Detector response and performance of a 500 µm thick GaAs attached to Timepix3 in relativistic particle beams

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Outline

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- Timepix3 and GaAs:Cr
- Basic sensor characterization
- Measurement in a 40 GeV/c pion beam
- Measurement in a mixed ion beam (330 GeV/c Pb ions on target)
- Conclusion

Motivation

Main driver for developement of high-Z compound semiconductor materials is X-rays imaging and γ-detection

Imaging applications profit form the higher stopping power (higher efficiency of photoeffect)

Why to use it for particle tracking?

- High charge carrier mobility → increased speed of operation
- Higher stopping power
- Expected higher radiation tolerance
- Particle identification using a combination of X-ray detection and tracking (Transition radiation detector)*

Disadvantages: Thermal stability, higher leakage current, sensor inhomogeneity, charge carrier lifetime ...

* F. Dachs *et al*, "Transition radiation measurements with a Si and a GaAs pixel sensor on a Timepix3 chip", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2019, https://doi.org/10.1016/j.nima.2019.03.092.

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Timepix3 detector and GaAs:Cr

Timepix3

- 256 x 256 pixels with 55 µm pitch ($1.98\ cm^2$ sensitive area)
- Minimal detection threshold in each pixel is 500 e^-
- 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)

Sensor layer:

- Chromium compensated GaAs from Tomsk State Universty
- Thickness 500 µm
- Ohmic contacting scheme

Readout:

- AdvaDAQ (pion measurement)
- Katherine readout (characterization, mixed ion beam)

Basic sensor characterization: I-V curve and count rate homogeneity

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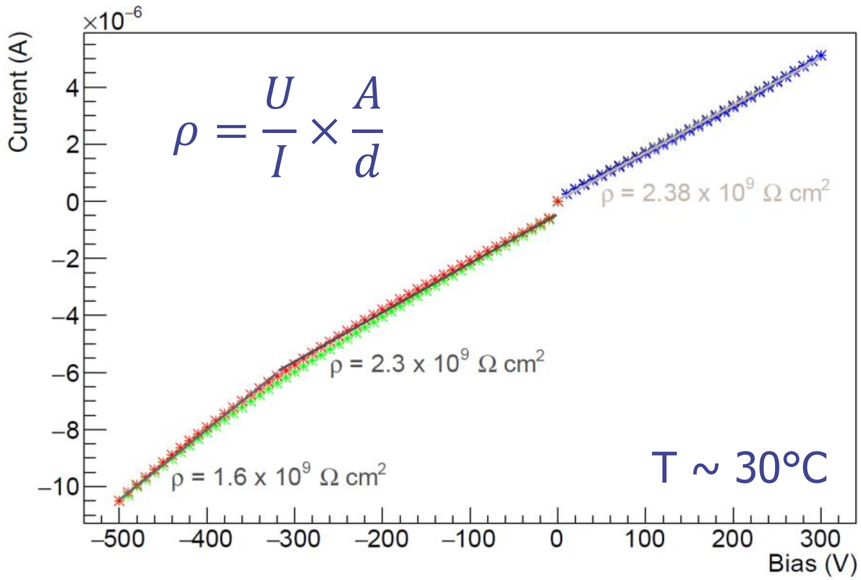
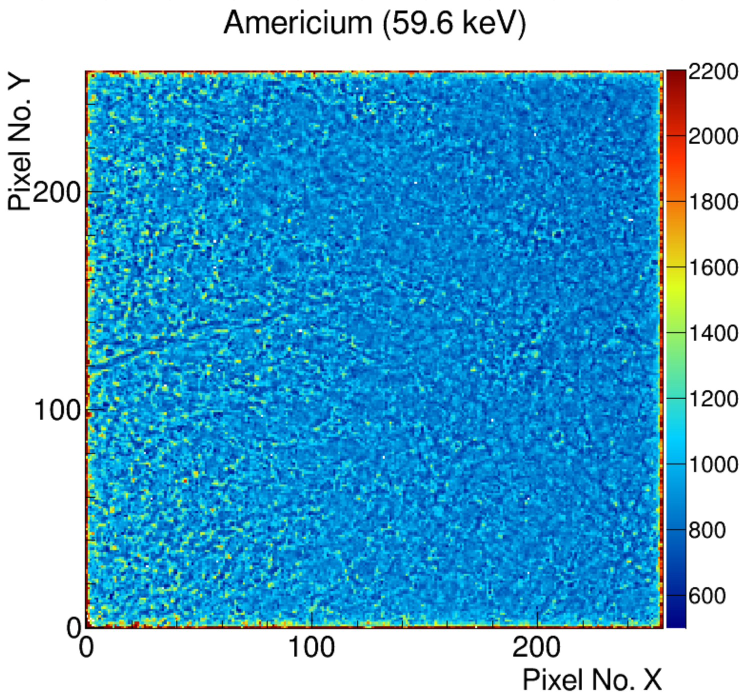
I-V curve measurement:

- Measurement of the leakage current as function of the applied bias
- Line fit used to determine the sensor resistivity





Count rate homogeneity:

- Sensor irradiated by 59.6 keV γ-rays from an ^{241}Am source
- Good homogeneity

Basic sensor characterization: Determination of the $\mu\tau_e$-product

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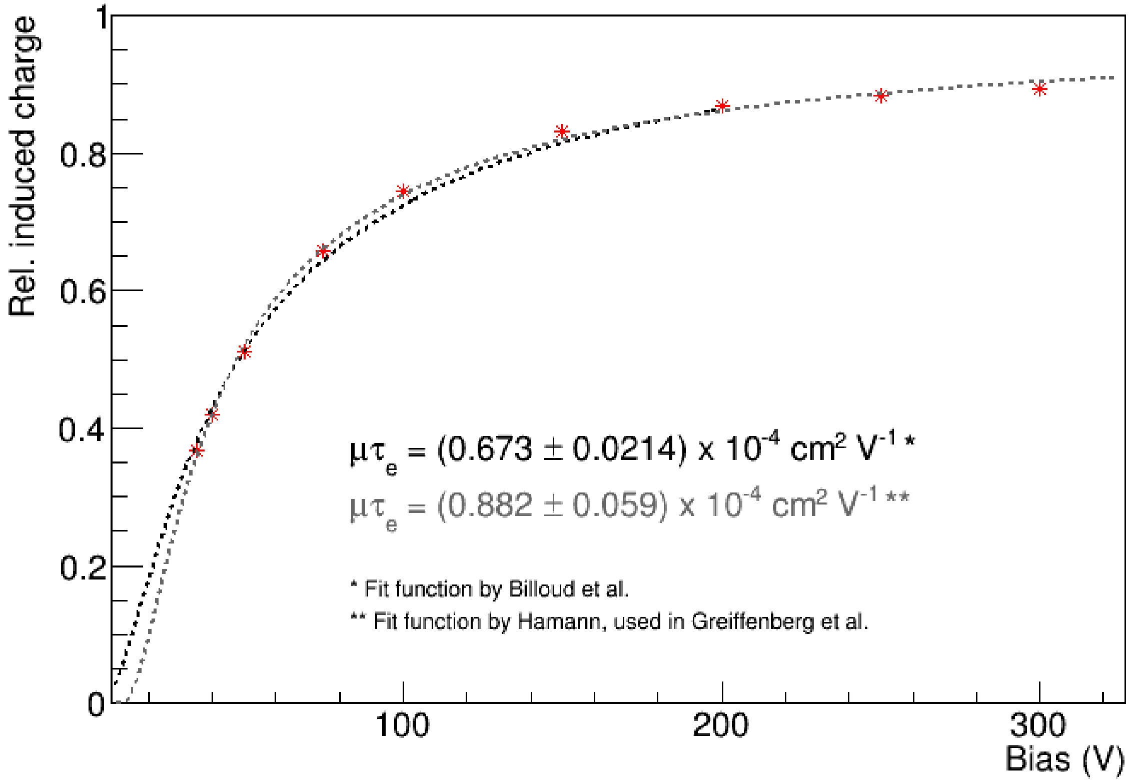
- Irradiation of the GaAs:Cr sensor with K-line photons of zirconium (15.77 keV)
- Determine the peak position of single pixel clusters E_{peak} as a function of the applied bias U_{bias}



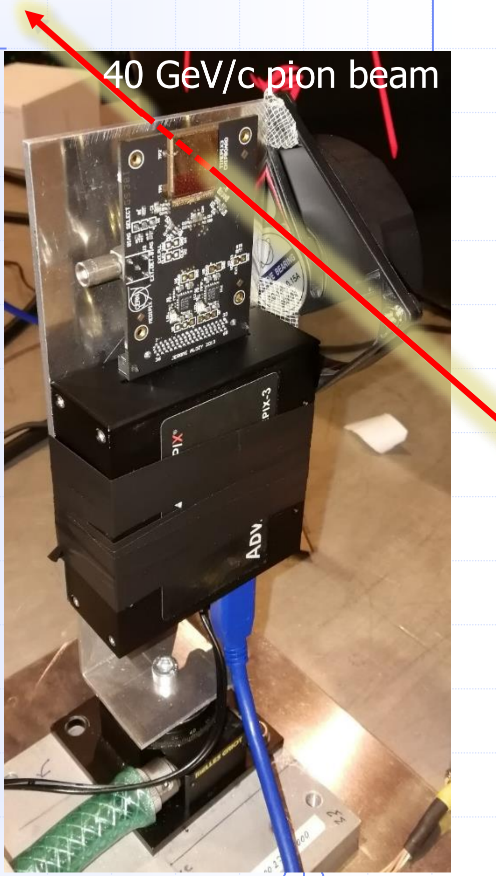
Induced charge is defined as $E_{peak}/E_{K\text{-line}}$

Sensor temperature: T_{sensor} ~ 50°C

* T. Billoud *et al*, "Homogeneity study of a GaAs:Cr pixelated sensor by means of X-rays", JINST 13 P04002, 2018.
** Greiffenberg *et al*, "Characterization of GaAs:Cr sensors using the charge-integrating JUNGFRAU readout chip", JINST 14 P05020, 2019.

Measurements in a 40 GeV/c pion beam

- Super-proton-synchrotron at CERN
- Irradiation at 60° wrt the sensor normal
- Sensor used in electron collection (negative polarity)
- Bias varied in the range from -25 V to -500 V
- Study of the sensor material properties (drift time, charge collection efficiency)



40 GeV/c pion beam: 60 deg – Typical tracks

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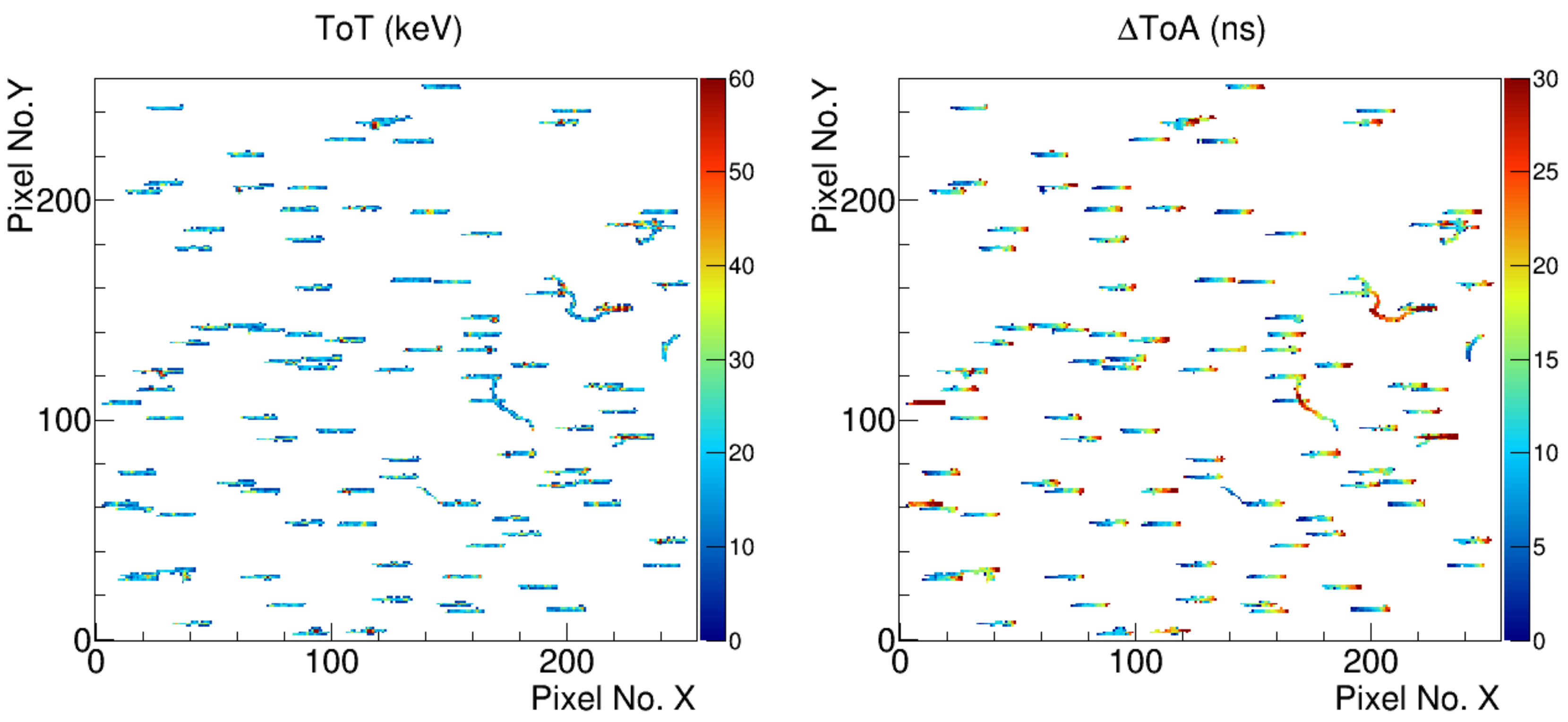
Collection of 100 tracks measured at 60 deg irradiation at bias -25 V

- Energy deposition (left)
- Relative time difference within a track (right)



40 GeV/c pion beam: 60 deg – Single event analysis

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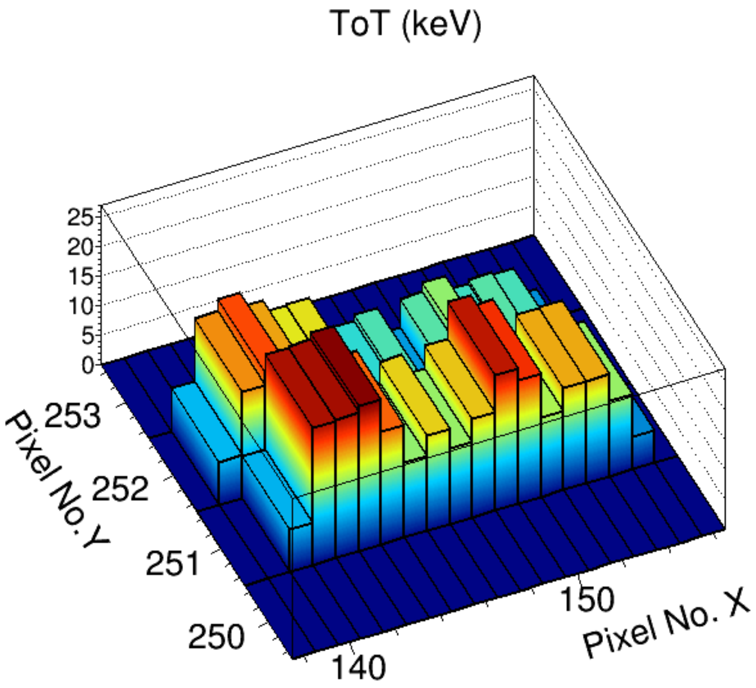
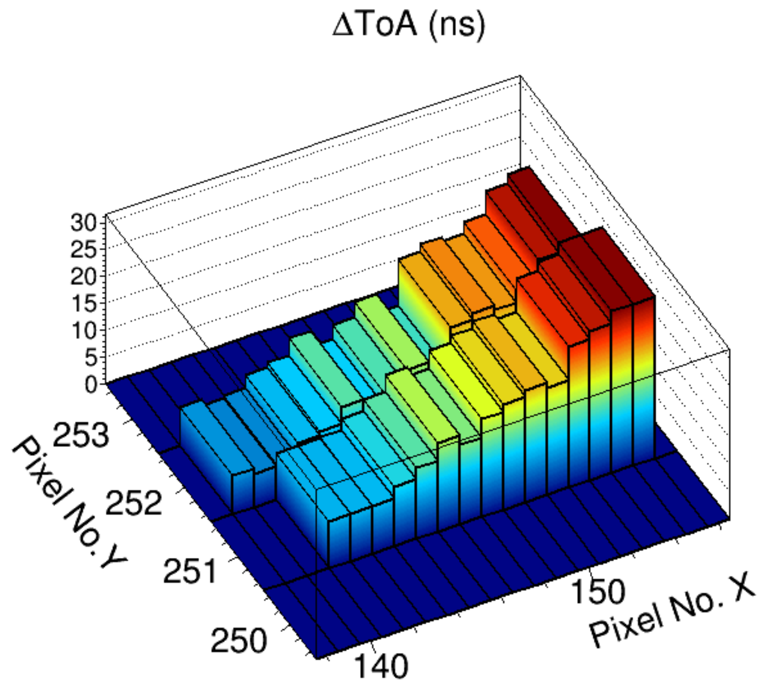
- Increase of the time with increasing distance to the pixel electrodes
- Overall decrease of energy with increasing distance to the pixel electrodes

→ Study drift time (ΔToA) and charge collection efficiency (ToT) as a function of z





Bias: -25 V

40 GeV/c pion beam: 60 degrees - Drift time analysis

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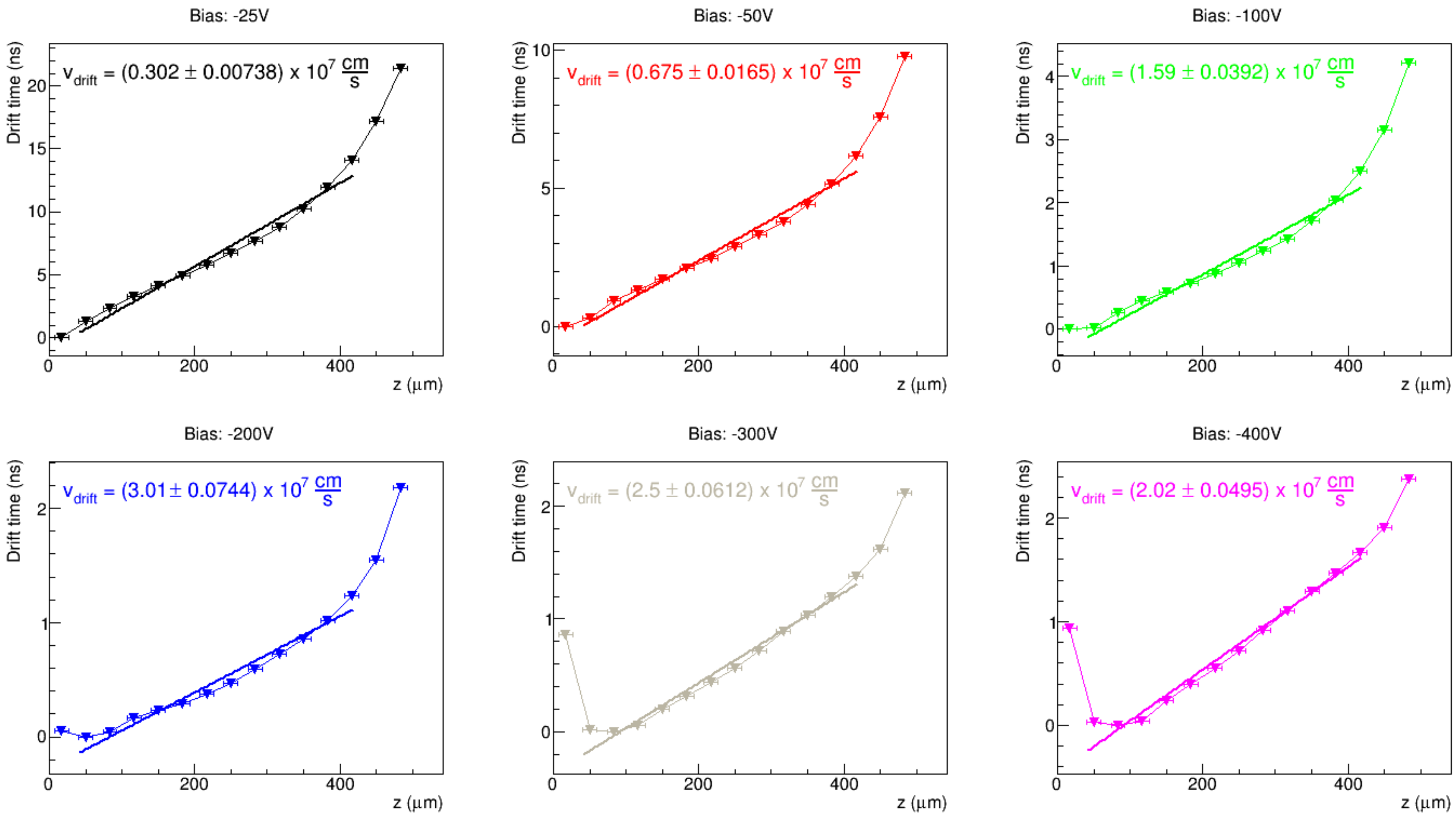
Slope of the presented curves is $\frac{1}{v_{drift}}$ (determined by fitting)



40 GeV/c pion beam: 60 degrees – Drift velocity and electron mobility

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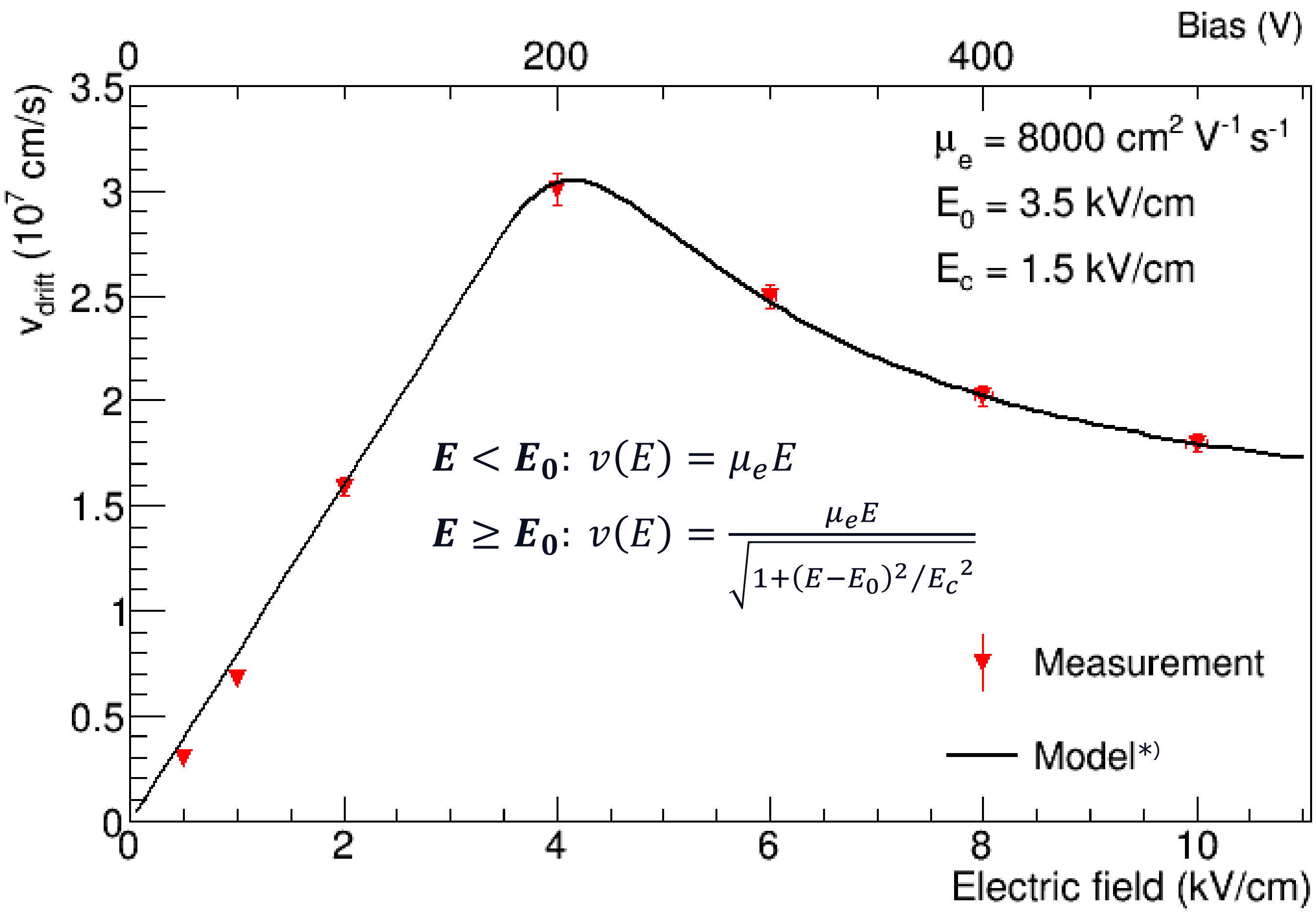


Electric field:

$$E = \frac{U_{Bias}}{d}$$

U_{bias}: Bias voltage

d: Thickness

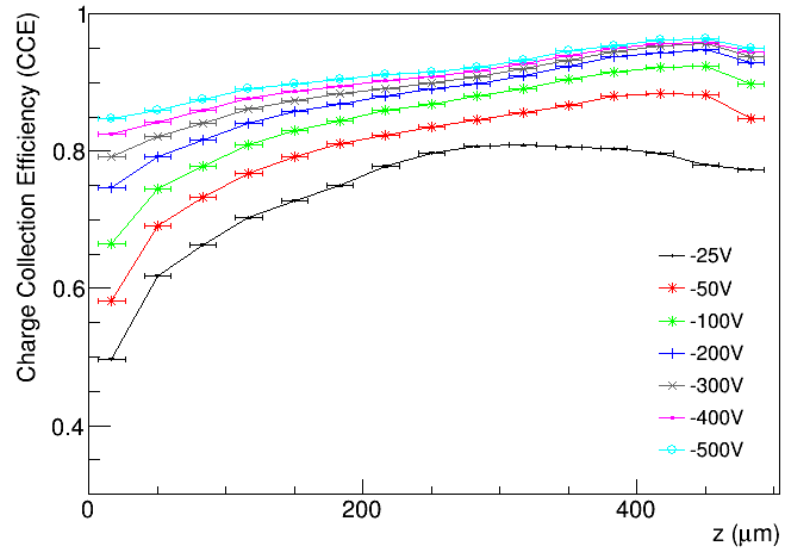
v_{drift} saturates and decreases above the electric field E_0

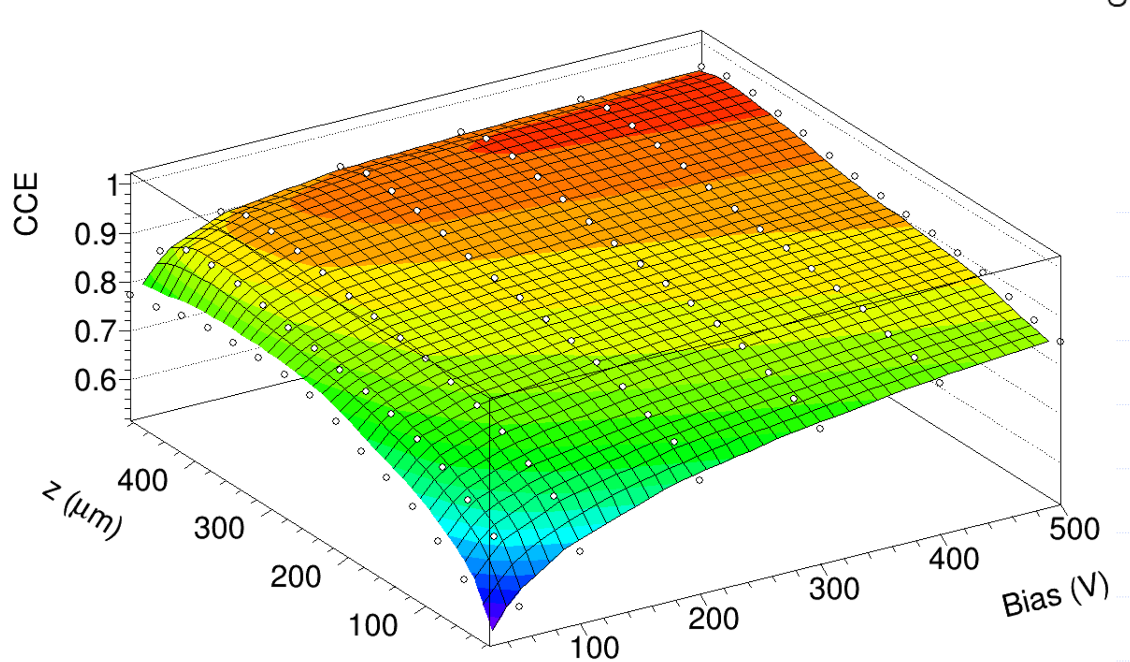
*) A. Dargys and J. Kundrotas, „Handbook on Physical Properties of Ge, Si, GaAs amd InP", Science and Encyclopedia Publishers, Vilnius, 1994

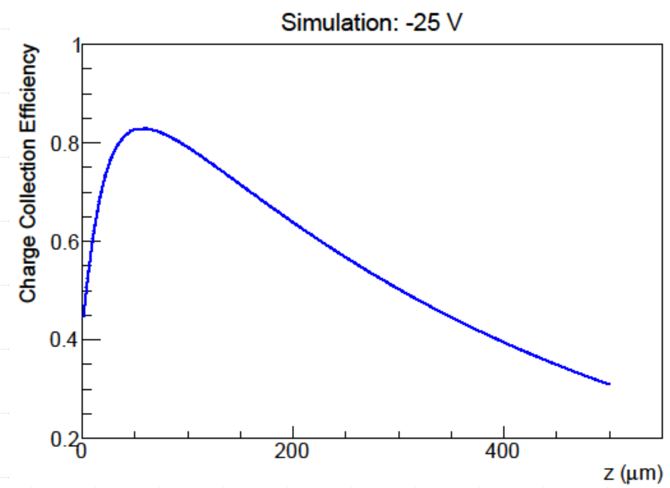
40 GeV/c pion beam – 60 degrees - Charge Collection Efficiency

CCE extracted from the energy deposition profile of the track

- Higher charge collection efficiency as expected from simulation
- Behavior of the charge collection efficiency cannot be explained

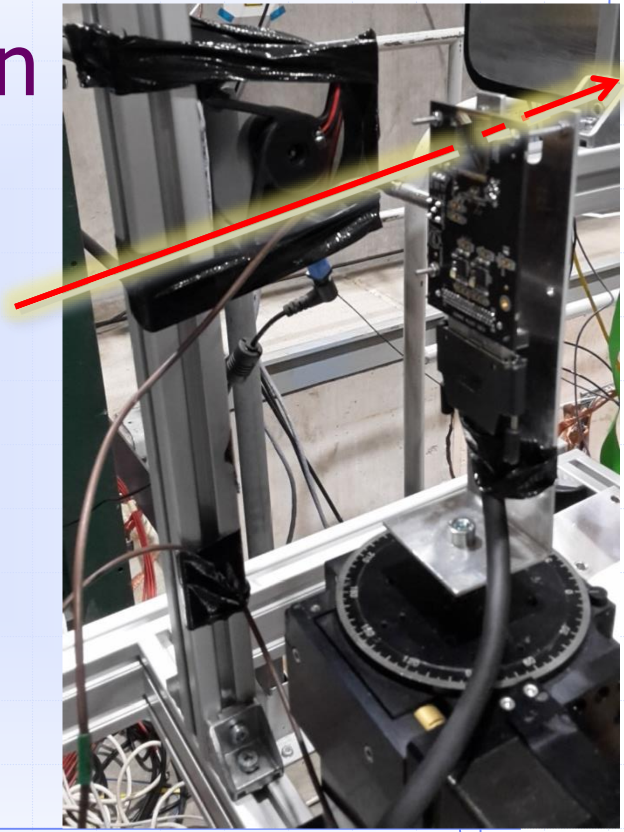






Measurements in mixed ion beam after 330 GeV/c Pb impact on target

- Super-Proton-Synchrotron at CERN
- Sensor used in electron collection (neg. polarity)
- Results at bias -200 V are shown
- Data at angles 0°, 25°, 50° and 75° (wrt the sensor normal)
- Study the detection and separation capability of multiply charged particles



330 GeV/c Pb impact on target: Stopping power spectra at different angles

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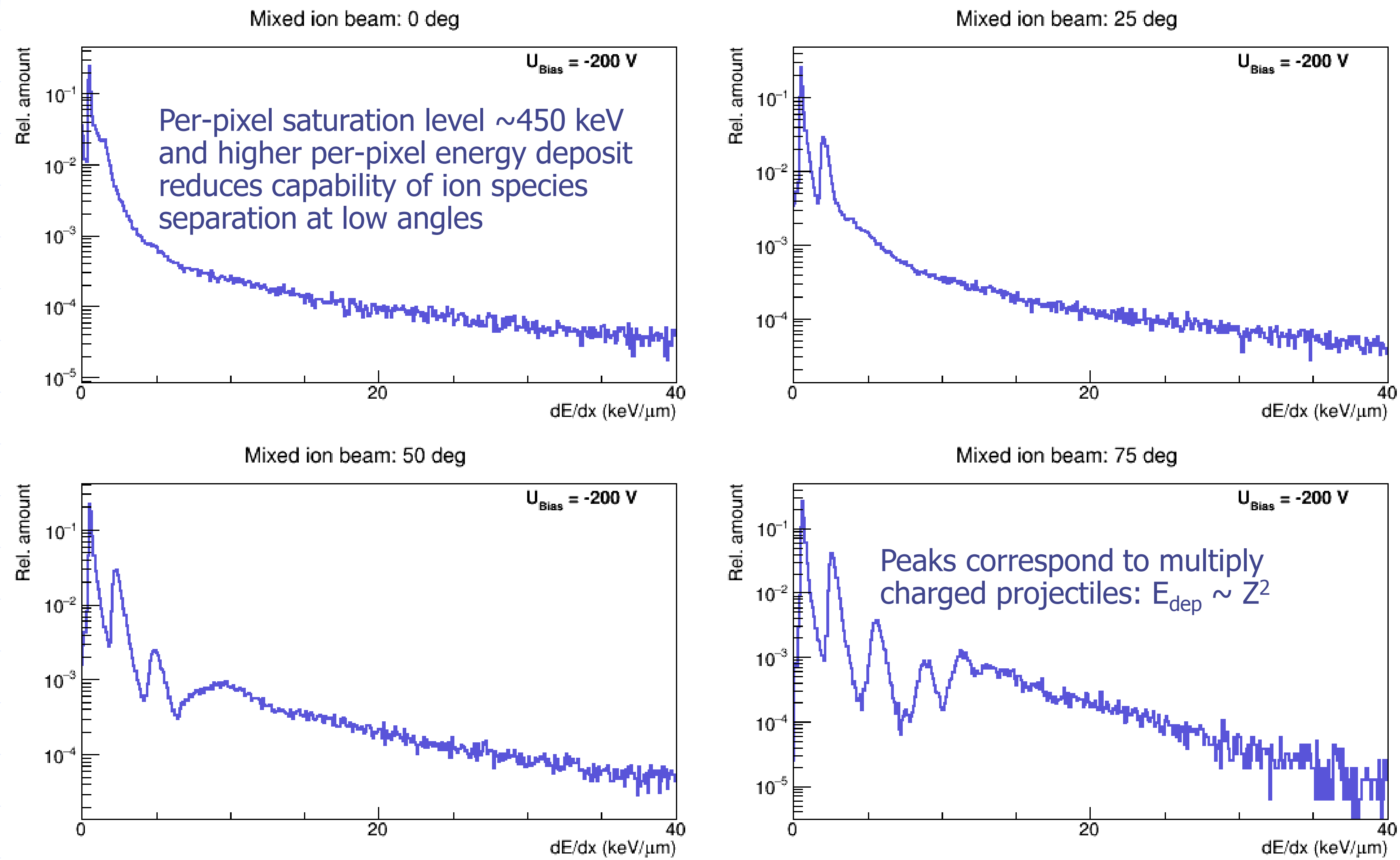

330 GeV/c Pb impact on target: Impact at 75 degree – Landau fitting and track shapes

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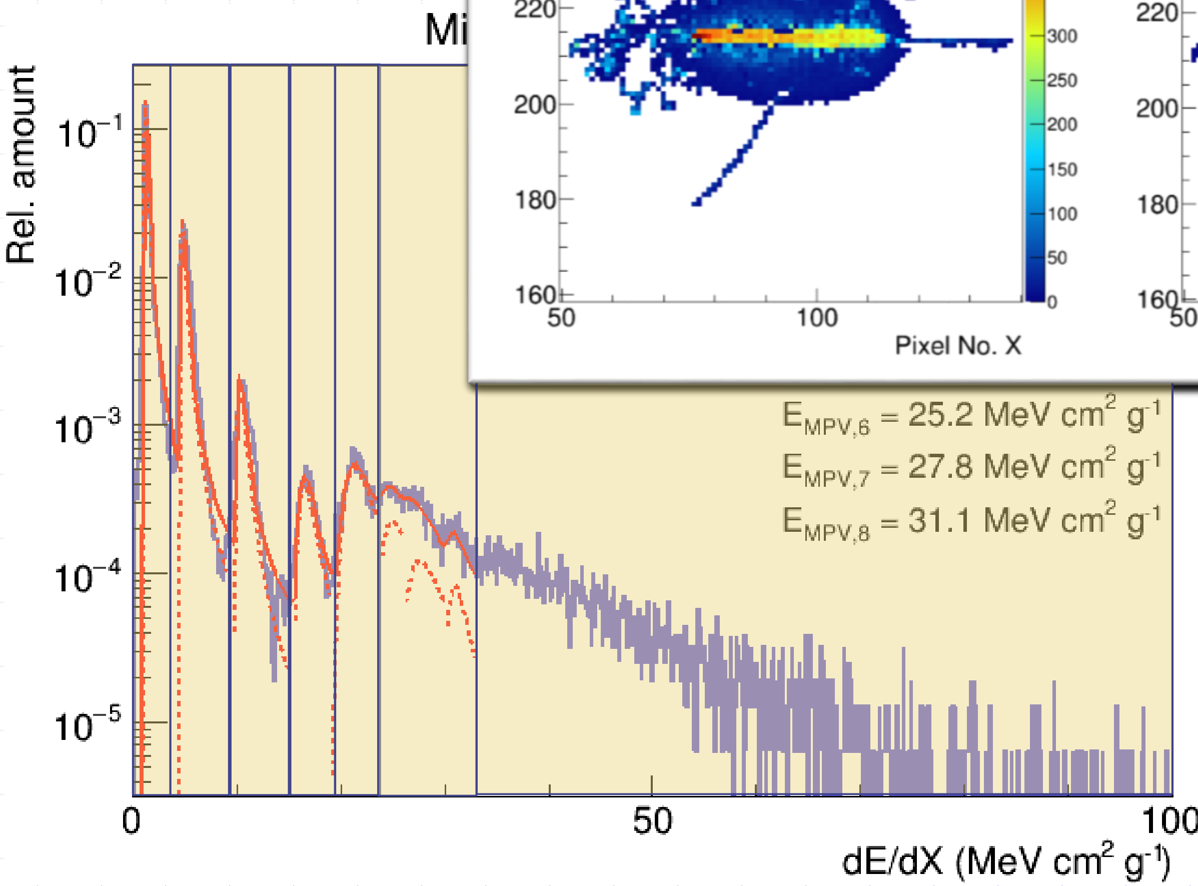
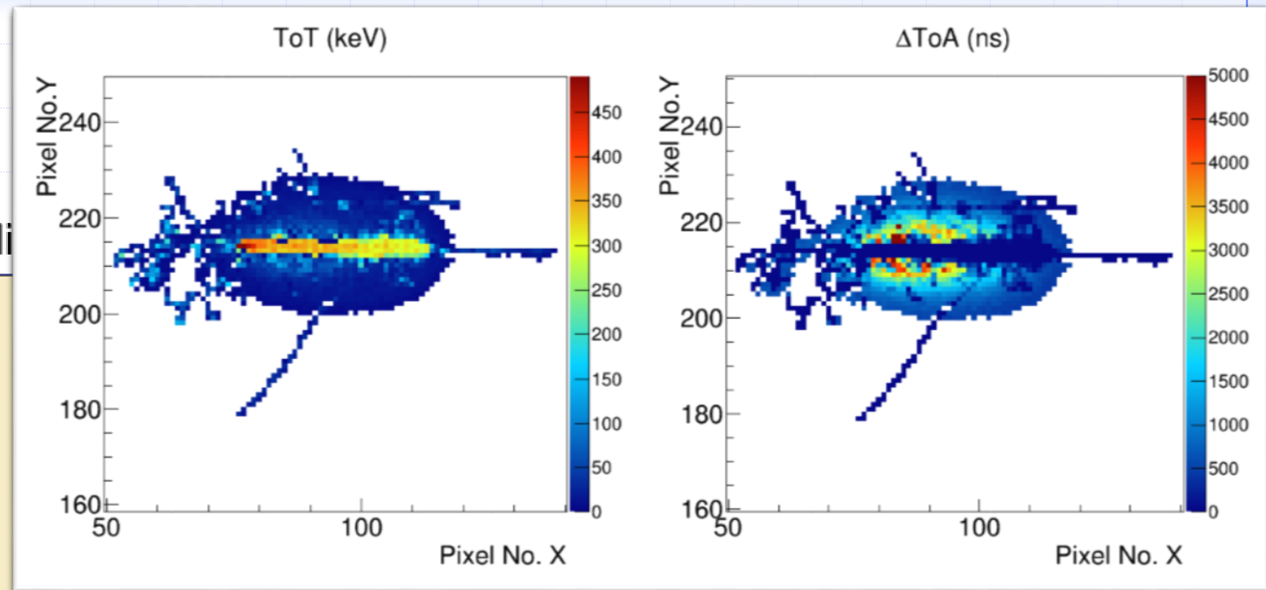
Energy deposition spectra described by Landau functions.





A halo becomes pronounced from the 3rd peak.

Halo starts to grow from the side, where the track is close to the pixels.

Conclusion

- The detector response of a 500 µm thick GaAs:Cr was studied in relativistic particle beams
- Measurement in a 40 GeV/c was used to study drift times of electrons and the charge collection efficiency as functions of interaction depth at different bias voltages
  - The drift time measurement was consistent with μ_e = 8000 $cm^2 V^{-1} s^{-1}$
  - Drift velocity saturation was found at electric fields above E_0 = 3.5 kV/cm
- The particle species separation capability was studied in a mixed relativistic ion beam at different angles
  - The higher the impact angle the more species could be identified by stopping power
  - For low angles saturation of pixel electronics (~500 keV) reduces particle species separation capability
  - For heavier ions a halo becomes visible. It is delayed by ~µs.

Thank you for your attention!

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Back-up

Electric field GaAs:Cr sensors

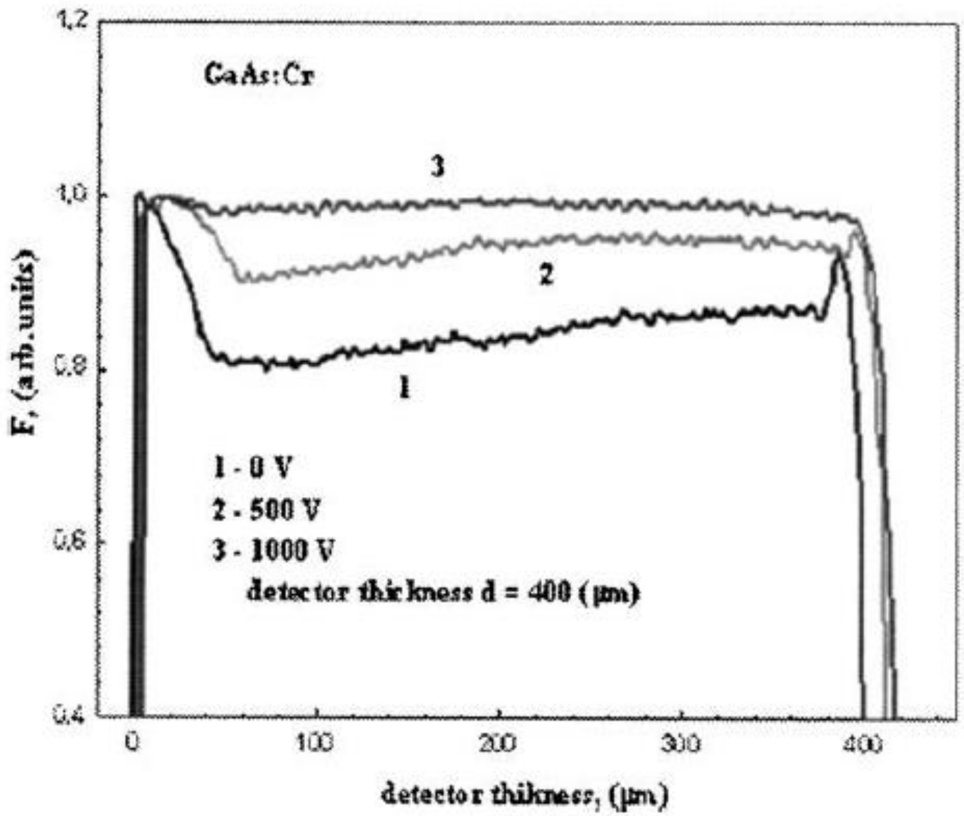

Fig. 8. The spatial distribution of function *F* through the detector thickness for various bias voltages (GaAs:Cr).

A.V. Tyazhev et al., "GaAs radiation imaging detectors with an active layer thickness up to 1mm", Nuclear Instruments and Methods in Physics Research A 509 (2003) 34–39.

40 GeV/c pion beam: 60 deg – Energy spectra

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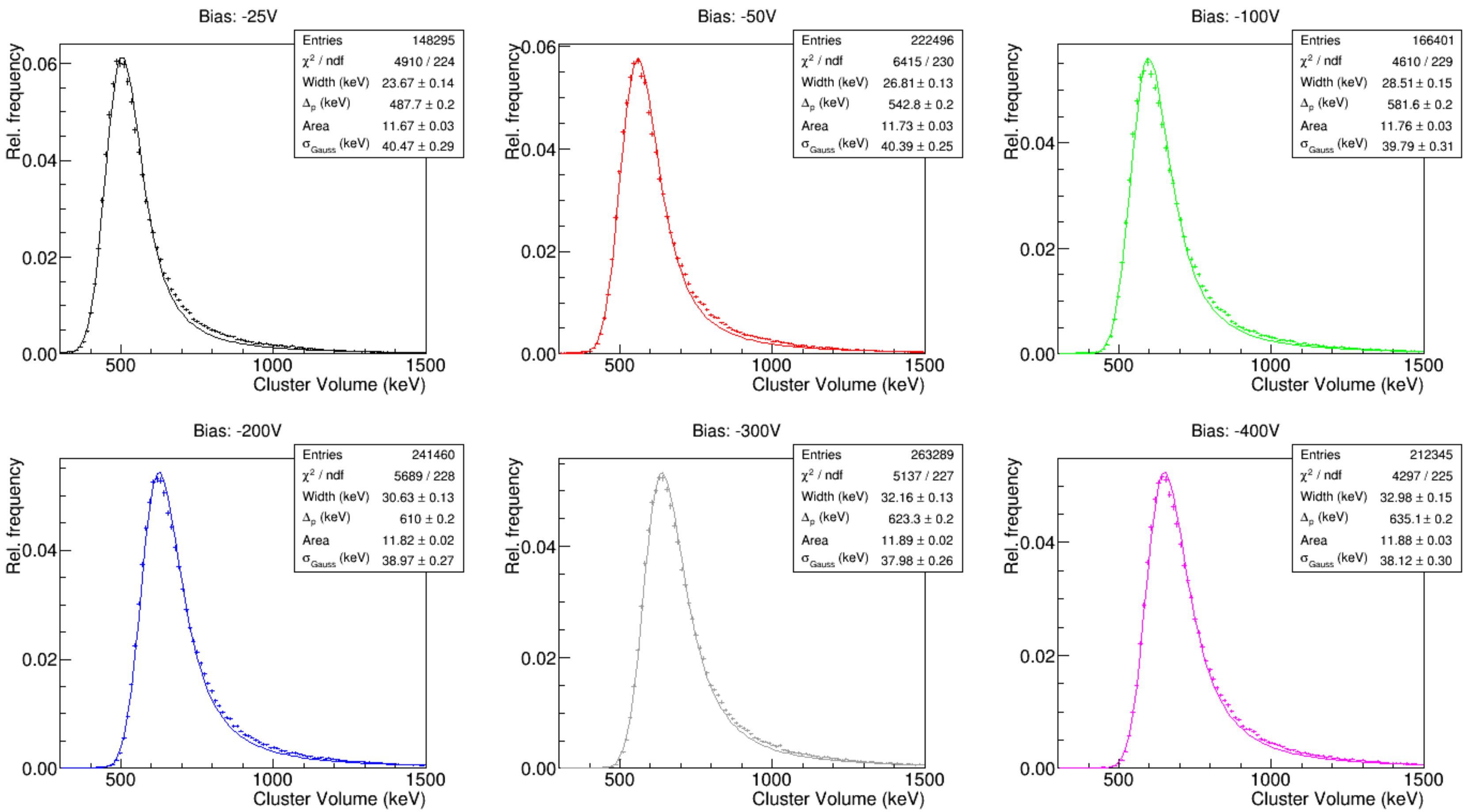
Energy deposition spectra are fitted by a Landau-distribution (physics of interaction in the medium) convoluted with a Gaussian (energy resolution)



40 GeV/c pion beam: 60 degrees – Most probable value vs. bias voltage

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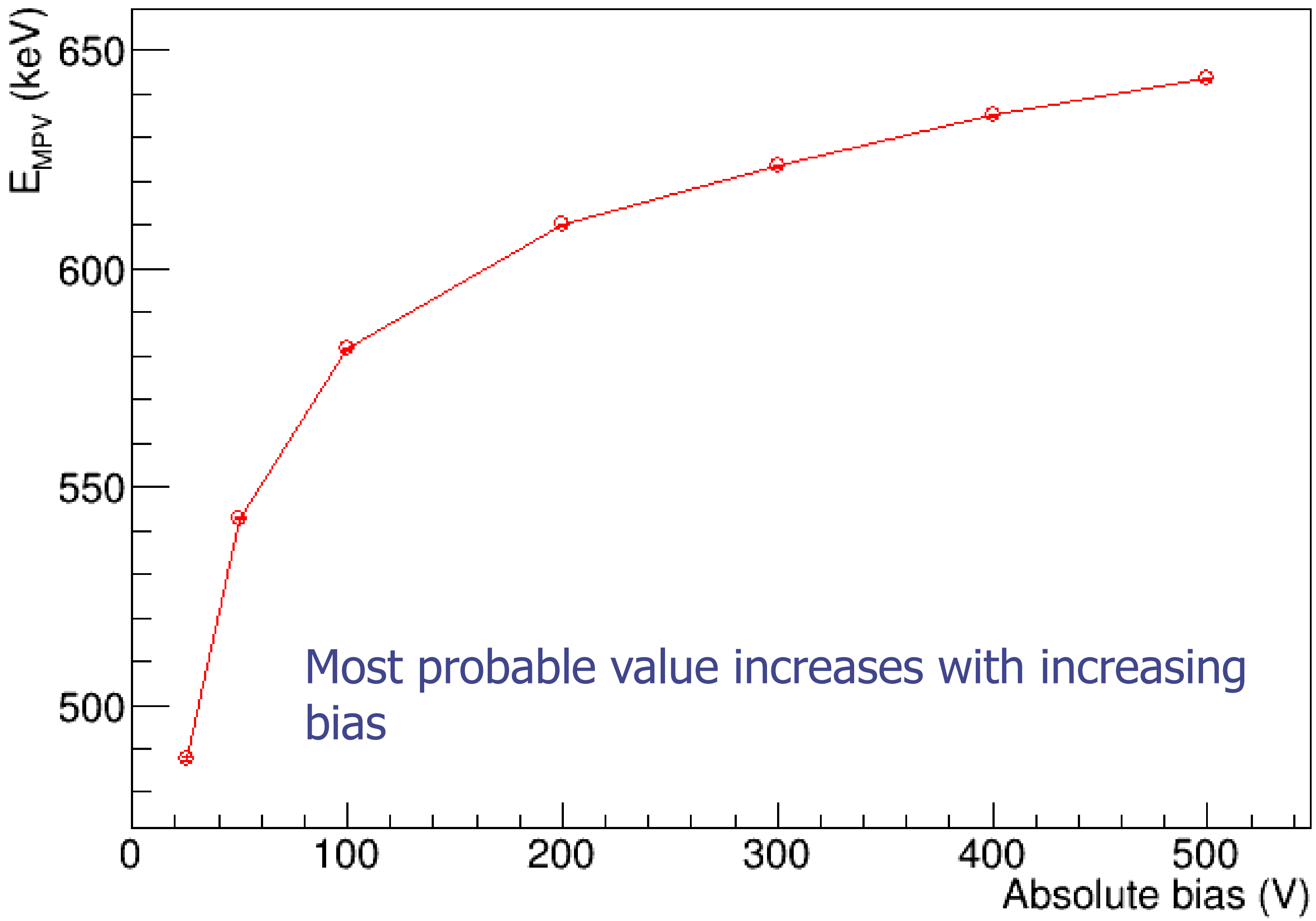

330 GeV/c Pb impact on target: Impact at 75 degree – Typical tracks

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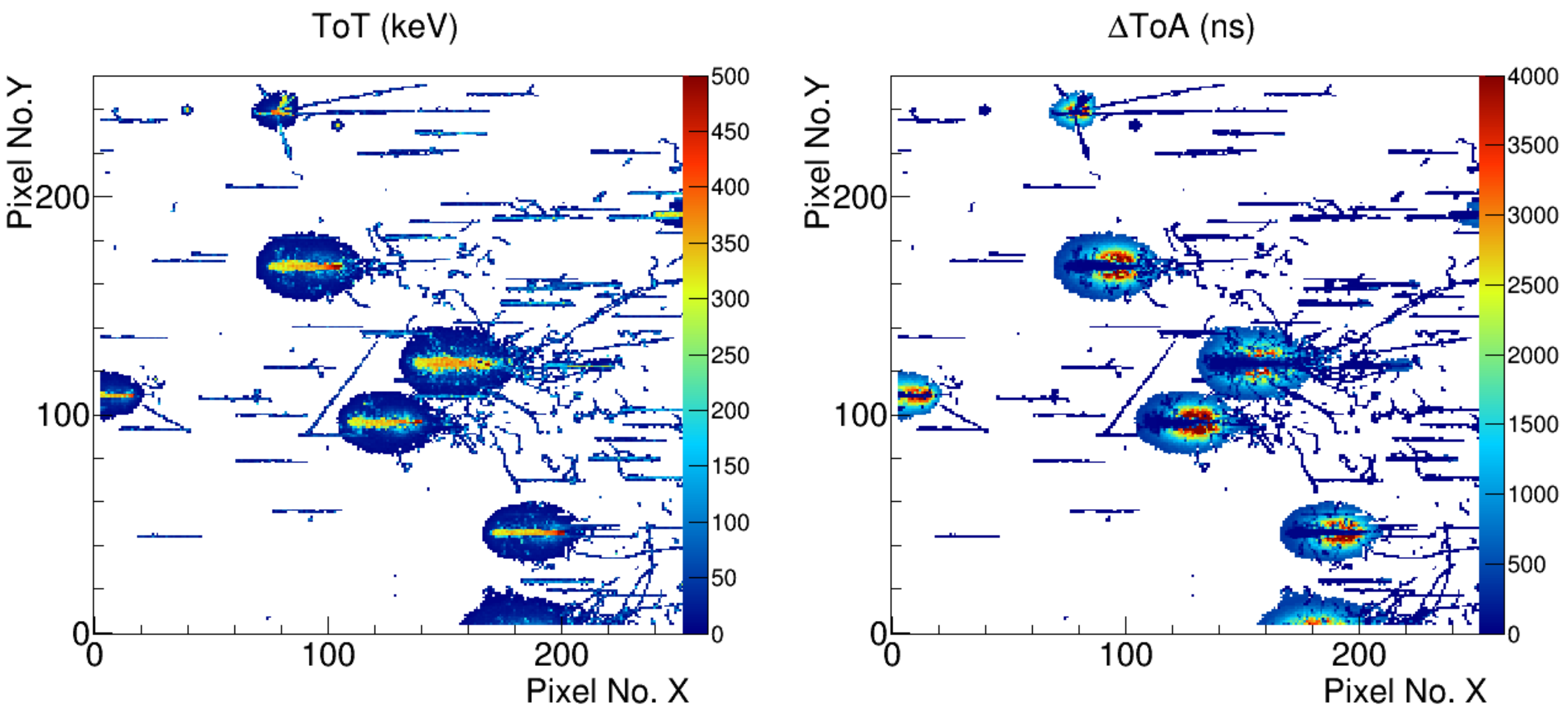
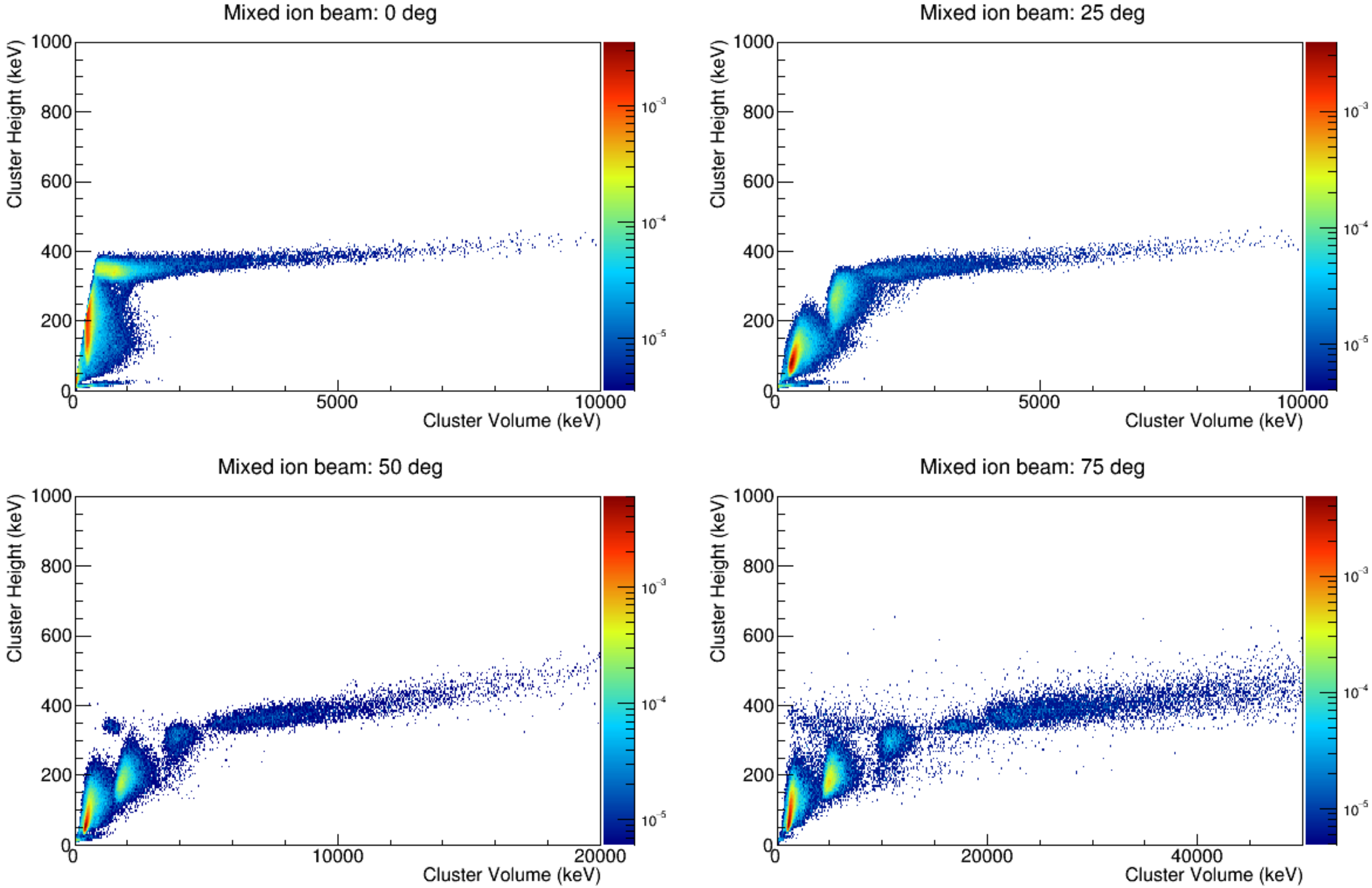
- Example tracks:



Events measured at an impact angle of 75 degrees

Pixel-saturation level

Per pixel energy saturation level ~500 keV independent of impact angle and bias



Measured energy vs. expected energy

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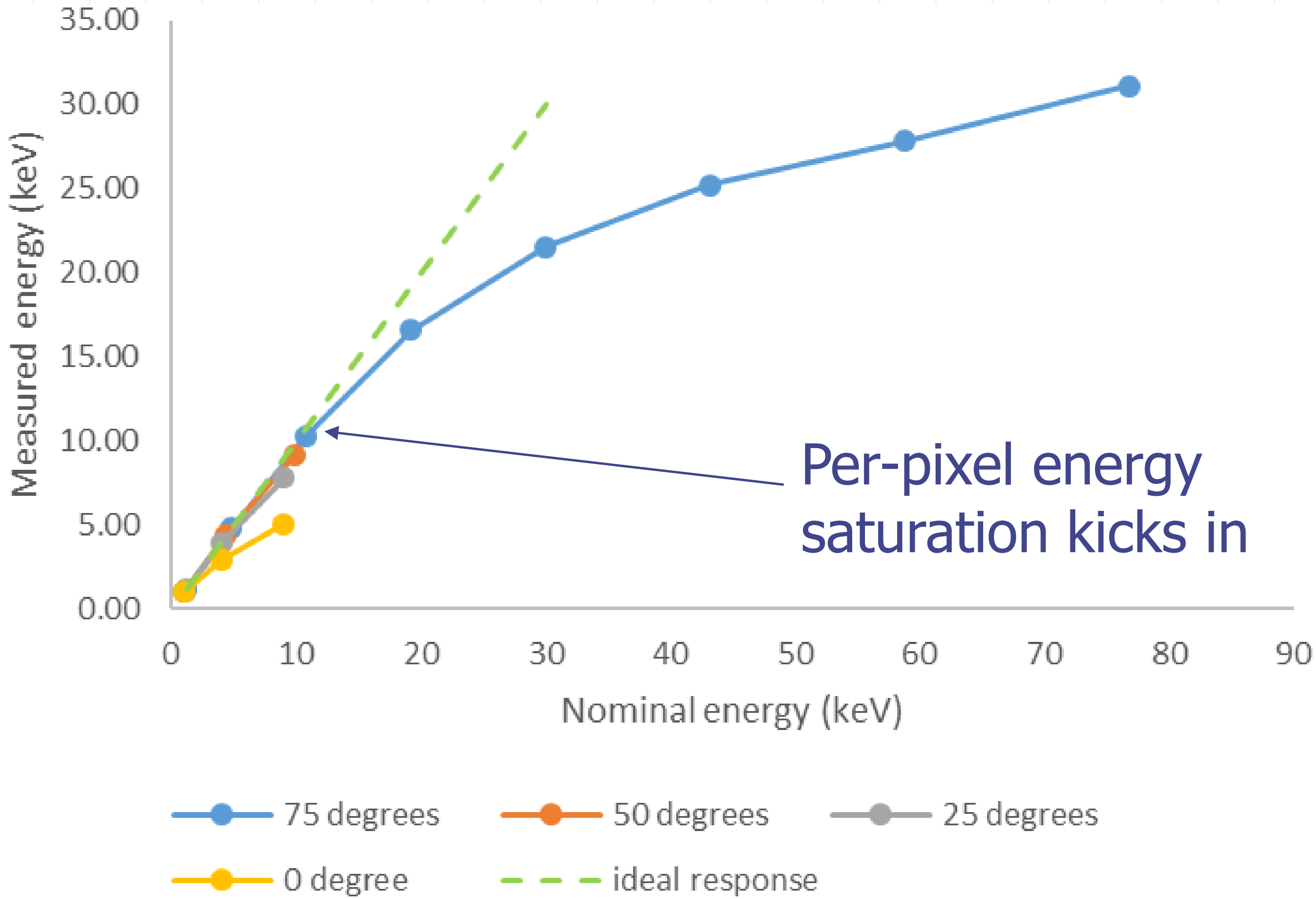
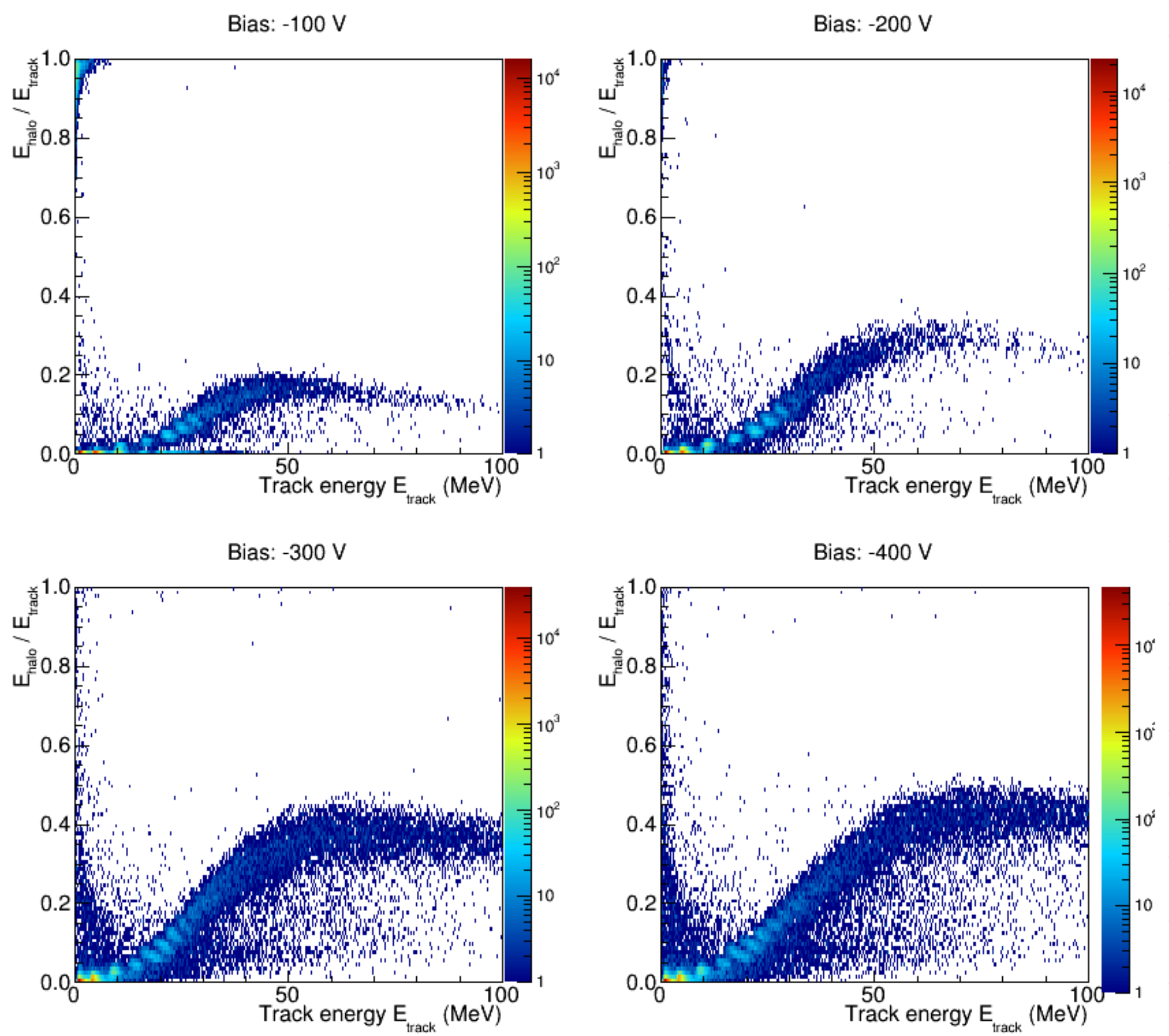


Halo vs. energy

- Relative amount of energy in the halo increases with increasing energy deposition

- Relative amount of energy in the halo increases with increasing bias voltage



330 GeV/c Pb impact on target: Single heavy ion event – Features

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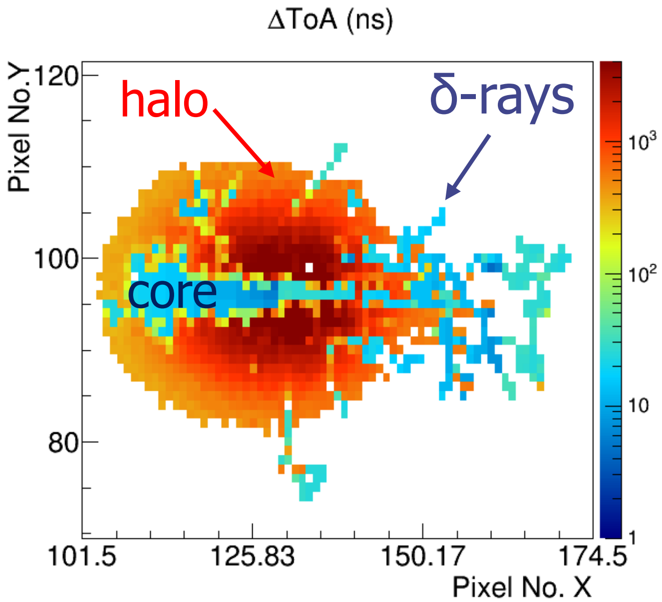
- Initial track (core) with outgoing δ-rays surrounded by a halo of pixels with lower energy measurements

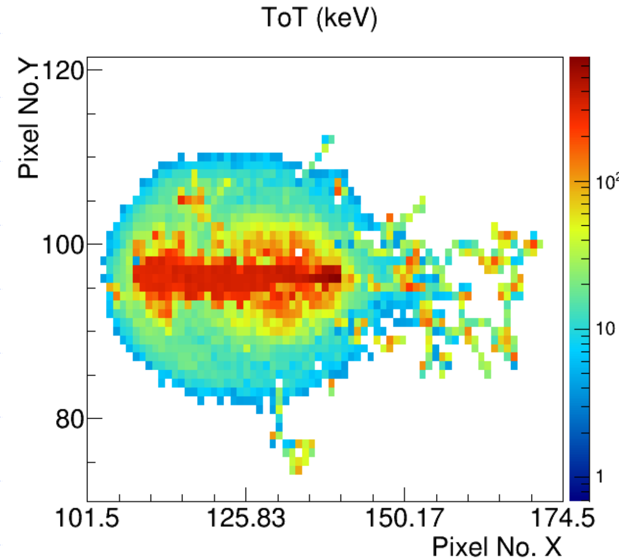


Halo pixels are seen with a delay in the order of µs

→ Time structure can be used to easily separate core and halo

→ Halo delay decreases with increasing bias voltage

→ Halo pixels' timestamp decreases with increasing distance to the core



- Number of halo pixels and energy in the halo increases with increasing bias
- Energy in the halo increases with energy deposition