Utrecht University

Nikhef

(Digital) Calorimeters Based on MAPS Sensors

T. Peitzmann, Utrecht University/Nikhef

ECFA Detector R&D Roadmap Task Force 6: Calorimetry Community Meeting

12 January 2023

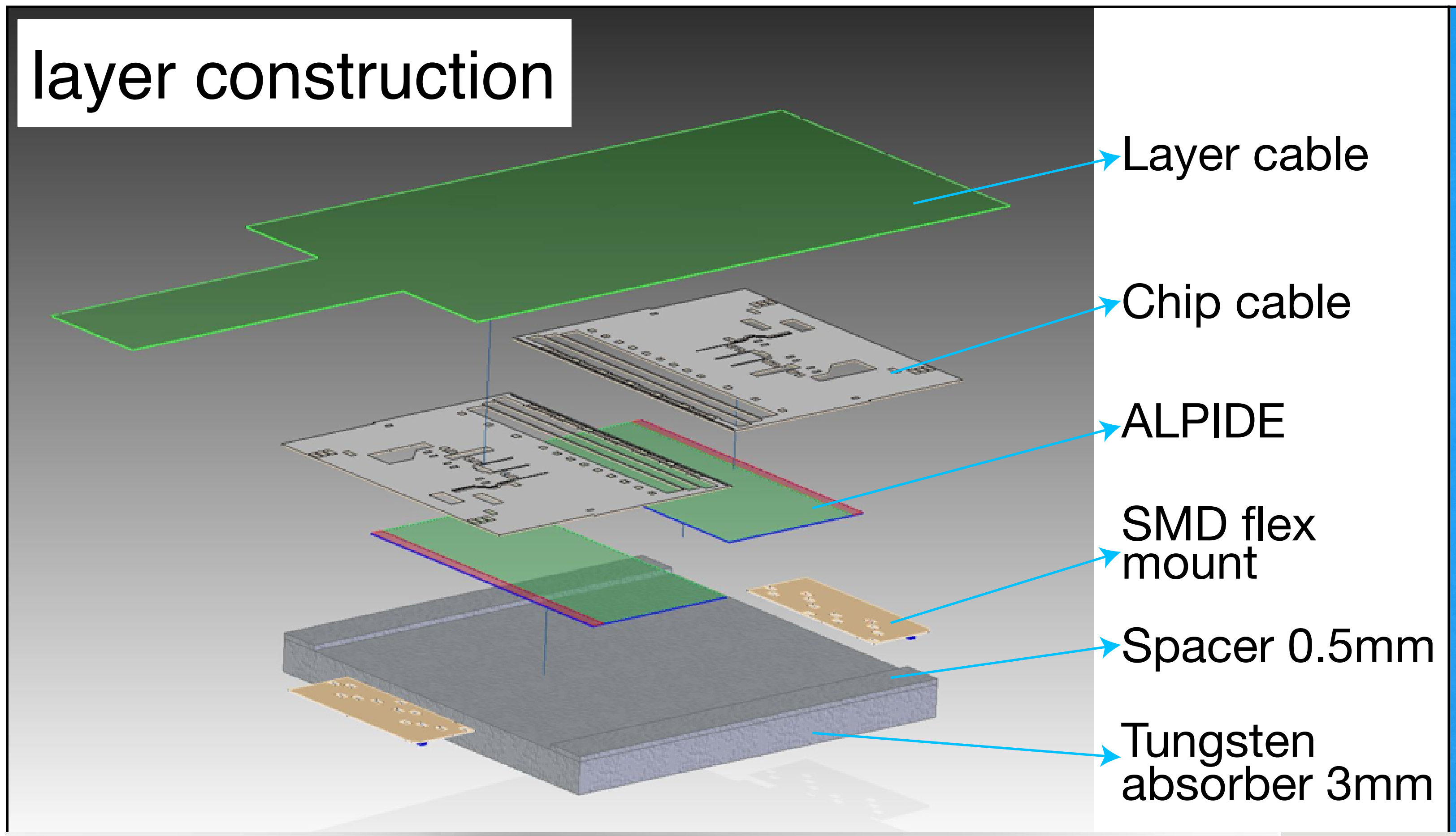
The Principle of Digital Calorimetry

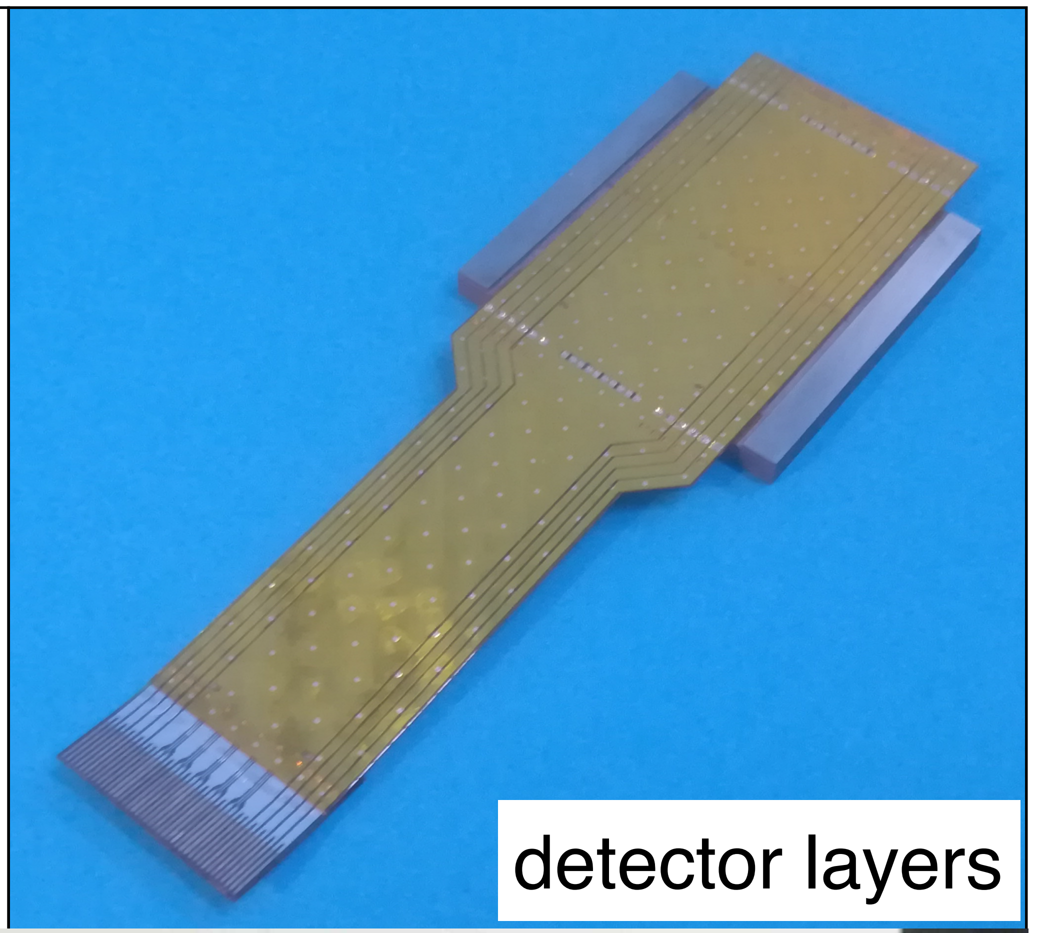
- Paradigm shift: Move from analog measures of energy deposit or total track length to shower particle counting in sampling layers.
  - Reduces contribution to resolution from Landau fluctuations in each layer
  - Needs very high granularity to avoid excessive multiple hits
- Can simultaneously use ultra-high granularity for shower reconstruction/PFA
  - Very good two-shower separation and position resolution
  - Extremely detailed information on shower shape
  - Effectively a **tracking calorimeter**
- Ideally suited for objective DRDT 6.2:
  - Develop high-granular calorimeters with multi-dimensional read-out for optimised use of particle flow methods

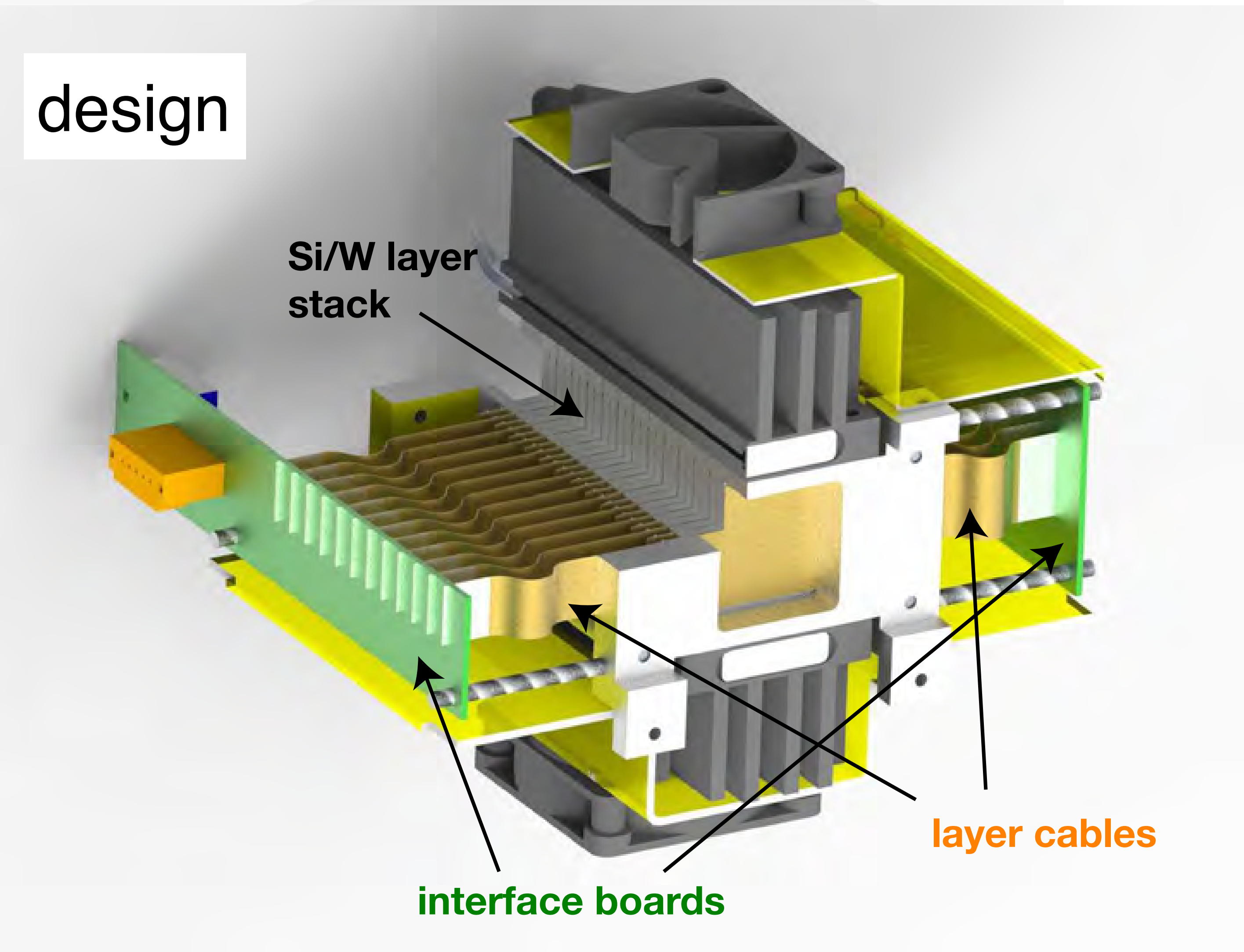
Recent History of Digital Pixel ECal R&D

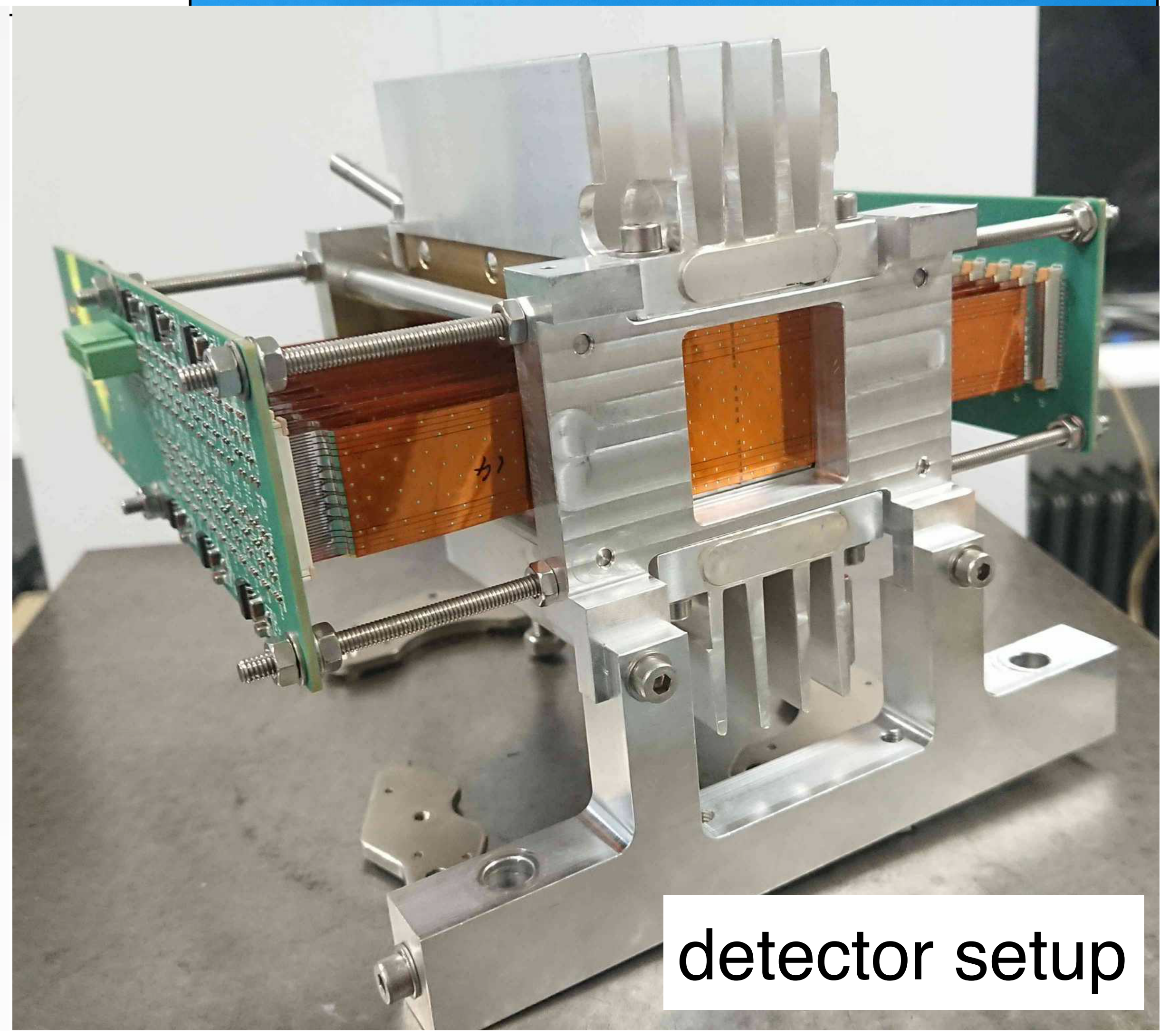
- Early R&D with single sensors in calorimetric environment (all SiW sandwich)
- Current main effort: a **fully digital pixel prototype**
  - Initiated in the context of the ALICE FoCal proposal, where pixel layers are used to ensure sufficient γ/π^0 discrimination power
  - Connects to previous sensor R&D effort in CALICE
    - See e.g. Ballin et al., LCWS08
  - Existing design strongly related to a digital tracking calorimeter for proton CT
- First prototype: EPICAL-1 using MIMOSA sensors
  - JINST 13 (2018) P01014
- Second prototype: **EPICAL-2** using **ALPIDE** sensors
  - First results accepted for publication in JINST (+ proceedings in NIM A 1045 (2023) 167539)
- Independent efforts by US groups related to ILC and EIC - options for collaboration
  - See e.g. Breidenbach et al.,Snowmass 2021

New Digital Calorimeter Prototype – EPICAL-2







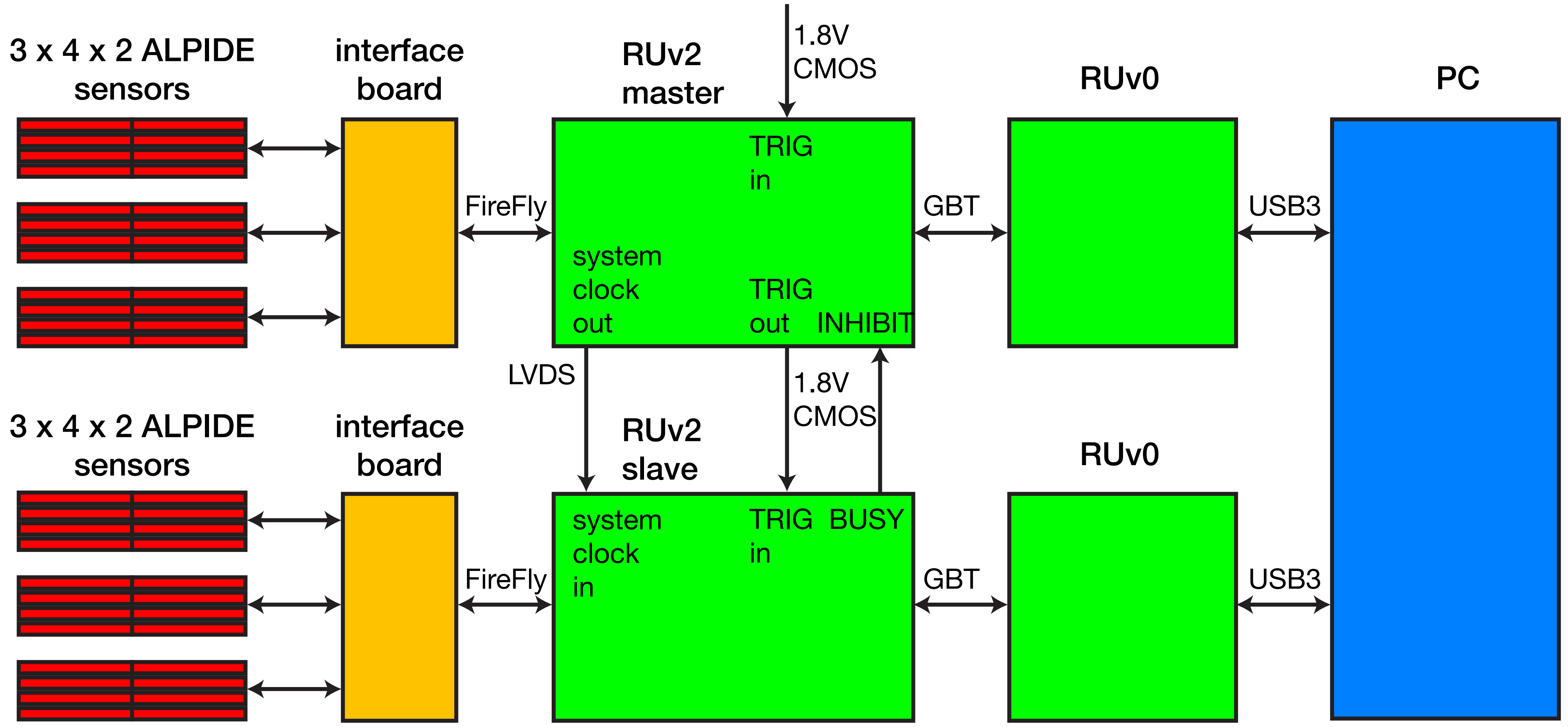


24 layers with each
- 3 mm W absorber
- 2 ALPIDE CMOS sensors
  - NIM A, 845:583–587, 2017
- ultra-thin flex cables (LTU Kharkiv)

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

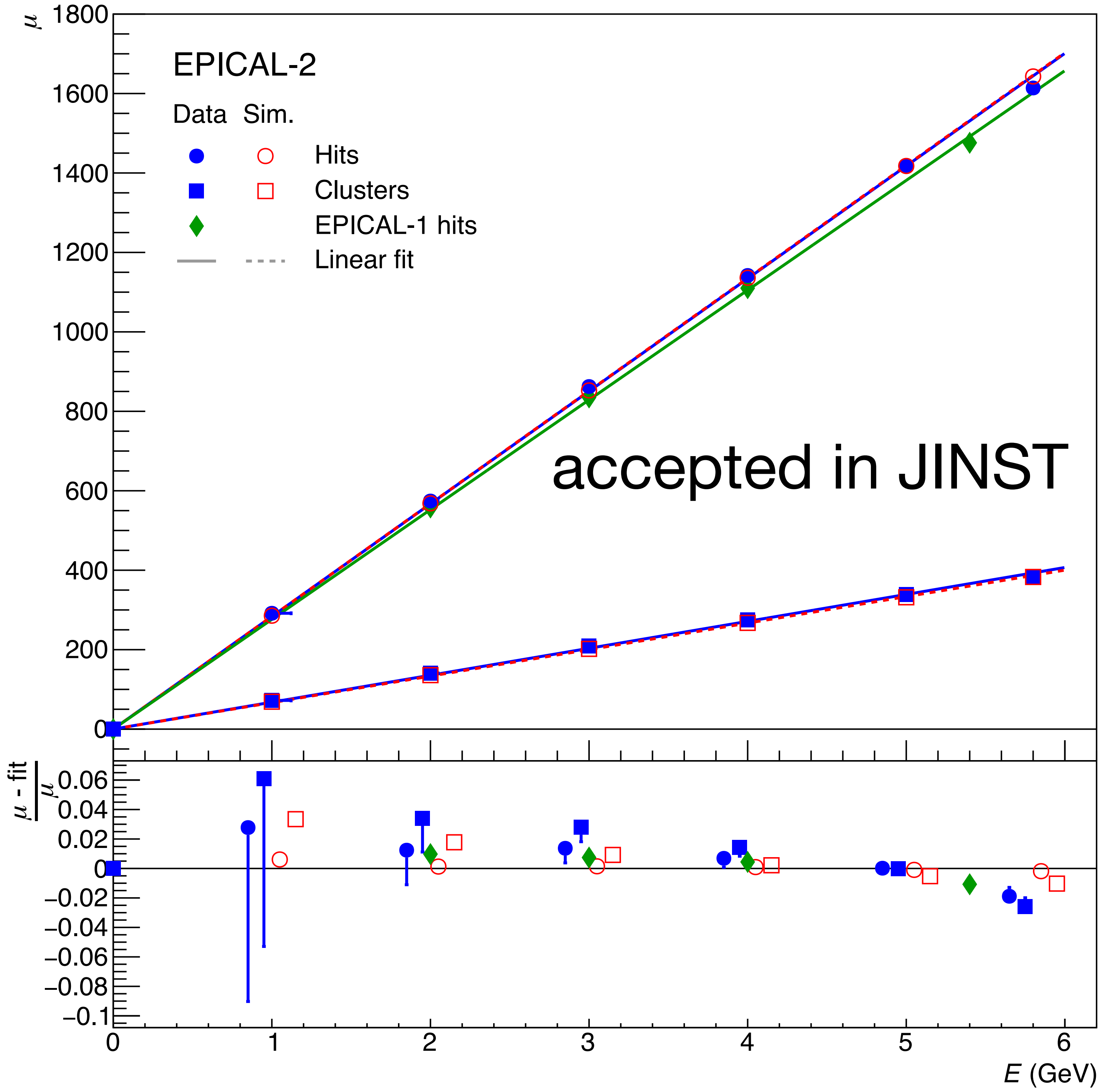
compact design: expect $R_M \approx$ 11 mm

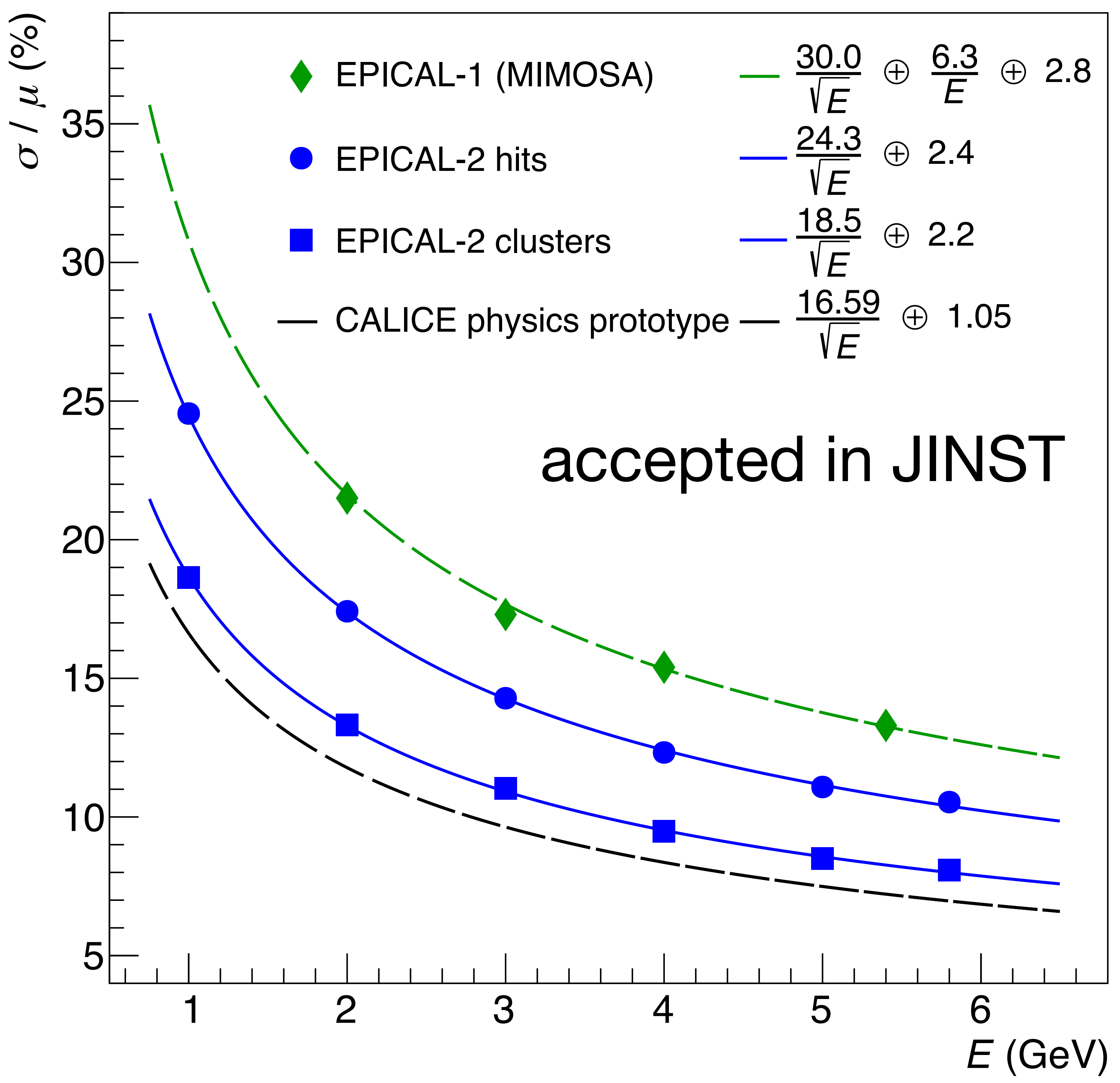
readout schematics

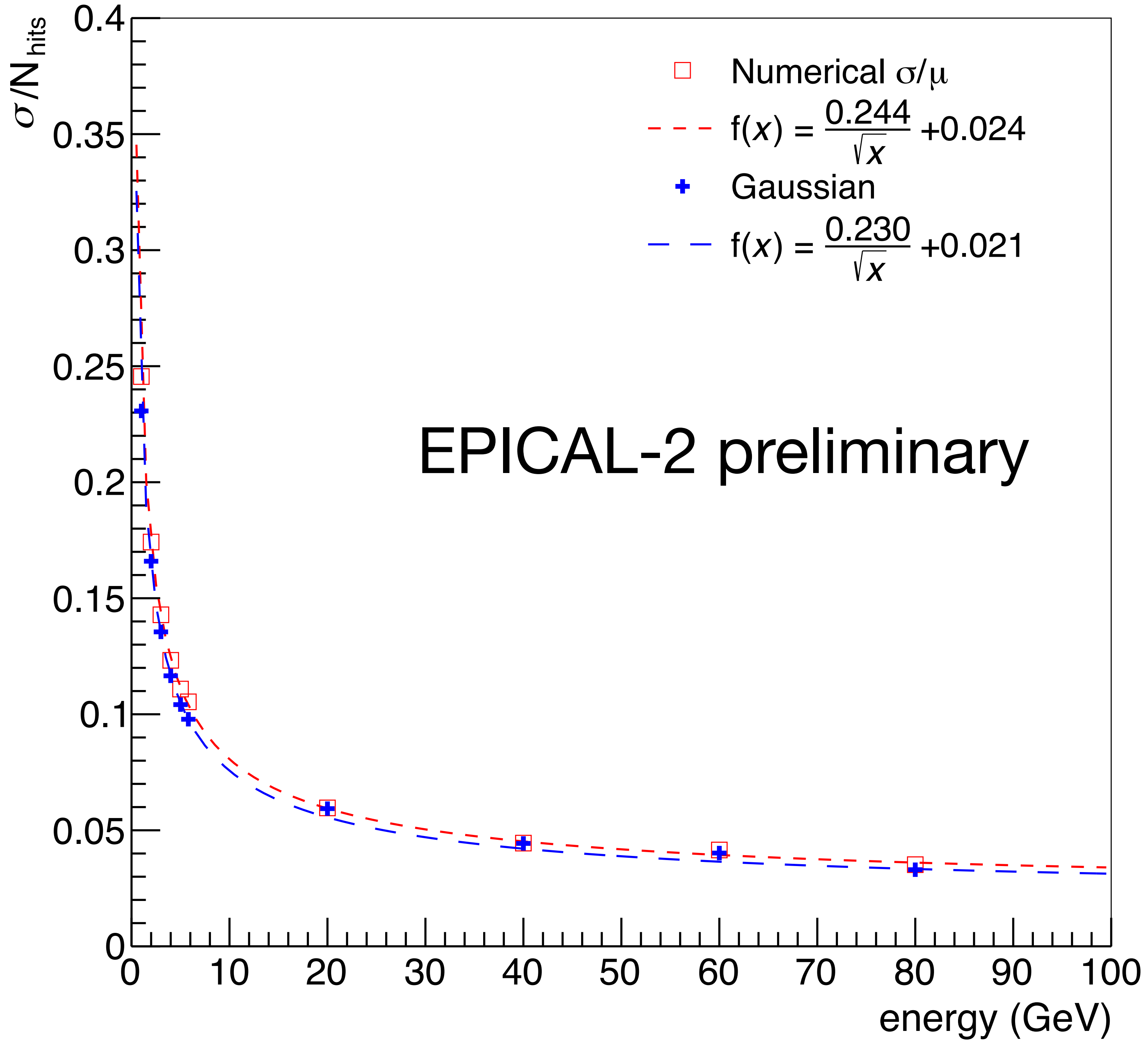


ALPIDE output via 1.2 Gb/s serial line
readout via 2 levels of FPGA

Good ‘Standard’ Performance





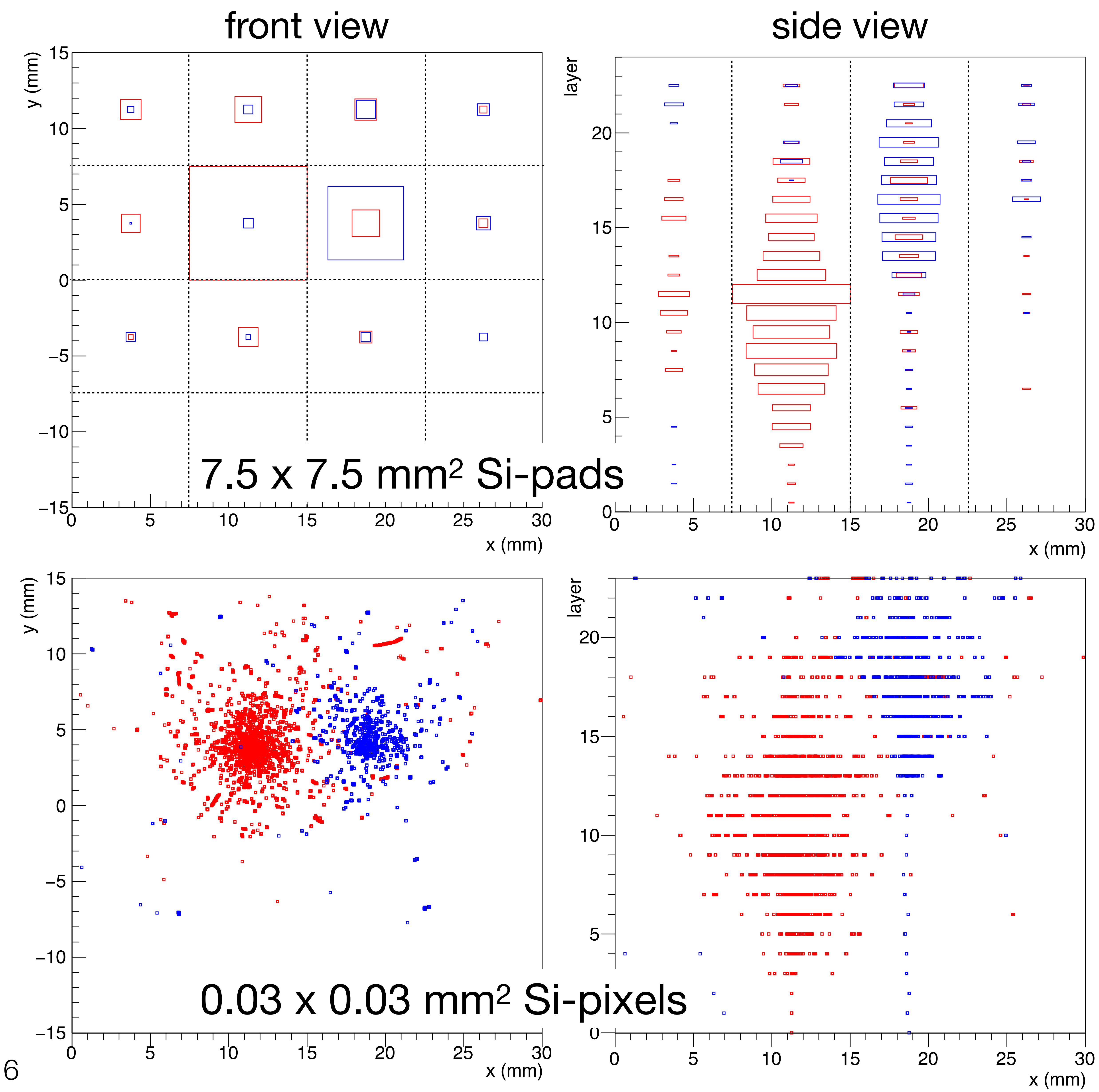


- Calorimetric response evaluated in test beams
  - ‘Conventional’ observables first: total number of hits or clusters
- Low energy (DESY)
  - Good linearity
  - ‘Particle counting’ (N_{clus}) shows competitive resolution at low energy

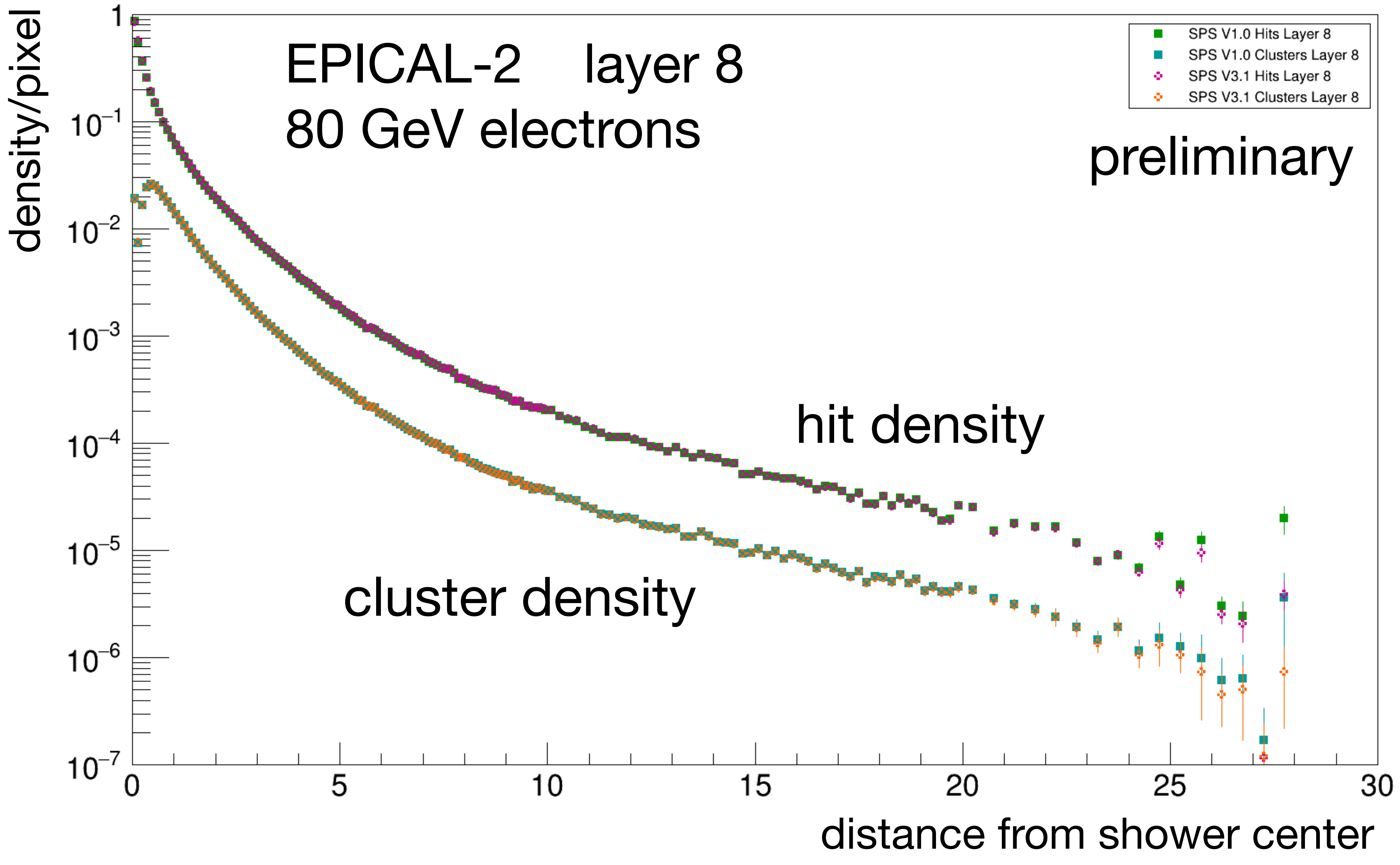
- High energy (SPS)
  - Resolution for N_{hits} consistent with low energy
  - Usage of N_{clus} observable under study

The Power of High Granularity

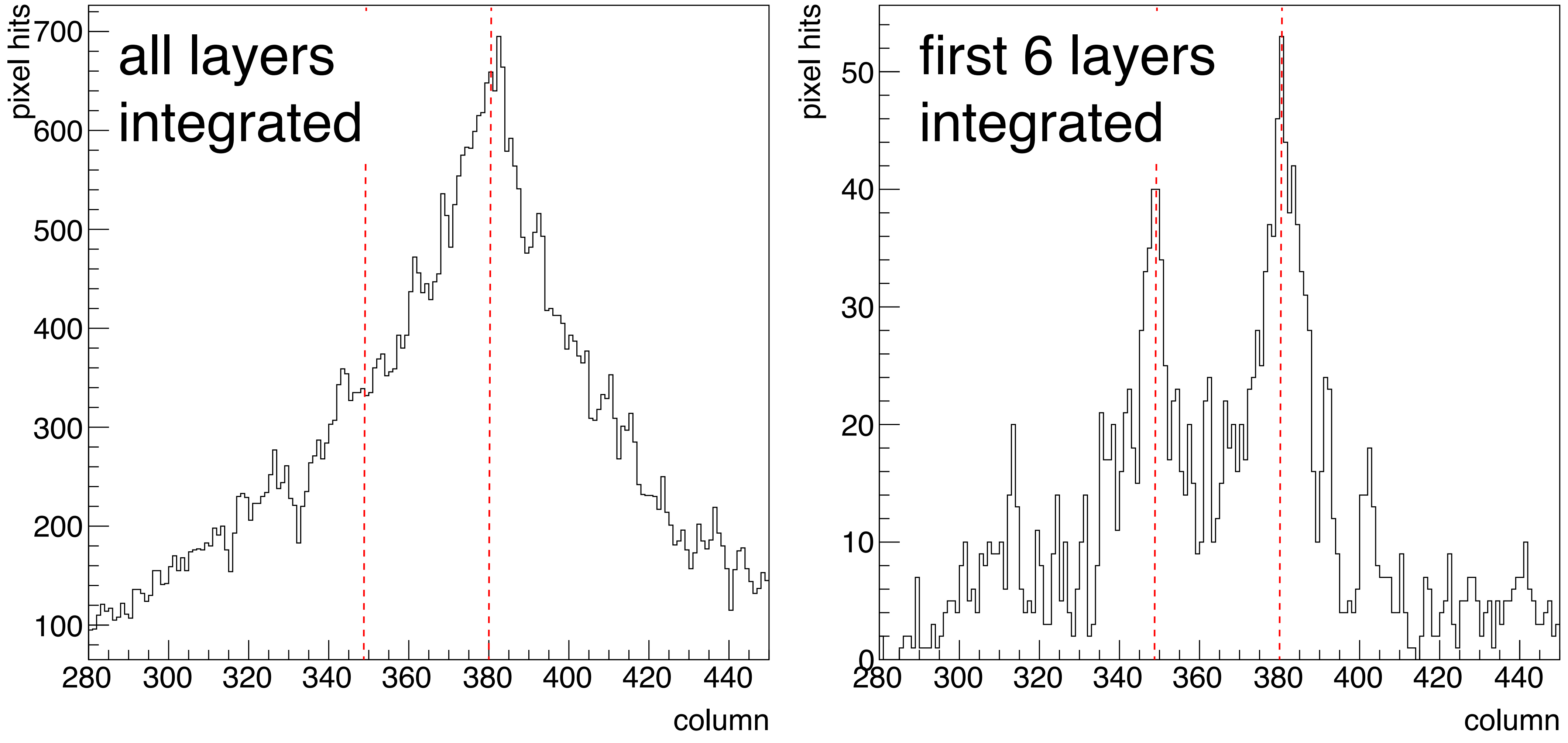
- Simultaneous measurement of 20 GeV electron and 40 GeV hadron at a distance of 7.5 mm
  - Conventional high-granularity Si-W calorimeter:
    - Impossible to fully reconstruct
  - Digital pixel calorimeter (EPICAL-2 measurements):
    - Topology clear (tracking, shower start, shower shape etc.)
    - Full reconstruction possible



R&D Steps: Short-Medium Term



Allpix² simulation: two-electron event



- Exploit existing data from prototype/ perform complementary measurements
  - Develop reconstruction algorithms for new calorimetric observable: hit (cluster) density
    - Potential dynamic range: $\geq 10\mathrm{bit/mm}^2$
    - Develop saturation correction
- Demonstrate full power of ultra-high granularity
  - Shower model fit
    - Improve energy measurement, PID with shower shape, two-shower separation, etc.
  - Tune existing PFA for ultra-high granularity

analysis/measurements with existing hardware

R&D Steps: Medium-Long Term

- On chip processing on CMOS sensors allows compact design
- Achieved in prototype: $R_M \approx 11\,\mathrm{mm}$
  - Ultra-thin flex cables for all connections
  - Cooling via tungsten plates (possible for small dimensions only?)
  - No dead area due to overlapping sensors
- Need to scale up integration to realistic detector size
  - Compactness (small Moliere radius) scalable?
  - Cooling solutions (e.g. micro channels)?
    - Requirements depend on sensor power consumption
  - First experience to be obtained in ALICE-FoCal for single pixel layers, to be extended to full pixel detector design

hardware/engineering R&D

R&D Steps: Long Term

- Develop dedicated pixel sensor for calorimeter (connection to DRD3)
  - Enhance rate capability
  - Move from binary to few bits
  - Add timing information?
  - More intelligent on-chip processing
    - Data reduction, reconfigurable pixel-arrays? Compromise on position accuracy?
    - Consider optimal threshold strategy
    - Trigger information?
  - Power consumption?
- Investigate alternative sensor technology (LGADs, …)?

hardware/CMOS sensor R&D

Summary

- Digital pixel calorimetry a natural avenue for
  highly granular calorimeters and PFA (DRDT 6.2)
- Process of understanding the working principle still ongoing
  - May influence hardware R&D choices, i.e. definition of requirements
  - Analysis of prototype data/simulation studies integral part of R&D
- Low-energy calorimetric response is competitive
- Performance at high energy and for PFA to be demonstrated
- CMOS sensors (ALPIDE) work in calorimeter environment
- Future applications need improved sensors
  - Rate capabilities, …?

Backup Slides

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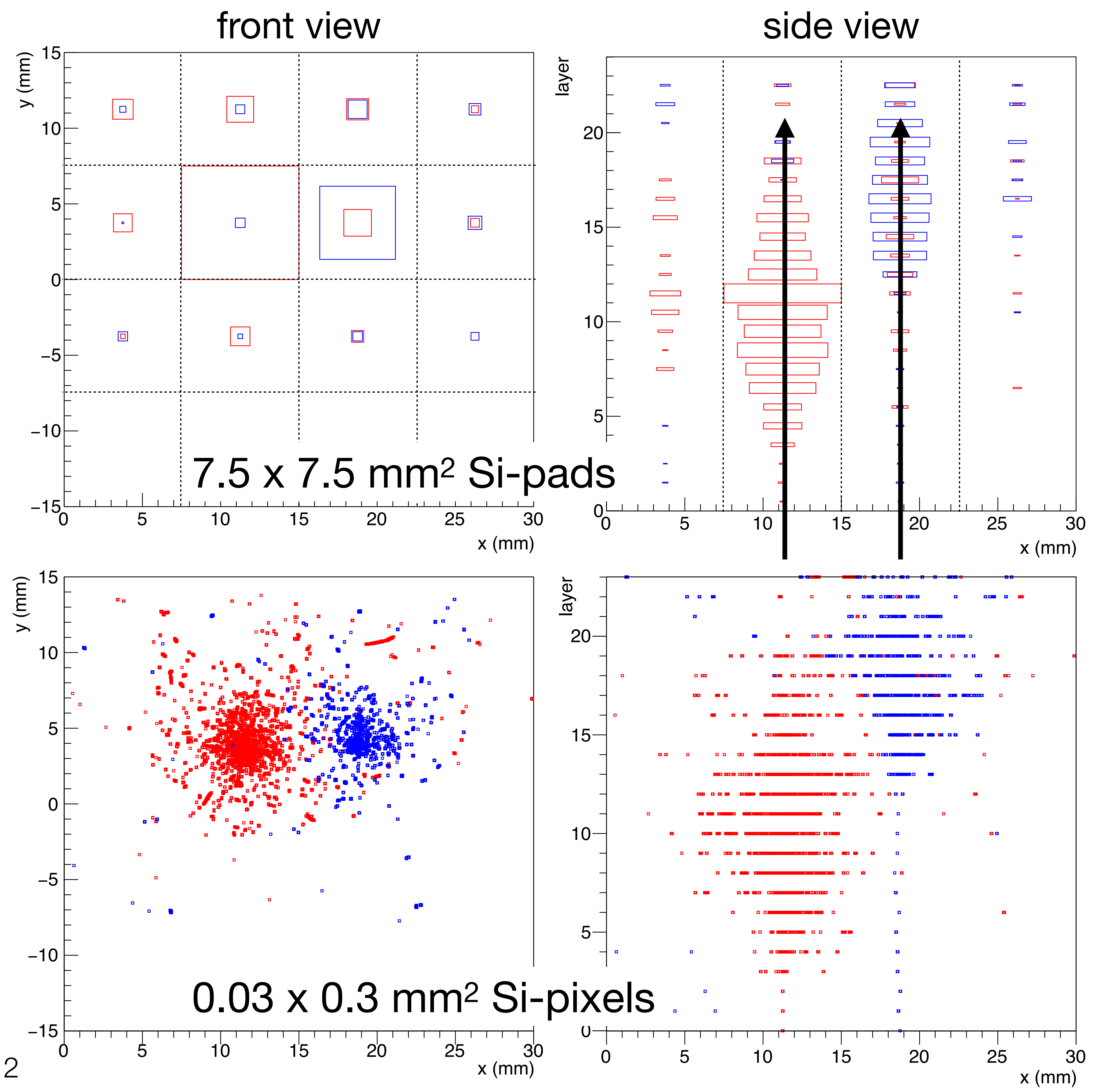

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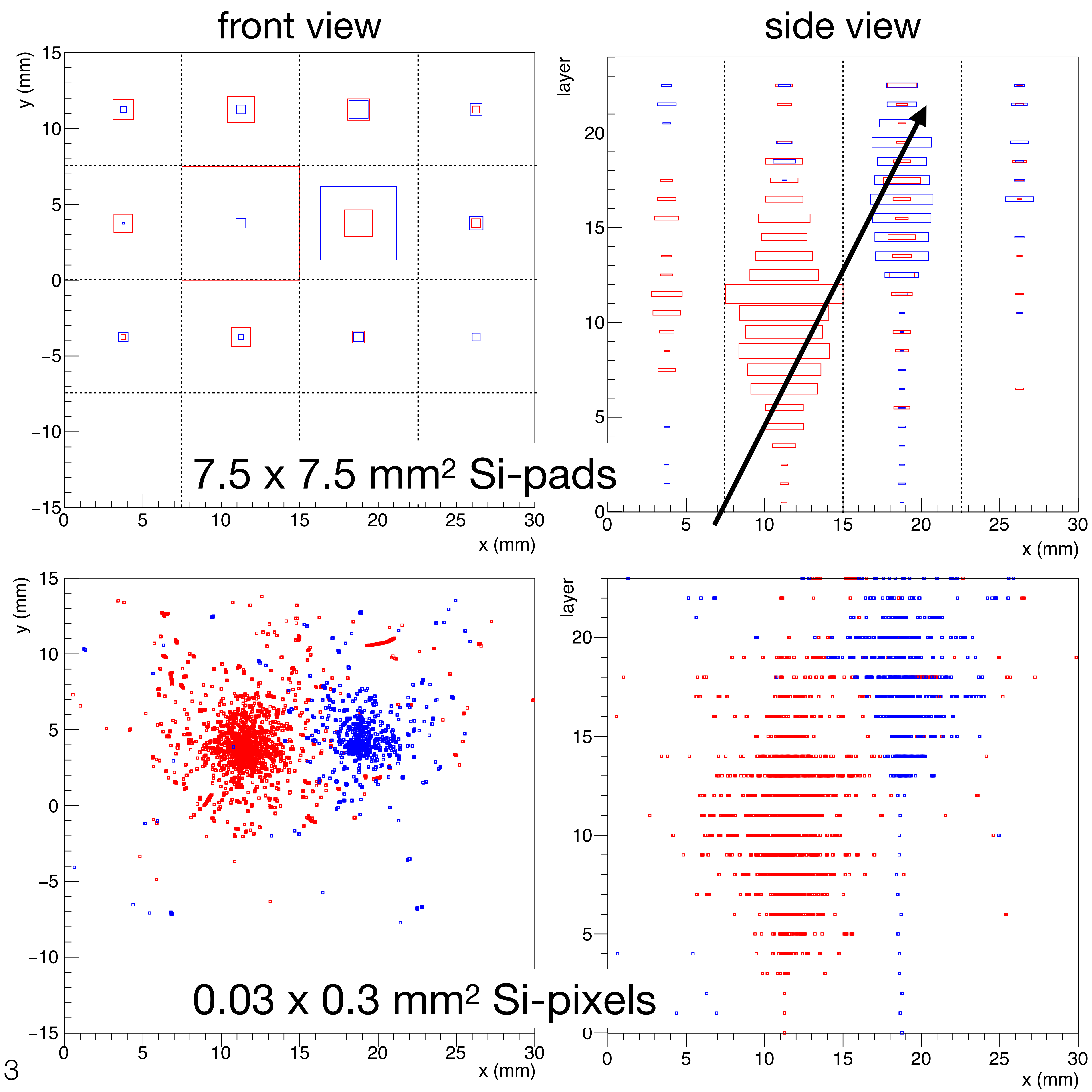
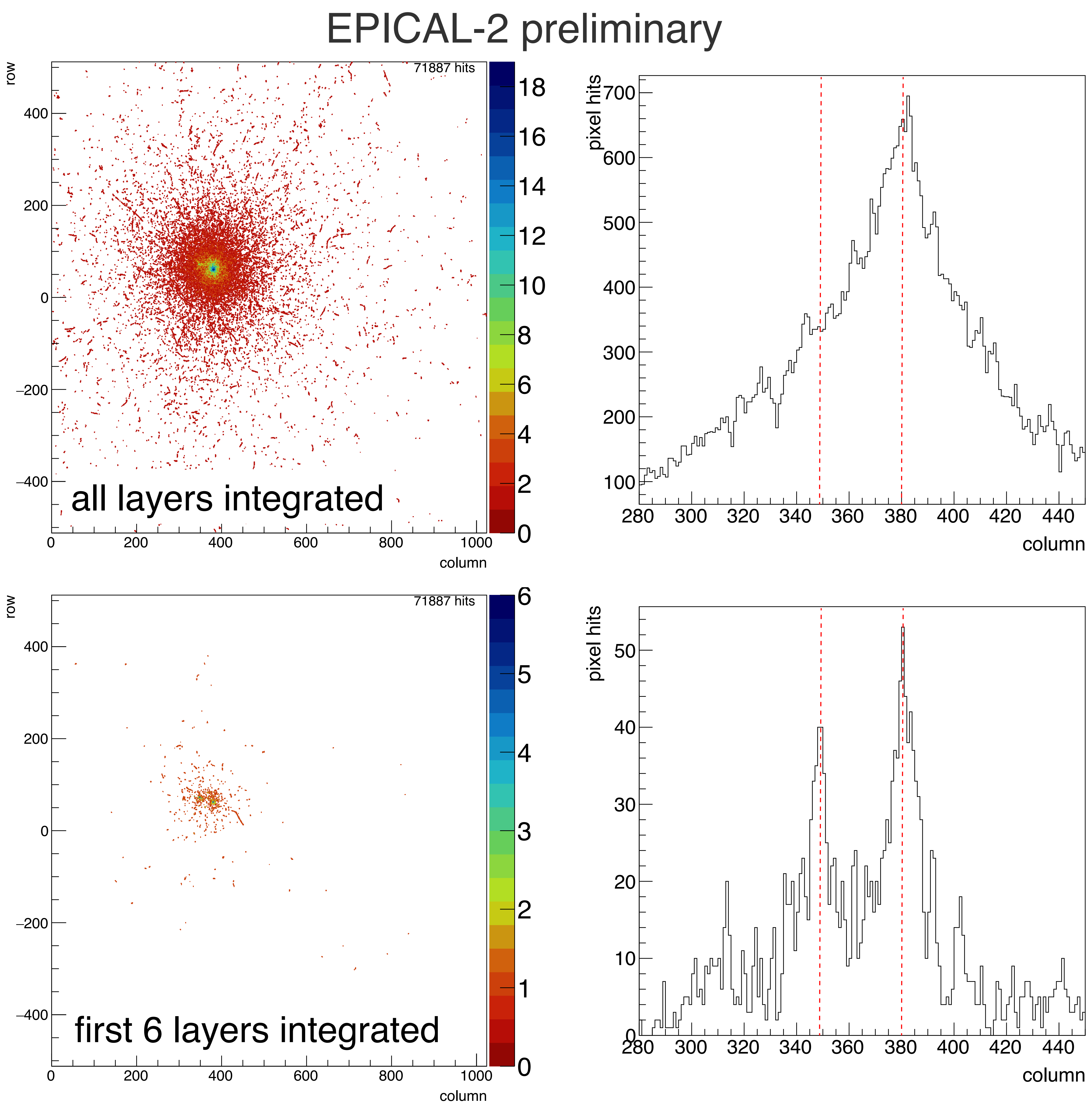


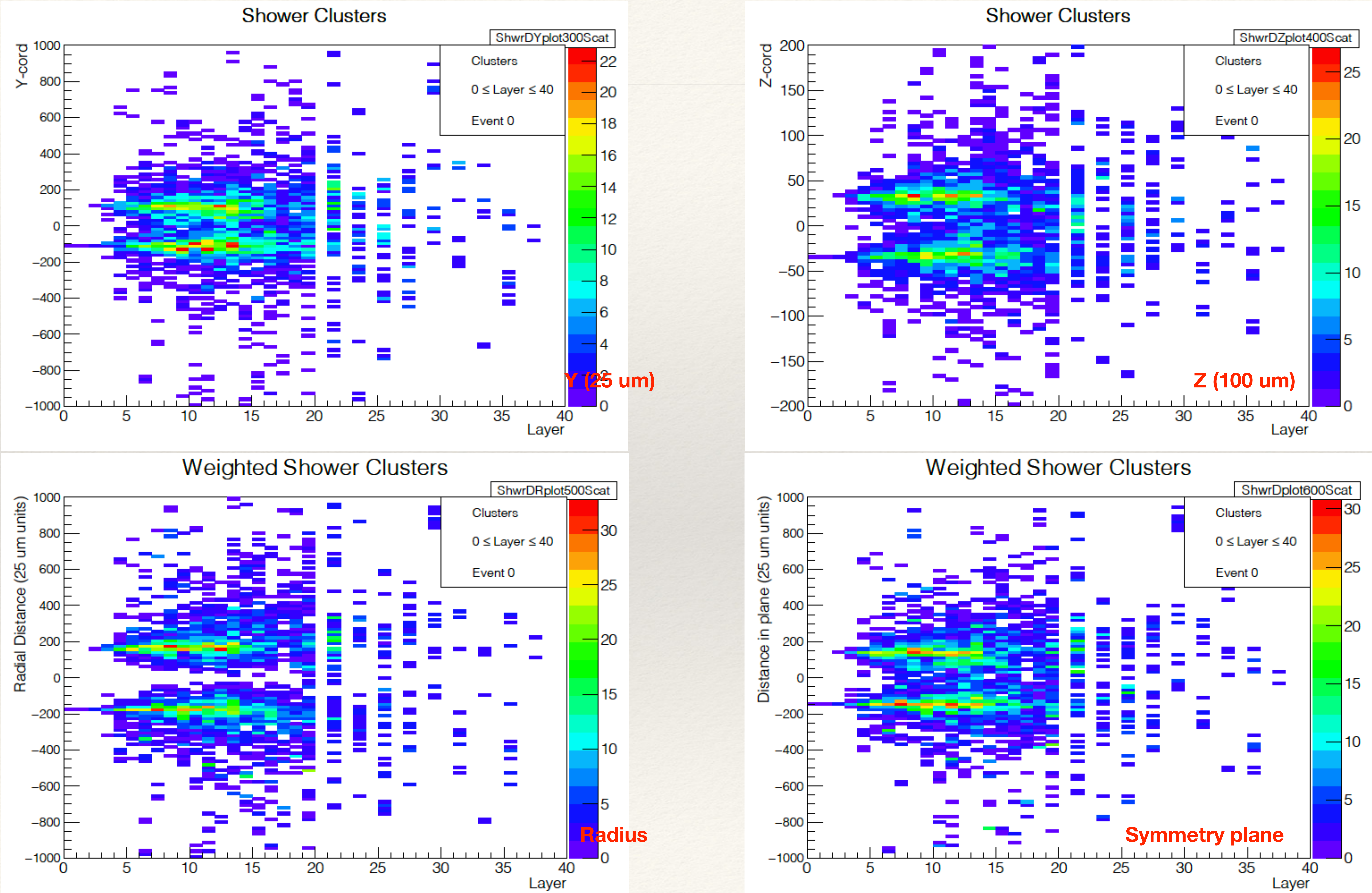
Application: Two-Shower Separation



- Allpix² simulation – single event:
  - 30 GeV e⁻ + 250 GeV e⁻ @1.2mm separation
- Longitudinally integrated distribution makes separation challenging
- Full pixel detector information very powerful
  - Two-shower separation down to 1 mm should be possible
- Systematic studies to be done

40 GeV $\pi^0 \rightarrow$ two 20 GeV γ's

Vertical bin
400 um



From talk by J. Brau at CALOR2022

Active Groups

- Reasonable number of groups involved in pixel R&D for ALICE FoCal
  - Approach: existing technology (ALPIDE) sufficient for FoCal goals, only short-term R&D possible
  - Currently no ambition for R&D beyond FoCal
- Groups with interest in generic R&D for next generation MAPS-based calorimeter
  - Utrecht, the Netherlands
  - Birmingham, UK
  - opportunity for new groups to contribute