

Beam Test Planning

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Motivation – Lab and Beam Tests

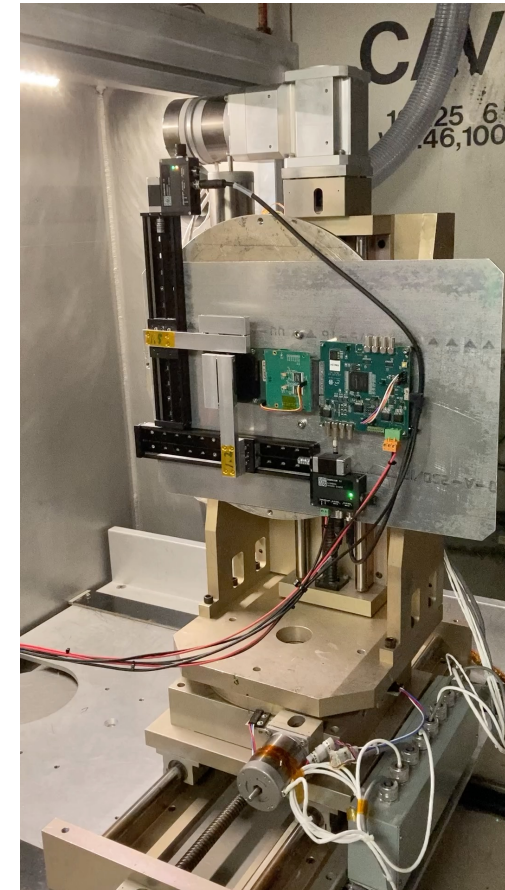
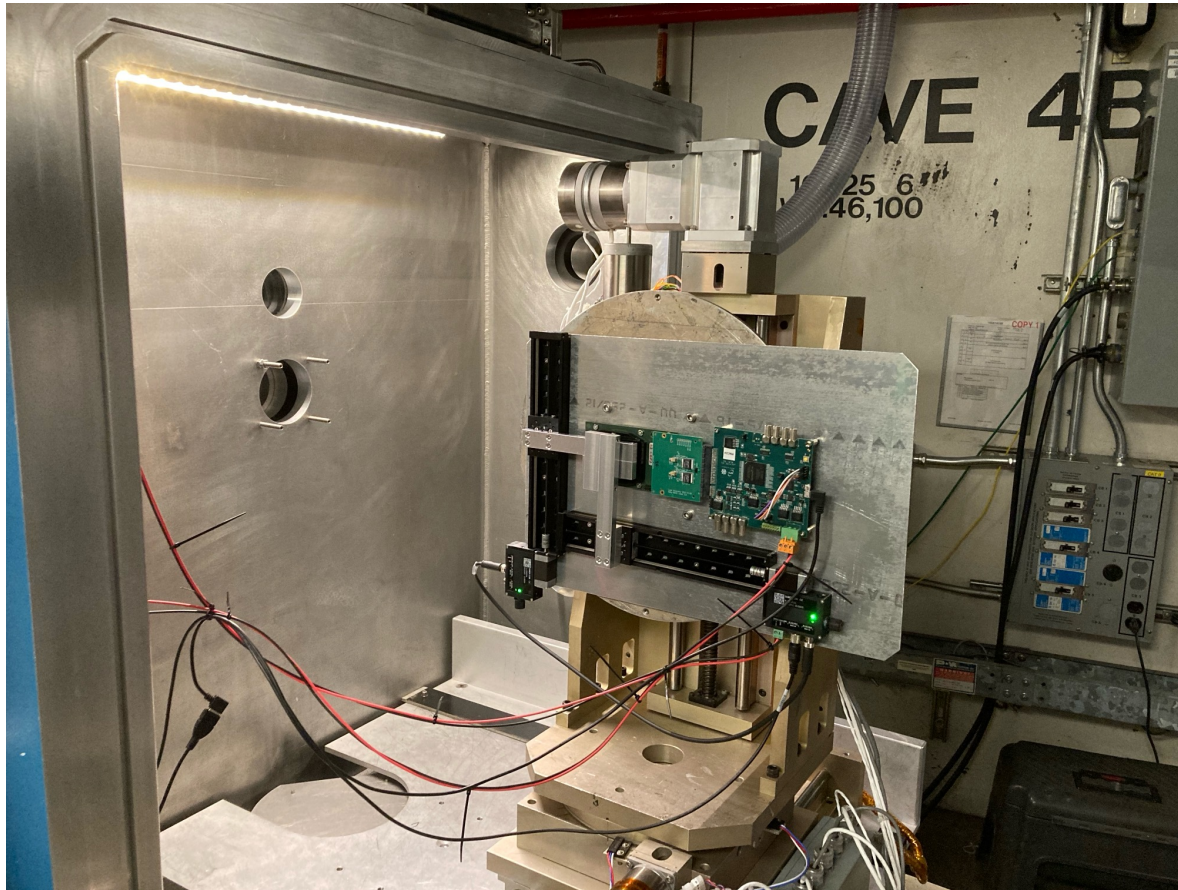
- Characterize and optimize the performance (noise, efficiency, resolution, cluster size, data rate, radiation damage etc) of a detector and/or its components in real experiment conditions during the development phase.
- Quality Control during the production phase.
- What can't or be difficult to learn from lab tests
 - Single event effects (SEL, SEU)
 - Radiation damage due to non-ionization energy loss (NIEL) effect
 - Response (efficiency, resolution, cluster size) to particles
 - ...



Single Event and Radiation Damage

Single Event Latch-up and Test Setup

A **latch-up** is a type of short circuit which can occur in an integrated circuit (IC). More specifically, it is the inadvertent creation of a low-impedance path between the power supply rails of a MOSFET circuit, triggering a parasitic structure which disrupts proper functioning of the part, possibly even leading to its destruction due to overcurrent. A power cycle is required to correct this situation.



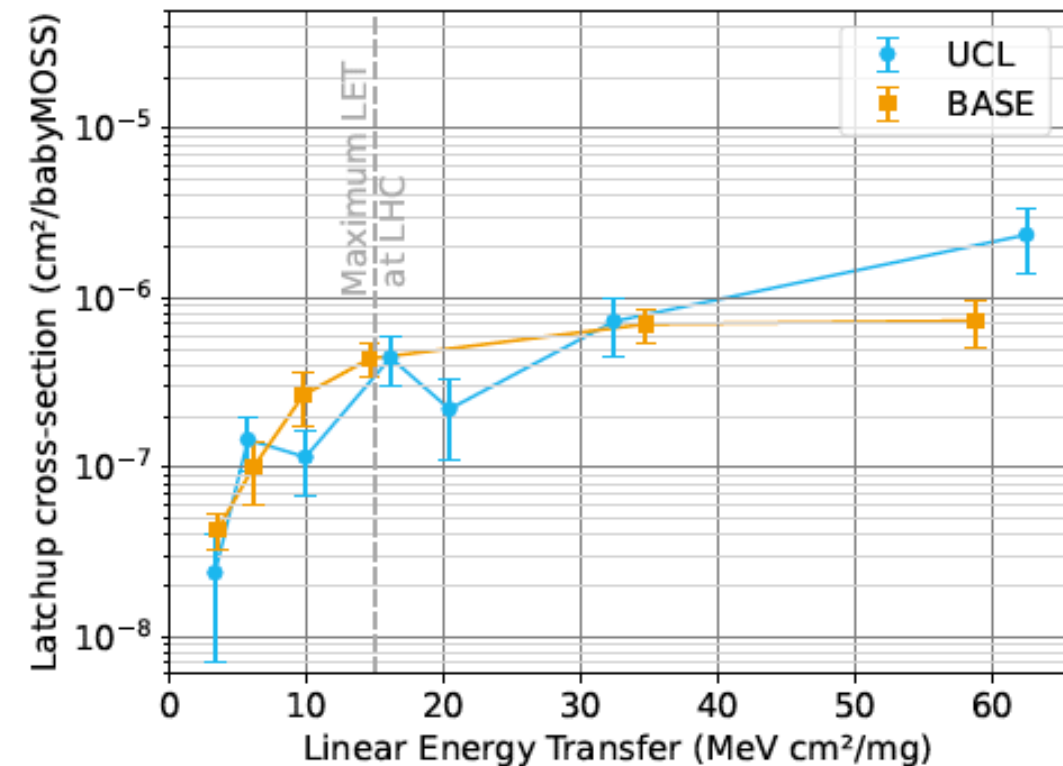
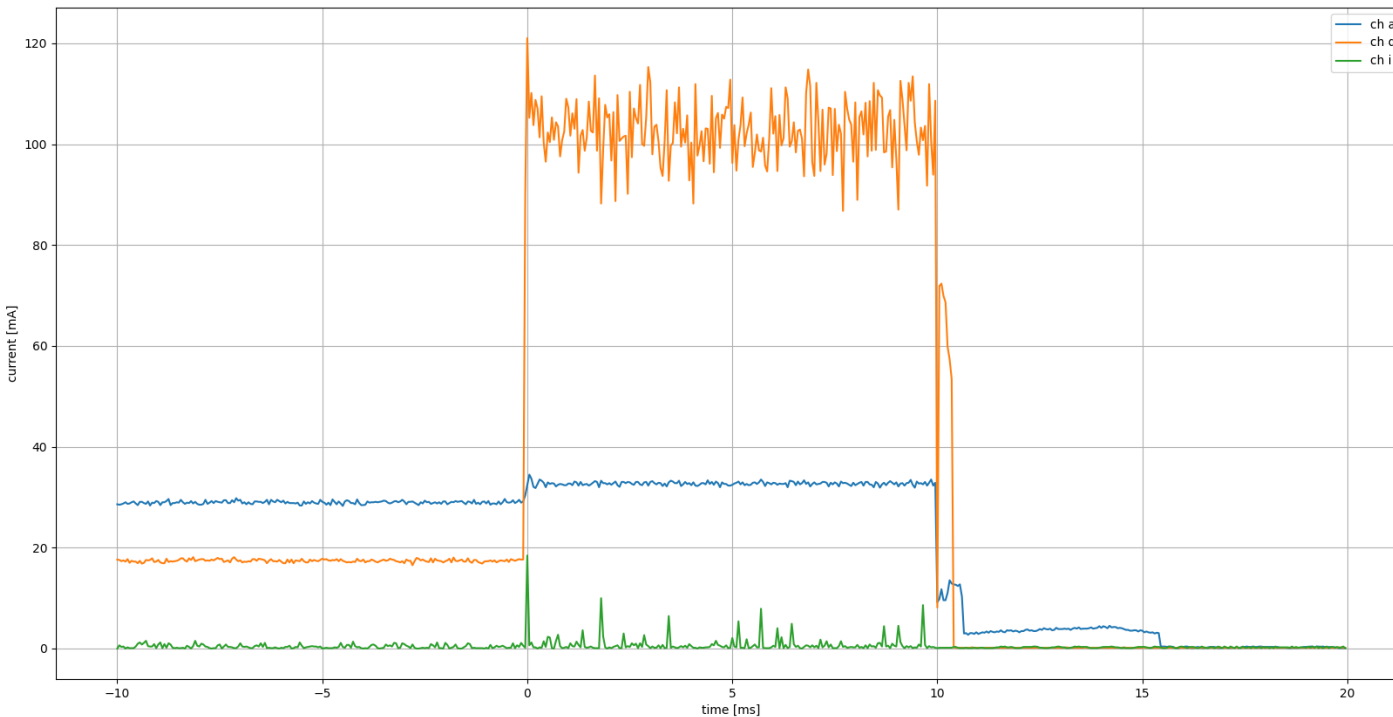
Ion	Cocktail (AMeV)	Energy (MeV)	Z	A	LET (Entrance) (MeV/mg/cm2)	Range in Si (Max) (μm)
B	10	108.01	5	11	0.89	307.2
O	10	183.47	8	18	2.19	222.2
Ne	10	216.28	10	22	3.49	166.1
Si	10	291.77	14	29	6.09	132.1
Ar	10	400.00	18	40	9.74	116.6
V	10	508.27	23	51	14.59	93.9
Cu	10	659.19	29	65	21.17	84.6
Kr	10	885.59	36	86	30.86	84.1
Y	10	928.49	39	89	34.73	68.9
Ag	10	1111.92	47	107	46.92	60.5
Xe	10	1232.55	54	124	58.78	49.0
Au*	10	1955.87	79	197	86.38	54.8

- Heavy ions with fluxes up to $10^7 \text{ cm}^{-2}\text{s}^{-1}$ and LET between 1-100 MeV/(mg/cm²)
- Proton and neutron beams are also available for SEU, TID, and NIEL studies

SEL in MOSS (ER1)

No SEL events were detected when irradiating the pixel array. An insufficient density of well contacts was identified in certain peripheral components, prompting corrections for subsequent iterations of the sensor design. SEL-sensitivity testing will be repeated on future designs (ER2) to assess the likelihood of latch-up under the expected operational conditions of ITS3.

[10.1016/j.nima.2026.171297](https://doi.org/10.1016/j.nima.2026.171297)

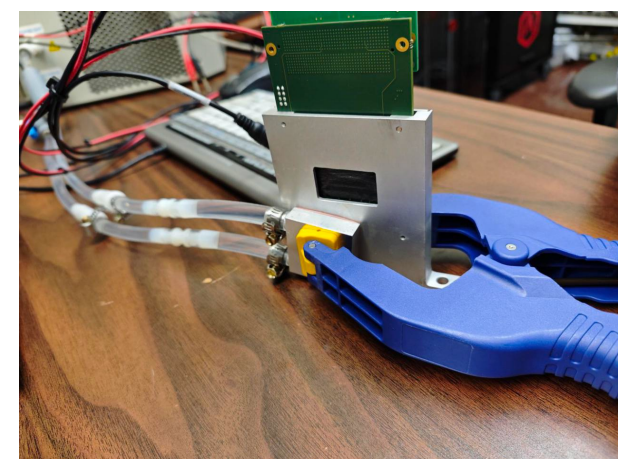
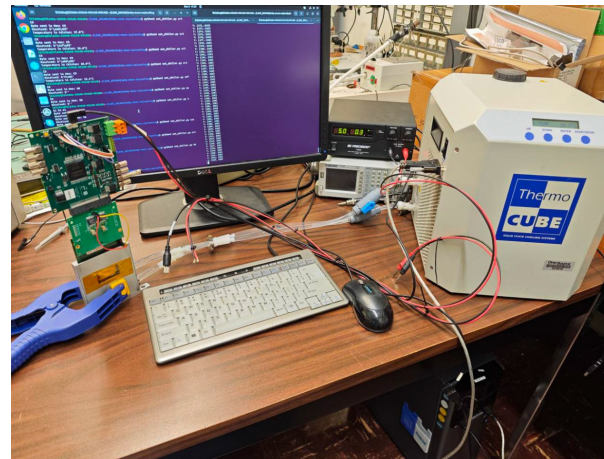
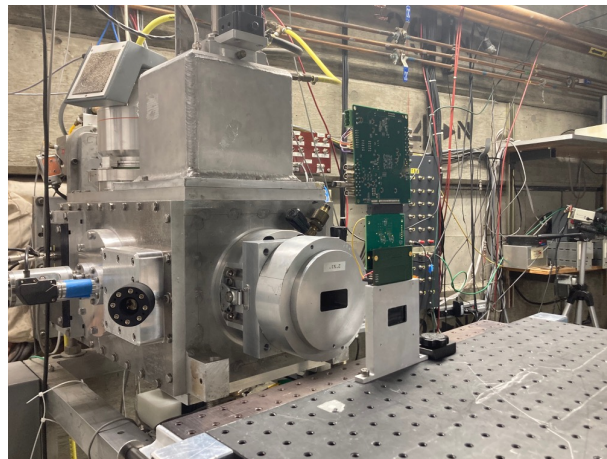
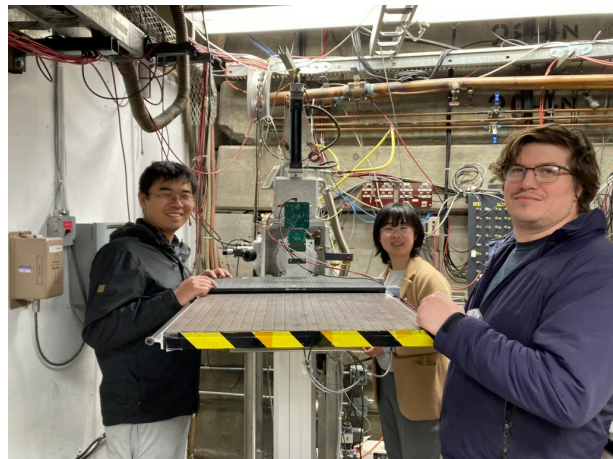


SEL in MOSAIX (ER2)

No SEL observed with babyMOSAIX at UCL. Upper limits are set on the SEL cross-section. We will conduct SEL tests with babyMOSAIX at the BASE facility on 10/23-10/25

- either confirm the non-observation and set stricter limits ($\sim 10\times$ higher beam intensity at BASE than UCL, $\sim 4\times$ longer beam time),
- or observe SEL to quantify the cross-section and identify SEL-sensitive circuit(s) for further design improvements

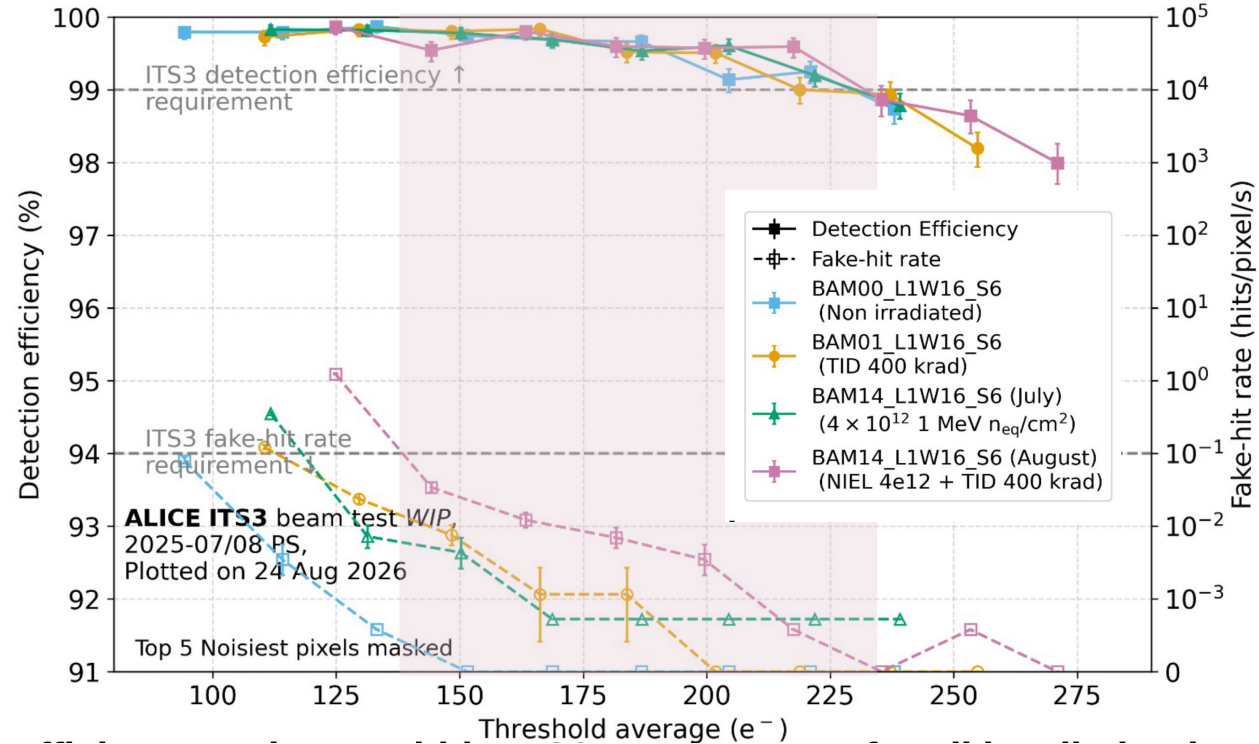
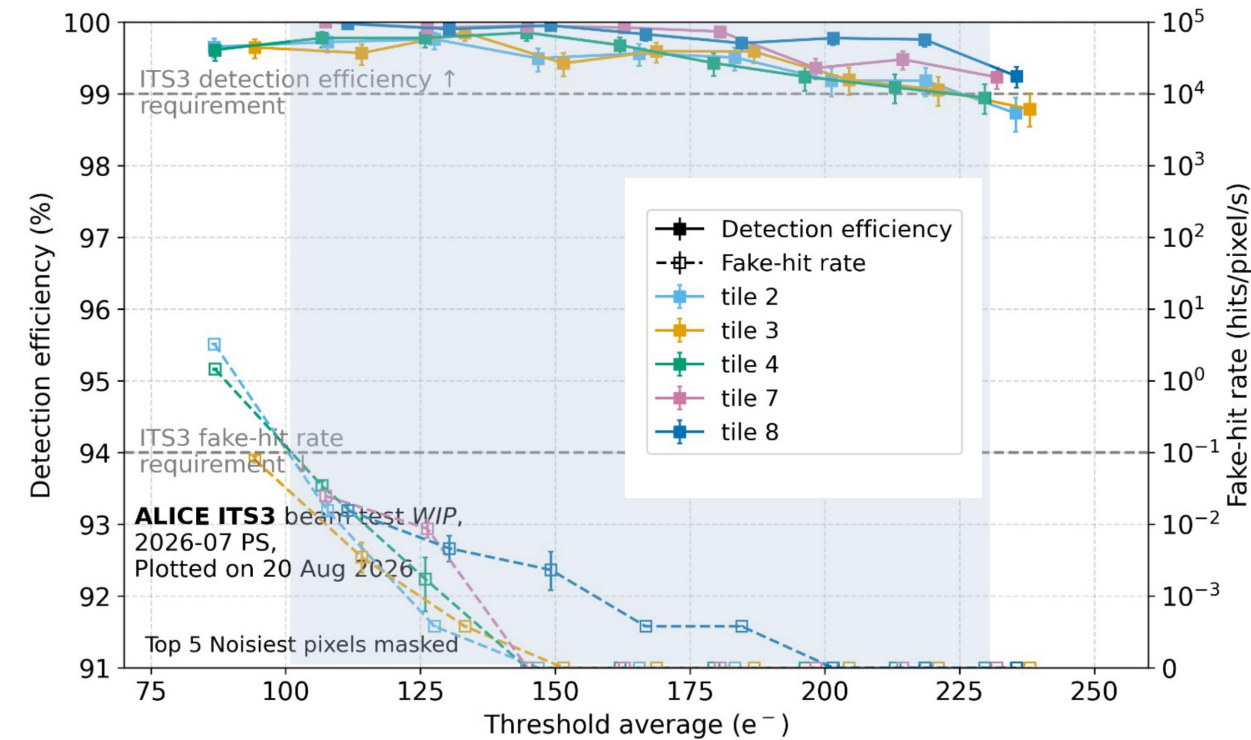
We should also conduct SEE, and NIEL tests on AncASIC MPW3 and EIC-LAS when they become available, to identify sensitive circuits and improve the design.





Sensor Response to Charged Particles

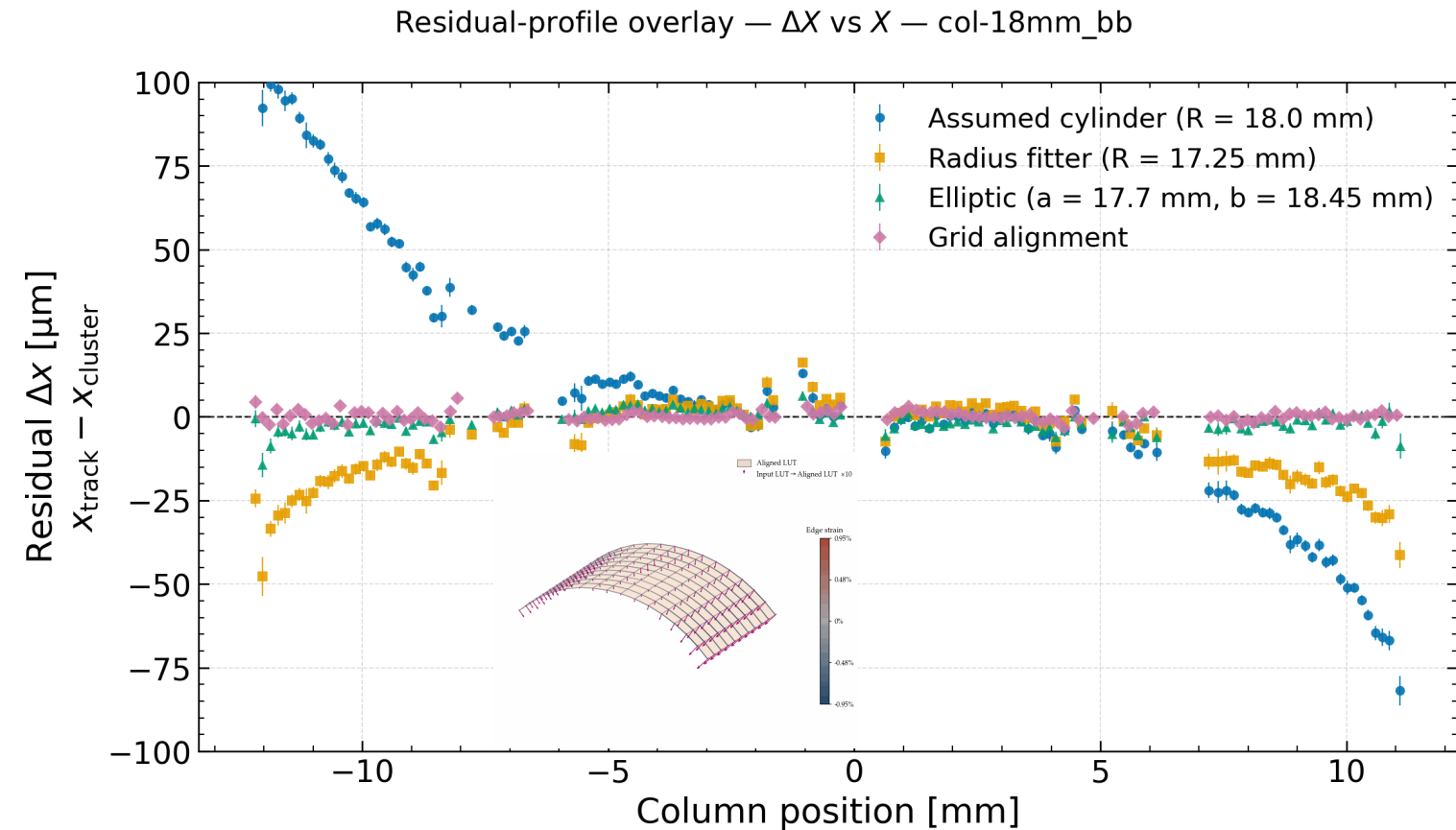
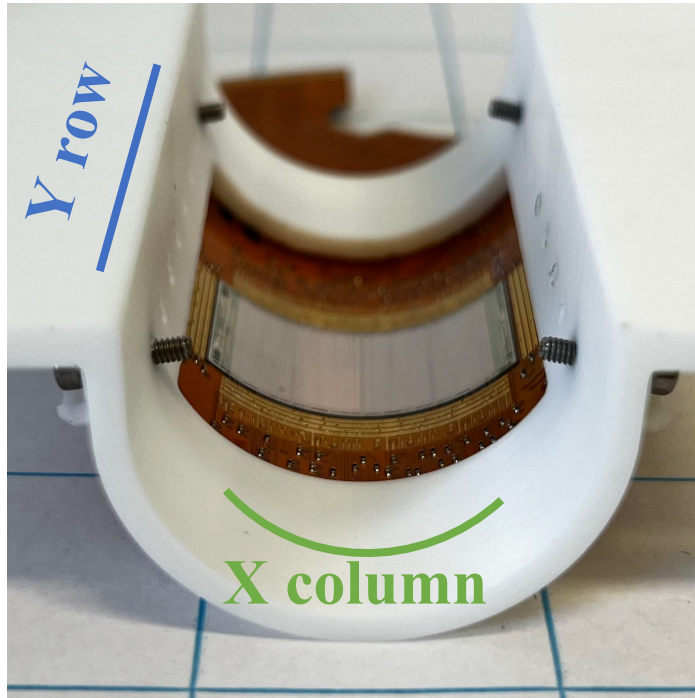
MOSAIX Tests with MIP Charged Particle Beam



- Efficiency, fake hit rate have been measured with beam before and after irradiation ($4e^{12}$ 1MeV n_{eq} + 400 krad)

<https://indico.cern.ch/event/1519426/contributions/7162481>

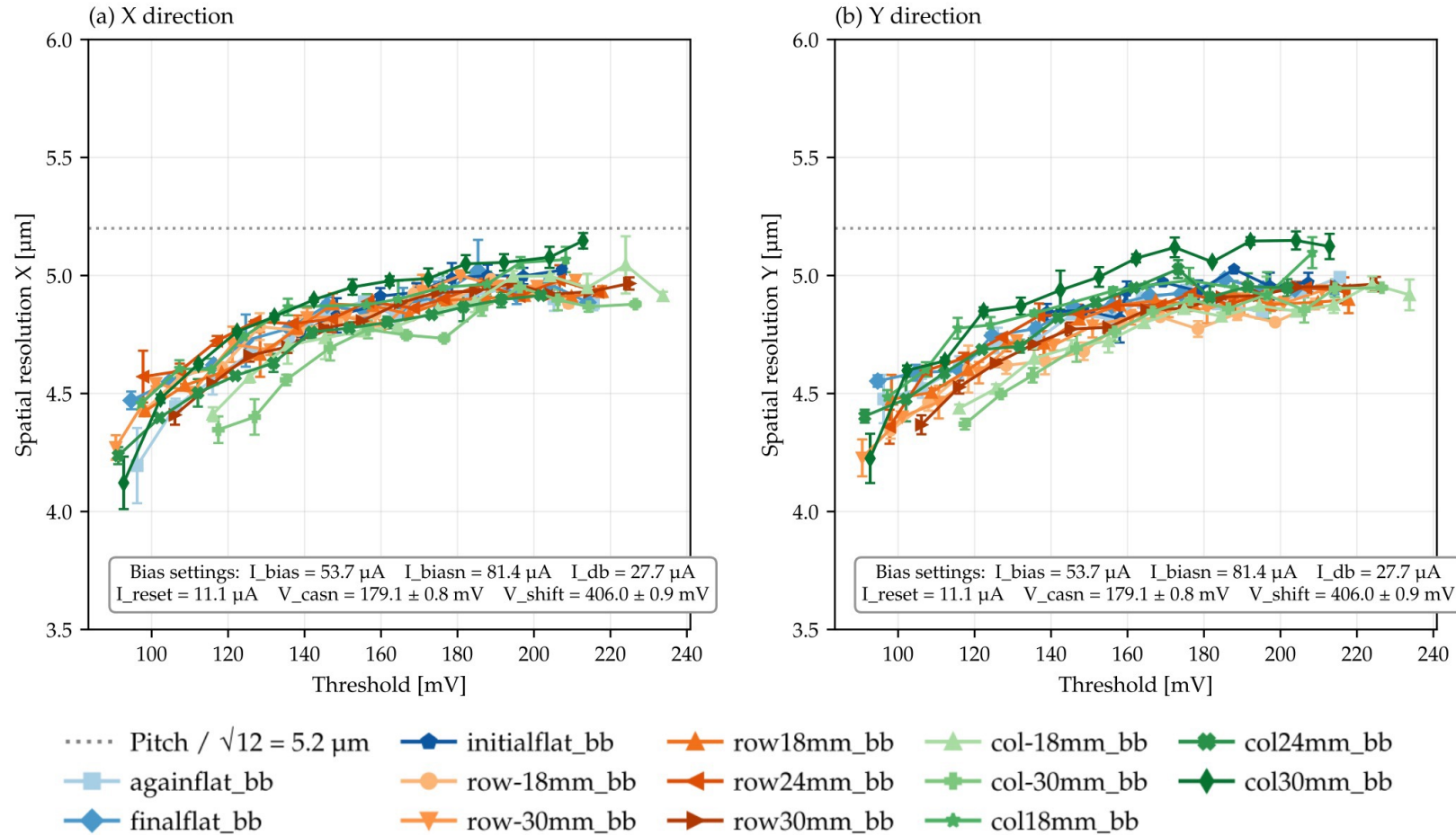
MOSAIX Tests with MIP Charged Particle Beam



- Residuals have been measured with bent babyMOSSs $\Rightarrow$ a grid with 50 pixel pitch is needed to describe the shape of the bent sensors

<https://indico.cern.ch/event/1519426/contributions/7162602>

MOSAIX Tests with MIP Charged Particle Beam



- Resolution has been measured with bent babyMOSSs, and compatible within intrinsic binary resolution

<https://indico.cern.ch/event/1519426/contributions/7162602>

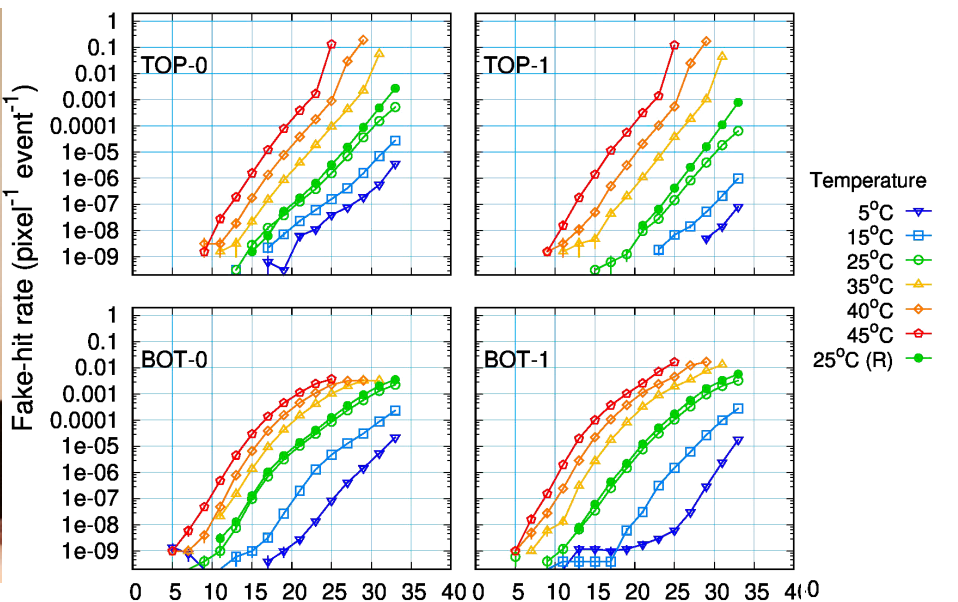
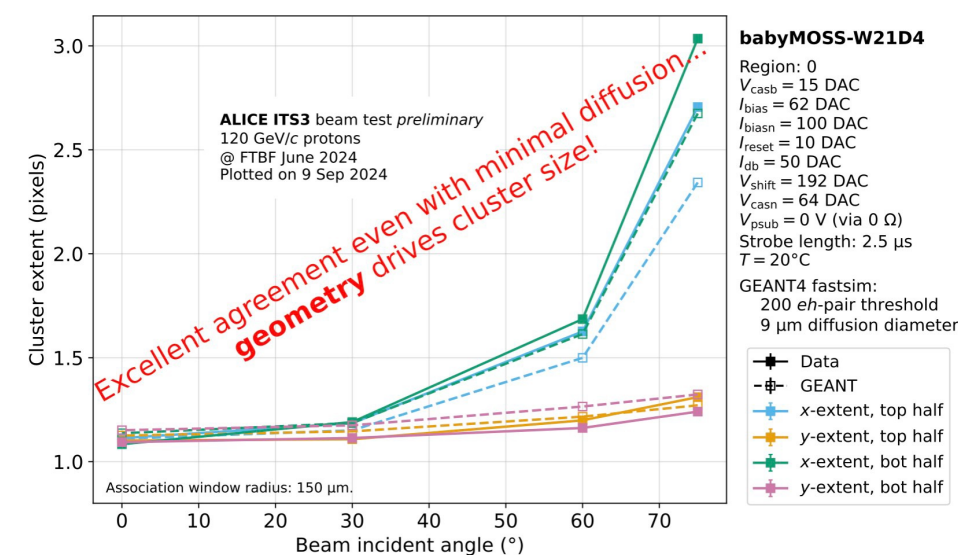
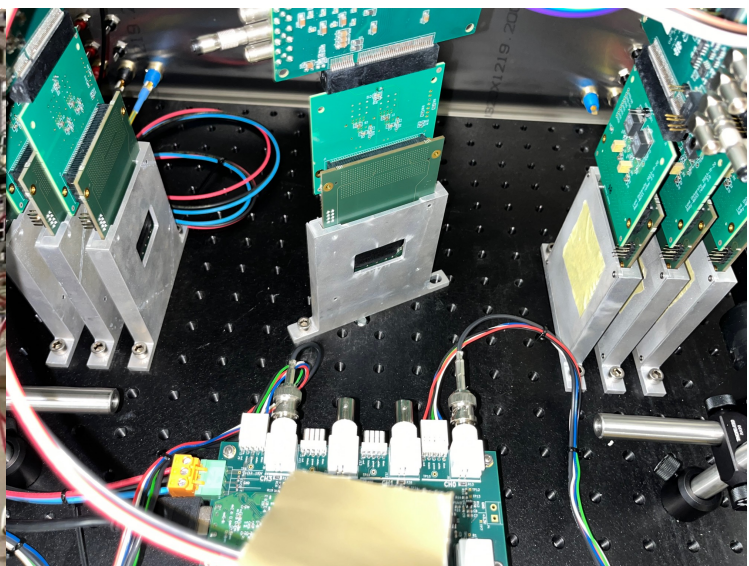
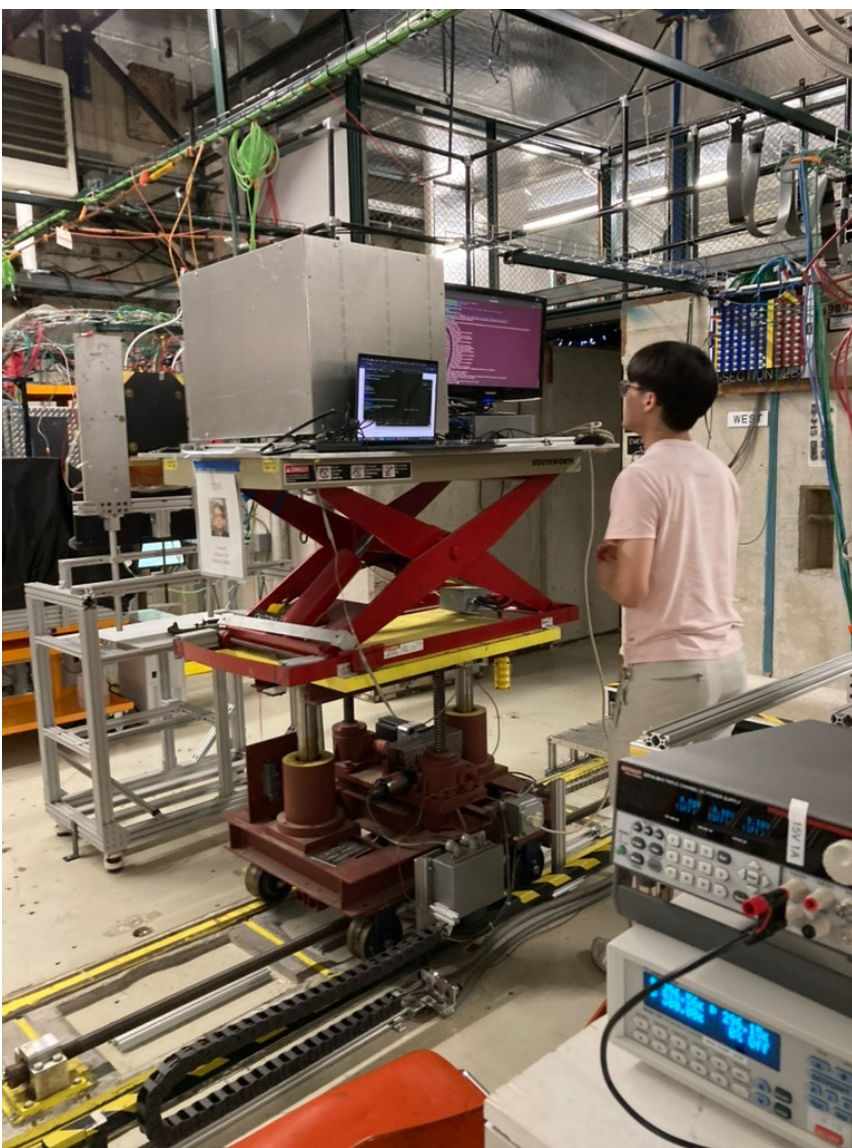
Beam Tests with MIP Charged Particle Beam

What have not been measured by ITS3, but are important to have accurate inputs for SVT design optimization and ePIC physics projections

- Efficiency, resolution and cluster size at the temperature and profile foreseen by ePIC
- Efficiency, resolution and cluster size versus incident angle
- Material budget distribution

We should conduct such studies not only with flat sensors on carrier PCBs, but also with IB half layers with bent sensors, OB and disk modules/staves including AncASIC, FPCs, with air flow, when they become available.

Beam Tests with babyMOSS (ER1)



Sensor Response to Photons

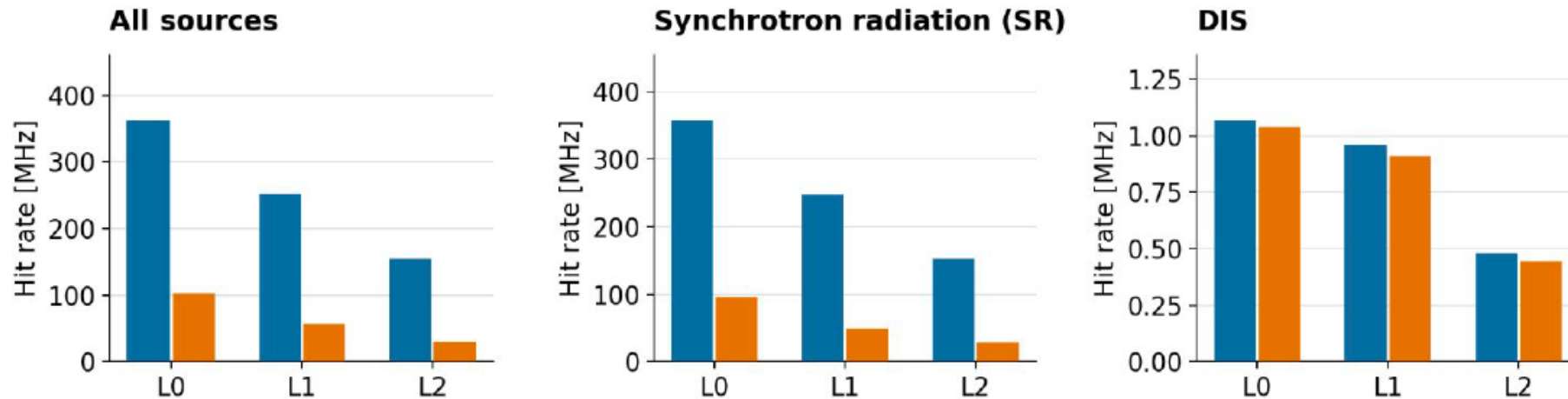
Sensor Structure

Impact on hit rate (example with IB, no noise):

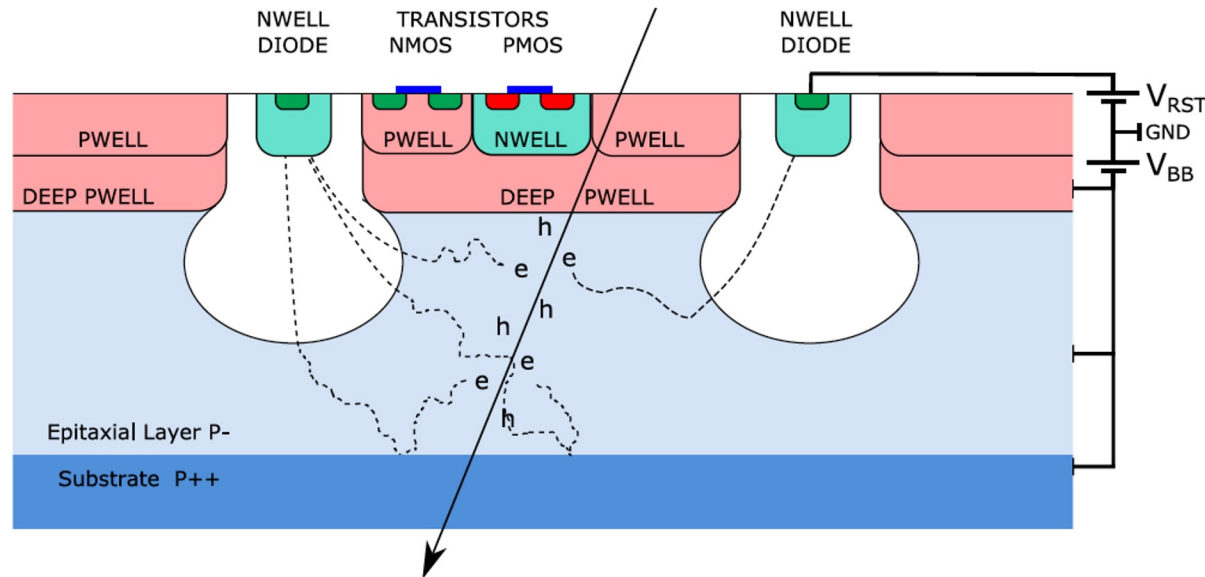
- SR (low energy photons) are sensitive to material thickness.
- Observed a factor of >3 reduction in **total rate per layer** driven by the reduced SR rate as expected.
- **TODO**: re-evaluate the **data rate** estimation after OB and disks geometry updates.

- **ePIC 26.04**: 40um-thick active silicon. used in the recent data rate estimation [\[link\]](#)
- **ePIC 26.08**: updated three-layer (Cu/Si/Si) structure.
- **event sample**: forced DIS ($Q^2 > 1$) +all background, 10x275. 1 event = 2us, rates are averaged over 1.9k and 9.9k event samples.

■ ePIC 26.04 · 1,900 events ■ ePIC 26.08 · 9,900 events



Sensor Responses



- P/N-well: high doping, electrical circuit
- Epitaxial: low doping, sensor active volume
- Substrate: high doping, mechanical handling

1. Particles interact with sensor and generate signal charges [1]
2. Signal charges collected through drifting and diffusion [2-7]
3. Collected charges are processed by integrated readout electronics

References

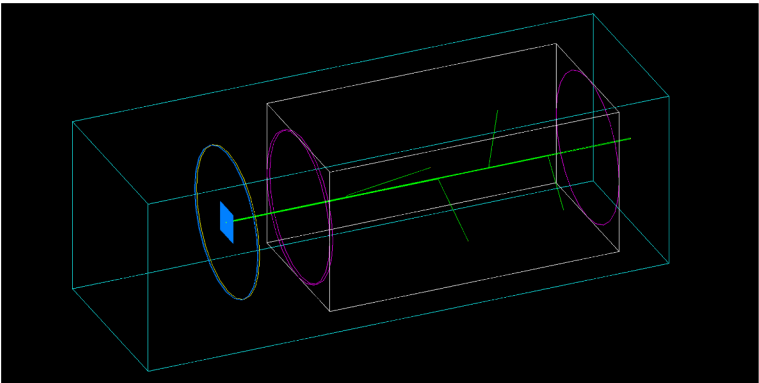
- [1] *Passage of Particles Through Matter*, S. Navas et al. (Particle Data Group), *Phys. Rev. D* 110, 030001 (2024)
- [2] *Simulation and measurements of charge collection in monolithic active pixel sensors*, Grzegorz Deptuch et al., *NIMA* 465 (2001) 92–100
- [3] *New Generation of Monolithic Active Pixel Sensors for Charged Particle Detection*, Grzegorz Deptuch (2002).
- [4] *Study of Monolithic Active Pixel Sensors for the Upgrade of the ALICE Inner Tracking System*, Miljenko Šuljić, *CERN-THESIS-2017-304*
- [5] *MC simulation of charge collection processes in Monolithic Active Pixel Sensors for the ALICE ITS upgrade*, Miljenko Šuljić, *NIMA* 950 (2020) 162882
- [6] *Development and performance study for the ALICE ITS3: the first truly cylindrical inner tracker*, Isabella Sanna, *CERN-THESIS-2024-359*
- [7] *TCAD and charge transport simulations of MAPS in 65nm for the ALICE ITS3*, Isabella Sanna et al., *JINST* 20 (2025) C06032

Sensor Response Studies in Simulation (Yu Hu)

Particles interaction with silicon



40 μm inactive + 10 μm active Si with
20x20 μm^2 pixels

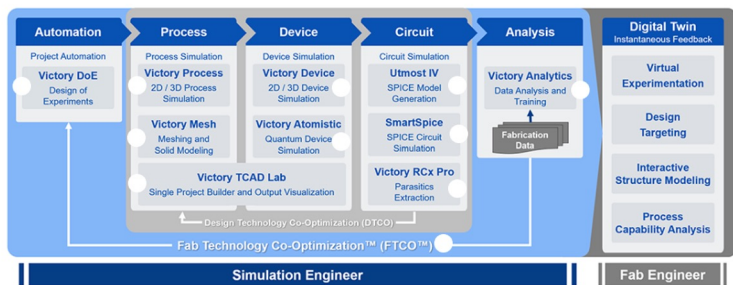


10 E_γ @ 80 keV

Sensor Doping profile and E-field

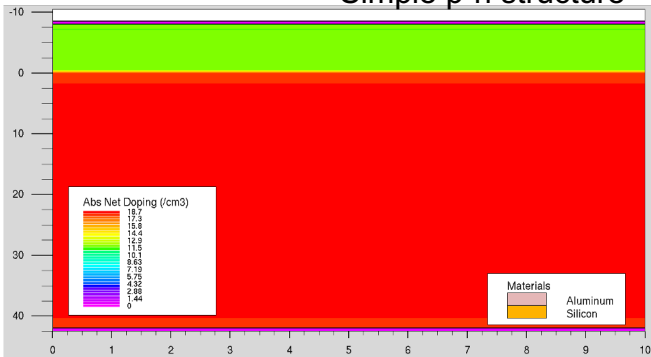
Semiconductor Process and Device Simulation

TCAD software solutions are key to developing new semiconductor processes and devices, dramatically reducing costs and time to market.



comprehensive suite of **Technology Computer-Aided Design (TCAD)** software tools to model semiconductor fabrication processes and device behaviors

Simple p-n structure



Transport model + Detector Response



Geometry Definition
Layout, materials

GEANT4 Wrapper
position + E_{dep}

Signal Formation
Charge $\rightarrow$ electrical signal

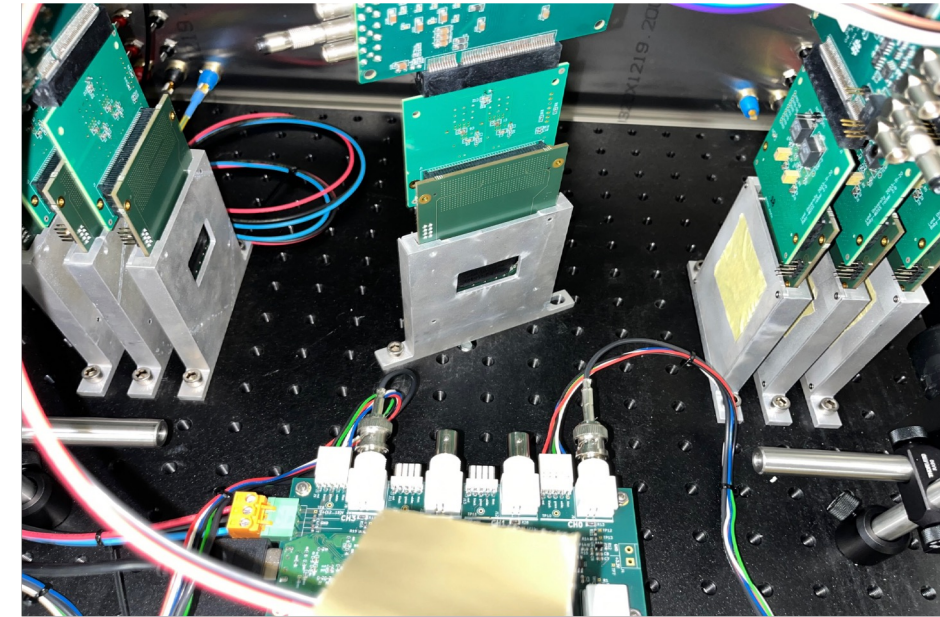
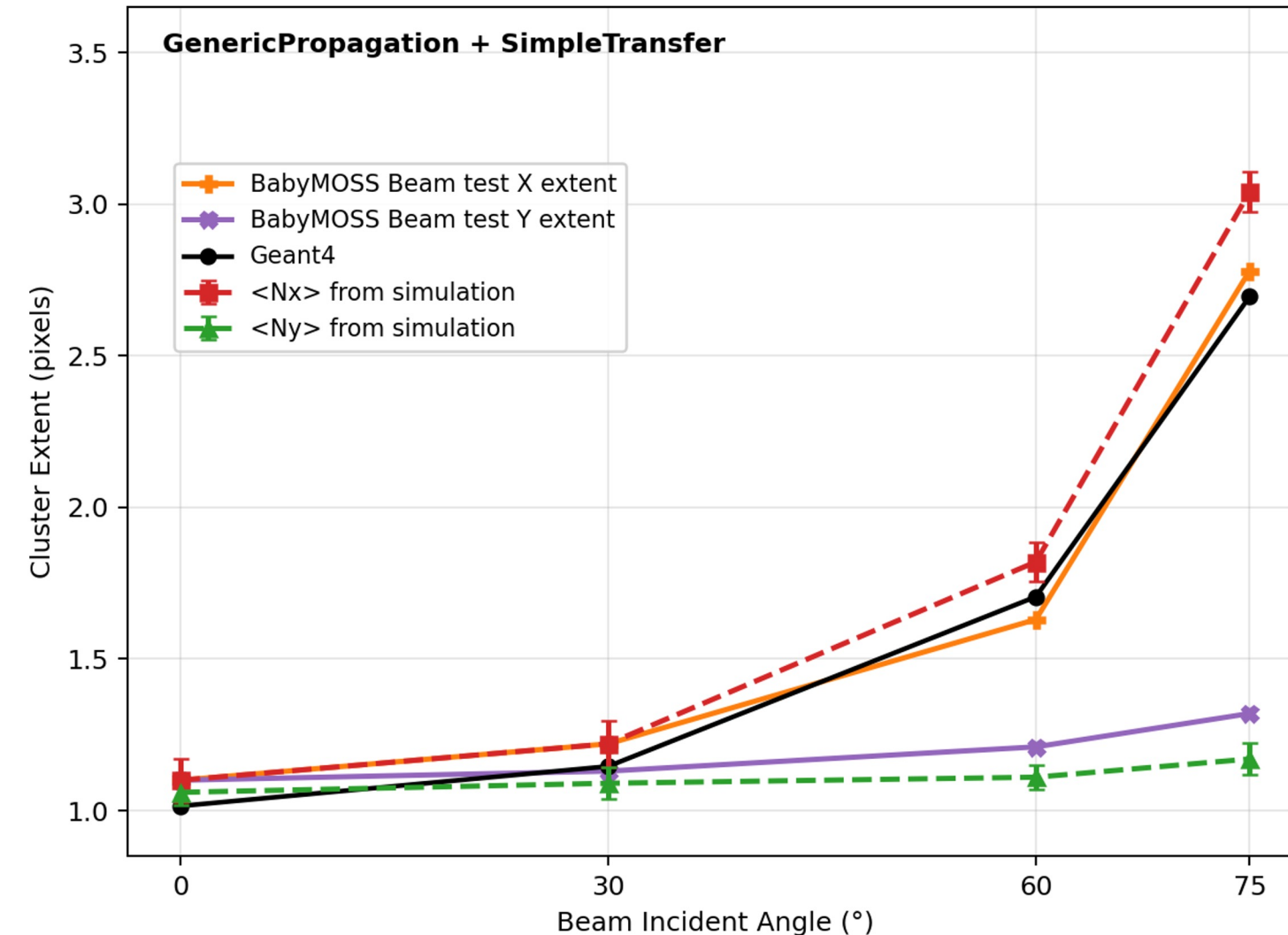
Charge Transport
Drift, diffuse...

Digitization
Thr. Noise, Elec response

Output
w. ROOT

Sensor Response to Charged Particle between Data and Simulation

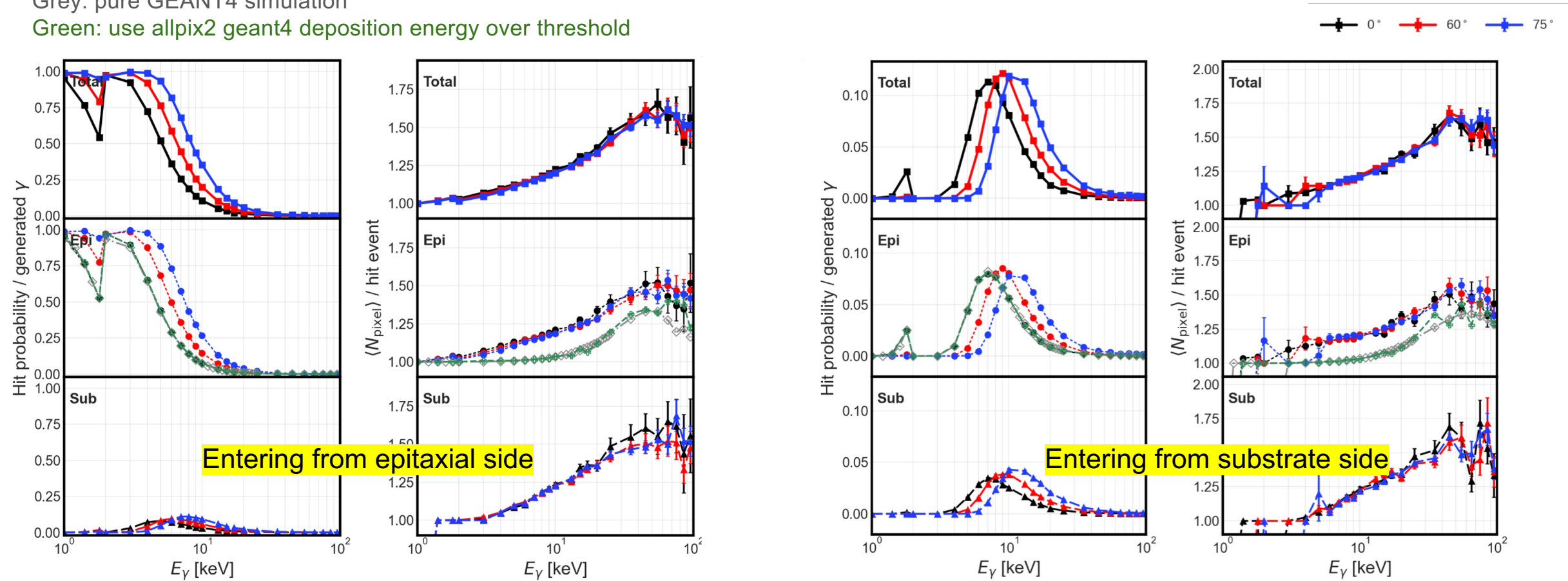
Danush Shekar, Tucker Hwang, Yu Hu



- Allpix² compatible with ER1 beam test data with 120 GeV protons, and with pure GEANT4 simulation
- Slightly higher <Nx> and lower <Ny> in simulation than data could partially be due to misalignment of the sensor w.r.t. beam

Sensor Response to Low Energy Photons in Simulation

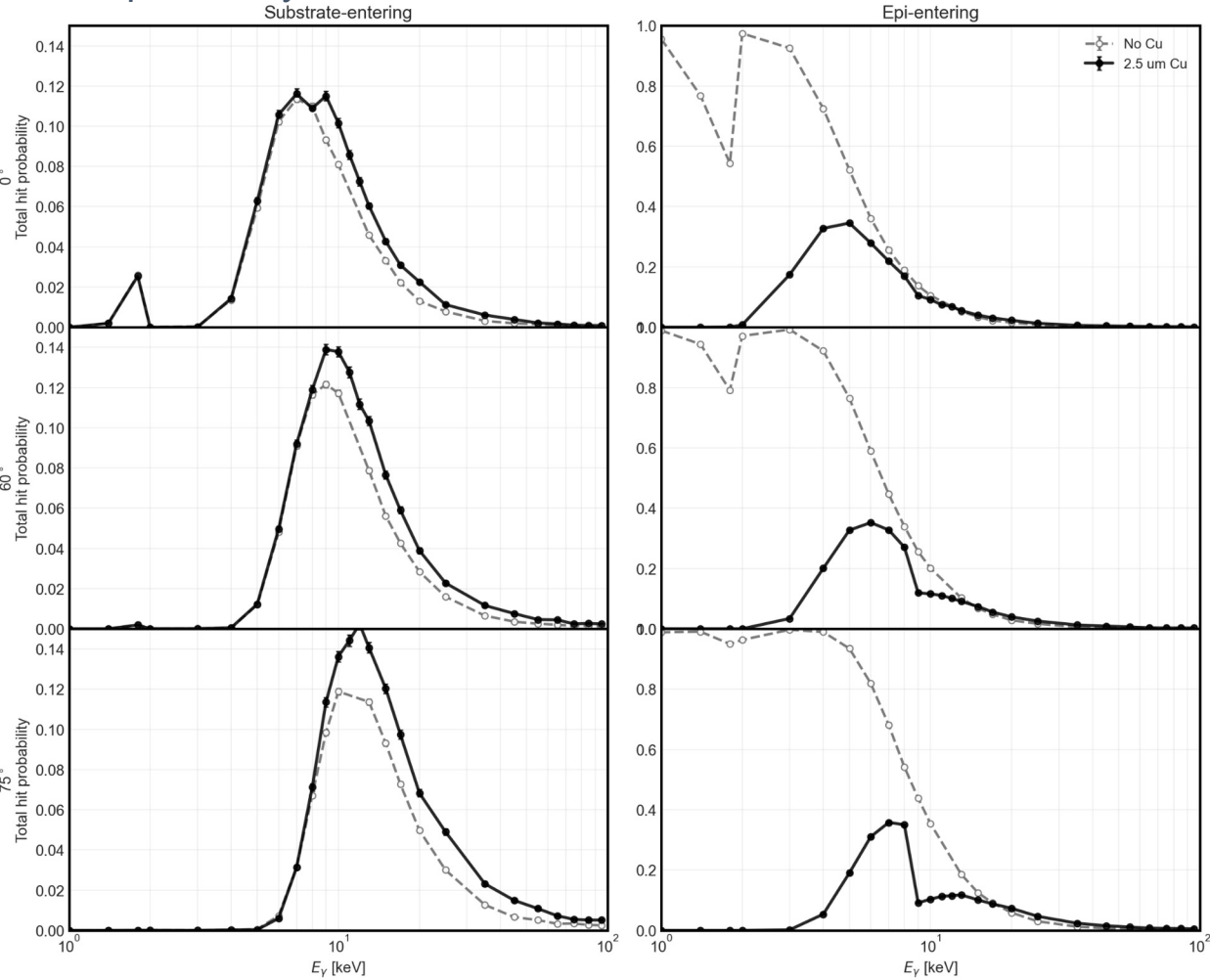
Grey: pure GEANT4 simulation
Green: use allpix2 geant4 deposition energy over threshold



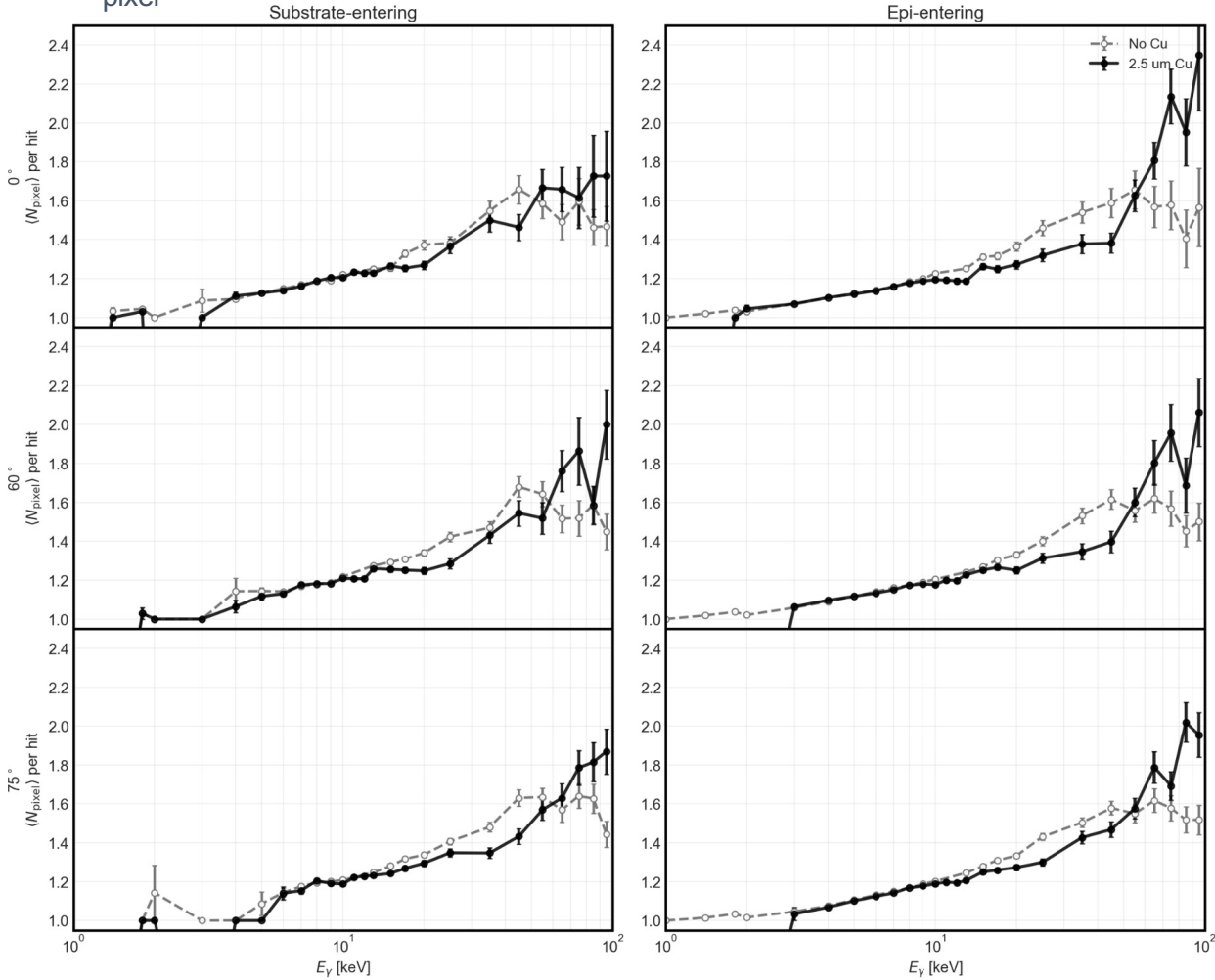
Significant dependence of cluster size on photon energy
Negligible dependence of cluster size on incident angle

Low Energy Photons in Allpix² - w./w.o. 2.5um Cu layer

Hit probability



$\langle N_{\text{pixel}} \rangle / \text{Hit}$



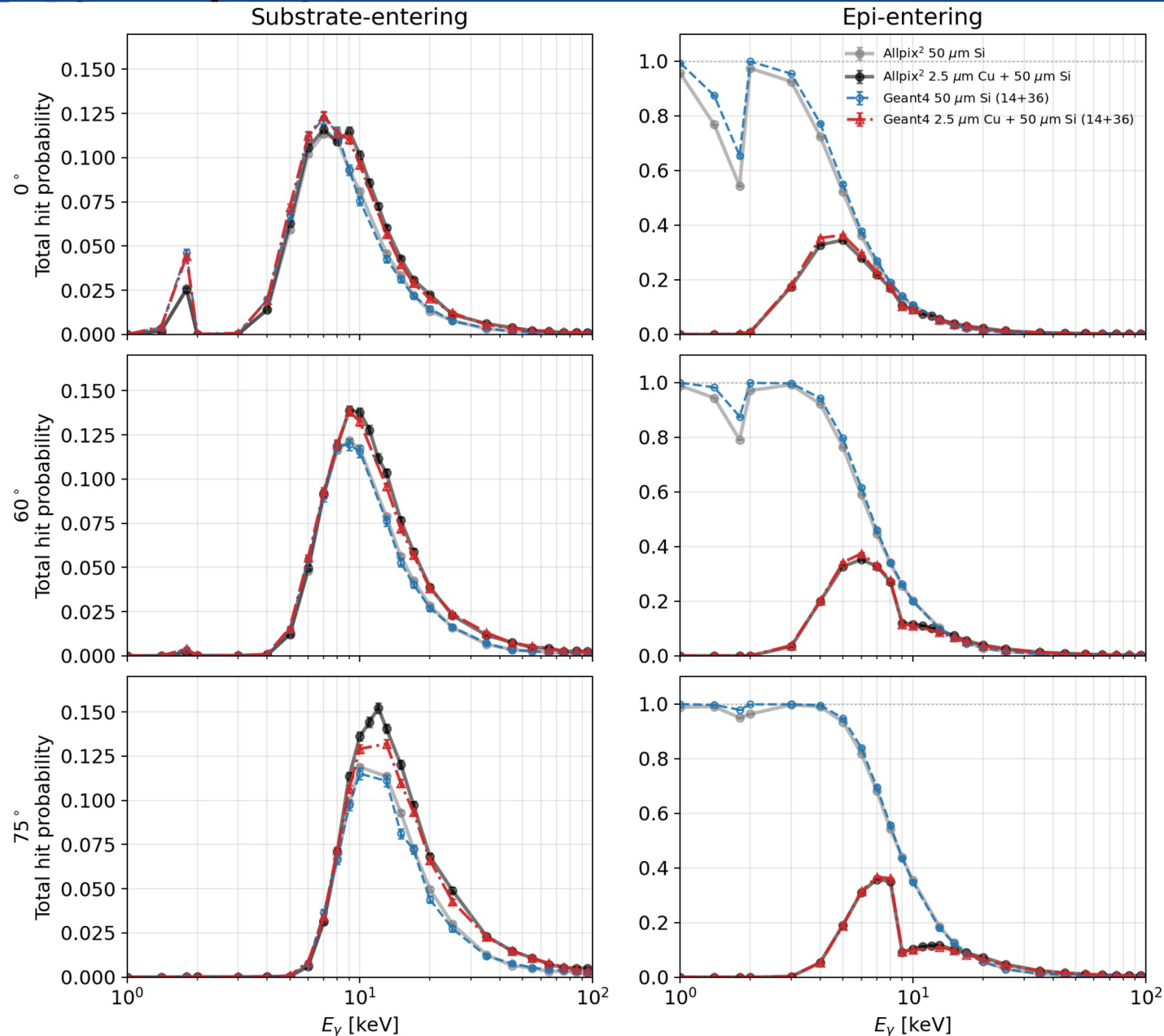
X-ray Absorption Edges

Element 29: Cu Atomic mass: 63.5460

Edge	keV	A
K	8.9789	1.3808
L-I	1.0961	11.3114

<http://skuld.bmsc.washington.edu/scatter/data/Cu.html>

Match Hit Probability in GEANT4 with Allpix2



Compare **black** with **red**

Pure GEANT4 simulation with 2.5 μm Cu
+ 14 μm active Si + 36 μm inactive Si

matches with Allpix2 hit probability (w.
Simple p-n structure) relatively well

Beam Tests with Low Energy Photons

What have not been measured, but are important to have accurate inputs for SVT design optimization (data rate $\Rightarrow$ sensor clock frequency $\Rightarrow$ power consumption) and ePIC physics projections (signal and beam background separation $\Rightarrow$ resolutions)

- Interaction probability and cluster size vs photon energy
- Interaction probability and cluster size vs photon incident angle

We can conduct such studies with synchrotron light sources

Summary and Outlook

- Beam tests are crucial to characterize and optimize detector design during the development phase and quality control during the construction phase for SVT.
 - Single event effects with low energy heavy ions
 - Radiation damage effects with protons or neutrons
 - Sensor responses to high energy charged particles and low energy photons
- Near term test beam plan
 - SEL for babyMOSAIX ER2
 - SEL, SEU for AncASIC MPW3
 - Charged particle for SVT temperature and incident angle dependence
 - Synchrotron light sources for low energy photons (EIC SR background)