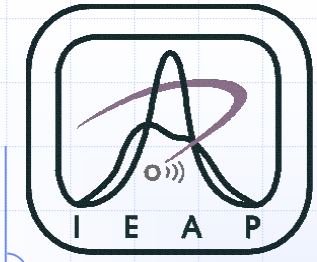

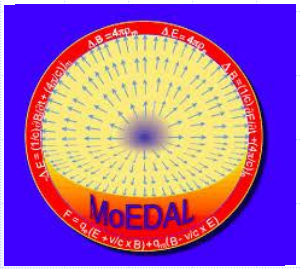

Radiation field characterization with the MoEDAL Timepix network

Benedikt Bergmann, Petr Burian, Claude Leroy, **Petr Manek**, Lukas Meduna, Stanislav Pospisil, Michal Suk

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Outline

- The MoEDAL TPX network
- Example of the improved capabilities of Timepix3
- Test beam measurements in mixed fields with heavy ions
- Novel approaches for in-depth track analysis and characterization
  - Line segment determination using the Hough Transform
  - AI approach for track classification
  - Star detection
- Characterization of radiation fields in MoEDAL
  - Neutron fluxes at TPX05
  - Stopping power and angle distributions

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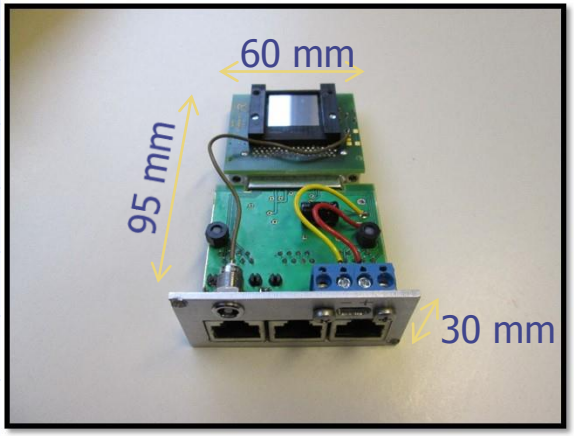
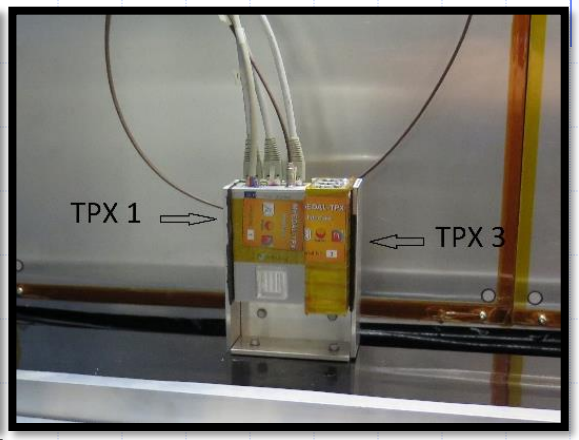
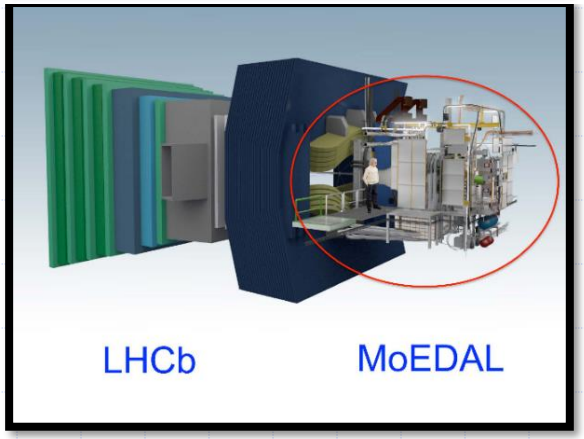
The TPX-MoEDAL network

The MoEDAL-TPX devices

- 5 Timepix devices were installed in the MoEDAL experiment at CERN.







Timepix devices in the MoEDAL experiment

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Positions of the MOEDAL-TPX devices

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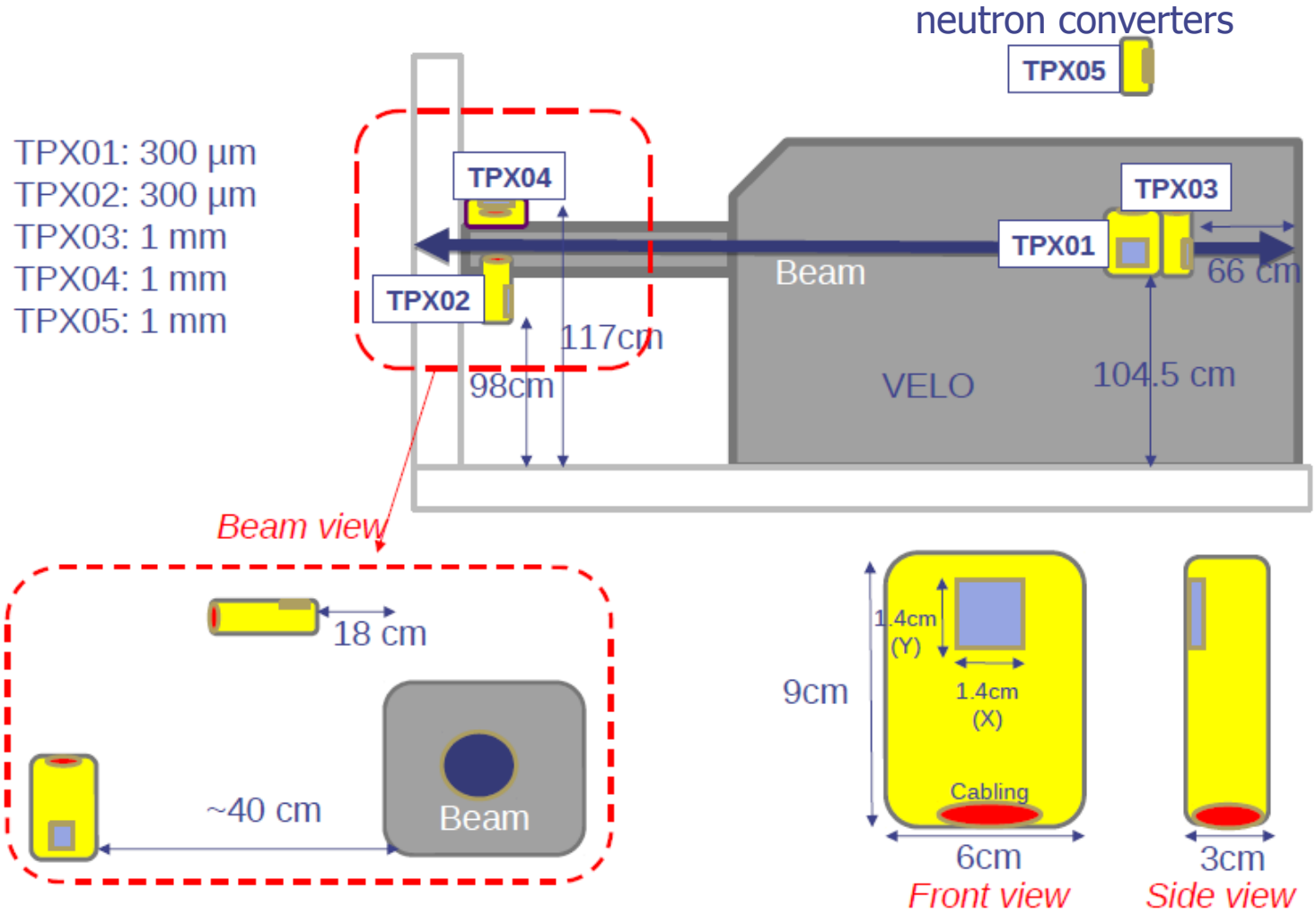

September 2018 - Upgrade of the network

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- The network was upgraded by the installation of 2 Timepix3 detectors

Timepix3:

- 256 x 256 pixels (pixel pitch 55 µm)
- Data driven readout up to 40MHits/cm^2/s
- ToT and ToA simultaneously (1.5625 ns)

- TPX01 and TPX02 were removed (radiation damage?)

Examples of the improved capabilites of Timepix3

New possibilities with Timepix3 detectors (1)

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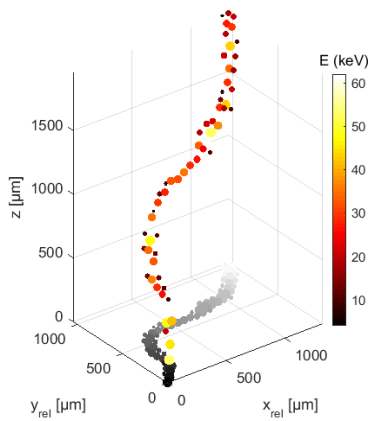
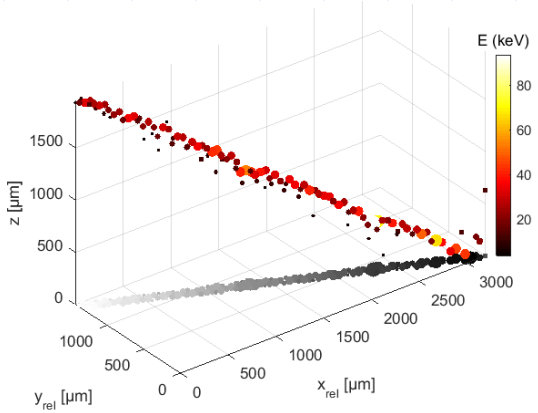
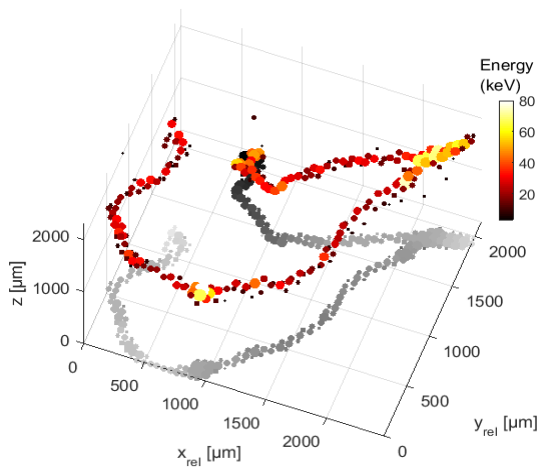
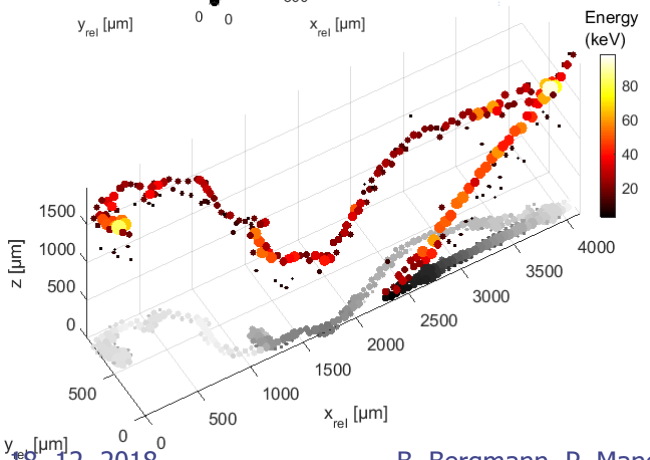
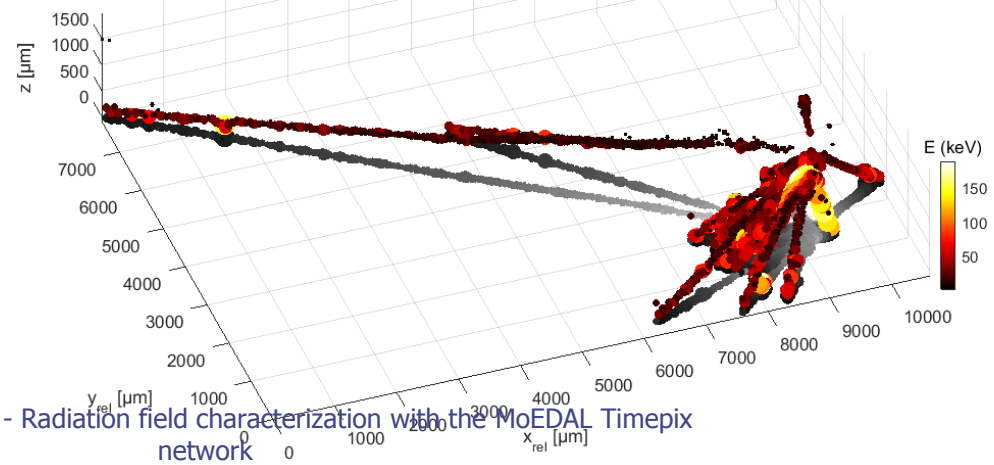
- Precise measurement of drift times in the sensor layer allows a 3D reconstruction of particle interactions (Timepix3 as an "Active nuclear emulsion")
- Voxel detector with voxel size 55 x 55 x 60 μm^3











New possibilities with Timepix3 detectors (2) – Timepix3 in ATLAS

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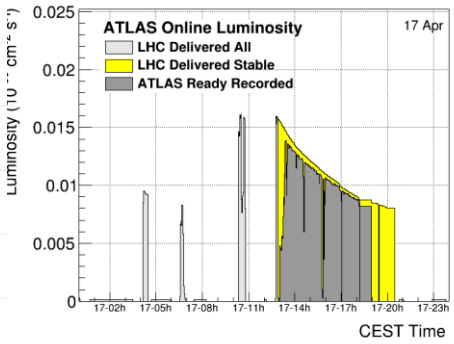
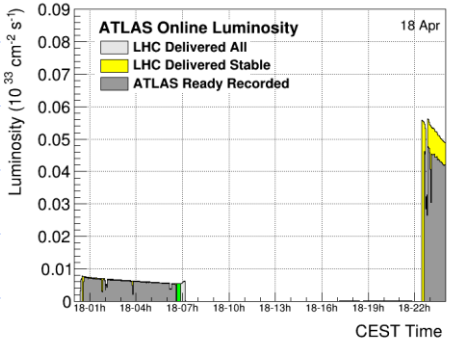
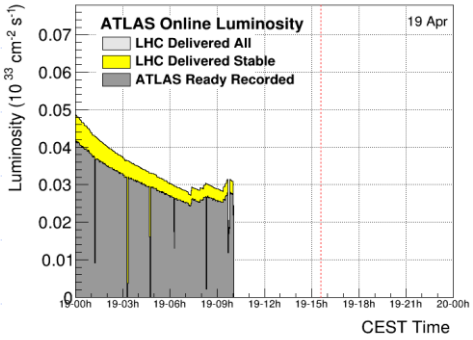
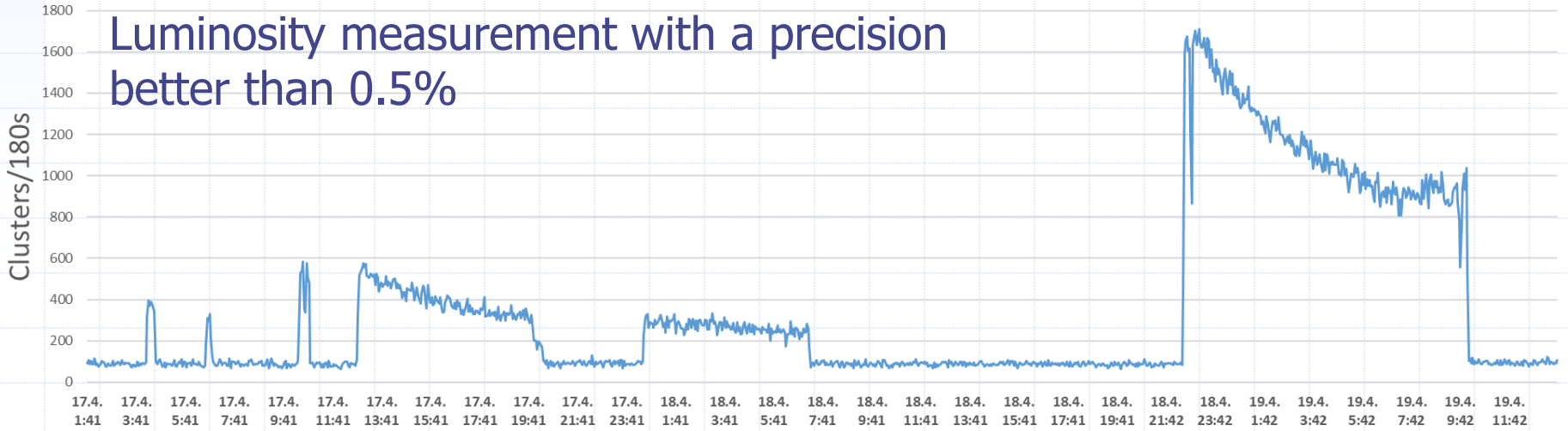
- (Quasi-) dead time free measurement of count rate (real-time analysis with latency < 50 ms possible)



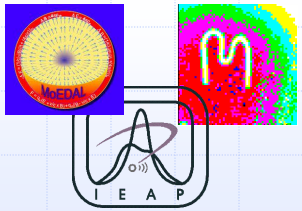




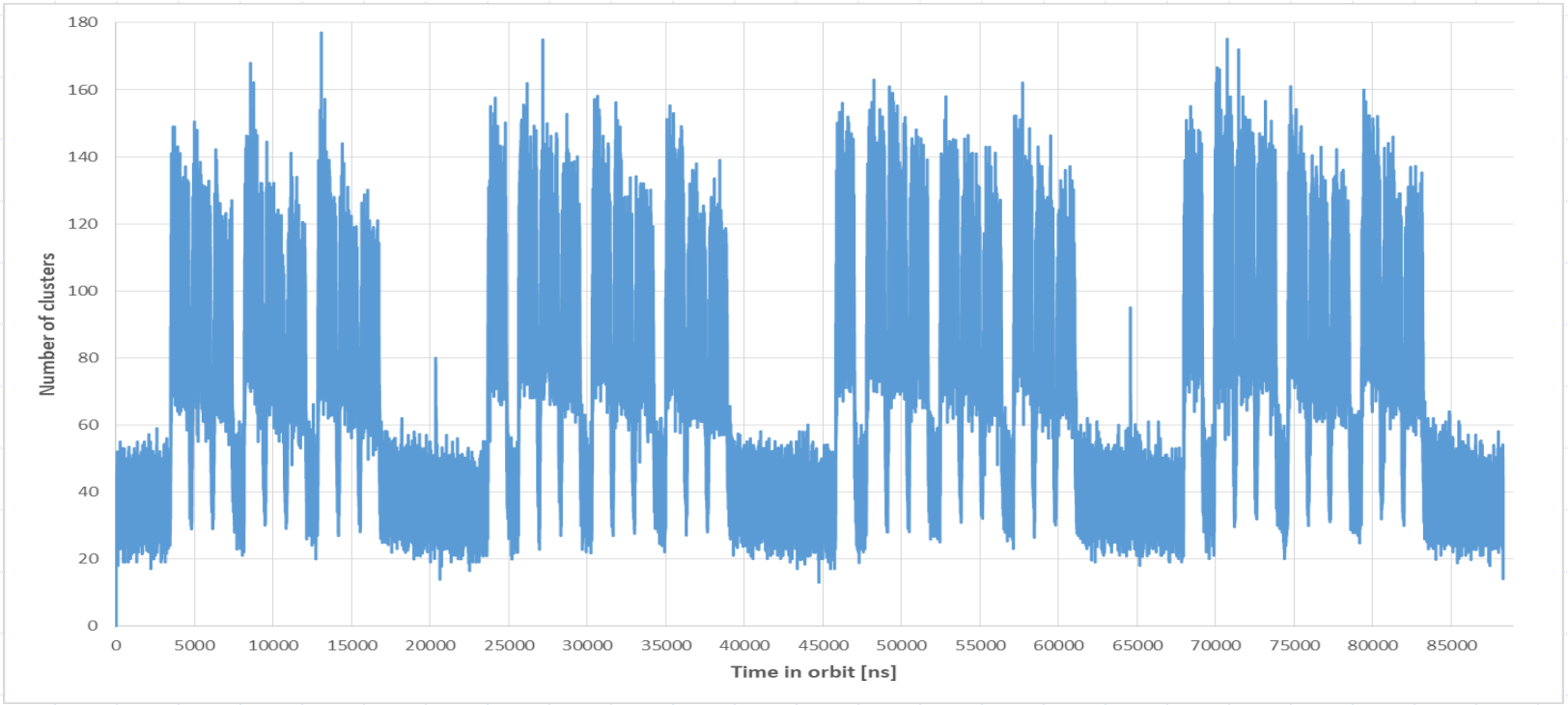
Luminosity measurement with a precision better than 0.5%



New possibilities with Timepix3 detectors (3) – Timepix3 in ATLAS



- Synchronization with ATLAS orbit clock



New possibilities with Timepix3 detectors (4) – Timepix3 in ATLAS

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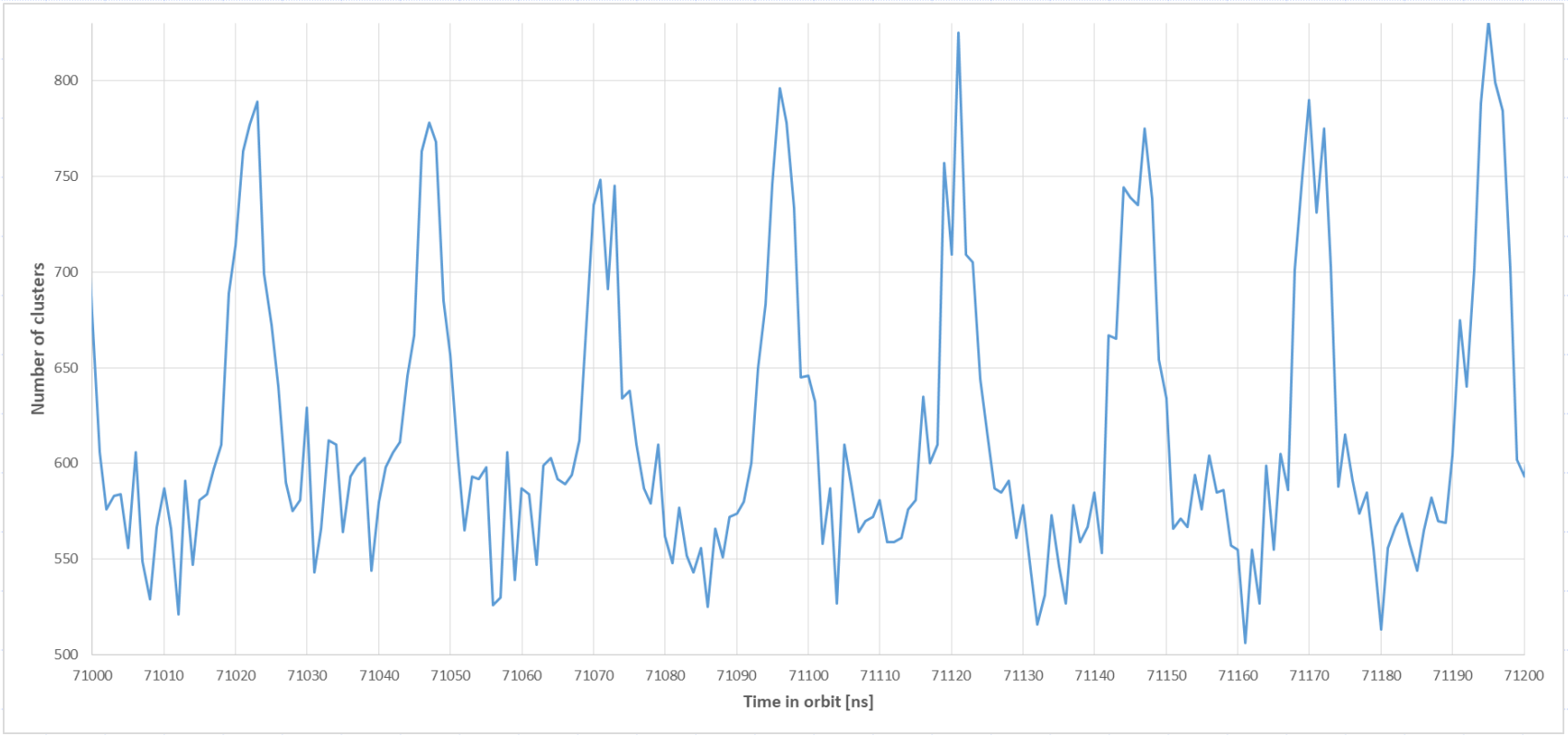
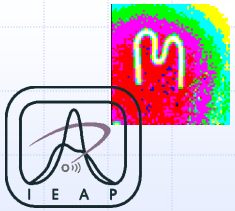
- Synchronization with ATLAS orbit clock



Sigma of ~ 2 ns

New possibilities with Timepix3 detectors (5) – Timepix3 in ATLAS



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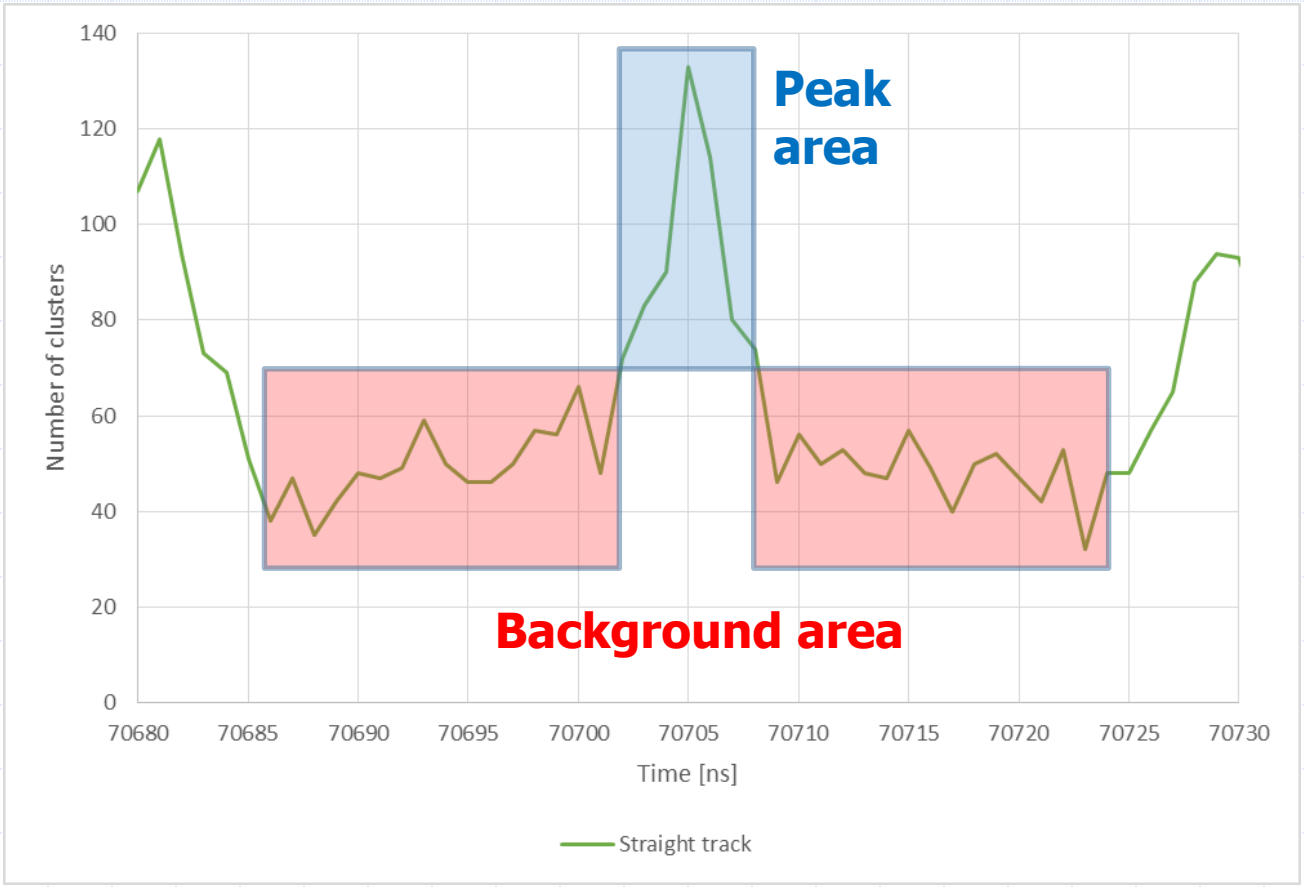
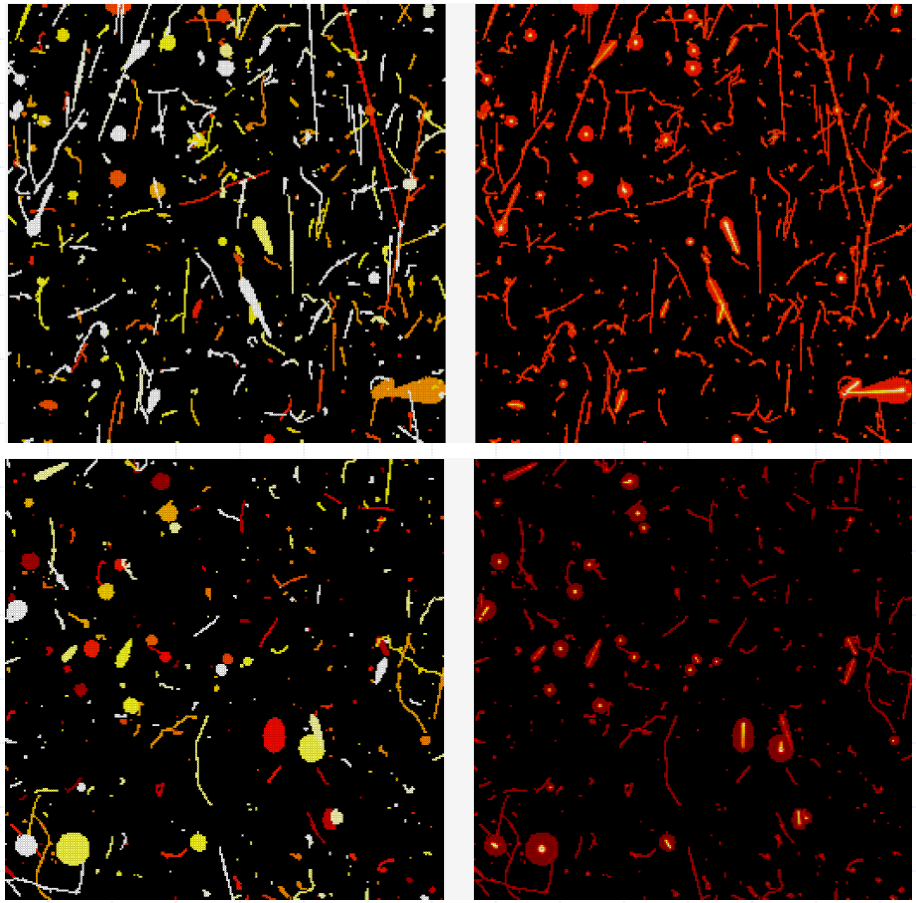


New possibilities with Timepix3 detectors (6) – Timepix3 in ATLAS



In the peak area in addition to the events also seen in the backgound area, highly aligned tracks (possibly MIPs from the interaction point are seen).

Test beam measurements in mixed fields with heavy ions

Test in heavy ion beam (Pb)

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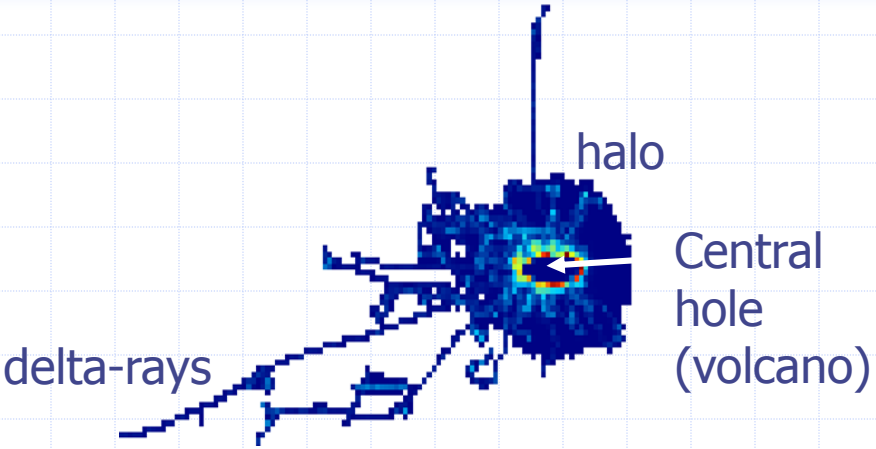
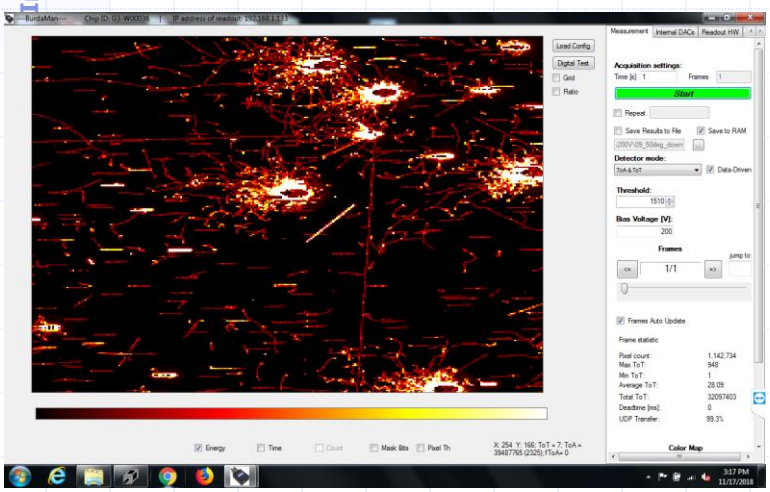
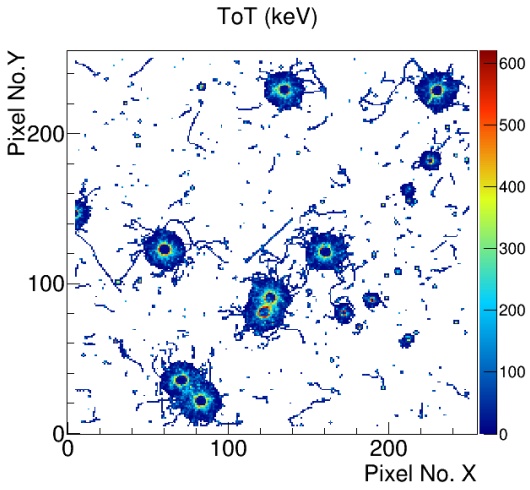
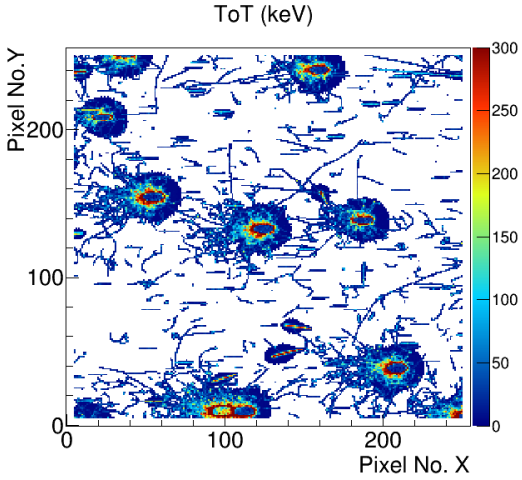
Extending the range of measured responses to high-Z.

- Pb ions ~150 GeV/c
- Timepix3 500 µm thick silicon
- Data-driven mode with 0.01 s acquisition time









Timepix in a mixed field (cocktail)

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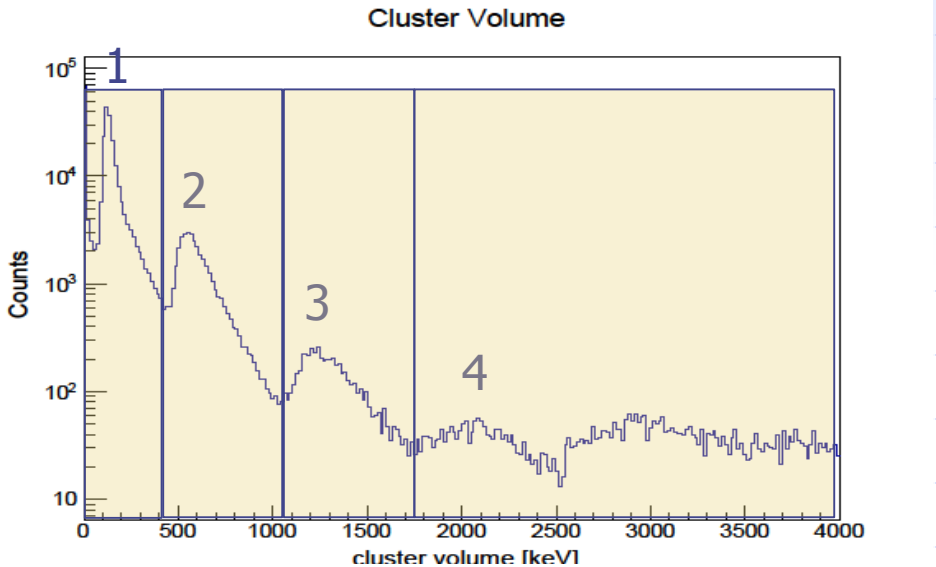
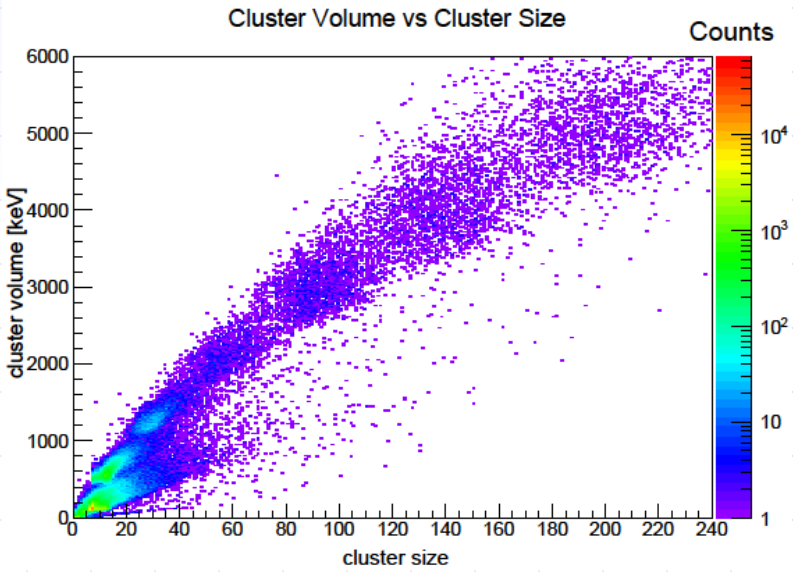
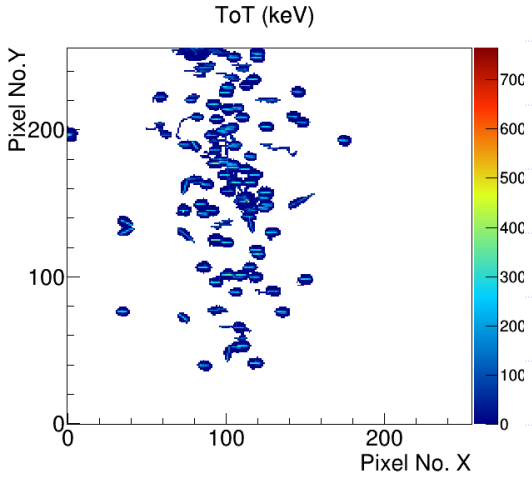
Understading the particle separation capability.

- Timepix3 with 300 µm thick silicon sensor
- Pb (~150 GeV/c) on target
- Angle of incidence 50°







Novel approaches for in-depth track analysis and characterization

Current data analysis methods – Pattern recognition

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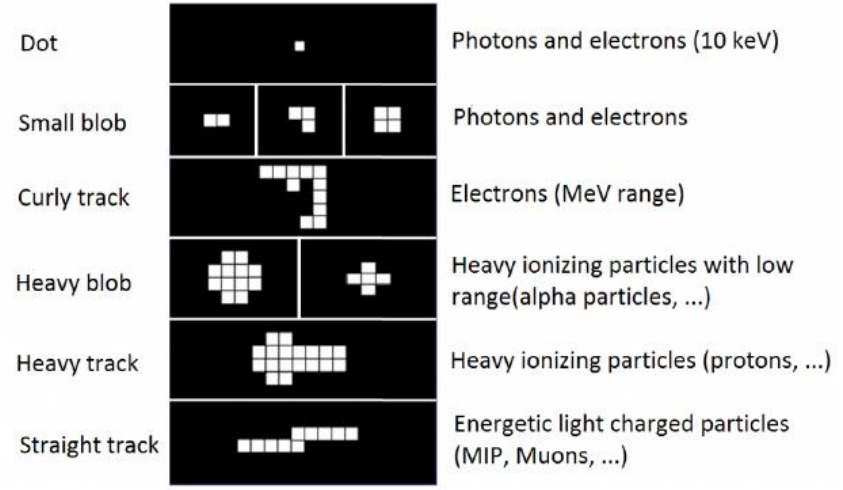
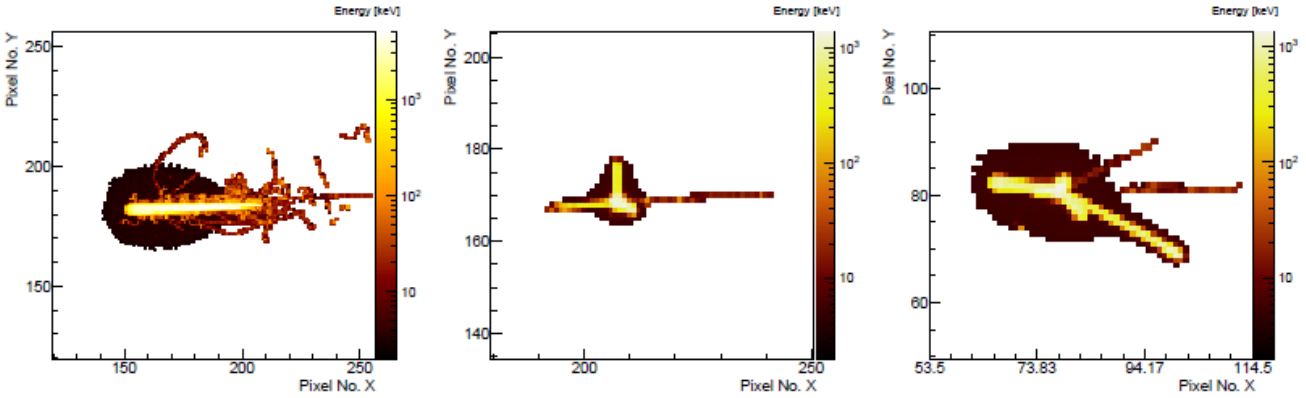
Pattern recognition developed by Holy et al. works well for separation of low energy transfer events from high energy transfer events.

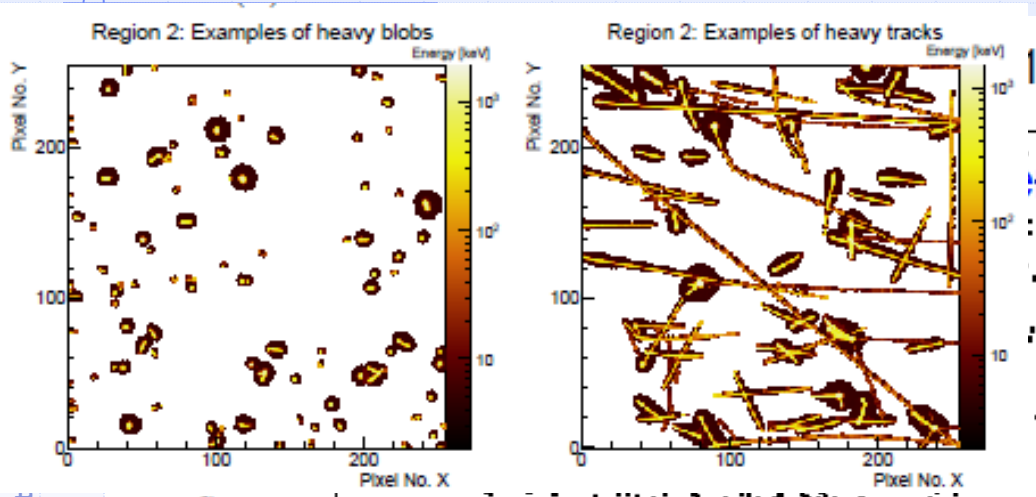
BUT:
Huge variety of different track shapes is put to the same category (Heavy tracks).

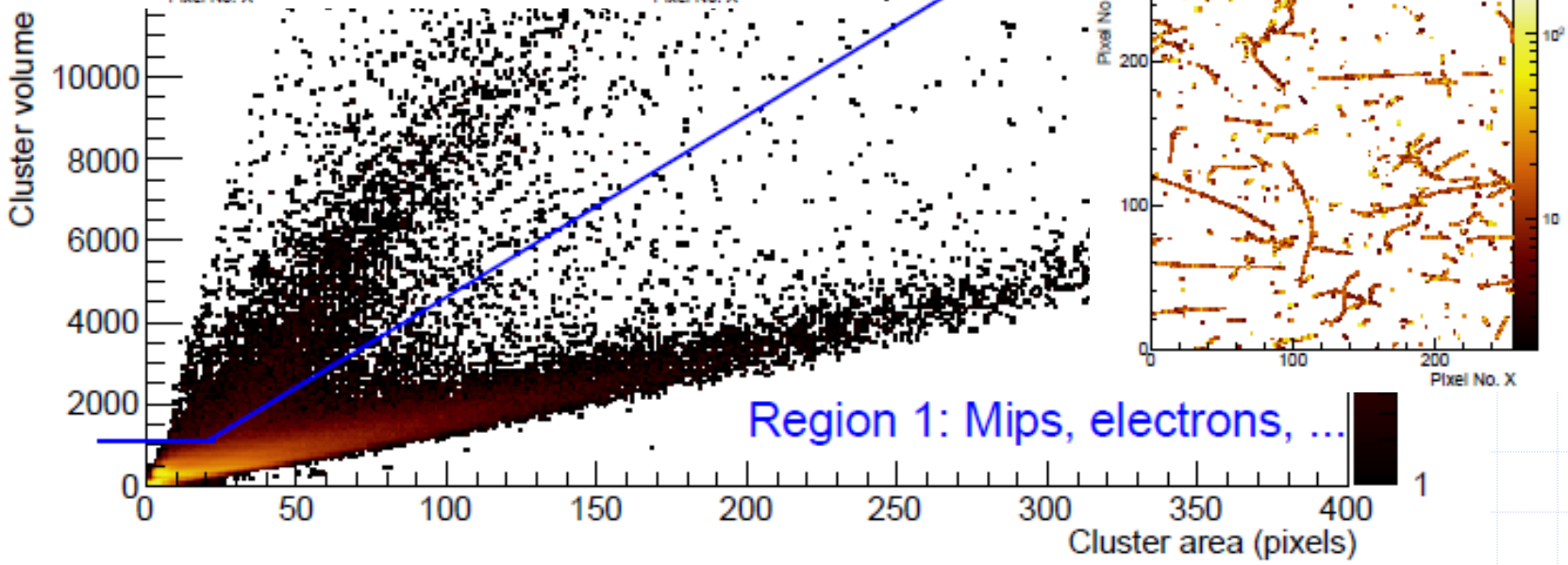


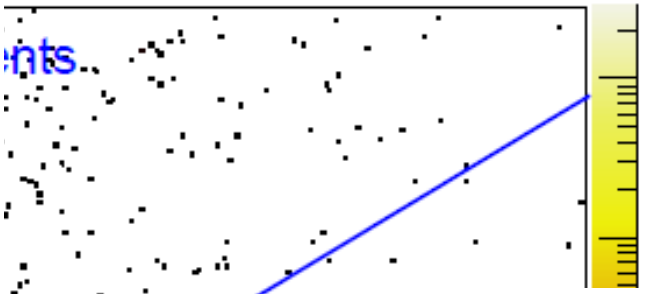
Examples:



First (naive) approach to look at the data:







Particle Trajectory Estimation by CV Approaches (1)

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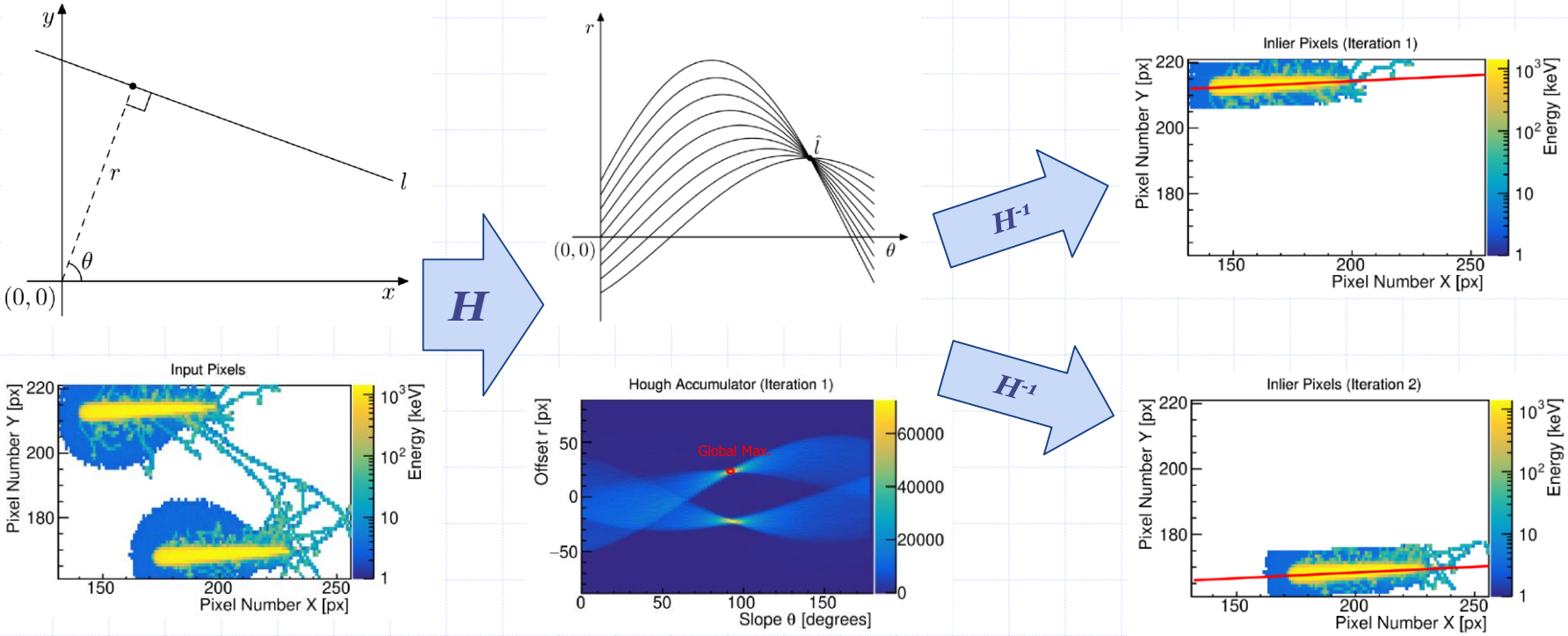
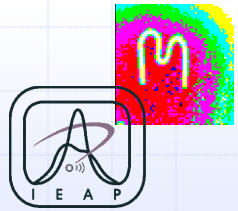
Problem #1: assuming linear trajectories, detect and separate overlapping clusters.

- Used Hough Tf. to map pixels to accumulator.
- Sub-clusters are sequentially subtracted by greedy algorithm under threshold is reached.



Particle Trajectory Estimation by CV Approaches (2)



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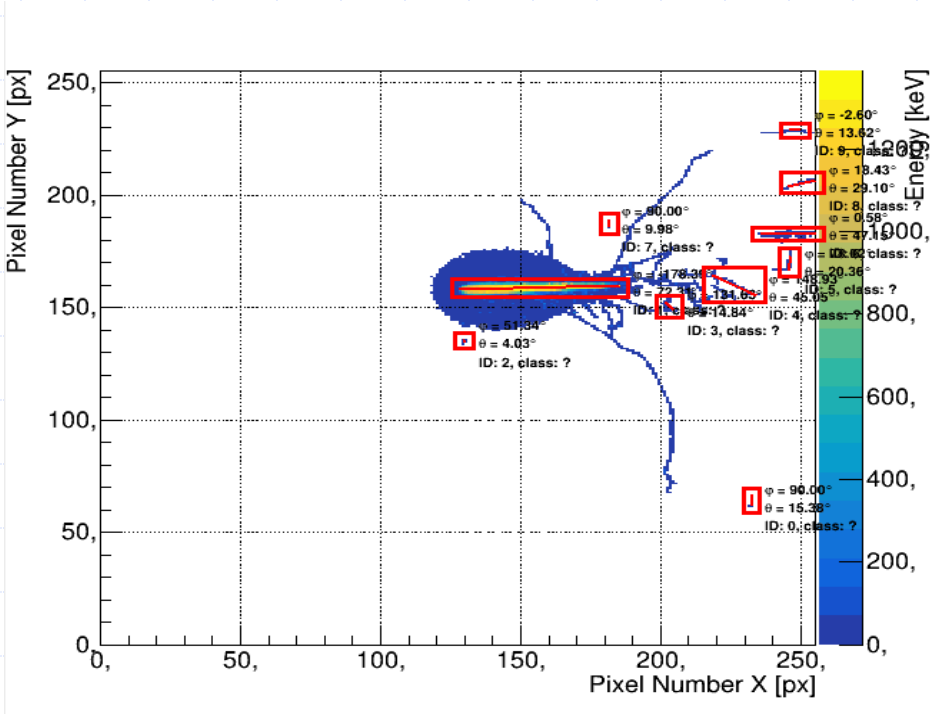
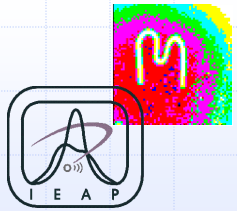
Problem #2: assuming linear trajectory, detect most likely points of entry and exit in a heavy blob / track.

- Parametrized by point of entry and spherical angles.
- Tested 3 RANSAC-like local energy maxizimers.
- Separated up to 20 overlaps.

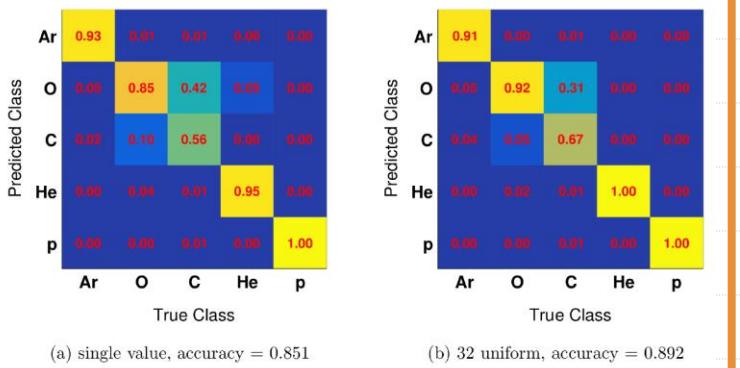


Heavy Ion Recognition by Energy Loss Model



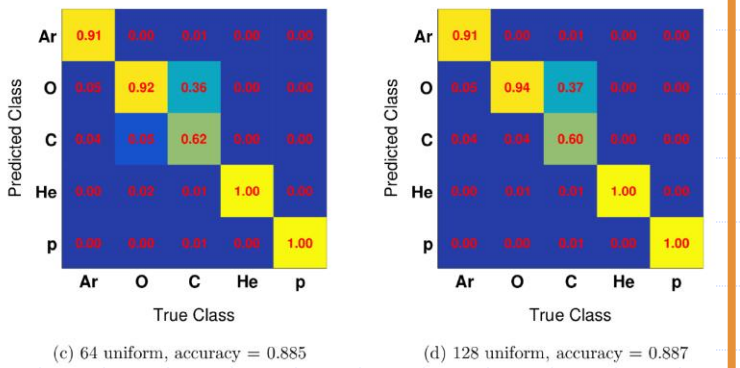
Problem: Classify estimated trajectories with corresponding X

- Defined feature model by sampling dE/dx along the trajectory.
- Implemented 3 different sampling models to avoid external noise.
- ML: used K nearest neighbors classifier without / with rejection option.
- Achieved up to 94% accuracy with rejection rate < 25%.



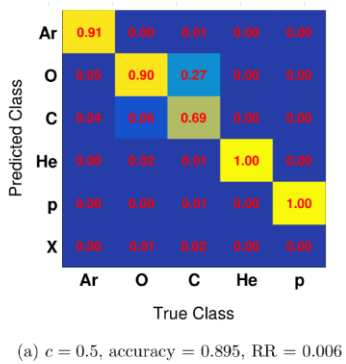
(a) single value, accuracy = 0.851

(b) 32 uniform, accuracy = 0.892

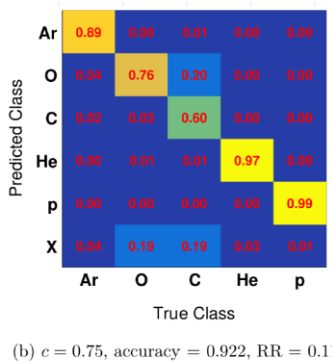


(c) 64 uniform, accuracy = 0.885

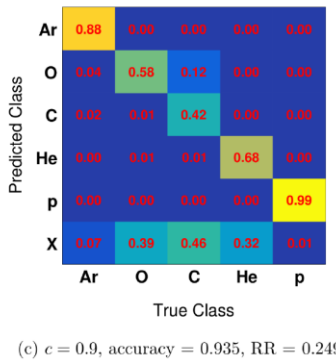
(d) 128 uniform, accuracy = 0.887



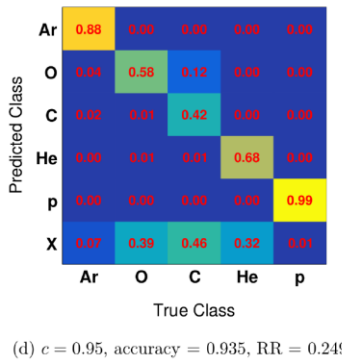
(a) $c = 0.5$, accuracy = 0.895, RR = 0.006



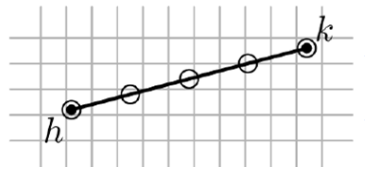
(b) $c = 0.75$, accuracy = 0.922, RR = 0.111

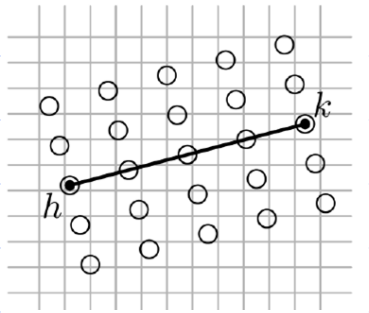


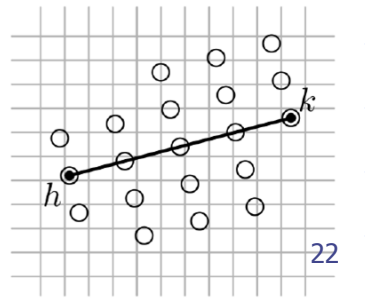
(c) $c = 0.9$, accuracy = 0.935, RR = 0.249



(d) $c = 0.95$, accuracy = 0.935, RR = 0.249





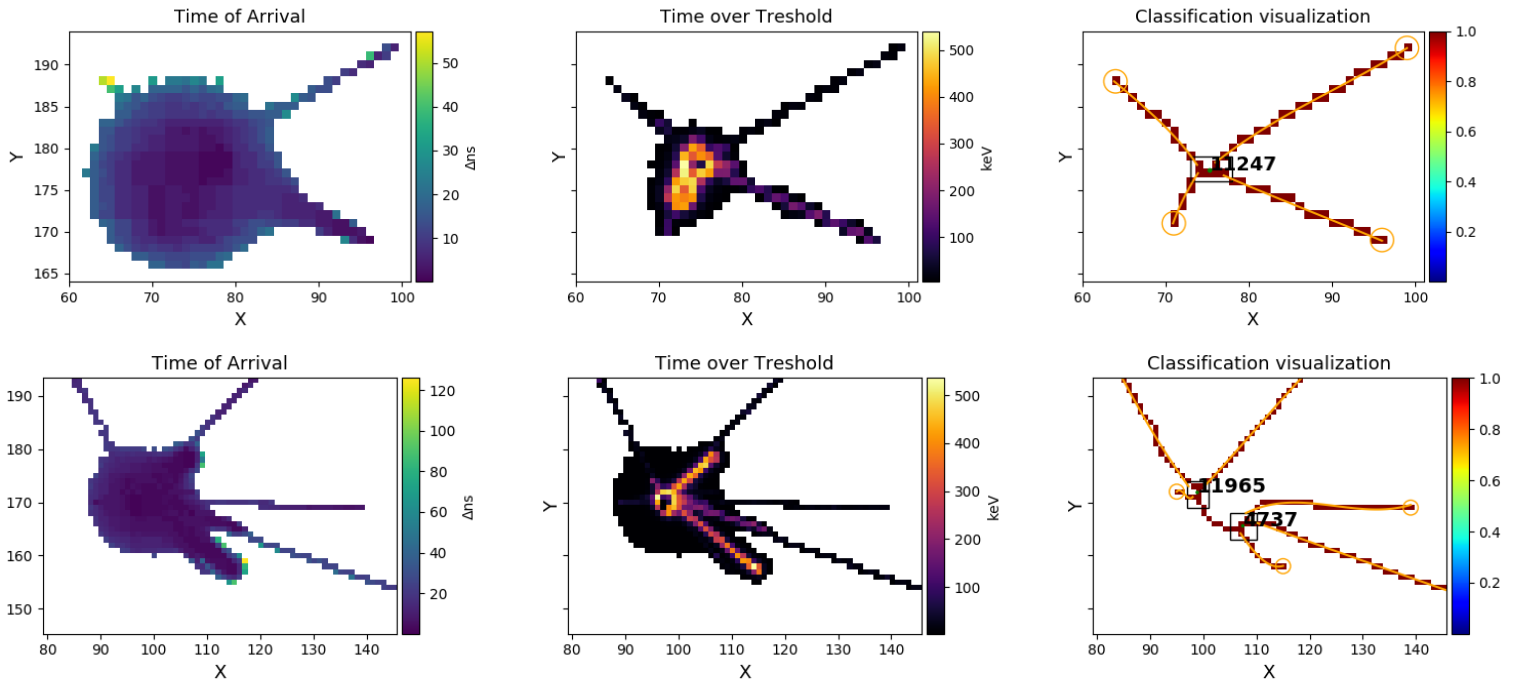


Analysis of star-like events (1)

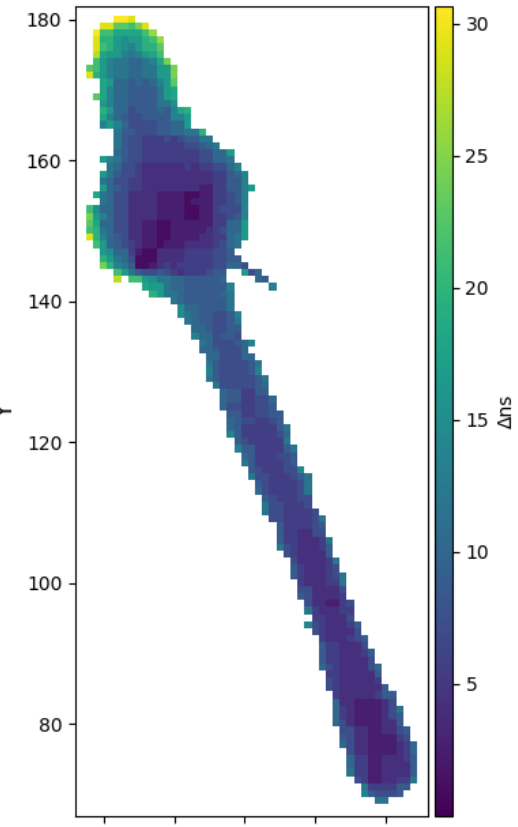
Characterize star-like events by the number of outgoing tracks N as N-prong event

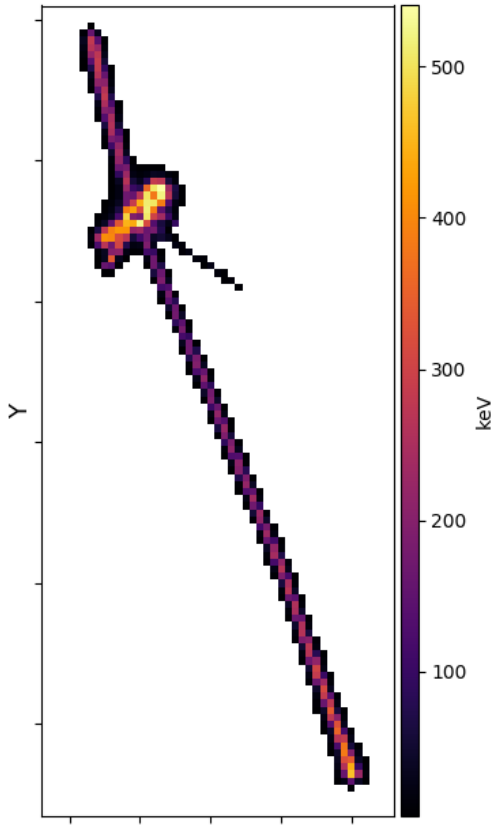
Strategy:

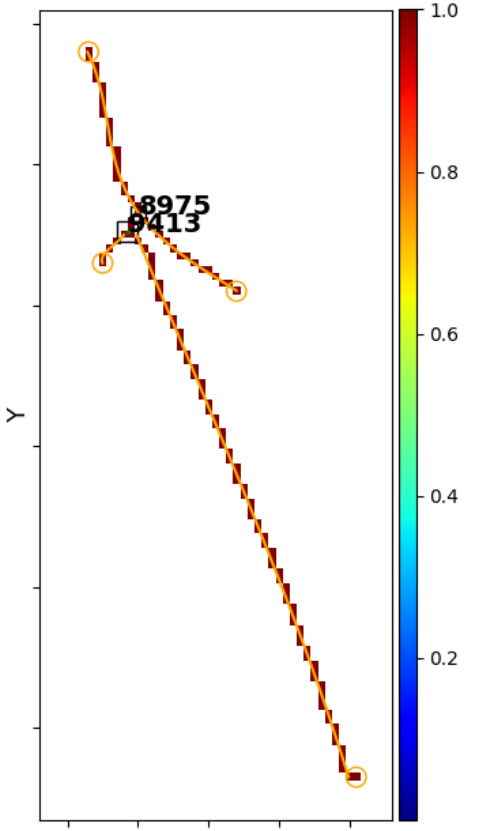
- Cut away low energy pixels (below 5 keV)
- Use an erosion algorithm to reduce the remaining track to the skeleton
- Find all branch ends



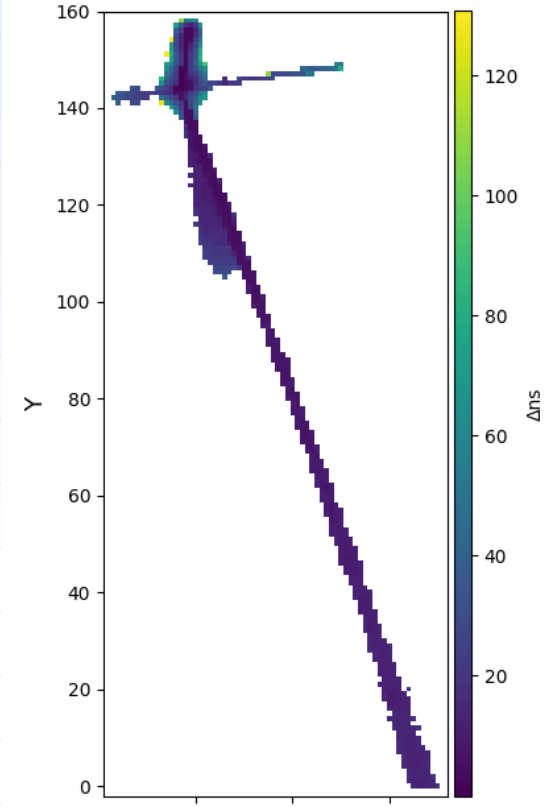
Analysis of star-like events (2)

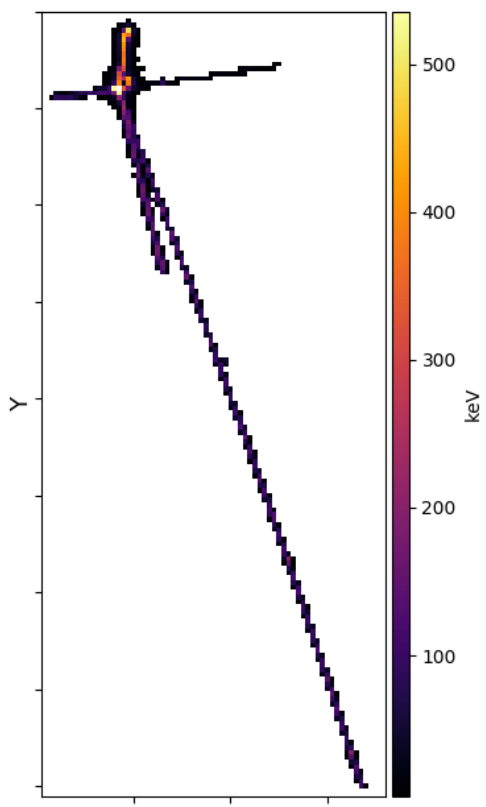


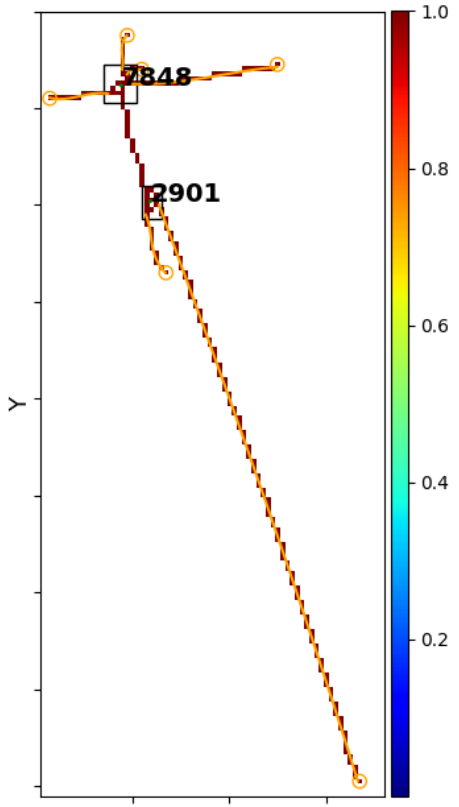




Analysis of star-like events (3)







Radiation field characterization in MoEDAL

Determination of neutron fluxes from TPX05 data

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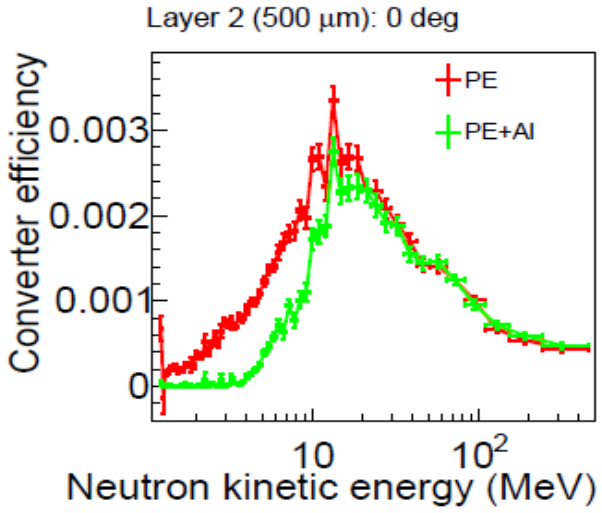
PE + Al	LiF
PE	free

- Converters and stopping foils:
  - ^{6}LiF (89% Li enrichment): thermal neutrons through tritons and αs Efficiency ~ 0.5 %
  - PE (~ 1 mm): fast neutrons through recoil protons
  - PE (~ 1 mm) + Al (80 μm): fast neutrons above 4 MeV (slow recoil protons absorbed in the aluminum)
  - Free: Subtraction of the non-neutron field

Source (E_{mean})	Efficiency (%)
^{252}Cf (2.2 MeV) (0°, layer 2)	0.047 ± 0.0024 (PE) 0.0118 ± 0.0002 (PE+Al)
^{252}Cf (2.2 MeV) (180°, layer 1)	0.0390 ± 0.0003 (PE) 0.0089 ± 0.0003 (PE+Al)
^{241}Am-Be (4.2 MeV) (0°, layer 2)	0.089 ± 0.002 (PE) 0.0290 ± 0.0003 (PE+Al)
^{241}Am-Be (4.2 MeV) (180°, layer 1)	0.0845 ± 0.0011 (PE) 0.0333 ± 0.0006 (PE+Al)



Determination of neutron fluxes from TPX05 data - Results

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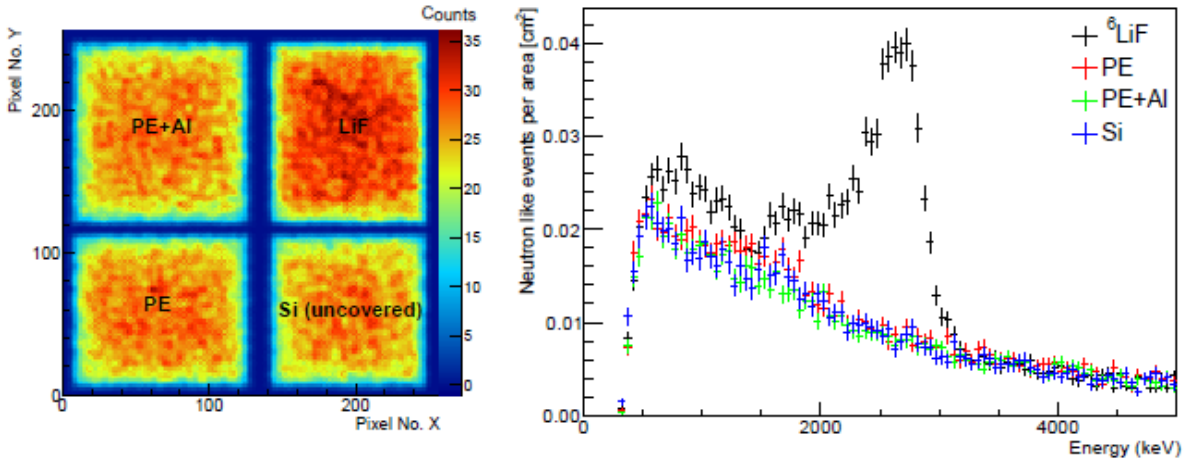
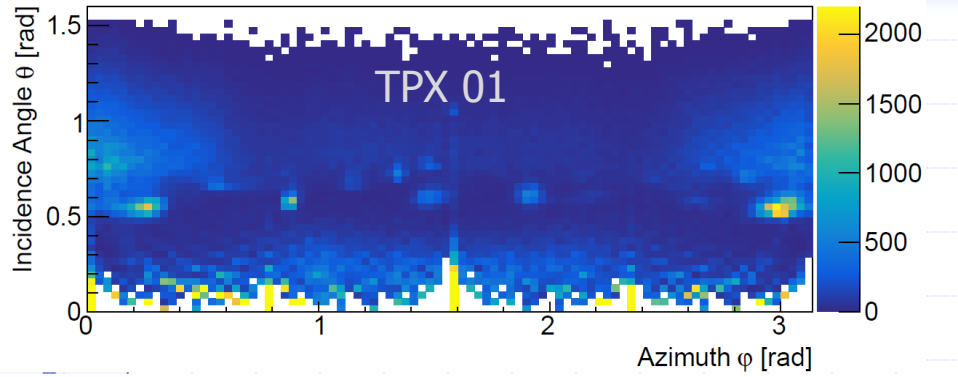
- Date: May 17, 2016 (ca. 27 nb^{-1})

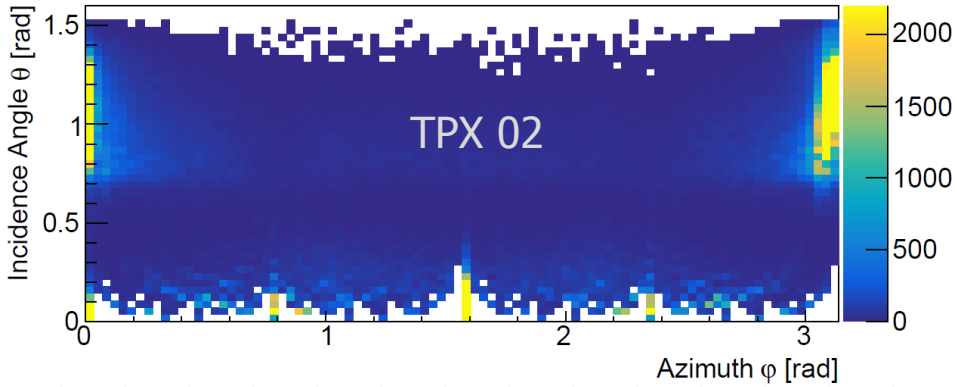


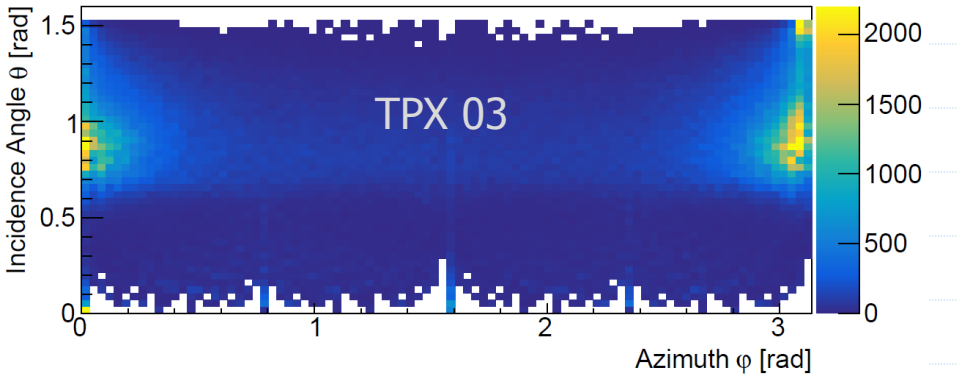
$$\Phi_{n,i} = \frac{N_i/A_i - N_{\mathrm{Si}}/A_{\mathrm{Si}}}{\epsilon_i N_{\mathrm{frames}} t_{\mathrm{acq.}}}$$

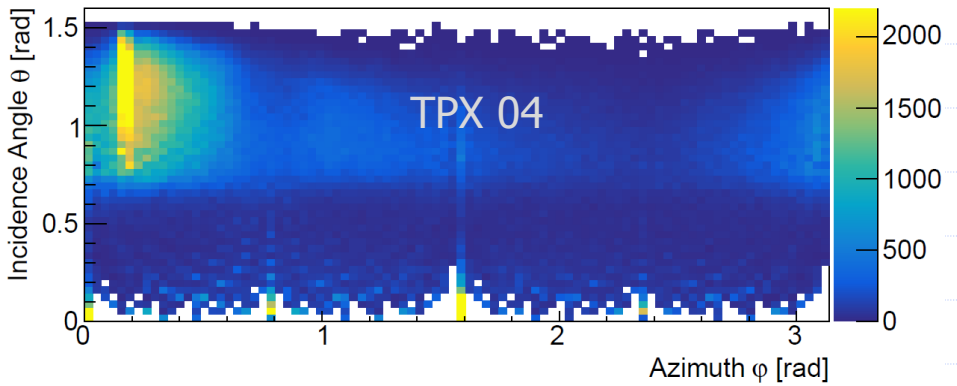
Region	^{6}LiF	PE	PE+Al	Si
N_i	88504	73213	86173	62858
A_i [cm^{-2}]	0.440	0.423	0.499	0.373
ϵ_i [%] [6]	(0.50 ± 0.05)	$0.02 - 0.32$	$0.02 - 0.25$	-
θ coverage	full	$0° - 75°$	$0° - 75°$	-
T_n	$\approx 25\,\mathrm{meV}$	$> 1\,\mathrm{MeV}$	$> 4\,\mathrm{MeV}$	-
Φ_n [$\frac{\mathrm{cm}^{-2}}{\mathrm{nb}^{-1}}$]	$(12.1 \pm 1.3) \times 10^3$	$(2.6 - 158.1) \times 10^3$	$(2.4 - 105.3) \times 10^3$	-

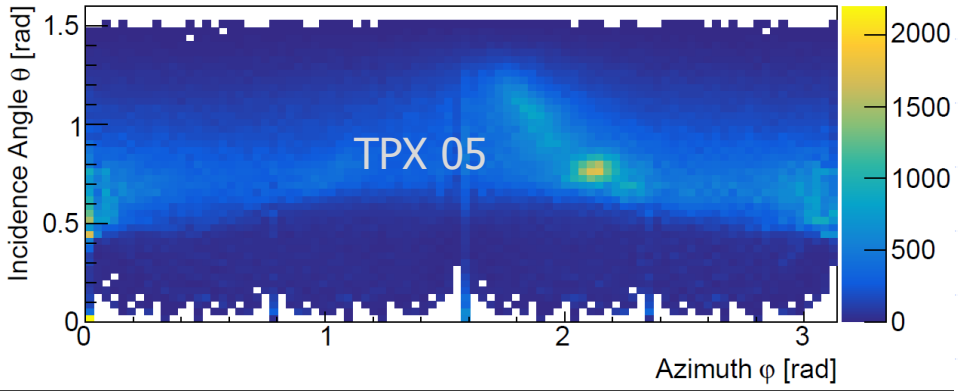
Application to MOEDAL data – Impact angle determination

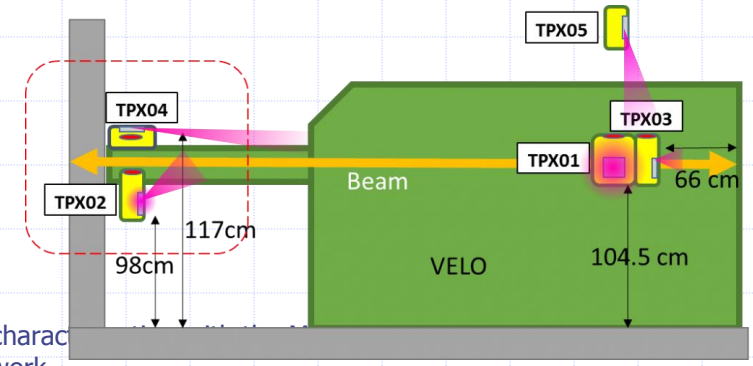




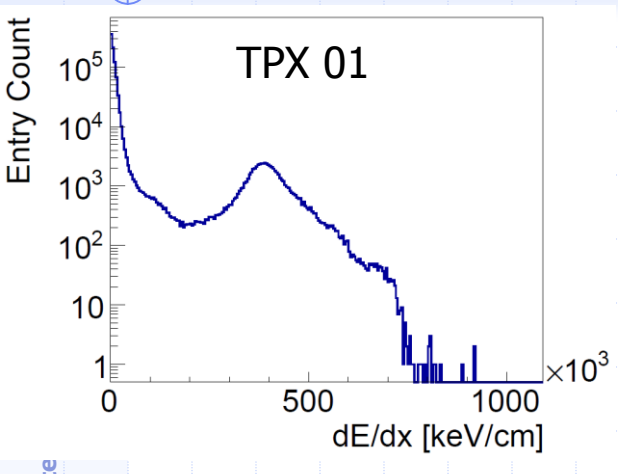


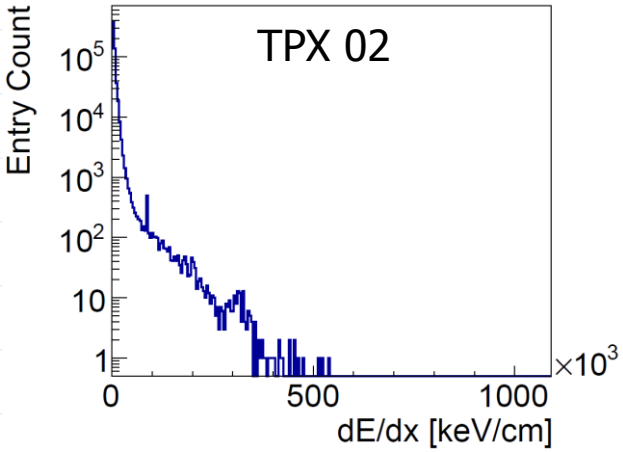


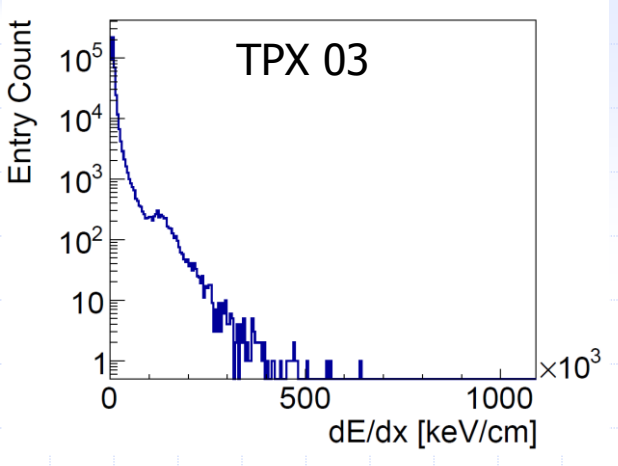


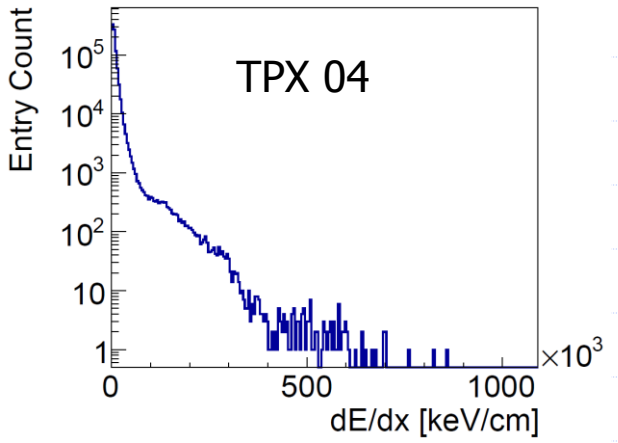


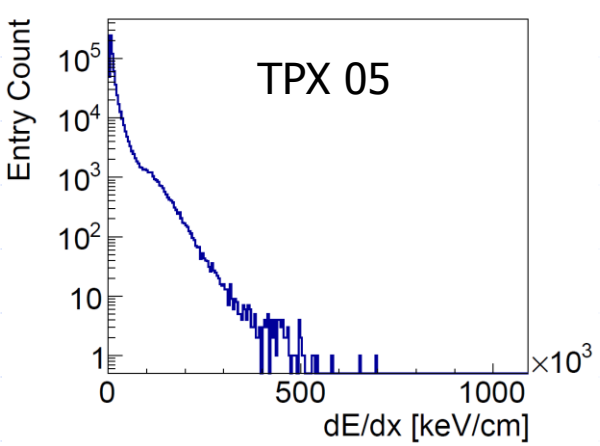
Application to MOEDAL data – Stopping power distributions

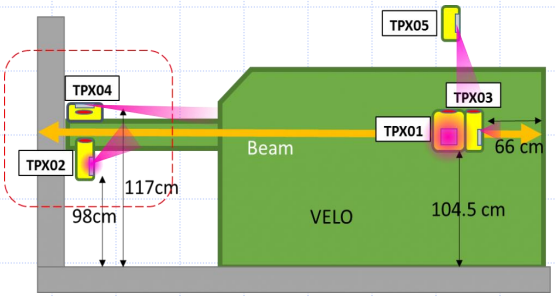












Conclusion

- The MoEDAL TPX network was upgraded in September 2018 with Timepix3 detectors
- Different data analysis methods were developed and applied to measured data.
- Thermal and Fast neutron fluxes were presented at the position of TPX05
- The directions of heavily ionizing particles and their stopping powers were shown at the different device positions.

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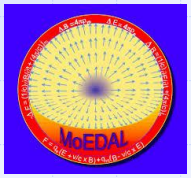
Thank you for your attention!

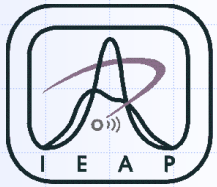
References:

[1] Bergmann, B., Pichotka, M., Pospisil, S. et al. Eur. Phys. J. C (2017) 77: 421. https://doi.org/10.1140/epjc/s10052-017-4993-4

[2] P. Burian et al 2018 JINST 13 C11024. http://iopscience.iop.org/article/10.1088/1748-0221/13/11/C11024

[3] B. Bergmann et al 2016 JINST 11 P10002. http://iopscience.iop.org/article/10.1088/1748-0221/11/10/P10002/meta





3D reconstruction: Measurement and reconstruction principle

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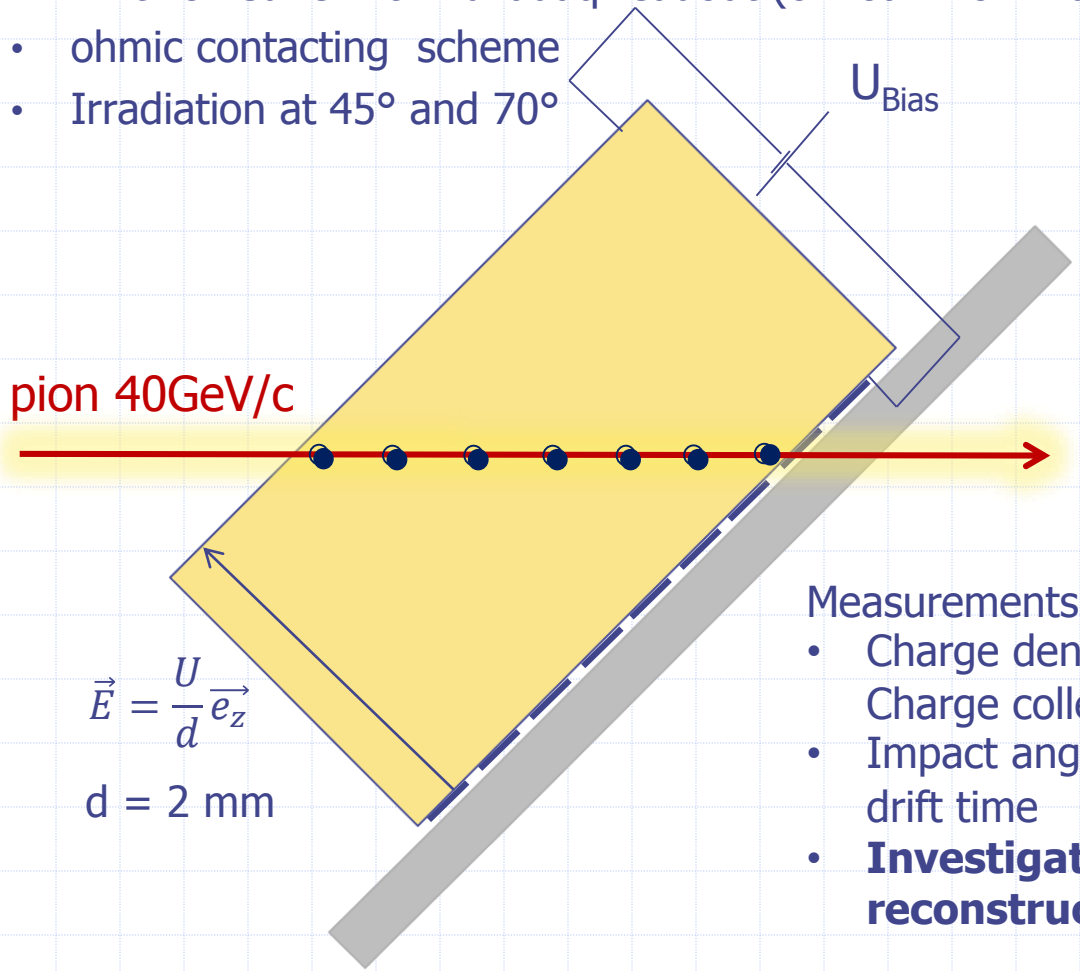
2 mm thick CdTe with Advadaq readout (on loan from Advacam):

- ohmic contacting scheme
- Irradiation at 45° and 70°



Measurements at different bias voltages:

- Charge density along trajectory constant → Charge collection efficiency
- Impact angle known → Measurement of the drift time
- **Investigate the 3D track reconstruction capability**