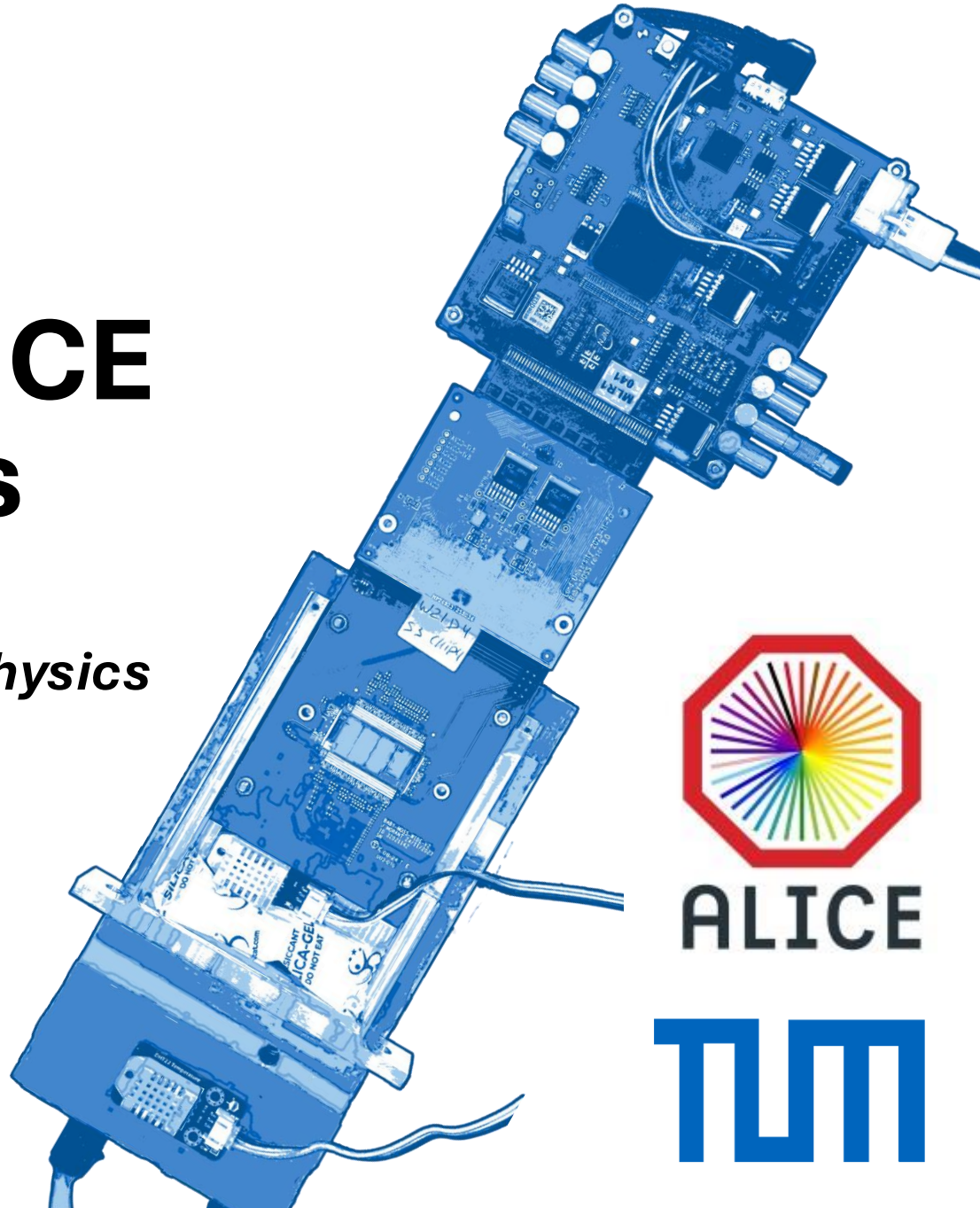
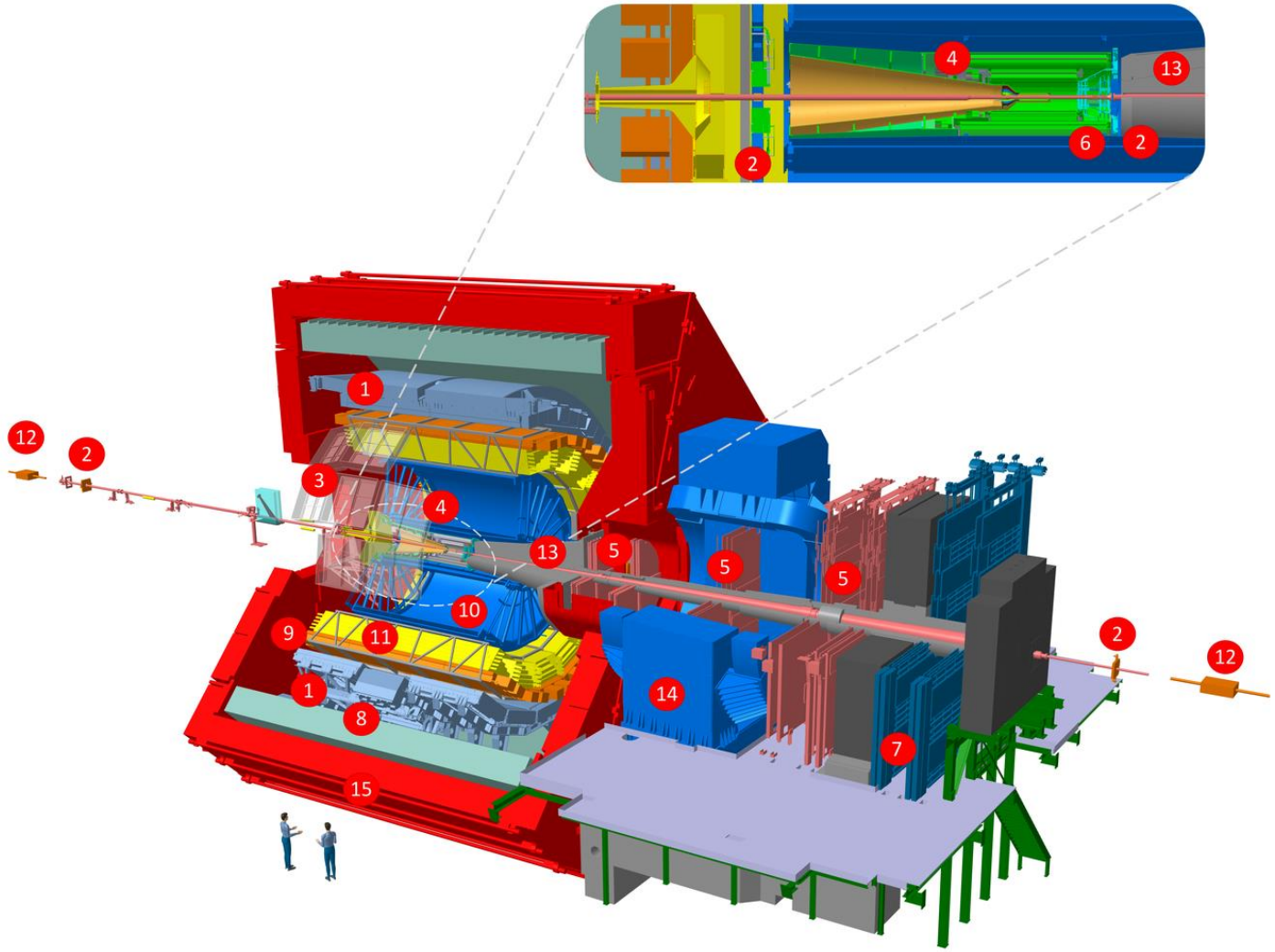
Exploring Amplitude Measurements with ALICE ITS3 MAPS Detectors



61st International Winter Meeting on Nuclear Physics
27 – 31 January 2025, Bormio

Henrik Fribert on behalf of the ALICE Collaboration

A **L**arge **I**on **C**ollider **E**xperiment

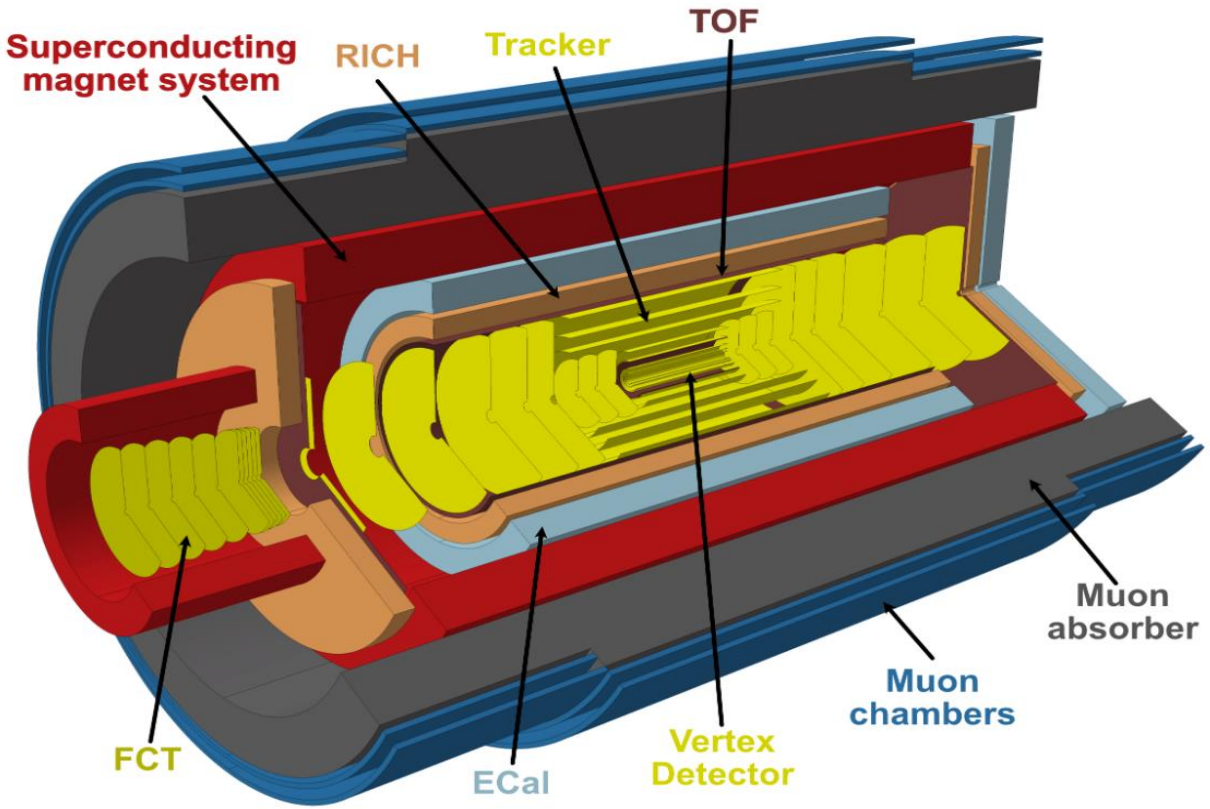


1. **EMCAL |** Electromagnetic Calorimeter
2. **FIT |** Fast Interaction Trigger
3. **HMPID|** High Momentum Particle Identification Detector
4. **ITS|** Inner Tracking System
5. **MCH|** Muon Tracking Chambers
6. **MFT|** Muon Forward Tracker
7. **MID|** Muon Identifier
8. **PHOS/CPV|** Photon Spectrometer
9. **TOF|** Time Of Flight
10. **TPC|** Time Projection Chamber
11. **TRD|** Transition Radiation Detector
12. **ZDC|** Zero Degree Calorimeter
13. **Absorber**
14. **Dipole Magnet**
15. **L3 Magnet**

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

ALICE 3

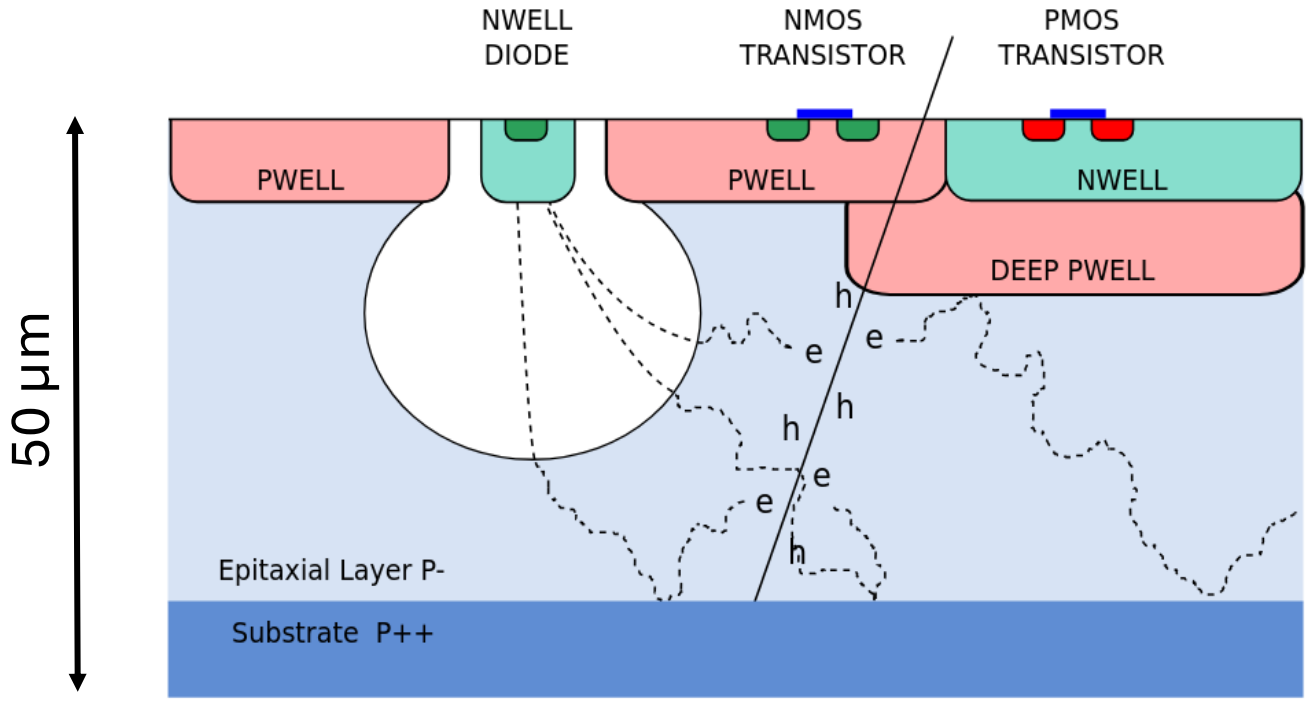
- ALICE3 is a planned new detector system based on large-area silicon detectors, starting data-taking in ~2035
  - Current pp-rate: 500 kHz / 1 MHz
  - ALICE3 pp-rate: 24 MHz
- Particles will be identified using TOF and RICH instead of a TPC
- Motivation to investigate additional energy loss measurement using trackers



ALICE3 LOI

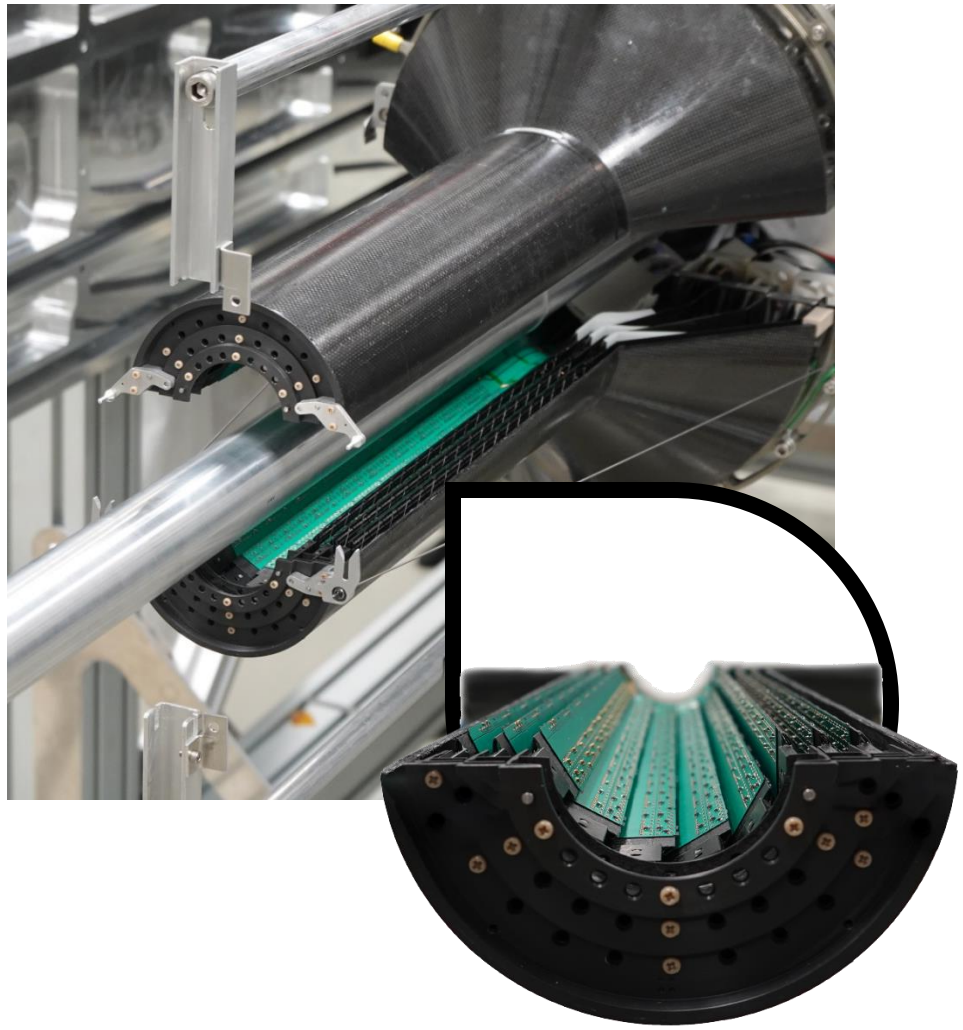
ALICE ITS Using CMOS MAPS

- 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



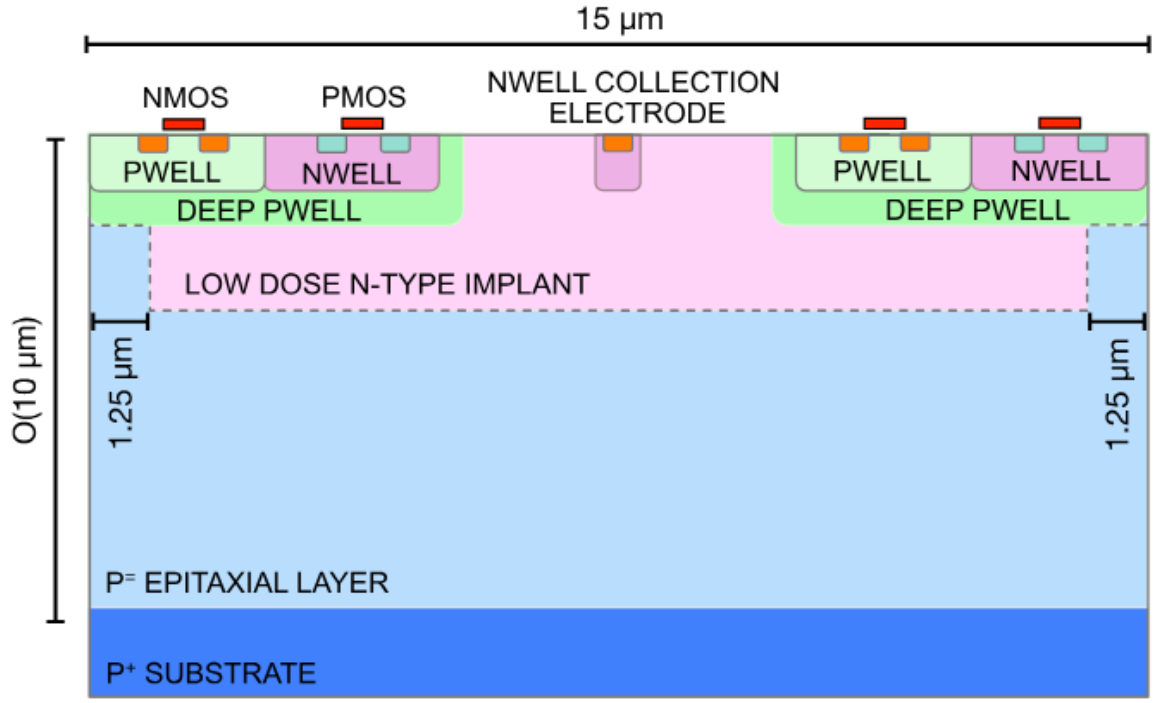
Technical Design Report for the Upgrade of the ALICE Inner Tracking System

ITS2 Inner Barrel



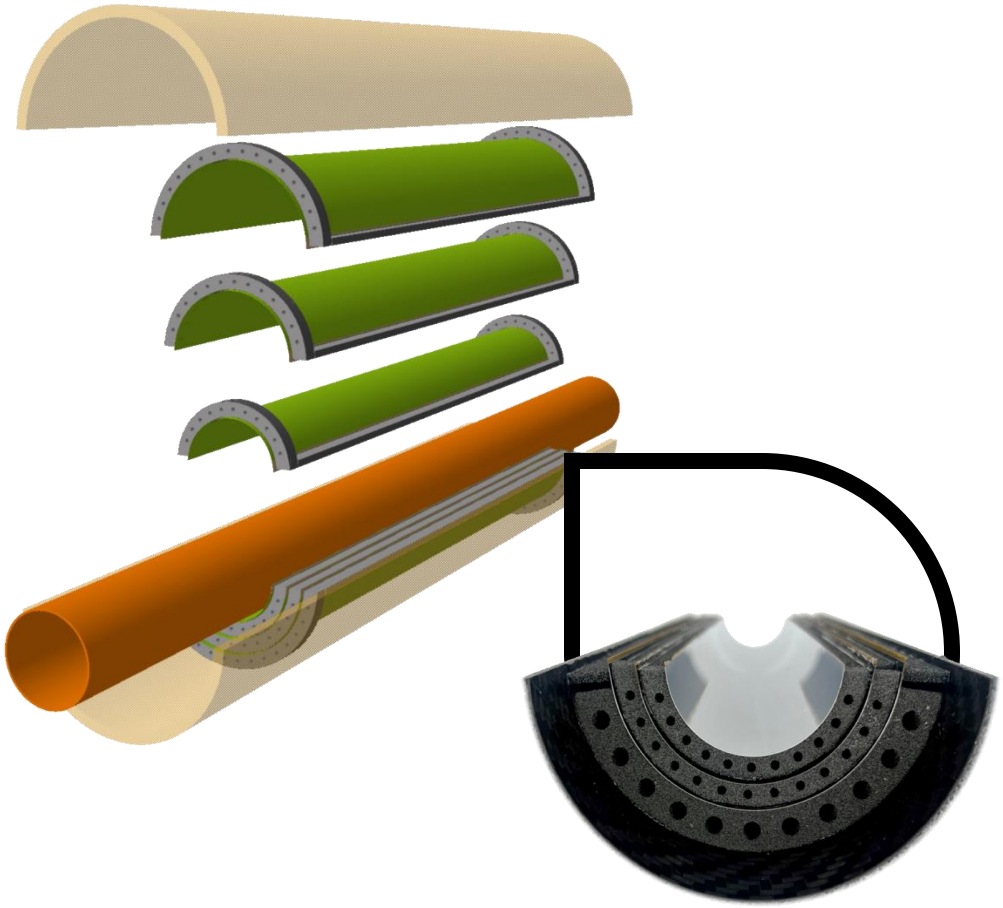
ALICE ITS Using CMOS MAPS

- 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

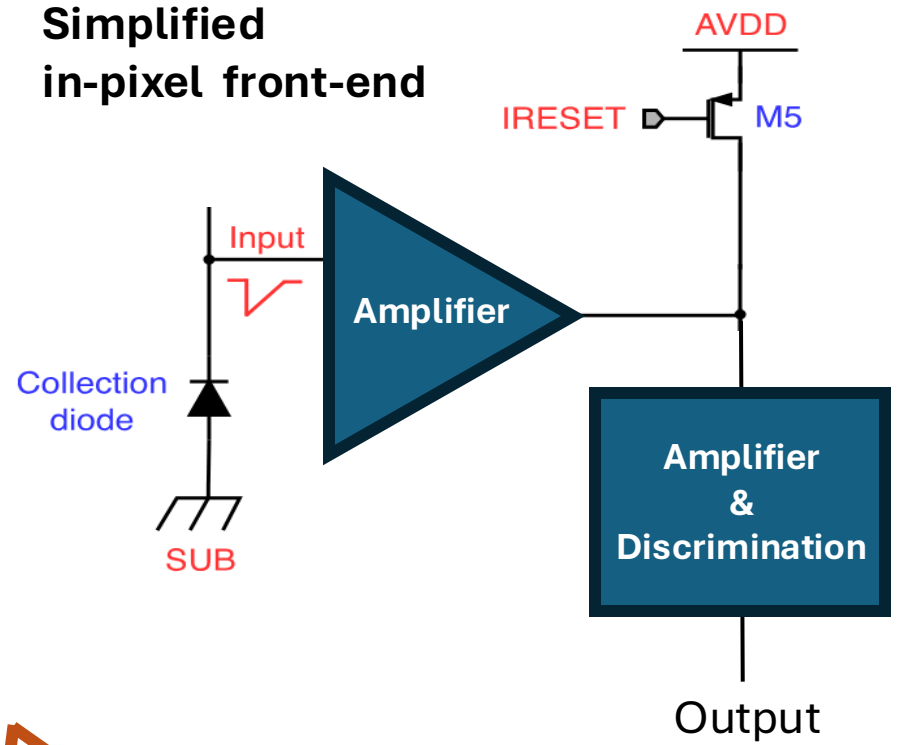
ALICE ITS3

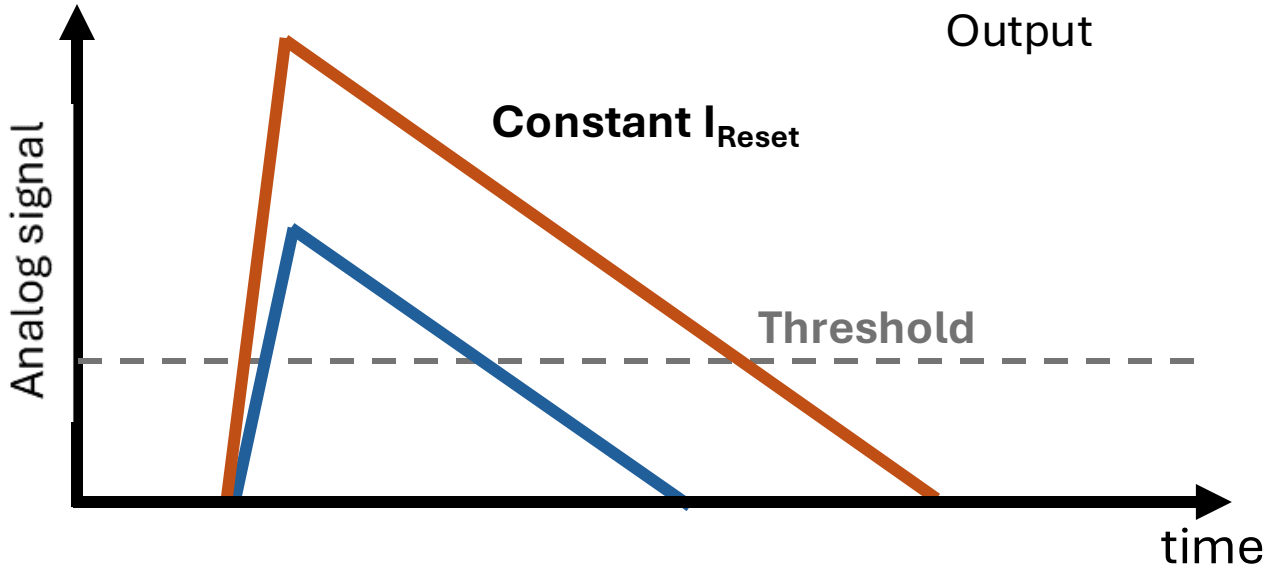


Amplitude Measurement

- 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?*

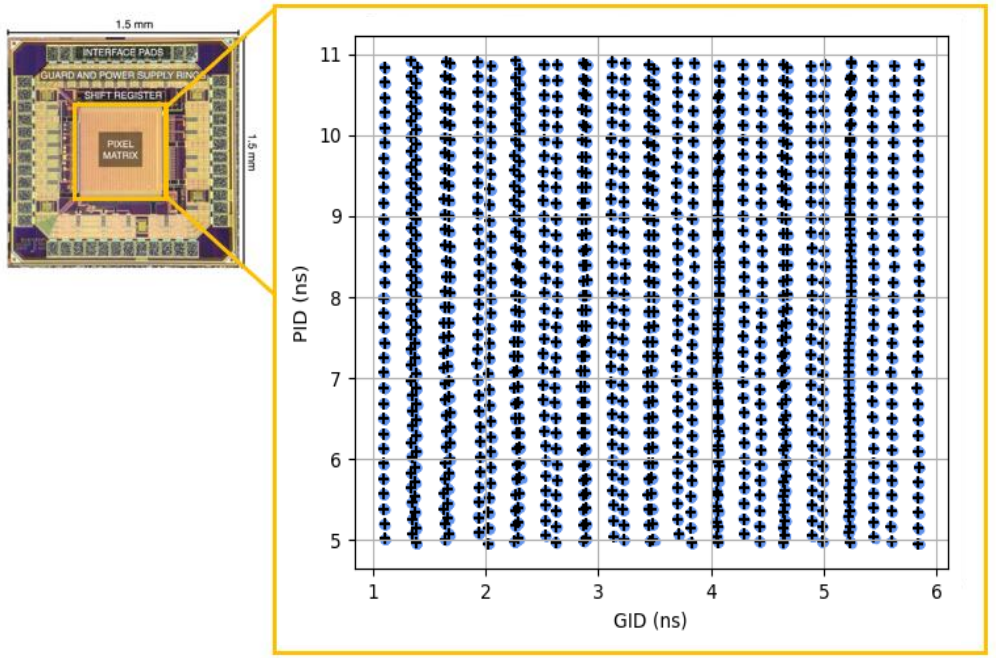
→ Use ToT (Time-over-Threshold), proportional to signal height due to constant I_{Reset} applied in the in-pixel front end



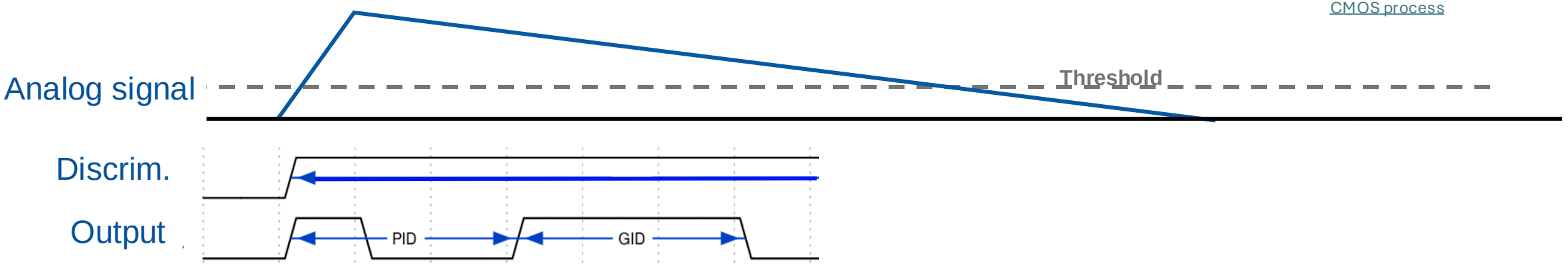


DPTS - Digital Pixel Test Structure

- 15x15 µm^2 pitch
- 32x32 = 1024 pixels
- Pixels read out via a single differential digital output line
- Hit position is time-encoded via delay lines



Digital pixel test structures implemented in a 65 nm CMOS process

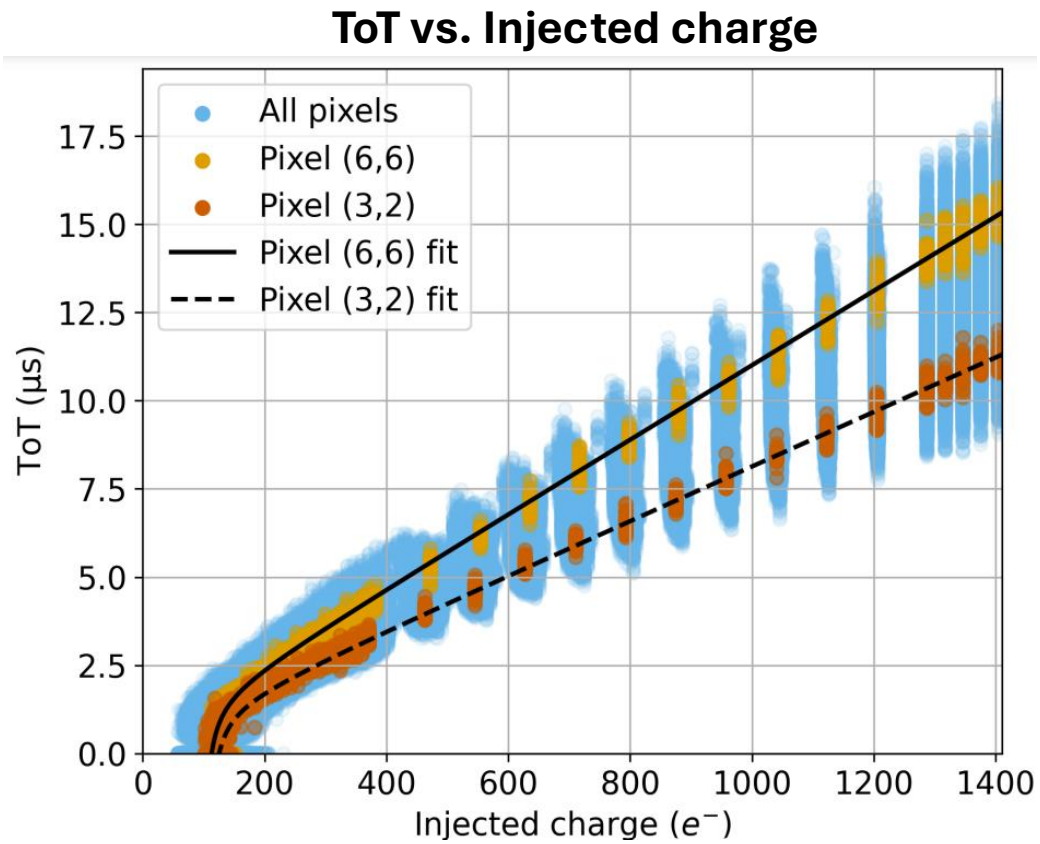


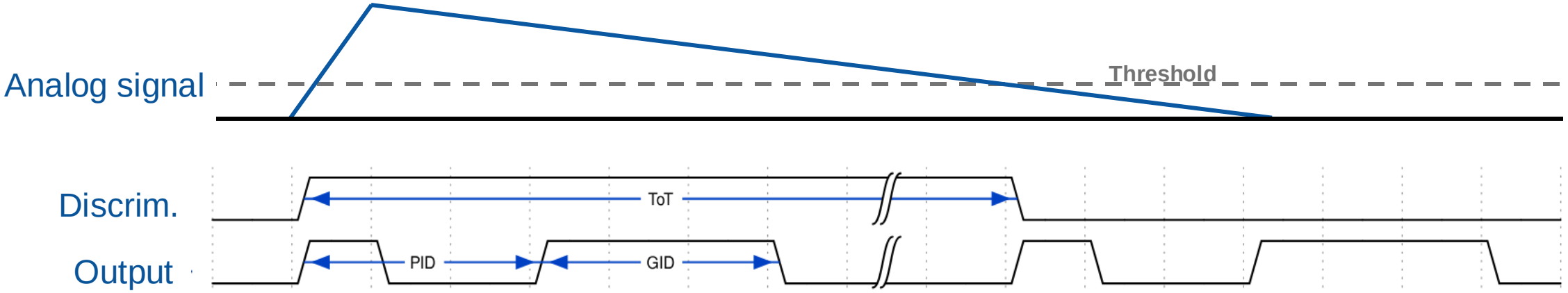
DPTS

- 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



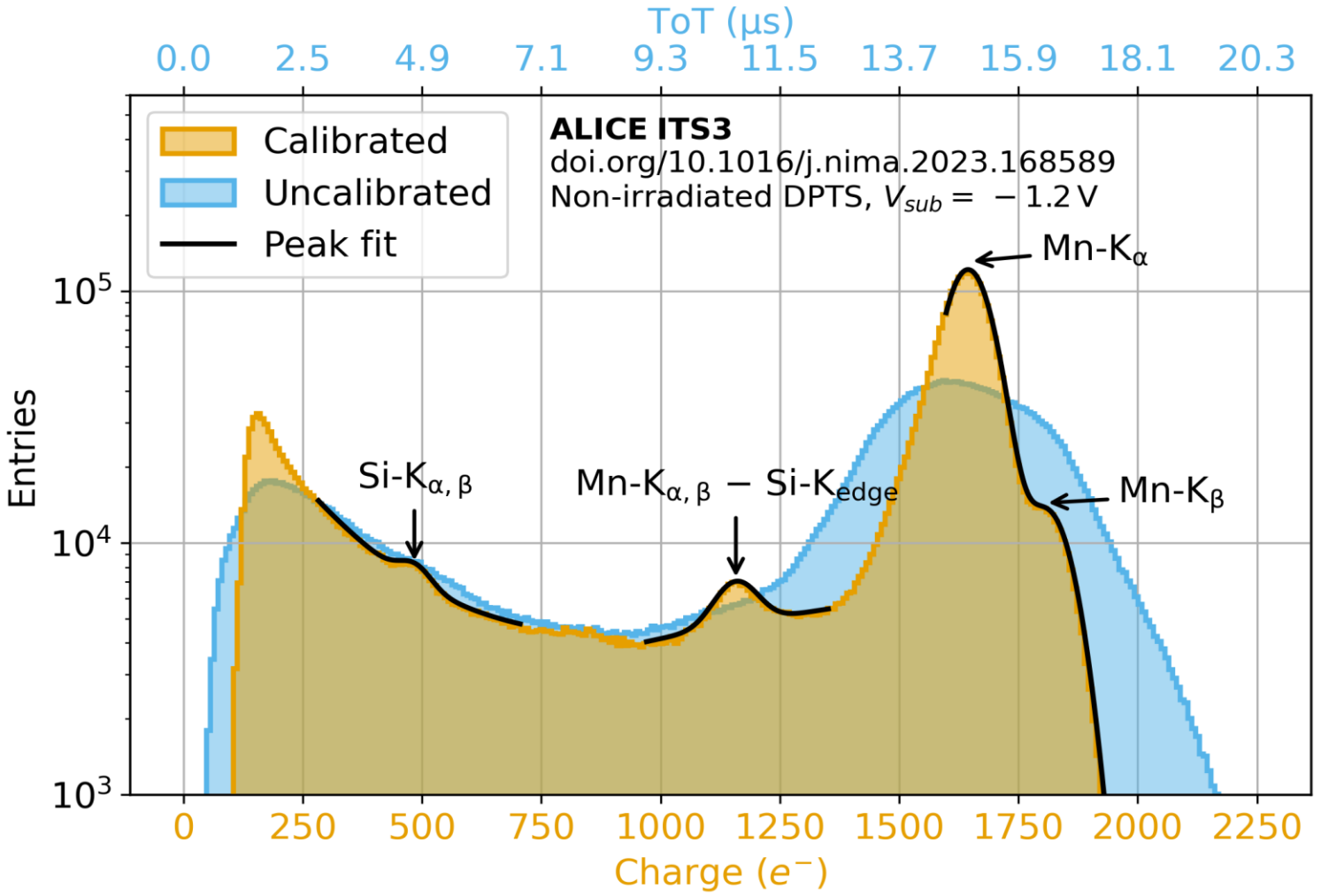


DPTS - Performance

- 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:

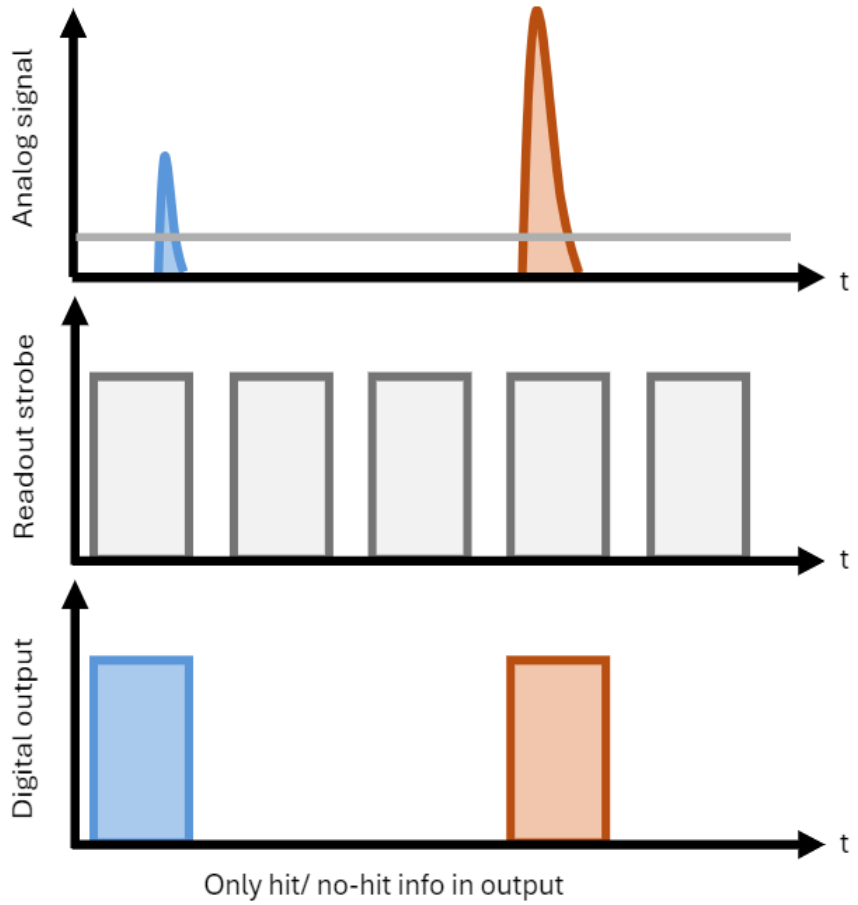
$$\frac{\text{FWHM}}{\mu} = 7.42\% \pm 0.01\%$$

- Silicon fluorescence and escape peak can be distinguished



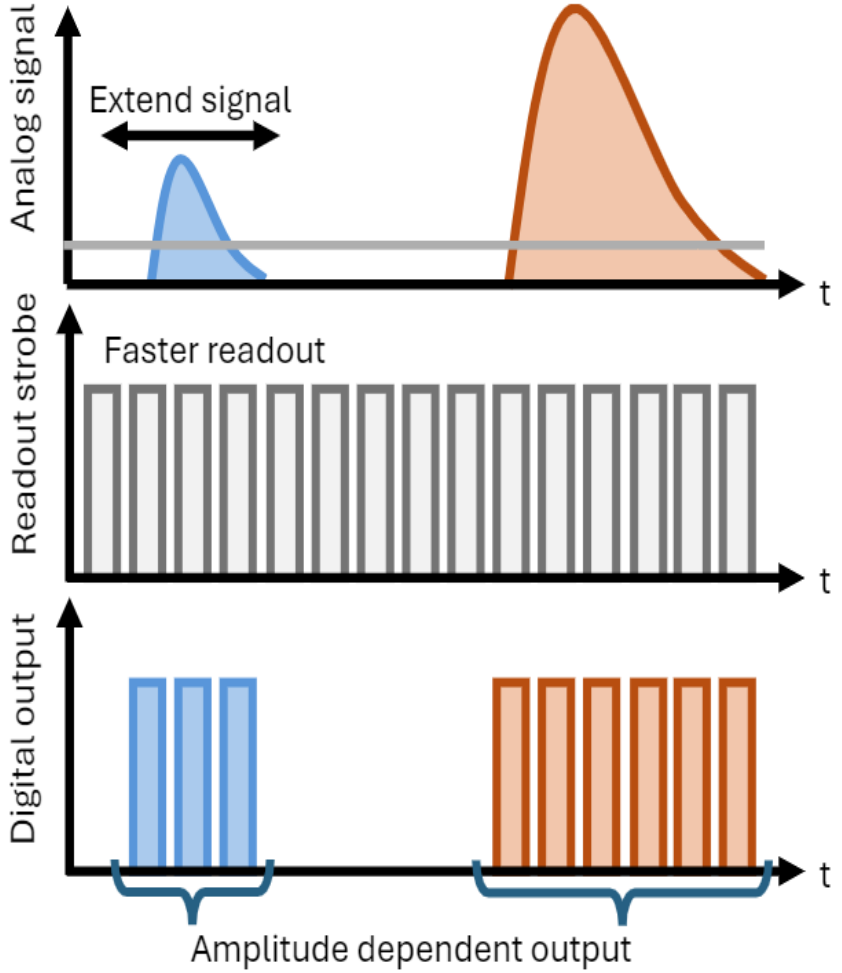
Digital Oversampling

Standard operation/sampling



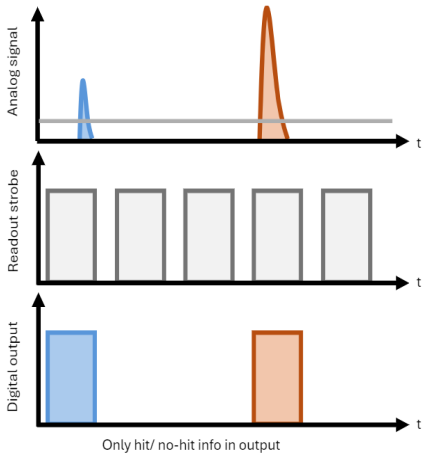
Faster sampling & shorter strobe

Digital oversampling

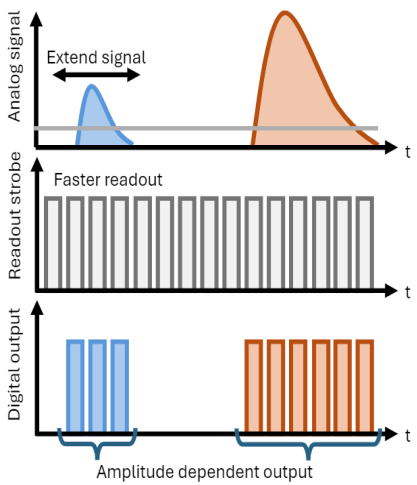


Digital Oversampling

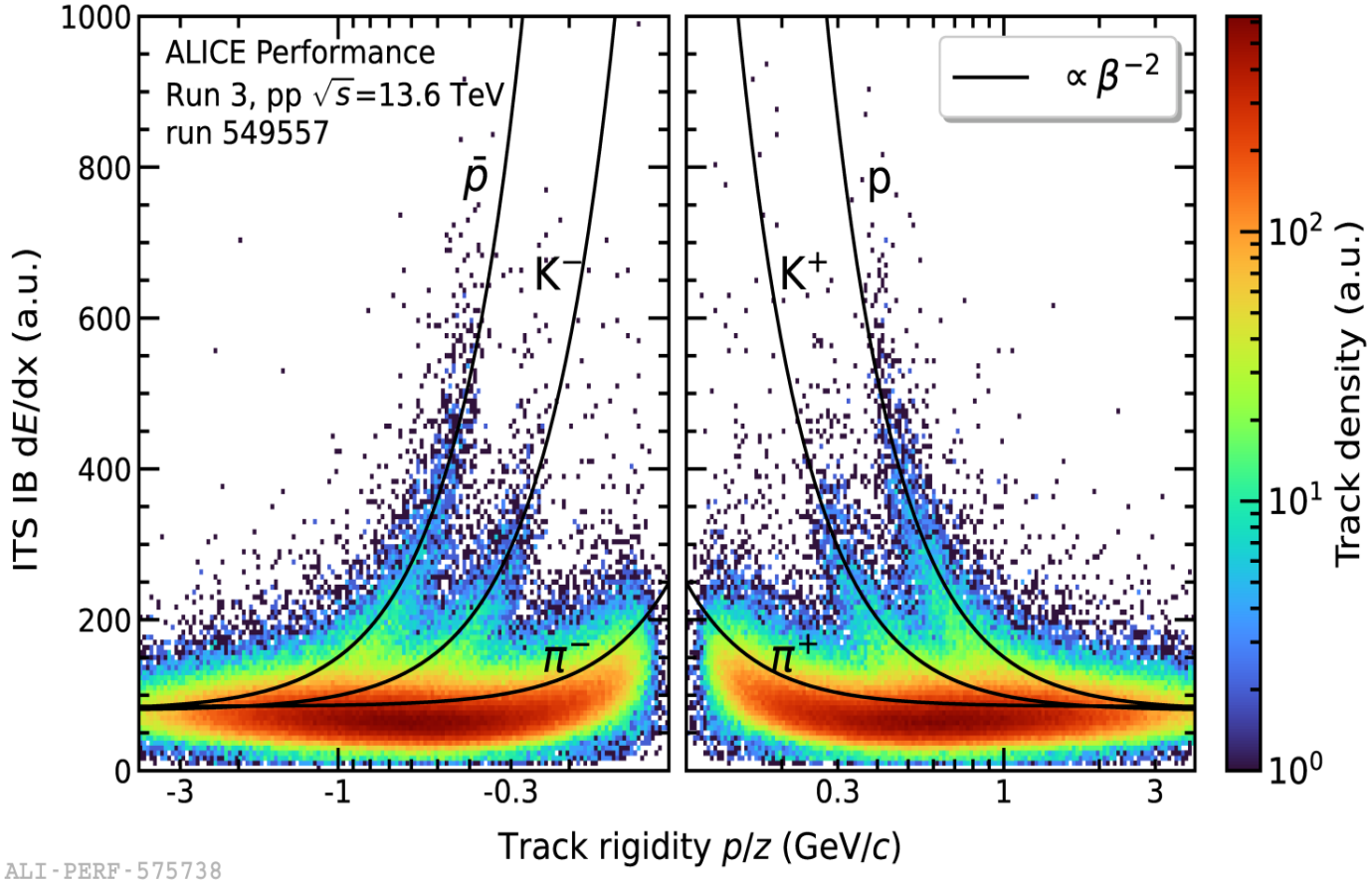
Standard operation



Digital oversampling



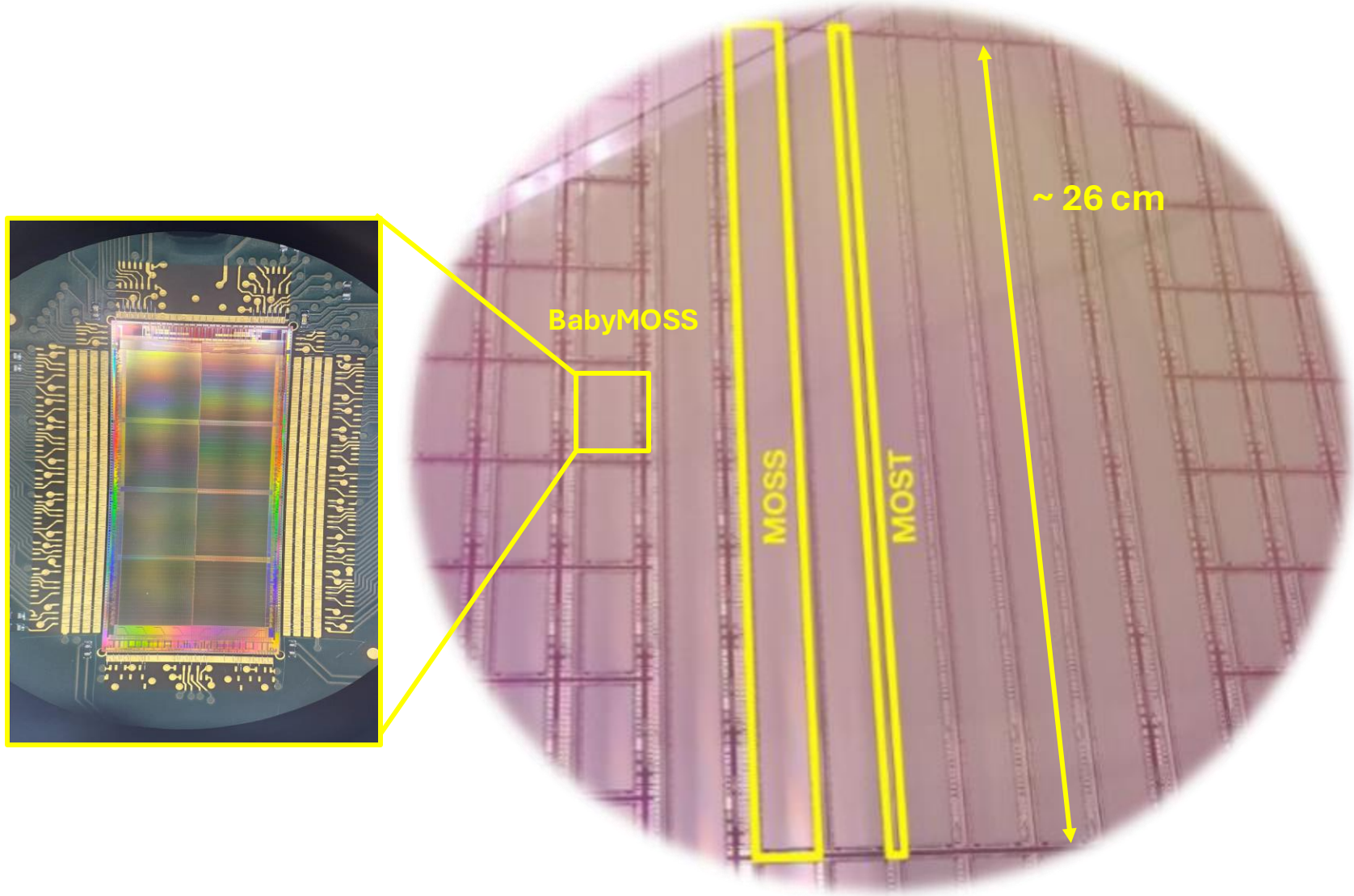
Example of ITS2 (ALPIDEs) oversampling at low interaction rate ~1kHz pp



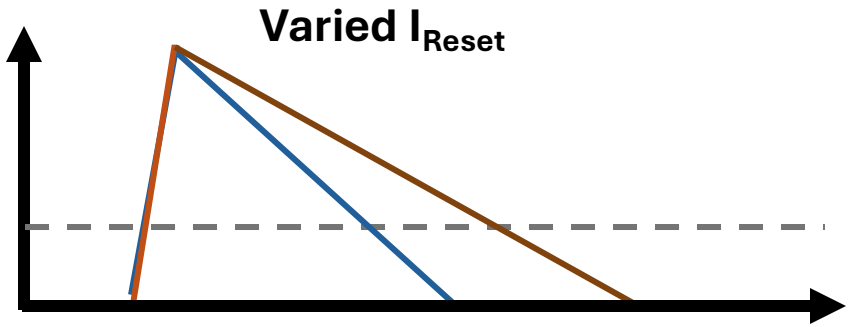
Andrea Sofia Triolo on behalf of the ALICE collaboration, Calibration and Performance of the Upgraded ALICE Inner Tracking System

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

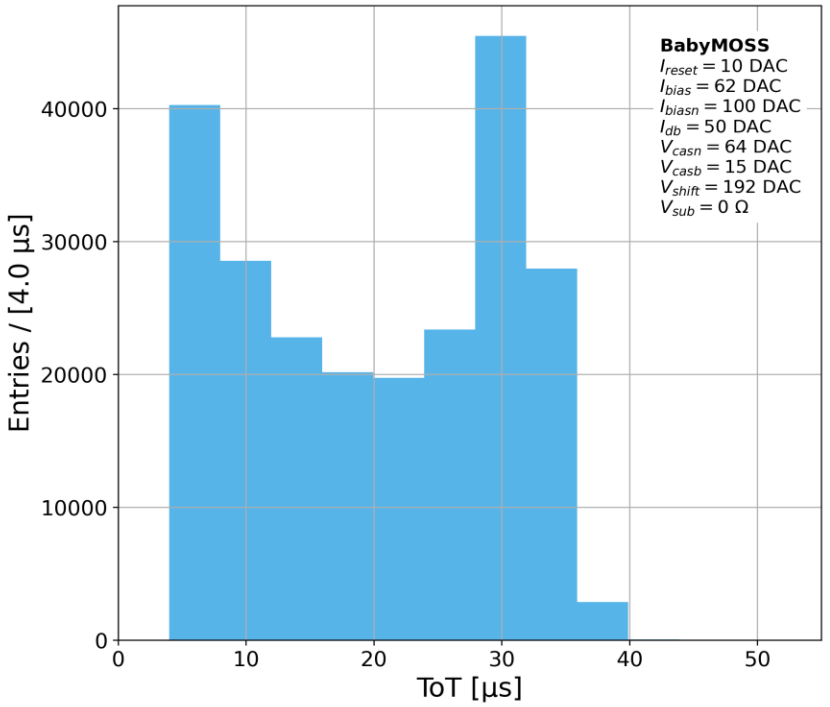


BabyMOSS – ^{55}Fe Spectra

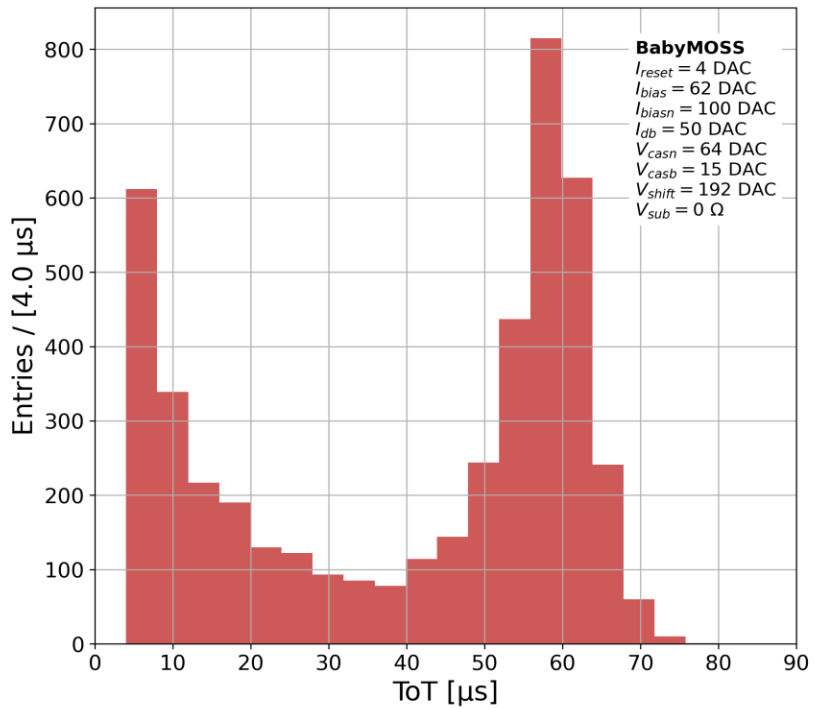


- Source measurements with an ^{55}Fe source
- Sampling period of 4 µs
- Main K_α peak can clearly be distinguished
- More pronounced by adjusting the settings and extending the signal length

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

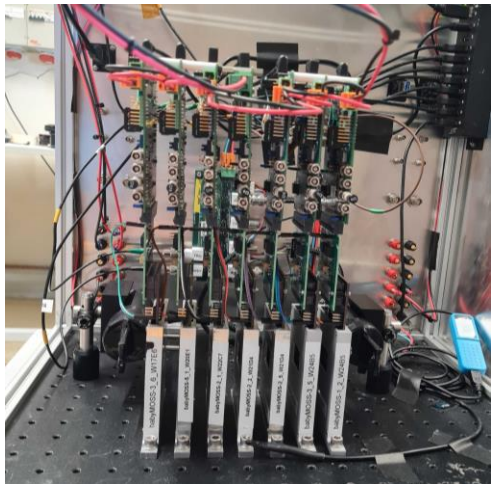


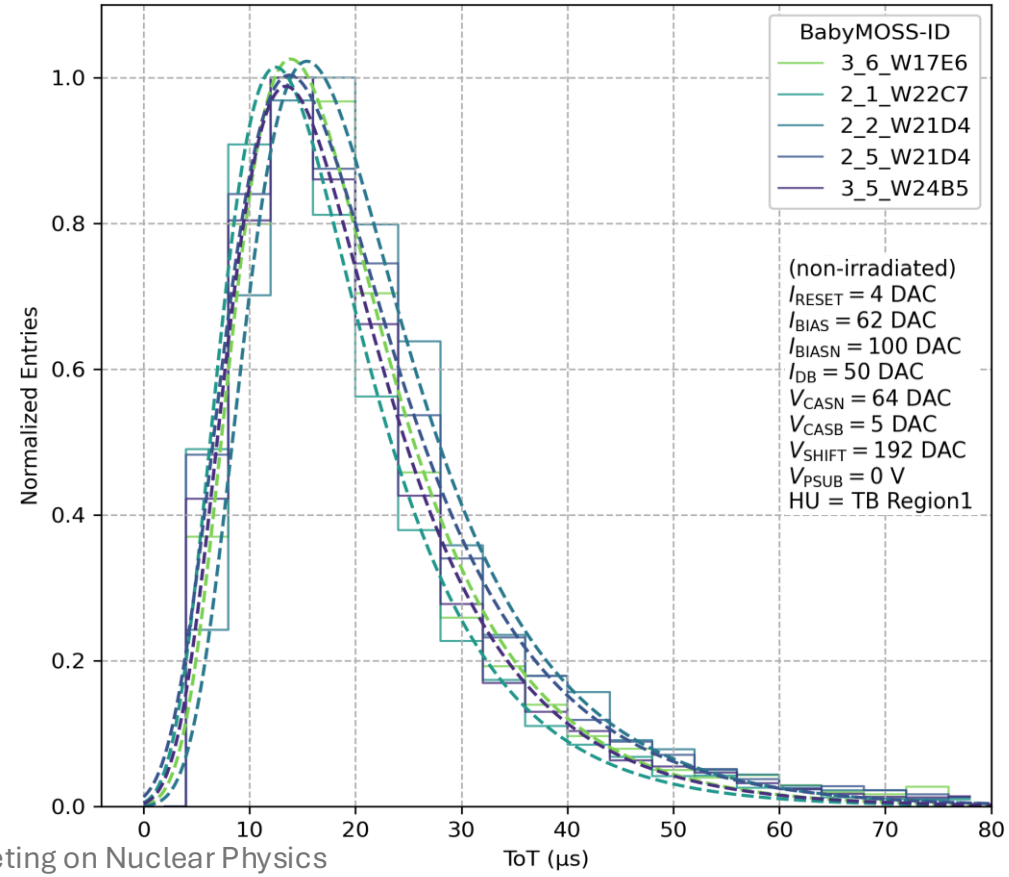
Lengthened signal (I_{Reset} = 4 a.u.)



Test Beam Measurements

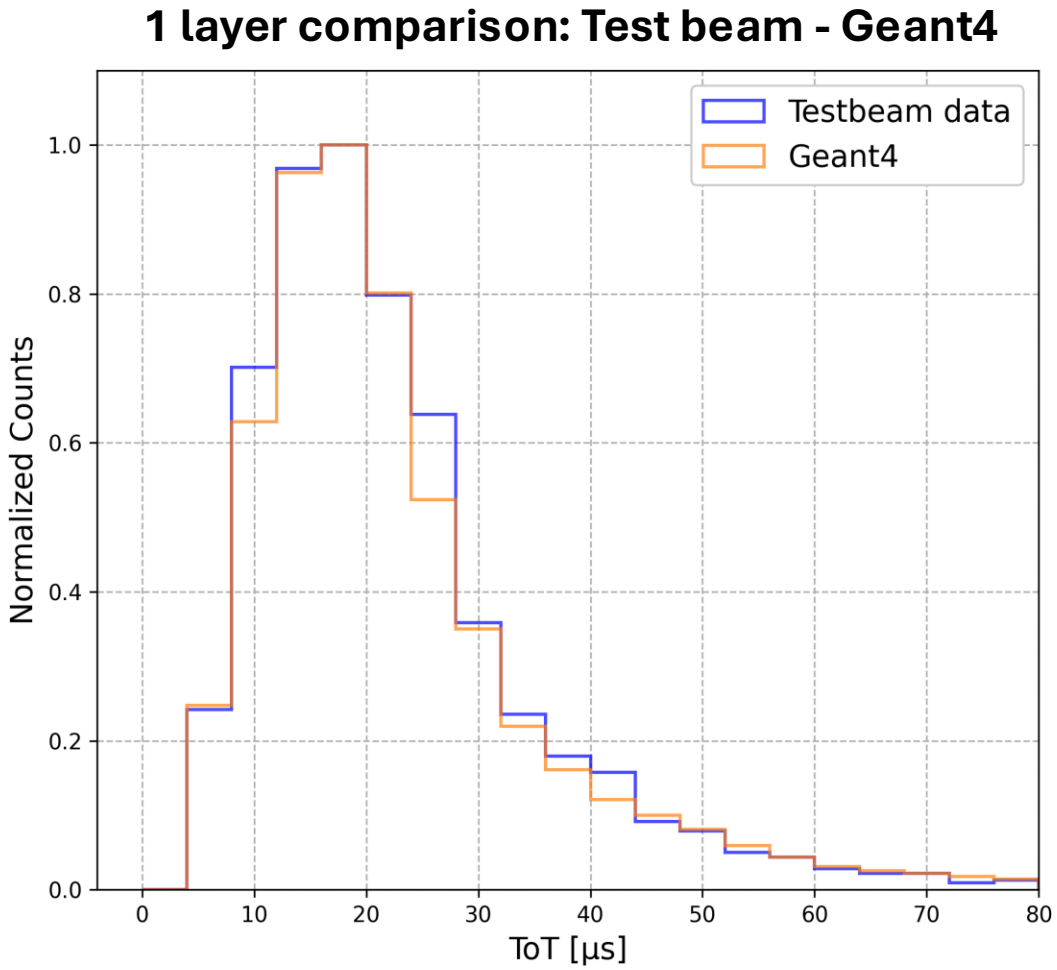
- Performed ToT measurements with 10 GeV/*c* pion beam at PS with 5 BabyMOSS
- The landau energy loss distribution can be observed
  - MPV within the expected energy range
- Different sensors behave similarly and consistently





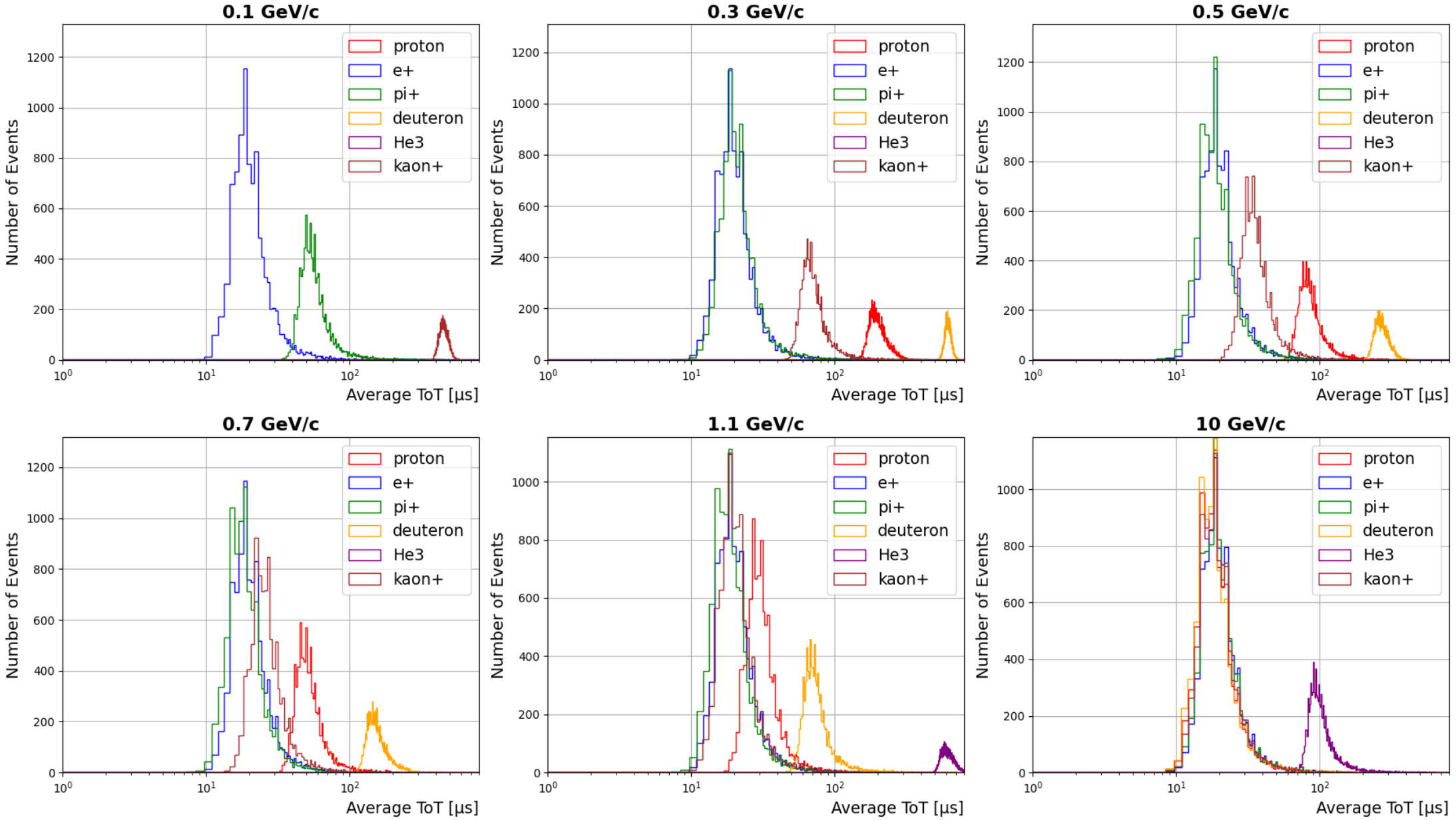
Geant4 Simulations

- 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)



Geant4

11 layers | 4 µs sampling | Lengthened signal (I_{Reset} = 4 a.u.)

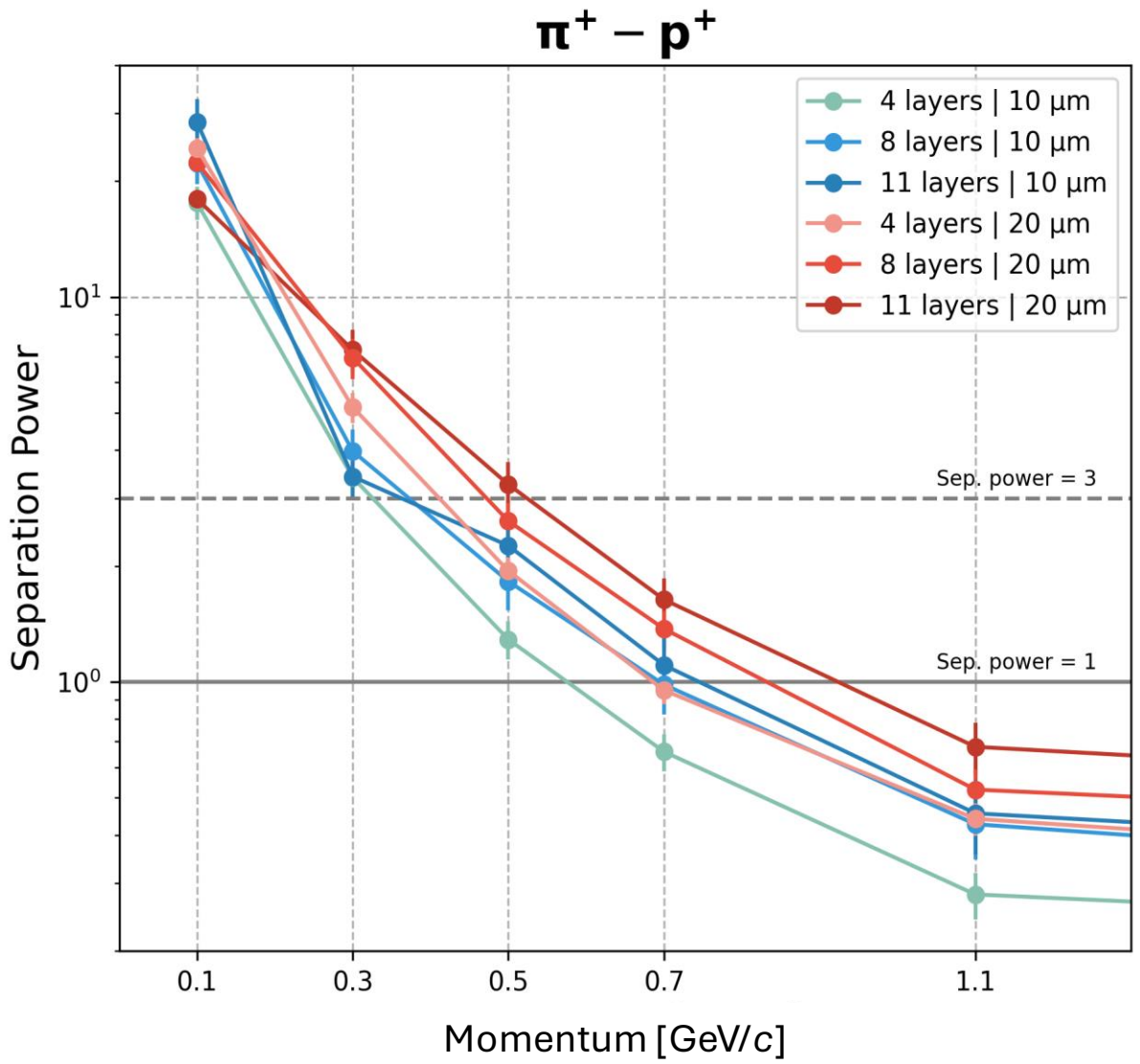


Geant4

- Quantify separation power between different particles

$$SP = \frac{|\mu_A - \mu_B|}{\sqrt{\frac{\sigma_A^2 + \sigma_B^2}{2}}}$$

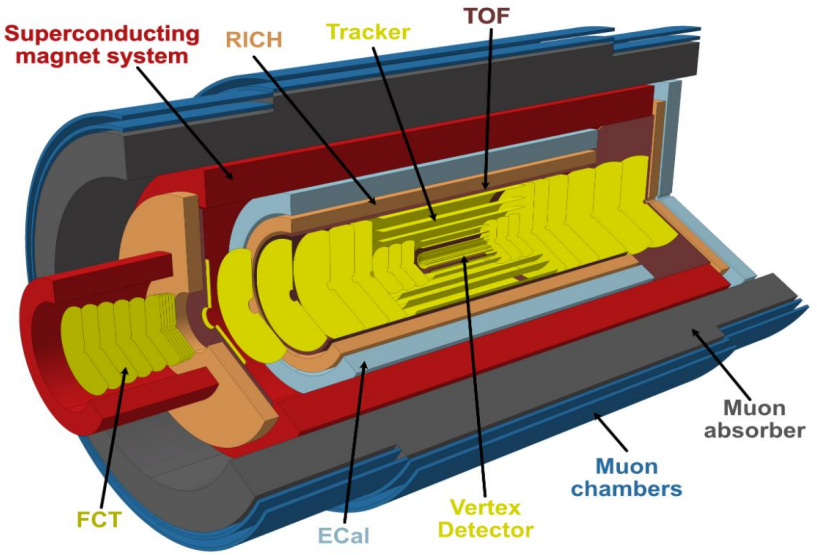
- Varying number of layers and thickness (replicate inclined tracks)
- Separation of 3σ up to 0.3-0.5 GeV/*c*



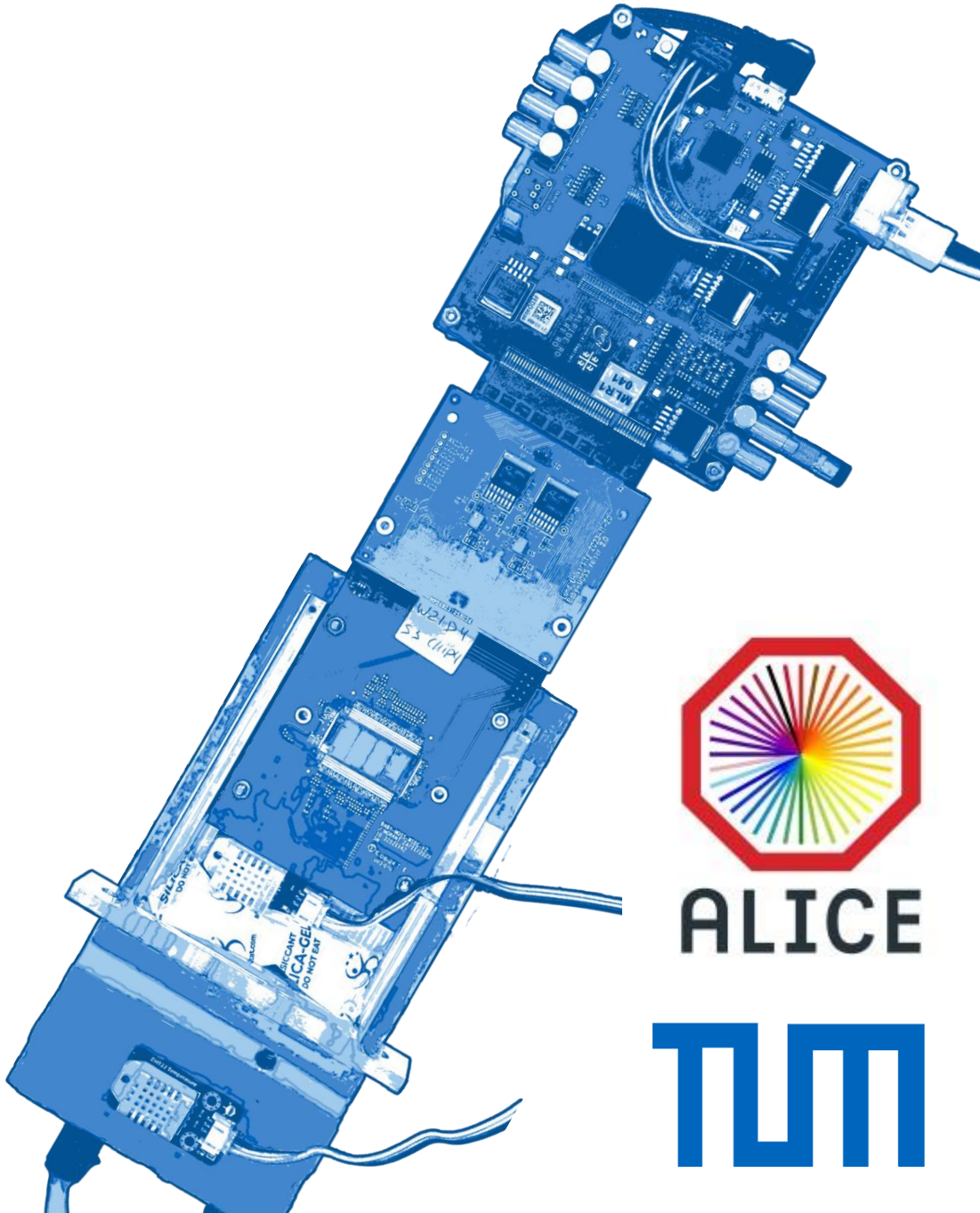
Separation power = 3

Conclusion

- Using prototype sensors developed for the ITS3 upgrade, different amplitude measurement methods using Time-over-Threshold were investigated
  - Time-encoded ToT using the DPTS chiplet
  - Using digital oversampling with the BabyMOSS sensor
- The results were backed up by Geant4 simulations, with a sufficient particle separation up to 0.5 GeV/*c* for pion-proton, and >10 GeV/*c* for light nuclei
- Amplitude measurement with MAPS offers promising advancements for next-generation detectors, such as ALICE3.



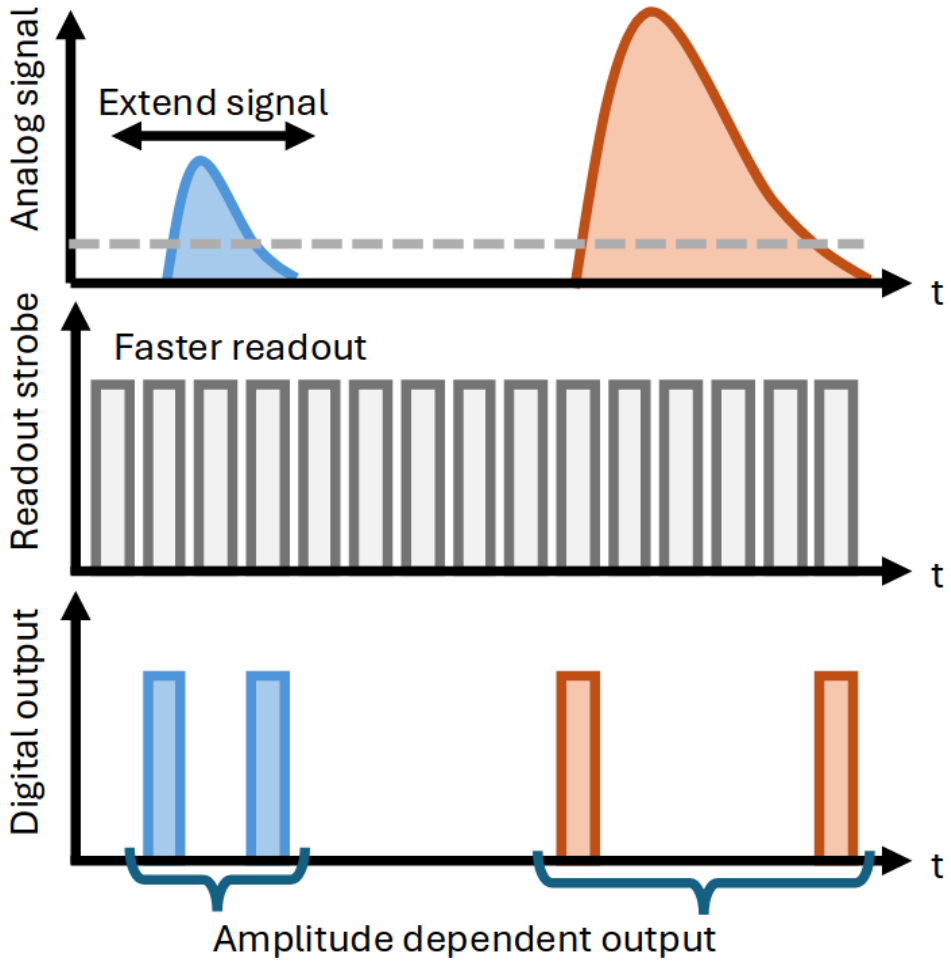
Thanks!



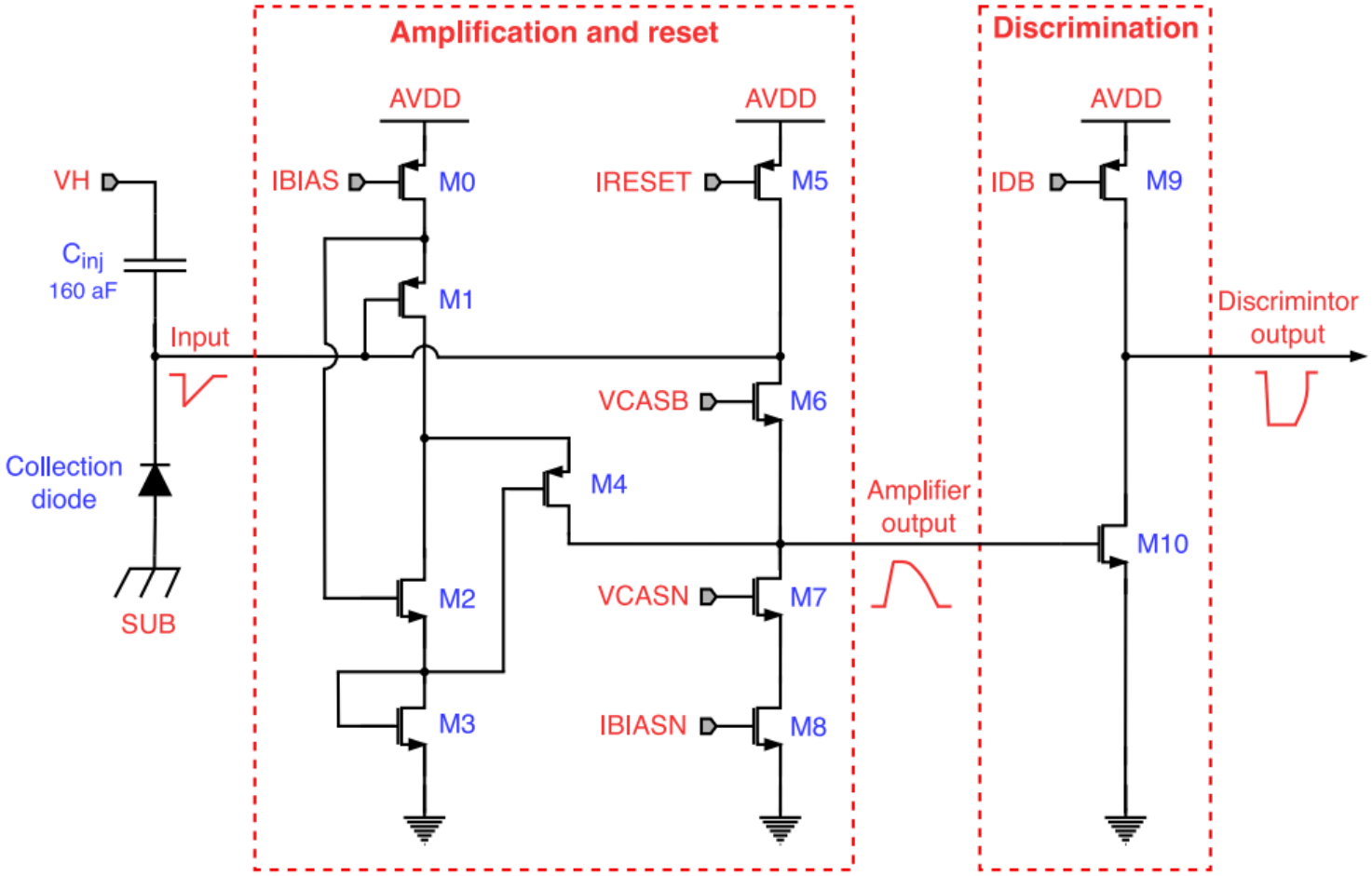
Backup

Idea For Future Improvement

- Send signal only at the edges
- Only doubling the data rate compared to no ToT
- Full ToT capability remains

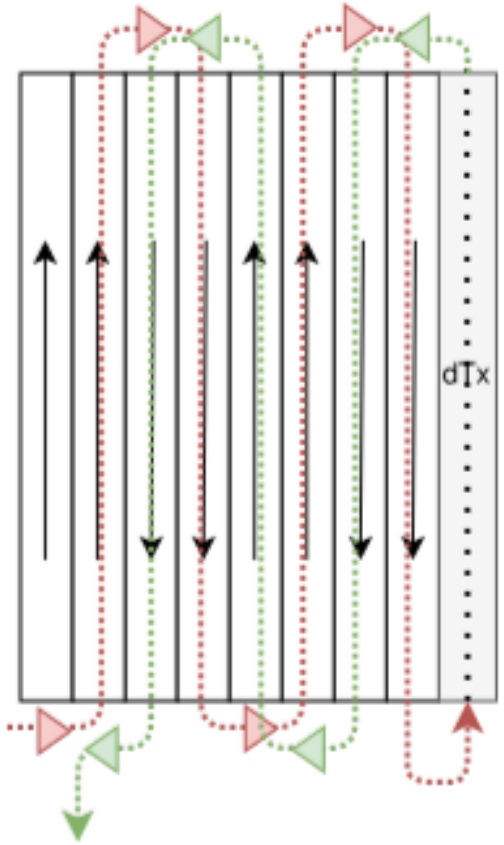


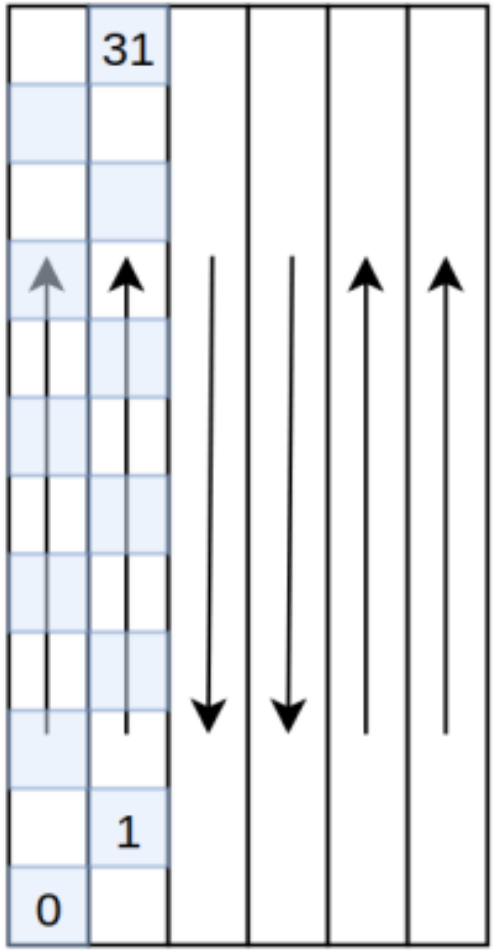
DPTS In-pixel Front-end



Digital pixel test structures implemented in a 65 nm CMOS process

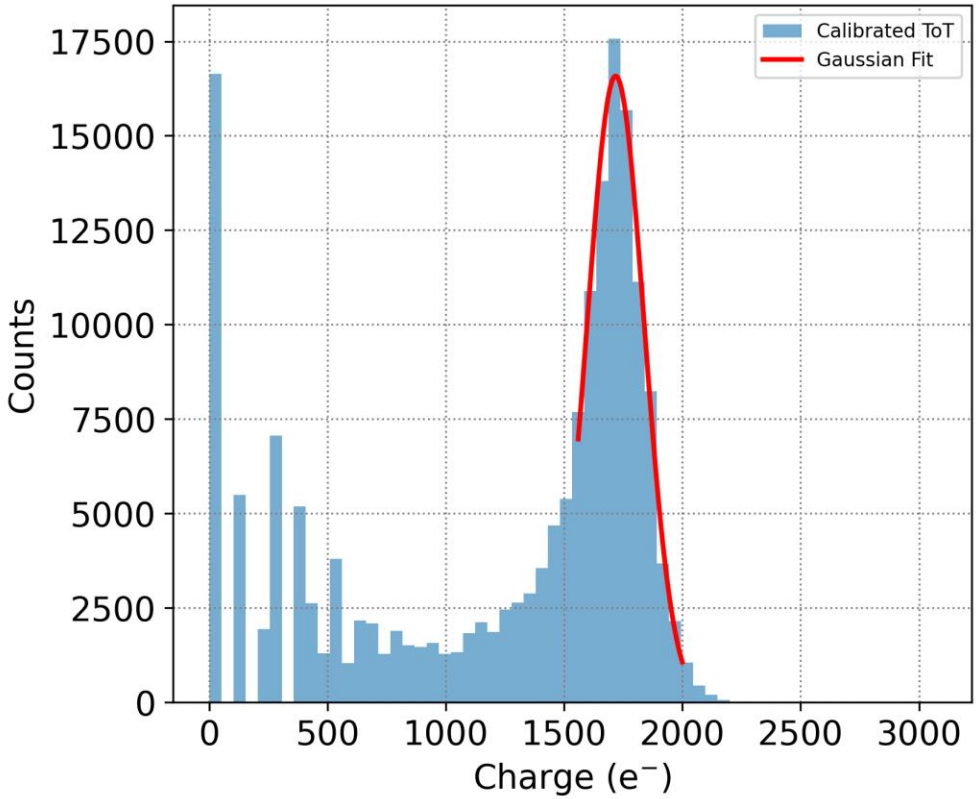
DPTS - Encoding

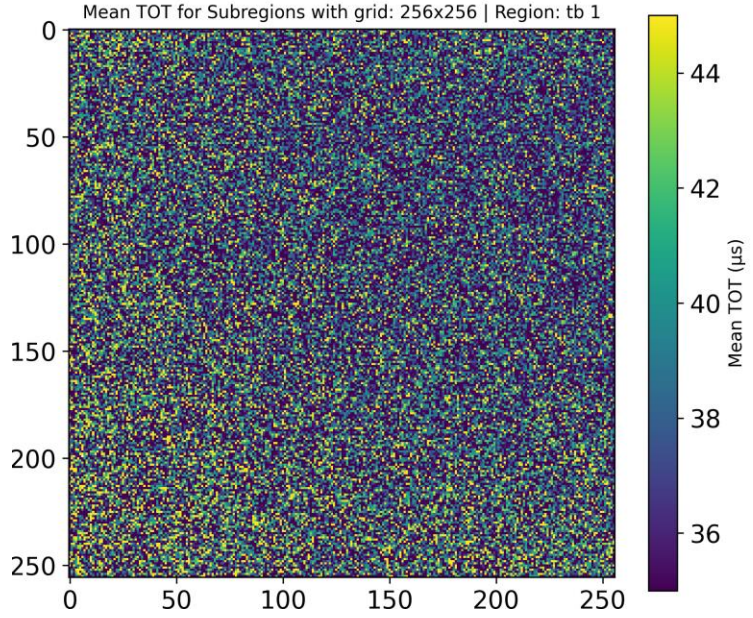


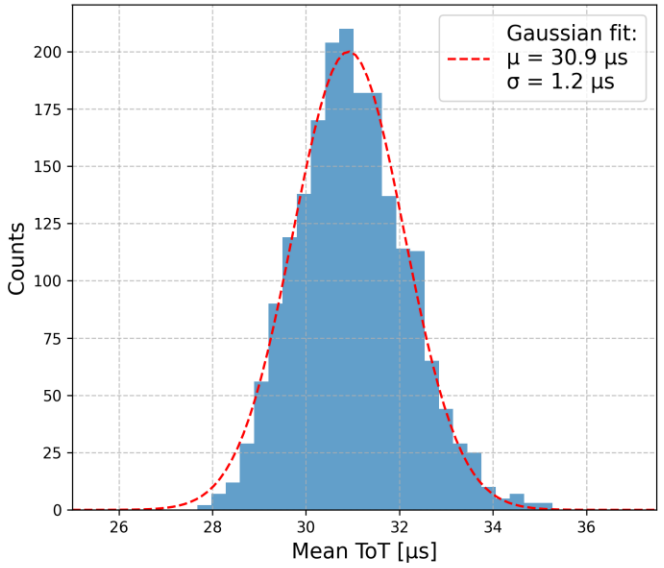


Digital pixel test structures implemented in a 65 nm CMOS process

BabyMOSS - ToT Calibration



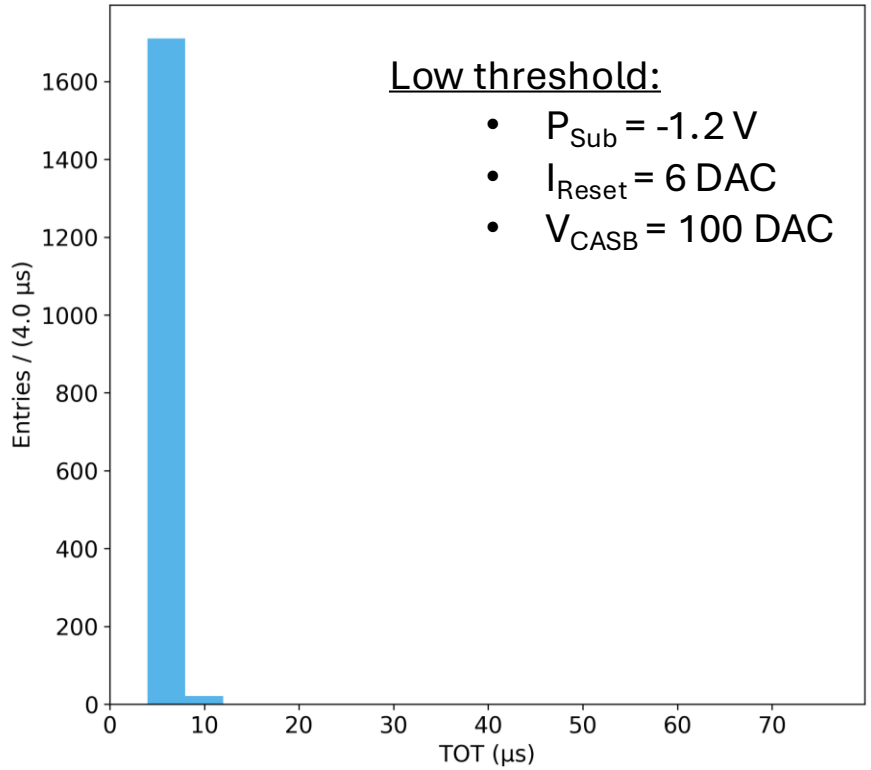


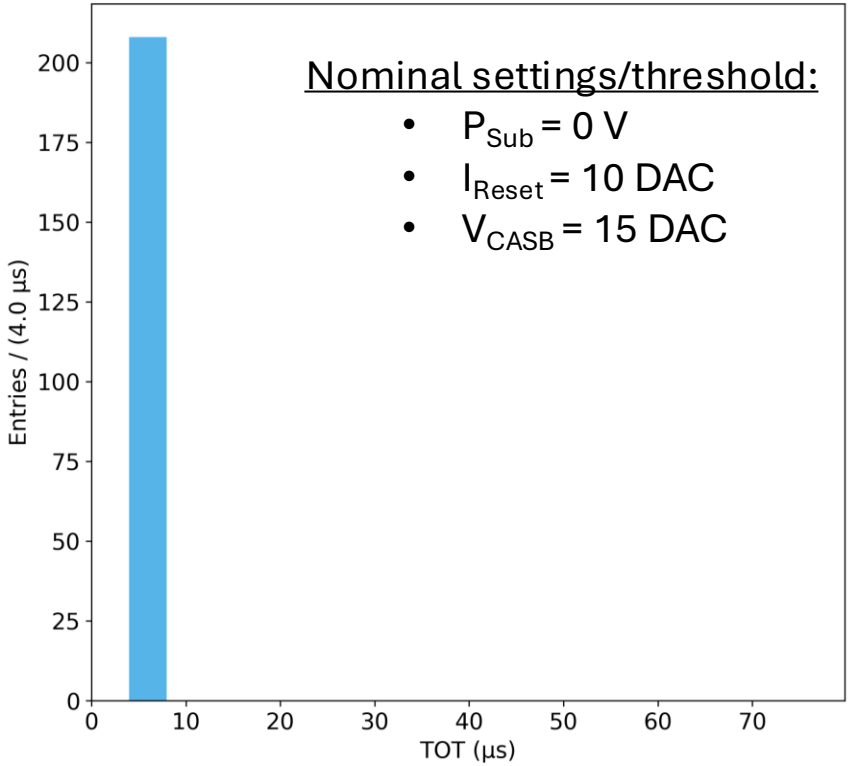


- Calibration does not seem to improve resolution
- Investigations ongoing

ToT From Noise

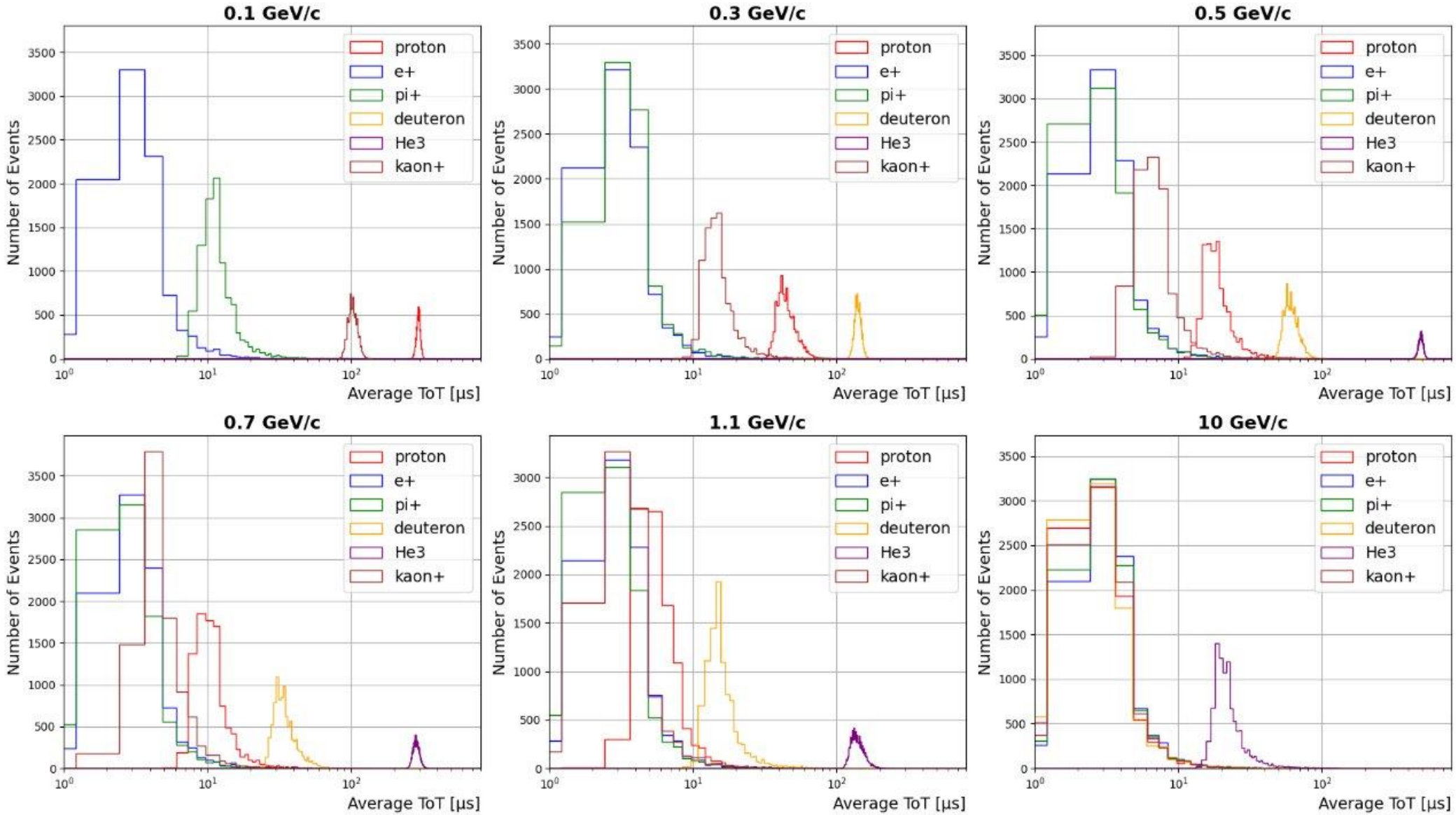
- Almost all ToT hits within the first bin





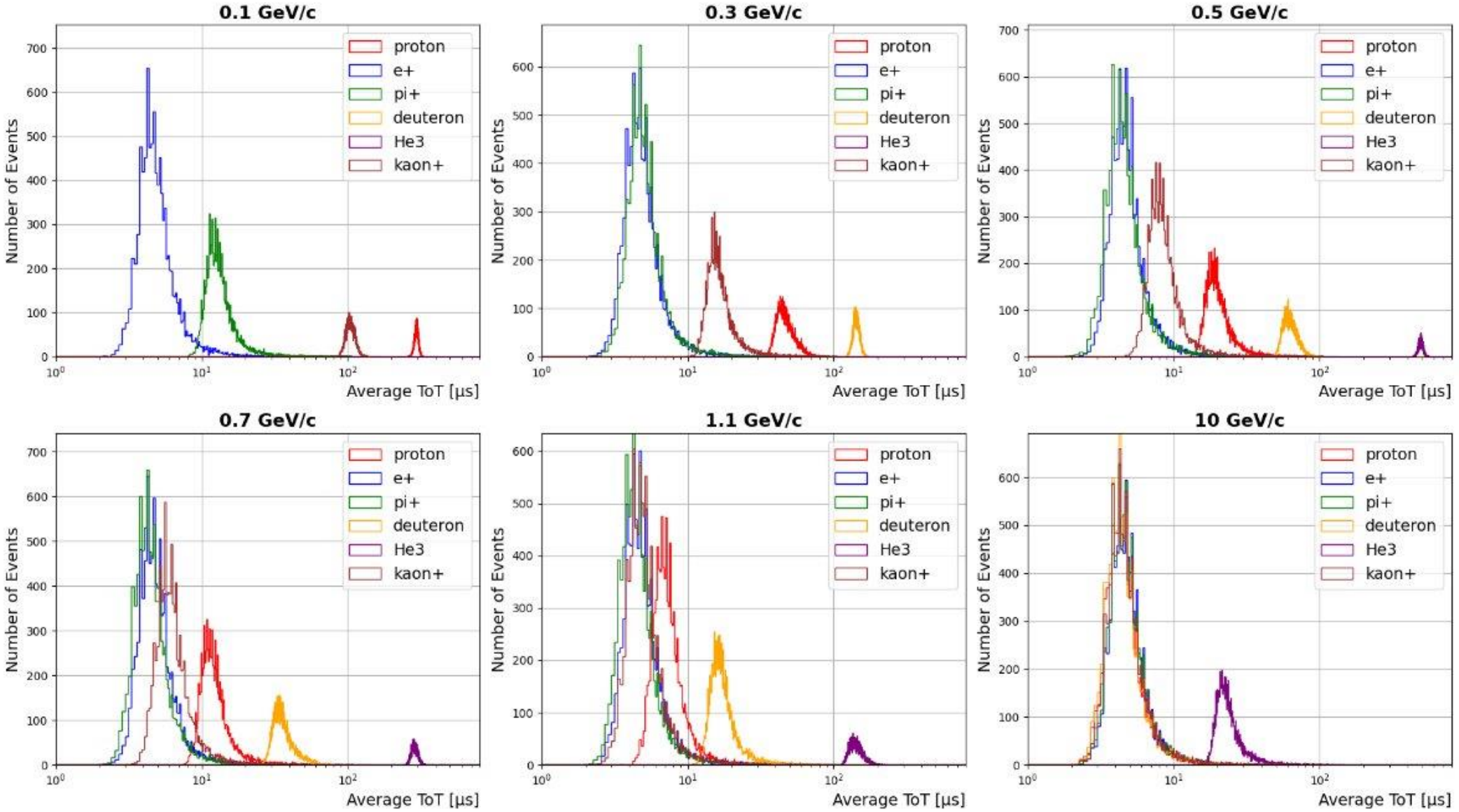
Geant 4

11 layers | 4 µs sampling | Shortened signal (I_{Reset} ~25)

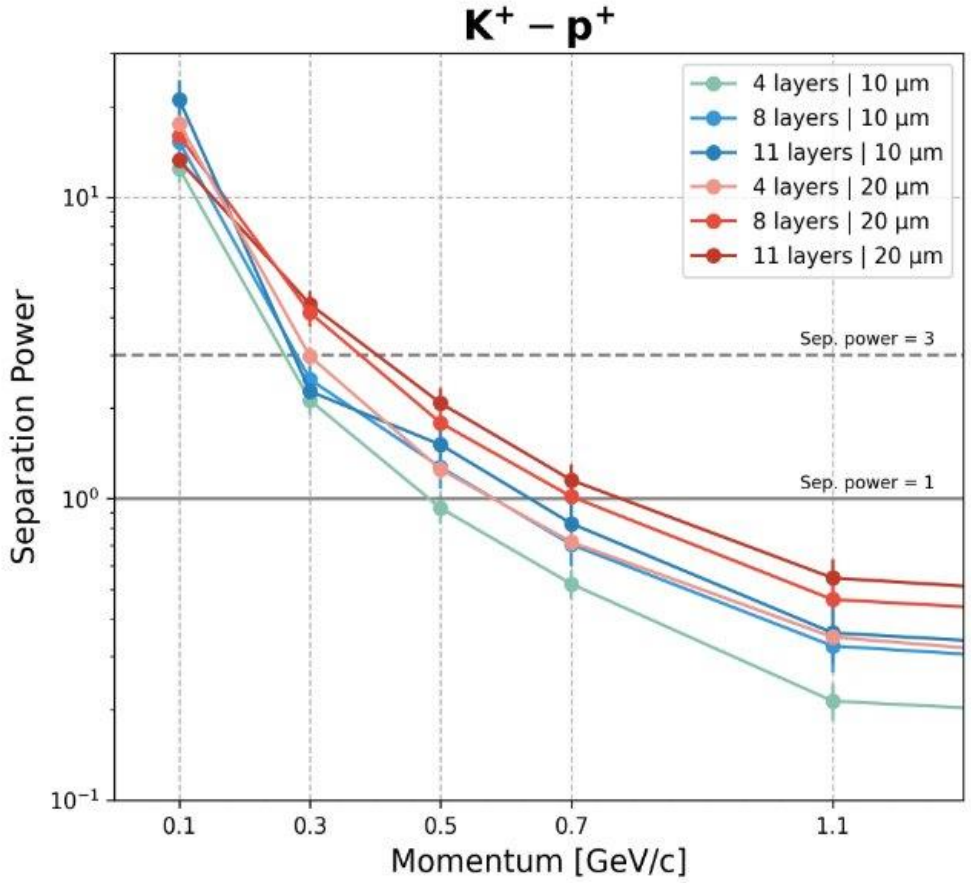


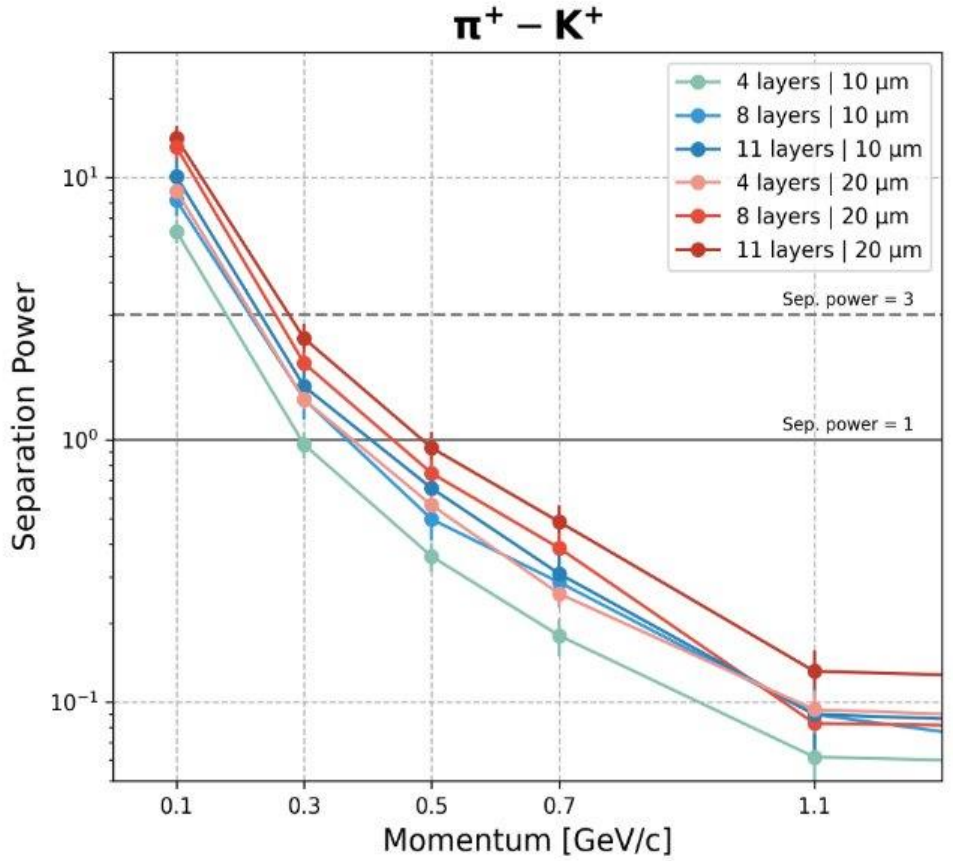
Geant 4

11 layers | 0.5 µs sampling | Shortened signal (I_{Reset} ~25)



Geant4


$K^+ - p^+$
4 layers | 10 µm
8 layers | 10 µm
11 layers | 10 µm
4 layers | 20 µm
8 layers | 20 µm
11 layers | 20 µm
Sep. power = 3
Sep. power = 1
Separation Power
10^1
10^0
10^{-1}
0.1
0.3
0.5
0.7
1.1
Momentum [GeV/c]


$\pi^+ - K^+$
4 layers | 10 µm
8 layers | 10 µm
11 layers | 10 µm
4 layers | 20 µm
8 layers | 20 µm
11 layers | 20 µm
Sep. power = 3
Sep. power = 1
Separation Power
10^1
10^0
10^{-1}
0.1
0.3
0.5
0.7
1.1
Momentum [GeV/c]

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 x 10^{12}	1 x 10^{16}	6 x 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