3D particle tracking with Timepix3

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on behalf of the

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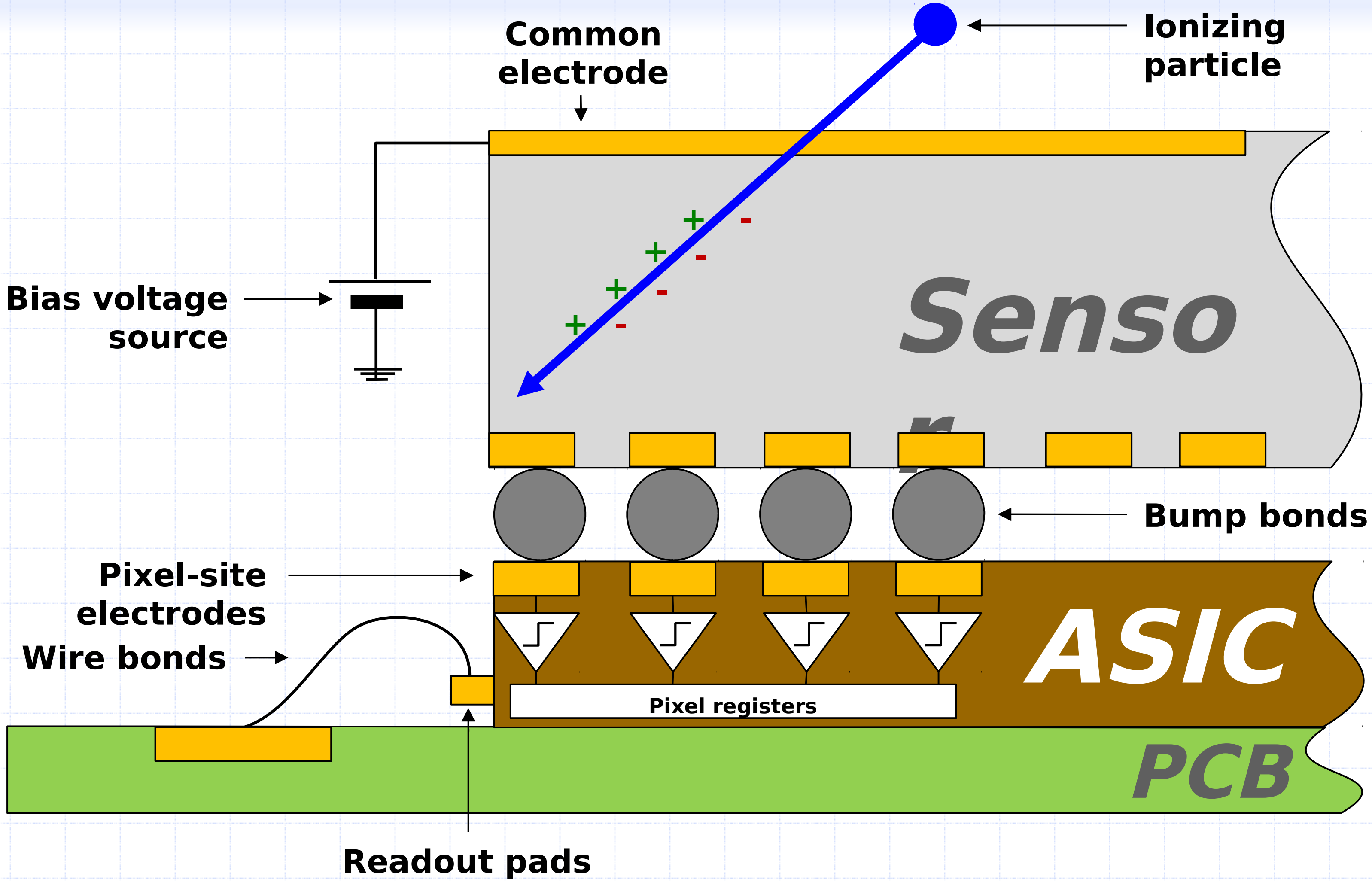
Outline

- Timepix3
- Detector responses to different types of ionizing radiation
- 3D particle tracking with Timepix3 detectors
  - 3D track reconstruction in a 500 µm thick silicon sensor
  - 3D track reconstruction in a 2 mm thick CdTe sensor

Timepix3 detector

- Hybrid pixel detector developed by Medipix collaboration, CERN
- 256 x 256 pixels with 55 µm pitch (1.98 cm^2 sensitive area)
- Minimal detection threshold in each pixel is 1.8 keV
- Each pixel measures energy desposit (ToT) and time of interaction (ToA, precision 1.5625 ns)
- Data driven-readout (data are send on an event-by-event base)

Working principle



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Simultaneous energy and time measurement with the Timepix3

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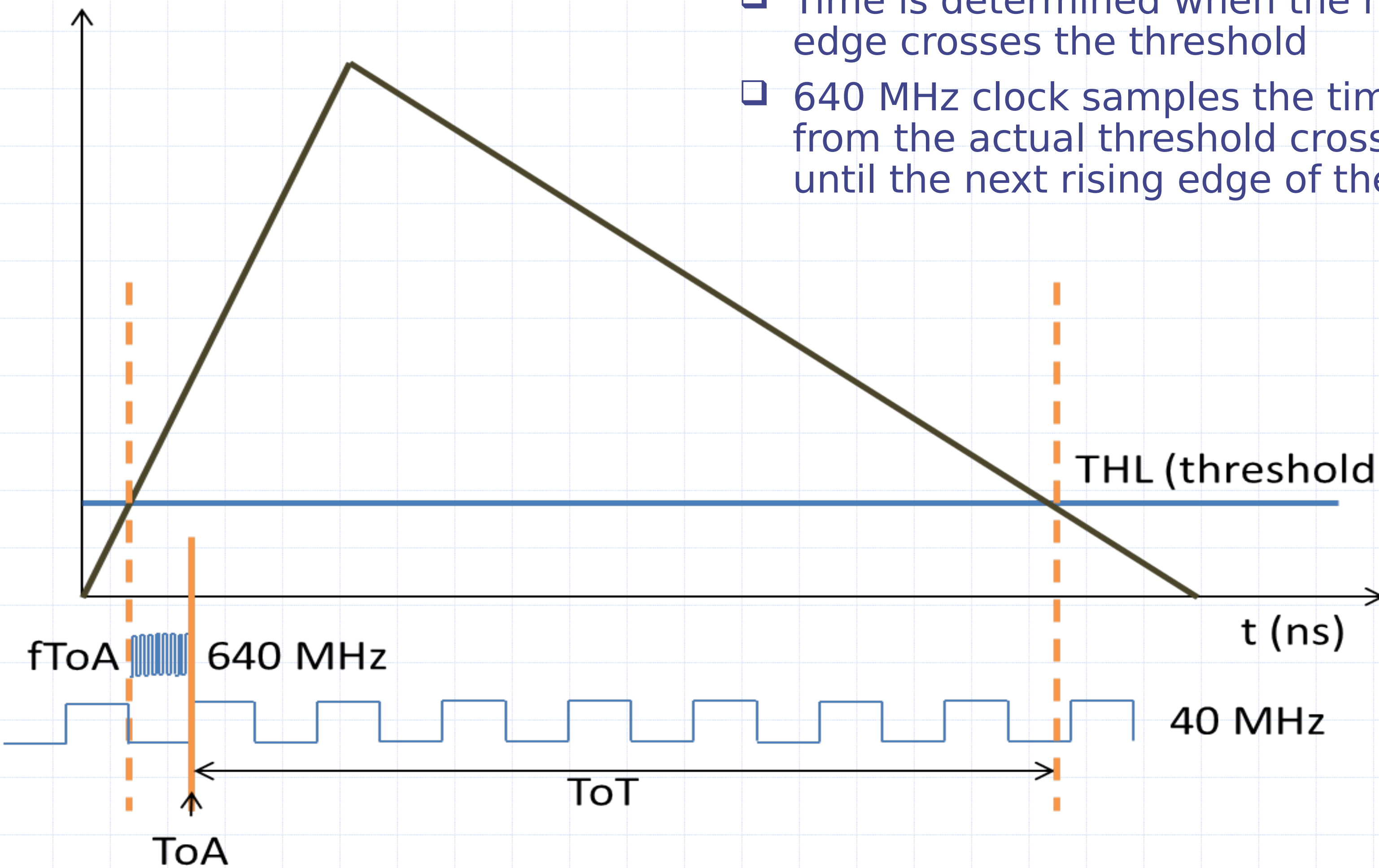

- Time is determined when the rising edge crosses the threshold
- 640 MHz clock samples the time from the actual threshold crossing until the next rising edge of the sToA

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Detector responses to different types of ionizing radiation

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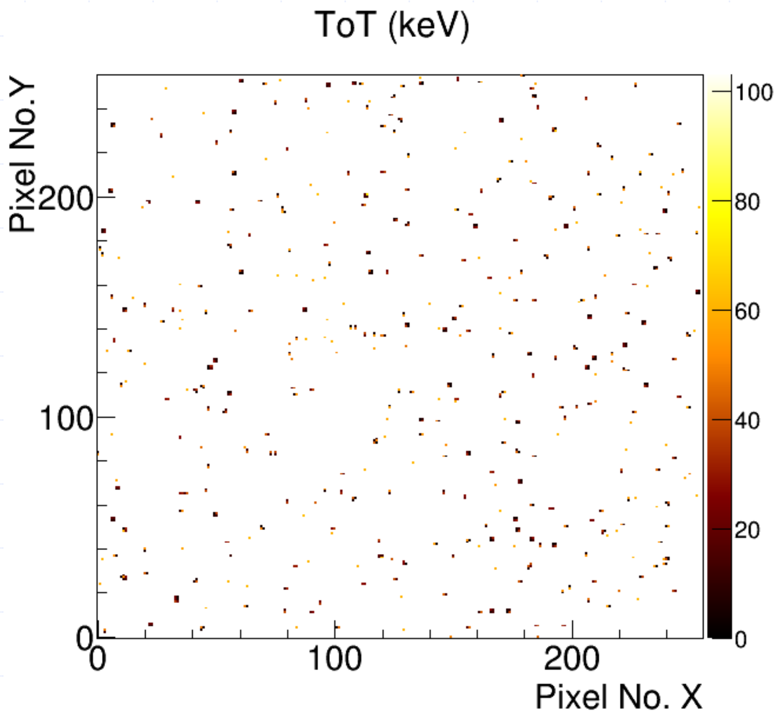
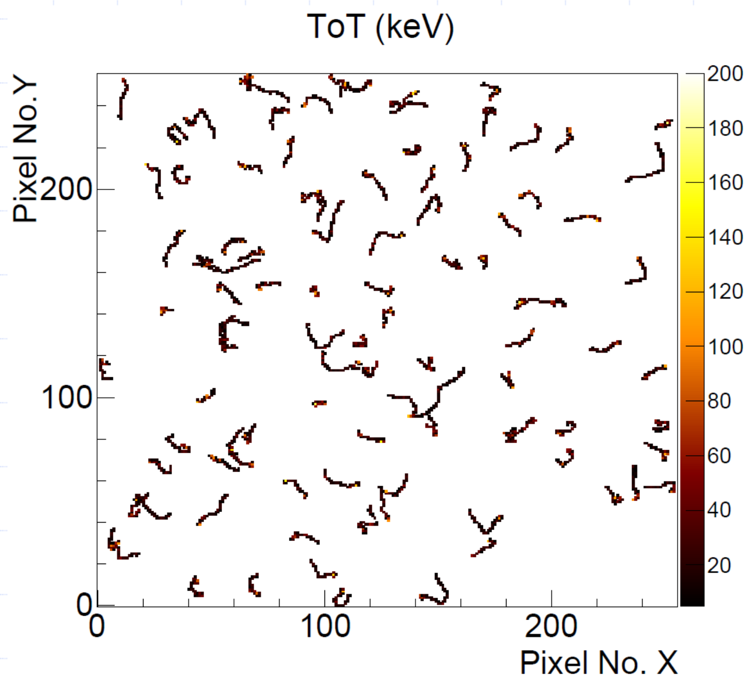
Photons and electrons

- X-rays and gamma interaction in the sensor creates photo- and compton electrons

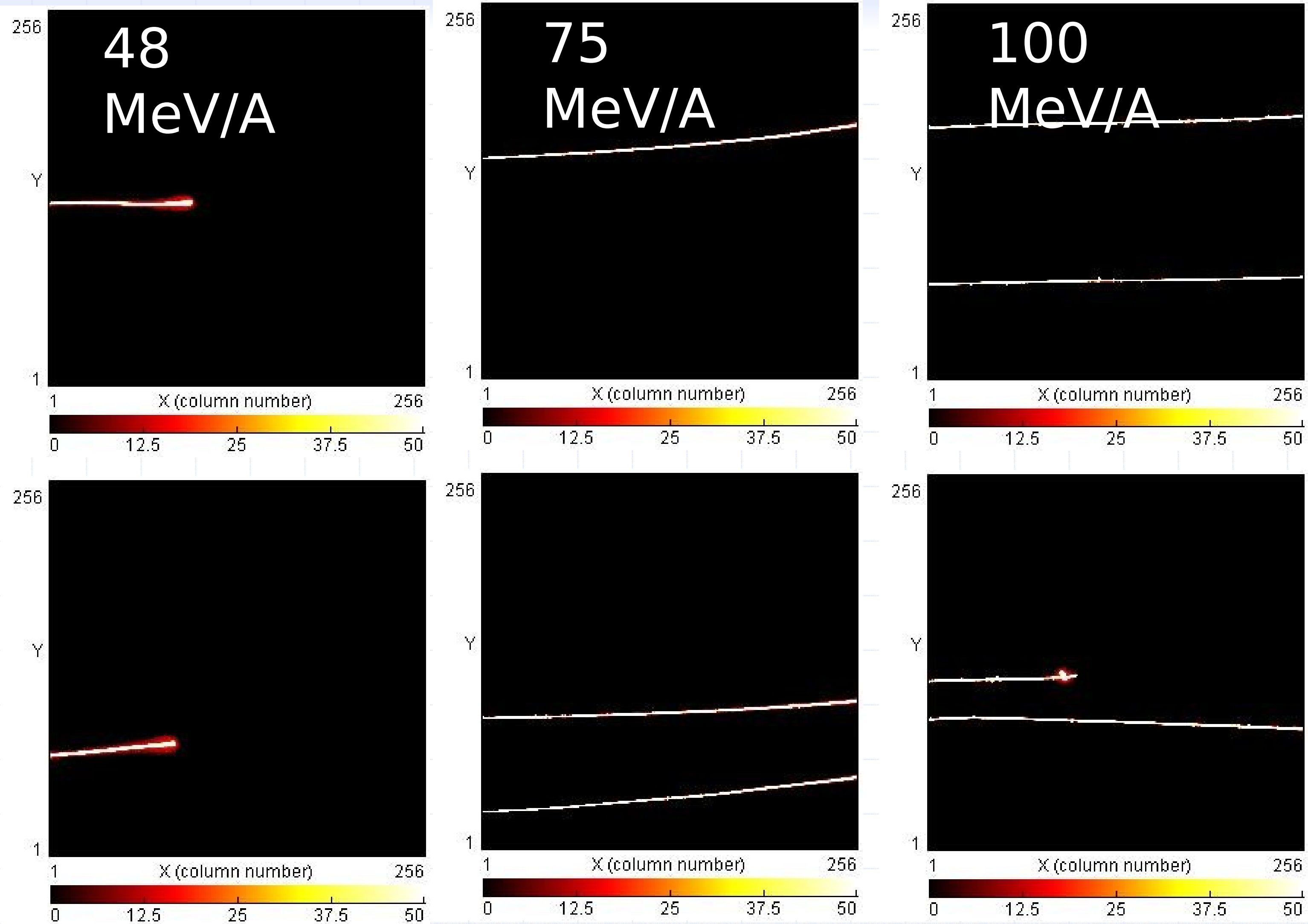




Photons of 60 keV

~ 830 keV electrons

Protons with different energies: 90 degree



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Alphas with different energies: 90 degrees

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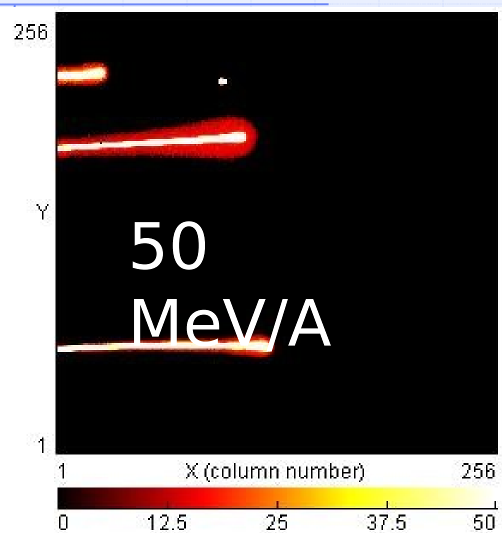

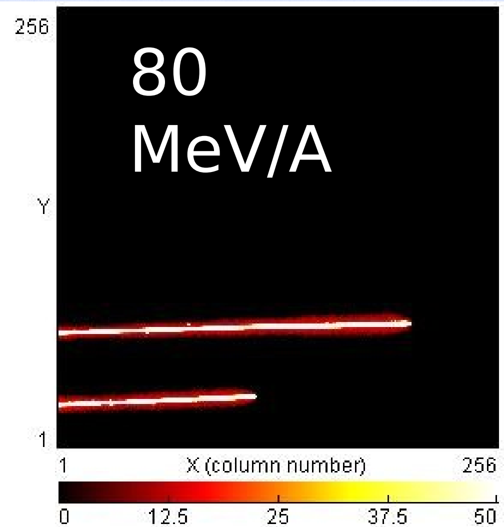

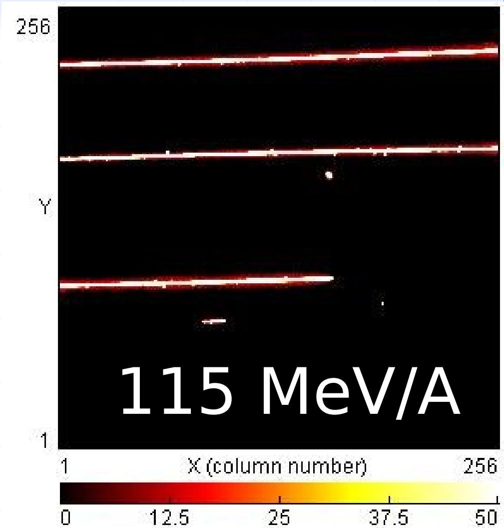

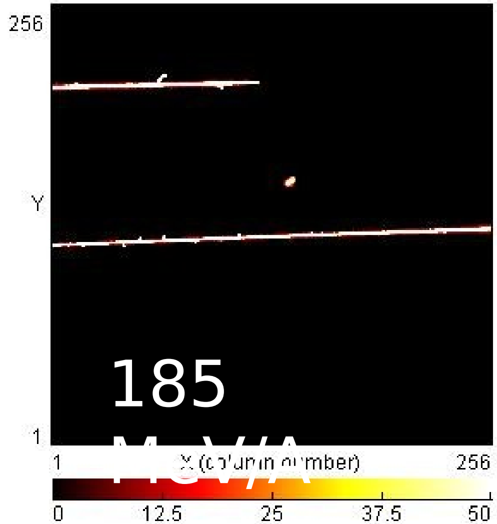

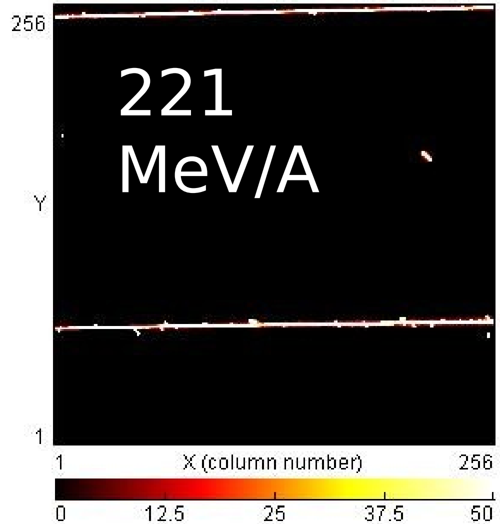

Bragg-peak (50 MeV/A alpha particle entering from the side)

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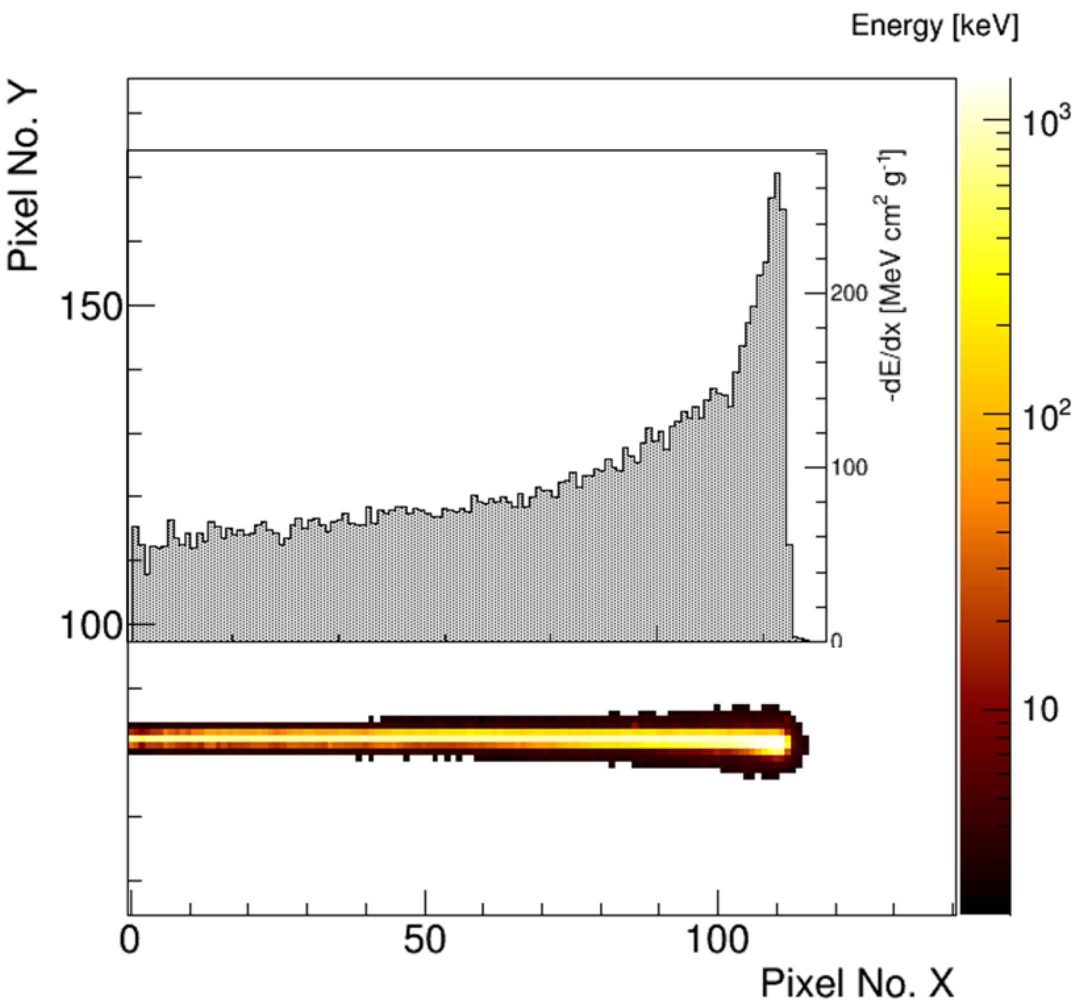
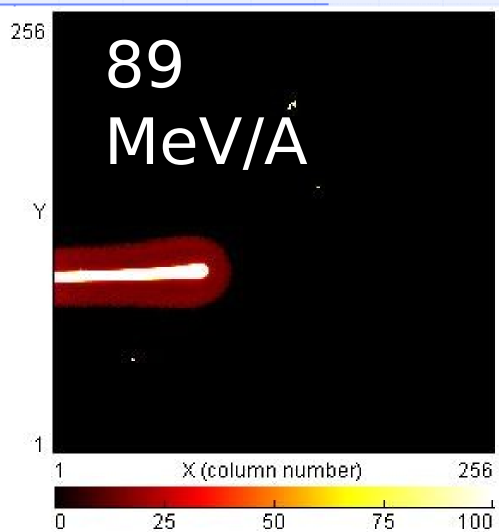
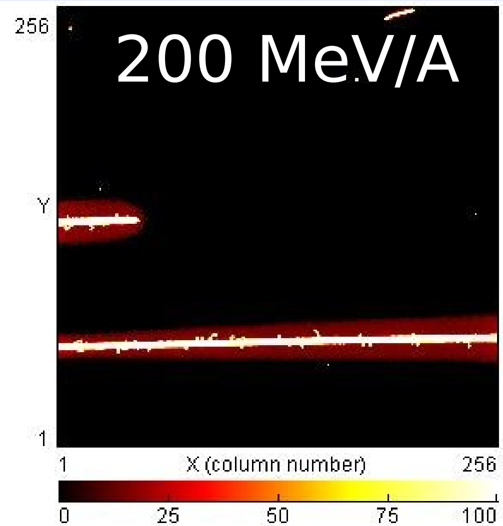


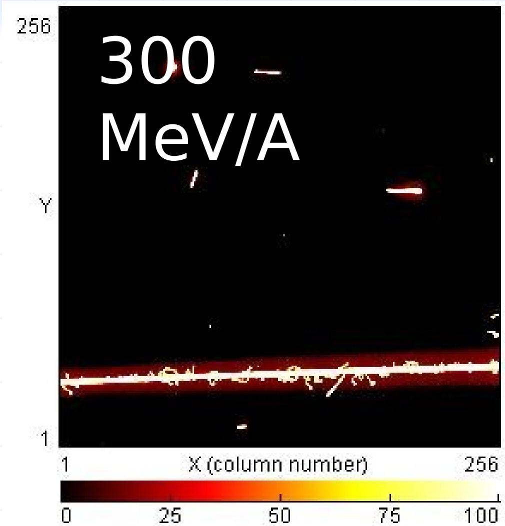
At the end of a particle range the slowing down of the particle relates to an increased energy deposit to the medium resulting in the Bragg-peak.

The Bragg behavior is used in particle therapy to deposit the highest doses to the carcinogenic tissue.

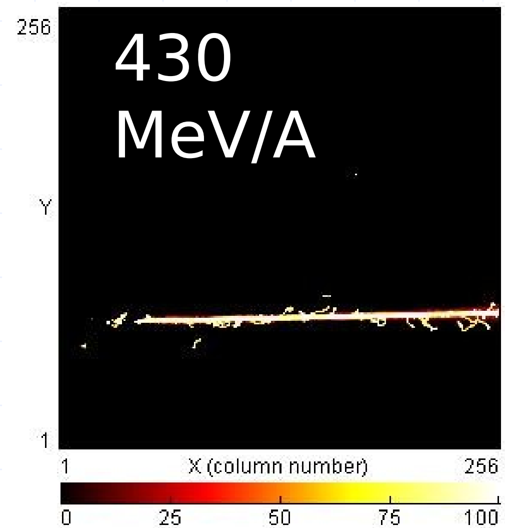
Carbon ions with different energies: 90 degrees







- Halo of pixel with low energy deposition around track - less pronounced for higher energies.
- Number of delta rays increases with increasing energy.



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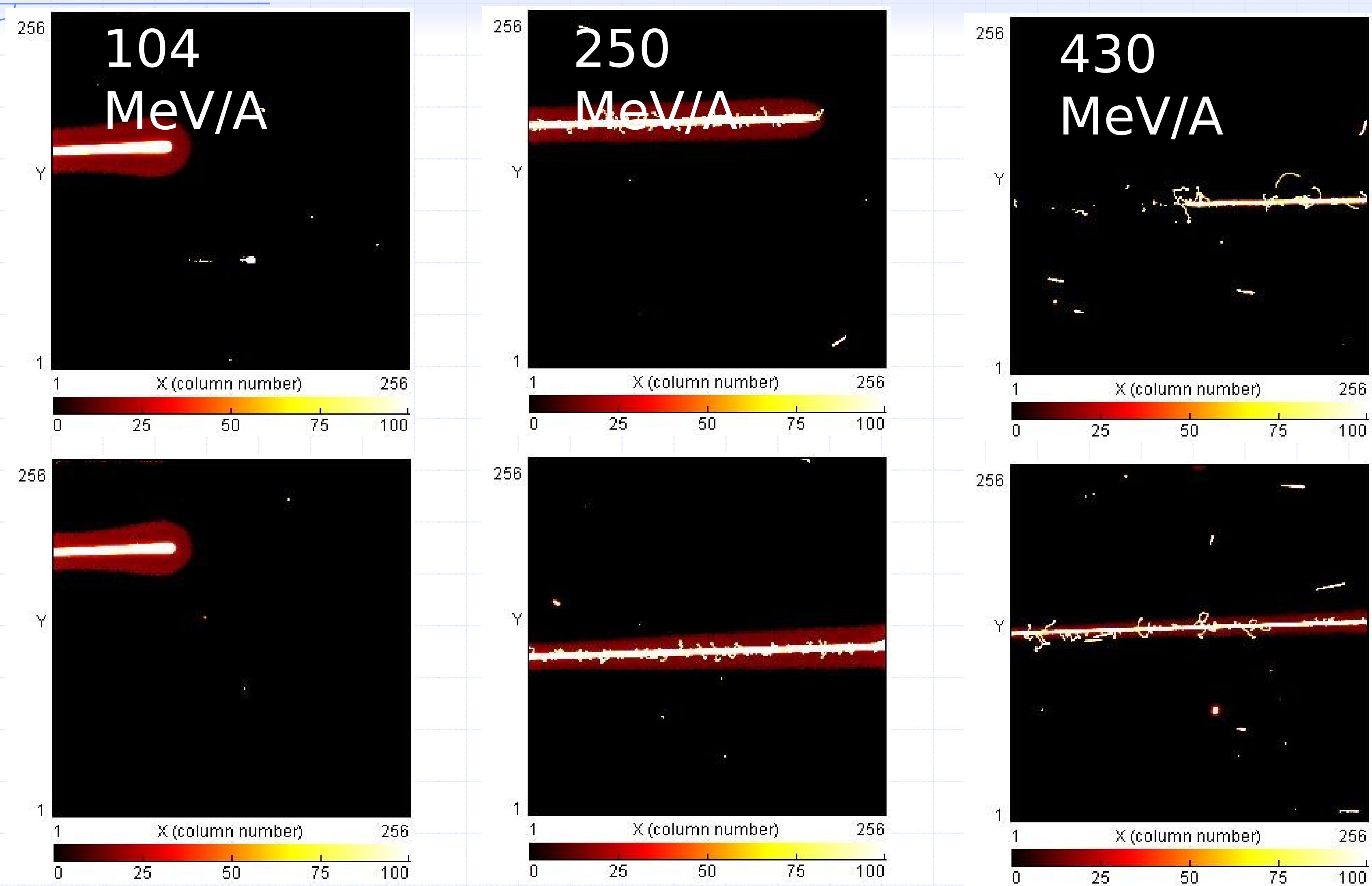
Oxygen ions with different energies: 90 degrees



3D track reconstruction with Timepix3

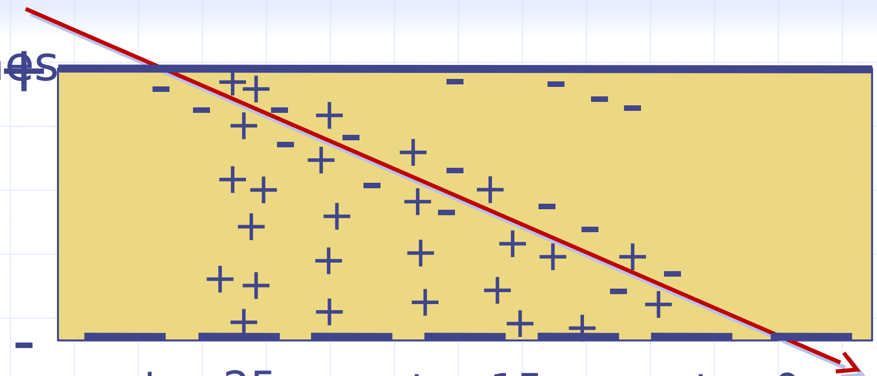
- 3D track reconstruction in a 500 µm thick silicon sensors
- 3D track reconstrution in a 2 mm thick CdTe sensor

Z-coordinate by drift time measurement

Idea: Use charge carrier drift times to reconstruct the z coordinate:
Idea: Use charge carrier drift times to reconstruct the z coordinate:

$$\overrightarrow{v_h} = \mu_h \vec{E}\,;$$

$$\vec{E}(z) = \frac{U_B}{d} + \frac{2U_{dep}}{d^2}\left(\frac{d}{2} - z\right)\overrightarrow{e_z}\,;$$



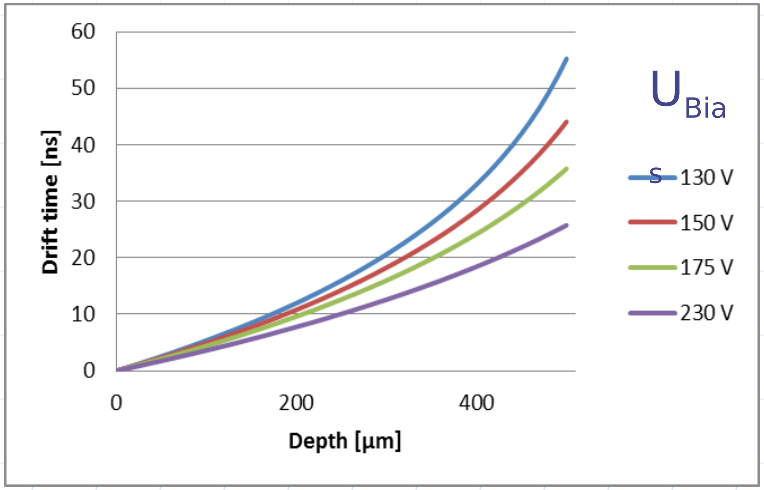
Differential equation:
Differential equation:

$$\frac{dz}{dt}\overrightarrow{e_z} = \frac{\mu_h U_B}{d}\overrightarrow{e_z} + \frac{2\mu_h U_{dep}}{d^2}\left(\frac{d}{2} - z\right)\overrightarrow{e_z}$$

Solution:
Solution:

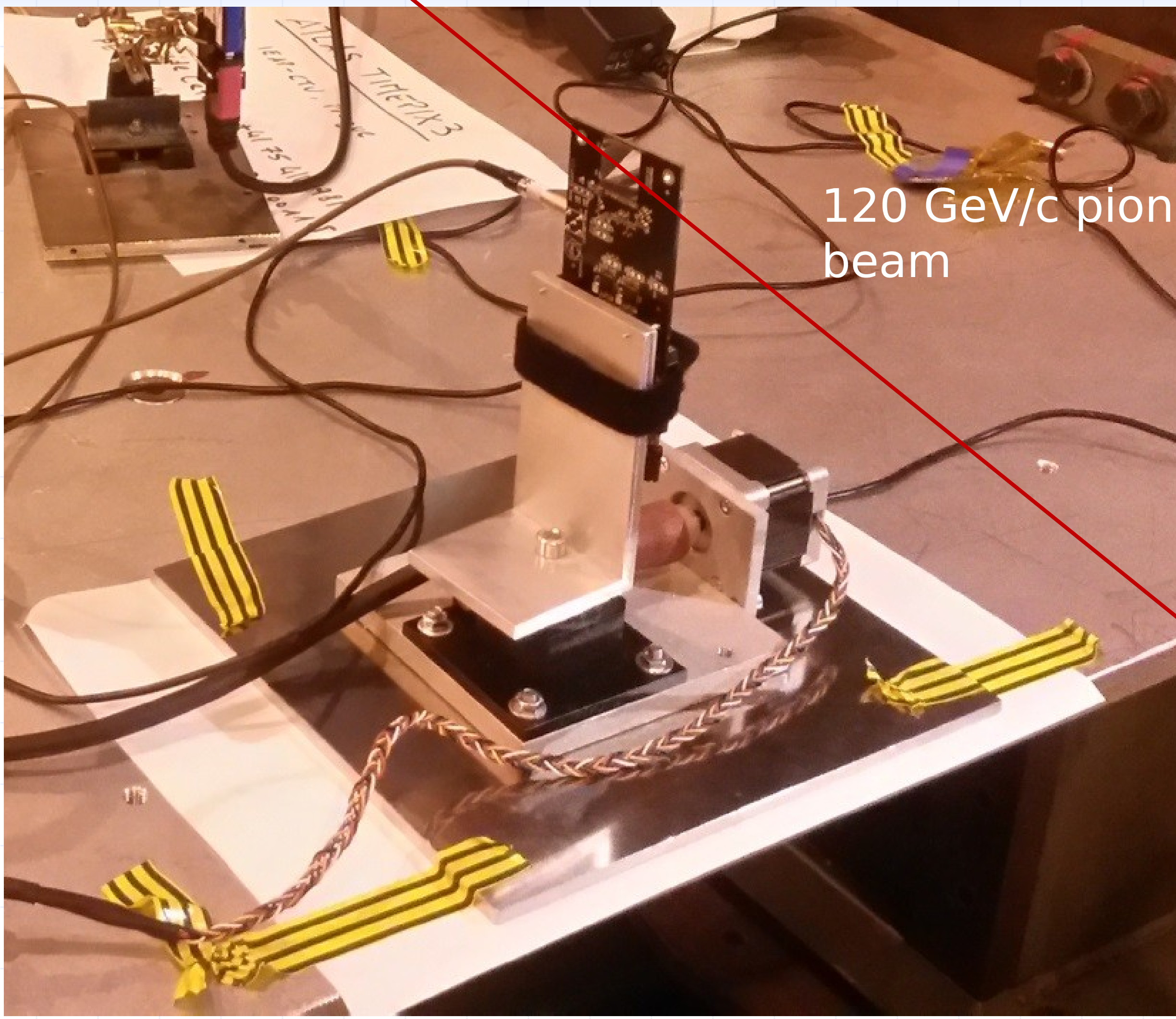
$$z(t) = \frac{d}{U_{dep}}\left(U_{dep} + U\right)\left[1 - \exp\left(-\frac{2U_{dep}\mu}{d^2}\cdot t\right)\right]$$

$$t(z) = -\frac{d^2}{2U_{dep}\mu}\ln\left(1 - \frac{2U_{dep}}{U_{dep} + U_B}\cdot\frac{z}{d}\right)$$



U_{dep} = 100 V, μ = 450 $cm^2 V^{-1} s^{-1}$, d = 500 µm

Measurement setup at the SPS at CERN



Sensor thickness: 500 µm

120 GeV/c pion beam hits the Timepix3 sensor at 60°

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Detector response in the form of the 2D projections of energy and time

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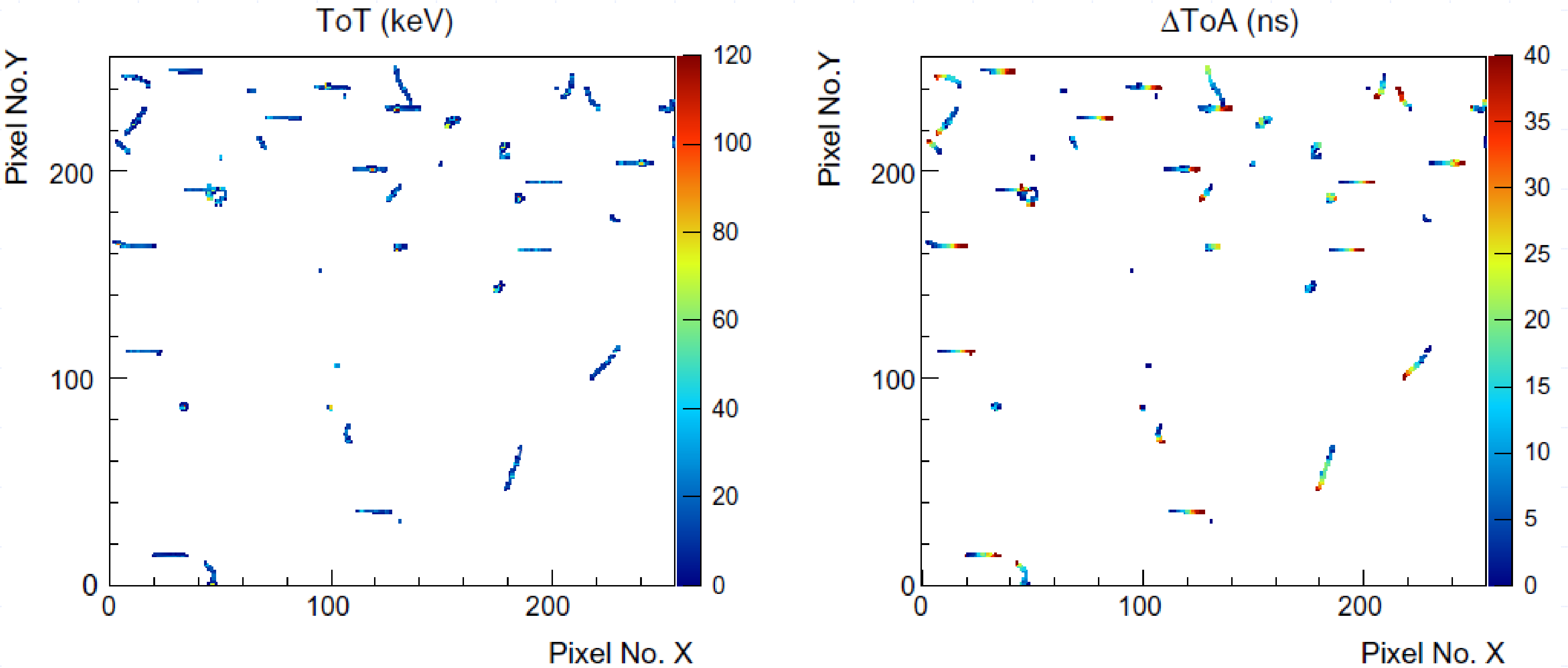

- Random set of 50 tracks from the measurement
- Pick tracks with the right geometry without delta-rays
- Determine the drift time as a function of interaction depth

Drift time as a function of interaction depths

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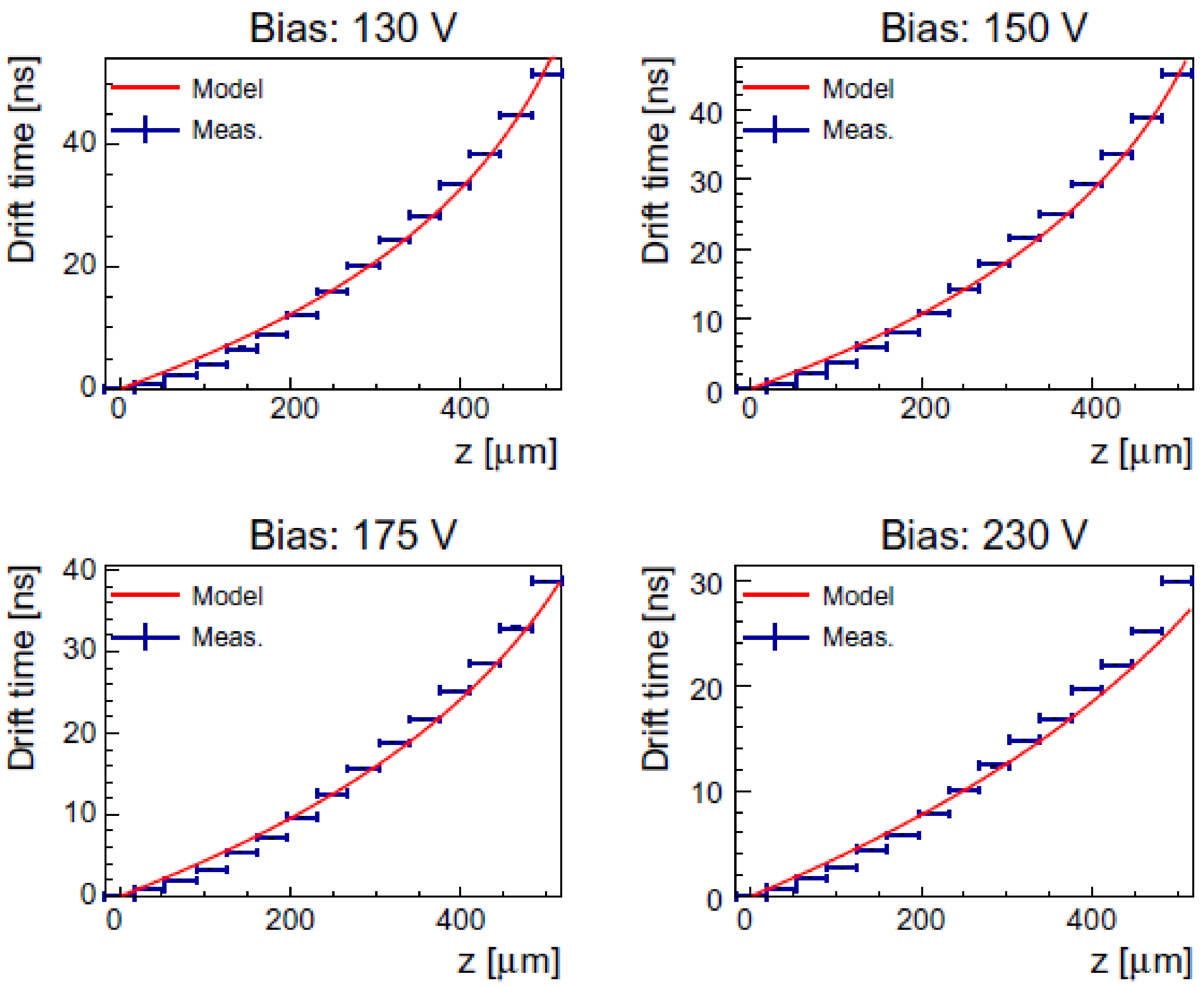
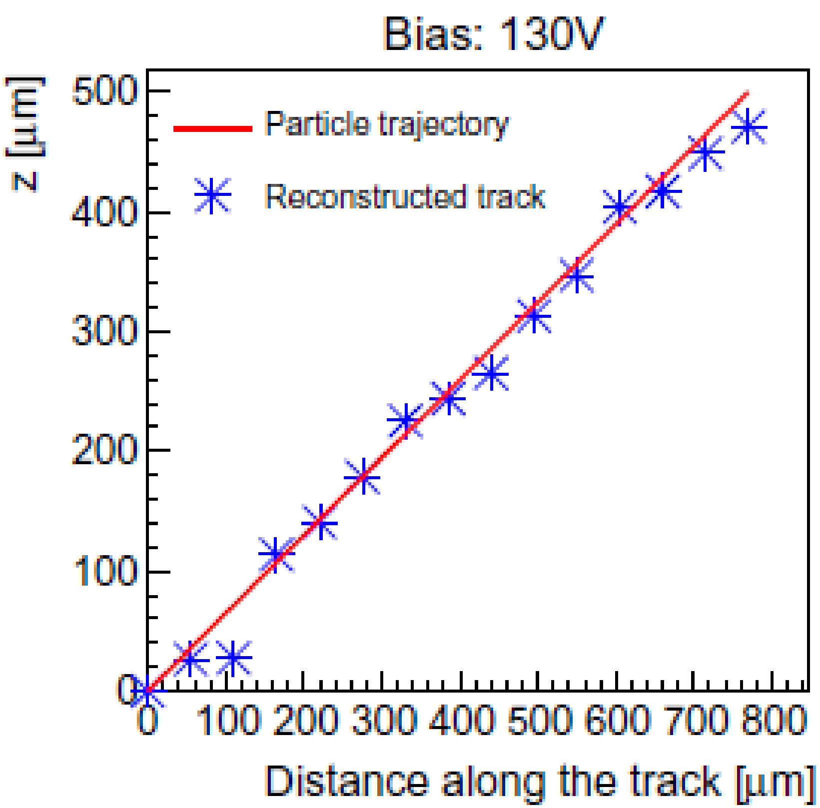


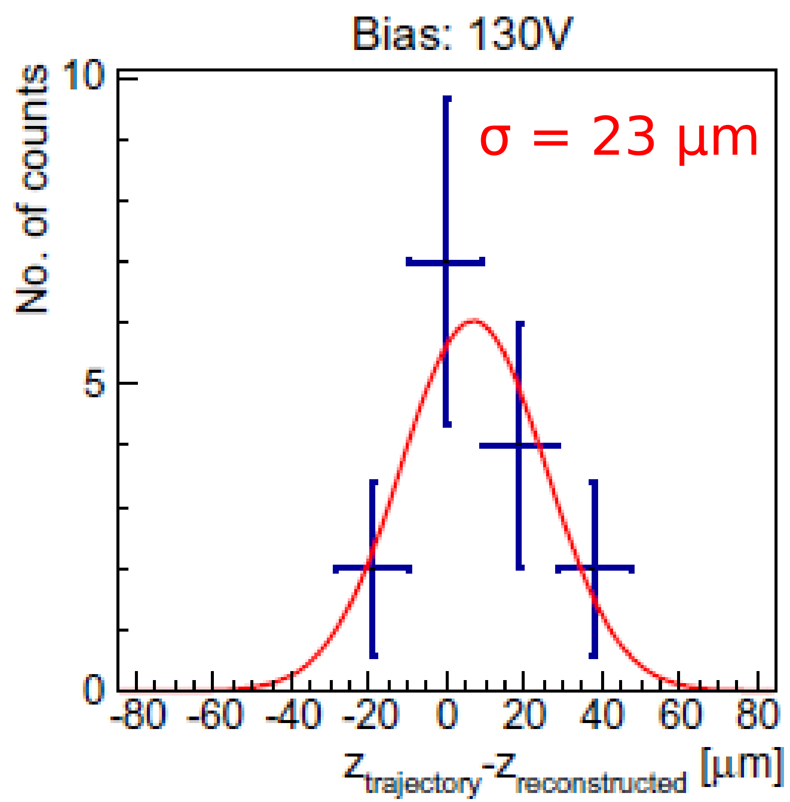
Average drift times for the whole set of measured tracks with the correct geometry as a function of interaction depth z.

Good agreement was between theoretical modelling and measurement was found.

Estimation of the z-resolution

- Deviation of the reconstructed z-positions from the particle trajectory for a single track





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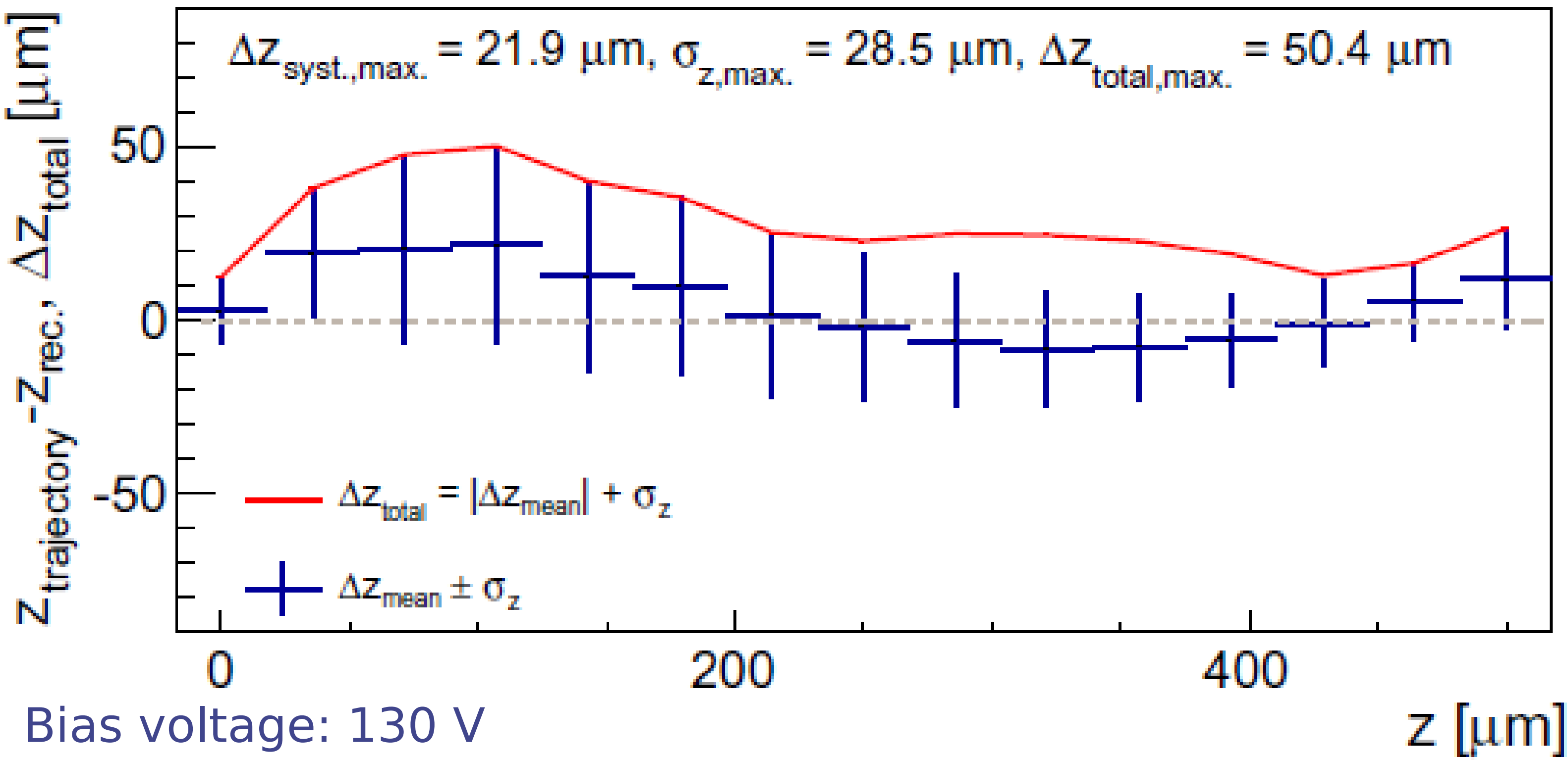
Depth dependent z-resolution

- Averaging over the set of selected tracks
- Uncertainty due to the time resolution σ_z
- Inaccuracies from the drift time model $\Delta z_{syst.}$



Bias voltage: 130 V

3D reconstructed pion track going through 500 µm silicon

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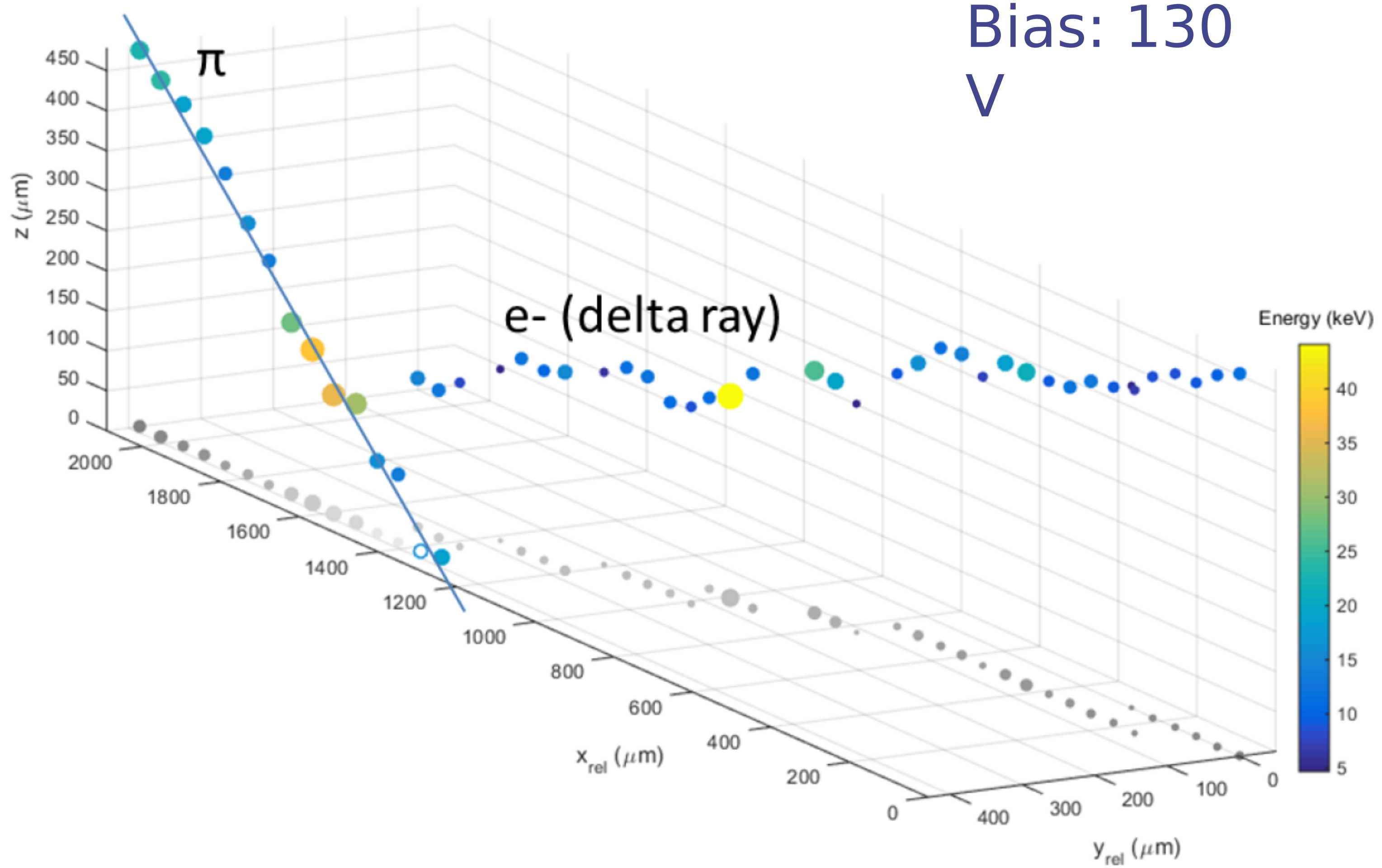

Reconstructed 3D particle trajectories in 500 µm thick silicon

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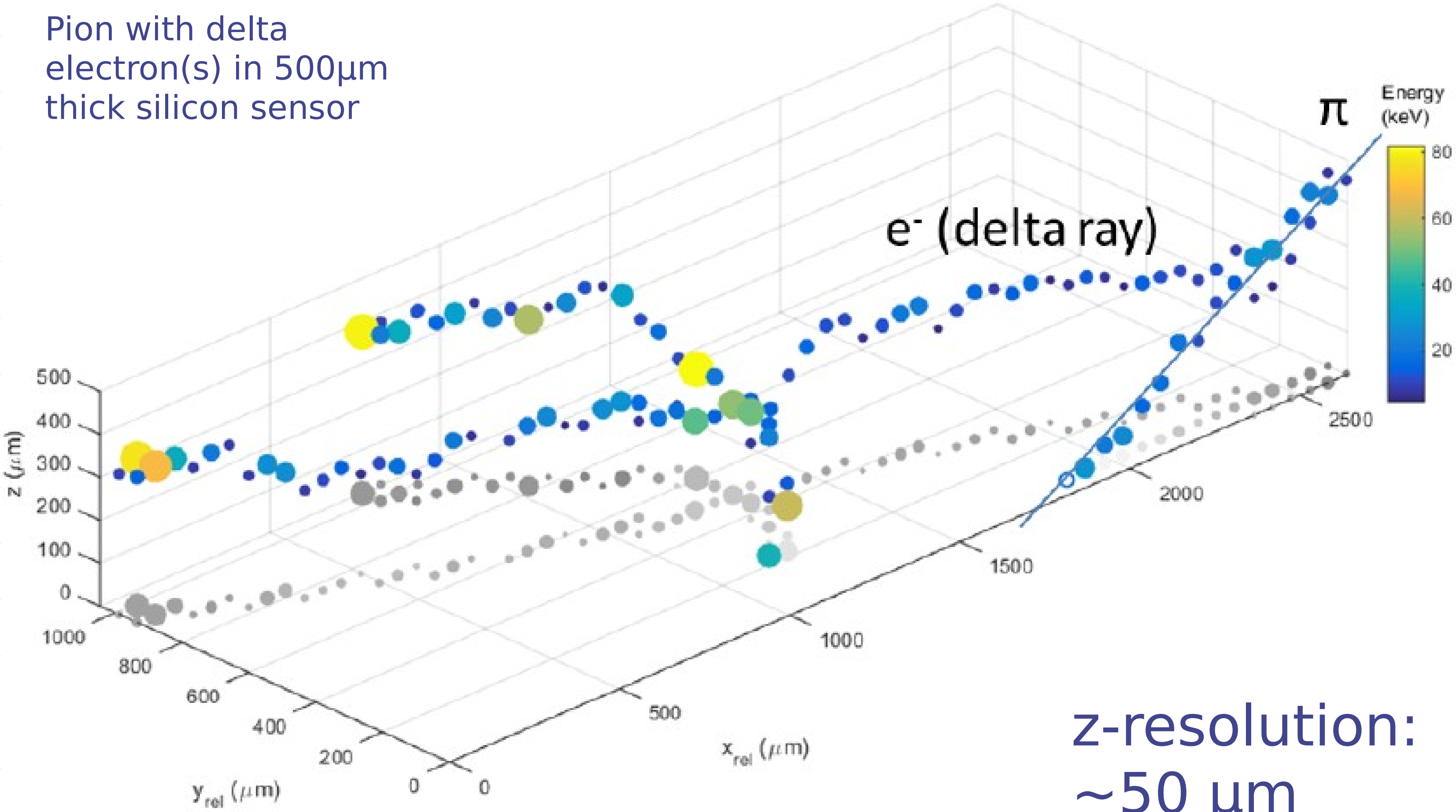
Pion with delta electron(s) in 500µm thick silicon sensor



z-resolution: ~50 µm

Cosmic muon track (natural background radiation in Prague)

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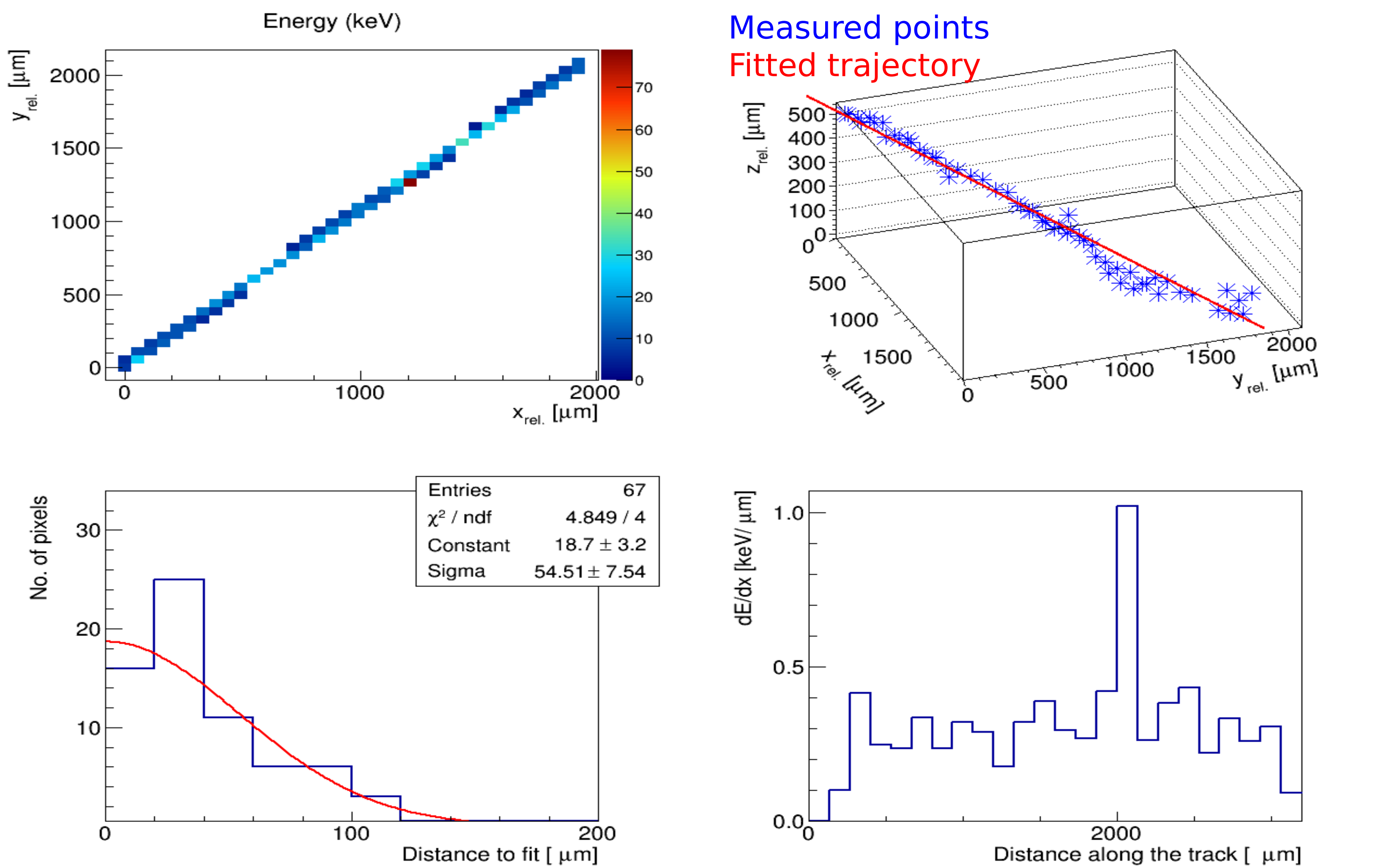

No neutrinos so far ...

Advances in High Energy Physics
Volume 2013, Article ID 105318, 20 pages
http://dx.doi.org/10.1155/2013/105318

Research Article

The Potential of Hybrid Pixel Detectors in the Search for the Neutrinoless Double-Beta Decay of ^{116}Cd

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Received 28 June 2013; Revised 17 September 2013; Accepted 19 September 2013

Academic Editor: Vincenzo Flaminio

detectors for the search of the neutrinoless double beta decay of Cd-116

Abstract

We investigated the potential of the energy resolving hybrid pixel detector Timepix contacted to a CdTe sensor layer for the search for the neutrinoless double-beta decay of ^{116}Cd. We found that a CdTe sensor layer with 3? mm thickness and 165?μm pixel pitch is optimal with respect to the effective Majorana neutrino mass ($m_{\beta\beta}$) sensitivity. In simulations, we were able to demonstrate a possible reduction of the background level caused by single electrons by approximately 75% at a specific background rate of 10^{-3} counts/(kg × keV × yr) at a detection efficiency reduction of about 23% with track analysis employing random decision forests. Exploitation of the imaging properties with track analysis leads to an improvement in sensitivity to $m_{\beta\beta}$ by about 22%. After 5 years of measuring time, the sensitivity to $m_{\beta\beta}$ of a 420?kg CdTe experiment (90% ^{116}Cd enrichment) would be 59?meV on a 90% confidence level for a specific single-electron background rate of 10^{-3} counts/(kg × keV × yr). The α-particle background can be suppressed by at least about six orders of magnitude. The benefit of the hybrid pixel detector technology might be increased significantly if drift-time difference measurements would allow reconstruction of tracks in three dimensions.

3D track reconstruction in 2 mm thick CdTe

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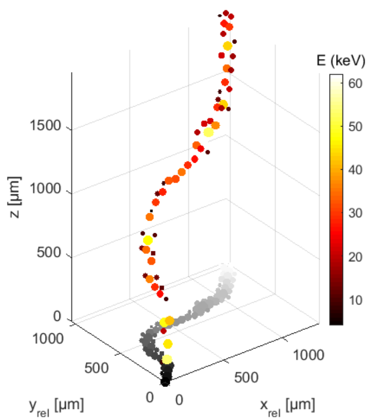
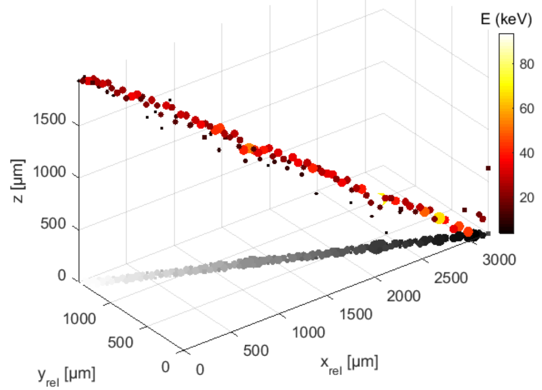
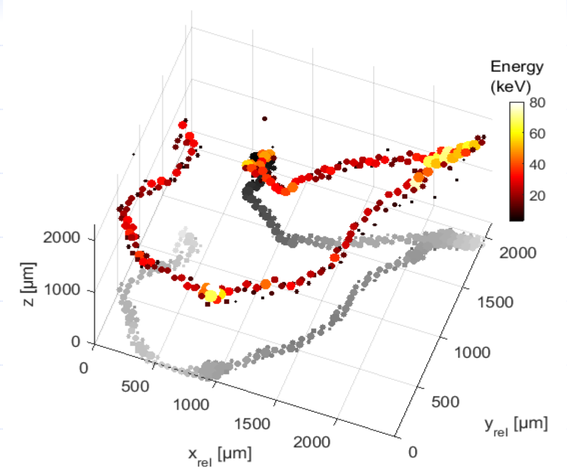
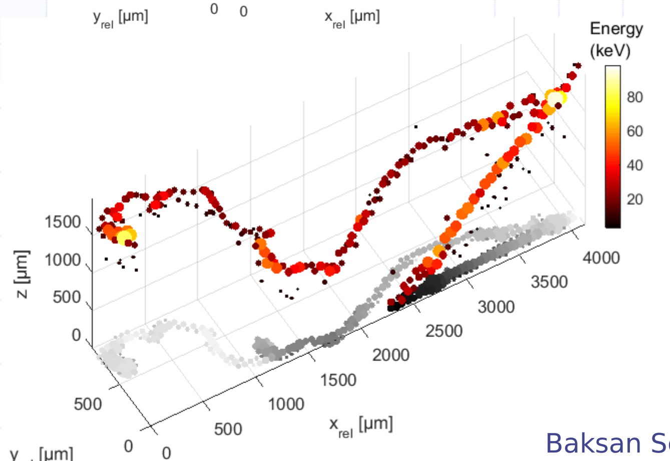
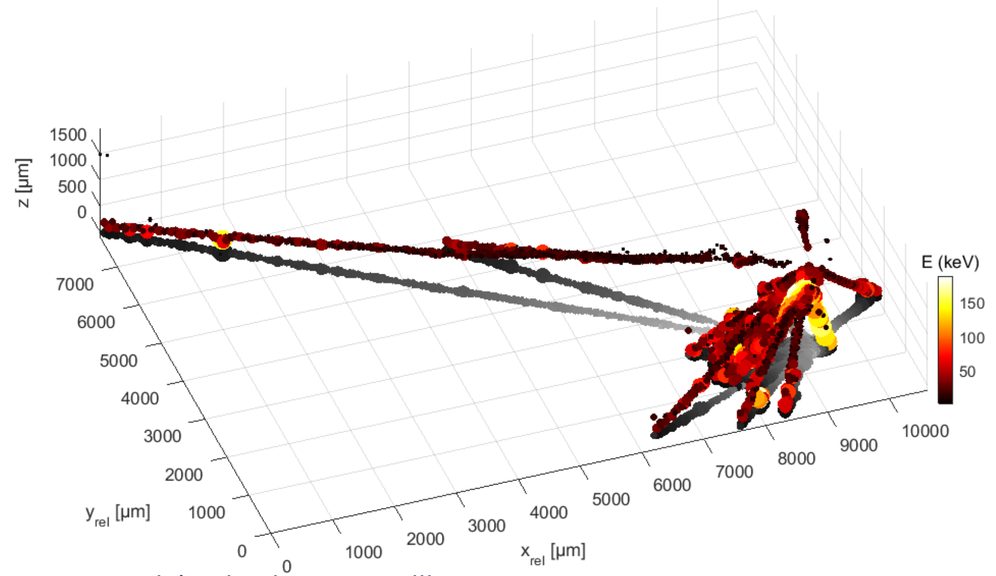
- Analogue analysis as described for silicon
- 40 GeV/c pion beam
- Z-resolution ~ 60 µm











Conclusion

- Timepix3 allows a 3D particle track reconstrucion
- In a 500 µm thick silicon, we found a z-resolution of ~ 50 µm
- In a 2 mm thick CdTe sensor, we found a z-resolution of ~ 60 µm

Results are published in:

- Bergmann et al. Eur. Phys. J. C (2017) 77: 421. https://doi.org/10.1140/epjc/s10052-017-4993-4
- Bergmann et al., Eur. Phys. J. C (2019) 79: 165. https://doi.org/10.1140/epjc/s10052-019-6673-z

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Thank you!