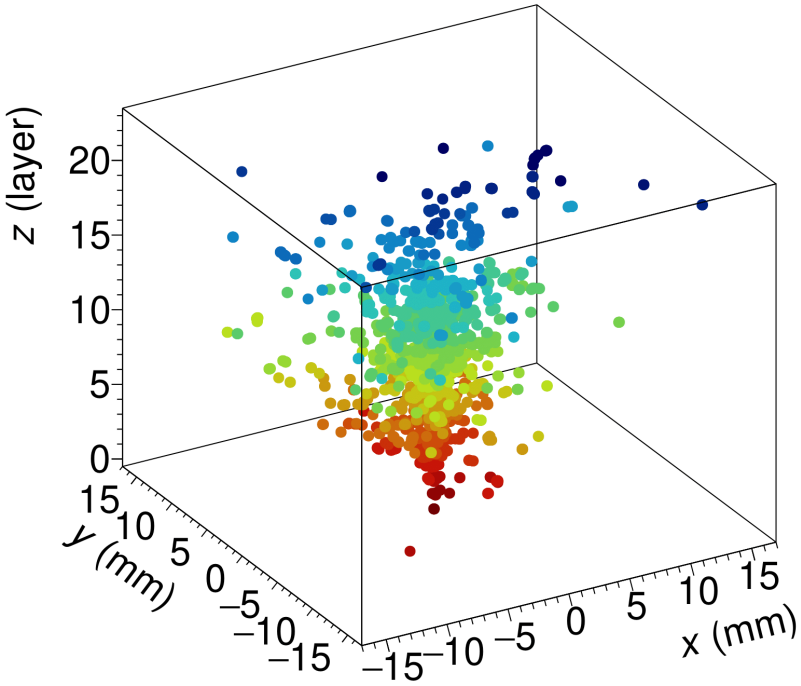
Performance and Shower-Shape Studies with EPICAL-2

Johannes Keul
for the EPICAL-2 team

VCI2025



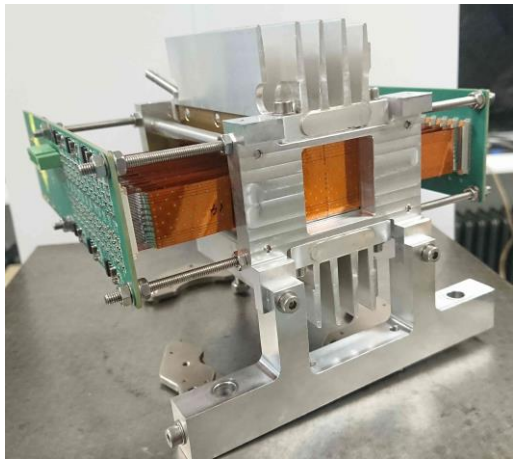
HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

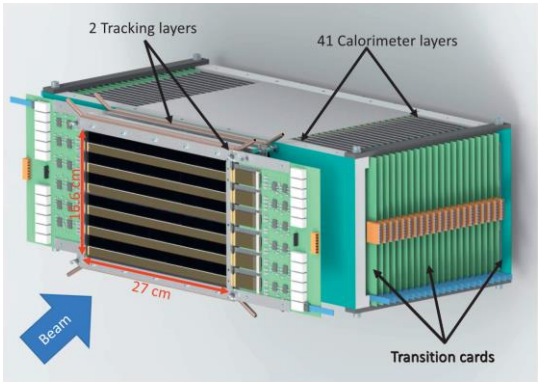
IKF
Institut für Kernphysik Frankfurt

18.02.2025

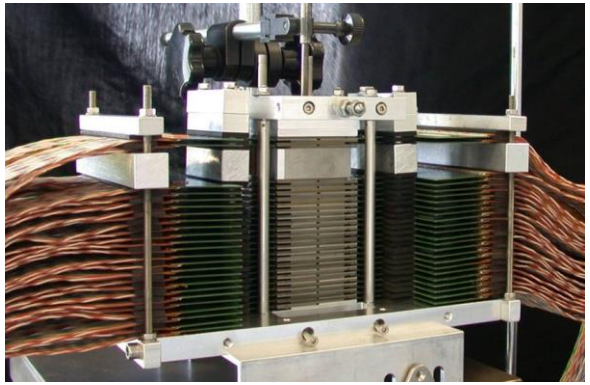
Digital Pixel Calorimeters



EPICAL-2



Bergen pCT



EPICAL-1

Concept:

- **Calorimetry** with **MAPS** technology
- Detection of individual **shower particles**

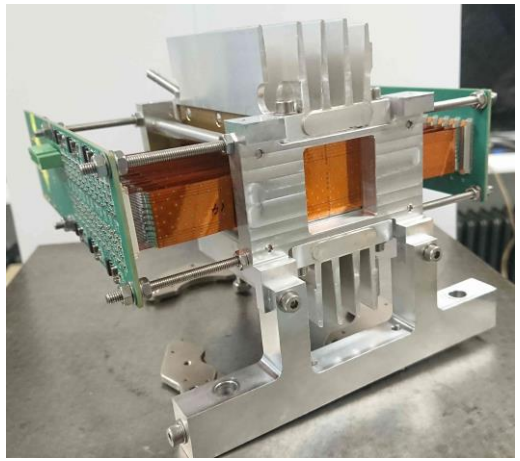
Feature:

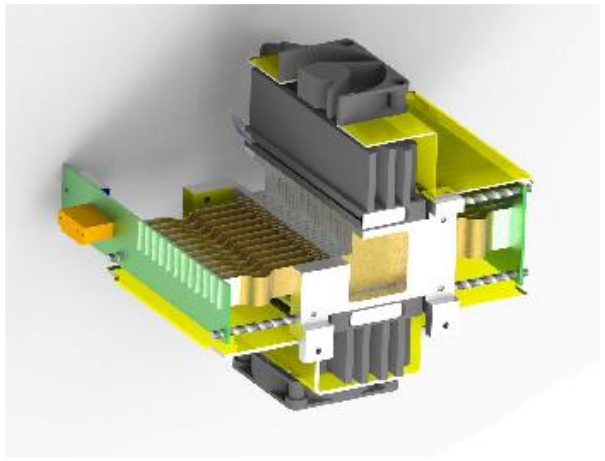
- **Ultra-high granularity**
- ➢ Good shower **separation** and **position resolution**

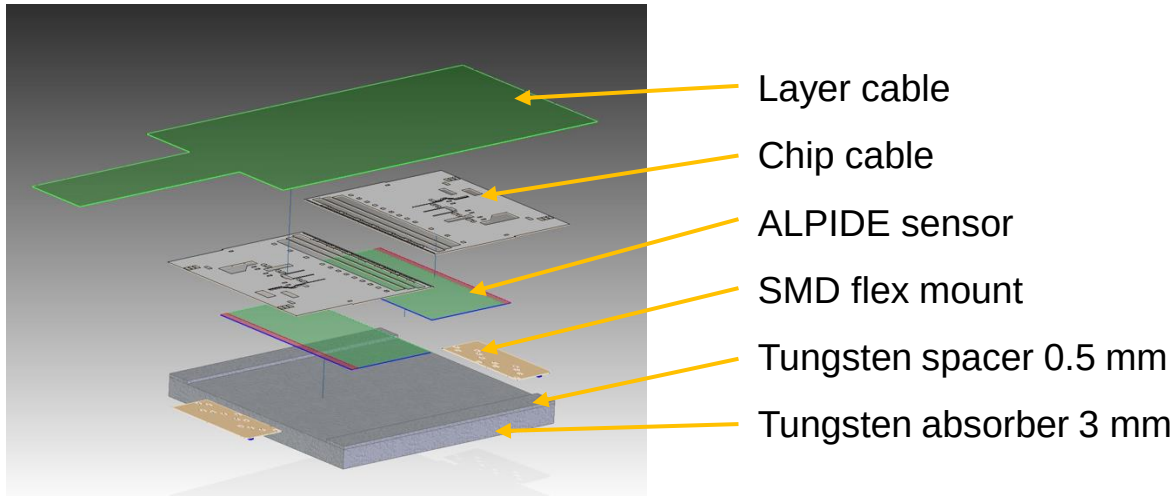
Context:

- Bergen pCT Front. Phys., 22 October 2020, Sec. Medical Physics and Imaging
- ALICE FoCal 2024 JINST 19 P07006, 2021 NIMA 988 164796, 2020 JINST 15 P03015, 2014 NIMA 764 24-29
- EPICAL-1 2017 JINST 13 P01014
- **EPICAL-2** 2023 JINST 18 P01038

EPICAL-2







Composition of single layer

Electromagnetic Pixel Calorimeter 2:

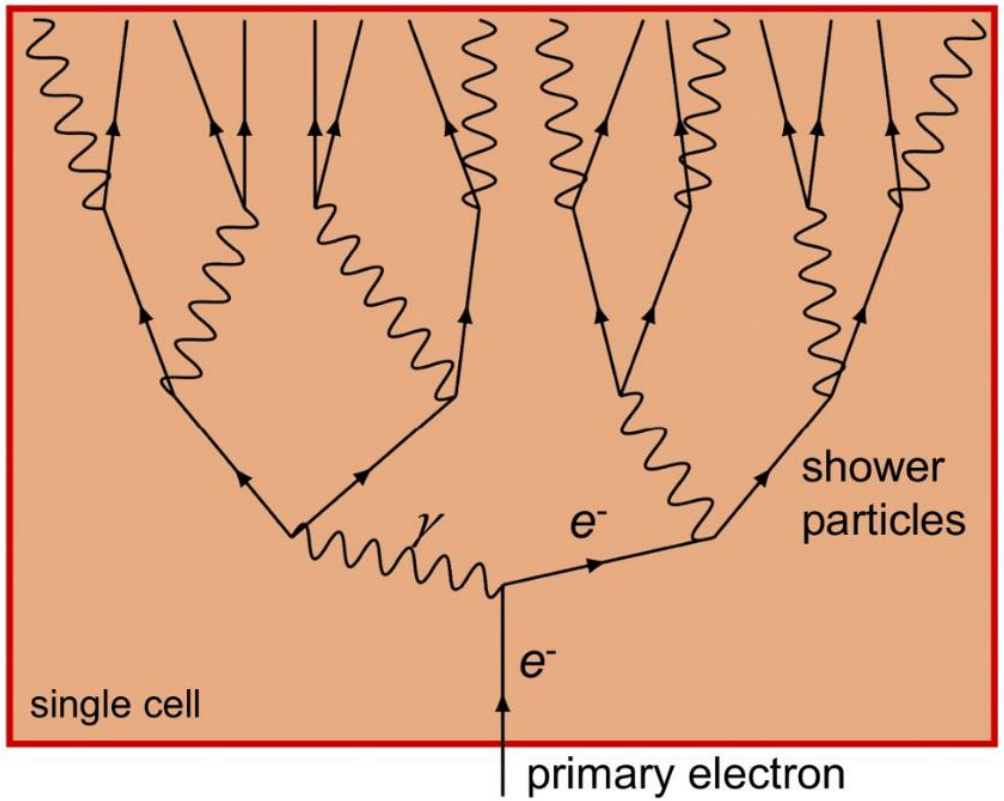
- **Prototype** of digital electromagnetic calorimeter
  - ➢ Explore potential of **digital calorimetry**
  - ➢ R&D for **ALICE FoCal** (2 pixel layers)

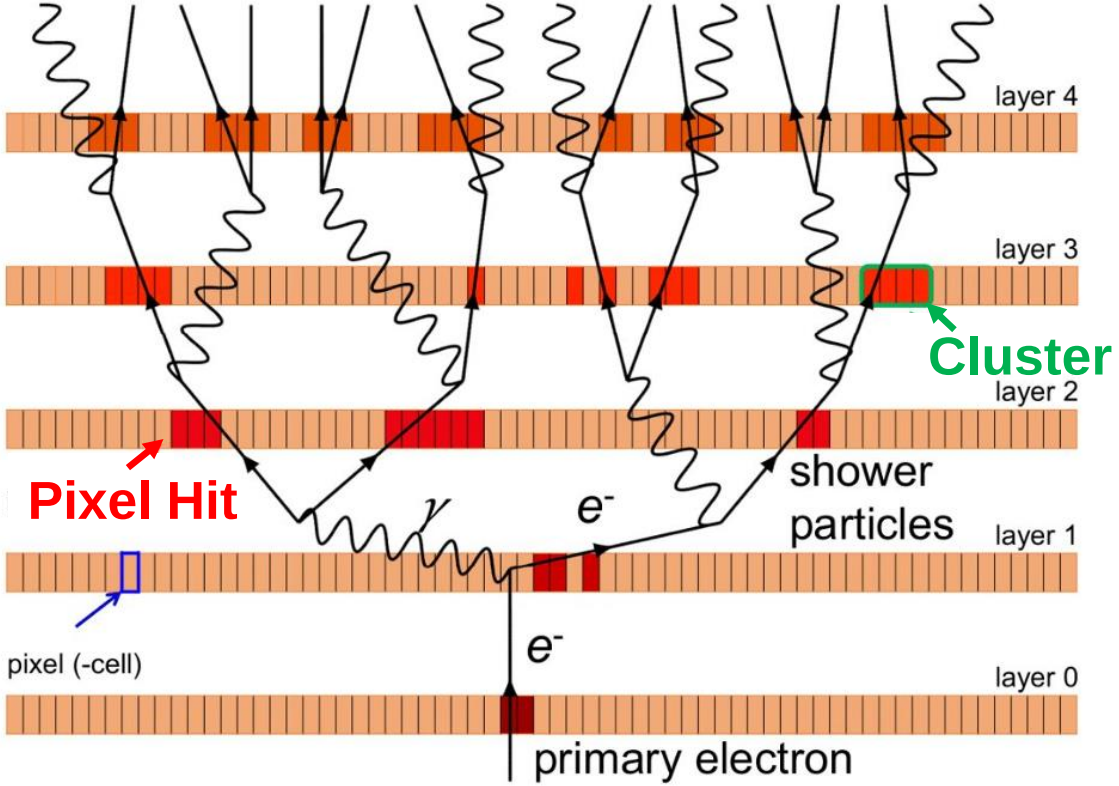
- **Si-W** sandwich design
- **≈ 20 radiation lengths**
- **24 layers**:
  - 2 adjacent **ALPIDE** sensors
  - 3 mm **tungsten absorber**
- Active area ≈ 27 x 30 mm^2
- ≈ 25 million pixels with 29.24 x 26.88 μm^2 size

Energy Measurement

Analog calorimeter:
- Energy deposit

Digital calorimeter:
- Number of hits or clusters





Data Taking & Simulation

Cosmic muons

- Utrecht University

Electron beam: 1.0 – 5.8 GeV

- DESY II test beam facility

Performance paper published:
2023 JINST 18 P01038

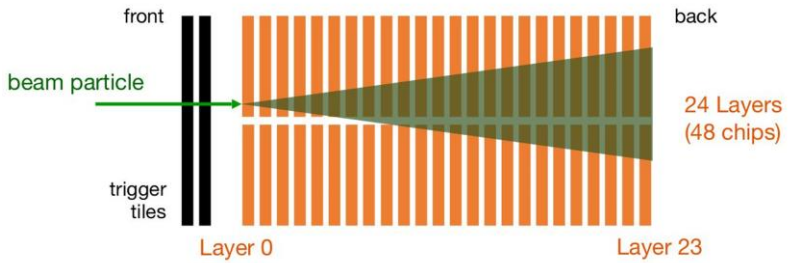
Electron + hadron + muon beam: 20 – 80 GeV

- CERN-SPS H6 test beam line

New! This talk

Allpix² simulation (version 3.0.2)

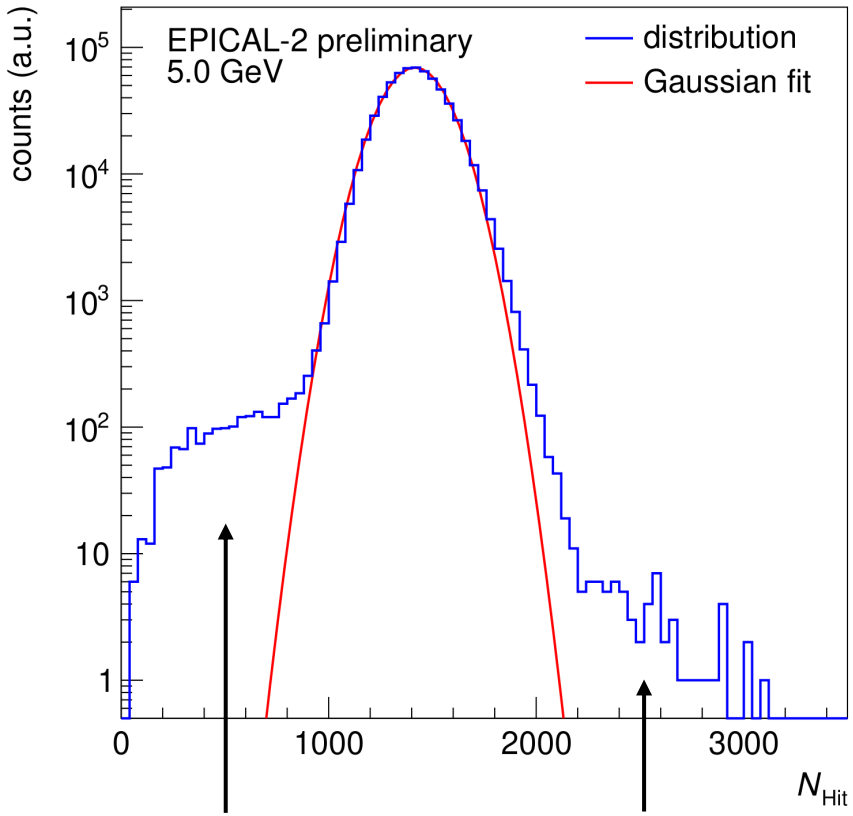
- Simulation includes **shower development**, charge deposition, propagation and **digitization**
- Detailed **EPICAL-2 geometry** implemented
- Additionally: **Enlarged** EPICAL-2 geometry implemented
  - ➢ More detailed studies



EPICAL-2 Performance

Detector Response

5 GeV, hits



Low-energy electrons and leakage

Pileup

Response observables:

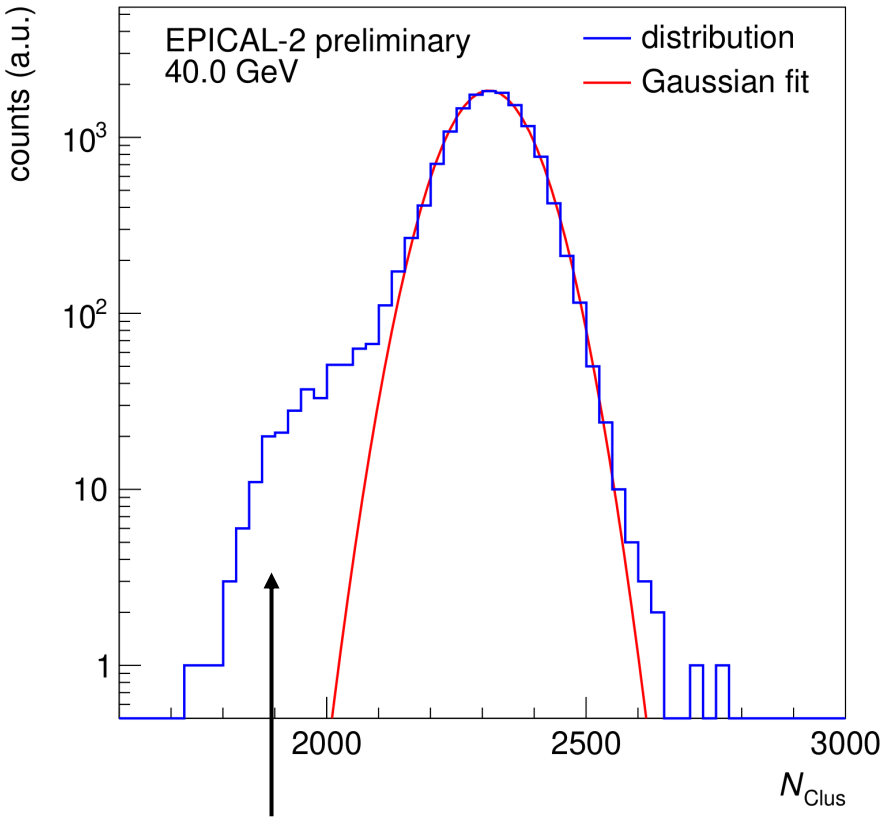
1. Pixel **hits**
2. Pixel hit **clusters**

Methods to determine mean μ and width σ:

A Arithmetic mean and standard deviation

B Gaussian parametrization in range $\mu \pm 2\sigma$

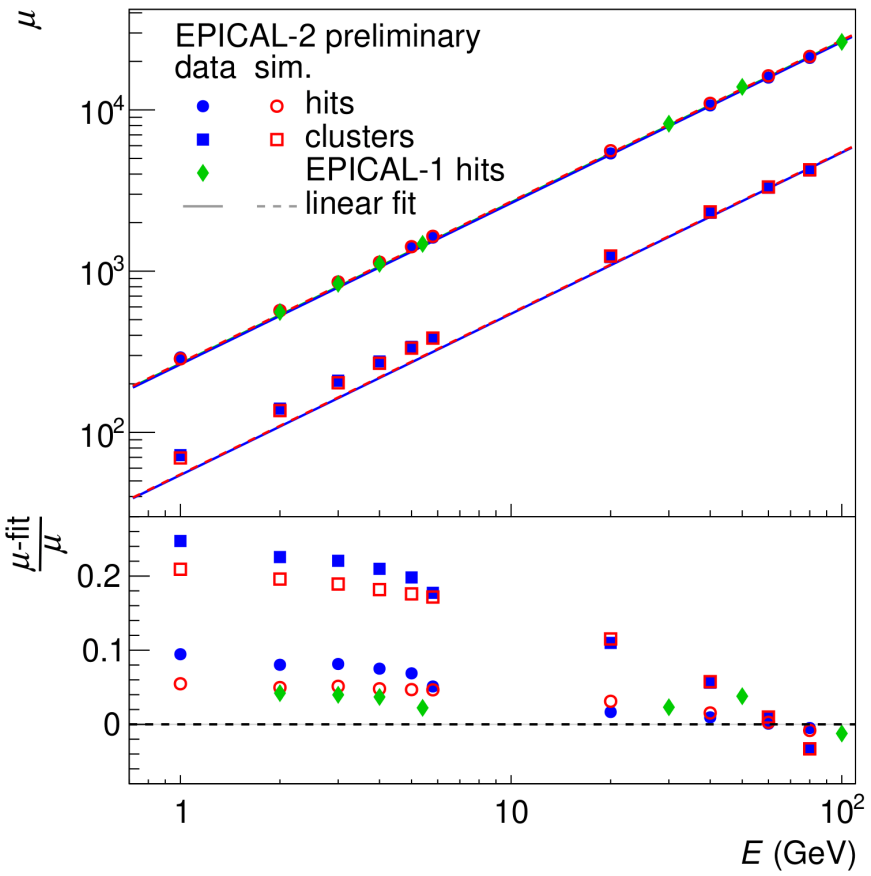
40 GeV, clusters



Hadron background and leakage

Linearity

A



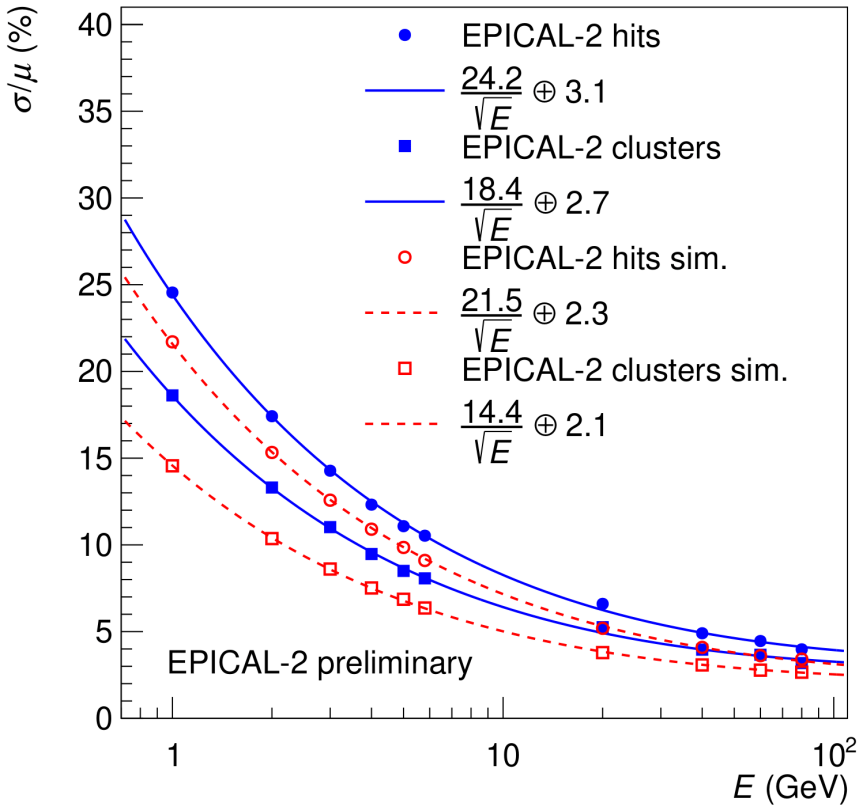
Mean μ of the detector response:

- A same as B
- **Parametrization** with:

$$\mu(E) = a * E$$

- **Simulation** describes data well
- **Good linearity for hits**, comparable to EPICAL-1
- Higher **deviations from linearity for clusters** due to cluster merging at high *E*

Resolution



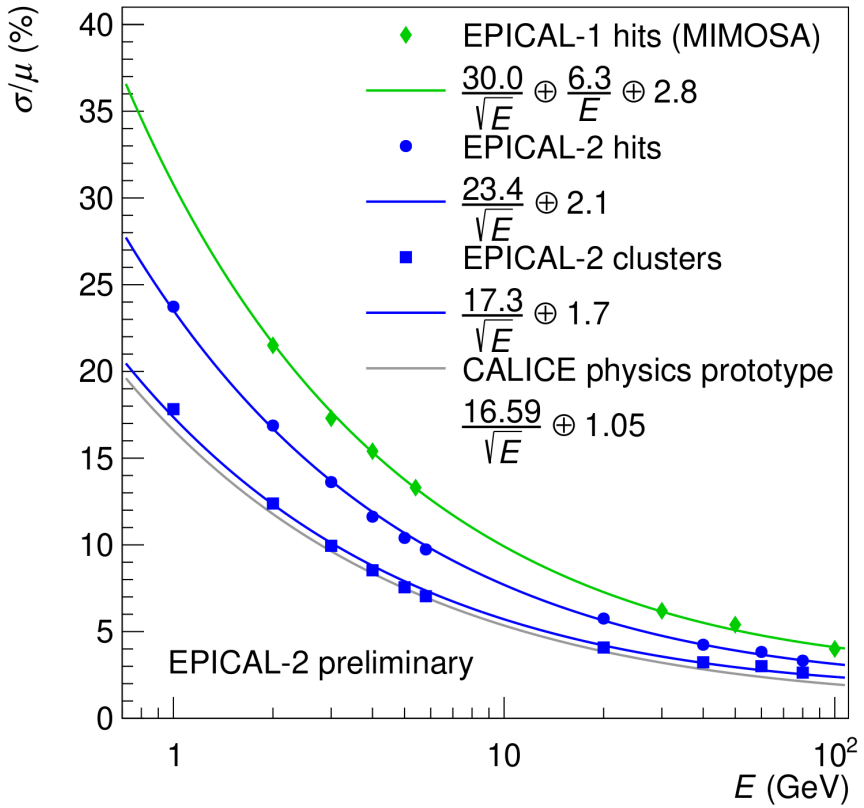
Resolution σ/μ:

- **Simulation** yields **better resolution** than data
  - Test beam energy spread not accounted for in simulation

- **Clusters** yield **better resolution** than hits
  - Statistical fluctuations of hits per cluster have no impact on N_{Clus}

Resolution

B



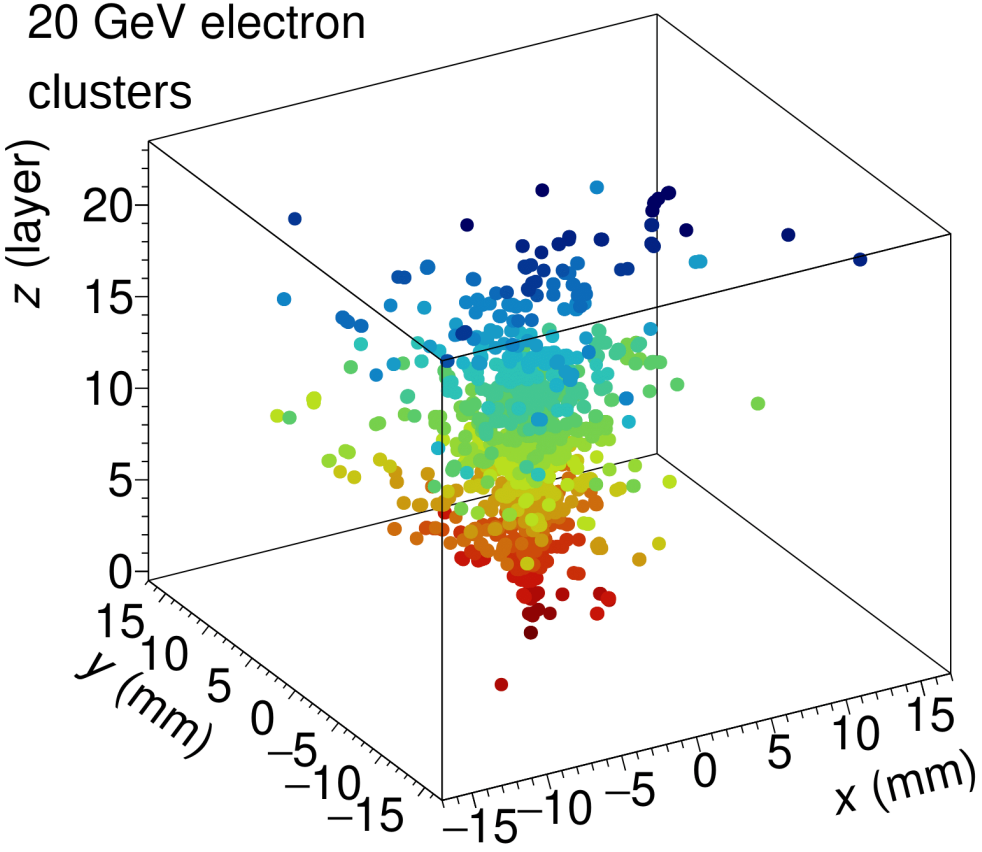
- **Fit method:** allows for **comparison** of the EPICAL-2 results with EPICAL-1 and CALICE

- B better resolution than A
- **Improved resolution** compared to **EPICAL-1**
- **Resolution for clusters** almost as good as **CALICE prototype**

Shower Shape

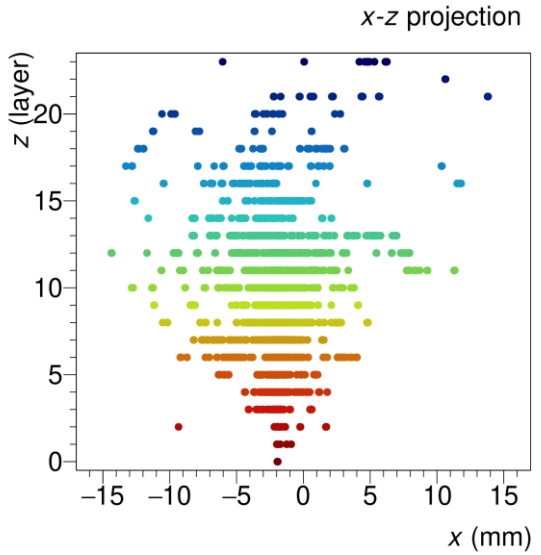
Event Display

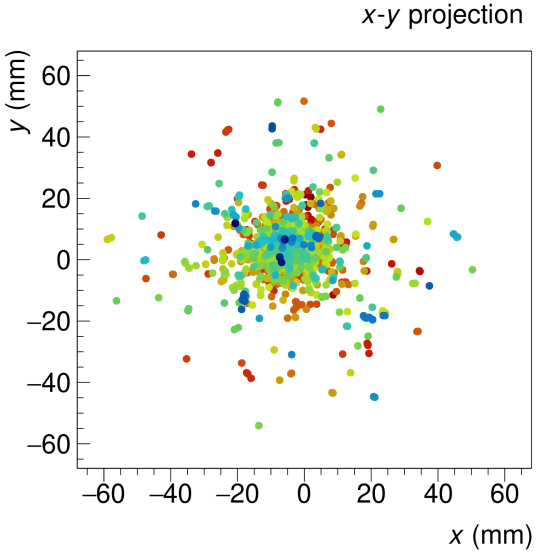
EPICAL-2 data
20 GeV electron clusters

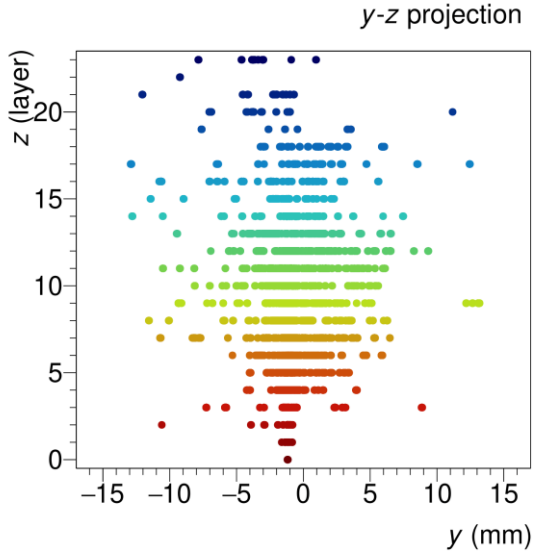


Detailed information about shower shape:

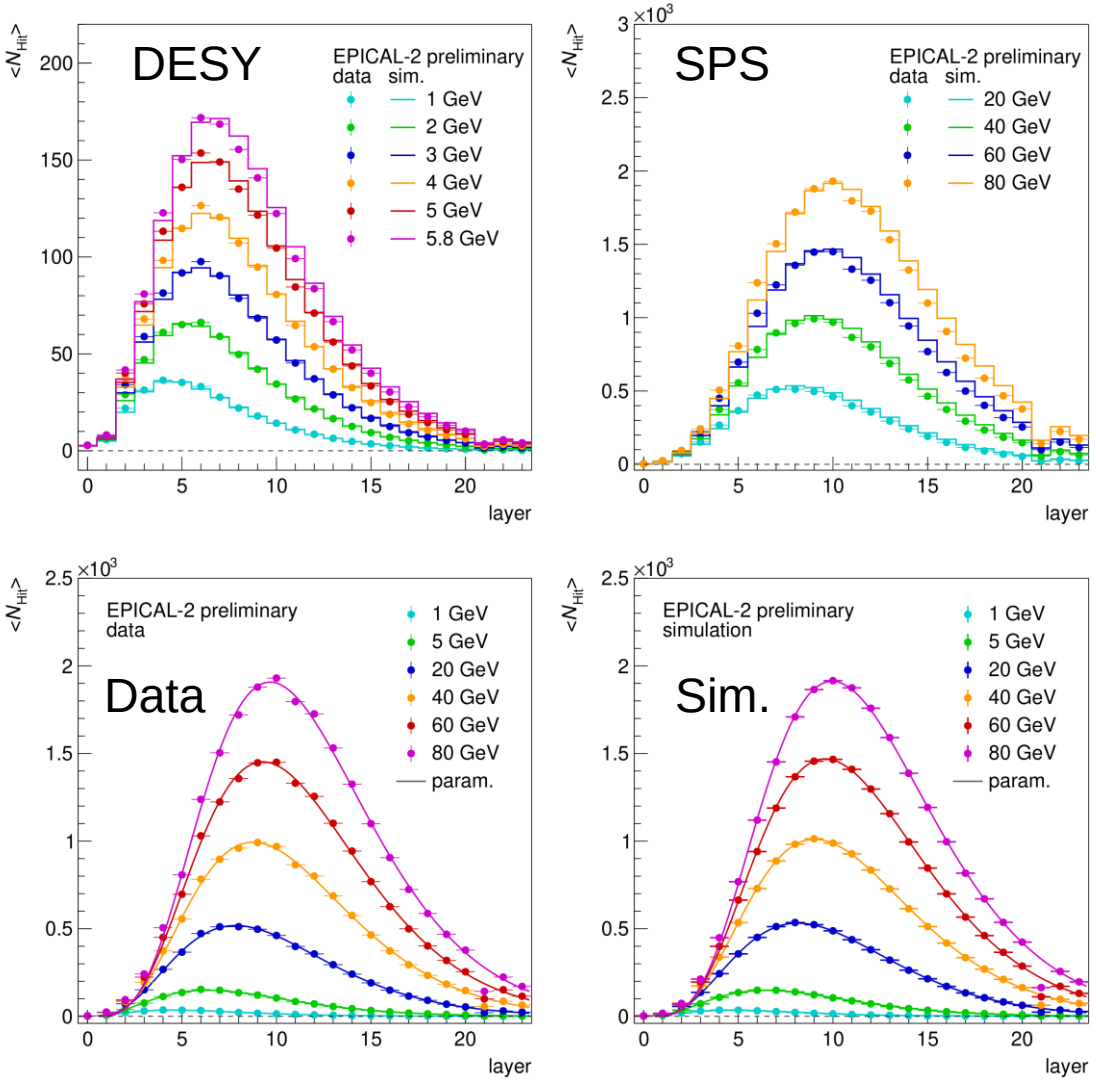
- **Longitudinal** (*z* direction)
- **Lateral** (*x*-*y* plane)







Longitudinal Profile



- Shower profiles described by **simulation**
- **Shower maximum shifts** with energy

Extraction of shower maximum position t_{max}:

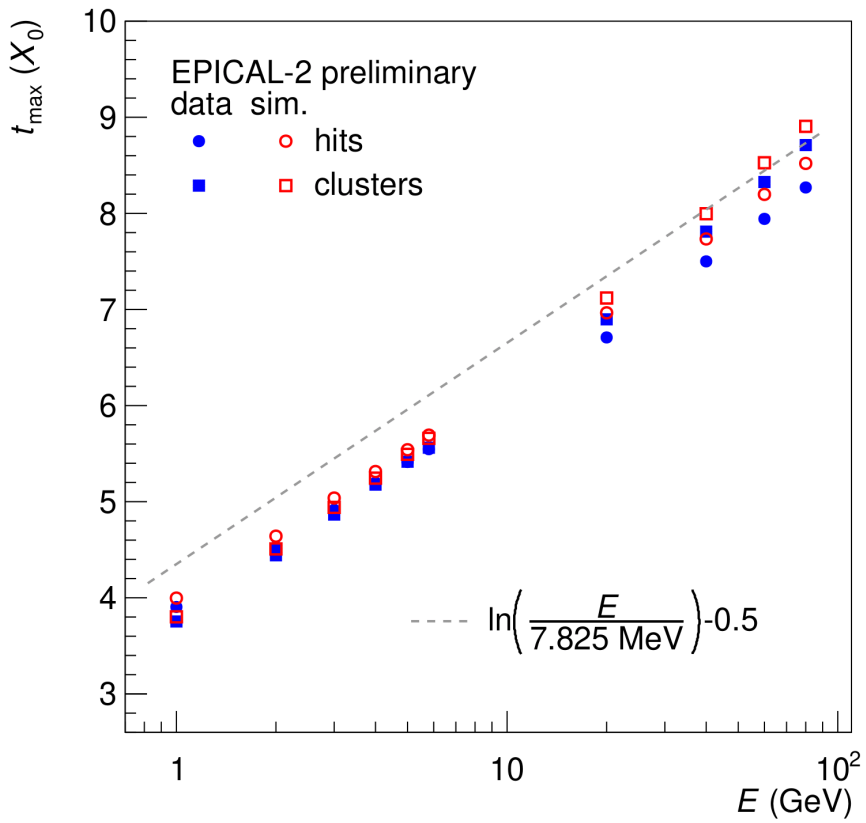
- **Parametrization** with empiric function

$$f(t) = A * t^{\alpha} * e^{-\beta * t}$$

- Shower maximum position

$$t_{\max} = \frac{\alpha}{\beta}$$

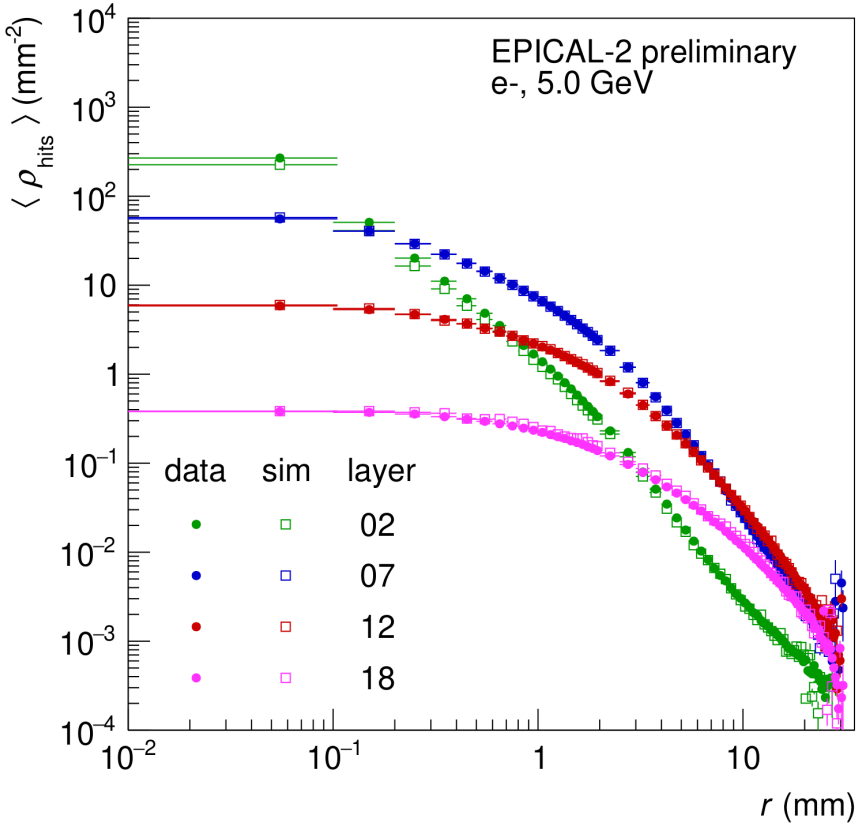
Longitudinal Shower Maximum

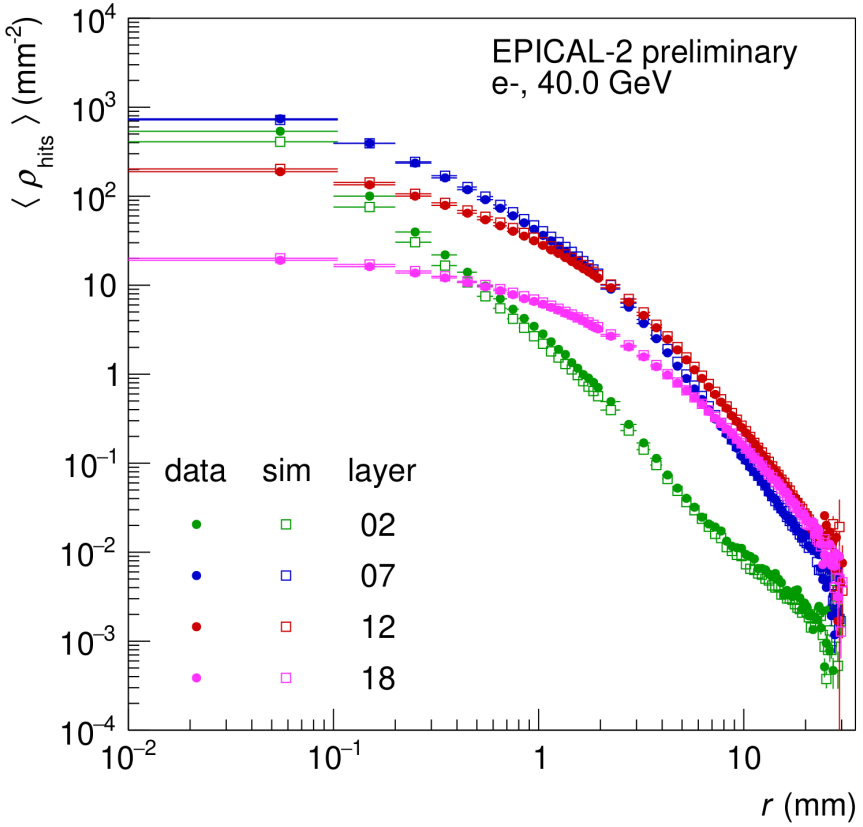


Depth of shower maximum:

- Increases logarithmically with *E*
- **For low *E*:**
  - Simulation describes data
  - Clusters and hits similar
- **For high *E*:**
  - Simulation overestimates data
  - Clusters diverge from hits
- Data and simulation **below phenomenological estimate**

Lateral Profile

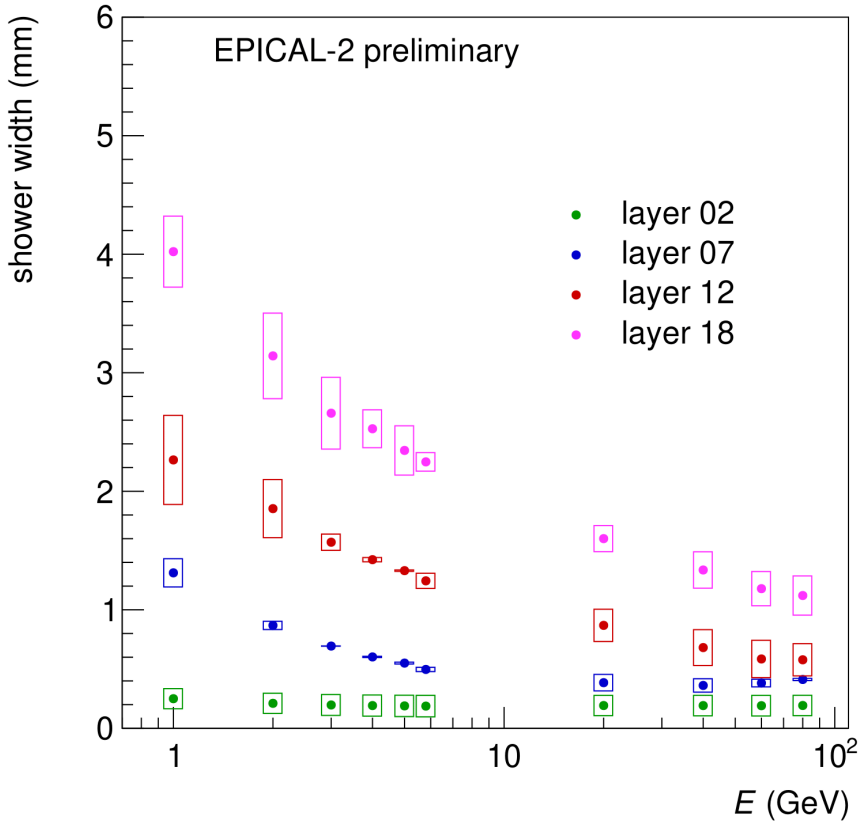




Lateral hit density profile:

- **Simulation** describes shower profiles
- **Shower widens** towards later layers

Shower Width

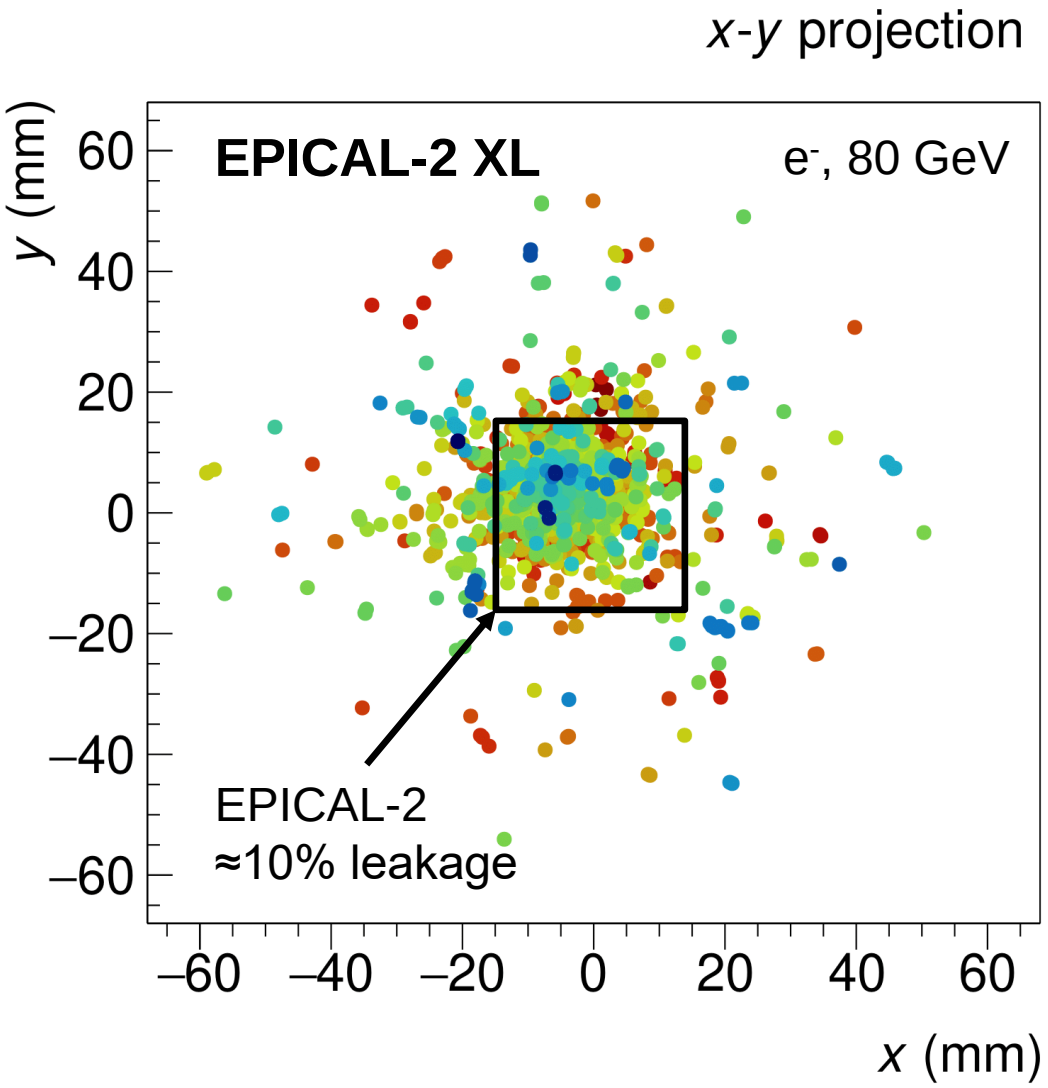


- **FWHM** of lateral hit density distribution

- Layer 02: shower not yet developed
- Shower gets narrower with increasing *E* at same layer
- Information on width as a function of *E* useful for optimization of **FoCal** pixel layer position
- Shower width on the order of few mm
  - ➢ **Strong shower separation power**

Molière Radius

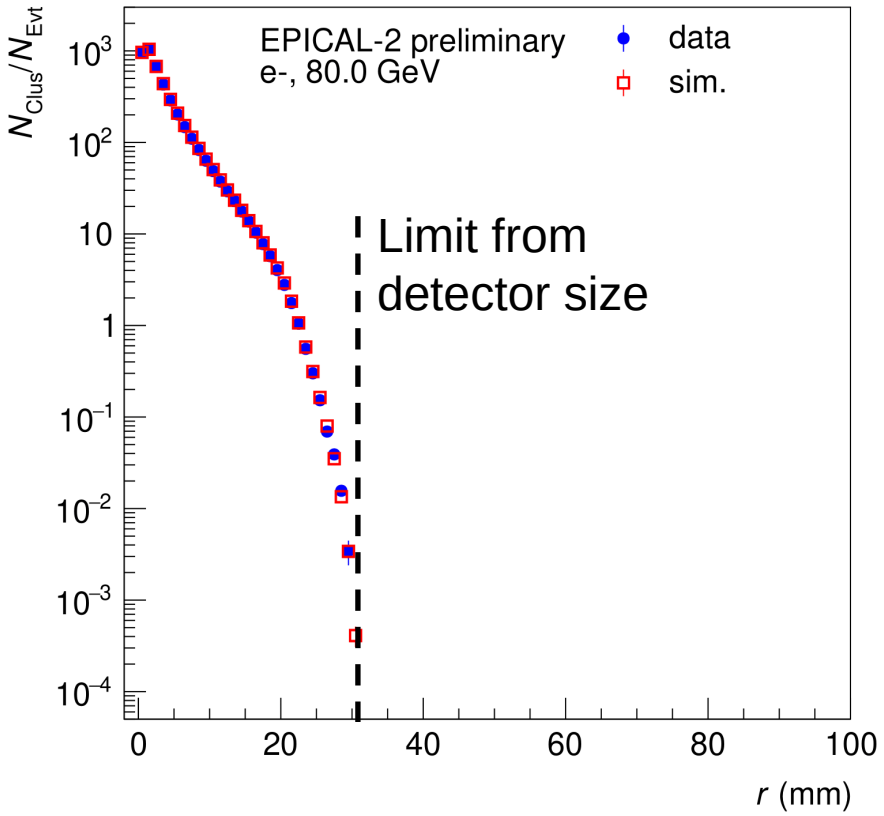
Introduction to Molière Radius Measurement

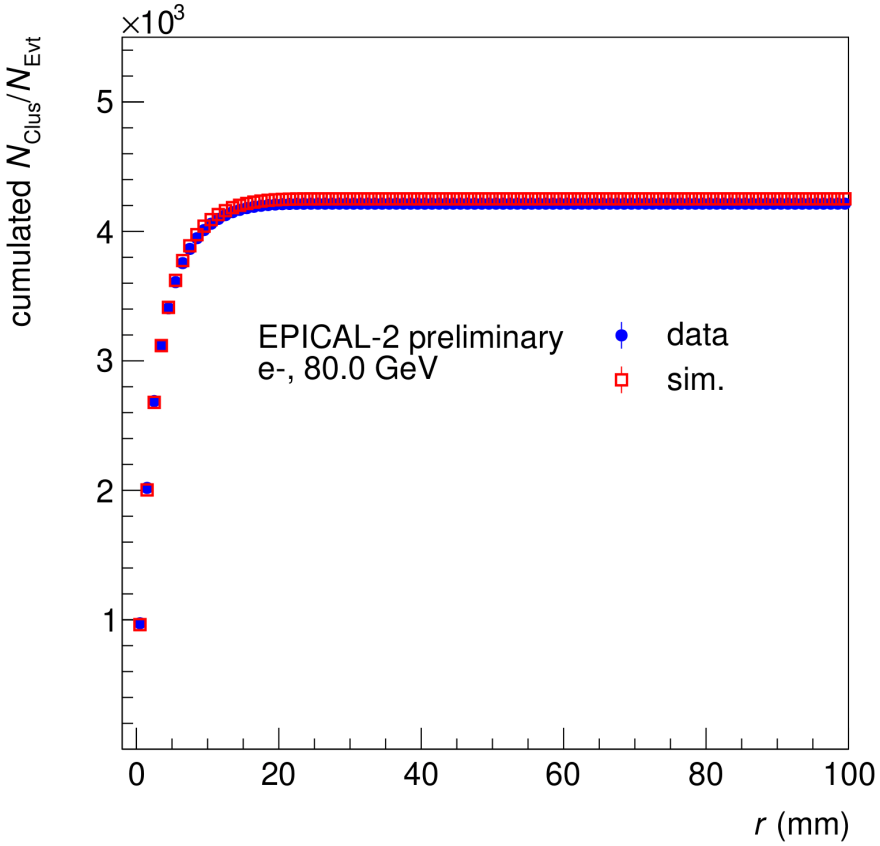


- **Small Molière radius** R_M expected from Si-W design
- Confirmation of small R_M with **measurement**
- Challenge from **small detector** size
- **Correction** with **EPICAL-2 XL** simulation

Lateral $N_{\text{Hit, Clus}}$ Profile

Differential → Integral over *r* → **Cumulated**



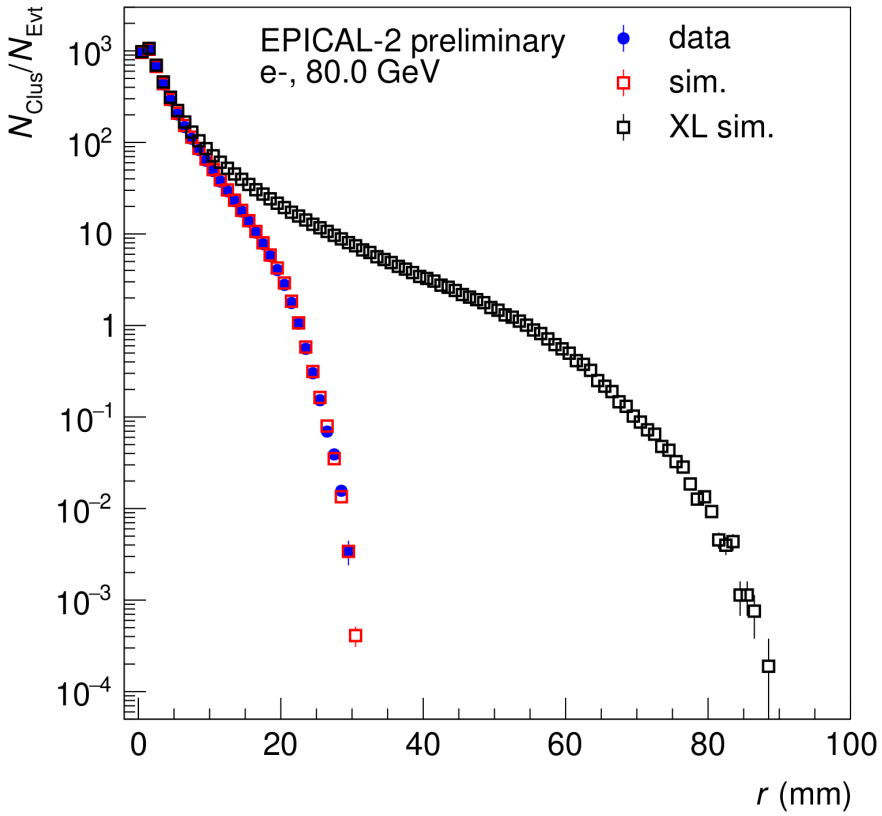


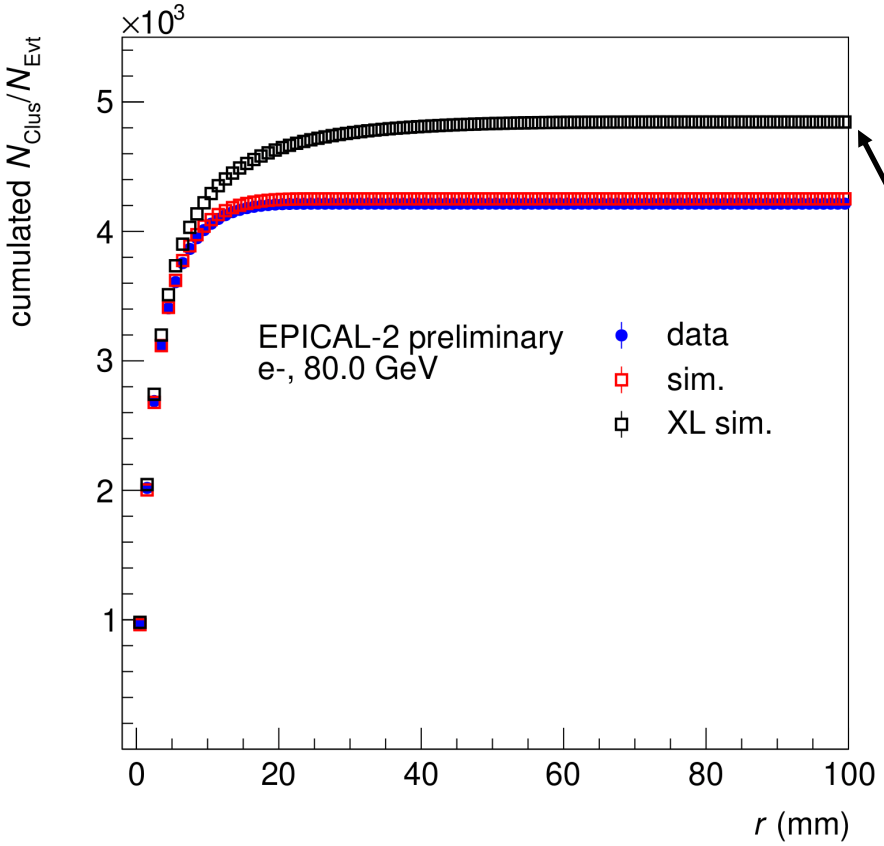
- Lateral $N_{\text{Hit, Clus}}$ profile, **summed** over all **layers**
  - **Differential**
  - **Cumulated** over ***r***

➢ Good **agreement** between data and **simulation**

Lateral $N_{\text{Hit, Clus}}$ Profile

Differential → Integral over r → **Cumulated**





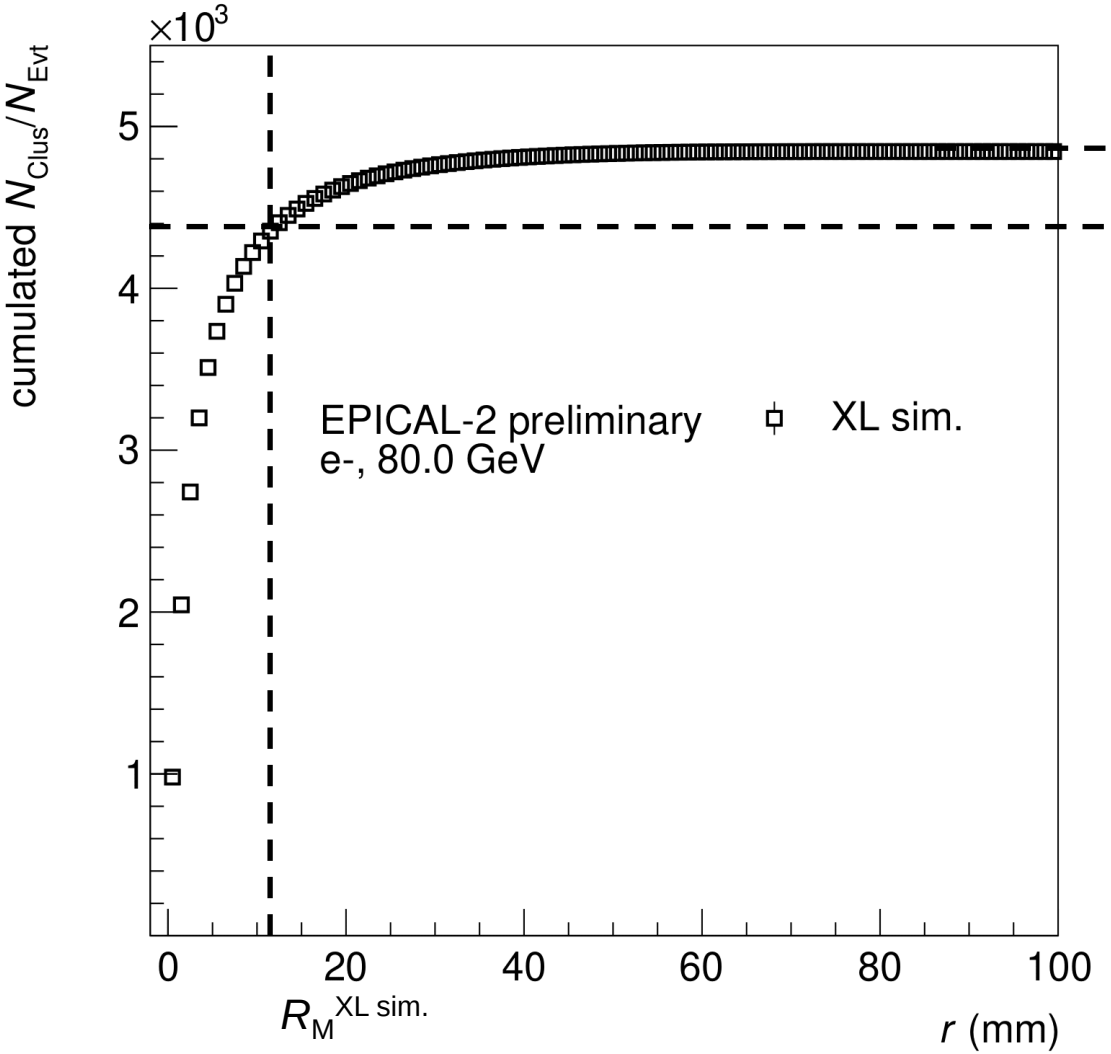
- Lateral $N_{\text{Hit, Clus}}$ profile, **summed** over all **layers**
  - **Differential**
  - **Cumulated** over ***r***

- Good **agreement** between data and **simulation**

XL simulation:

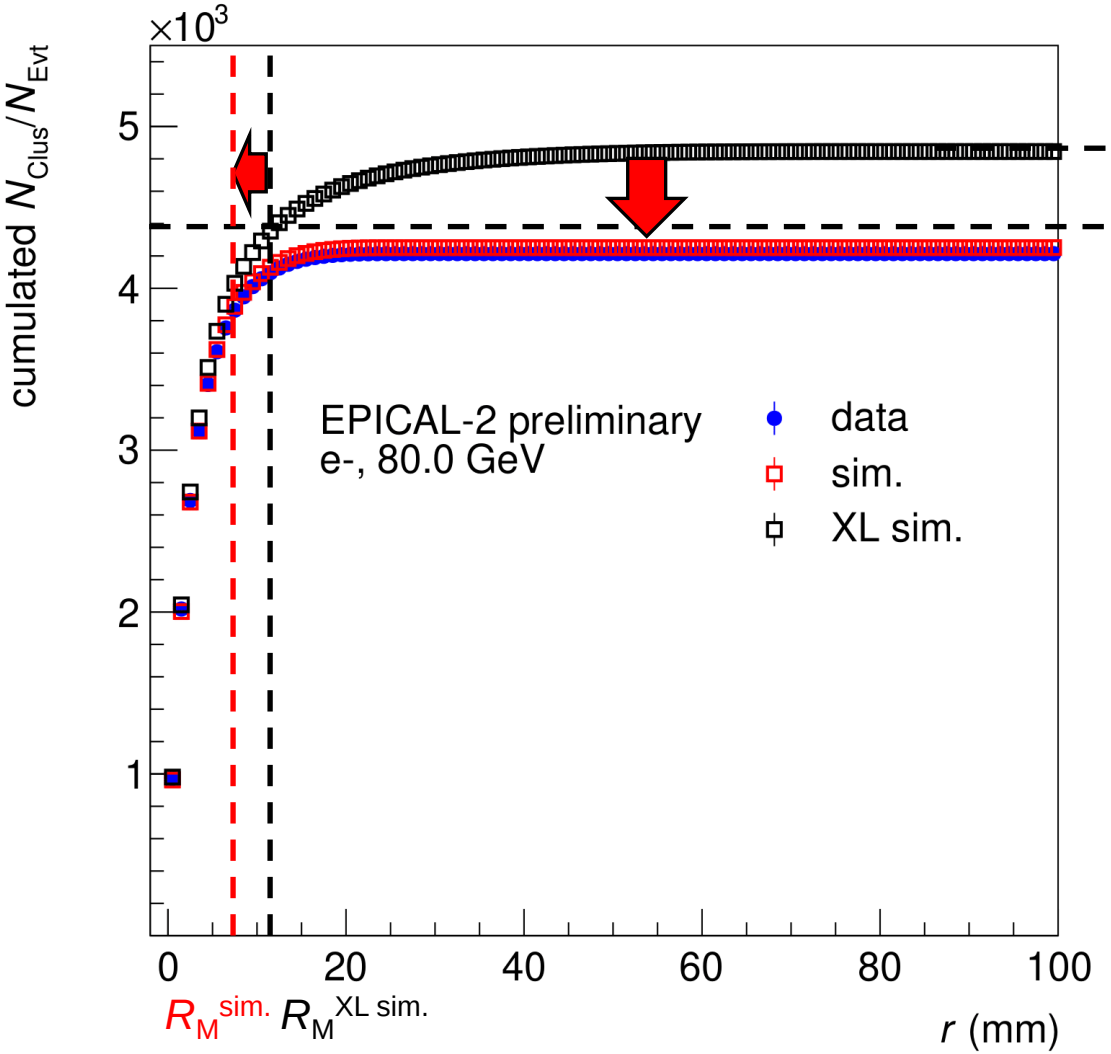
- **Increased size** (4x) of EPICAL-2 in all directions
- **Leakage negligible**
- Used for **correction**

Measurement of the Molière Radius R_M



- R_M: largest r where **cumulated response < 90%** of full response

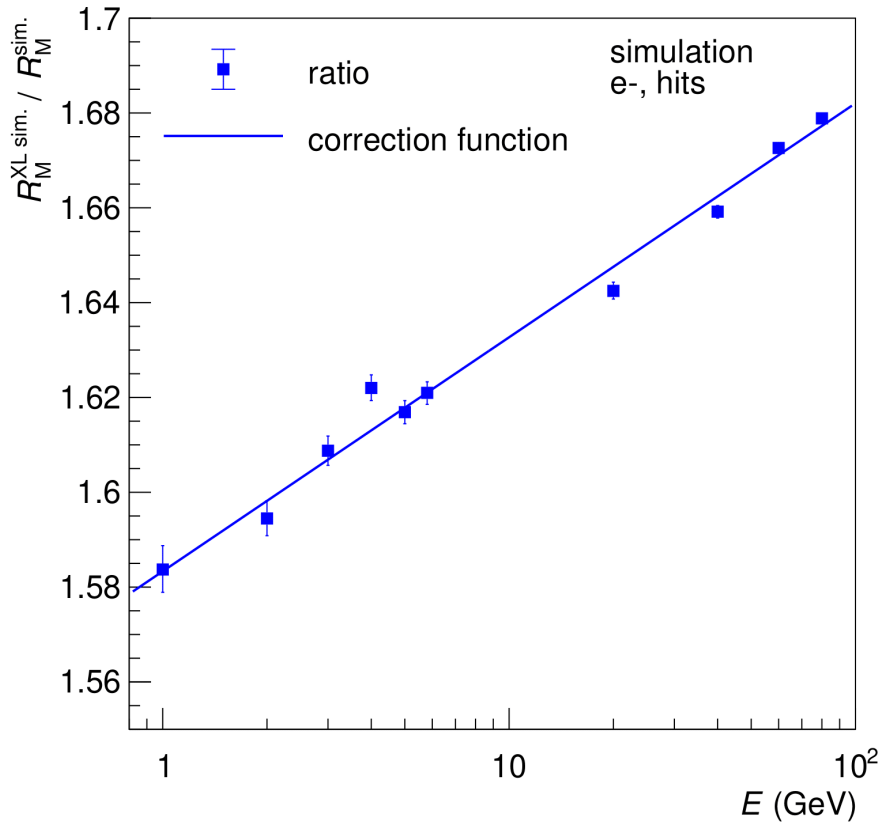
Measurement of the Molière Radius R_M



- R_M: largest r where **cumulated response < 90%** of full response

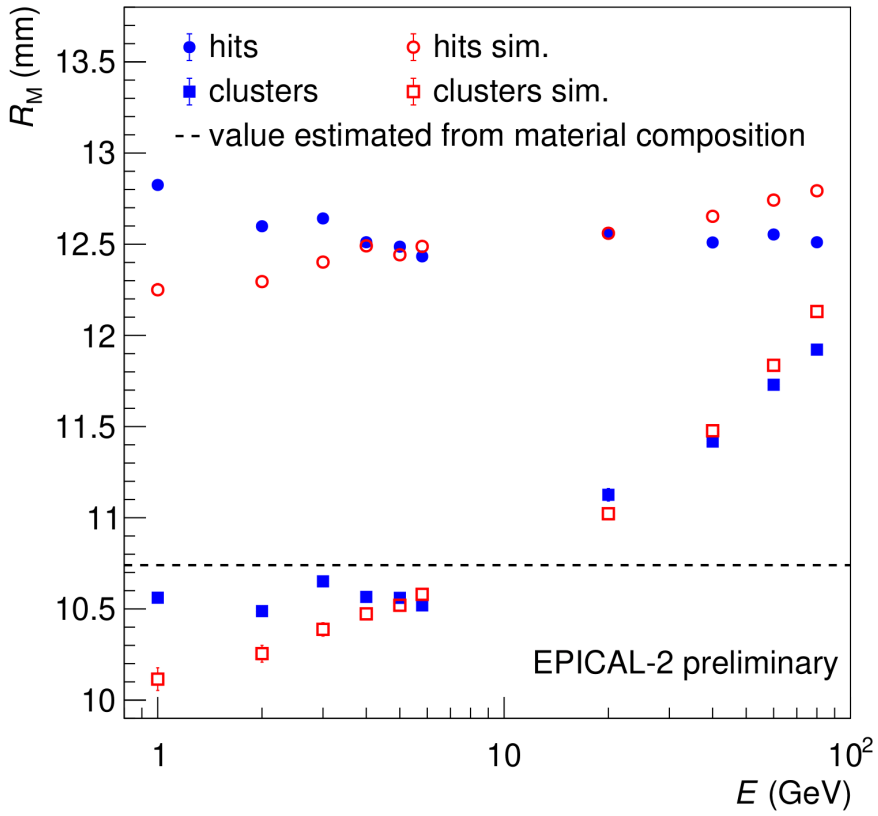
- **Bias on R_M** from limited detector size
- To be **corrected** with **large simulation**

Correction



- Using **ratio** $R_M^{XL\ sim.} / R_M^{sim.}$ for **correction**
- **Parametrization** with correction function
- **Multiplication of R_M** in data with correction function to correct for limited detector size

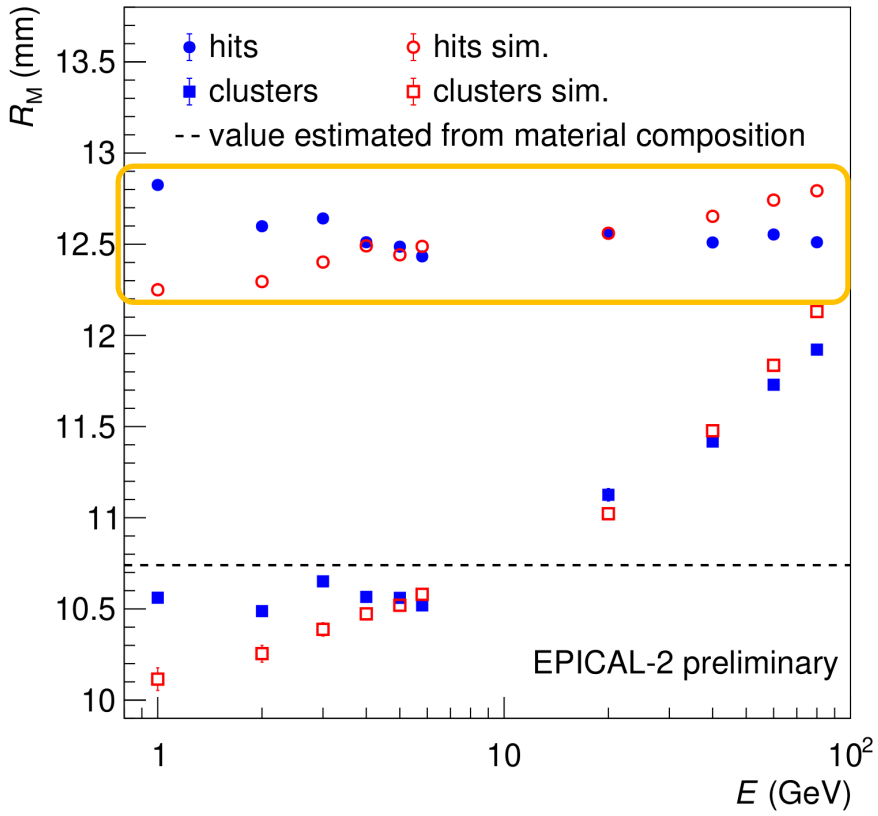
Measured R_M



Simulation:

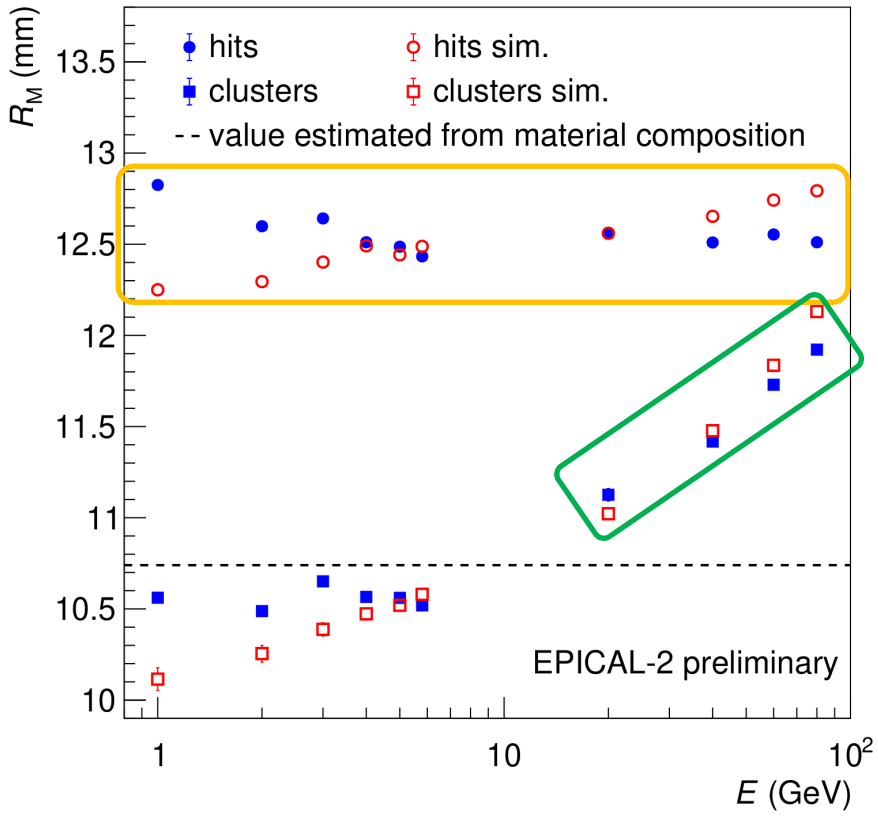
- **Underestimates** R_M for small E
- **Overestimates** R_M for large E

Measured R_M



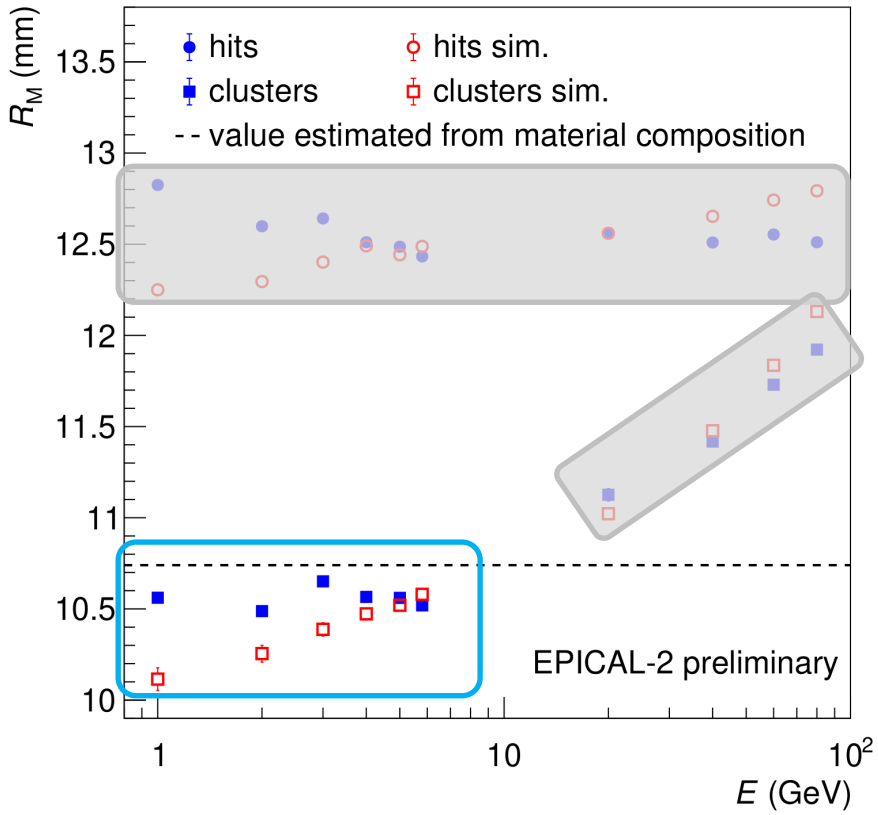
- **Measurement influenced** by two effects:
  1. **Hits:** shower particles' **angle of incident**
     - **Large *r***

Measured R_M



- **Measurement influenced** by two effects:
  1. **Hits:** shower particles' **angle of incident**
     - **Large *r***
  2. **Clusters: cluster merging**
     - **Small *r***
     - **Large *E***
- Effects lead to **overestimation** of R_M

Measured R_M



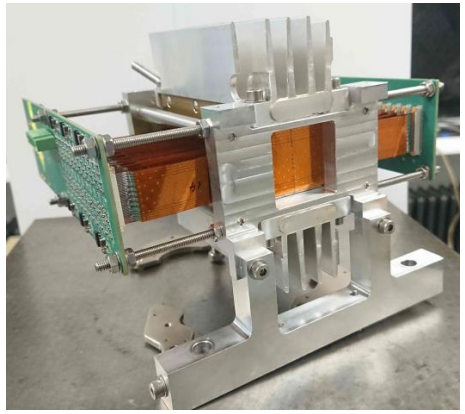
- **Measurement influenced** by two effects:
  1. **Hits:** shower particles' **angle of incident**
     - **Large *r***
  2. **Clusters: cluster merging**
     - **Small *r***
     - **Large *E***
  - Effects lead to **overestimation** of R_M
- R_M at ***E* ≤ 5.8 GeV** for **clusters unaffected** by both effects

➢ **Measured R_M close to expected R_M**

Summary

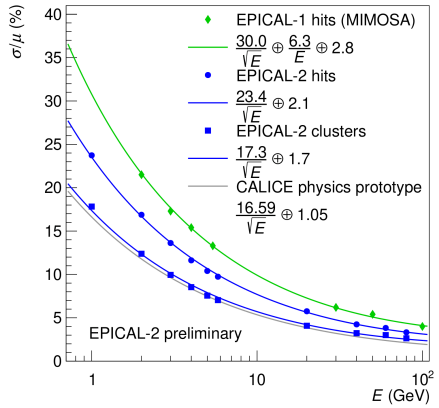
EPICAL-2:

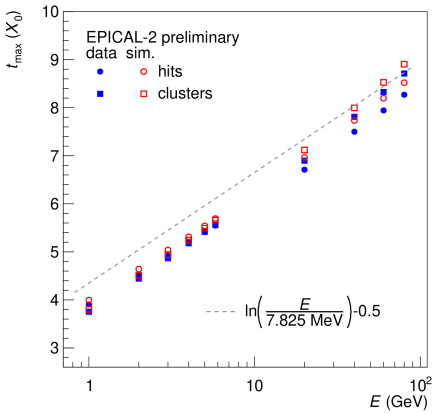
- High granular digital pixel calorimeter
- Silicon MAPS + tungsten absorber
- ≈ 29 x 27 μm² pixels



Performance:

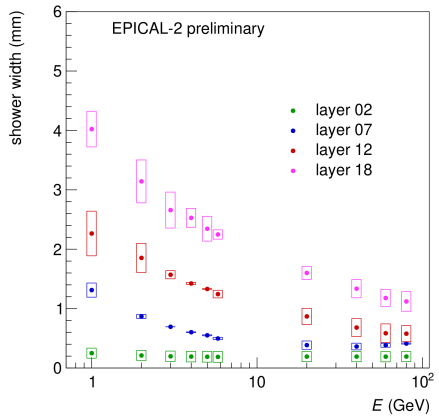
➢ **Good linearity and resolution**





Shower shape:

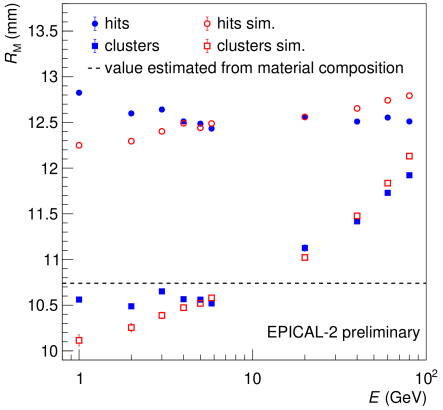
➢ Shower width in order of few mm



Molière radius:

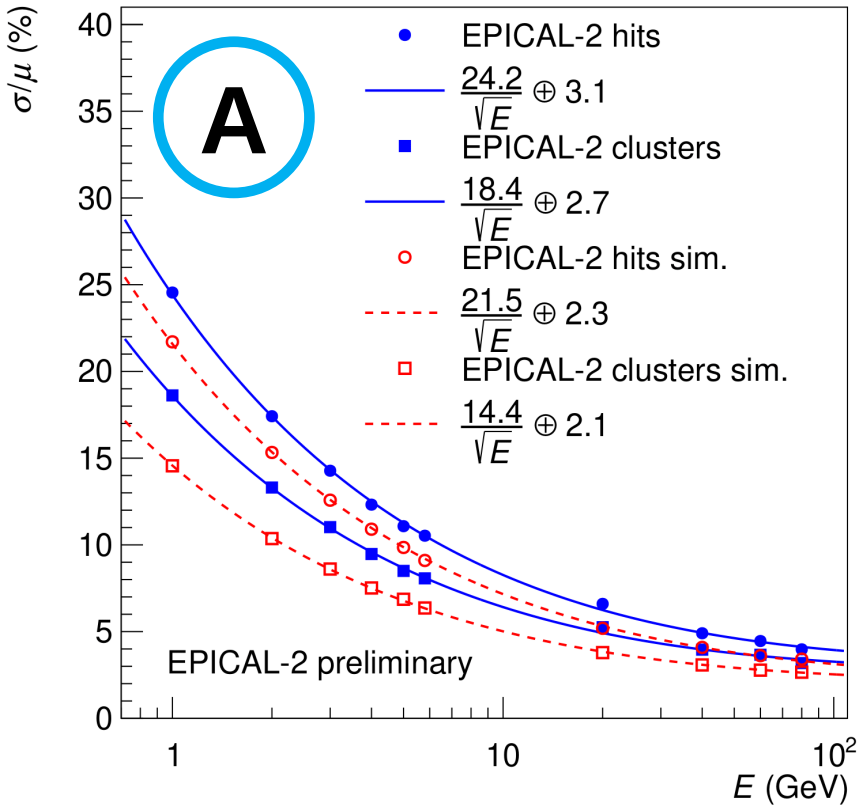
➢ Small Molière radius, as expected

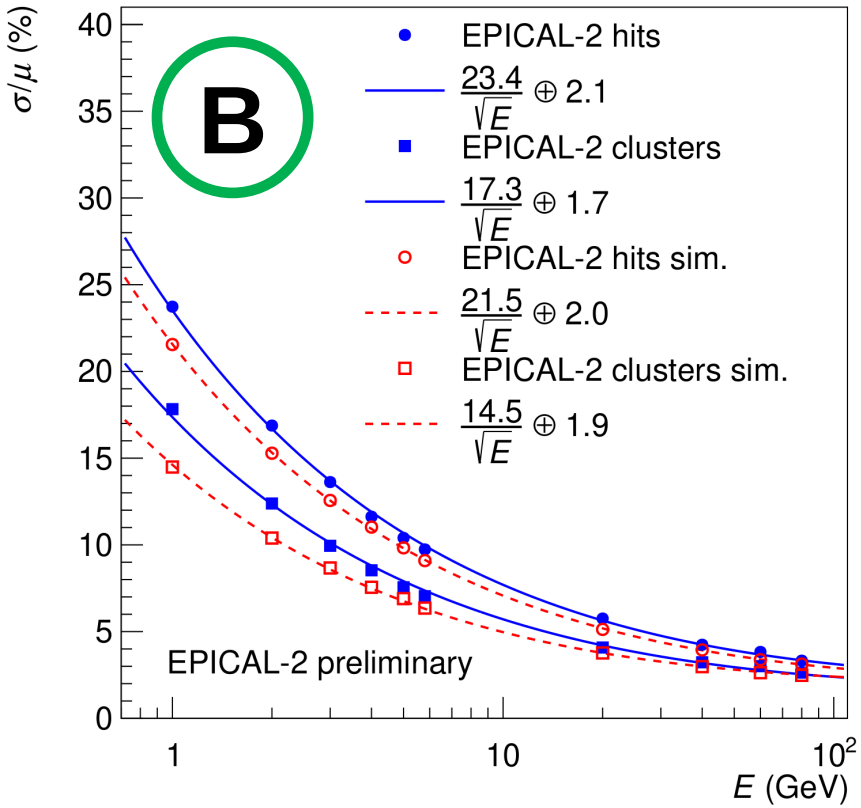
Strong shower separation power



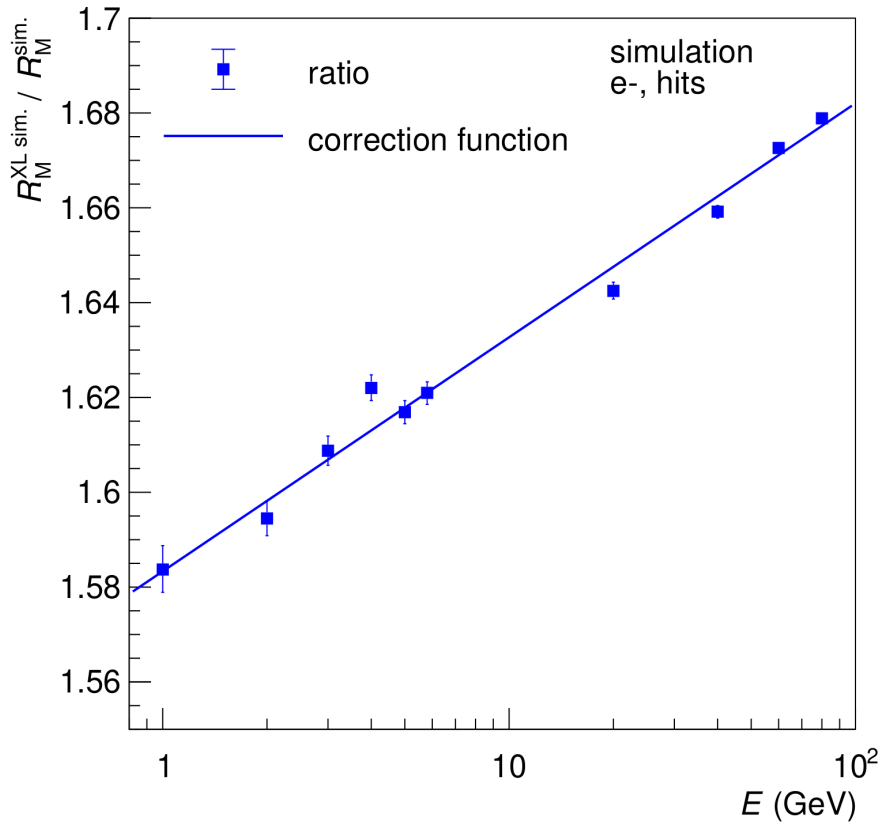
Backup

Resolution


A
EPICAL-2 hits
$\frac{24.2}{\sqrt{E}} \oplus 3.1$
EPICAL-2 clusters
$\frac{18.4}{\sqrt{E}} \oplus 2.7$
EPICAL-2 hits sim.
$\frac{21.5}{\sqrt{E}} \oplus 2.3$
EPICAL-2 clusters sim.
$\frac{14.4}{\sqrt{E}} \oplus 2.1$
EPICAL-2 preliminary
σ/μ (%)
E (GeV)


B
EPICAL-2 hits
$\frac{23.4}{\sqrt{E}} \oplus 2.1$
EPICAL-2 clusters
$\frac{17.3}{\sqrt{E}} \oplus 1.7$
EPICAL-2 hits sim.
$\frac{21.5}{\sqrt{E}} \oplus 2.0$
EPICAL-2 clusters sim.
$\frac{14.5}{\sqrt{E}} \oplus 1.9$
EPICAL-2 preliminary
σ/μ (%)
E (GeV)

Correction



- Using **ratio** $R_M^{XL\ sim.} / R_M^{sim.}$ for **correction**
- **Parametrization** with correction function

$$f(E) = a * \ln\left(\frac{E}{1\mathrm{GeV}}\right) + b$$

- **Multiplication of R_M** in data with correction function to correct for limited detector size