Utrecht University

Nikhef

Ultra-high granularity electromagnetic calorimetry – Results from the EPICAL-2 prototype and perspectives for digital calorimeters

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for the EPICAL-2 team

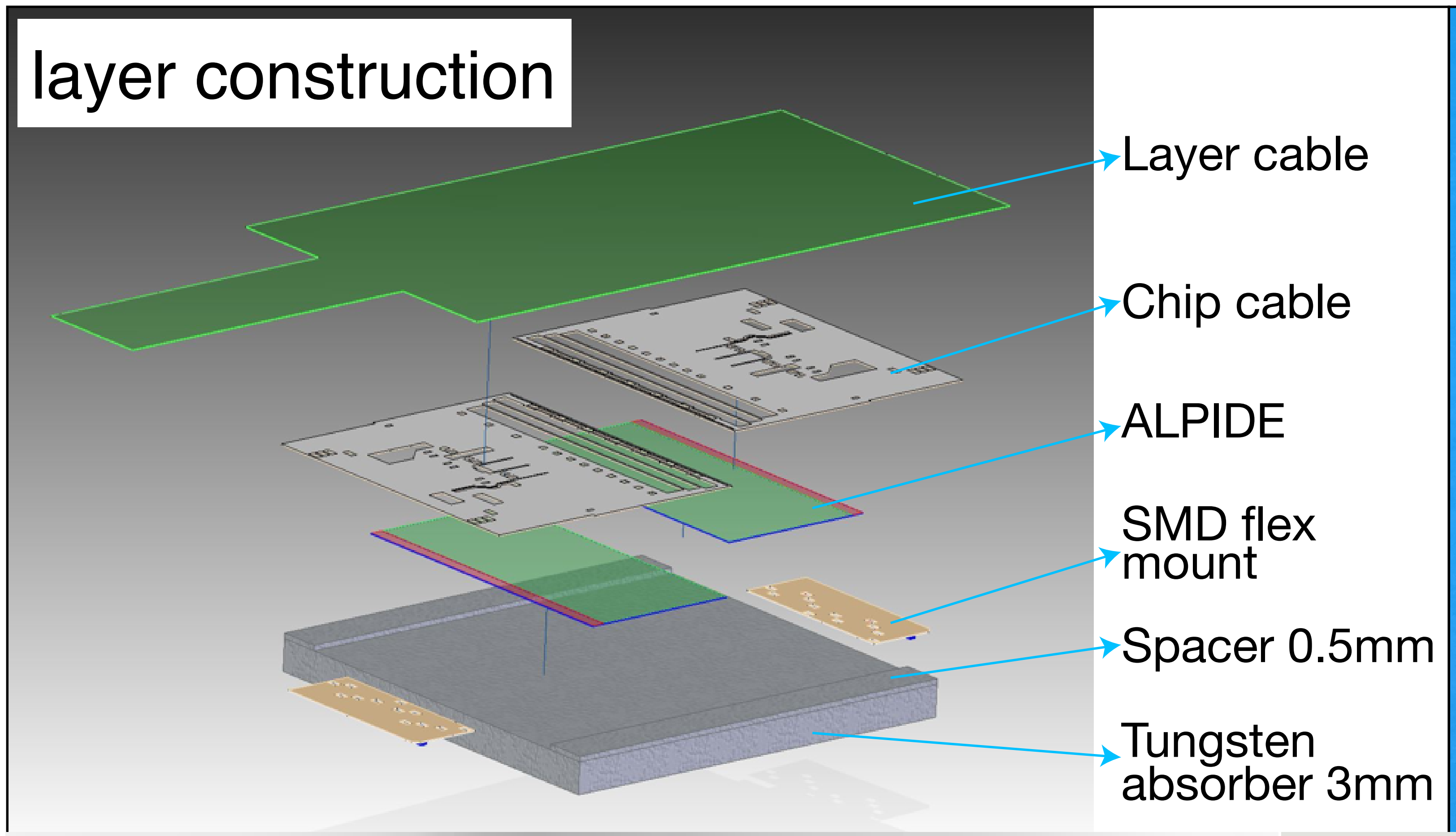
CALOR2024, 20th International Conference
on Calorimetry in Particle Physics

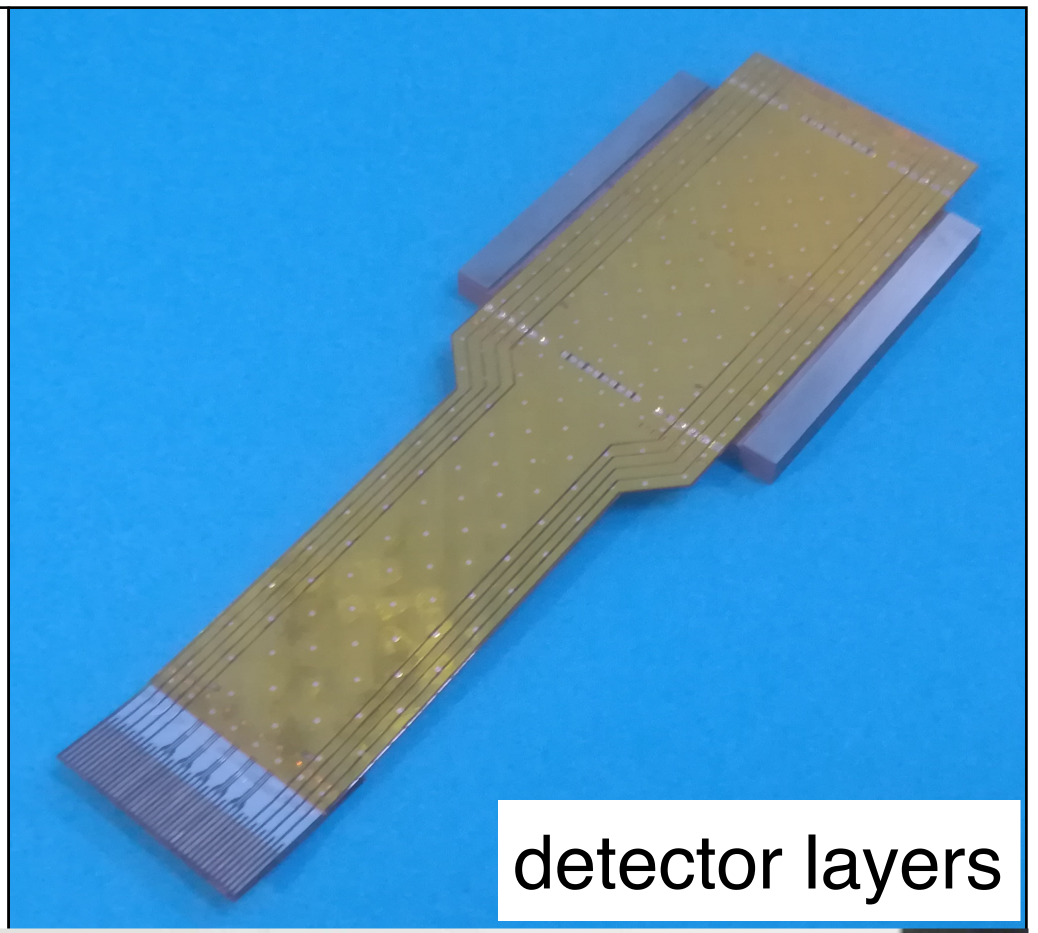
Tsukuba, Japan, 22/05/2024

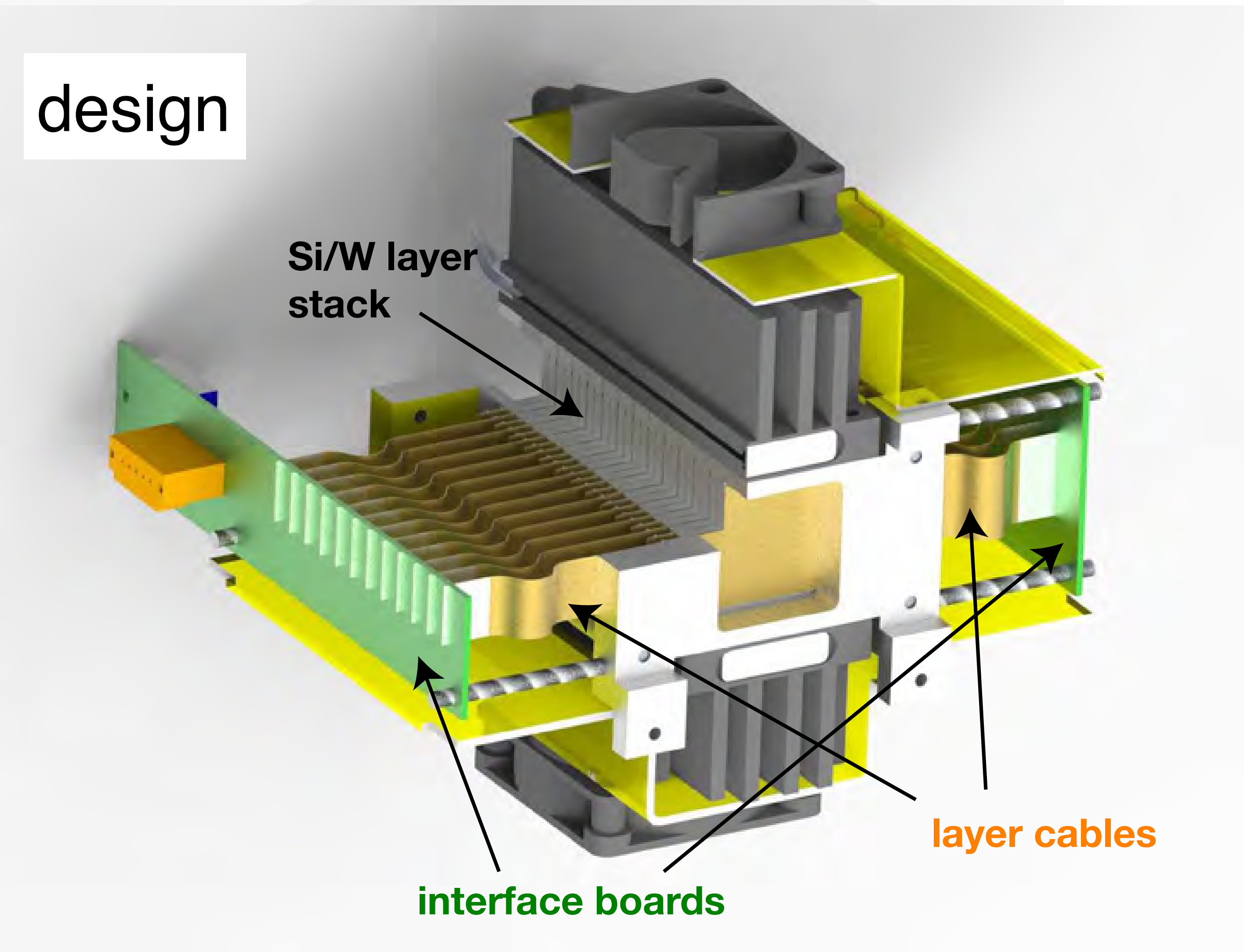
Introduction

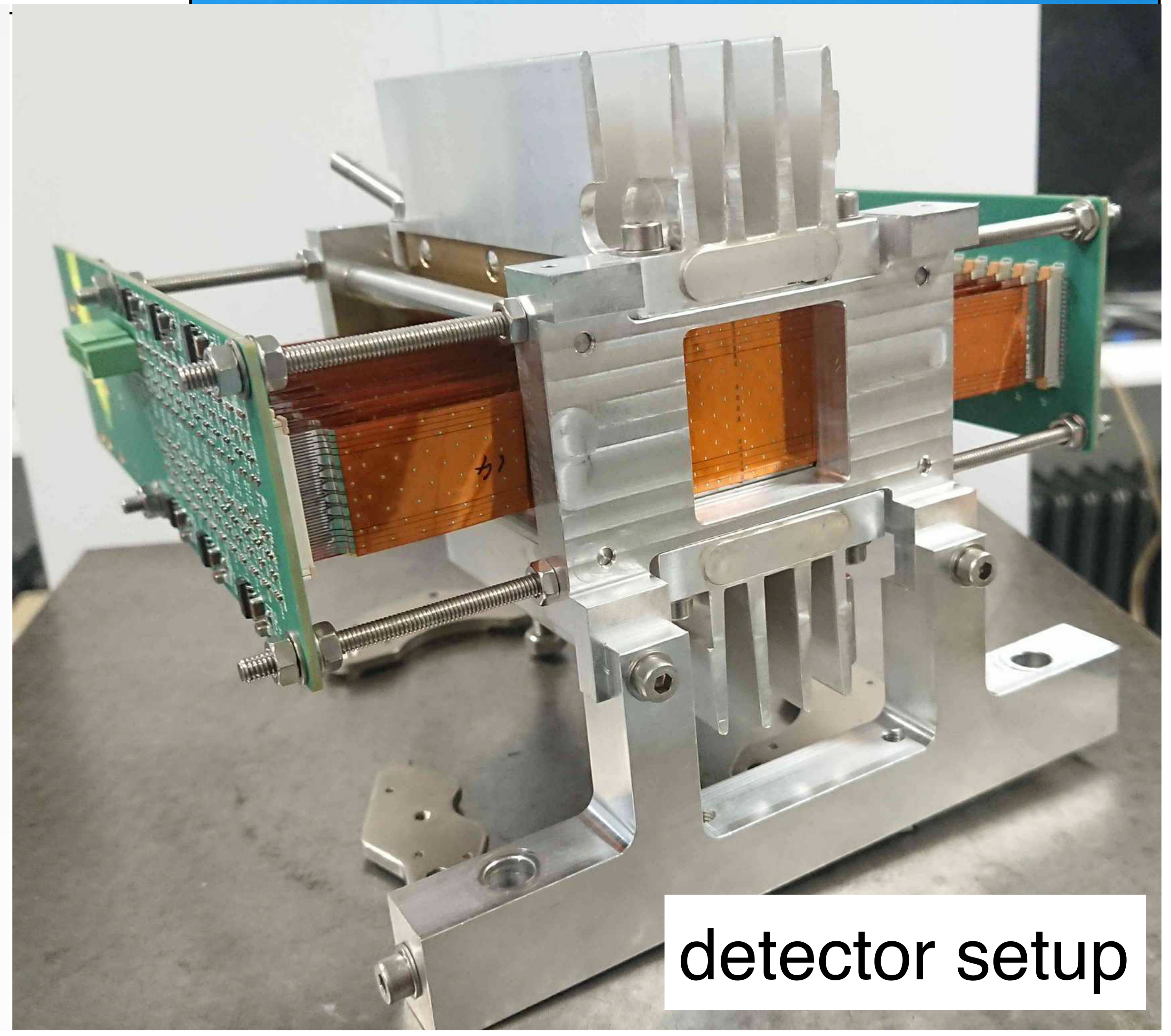
- Digital calorimetry: count number of charged shower particles in sampling layers
  - Ideally: potential to reduce fluctuations from individual sampling layers
  - High granularity required due to high particle density
- State-of-the-art all-pixel calorimeter prototype
  - Follow up on proof of principle EPICAL-1 (JINST 13 (2018) P01014)
  - EPICAL-2: Si/W stack using ALPIDE sensors, detailed simulation in Allpix^2
- Main Motivation:
  - R&D for pixel technology for ALICE FoCal
  - Demonstrate potential of digital pixel EMCal beyond
  - Provide unique shower data to MC developers
- Performance results from test-beam measurements (DESY and SPS)
  - First results at low energy published (JINST 18 (2023) P01038)
  - Update on energy linearity and resolution
  - First studies of shower shape

Digital Calorimeter Prototype – EPICAL-2







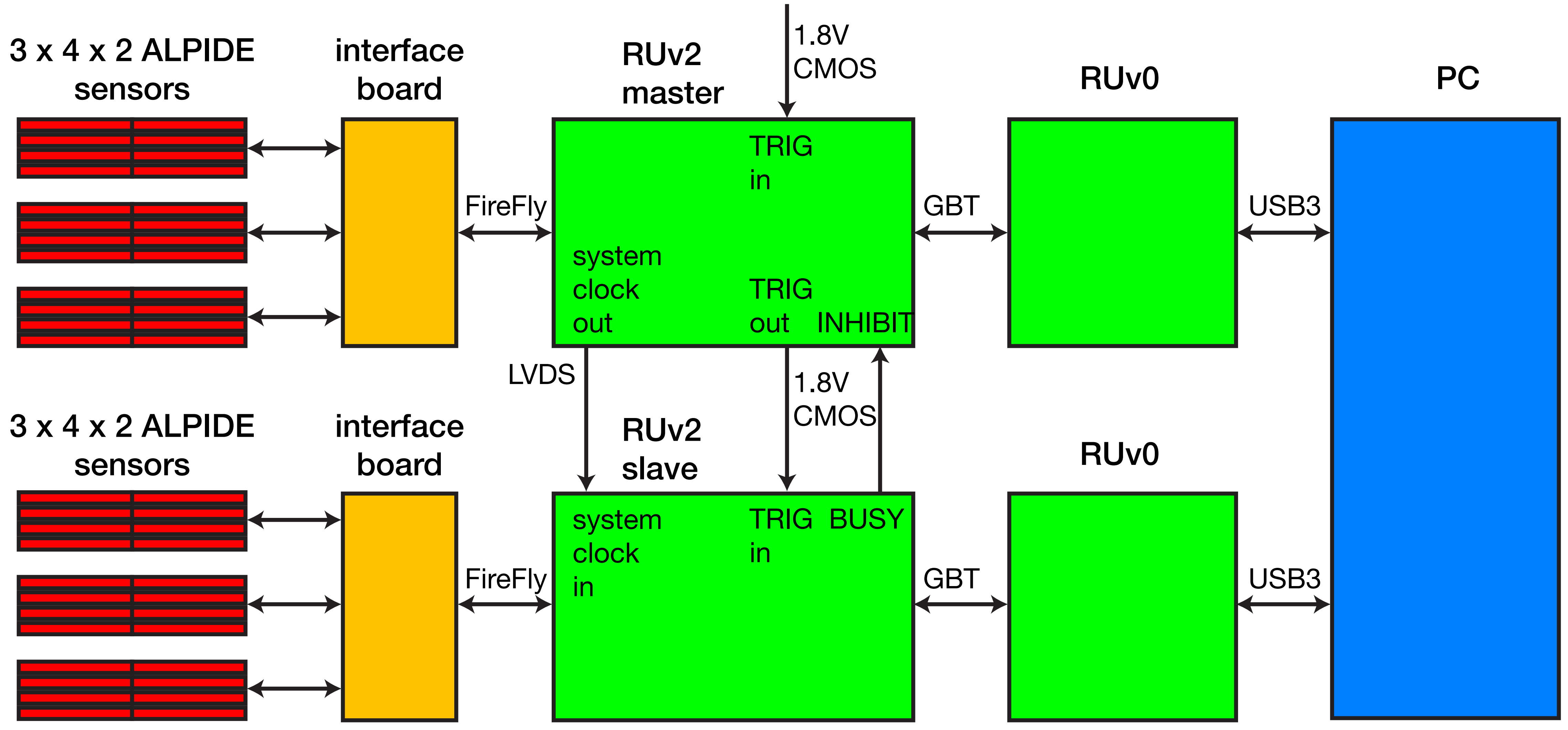


24 layers with each
- 3 mm W absorber (≈ 0.857 X_0)
- 2 ALPIDE CMOS sensors
  - NIM A, 845:583–587, 2017
- ultra-thin flex cables (LTU Kharkiv)

29.24 x 26.88 μm^2 pixel size
active cross section 3 x 3 cm^2

compact design: expect R_M ≈ 11 mm

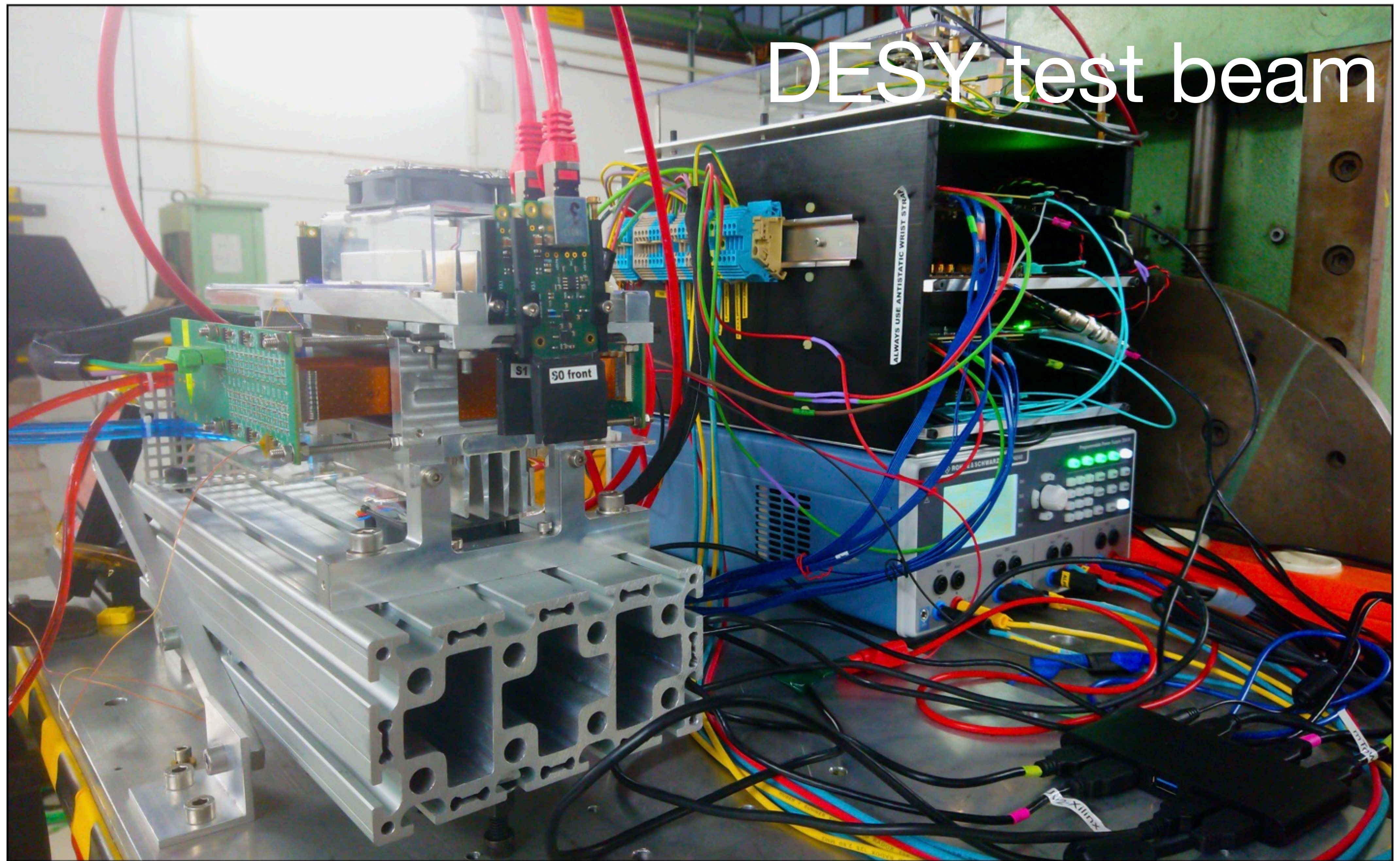
readout schematics

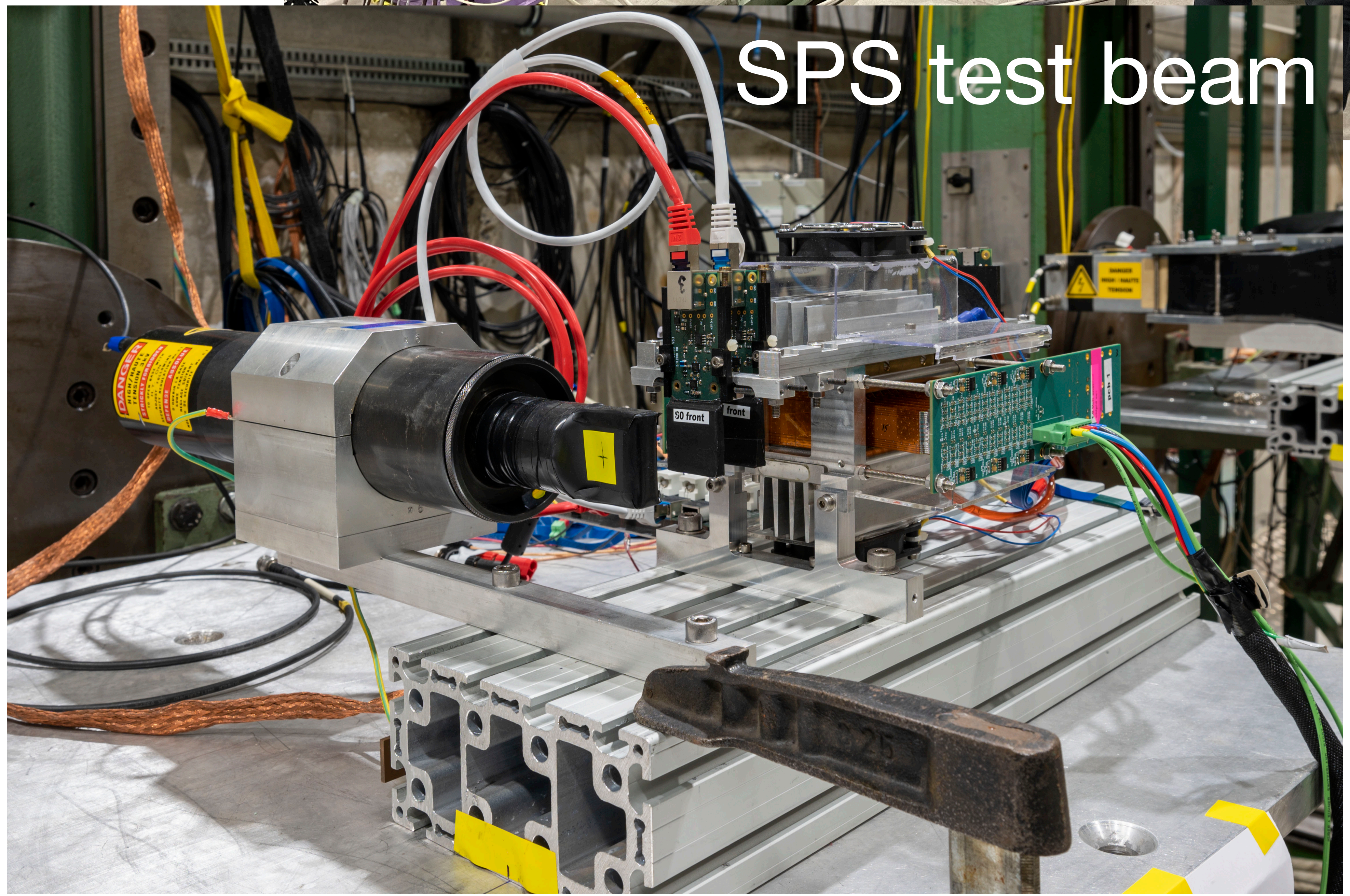


ALPIDE output via 1.2 Gb/s serial line
readout via 2 levels of FPGA

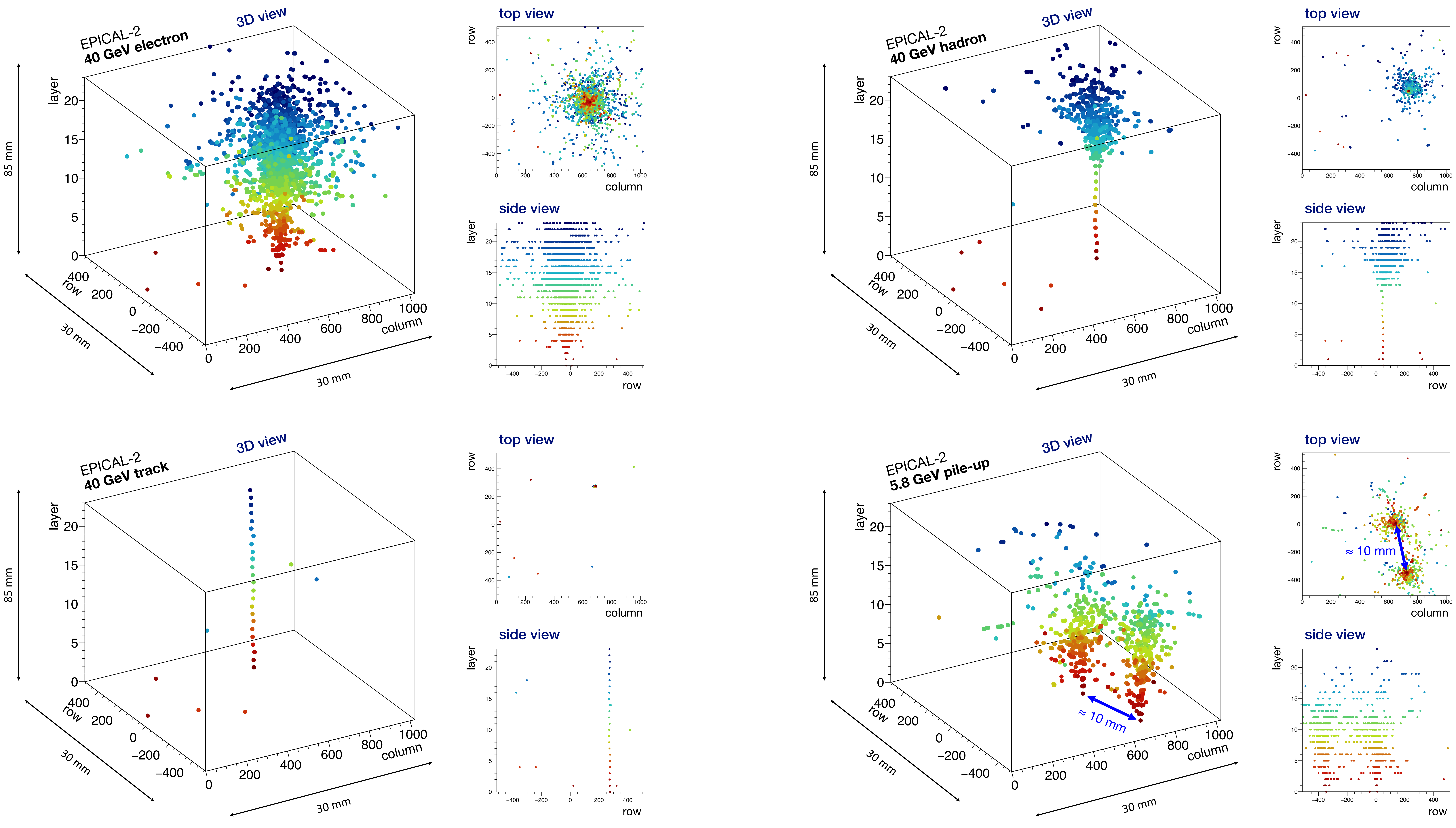
EPICAL-2 Measurements

- Cosmic muons (Utrecht University, 2020)
- Test beam DESY (Feb. 2020)
  - Electron/positron, E = 1.0 - 5.8 GeV
- H6 test beam SPS (Sept./Oct. 2021)
  - Mixed beam, E = 20 - 80 GeV

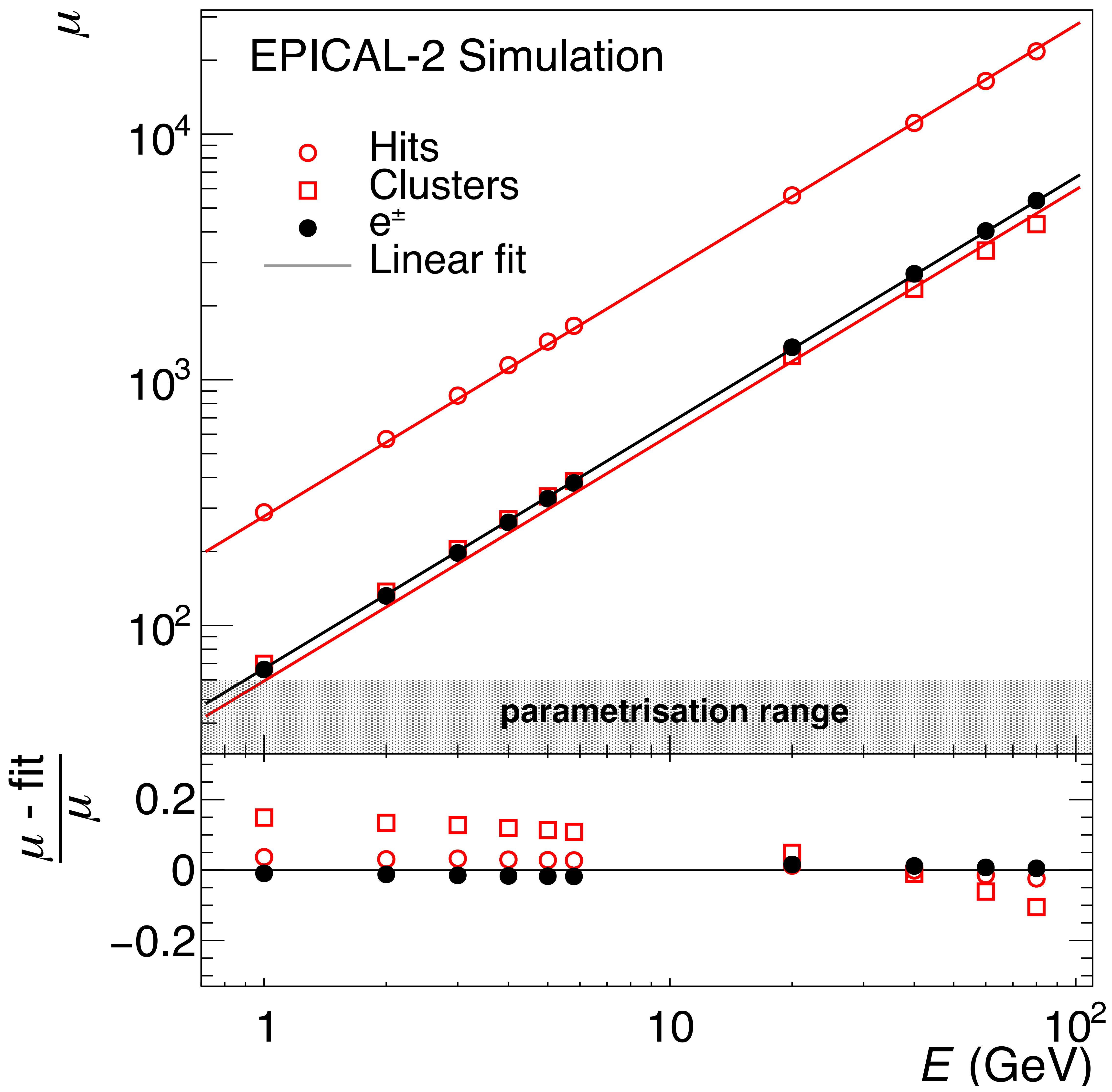




EPICAL-2 Event Displays

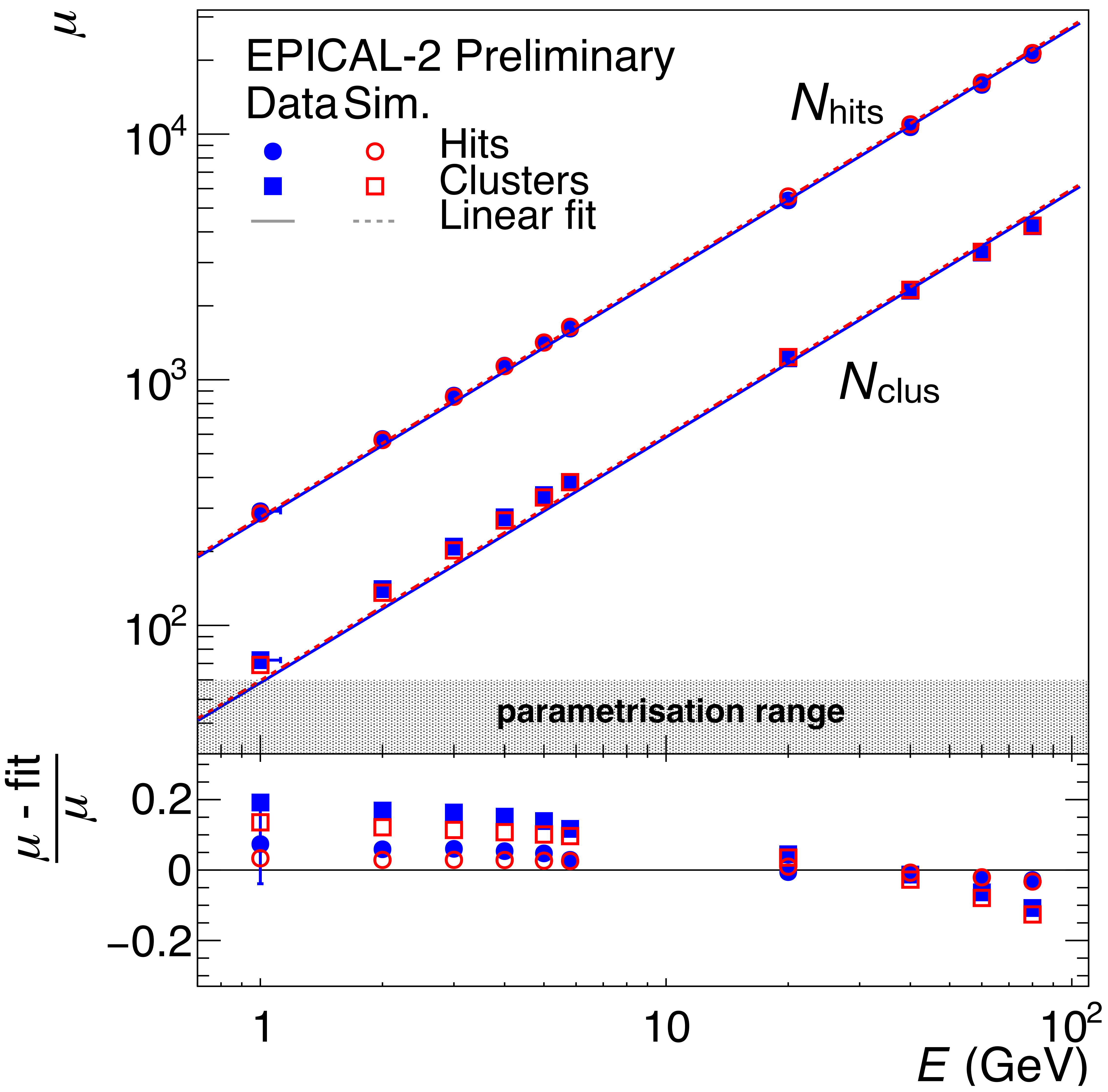


Linearity of Response



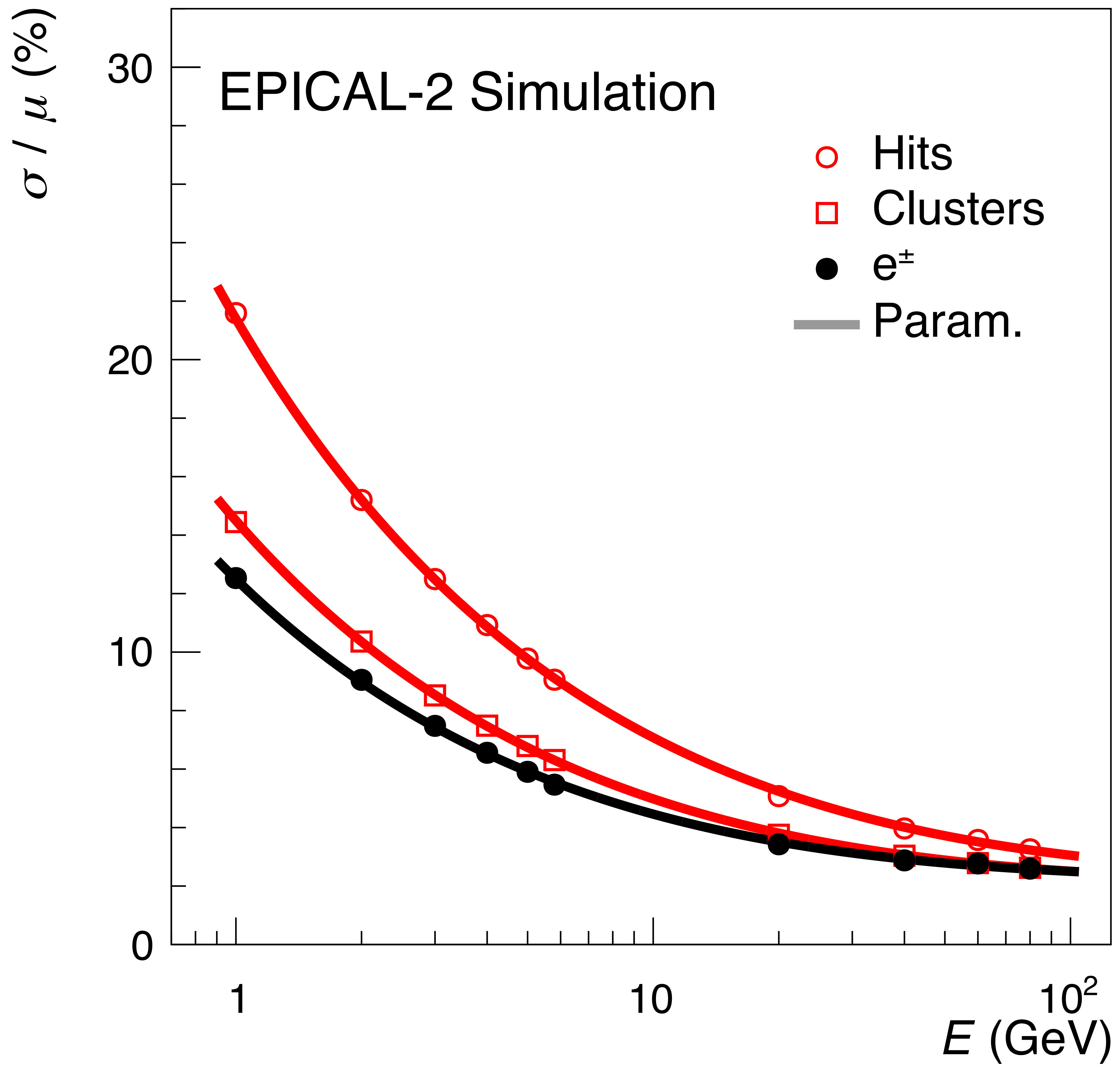
- Average response as a function of beam energy from MC simulation
- Alternative response variables:
  - Number of $e^{\pm}$ traversing sensors
    - Ideal measure: very good linearity
  - Number of clusters N_{clus}
    - Close to ideal number of $e^{\pm}$
    - Significant non-linearity, saturation most likely due to cluster overlap
  - Number of hits N_{hits}
    - Larger values due to cluster size
    - Small non-linearity, saturation due to hit overlap less relevant

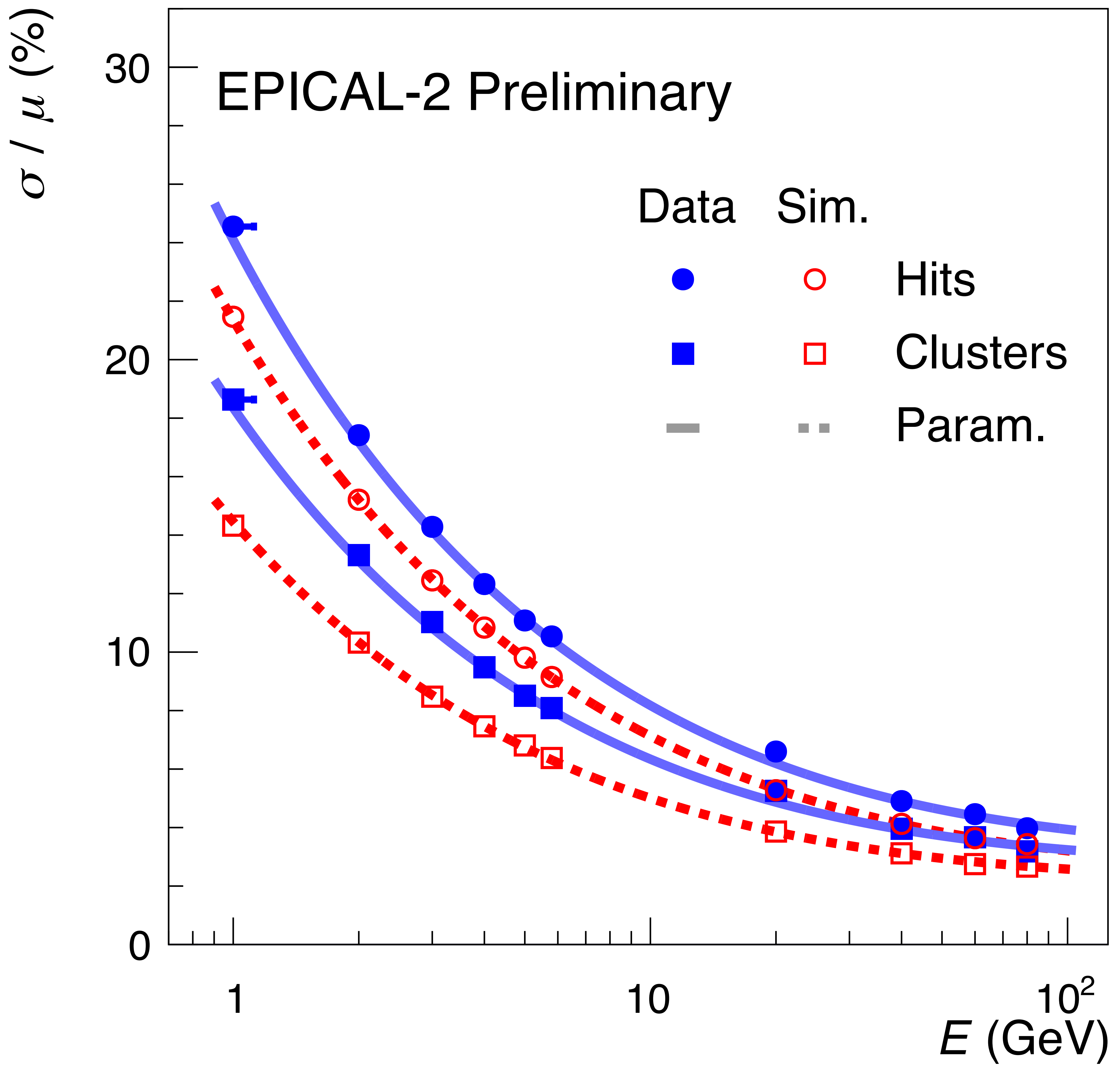
Measured Energy Linearity



- Average response as a function of beam energy
- Qualitative behaviour of data reproduced by simulation: similar difference between clusters and hits
- Slightly stronger non-linearity in data
    - Seen in both clusters and hits
    - Apparent non-linearity influenced by uncertainty in DESY beam energy
- Good linearity for N_{hits}

Energy Resolution

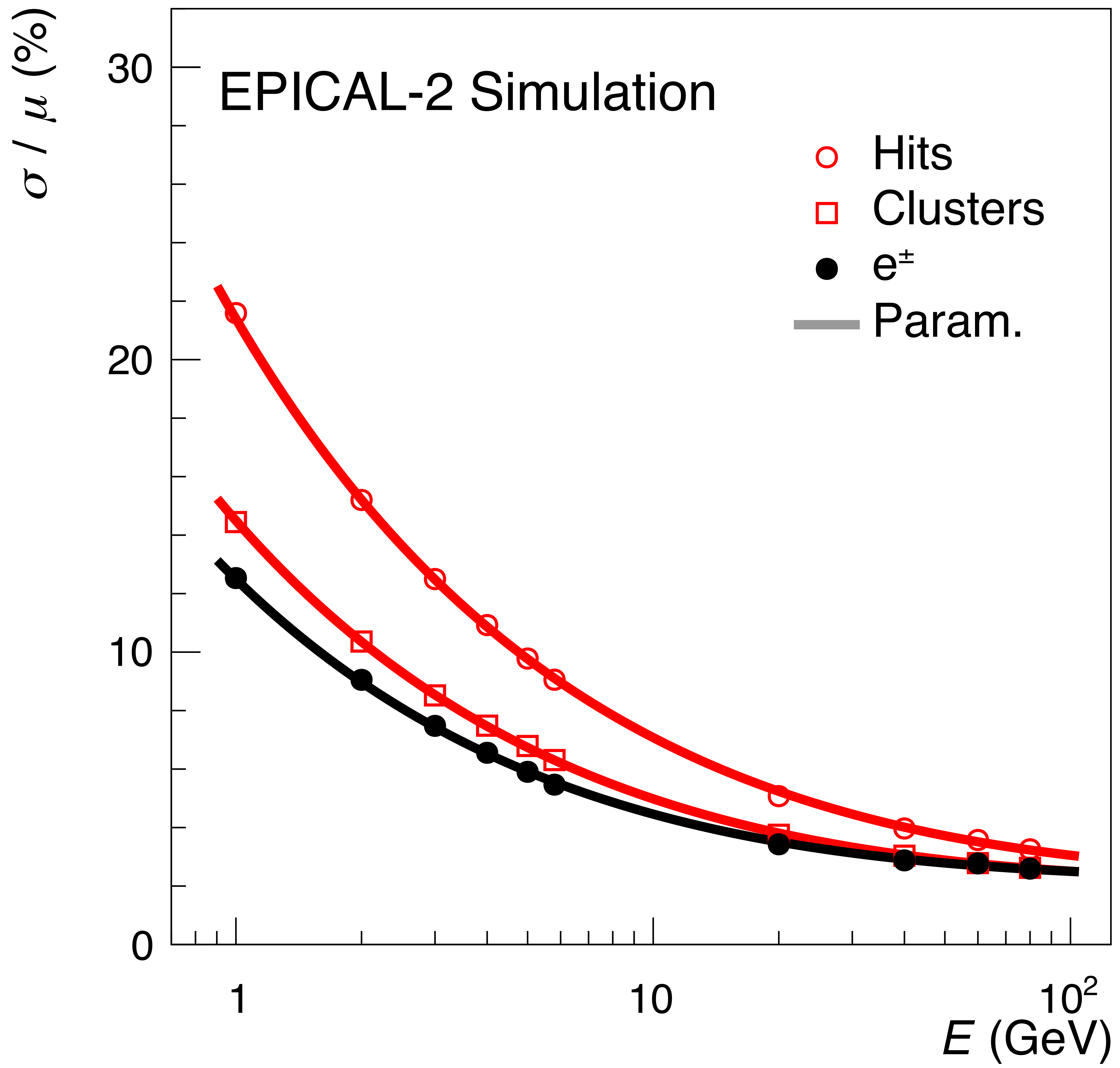


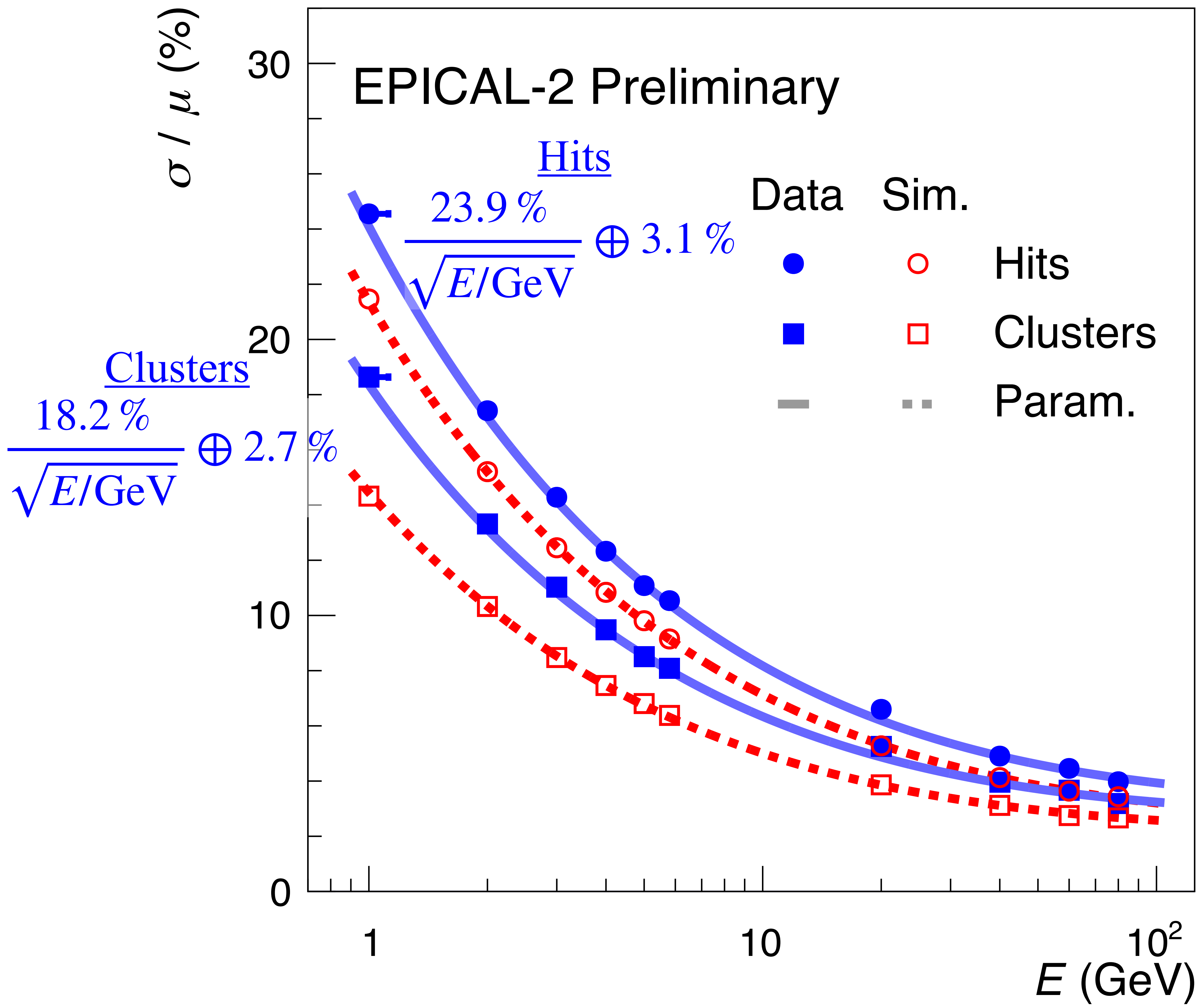


- Resolution shows expected behaviour
- Superior performance for "particle counting" $\sigma(N_{\text{clus}}) \approx \sigma(N_{\text{e}})$

- Experimental data show slightly worse resolution
  - Partially due to contribution from test beam energy spread
- Resolution comparable to state of the art

Energy Resolution





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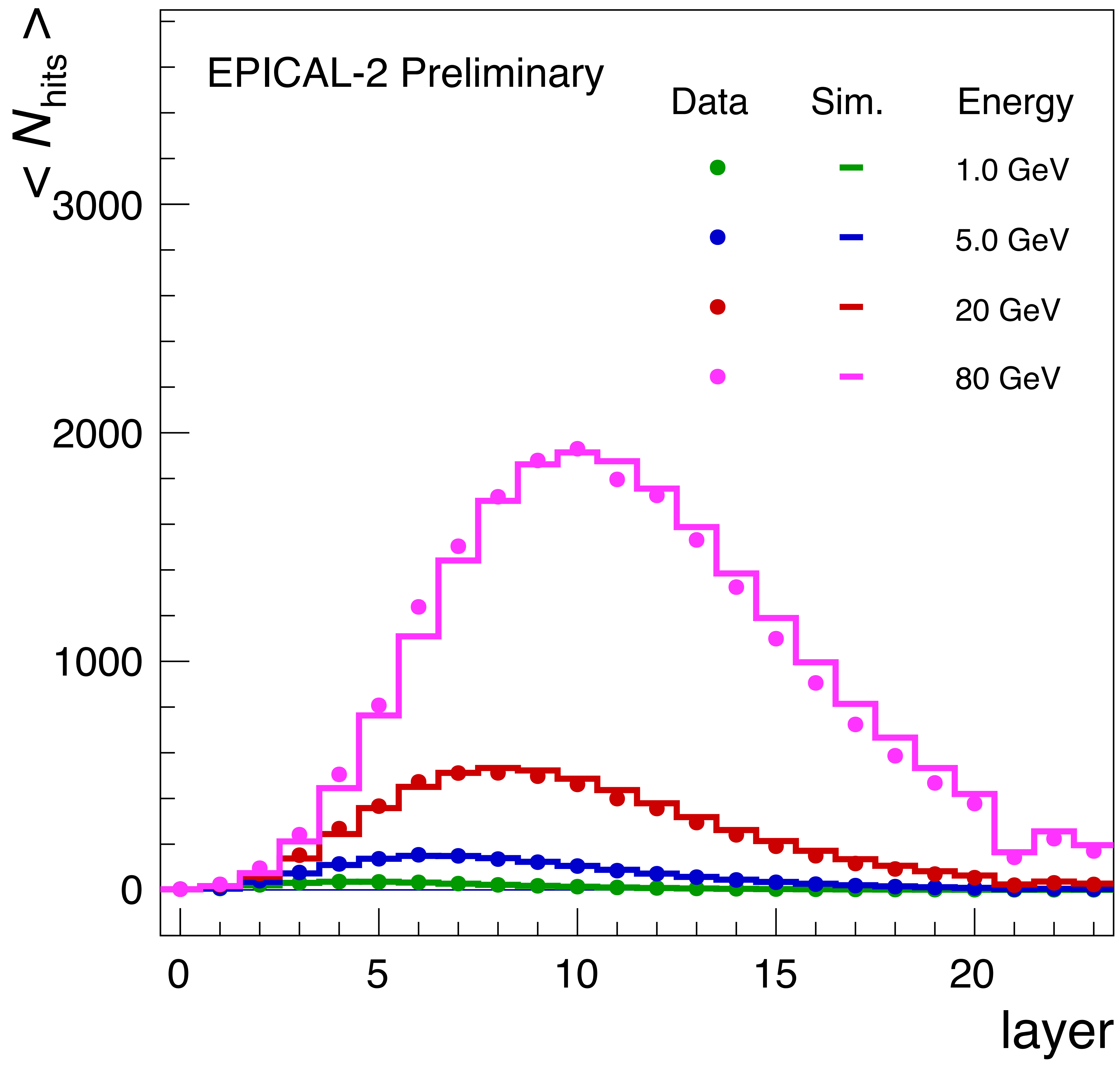
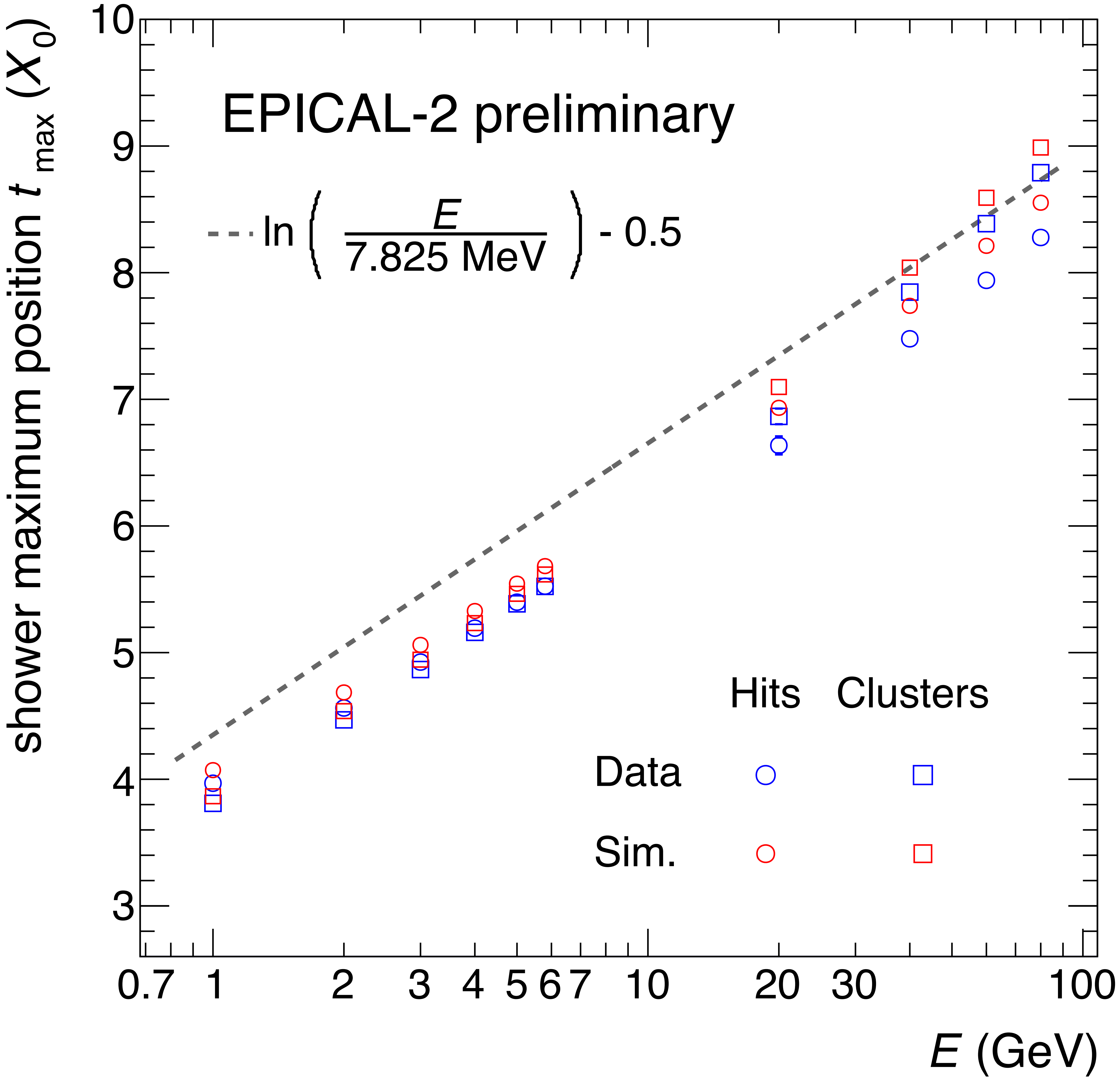
Longitudinal Shower Profiles



- Average response (N_{hits}) as a function of depth
  - Each layer equivalent to 85.7% X_0
- Similar for N_{clus}
- Qualitatively well described by simulation
  - Small differences: deeper shower in simulations

Shower Maximum

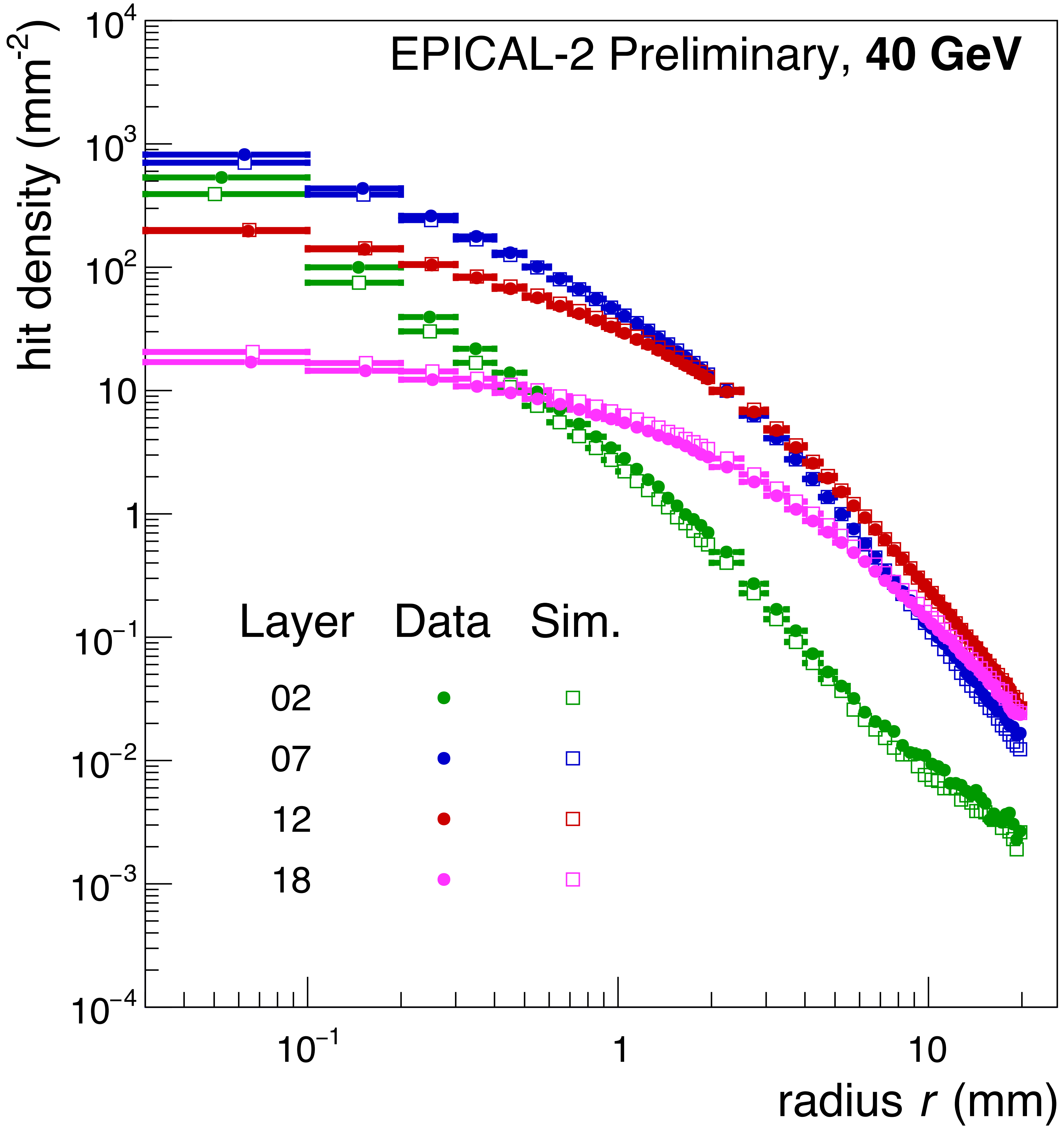


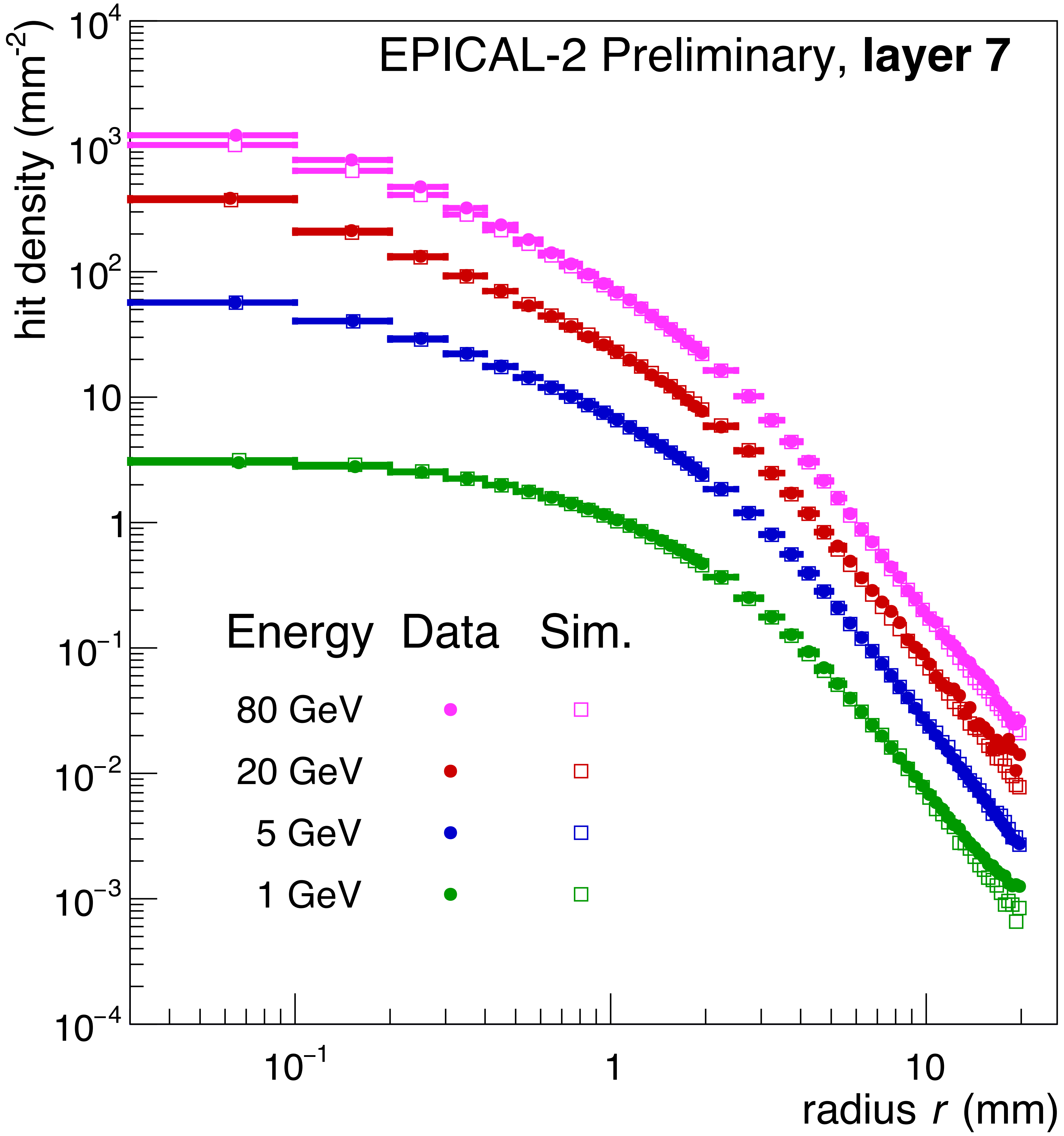
- Shower maximum $t_{\max}$ obtained from fits of Γ distribution
- Depth increases with $\approx \ln E$
  - In most cases, $t_{\max}$ smaller than literature estimate

$$\ln\left(E/E_c\right) - 0.5$$

- Deeper maximum for hits vs clusters at low energy, reversed at high energy
  - Most likely subtle interplay of cluster size and saturation for varying depth
  - Significant bias from saturation for clusters
- Deeper maximum for simulation, but qualitative features described

Lateral Shower Profiles

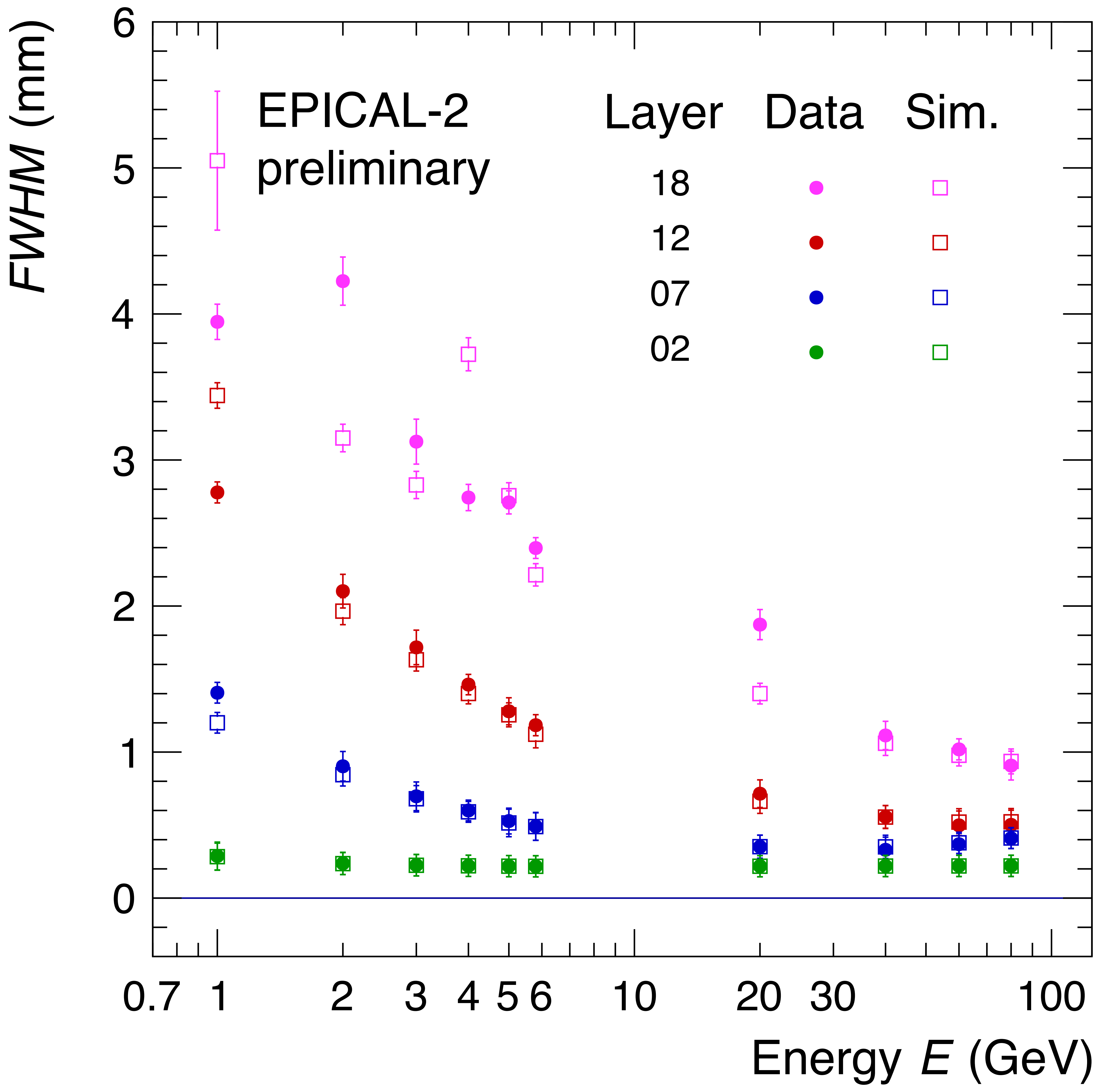




- Detailed measurements of hit density evolution
- Narrow shower at start broadens in deeper layers

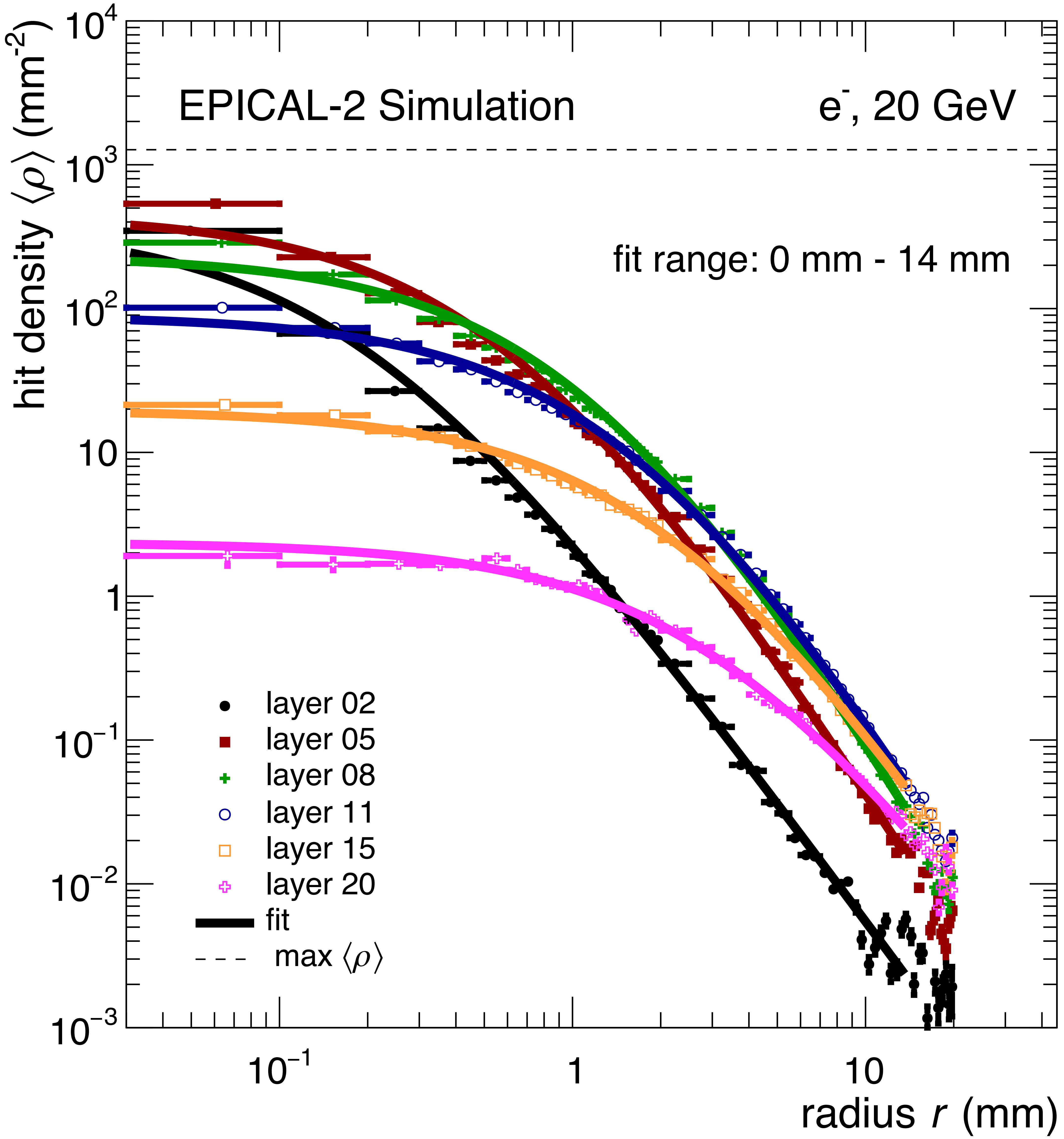
- Expected evolution as a function of energy
- Good agreement of simulation
  - Basis for 3D description of shower shape

Shower Width



- Shower becomes more narrow with decreasing depth and increasing energy
- Early part of shower has sub-mm width for all energies
- Basis of extremely good two-shower separation
- Also useful for PFA
- Event-by-event fluctuations to be studied

Fits of Lateral Shower Profiles

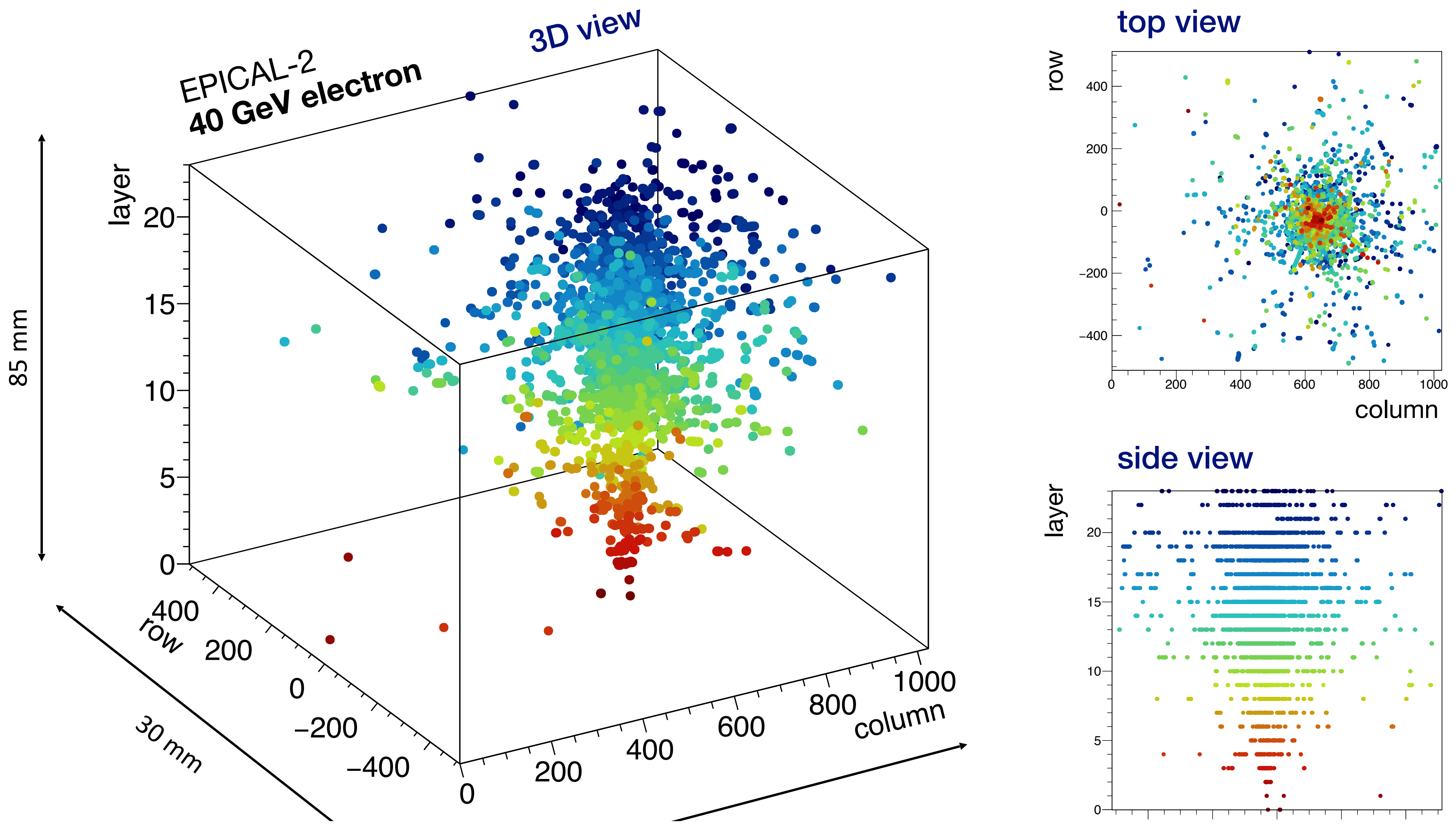


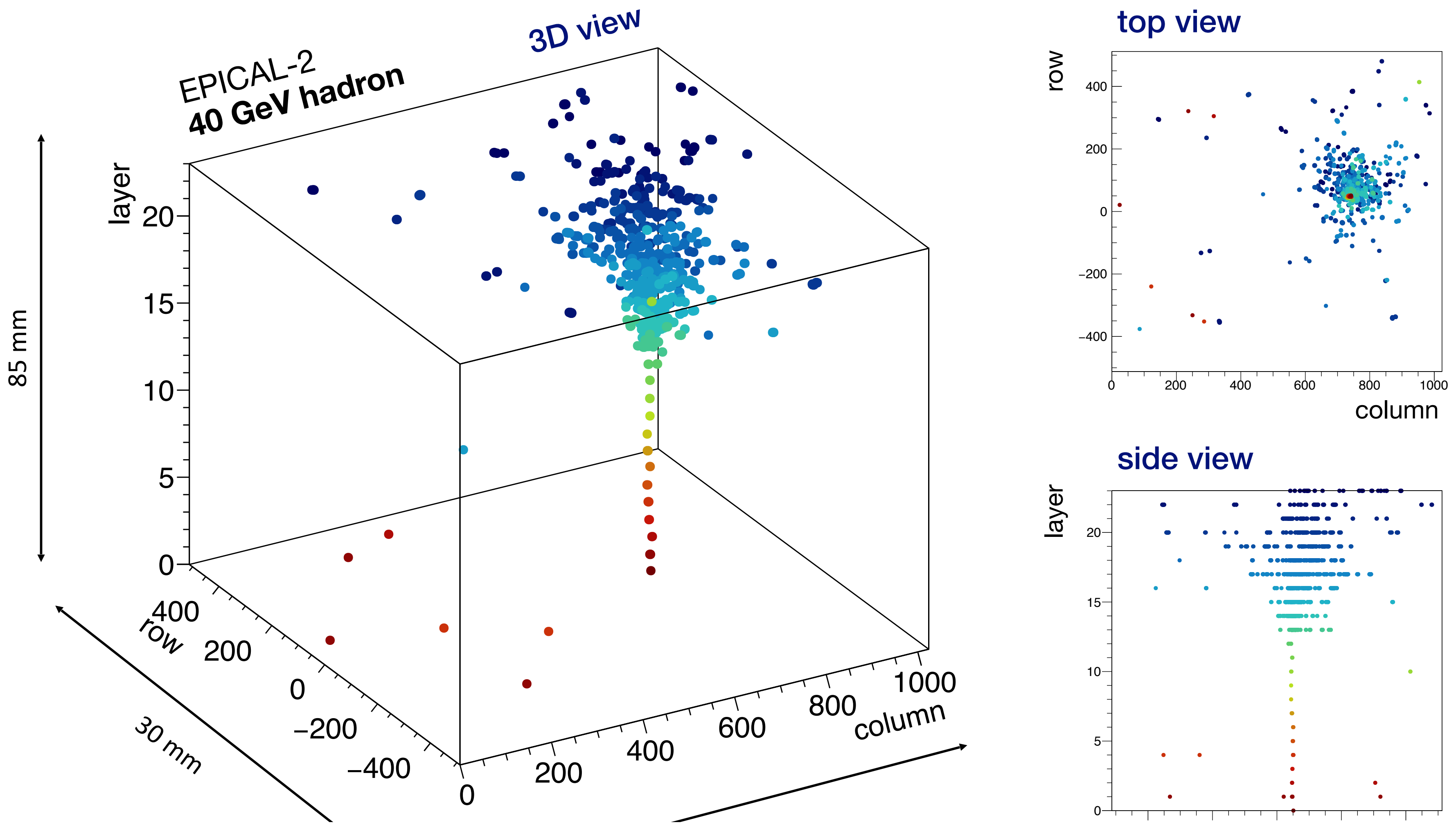
- Lateral hit density distribution for different depths
- Well described by fits of power-law like function

$$g(r) = p_0 \left(\frac{p_1^2 - 3p_1 + 2}{2\pi p_1^2 p_2^2} \right) \left(1 + \frac{r}{p_1 p_2} \right)^{-p_1}$$

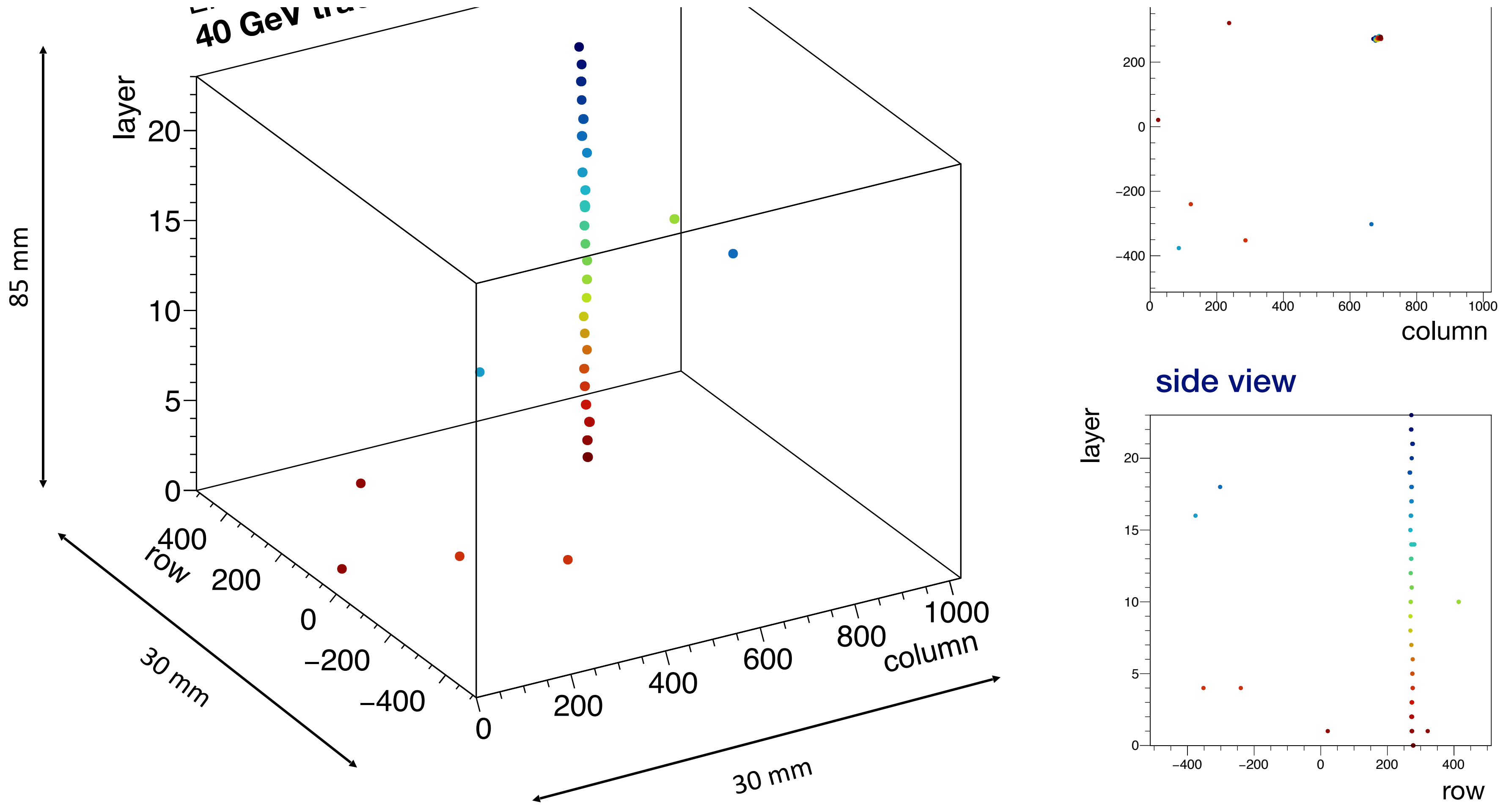
- Starting point of analytical 3D shower shape model
  - Should allow improved shower reconstruction
  - Work in progress

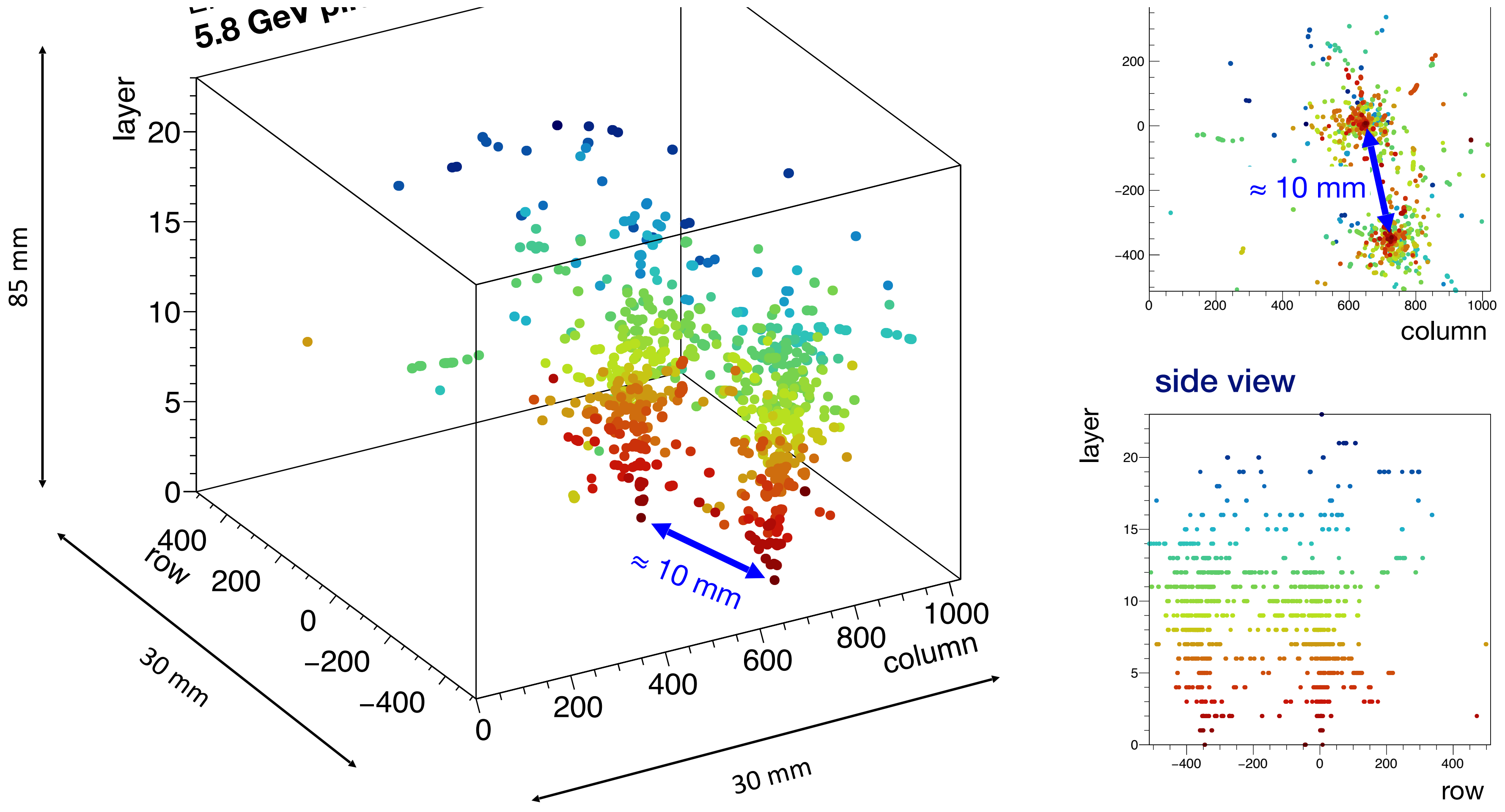
EPICAL-2 Event Displays



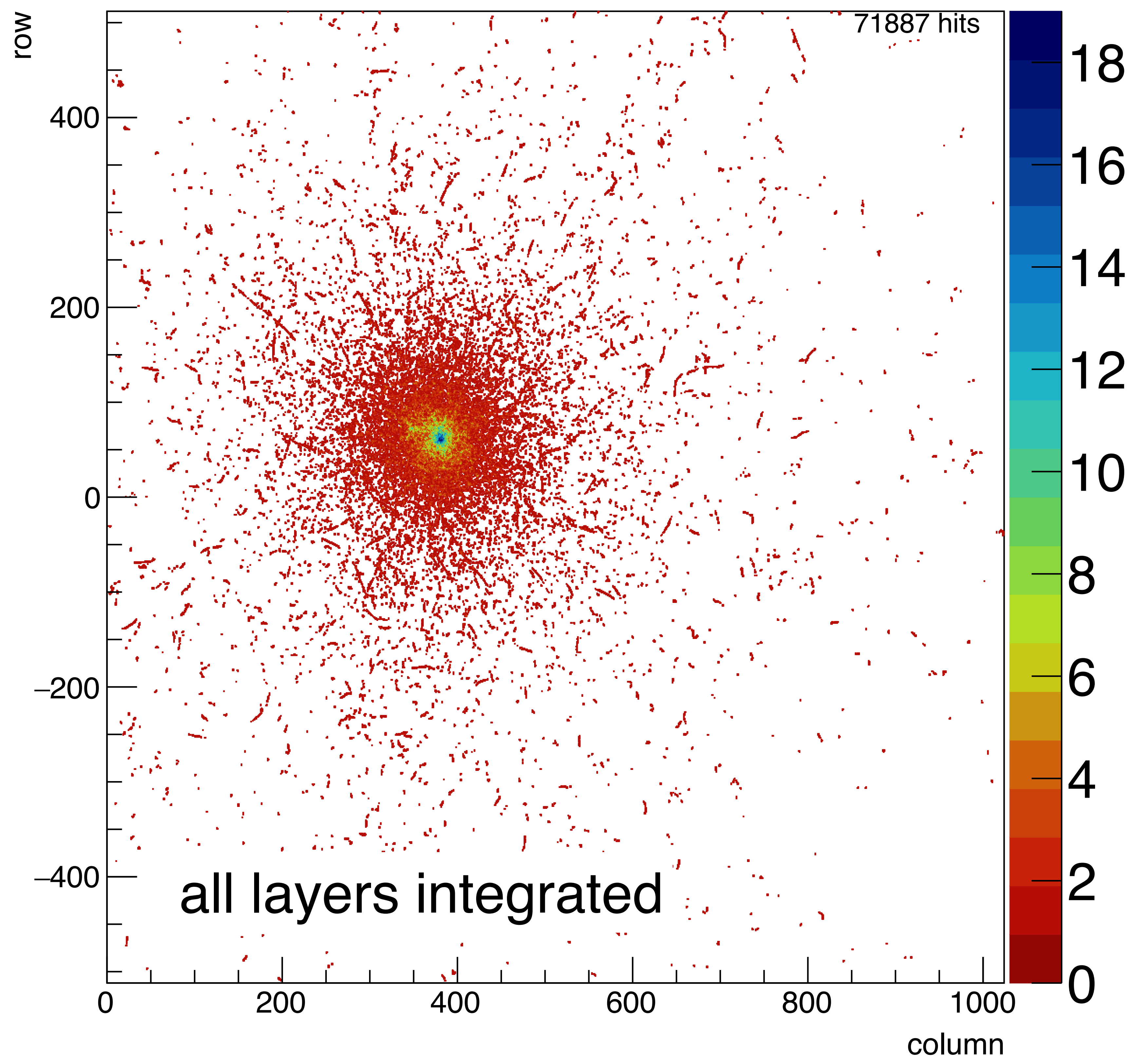


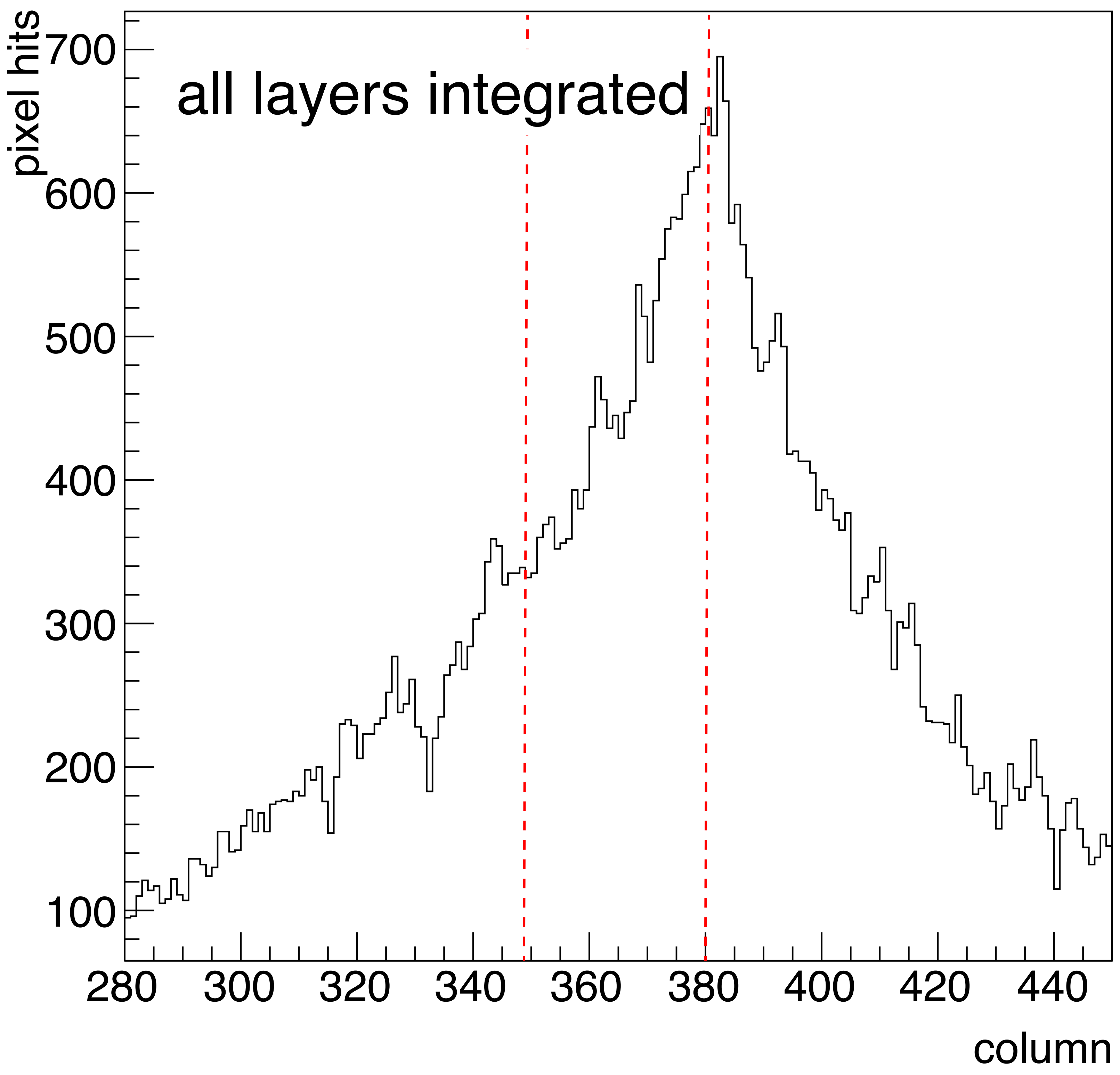
High potential of pixel technology for more sophisticated shower reconstruction e.g. advancement of PFA?





Application: Two-Shower Separation



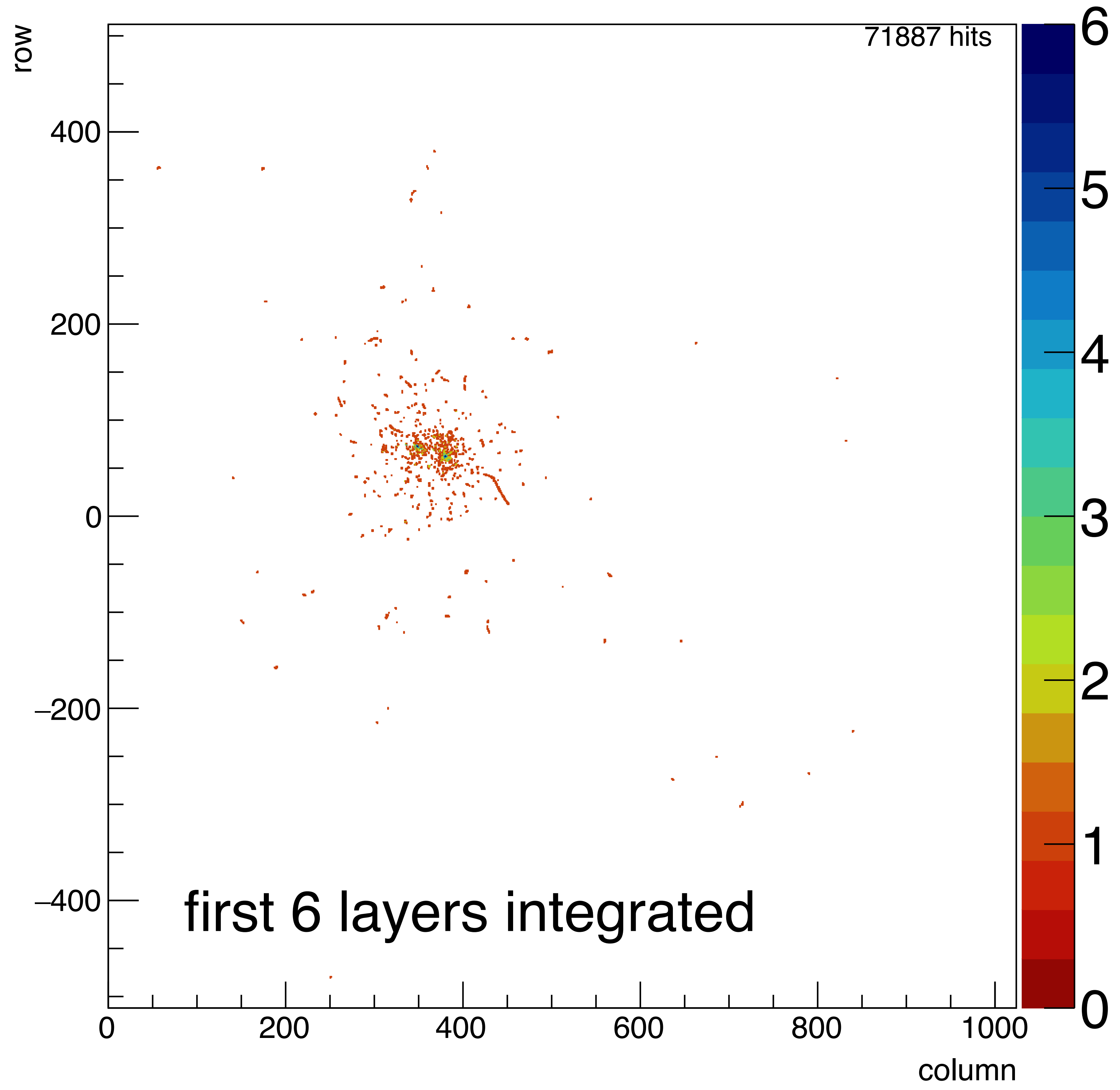


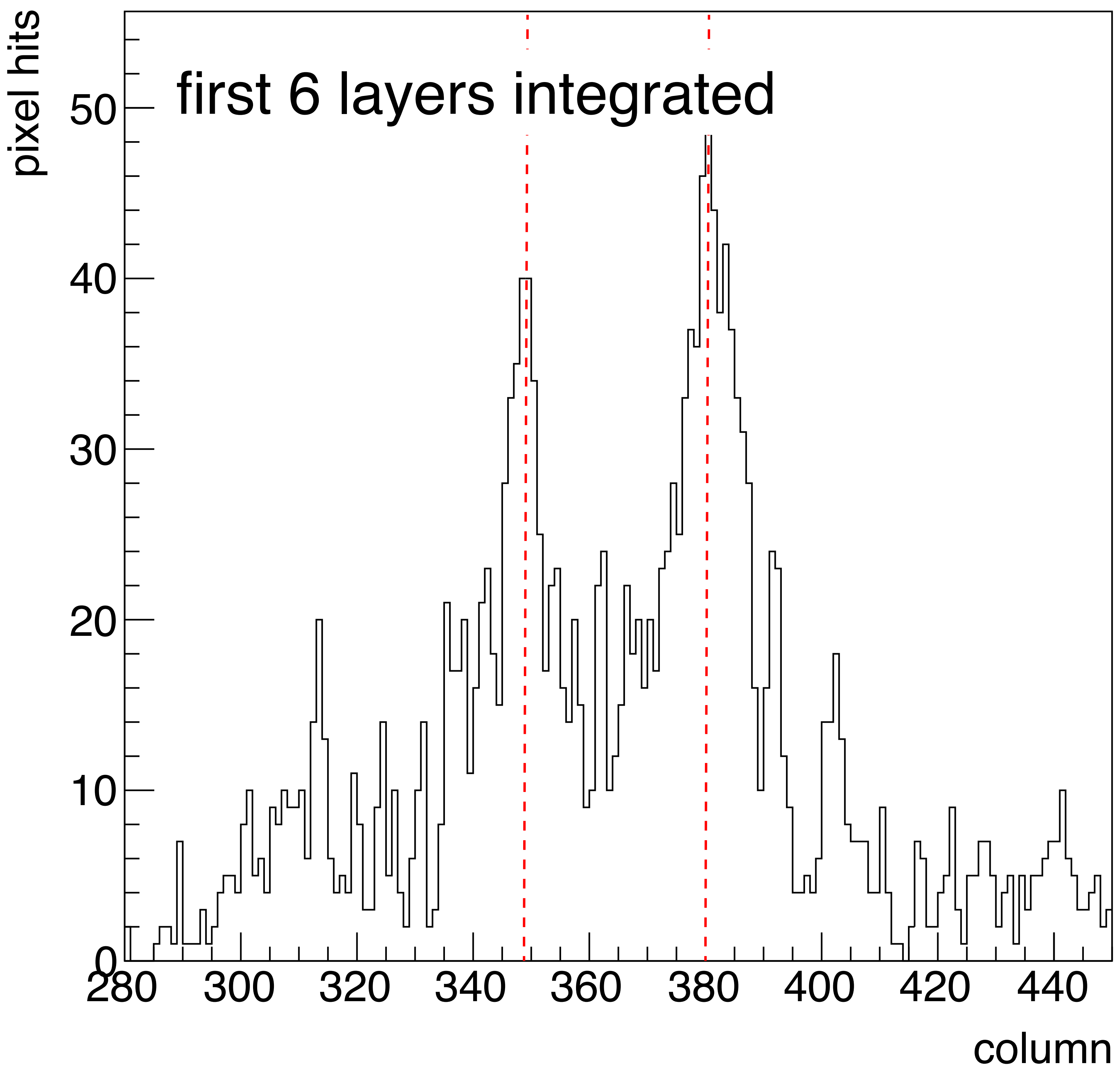
EPICAL-2
Allpix² simulation

30 GeV e⁻ + 250 GeV e⁻
1.2 mm separation
single event

- Longitudinally integrated distribution makes separation challenging
- Much more information available in high-granularity 3D distributions

Application: Two-Shower Separation





EPICAL-2
Allpix² simulation

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

- Full pixel detector information very powerful
  - Two-shower separation down to 1 mm should be possible
- Systematic studies to be done

Summary

- Digital calorimetry works
  - Very good performance of EPICAL-2
    - ALPIDE sensor: very low noise, readout speed compatible with modern experiments
  - Technology suitable for ALICE FoCal pixel layers
- Good energy linearity and resolution
  - Study limited by accelerator properties at DESY
- Very strong potential – so far “scratching the surface”
  - Use full 3D shower information for single- and multi-particle reconstruction
  - Improved jet measurements?
    - Study performance for particle flow algorithms
- Possible limit of current technology at high energy from saturation
  - R&D for dedicated calorimeter pixel chip required

Outlook on Digital Calorimetry

- Beyond proof of principle: digital electromagnetic calorimetry works
- Very high potential
  - Standard calorimeter performance is good - further improvements possible
  - Possible improvement by orders of magnitude in
    - Two-shower separation, position/angular resolution
  - Unique information for fine-tuning MC
  - Adaptation/optimisation of PFA and PID to be done
- Major challenges
  - Development of dedicated sensor
    - Local dynamic range: optimise granularity and bit depth
    - Power consumption, rate capabilities, data reduction, radiation, trigger capability(?), timing(?)
  - Integration: preserve compactness for small R_M
    - Cooling, cabling, etc.

EPICAL-2 Team

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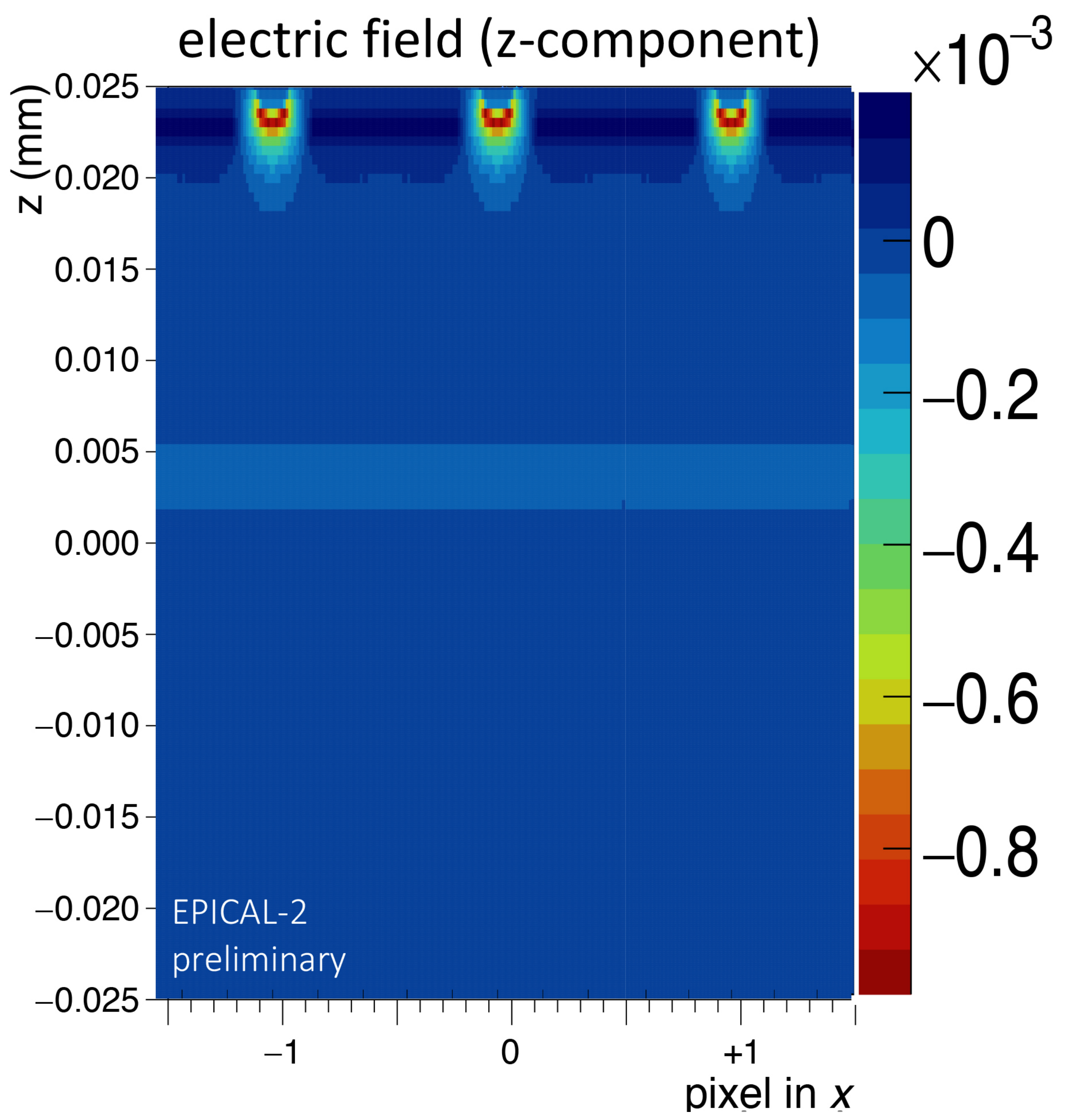
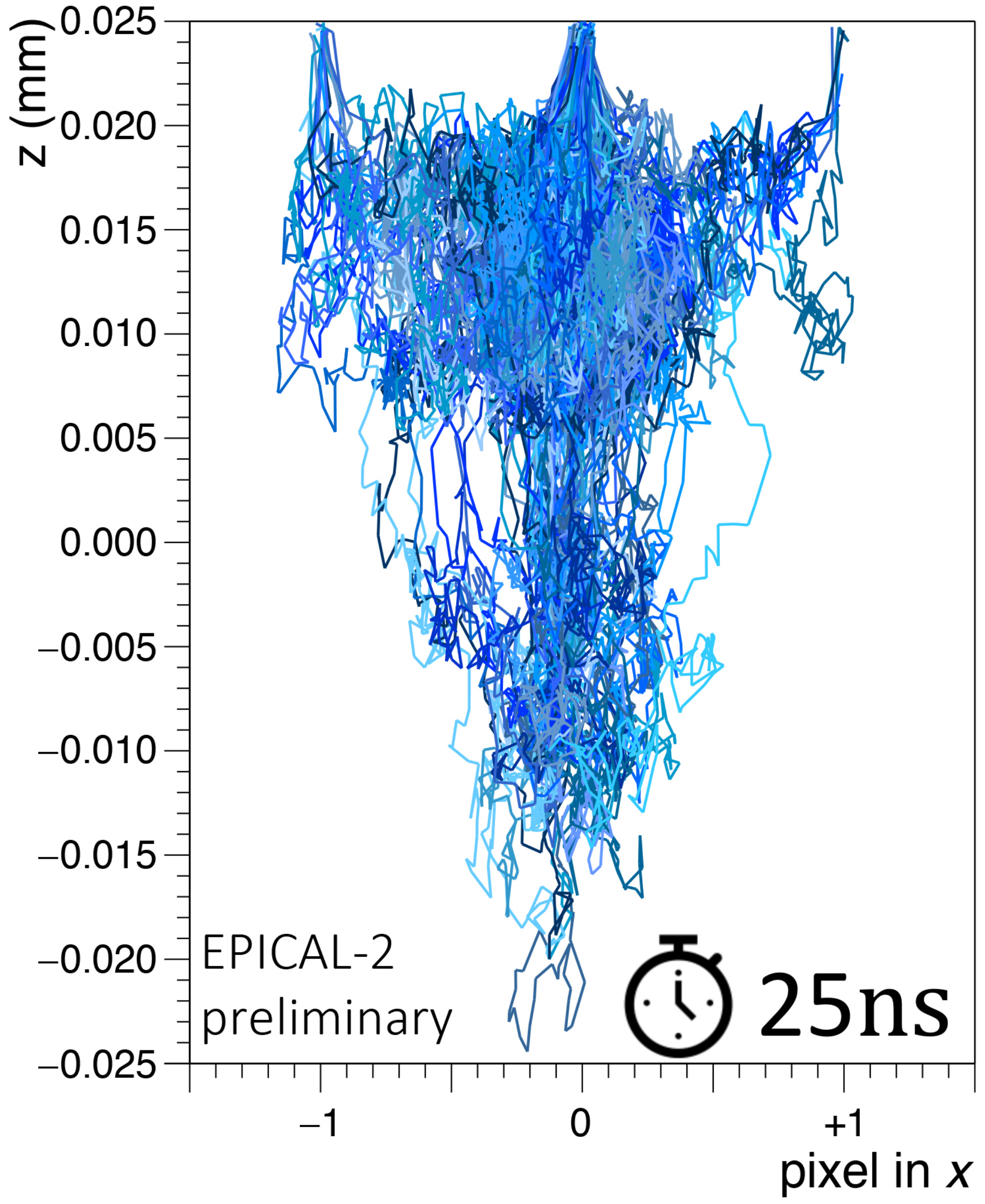
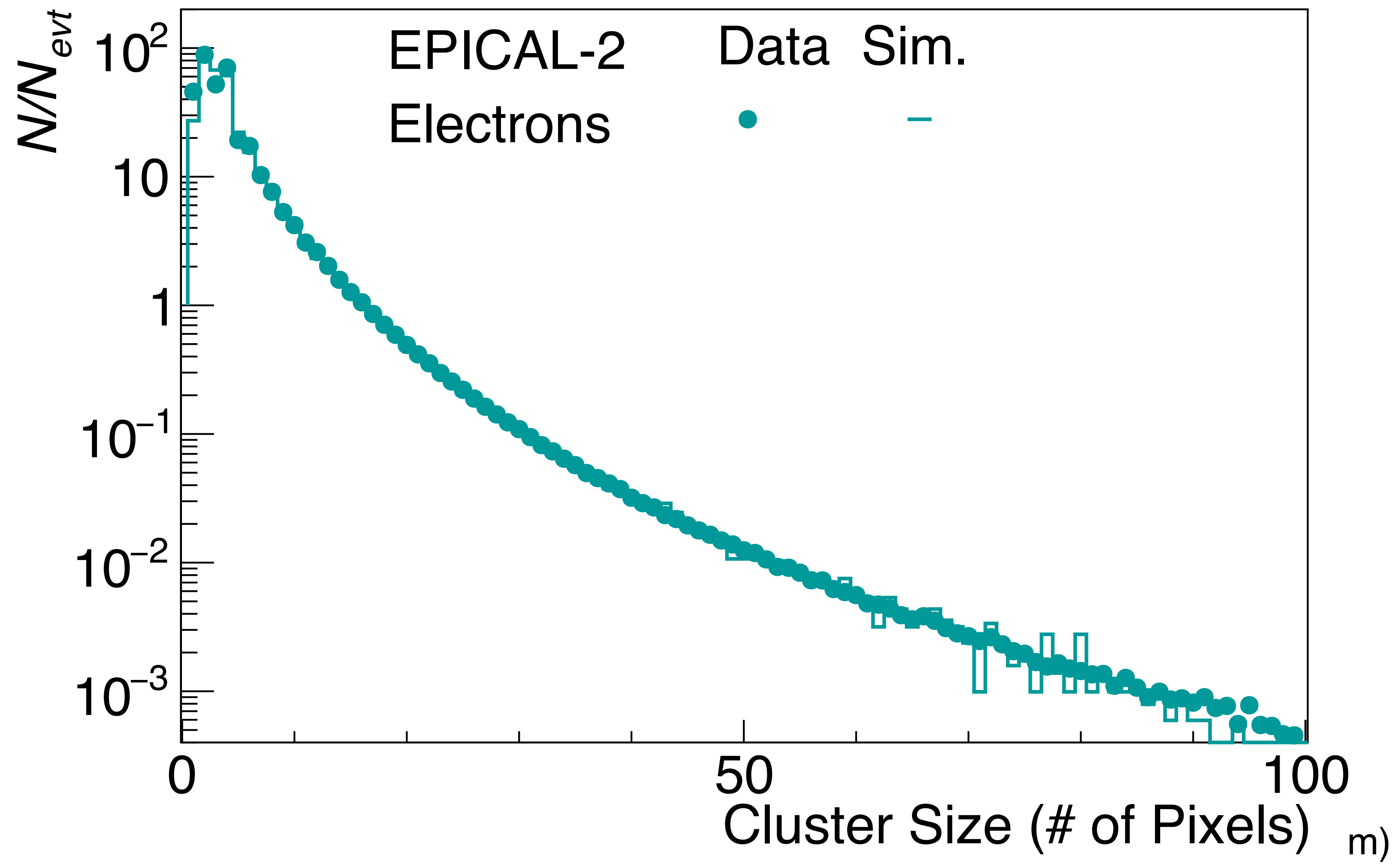
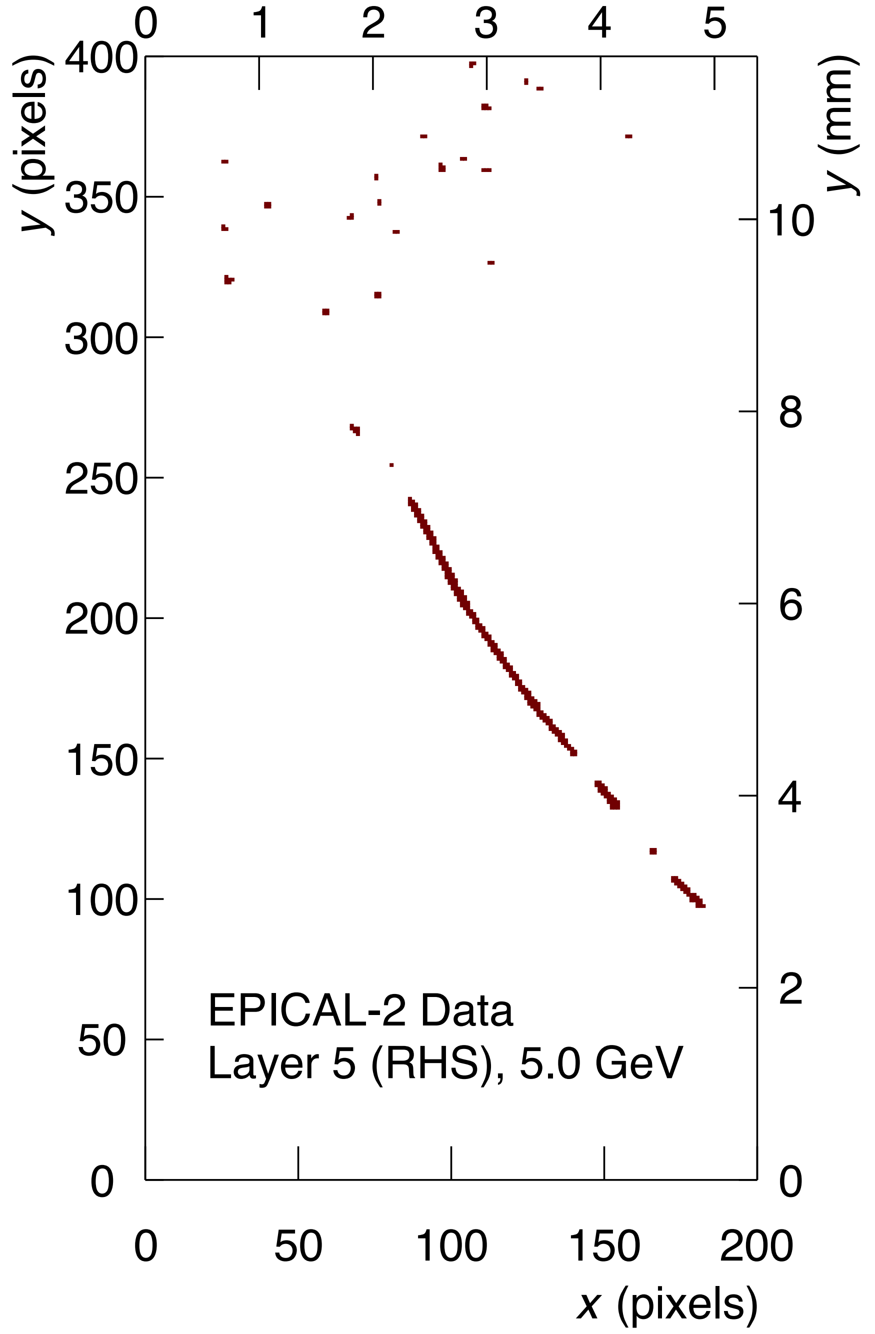
Backup

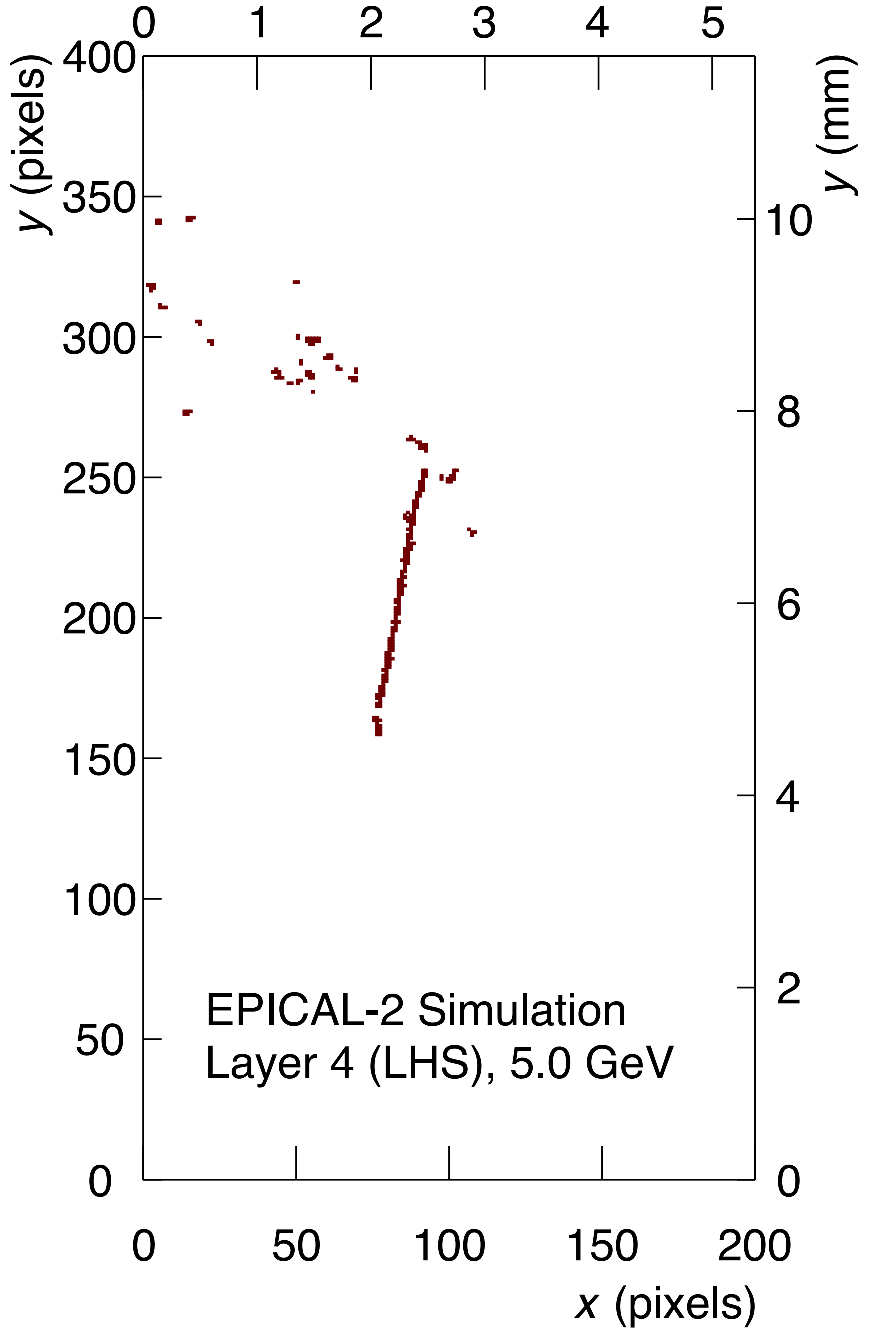
Allpix² Simulations







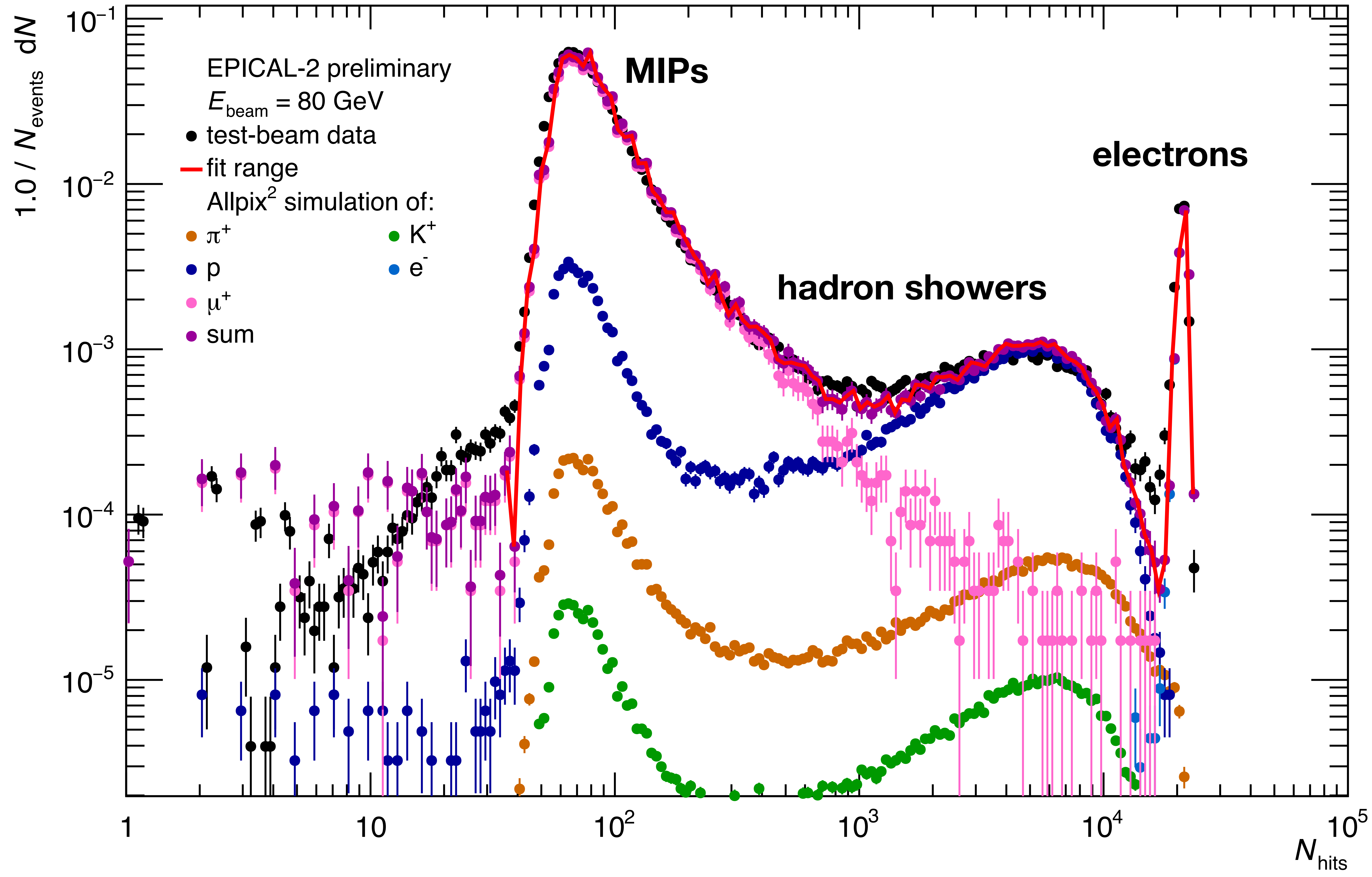




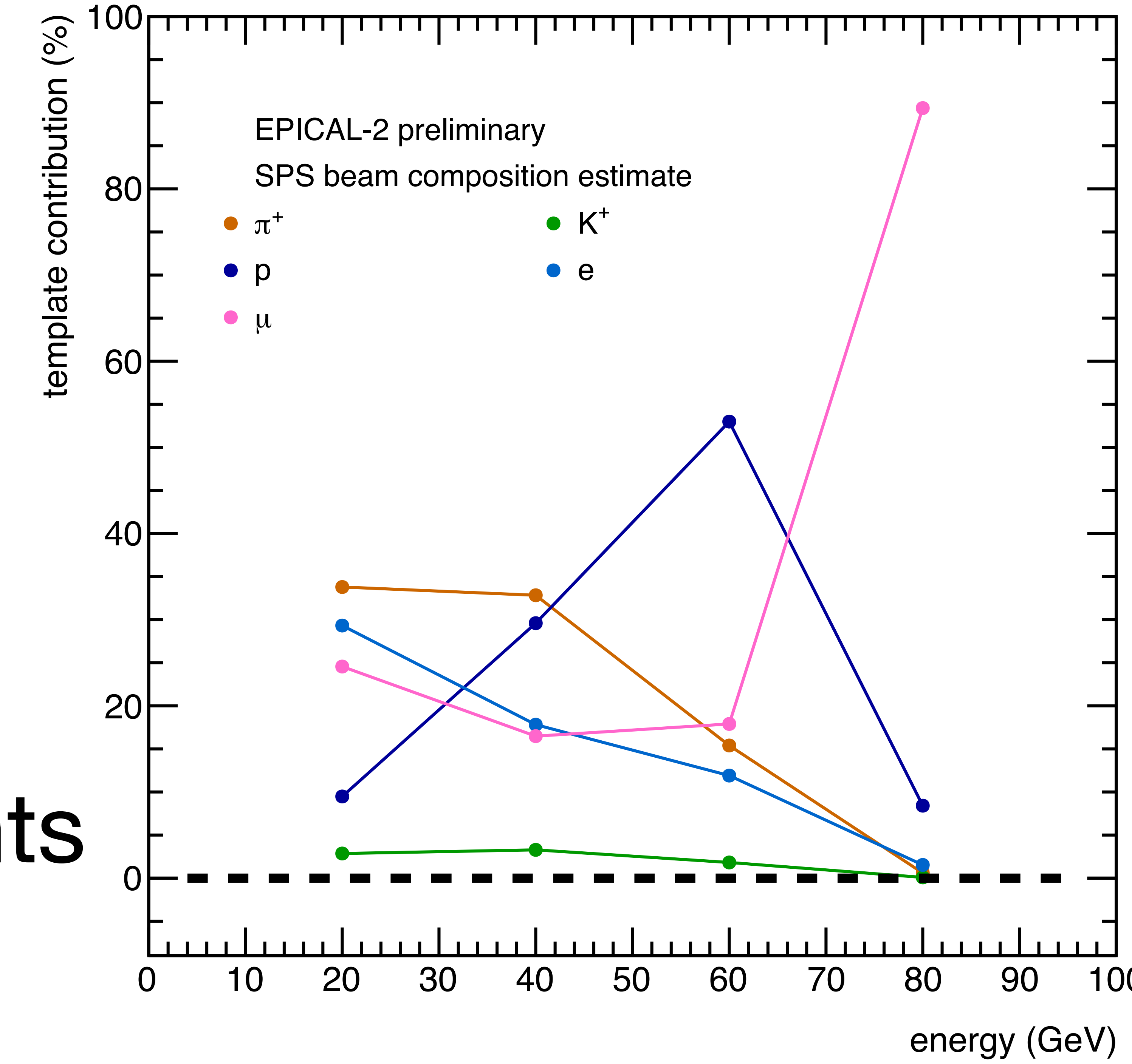
- Detailed implementation of ALPIDE sensor and detector geometry
- Good description of detector behaviour

Allpix²: NIM A, 901:164–172, 2018

SPS H6 Beam Composition

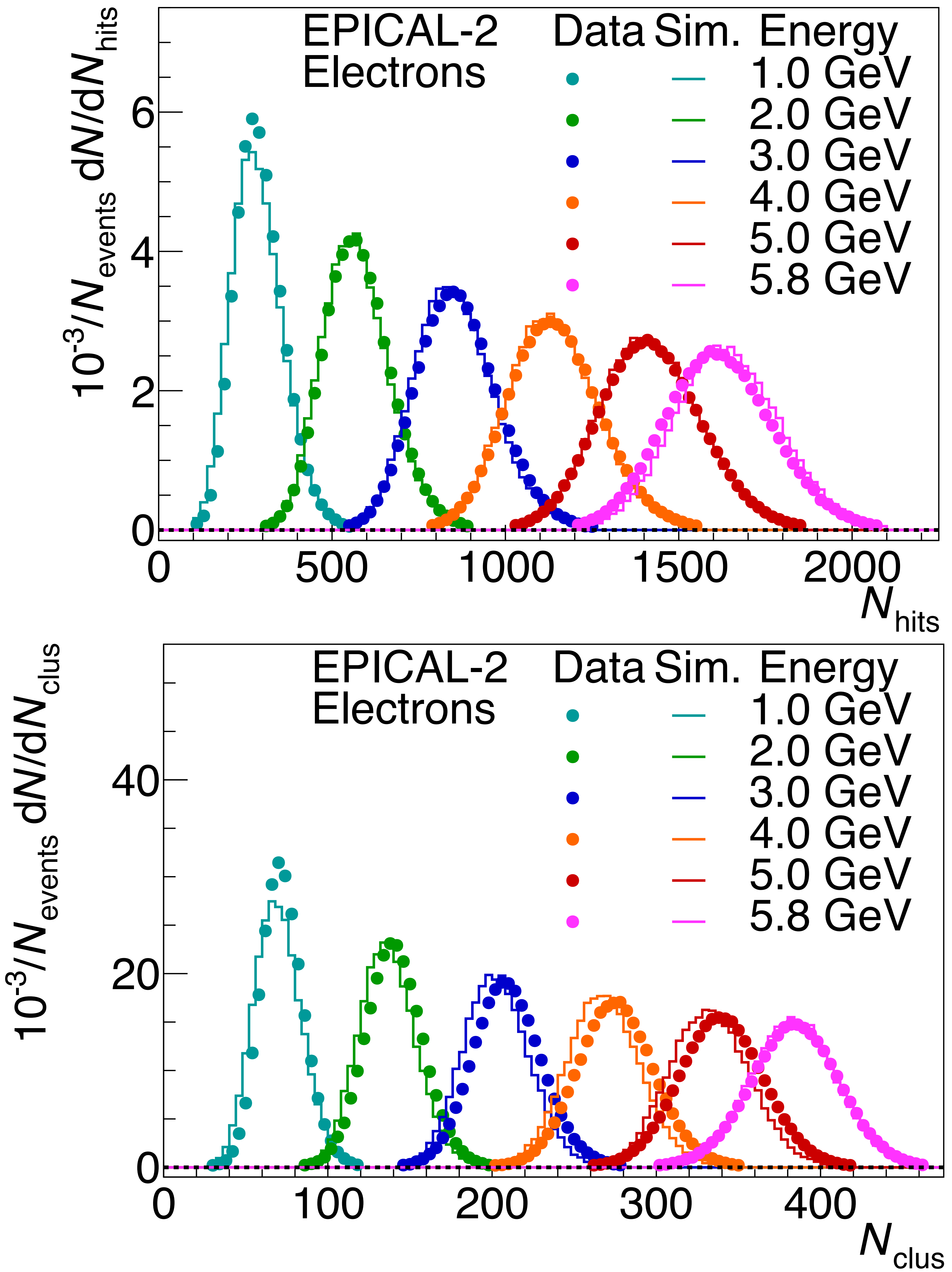


- Allows precise extraction of beam composition
- Hadron contamination of electron peak under control



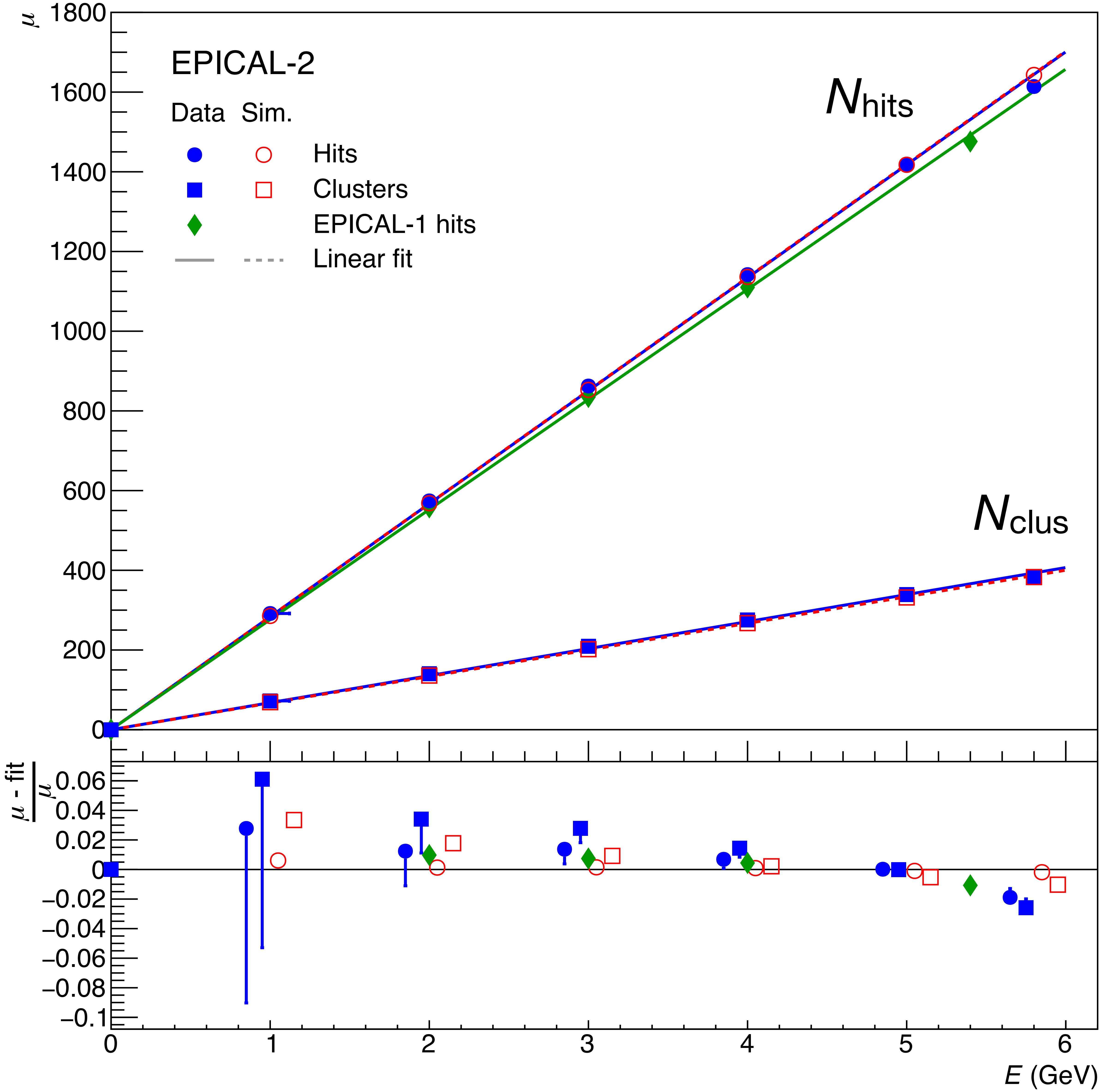
- Detailed MC simulation (Allpix²) describes all components of calorimetric energy spectra very well

Detector Response



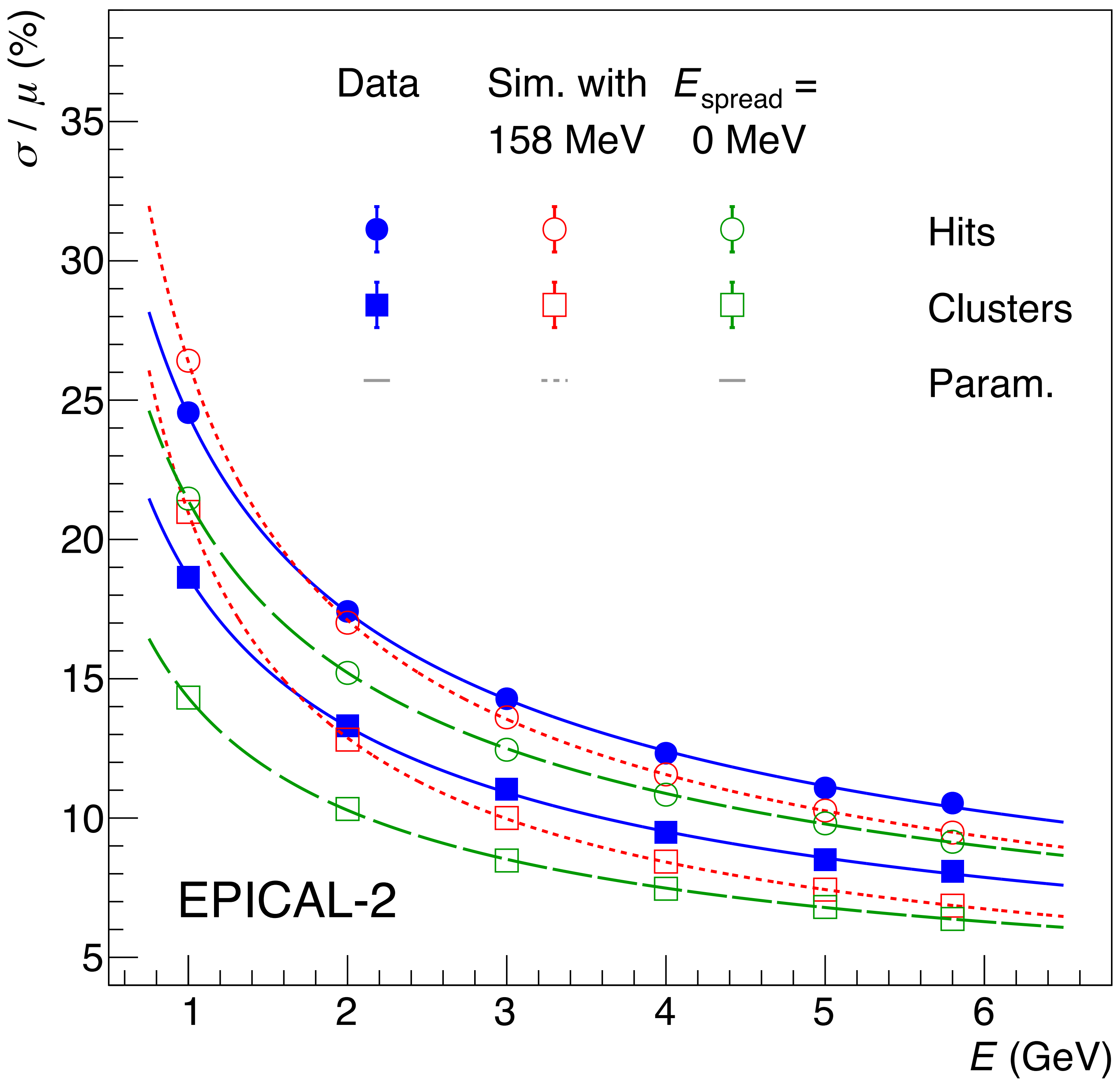
- Number of hits (N_{hits}) or number of clusters (N_{clus}) usable as response observable
  - Well defined peaks scaling with beam energy
- Allpix^2 simulation
  - Tuned to number of hits at 5 GeV
  - Very good description for hits at all energies
  - Good description for clusters
    - Sensitive to details of cluster algorithm

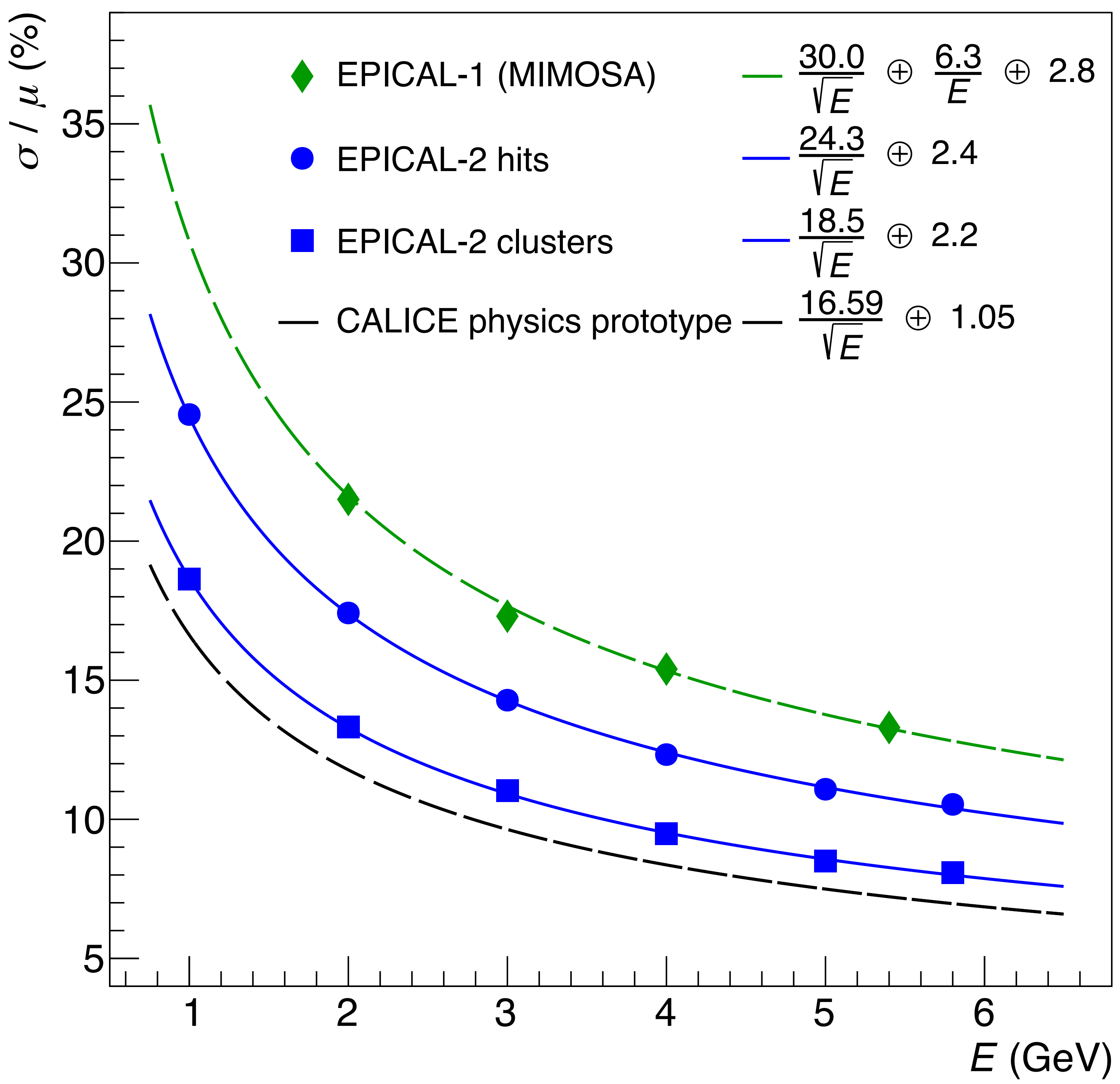
Energy Linearity



- Average response as a function of beam energy
  - Described by linear fit
    - Constrained to (0,0) by pedestal measurements
  - Behaviour reproduced by simulation
- Small apparent deviations from linearity in ratio
  - Perfect linearity in hits from simulation
  - Hits in data agree with EPICAL-1
    - Non-linearity in hits strongly influenced by uncertainty in DESY beam energy
      - NIM A, 922:265–286, 2019
  - Stronger non-linearity from N_{clus}
    - Reproduced in simulation
- Response consistent with full linearity at low energy

Energy Resolution





- Resolution shows the expected behaviour for calorimeters
- Experimental data likely contain a significant contribution from beam energy spread at DESY
- “Particle counting” (N_{clus}) shows superior performance here
  - Confirmed by simulations

- Resolution from hits better than EPICAL-1 results
- Resolution from N_{clus} close to analog SiW ECAL (CALICE) physics prototype [NIM A 608:372-383, 2009]
- Cluster algorithm not yet optimised