Utrecht University

Nikhef

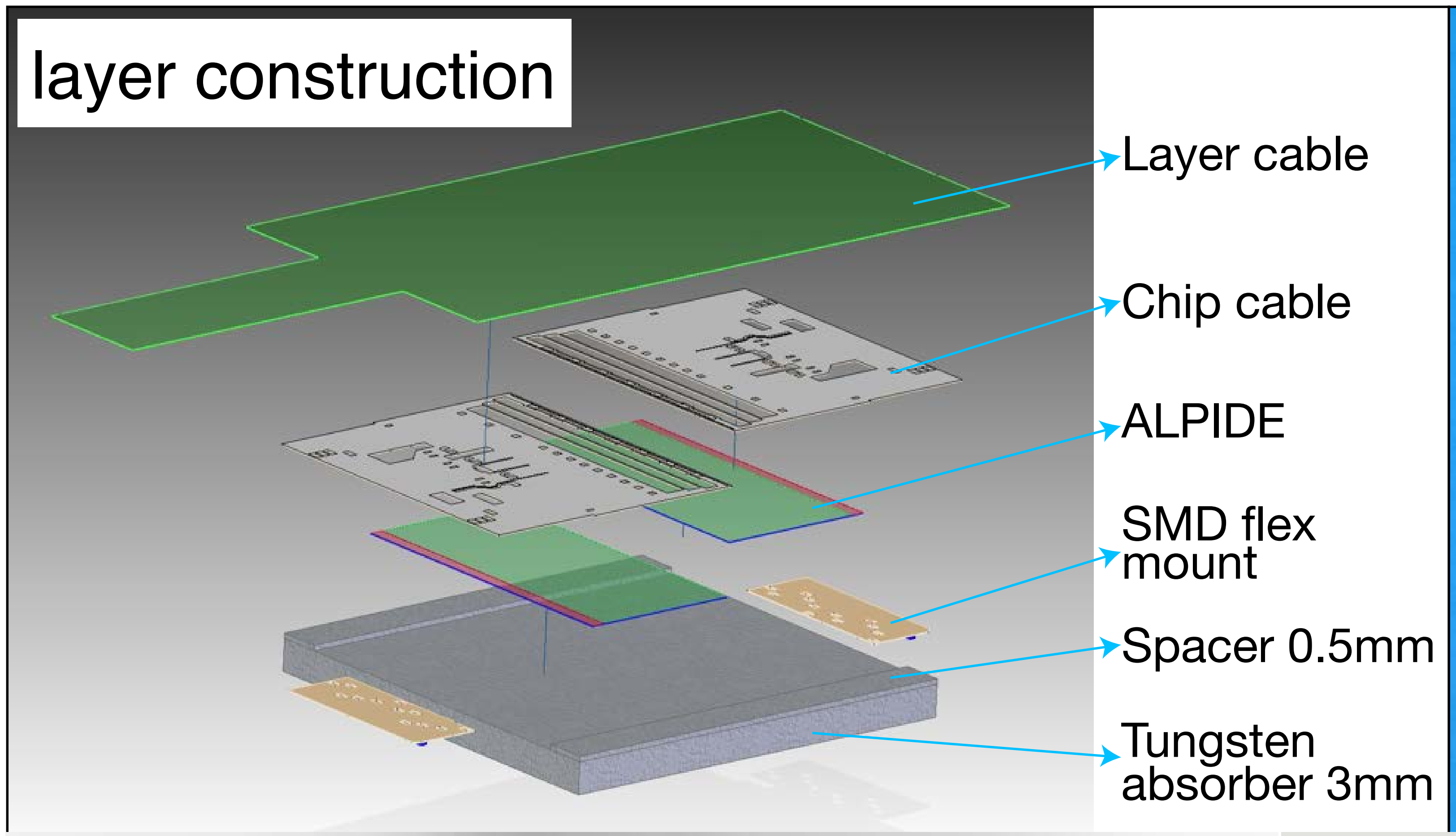
# Results from the EPICAL-2 Ultra-High Granularity Electromagnetic Calorimeter Prototype

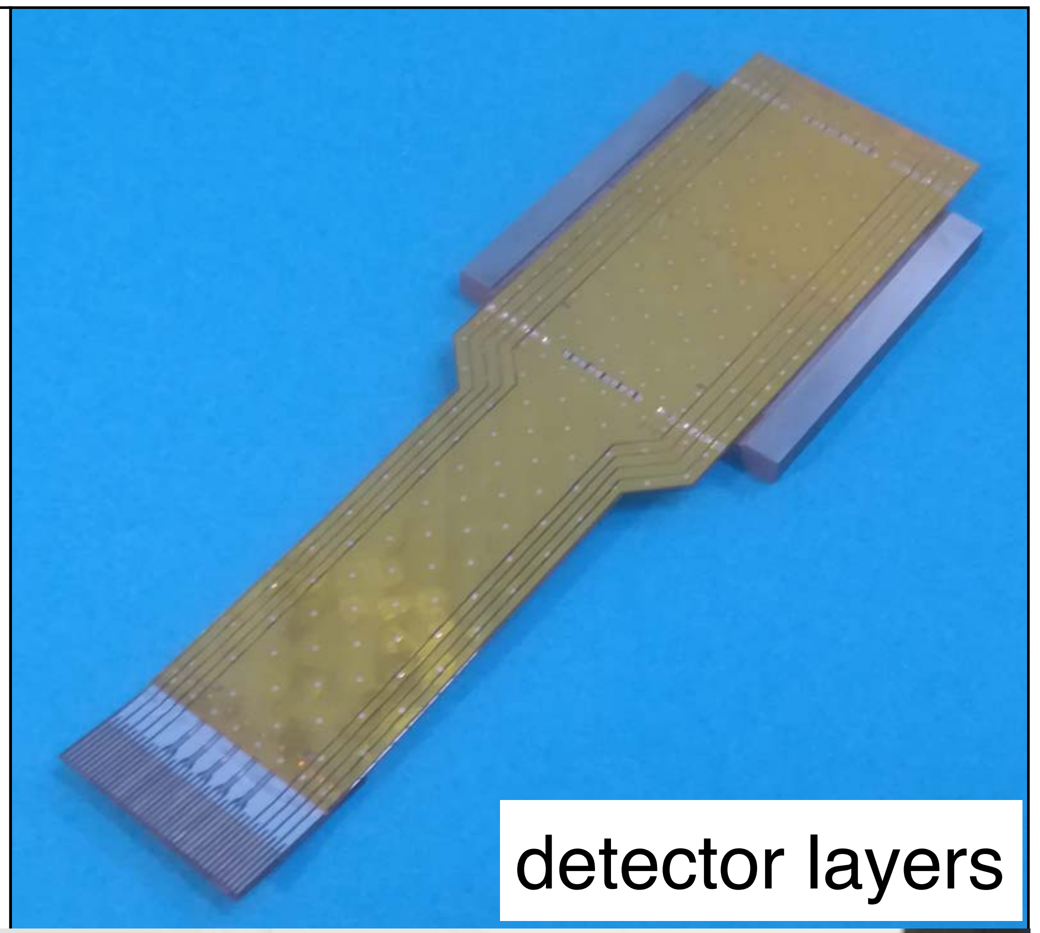
T. Peitzmann (Utrecht University/Nikhef)
for the EPICAL-2 team

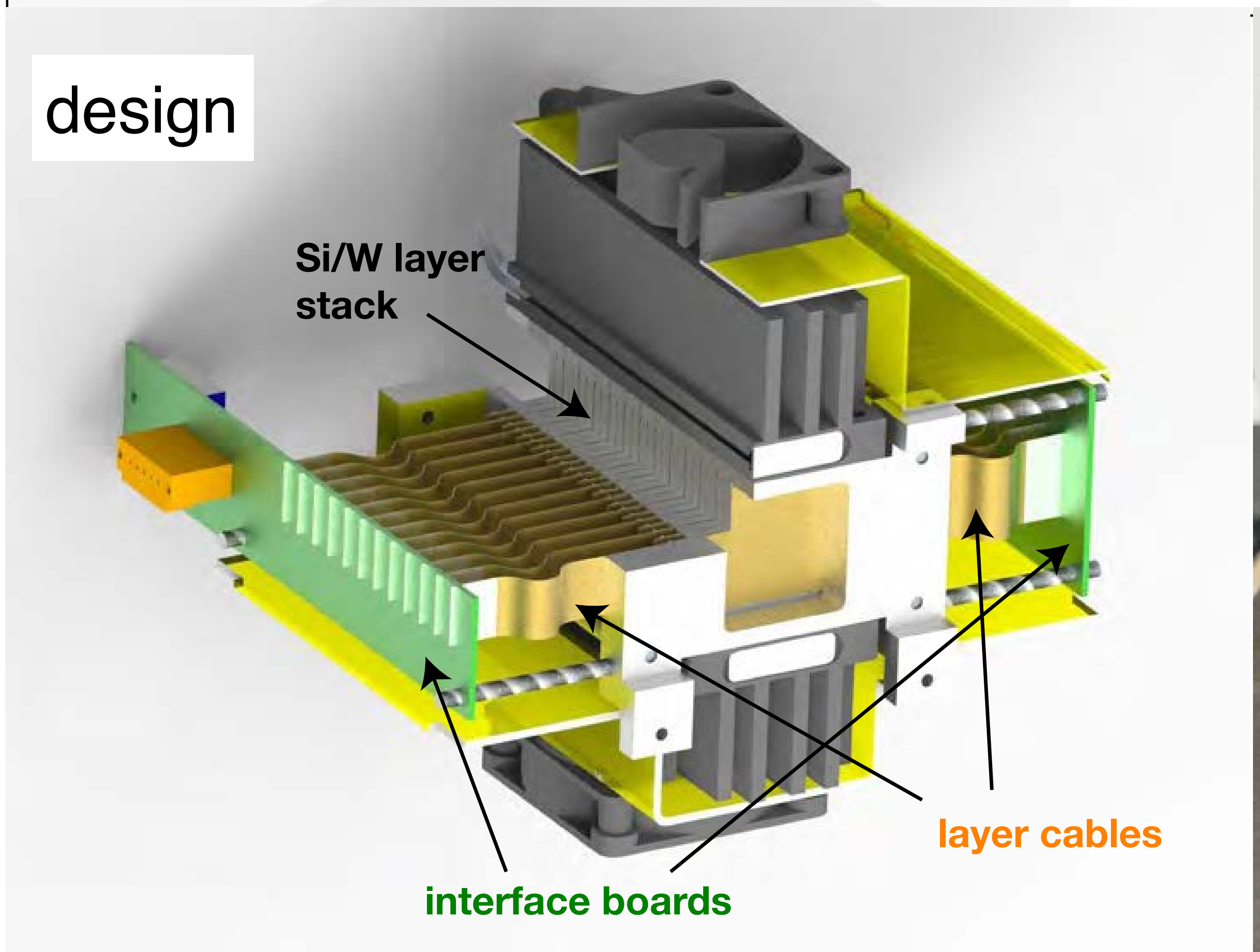
# Introduction

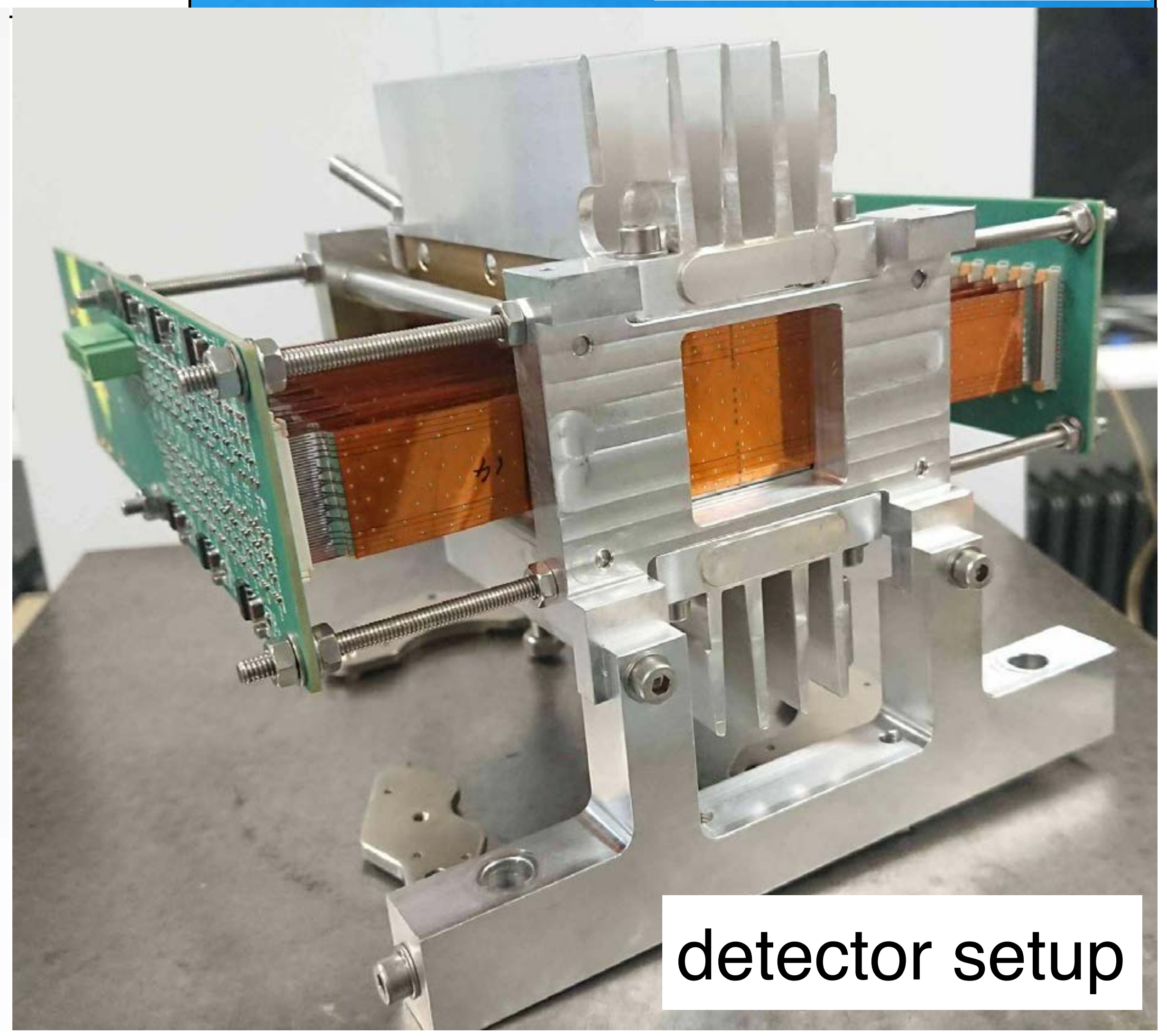
- Digital calorimetry: count number of charged shower particles in sampling layers
  - Ideally: potential to reduce fluctuations from individual sampling layers
  - High granularity required due to high particle density
- State-of-the-art all-pixel calorimeter prototype
  - Follow up on proof of principle EPICAL-1 (JINST 13 (2018) P01014)
  - EPICAL-2: Si/W stack using ALPIDE sensors, detailed simulation in Allpix$^2$
- Calorimetric performance from test-beam measurements
  - Detailed study at low energy (DESY)
  - First preliminary results from high energy (SPS)

# New Digital Calorimeter Prototype – EPICAL-2



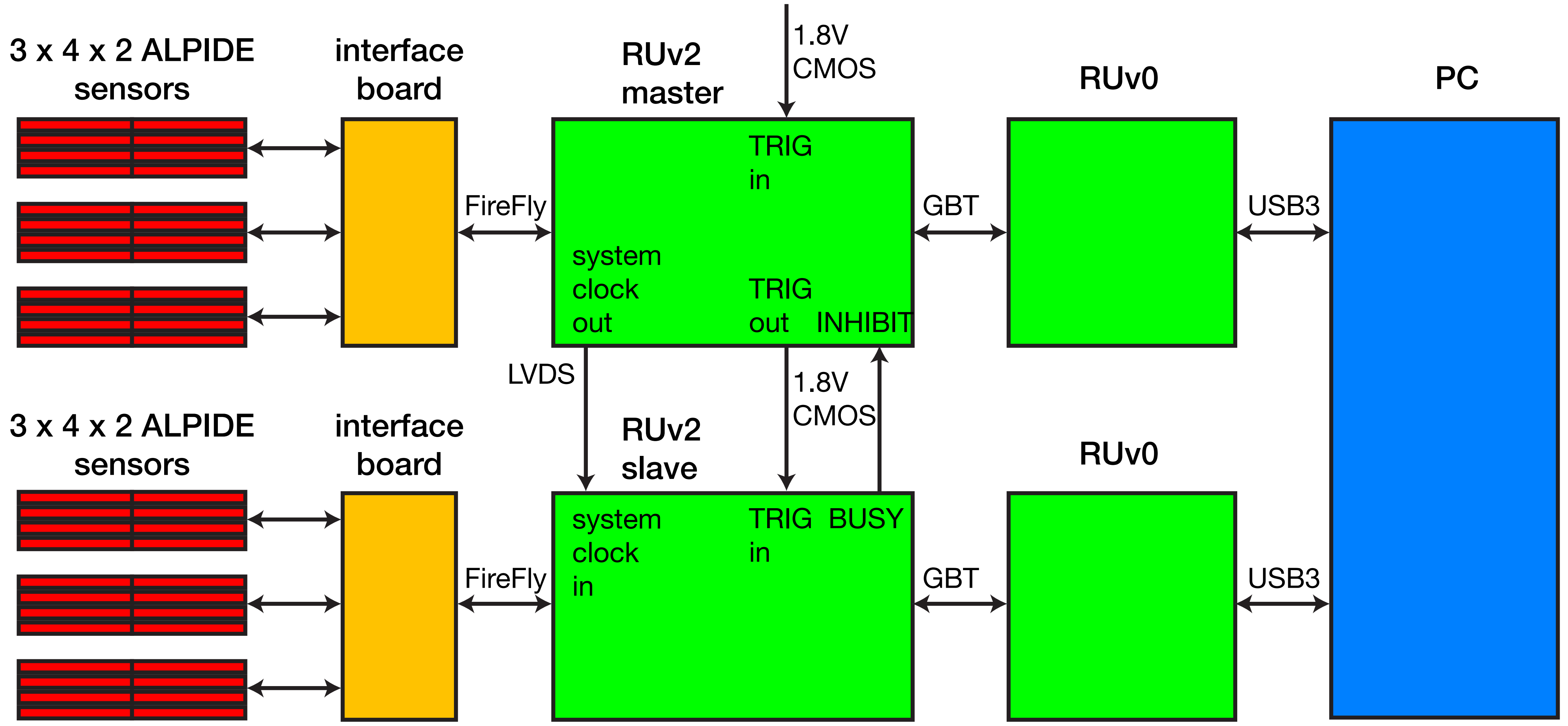

24 layers with each

- 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 $\mu m^2$ pixel size
active cross section 3 x 3 $cm^2$

compact design: expect $R_M \approx$ 11 mm

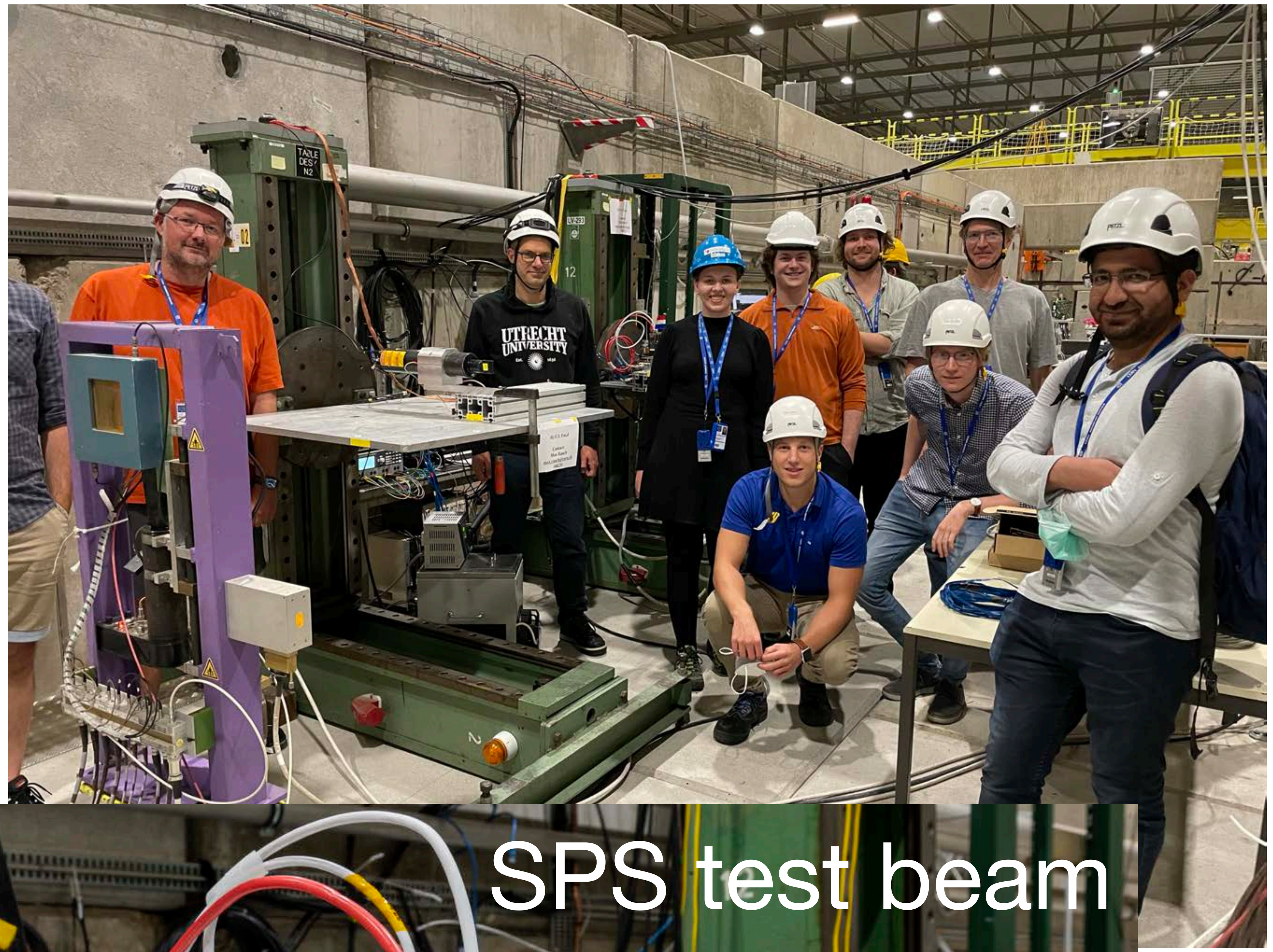
readout schematics

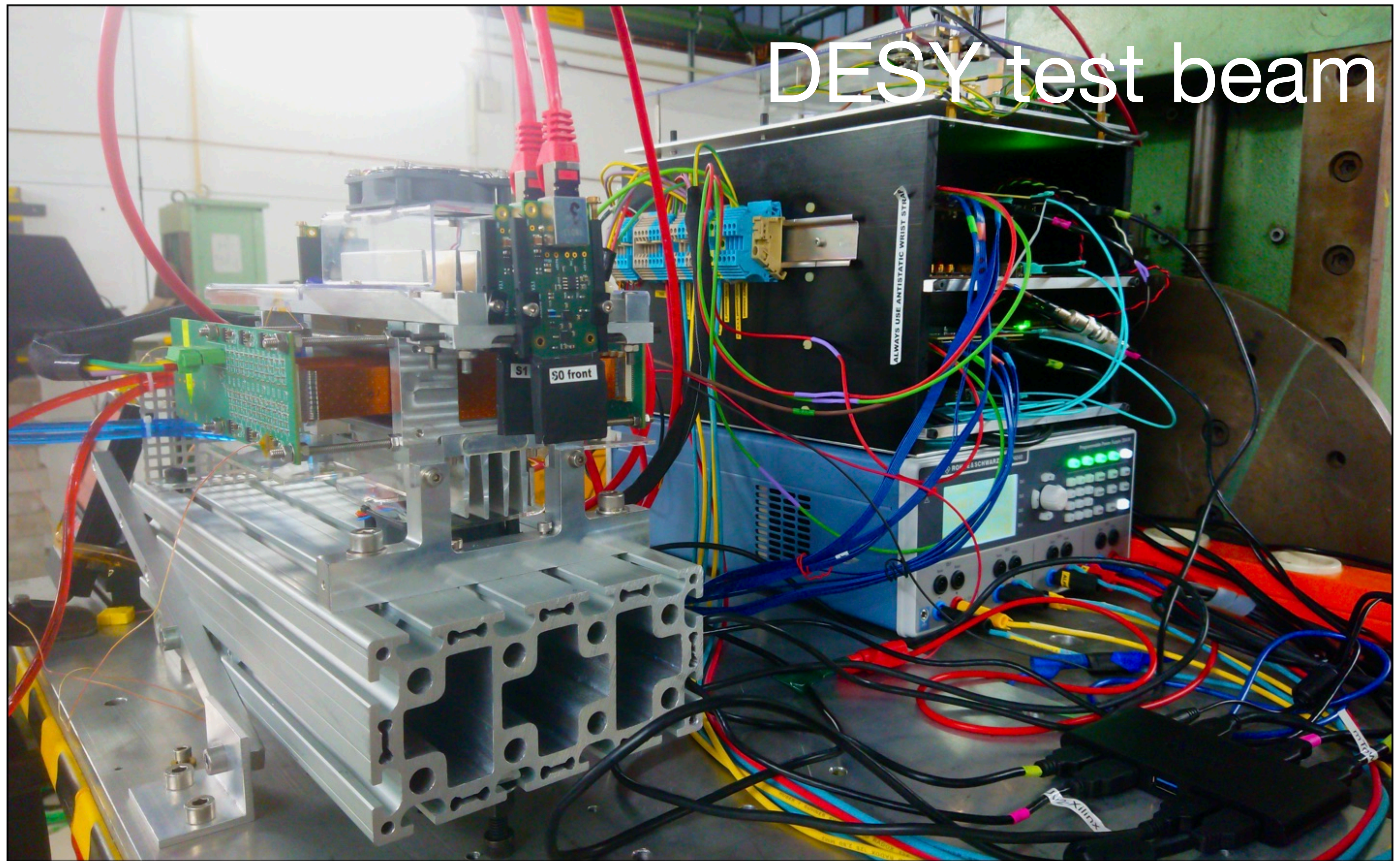



ALPIDE output via 1.2 Gb/s serial line
readout via 2 levels of FPGA

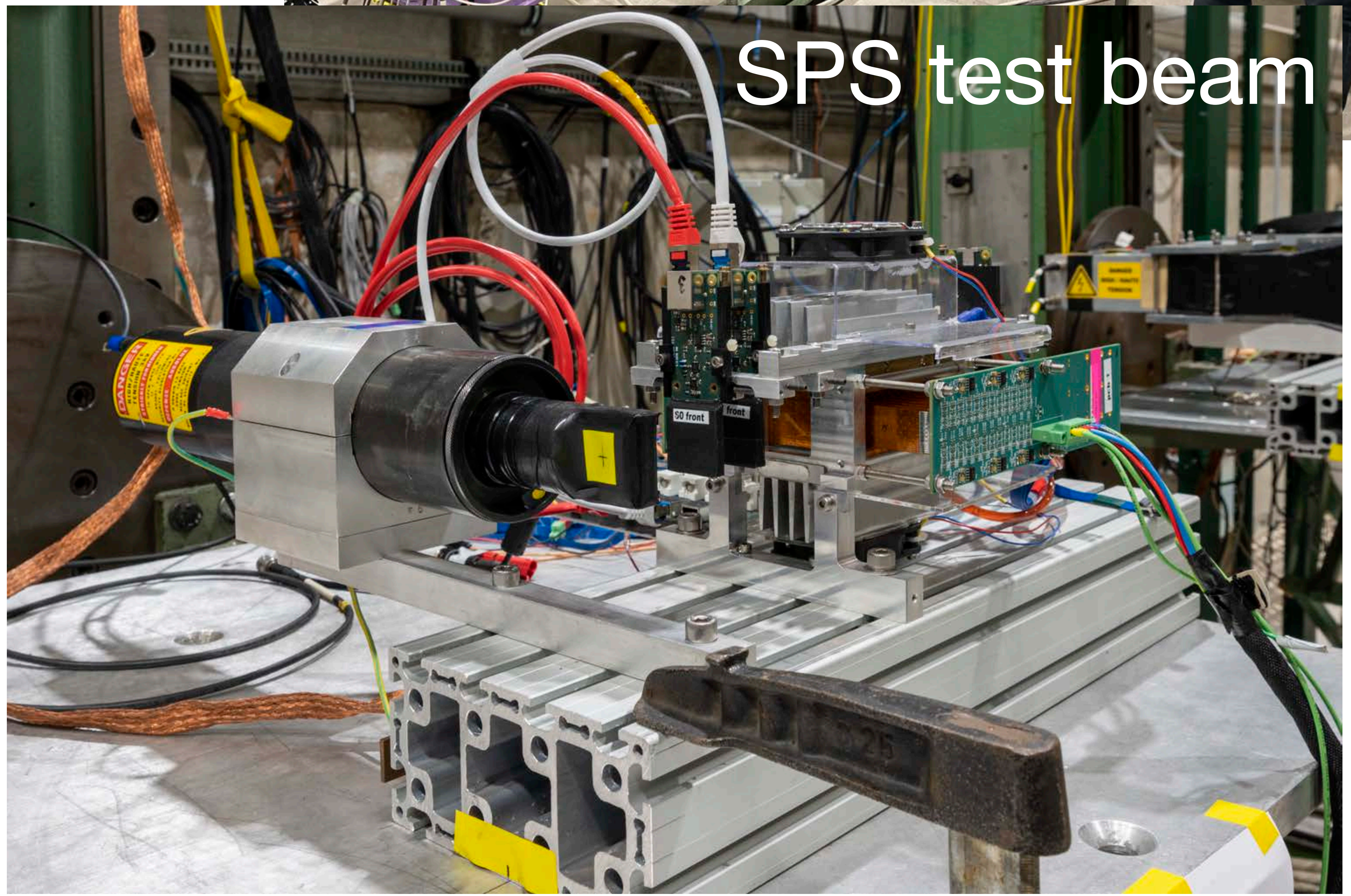
# EPICAL-2 Measurements

- 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



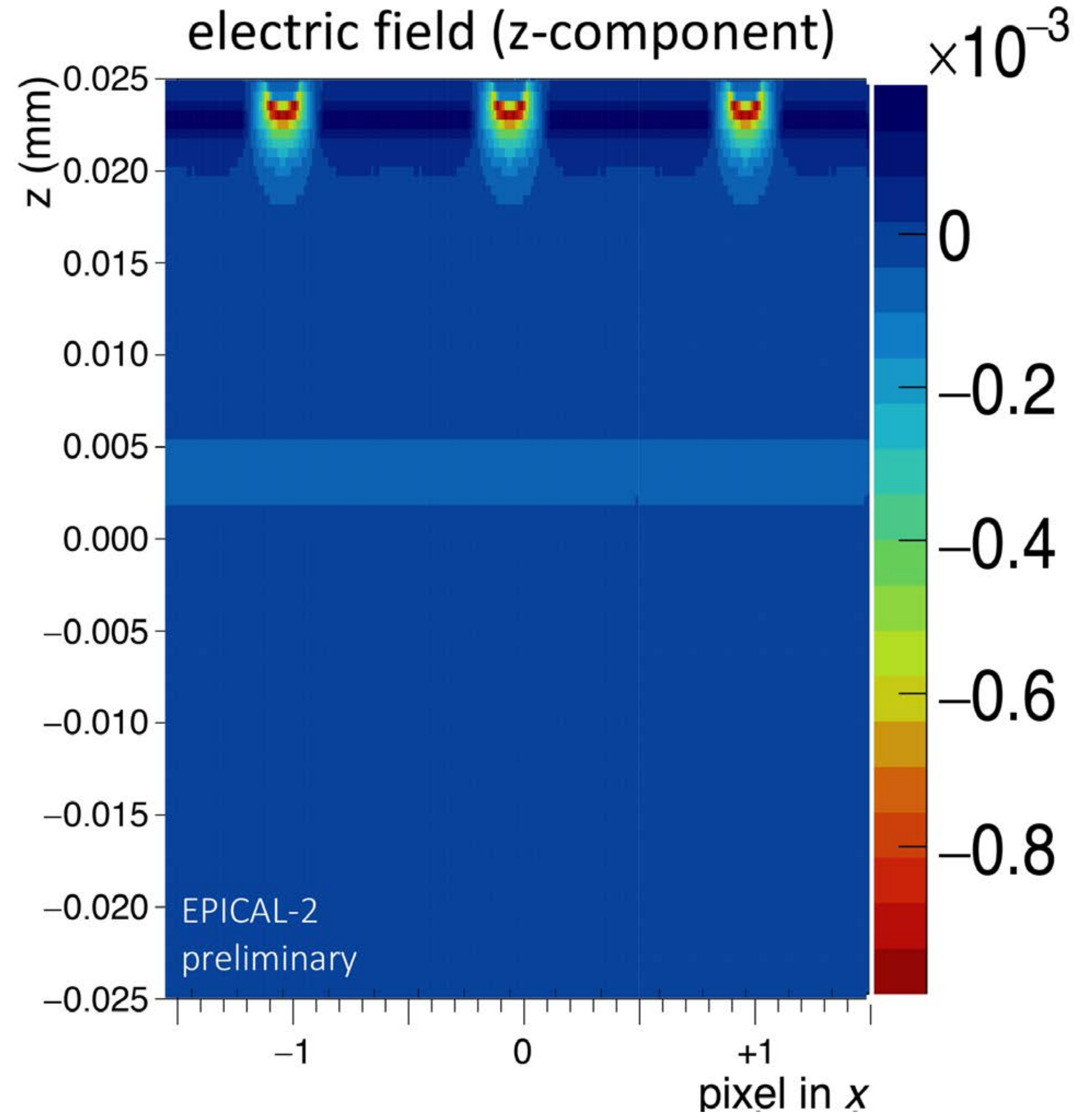


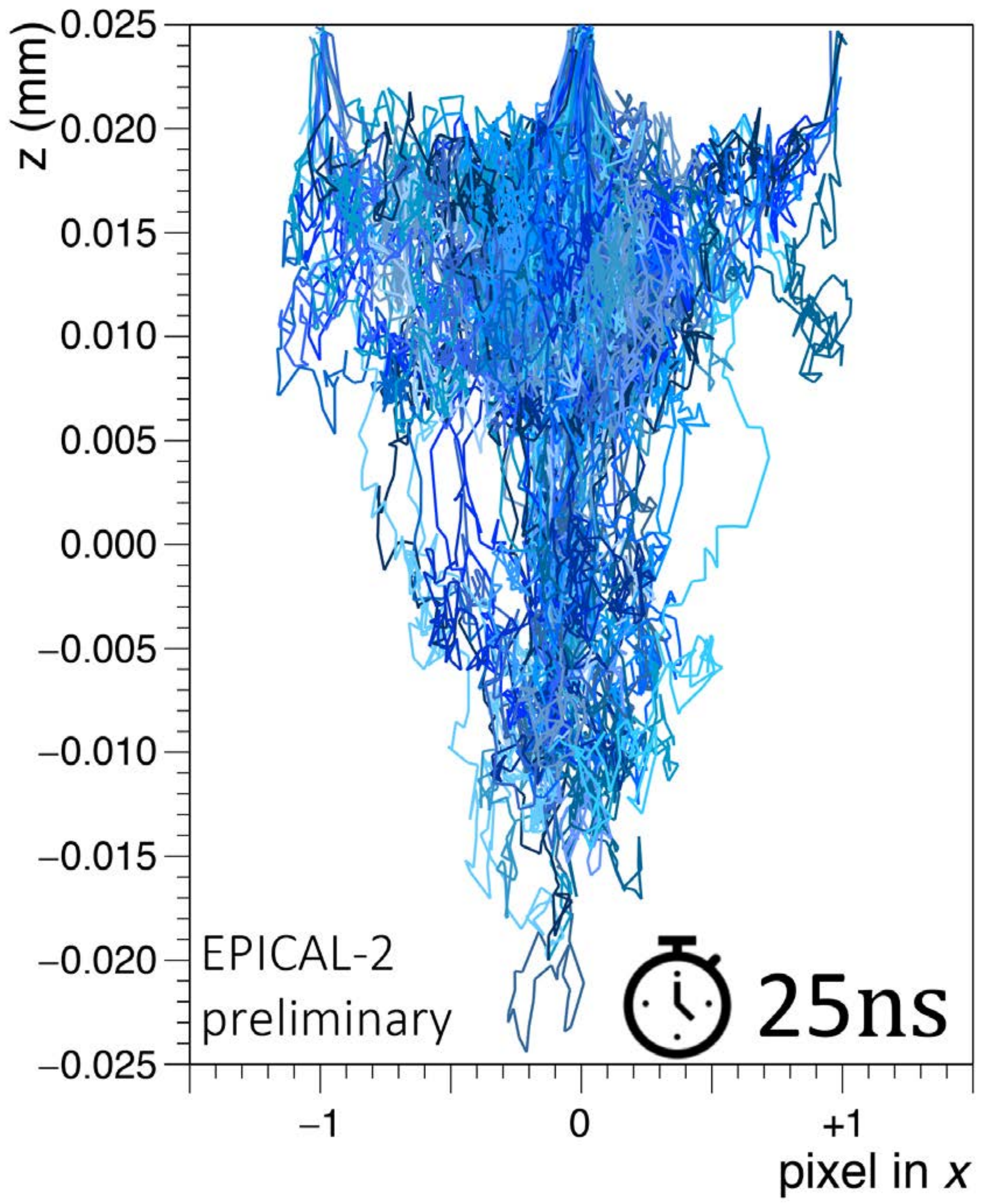
DESY test beam

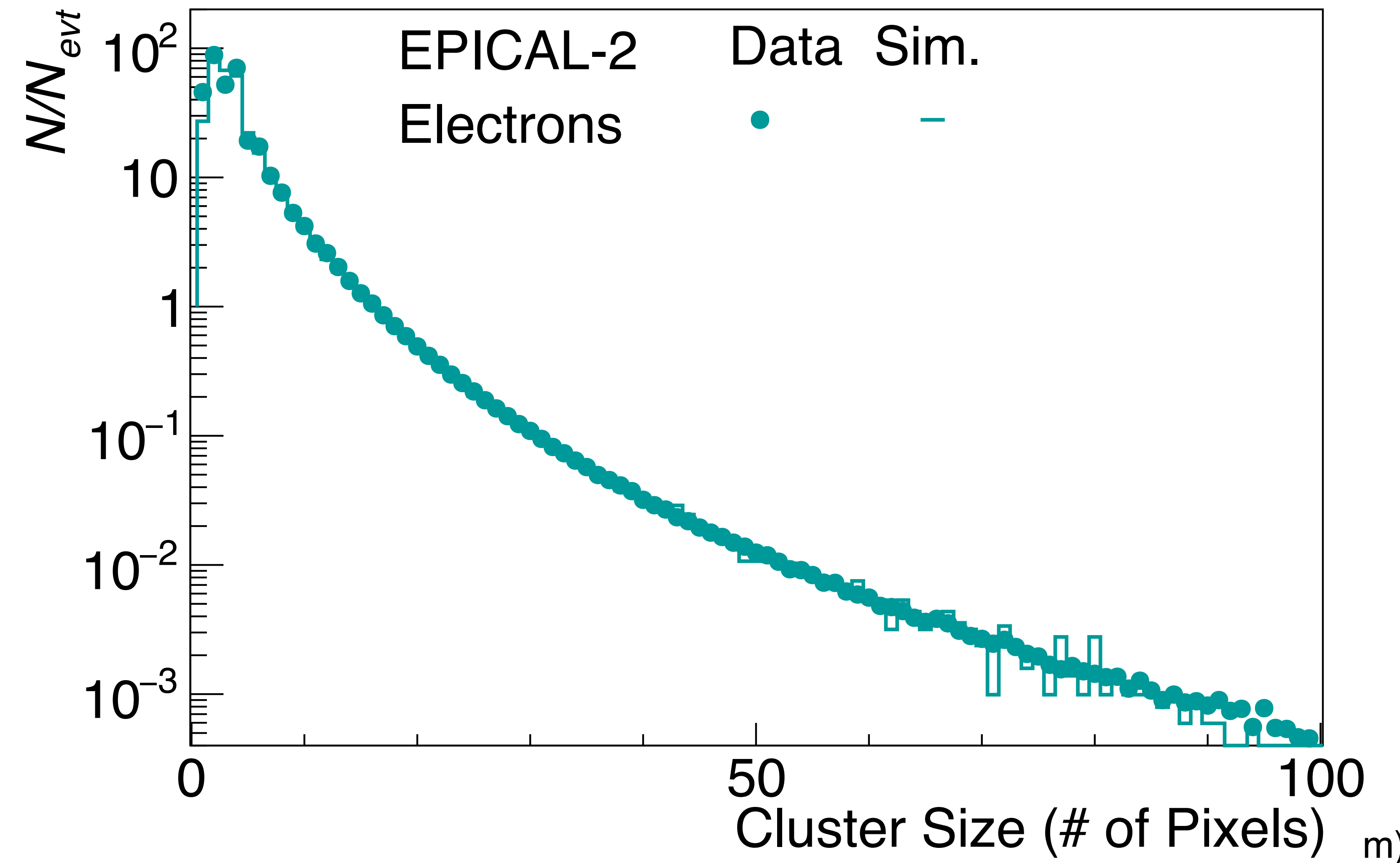


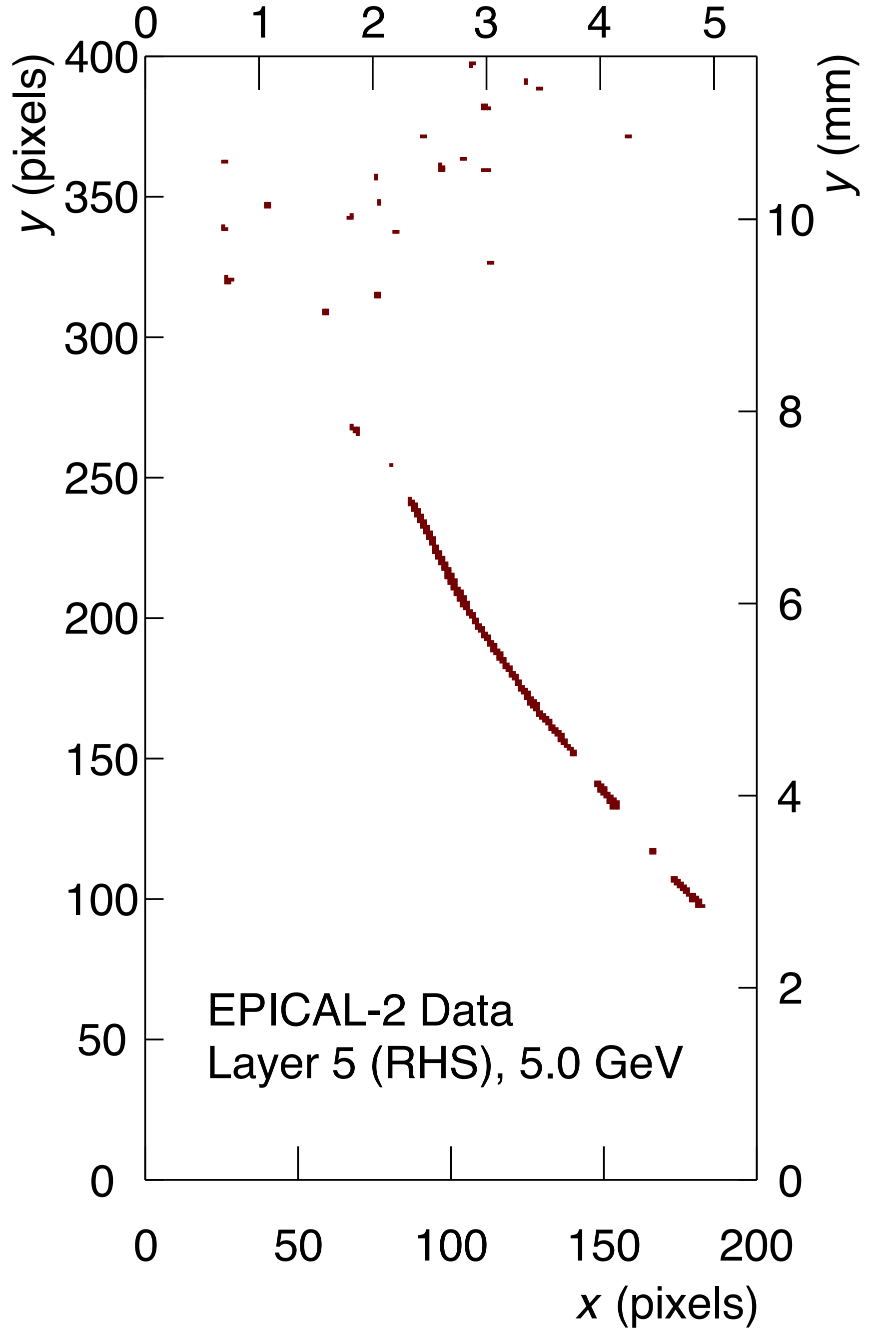
SPS test beam

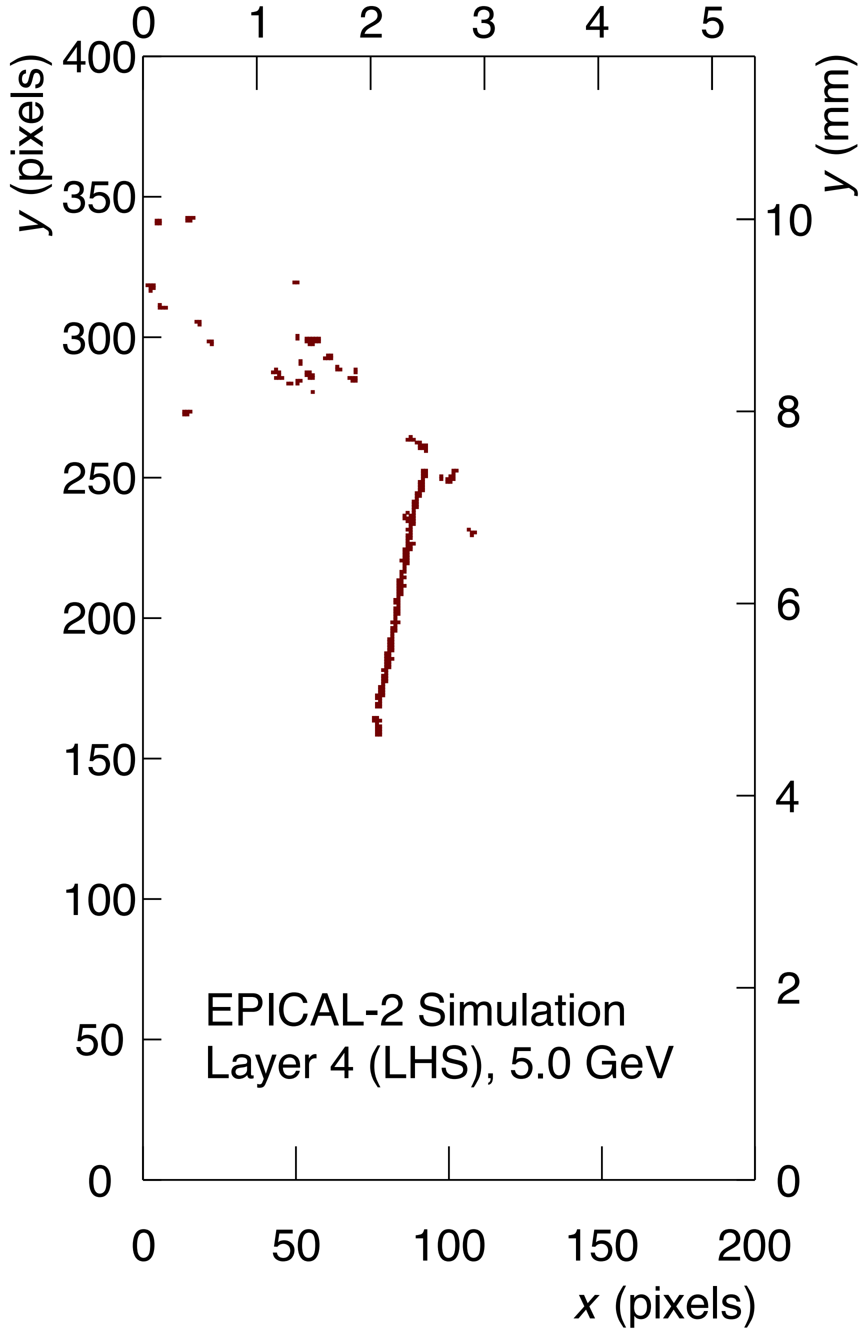
# Allpix² Simulations




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

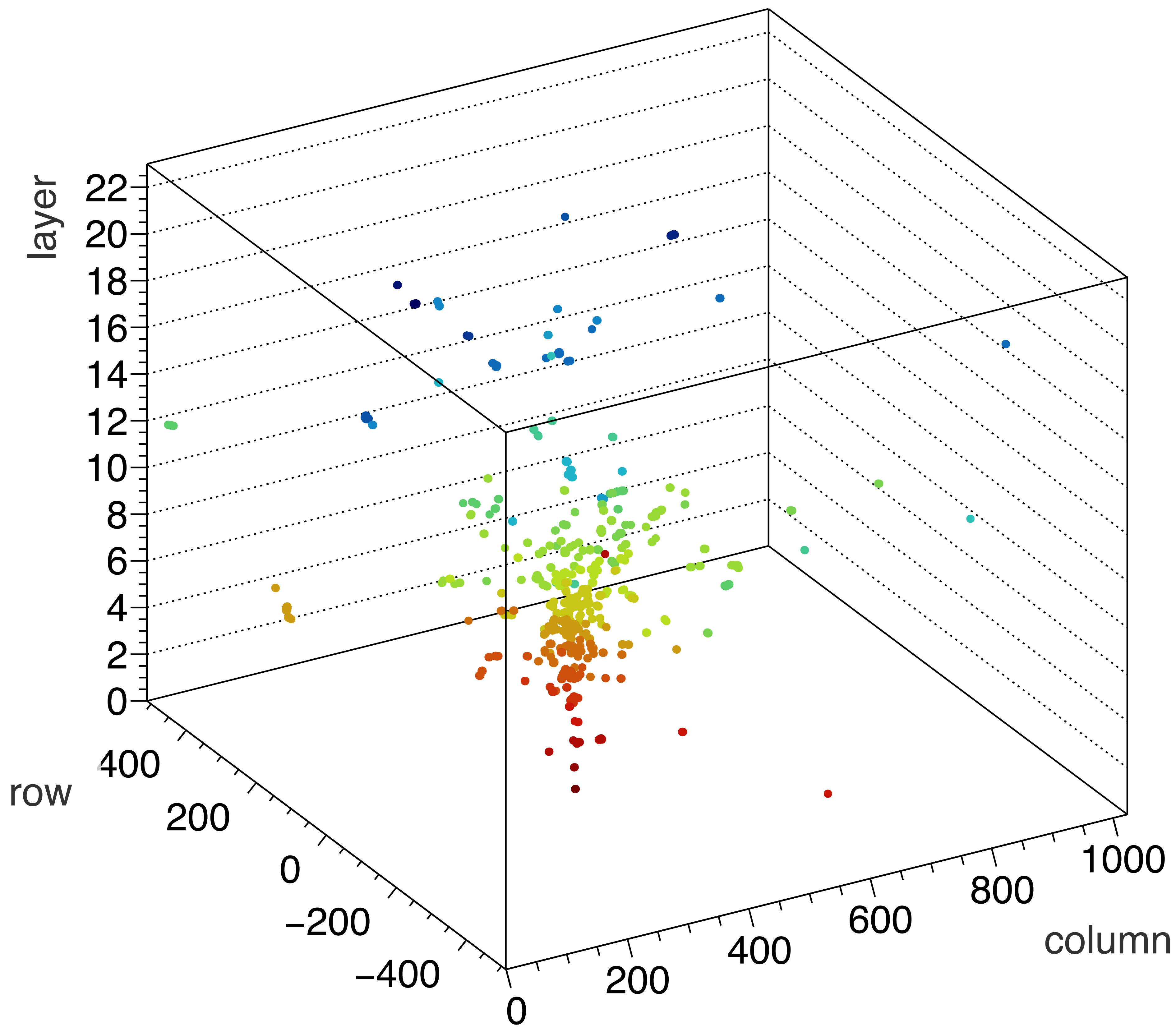
**Allpix²: NIM A, 901:164–172, 2018**

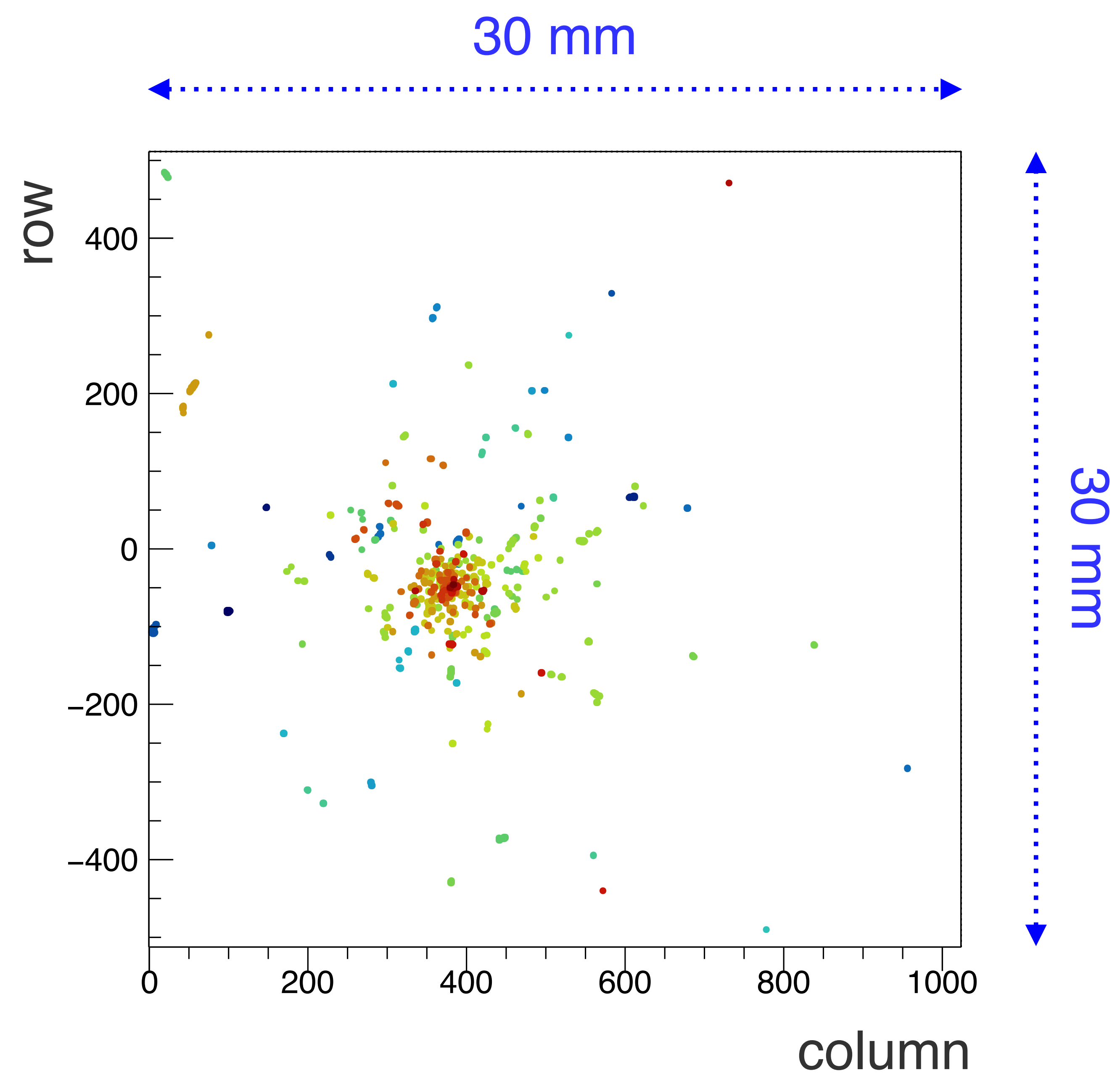
EPICAL-2

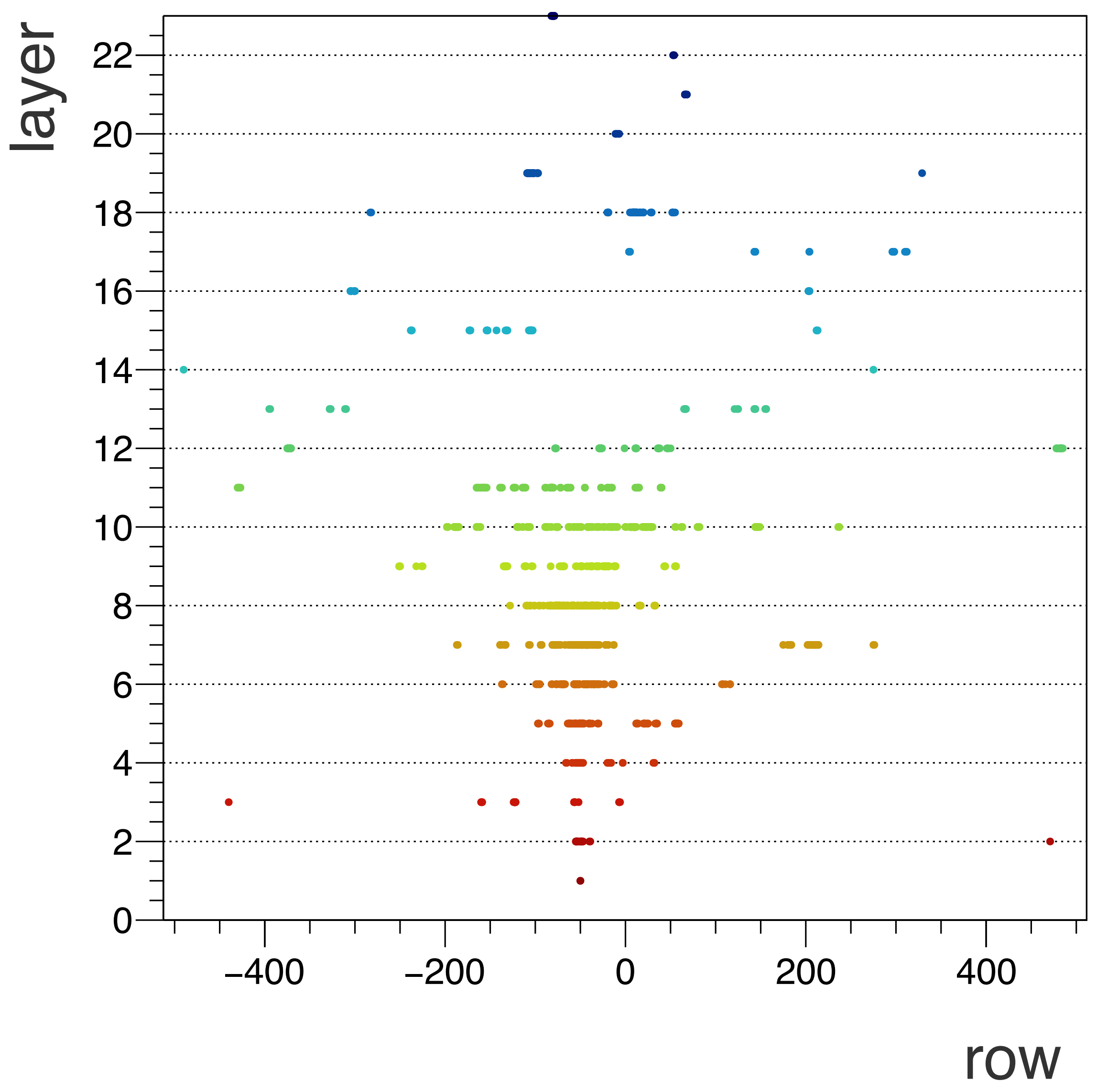
# Event Displays

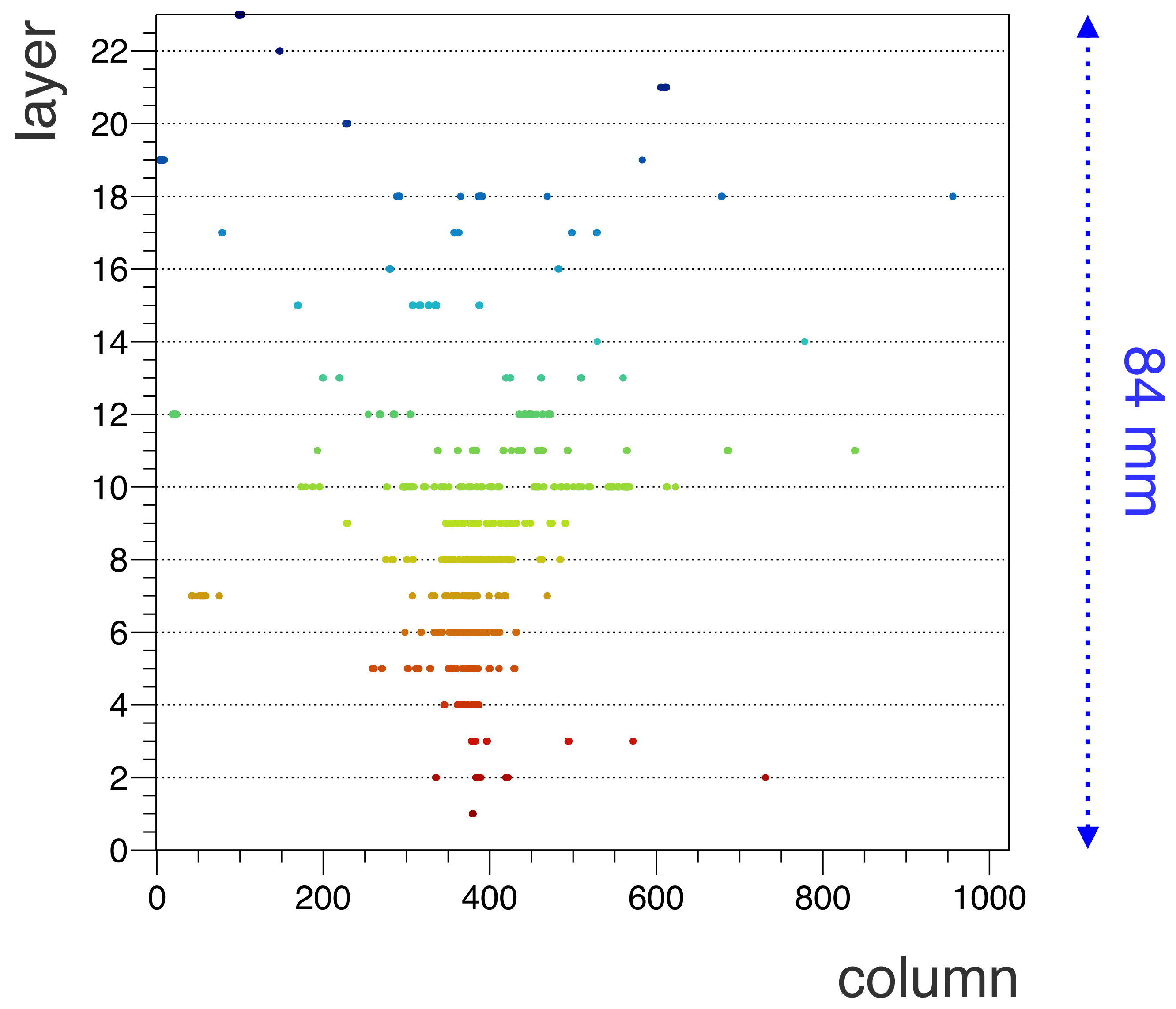
single electron event
5 GeV
raw data

colour → layer number

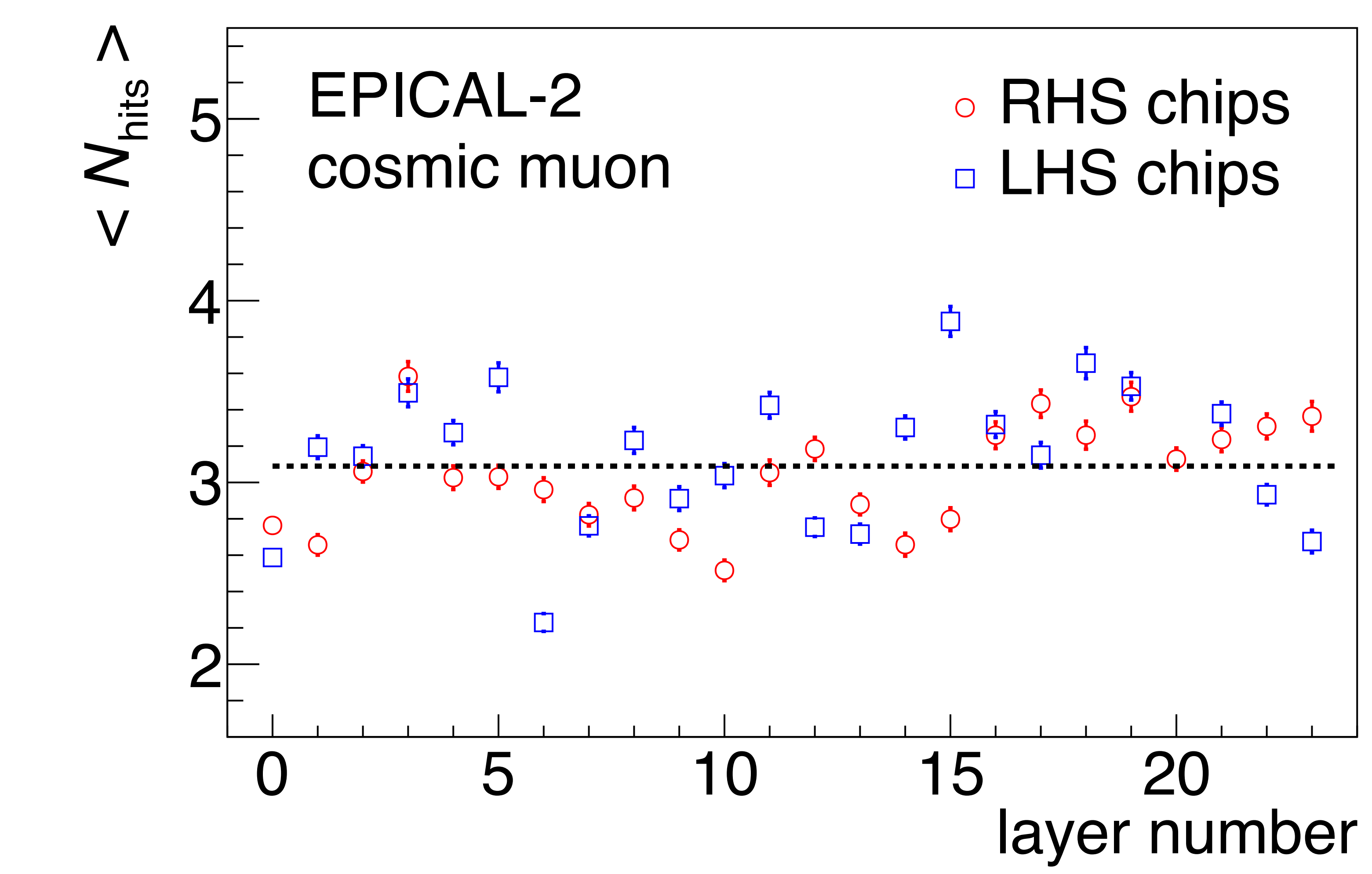


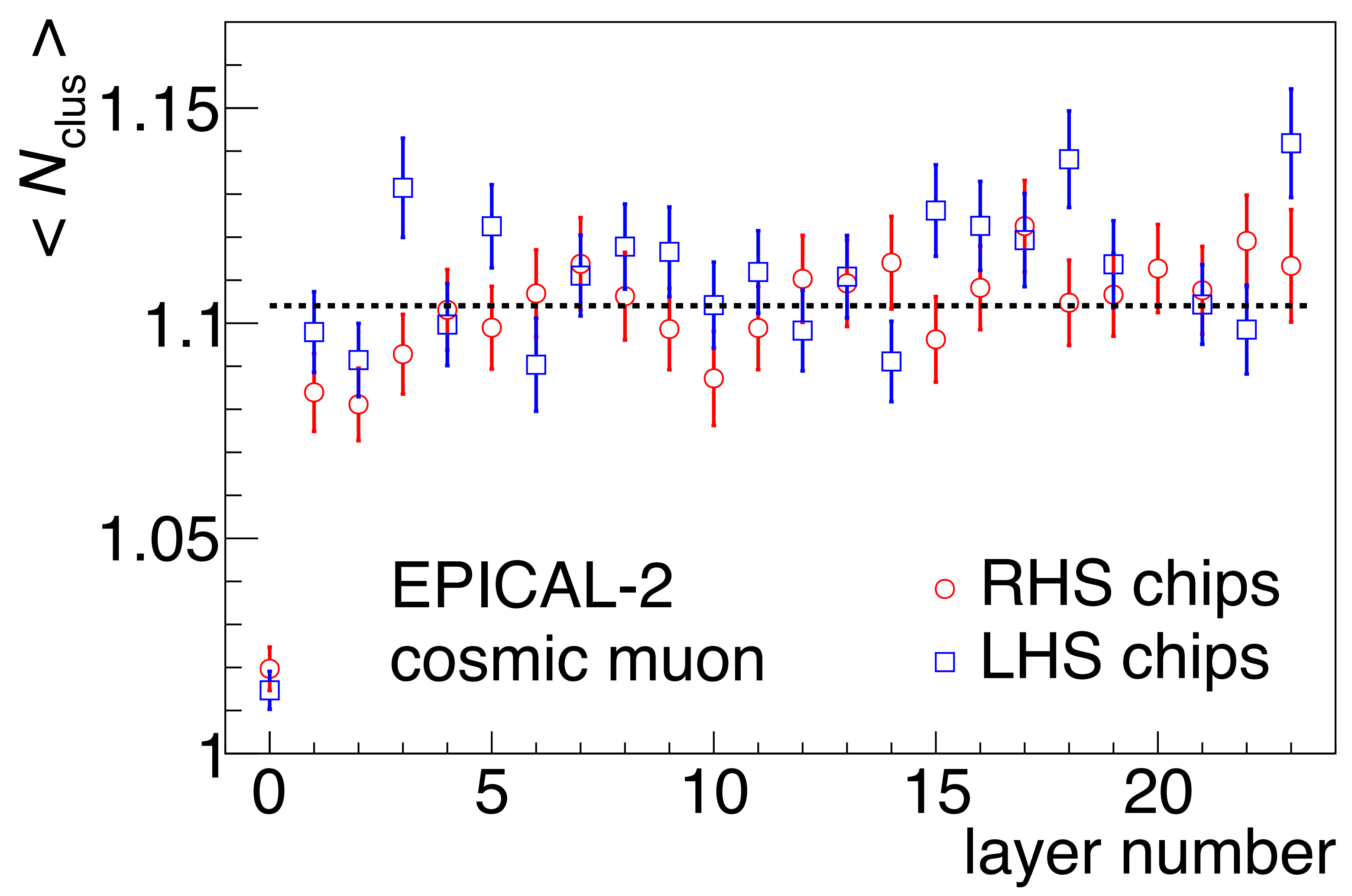



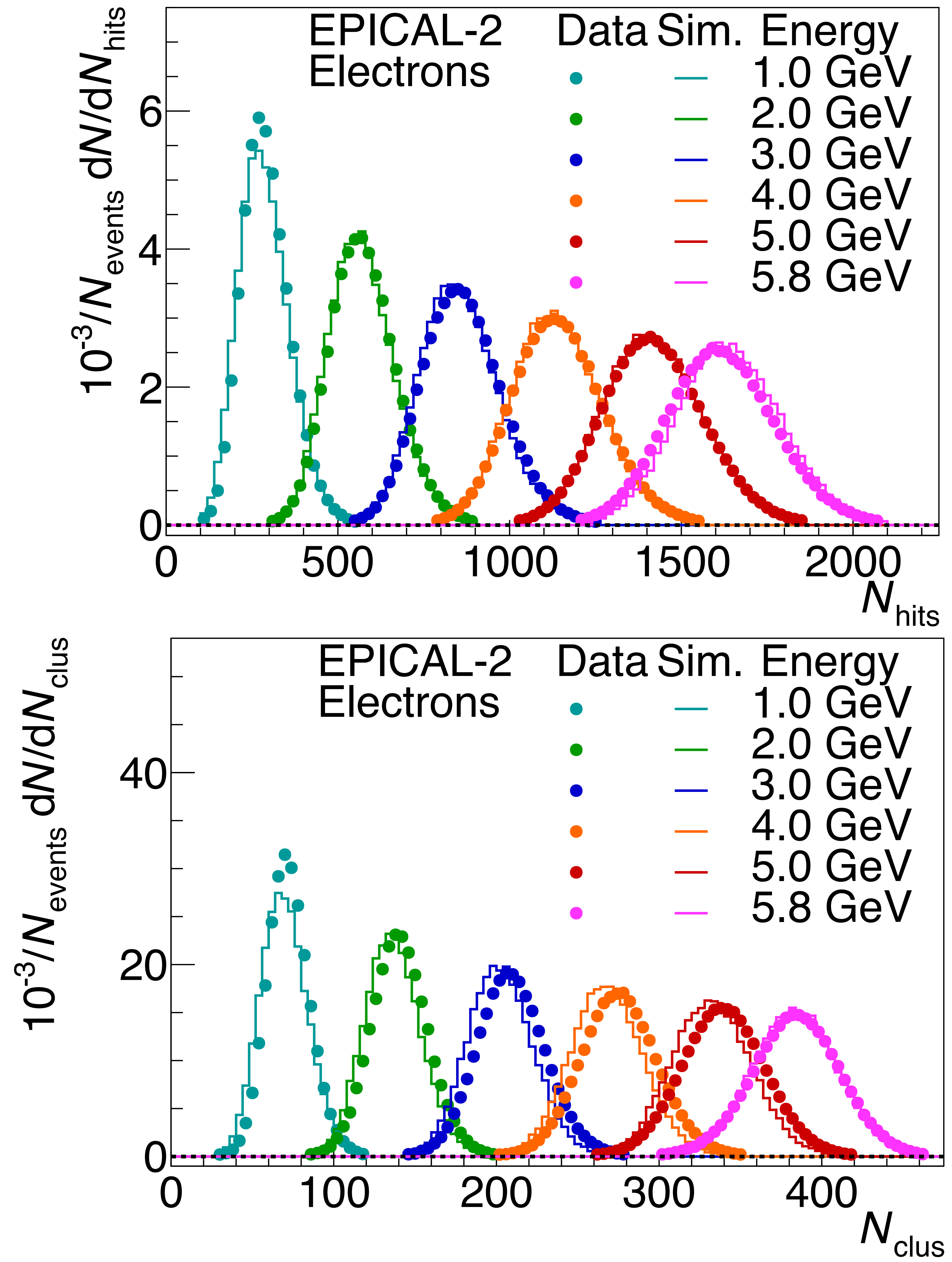
# Sensor Calibration



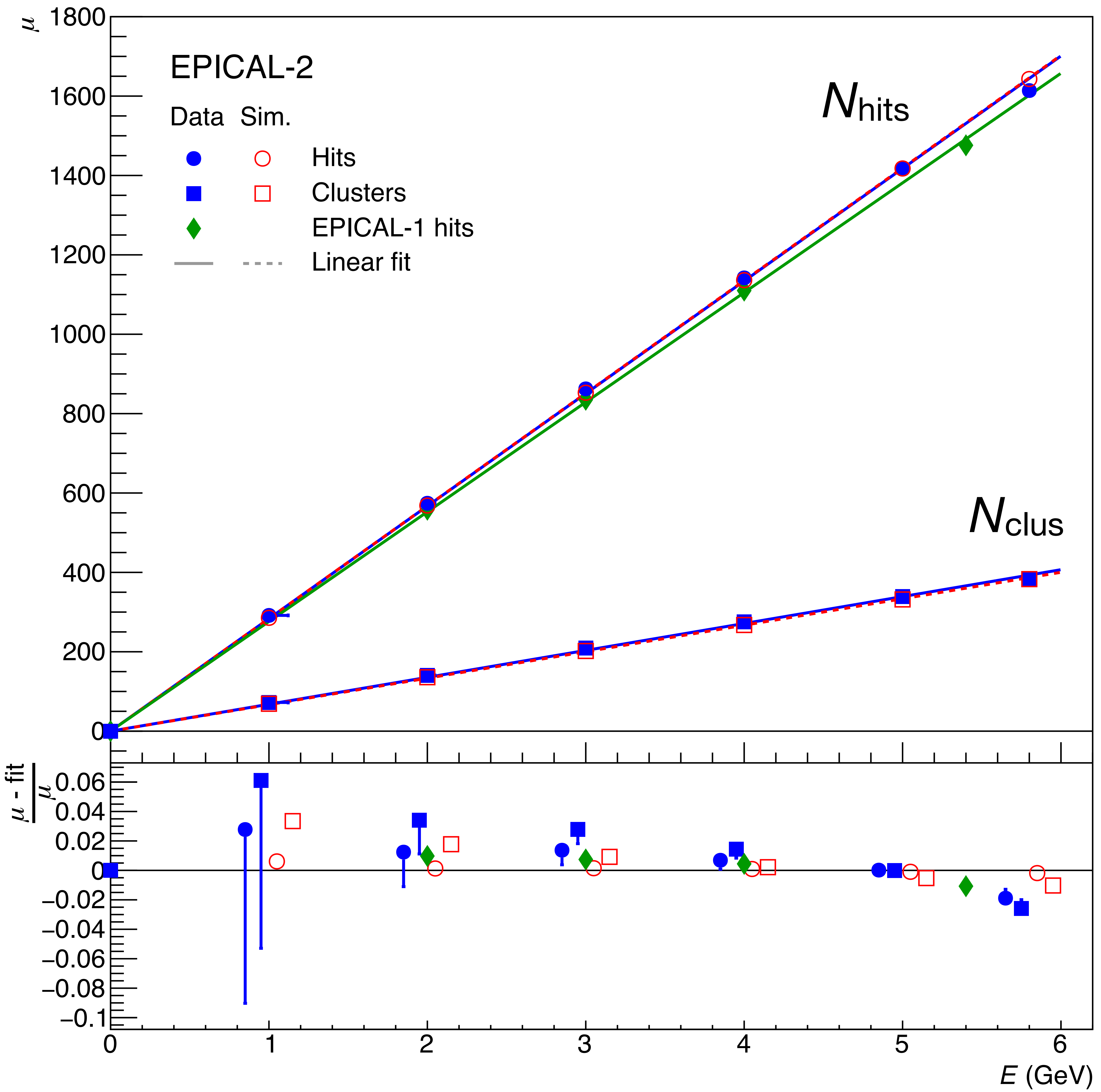

- Use muons (from cosmics or in-beam) for relative calibration of sensors with different sensitivities
  - Expect identical response to muons in all layers in terms of hits and clusters
  - Ignore in-sensor variation of sensitivity
- Significant sensitivity variation observable in number of hits
- Minor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

# Detector Response



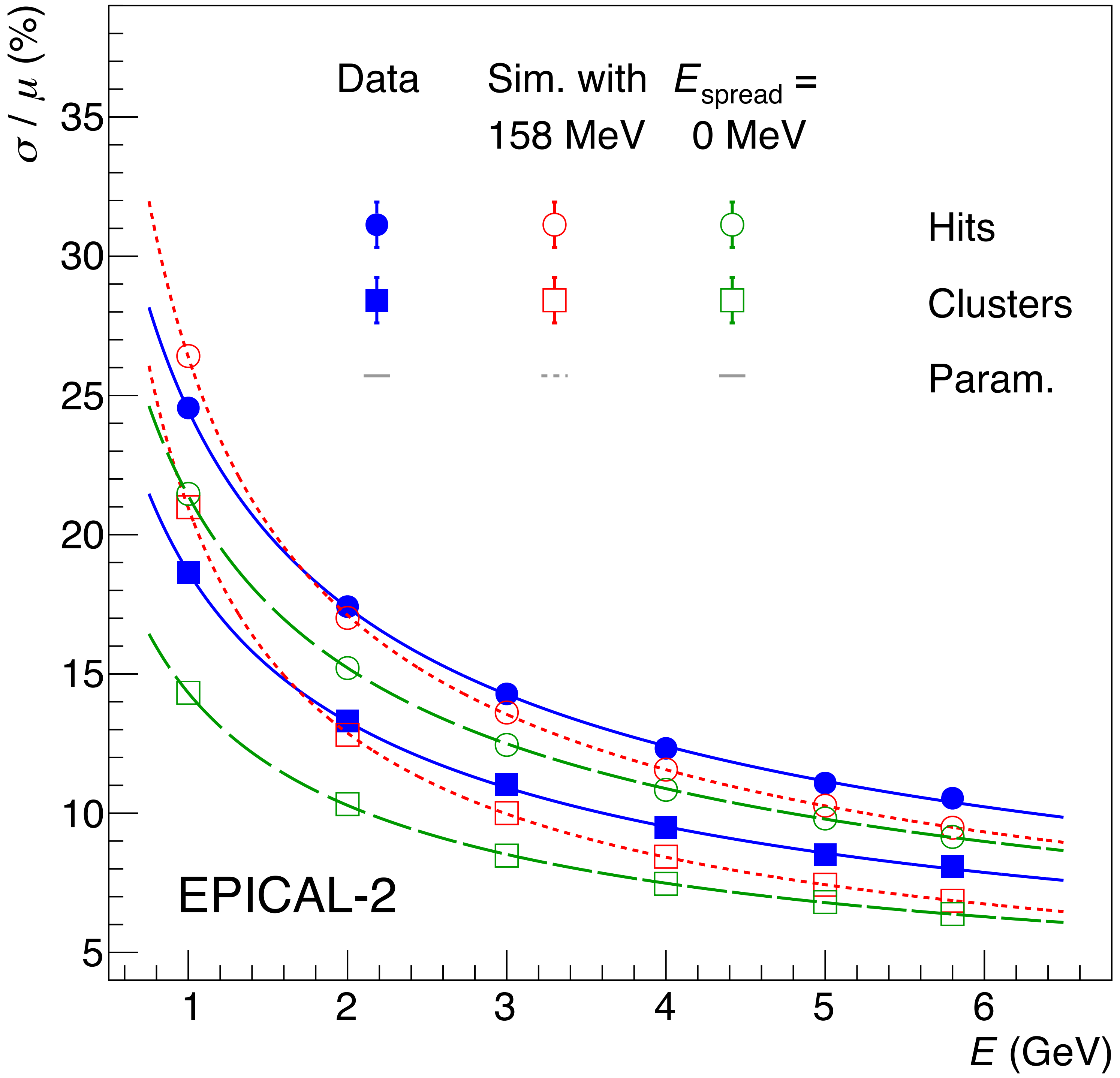

- Number of hits ($N_{hits}$) or number of clusters ($N_{clus}$) usable as response observable
  - Well defined peaks scaling with beam energy
- Allpix² simulation
  - Tuned to number of hits at 5 GeV
  - Very good description for hits at all energies
  - Good description for clusters
    - Sensitive to details of cluster algorithm

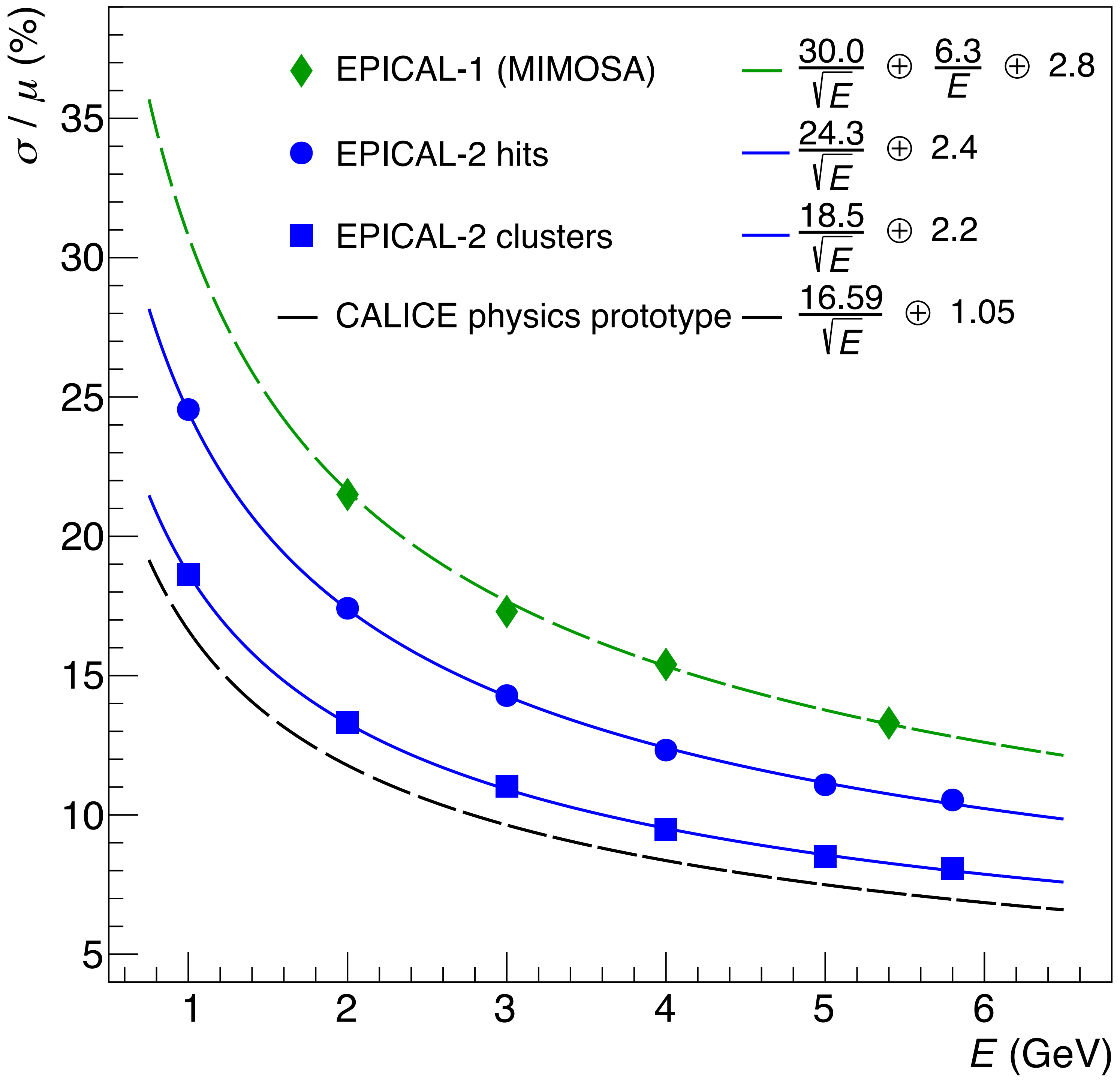
# Energy Linearity




- 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 $N_{\text{clus}}$
    - Reproduced in simulation
- Response consistent with full linearity at low energy

# Energy Resolution

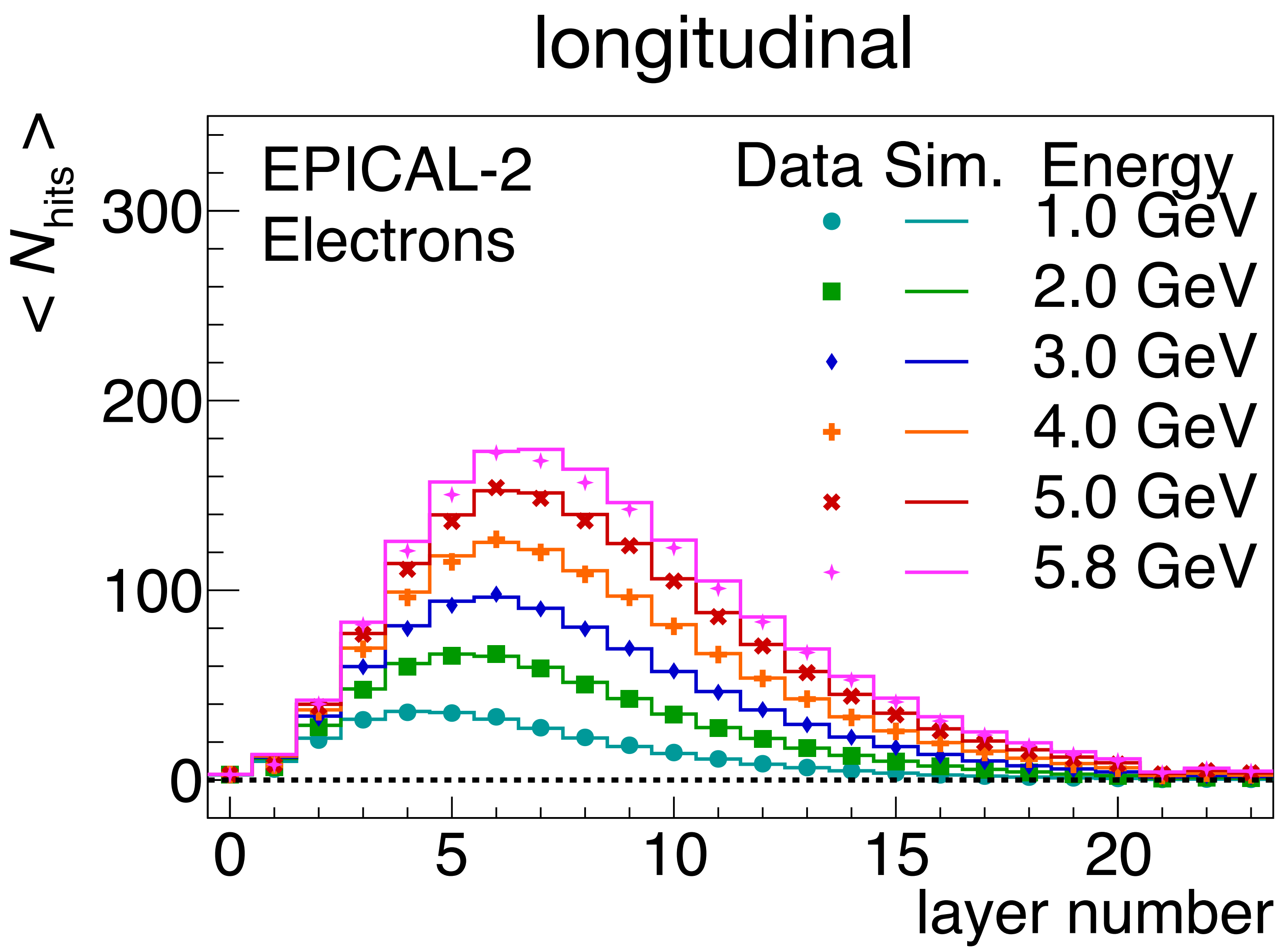


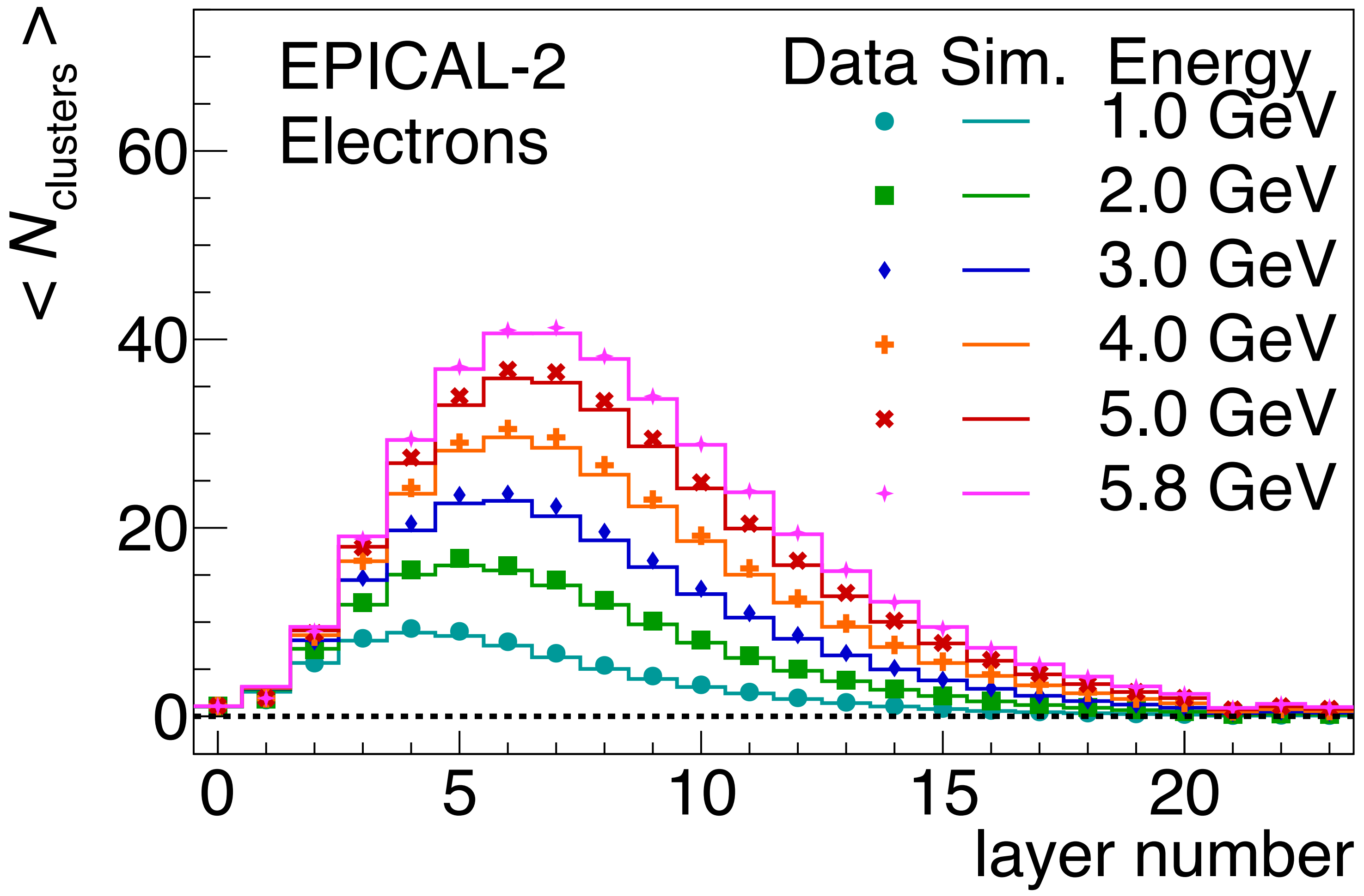



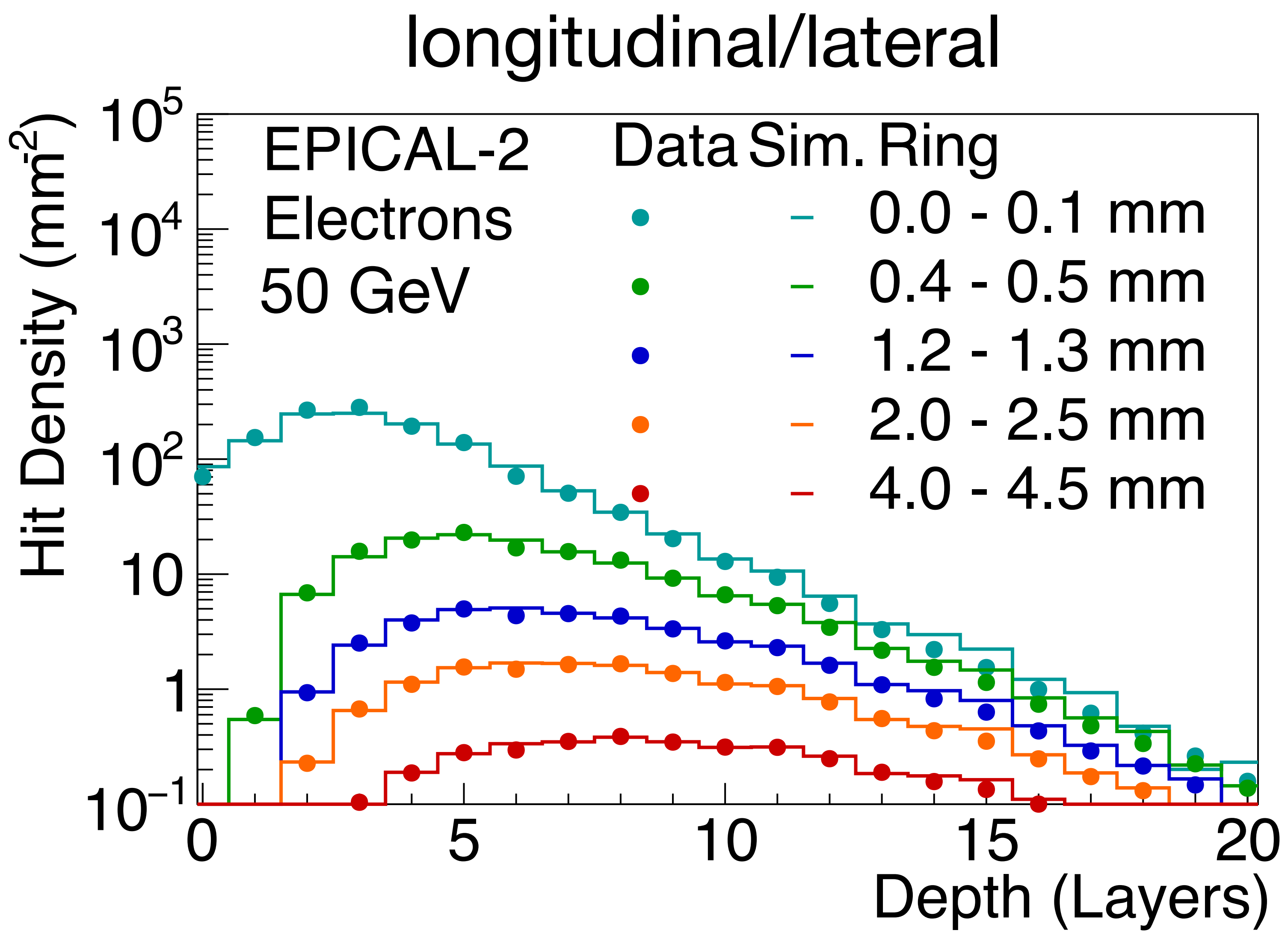

- Resolution shows the expected behaviour for calorimeters
- Experimental data likely contain a significant contribution from beam energy spread at DESY
- “Particle counting” ($N_{clus}$) shows superior performance here
  - Confirmed by simulations

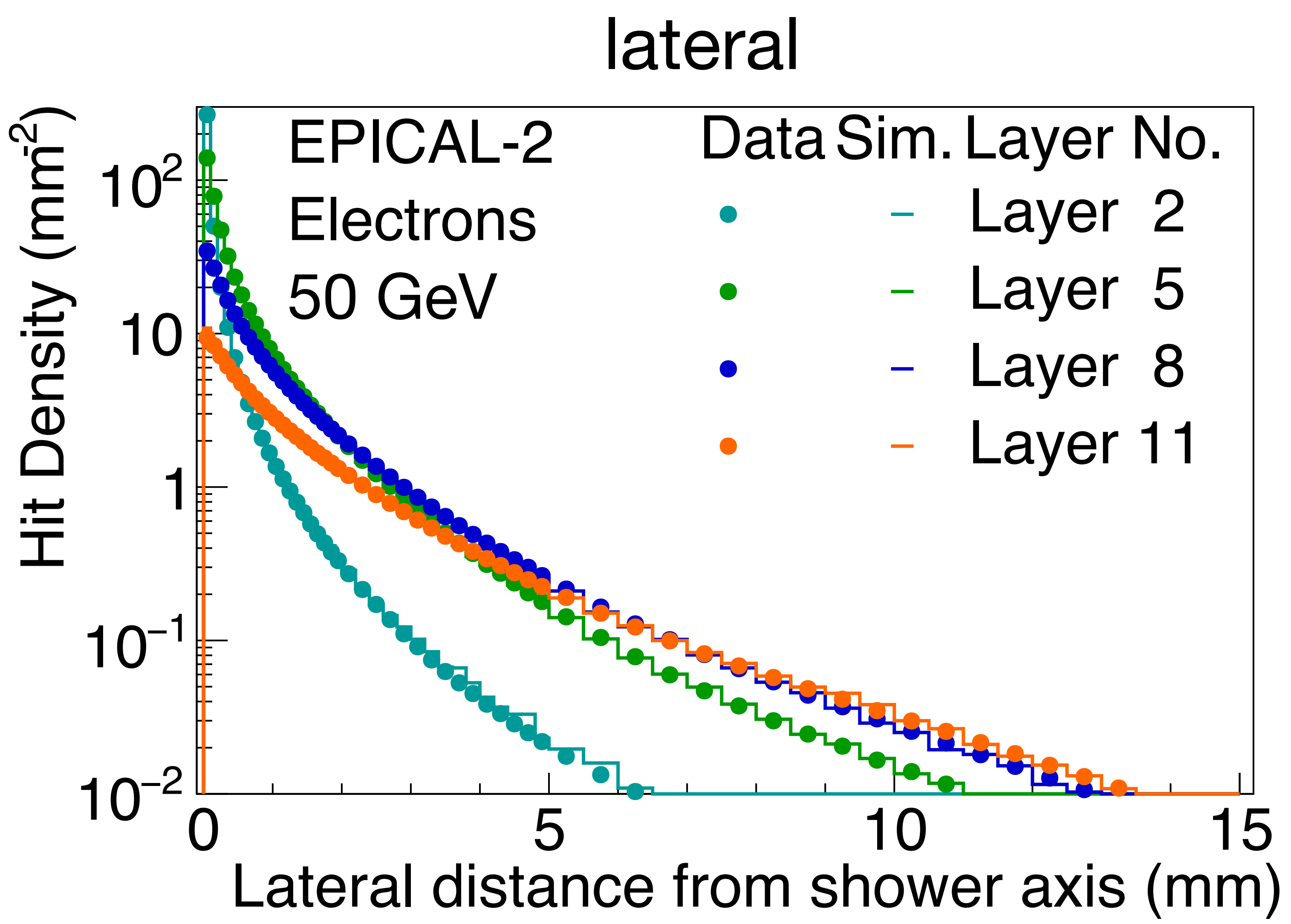
- Resolution from hits better than EPICAL-1 results
- Resolution from $N_{clus}$ close to analog SiW ECAL (CALICE) physics prototype NIM A 608:372-383, 2009
- Cluster algorithm not yet optimised

# Shower Profiles



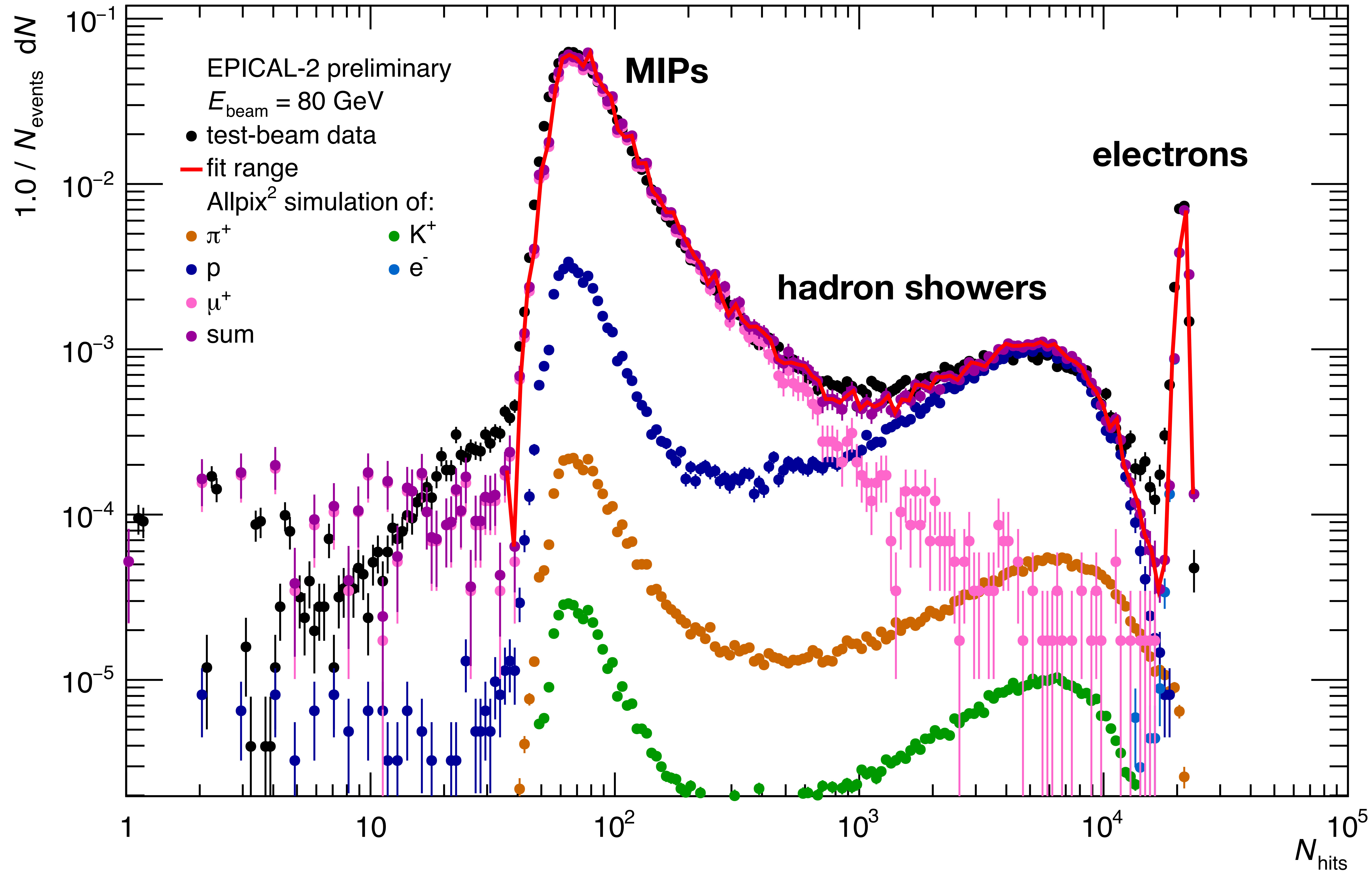



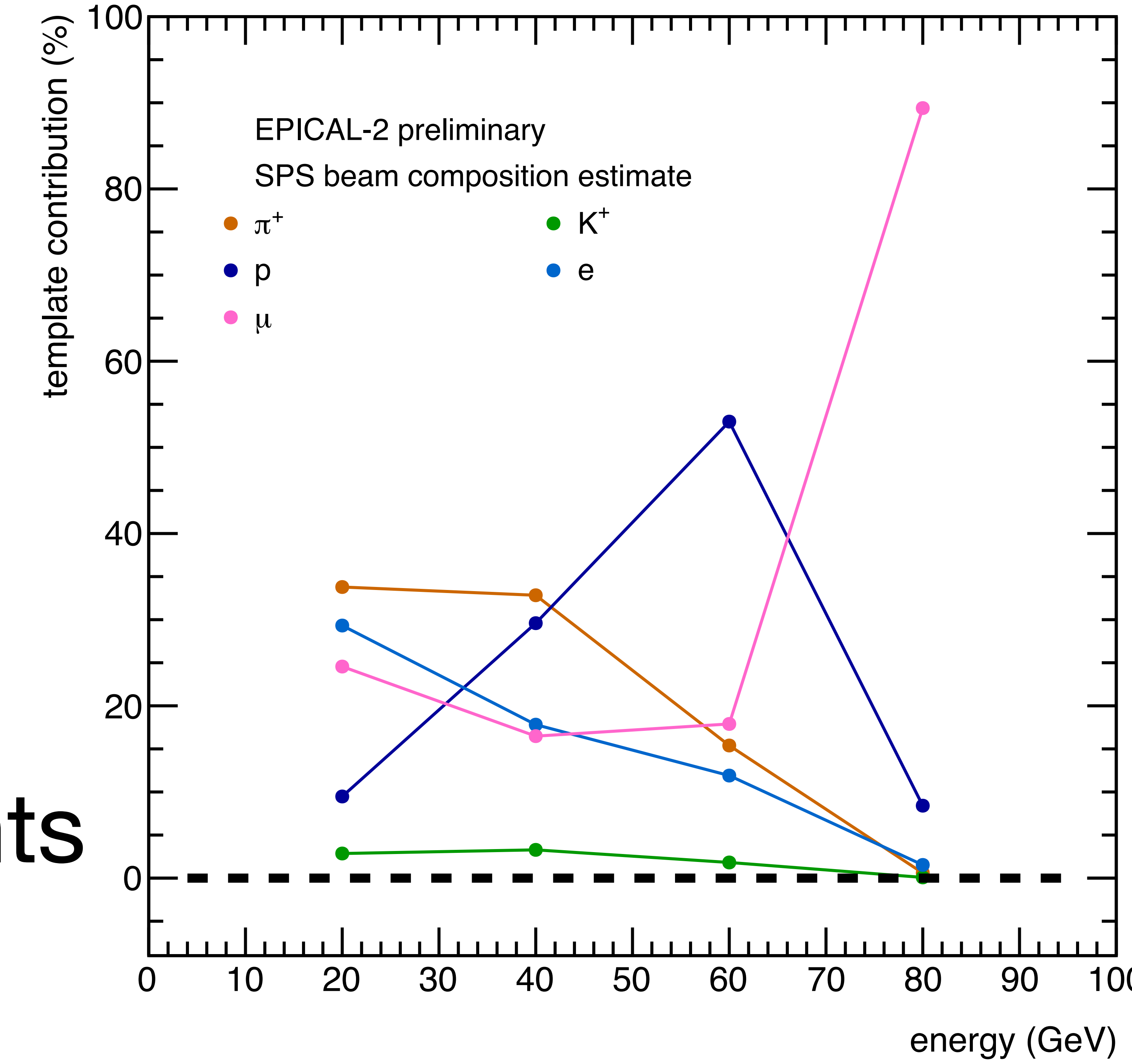




- Longitudinal and lateral shower distributions show expected behaviour
  - Similar for $N_{clus}$ and $N_{hits}$
- Wealth of information to extract details of shower development: work in progress
- Hit density well below saturation limit at low energy
  - Maximum at 5 GeV: ≈ 300 hits/mm$^2$
  - Saturation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

# SPS H6 Beam Composition

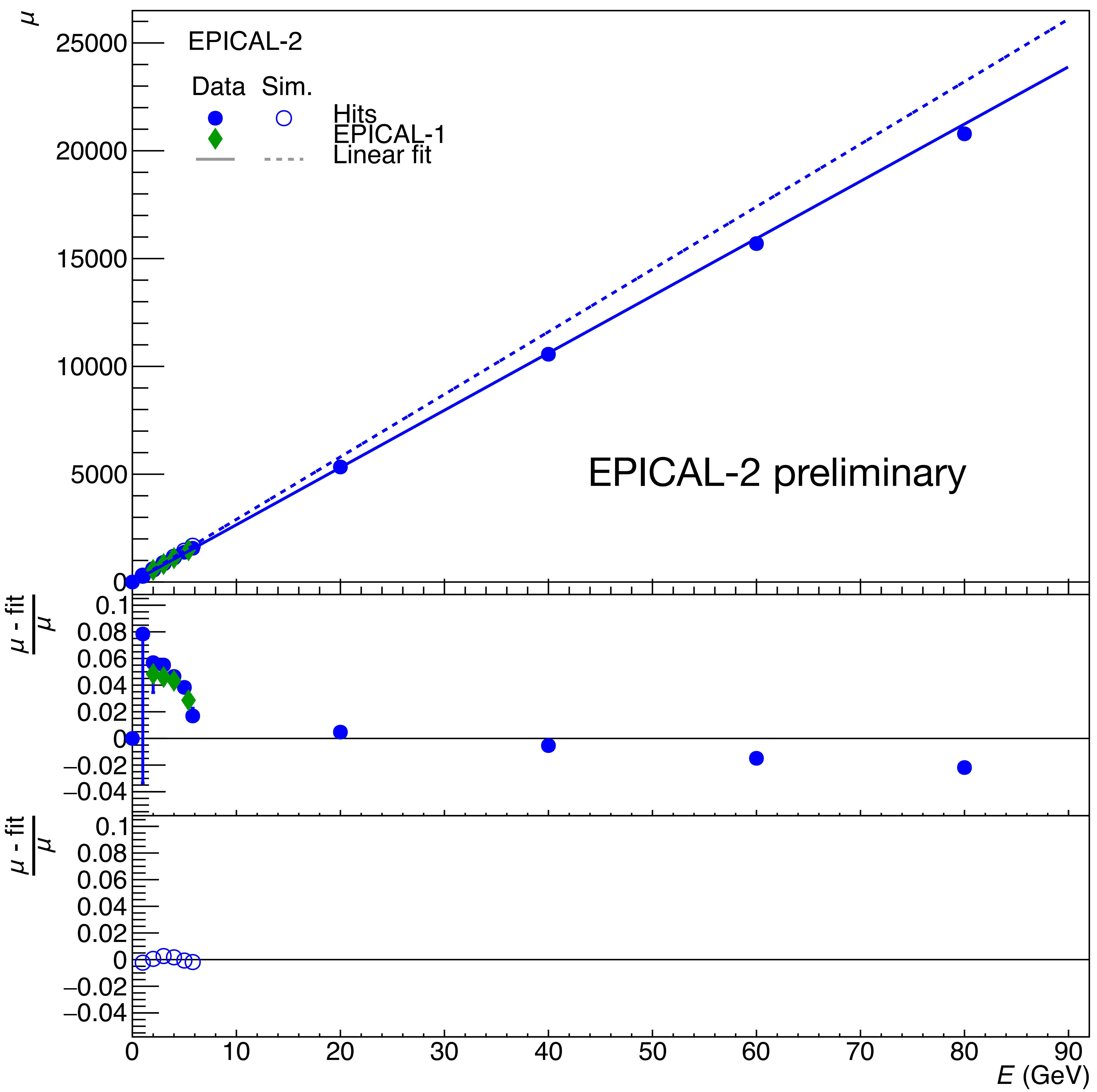



- Allows precise extraction of beam composition
- Hadron contamination of electron peak under control



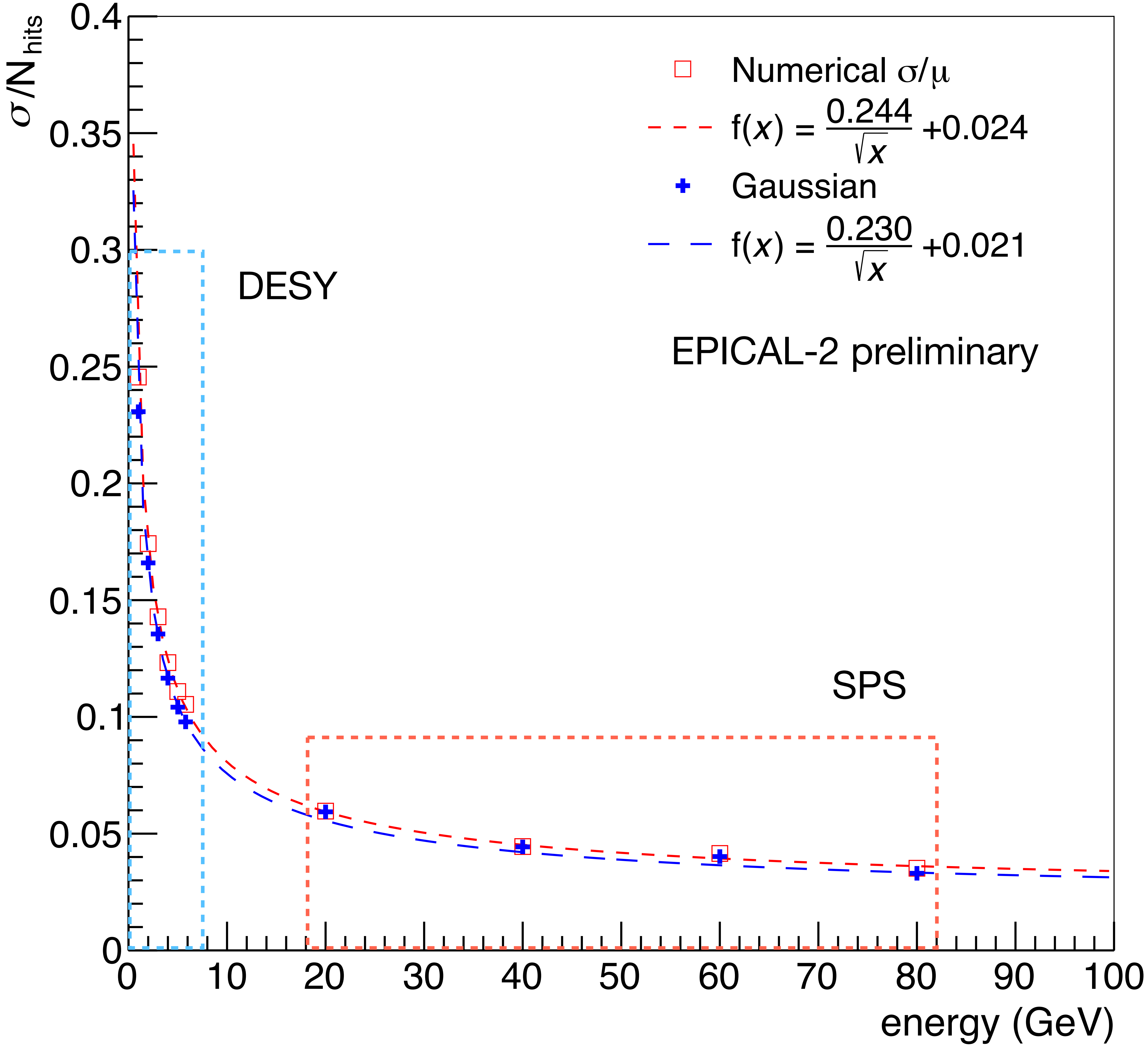

- Detailed MC simulation (Allpix²) describes all components of calorimetric energy spectra very well

# Energy Linearity at High Energy



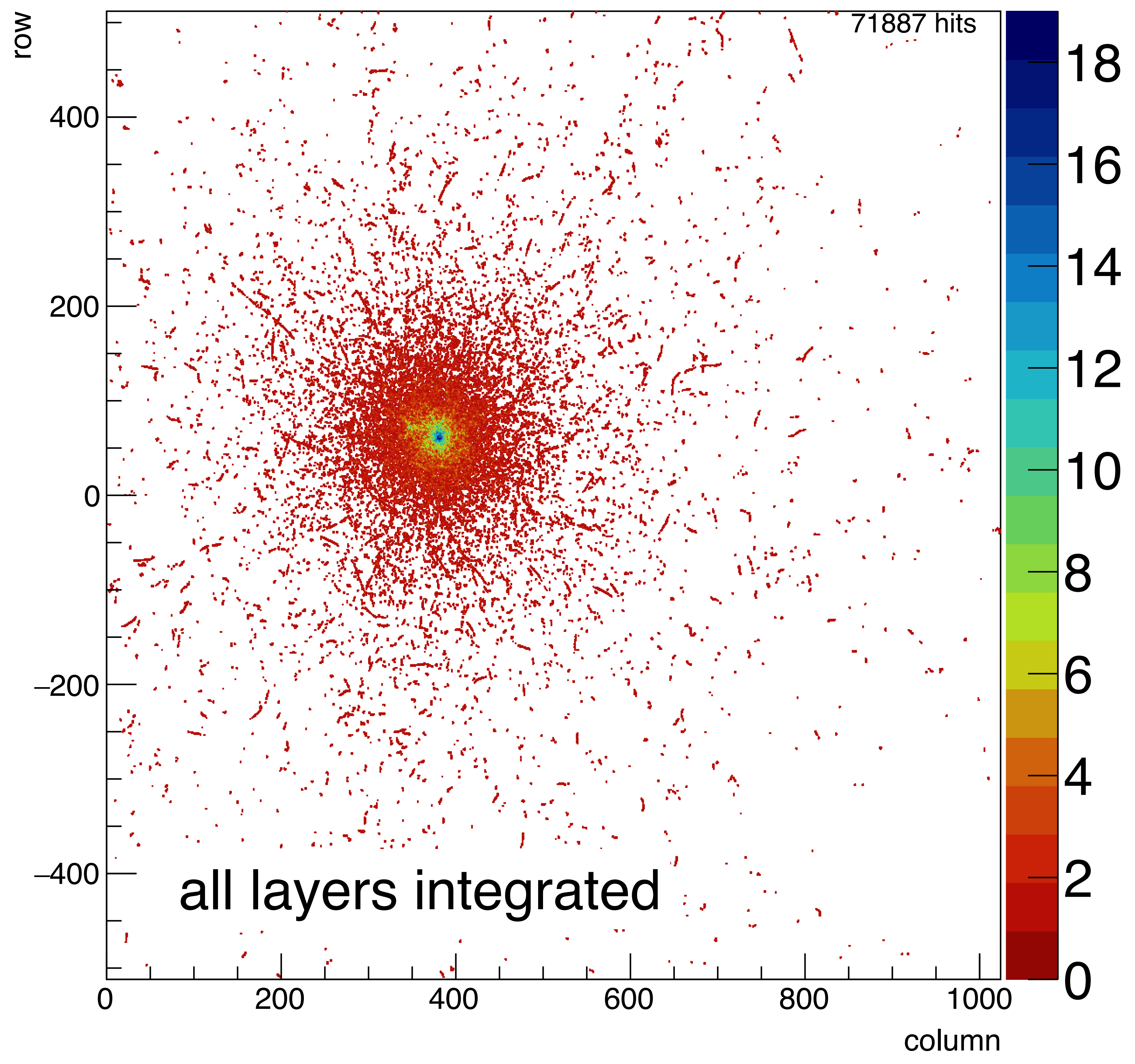

- Electron peak position ($N_{\text{hits}}$) extracted for different beam energies
- Behaviour at high energy matches well to low energy
- Good linearity at high energy
  - Confirms observed non-linearity at DESY to be related to test beam properties

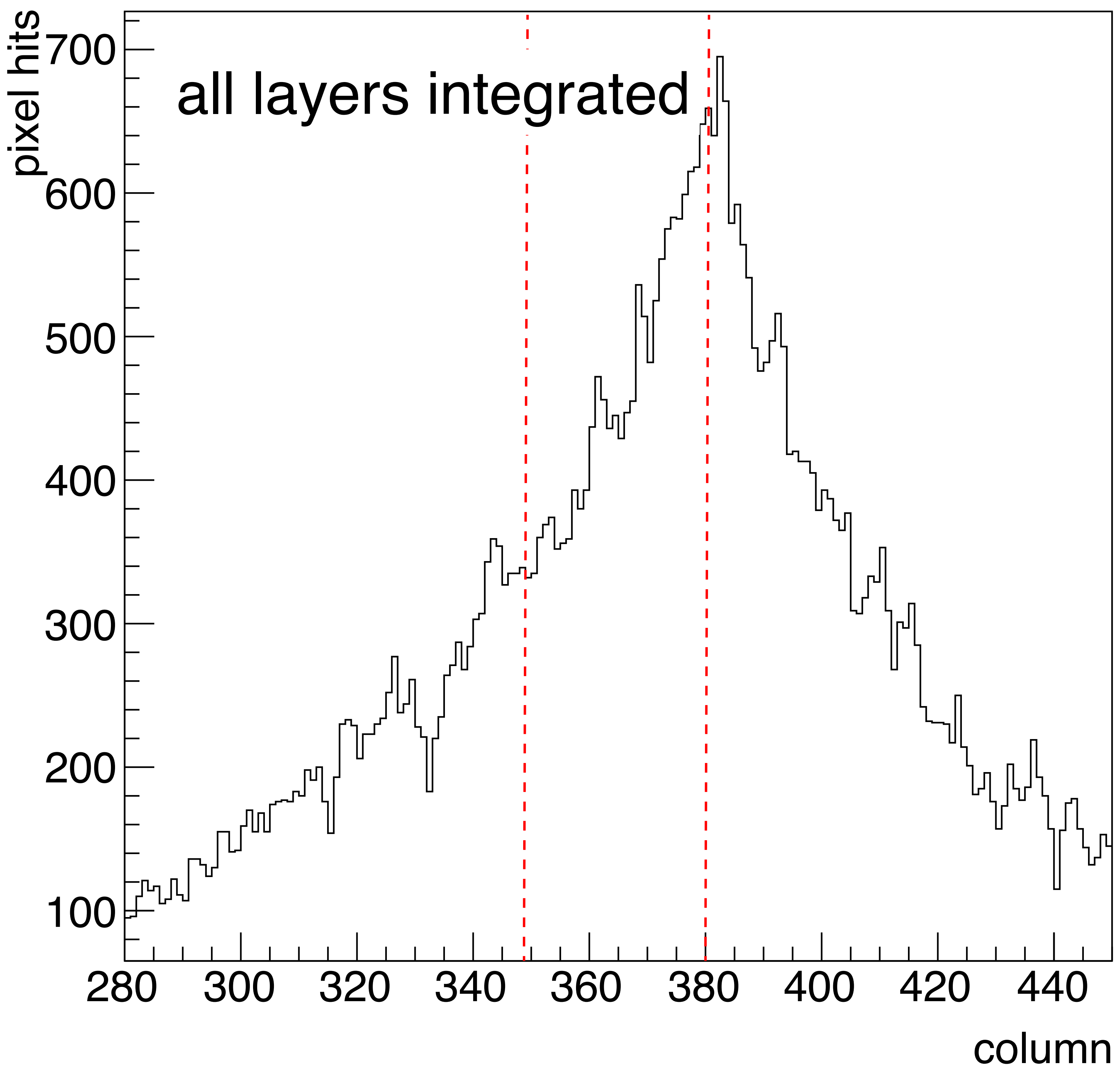
# Energy Resolution at High Energy




- Results of preliminary analysis from SPS data:
  good energy resolution from $N_{hits}$
  - High energy (SPS) consistent with extrapolation from low energy (DESY)
- Work in progress:
  - $N_{clus}$ seen to yield better energy resolution at low energy, cluster algorithm needs to be adjusted for high energy

# Application: Two-Shower Separation



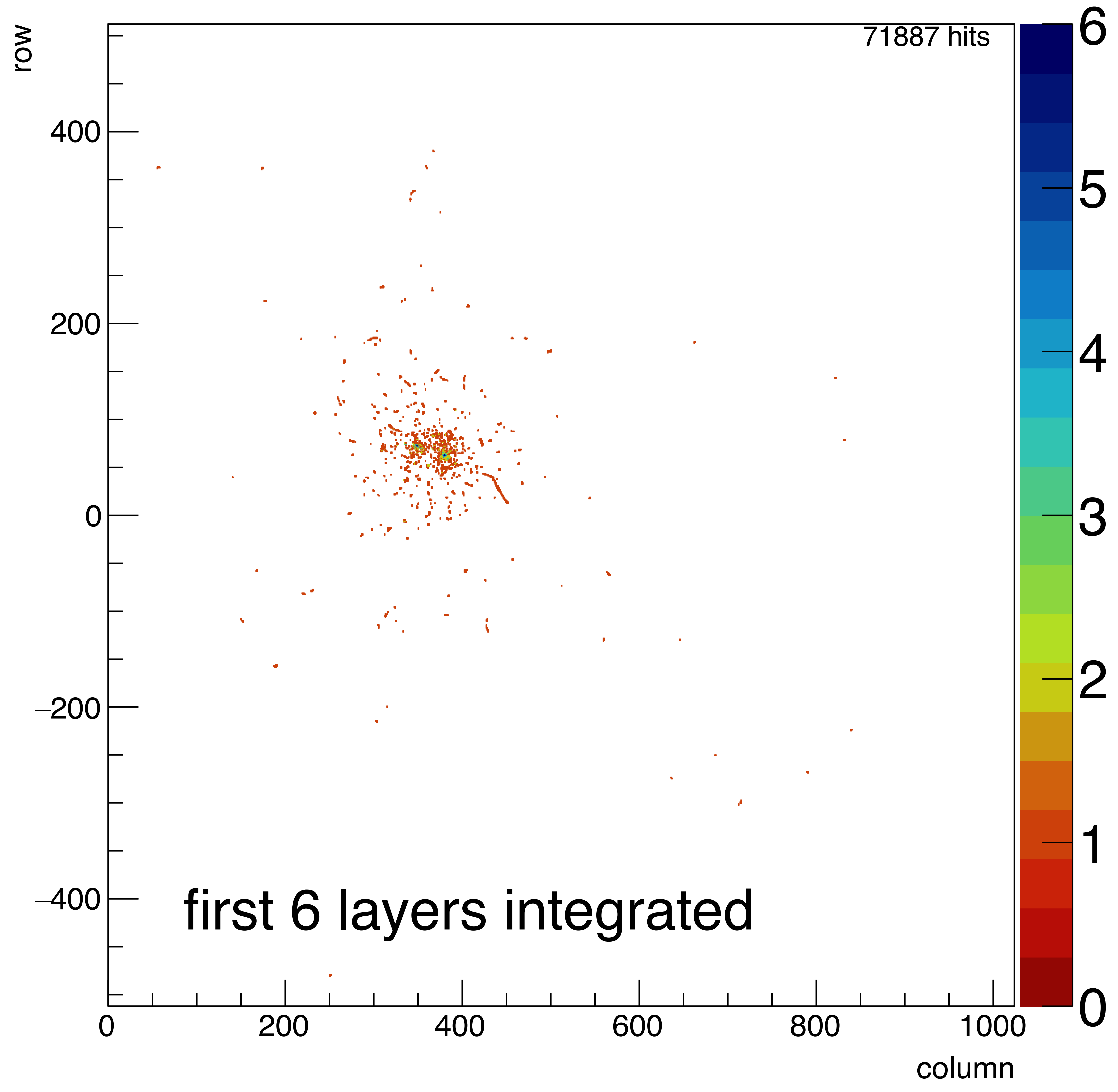



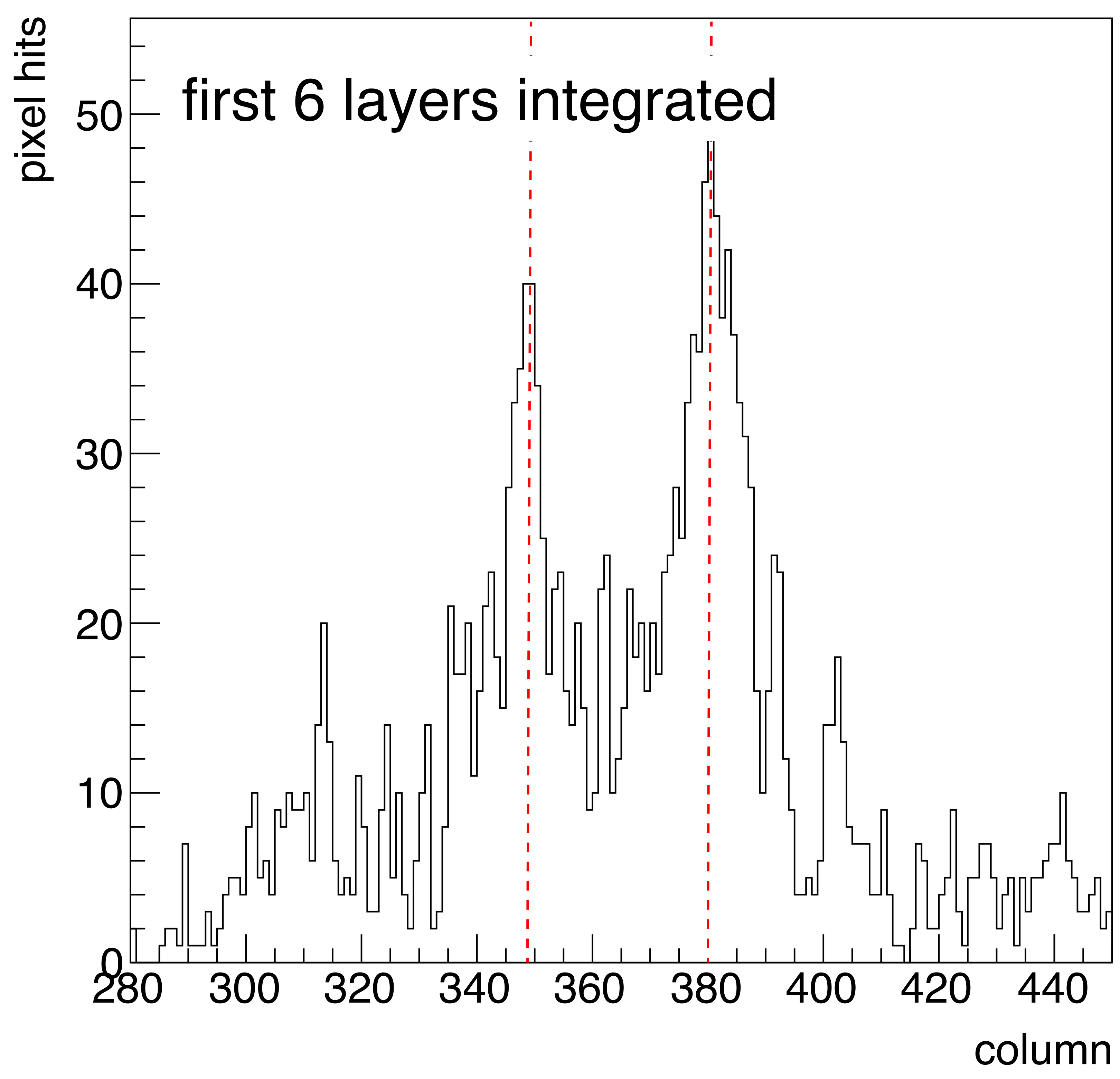

EPICAL-2 preliminary
Allpix² simulation

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 preliminary
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
  - 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
  - Study limited by accelerator properties at DESY
  - To be confirmed at high energy – preliminary results very promising
- 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

J. Alme,[a] R. Barthel,[b] A. van Bochove,[b] V. Borshchov,[c] R. Bosley,[d] A. van den Brink,[b] E. Broeils,[b]
H. Büsching,[e] V.N. Eikeland,[a] O.S. Groettvik,[a] Y.H. Han,[f] N. van der Kolk,[b,g] J.H. Kim,[f] T.J. Kim,[f]
Y. Kwon,[f] M. Mager,[h] Q. W. Malik,[i] E. Okkinga,[b] T.Y. Park,[f] T. Peitzmann,[b]1 F. Pliquett,[e] M. Protsenko,[c]
F. Reidt,[h] S. van Rijk,[b] K. Røed,[i] T.S. Rogoschinski,[e] D. Röhrich,[a] M. Rossewij,[b] G.B. Ruis,[b]
E. H. Solheim,[a,i] I. Tymchuk,[c] K. Ullaland,[a] N. Watson,[d] H. Yokoyama[b,g]

a Department of Physics and Technology, University of Bergen, Bergen, Norway
b Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands
c Research and Production Enterprise "LTU" (RPE LTU), Kharkiv, Ukraine
d School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
e Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
f Yonsei University, Seoul, Republic of Korea
g Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
h European Organization for Nuclear Research (CERN), Geneva, Switzerland
i Department of Physics, University of Oslo, Oslo, Norway