Randomized Computer Vision Approaches for Pattern Recognition in Timepix and Timepix3

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Aim of the talk

- Give brief overview of Timepix pixel detectors.
- Describe previous analysis works.

- Introduce *new* analysis work:
  - Extend current approaches to utilize new information,
  - CV-inspired overlap detection and separation,
  - Randomized regression of spatial trajectories in 2D and 3D,
  - ML: particle species classification.

Introduction

Timepix detectors

- Active pixel detector developed by Medipix collaboration, CERN
- 256 x 256 pixels with 55 μm pitch (1.98 cm^2 sensitive area)
- Hybrid design:
  - Sensor – thin layer of semiconductive material (Si, GaAs, CdTe),
  - ASIC – signal pre-amplifiers and counting circuitry (CMOS-based).

Working principle

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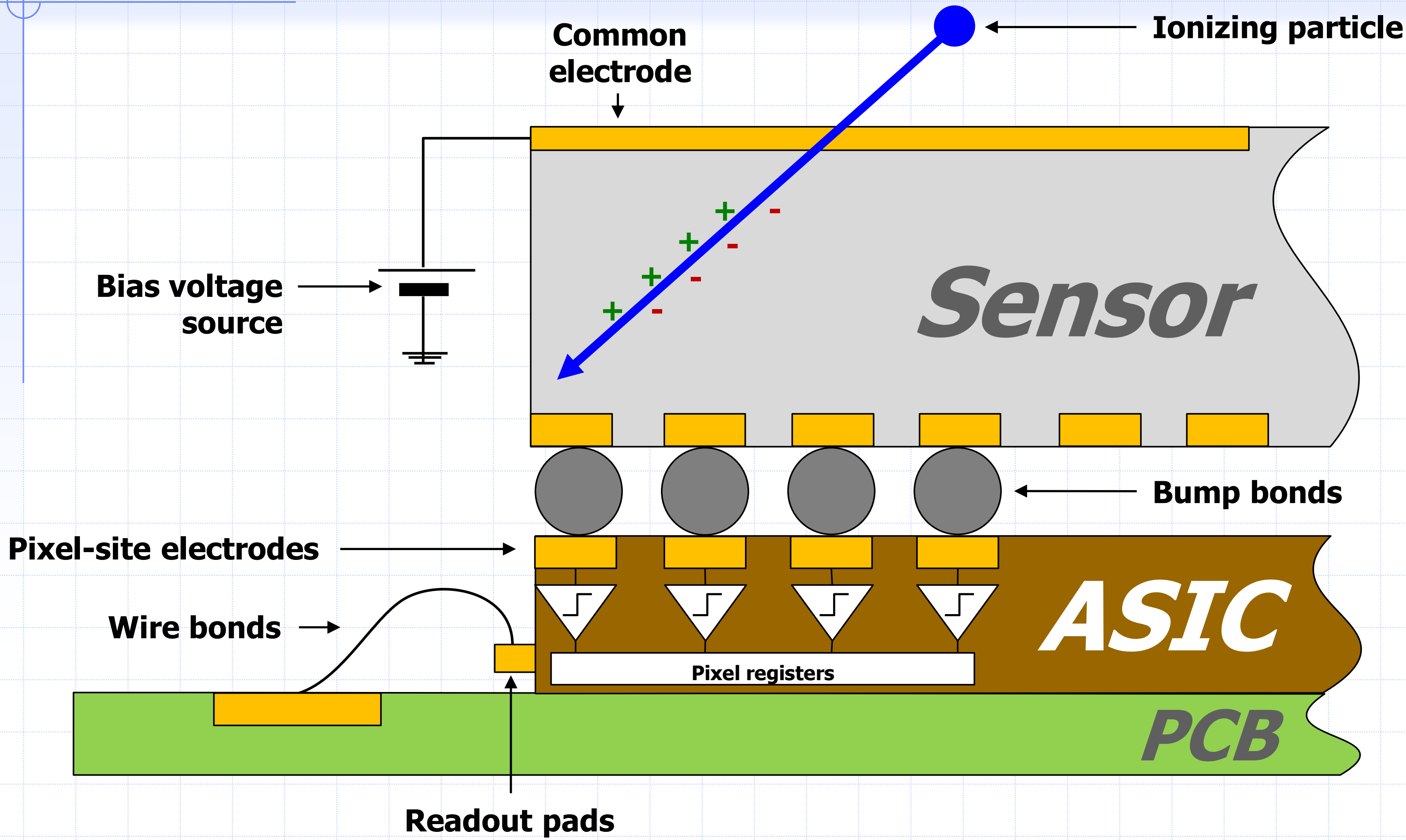

Operation modes

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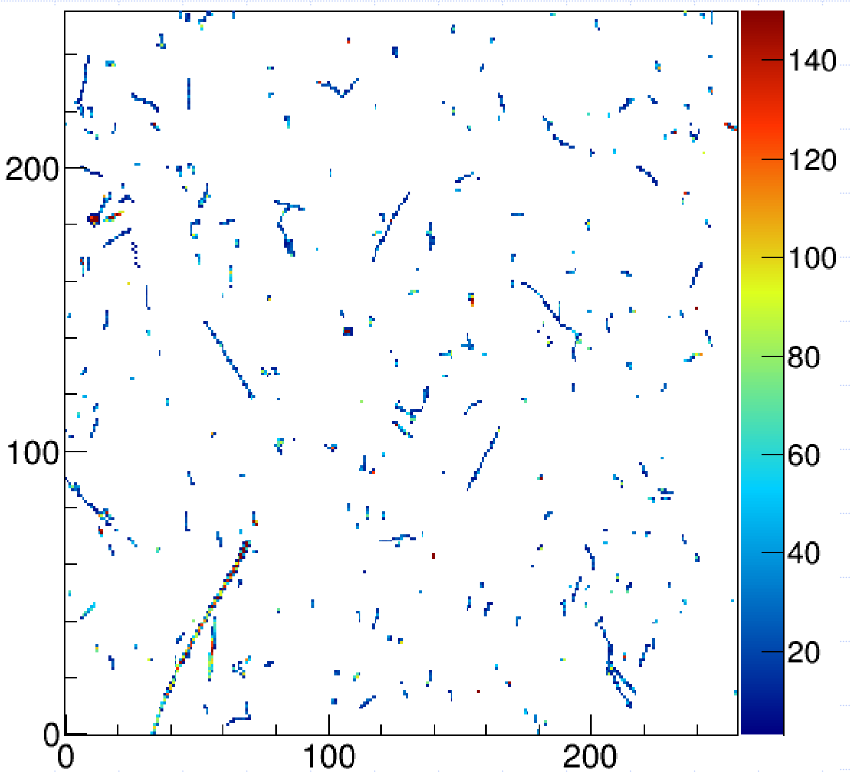
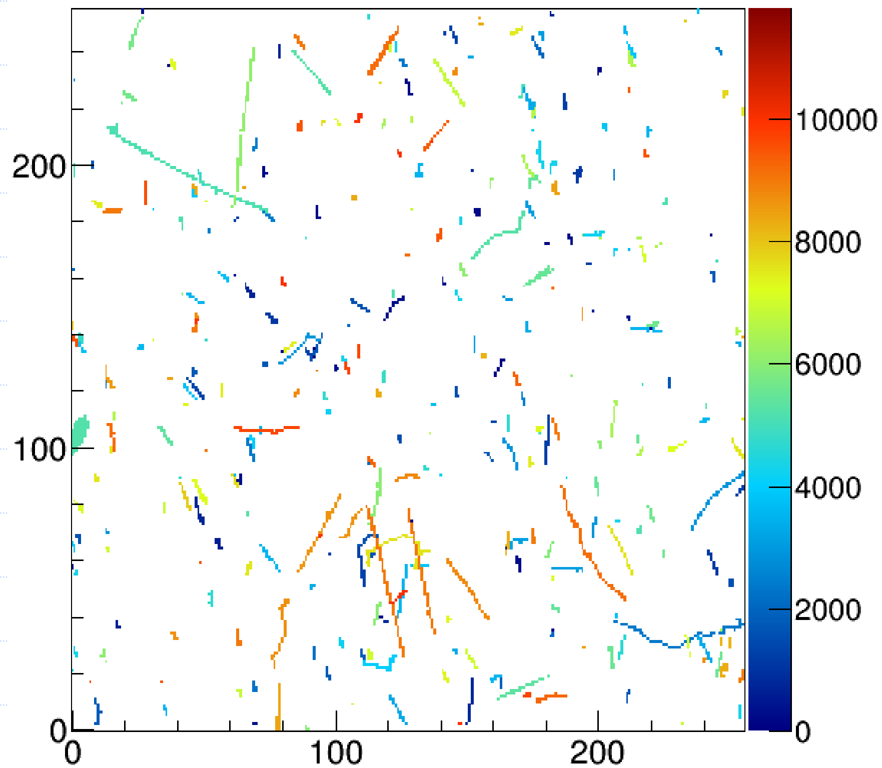
Time over Threshold (ToT)

Pixel intensity encodes amount of deposited energy.



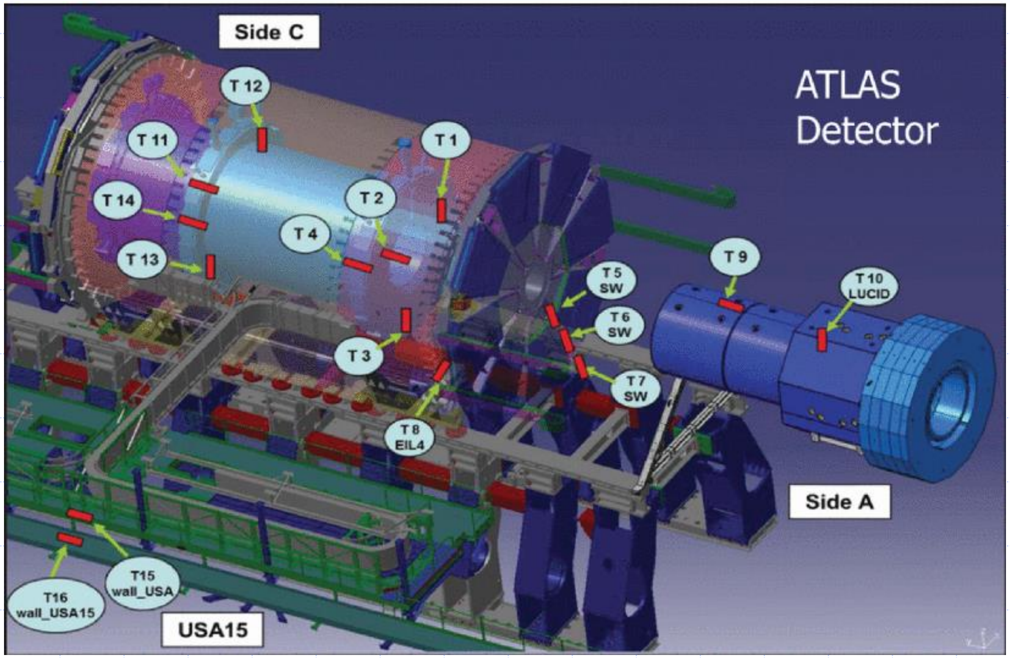
Time of Arrival (ToA)

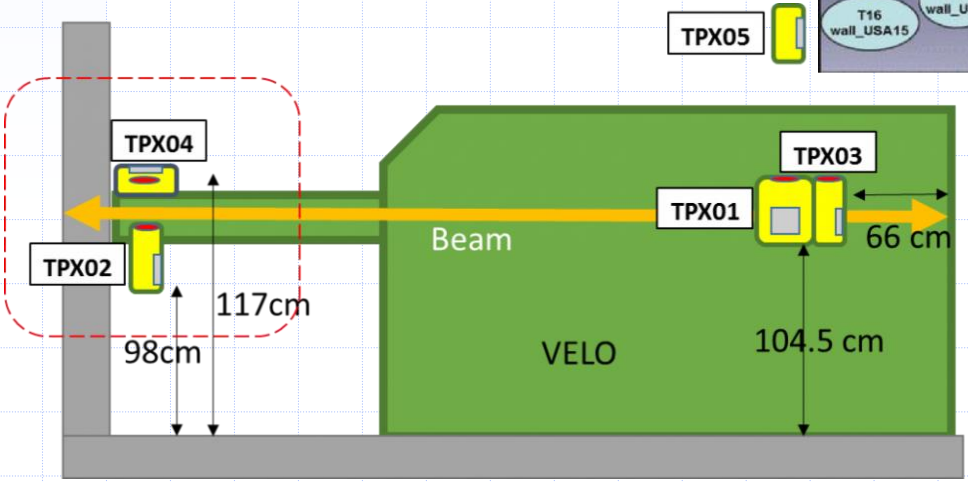
Pixel intensity encodes incidence time since acquisition start.



Detector networks at LHC

- ATLAS
  - Medipix (run 1),
  - Timepix (run 2),
  - Timepix3 (run 2)
- MoEDAL, LHCb
  - Timepix (run 2),
  - Timepix3 (run 2)

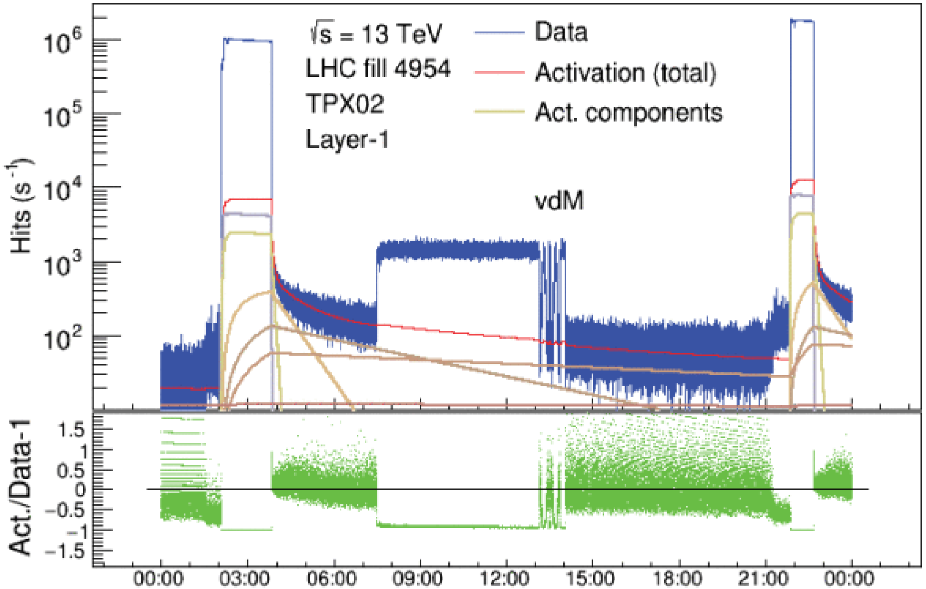




Notable applications at LHC

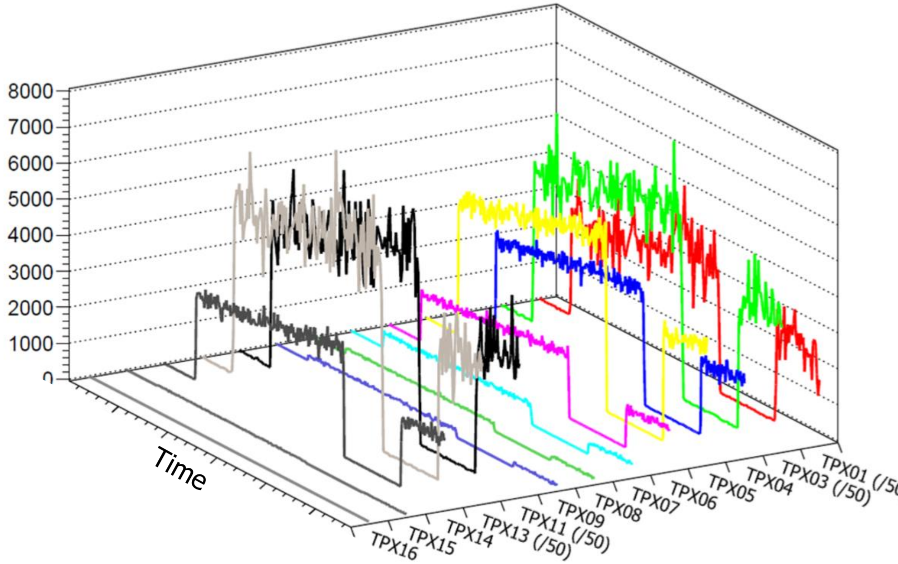
Determination of absolute luminosity and induced radioactivity

Ref: A. Sopczak *et al.*, "Precision Measurements of Induced Radioactivity and Absolute Luminosity Determination With TPX Detectors in LHC Proton–Proton Collisions at 13 TeV," in *IEEE Transactions on Nuclear Science*, vol. 65, no. 7, pp. 1371-1377, July 2018.



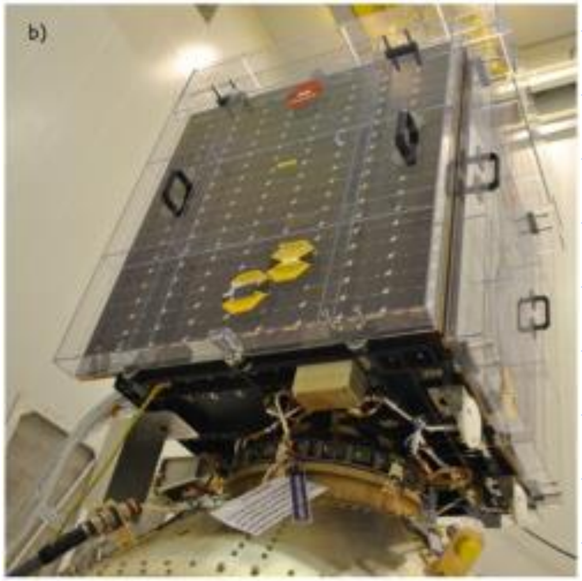
Characterization of mixed radiation fields at different positions

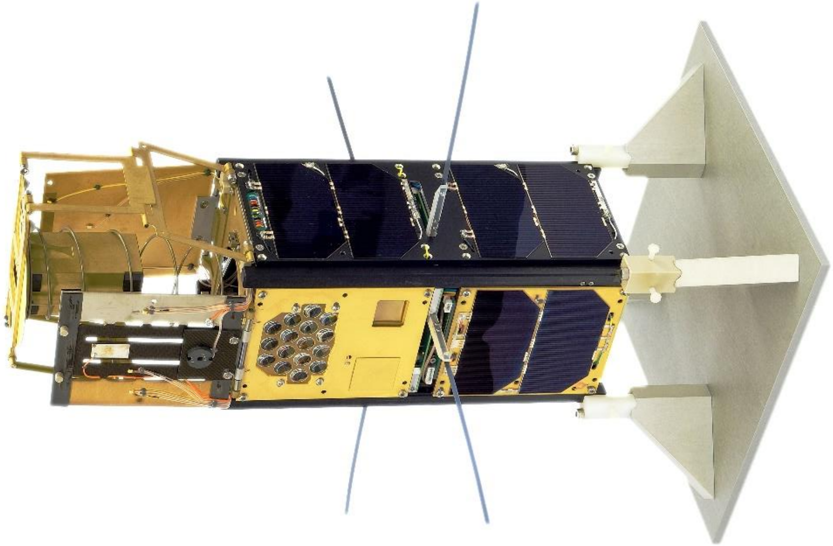
Ref: Bergmann, B., *et al.* "ATLAS-TPX: a two-layer pixel detector setup for neutron detection and radiation field characterization." *Journal of Instrumentation* 11.10 (2016): P10002.

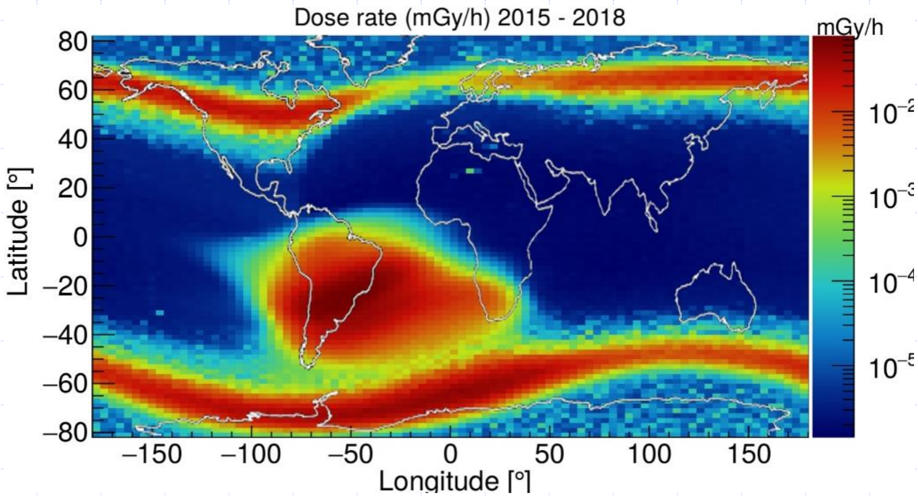


Notable applications in space

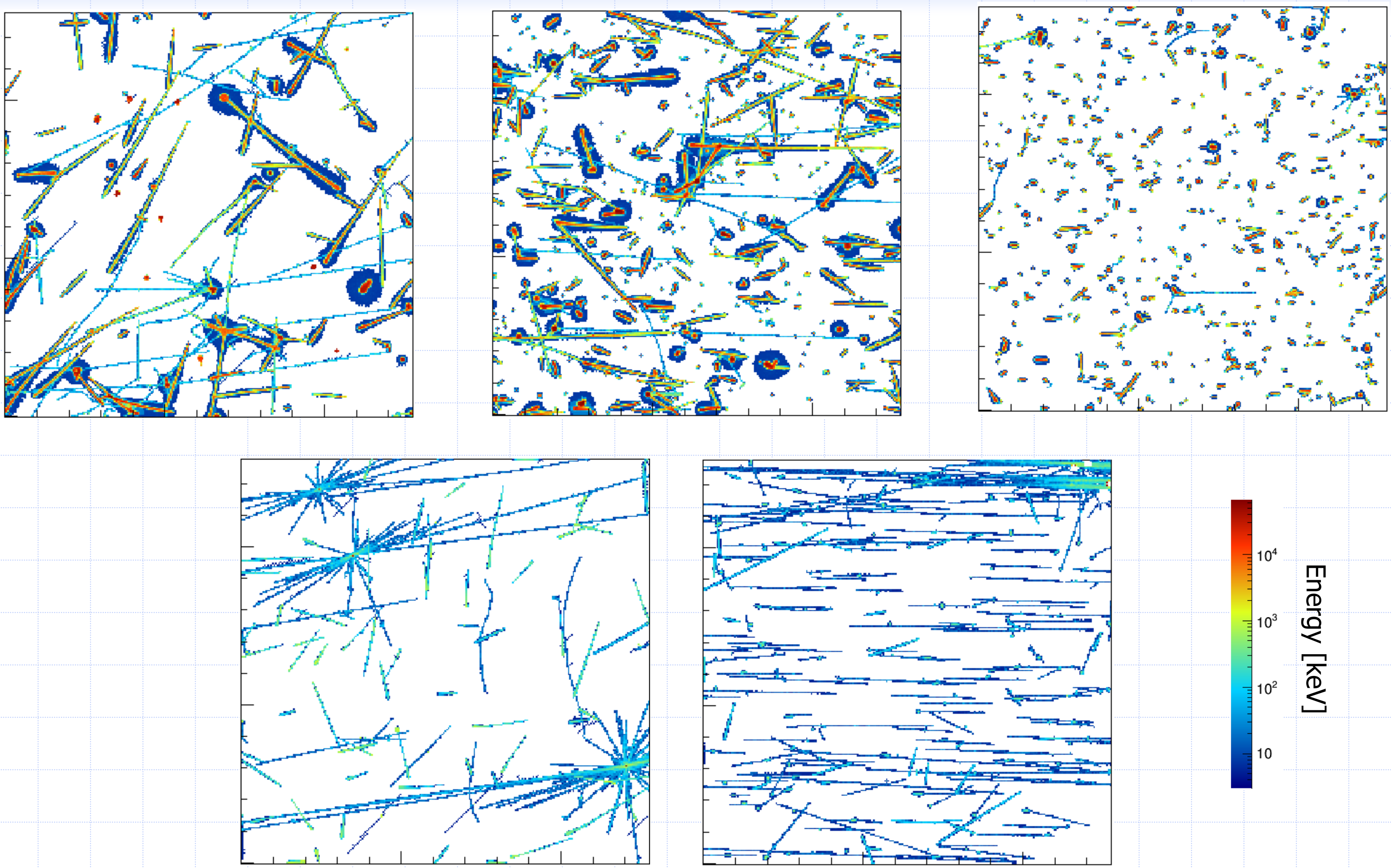
- Proba-V satellite (2013)
  - LEO, altitude: 820 km
  - SATRAM = Timepix-based spacecraft radiation monitoring platform
- VZLUSAT-1 nanosatellite (2017)
  - LEO, altitude: 450 km
  - Timepix-based X-ray telescope on board







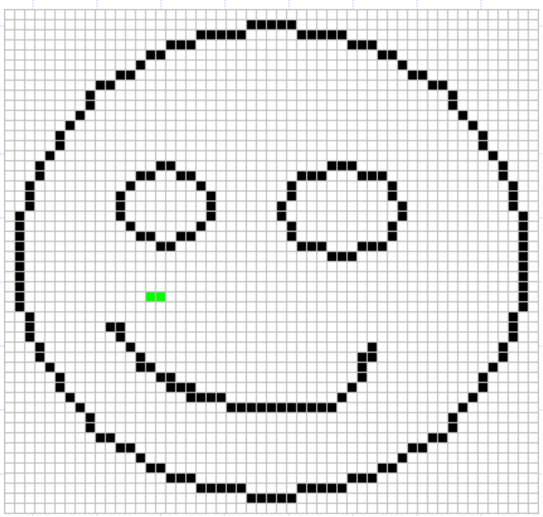
Data examples

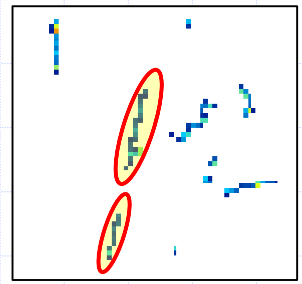


Morphological clustering

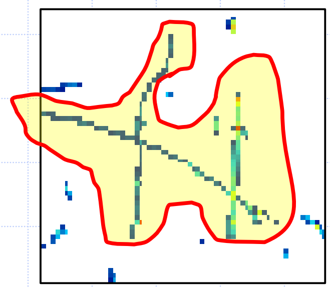
- Idea: separate pixels into tracks by their spatial adjacency

- Possible failures:
  - Broken up tracks
  - Overlaps





Do these tracks correspond to 1 or 2 incidence events?

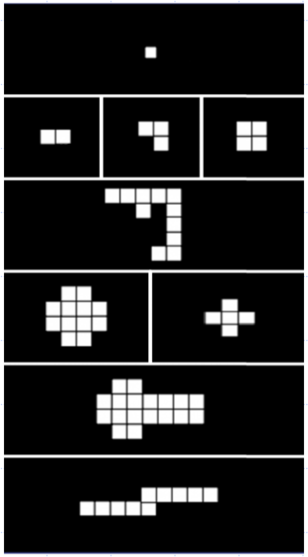


Should all these pixels be considered a single track?

Ref: Holy, T., et al. "Pattern recognition of tracks induced by individual quanta of ionizing radiation in Medipix2 silicon detector." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 591.1 (2008): 287-290.

Morphological classification

- Various thresholds on linearity, roundness, convex hull, etc.
- Powerful & simple discrimination between track types.
- Often combined with *a priori* info (about beam, converters, etc.)



- **Dots**
  photons and electrons (10 keV)
- **Small Blobs**
  photons and electrons
- **Curly Tracks**
  electrons (MeV range)
- **Heavy Blobs**
  heavy ionizing particles with low range
- **Heavy Tracks**
  heavy ionizing particles (photons)
- **Straight Tracks**
  energetic light charged particles (MIP)

Ref: Holy, T., et al. "Pattern recognition of tracks induced by individual quanta of ionizing radiation in Medipix2 silicon detector." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 591.1 (2008): 287-290.

Extension points

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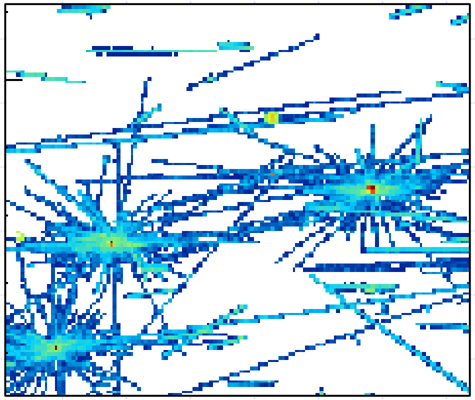
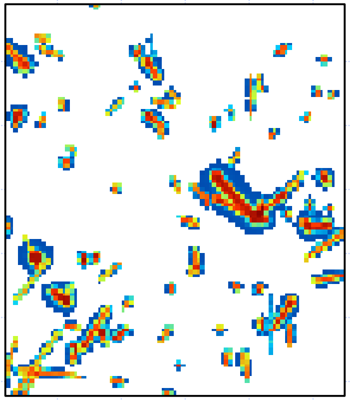
- Both techniques originally developed for Medipix2 (binary pixels)
  - ToT information not utilized
  - Susceptible to pile-up → acquisition time tuning

- 6 classes have proven insufficient for more complex tracks, e.g.:
  - δ-ray emissions,
  - collisions, fragmentation events,
  - exotic particles





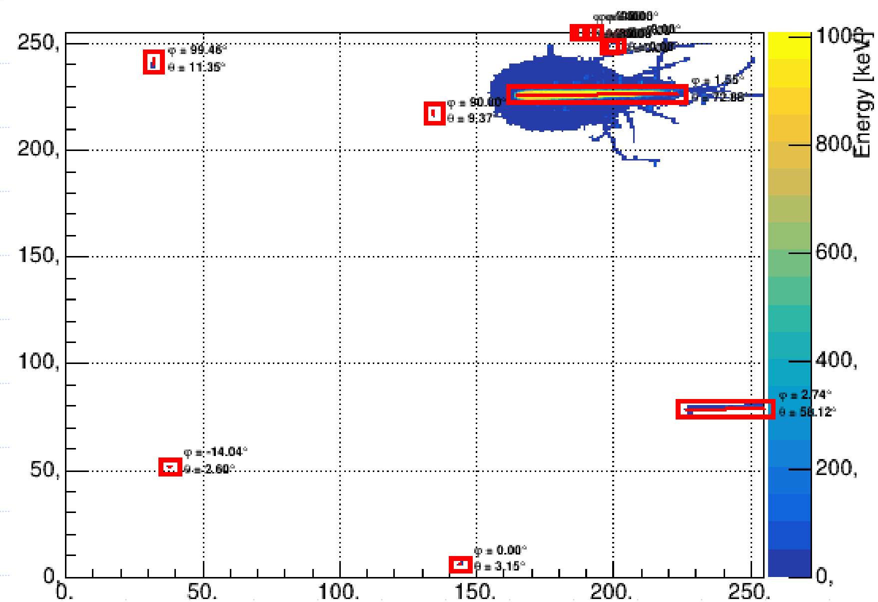
2D Analysis

CV-inspired ideas

- Re-formulate task as an object detection problem
  - Treat ToT as "intensity" and frame as "image"

Photography:

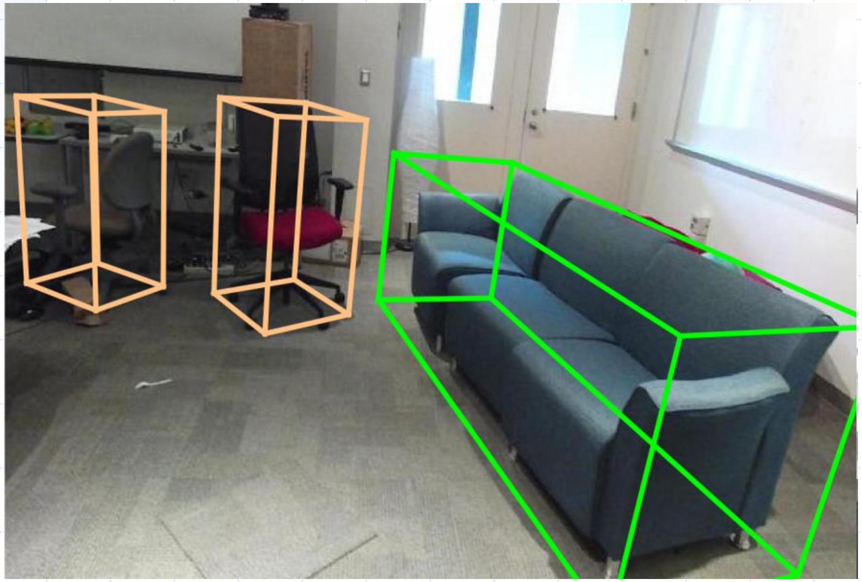
Timepix:



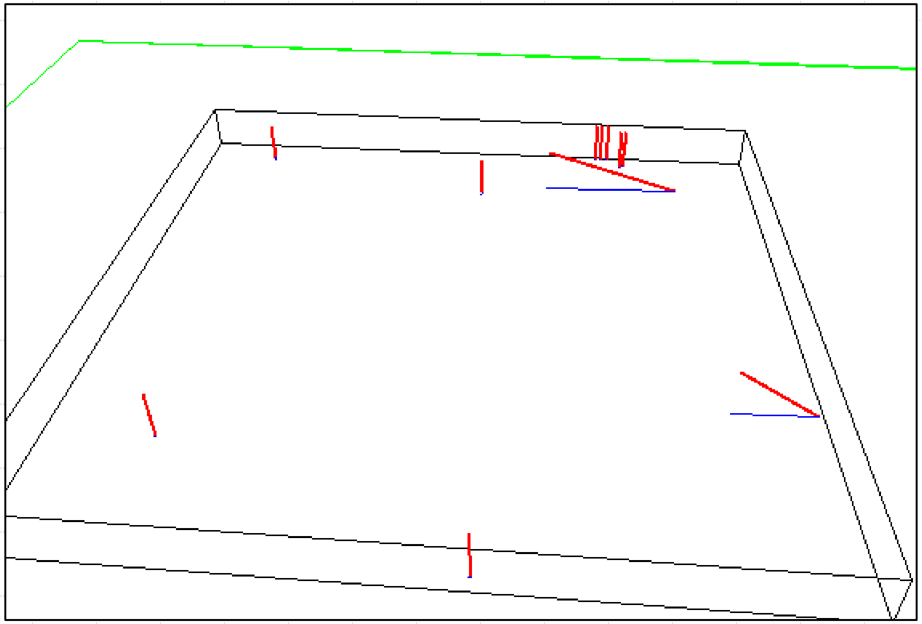
CV-inspired ideas

- Re-formulate task as an object detection problem
  - Treat ToT as "intensity" and frame as "image"
- Combine data with *a priori* known information in order to achieve 3D results.

Photography:

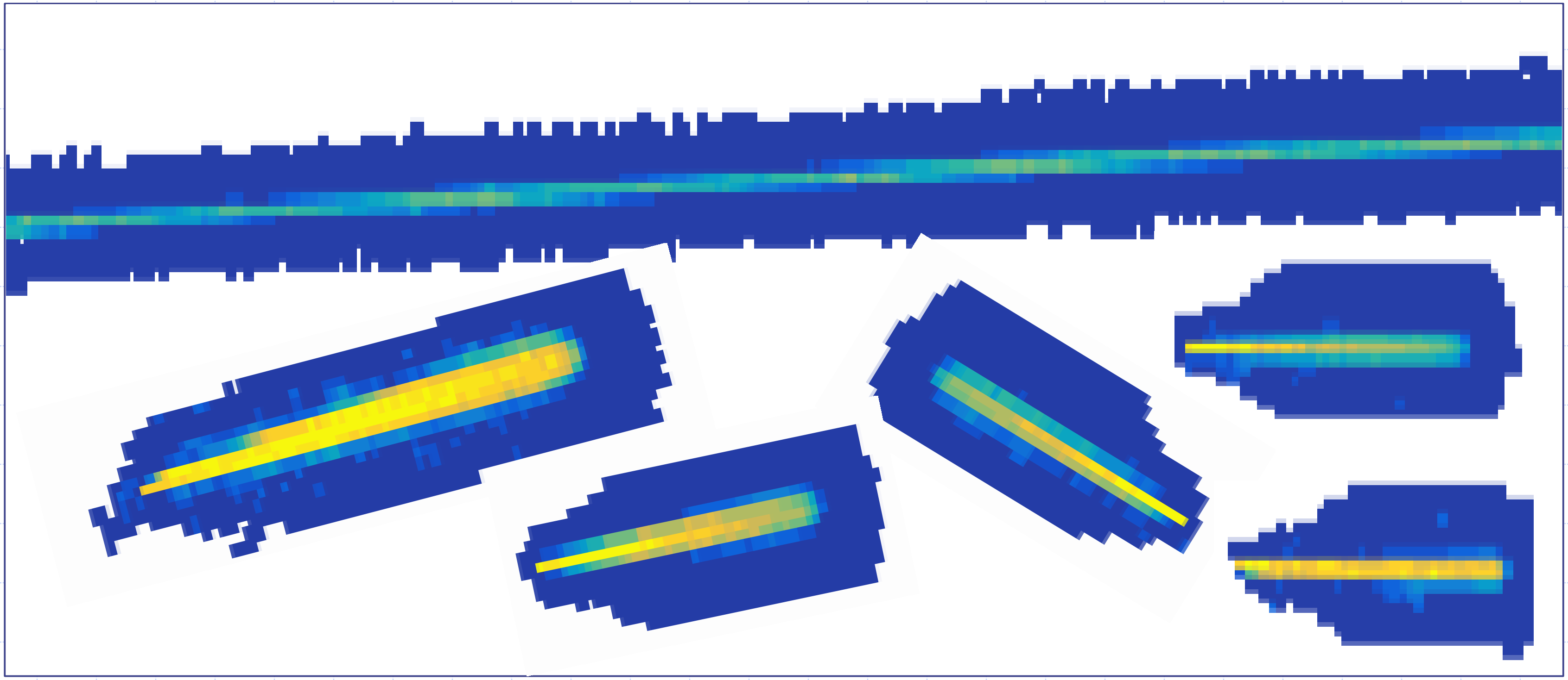


Timepix:



Object class: heavy ions

- Desirable properties:
  - Large momentum → assumption of linear trajectory
  - Hidden parameters can be approximated with a line segment.
  - Charge sharing produces continuous pattern → suitable for LO.



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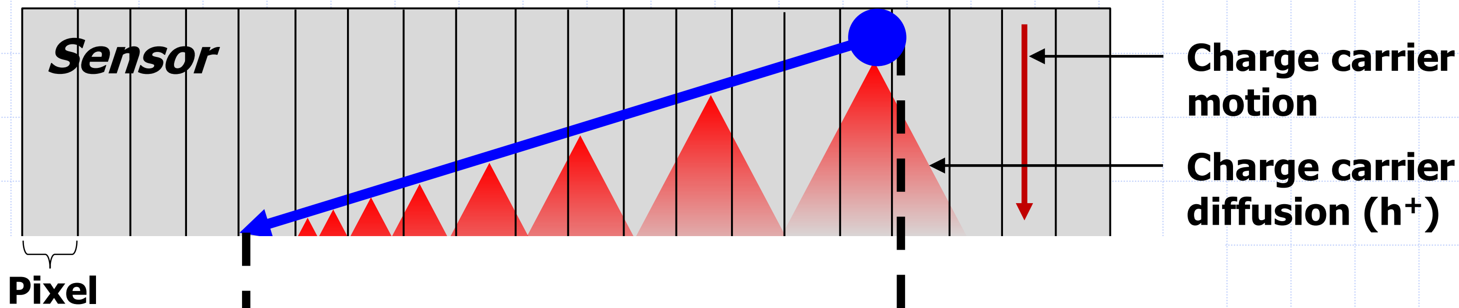
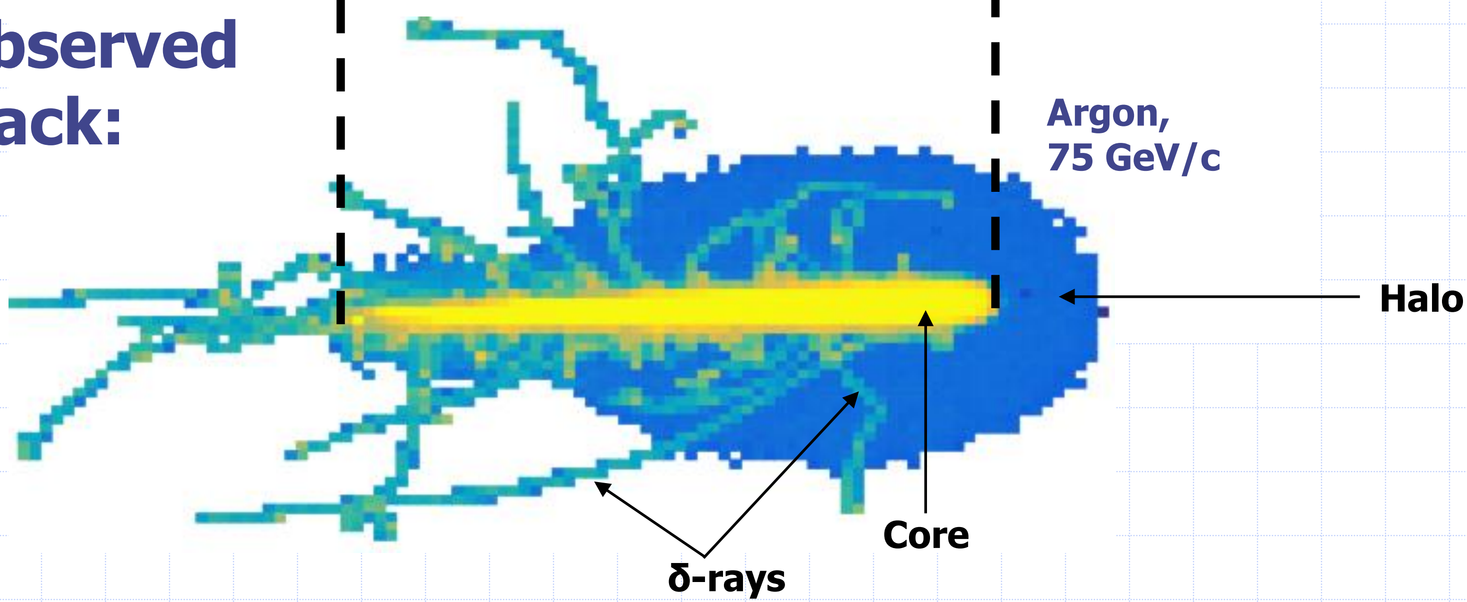
Heavy ion tracks

Cross-section:



Observed track:



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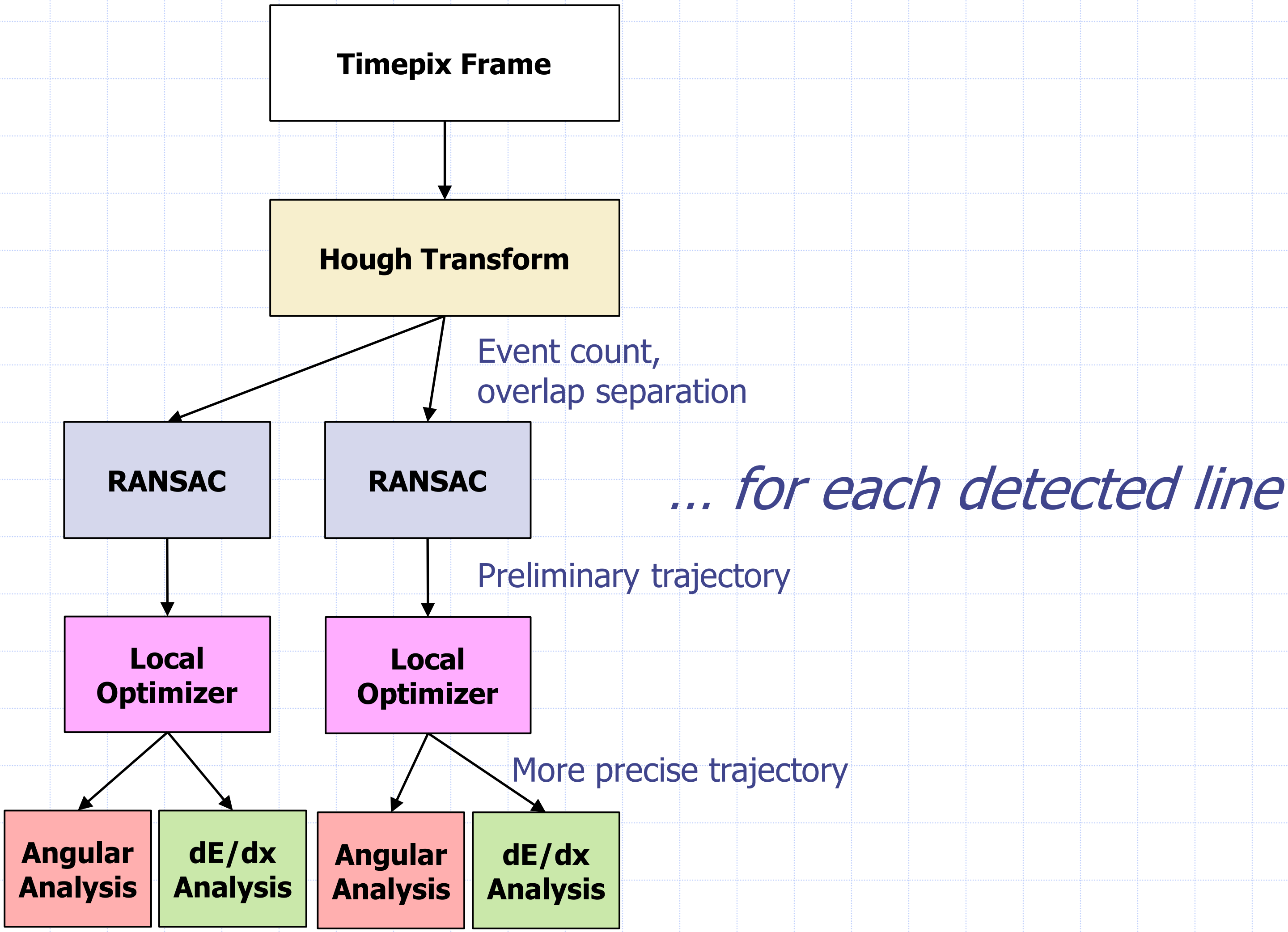
The Algorithm



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The Algorithm

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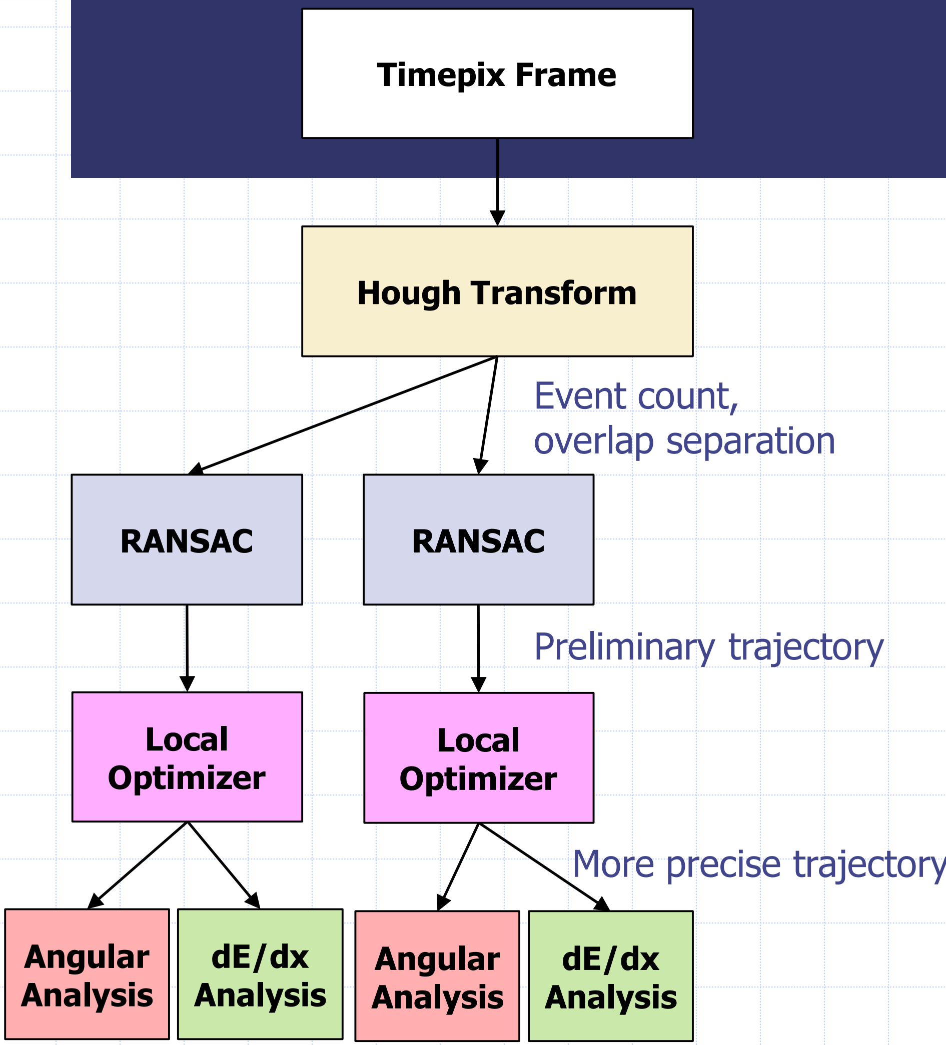
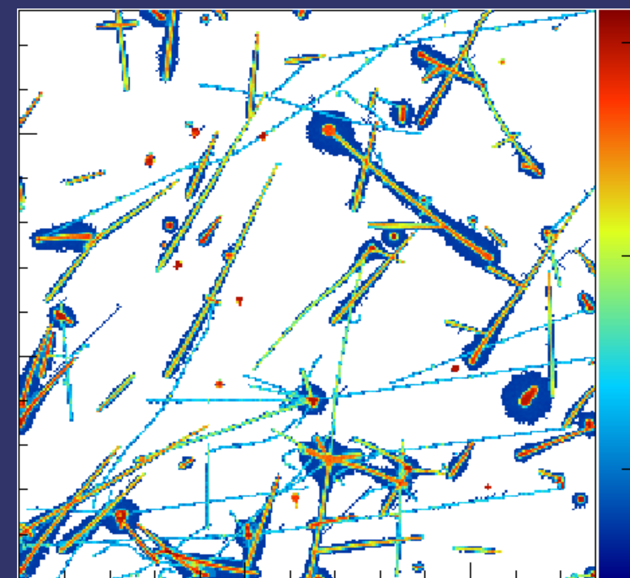


Detector frame:



MoEDAL, detector #4
2015-09-12

The Algorithm

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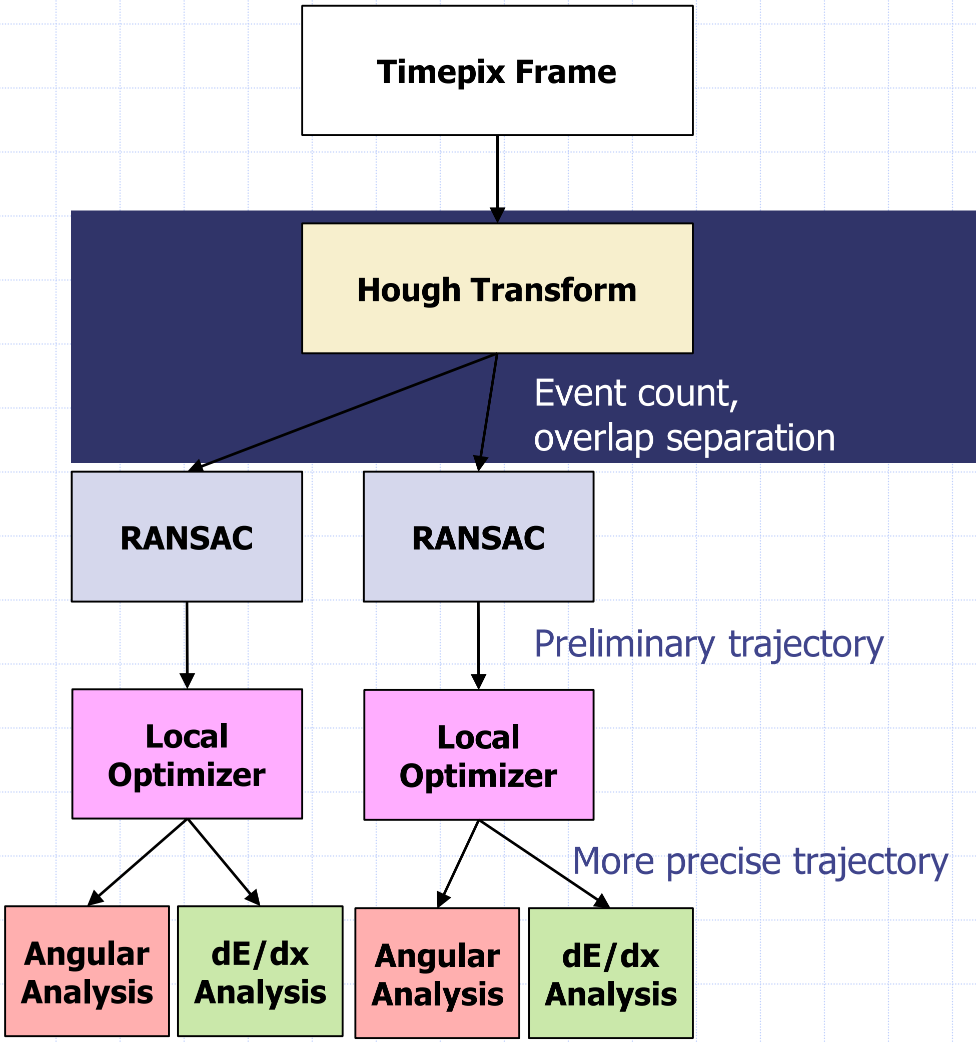
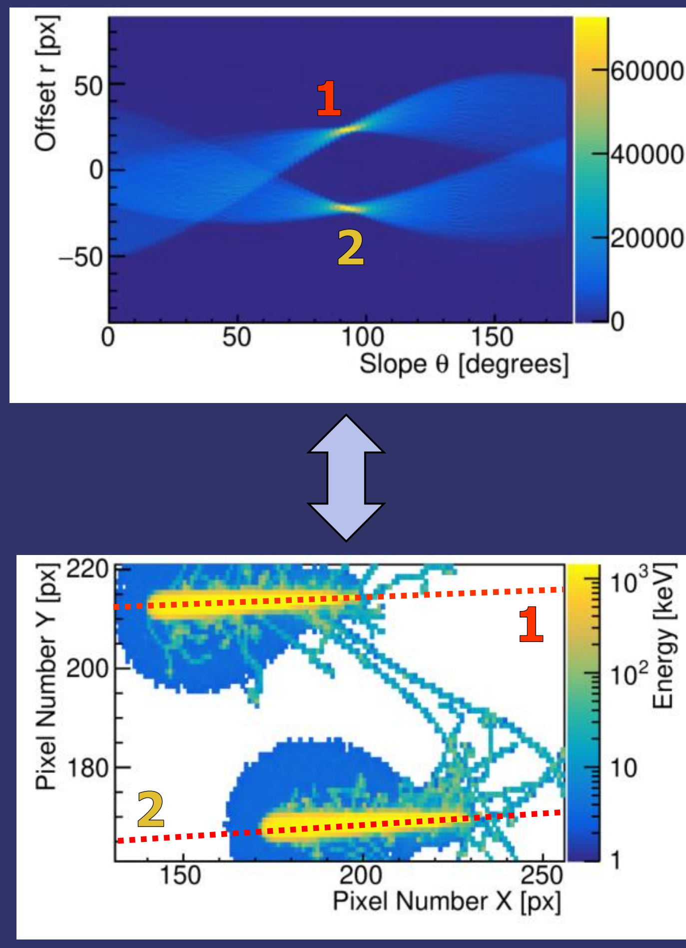
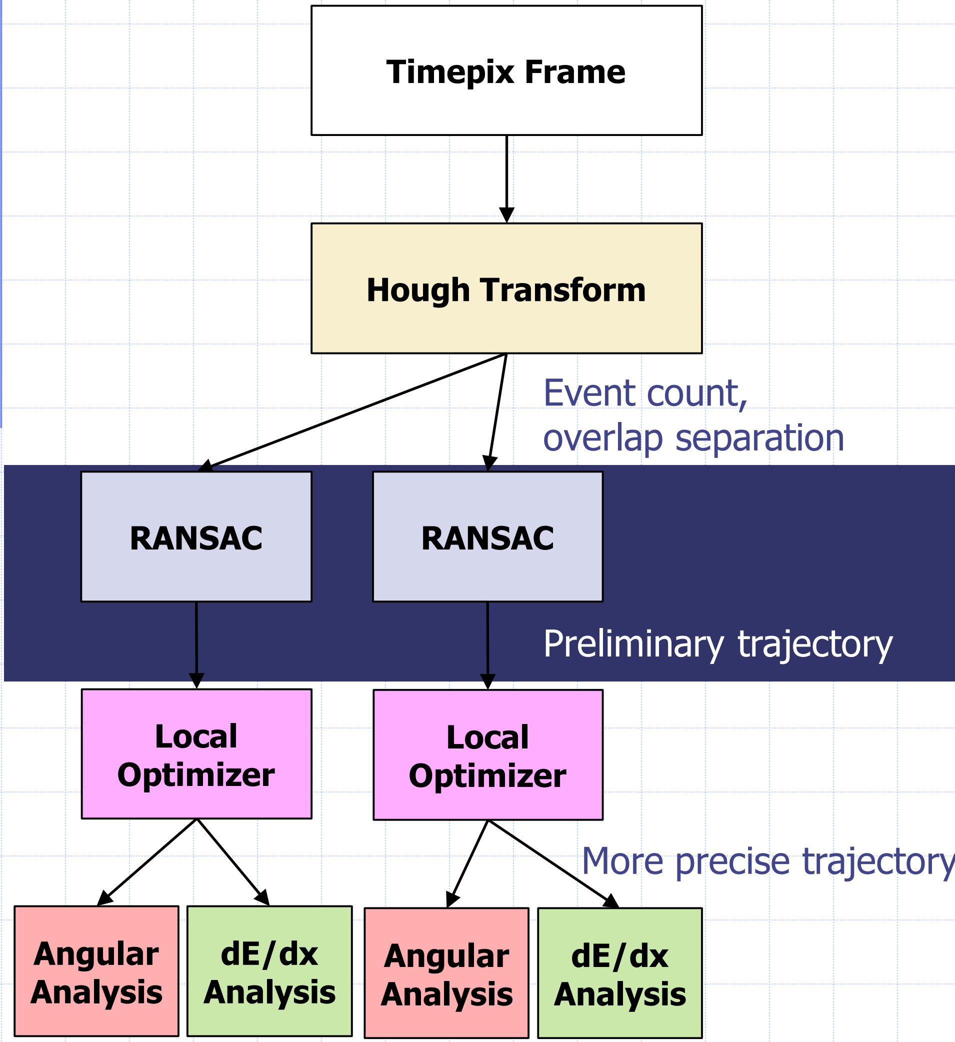


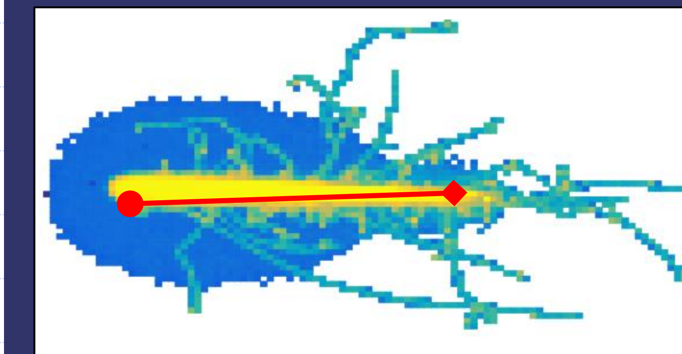
Hough accumulator:



The Algorithm



Segmented track + fit:



◯ ... Entry point

◇ ... Exit point

θ ... Incidence angle

φ ... Azimuth

The Algorithm

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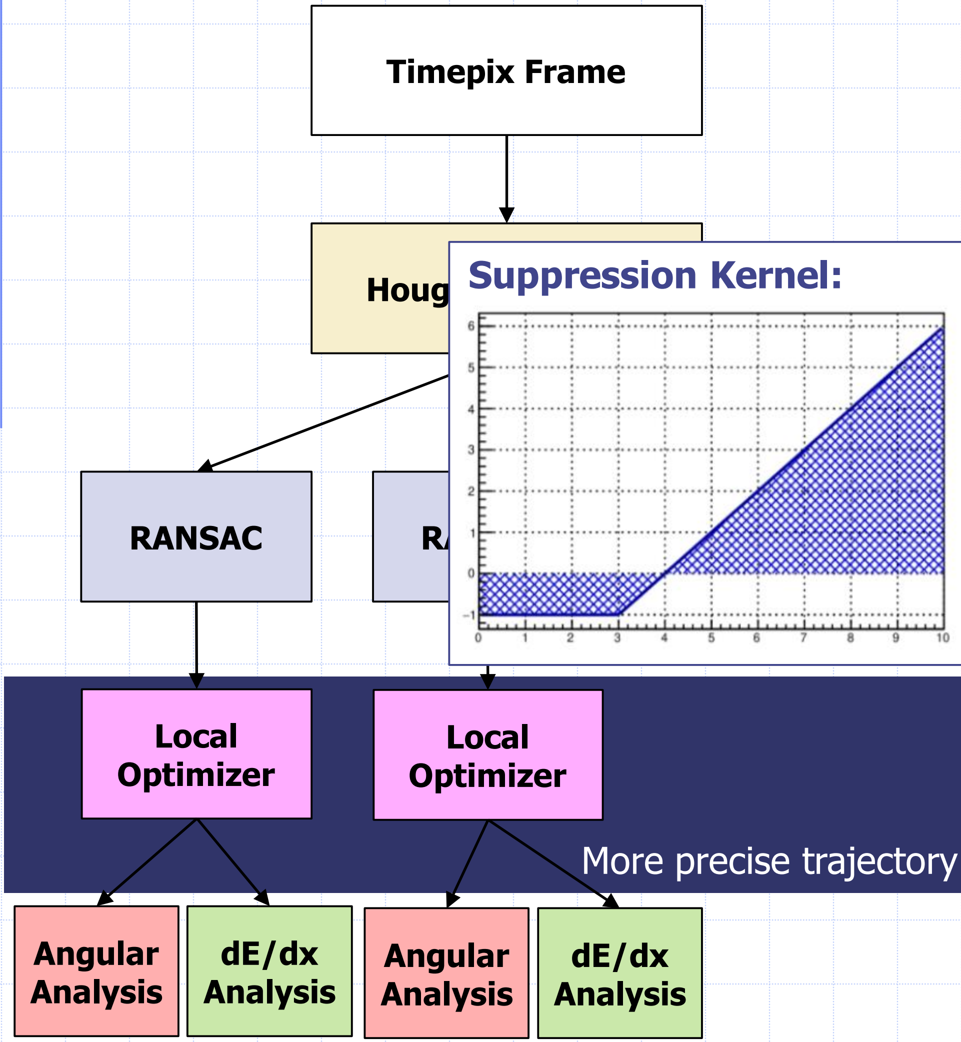
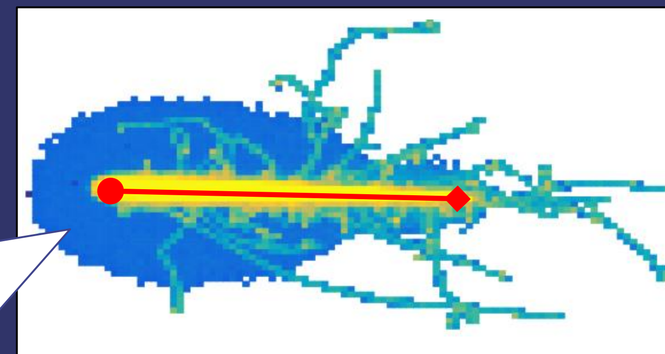


Segmented track + fit:



○ … Entry point

◇ … Exit point

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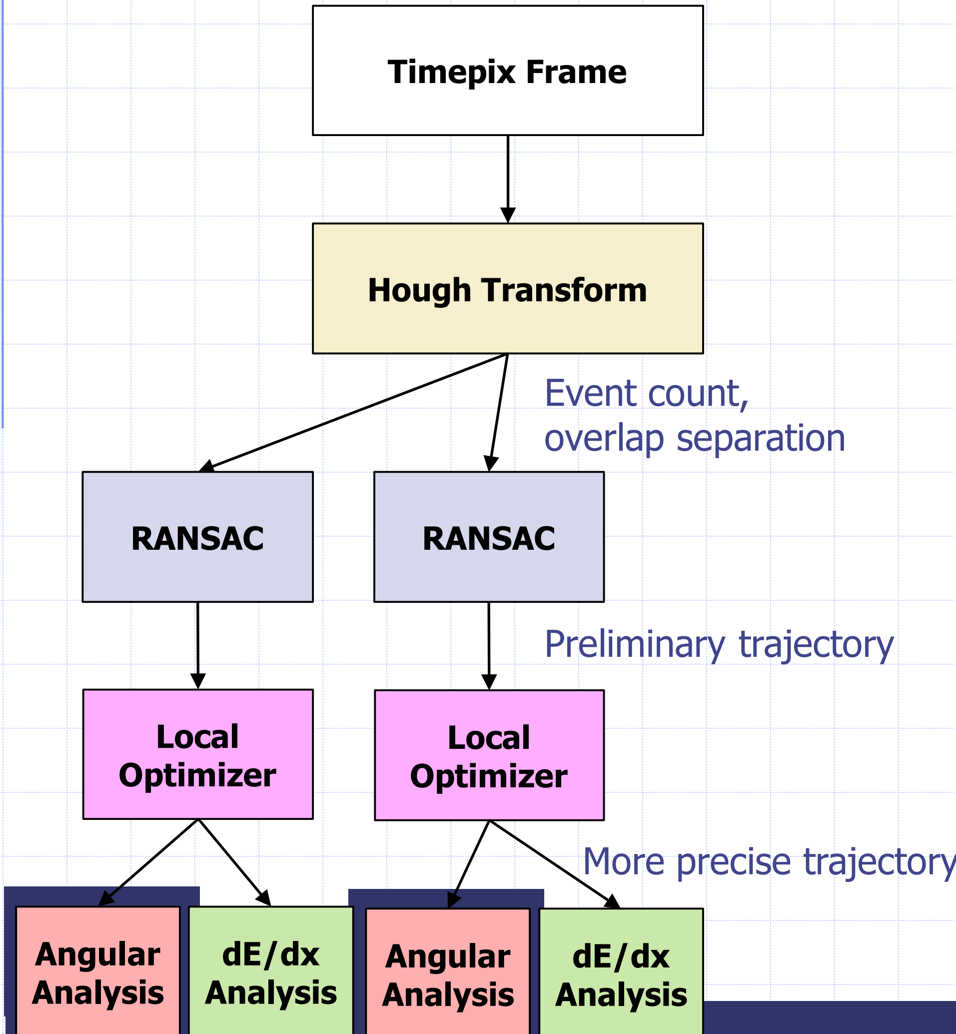
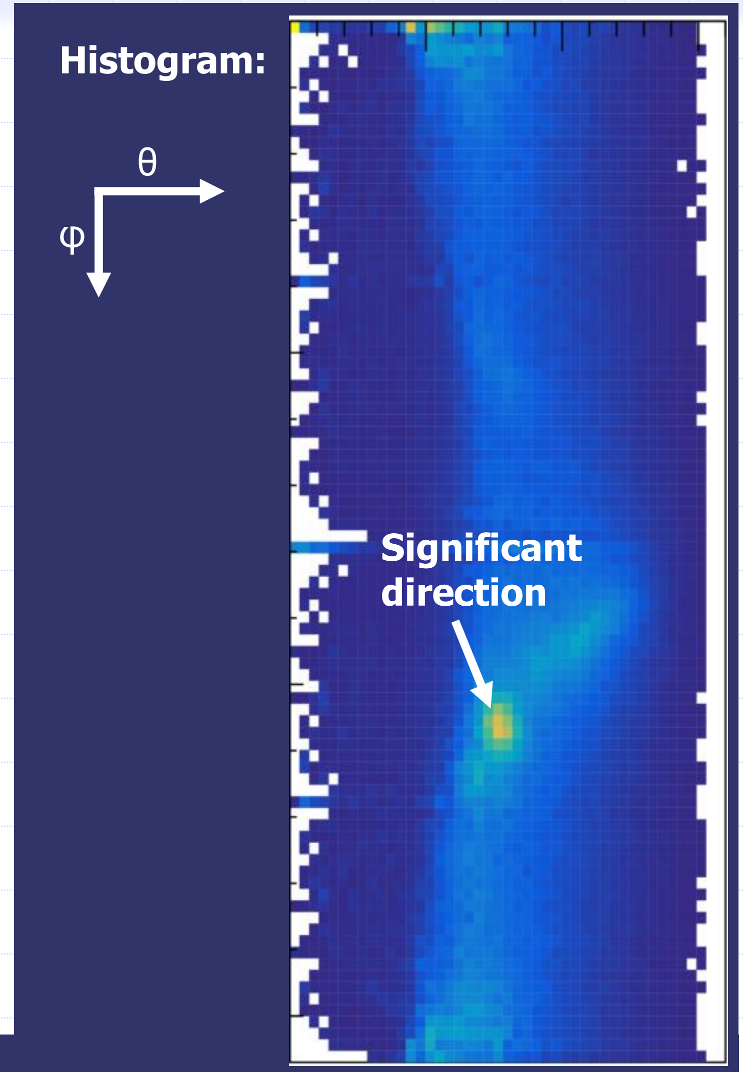
φ … Azimuth

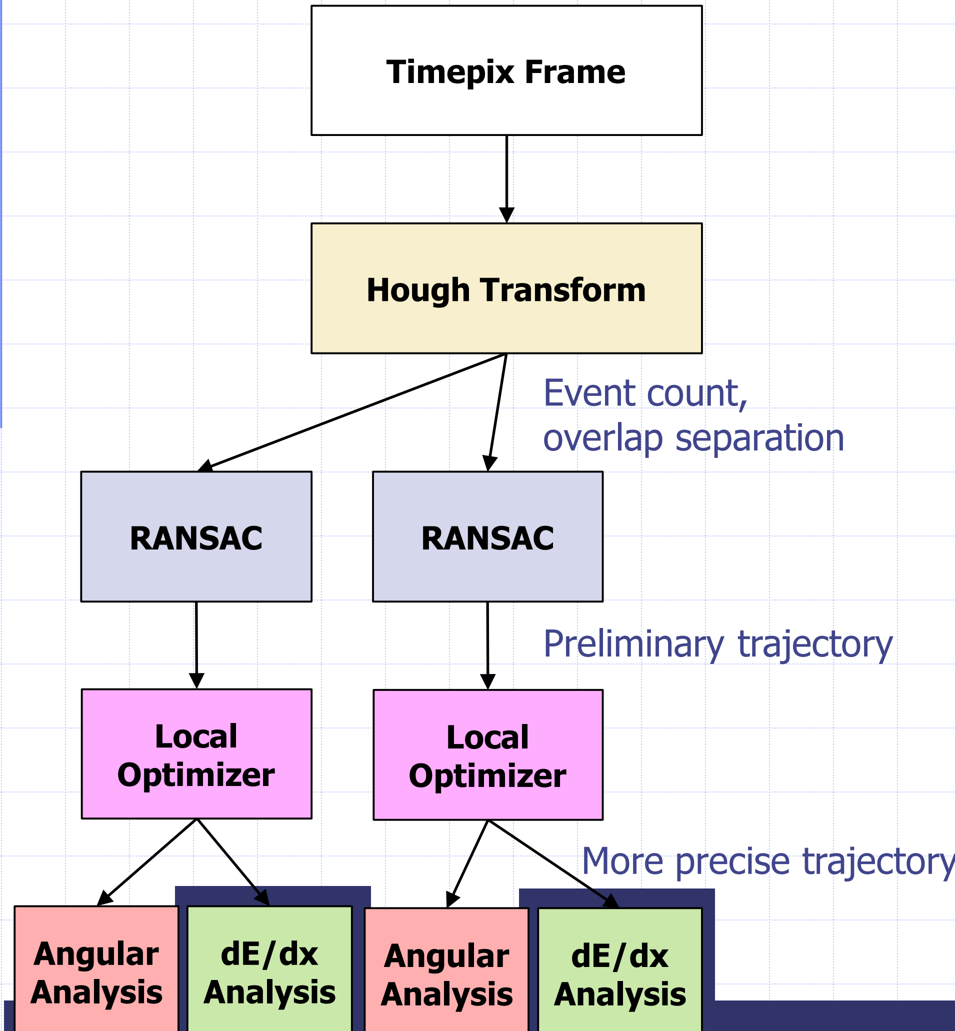
Difference:
Utility weighted by pixel intensity.

The Algorithm

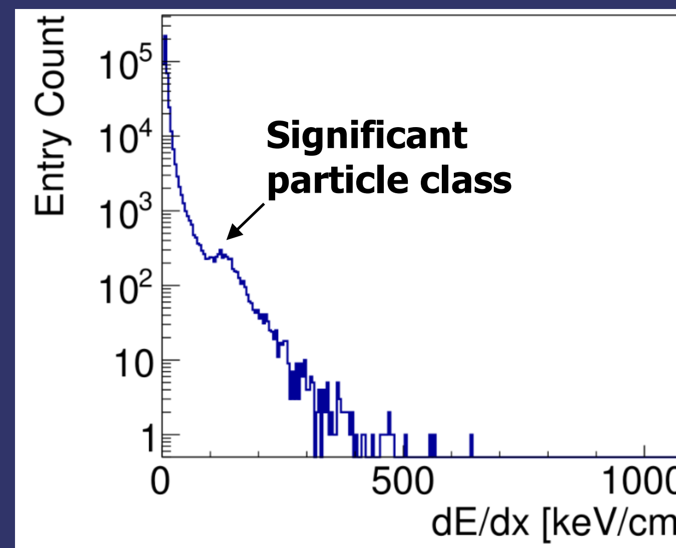




The Algorithm



Histogram:



$$-\frac{dE}{dx} \cong \frac{\sum_i E_i}{trajectory\ length}$$

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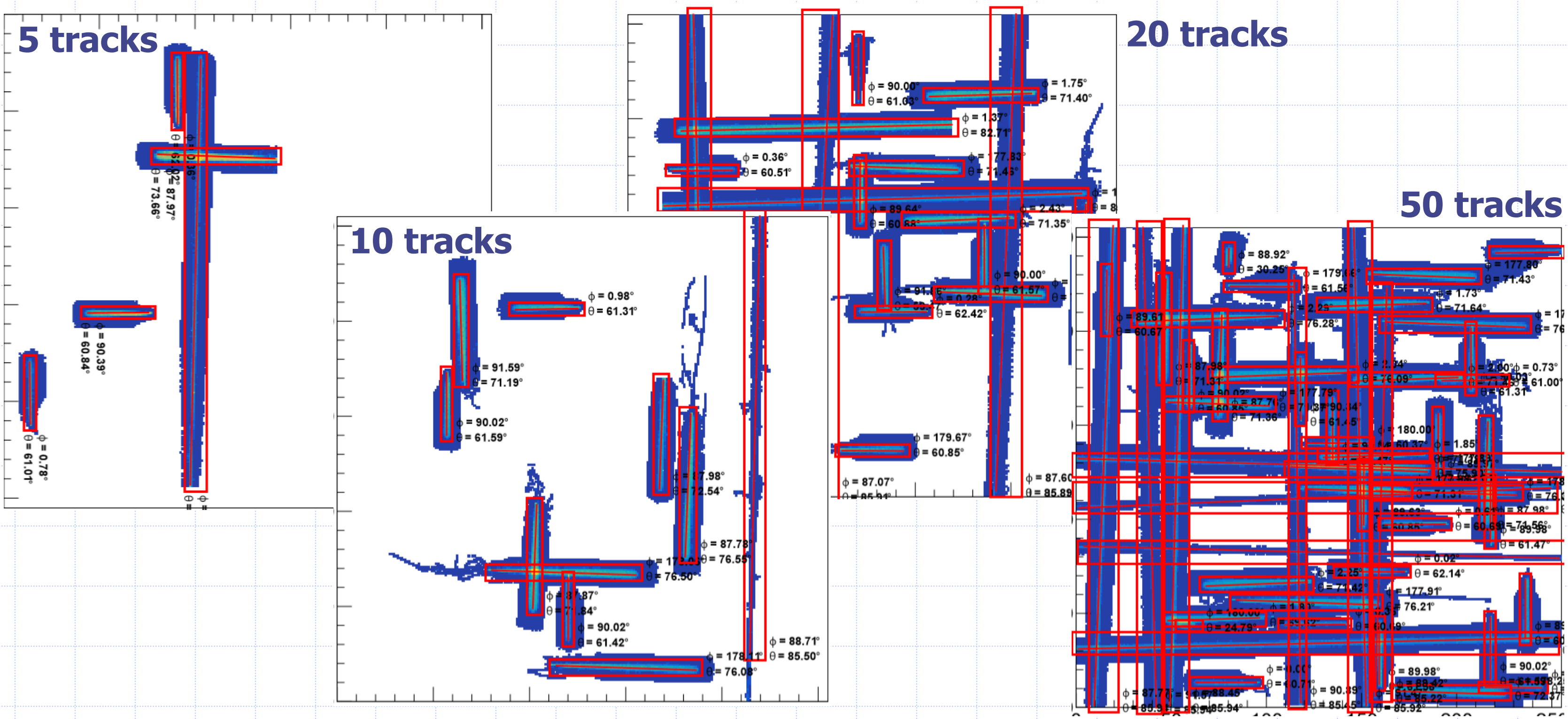
Hough Transform:
Overlap separation example

- Question: with Hough, are RANSAC & LO *really* necessary?
- Benchmarked performance, spatial and angular accuracy.
- Generated random frames from manually curated dataset of over 1K experimentally observed tracks.



Hough Transform:
Overlap separation example

- Question: with Hough, are RANSAC & LO *really* necessary?
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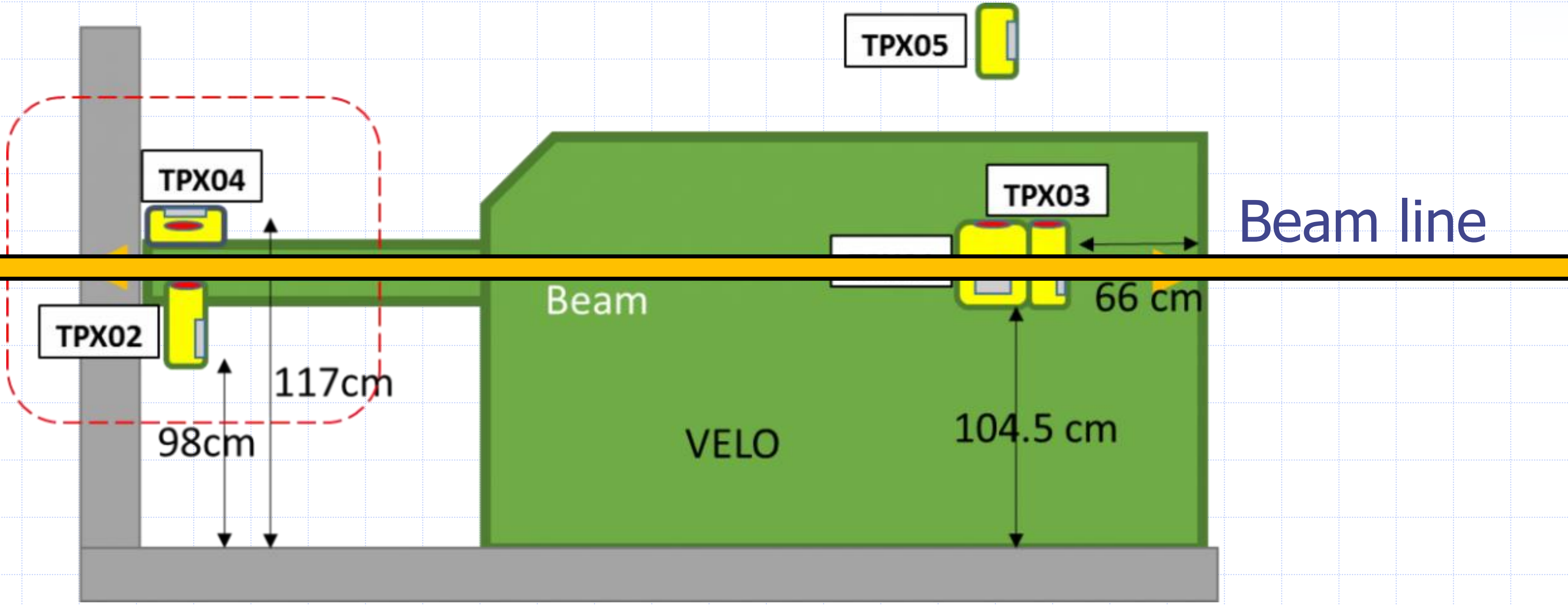
Algorithm	n	$\langle FR \rangle$	$\langle E(x_{\text{far},1}) \rangle$	$\langle E(x_{\text{far},2}) \rangle$	$\langle E(\varphi) \rangle$	$\langle E(\theta) \rangle$	$\langle t \rangle$ [ms]
RANSAC	5	0.107	4.344	4.266	5.244	10.085	4,492.2
	10	0.253	6.413	6.384	9.030	10.826	9,123.3
	20	0.544	10.264	9.776	12.012	11.786	20,626.7
	50	0.772	14.852	14.572	14.655	10.226	38,161.3
LO-RANSAC	5	0.104	4.194	3.953	5.169	11.709	24,105.5
	10	0.242	6.096	6.219	8.549	12.250	57,995.2
	20	0.532	9.777	9.311	11.620	12.682	125,795.0
	50	0.770	14.034	13.888	13.960	10.167	294,498.0
SA-RANSAC	5	0.105	4.026	3.938	5.115	12.205	20,882.6
	10	0.238	6.088	6.064	7.833	12.539	19,708.4
	20	0.528	9.768	9.163	10.912	12.578	39,827.8
	50	0.769	14.324	14.111	12.535	9.892	83,365.4

Application at LHCb

- 5 Timepix detectors at MoEDAL (LHCb, CERN)
- Known locations, orientations of source and detectors.
- Unknown field composition, secondaries.



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Angular Analysis

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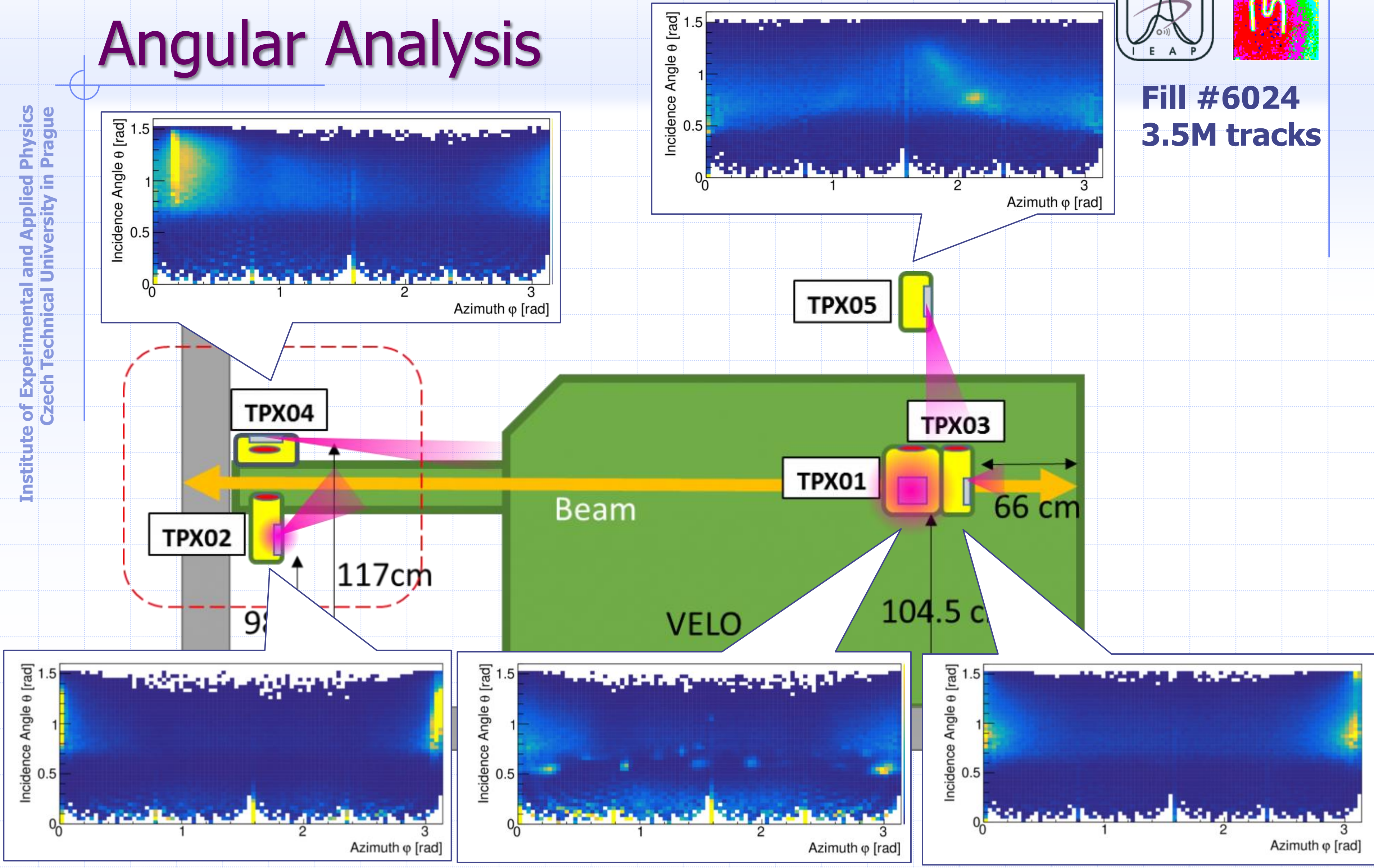
Fill #6024
3.5M tracks



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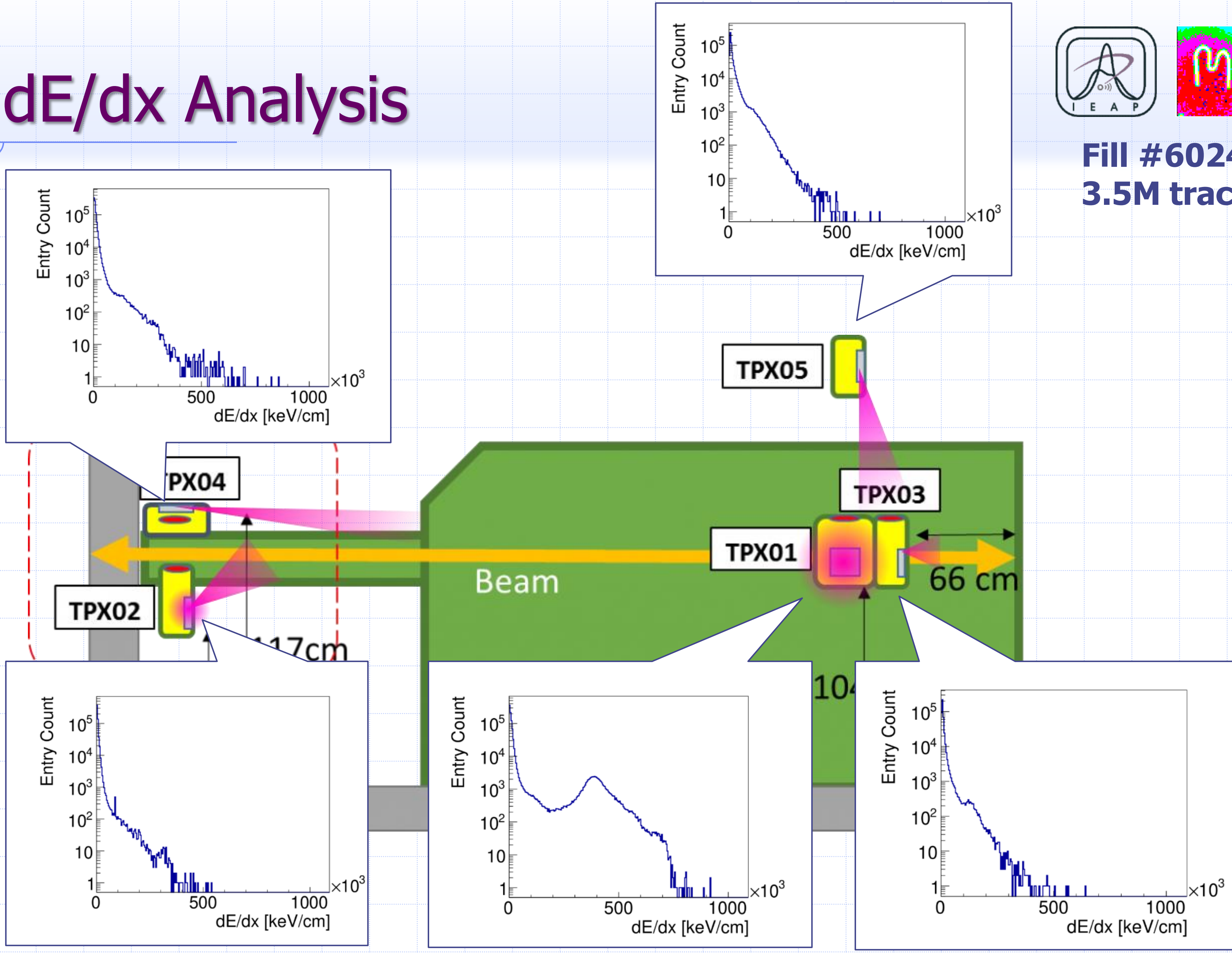
dE/dx Analysis

Fill #6024
3.5M tracks



Particle Identification

Motivation

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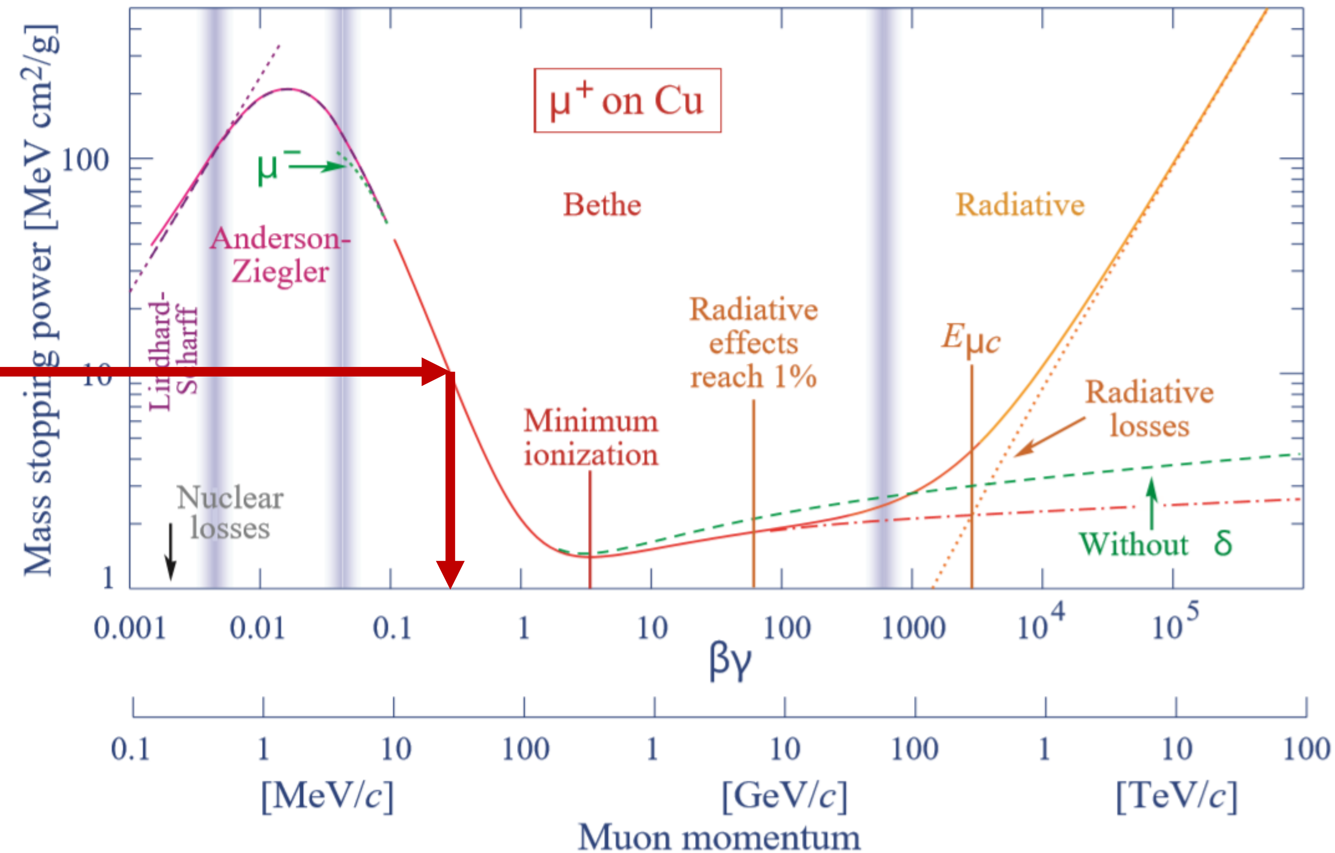
- dE/dx includes information about particle species and momentum

Theory:

Observed dE/dx



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Motivation

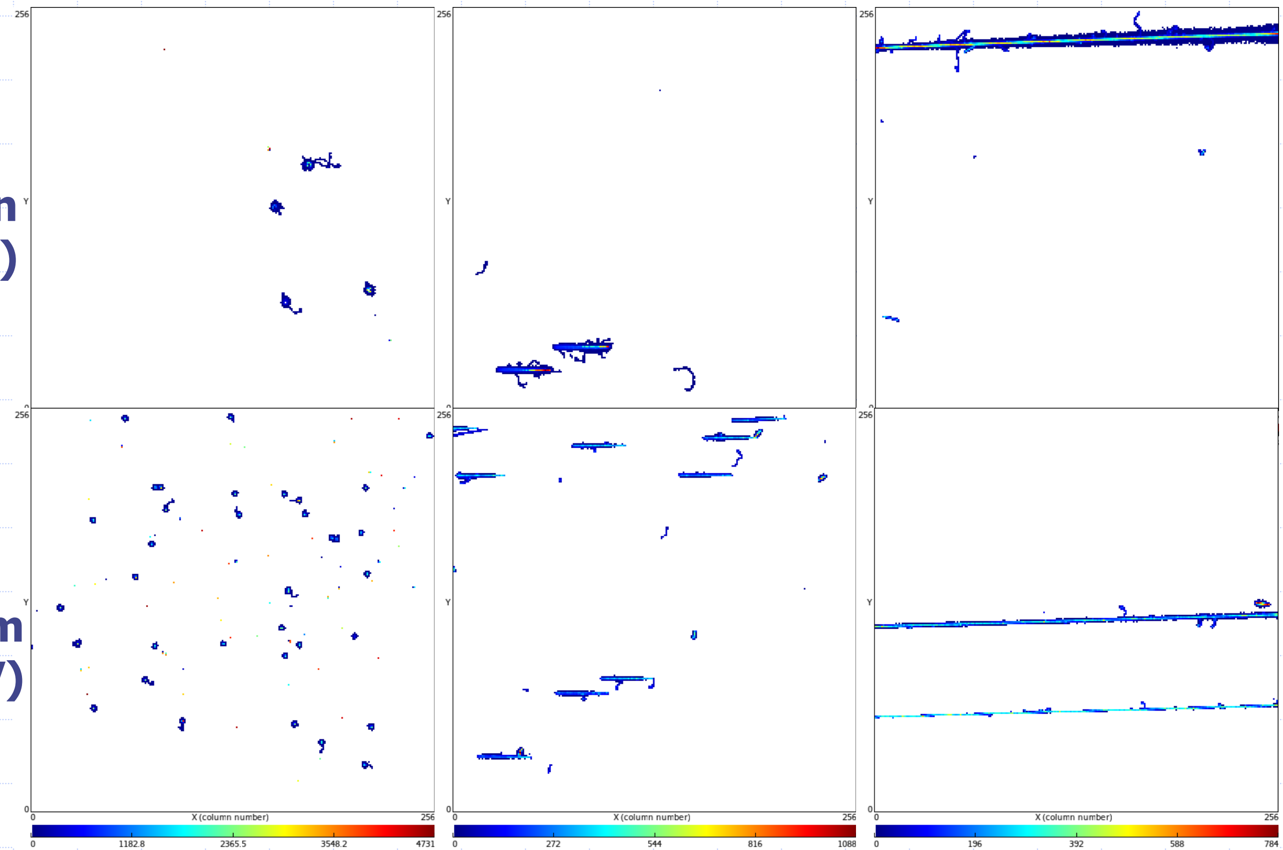
- dE/dx includes information about particle species and momentum.

Measurement:

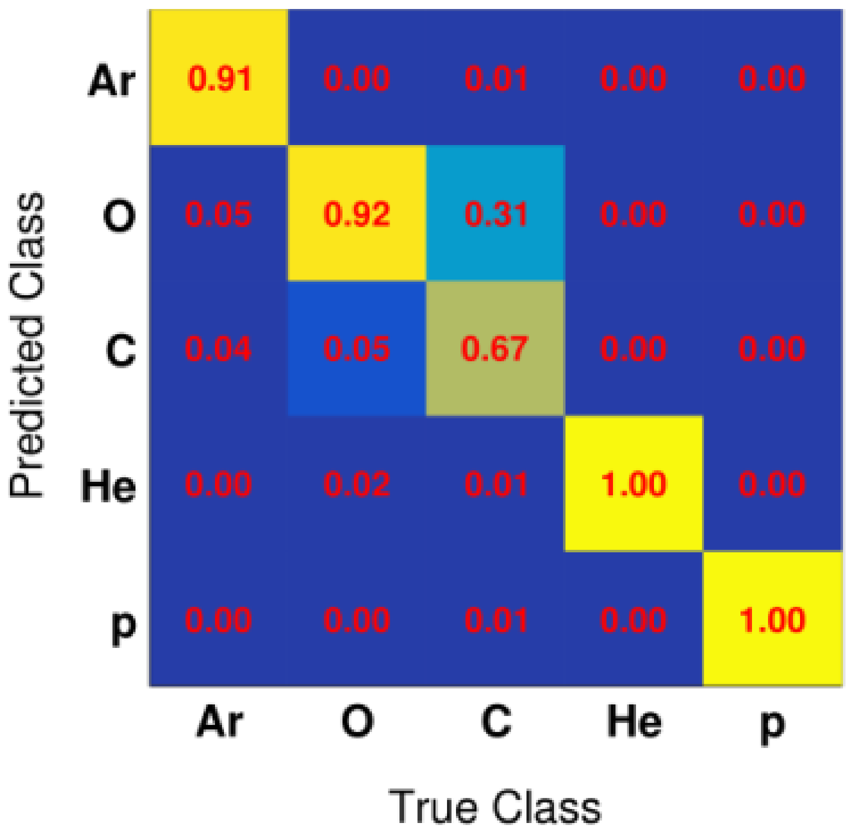
θ = 0° | **θ = 60°** | **θ = 90°**

Oxygen (430 MeV)

Helium (221 MeV)



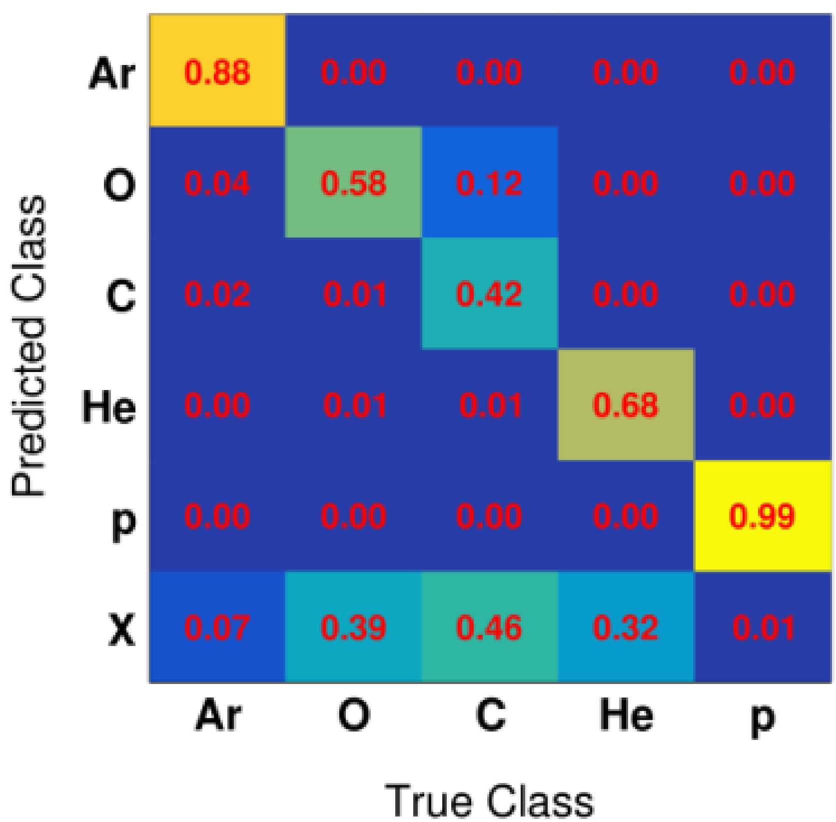
Results (5 classes)



Configuration:
- k-NN classifier (k=7)
- 32 uniform dE/dx bins

Results:
- Accuracy = 0.89

Results (5 classes + rejection)



Configuration:

- k-NN classifier (k=7)
- 32 uniform dE/dx bins
- Confidence >= 0.95

Results:

- Accuracy = 0.94
- Rejection Ratio = 0.25

WIP:
3D Analysis

Timepix3 vs. Timepix

- Simultaneous ToT and ToA operation mode

- Data-driven readout
  - Hits are reported <u>during</u> acquisition → need to work with incomplete information in online scheme
  - Temporal consistency: hits may be out of order
  - Large data throughput (theoretically up to 80 MHz)

- Increased time resolution
  - Fast ToA clock at 640 MHz → resolution: 1.56 ns
  - TDC synchronization → coincidence analysis

Online morphological clustering

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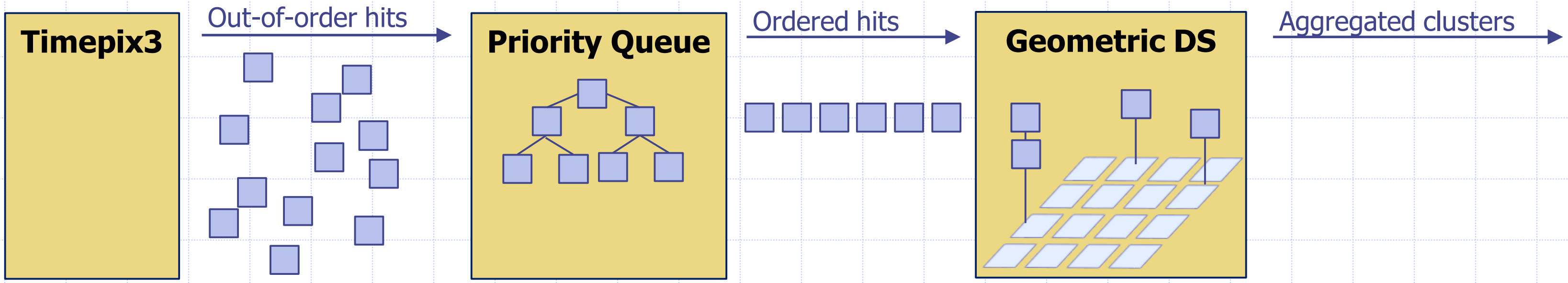
- Conventional morphological clustering *cannot* be used in Timepix3
  → The algorithm needs to be extended.

- Data-driven mode: no frames, pixels are reported continuously
- Out-of-order timestamps: hit buffering in a priority queue
- Geometric DS: efficient adjacency test



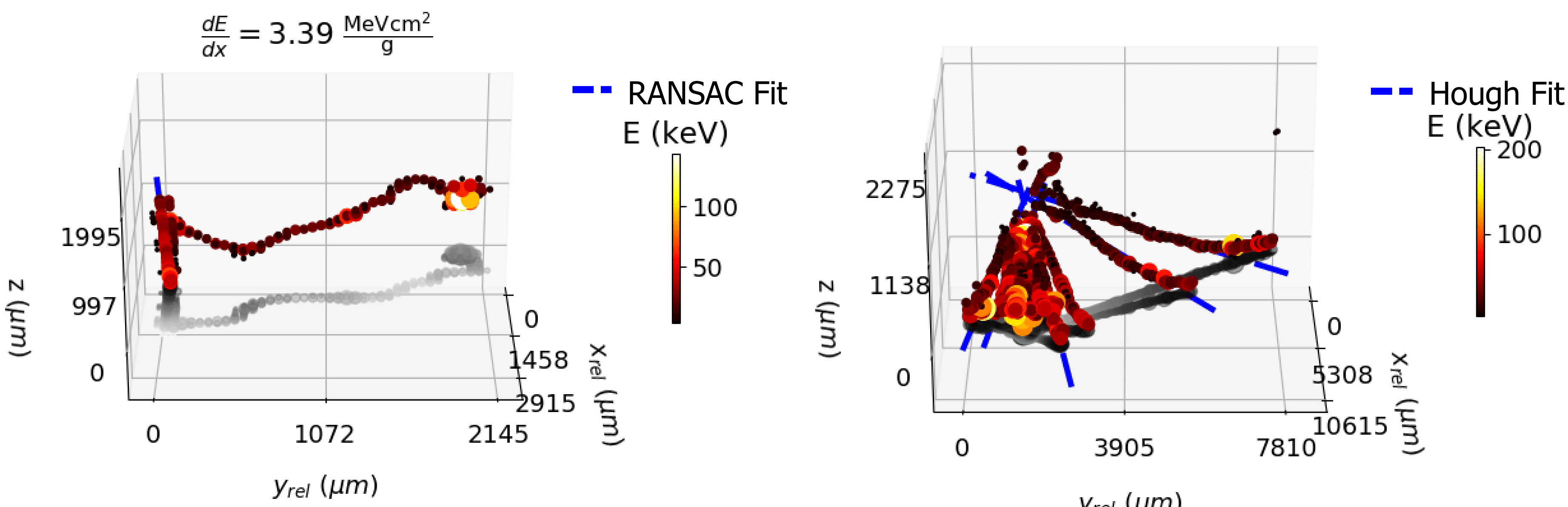
→ **Advertisement:** L. Meduna *et al.* Real-time Timepix3 data clustering, visualization and classification with a new Clusterer framework

3D event reconstruction

- Estimation of relative depth from fToA → 3D point clouds

Ref: Bergmann B. *et al*, “3D track reconstruction capability of a silicon hybrid active pixel detector" *The European Physical Journal* C 77.6 (2017): 421.

- RANSAC and Hough methods easily generalize to 3D.
- Results:



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Conclusion

- Previously developed pattern recognition methods updated for new detectors (Timepix, Timepix3):
  - Utilized ToT, fToA (increased precision, online clustering alg., 3D reconstruction)
  - Updated clustering for data-driven readout mode → online algorithm
- New methods for HETE analysis developed and evaluated:
  - Randomized → accurate results, good performance
  - Trans-dimensionality → well-suited for overlap separation (simulated up to 20)
  - ML → basic feature model has shown accuracy up to 93.5%
- New methods tested in various applications:
  - Angular, dE/dx analysis (MoEDAL)
  - Particle identification (Heidelberg Ion-Beam Therapy Center)

The authors would like to express their sincere gratitude to the Medipix2 and Medipix3 Collaboration for their permanent support.

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Further work

- ❑ Analysis of non-linear trajectories (under assumption of continuity)
  - Polynomial / spline interpolation
  - Principal curves
- ❑ Detection of interactions between events within detector.
  - Branch detection
  - Prong detection
- ❑ Application of deep learning (2D CNNs).
- ❑ Bus saturation → offload to readout hardware (FPGA).

Thank you for your attention. Questions?

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Literature:

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