic muons
  - Utrecht University, May - October 2020
  - total ≈ 9000 events

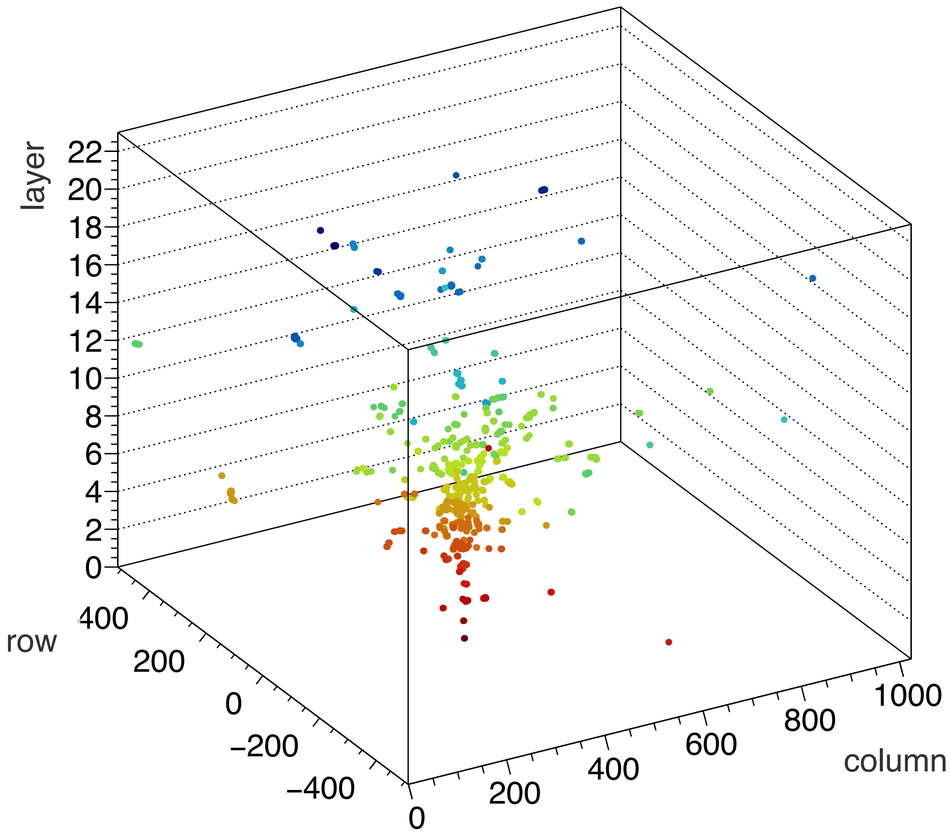


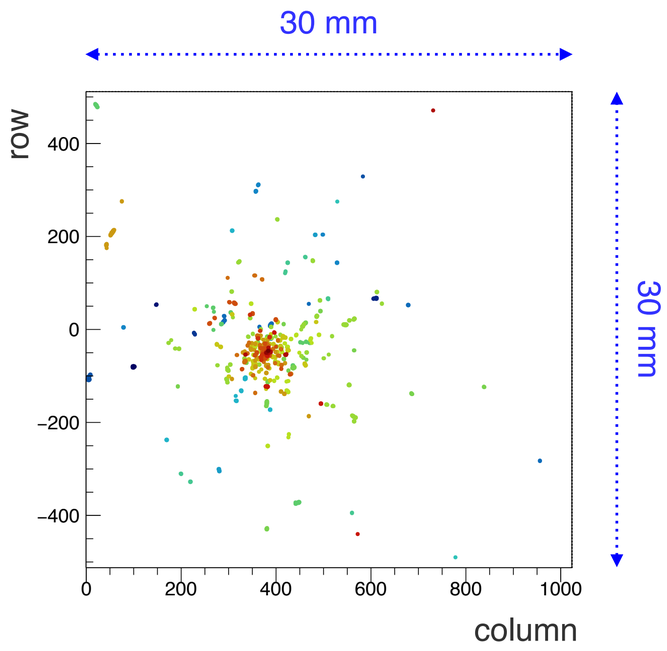
EPICAL-2

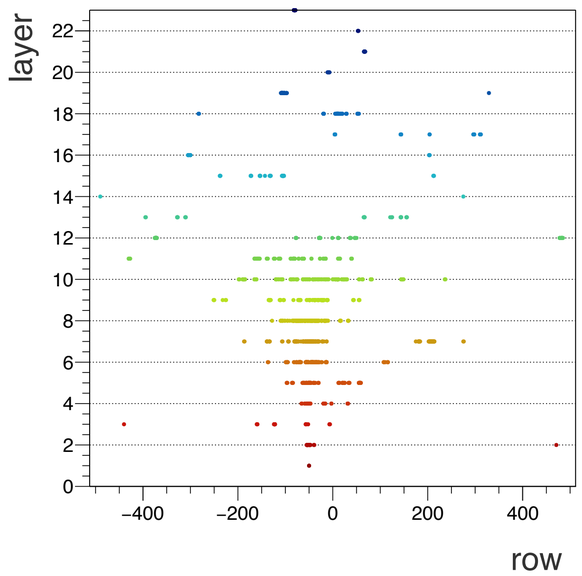
Event Display

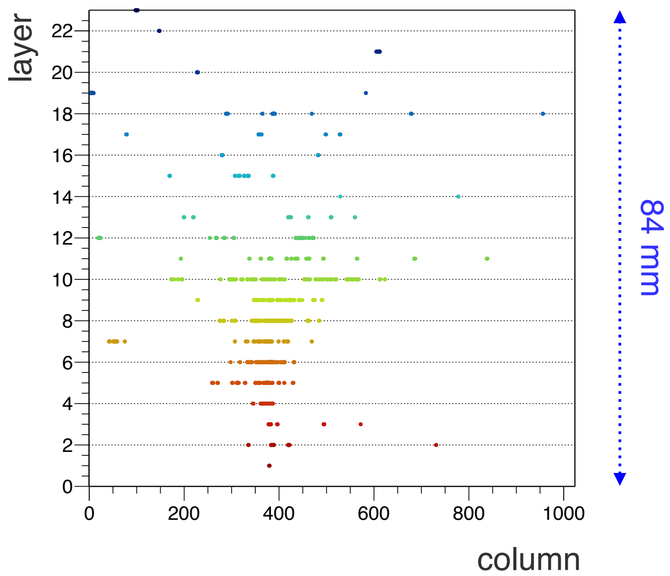
single electron event
5 GeV
raw data

colour → layer number

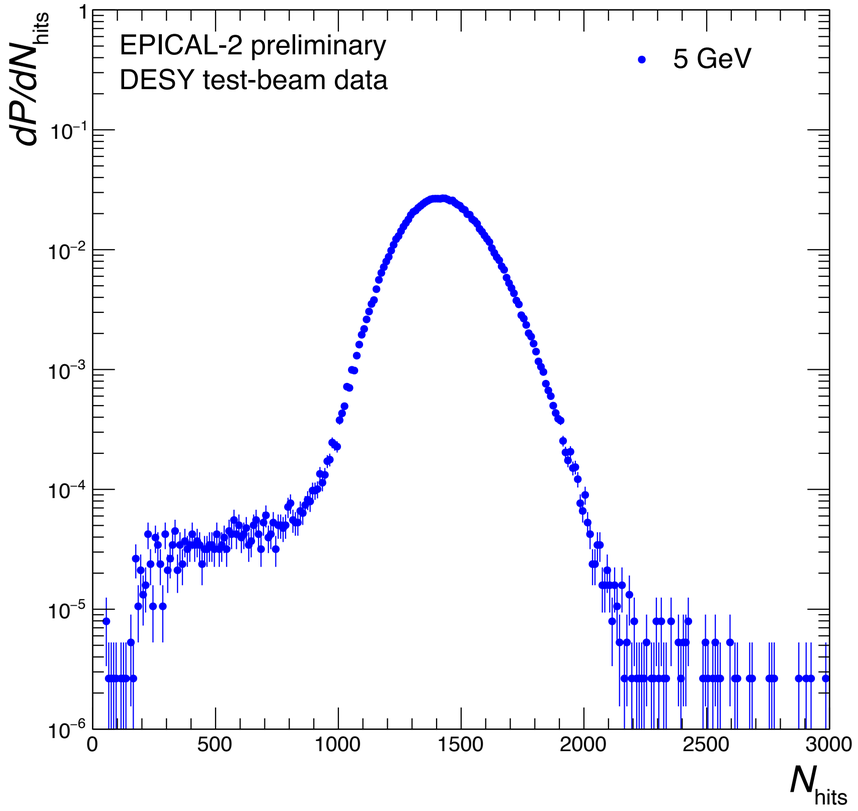


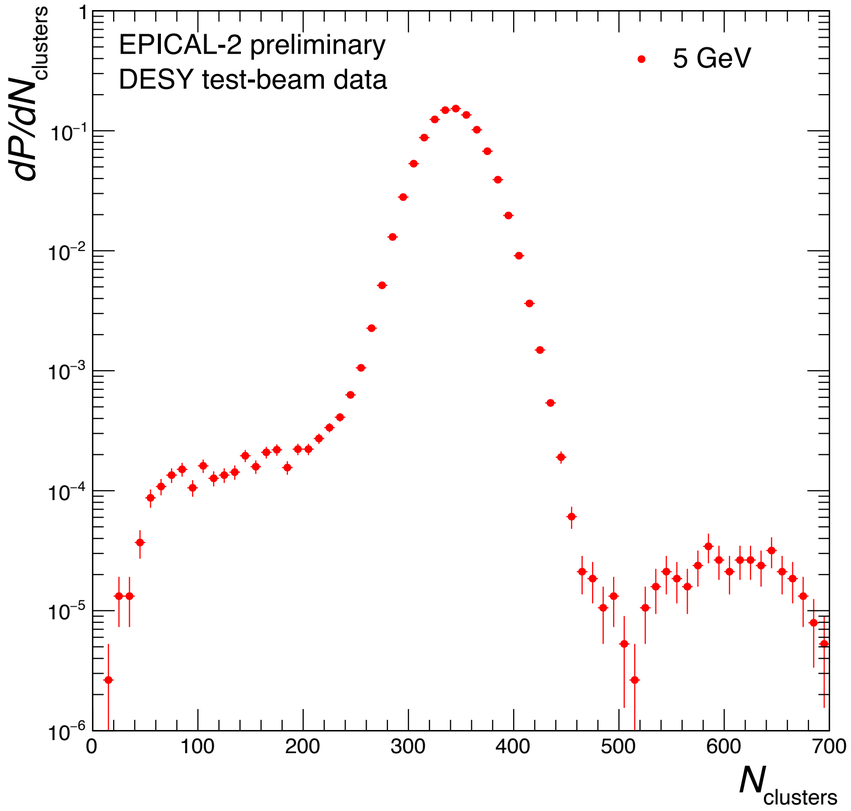






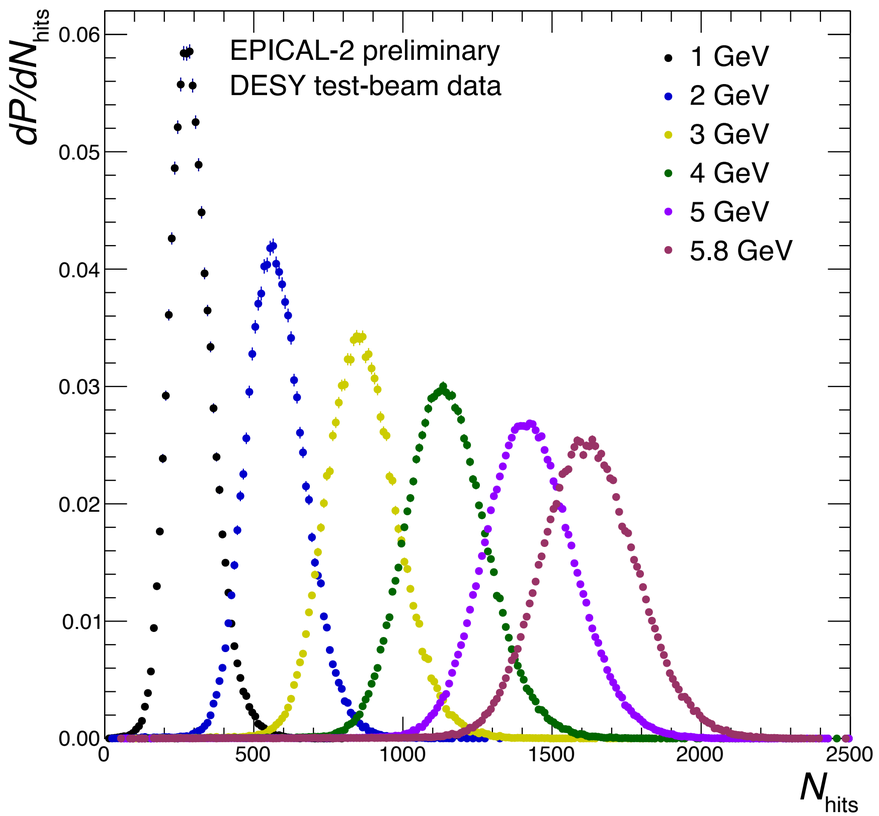
Energy Measurement – Hits vs Clusters

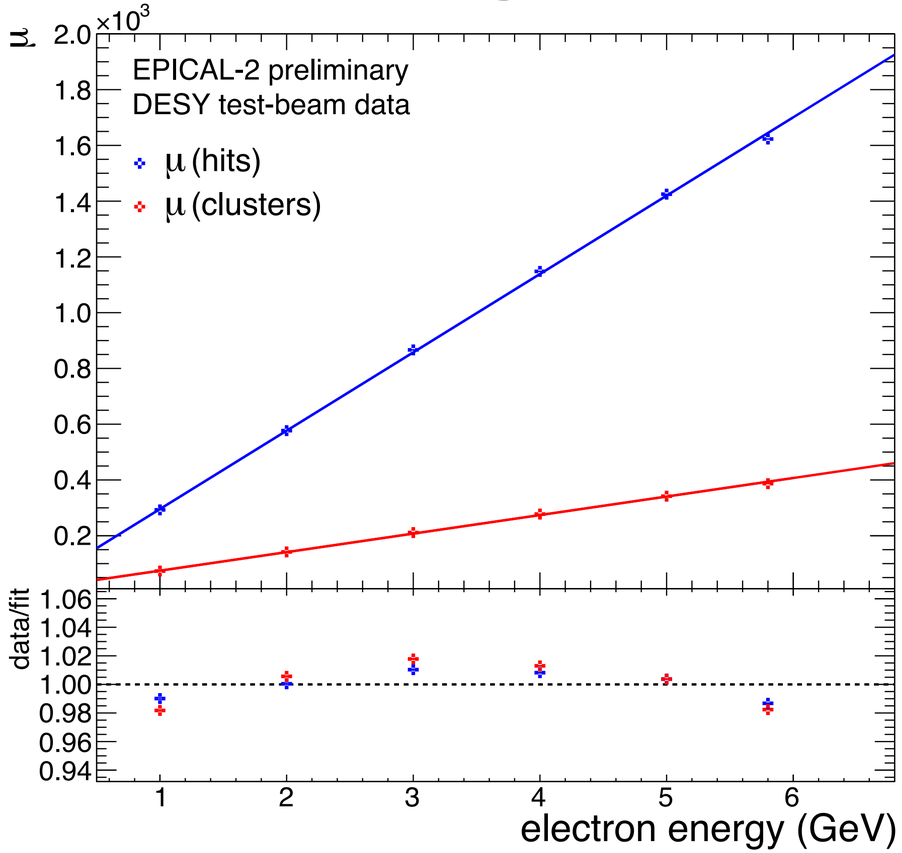




- Gaussian shape with small asymmetry
  - smaller width for clusters
  - tail at high energy side: residual pileup
  - tail at low energy side: low-energy contamination of beam
- current analysis: use numerical mean and standard deviation

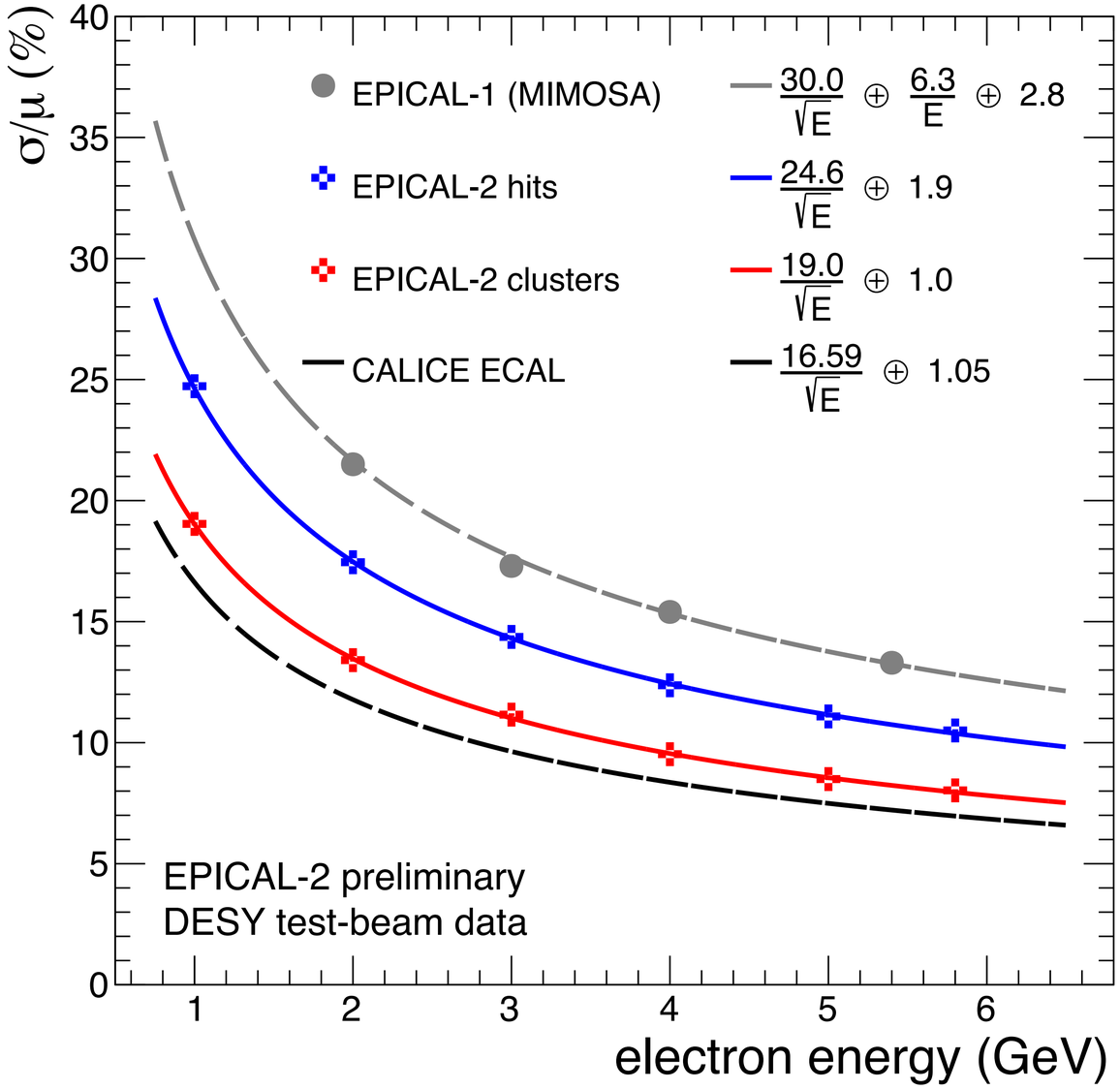
Energy Linearity





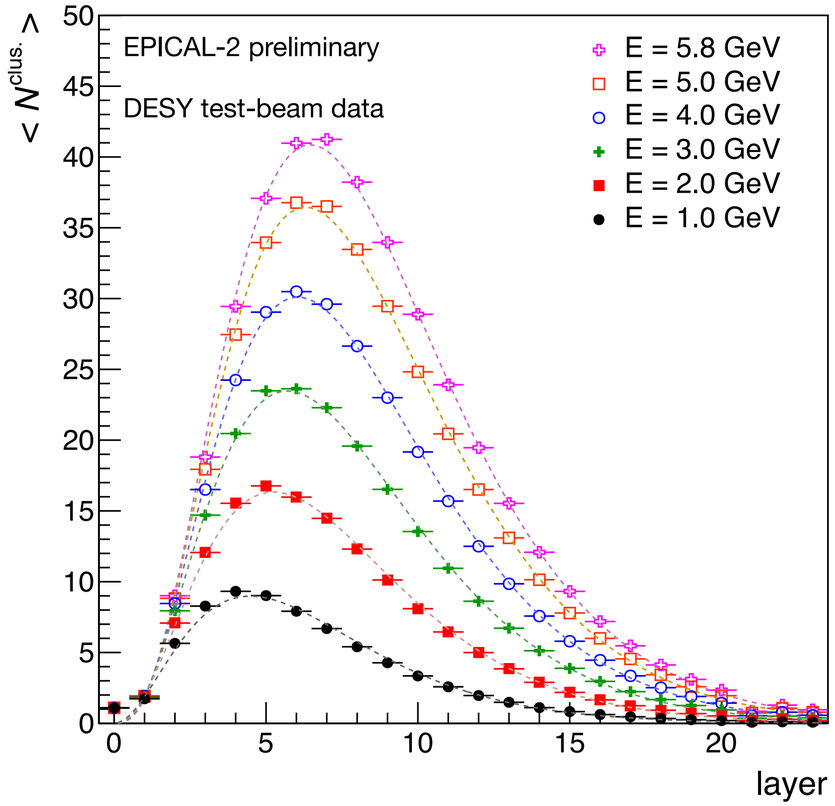
- clear energy dependence of number of hits/clusters
  - small deviations from linearity (stronger for clusters)
  - possibly caused by low-energy contamination, cluster overlap
- work in progress

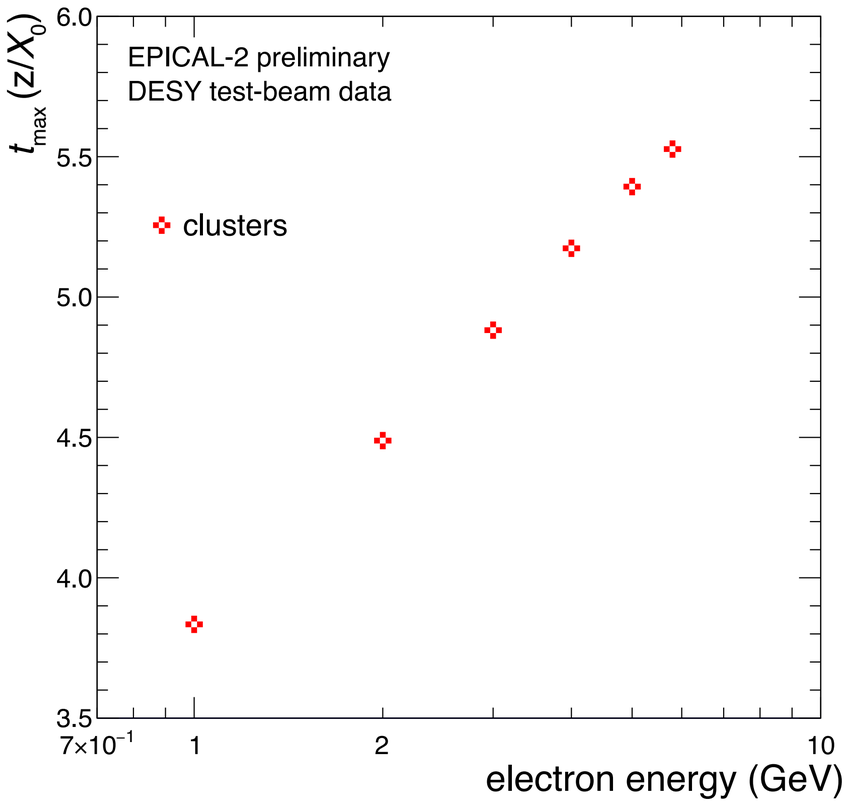
Energy Resolution



- good energy resolution
  - better for clusters compared to hits
  - better than EPICAL-1 (MIMOSA) JINST 13 (2018) P01014
  - close to analog SiW ECAL (CALICE) physics prototype NIM A608 (2009) 372
- work in progress

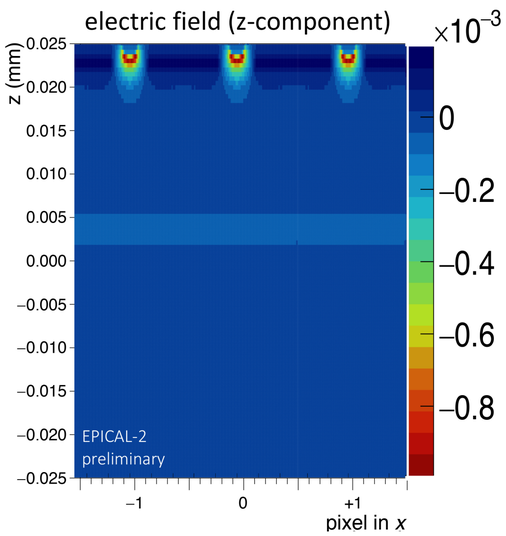
Longitudinal Shower Profiles

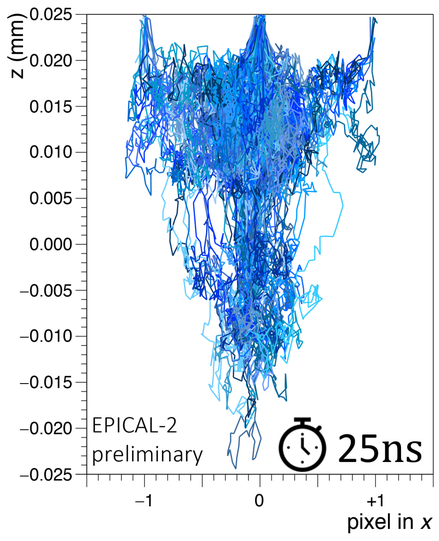


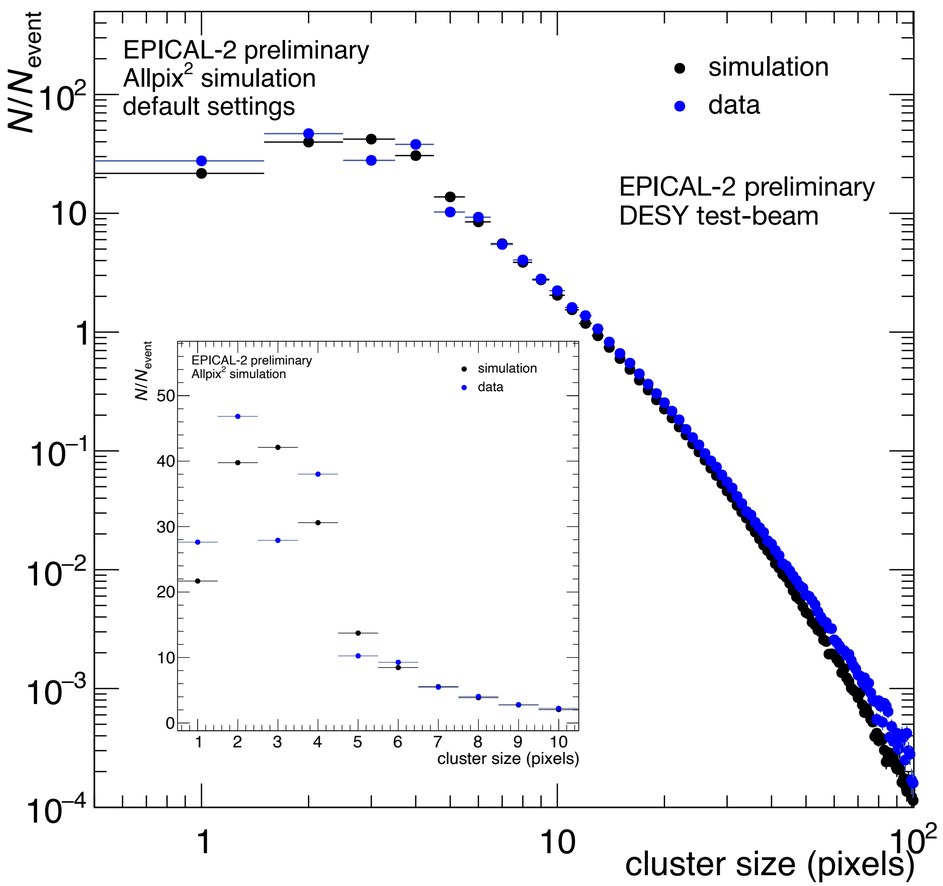


- distribution of clusters as a function of layer
  - reasonable description by gamma distribution
  - depth of shower maximum moves with energy
- first step in detailed analysis of shower shape, stay tuned!

Allpix² Simulations

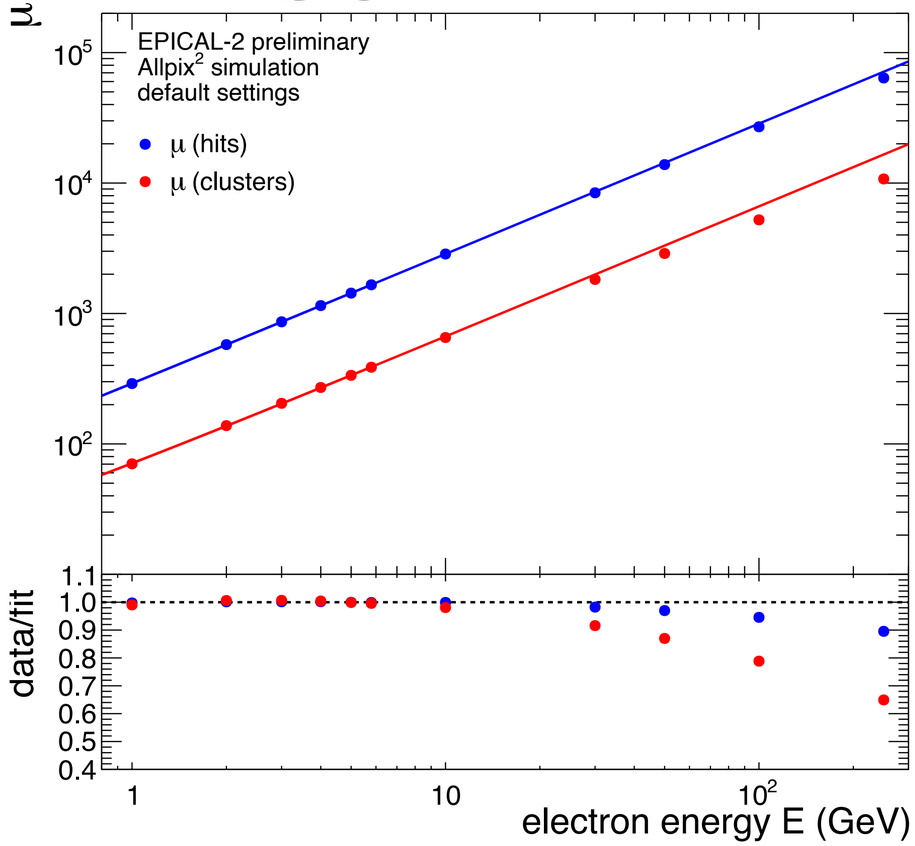


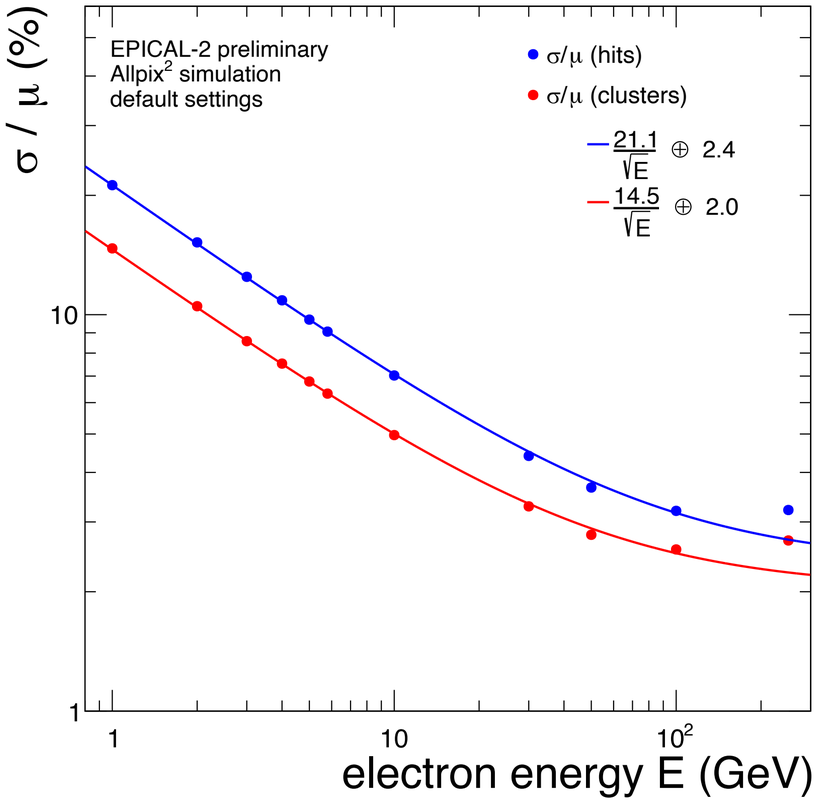




- detailed implementation of ALPIDE sensor and detector geometry
- good description of detector behaviour

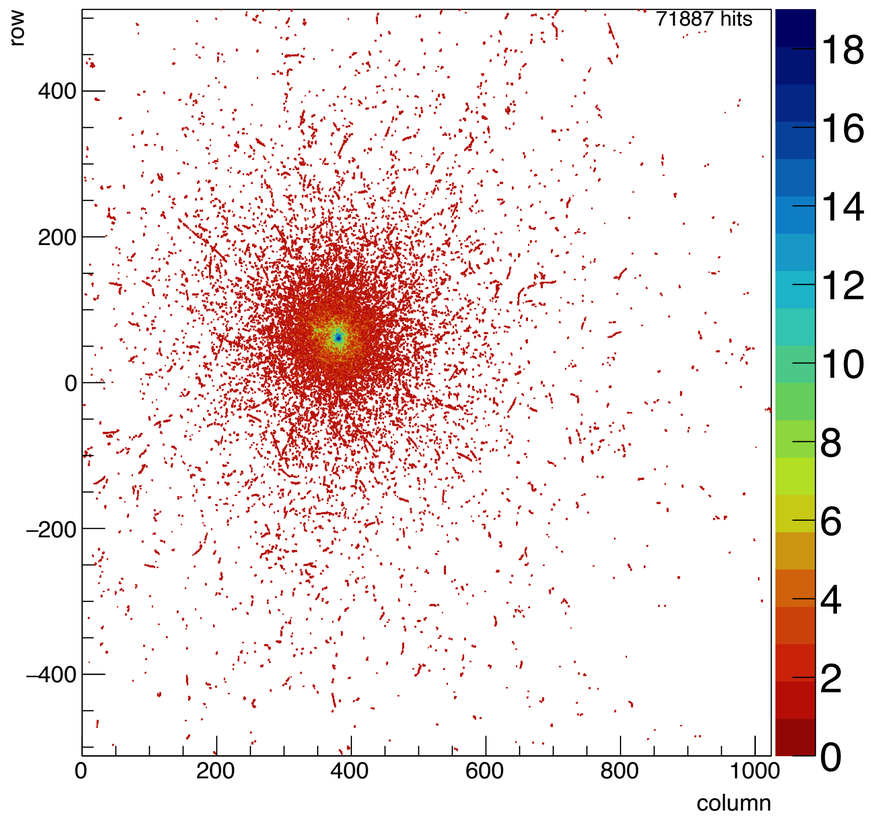
Energy Linearity and Resolution

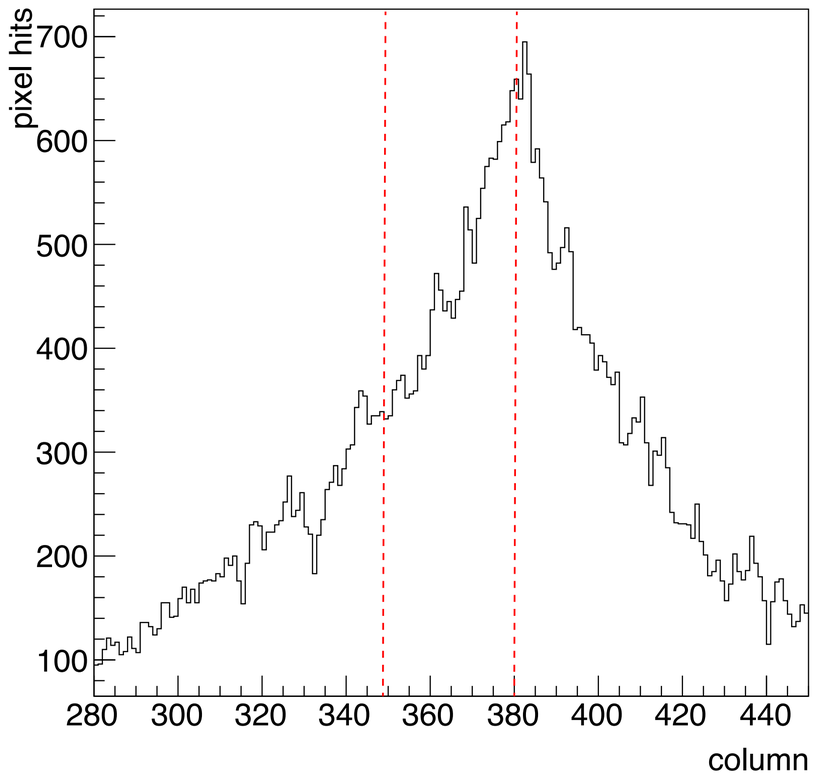




- good linearity and resolution at low energies, deviations at high energies
  - effects expected from leakage for $20X_0$ detector, straightforward to overcome
  - additional effect from cluster overlap (stronger for clusters compared to hits), corrections to be investigated
- need for further optimization of sensor for high-energy measurements?

Two-Shower Separation



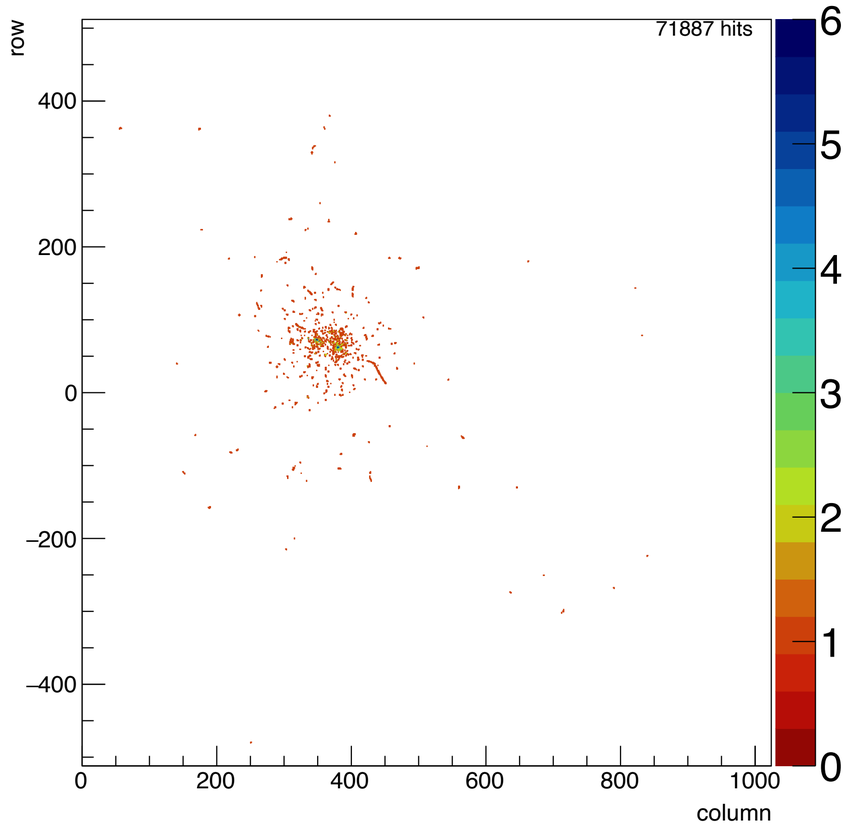


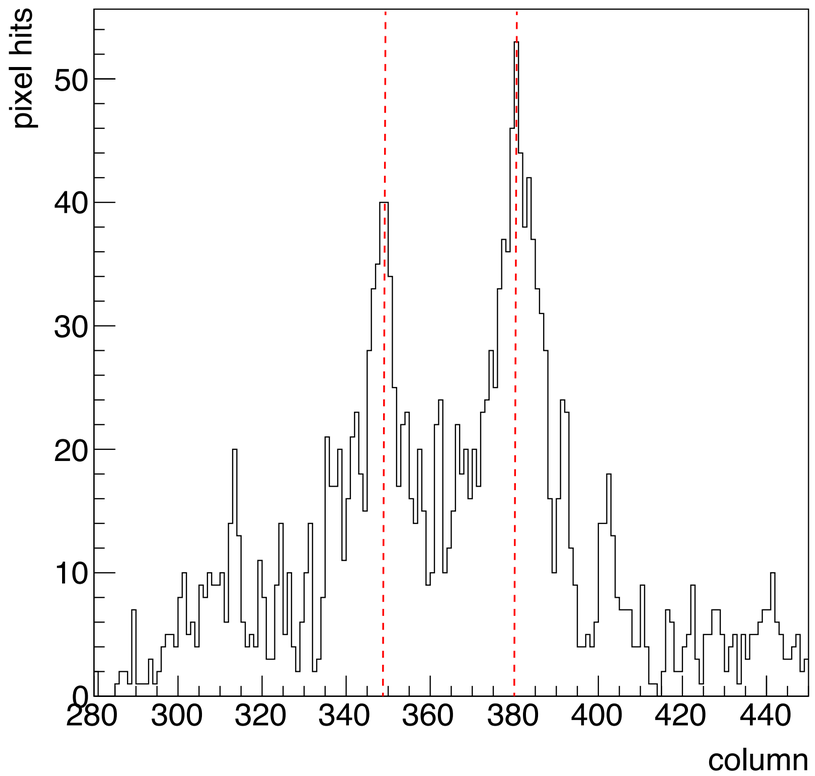
EPICAL-2 preliminary
Allpix^2 simulation

30 GeV e^- + 250 GeV e^-
1.2 mm separation
single event

all layers integrated

Two-Shower Separation





EPICAL-2 preliminary
Allpix^2 simulation

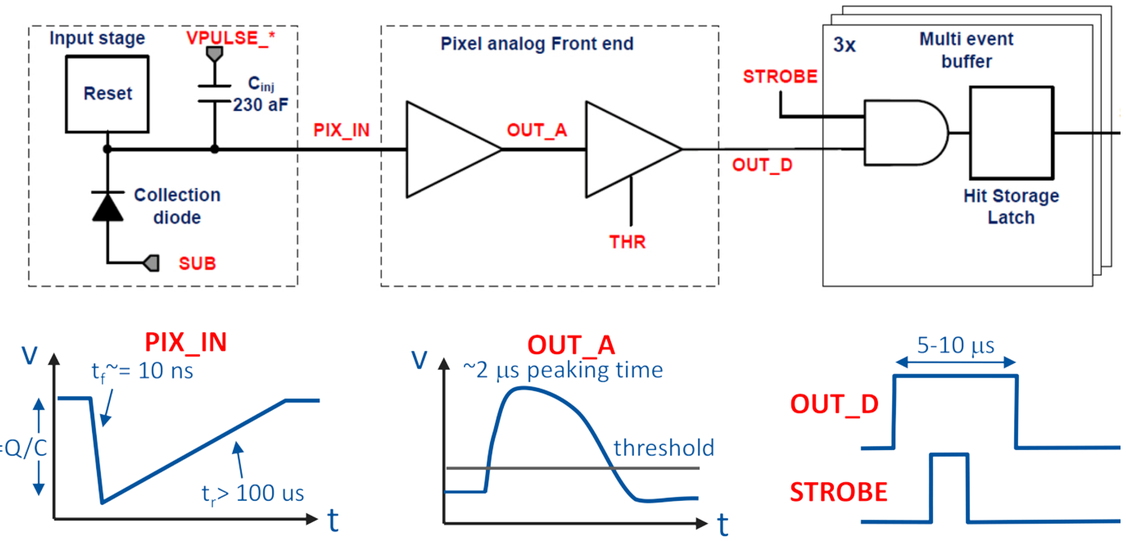
30 GeV e^- + 250 GeV e^-
1.2 mm separation
single event

first 6 layers integrated

- two-shower separation down to 1 mm should be possible
- systematic studies to be done

Future Steps: Rate Capabilities

- Pileup limitation from shaping time of analog pixel front end
  - time over threshold ≈ 5-10 μs
  - faster shaping could enhance rate capability
- Readout rate
  - defined by matrix readout of multi-event buffers (chip-internal, 40 MHz) and bandwidth of serial output (1.2 Gbps max)
  - total latency dependent on hit density in sensor
- Sufficient for application in FoCal
- Possible future design improvements
  - increase readout rate by higher internal/external bandwidth, more multi-event buffers
  - resolve pileup by faster shaping, timing information(?)
  - drawback: increase complexity, power consumption

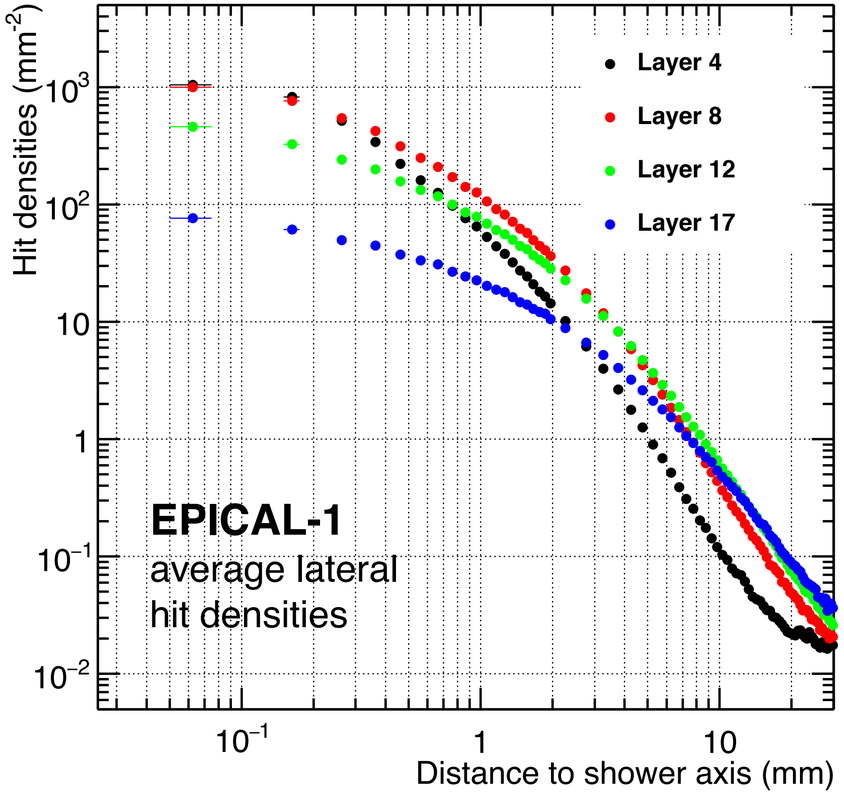


Data Volume/Compression

- High granularity leads to high data volume
  - normal zero suppression not effective in shower measurement, sensors may have high occupancy
  - spatial information on pixel level not needed, compromise possible
- On-chip compression with macro pixels
  - define pixel region (e.g. 10x10), count pixel hits: reduce 100 bit info to one 7 bit value
  - coarser effective granularity: from 30 μm to 300 μm
- Exact configuration depends on application
  - here 300 μm info is useful
  - other applications may tolerate still coarser granularity
    - e.g. 33x33 pixels: 1 mm cell size, 1000 bits →10 bits

High-Energy Performance

- Saturation expected for high particle density in shower
  - limiting density ≈10^3/mm^2,
    effect plausible at lower density from correlations
  - effect seen in non-linearity at high energy,
    still reasonable resolution
  - correction for reconstructed showers should be possible
    - e.g. reconstruct shower shape,
      need only correction
      of high density part of shower
- Sensor modifications for very high energy?
  - further reduce pixel size?
  - increase pixel resolution: >1bit/pixel



Summary

- Successful test of full digital pixel calorimeter (EPICAL-2)
  - ALPIDE sensor suitable for calorimeter use
  - Technology suitable for high-granularity layers of FoCal (e.g. separation power)
- Good performance from low-energy test
  - Good linearity
  - Energy resolution improved compared to EPICAL-1,
    close to CALICE SiW ECAL physics prototype
- Next steps
  - Detailed study of shower development
  - Further studies of high-energy behaviour (simulation and SPS test beam)
- Strong potential for other applications

EPICAL-2 Team

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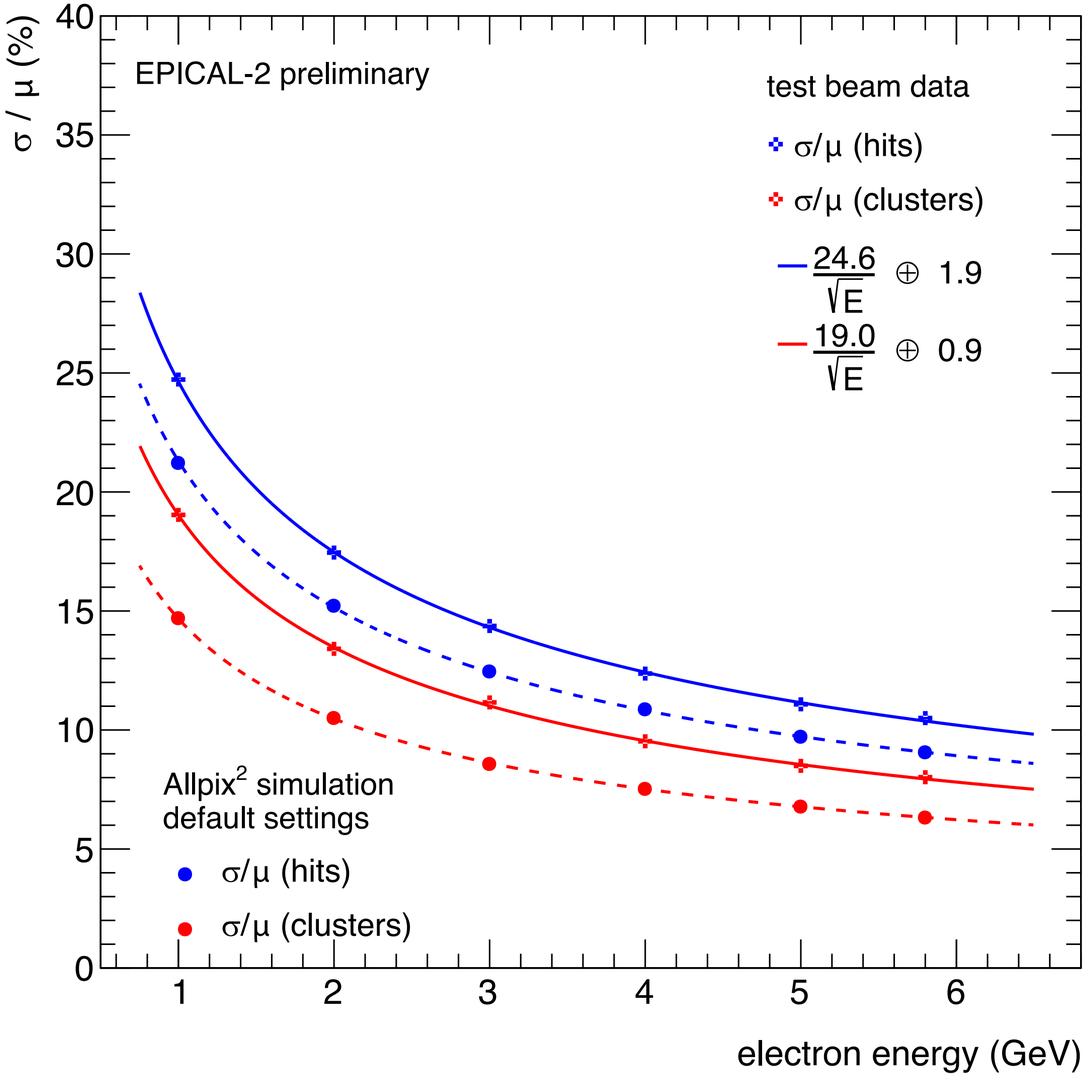
Robert Bosley
Nigel Watson

University of Oslo

Qasim Malik

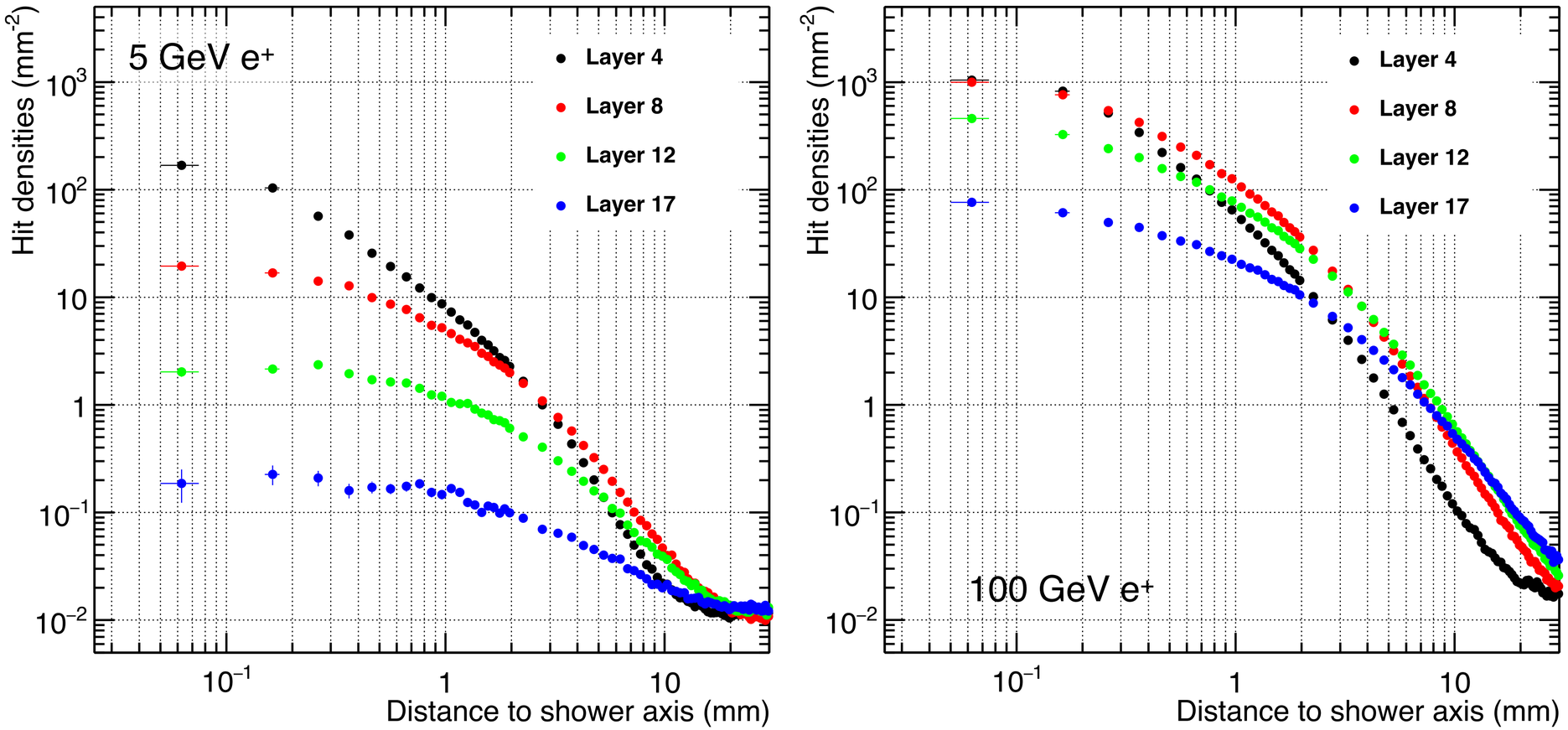
Backup

Energy Resolution (Simulation)



- comparison to full simulation with Allpix2
  - qualitative agreement with data
  - resolution better in simulation
    - data has residual influence from pileup and low-energy contamination

EPICAL-1 – Lateral Profiles



average hit densities as a function of radius for different layers $\frac{dN_{\text{hit}}}{dA}(r)$

shower measurements with unprecedented detail!

in early layers very narrow shower core