EPICAL-2

Test-Beam Performance of a Digital Pixel Calorimeter

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CALICE Collaboration Meeting

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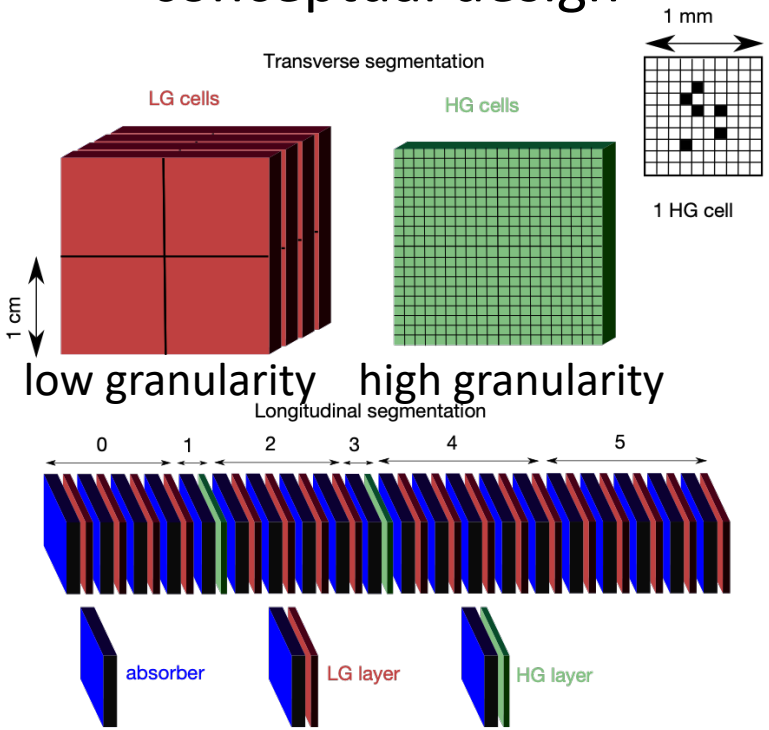
HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

EPICAL-2 Prototype

in the context of R&D
for the ALICE
Forward Calorimeter upgrade

FoCal-E (electromagnetic)
conceptual design



objective:
two-photon separation at few mm distance
- high-granularity layers in FoCal
- CMOS MAPS sensors – binary readout

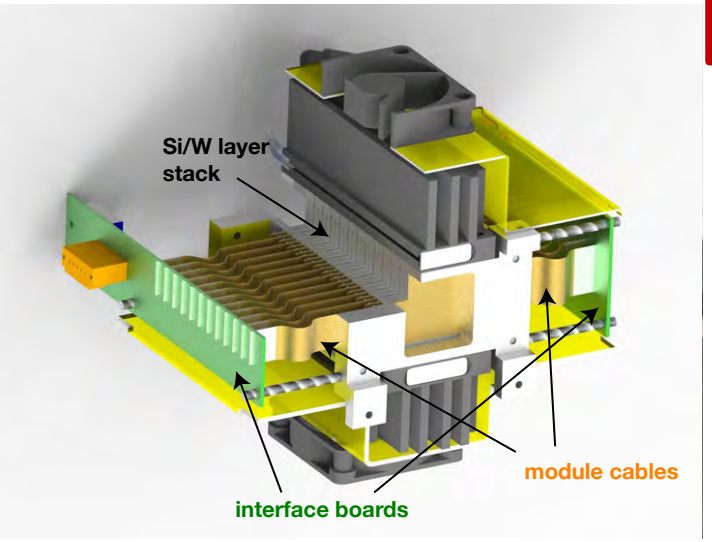
shower reconstruction
- single shower particle measurement
- 3D shower shapes

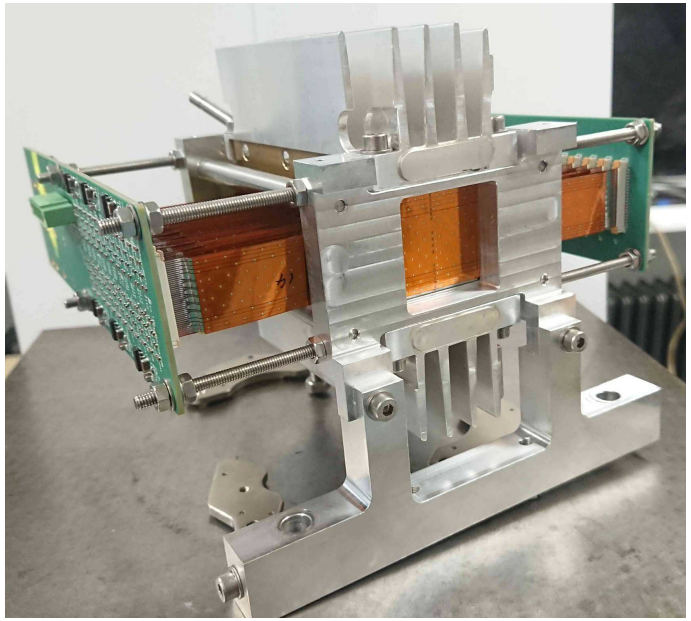
effective for particle flow approach

→ digital calorimeter with very small pixels

EPICAL-2 Prototype

high-granularity digital Electromagnetic PIxel CALorimeter



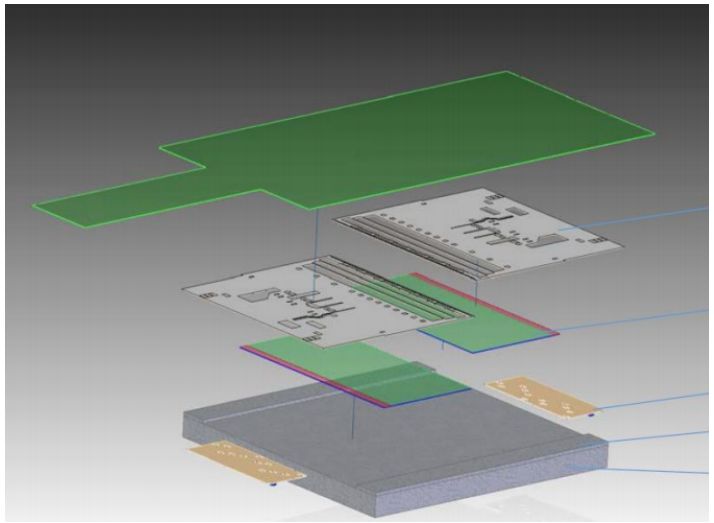


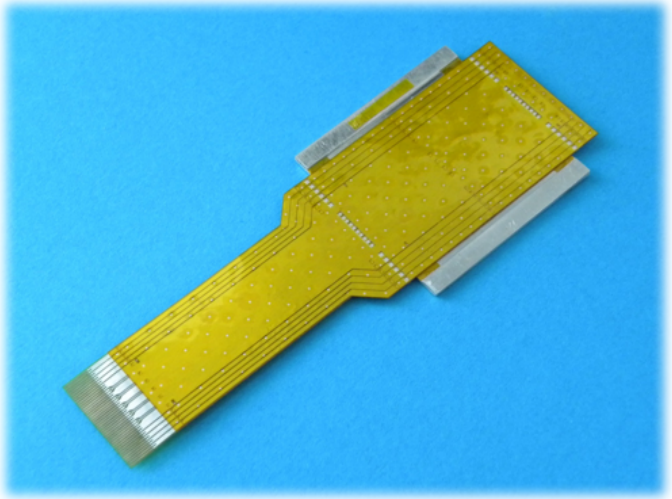
ALPIDE (MAPS)

- chip size 1.5 x 3 cm^2
- pixel size 29.24 x 26.88 μm^2
- 1024 x 512 pixel matrix

setup of prototype

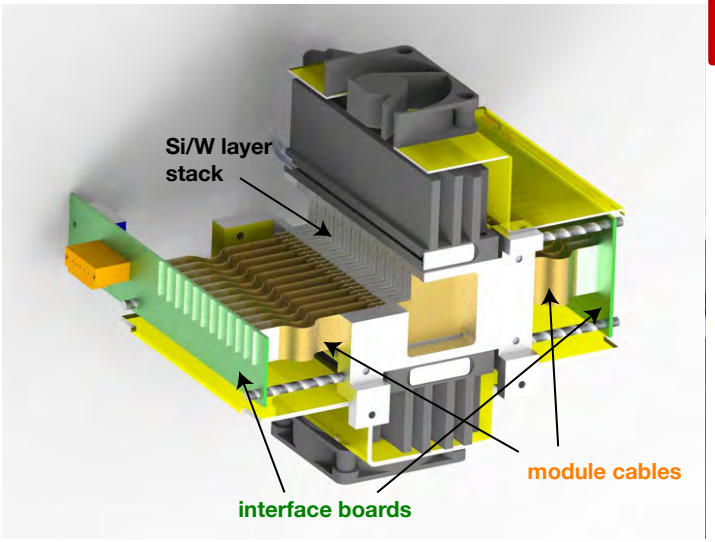
- 24 layers with two sensors each
  → active area 3 x 3 cm^2 ($R_M \approx 11$ mm)
- 48 x 1024 x 512 = 25 M pixels
- 3 mm W (X_0 = 3.5 mm) absorber per layer
- water cooling system
- trigger: two SiPM scintillation counters

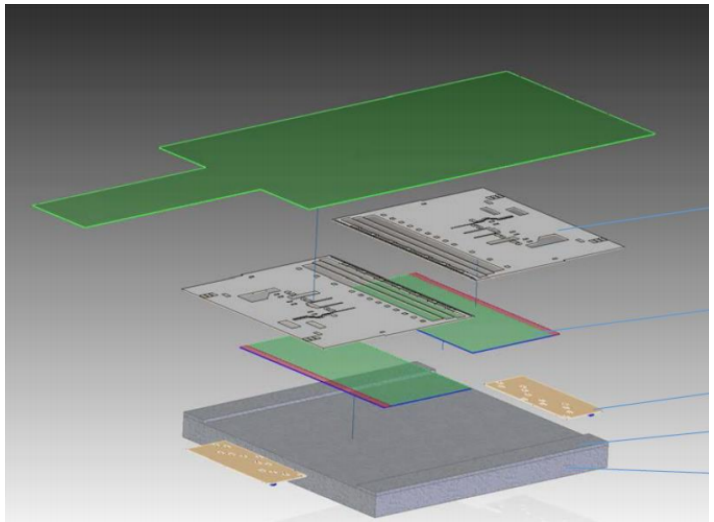




EPICAL-2 Prototype

high-granularity digital Electromagnetic PIxel CALorimeter





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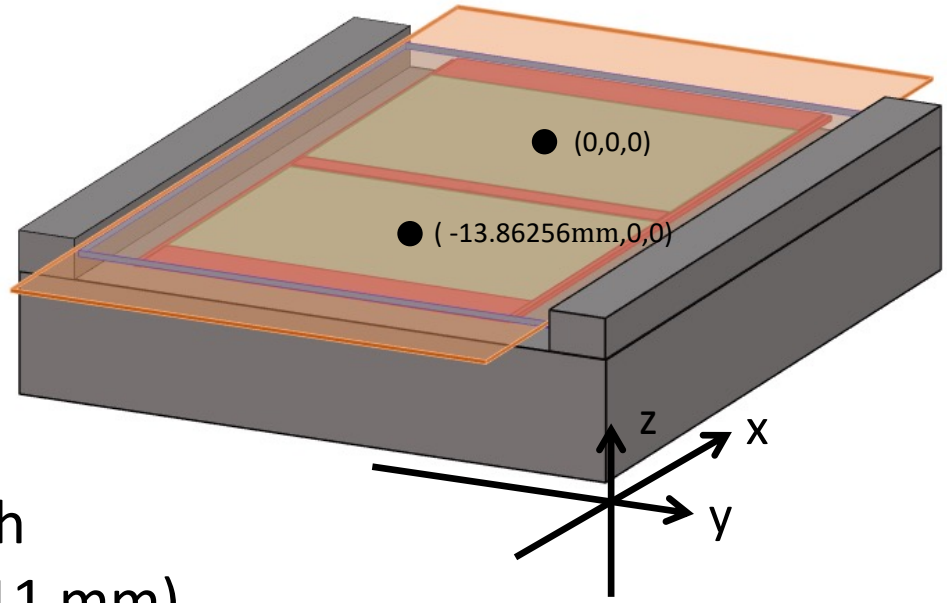
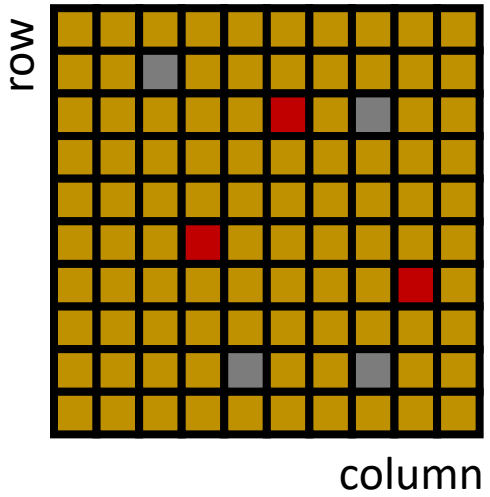


simulation utilizing Allpix² framework
→ precise geometry implementation

Analysis Setup

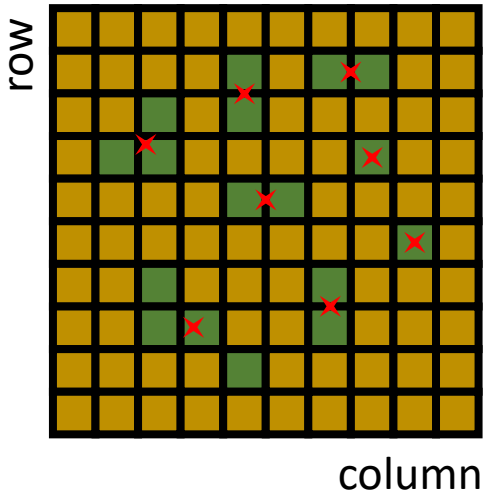
pixel masking

- noisy and dead pixel removal
- input:
  - chip classification from serial testing
  - pedestal runs
  - beam runs



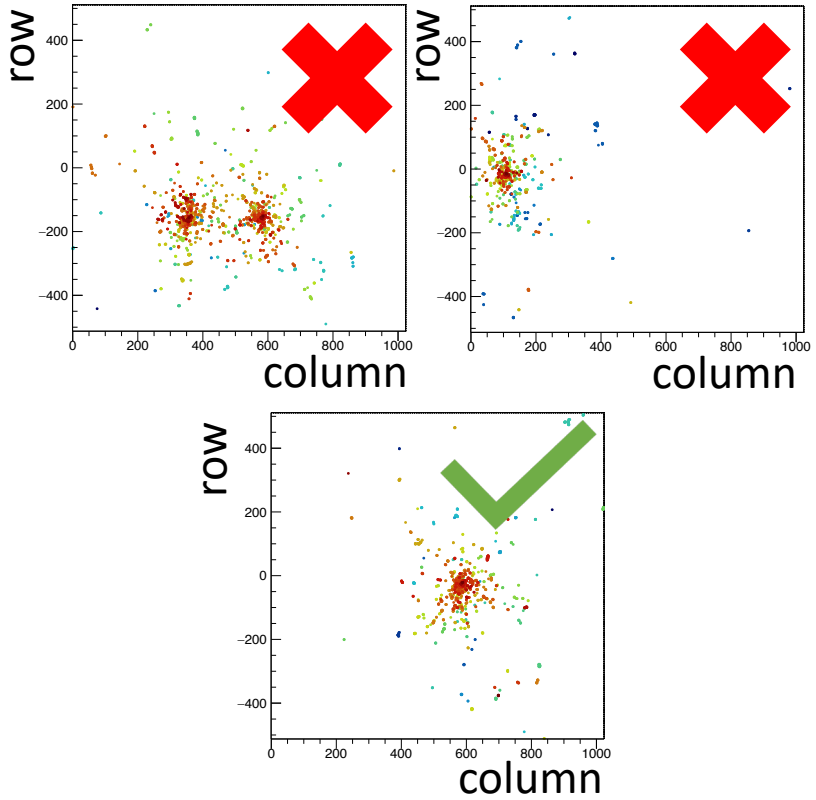
clustering

- pixel hits -> cluster
- DBSCAN algorithm
- cluster comprised of adjacent hit pixels (eight neighbors)



event selection

- single particles
- minimal lateral leakage



Data Taking Setup

1 Cosmic Muons

- May through October 2020 at Utrecht University
- charged particle tracks from cosmic muons

→ ≈ 9000 events

2 Electron Test Beam

- February 2020 at DESY TB22
- electron (positron) beam
- beam energies:
  1.0, 2.0, 3.0, 4.0, 5.0 and 5.8 GeV
- incident angles:
  0°, 2°, 10°, 20° and 180°
- various beam positions
- detector temperatures:
  20°C, 25°C and 30°C

→ ≈ 44 million events

Data Taking Setup

1 Cosmic Muons

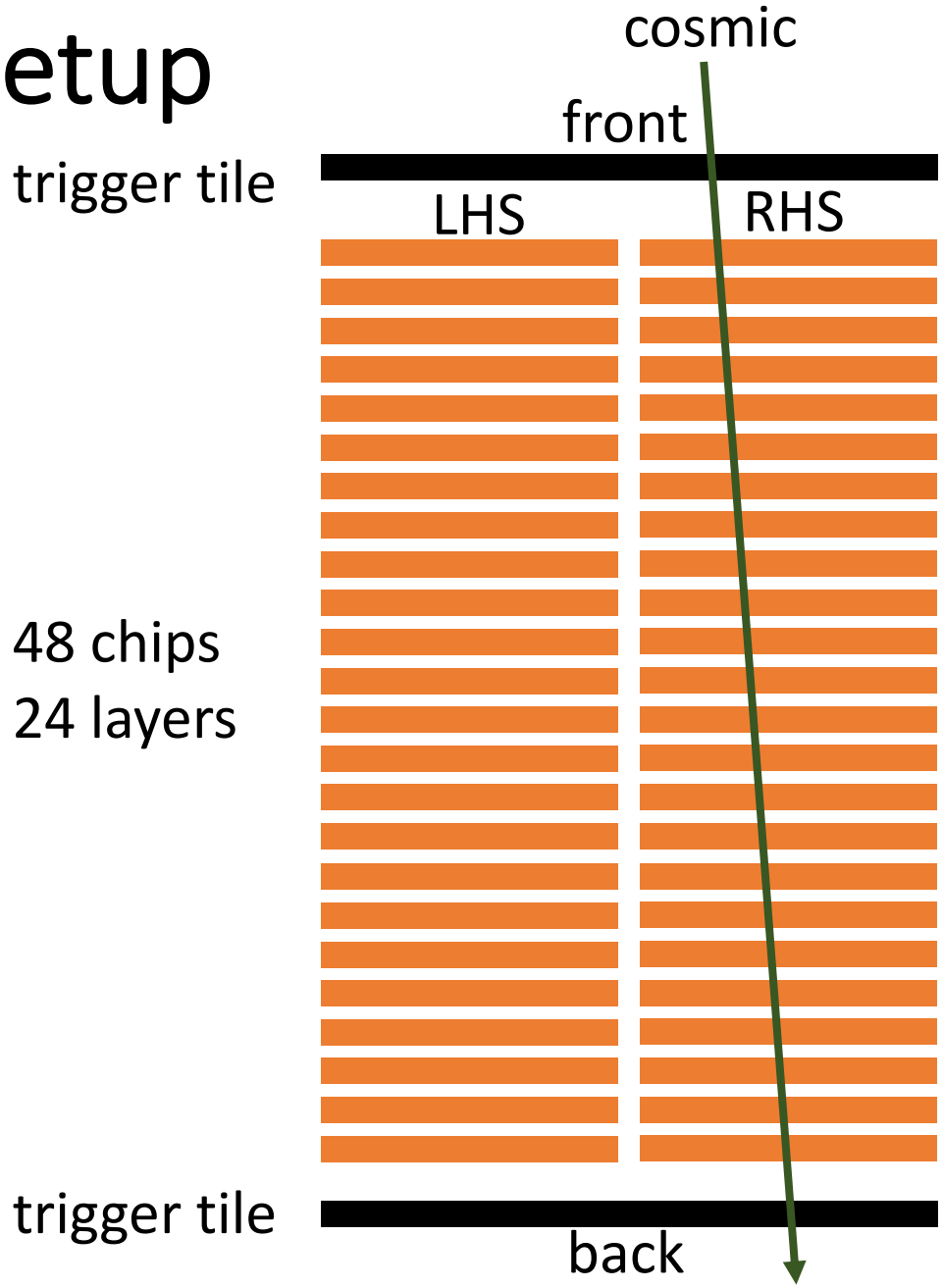
- May through October 2020 at Utrecht University
- charged particle tracks from cosmic muons

→ ≈ 9000 events

non-showering particle

- well-defined track
- uniform mean energy deposition over all layers

→ alignment, calibration



LHS: left-hand side
RHS: right-hand side

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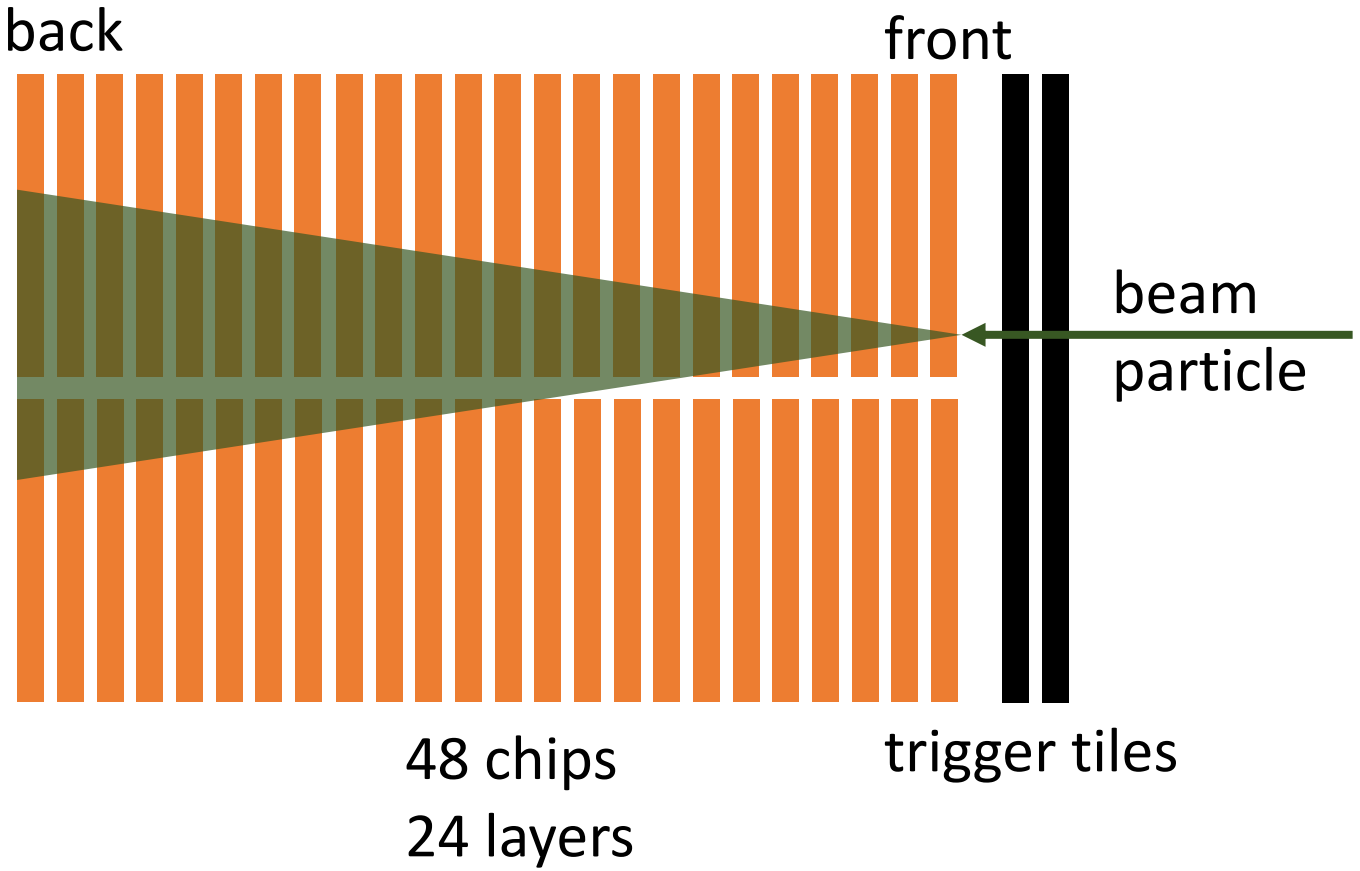

showering particle
- secondary particle production in absorbers
- number of hit pixels or clusters as calorimeter signal

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  0°, 2°, 10°, 20° and 180°
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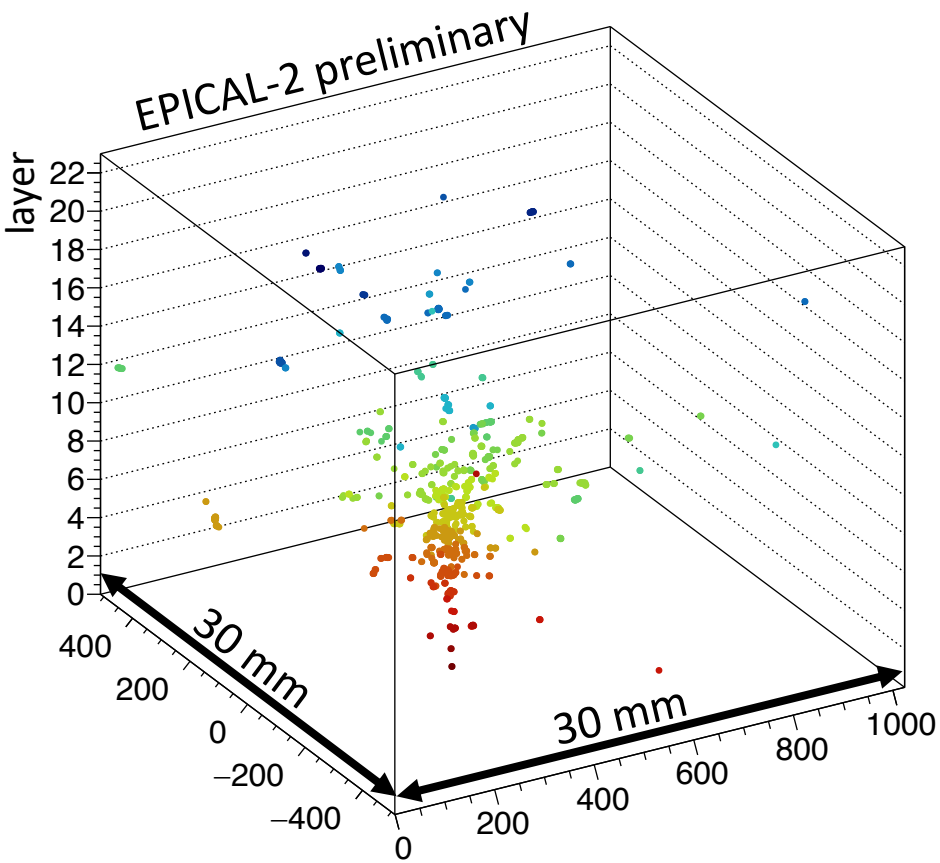
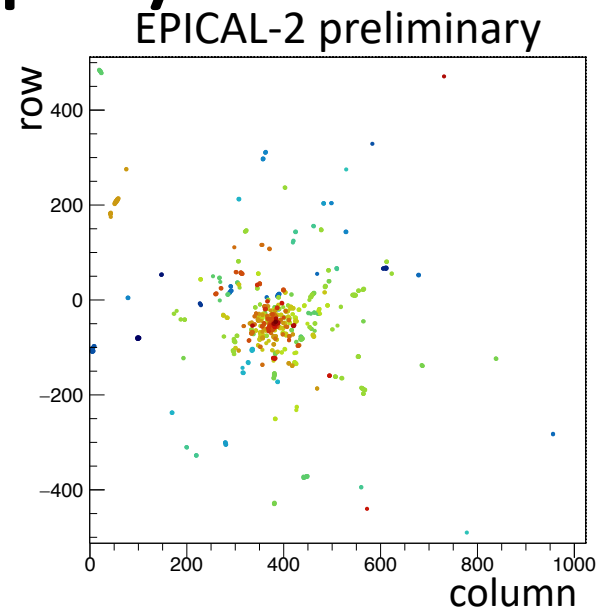
→ ≈ 44 million events

→ **energy linearity, energy resolution, shower profiles**

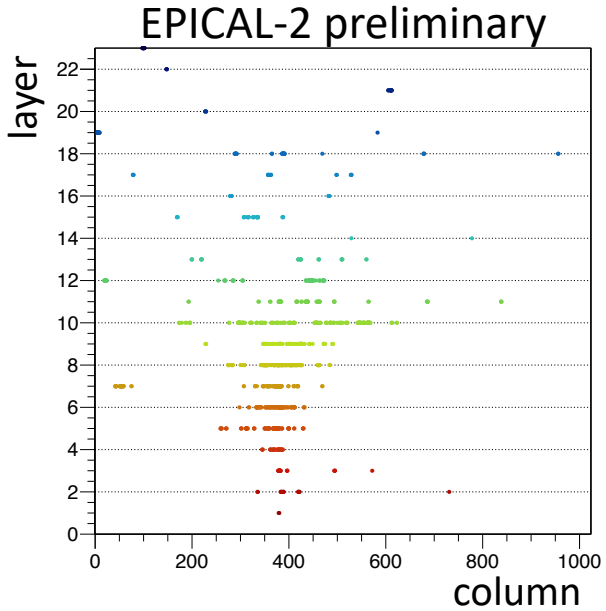
Event Display

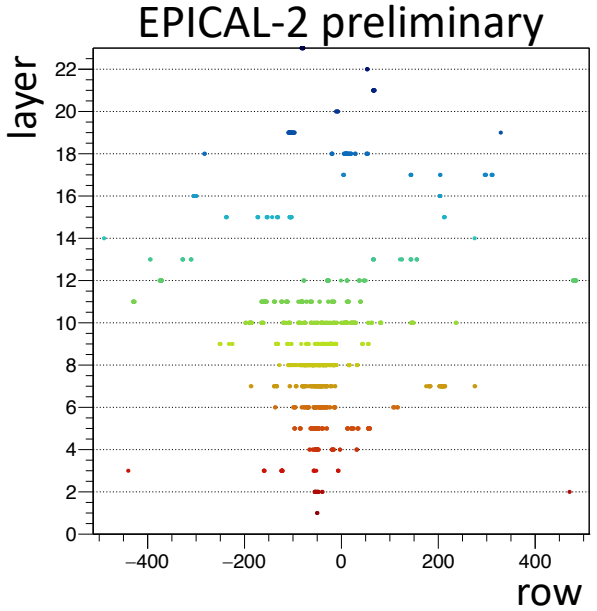
one-electron event
5 GeV
raw data





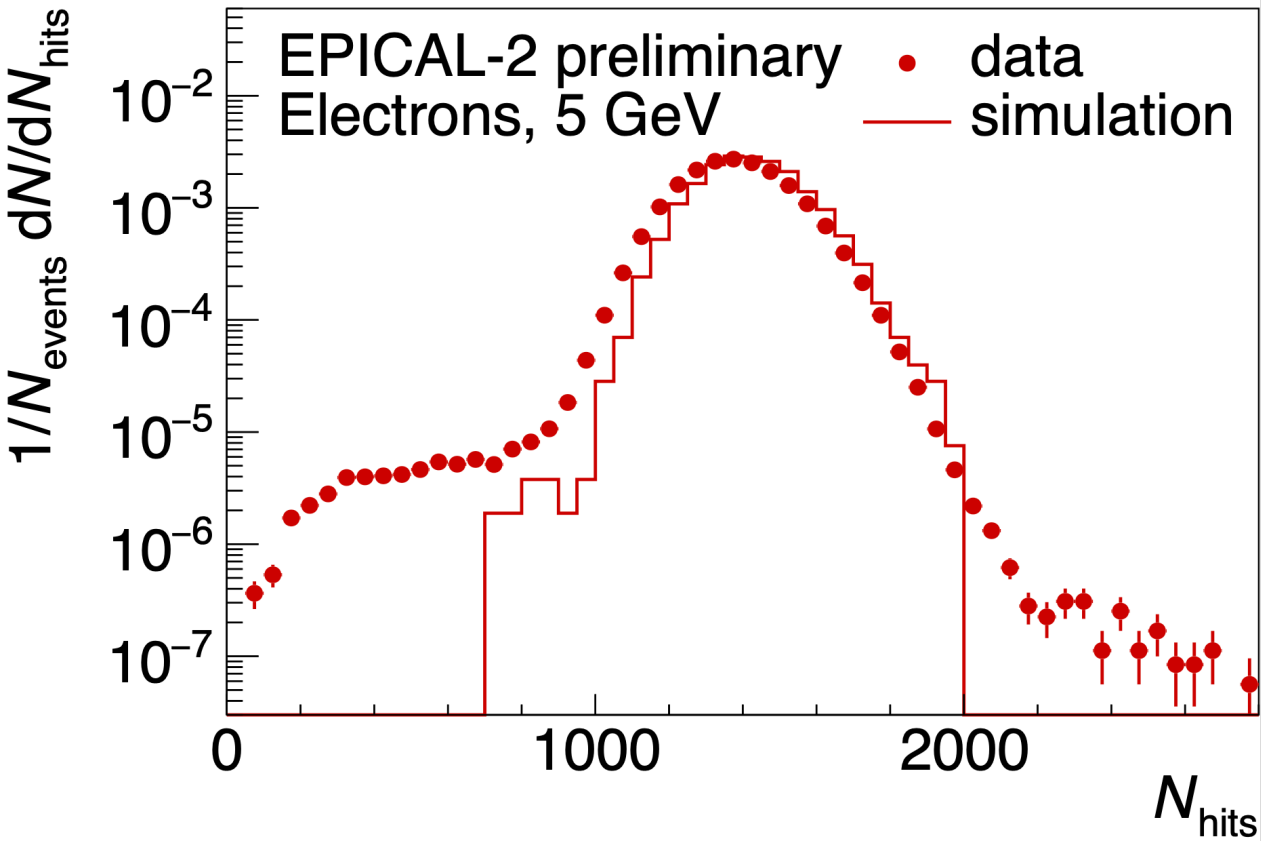
color coding
→ layers

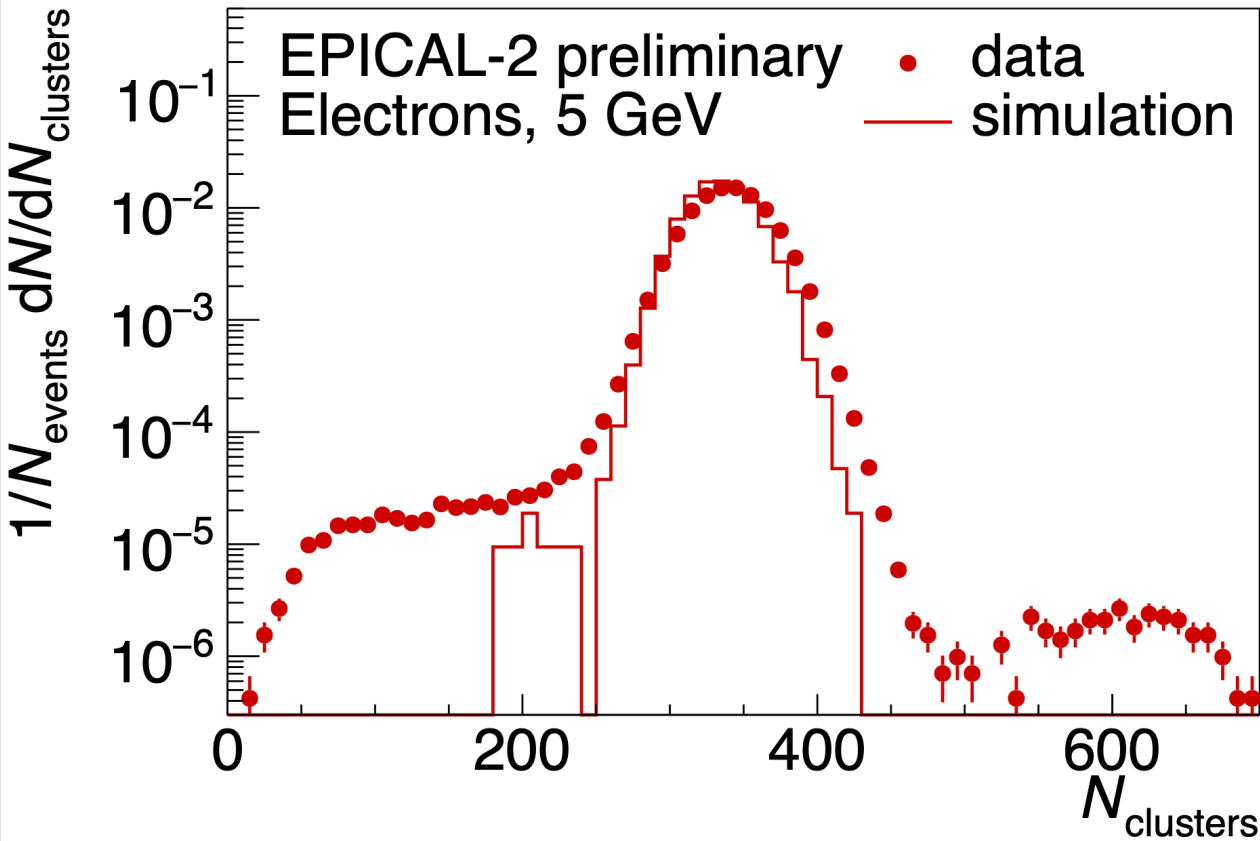




→ detailed evolution of shower

Signal Distribution

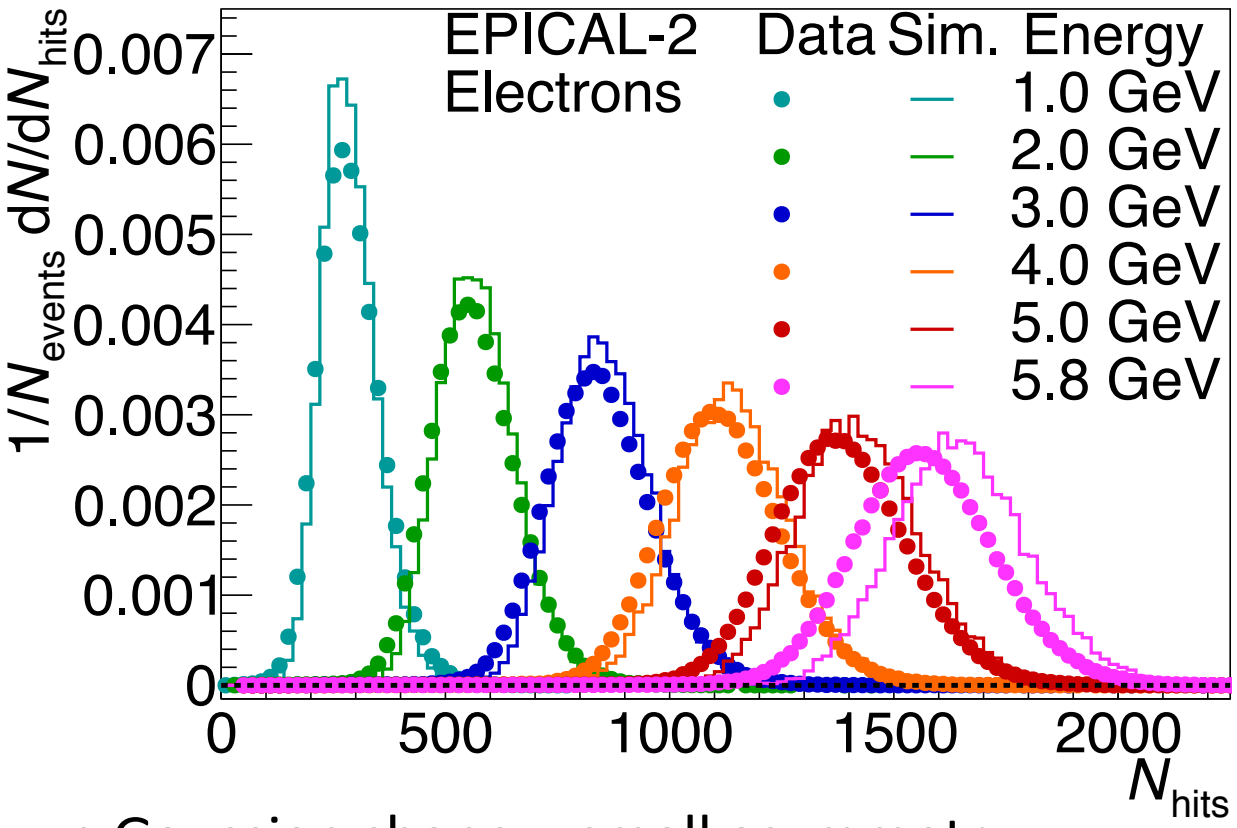


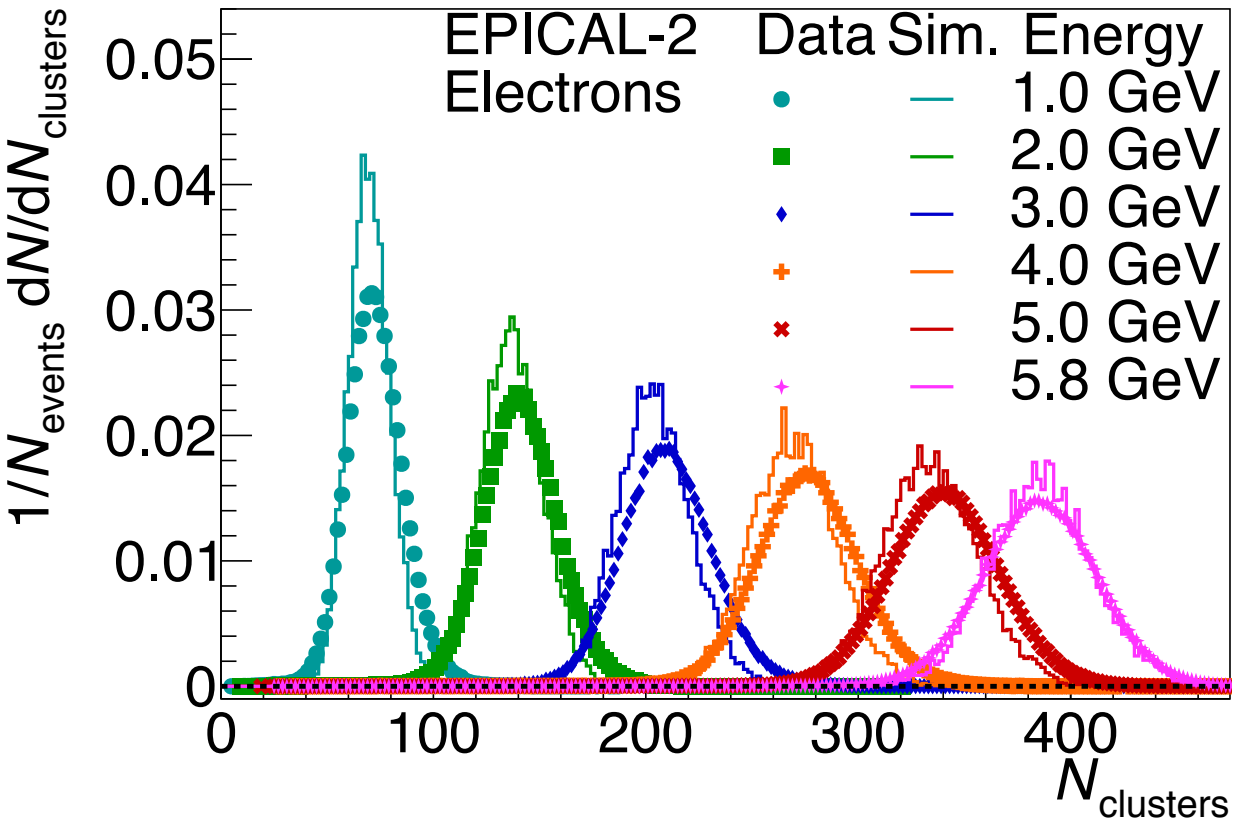


- Gaussian shape – small asymmetry
- residual pile-up at higher $N_{hits}/N_{clusters}$ side
- low-energy contamination of electron beam
- good agreement with simulation

→ **arithmetic mean and standard deviation of distribution**

Signal Distribution





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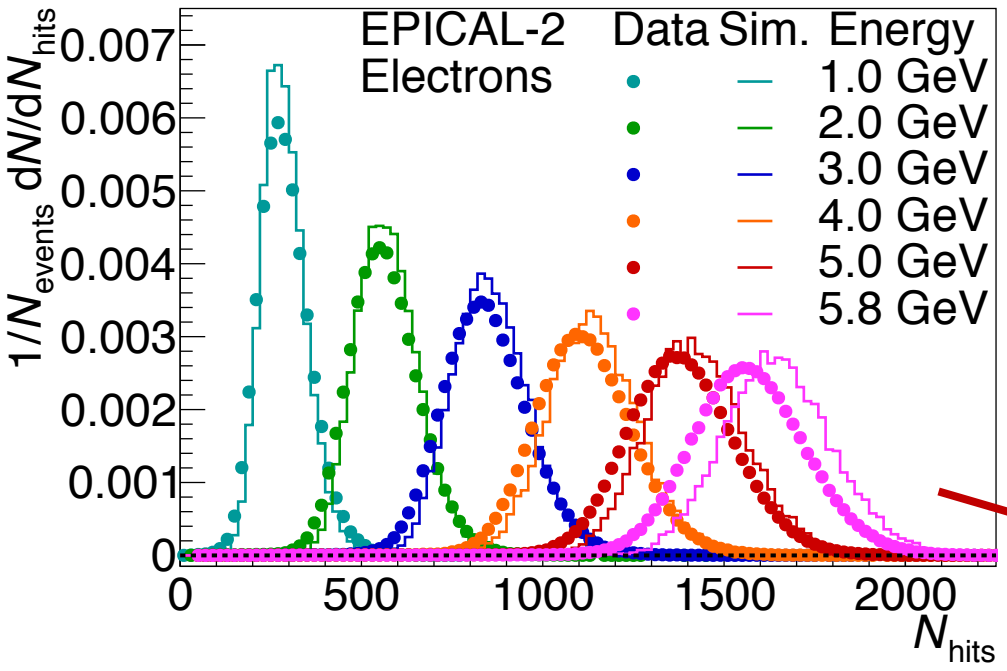
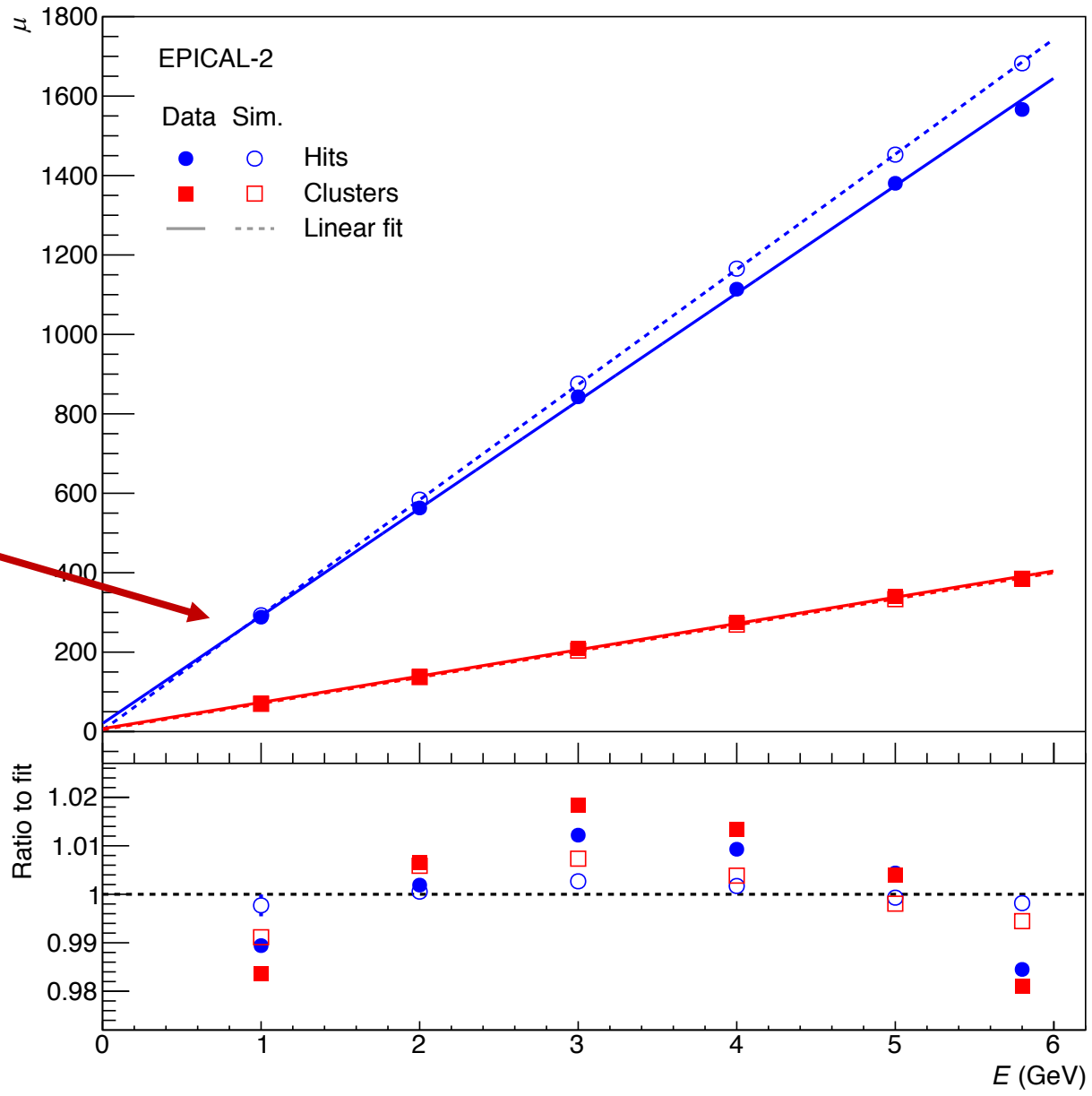
Energy Linearity





arithmetic mean (μ) and standard deviation (σ) of hit and cluster distributions

- dependence of mean on test-beam energy
- similar performance for hits and clusters
- good description of trend by simulation

→ preliminary energy-linearity check

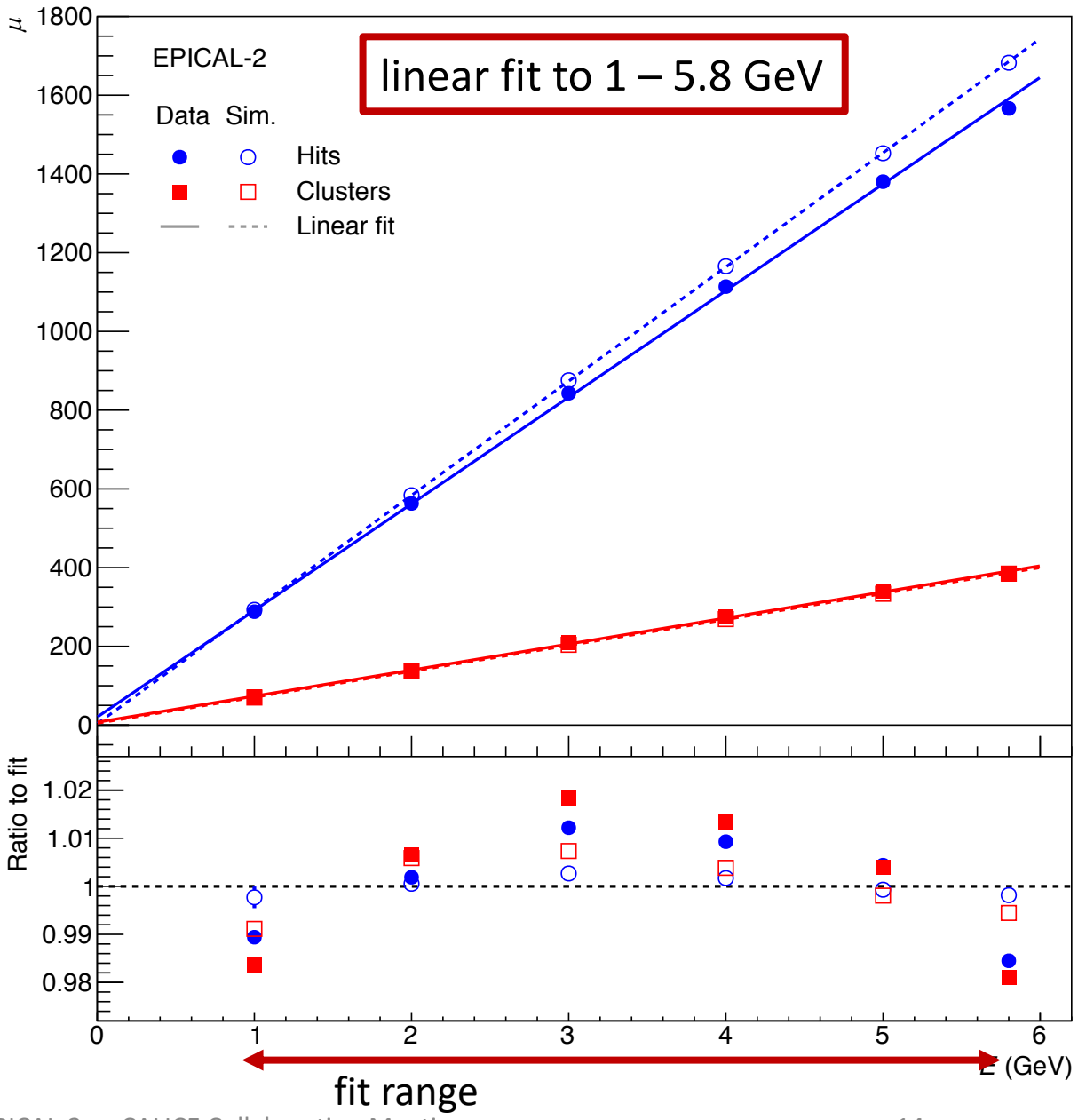
Energy Linearity

linearity studies:

- **y intercept**

y intercept

	hits	clusters
data	20.4 ± 0.1	7.30 ± 0.03
sim.	3.5 ± 0.7	4.7 ± 0.1



Energy Linearity

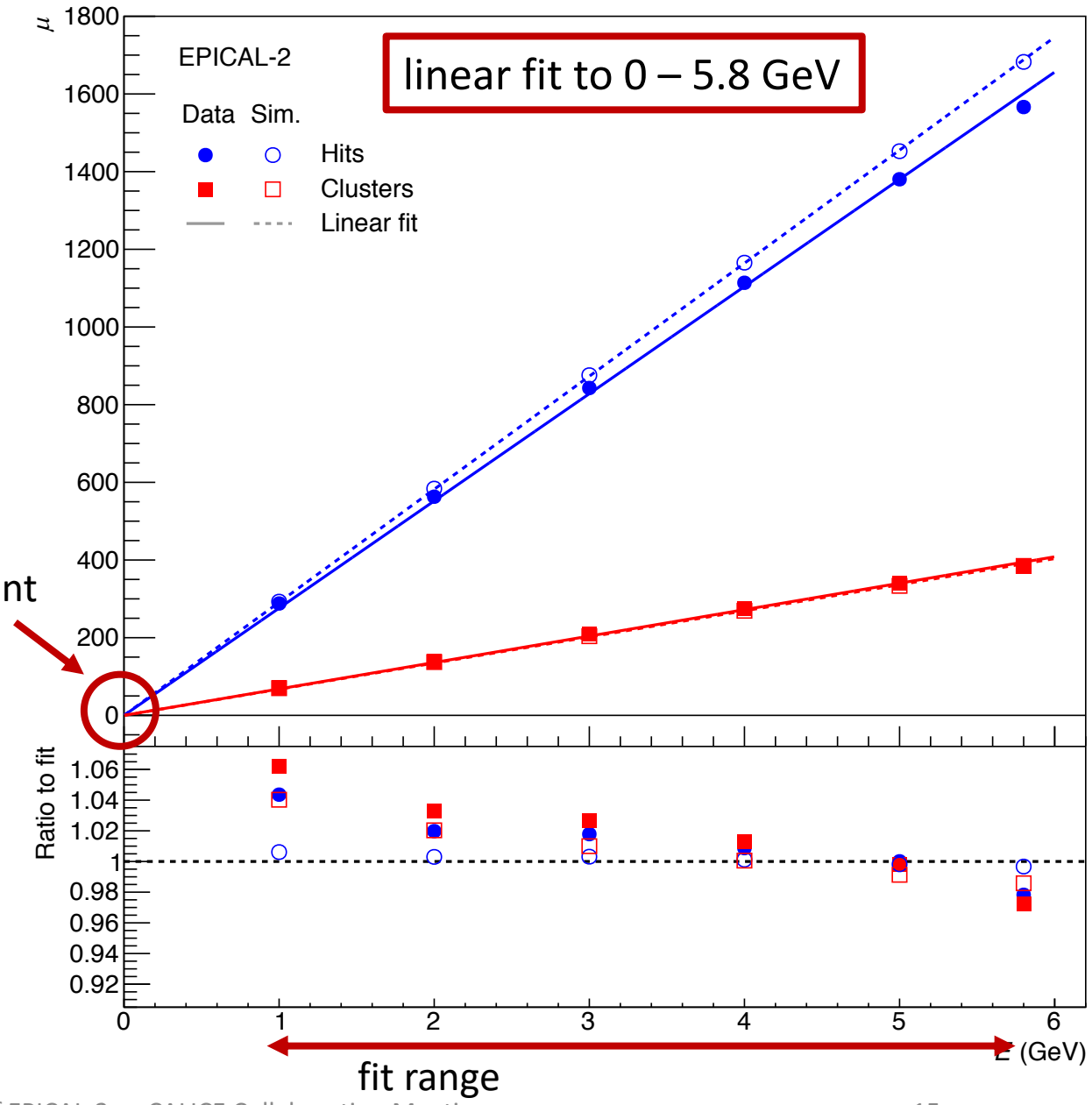
linearity studies:

- y intercept
  → **noise estimate from pedestals 2.91×10^{-3}**

constraint from noise measurement

y intercept

	hits	clusters
data	2.91×10^{-3}	2.91×10^{-3}
sim.	2.91×10^{-3}	2.91×10^{-3}



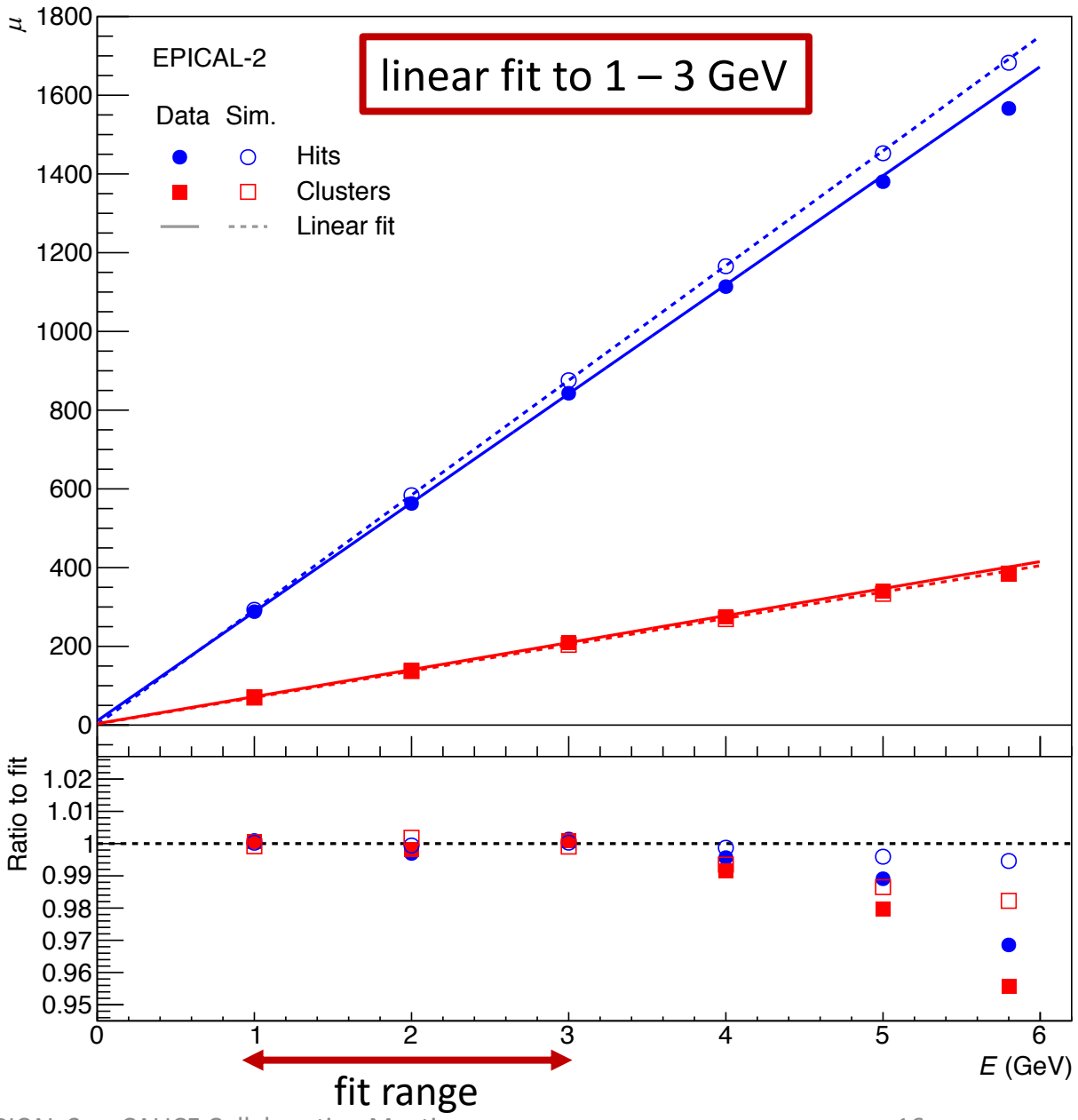
Energy Linearity

linearity studies:

- y intercept
  → noise estimate from pedestals
  2.91×10^{-3}
- **varying fit ranges**

y intercept

	hits	clusters
data	10.8 ± 0.2	3.63 ± 0.04
sim.	1.3 ± 1.0	3.1 ± 0.2



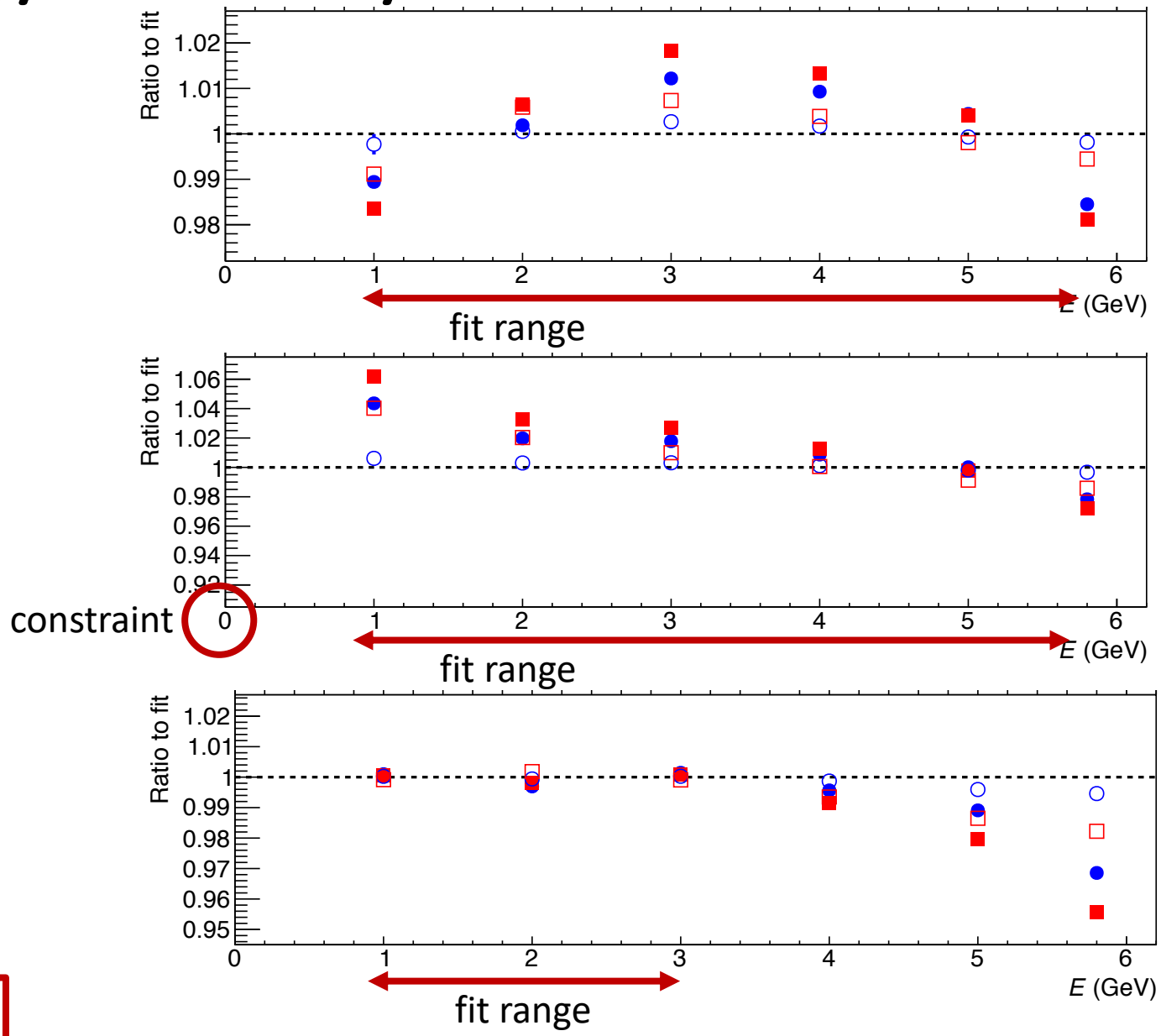
Energy Linearity

y intercept

	hits	clusters
data	20.4 ± 0.1	7.30 ± 0.03
sim.	3.5 ± 0.7	4.7 ± 0.1

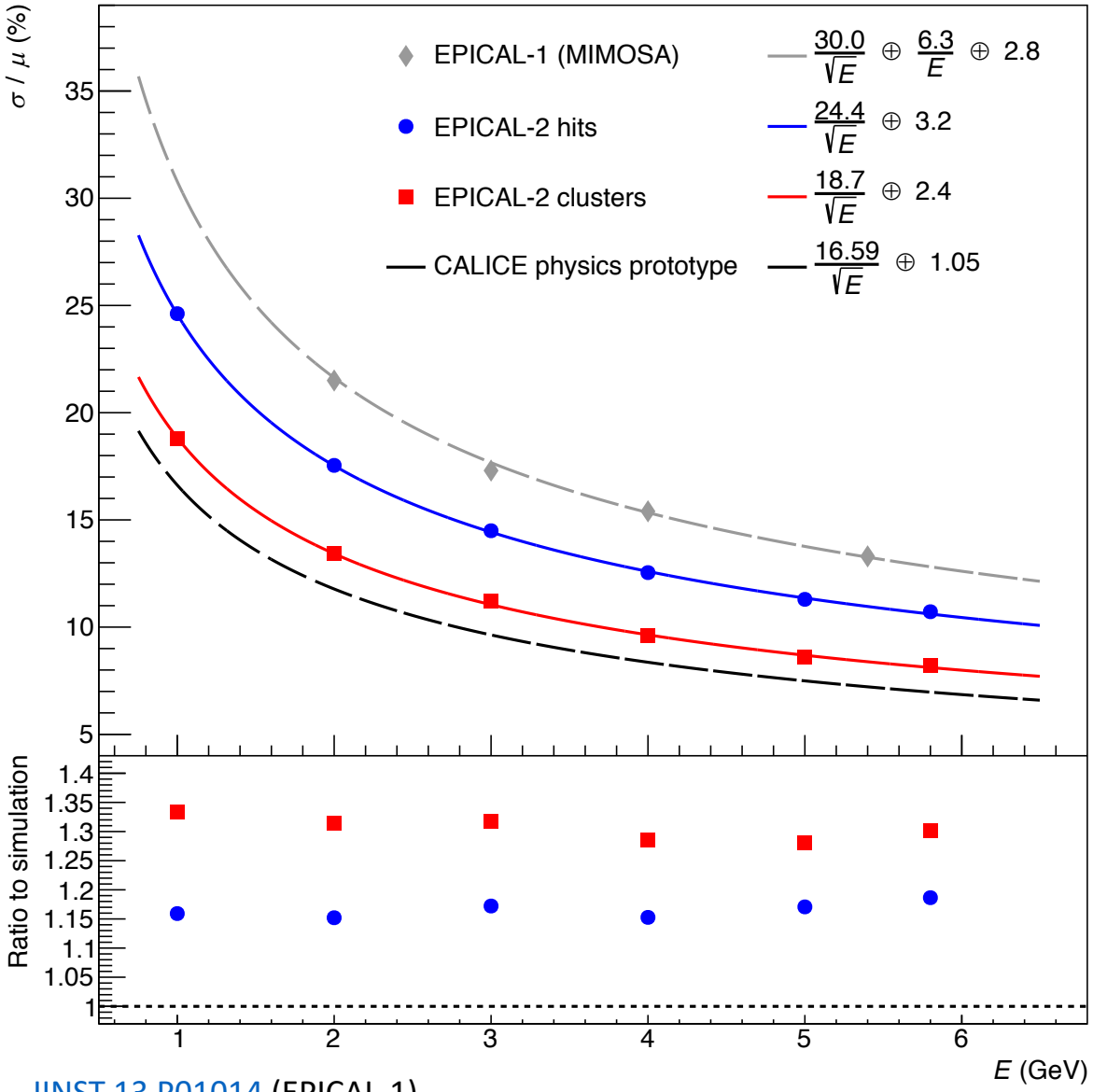
	hits	clusters
data	2.91×10^{-3}	2.91×10^{-3}
sim.	2.91×10^{-3}	2.91×10^{-3}

	hits	clusters
data	10.8 ± 0.2	3.63 ± 0.04
sim.	1.3 ± 0.1	3.1 ± 0.2



→ non-linearity under investigation

Energy Resolution



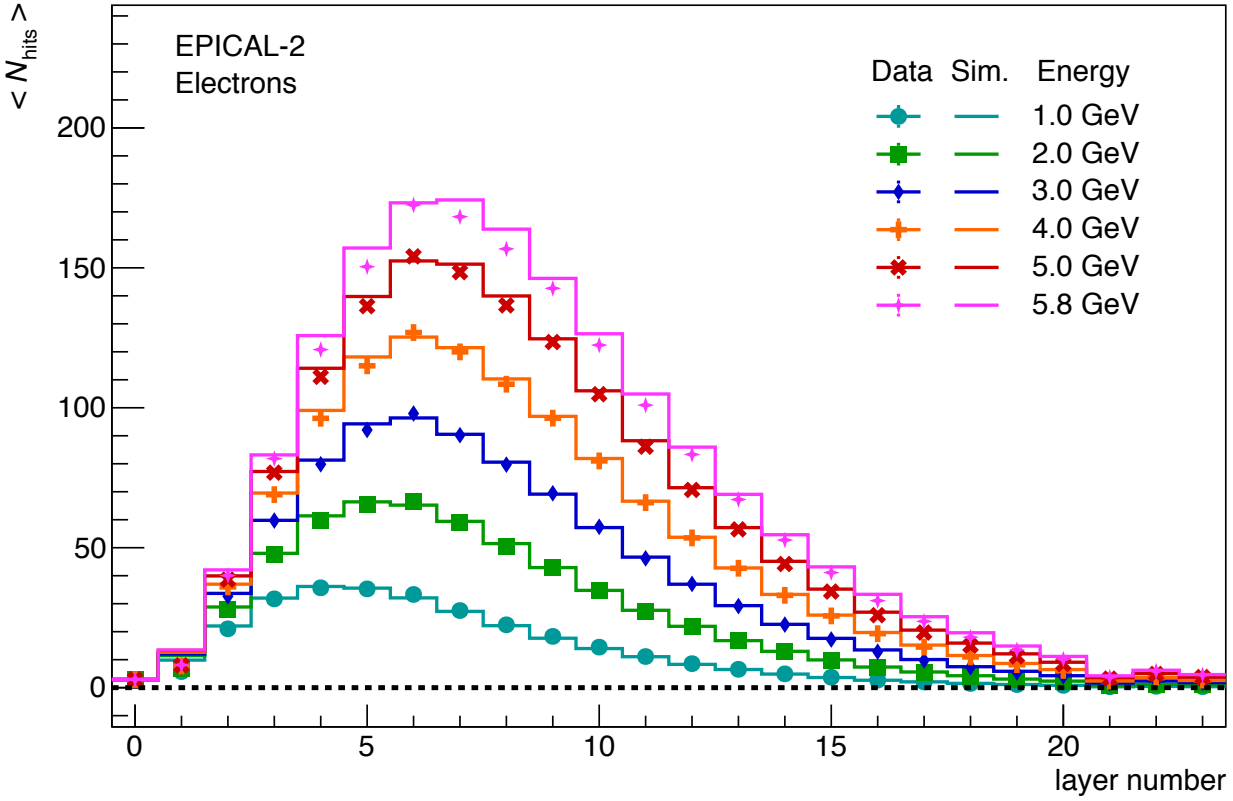
JINST 13 P01014 (EPICAL-1)
NIM A608 (2009) 372 (CALICE ECAL)

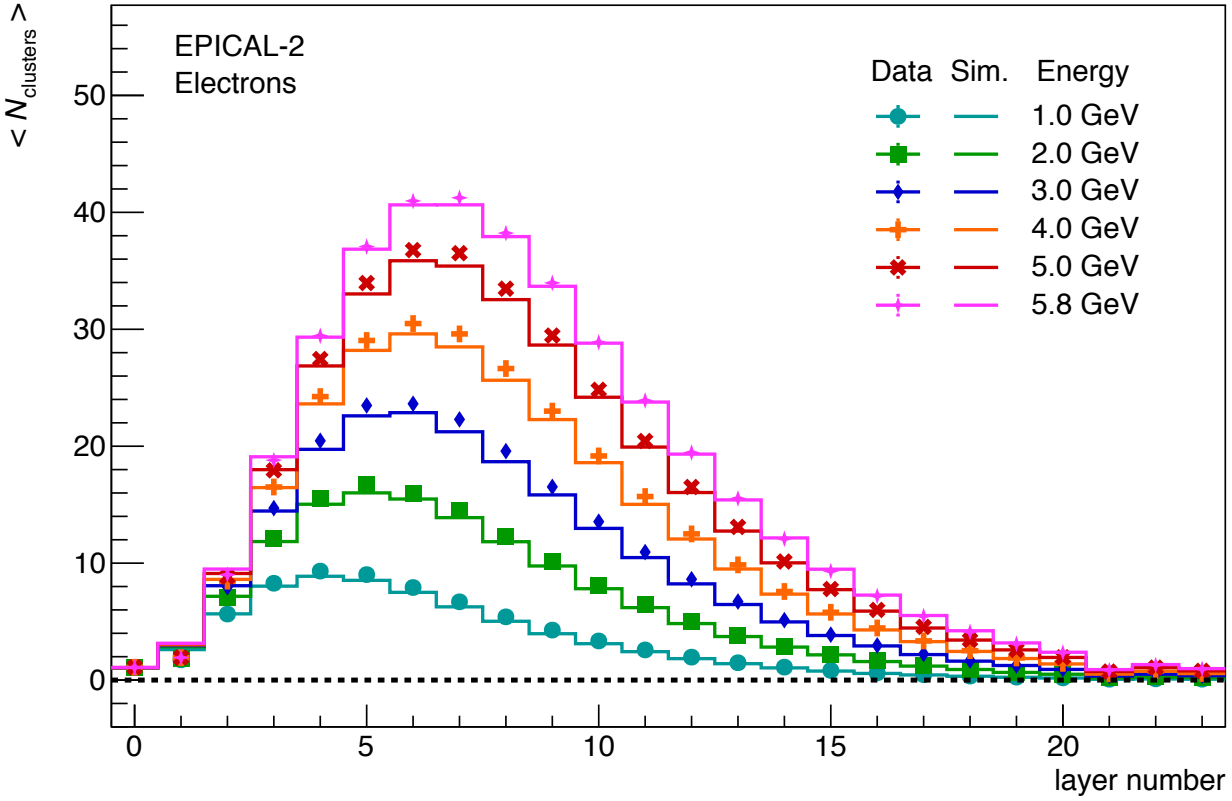
arithmetic mean and standard deviation from corresponding distributions:

- noise term negligible
- better performance for clusters
- additional effects in test beam data (e.g. energy spread, residual pile-up)

→ energy resolution superior to previous prototype

Longitudinal Shower Profiles





longitudinal shower profiles

- good performance for hits and clusters
- clear shower shape
- accurate description by simulation

→ first step in detailed shower-shape analyses

Status/Open questions

qualitative comparison of **hit** and **cluster** measurements:

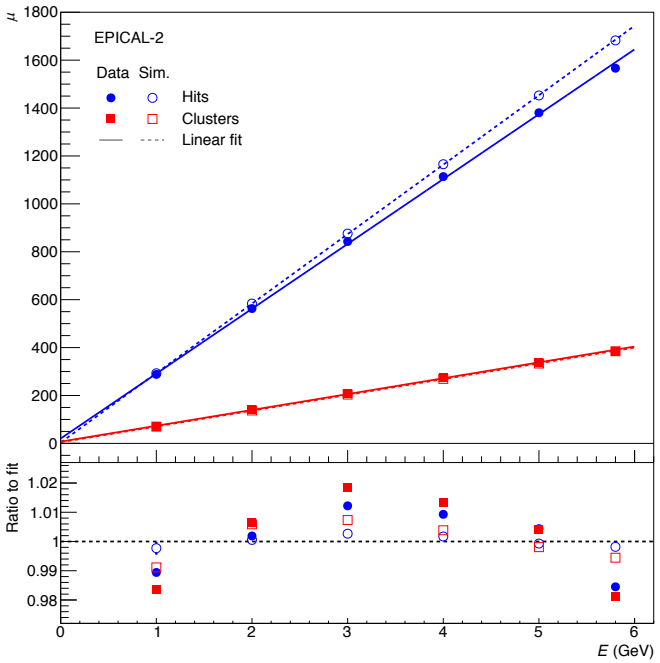
- better linearity for hits (cluster algorithm under investigation)
- better resolution for clusters

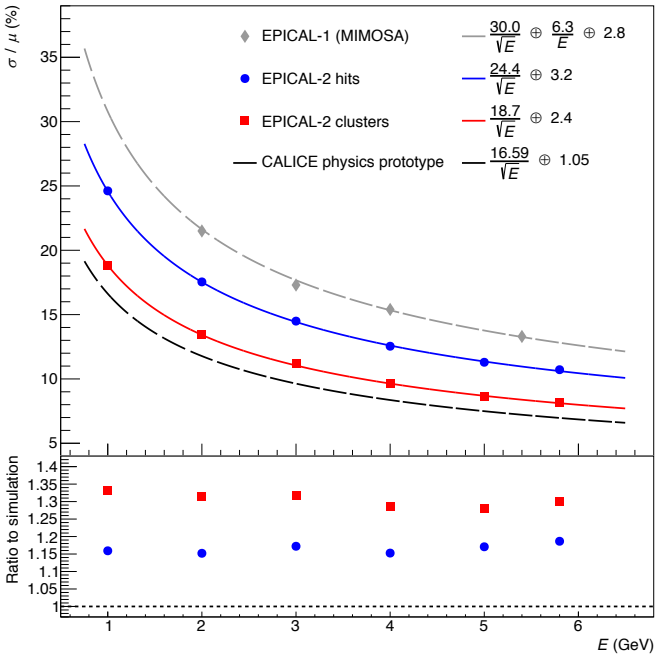
comparison of **data** and **simulation**:

- good general description of detector response by simulation
- some difference due to preliminary tuning of simulation
- significant differences when studying more detailed behaviour
  → better linearity in simulation
  → better resolution in simulation

questions under investigation:

- deviation in linearity and resolution related?
- role of potentially different beam momentum distribution?
- behaviour at higher beam energies?

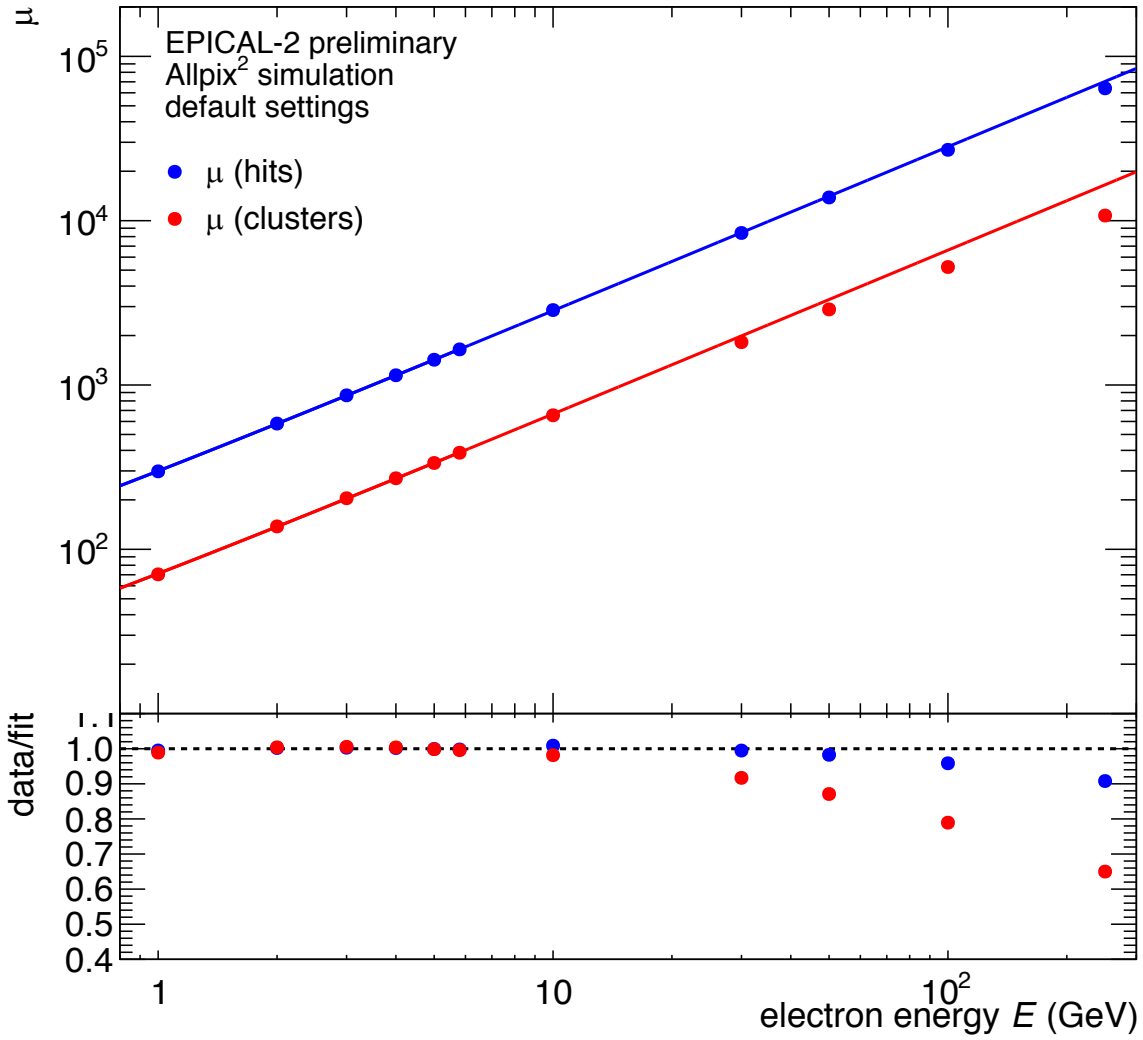




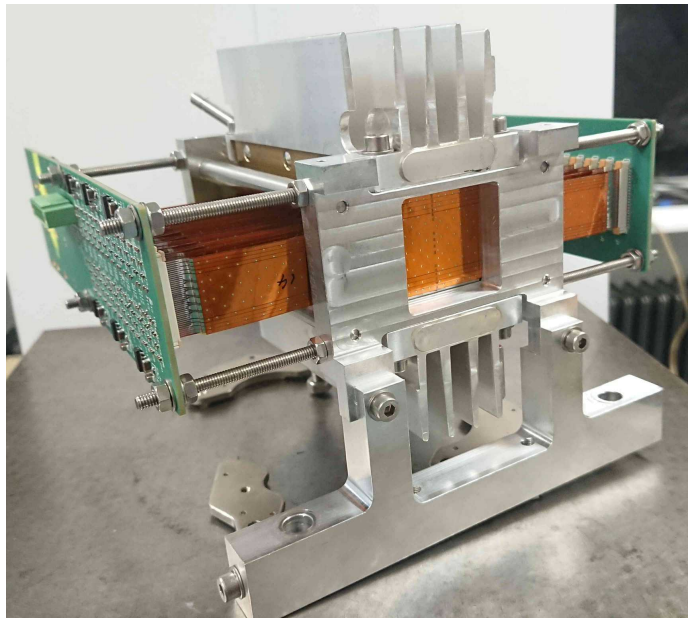
SPS Test Beam Preparation

Test beam at SPS scheduled for end of September (13 days):

- shared with FoCal calorimeters
- measurements
  - → at higher energies (20 to 160 GeV)
  - → with external bias
  - → with hadron beam



Summary



EPICAL-2

- high-granularity digital Electromagnetic PIxel CALorimeter
- 24 layers of
  - two CMOS MAPS chips (30 x 30 μm^2 pixel size)
  - tungsten absorber

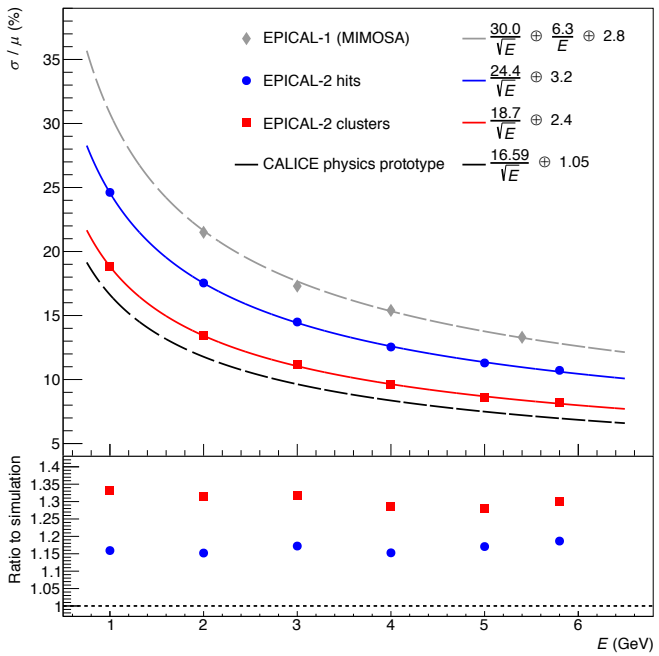
→ compact design with very small pixel size

simulation

- precise geometry implementation with Allpix^2
- good description of data in all observables

electron test beam

- energy resolution superior to previous MIMOSA prototype
- first step in detailed shower-shape analyses
- SPS test beam in preparation



EPICAL-2 Team

University of Bergen

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Research and Production Enterprise LTU Kharkiv Ukraine

Utrecht University/Nikhef

Yonsei University

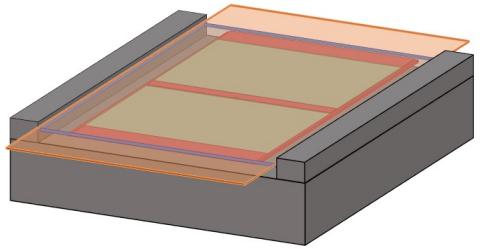
backup

EPICAL-2 simulation utilizing Allpix²

A Monte Carlo simulation tool for silicon pixel detectors
From incoming particle(s) to readout

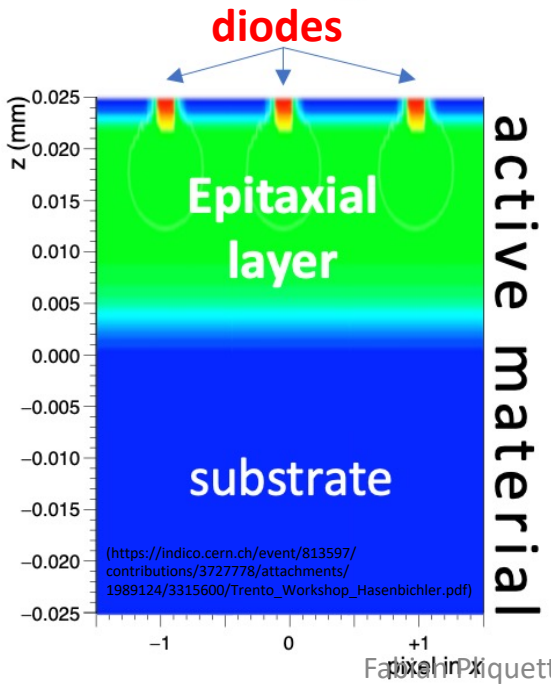
simulation chain:

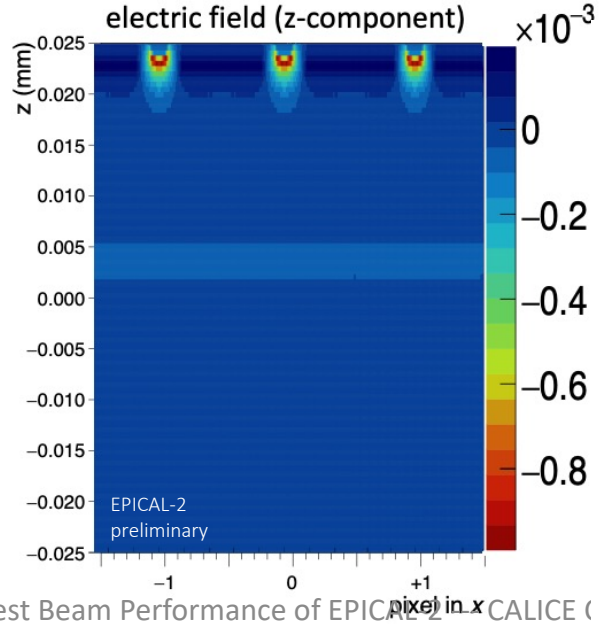
geometry builder → electric field initialization → energy deposition →

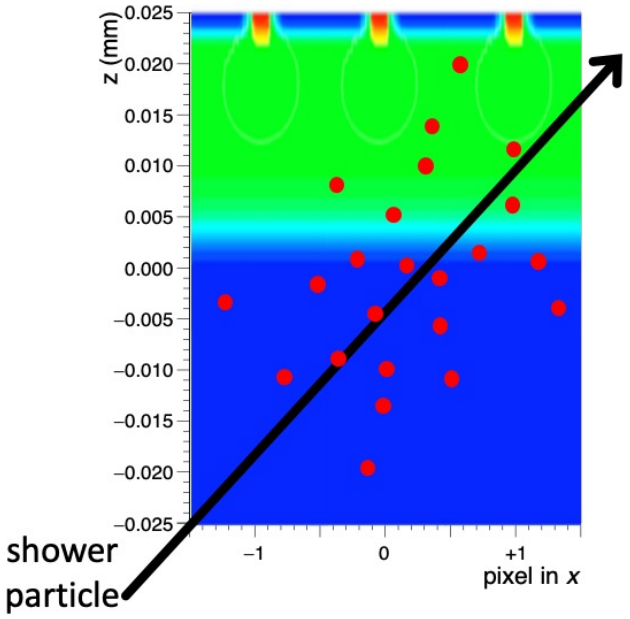


- electric field obtained from **TCAD** simulation by Jan Hasenbichler
- total reverse bias voltage of $V_{RB} = 1.4\ \mathrm{V}$

- particle transport and deposition of charges ● in active materials







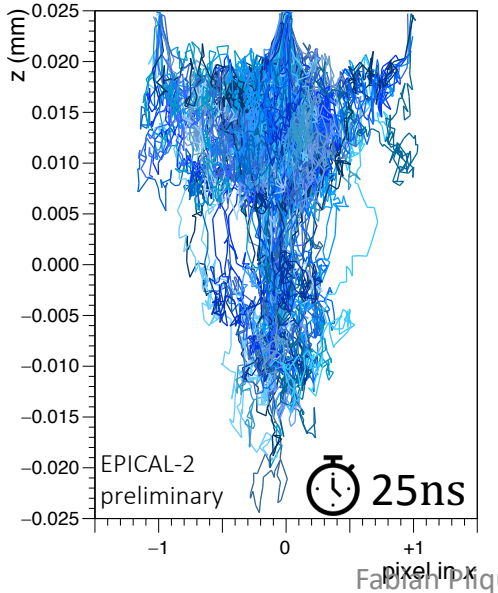
EPICAL-2 simulation utilizing Allpix²

A Monte Carlo simulation tool for silicon pixel detectors
From incoming particle(s) to readout

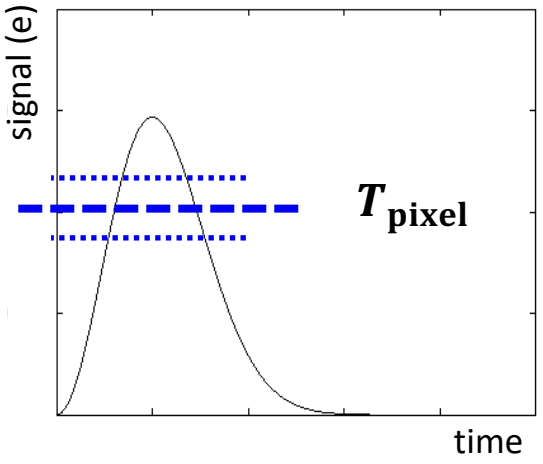
simulation chain:

propagation and transfer → **digitizer** → **output**

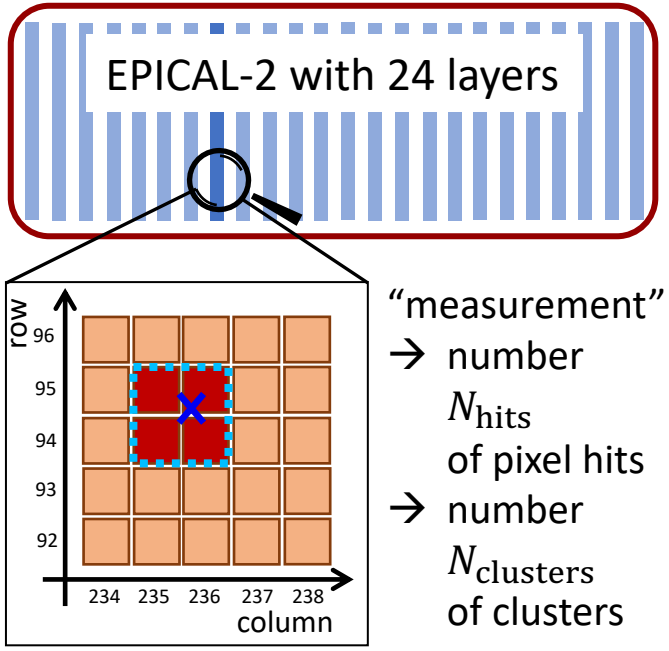
- propagation of charge carrier groups
  → set to **50 charges per group**
- diffusion and drift of groups within integration time t_{int}
  → set to $\boldsymbol{t_{\mathrm{int}} = 25.5\ \mathrm{ns}}$
- pixel assignment of charges



- noise added by Gaussian (width σ_{noise}) to each pixel
  → set to $\boldsymbol{\sigma_{\mathrm{noise}} = 20\ \mathrm{e}}$
- accept as hit: pixel charges surpassing threshold value T_{pixel}
  (T_{pixel} is set per chip)
  mean: $< \boldsymbol{T_{\mathrm{pixel}}} > = \boldsymbol{82\ \mathrm{e} \pm 20\ \mathrm{e}}$



- 2D information of hits per layer
  → column and row



"measurement":
→ number N_{hits} of pixel hits
→ number N_{clusters} of clusters

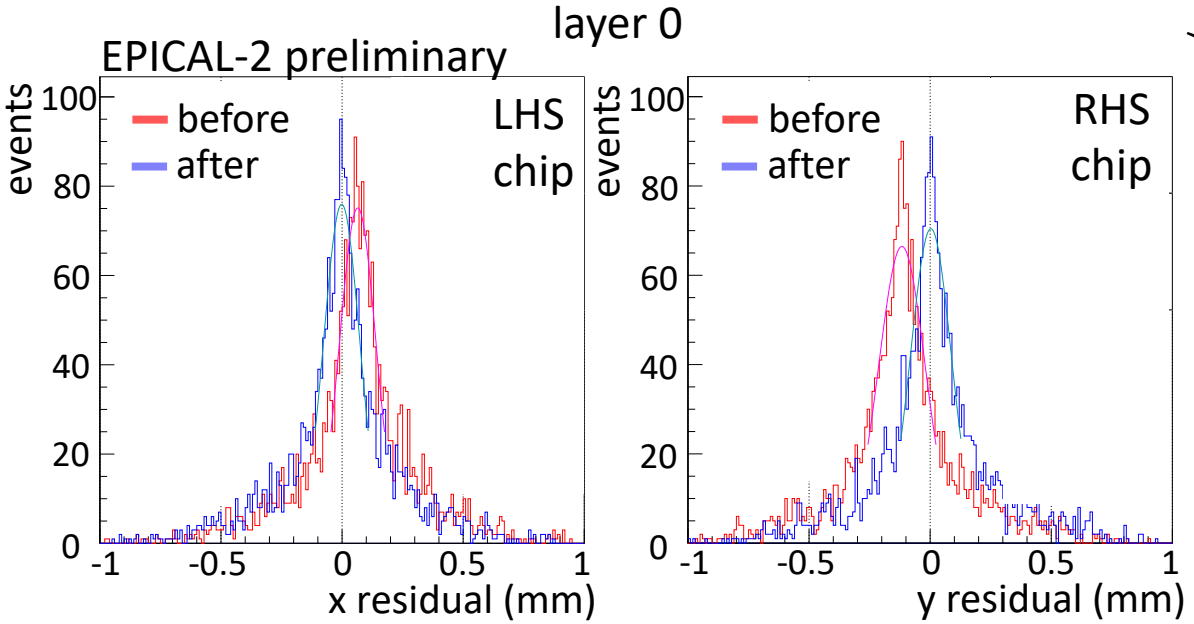
× shower particle
cluster
pixel with hit
pixel without hit

① Cosmics

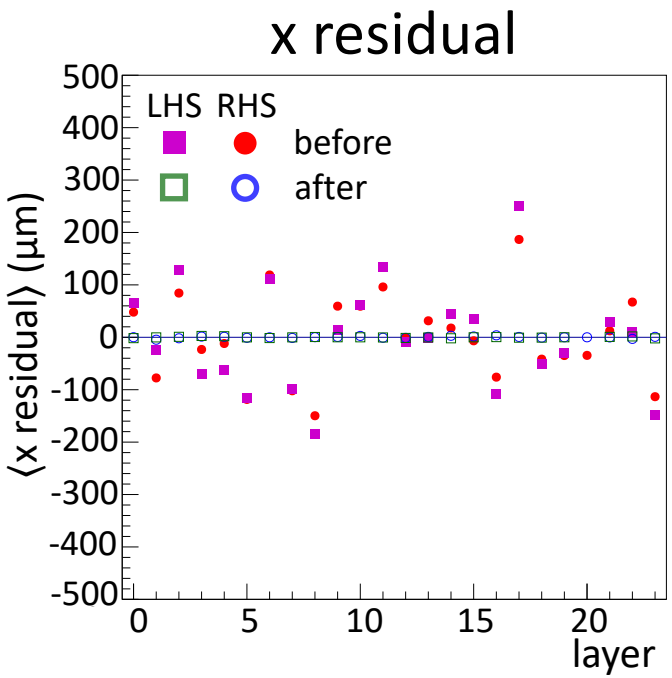
Alignment

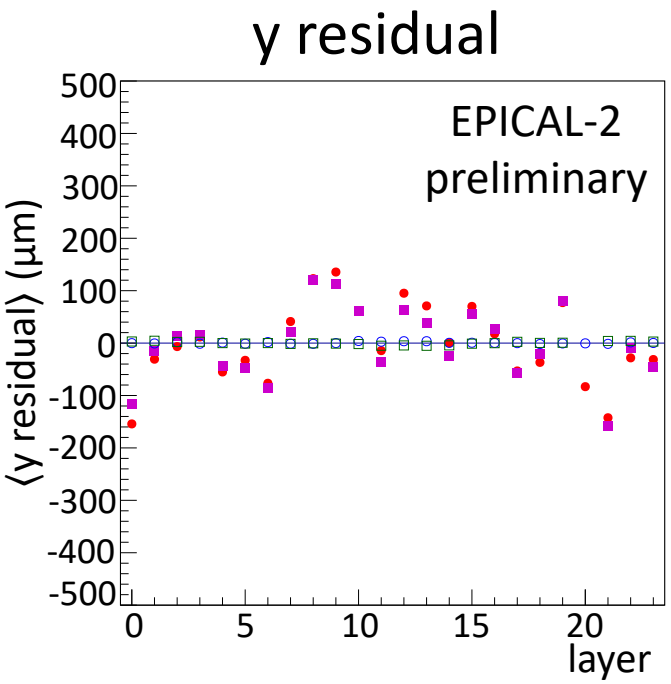
chip-by-chip alignment

- longitudinal position fixed by absorber
- three parameters for lateral position
  → shift in chip plane (dx, dy)
  → rotation around z axis (dΘ)



residual: track fit - cluster position



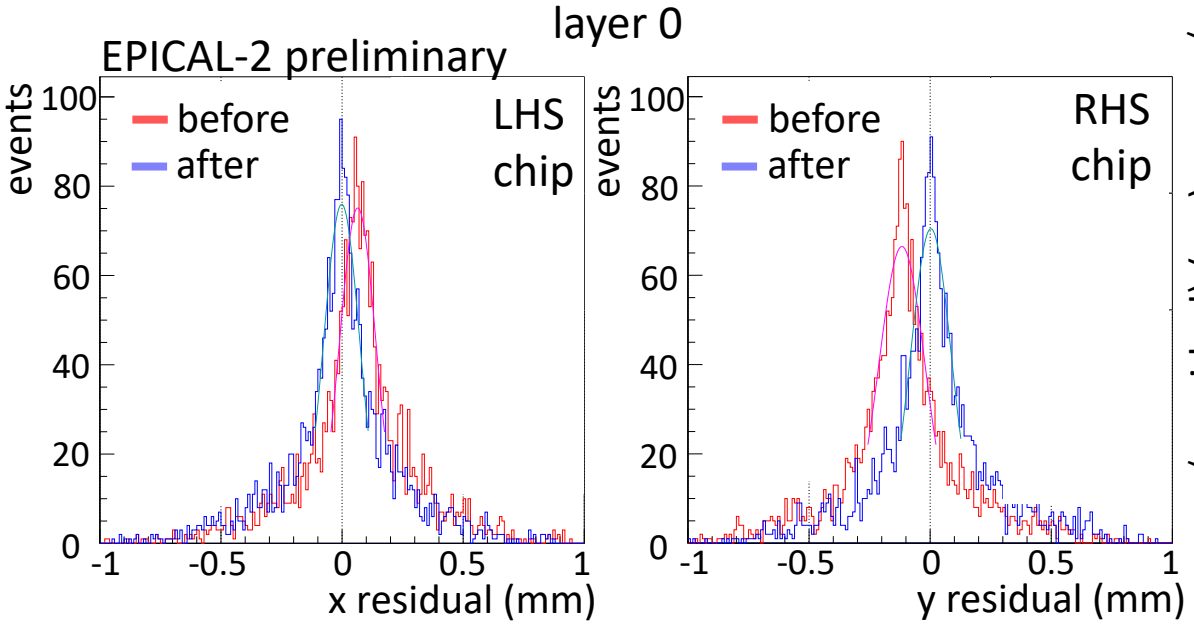


① Cosmics

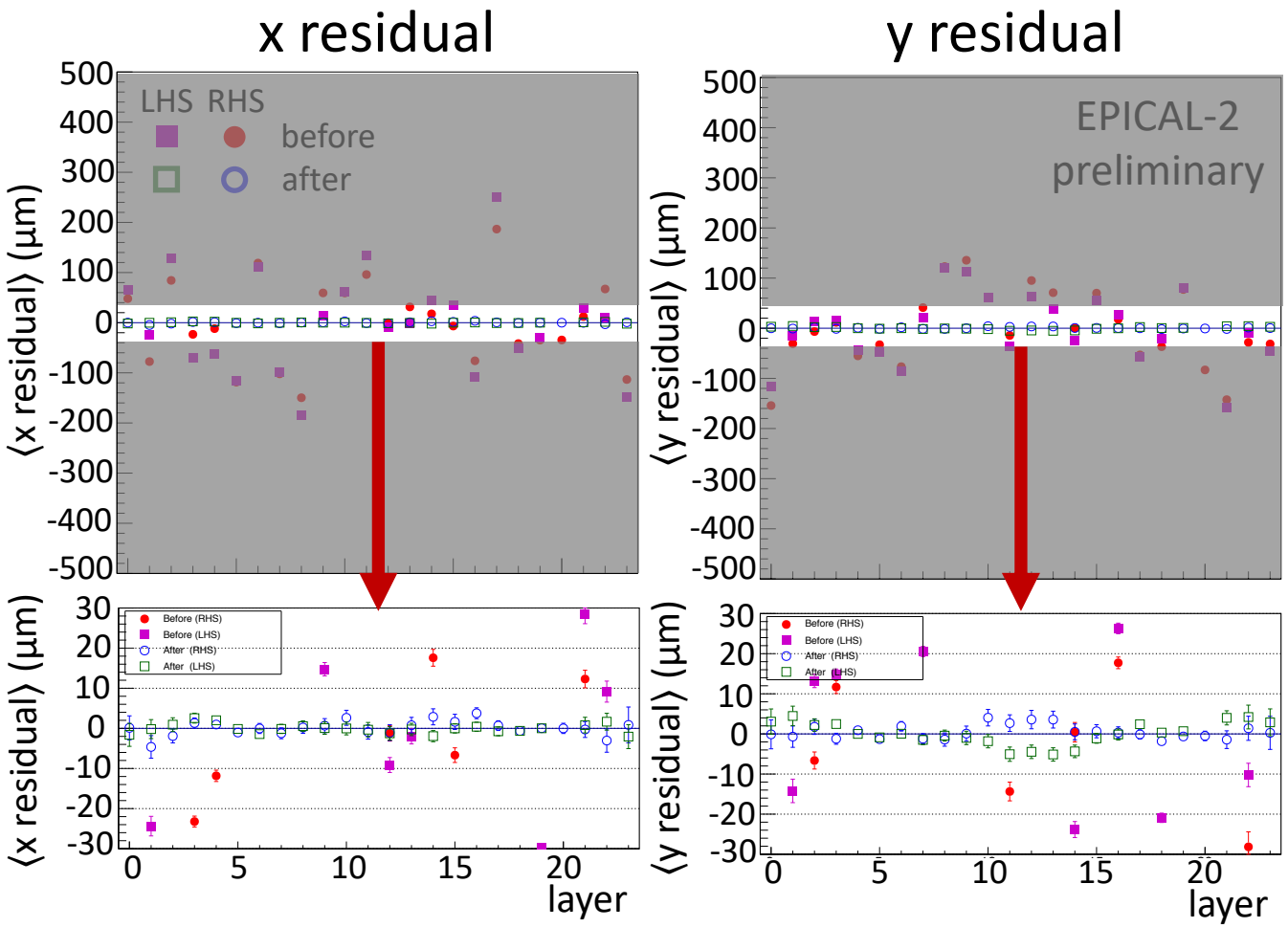
Alignment

chip-by-chip alignment

- longitudinal position fixed by absorber
- three parameters for lateral position
  → shift in chip plane (dx, dy)
  → rotation around z axis (dΘ)



residual: track fit - cluster position

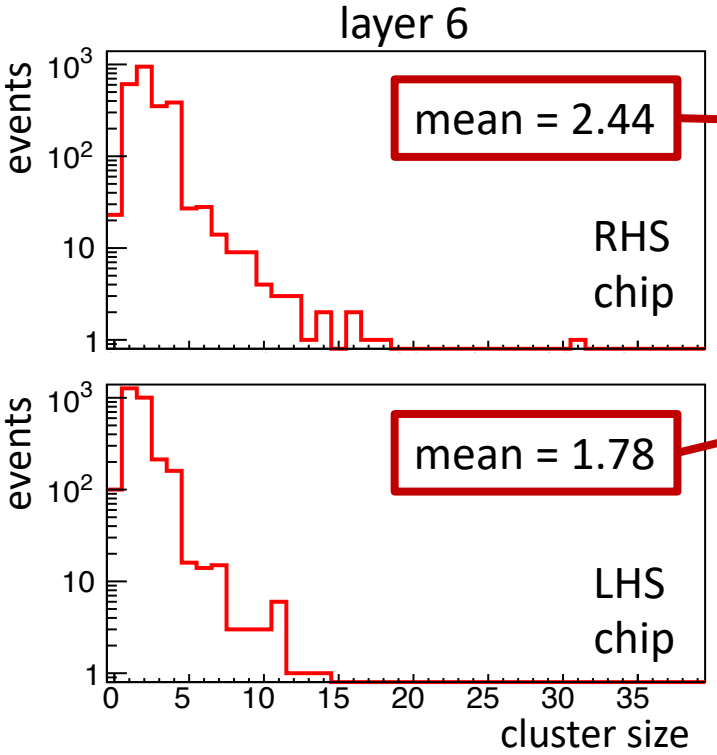


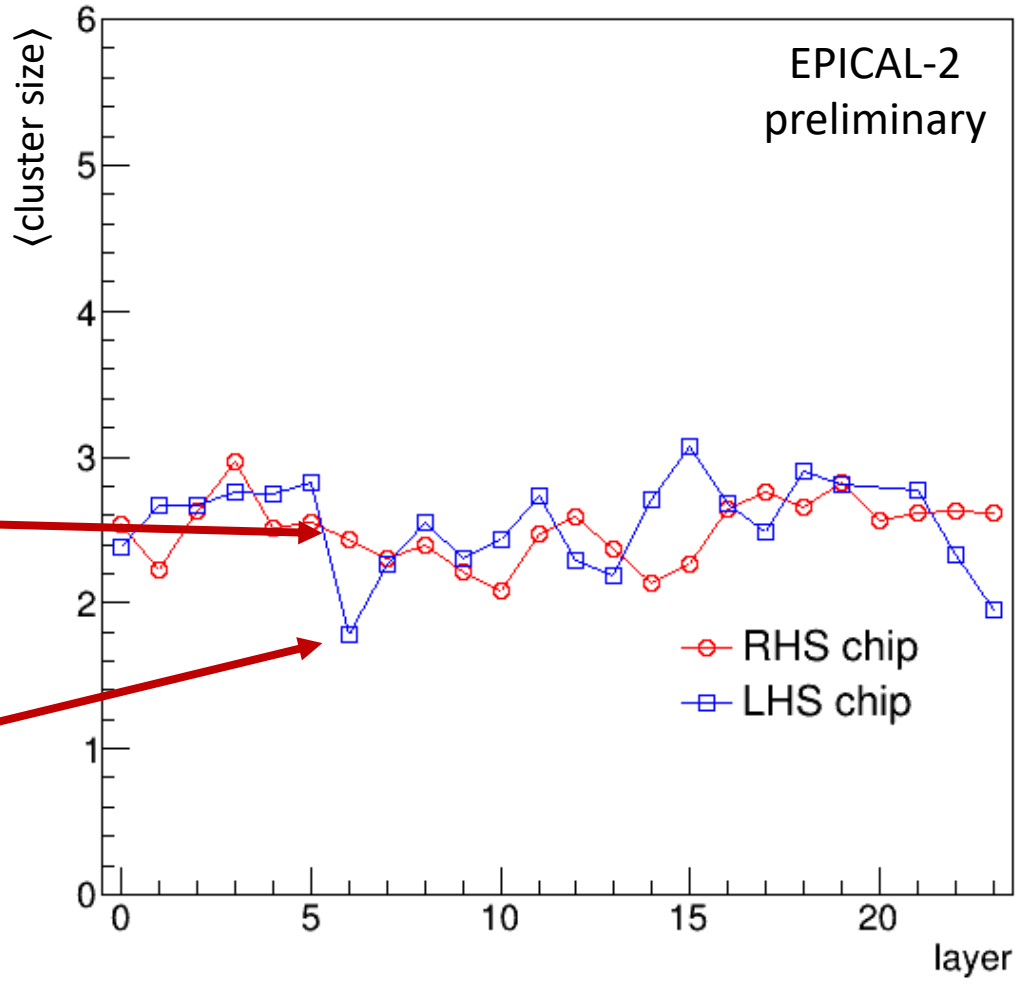
→ alignment precision better than 10 µm

Calibration

chip-by-chip calibration

- mean from cluster-size distributions
- equalization of mean cluster sizes





→ calibration of chip responses

Energy Linearity

linearity studies:

- y intercept
  → noise estimate from pedestals
  2.91×10^{-3}
- varying fit ranges
- **power law fit**

power law exponent

	hits	clusters
data	0.9654 ± 0.0002	0.9503 ± 0.0002
sim.	0.9942 ± 0.0010	0.9686 ± 0.0007