Utrecht University

Nikhef

R&D on Truly High-Granularity Calorimetry with EPICAL-2

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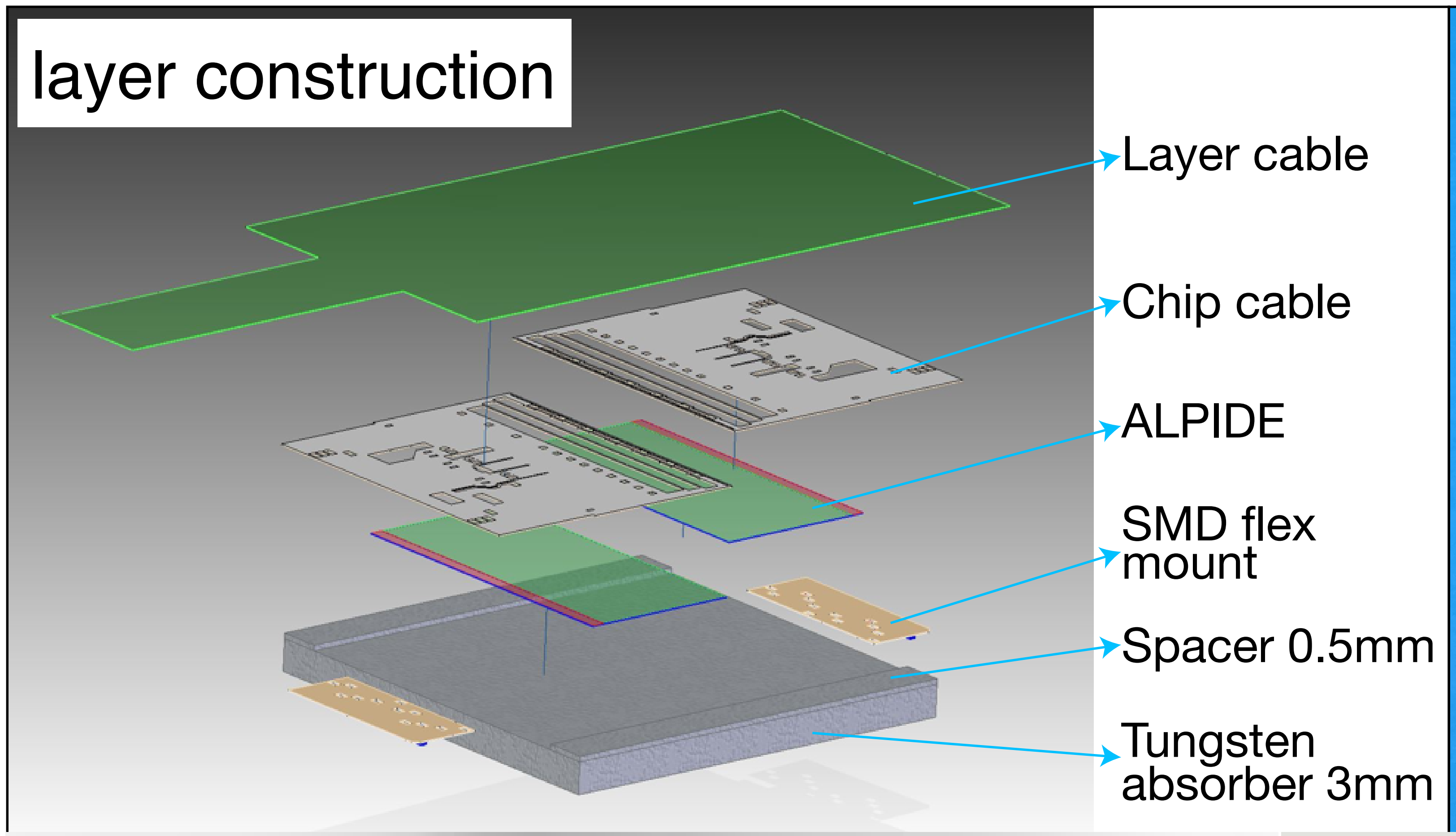
2nd International Workshop on Forward Physics and Forward Calorimeter Upgrade in ALICE

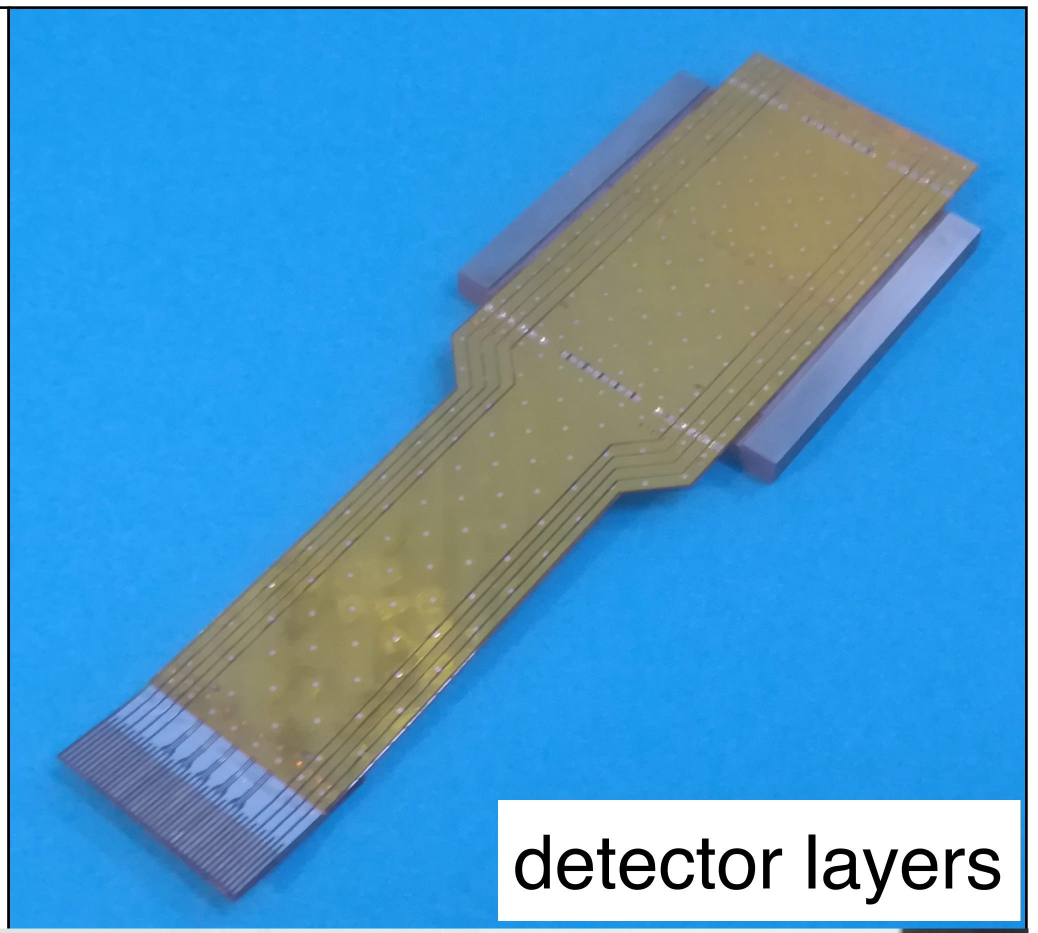
Tsukuba, Japan, 13-15 March 2023

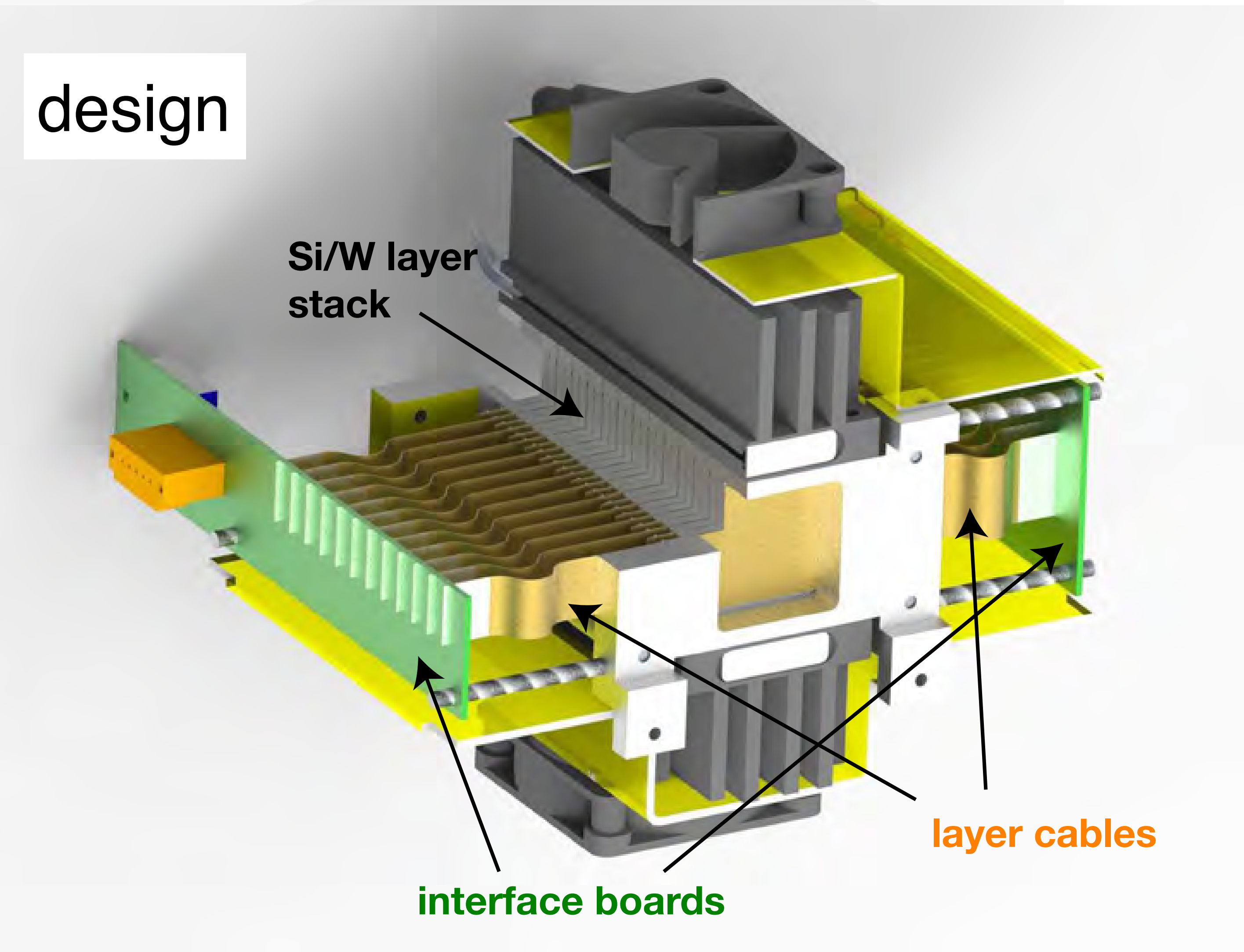
Introduction

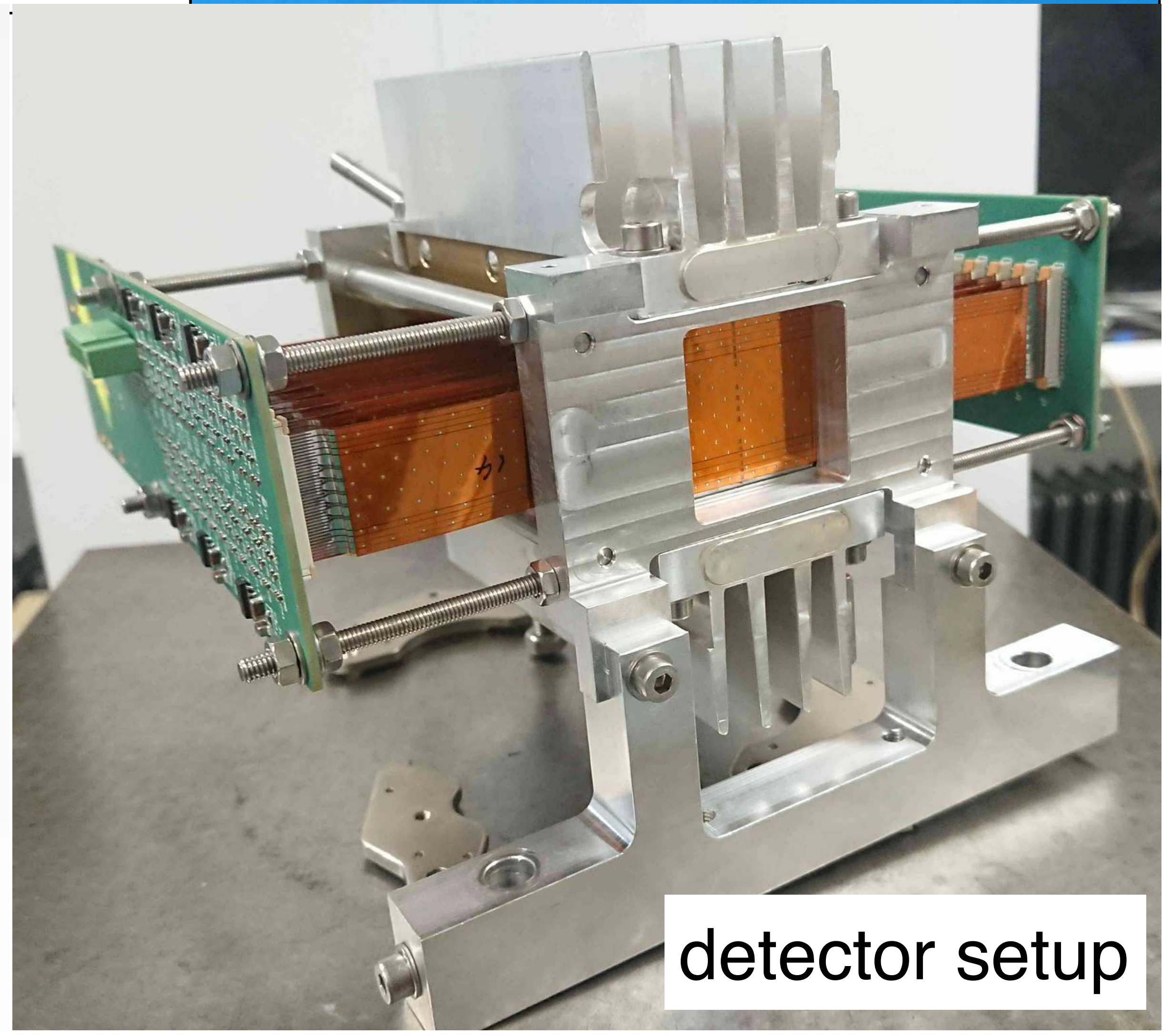
- Digital calorimetry: count number of charged shower particles in sampling layers
  - Ideally: potential to reduce fluctuations from individual sampling layers
  - High granularity required due to high particle density
- State-of-the-art all-pixel calorimeter prototype
  - Follow up on proof of principle EPICAL-1 (JINST 13 (2018) P01014)
  - EPICAL-2: Si/W stack using ALPIDE sensors, detailed simulation in Allpix^2
- Two-fold purpose:
  - Generic R&D for future calorimeters
  - “Test bench” for the FoCal-E pixel planes
- Calorimetric performance from test-beam measurements
  - Detailed study at low energy (DESY)
  - Preliminary results from high energy (SPS)

Digital Calorimeter Prototype – EPICAL-2







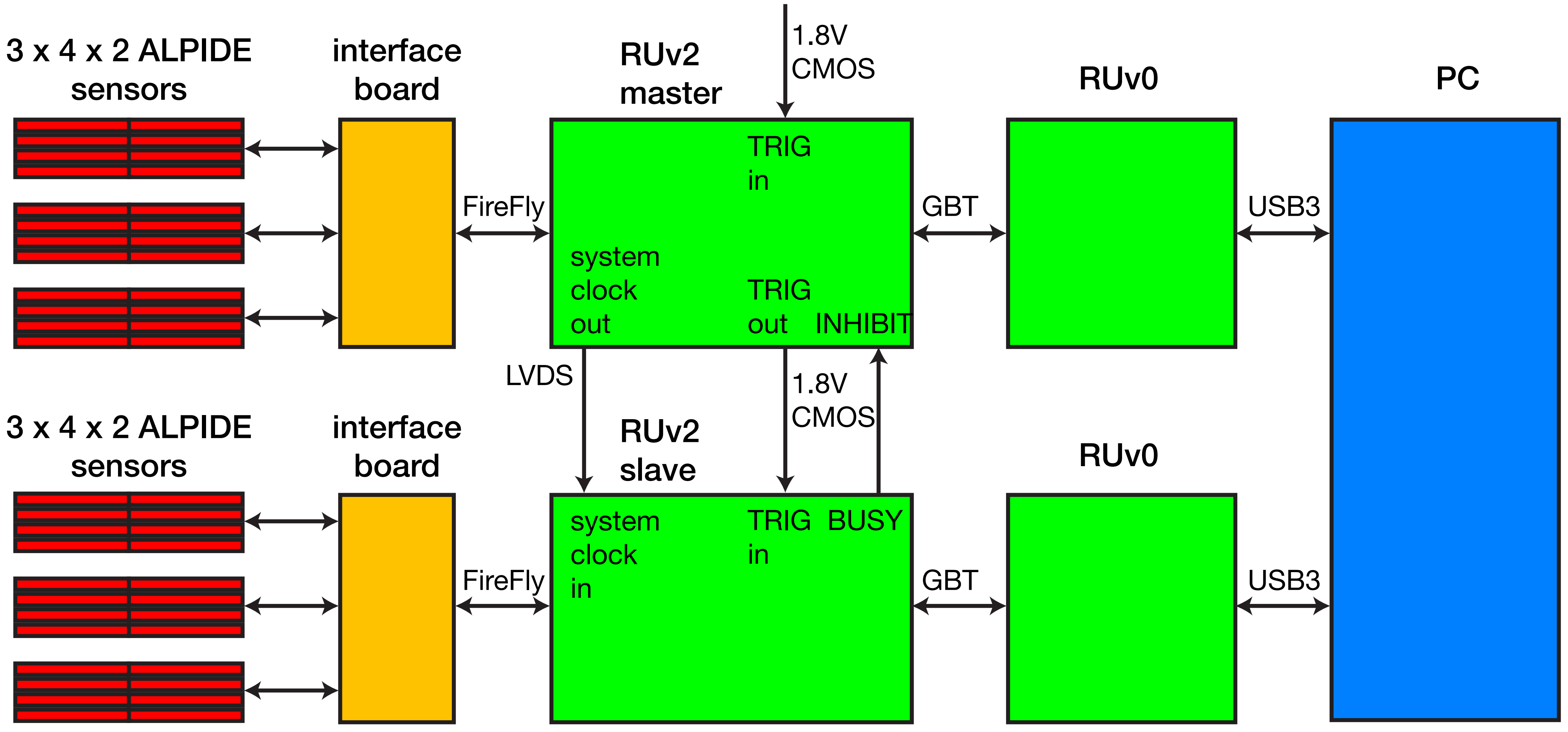


24 layers with each
- 3 mm W absorber
- 2 ALPIDE CMOS sensors
  - NIM A, 845:583–587, 2017
- ultra-thin flex cables (LTU Kharkiv)

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

compact design: expect $R_M \approx$ 11 mm

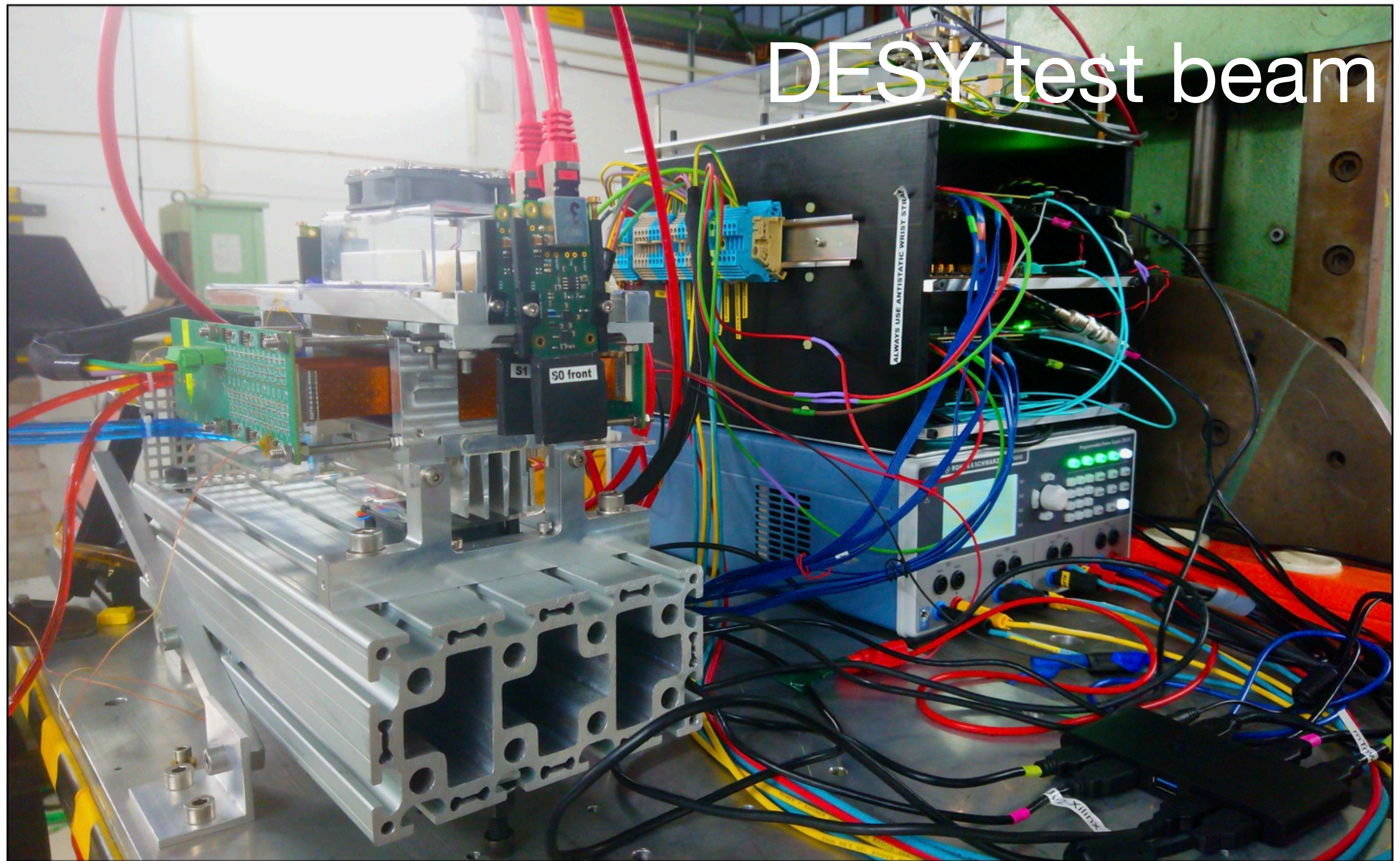
readout schematics



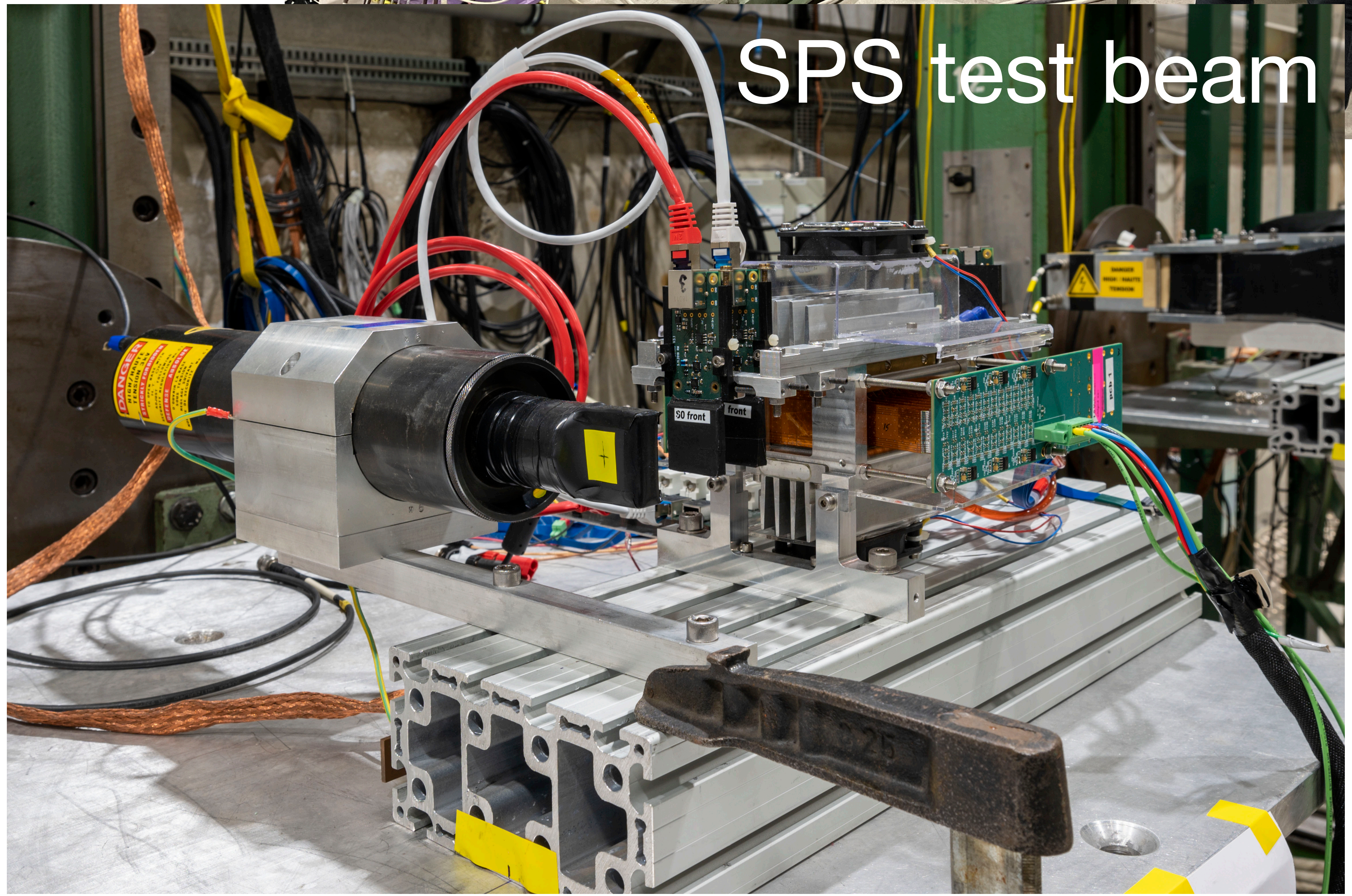
ALPIDE output via 1.2 Gb/s serial line
readout via 2 levels of FPGA

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

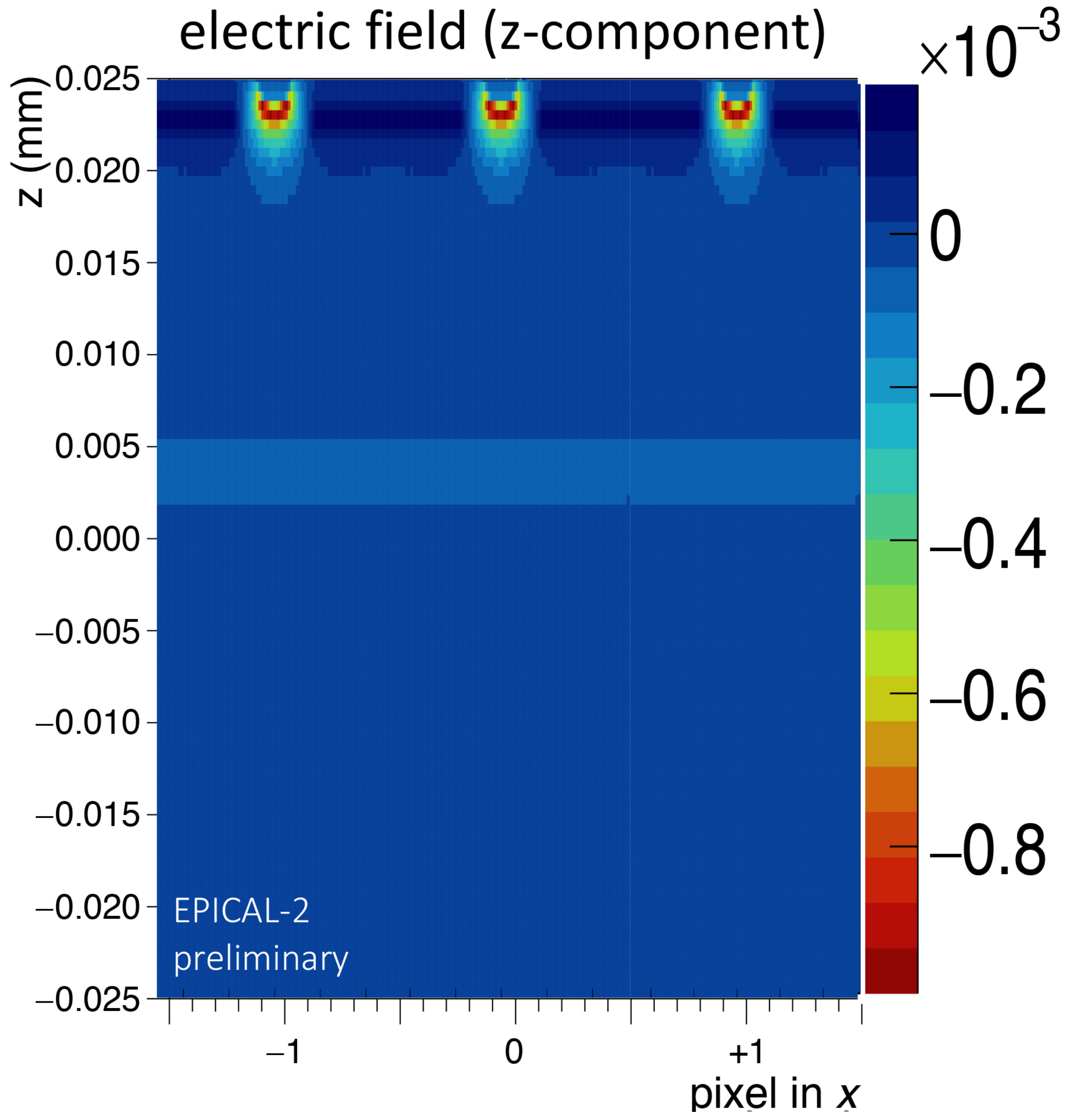


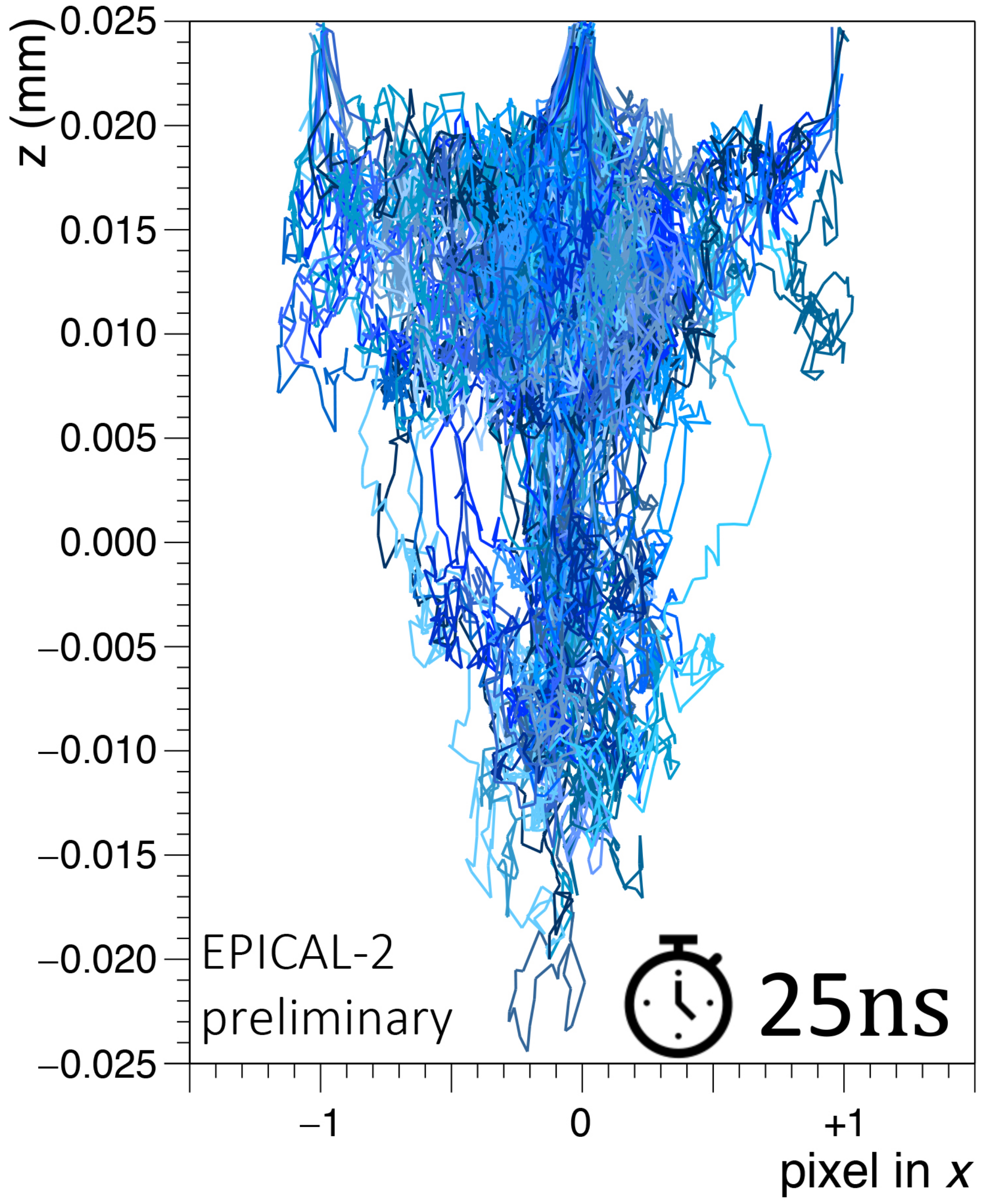
DESY test beam

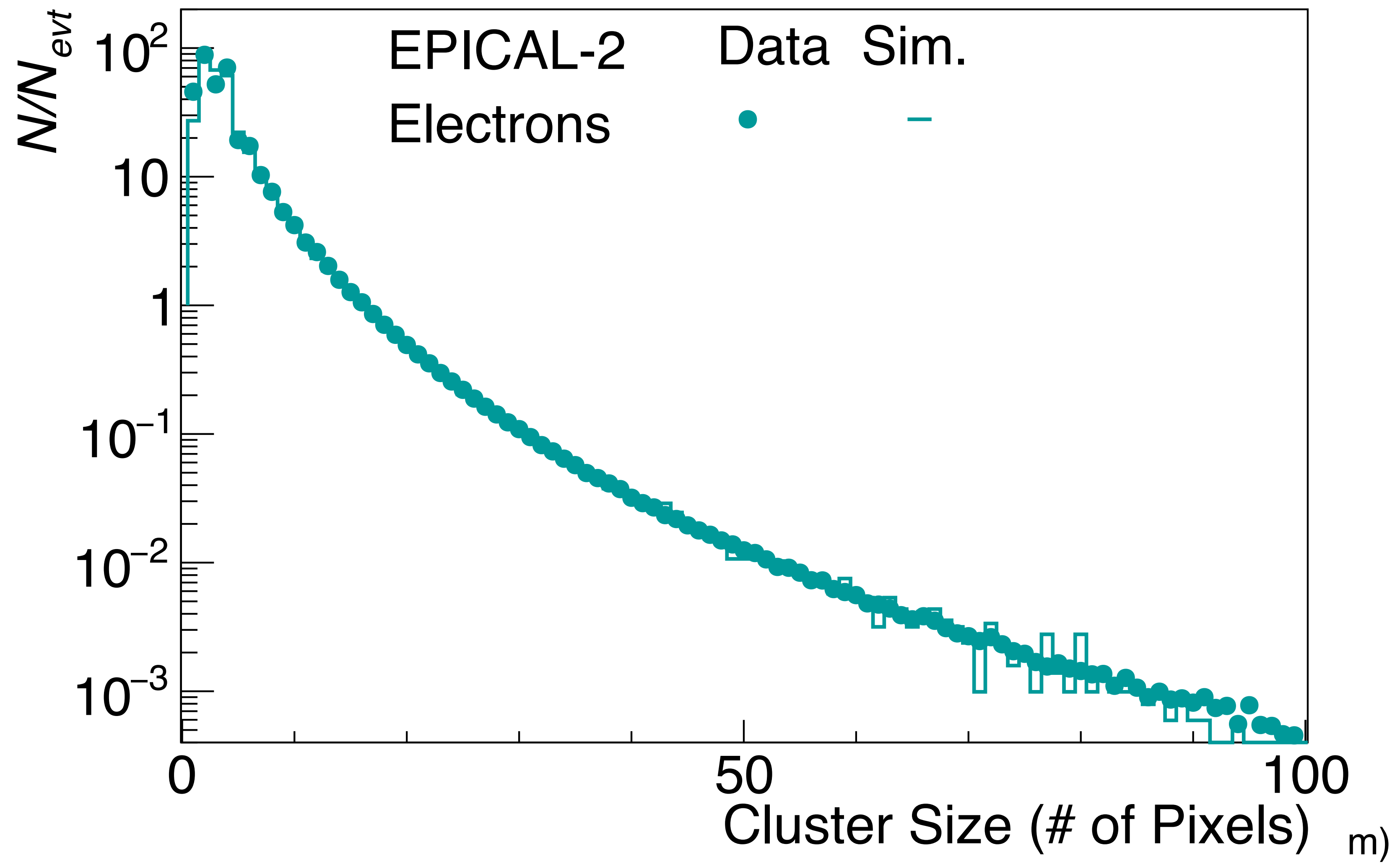


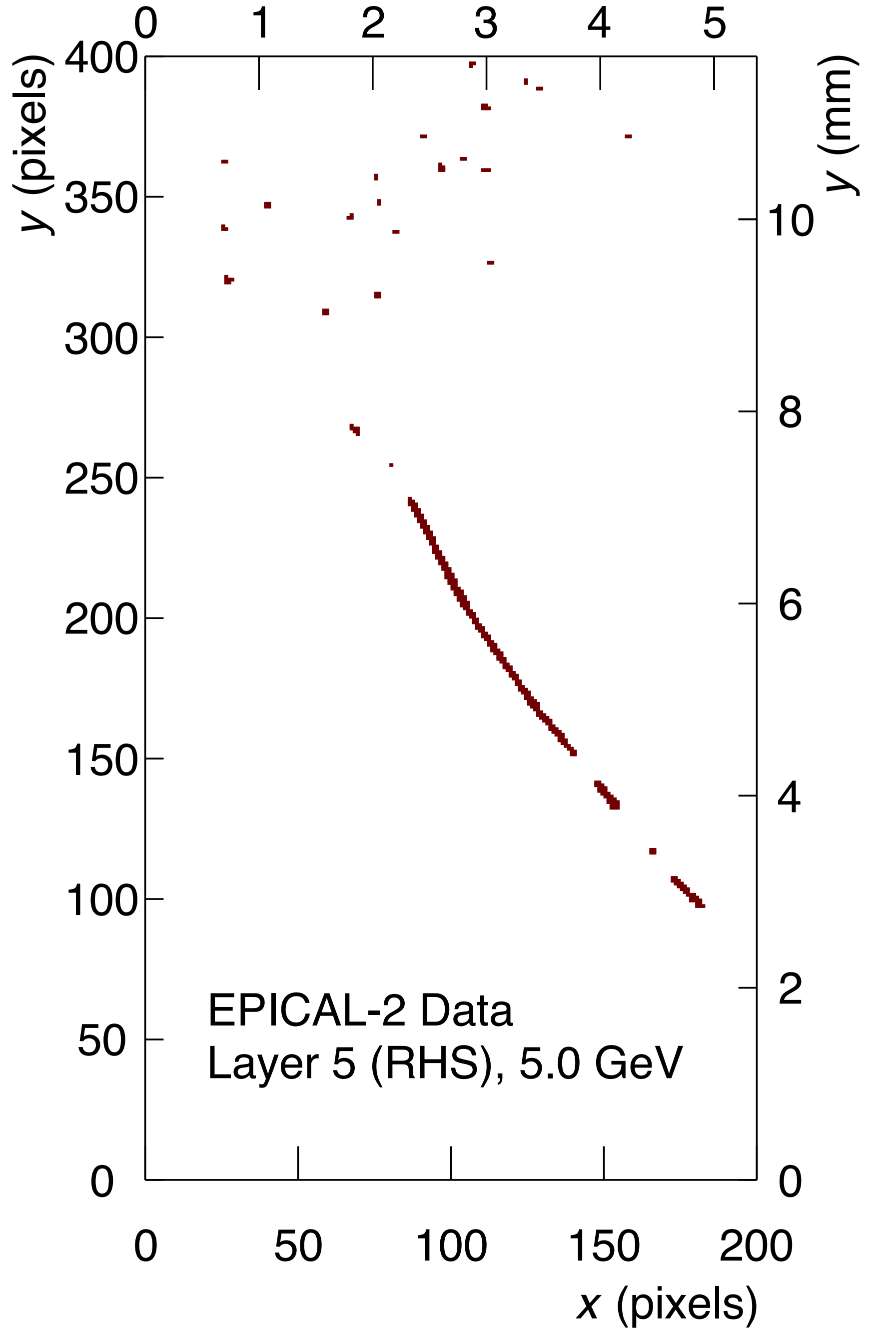
SPS test beam

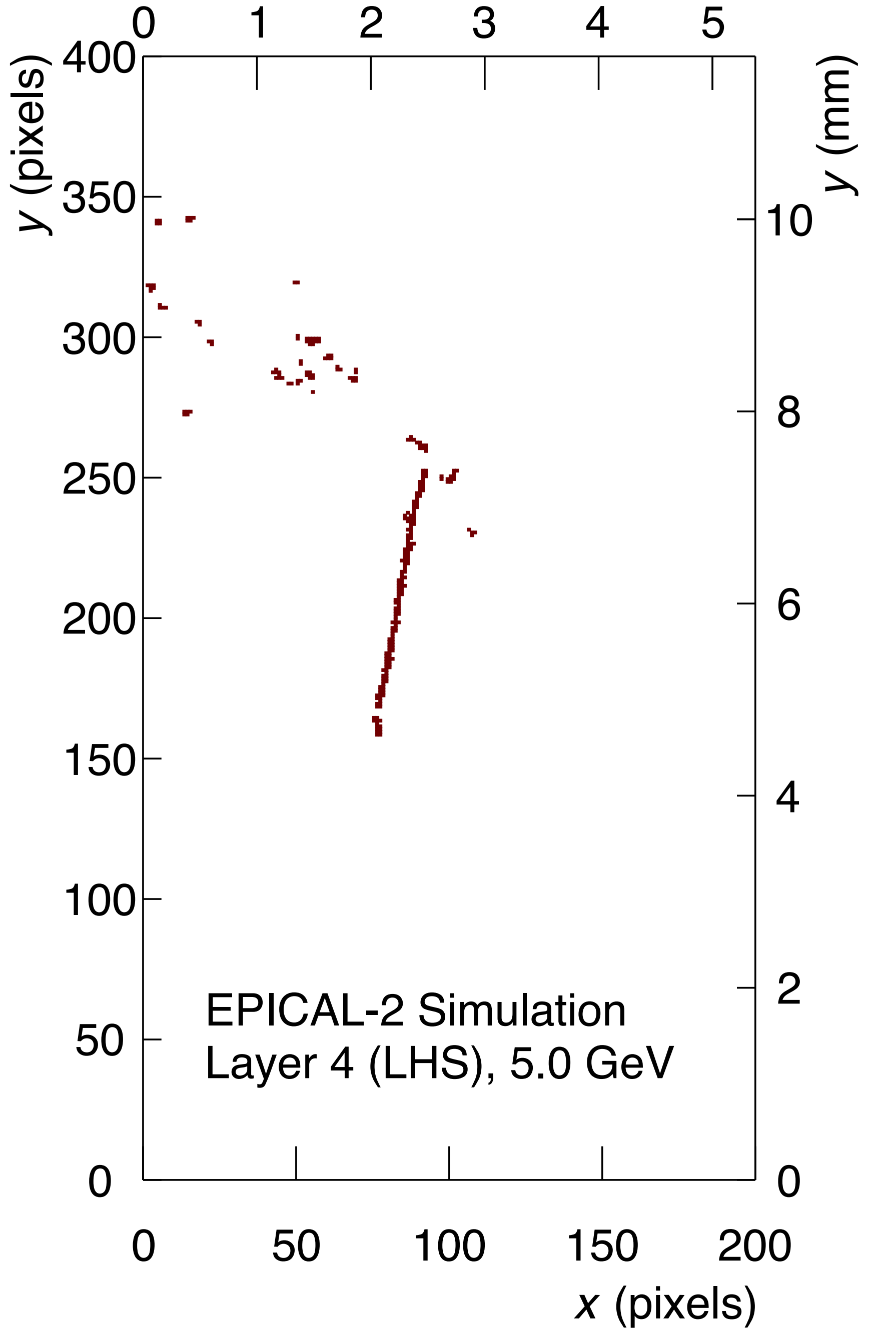
Allpix² Simulations







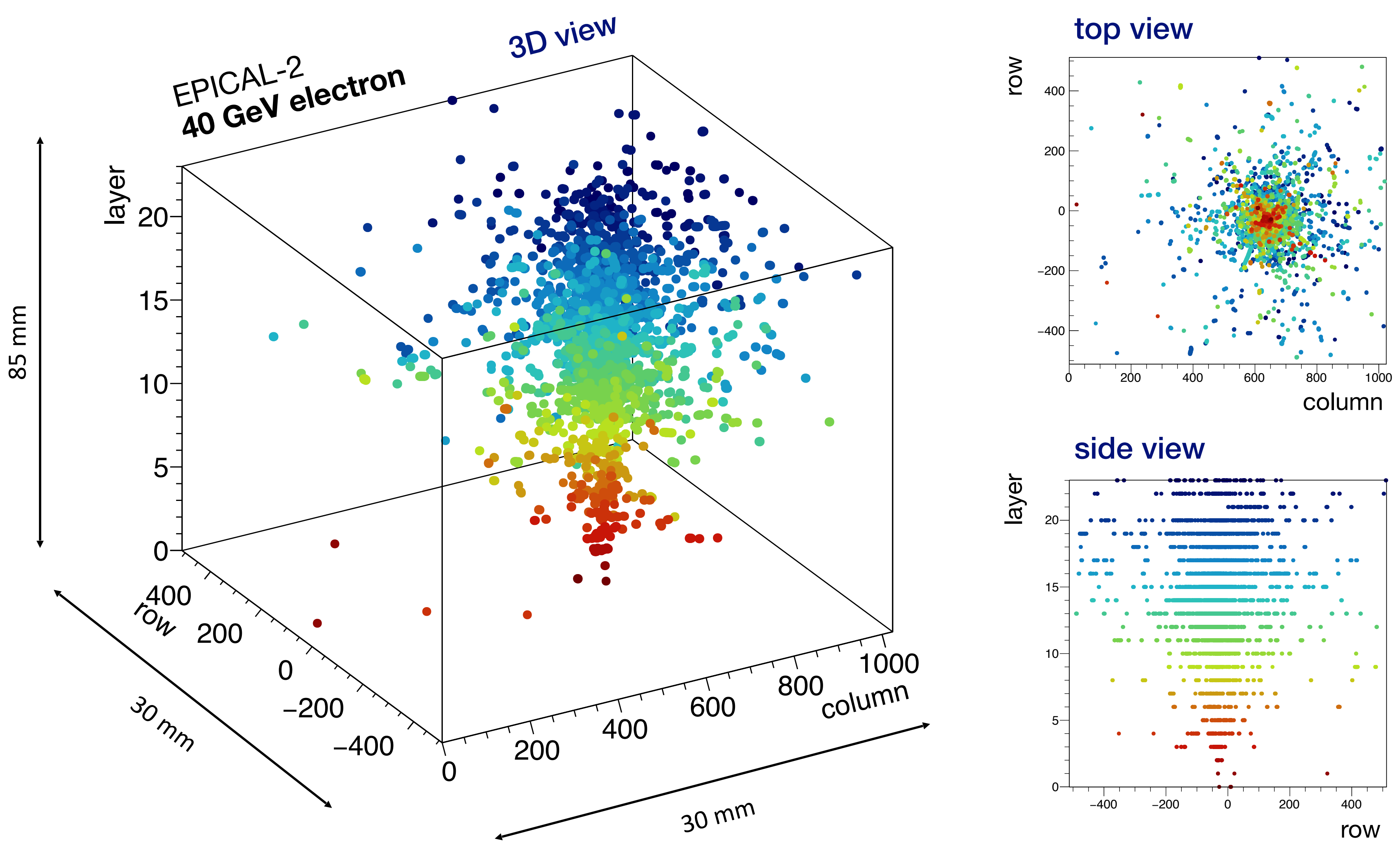


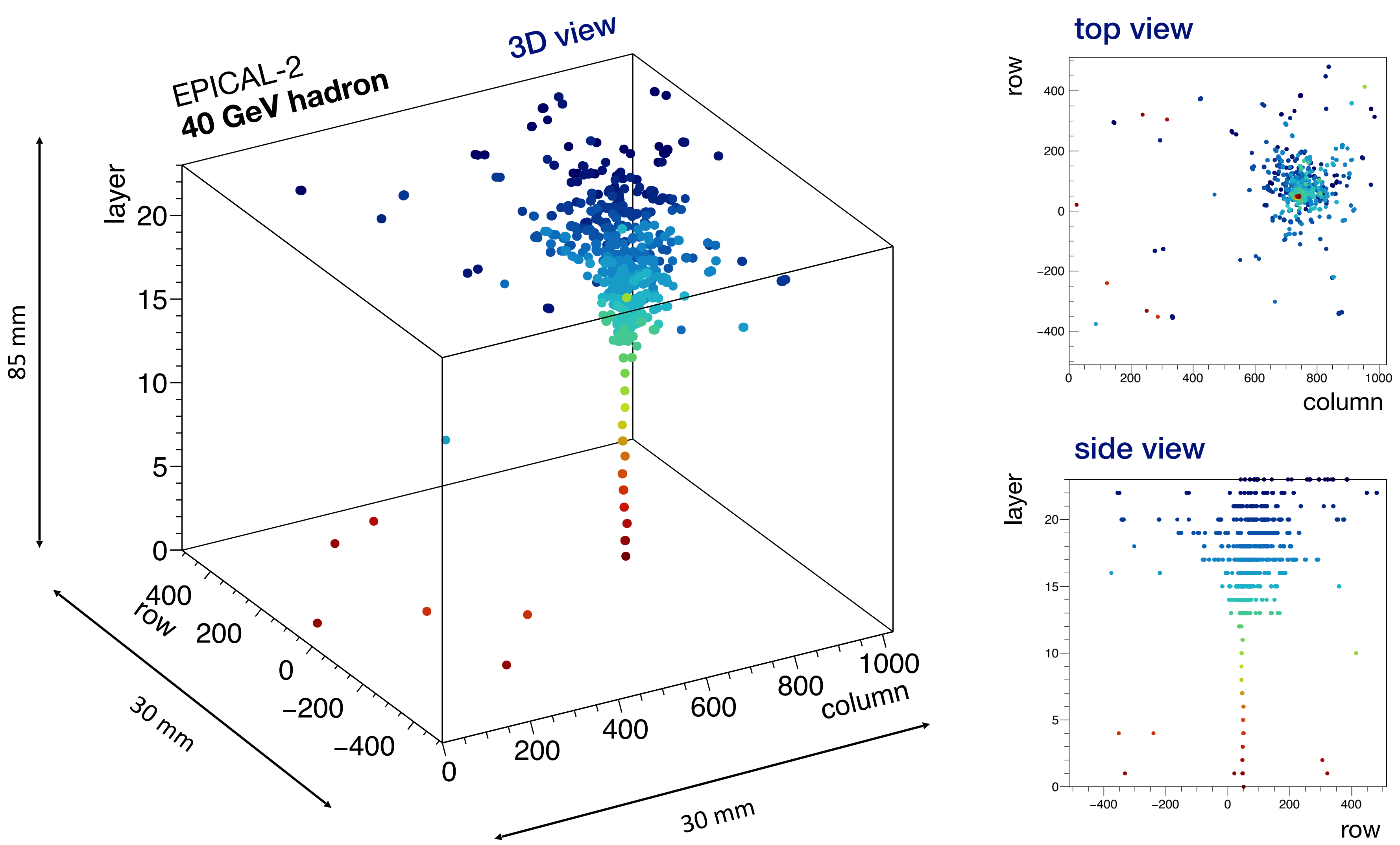


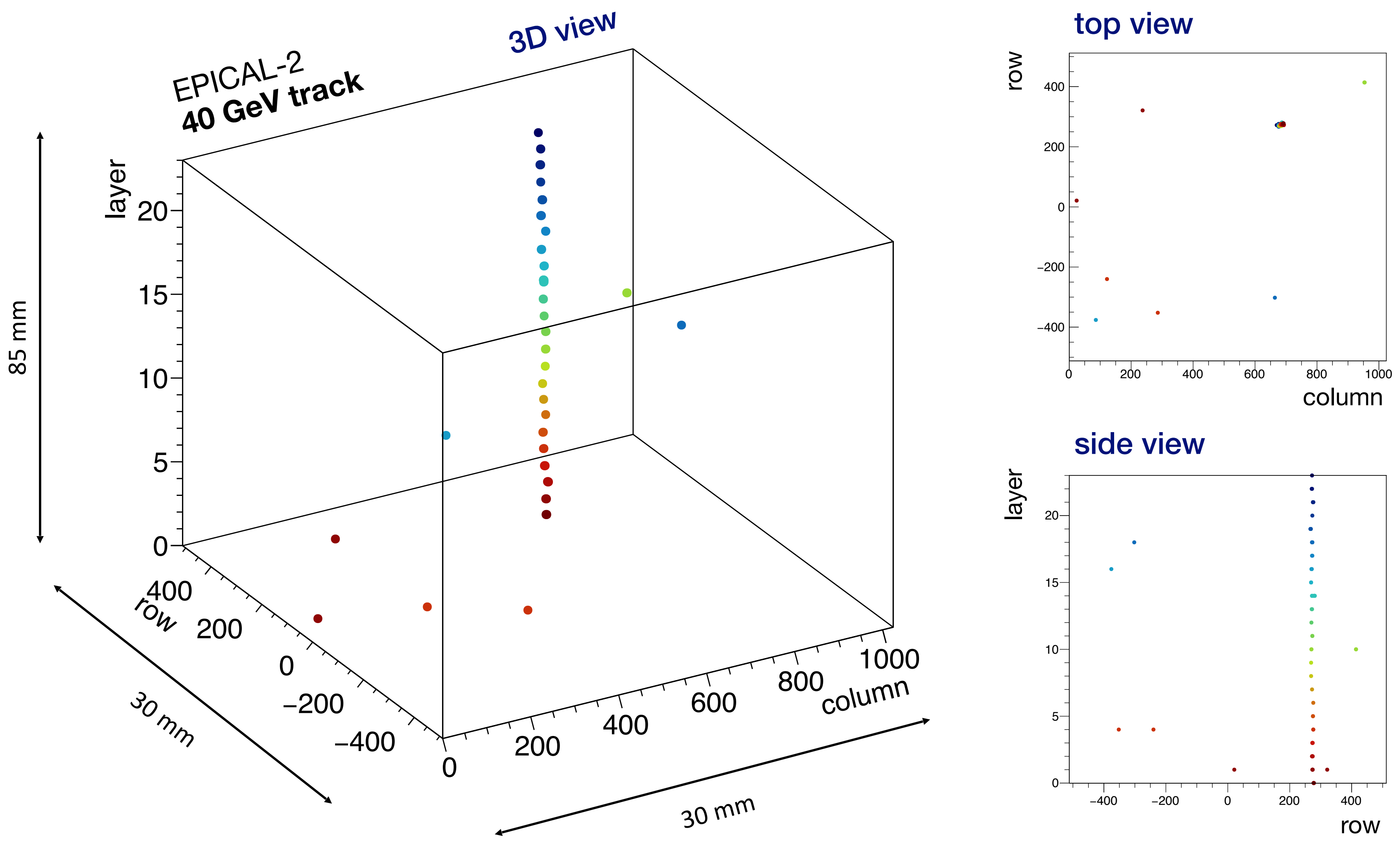
- Detailed implementation of ALPIDE sensor and detector geometry
- Good description of detector behaviour

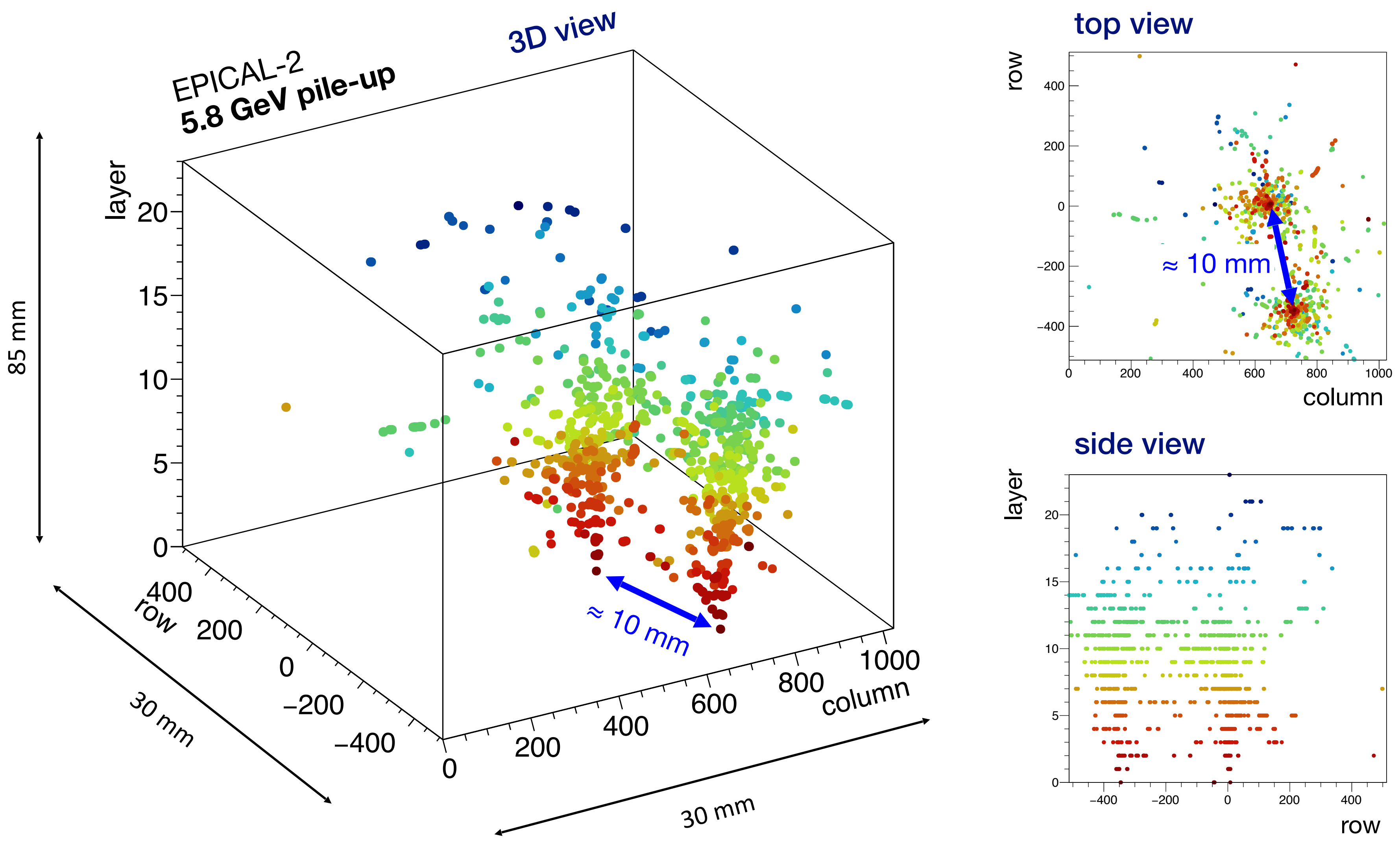
Allpix²: NIM A, 901:164–172, 2018

EPICAL-2 Event Displays









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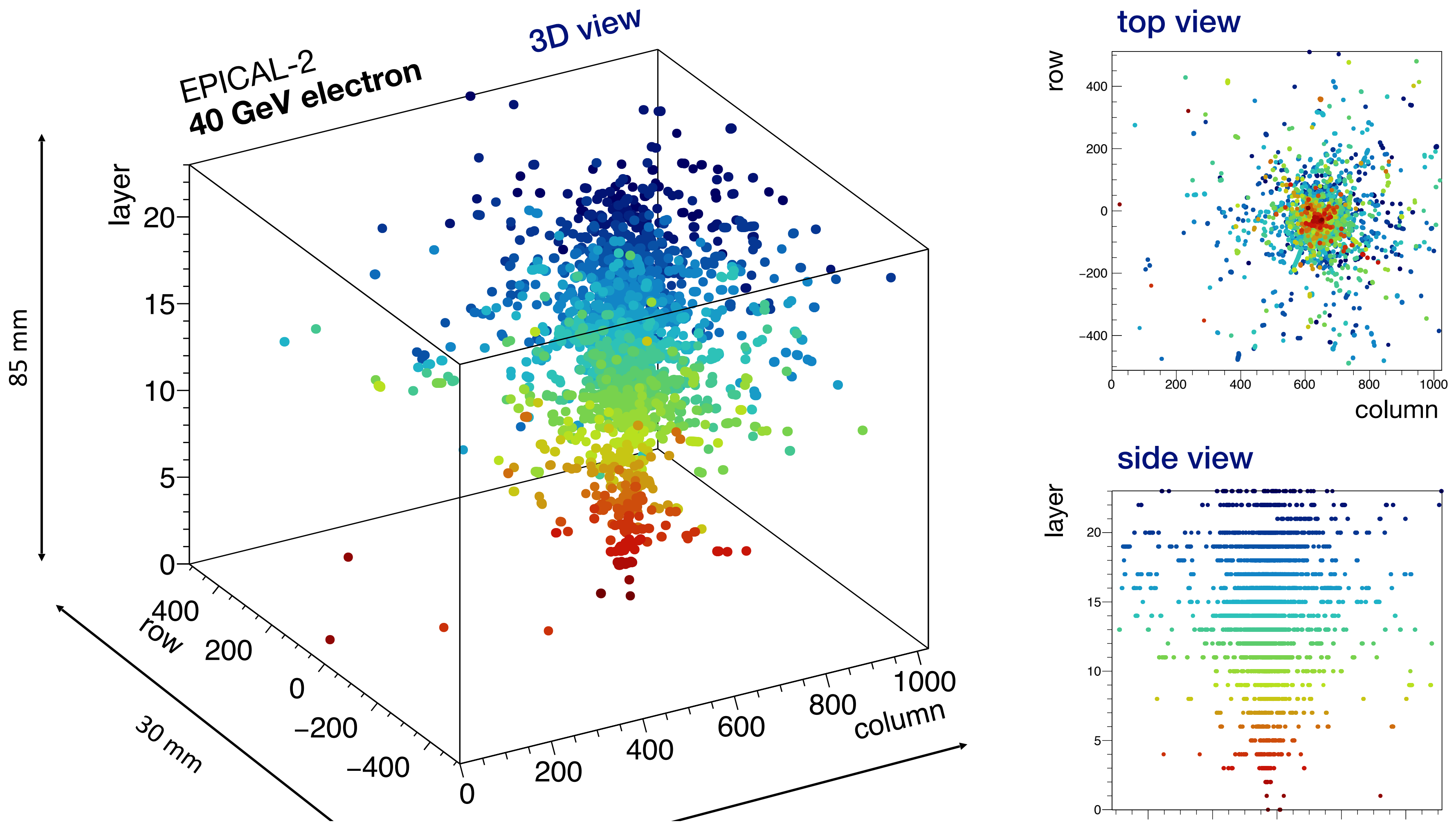
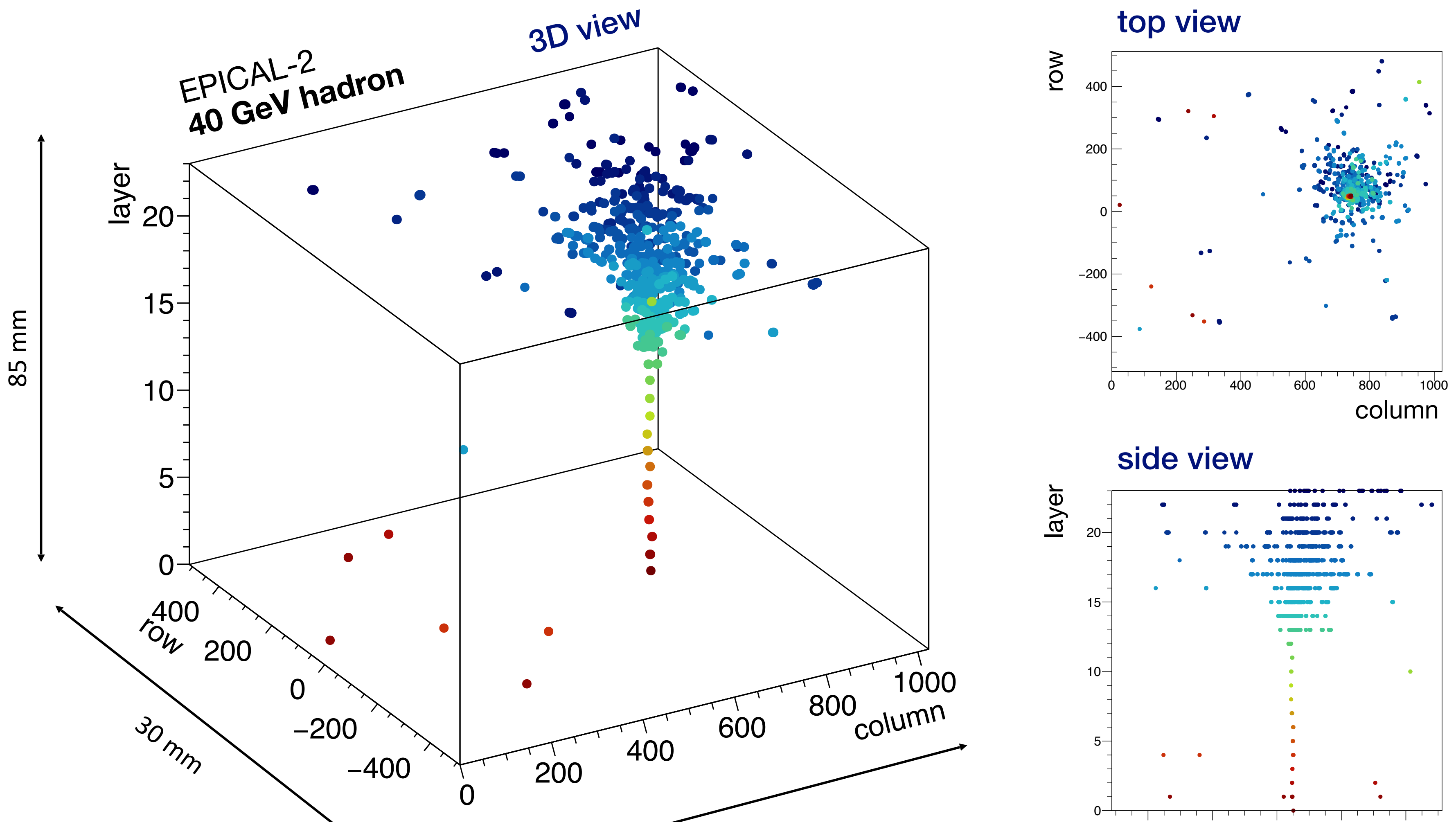
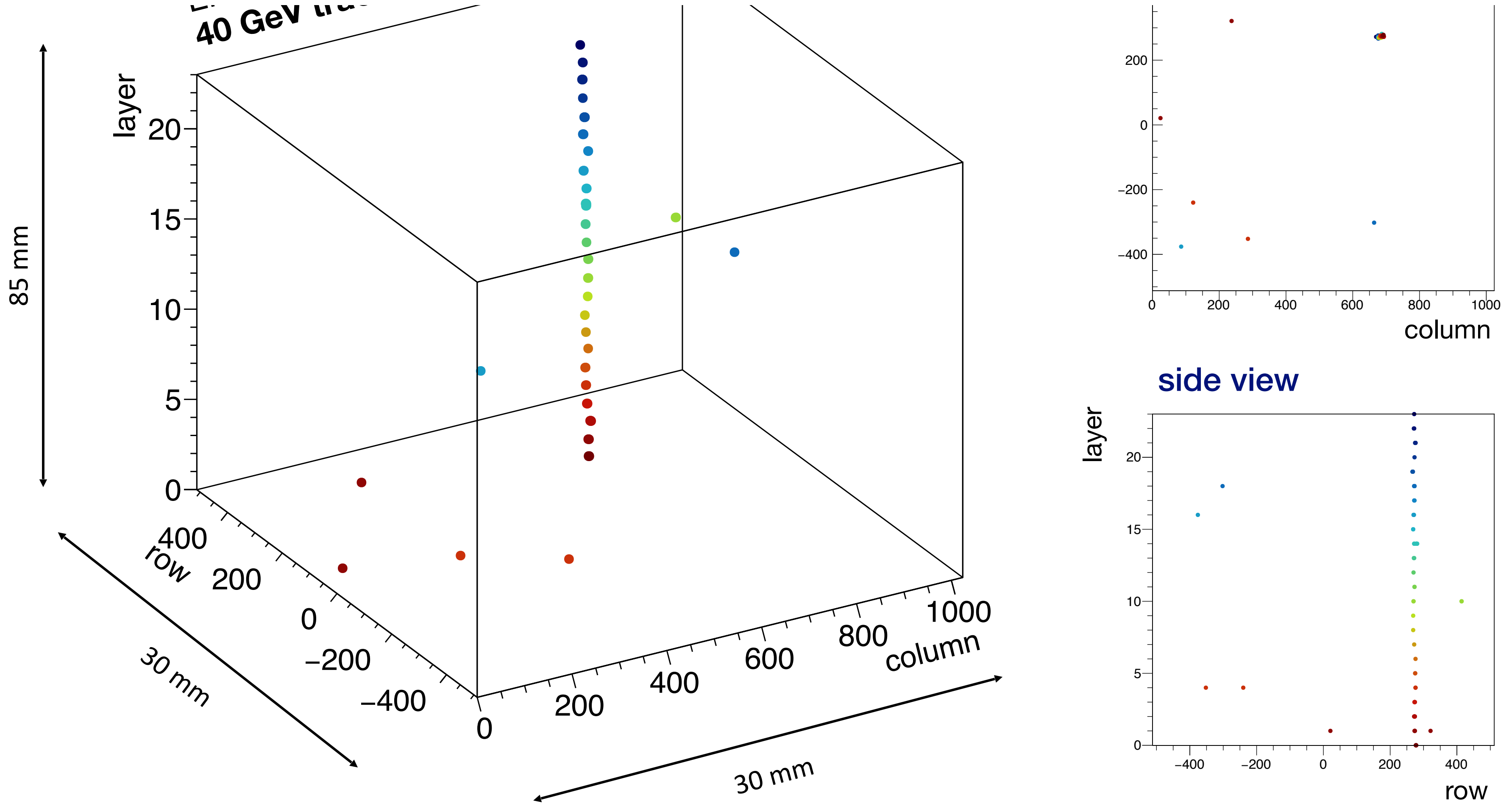
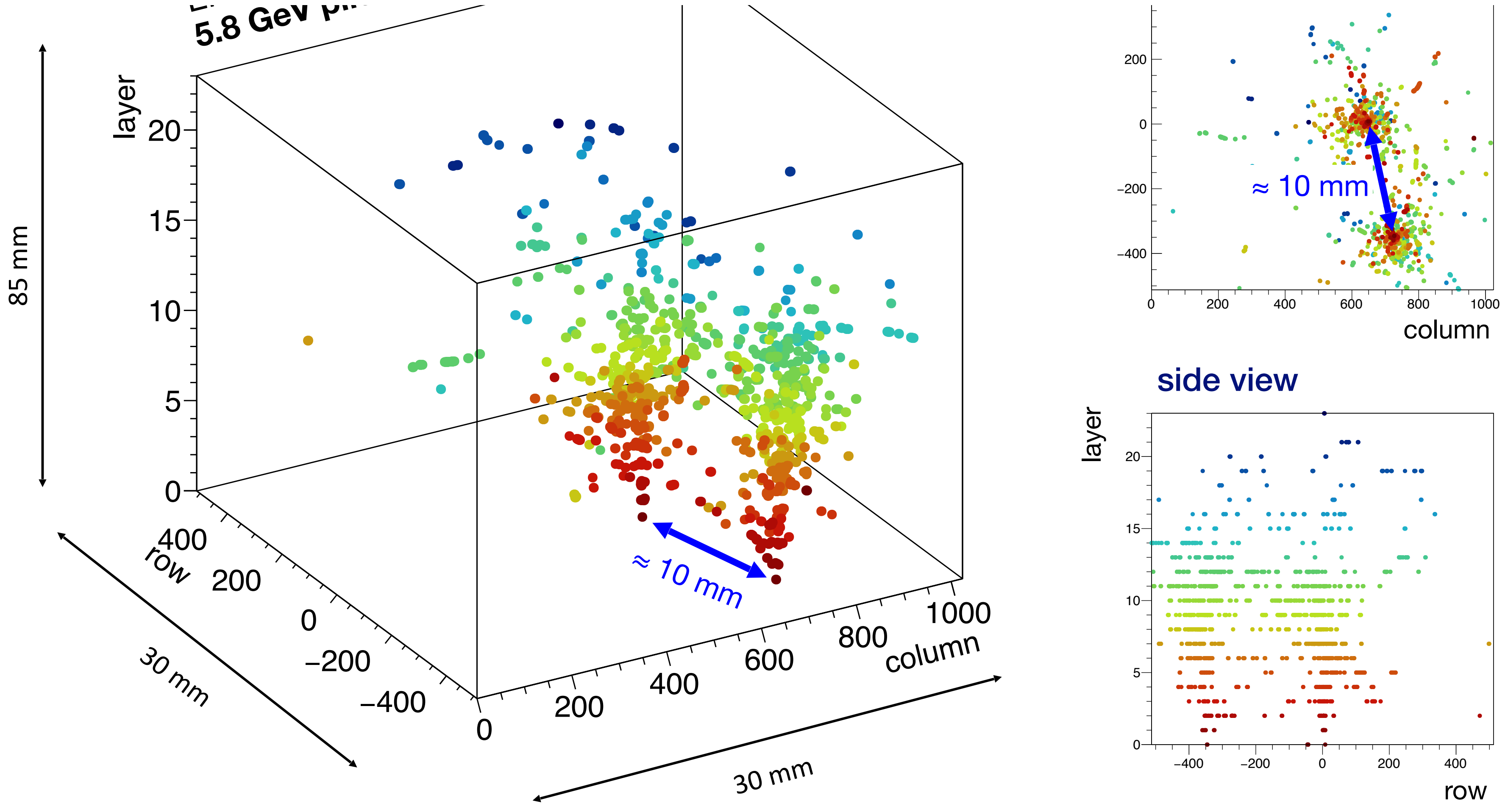


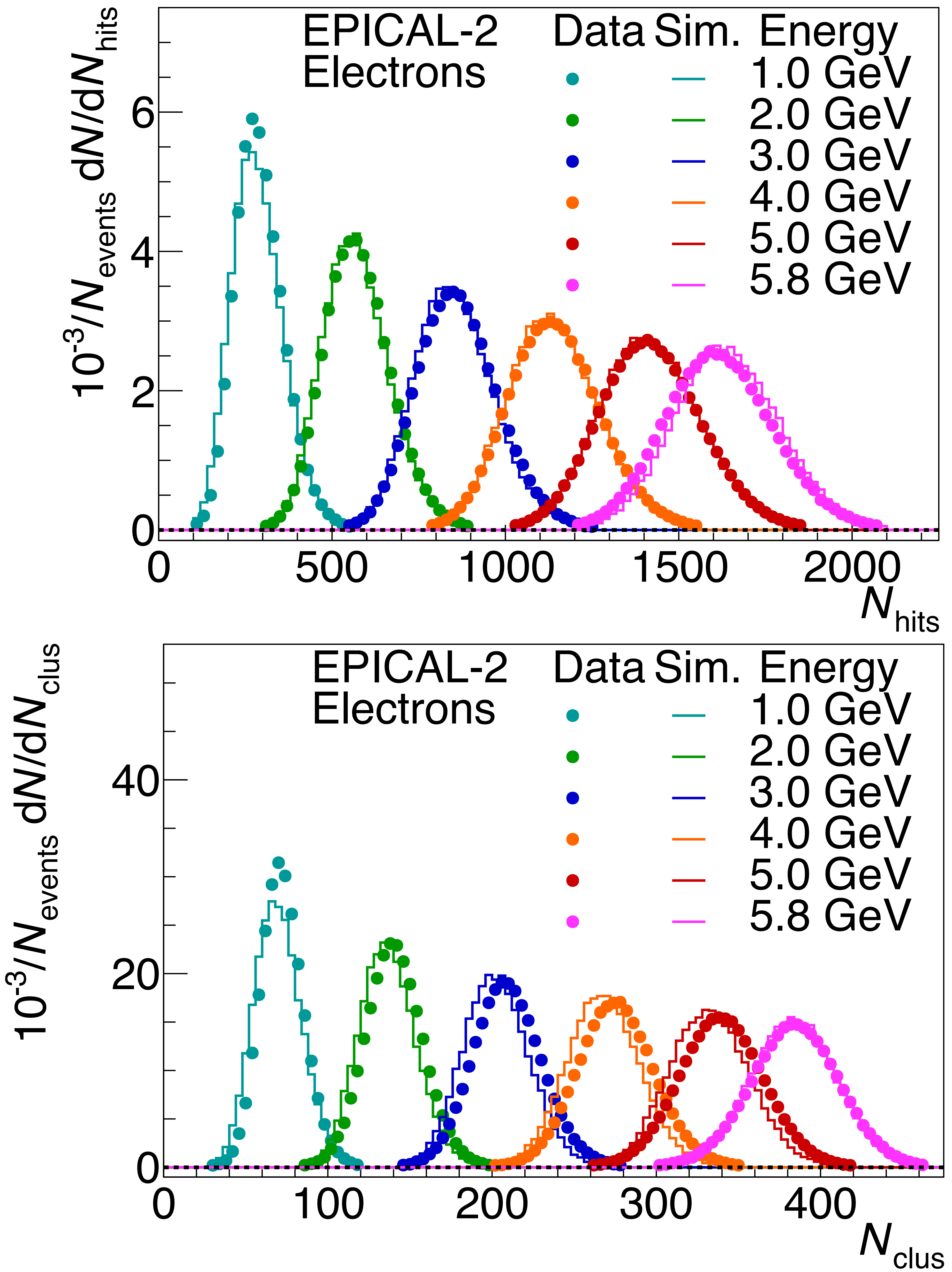


High potential of pixel technology for more sophisticated shower reconstruction
e.g. advancement of PFA?





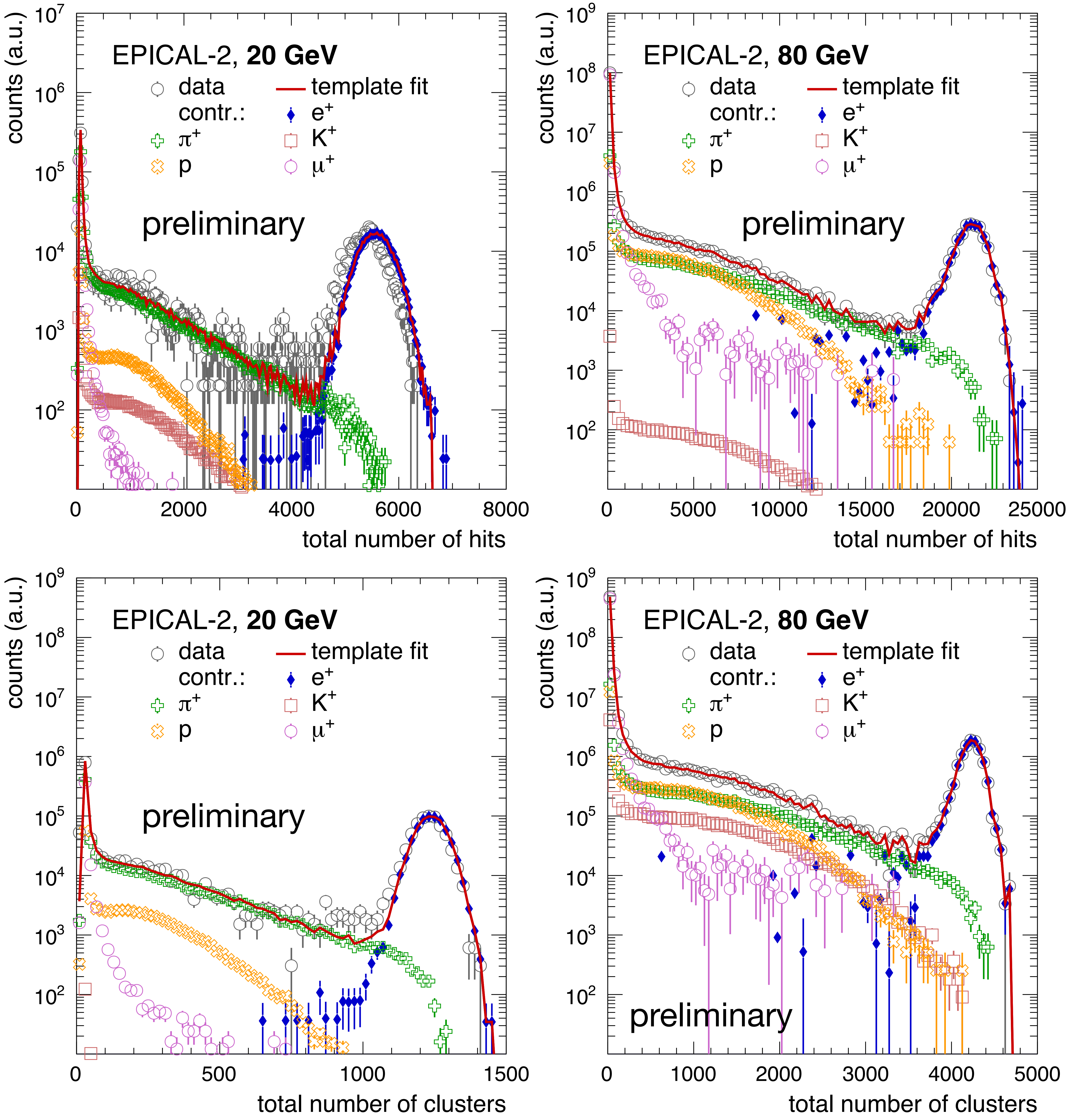
Detector Response at DESY



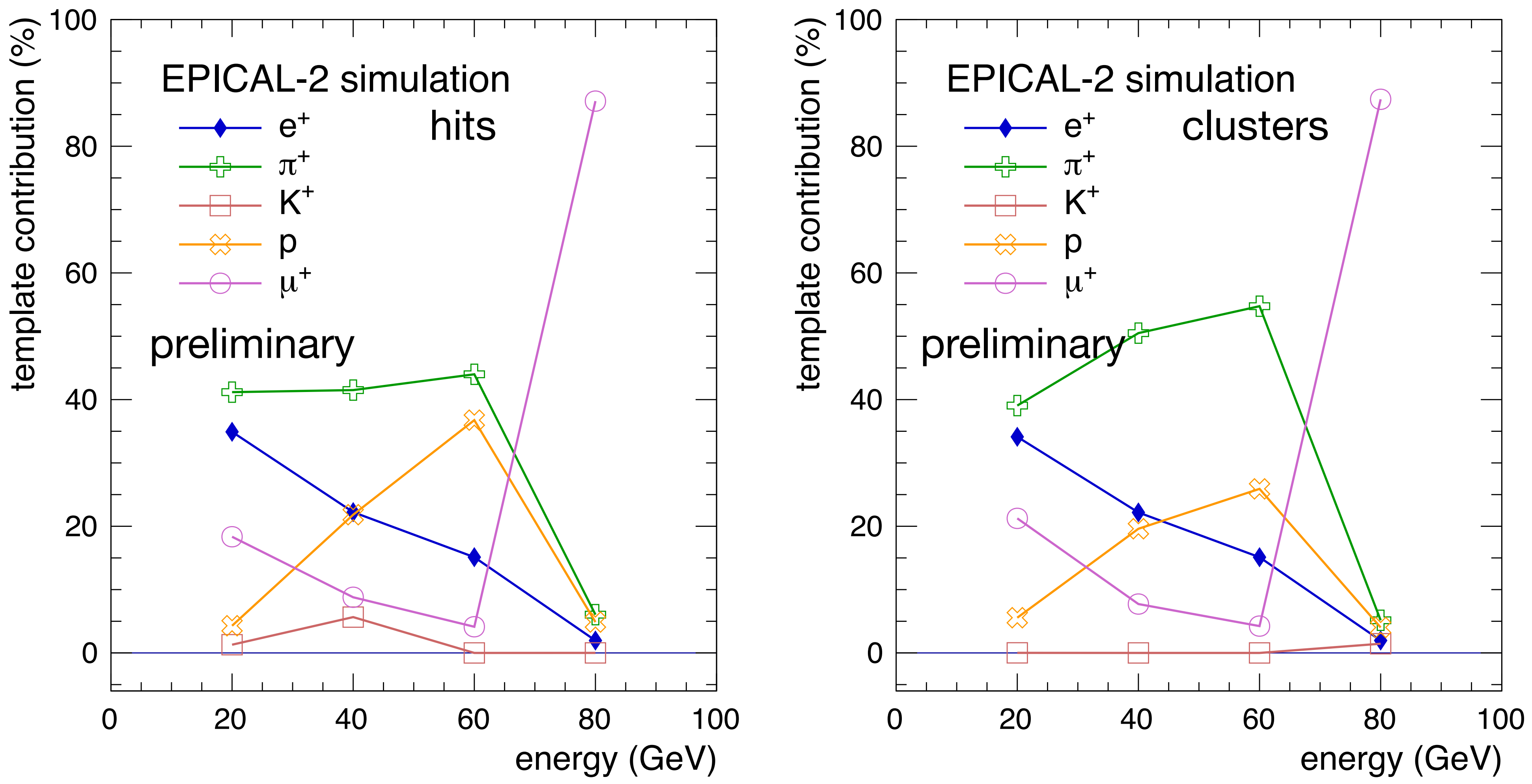
- Data cleaned up with pile-up rejection
  - Significant at DESY
- Number of hits (N_{hits}) or number of clusters (N_{clus}) usable as response observable
  - Well defined peaks scaling with beam energy
- Allpix² simulation
  - Tuned to number of hits at 5 GeV
  - Very good description for hits at all energies
    - Small deviations related to beam energy uncertainty
  - Good description for clusters
    - Sensitive to details of cluster algorithm

Tim Rogoschinski

Detector Response at SPS

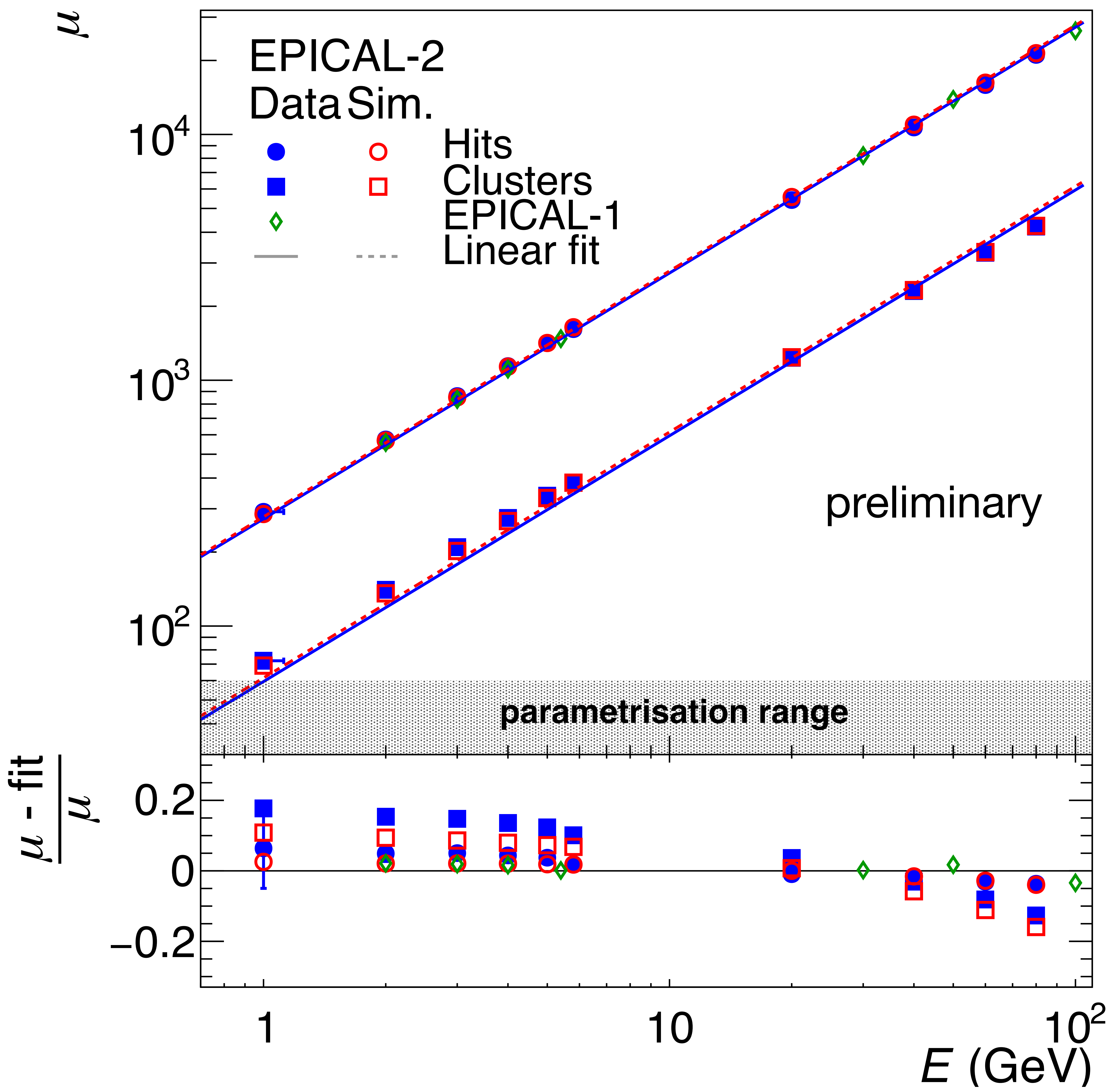


- SPS measurements with mixed beam
  - Relatively small electron component
- Model beam composition with simulation
  - Use simulation as tuned for DESY
  - Fit templates for different species
  - Good description for N_{hits} and clusters N_{clus}
- Obtain beam composition
- Electrons well separated



EPICAL-2 – Energy Linearity

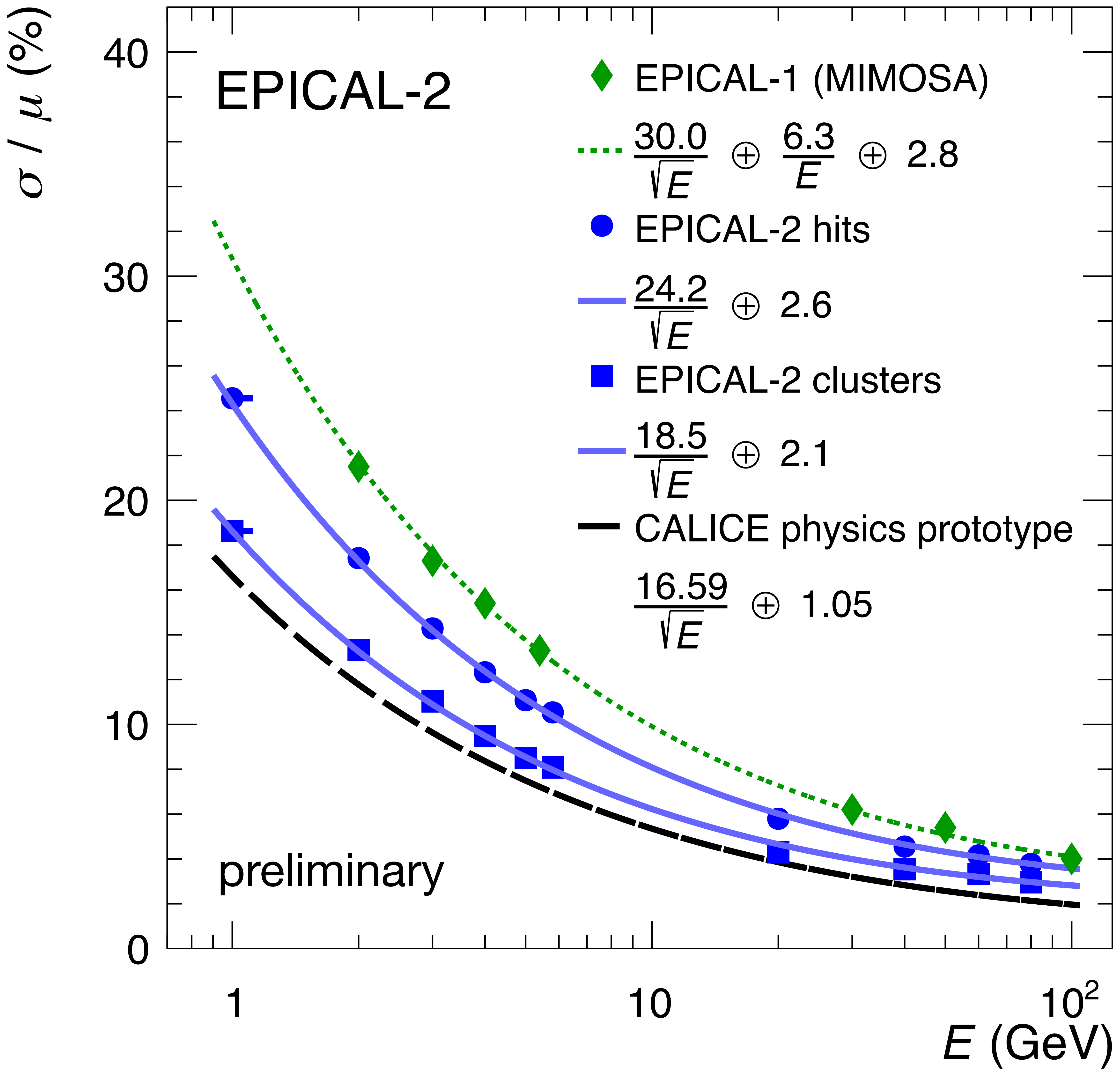
Tim Rogoschinski



- Energy response extracted from N_{hits} and N_{clus} for electrons at different beam energies
  - Test beams at DESY and SPS
- Very good linearity for number of hits
- Significantly stronger non-linearity for number of clusters
  - Related to cluster overlap/saturation
- Good agreement with simulation
  - Contribution to apparent additional non-linearity in data at low energy from systematic uncertainty of test beam momentum at DESY

EPICAL-2 – Energy Resolution

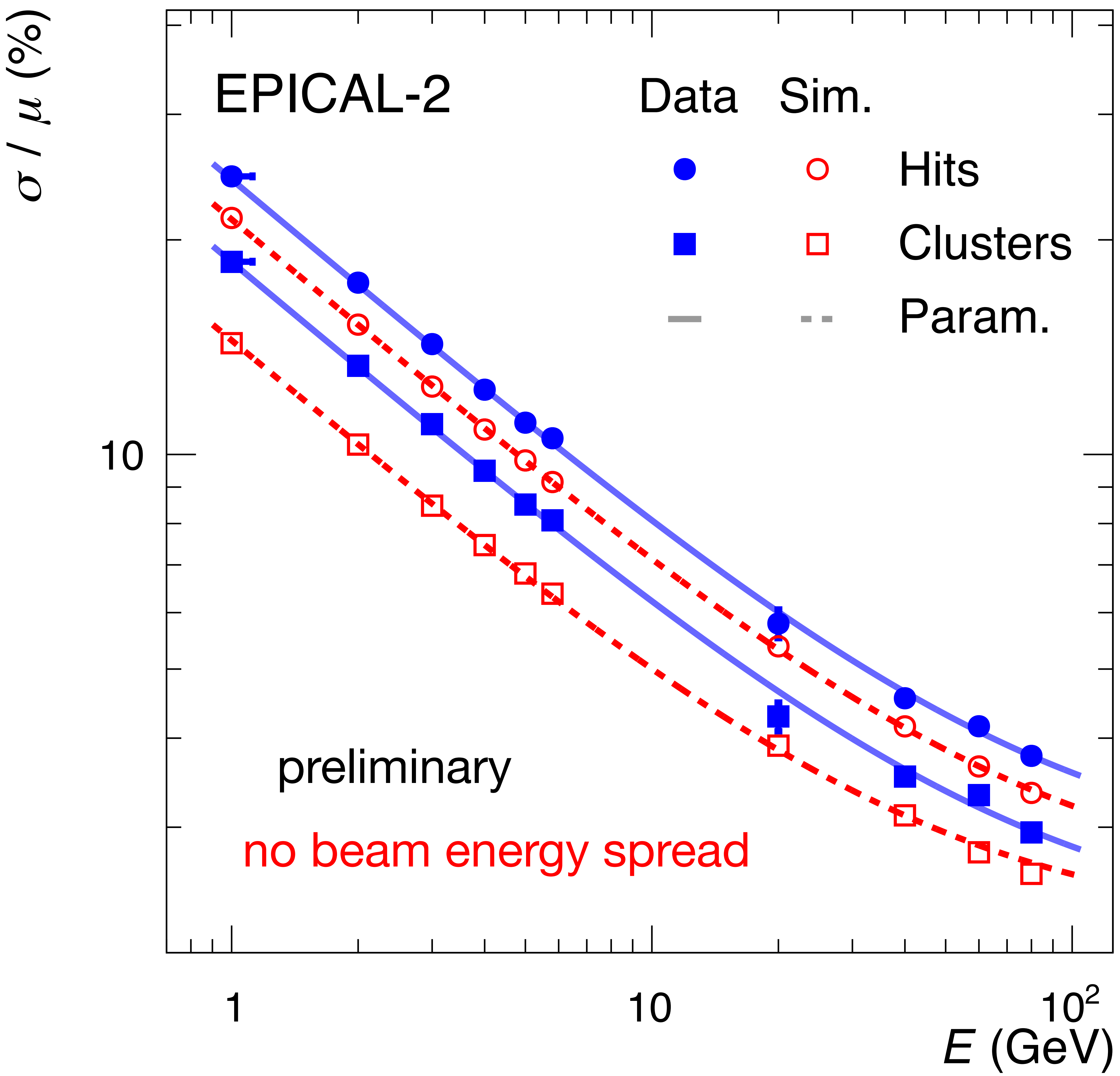
Tim Rogoschinski

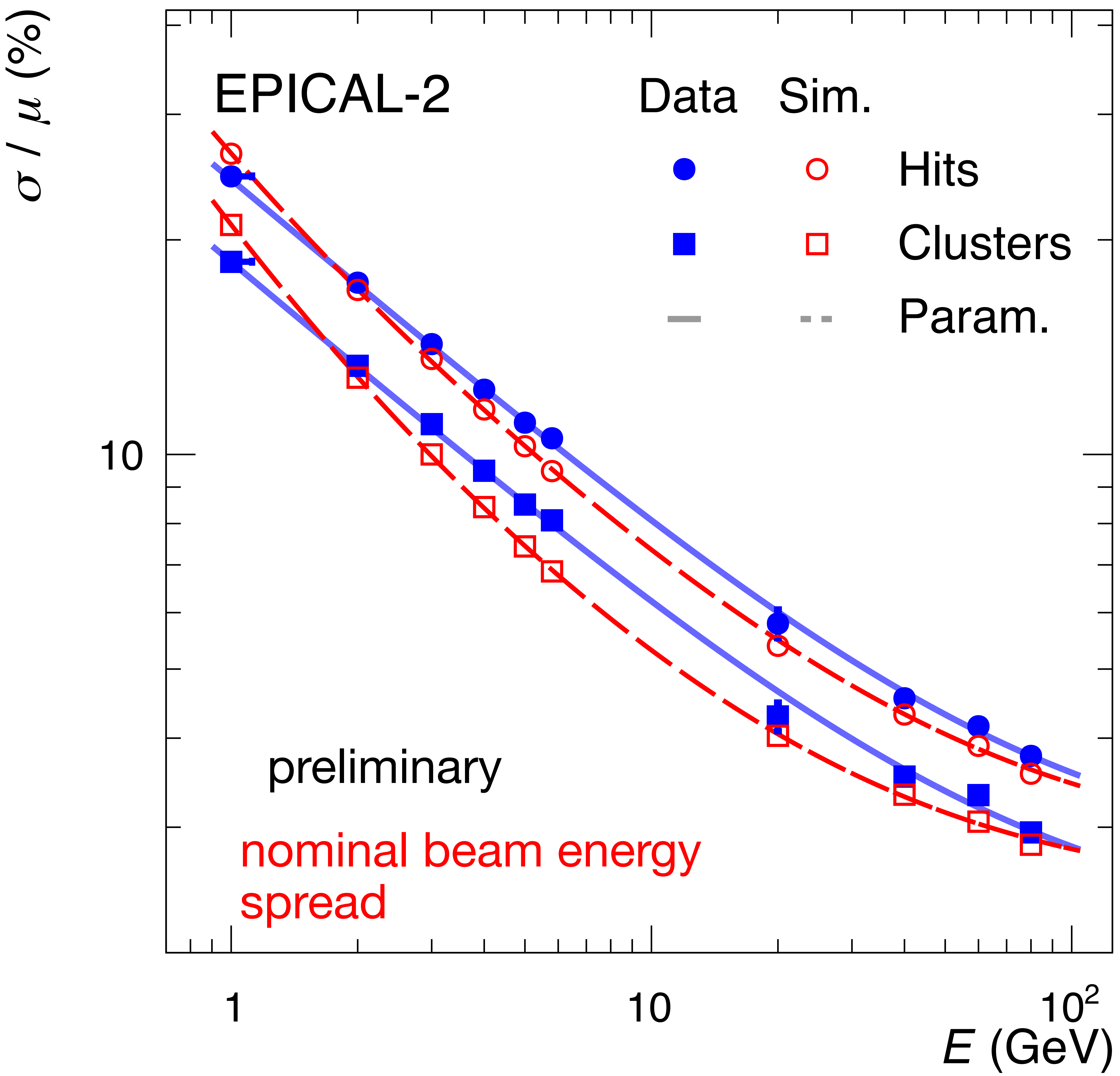


- Good energy resolution from N_{hits}
  - Significantly better compared to first prototype (EPICAL-1 using MIMOSA)
- Very good energy resolution from N_{clus}
  - Comparable to CALICE SiW physics prototype
    (NIM A 608 (2009) 372-383)
  - EPICAL-2 data not corrected for beam energy spread
    - Simulation yields still significantly better resolution

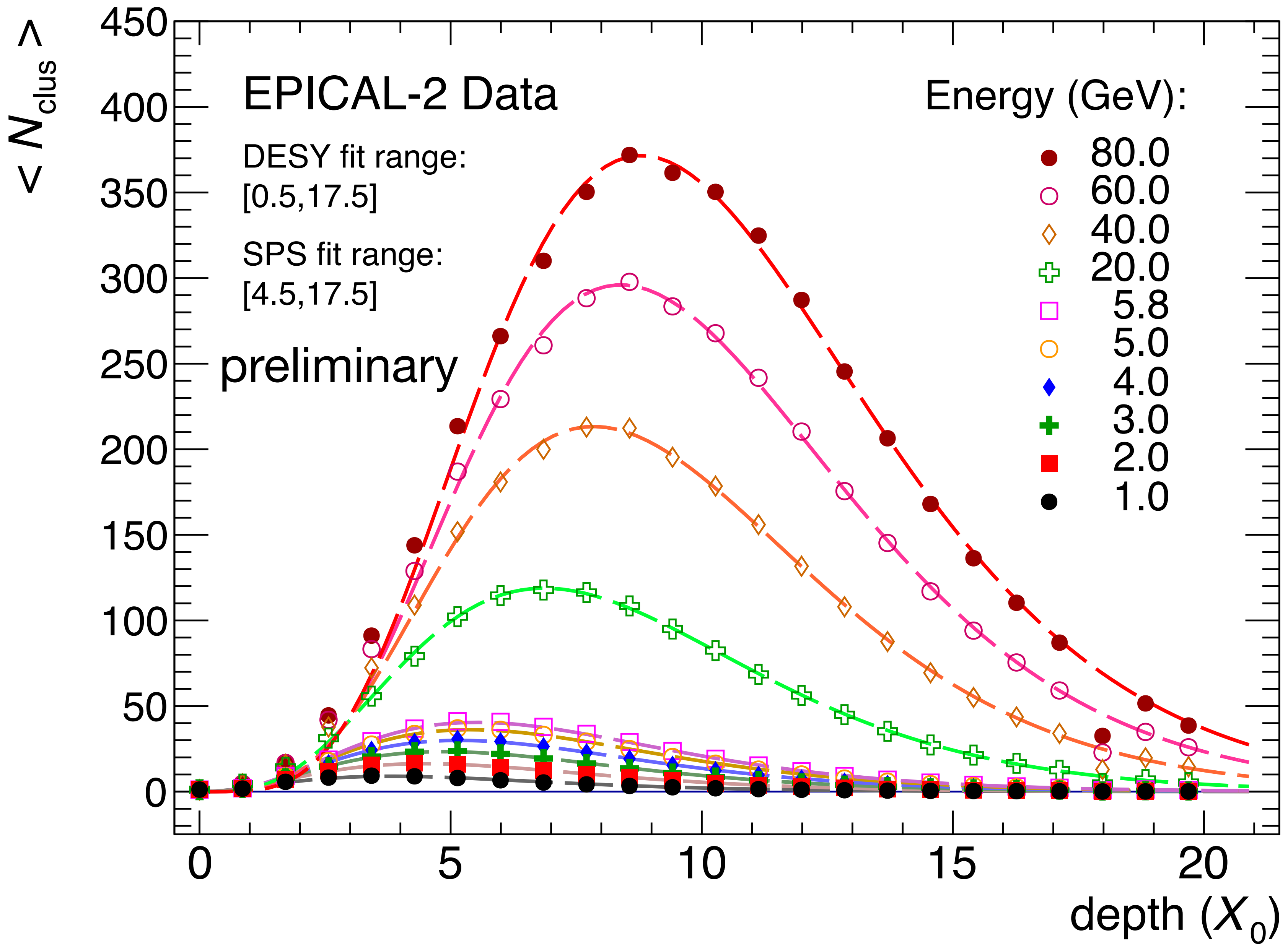
EPICAL-2 – Energy Resolution

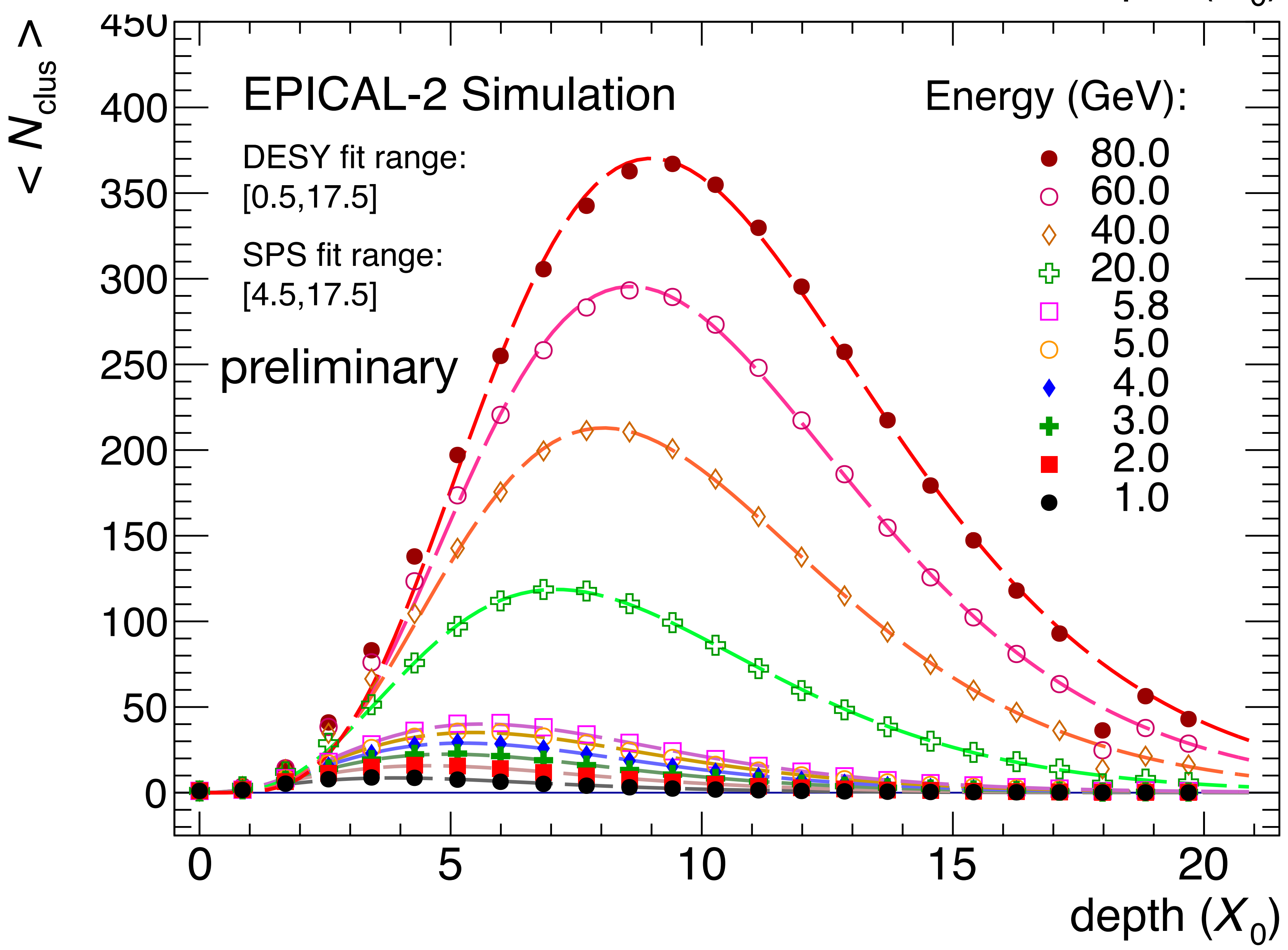
Tim Rogoschinski

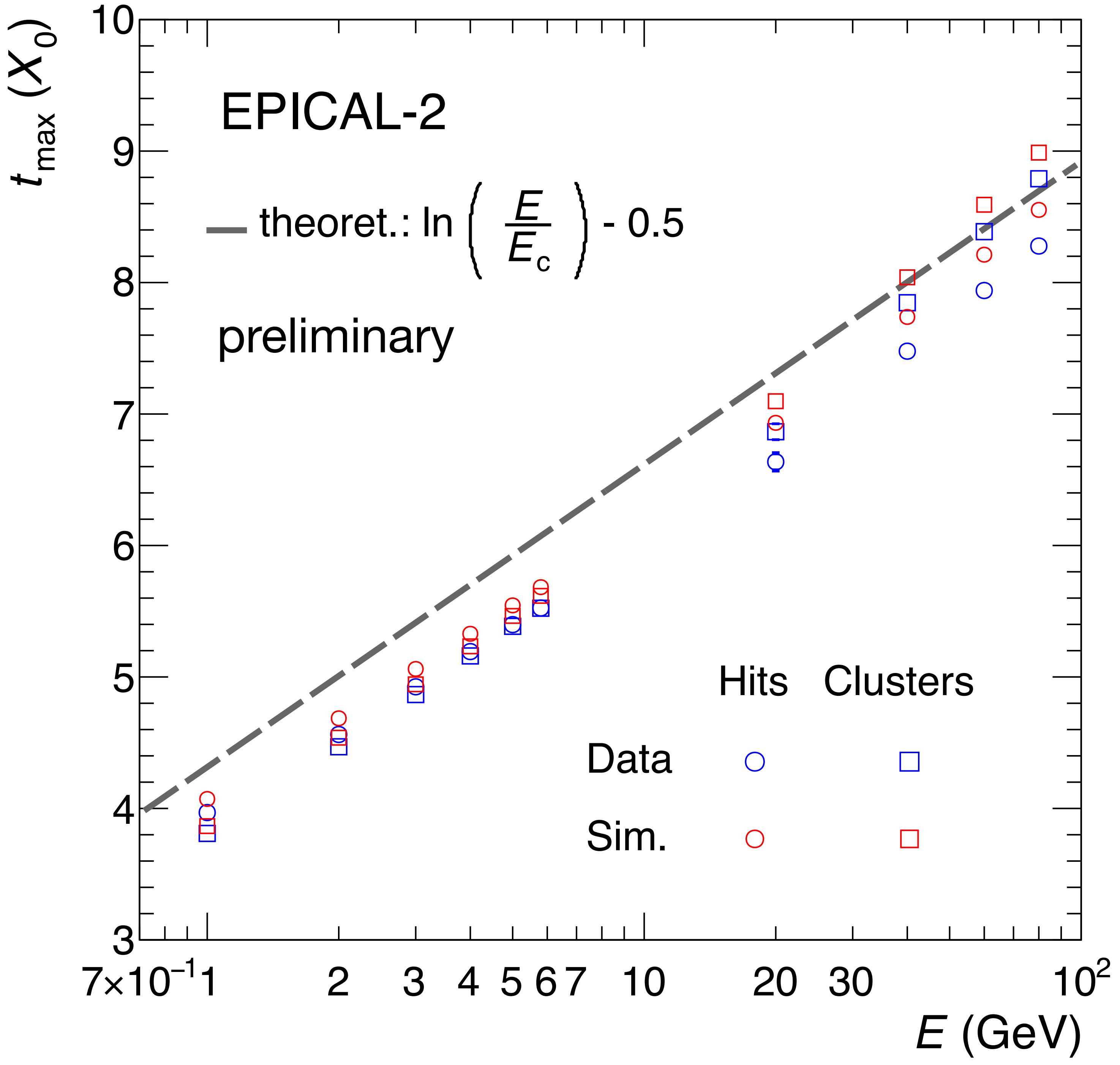




Longitudinal Shower Profiles





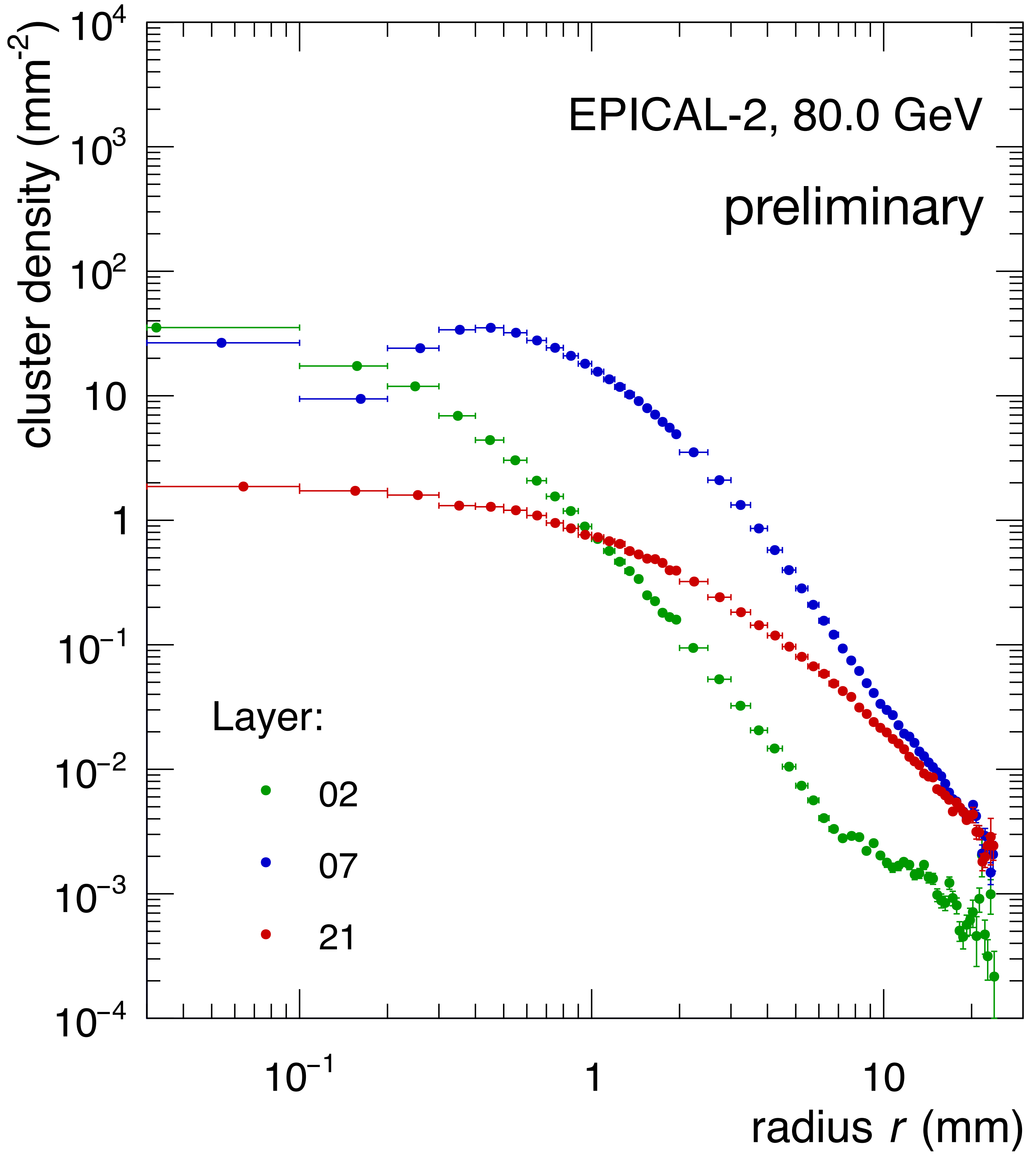


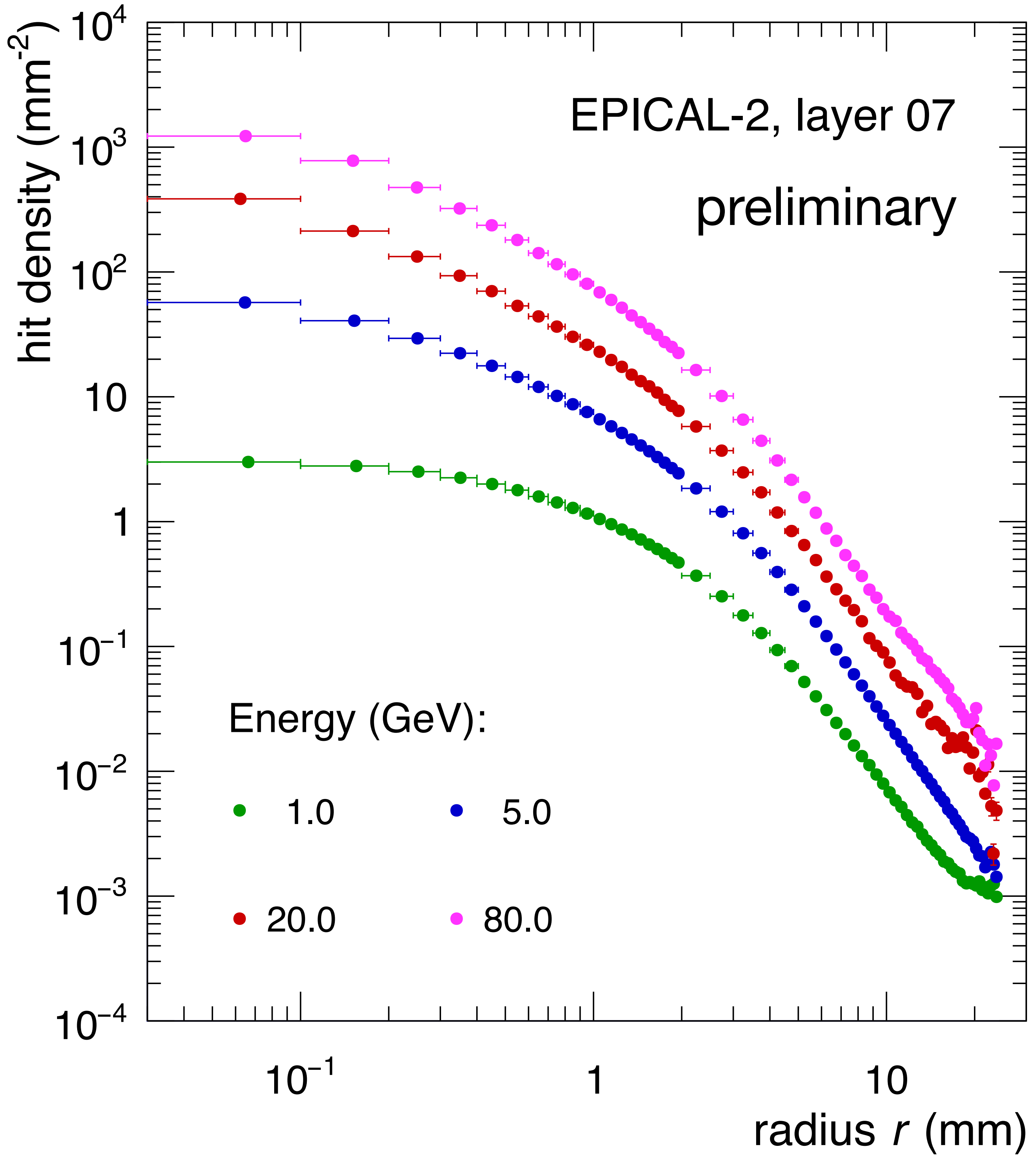
- Longitudinal and lateral shower distributions show expected behaviour
  - Similar for N_{clus} and N_{hits}
- Good qualitative agreement with simulation
- Interesting quantitative differences in shower maximum t_{max}
  - Larger for hits vs clusters at low energy - reverses at high energy
  - Larger for simulation vs data

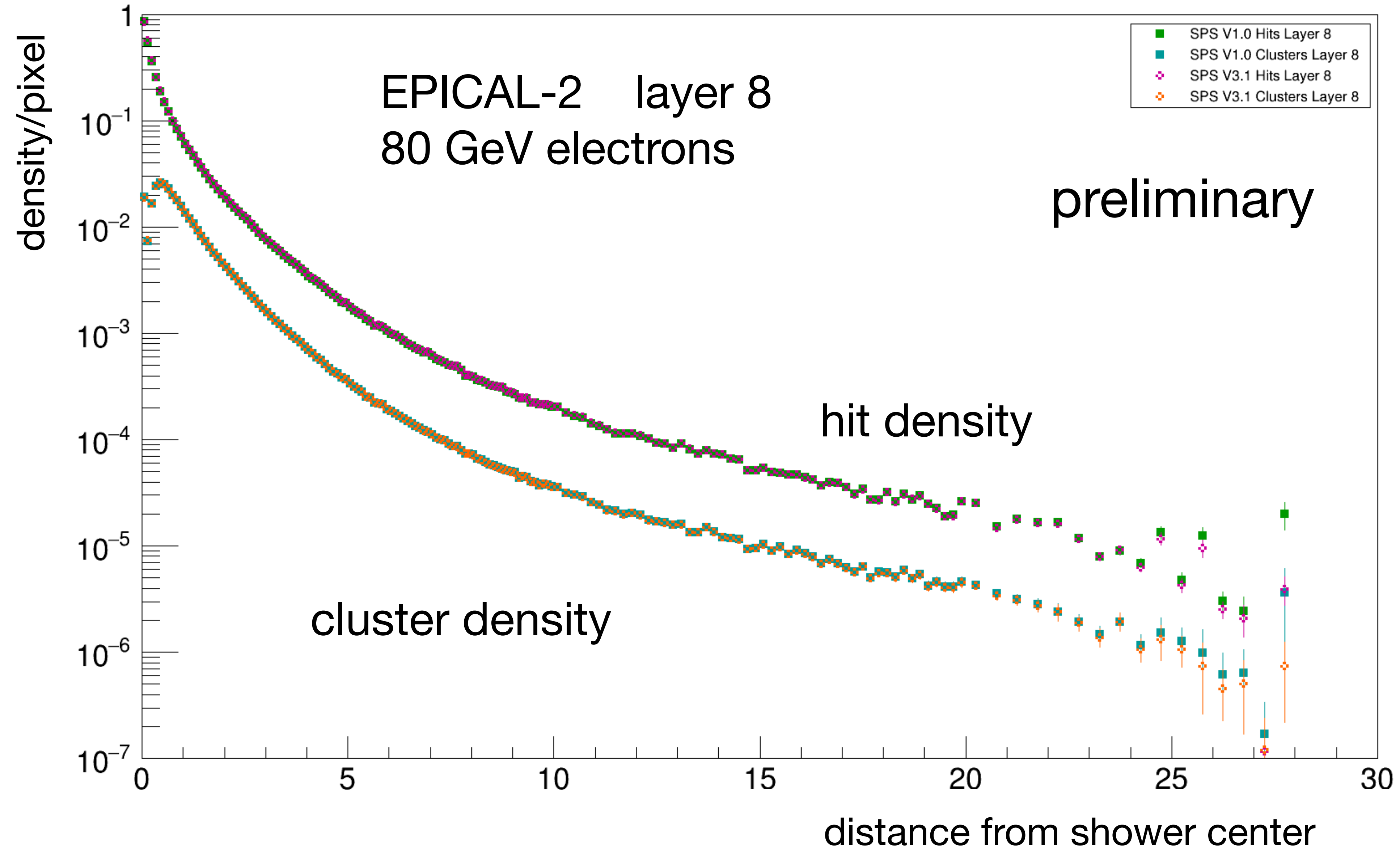
Tim Rogoschinski

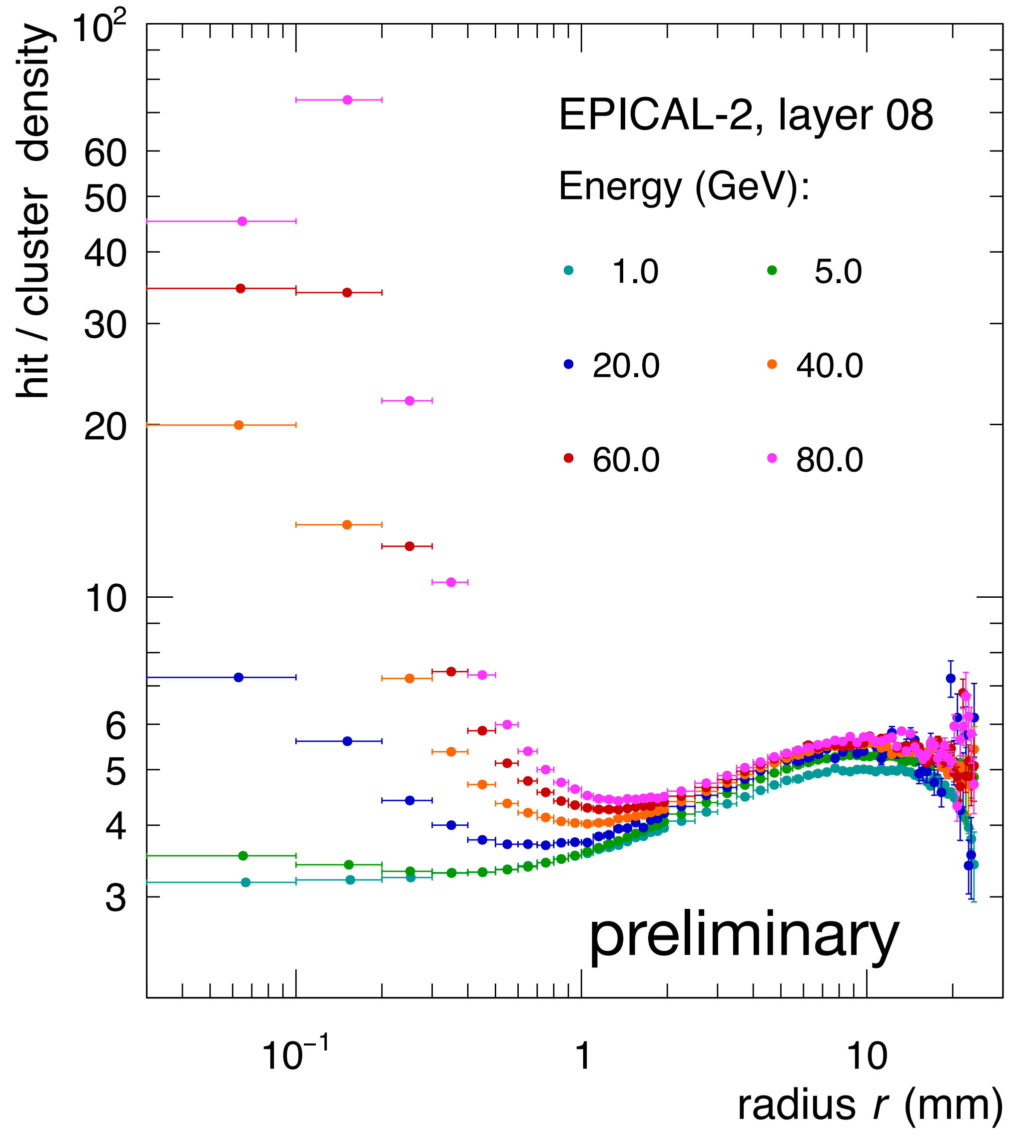
Lateral Shower Profiles

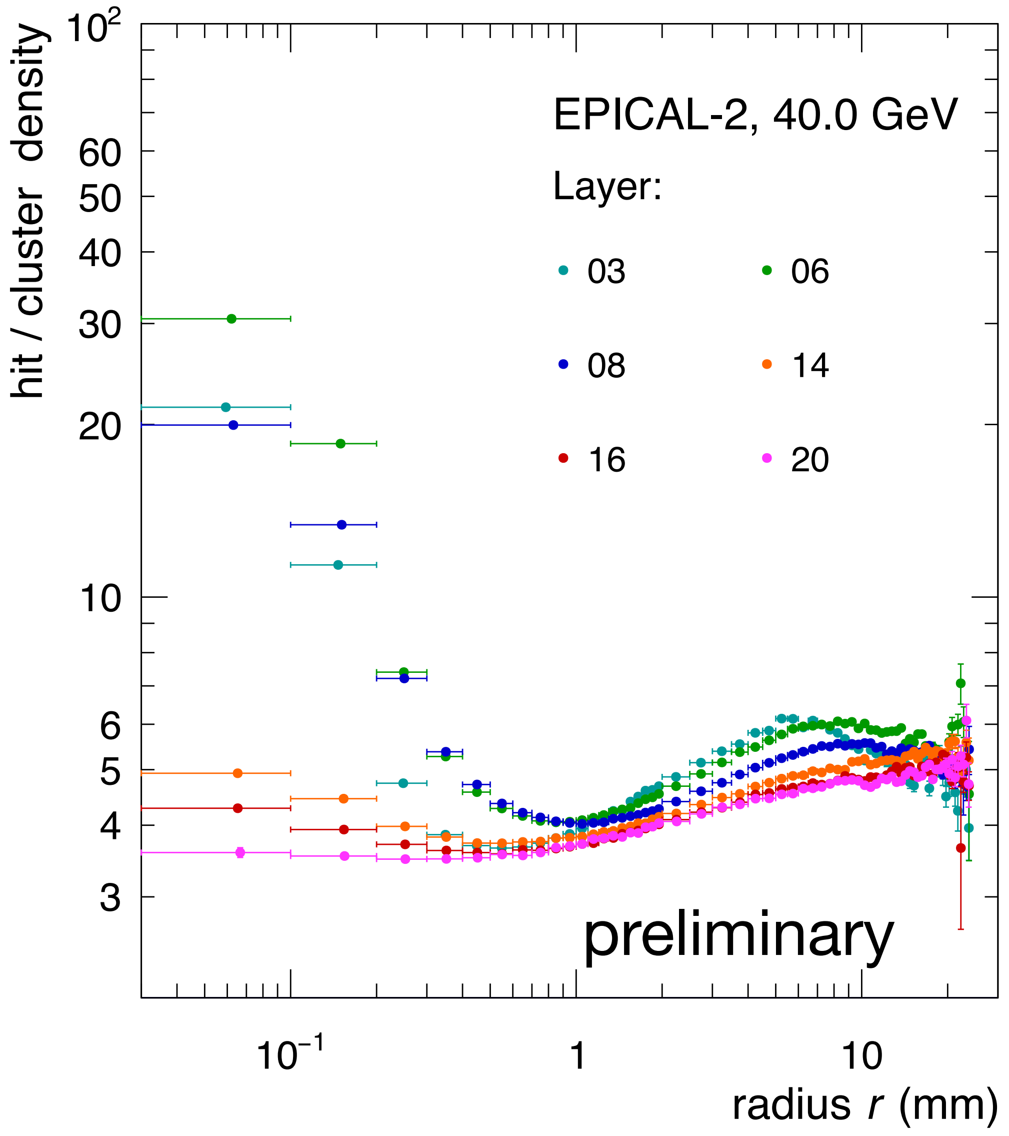
Finn Smits







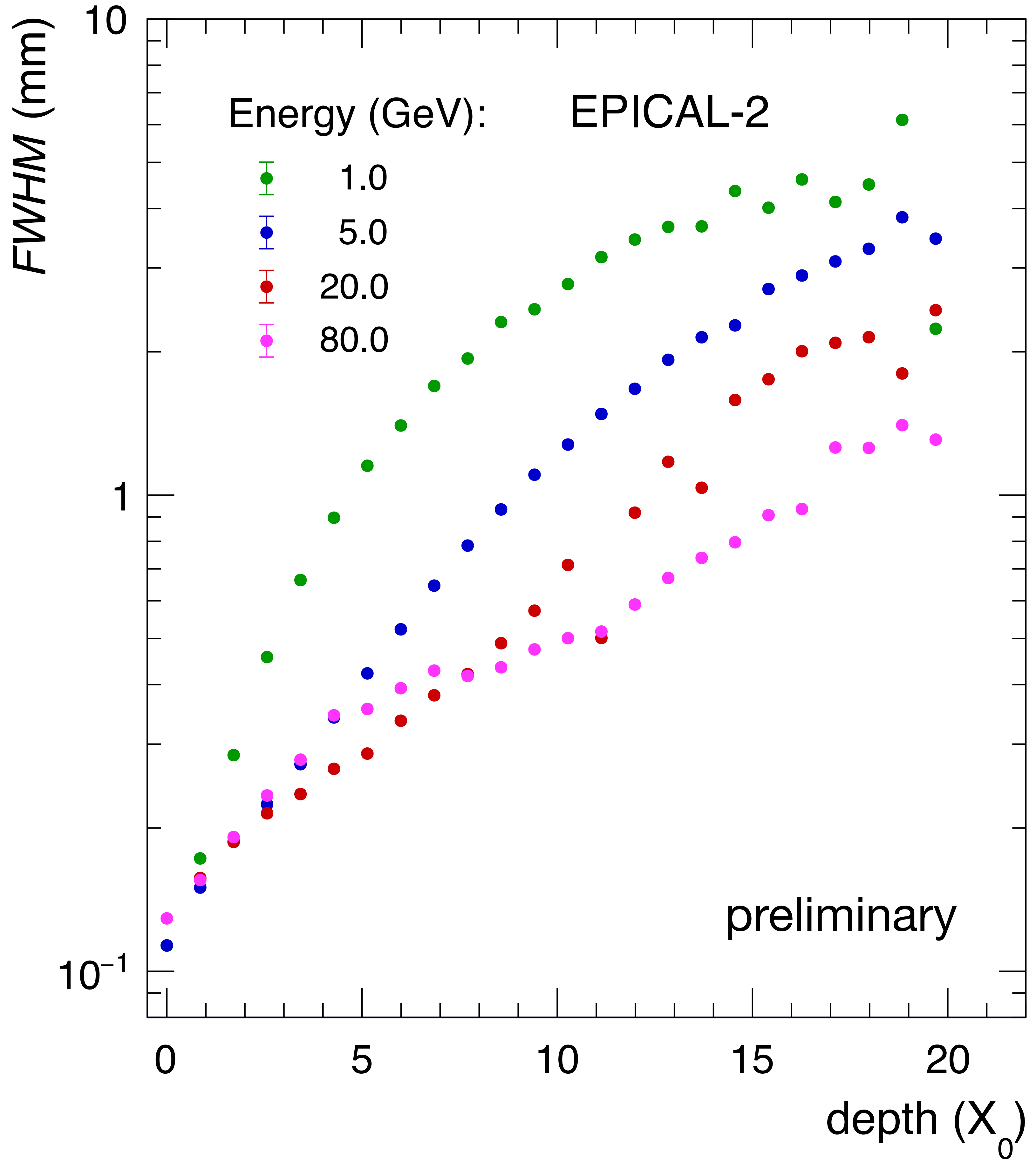


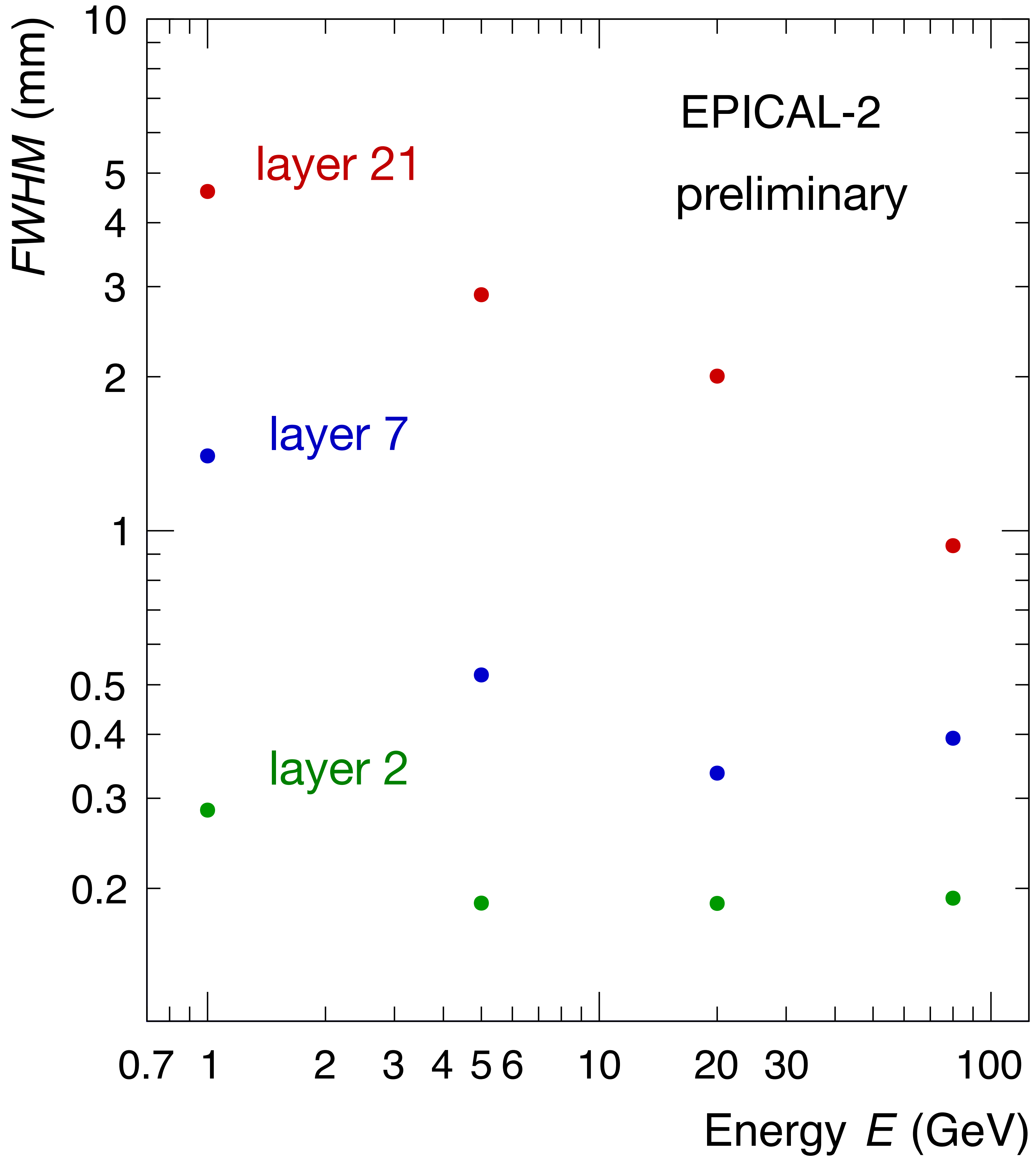


- Cluster density shows saturation in shower core
  - More subtle for hit density - use for first analysis
- First step: study lateral width

Tim Rogoschinski

Lateral Shower Width





- Shower width
  - Increases with depth
  - Decreases with energy
- Should allow two-shower separation on (sub-)mm scale

- FWHM of lateral hit densities per layer
  - Extracted with spline approximation
- Study as a function of shower depth and energy

More on Response Variables

total number of hits/clusters

$$N_{\text{hits}}(R) = \sum_{R_i=0;l=0}^{R_i=R;l=23} N^{(l)}_{\text{hits}}(R_i, \Delta R_i) \qquad N_{\text{clus}}(R) = \sum_{R_i=0;l=0}^{R_i=R;l=23} N^{(l)}_{\text{clus}}(R_i, \Delta R_i)$$

integrated density of hits/clusters (can correct for limited acceptance)

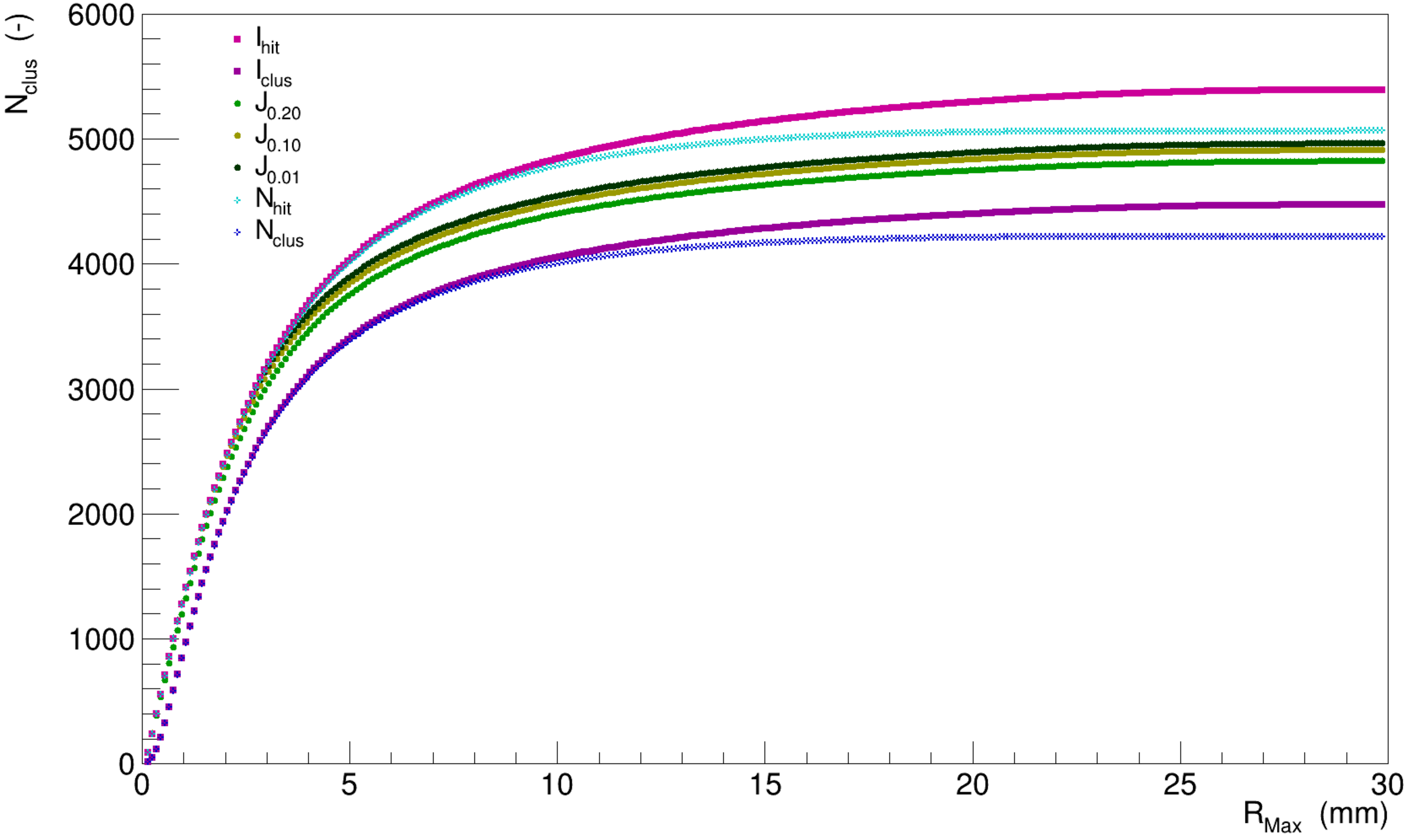
$$\rho^{(l)}_{\text{hits}}(R_i, \Delta R_i) = \frac{N^{(l)}_{\text{hits}}(R_i, \Delta R_i)}{S_{\text{pixel}} \cdot N^{(l)}_{\text{pixel}}(R_i, \Delta R_i)}; \quad I_{\text{hits}}(R) = \sum_{R_i=0}^{R_i=R} 2\pi R_i \Delta R_i \sum_{l=0}^{l=23} \rho^{(l)}_{\text{hits}}(R_i, \Delta R_i)$$

$$\rho^{(l)}_{\text{clus}}(R_i, \Delta R_i) = \frac{N^{(l)}_{\text{clus}}(R_i, \Delta R_i)}{S_{\text{pixel}} \cdot N^{(l)}_{\text{pixel}}(R_i, \Delta R_i)}; \quad I_{\text{clus}}(R) = \sum_{R_i=0}^{R_i=R} 2\pi R_i \Delta R_i \sum_{l=0}^{l=23} \rho^{(l)}_{\text{clus}}(R_i, \Delta R_i)$$

integrated hybrid density (combine strengths of hits and clusters, transition where cluster saturation is significant)

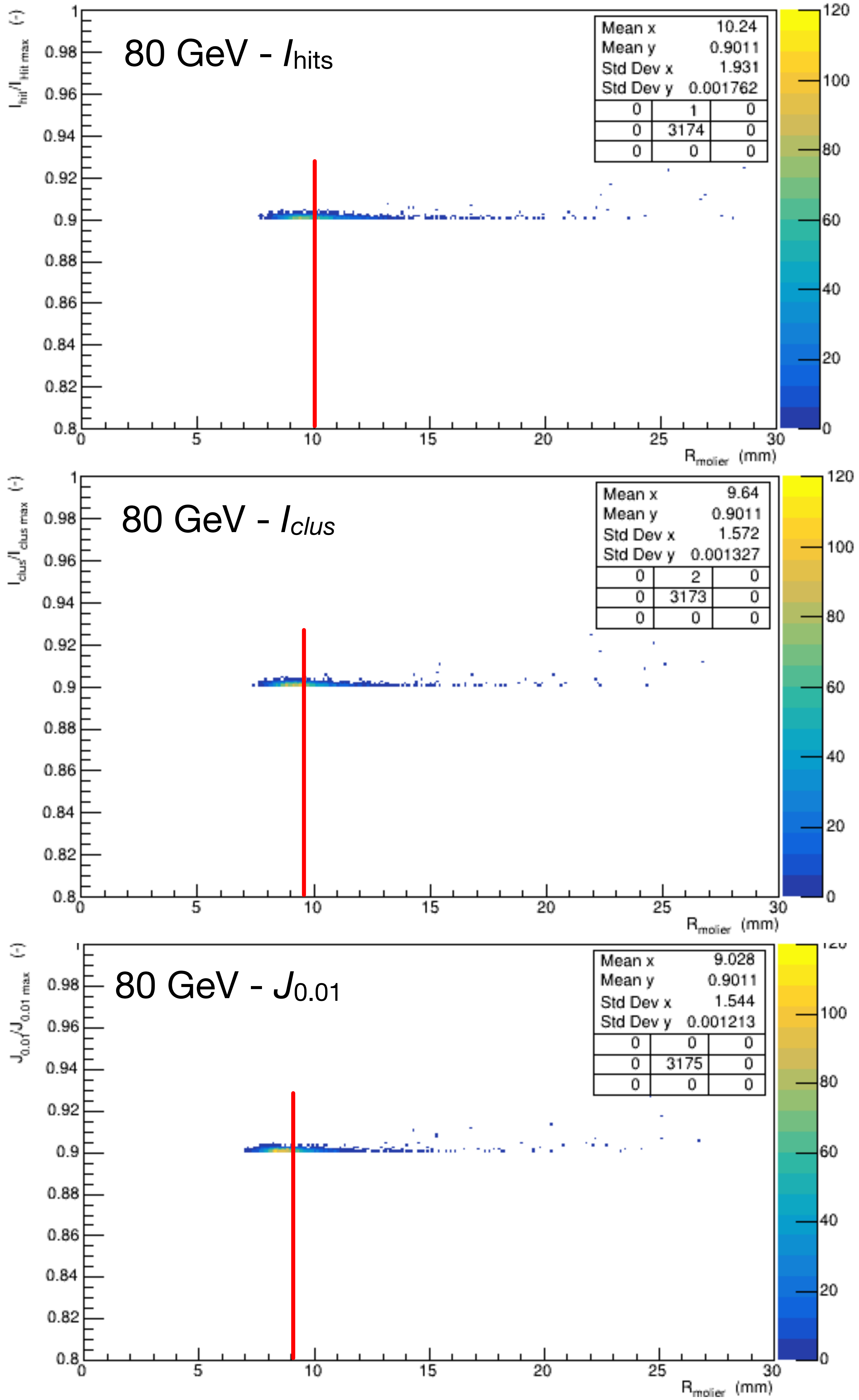
$$J_x(R) = \frac{1}{A^{(l)}_{\text{clus}}} \sum_{R_i=0}^{R_i=R_x} 2\pi R_i \Delta R_i \sum_{l=0}^{l=23} \rho^{(l)}_{\text{hits}}(R_i, \Delta R_i) + \sum_{R_i=R_x}^{R_i=R} 2\pi R_i \Delta R_i \sum_{l=0}^{l=23} \rho^{(l)}_{\text{clus}}(R_i, \Delta R_i)$$

Cumulative Distributions



- Optimisation of response observables studied as a function of integration radius
  - N_{clus} and N_{hits} – numerical sum
  - I_{clus} and I_{hits} – integral of densities, acceptance corrected
  - J_x – hybrid variable (combining N_{clus} and N_{hits})
- Extraction of Moliere radius can use I_{clus}, I_{hits} and J_x
  - Asymptotic value reached?

Finn Smits



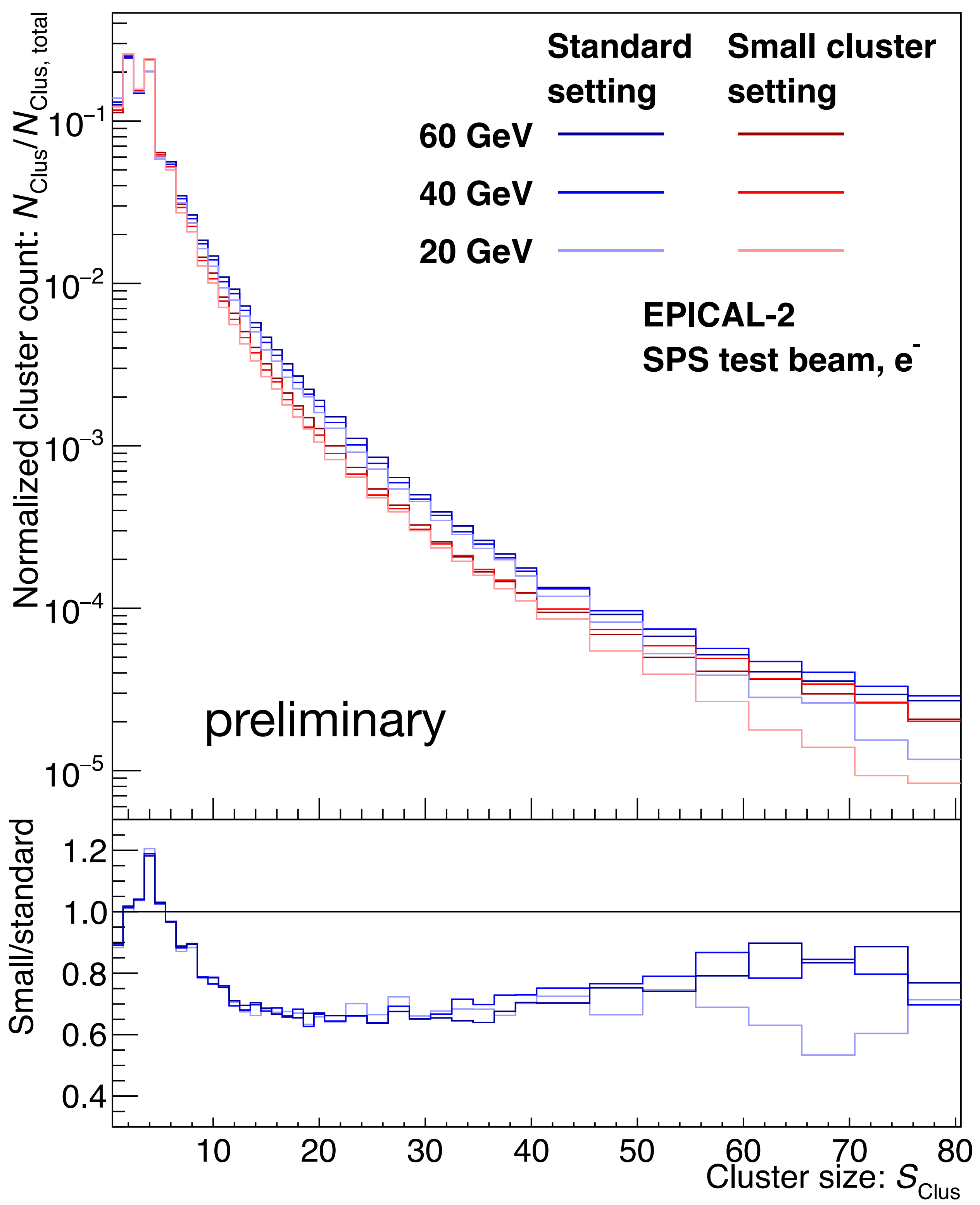
Event-by-Event Moliere Radius

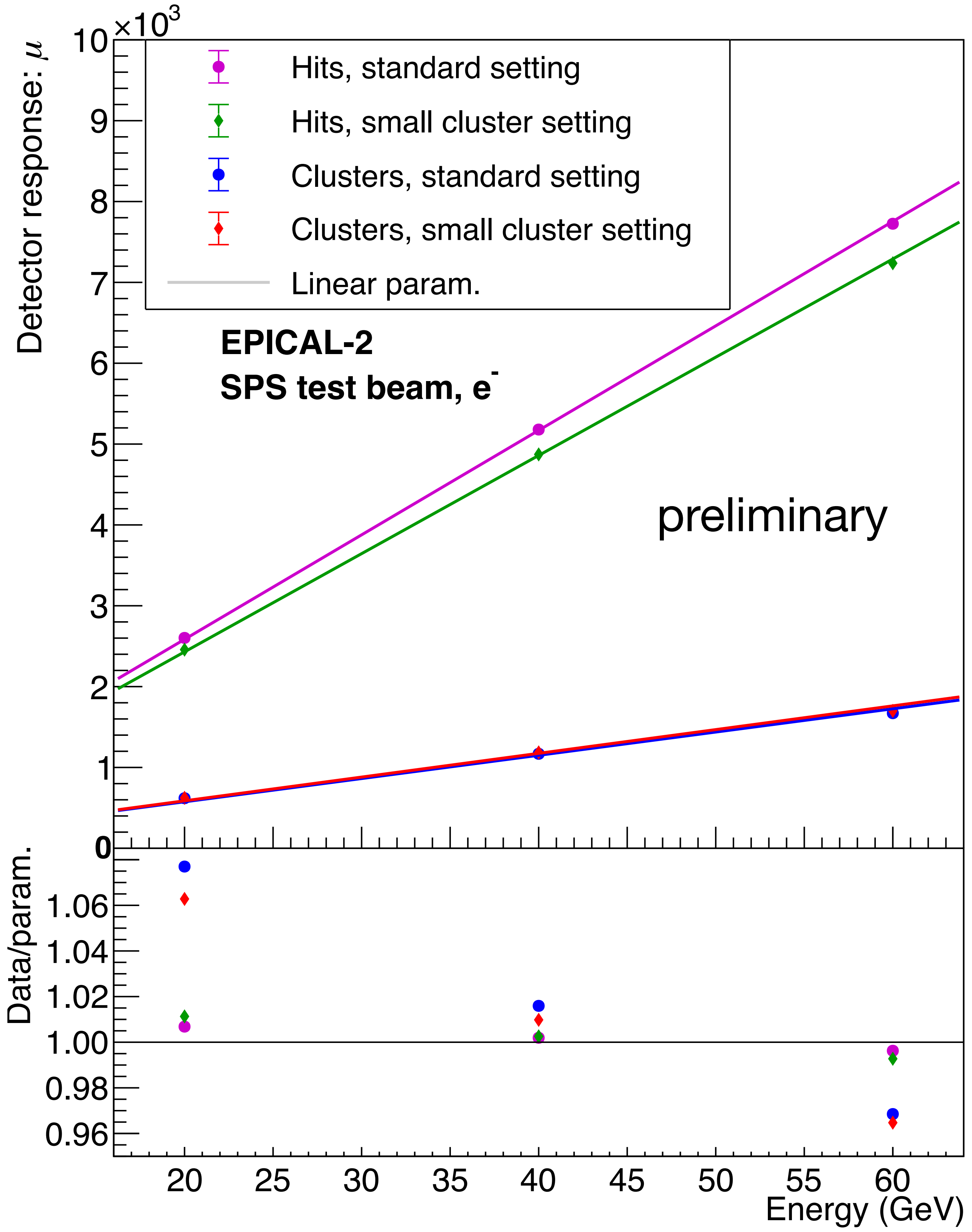
- Obtain asymptotic value of response A_{max} at $R_{max} = 29\ \text{mm}$
- Find minimum R, where $A(R) \geq 0.9A_{max}$
  - N_{clus} and N_{hits} don't get asymptotic value right.
  - I_{clus}, I_{hits} and J_x possible
  - Have to converge on best estimate and systematic errors
- Work in progress

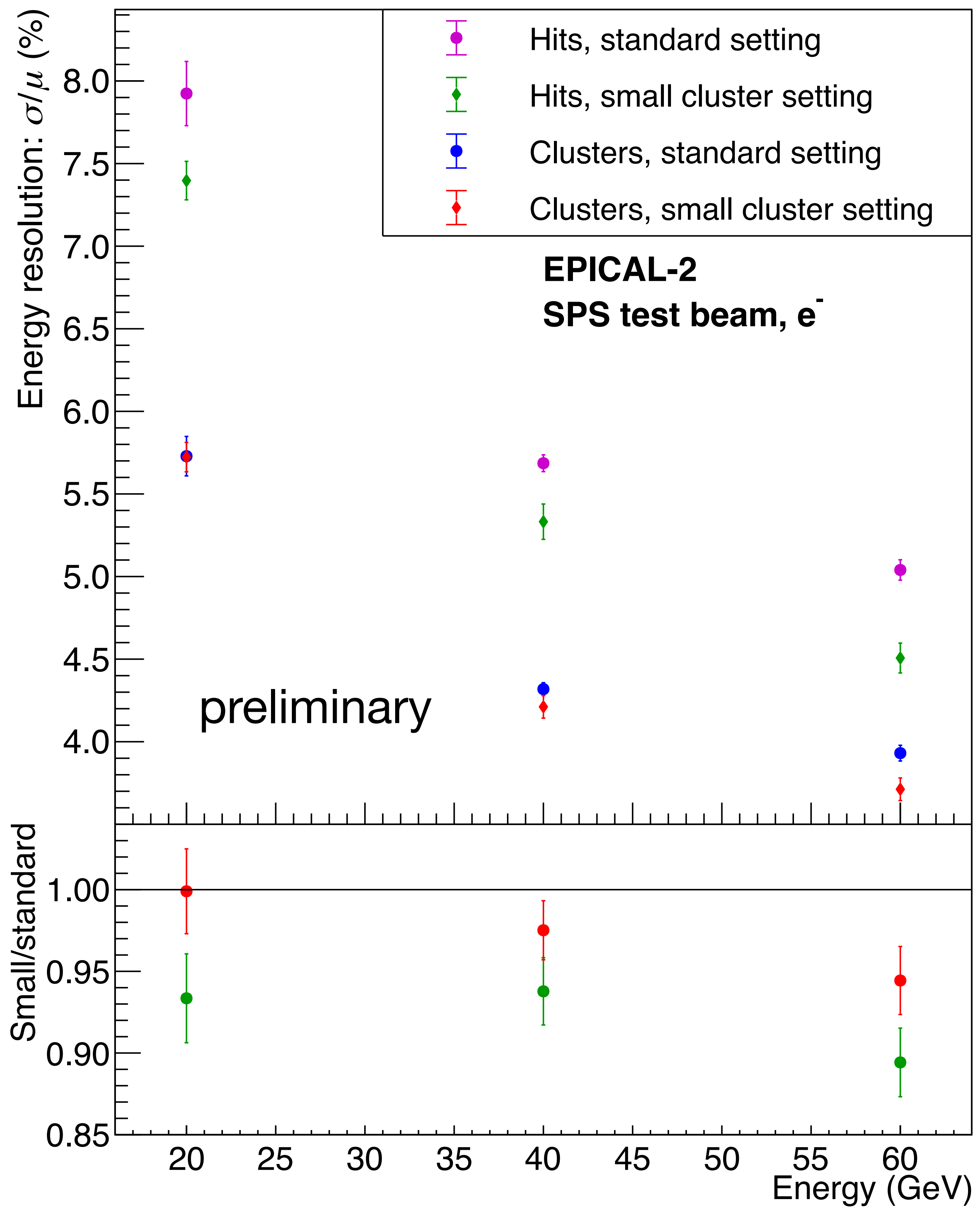
observable	R_M (mm)	σ_{RM} (mm)
I_{hits}	10.24	1.93
I_{clus}	9.64	1.57
$J_{0.01}$	9.02	1.54
$J_{0.1}$	9.09	1.55
$J_{0.2}$	9.20	1.58

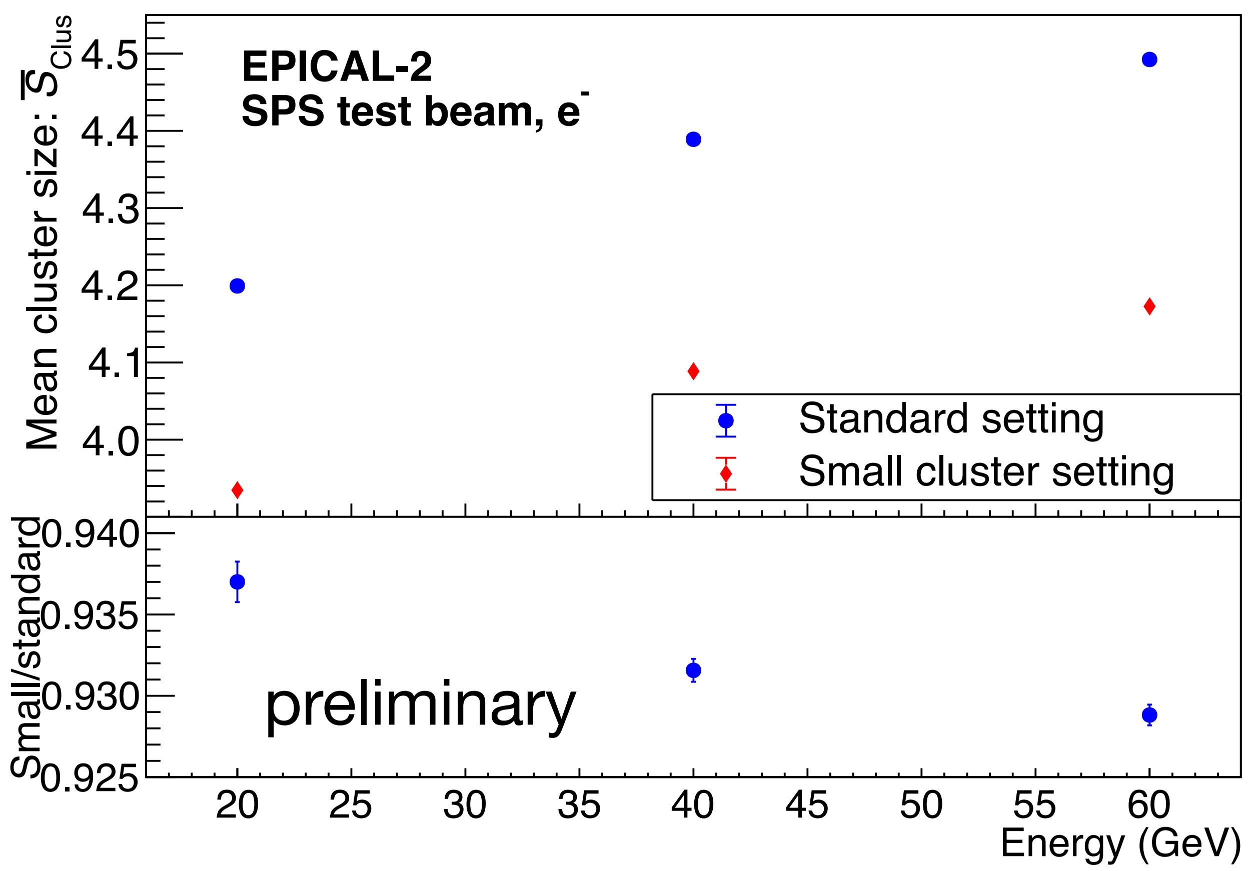
Finn Smits

Back Bias and Cluster Size





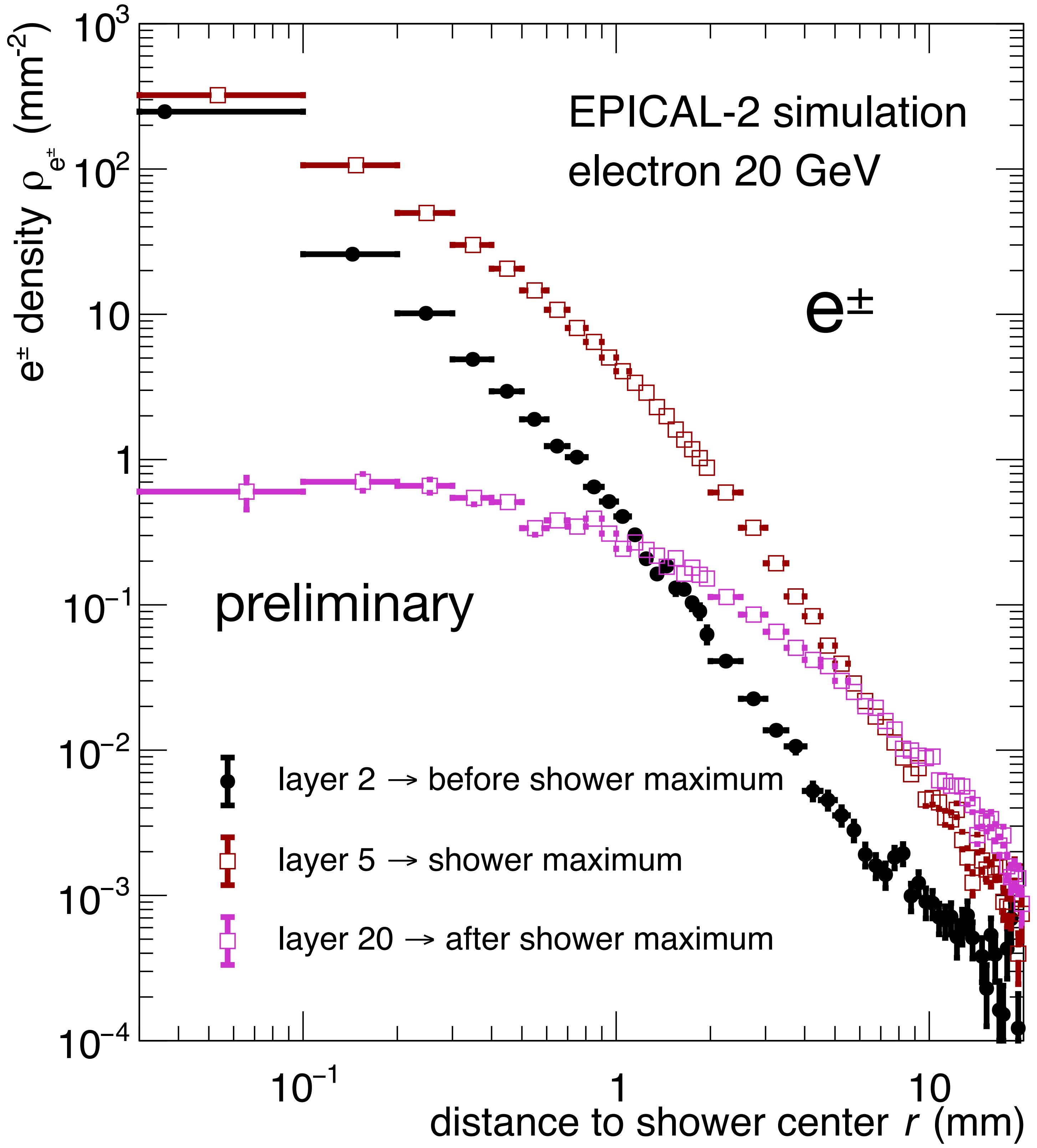


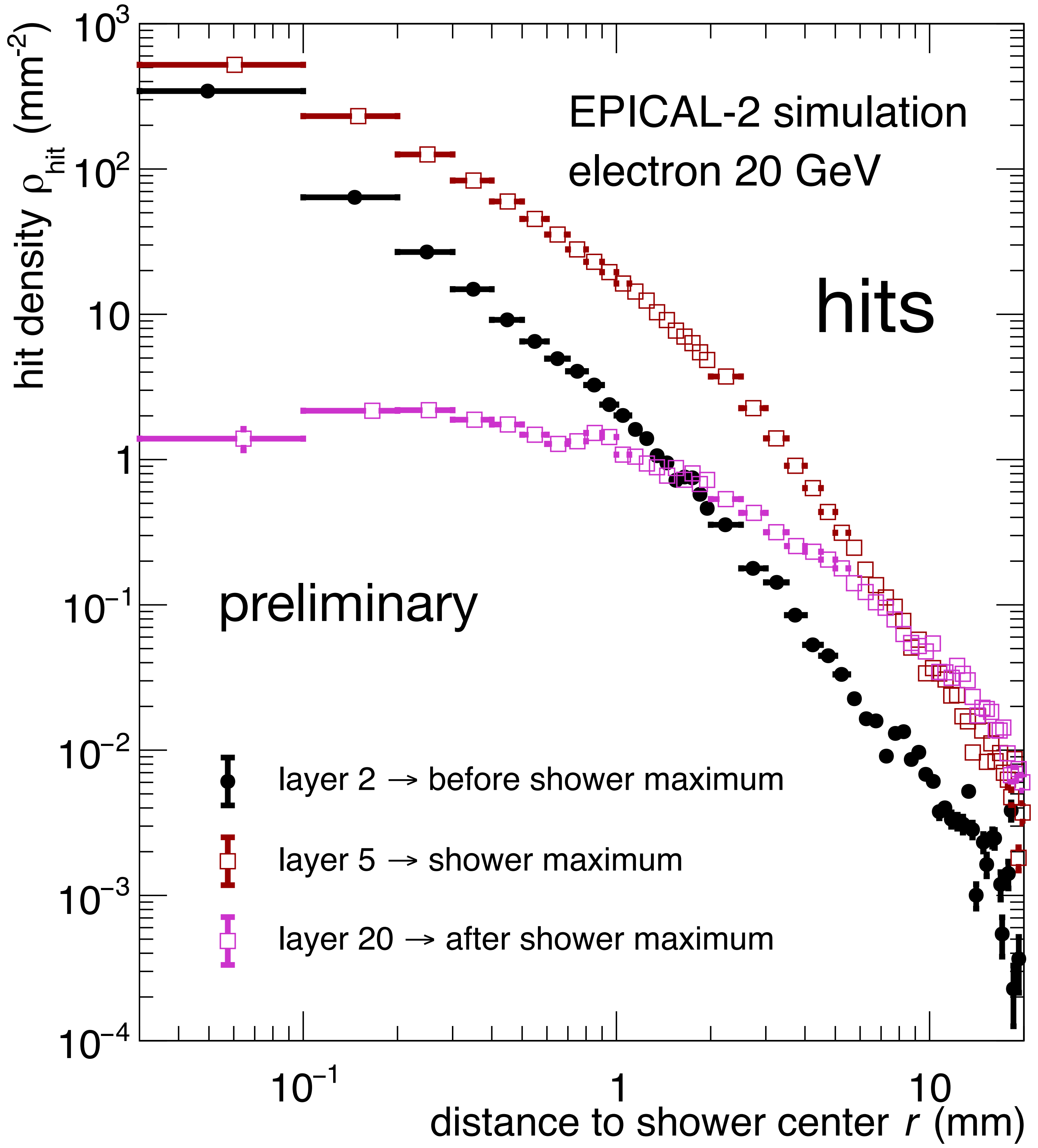


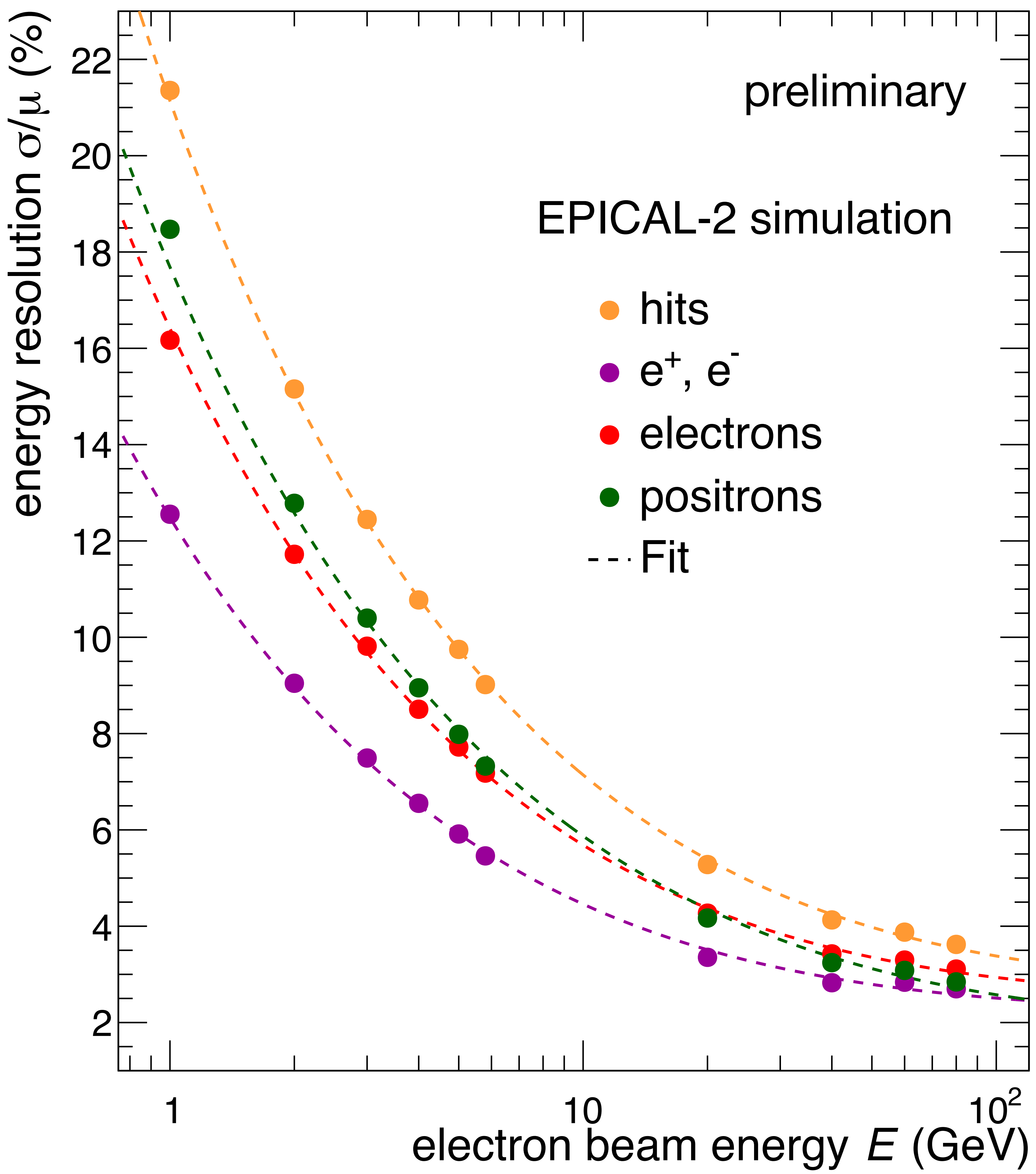
- Finite back bias results in smaller cluster size
  - Small effects for N_{hits} : better resolution
  - Negligible effects for N_{clus}
  - Caveat: measurements performed towards end of beam time, not all settings properly documented

Johannes Keul

Ideal Monte-Carlo Response



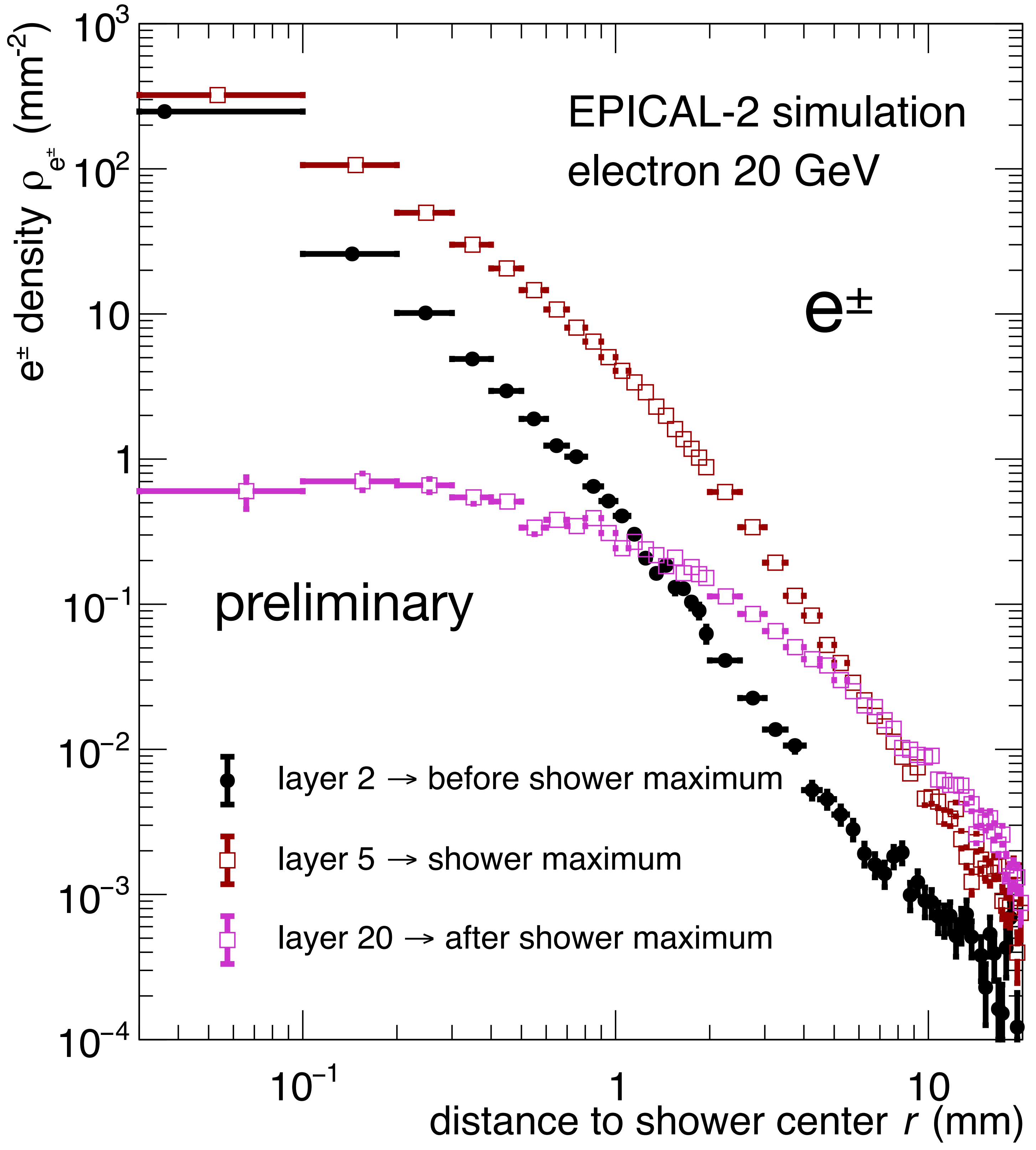


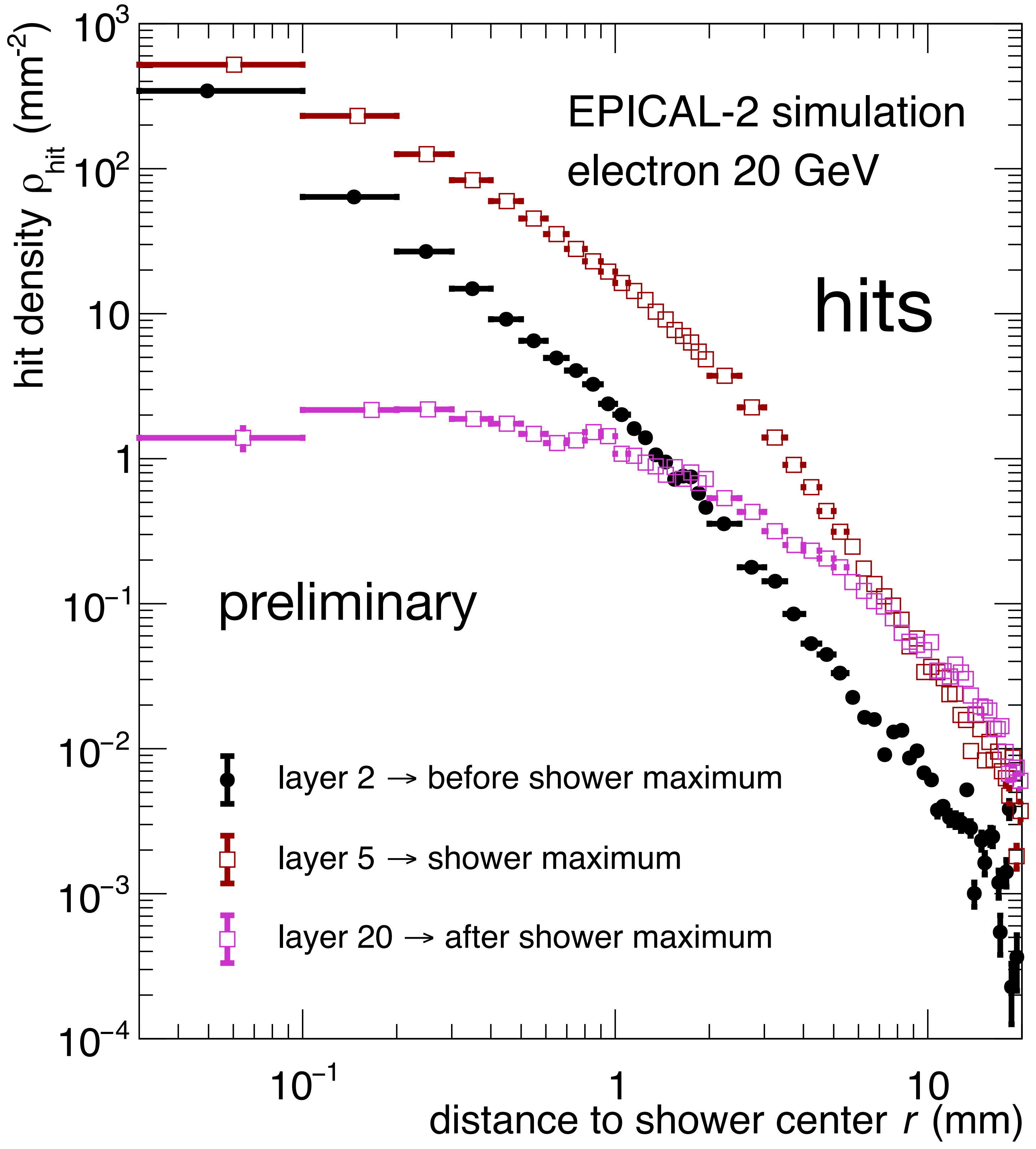


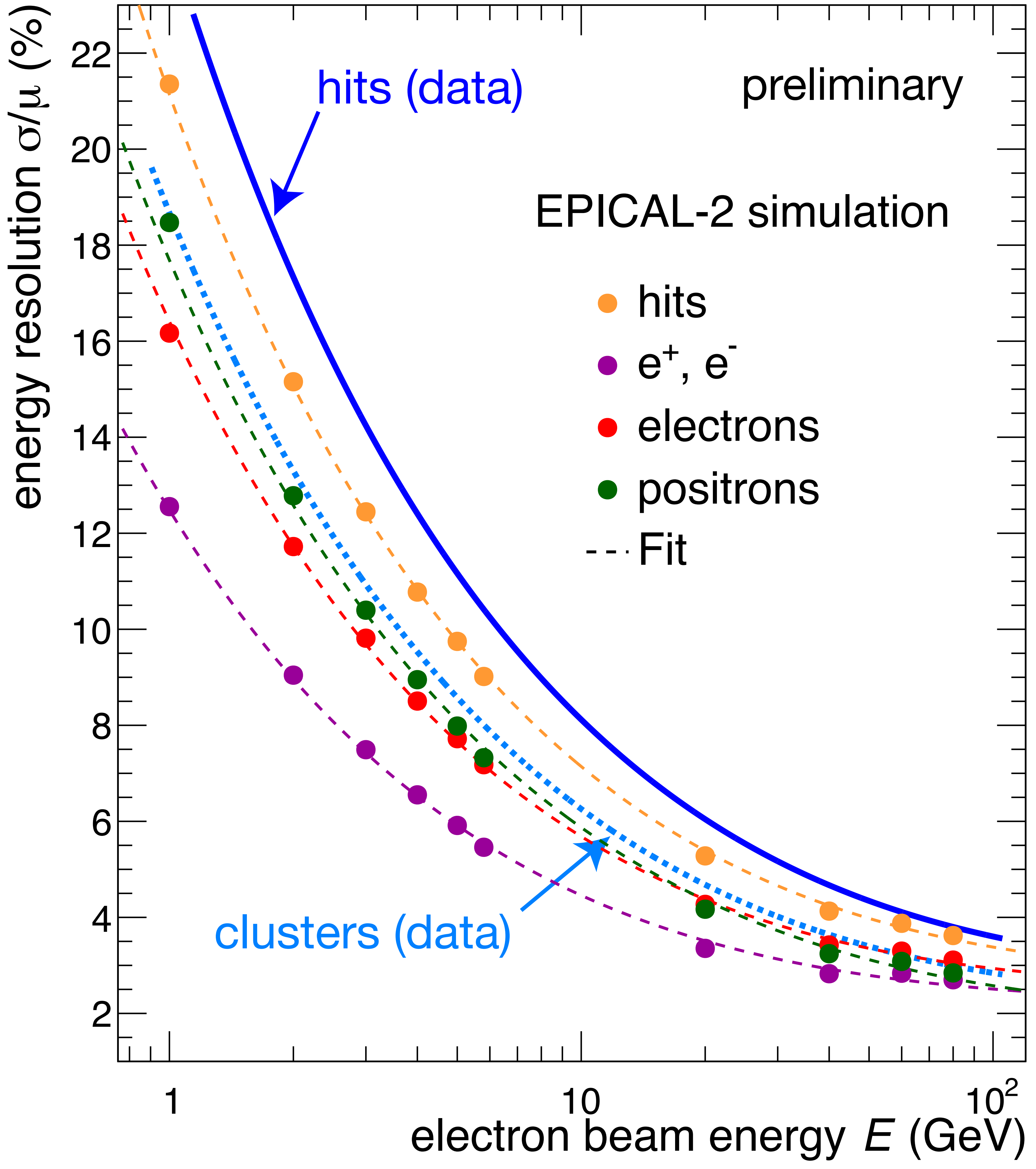
- Compare e^+/e^- density to hit density
  - e^+/e^- density defines limit of performance
- Shows potential improvement of resolution

Jan Schöngarth

Ideal Monte-Carlo Response



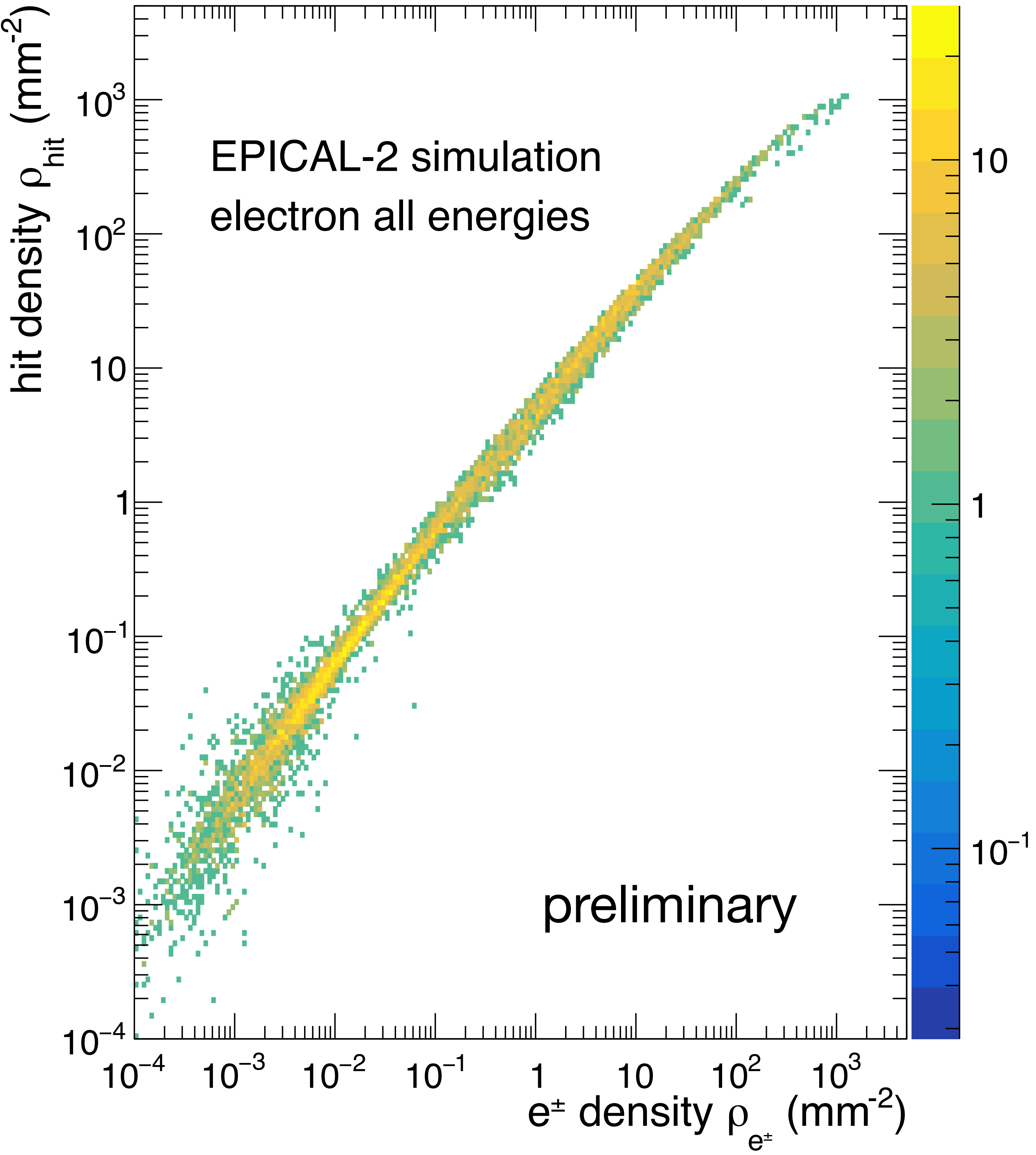


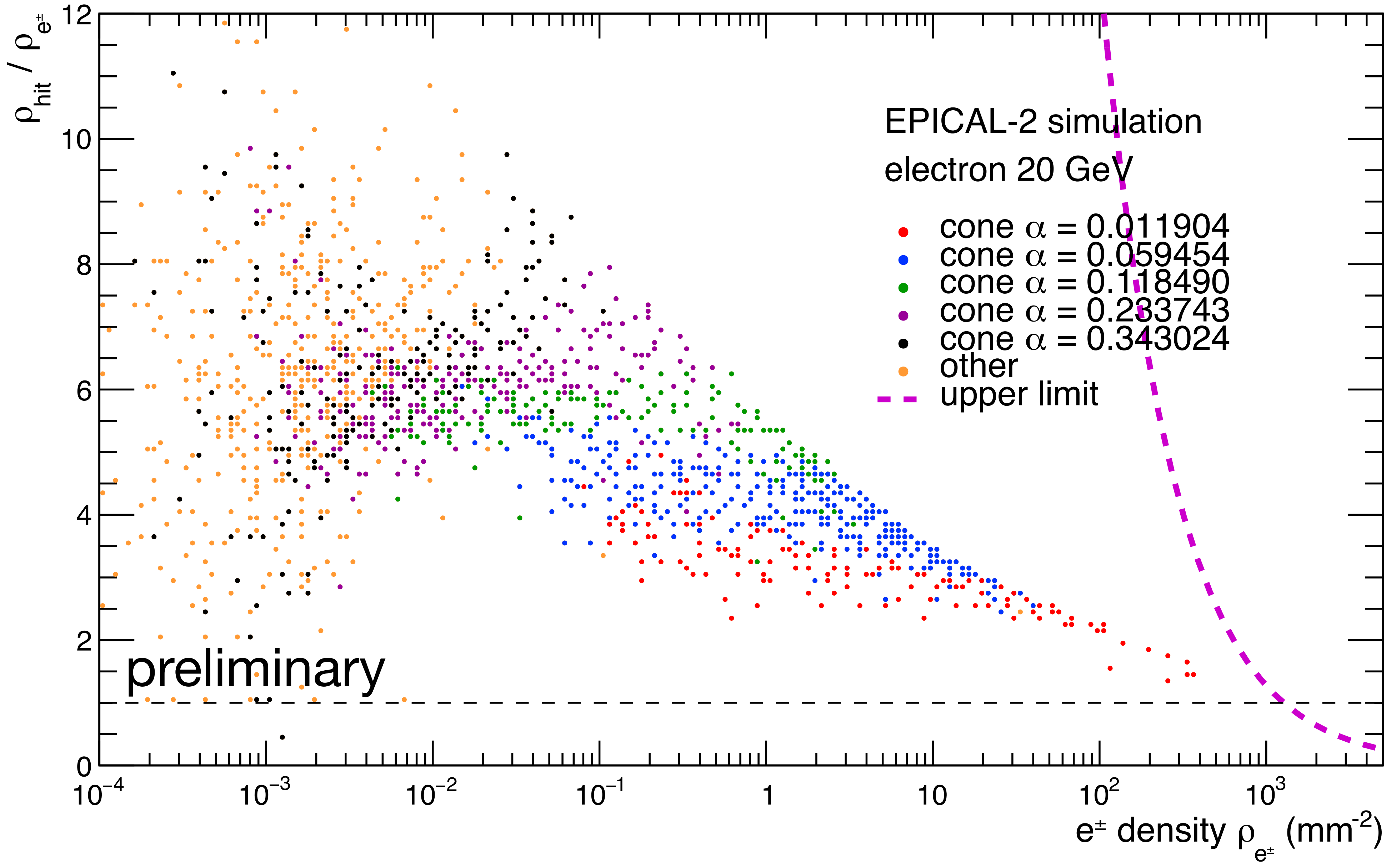


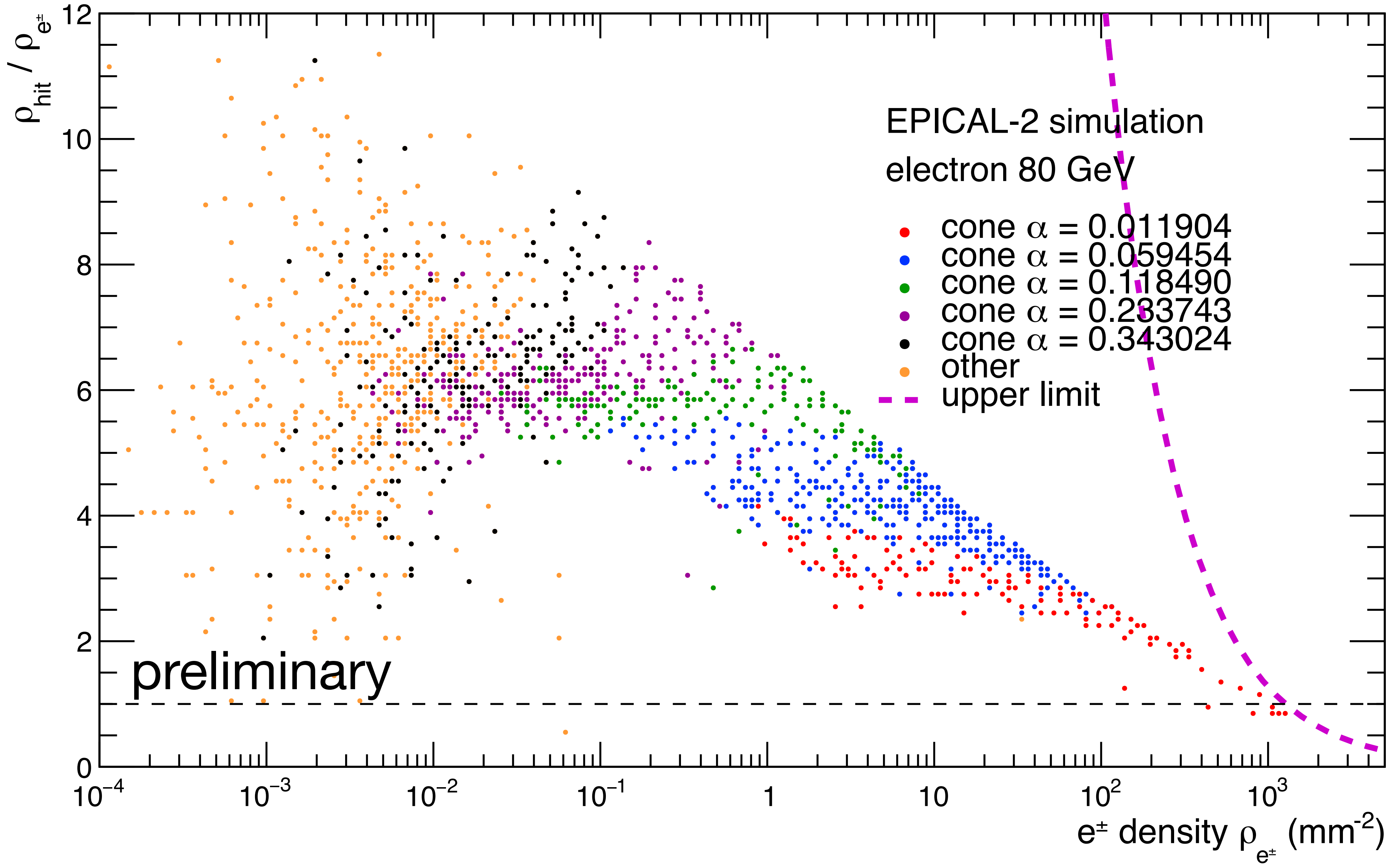
- Compare e^+/e^- density to hit density
  - e^+/e^- density defines limit of performance
- Shows potential improvement of resolution

Jan Schöngarth

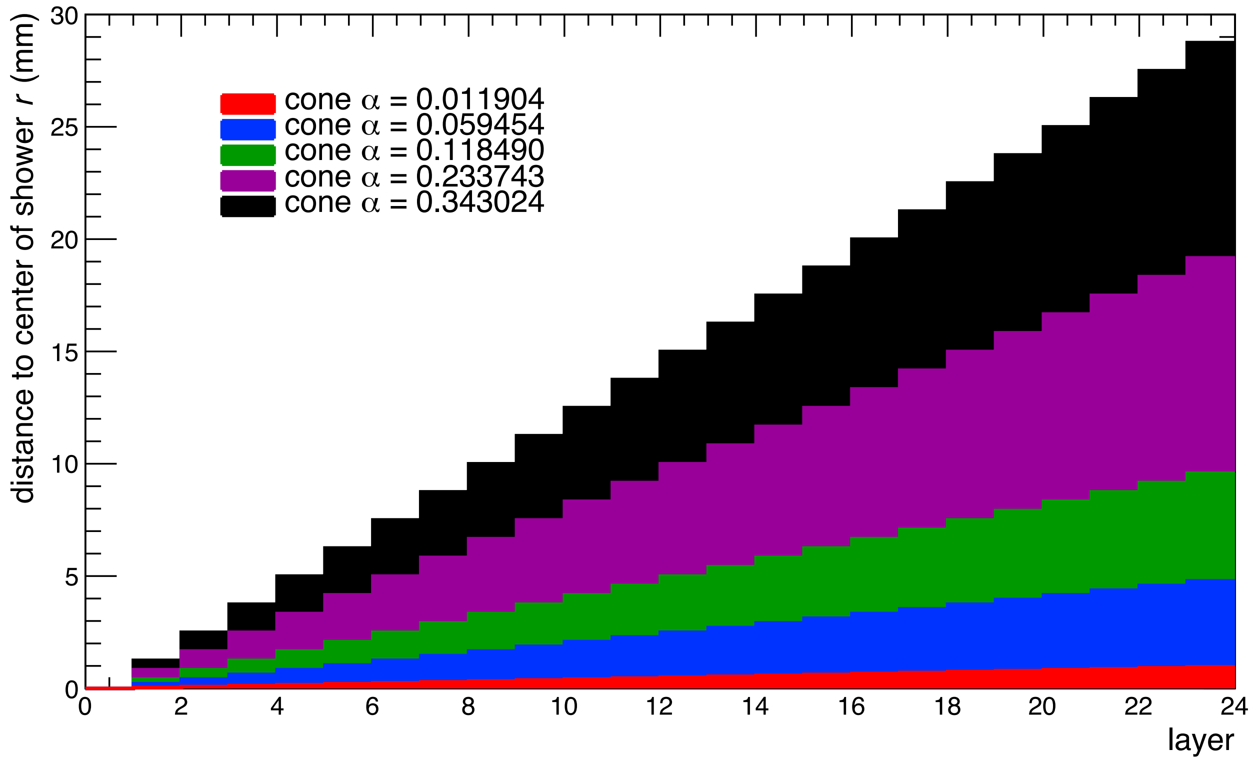
Response Fluctuations and Saturation







- Study ratio of hit to particle density
  - Ratio varies strongly with density
- Dominant effect: varying cluster size
  - Shower particle angle is correlated with density
  - Larger clusters for large angles
- Need to disentangle from possible saturation effects



- Studies of event-by-event density fluctuations
- Effects of Saturation?
- Event-by-event correction possible?

Jan Schöngarth

Summary

- Digital calorimetry works
  - New prototype confirms findings with EPICAL-1
  - Much better 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
  - First results published *(JINST 18 (2023) P01038, NIM A1045 (2023) 167539)*
- Unique shower shape studies
- Working on improved reconstruction algorithms
- 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

EPICAL-2 Team

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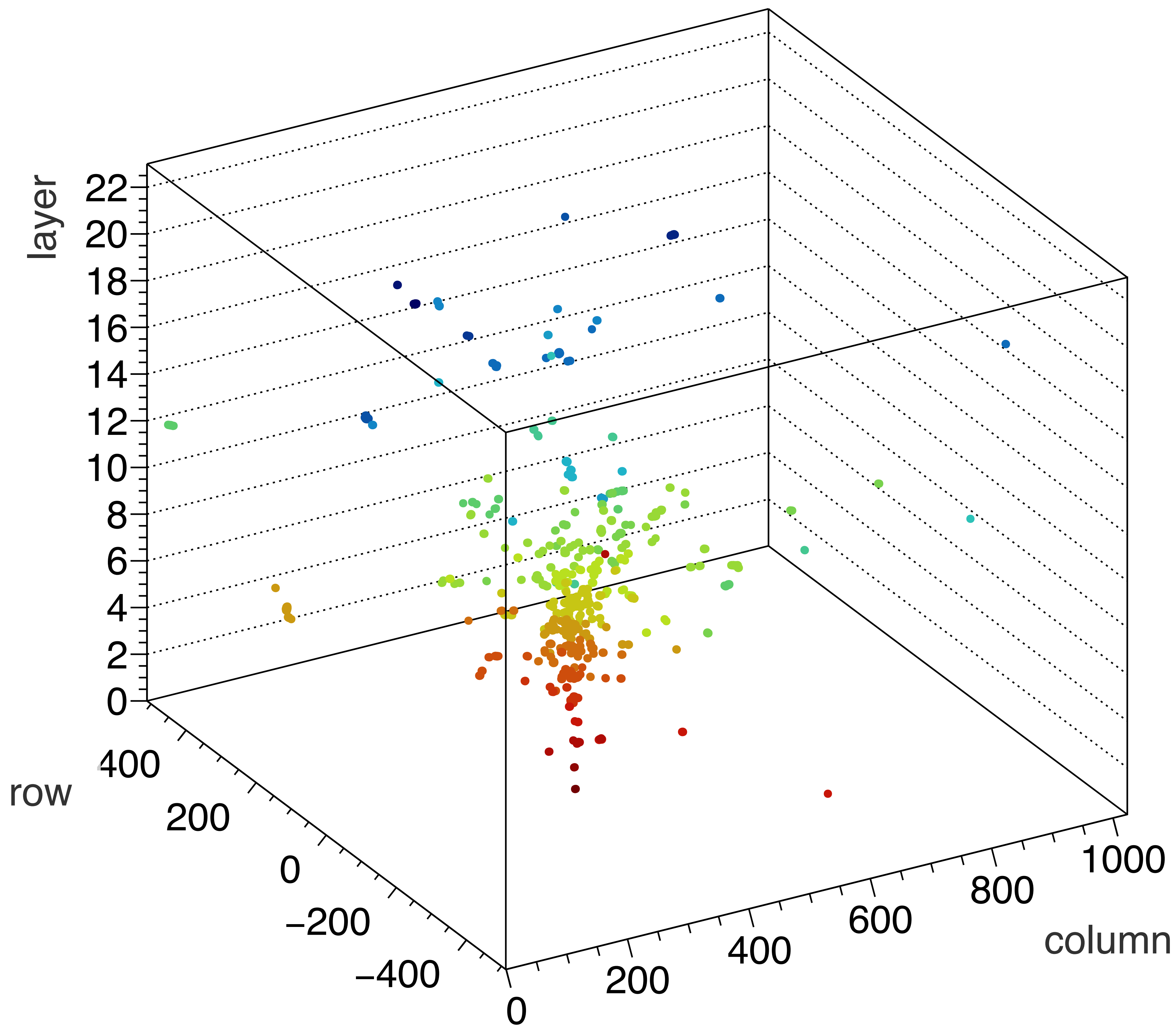
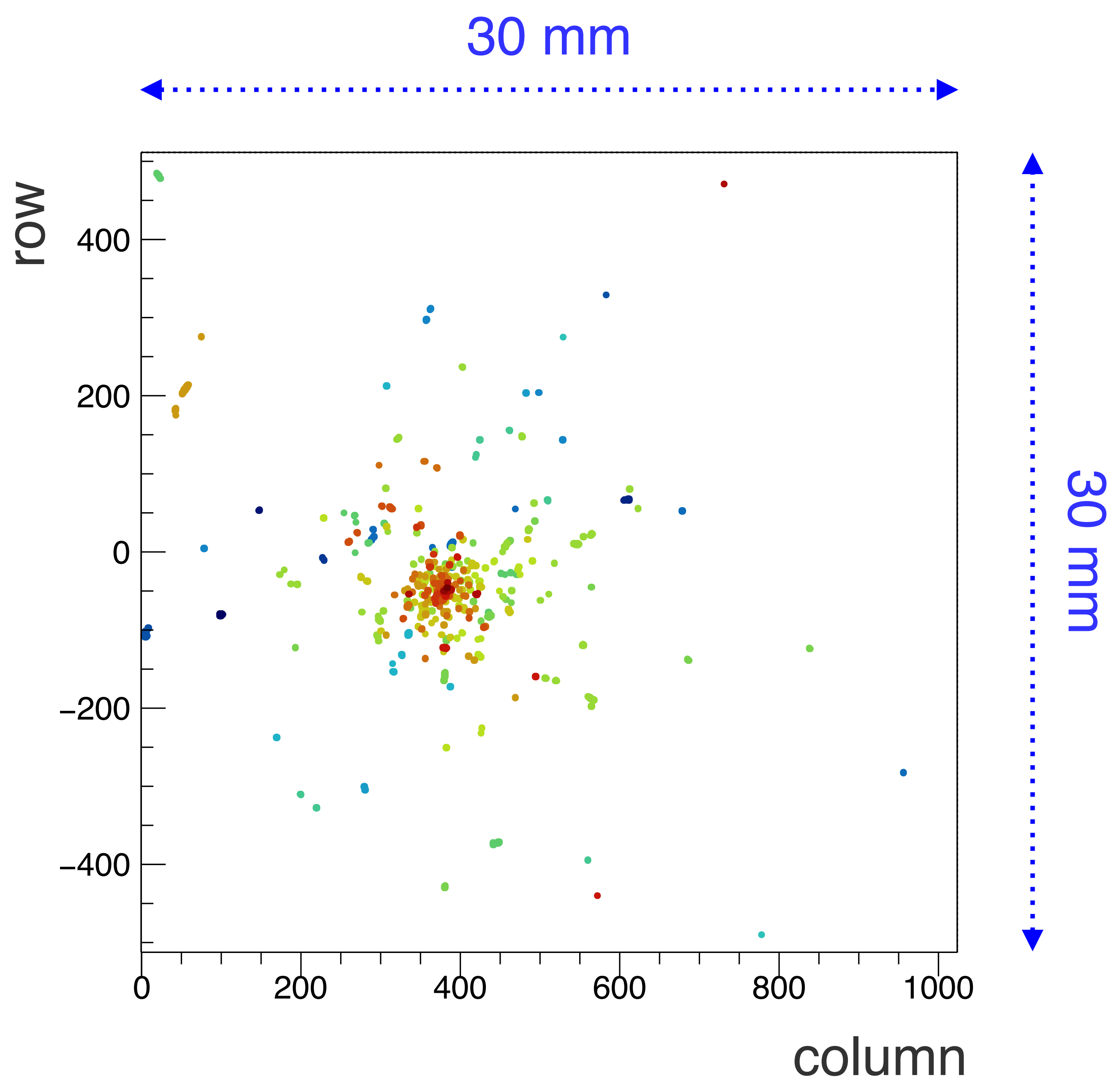
EPICAL-2

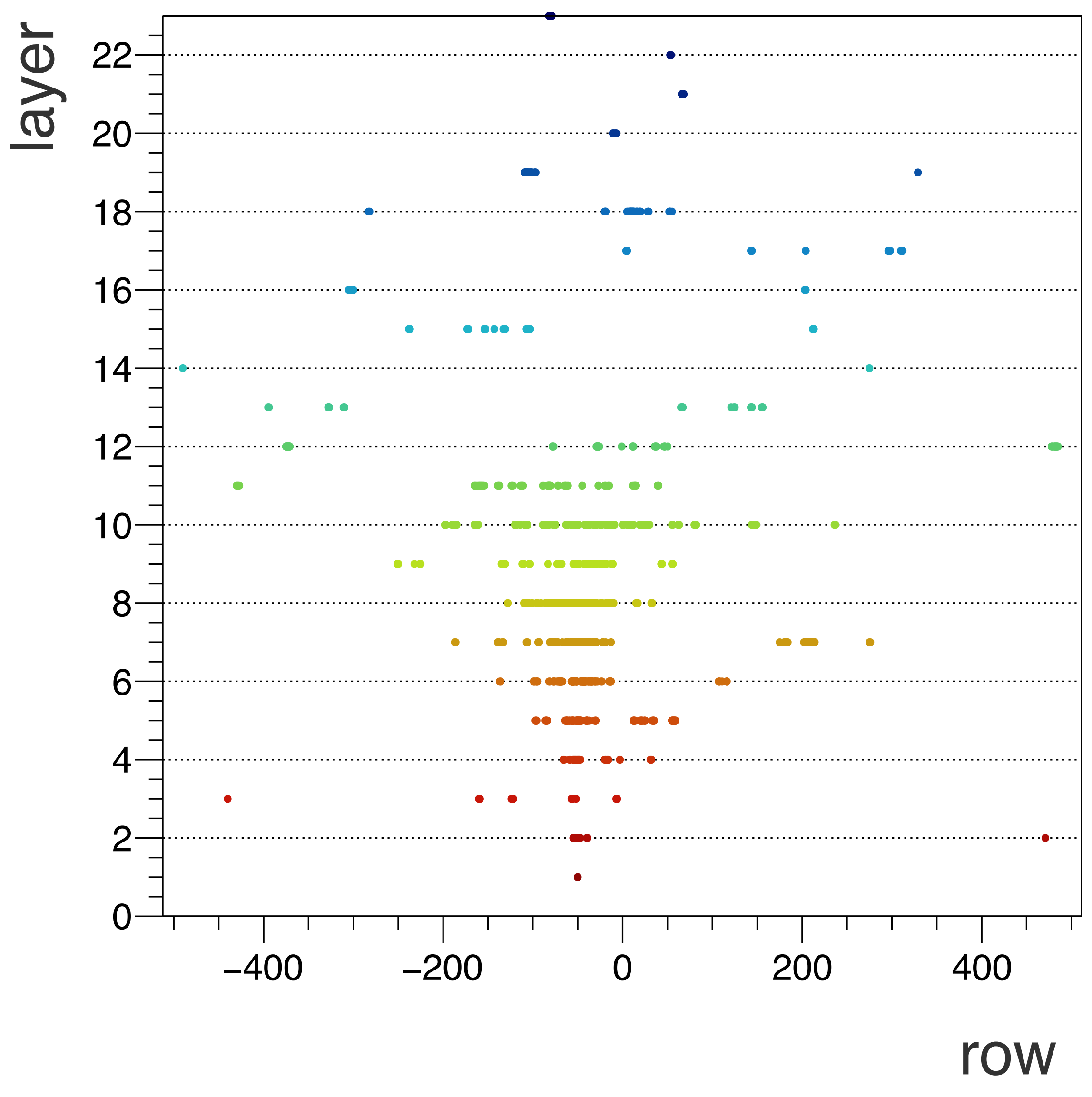
Event Displays

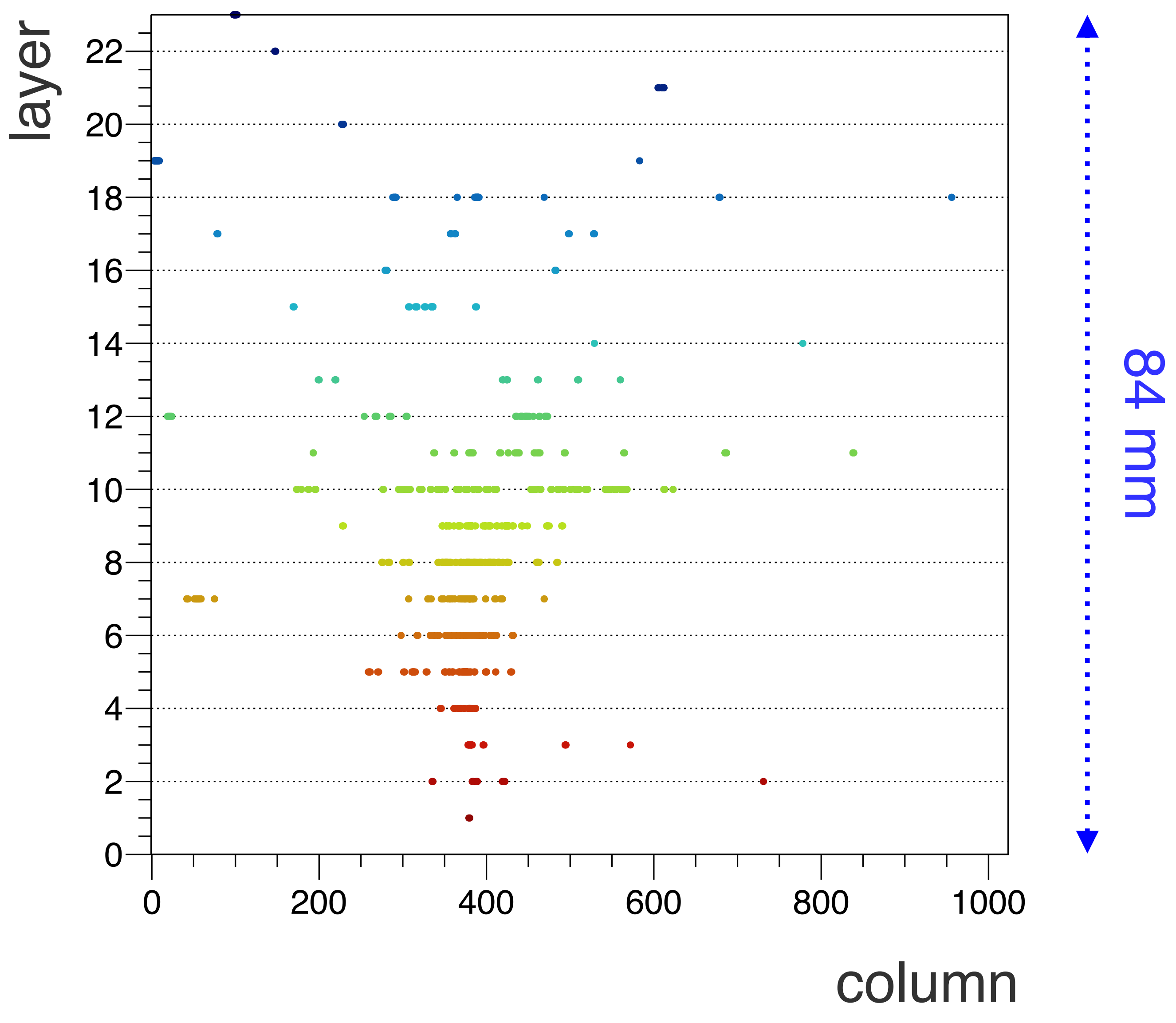
single electron event
5 GeV
raw data

colour → layer number

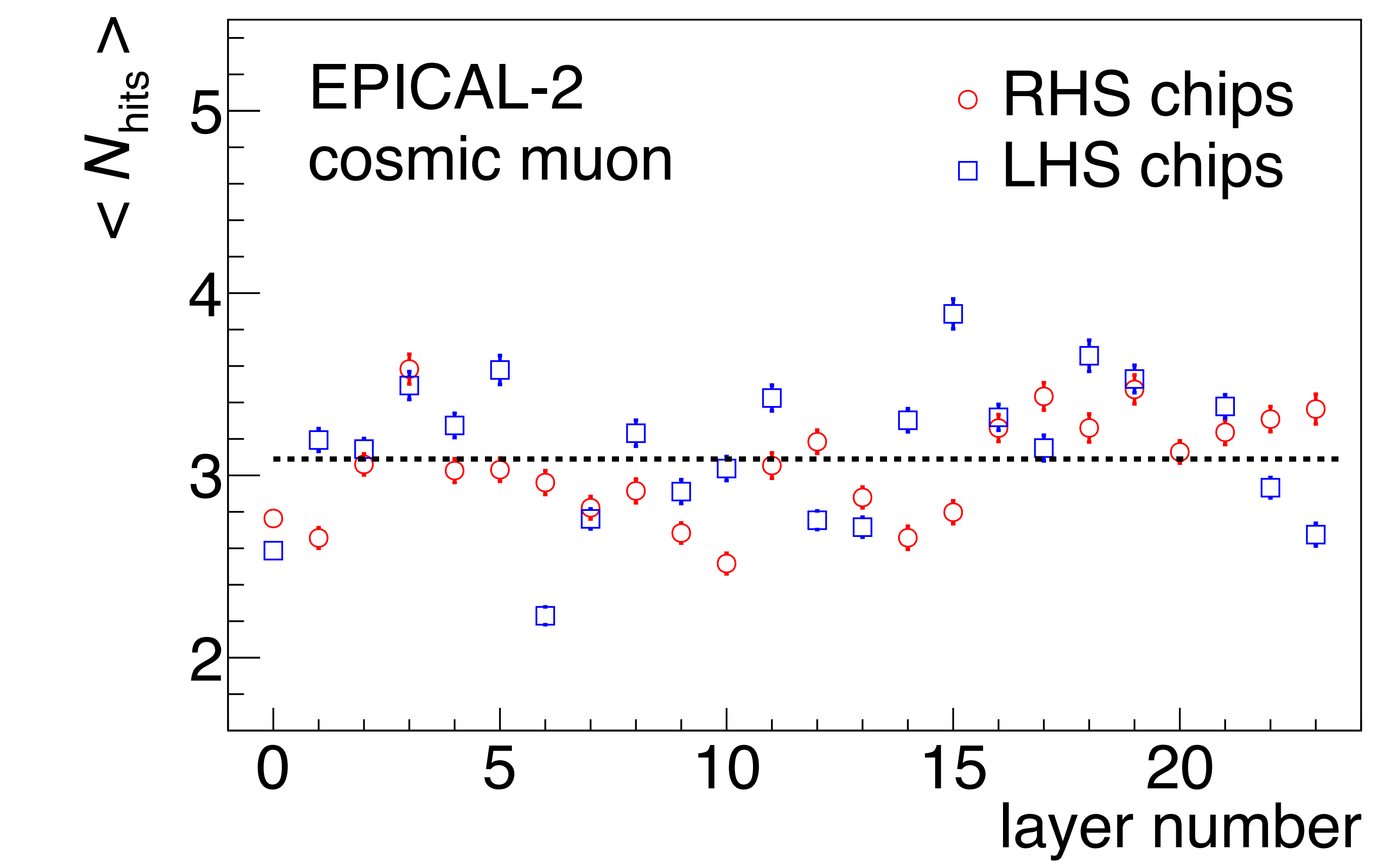


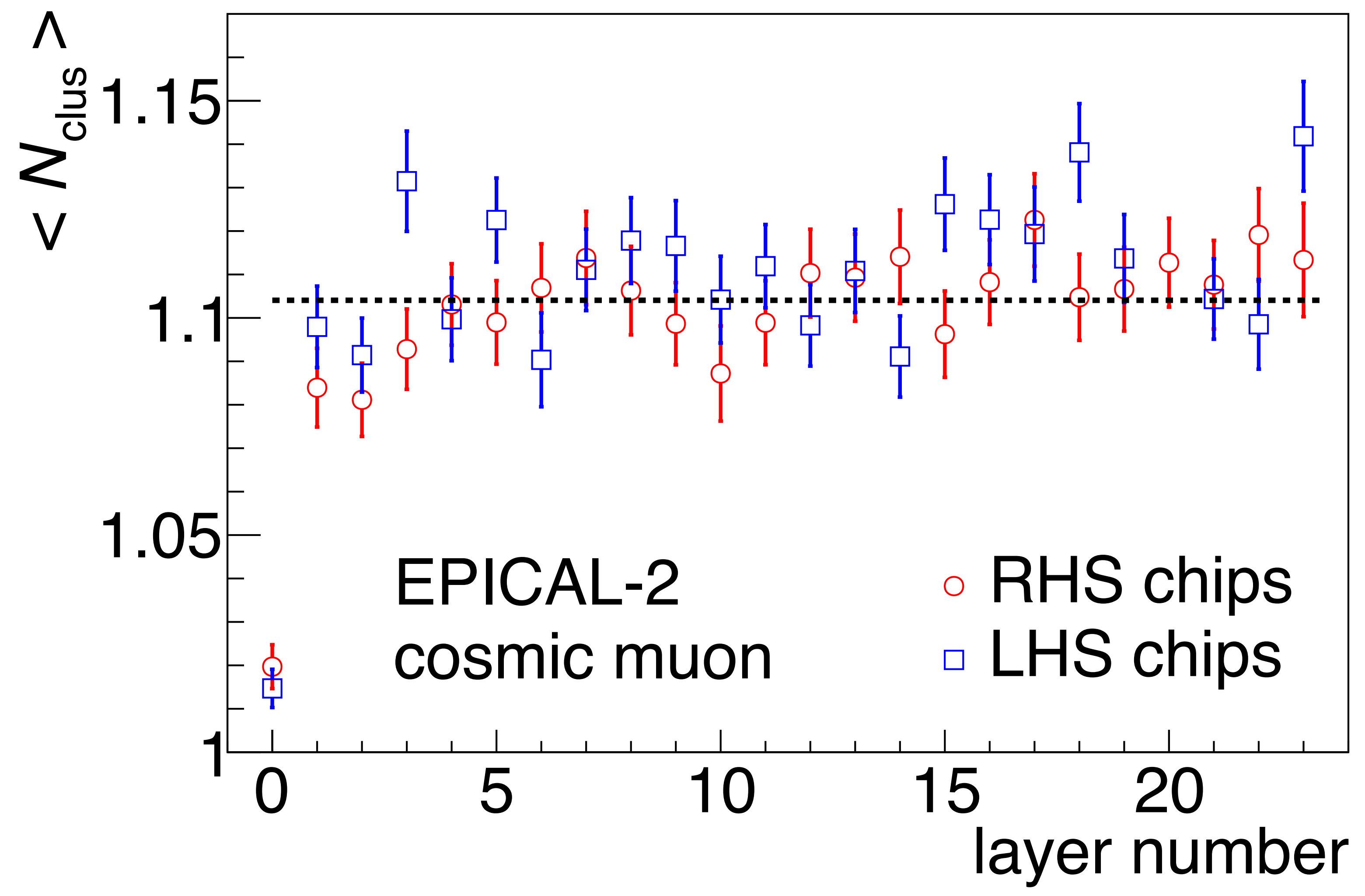






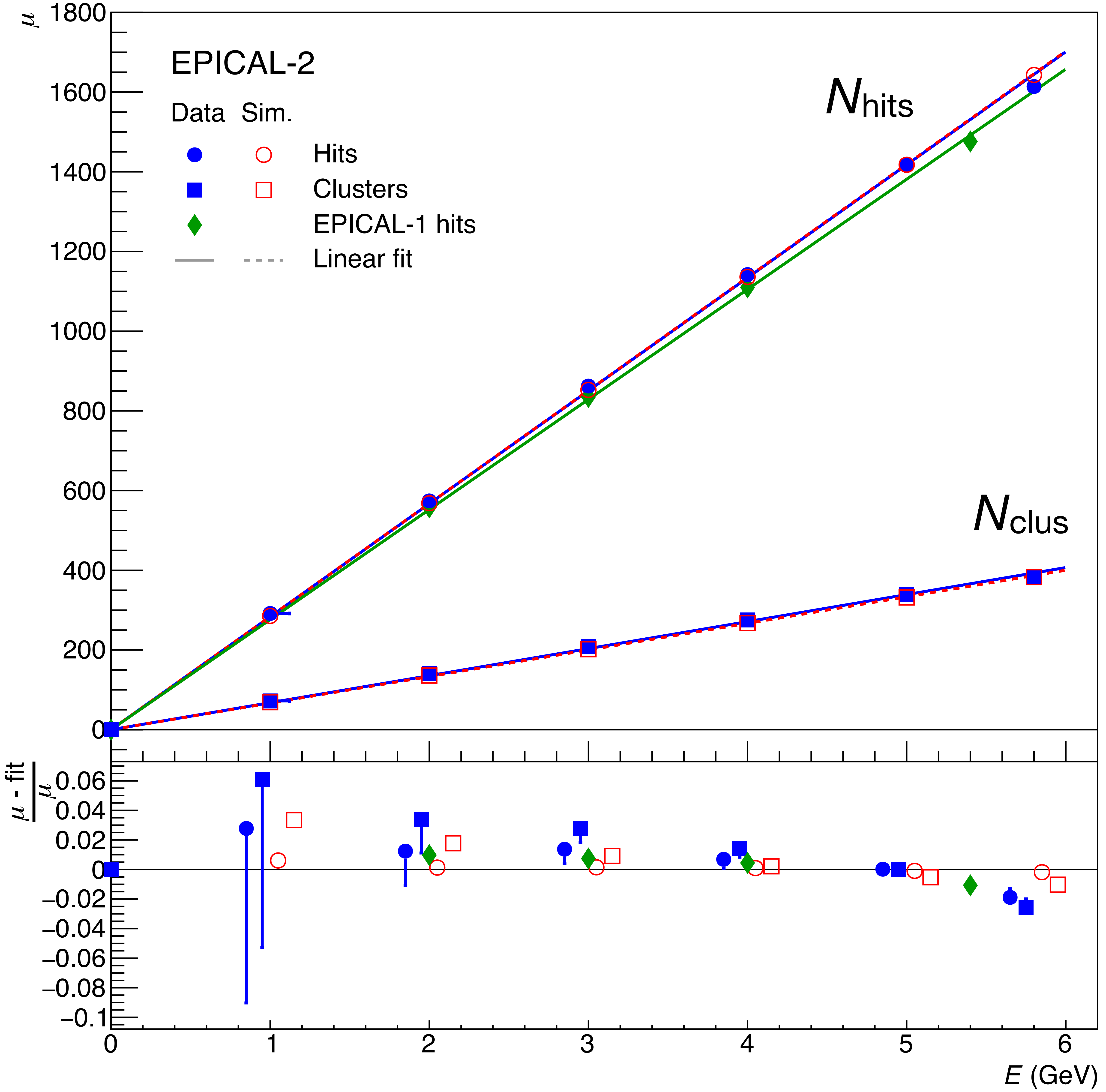
Sensor Calibration





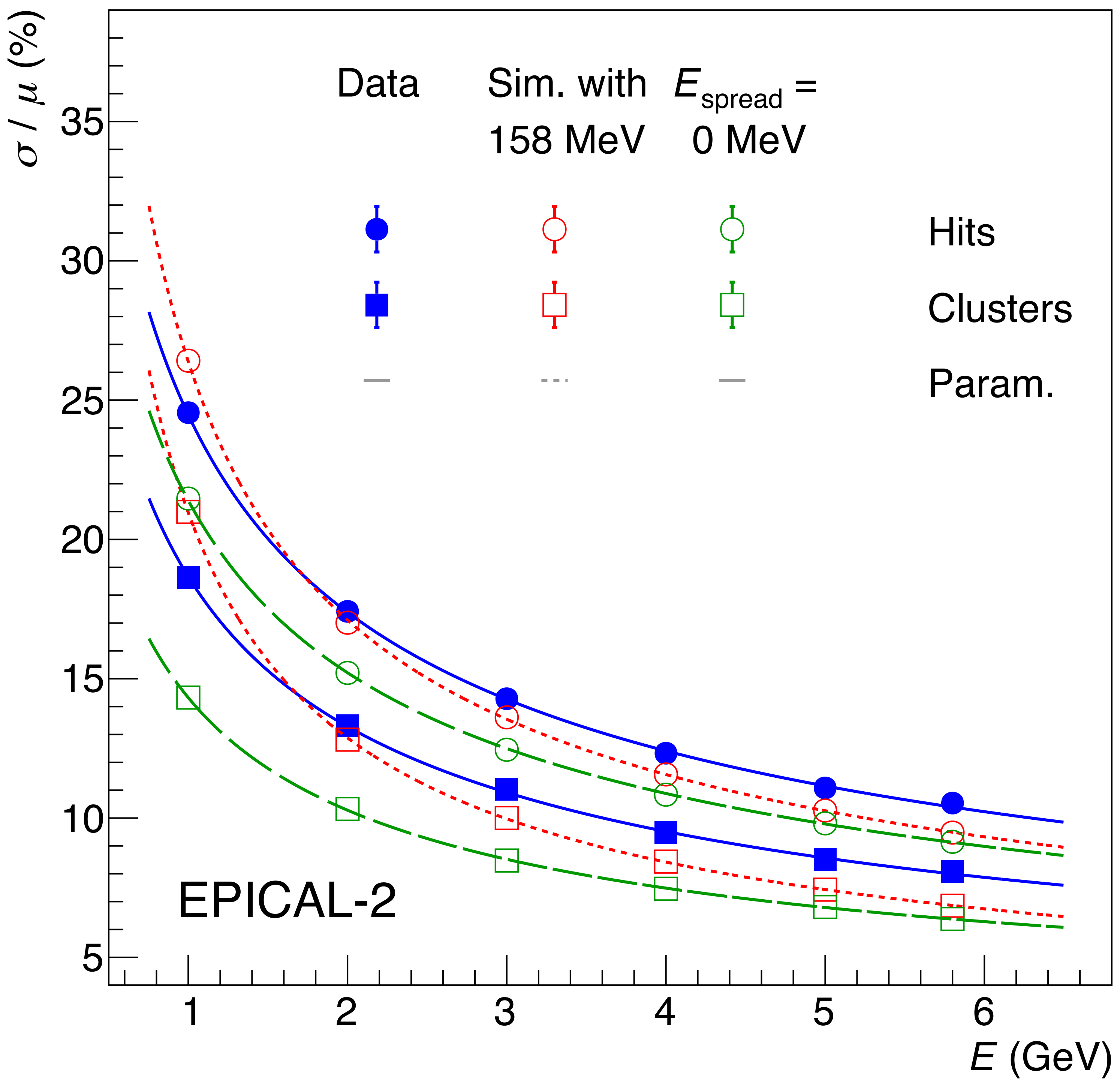
- Use muons (from cosmics or in-beam) for relative calibration of sensors with different sensitivities
  - Expect identical response to muons in all layers in terms of hits and clusters
  - Ignore in-sensor variation of sensitivity
- Significant sensitivity variation observable in number of hits
- Minor variation in number of clusters
  - Number of clusters less susceptible to threshold variations

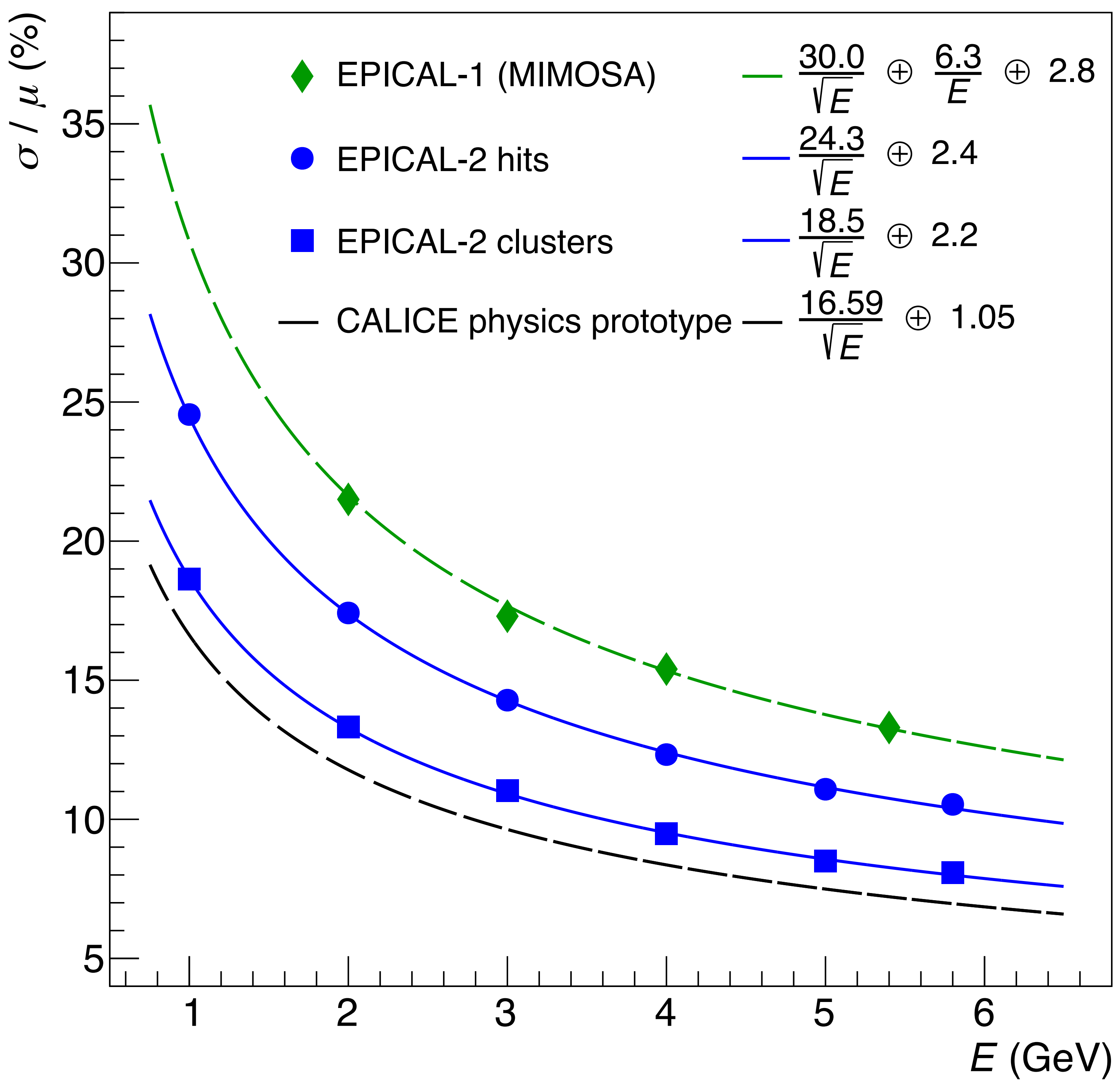
Energy Linearity



- 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



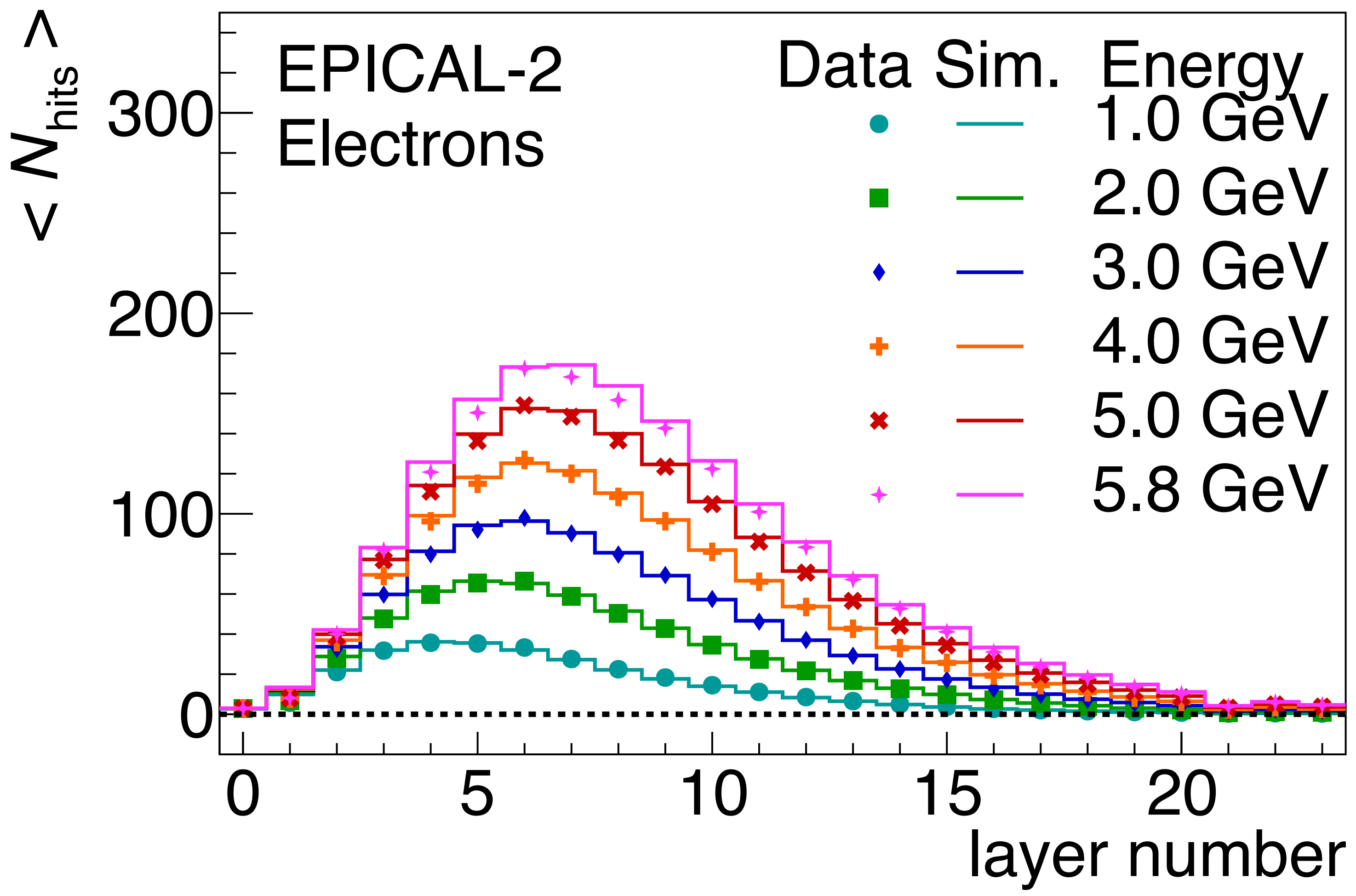


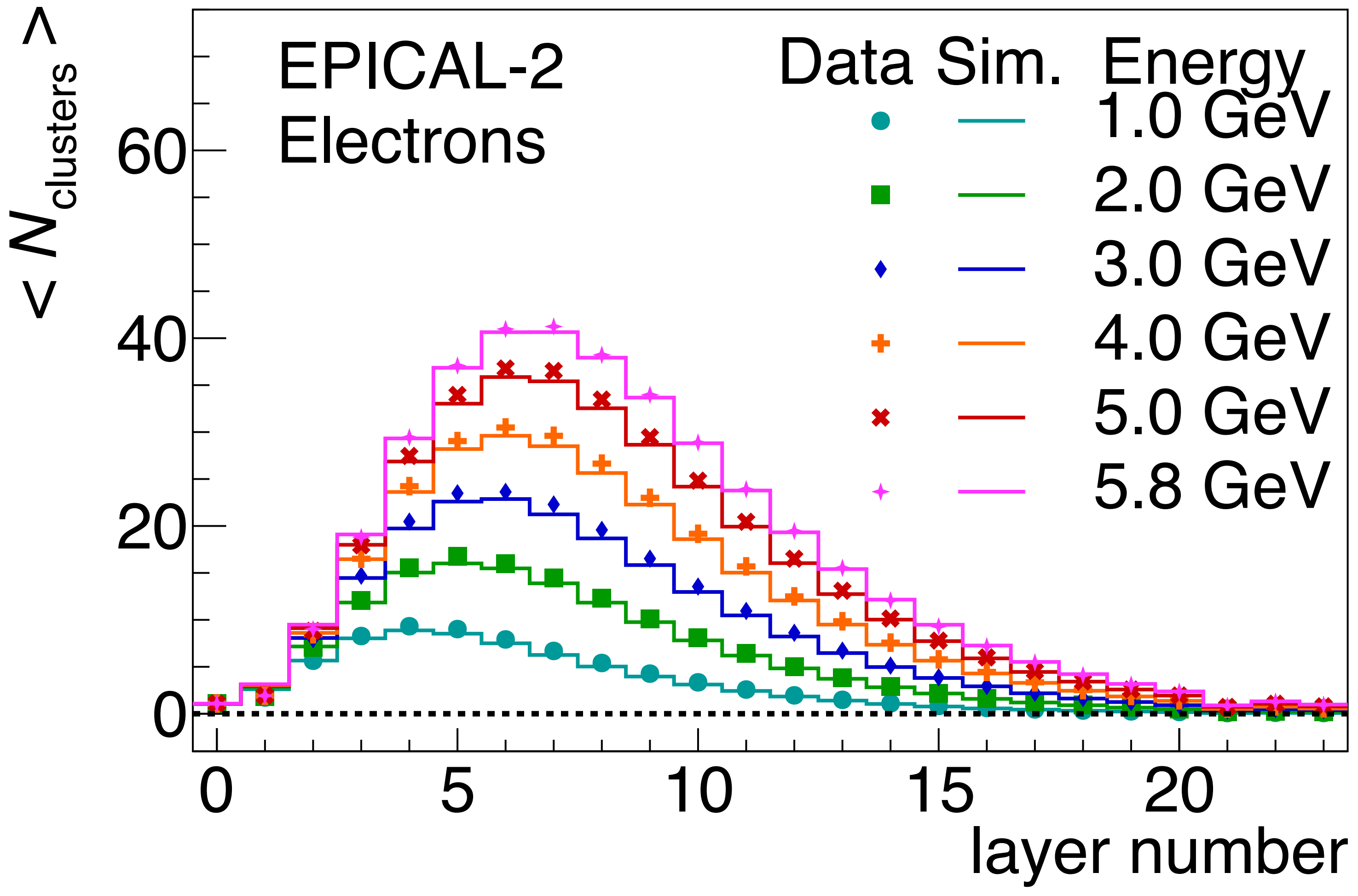
- Resolution shows the expected behaviour for calorimeters
- Experimental data likely contain a significant contribution from beam energy spread at DESY
- “Particle counting” (N_{clus}) shows superior performance here
  - Confirmed by simulations

- 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

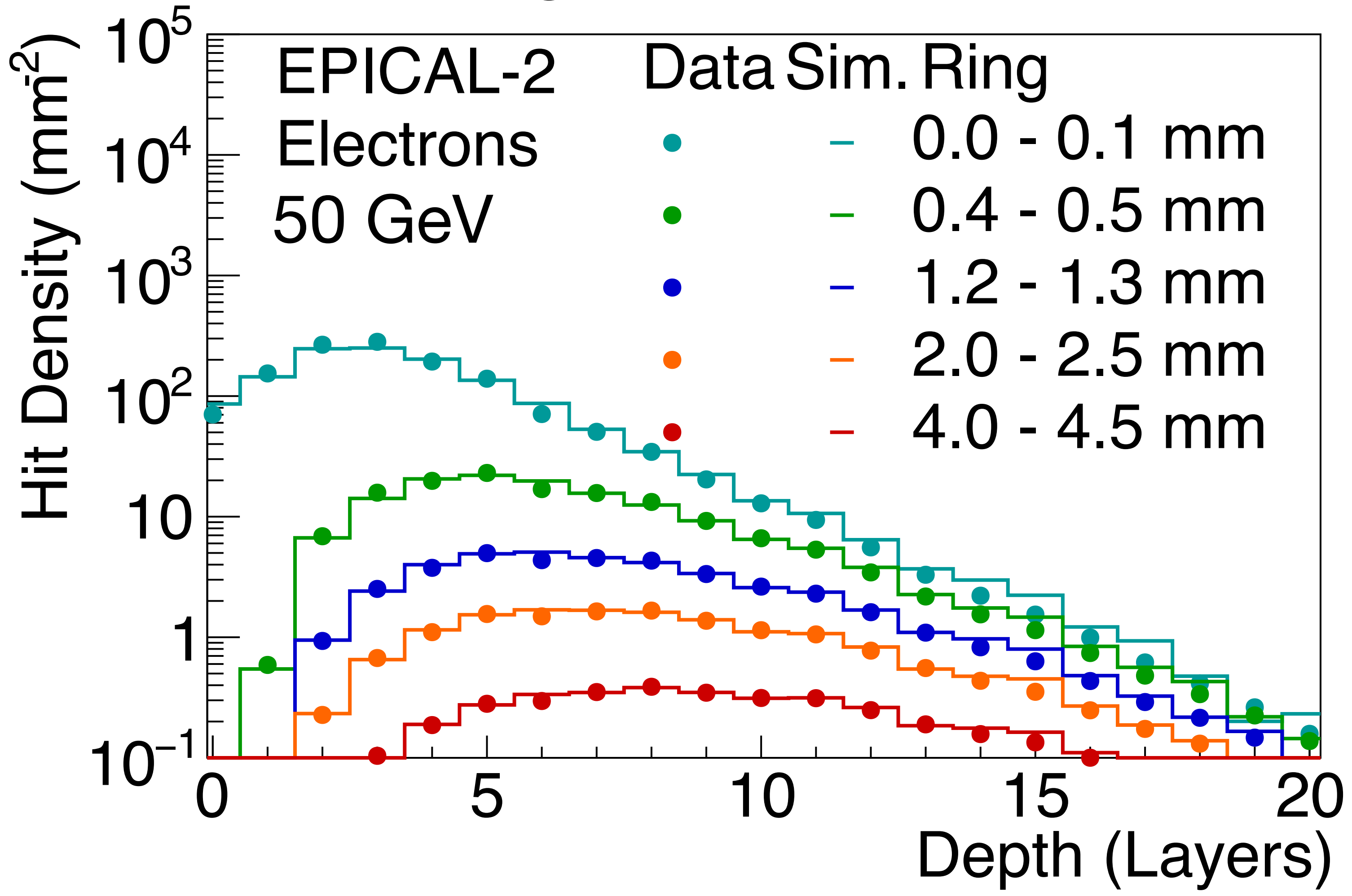
Shower Profiles

longitudinal

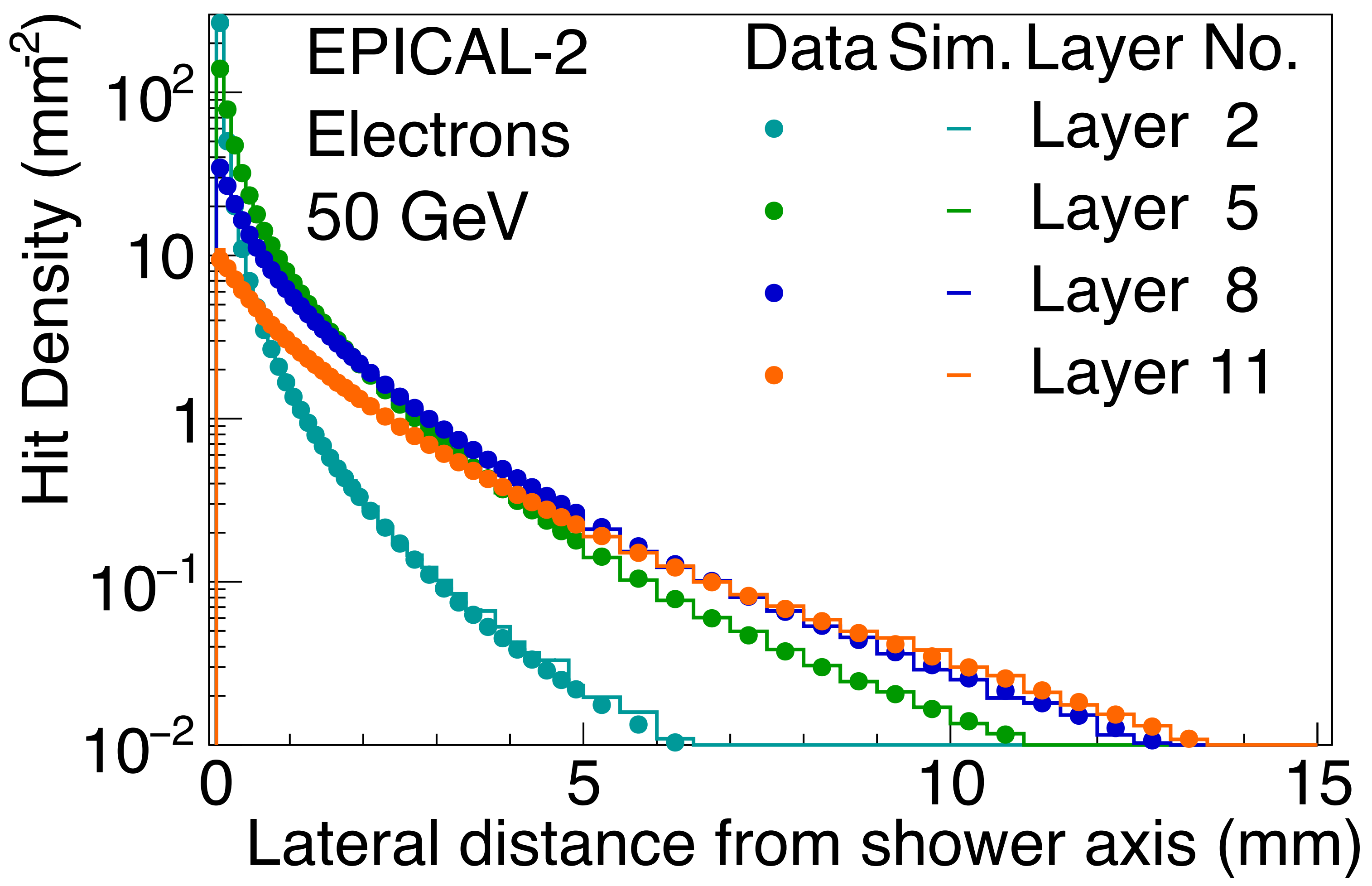




longitudinal/lateral



lateral



- Longitudinal and lateral shower distributions show expected behaviour
  - Similar for N_{clus} and N_{hits}
- Wealth of information to extract details of shower development: work in progress
- Hit density well below saturation limit at low energy
  - Maximum at 5 GeV: ≈ 300 hits/mm^2
  - Saturation at 1272 hits/mm^2
  - Limit will be reached at high energy: correction required