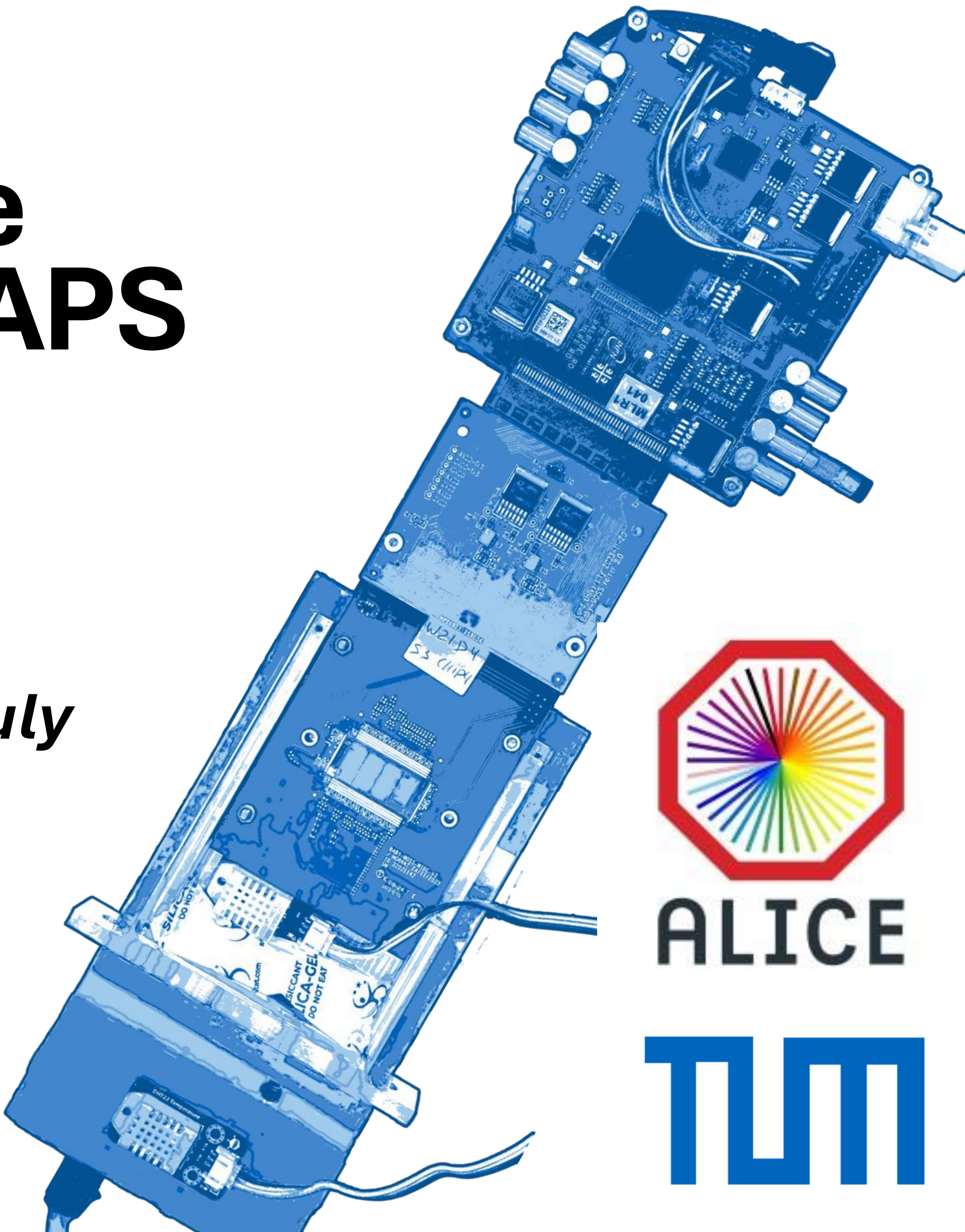
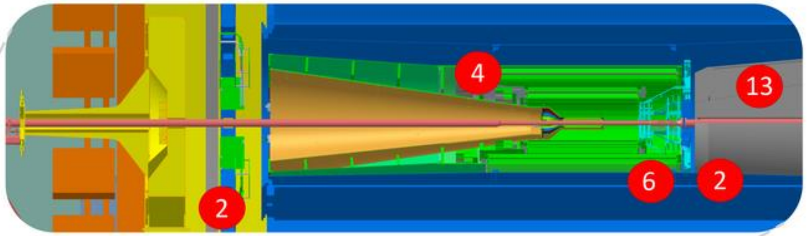
Exploring Amplitude Measurements with MAPS Trackers for Future Experiments

IMPRS Recruitment Workshop - 17 July

Henrik Fribert



A Large Ion Collider Experiment

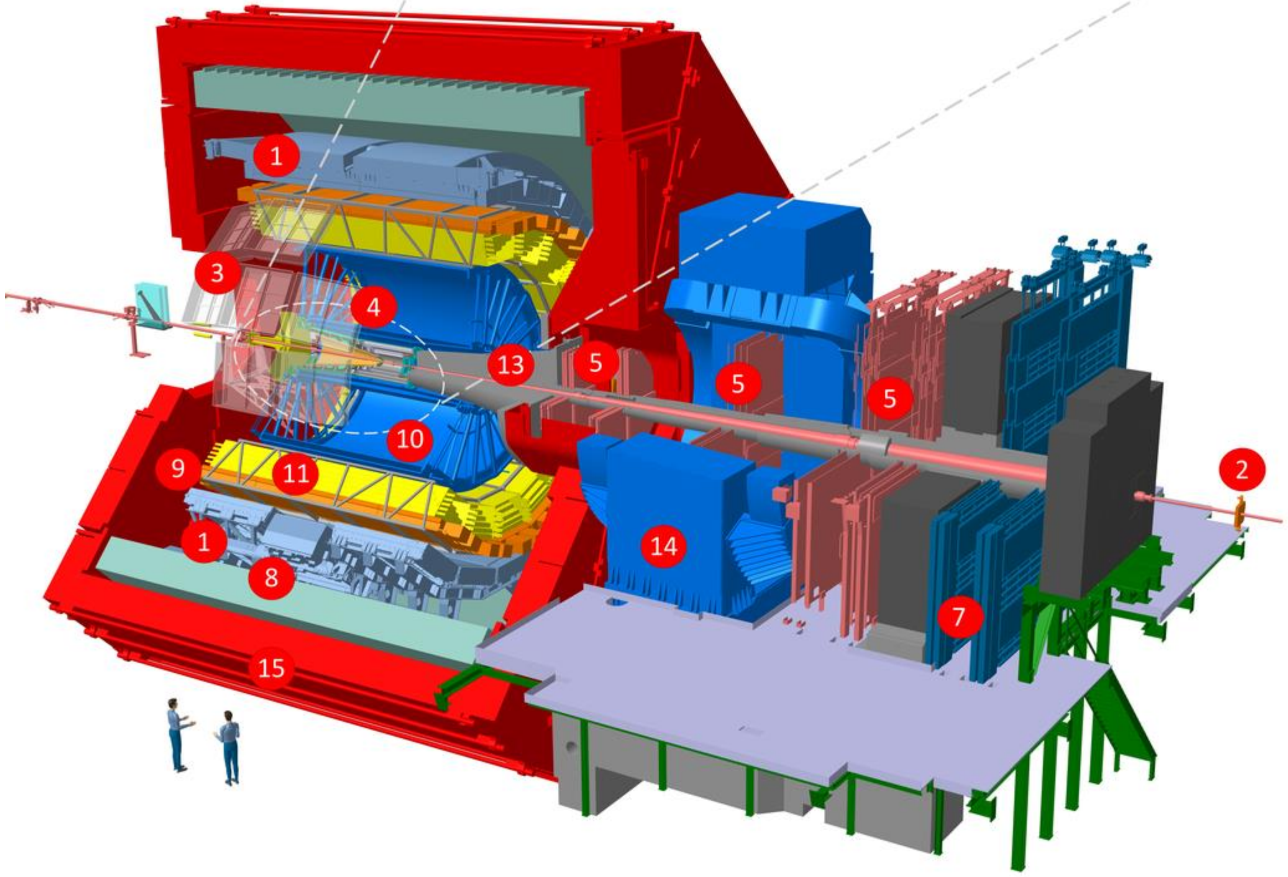


https://iopscience.iop.org/article/10.1088/1748-0221/19/05/P05062

- ALICE uses an Inner Tracking System (ITS) and a Time-Projection Chamber (TPC) as tracking detectors

- Current ITS 2 (MAPS) ‘only’ measures hits with a pointing resolution of 5-100 μm
  → no dE/dx measurement
  ALICE ITS3 TDR

- Particle Identification (PID) is mainly done via TPC and TOF

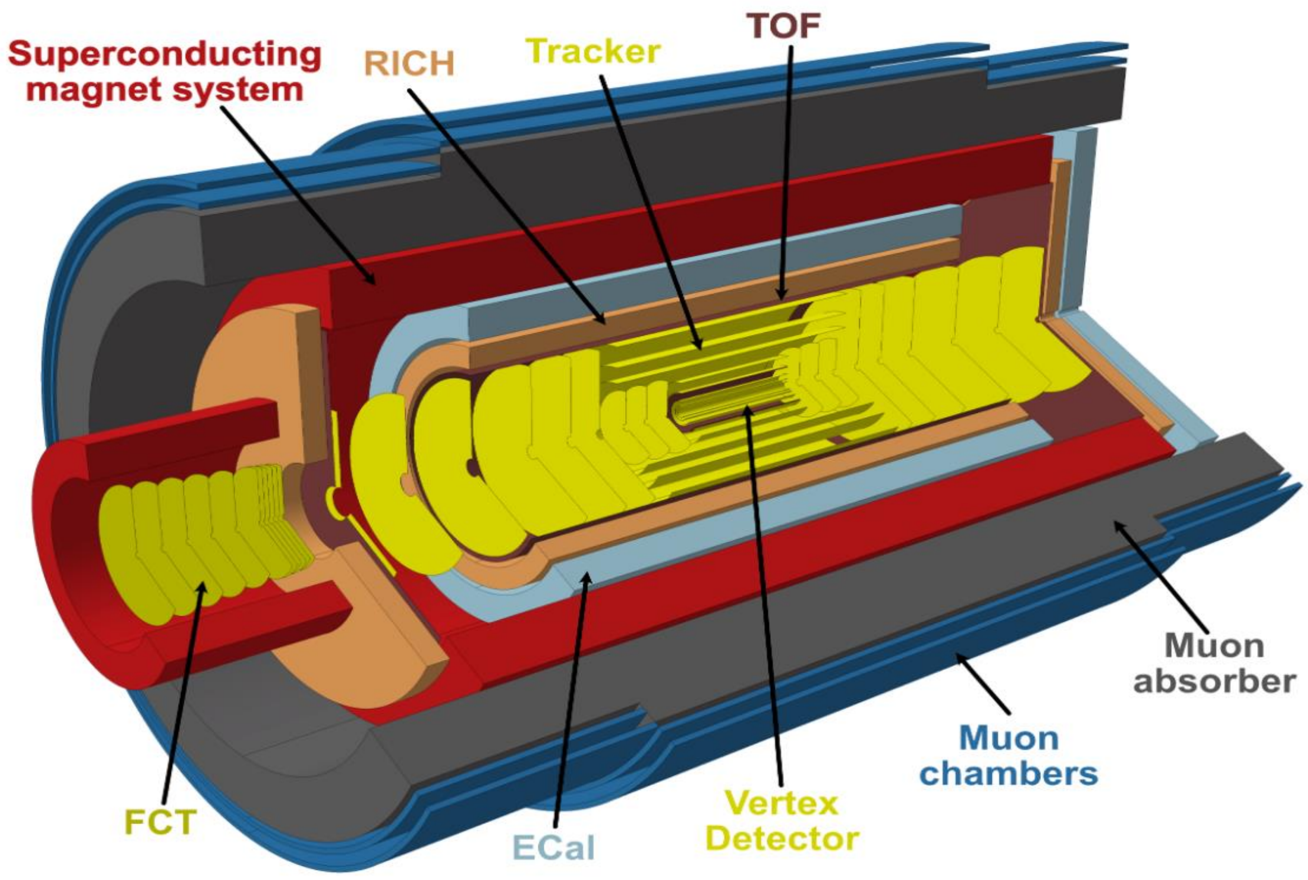


ALICE 3

- ALICE 3 is a planned new detector system based on large-area silicon detectors starting data-taking in 2036
  - Precursor and R&D base for future particle physics experiments, including the FCC (Future Circular Collider)

- Based fully on silicon technology (60 m^2 of MAPS tracker)
  - Current pp-rate: 500 kHz / 1 MHz
  - ALICE 3 pp-rate: 24 MHz

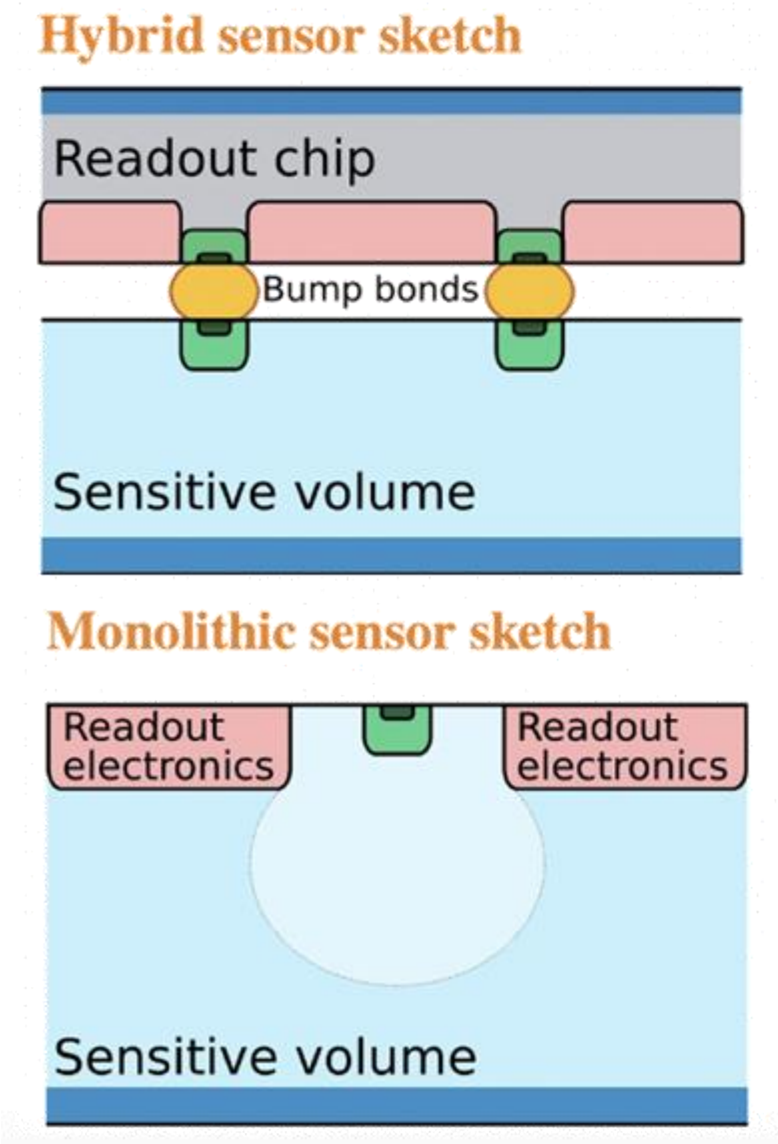
- *Can we exploit the full potential of MAPS trackers?* → Amplitude measurement



ALICE3 LOI

Monolithic **A**ctive **P**ixel **S**ensors

- Single silicon chip contains both the detection volume and the readout electronics
- Advantages:
  - Low capacitances = low power (10-100 mW/cm^2)
  - Thin: < 50 µm (0.05% X_0 per MAPS)
  - Highly integrated (around 100 transistors in-pixel)
  - Commercially available process (CMOS technology) & scalable to large detector areas
- See detector seminar on MAPS at CERN by W. Snoeys



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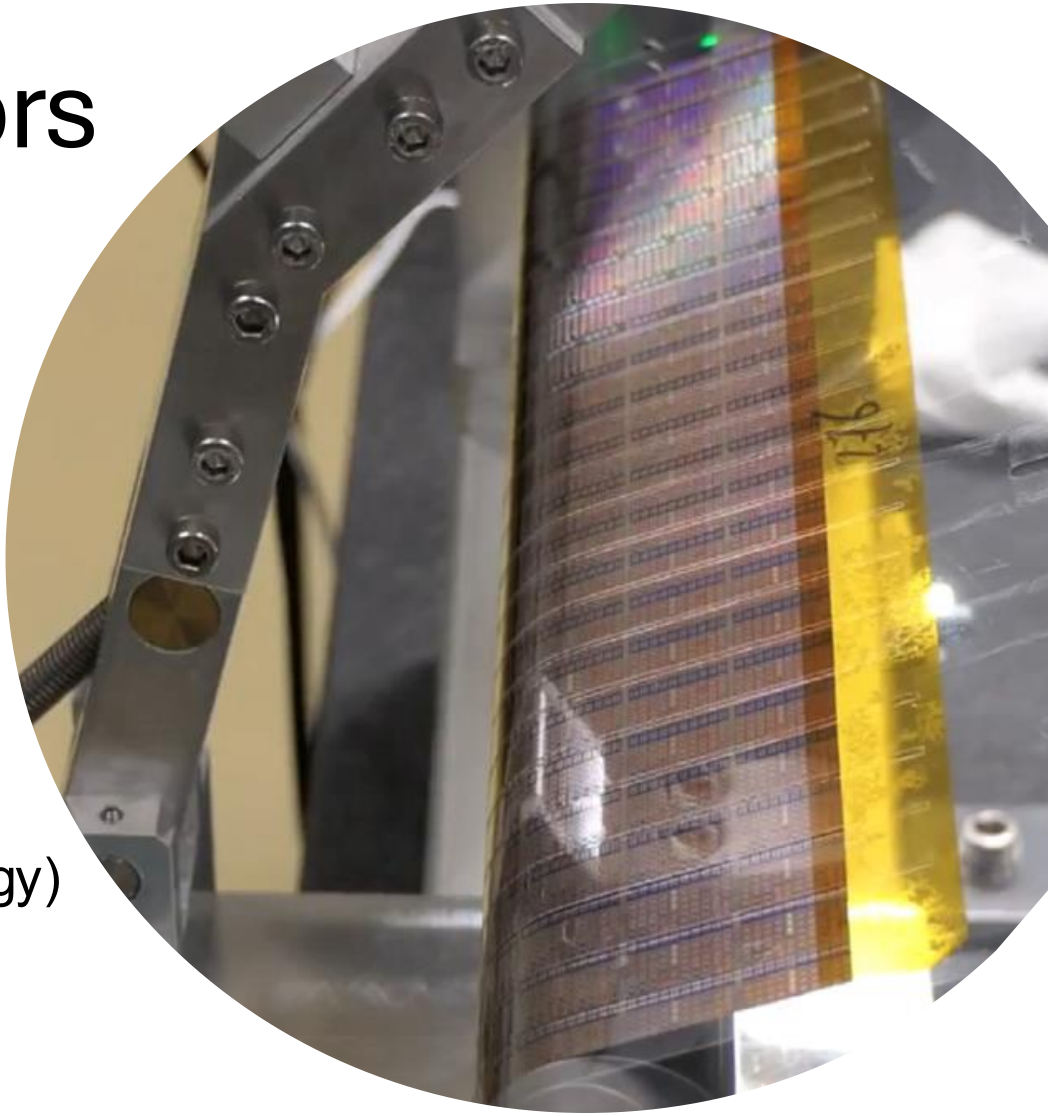


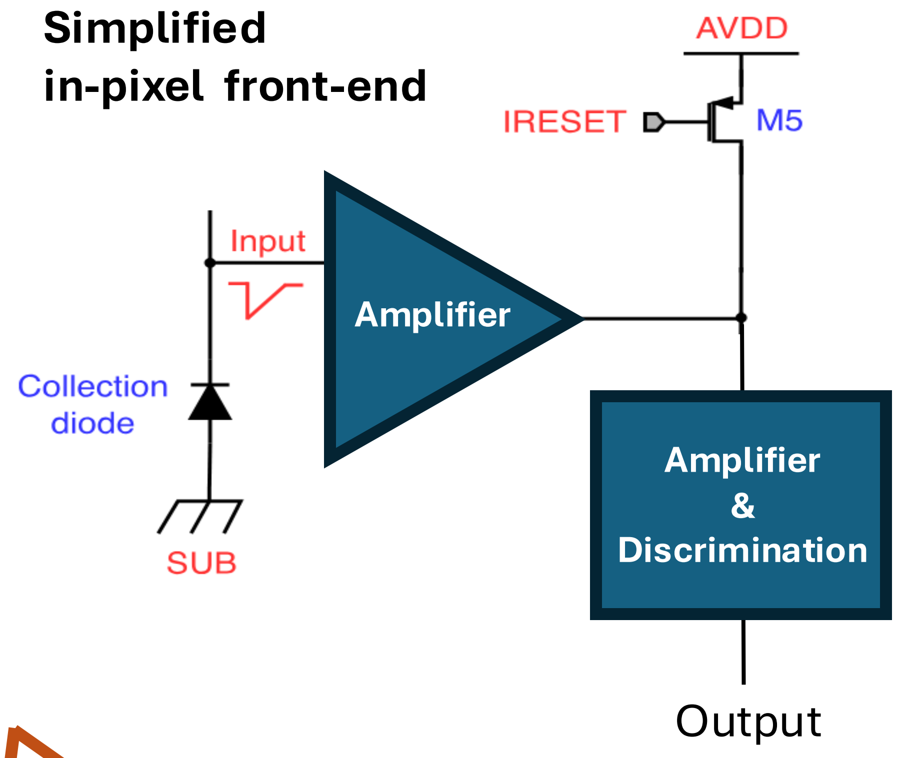
Nuclear Inst. and Methods in Physics Research, A 1064 (2024) 169447

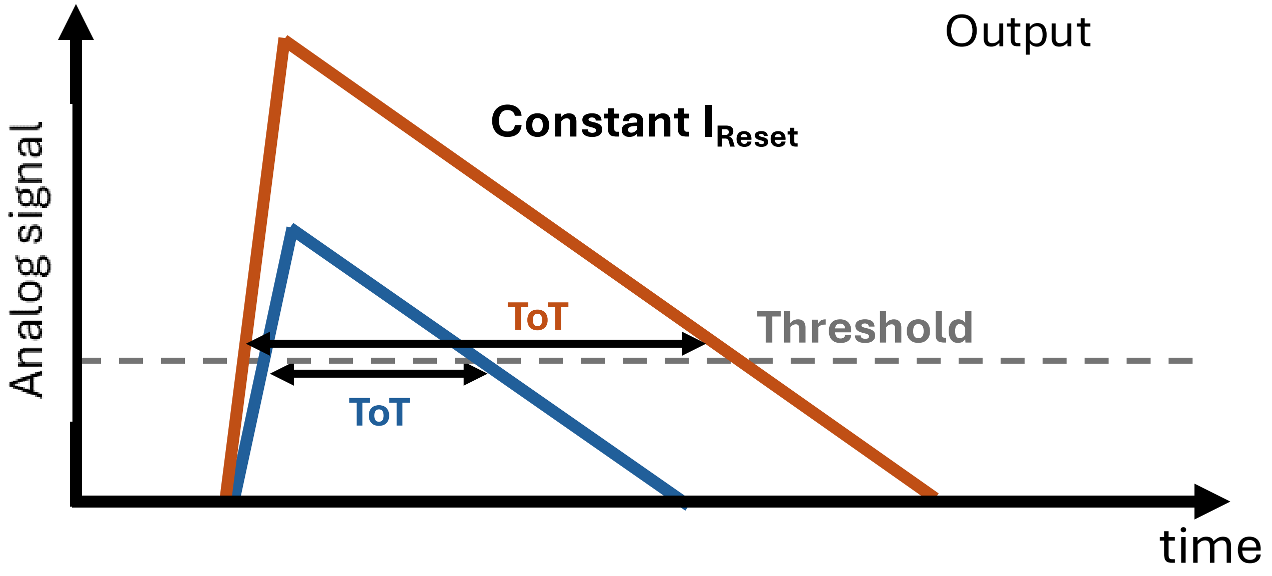
Amplitude Measurement

- Currently tracker only measuring binary hit information: 1 (hit) or 0 (no hit)

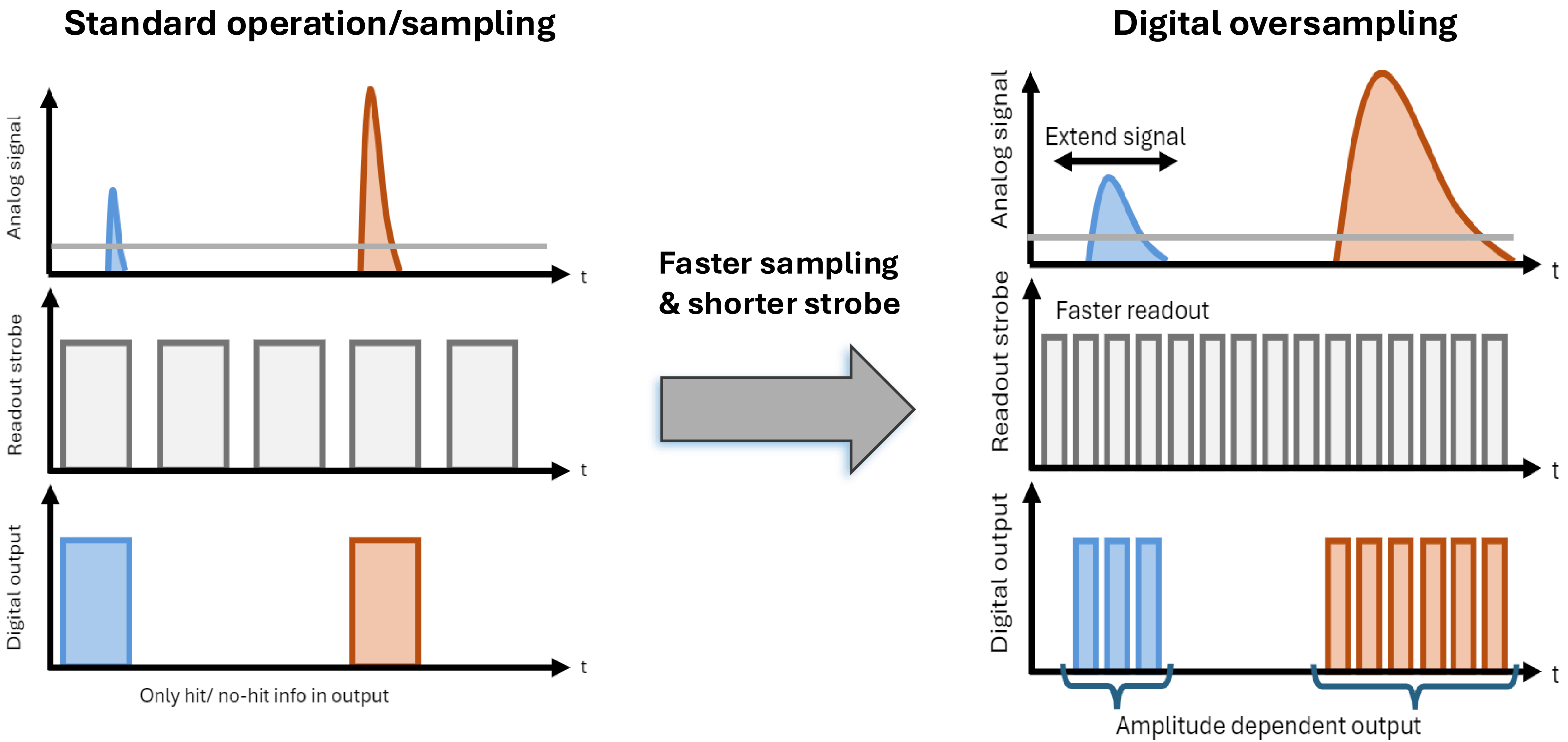
- *How can we gain information on the energy loss/amplitude of the signal?*

→ Use ToT (Time-over-Threshold), linearly dependent on signal height due to constant I_{Reset} applied in the in-pixel front-end





Digital Oversampling



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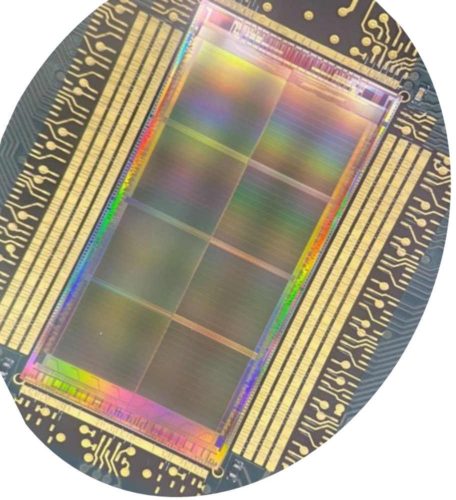
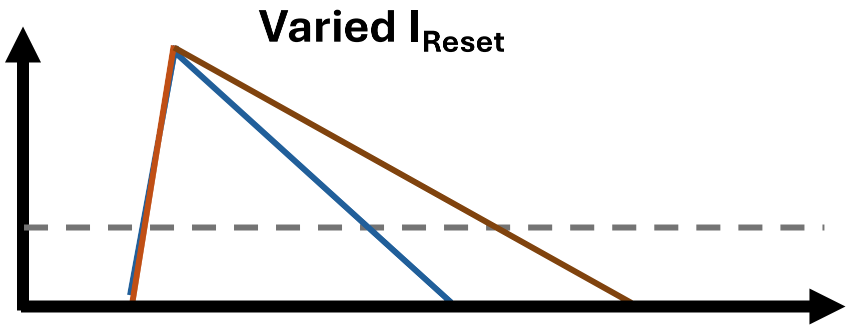
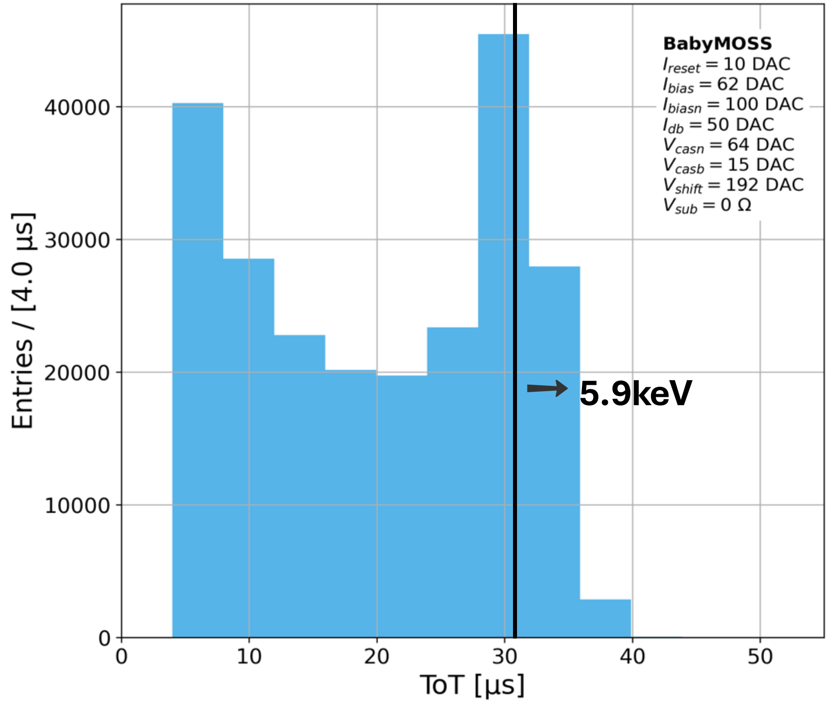


BabyMOSS

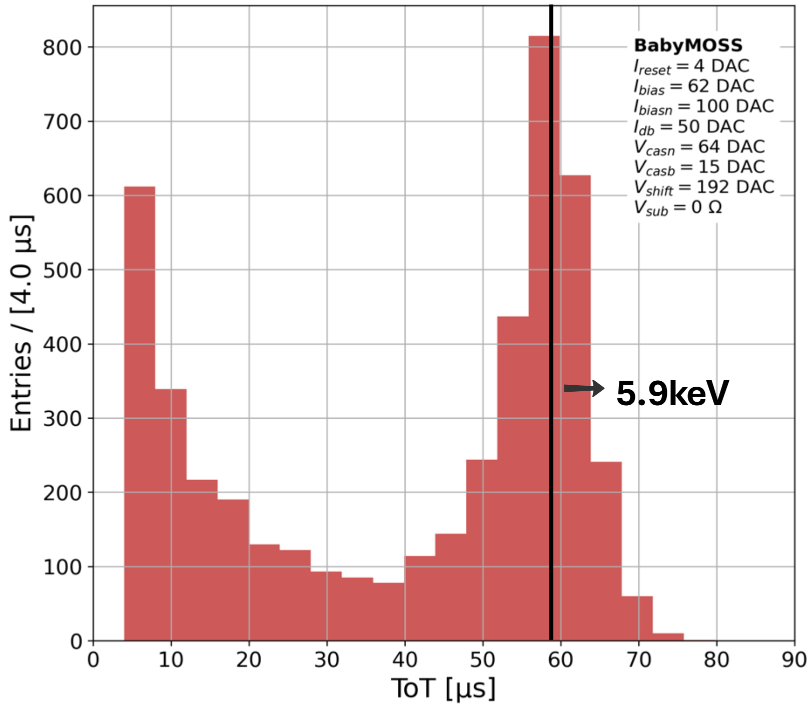


- Source measurements with an ^{55}Fe source
- Sampling period of 4 μs
- Main K_α peak can clearly be distinguished
- More pronounced by adjusting the settings and extending the signal length

Nominal settings (I_{Reset} = 10 a.u.)



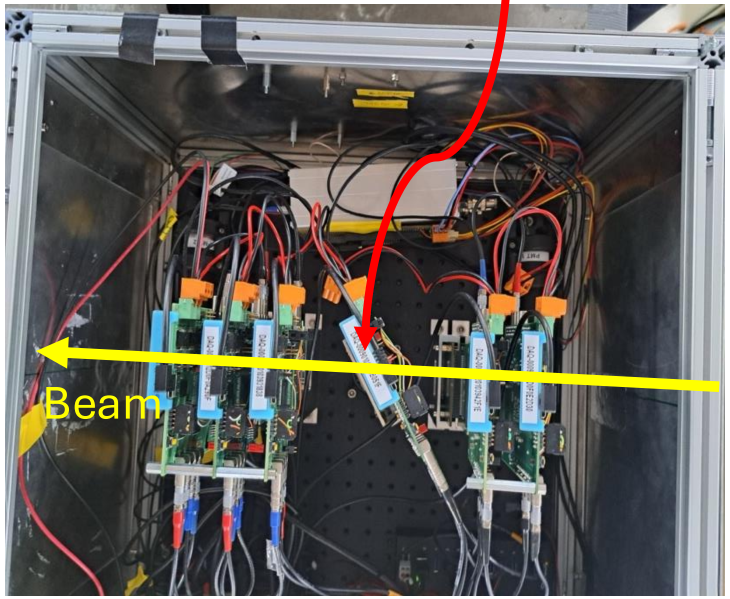
Lengthened signal (I_{Reset} = 4 a.u.)

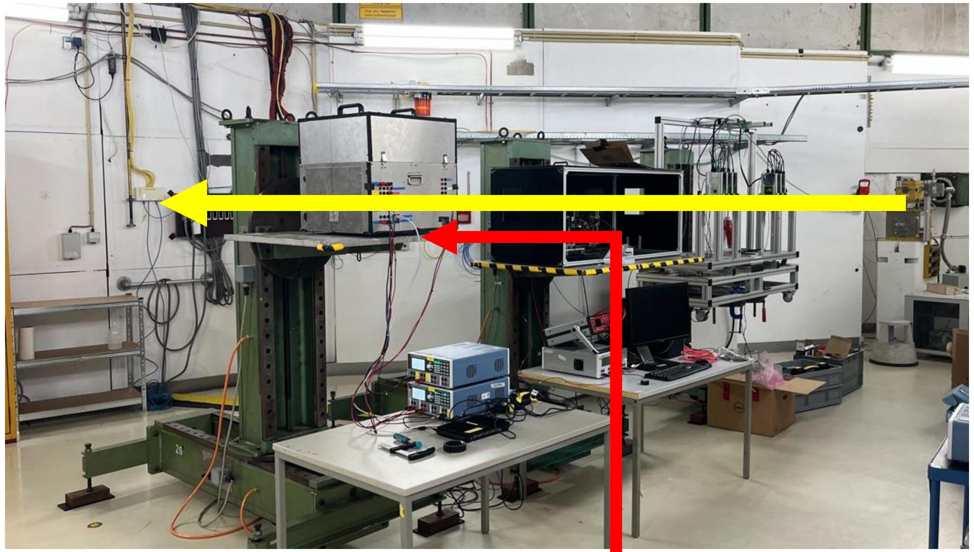


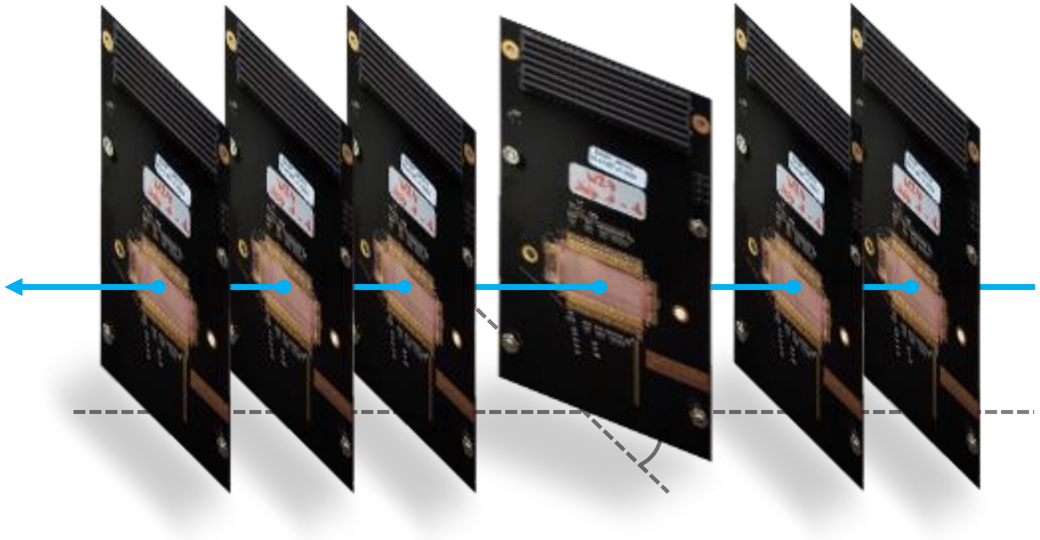
Testbeam at DESY

- We built and commissioned a beam telescope in collaboration with the HLL as part of the Origins Cluster Seed Project 2024-1
- BabyMOSS telescope operated with DUT:
  - Tilted BabyMOSS (general characterization and ToT)

BabyMOSS on rotating stage



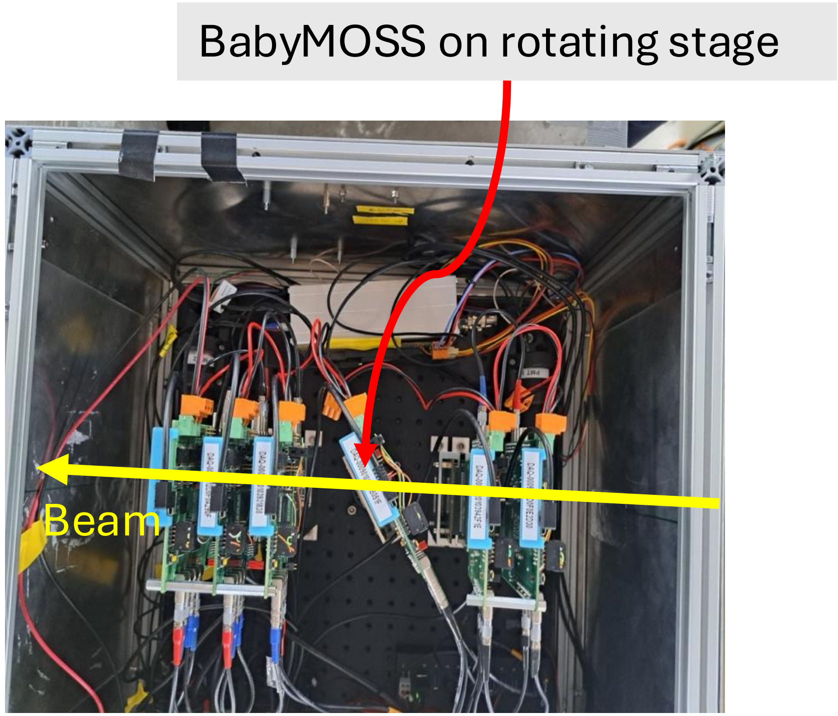


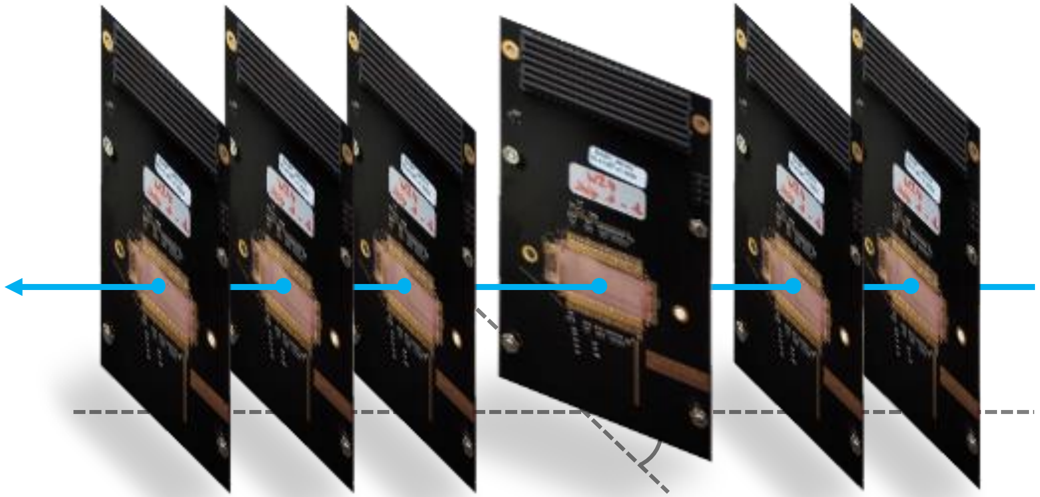


TUM Telescope Box

Testbeam at DESY

- Electron beam of 2.4 GeV/*c*
- Study ToT measurement using 'oversampling' method with BabyMOSS sensor
- Varied angles of DUT (Device Under Test) of 0°, 30°, 45°, and 60° to investigate the change of energy deposition

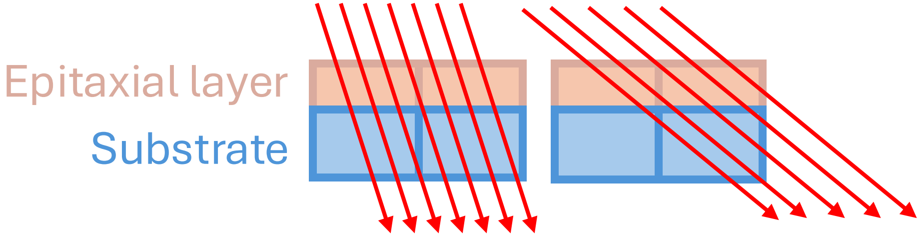


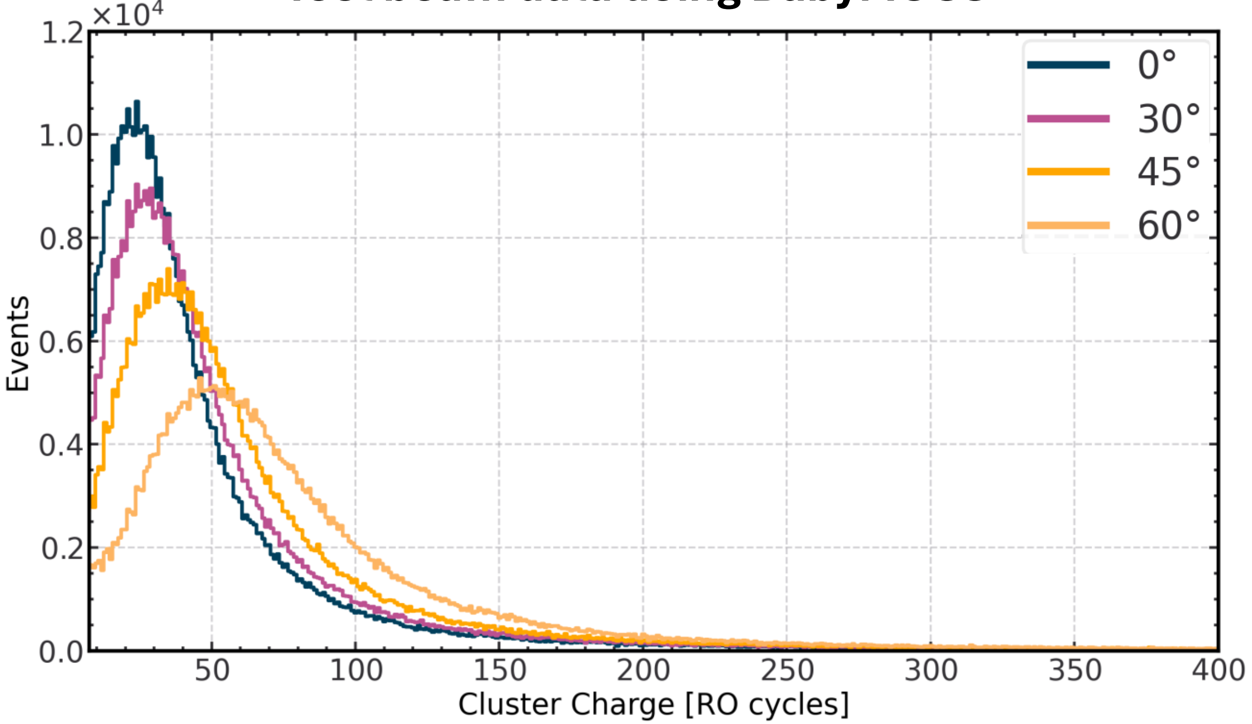


BabyMOSS telescope with inclined BabyMOSS as DUT

Testbeam at DESY

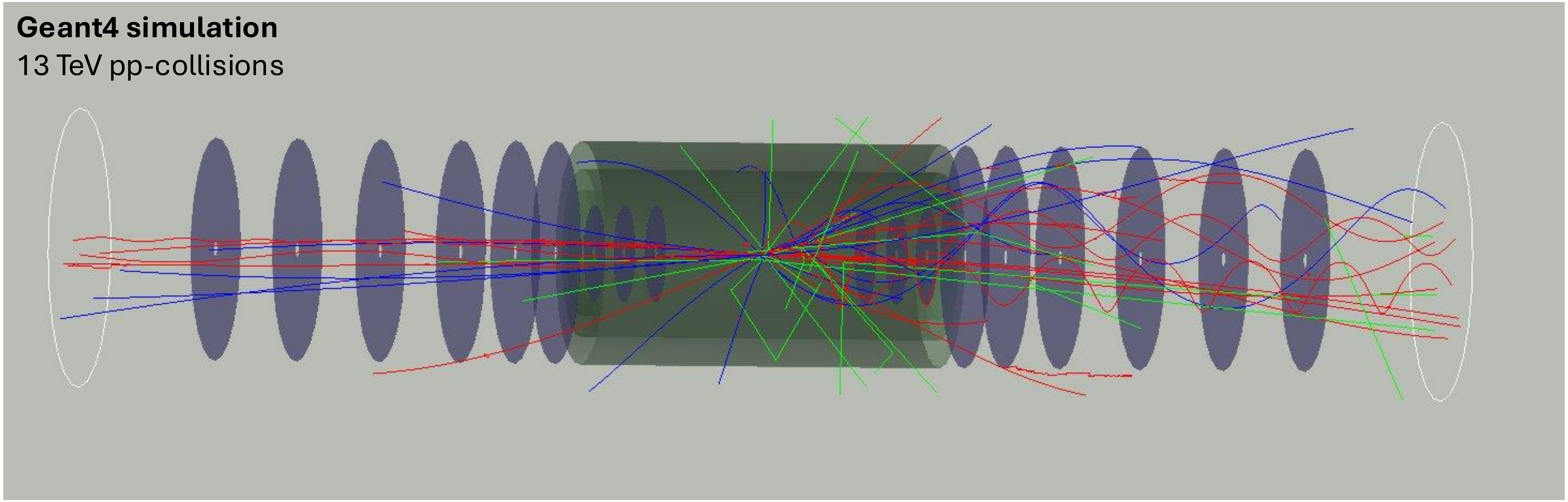
- Charge distribution (all clustersizes) for different angles
- Increase in deposited charge since the particles traverse more active volume





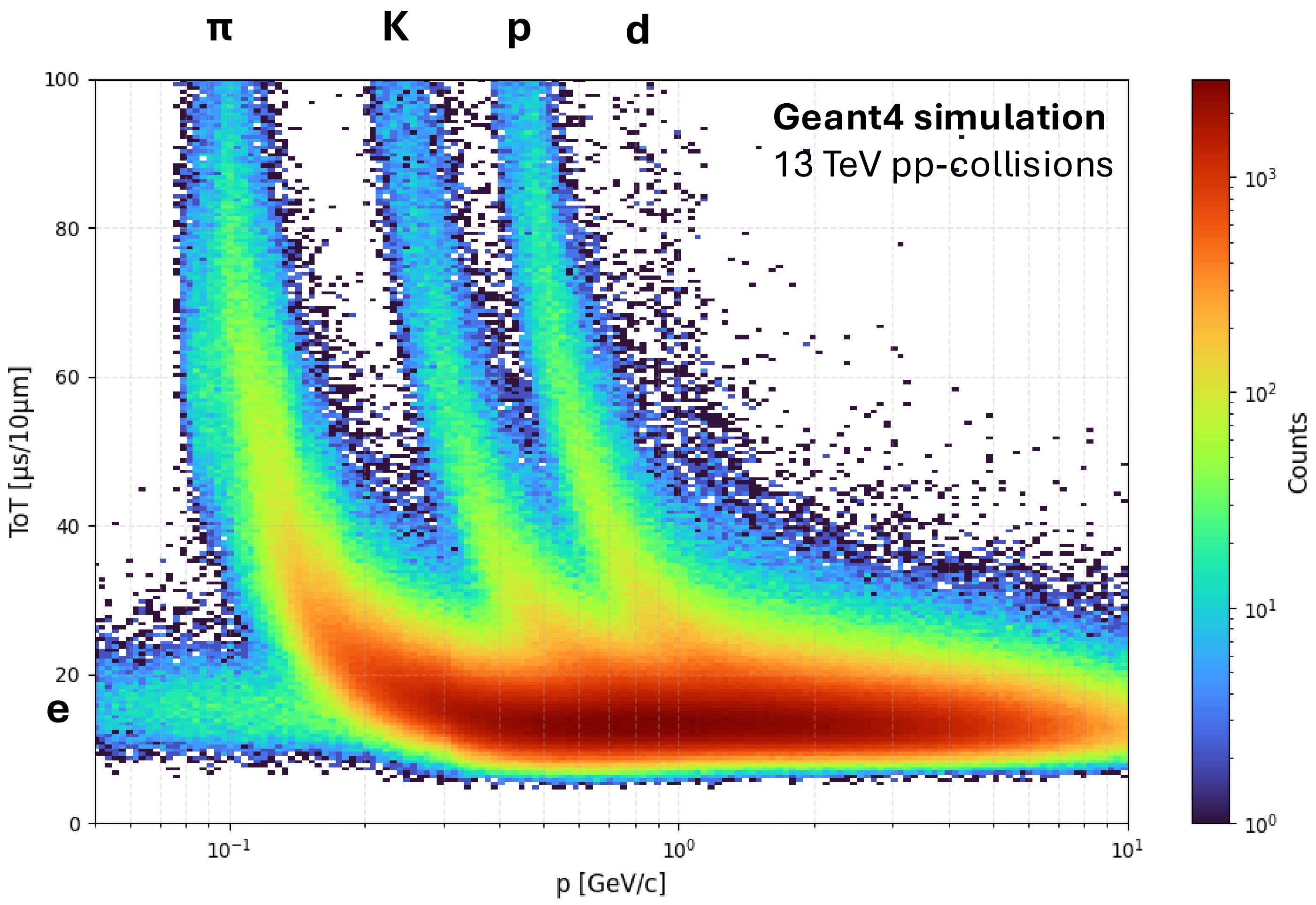
Example Use Case ALICE 3

- Implemented simplified ALICE 3 tracker geometry (LOI version) in Geant4 with magnetic field of 2 T
- Events were generated with Pythia (pp-collisions at 13 TeV) and used as input for Geant4



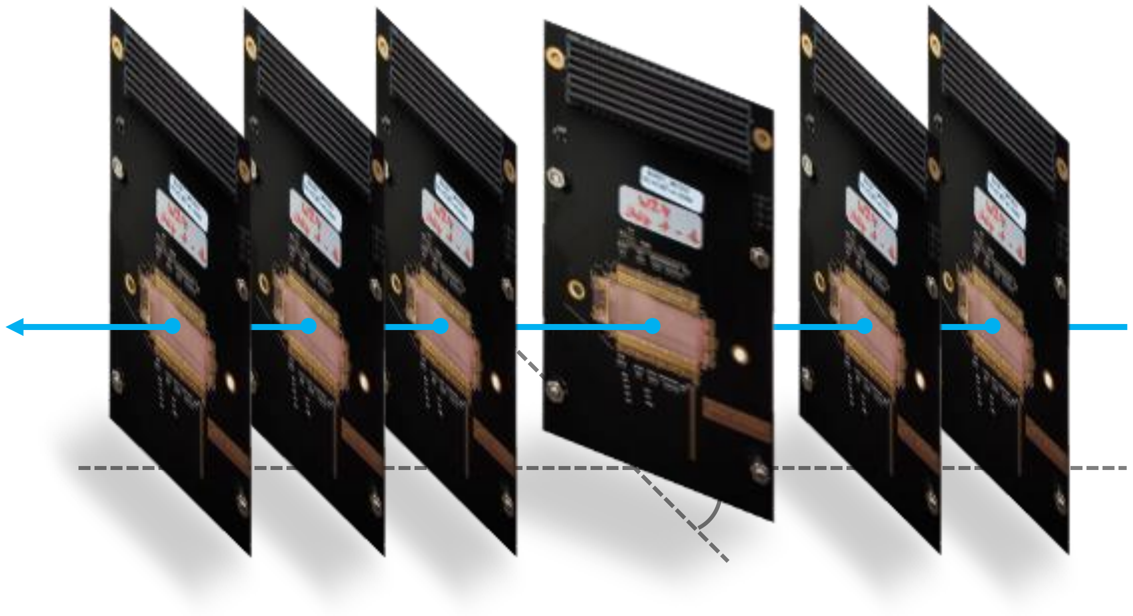
Example Use Case ALICE 3

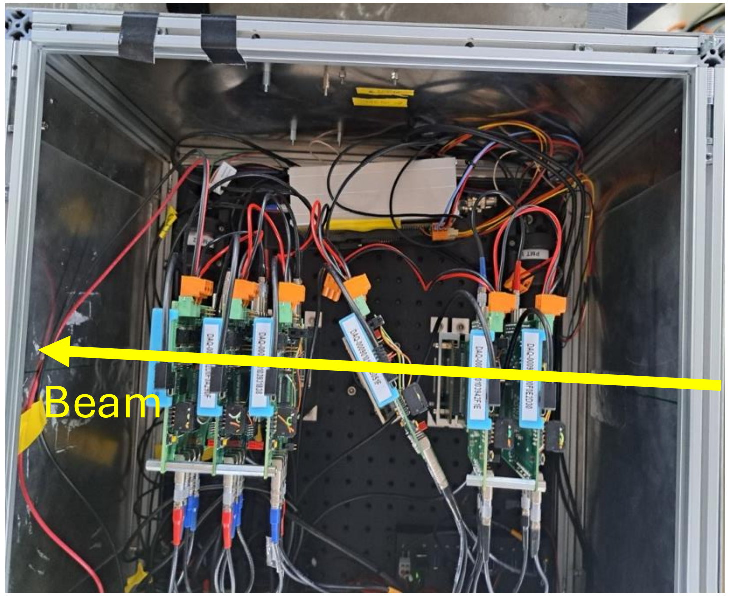
- Extract dE/dx information from Geant4 (energy deposition corrected by track length)
- Estimation of performance and separation power between particle pairs
  - Up to p ~ 0.9 GeV/c for kaon-proton pair
  - Up to p ~ 0.5 GeV/c for pion-kaon pair
  - Up to p ~ 0.15 GeV/c for electron-pion pair
- Significant separation expected for light nuclei at lower momenta



Summary & Outlook

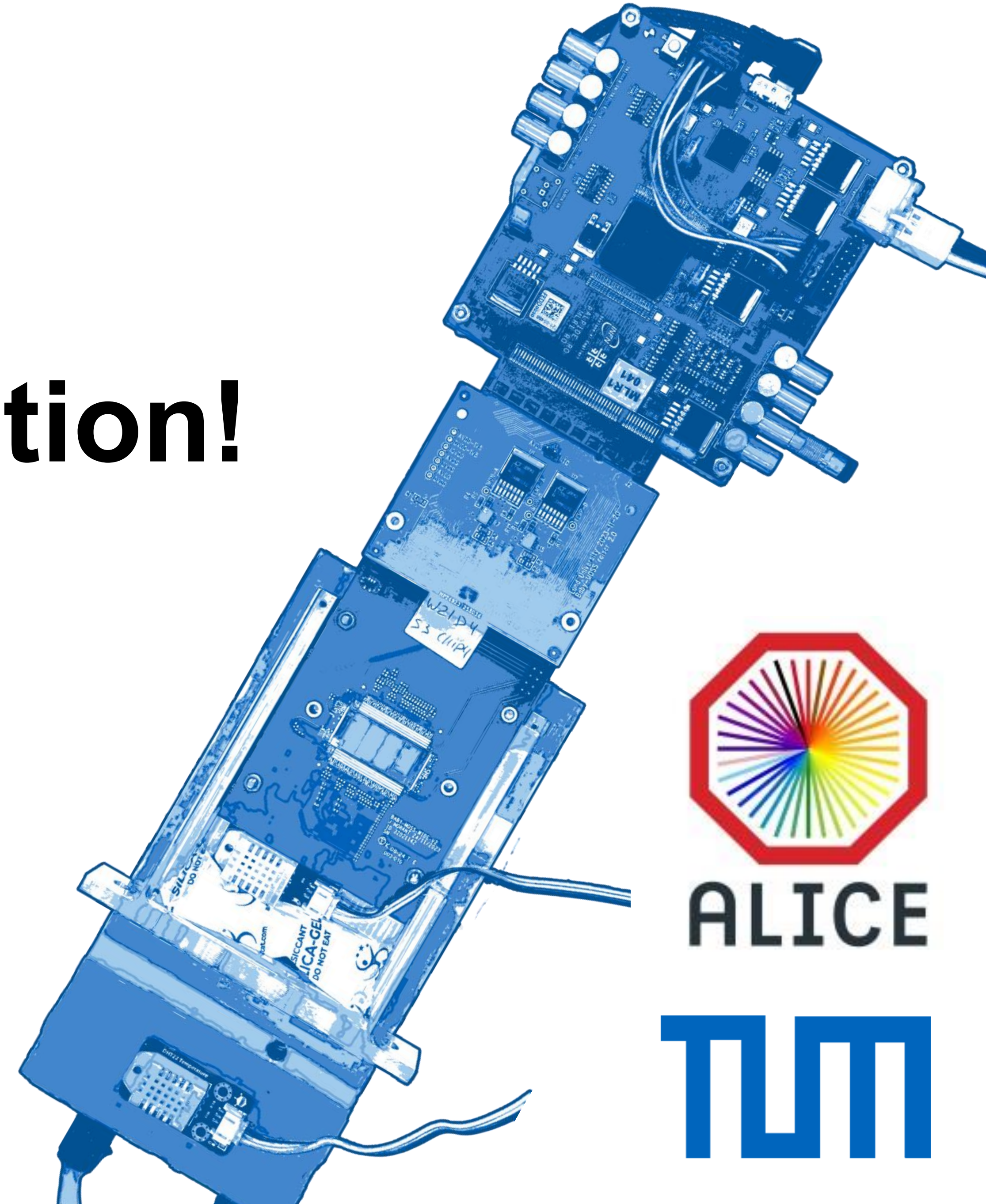
- The ToT-based approach looks like a promising method for the future of tracking detectors
- We have expertise in building and operating CMOS MAPS beam telescopes at TUM
- Investigate additional advantages of using a ToT-based approach (increased spatial resolution, time-walk correction, improvement in tracking, etc.)
- Finalize the performance simulation and quantify how useful ToT is for PID, especially for light nuclei
    - See for example separation power for different detectors in the ALICE 3 scoping document





Thanks for your attention!

Any questions?

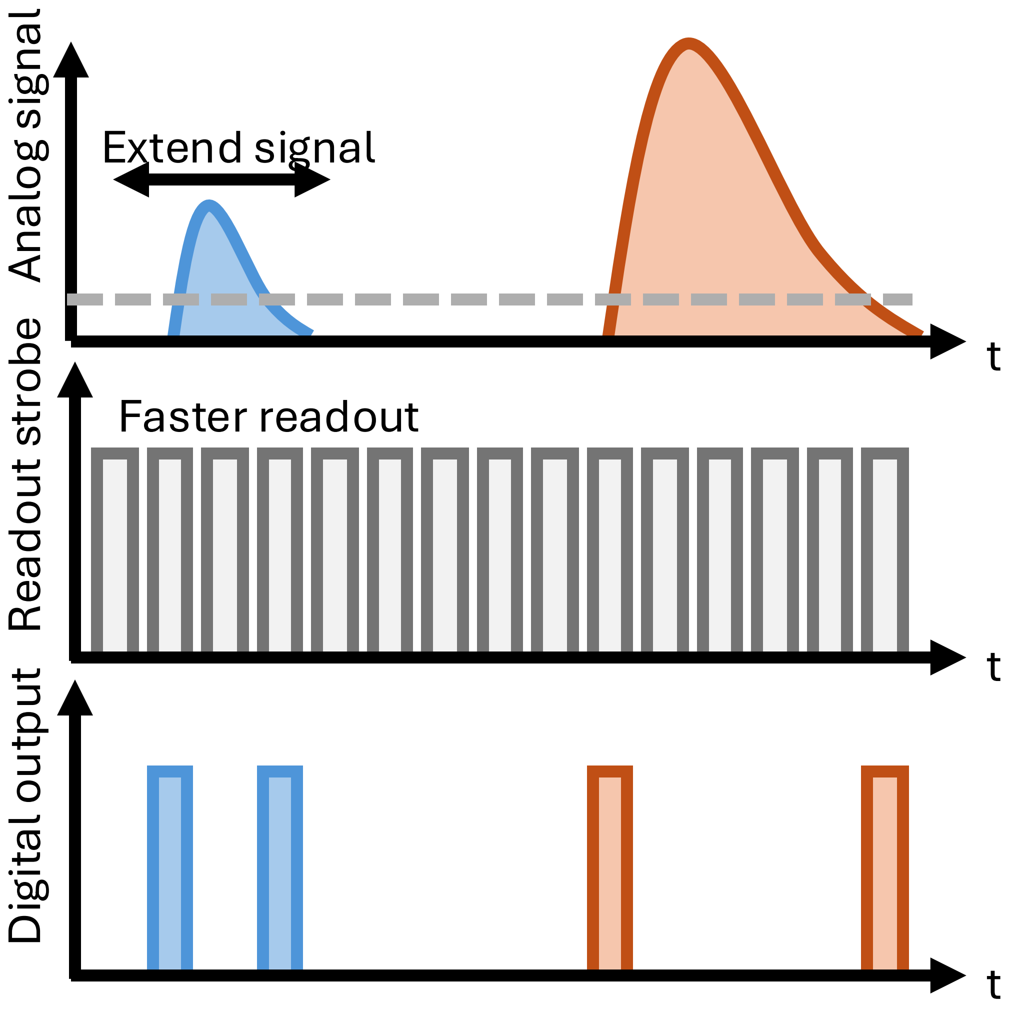


ALICE

Backup

Idea For Future Improvement

- Over-sampling increases the data rate substantially, factor O(30)
- Proposed implementation idea:
  - Send signal only at the edges using digital front-end sensitive to rising and falling edge
  - Data rate only doubled for as precise ToT measurement
- Similar approach utilized in DPTS and MOST sensors already
- Additional bit can be added to differentiate the two types of hits
  - Robustness in reconstruction



Amplitude dependent output by counting time gap

ALICE3

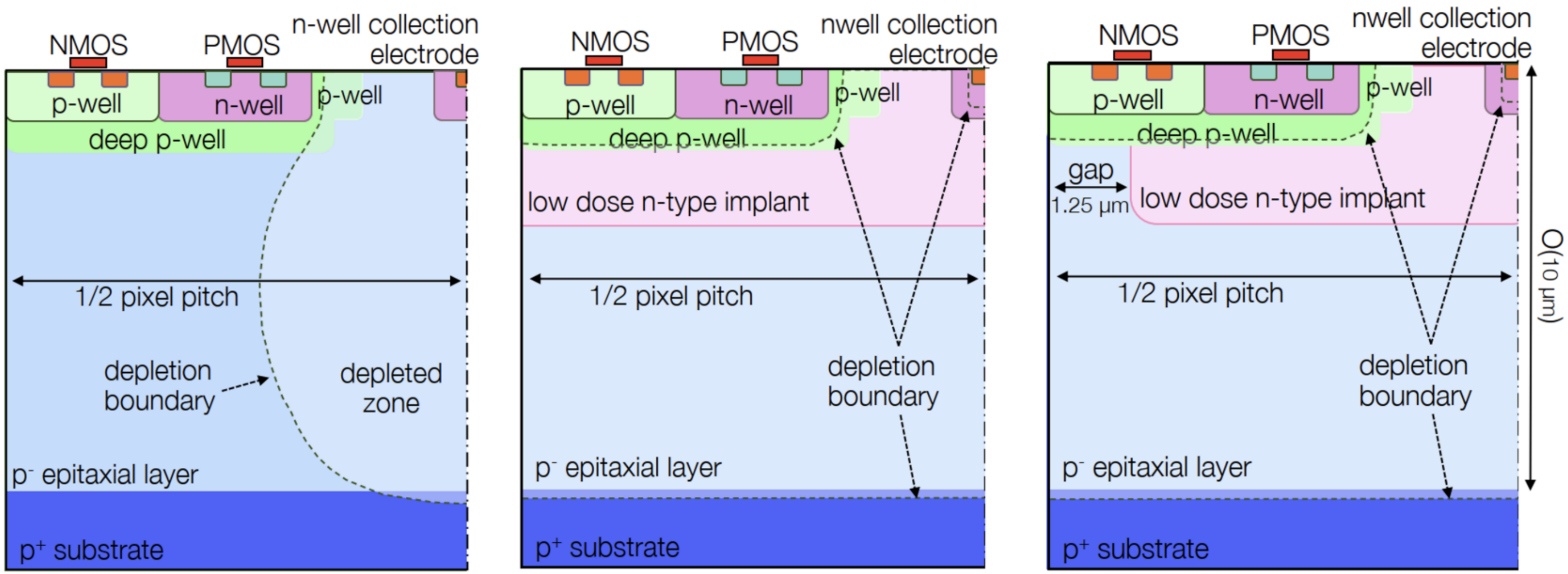
	ALICE ITS3	ALICE 3	
		Vertex Detector	Tracker (ML/OT)
Position resolution (µm)	5	2.5	10
Pixel size (µm^2)	*O*(20 x 20)	*O*(10 x 10)	*O*(50 x 50)
Time resolution (ns RMS)	O(1000)	100	100
In-pixel hit rate (Hz)	54	**120** ~~94~~	**54** ~~42~~ (barrel)
Fake-hit rate (/ pixel / event)		$<10^{-7}$	
Power consumption (mW / cm^2)	35	70	20
Particle hit density (MHz / cm^2)	8.5	**120** ~~94~~	**0.8** ~~0.6~~
Non-Ionising Energy Loss (1 MeV n_{eq} / cm^2)	3×10^{12}	1×10^{16}	6×10^{13}
Total Ionising Dose (Mrad)	0.3	300	3 (barrel)
X/X_0 / layer	0.09% (average) 0.07% (most of active region)	0.1%	1.0%

- A Pb-Pb interaction rate of the ~ 300 kHz corresponds to hit rates similar to 24 MHz pp

https://indico.cern.ch/event/1415726/contributions/6170003/attachments/2943674/5174703/2024-10-09_VertexDetectPixelSenor_freidt.pdf

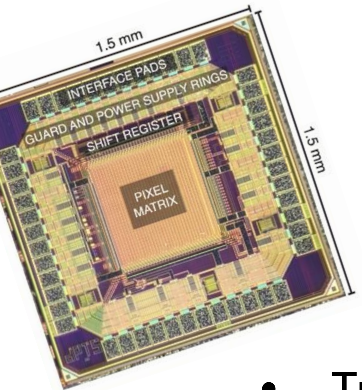
CMOS MAPS with 65 nm Technology

- State-of-the-art is the ALICE ITS3 upgrade which utilizes 65 nm CMOS technology (compared to previously 180 nm)
  - Lower power consumption, more complex in-pixel logic, supports wafer stitching (dependent on foundry)



Standard Modified Modified-with-gap

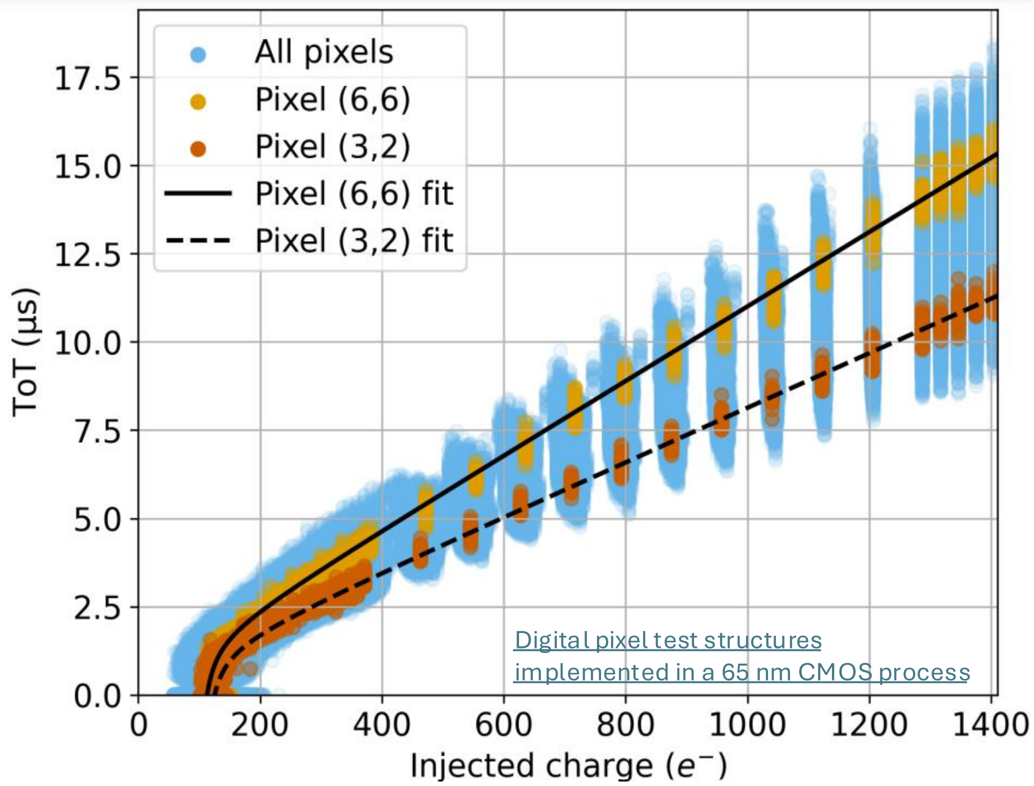
doi.org/10.48550/arXiv.2309.14814

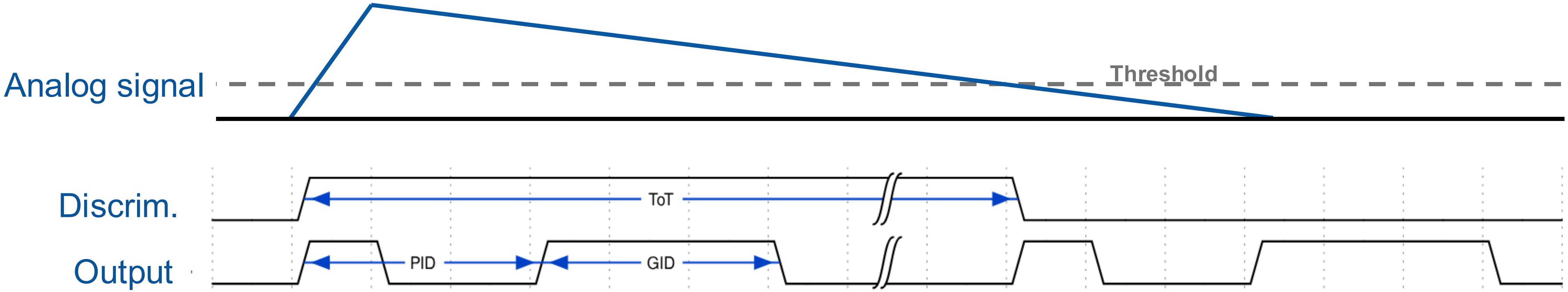


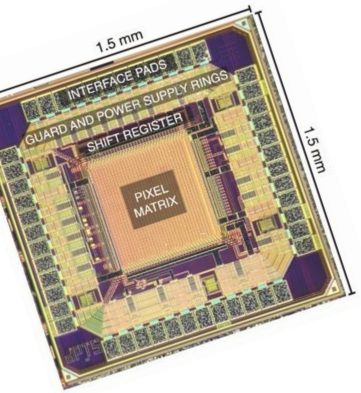
DPTS

- Train of signals is sent at both the rising and falling edge of the analog signal
  → Time-over-Threshold
- ToT proportional to collected charge due to constant I_{Reset}
- Pixel-to-pixel variations can be improved via calibration

ToT vs. Injected charge





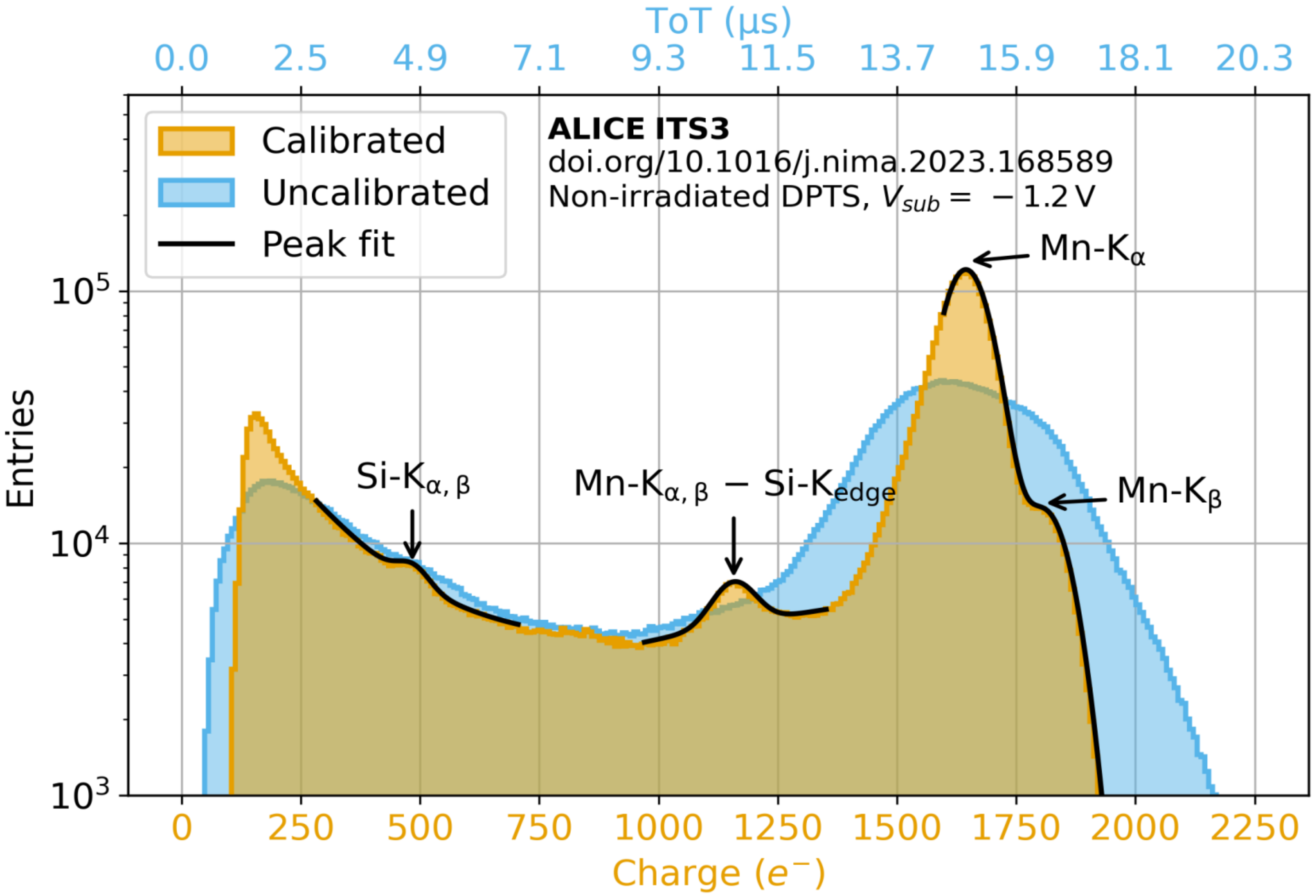


DPTS

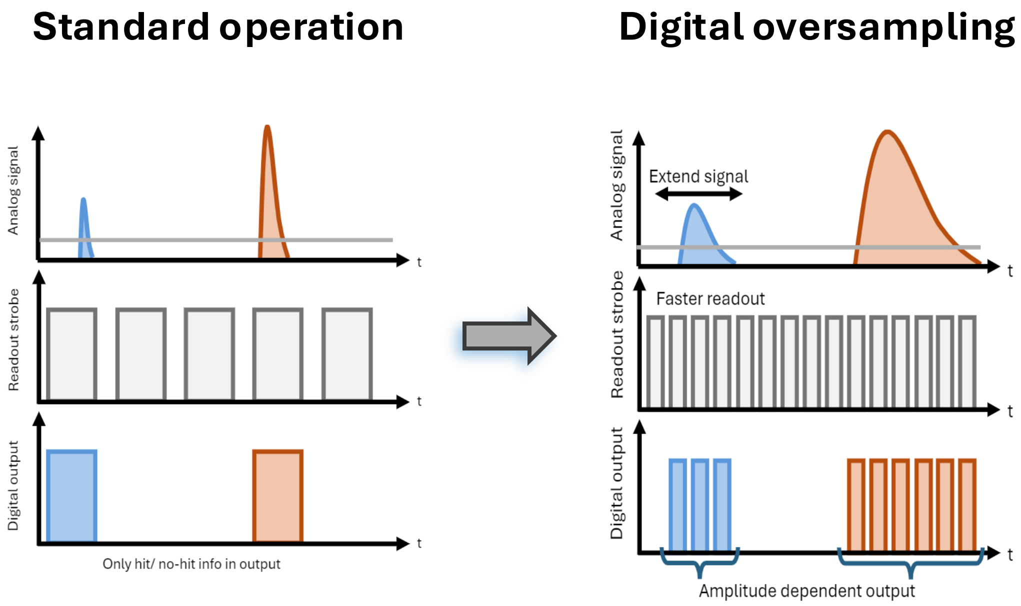
- Source measurements with an ^{55}Fe X-ray source
  - 5.90 keV Mn-K_α main peak
  - 6.49 keV Mn-K_β peak
- Energy resolution of the K_α peak:

$$\frac{\text{FWHM}}{\mu} = 7.42\% \pm 0.01\%$$

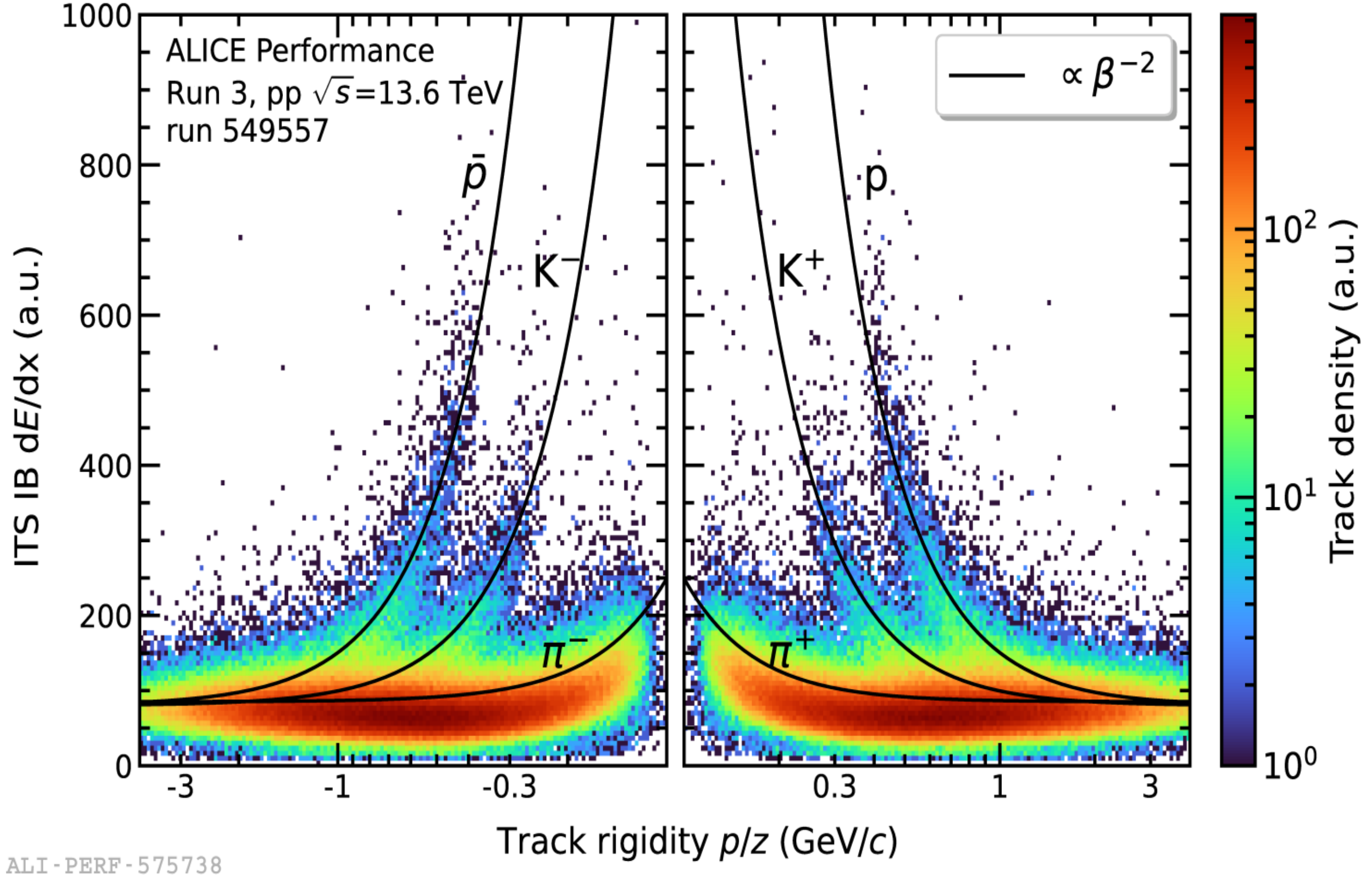
- Silicon fluorescence and escape peak can be distinguished



Digital Oversampling



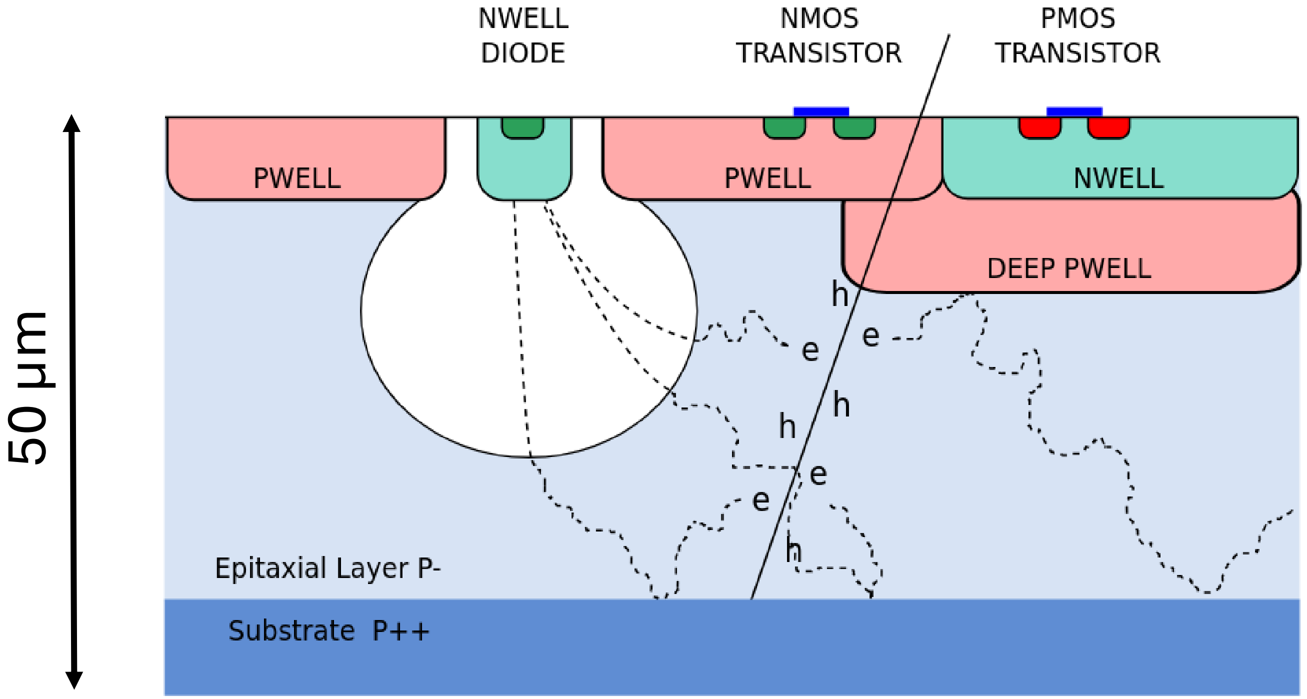
Example of ITS2 (ALPIDEs) oversampling at low interaction rate ~1kHz pp



[Andrea Sofia Triolo on behalf of the ALICE collaboration, Calibration and Performance of the Upgraded ALICE Inner Tracking System]

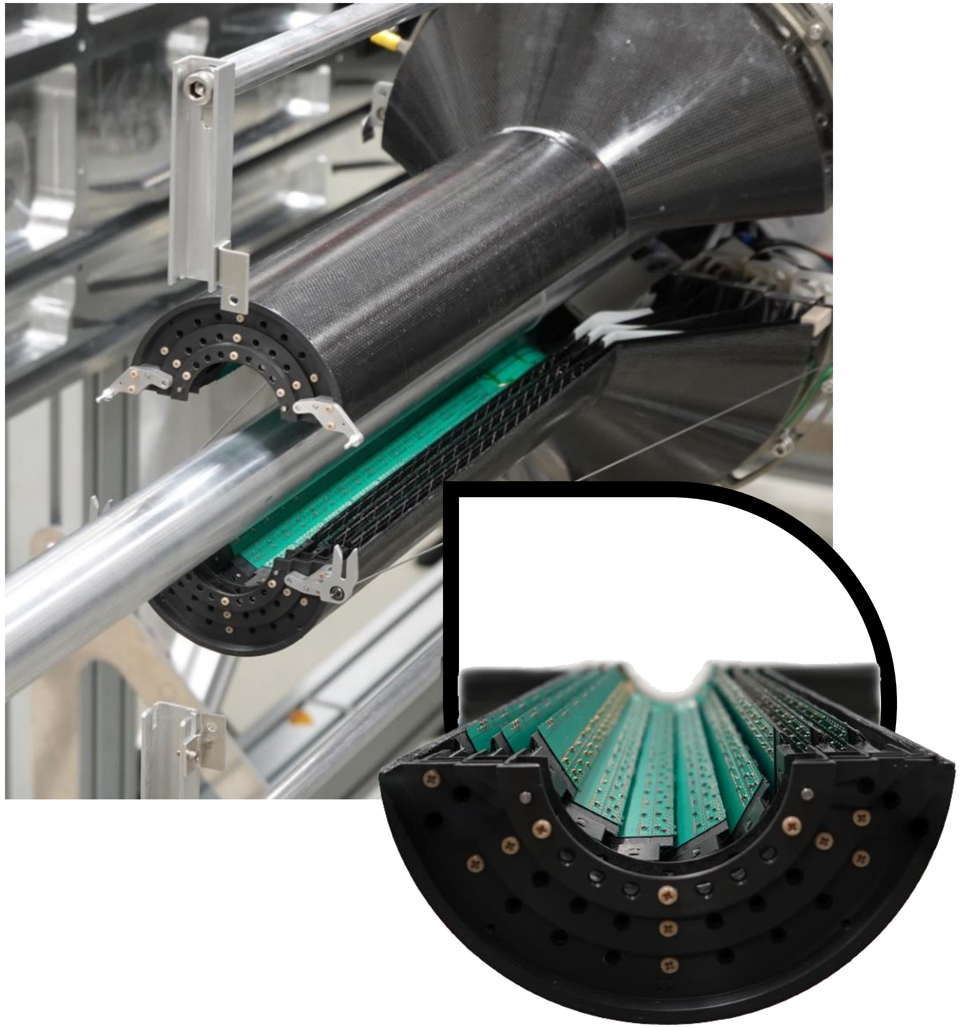
ALICE ITS Using CMOS MAPS

- Integrate the sensing diodes and the readout circuitry into the same pixel
- State-of-the-art is the ITS2 (Inner Tracking System) with an upcoming upgrade towards ITS3



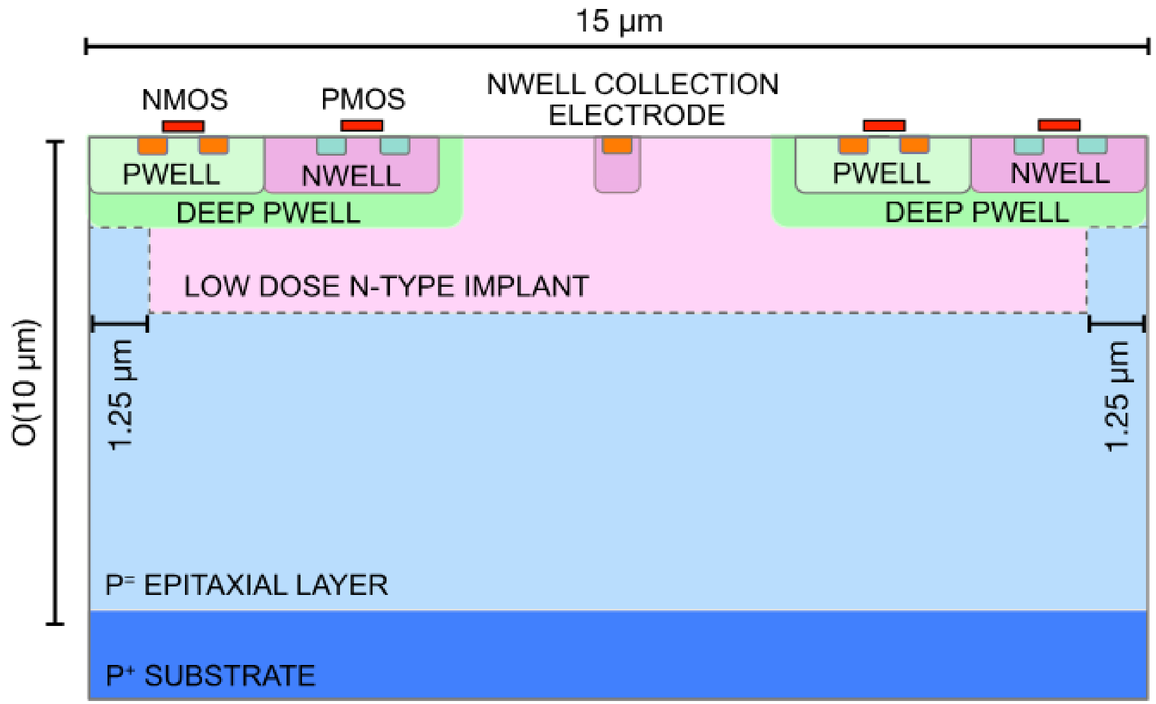
Technical Design Report for the Upgrade of the ALICE Inner Tracking System

ITS2 Inner Barrel



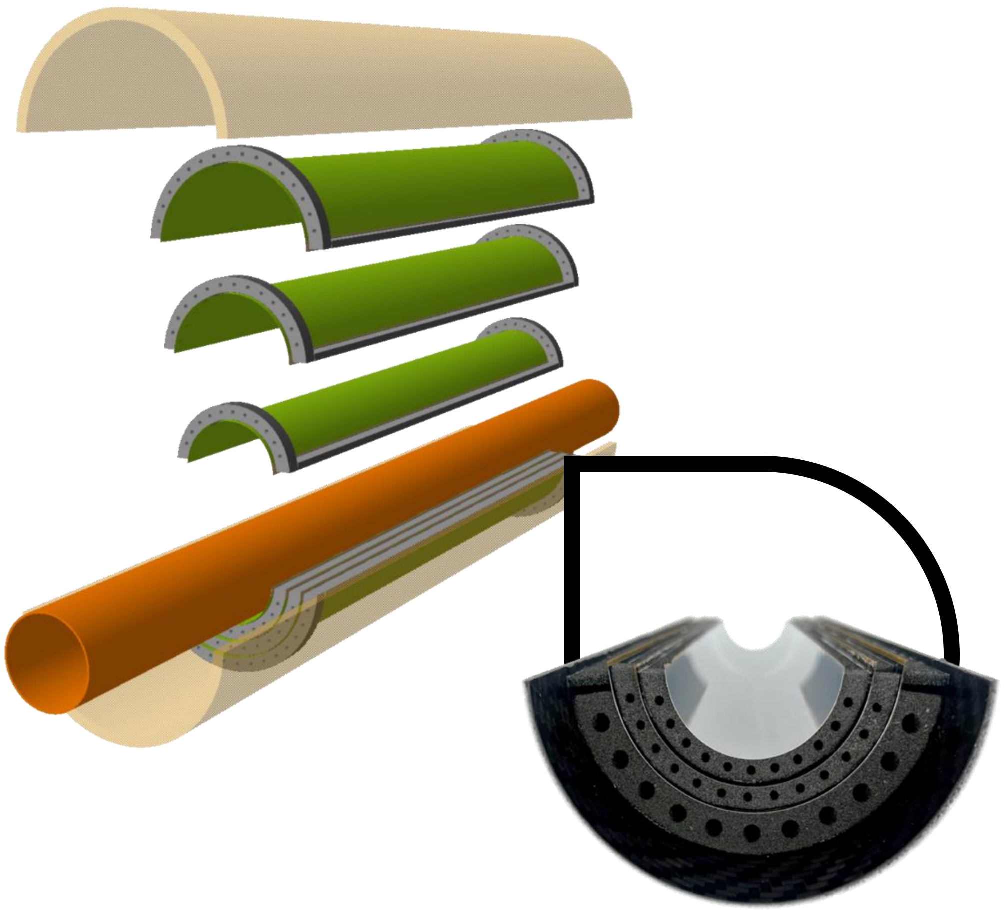
ALICE ITS Using CMOS MAPS

- Current ITS2 will be replaced by ITS3
- First bent wafer-scale detector using MAPS
- Various sensor prototypes were developed for testing and characterization of the improved technology



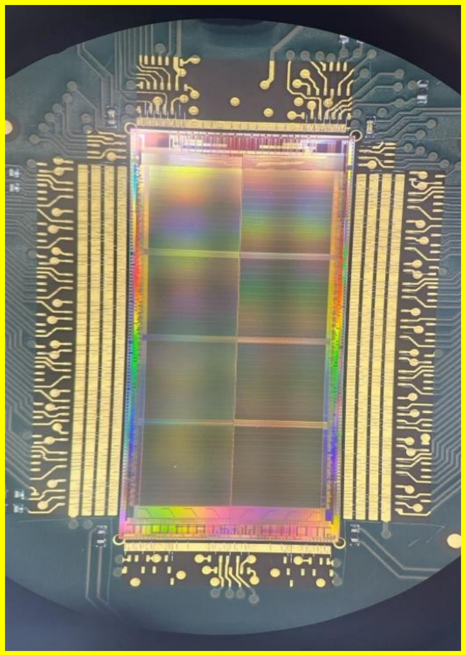
Digital pixel test structures implemented in a 65 nm CMOS process

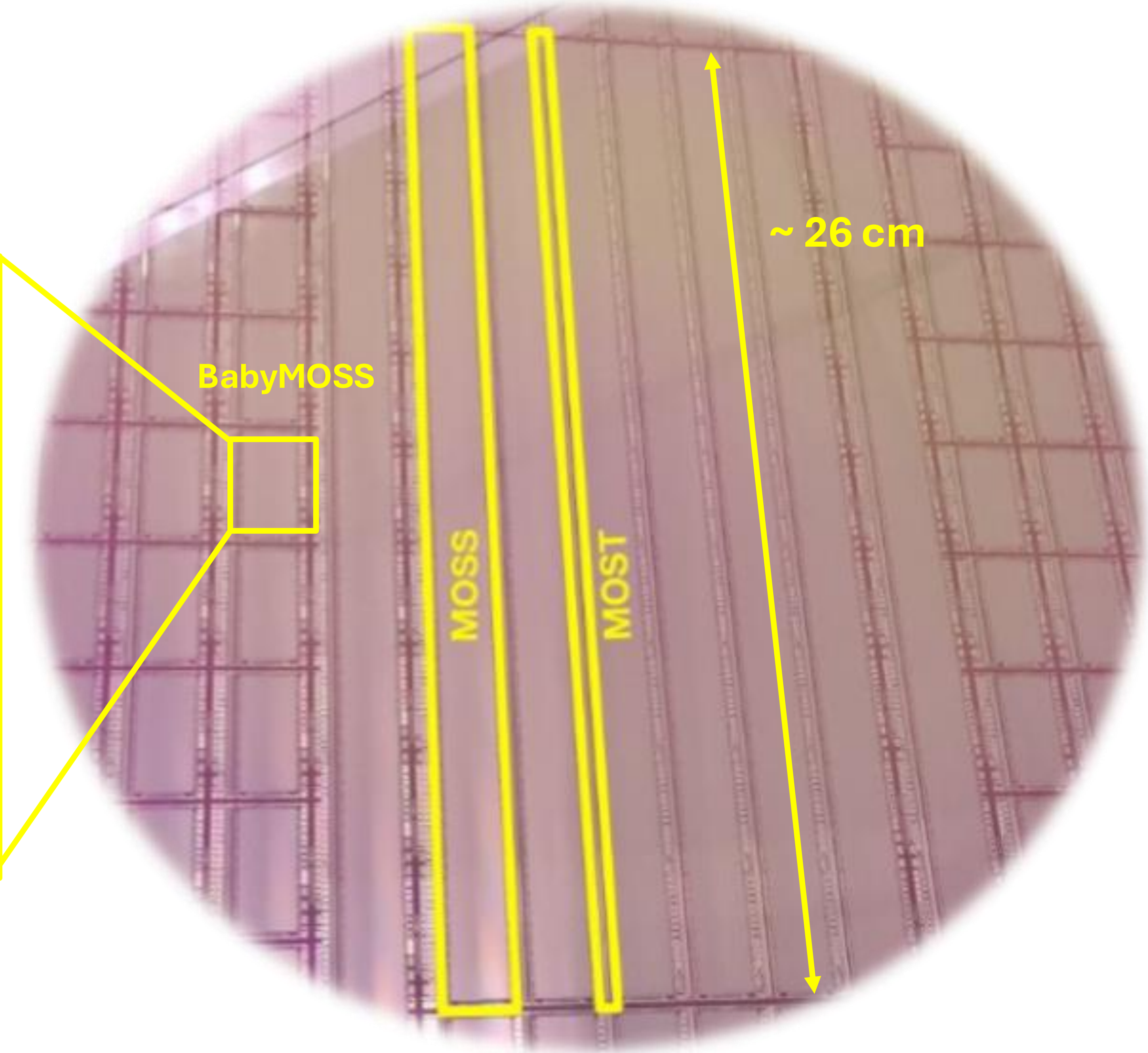
ALICE ITS3



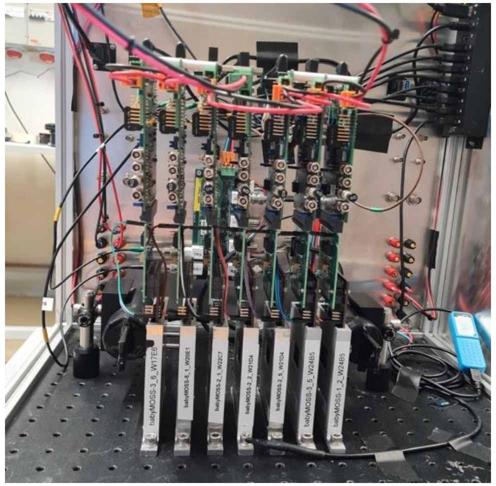
BabyMOSS

- **MO**nolithic **S**titched **S**ensor
- BabyMOSS is one RSU (Repeating Sensor Unit) with 0.67 megapixels
- Pixel matrix consists of 8 regions
  - Top half: 256x256 22.5 µm
  - Bottom half: 320x320 18 µm

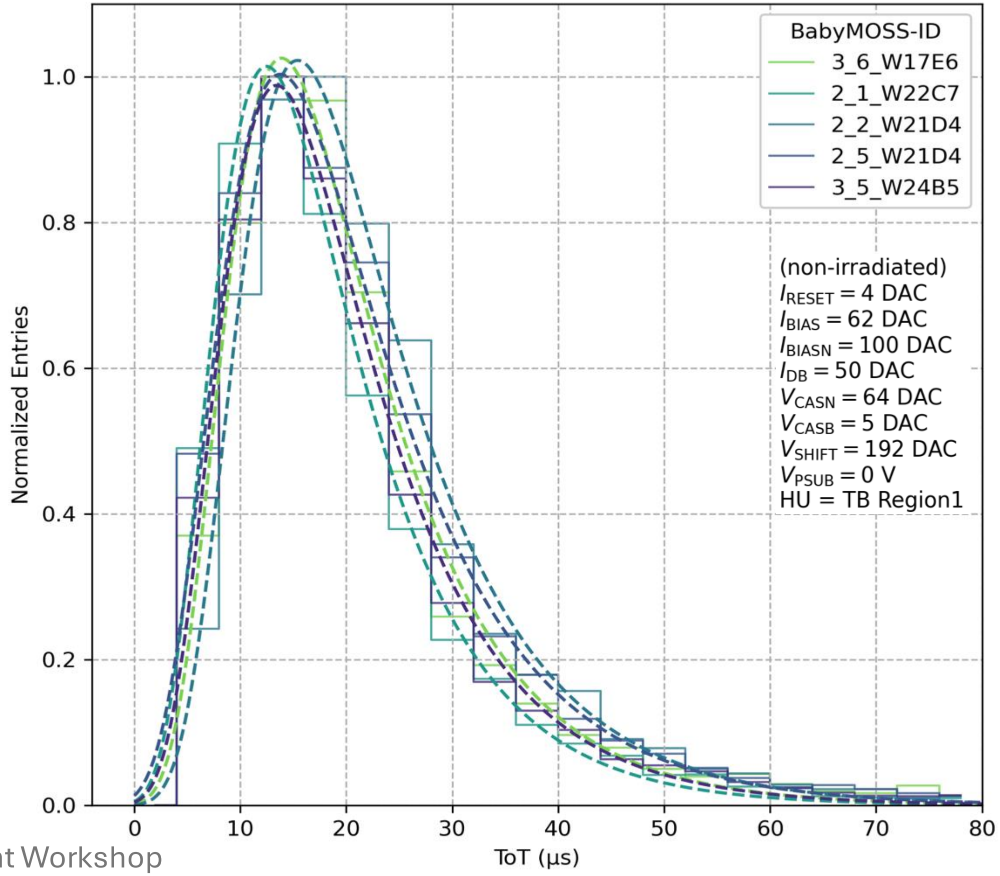




Test Beam Measurements



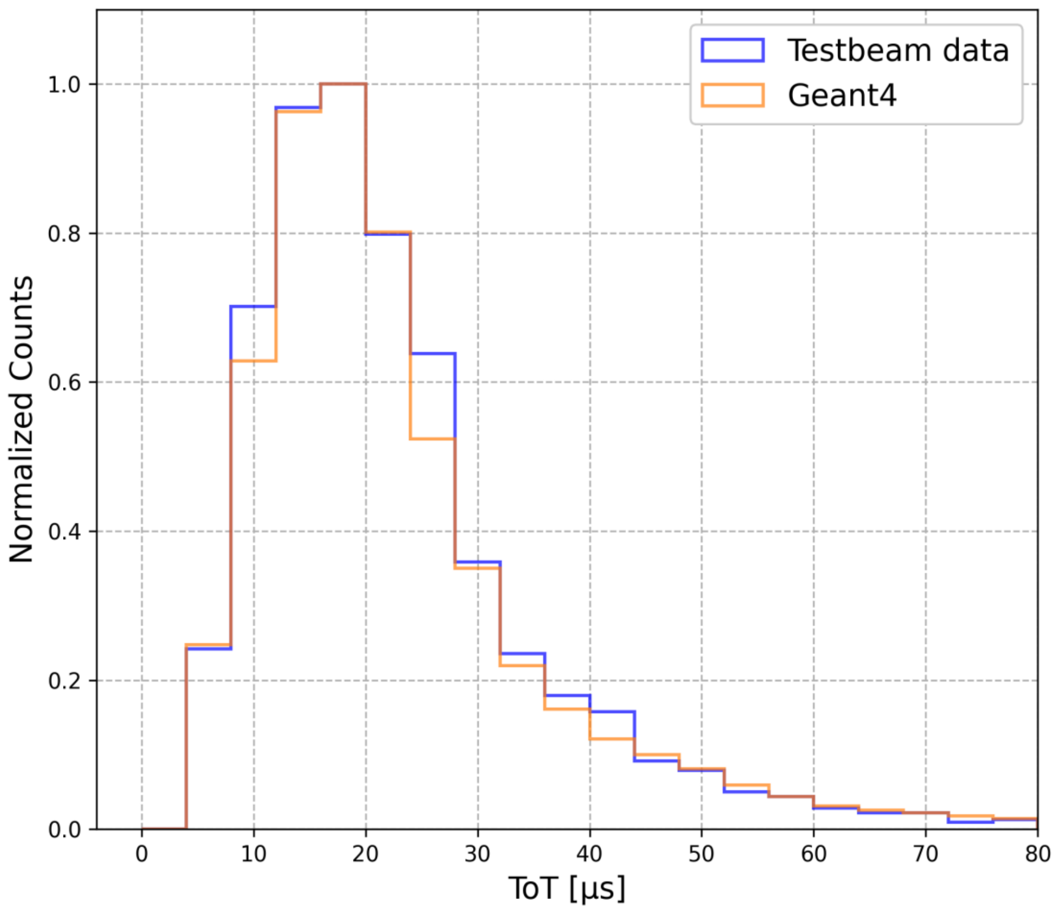
- Performed ToT measurements with 10 GeV/*c* pion beam at PS with 5 BabyMOSS
- The landau energy loss distribution can be observed
  - MPV within the expected energy range
- Different sensors behave similarly and consistently



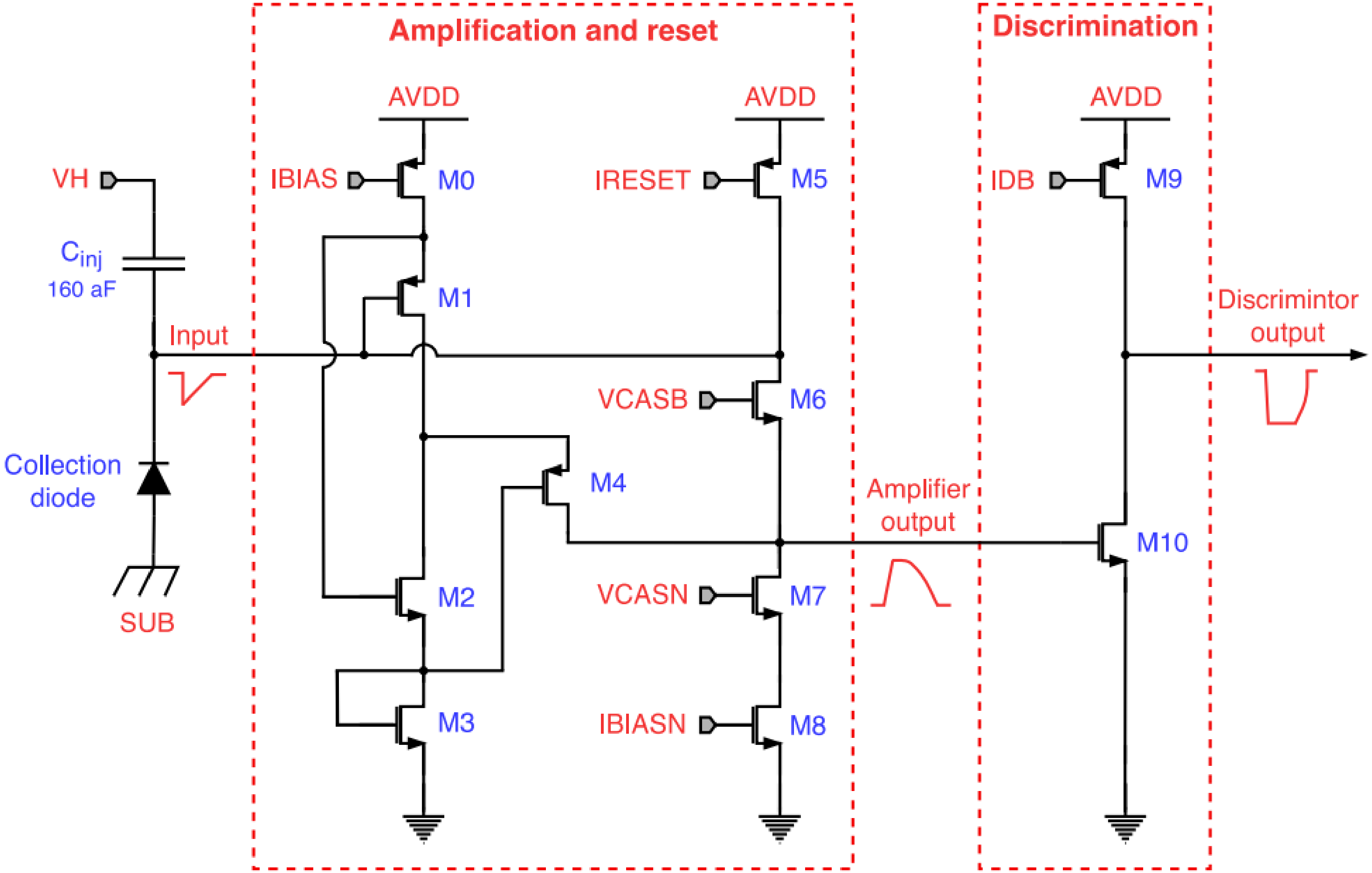
Geant4 Simulations

- Use Geant4 to assess impact of multiple silicon layers on PID & particle separation power
- Extract the energy deposition from Geant and sample in '4 μs'
  - Use BabyMOSS measurements to estimate ToT-to-energy conversion
- Set a threshold of approximately 200 electrons (setting used in test beam)

1 layer comparison: Test beam - Geant4



DPTS In-pixel Front-end



Digital pixel test structures implemented in a 65 nm CMOS process