



Timepix4 for Beam Particle Identification via Time of Flight

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Outline



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- Material content significance in Particle Physics experiments
- MONSTAR telescope to image fractional radiation length of detector structures
- Calibration of Timepix4 detector for particle identification
- Positron selection results



Motivation for Detector Material Imaging



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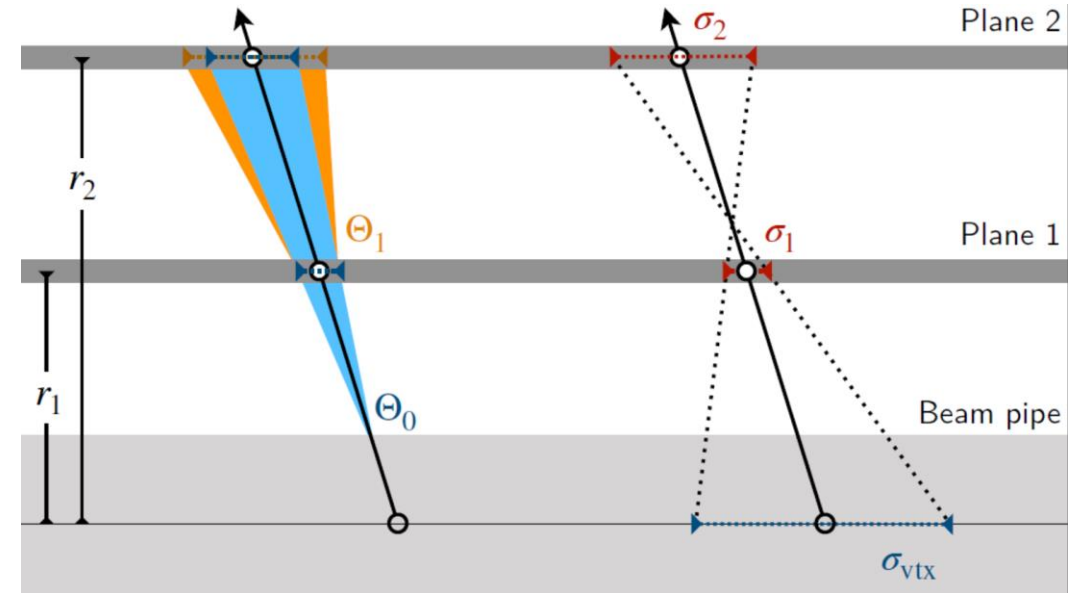
- Detector material effects have a significant impact on track reconstruction, vertexing resolution, b-tagging, momentum resolution in ATLAS, CMS, Mu3e and similar detectors
 - Material usually only estimated during R&D phase, validated post-commissioning
 - “Material models” assume $O(10\% - 30\%)$ uncertainties on material
- Minimisation of material, precise simulations – best done during design phase
 - Obtain material estimate during prototyping phase
 - Past measurements at DESY [1], [2]: thick subjects, non-instrumented detectors
 - Recent detector module measurements by CMS [3], electron CT [4]

Multiple Scattering



- Multiple scattering of low-energy EM particles
 - The projected scattering distributions have a Gaussian core (soft scatters)
 - Lynch & Dahl revision of the Highland formula: RMS of Gaussian core
 - Link between **material content** (in radiation lengths X_0) and an **observable** – the distribution of scattering angles projected on a reference plane, parallel to incidence
 - For relativistic e/mu/pi

$$\theta_{\text{plane}}^{RMS} = \frac{13.6 \text{ MeV}}{\beta c p} \sqrt{x/X_0} [1 + 0.038 \ln(x/X_0)]$$



[5] PDG rev.27
[6] Lynch & Dahl

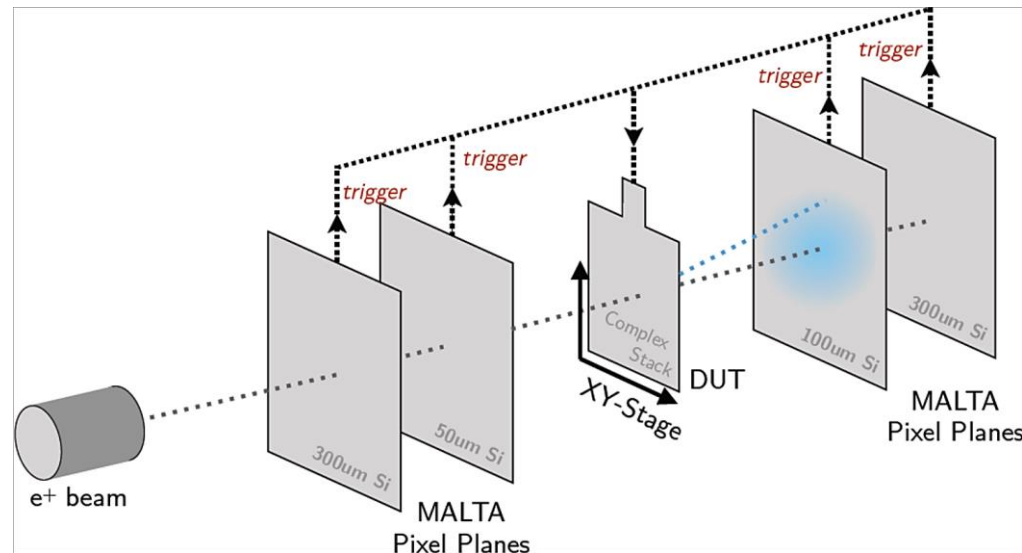


MONSTAR Telescope



The MONSTAR telescope (Multiple Or Negligible Scattering Telescope, As Required) is a purpose-built telescope for measuring material content.

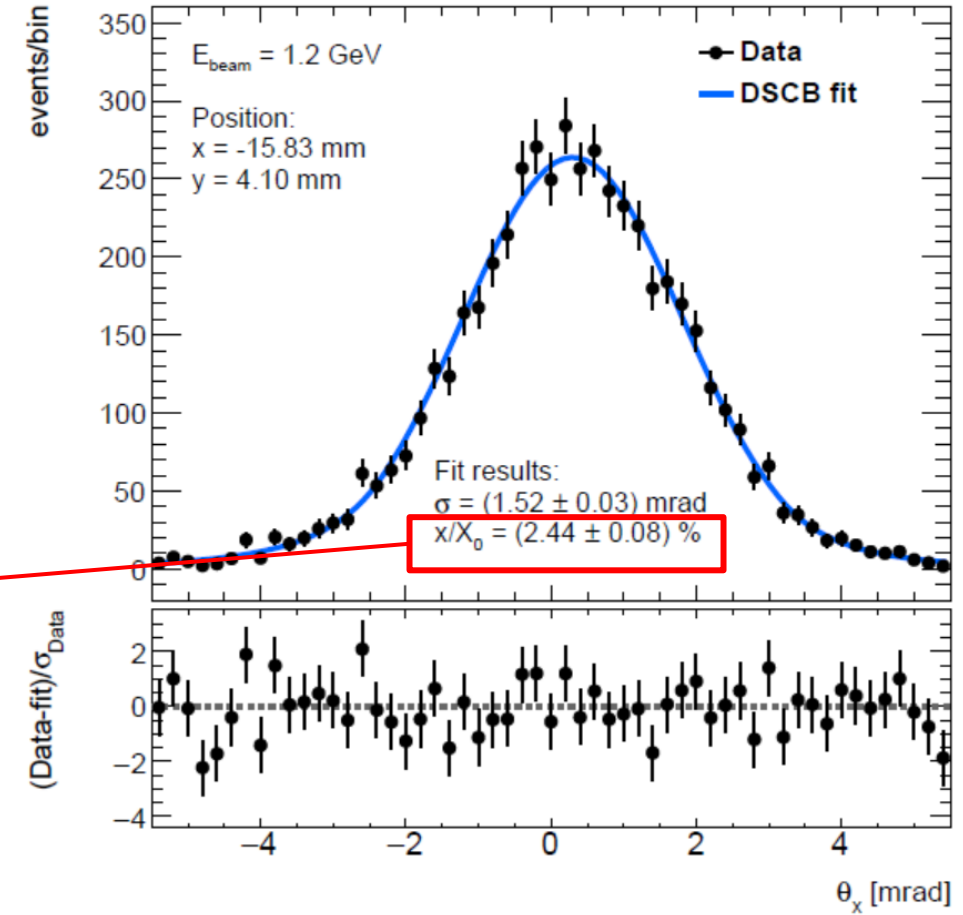
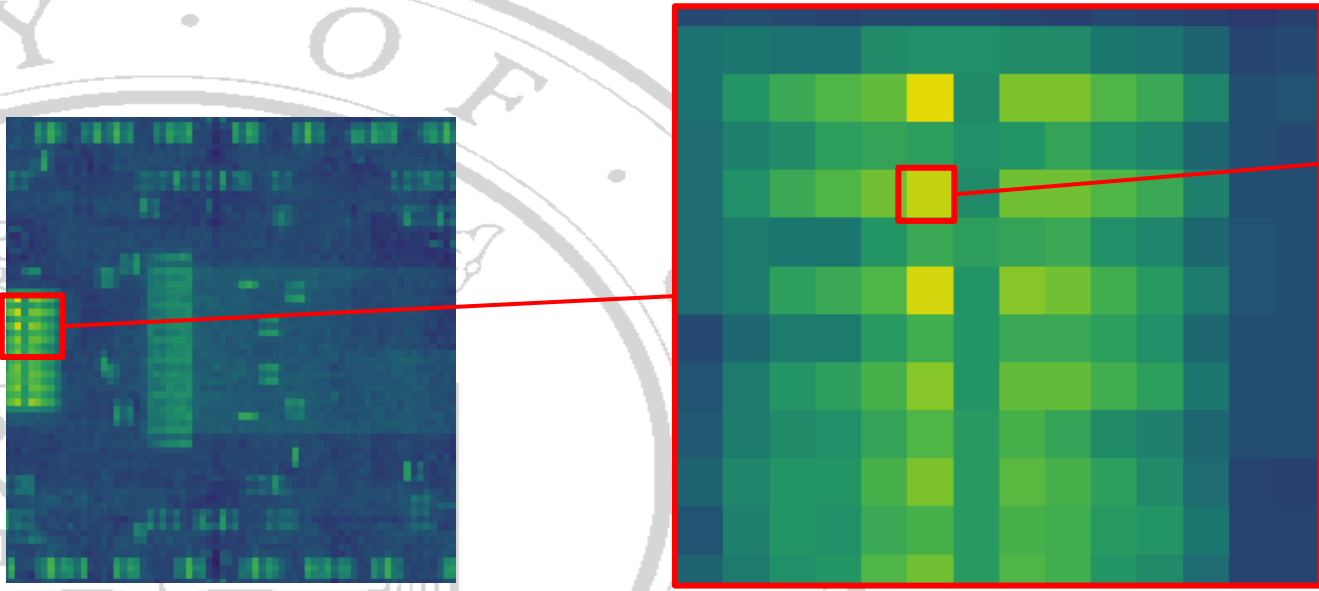
- MONSTAR: low- X_0 telescope to measure multiple scattering of e^+
 - MALTA monolithic pixel sensors, 512x512, 36.4 μm pixel pitch
 - Middle plane thickness down to 50 μm , with PCB cutout
 - DUT on x-y linear stage as central plane
 - Long (~ 1 m) lever arm, allowing for passive material measurement
 - Angular resolution better than 1%



2023 First Measurement



- Previous measurement with 1.2 GeV e^+ at CERN PS (May 2023)
 - Purity: $> 99\%$ e^+
 - Rate: 6 k e^+ per spill; 2-3 spills per 40 s
 - DUT: ATLAS ITkPix Quad Module, 4 x 4 cm²
- Projected distributions θ_x, θ_y fitted by double-sided crystal ball function



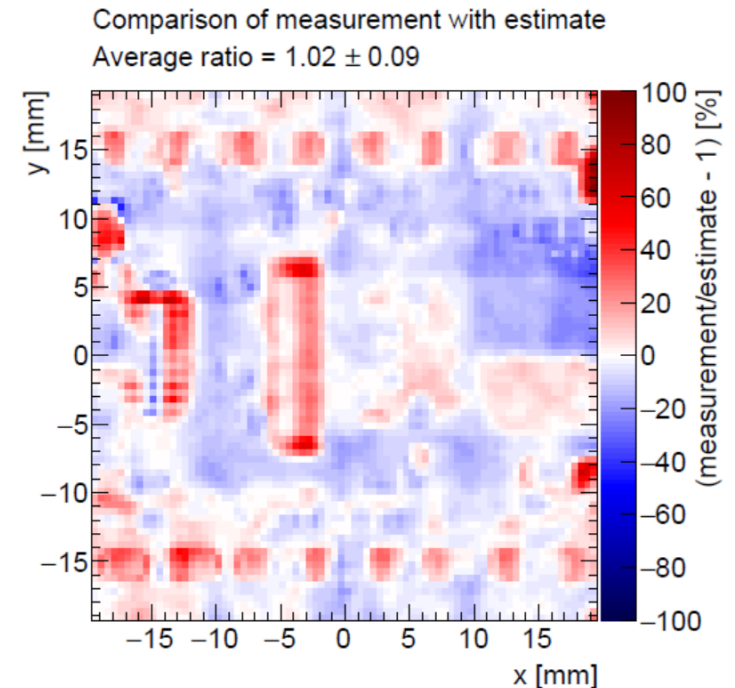
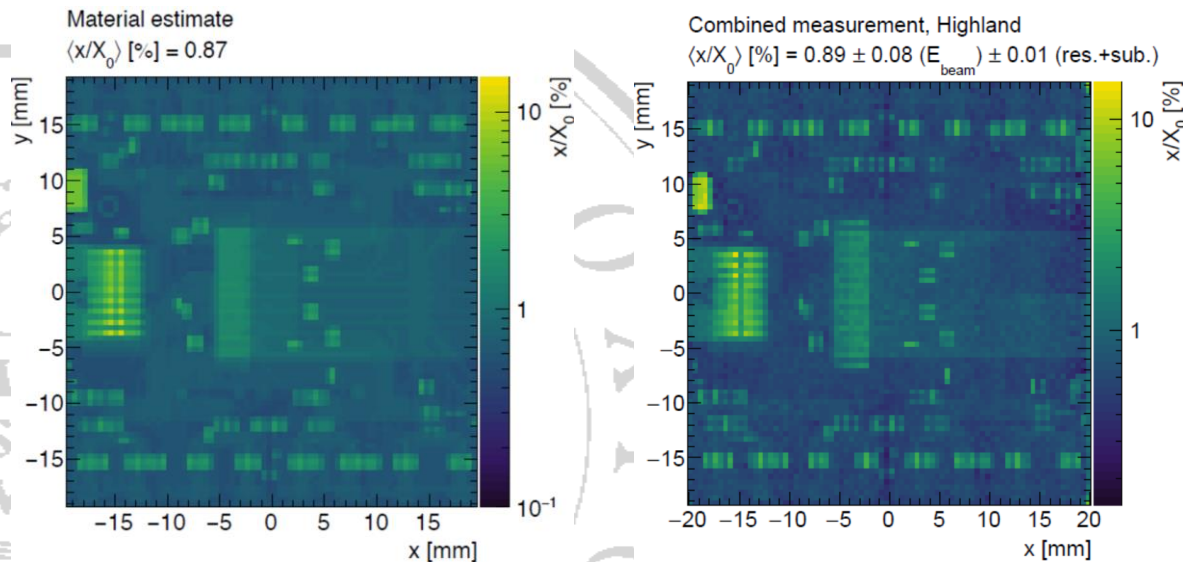
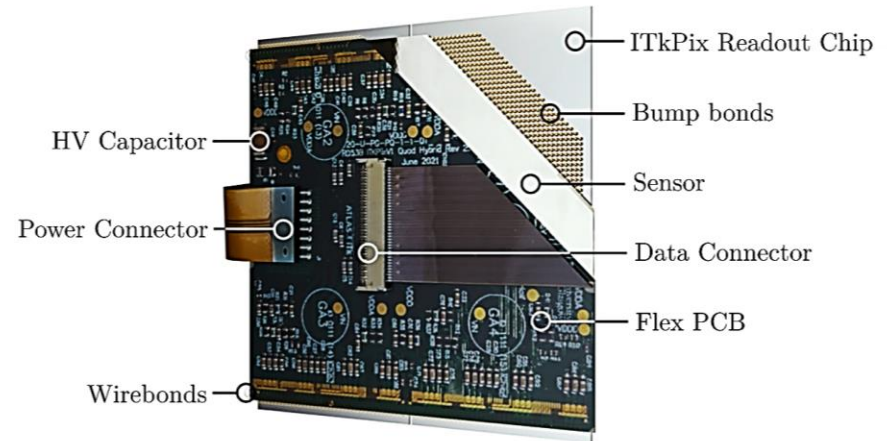
[7] MONSTAR

2023 First Measurement



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- Result showed good agreement with estimate
 - Estimate directly from PCB design files and product data-sheets for this module
 - Sub-mm resolution, $O(10\%)$ uncertainties
- Dominant uncertainty: beam momentum band, 5% FWHM
- Limiting factor: low positron rate



For methodology used see:
[7] MONSTAR

2024 PSI PiM1 Measurement

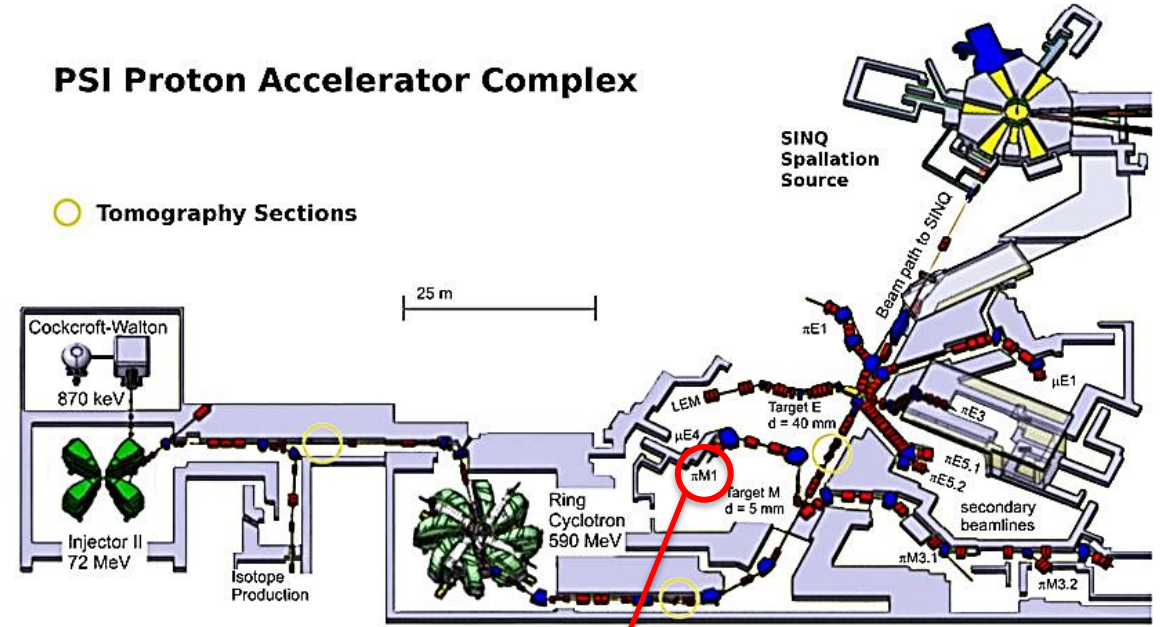


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- Follow-up measurement on detector modules and support structures, Oct 2024
- PSI PiM1 beamline, 117 MeV beam
 - Continuous 10 kHz rate
 - Momentum band upper bound: 1σ of 0.44%
- Modified MONSTAR telescope geometry due to lower energy
 - ~ 20 cm overall length
- Measured $> 550 \text{ cm}^2$ of on-detector PCBs, pixel detector modules, calibration samples
- Collaboration with ATLAS, CMS, mu3e, Oxford, ETH Zurich
 - No results from collaborations will be shown
 - Paper planned for later in 2025

PSI Proton Accelerator Complex

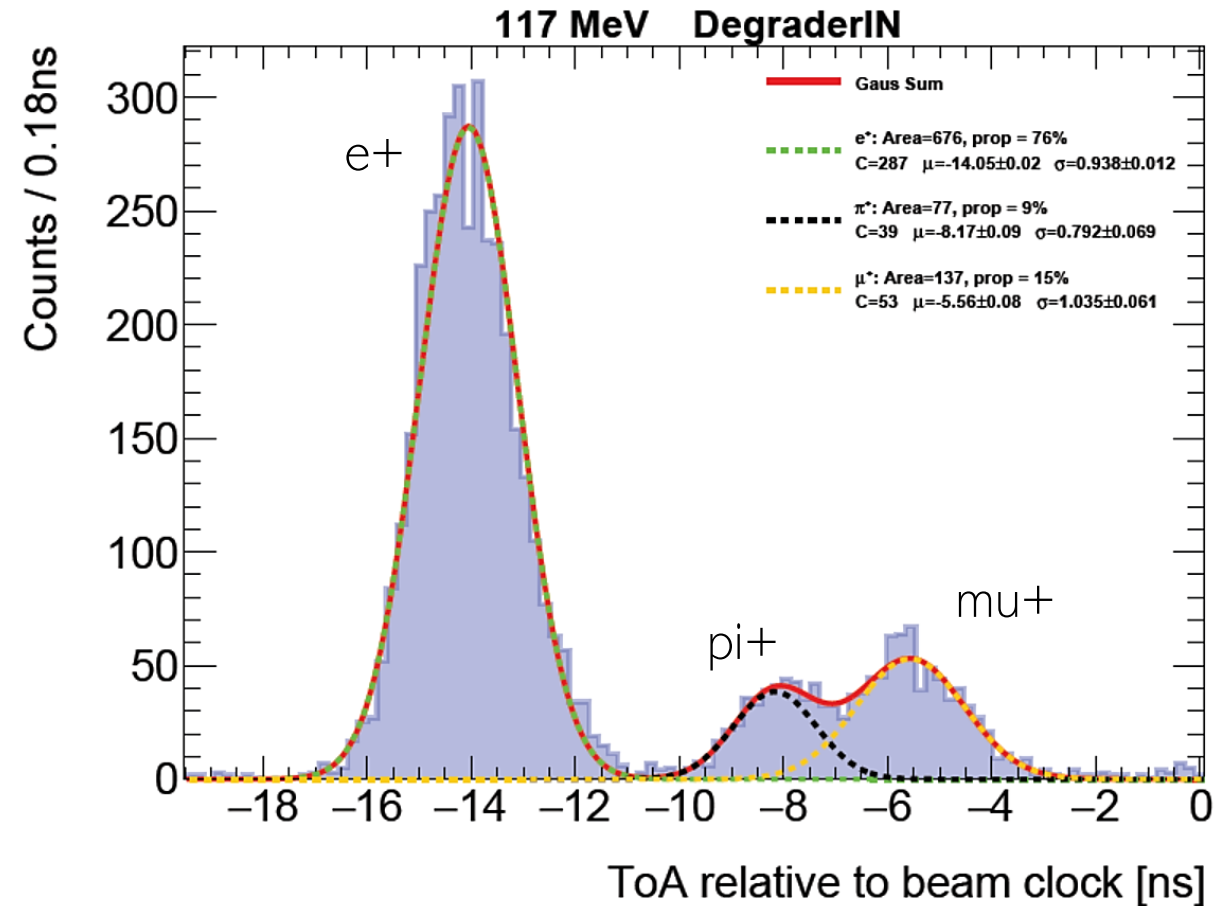
○ Tomography Sections



2024 PSI PiM1 Measurement



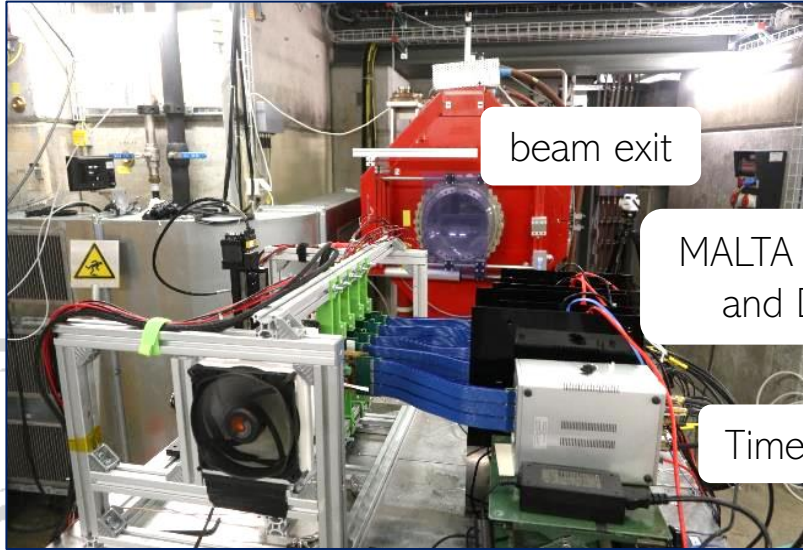
- New challenge: mixed beam (π and μ components)
 - Scattering models dependent on scattering species
- Solution: measuring Time-of-Flight (ToF)
 - Flight length from beam target ~ 24 m
 - Expected ~ 5 ns separation between species, once accounted for beamclock periodicity
 - Need ns-event tagging at high rate



2024 PSI PiM1 Measurement



Need ns-event tagging at high rate: Timepix4 as a timing plane

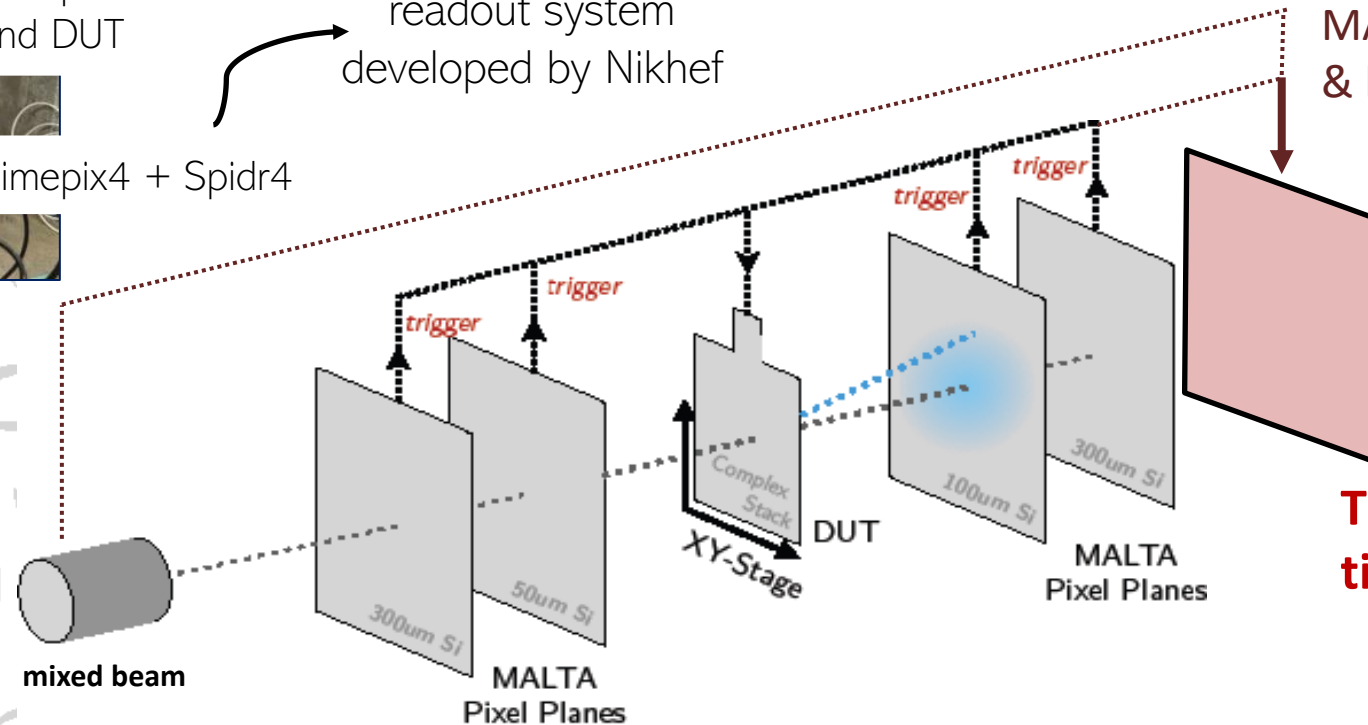


Modified MONSTAR

hybrid, placed at end of telescope

readout system developed by Nikhef

MALTA event trigger & beamclock



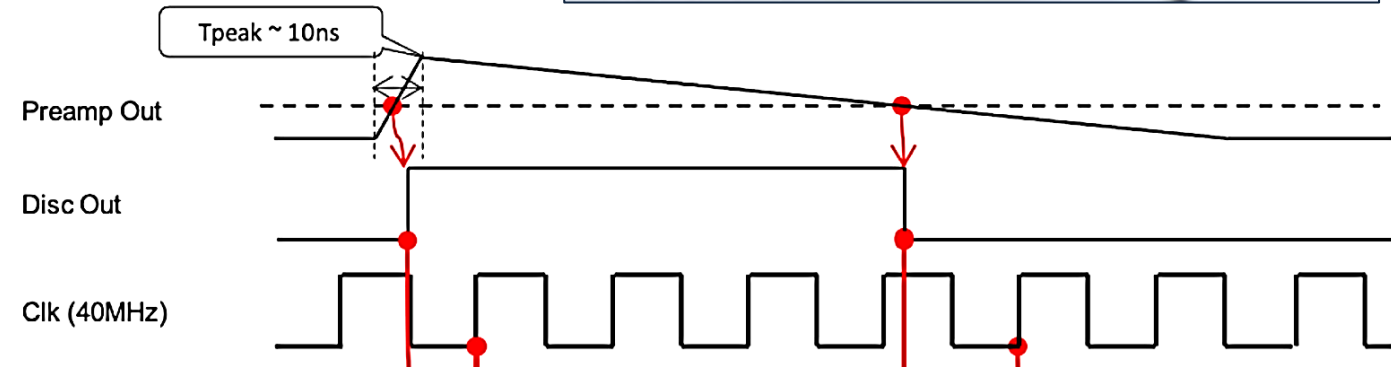
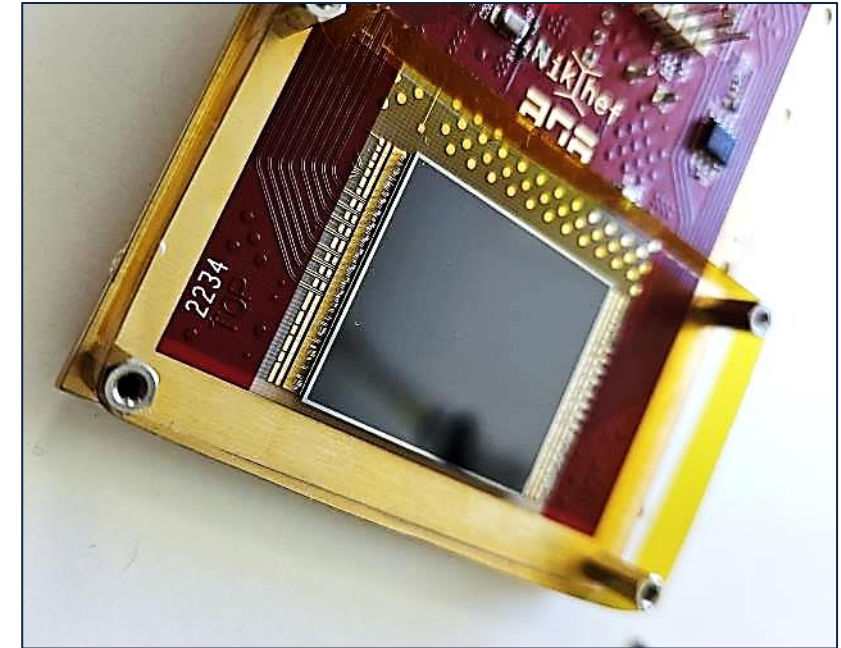
Timepix4 as a timing plane



Timepix4

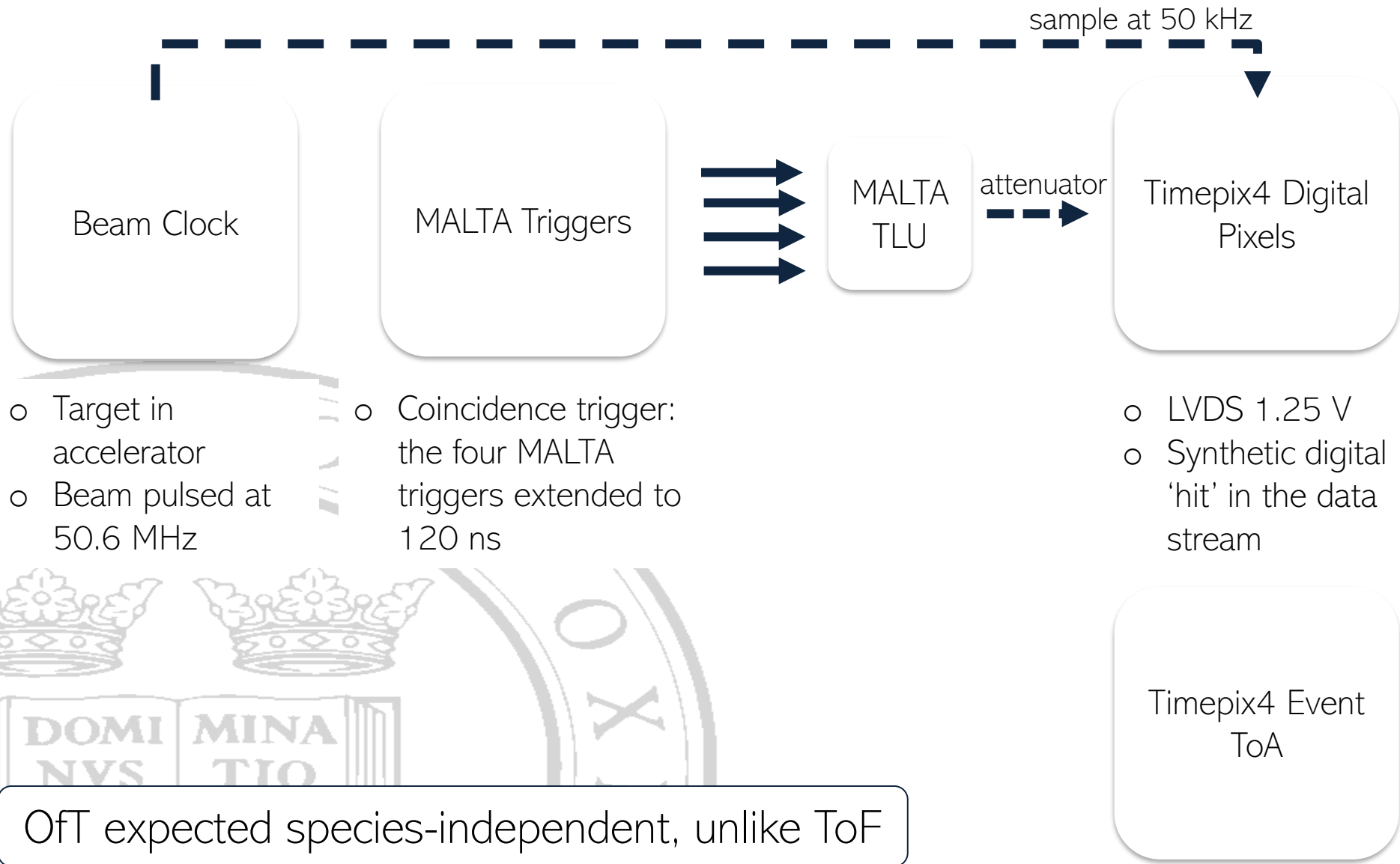


- Timepix4 hybrid pixel ASIC bump-bonded to a 300 μm p-on-n Si sensor
 - Spidr4 readout system
 - 448 x 512, 55 μm pixels
- Data-driven readout
 - 5.12 Gbps readout rate, 90 khits/ mm^2/s
 - Digital pixel input
 - Per-hit, per-pixel information
- Time over Threshold (ToT)
 - Measure of the number of electrons collected by the pixel
 - $\sim 700 e^-$ FWHM in sensor
- Time of Arrival (ToA)
 - 195 ps hit-binning
 - Allows for extraction of Time of Flight (ToF) with respect to the beamclock



[8] Timepix4

Event Time Reconstruction



- Target in accelerator
- Beam pulsed at 50.6 MHz

- Coincidence trigger: the four MALTA triggers extended to 120 ns

- LVDS 1.25 V
- Synthetic digital 'hit' in the data stream

Time of Flight

- ToA – Beam Clock
- ~ 24 m flight
- Wrap-back: pions arrive in following beamclock cycle

Offset from Trigger

- MALTA Trigger – ToA
- Delayed, after Timepix4 event
- ~ 20 cm flight

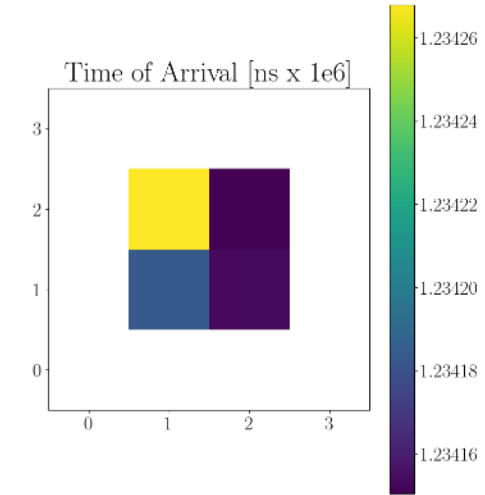
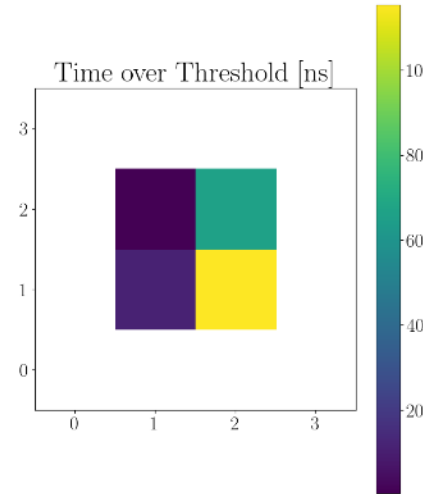
OfT expected species-independent, unlike ToF

Event Identification in Timepix4



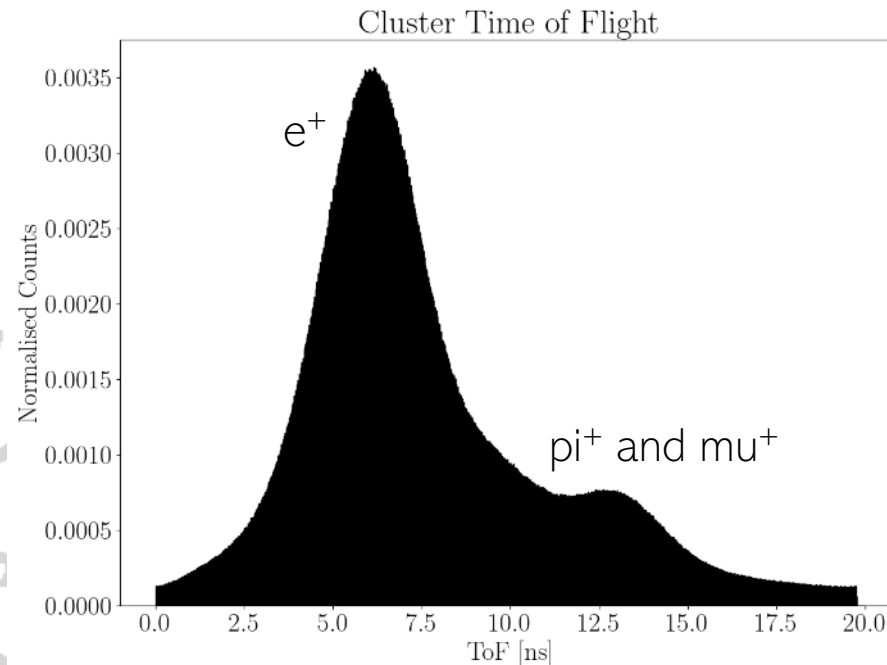
o Event identification

- MALTA coincidence trigger > 90% efficiency
- Event cluster in Timepix4: all neighbouring pixels with ToA within 100 ns
- Define the **event 'seed'** as the pixel with highest ToT (most charge): perpendicular incidence

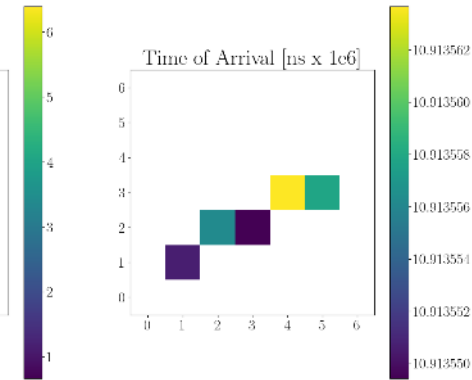
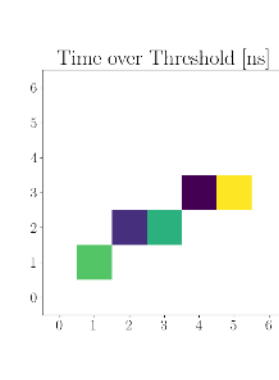


o Time of Flight (ToF)

- Of cluster seed, wrt beamclock



Raw ToF measured by Timepix4:
wide positron peak



Cluster size and shape selection to exclude delta-rays;
98.9% of events retained.

Improving Time of Flight Measurement

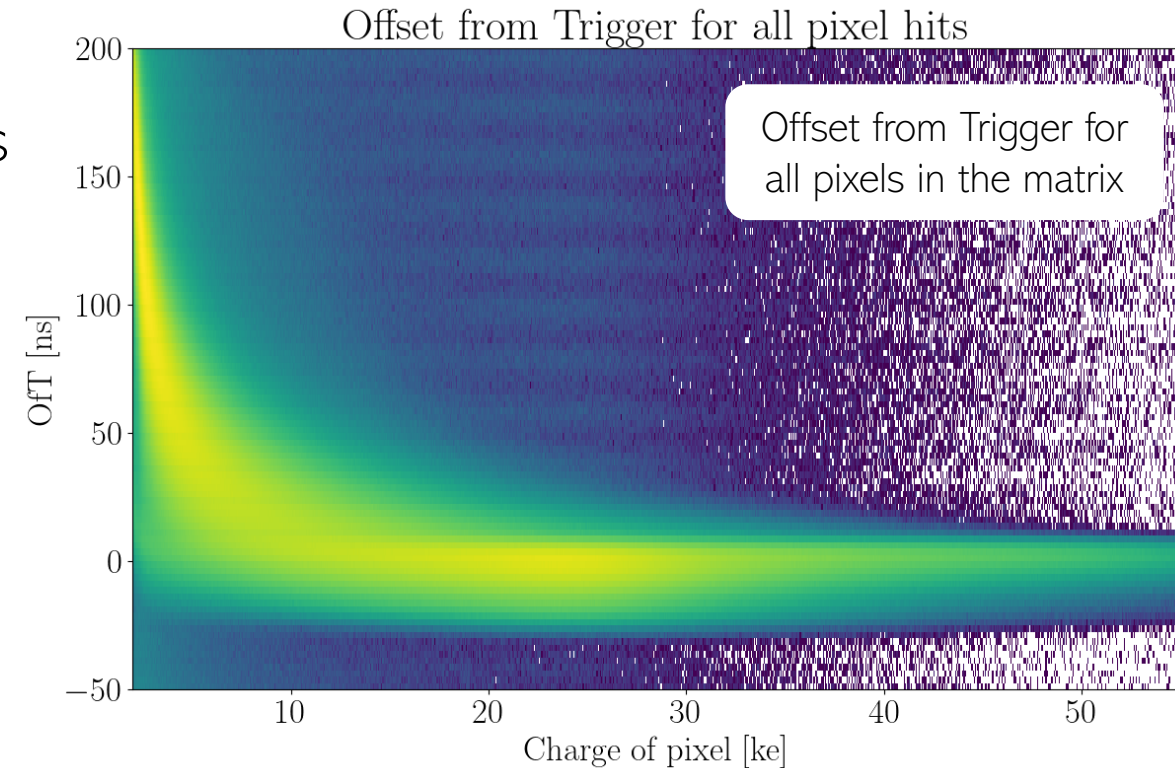


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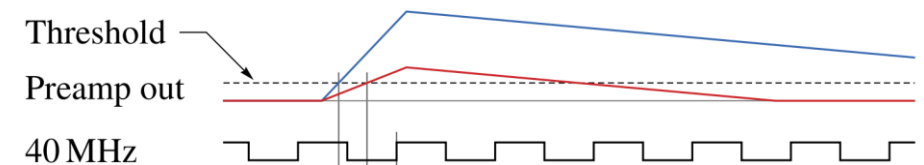
ToF = ToA – beamclock: need **greater accuracy on ToA**

- Measure Offset from Trigger (OfT) of event seeds
 - OfT is assumed species-independent
 - OfT is expected to be constant with ToT
- Front-end performance varies **pixel-to-pixel**
 - **Different ToT response** to fixed deposited charge (amplifier gain variations)
 - **Different ToA response** to fixed deposition time (rise time and shaping variations, clock distribution)
 - **Timewalk** making the ToA measurement dependent on the ToT response

Timewalk: variation in the measured time of detection (ToA) between events with different signal pulse amplitudes (ToT)



[8] Timepix3 VELO



Obtaining a Corrected Time of Flight



Per-pixel
ToT-charge calibration

pixel electronics

DOMI
NVS
ILLV

MINA
TIO
MEA

Per-pixel
OfT correction

pixel electronics
+
ToT response



More accurate ToF

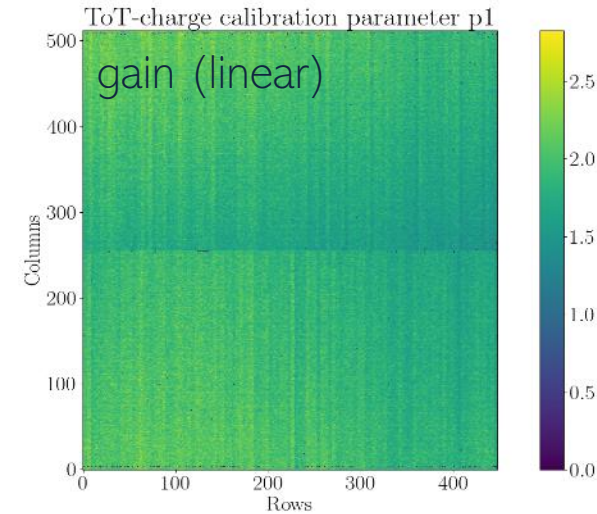
ToA measurement

Per-pixel ToT Calibration

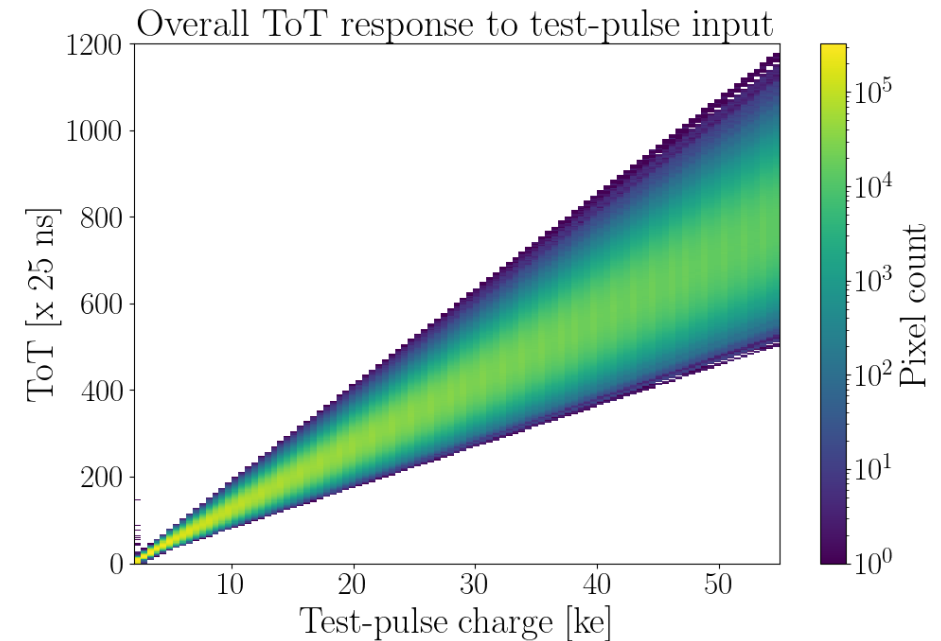
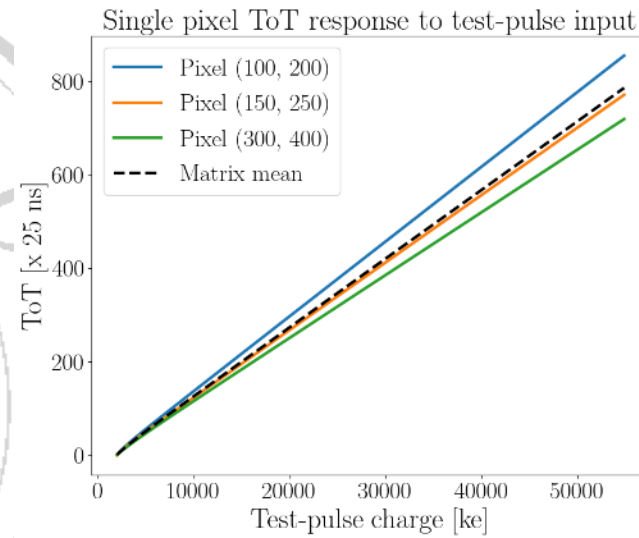
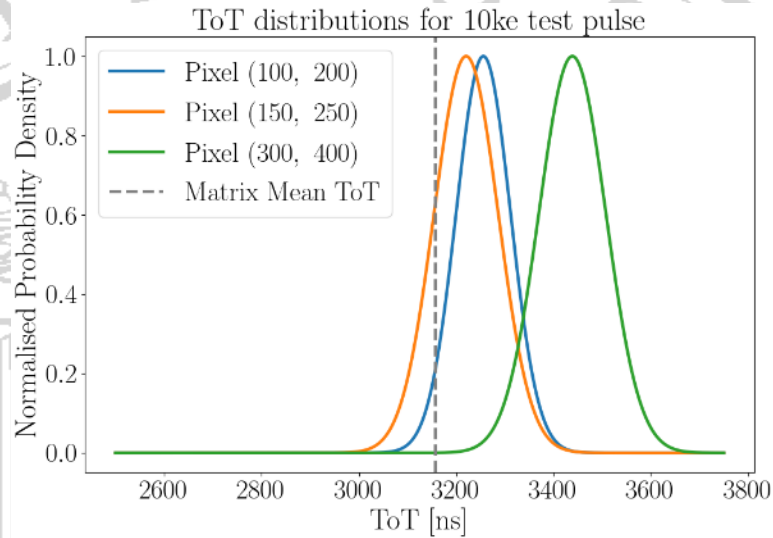


- ToT-charge calibration
 - Test-pulses: charge injected into the pre-amp, avoiding sensor effects
 - Std. dev. ~ 1 us ToT @ 30 ke input

$$ToT = p_0 + p_1 q - \frac{p_2}{q - p_3}$$



Variation of the conversion gain p_1 across the chip

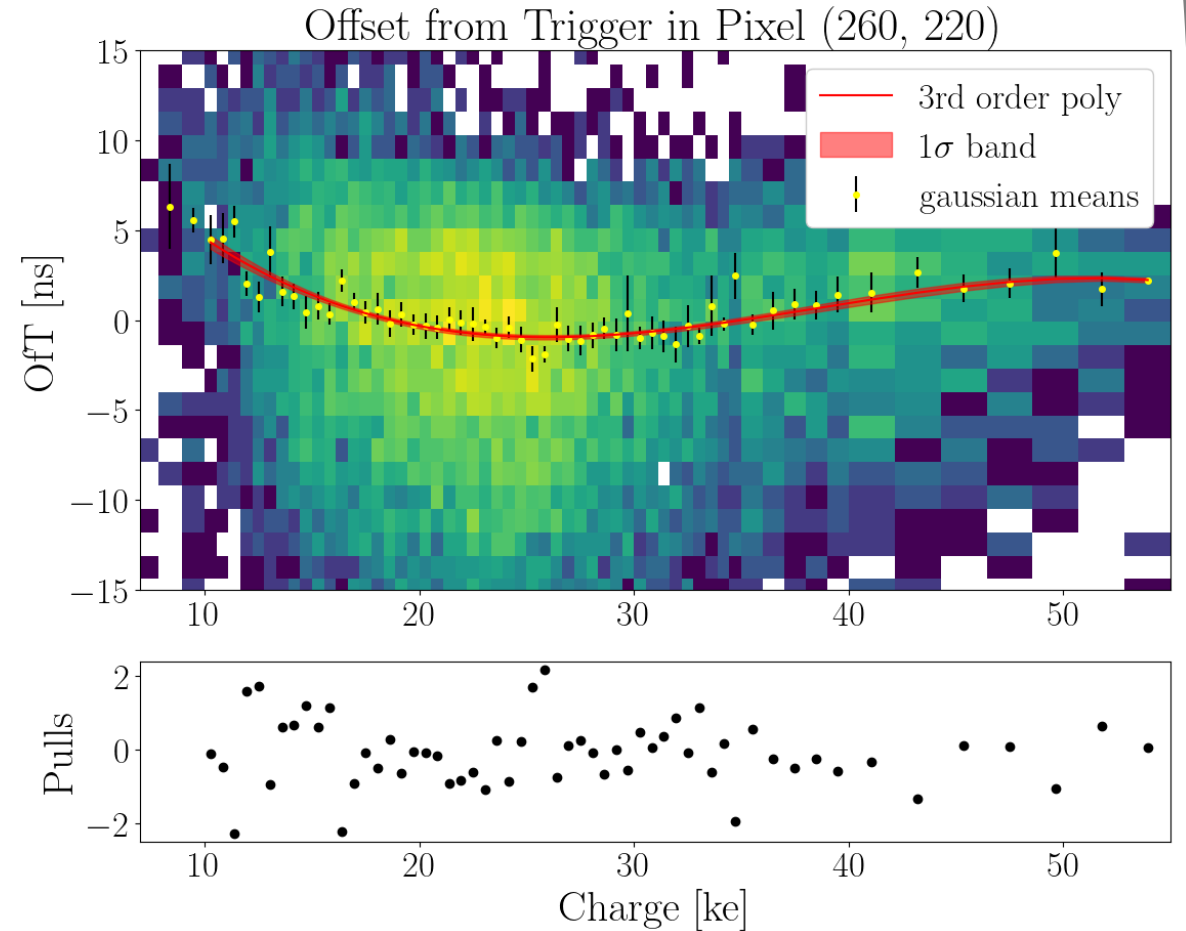


Per-pixel ToA Correction

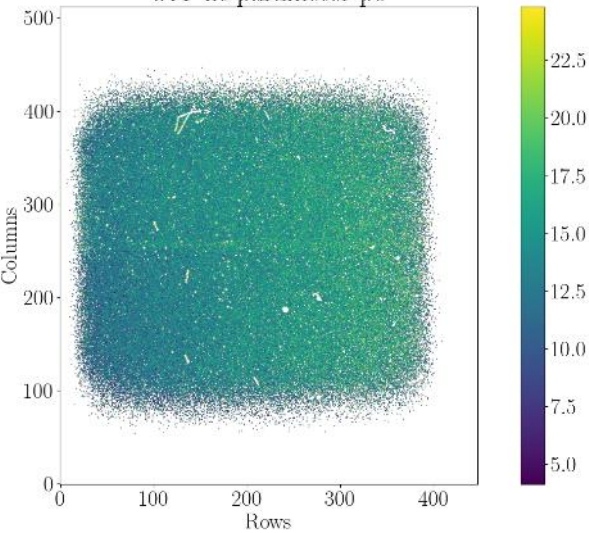


- Using testbeam data
- **Low-ToT**: time residual behaves as expected for timewalk in the analog front-end
 - OfT corrected to be constant with ToT
- **High-ToT**: additional effects
 - Species dependence

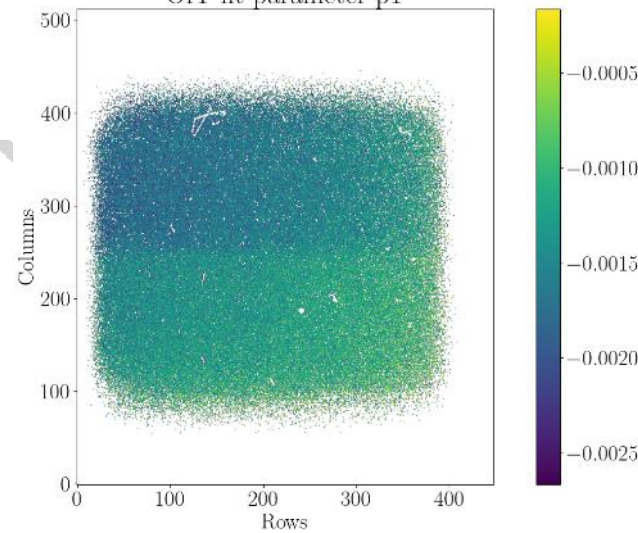
pions and muons with higher energy loss



OfT fit parameter p0



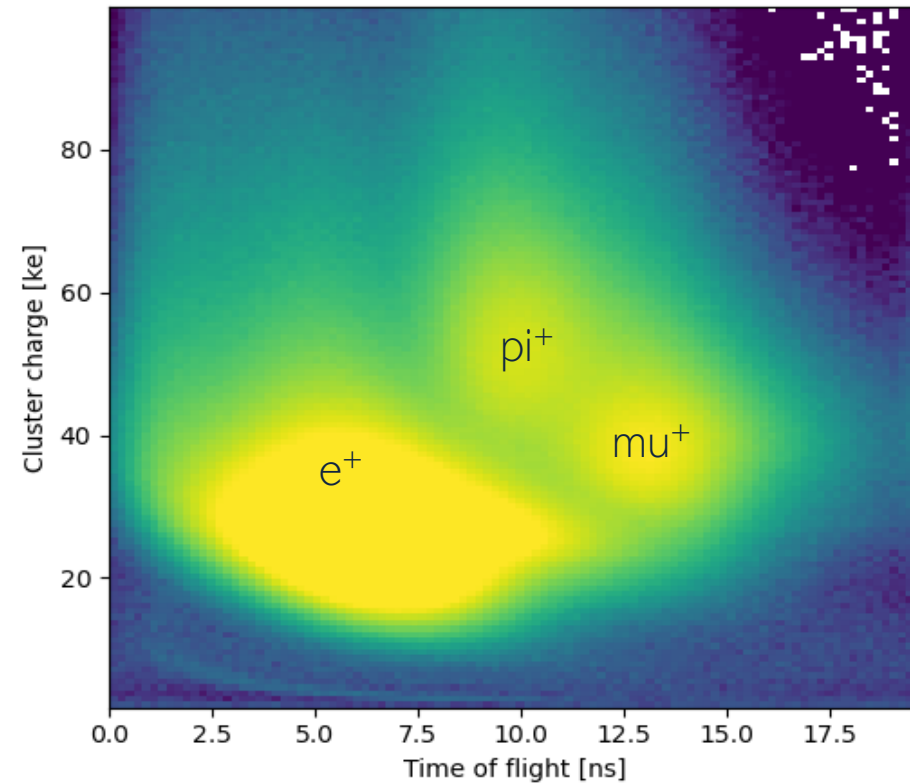
OfT fit parameter p1



Time of Flight Distribution



- Particle identification (PID)
- Smearing positron peak
 - Correct lower energy end, affected primarily by timewalk
 - Pixels with charge up to 25 ke

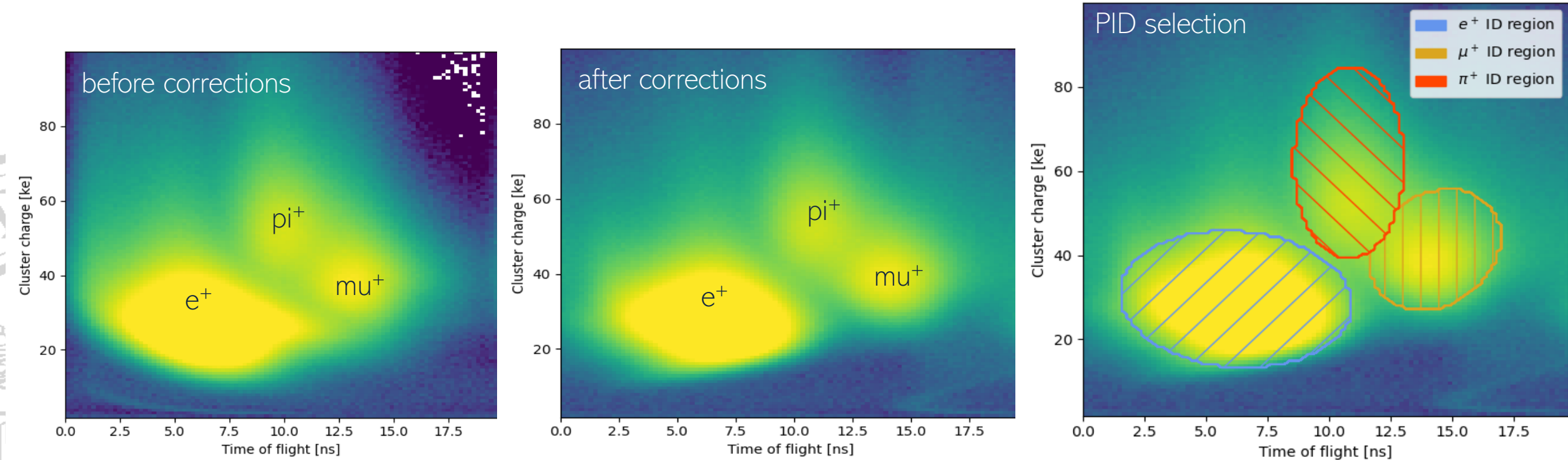


Corrected Time of Flight



PID: 82.95% positrons (8.96% muons, 8.09% pions)

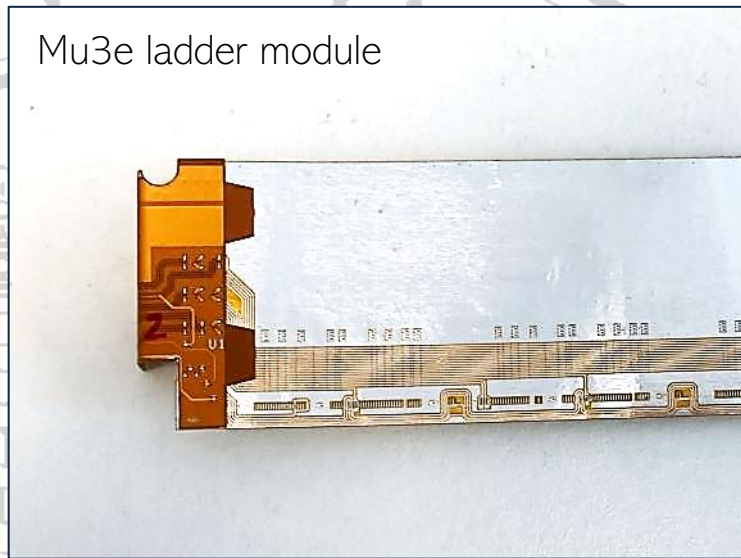
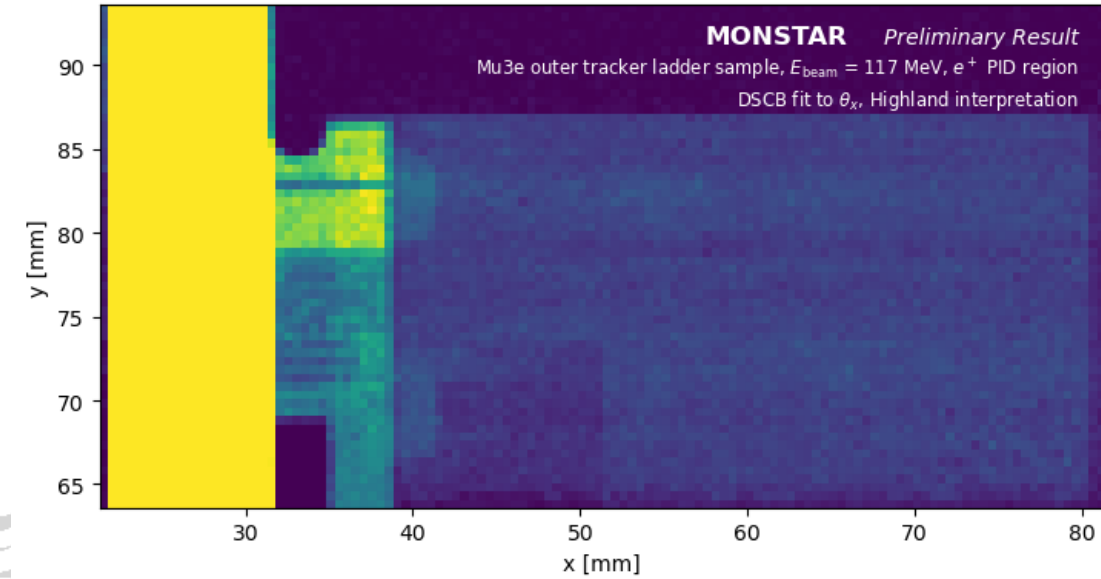
of particles in identification regions, 11.2% of all detected events not identified



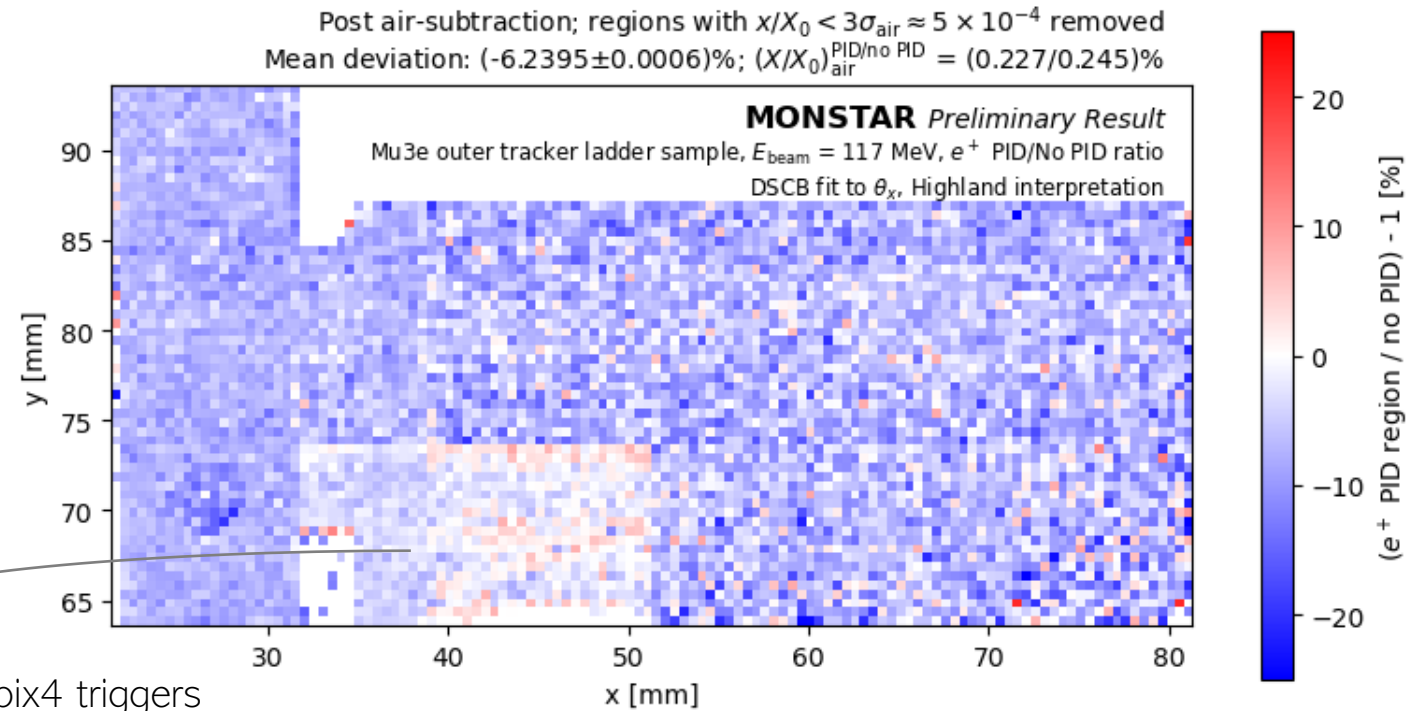
Mu3e Outer Tracker Ladder Sample



Mean deviation in fractional radiation length x/X_0
with PID vs without PID $\sim 6\%$



Issue with Timepix4 triggers



Conclusions



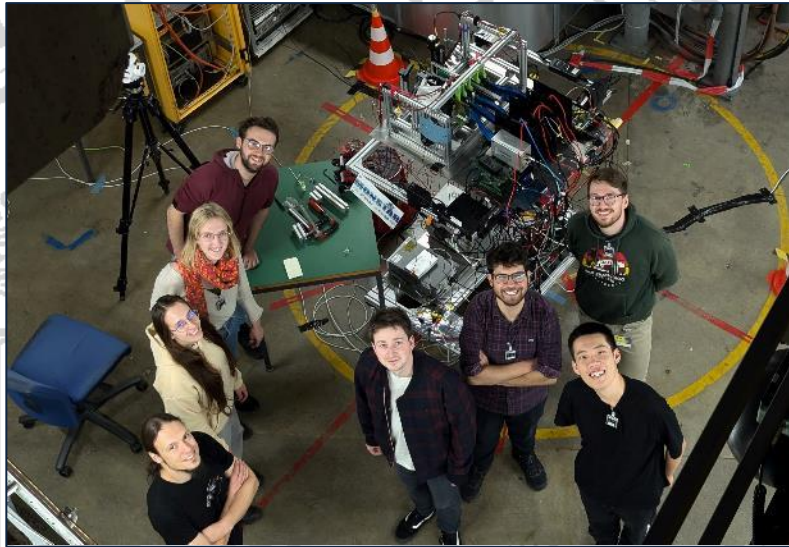
- **MONSTAR telescope** measuring positron multiple scattering to estimate fractional radiation length of material in detector modules
- Recent measurement at **PSI PiM1**, mixed species beam
- **Timepix4 for Particle ID**
 - Needs careful calibration for best performance
- Per-pixel ToT-charge calibration using test pulses
- Per-pixel ToA correction
 - Effects beyond timewalk
- Data taken with calibration samples, ATLAS and CSM pixel modules, ATLAS interconnect PCBs, ATLAS half ring passive material, mu3e outer system ladders
 - > 550 cm² in a week
 - 3mil events per cm² (1.5bil events in total)

Thank you



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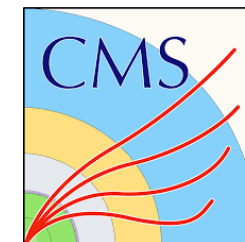
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References



- [1] Mapping the material distribution of a complex structure in an electron beam
<https://doi.org/10.1088/1748-0221/16/01/P01010.arXiv:2105.10128>
- [2] Analysis of pixel detector material budget based on test beam <https://doi.org/10.1088/1748-0221/16/06/T06004>
- [3] Measurement of the fractional radiation length of a pixel module for the CMS Phase2 upgrade via the multiple scattering of positrons <https://doi.org/10.1088/1748-0221/19/10/P10023.arXiv:2407.13721>
- [4] An Imaging Technique Using Very-high Energy Electrons <https://arxiv.org/abs/2409.20091>
- [5] Particle Data Group, Review of particle physics. Prog. Theor. Exp. Phys. 2022(8), 083-01 (2022)
- [6] Approximations to multiple Coulomb scattering [https://doi.org/10.1016/0168-583X\(91\)95671-Y](https://doi.org/10.1016/0168-583X(91)95671-Y)
- [7] Measuring the ATLAS ITk pixel detector material via multiple scattering of positrons at the CERN PS <https://doi.org/10.1140/epjc/s10052-025-14092-2>
- [8] Timepix4, a large area pixel detector readout chip which can be tiled on 4 sides providing sub-200 ps timestamp binning <https://doi.org/10.1088/1748-0221/17/01/C01044>
- [9] Timing performance of the LHCb VELO Timepix3 Telescope <https://doi.org/10.48550/arXiv.2008.04801>



Backup



We've also validated against simulations and alternate models and they agree to $\sim 5\%$.

The Bethe prescription of Molière theory [2] provides robust modelling of multiple soft electromagnetic scatters of charged particles, with accuracy generally to within 1% observed in experiment [10]. The distribution of scattering angles projected onto a reference plane comprises a Gaussian core that carries over to the Rutherford formula at large angles, and a correction. Due to the analytic complexity of pure Molière theory, Highland et al. [11] performed a fit to the theory to derive an expression for the central Gaussian core. The modern revised version by Lynch and Dahl [15] gives the root-mean-square (RMS) projected scattering angle of the central Gaussian for particles of a given speed βc , momentum p , and charge z along a trajectory of length x through a scatterer with radiation length X_0 as

$$\Theta := \theta_{\text{plane}}^{\text{RMS}} = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{x/X_0} (1 + 0.038 \ln(x/X_0)). \quad (1)$$

The fractional radiation length can be calculated from a distribution of projected scattering angles by analytically inverting the formula to give

$$\begin{aligned} \frac{x}{X_0} &= \exp\left(2 \cdot W_0(w) - \frac{1}{0.038}\right), \quad \text{with} \\ w &= \frac{1}{2 \cdot 0.038} \exp\left(\frac{1}{2 \cdot 0.038}\right) \frac{\beta c p}{13.6 \text{ MeV} \cdot z} \Theta. \end{aligned} \quad (2)$$

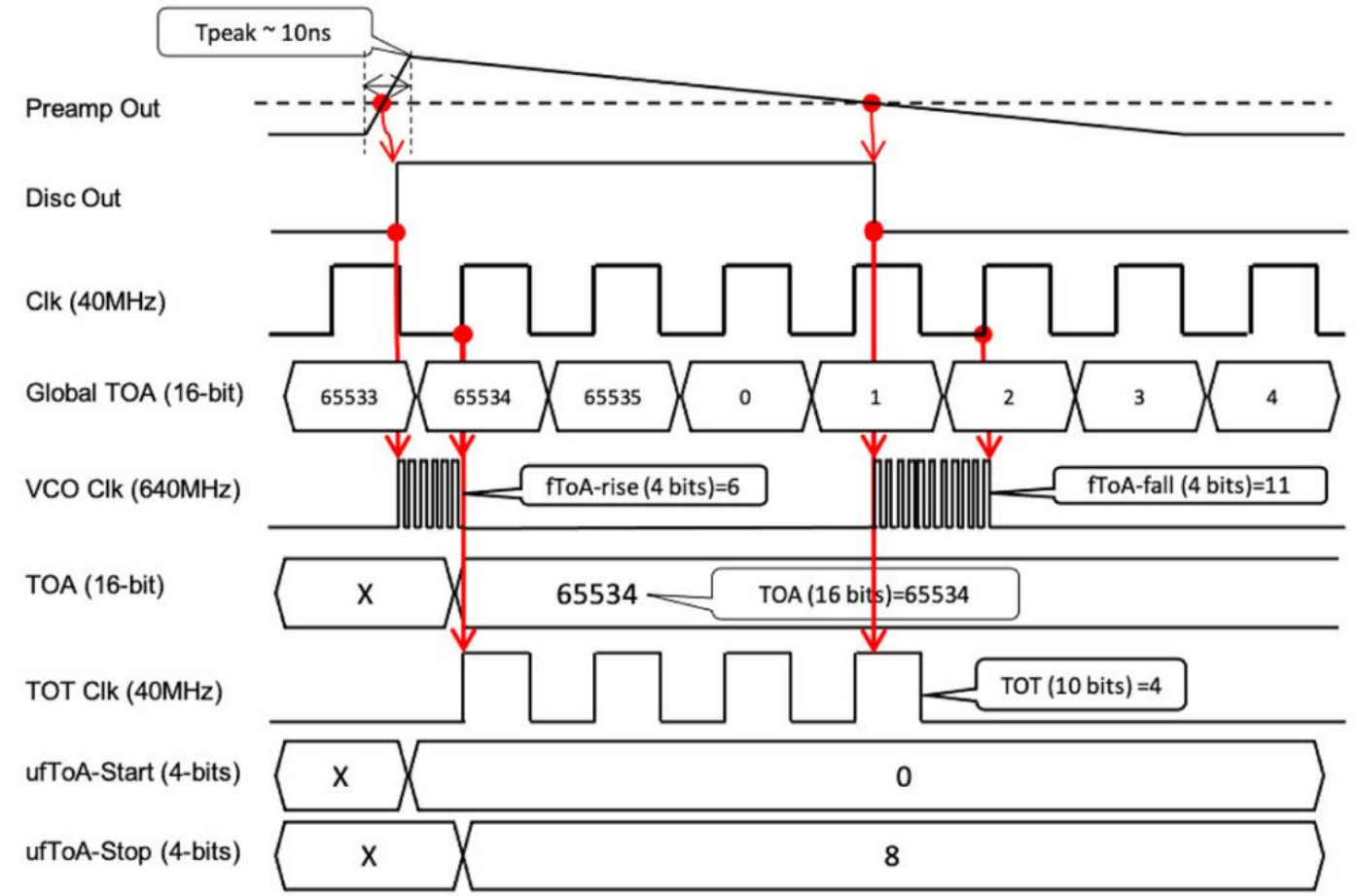
Here, W_0 is the principal branch of the Lambert W function [5].



Time Stamping



[8] Timepix4



Per-pixel Response

- Front-end performance varies pixel-to-pixel
 - Pixel electronics fabrication
 - Different ToT response to fixed deposited charge
 - Different ToA response to fixed deposition time

[8] Timepix4

ToA depends on pixel and ToT
ToT depends on pixel

- Cluster seed (max ToT) chosen to minimise timewalk effect
 - Perpendicular incidence

