Radiation field characterization and particle tracking with Timepix3 in ATLAS and MoEDAL

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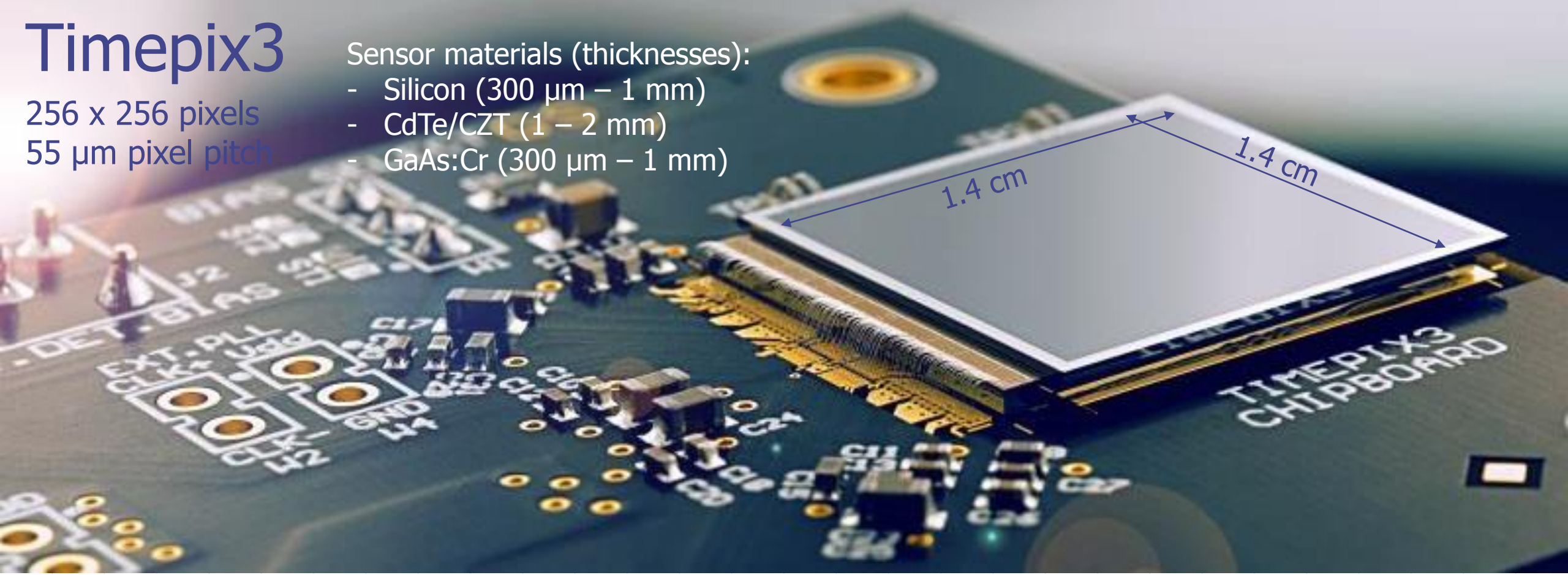
Timepix3

256 x 256 pixels
55 µm pixel pitch

Sensor materials (thicknesses):
- Silicon (300 µm – 1 mm)
- CdTe/CZT (1 – 2 mm)
- GaAs:Cr (300 µm – 1 mm)



- Data-driven readout scheme with up to 40 MPix/cm^2/s (per pixel dead-time: 475 ns)
- Simultaneous measurement of energy (ToT) and time of arrival (ToA) in each pixel
- Energy resolution: ~1.4 keV (sigma) @ 60 keV (in silicon)
- **Time binning: 1.56 ns**
- Minimal detectable energy: ~ 2.5 keV

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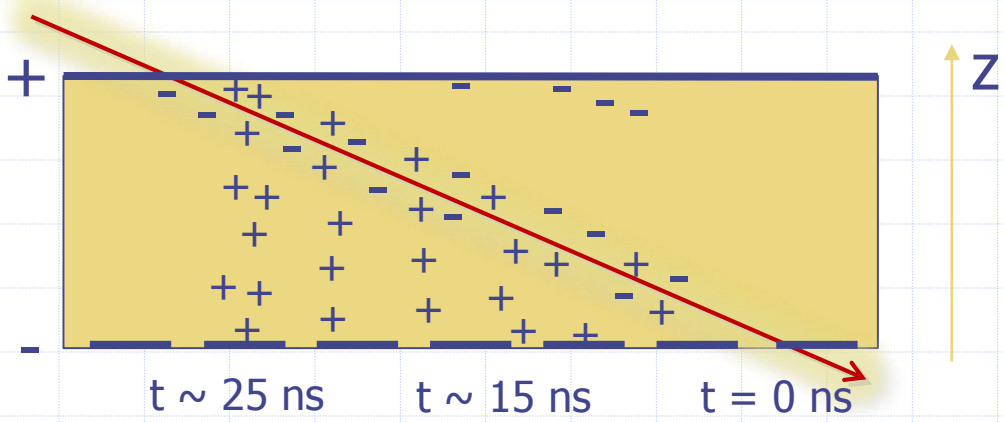
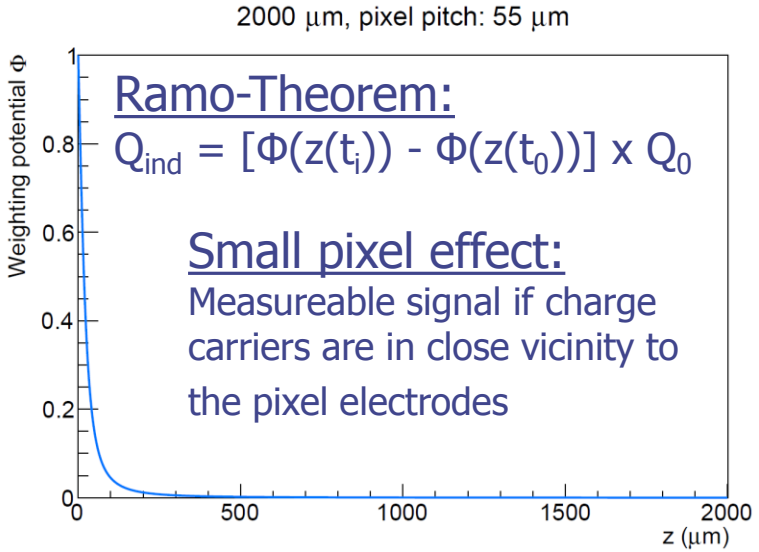
Solid-state Time-Projection Chamber:

3D reconstruction of particle tracks





Ramo-Theorem:

$Q_{ind} = [\Phi(z(t_i)) - \Phi(z(t_0))] \times Q_0$

Small pixel effect:

Measureable signal if charge carriers are in close vicinity to the pixel electrodes

Charge carrier drift motion:

e^- and h^+ drift described by

$$v_e = -\mu_e \times E(z)$$
$$v_h = \mu_h \times E(z)$$

$\mu_{e/h}$: Mobility of e^-/h^+

Electric field parametrization:

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

CdTe: $\vec{E}(z) = \frac{U_B}{d}\vec{e_z}$

U_B: Bias voltage; U_{dep}: Depletion voltage; d: Sensor thickness

→ Look-up table: $z(t_{meas.}, E_{meas.})$

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

Test measurement:
500 μm thick silicon sensor

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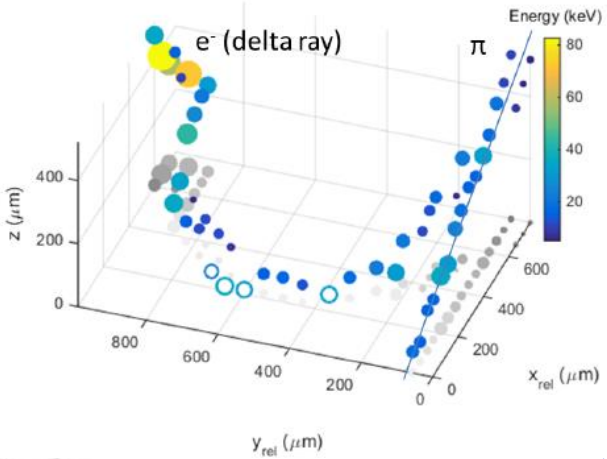
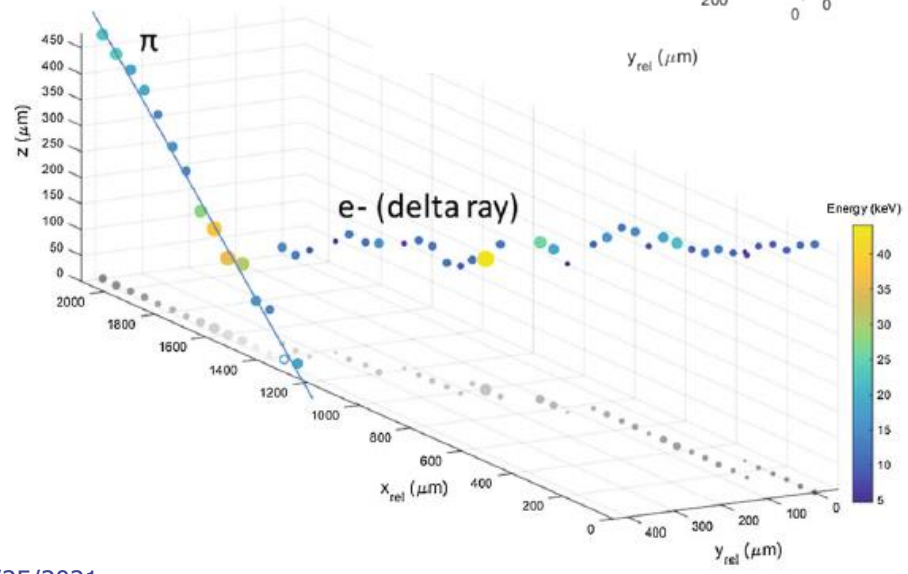
120 GeV/c pion tracks accompanied by δ-rays:

z-resolution:

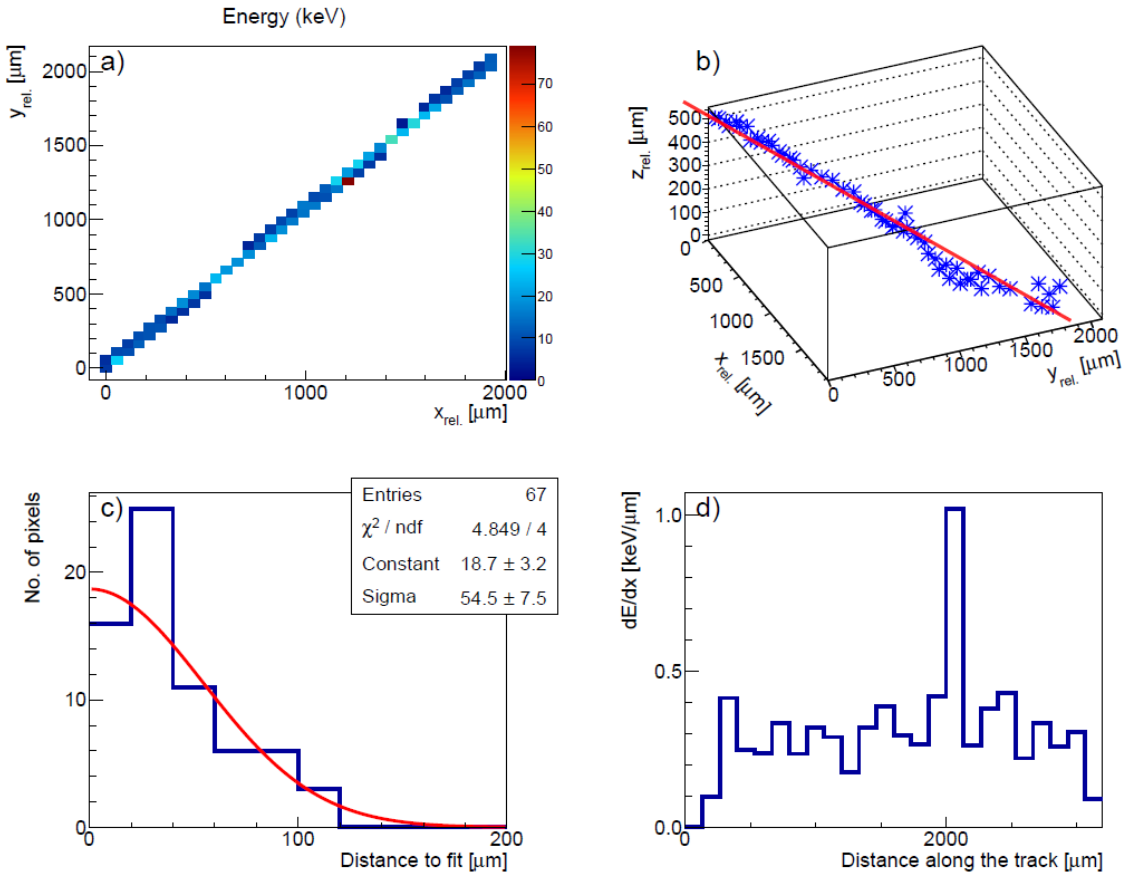
$\sigma_z \sim 30$ μm

$\Delta z_{syst} \sim 25$ μm





A cosmic μ measured in the Prague laboratory:



Bergmann et al. Eur. Phys. J. C (2017) 77: 421.
https://doi.org/10.1140/epjc/s10052-017-4993-4

Test measurement:
2 mm thick CdTe sensor

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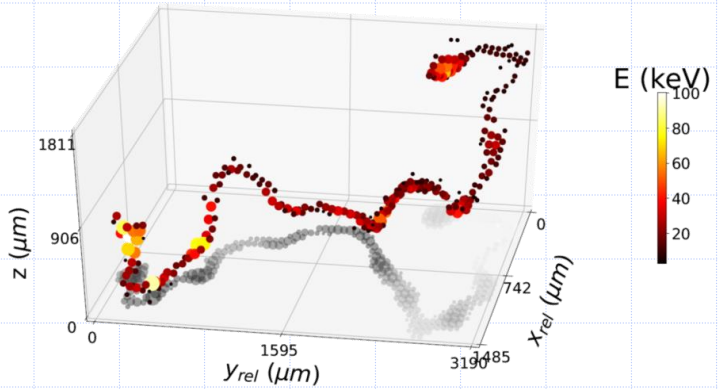
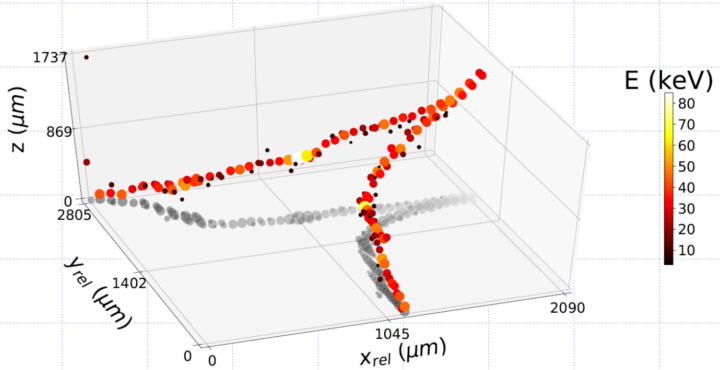
$E_{dep} = 5.66$ MeV

$e^{-/+}$ like event



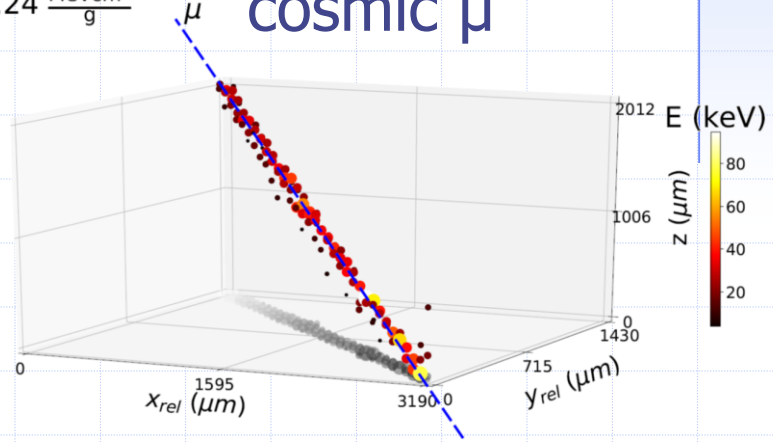
$E_{dep} = 3.96$ MeV

pair production (!?)



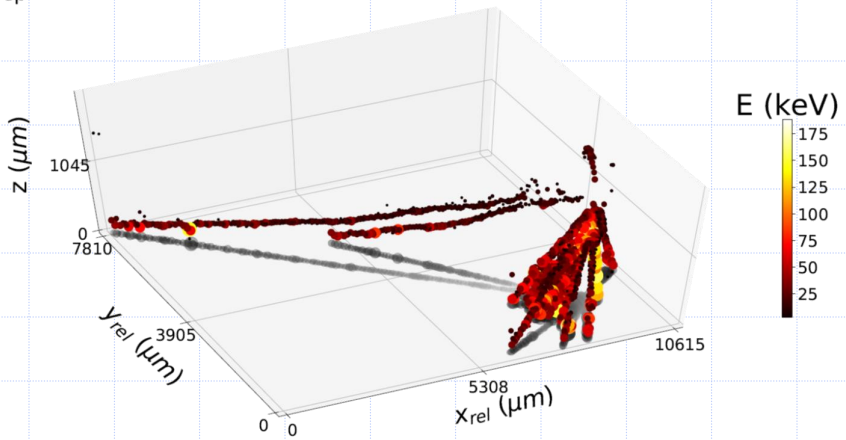
$\frac{dE}{dx} = 1.24 \frac{\text{MeVcm}^2}{\text{g}}$

cosmic μ



$E_{dep} = 37.06$ MeV

fragmentation



z-resolution: $\sigma_z \sim 60$ μm

→ Improved determination of track directions

→ Improved separation of different particle classes

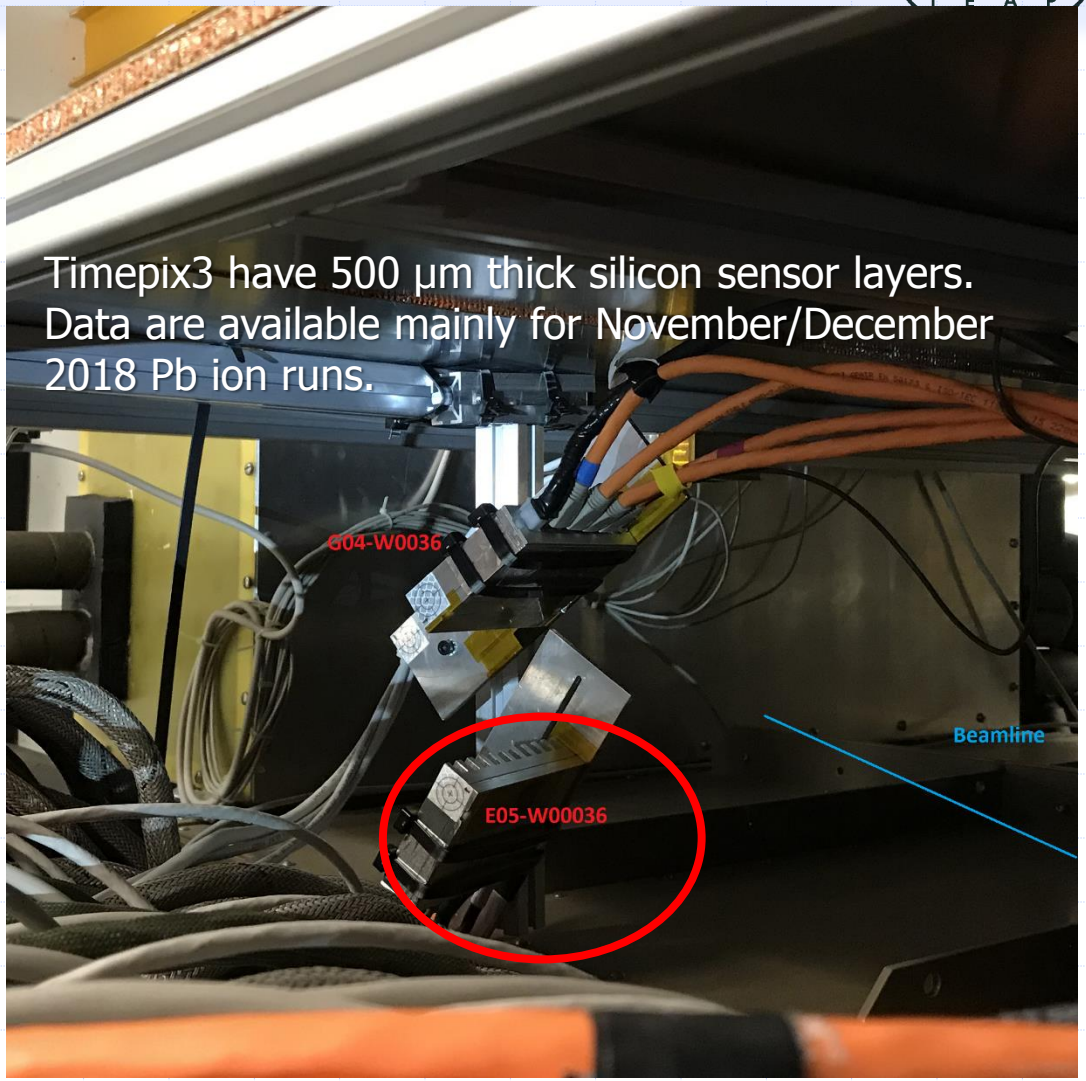
Bergmann et al., Eur. Phys. J. C (2019) 79: 165.
https://doi.org/10.1140/epjc/s10052-019-6673-z

Timepix3 in MoEDAL

Installation of 2 Timepix3 detectors in MoEDAL in September 2018.

MoEDAL = **Mo**nopole and **E**xotics **D**etector **A**t **L**HCb

Timepix3 are placed at 1.1 m distance to IP8



Timepix3 have 500 μm thick silicon sensor layers. Data are available mainly for November/December 2018 Pb ion runs.

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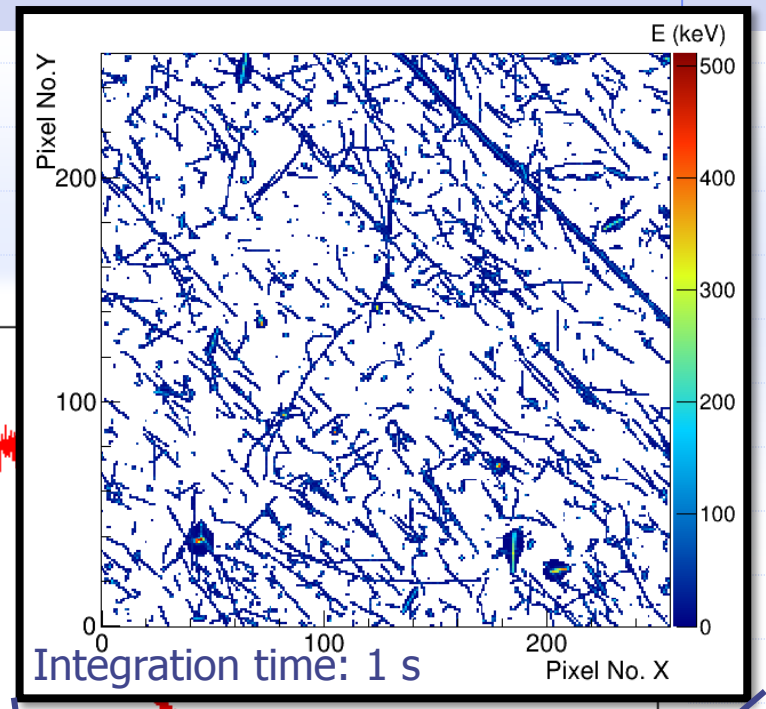
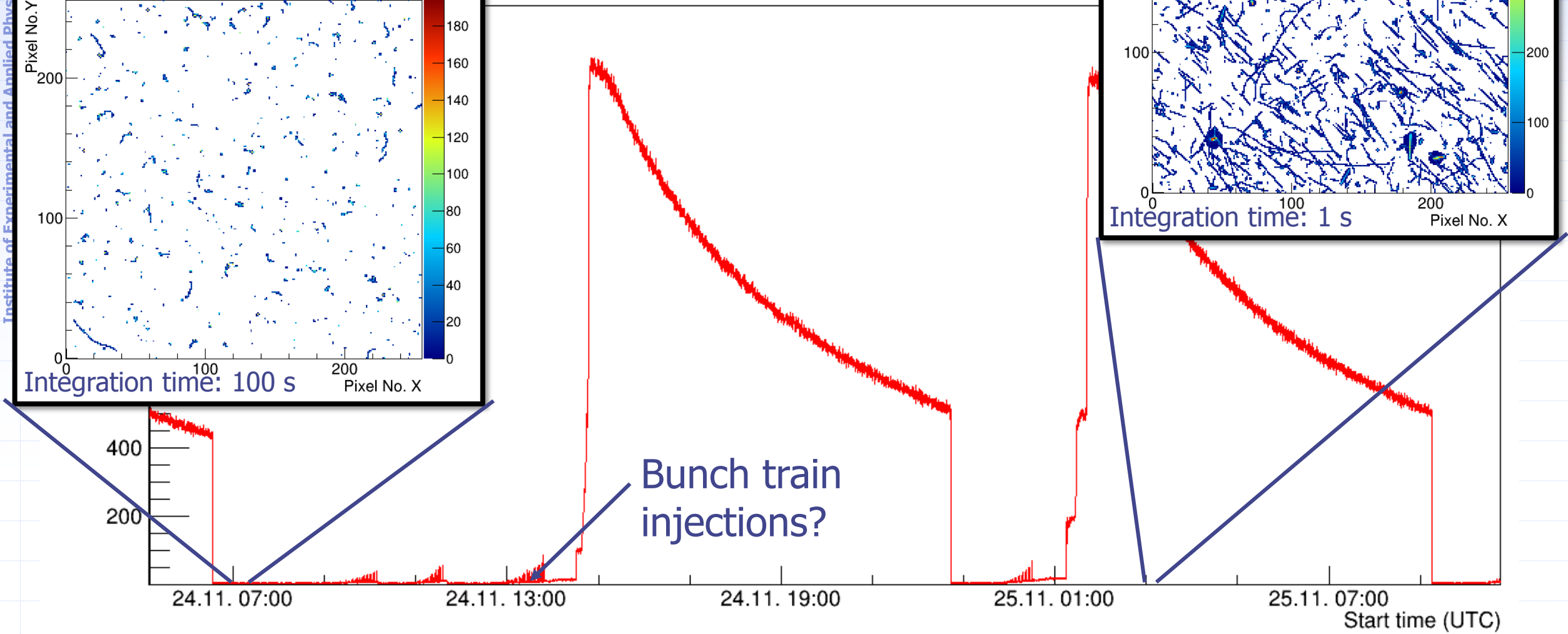
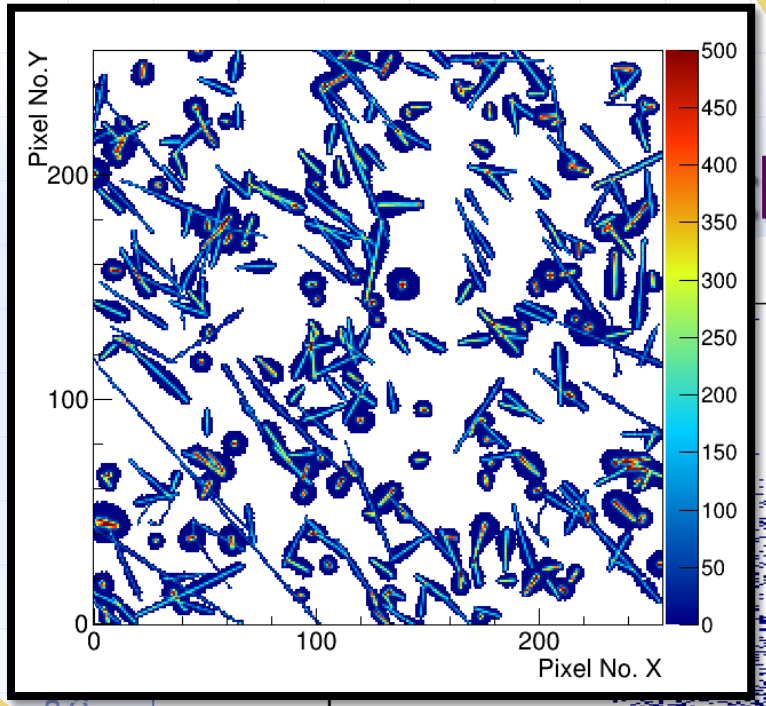
Timepix3 in MoEDAL:

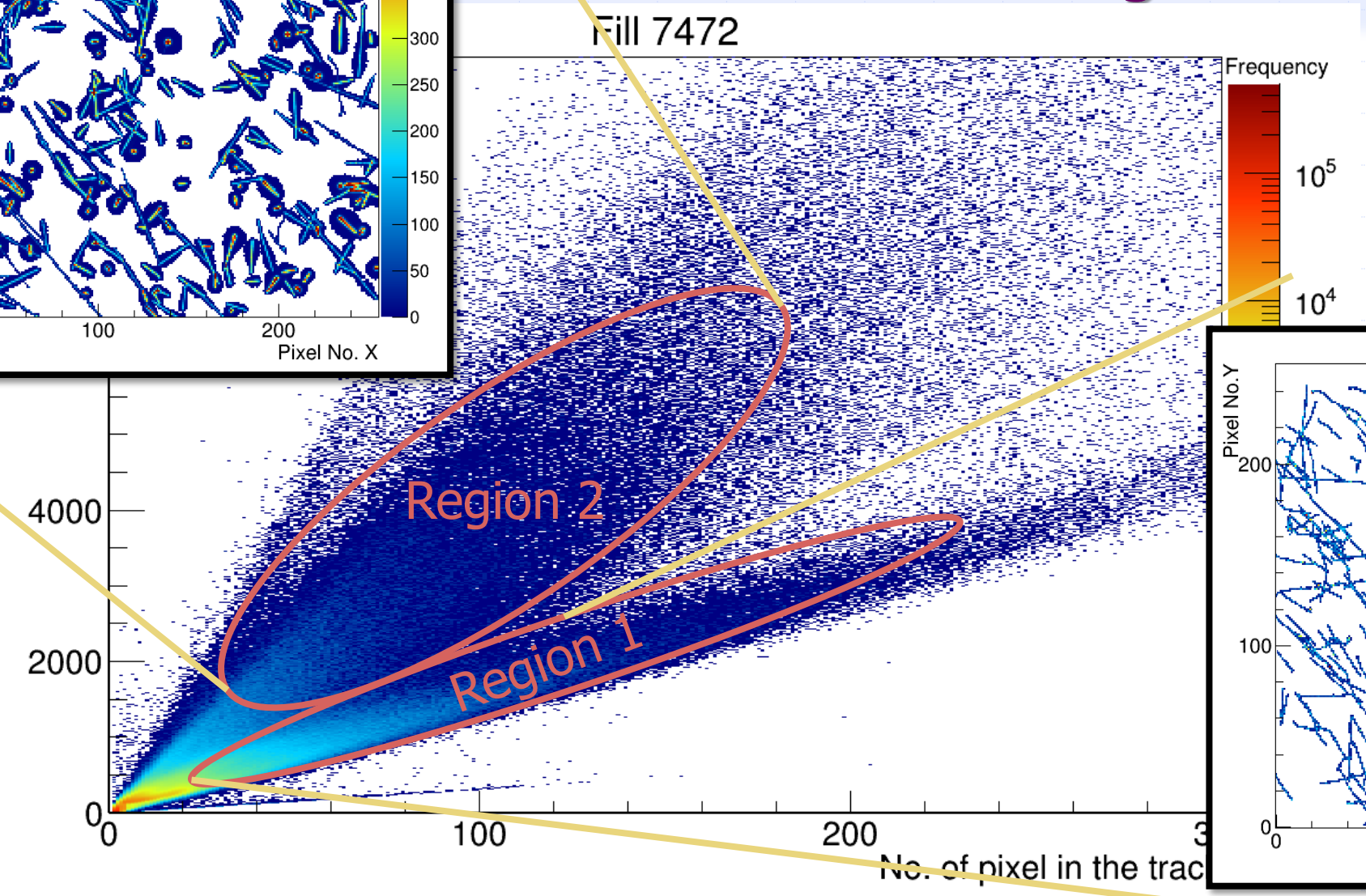
November 24 – 25, 2018
Cluster rate as a function of time

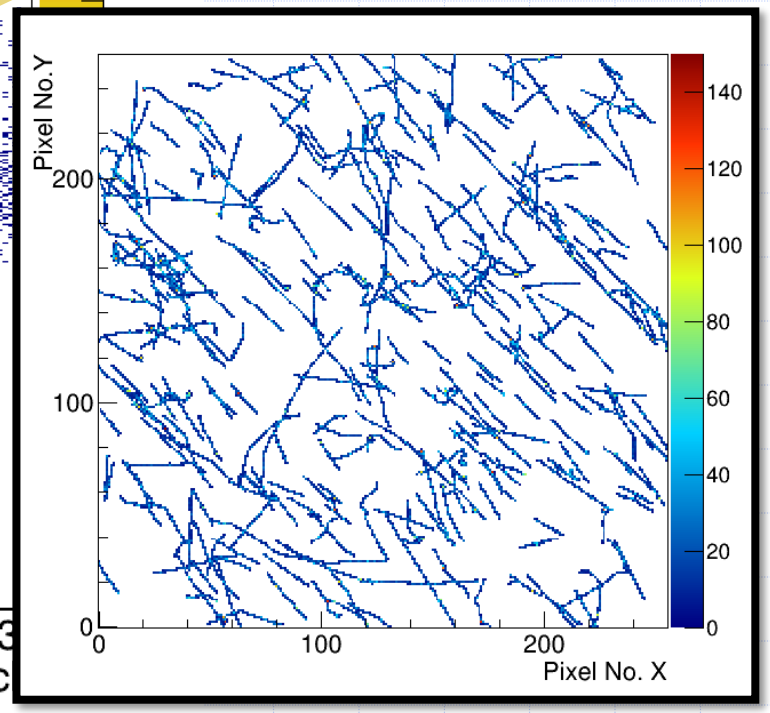




haracterization – during collisions







Basic categorization of tracks using the ratio of energy per track and the number of pixels

Timepix3 in Moedal:

Directionality map

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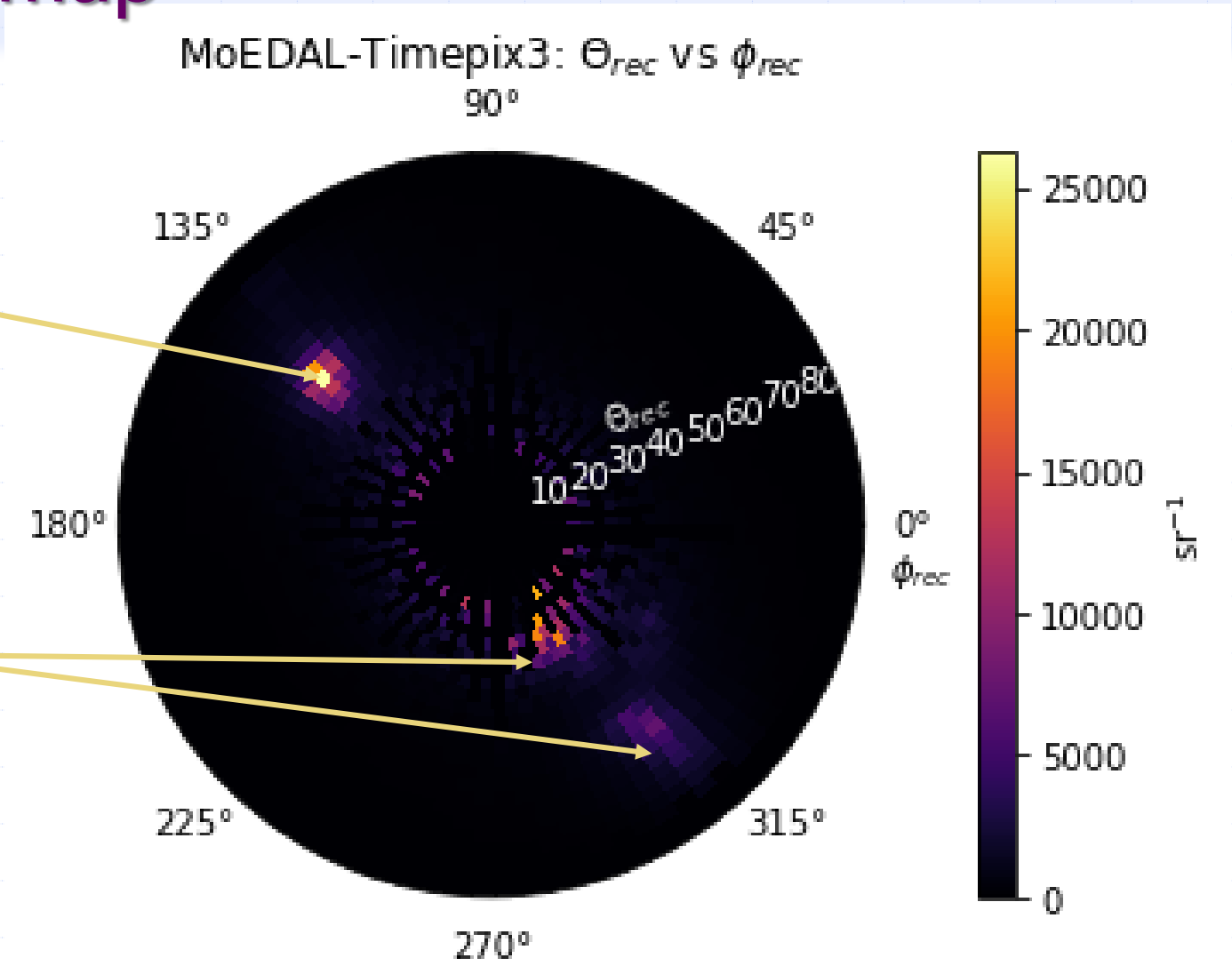
Primary peak:

Particles (p^+, μ, π, ...) from the IP

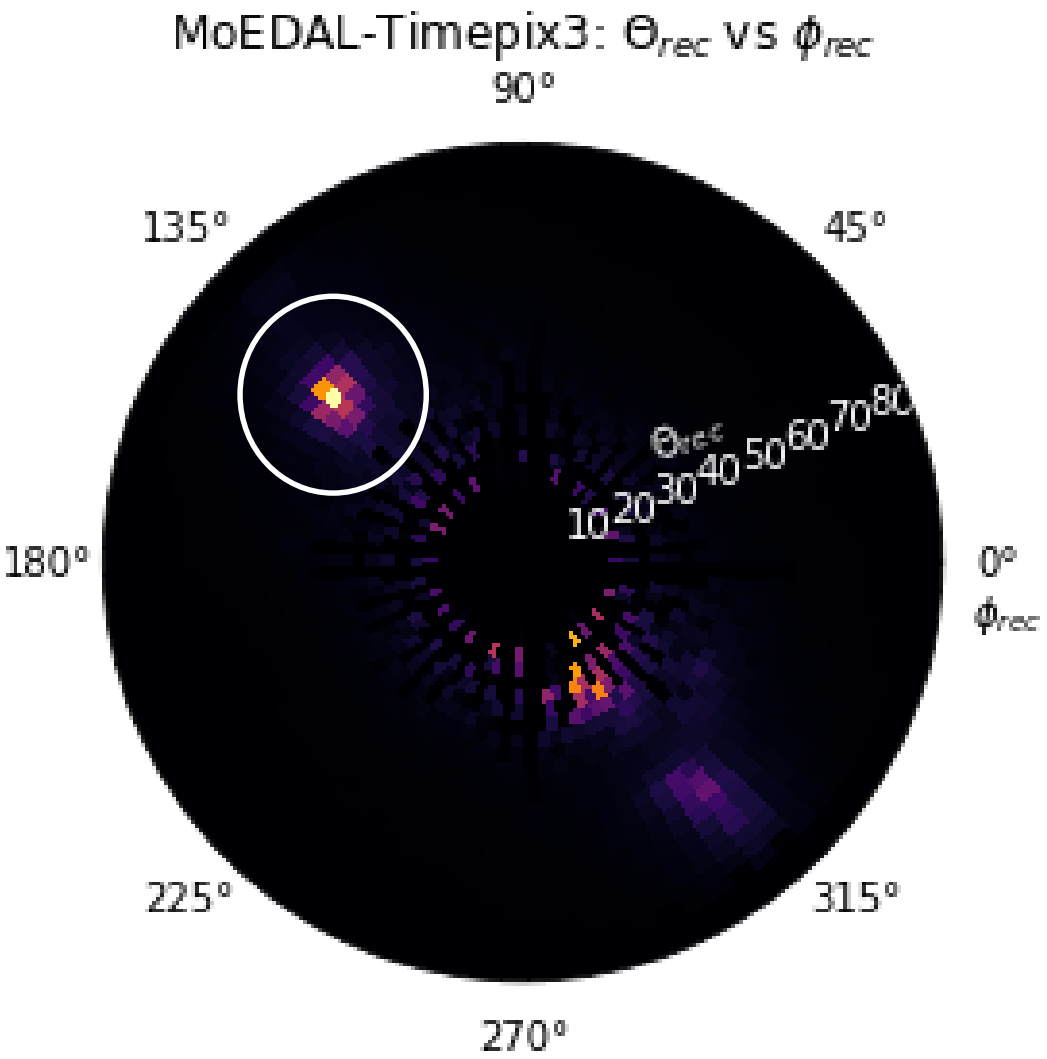
Secondary peak(s):

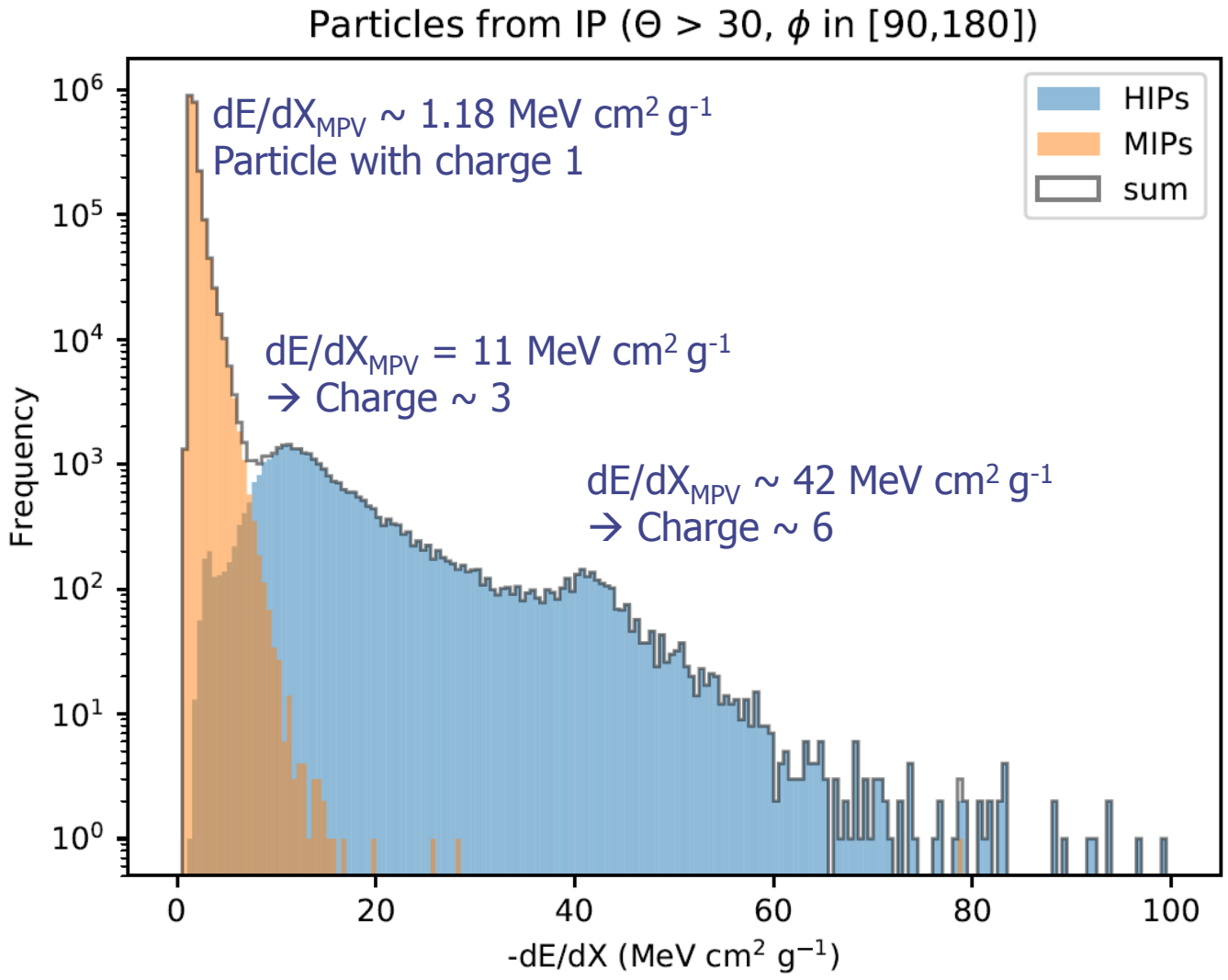
Particles (p^+, μ, π, ...) from collimators / beam pipe (?)



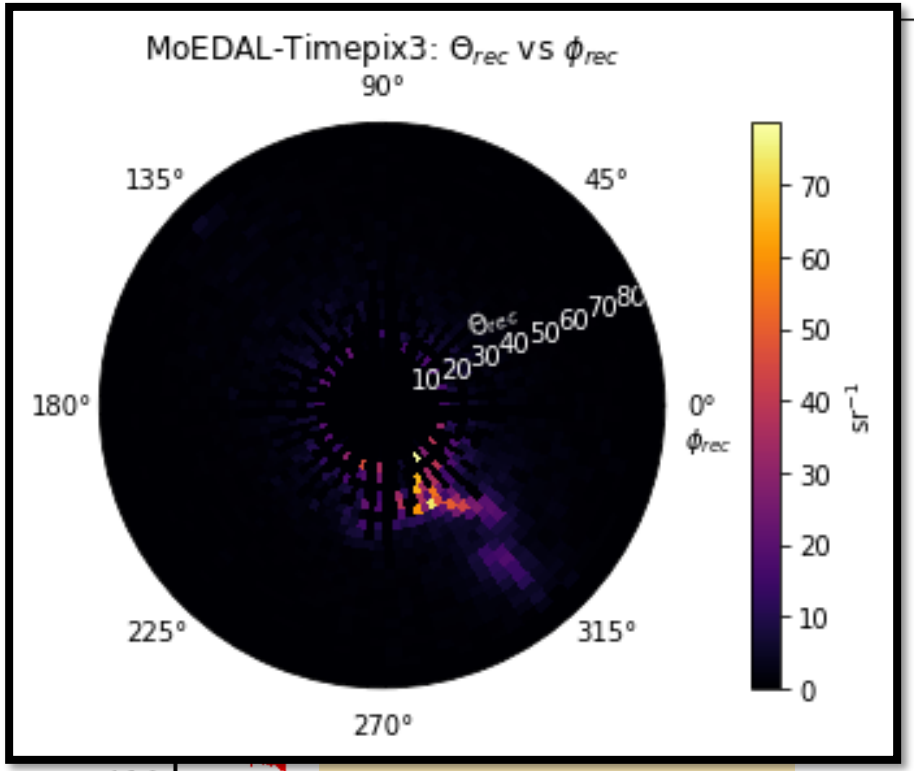
Timepix3 in MoEDAL:

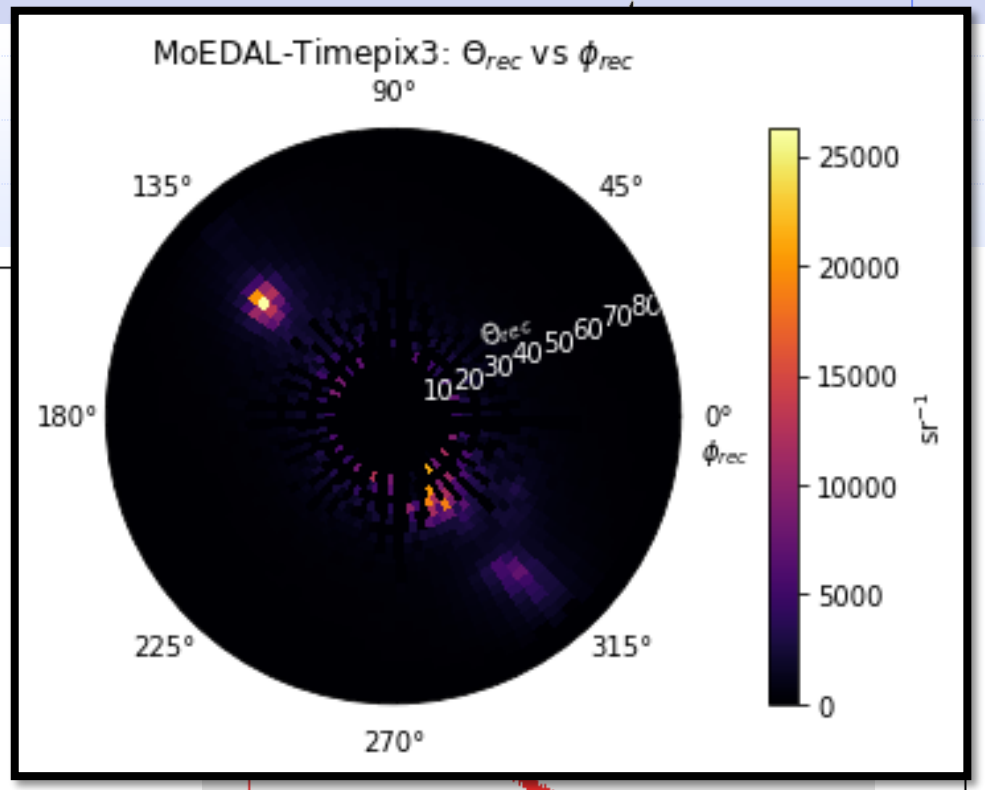
Directionality map

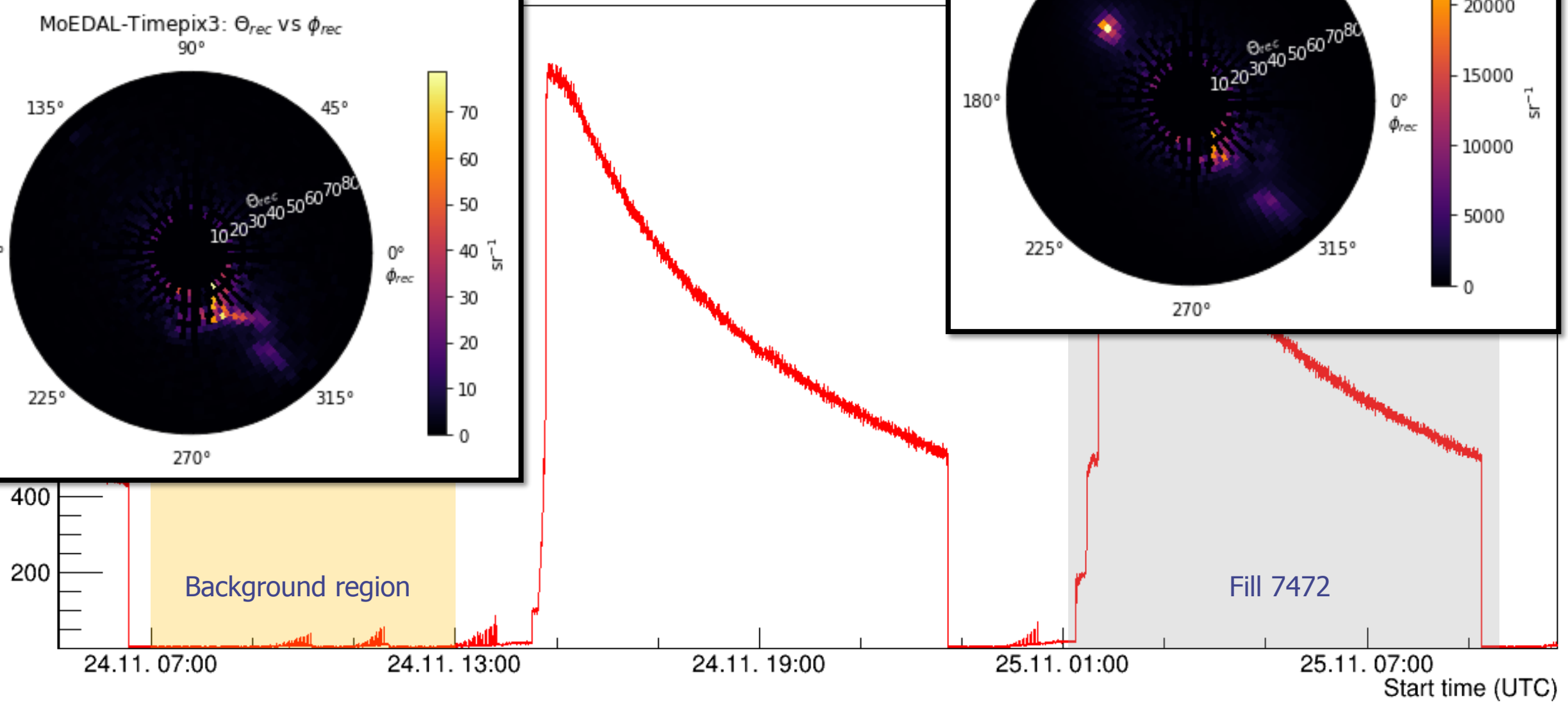




Timepix 3 in MoEDAL:
Directionality maps – During and after collision period(s)

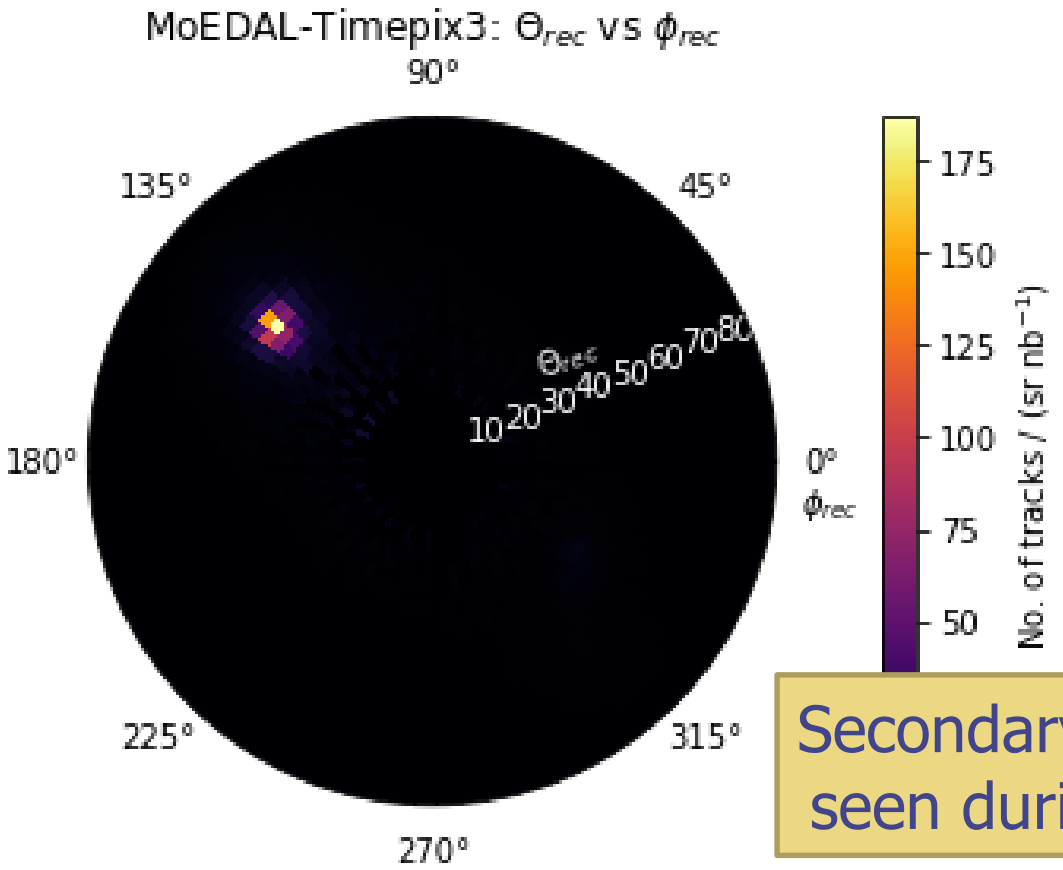


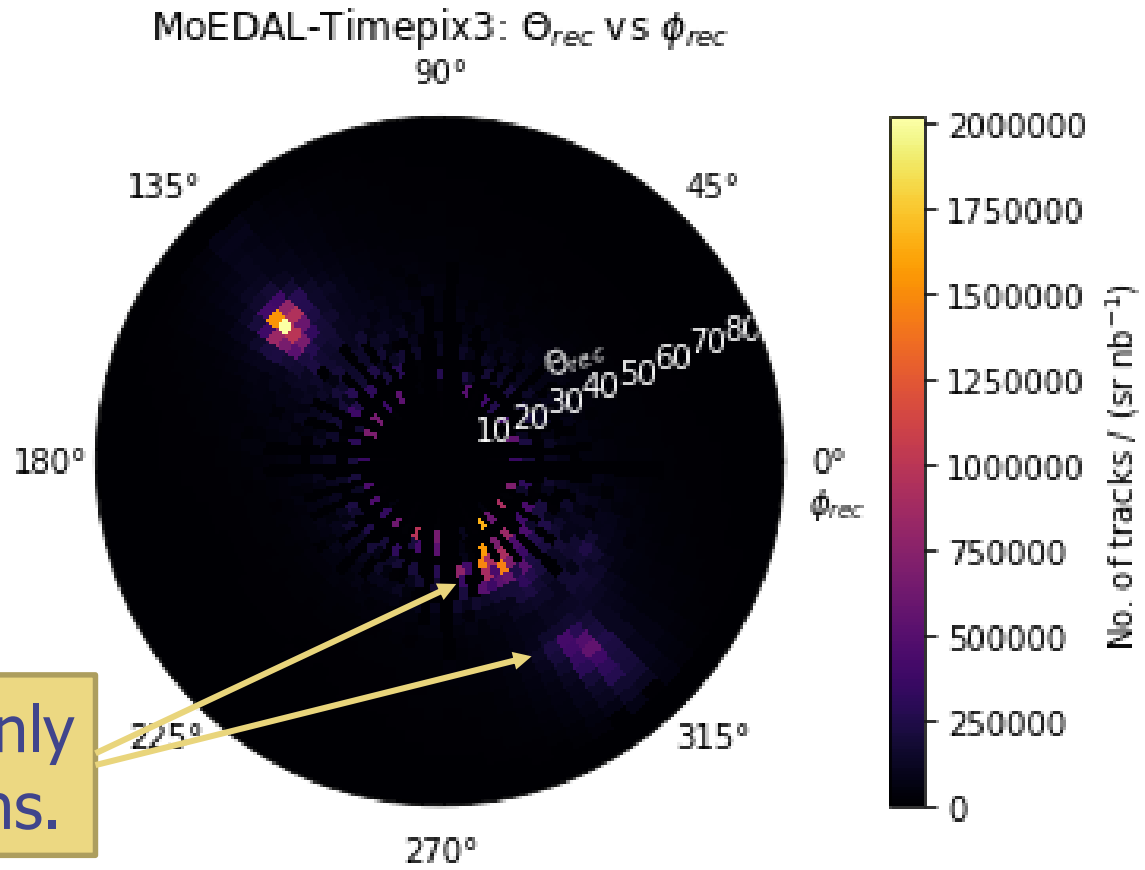




Timepix3 in MoEDAL:

Comparison of the directionality maps during pp- and PbPb-collision periods





Secondary peaks only seen during Pb-runs.

pp-collision period on September 24, 2018

Pb-run on November 25, 2018

Timepix3 in ATLAS:

Positions and goals

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2017: 2 Timepix3 (position TPX3-2) detectors were installed far away from the IP

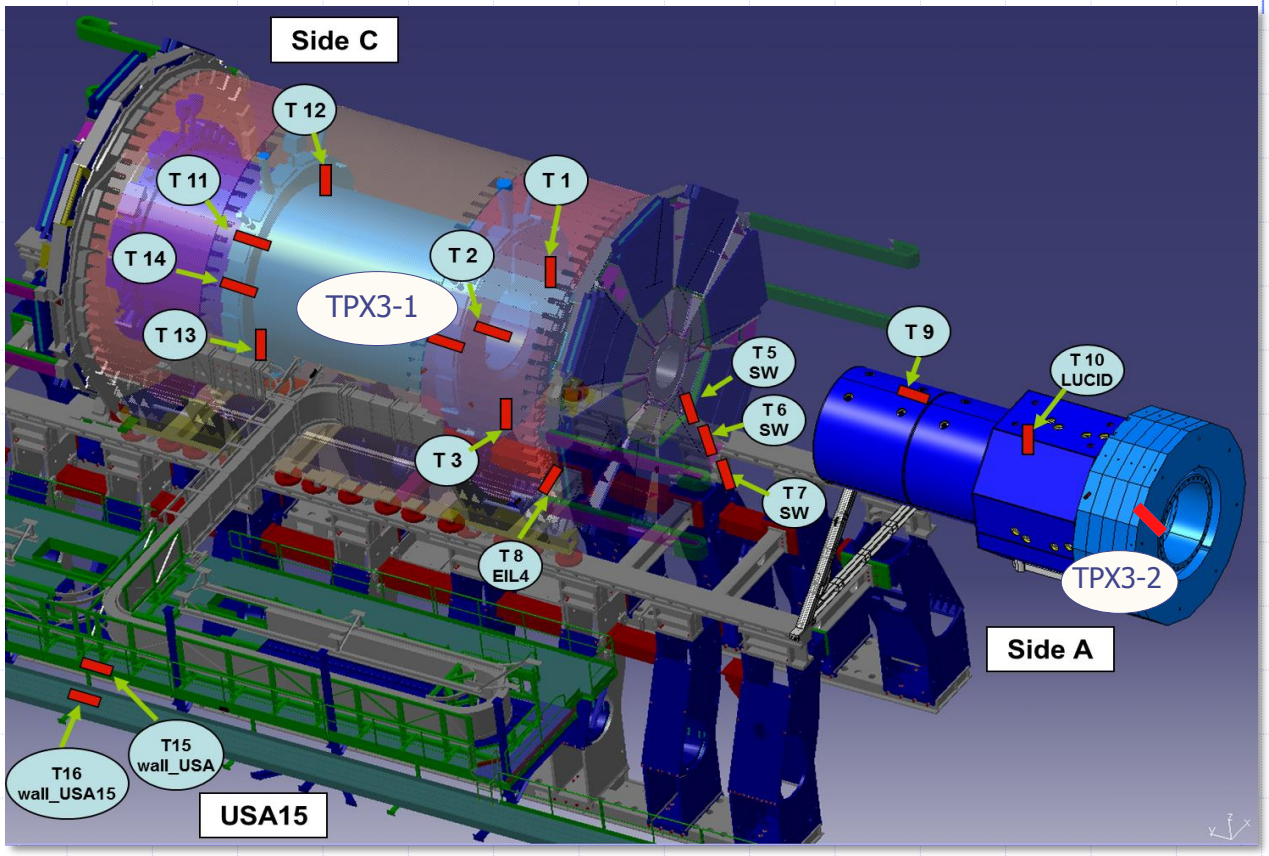
→ Time resolved study of radiation created in the collimators

2018: 2 Timepix3 detectors were installed on the extended barrel to study their capabilities

- Study the radiation fields during and after collision periods
- Measure the luminosity

LHC Run-3 upgrade: Installation of 13 Timepix3 two-layer stacks synchronized with LHC orbit clock

- Bunch-by-bunch absolute (?) luminosity measurement



Timepix3 in ATLAS:

Timeline – May 2018

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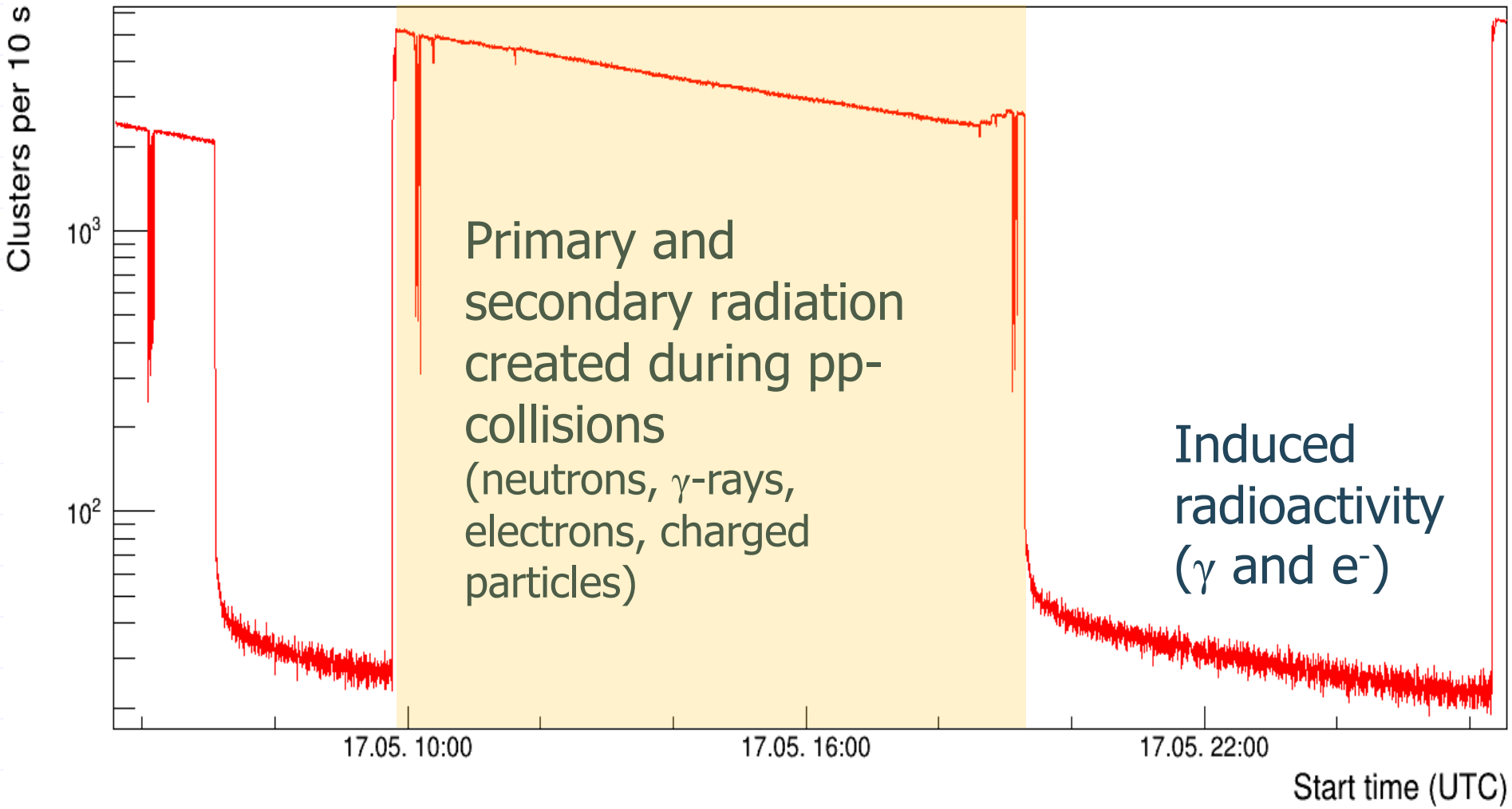

Timepix3 in ATLAS:

Measurement of charged particle fluence and particle directions

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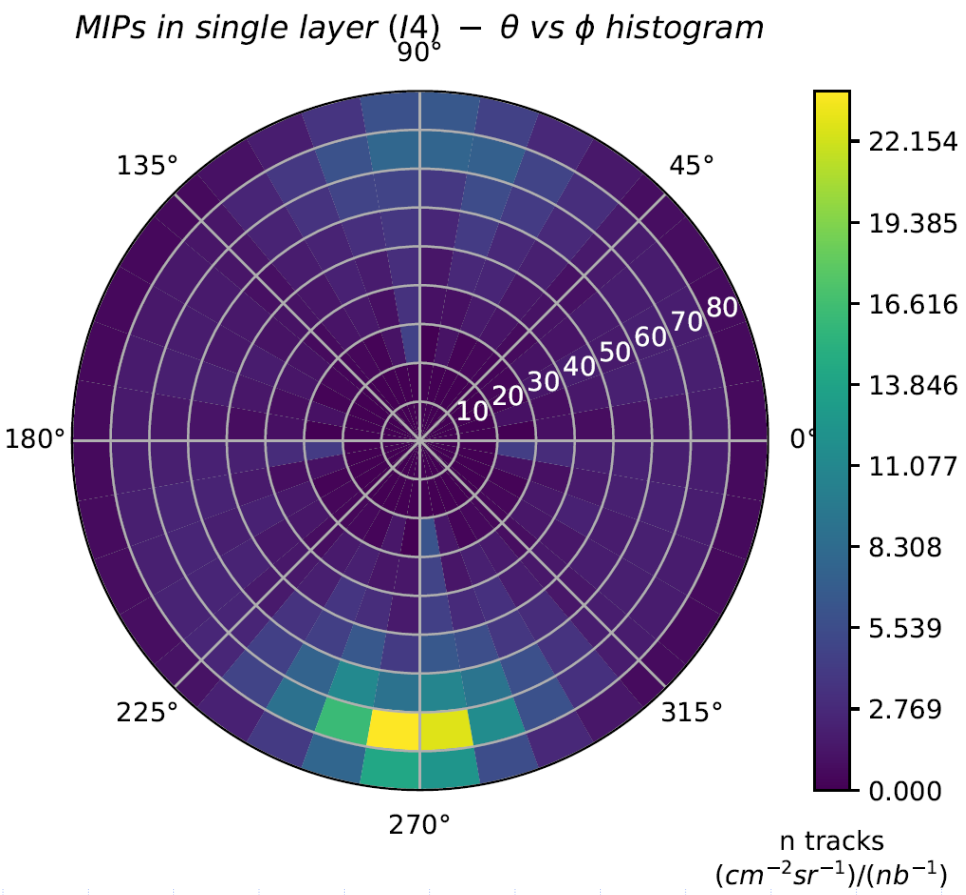
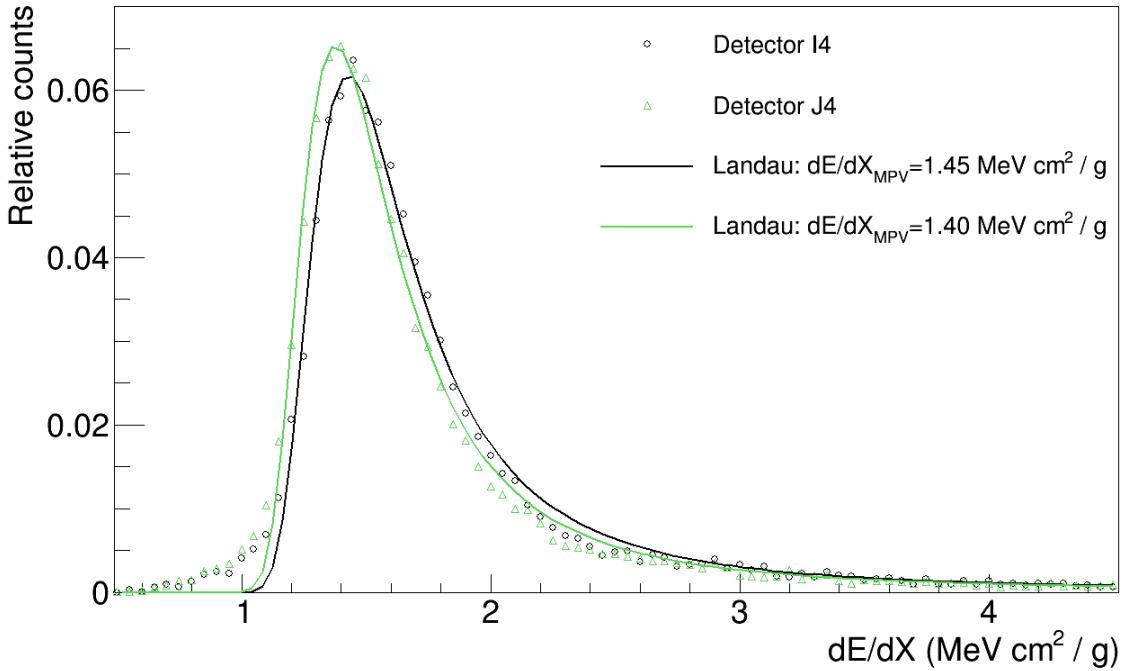
Directionality map:





Billoud et al., "Particle tracking and radiation field characterization with Timepix3 in ATLAS", Nucl. Inst. Meth. A, 2020, 164401, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2020.164401.

Timepix3 in ATLAS:
Timeline – May 2018

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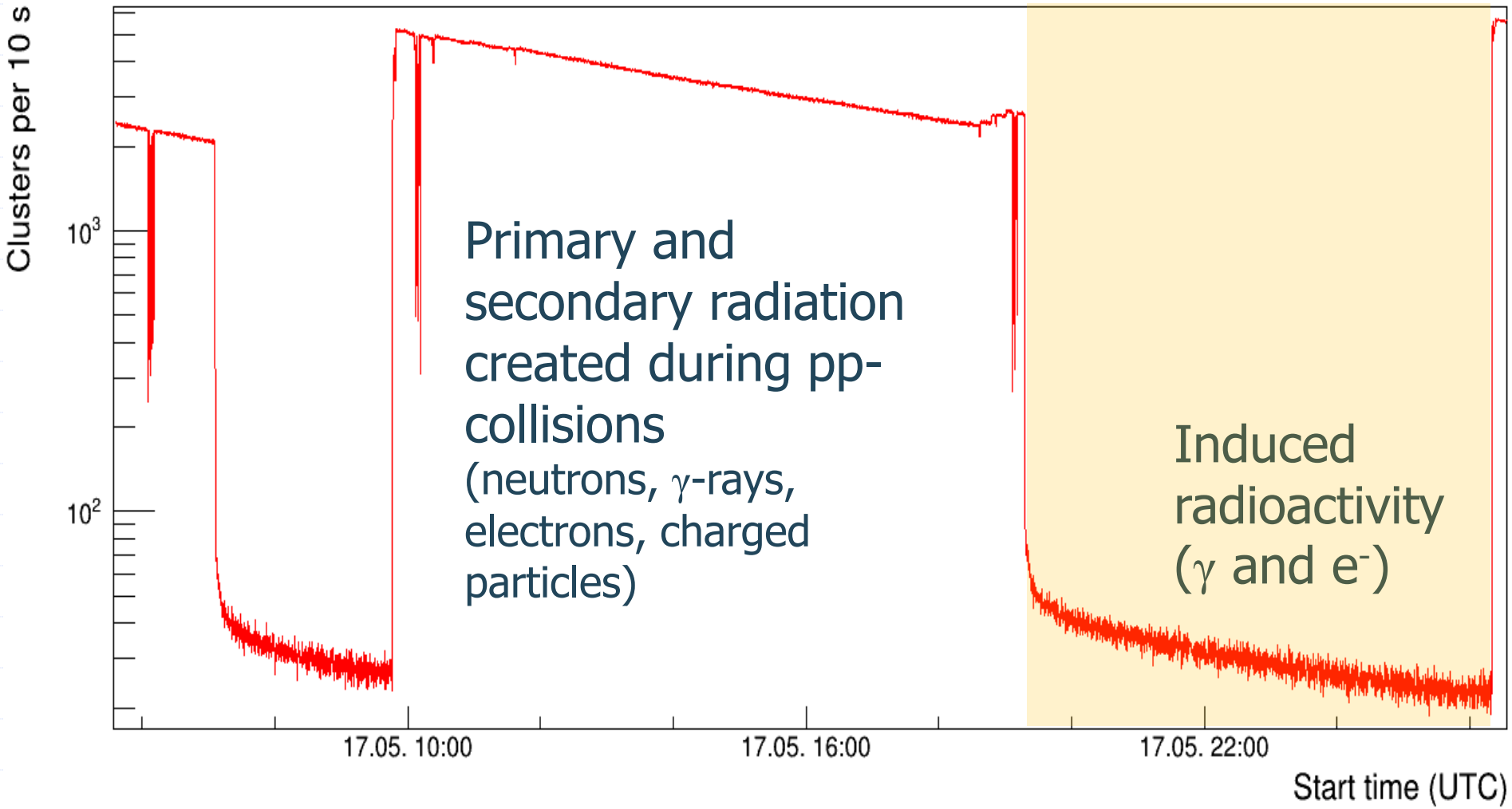

Timepix3 in ATLAS:

Equation to describe the growth and decay of induced radioactivity

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$$M_{act}^{i} = \underbrace{\sum_{k=1}^{n} M_{act}^{i-1,k} \times e^{-\lambda_k t}}_{\text{Decay of atoms activated before i-th time bin}} + \underbrace{\left(M_{tot}^{i} - M_{act}^{i-1}\right) \times \theta\left(M_{tot}^{i} - M_{act}^{i-1}\right) \times \sum_{k=1}^{n} Y_k \times \left(1 - e^{-\lambda_k t}\right)}_{\text{Activation during i-th time bin (valid only during collisions)}}$$

M_{tot}	total count rate measured in the given TPX frame (normalized to unit time)
M_{act}	count rate caused by all activation products
λ	decay constant, $\lambda = \ln(2)/T_{1/2}$; $T_{1/2}$ is the half-life
t	time period between the end of (i-1)-th bin and the end of i-th bin
Y_k	normalization constant, used to fit the growth/decay curve to the measured data

Timepix3 in ATLAS:

Measurement of the induced radioactivity in the ATLAS cavern

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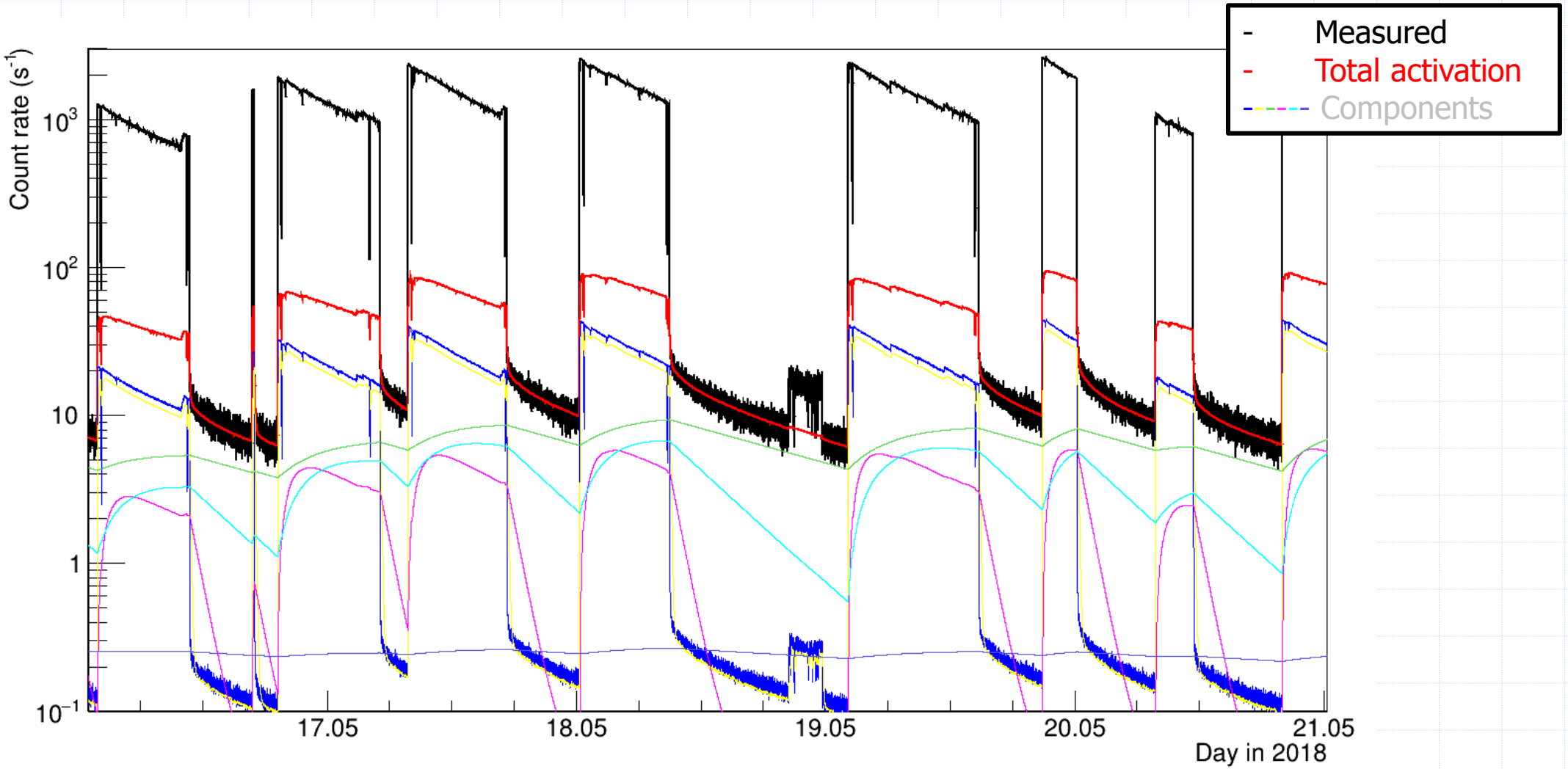

Conclusion

- Timepix3 detectors were installed in ATLAS and MoEDAL and used to characterize the charged particle fields.
- Their particle tracking capablility and the possibility to separate different particle species was used to study particle directions and trace them back to the interaction points.
- The creation and decay of radioisotopes was described by a model and applied to the data allowing the identification of few created radioisotopes.

Thank you very much for your attention!

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Timepix3 in ATLAS:
Identification of radioisotopes

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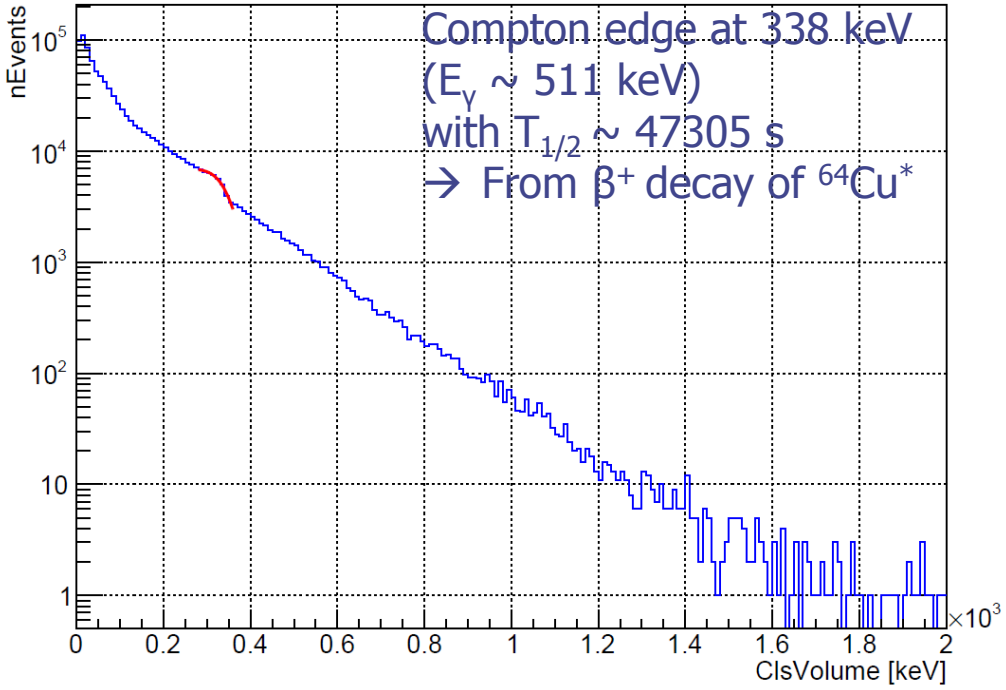
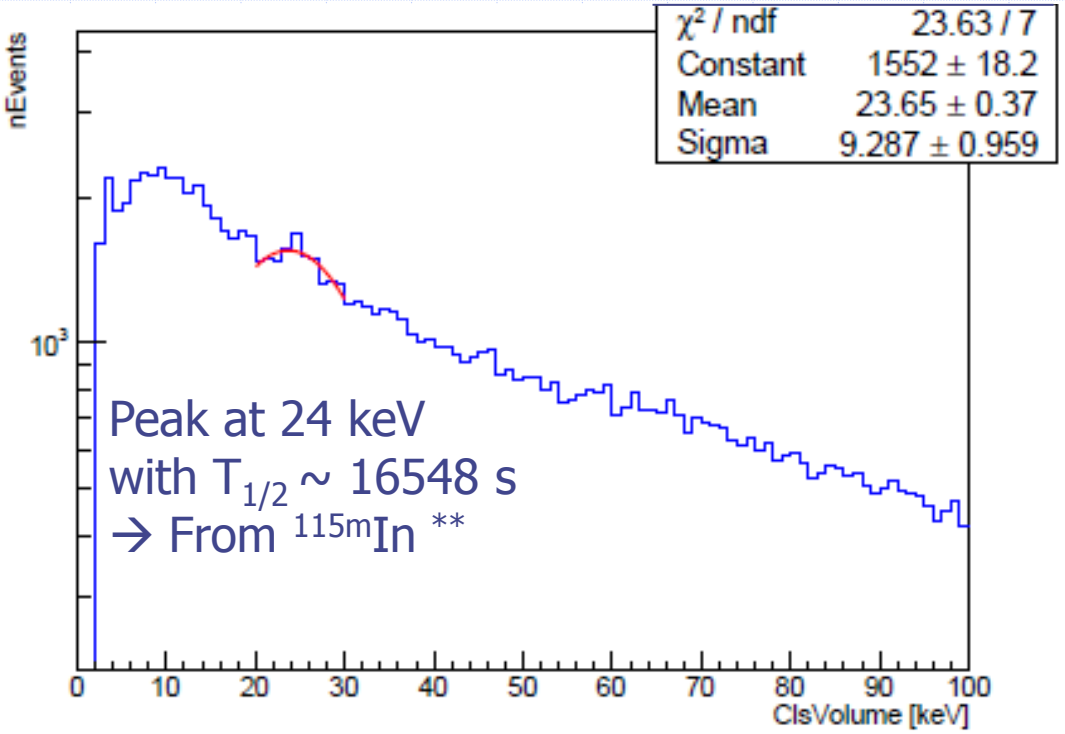
Determined half-lifes are not sufficient to really indicate which isotope was present. What about the energy spectrum?



*) ^{64}Cu can be created by: $^{63}Cu(n, \gamma)^{64}Cu$



**) ^{115m}In can be created by: $^{115}In\ (n, n')^{115m}In$

Timepix3 in ATLAS:

Measurement of MIP fluence and particle directions

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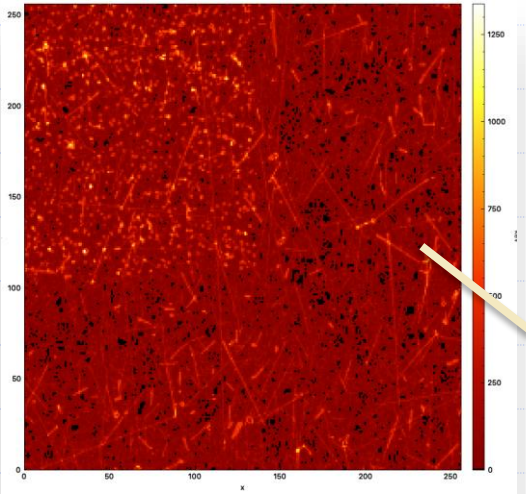
- Using filtering on track properties events of interest can be filtered out of the data set
- Minimum Ionizing Particles (MIPs) were selected using linearity criterion

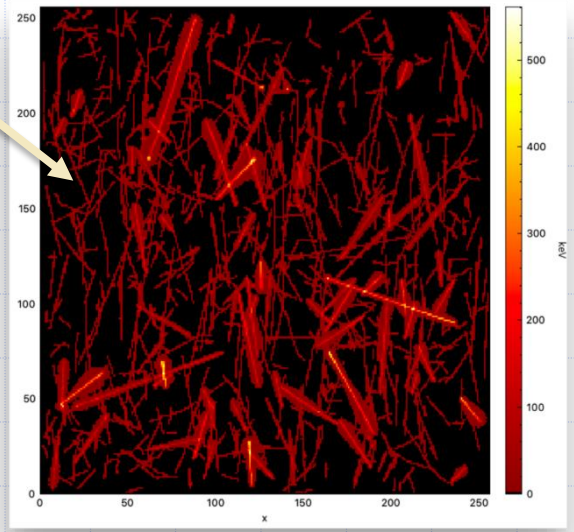


Unfiltered data set:

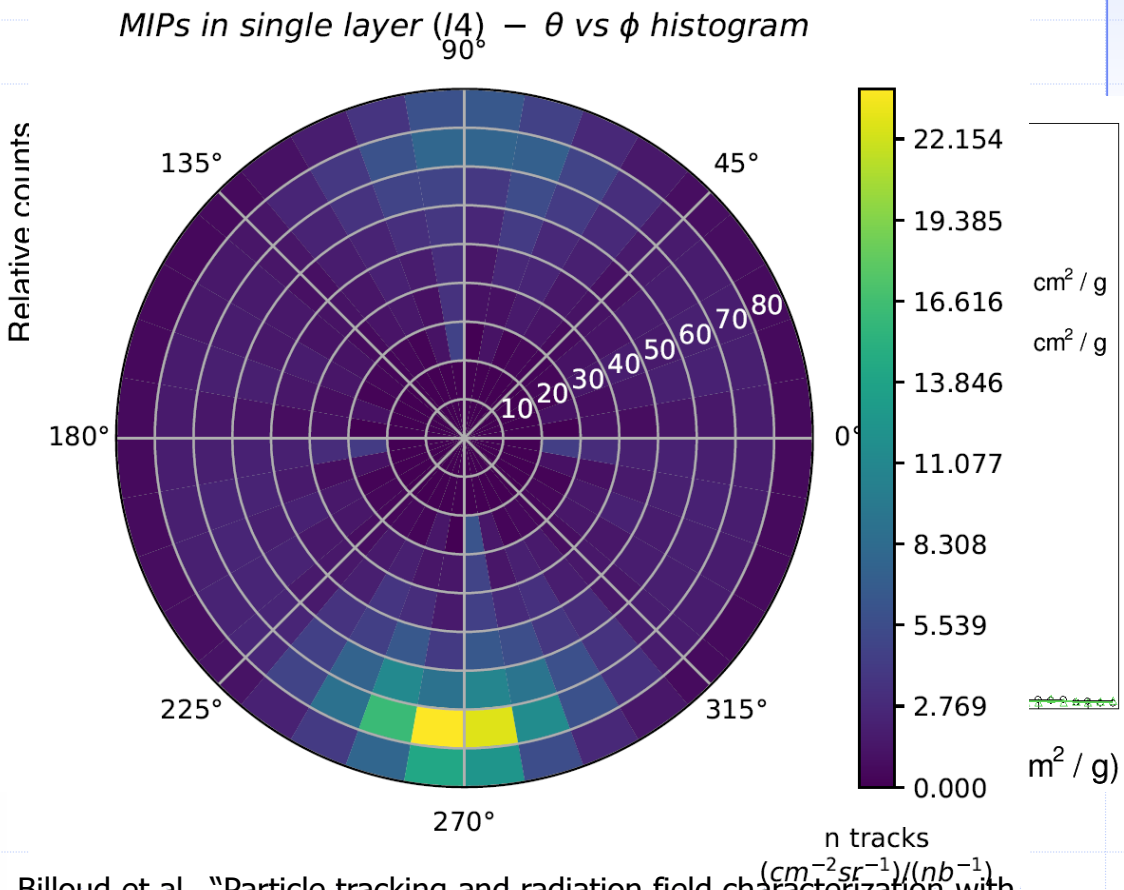
10 s integration time

Selected straight tracks:

10 s integration time



Directionality map of MIPs:



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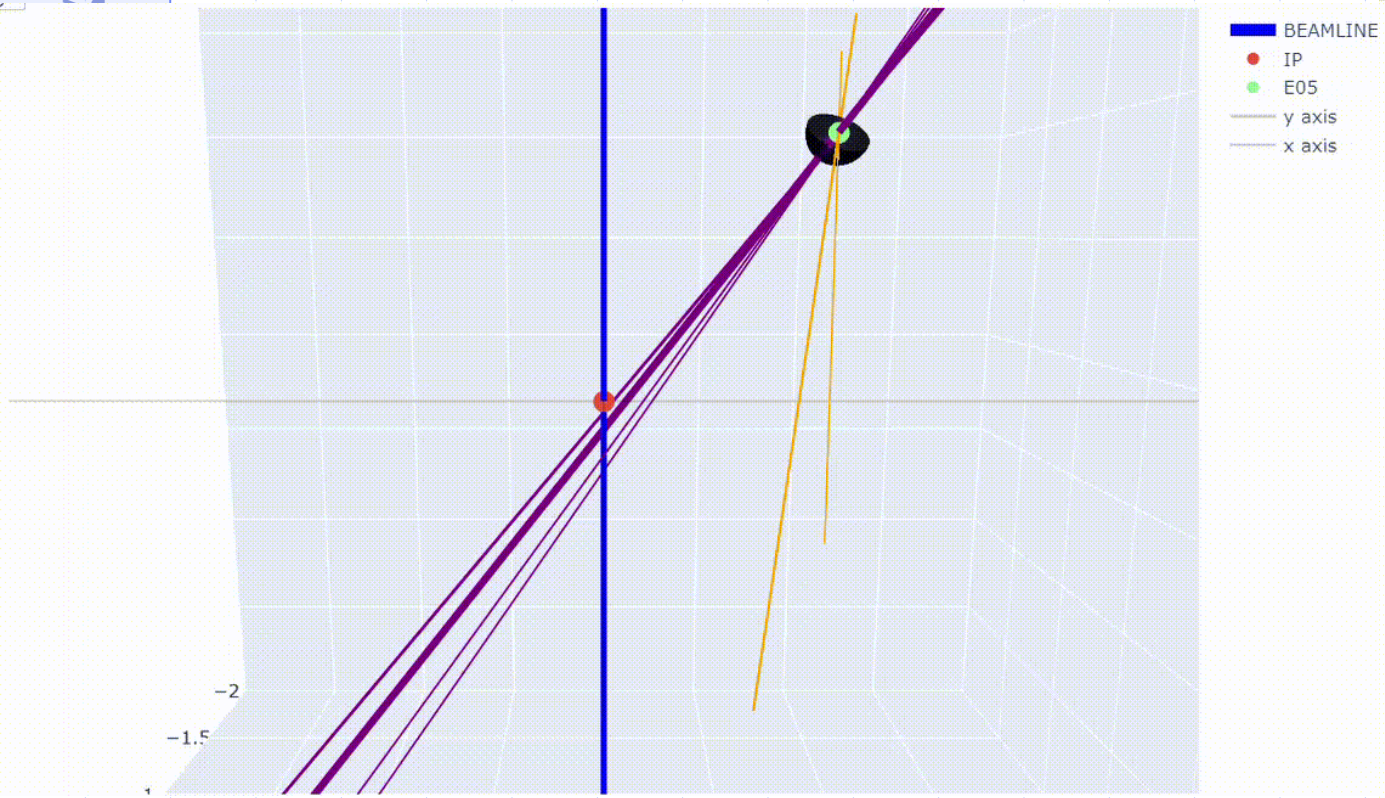
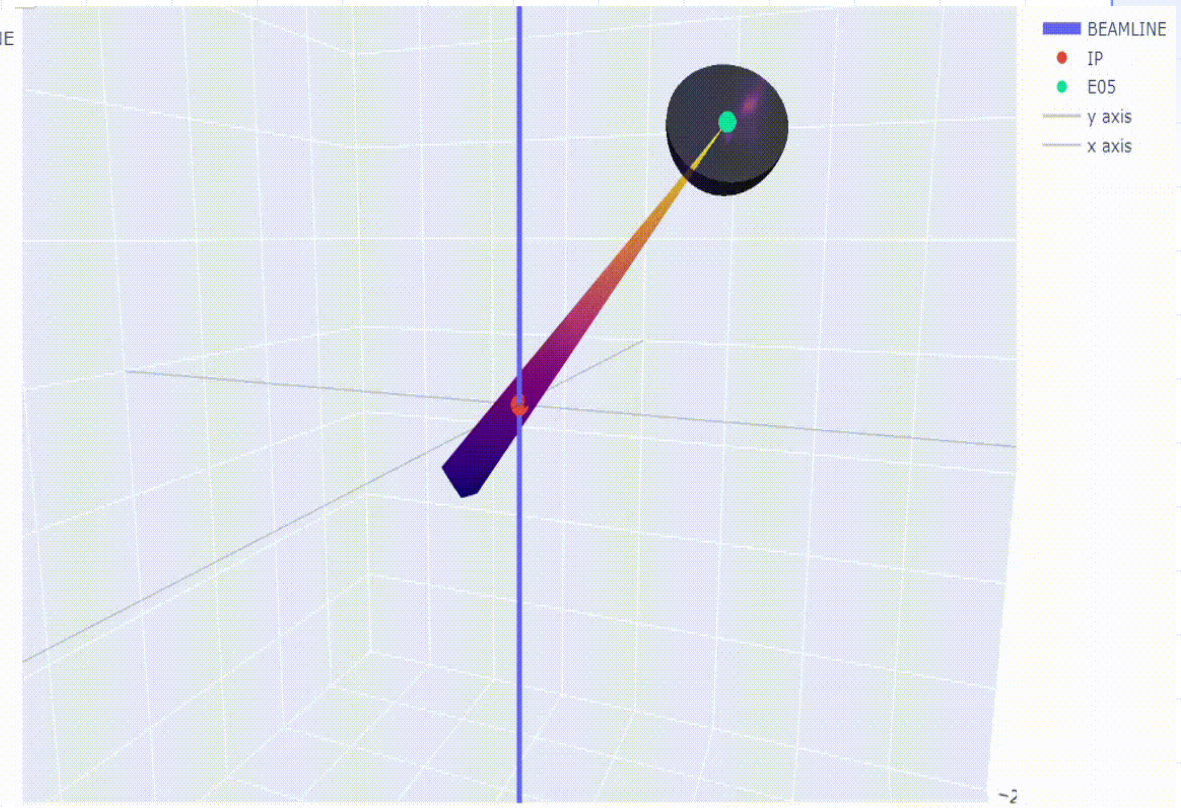
Understanding the angles in the physical coordinate system – MoEDAL





Pb-run on November 25 (line with indicates intensity):

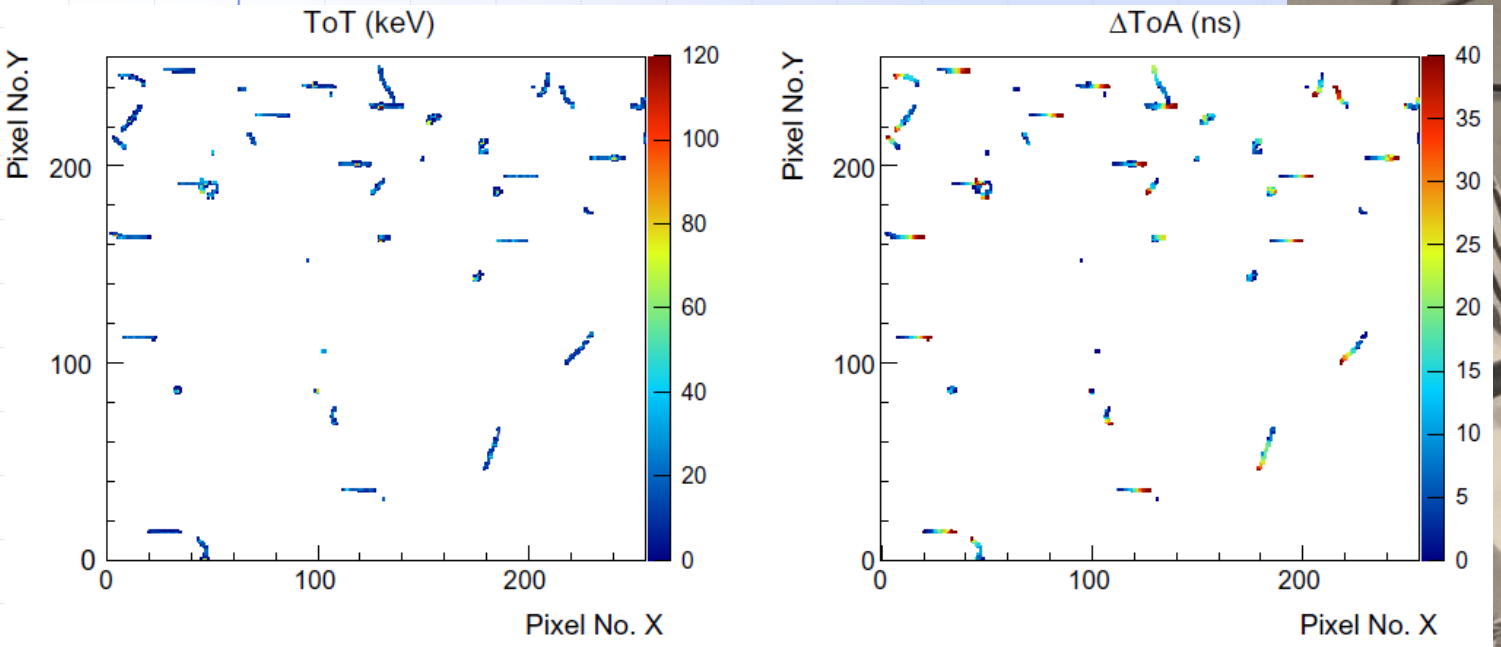
- The primary peak points back to IP8.

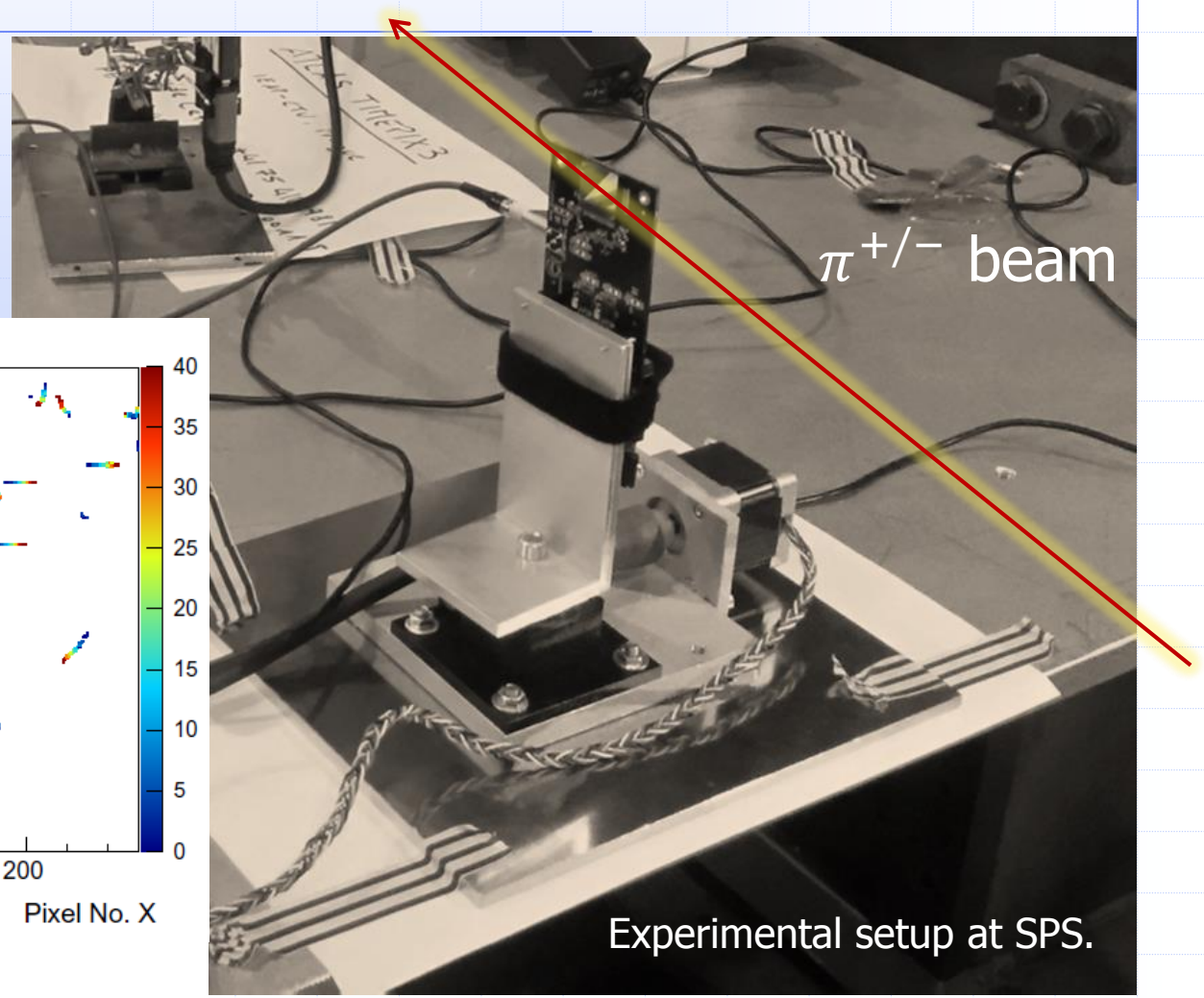
pp-collision period on September 24 (backprojection of the bin with the highest number of events).

Methodology verification and precision

Experiments:

- Pion test beams (120 GeV/c, 40 GeV/c) at the Super-Proton-Synchrotron at CERN
- Cosmic muons





Experimental setup at SPS.

"Raw data": Detector response in the form of 2D projections.
500 µm thick silicon

Test beam measurement (40 GeV/c pion beam):
2 mm thick CdTe sensor

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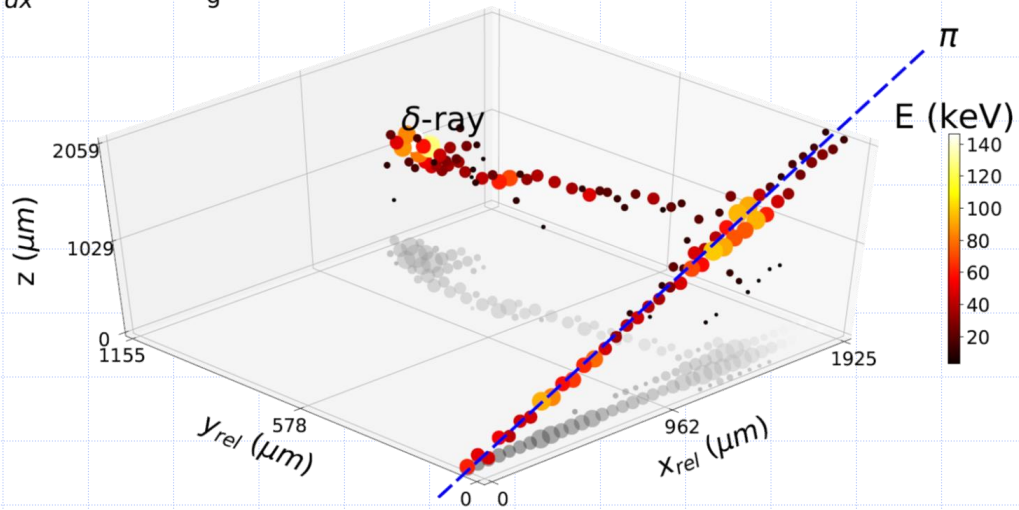
Charge collection efficiency correction:

Energy correction: $E_{corr.,i} = E_{meas,i}/\varepsilon_{cc}(z)$

$\varepsilon_{cc}(z)$ was determined in the measurement

$\frac{dE}{dx} = 2.71\ \frac{\mathrm{MeVcm^2}}{\mathrm{g}}$



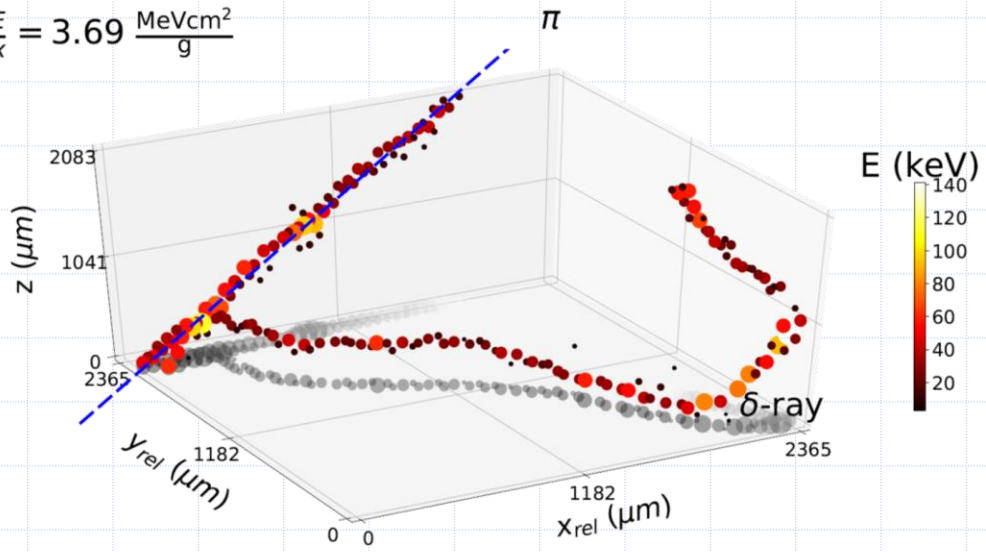
dE/dX determination:

Separation of δ-rays and initial tracks by Hough line detection (blue line)

→ Track length l_{track}

→ Stopping power: $\frac{dE}{dX} = \frac{\sum_i E_{corr.,i}}{l_{track} \times \rho_{CdTe}}$

$\frac{dE}{dx} = 3.69\ \frac{\mathrm{MeVcm^2}}{\mathrm{g}}$



Achieved z-resolution ~60 μm

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https://doi.org/10.1140/epjc/s10052-019-6673-z

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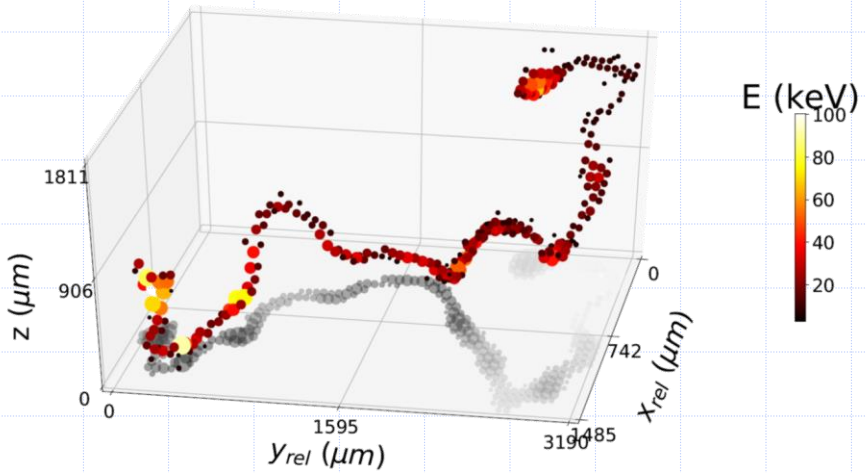
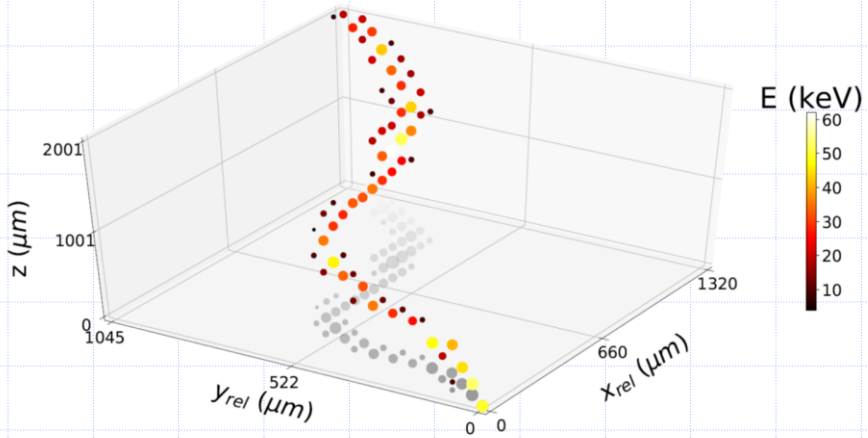
Test beam measurement (40 GeV/c pion beam):

2 mm thick CdTe sensor – $e^{-/+}$ like events

$E_{dep} = 5.66$ MeV

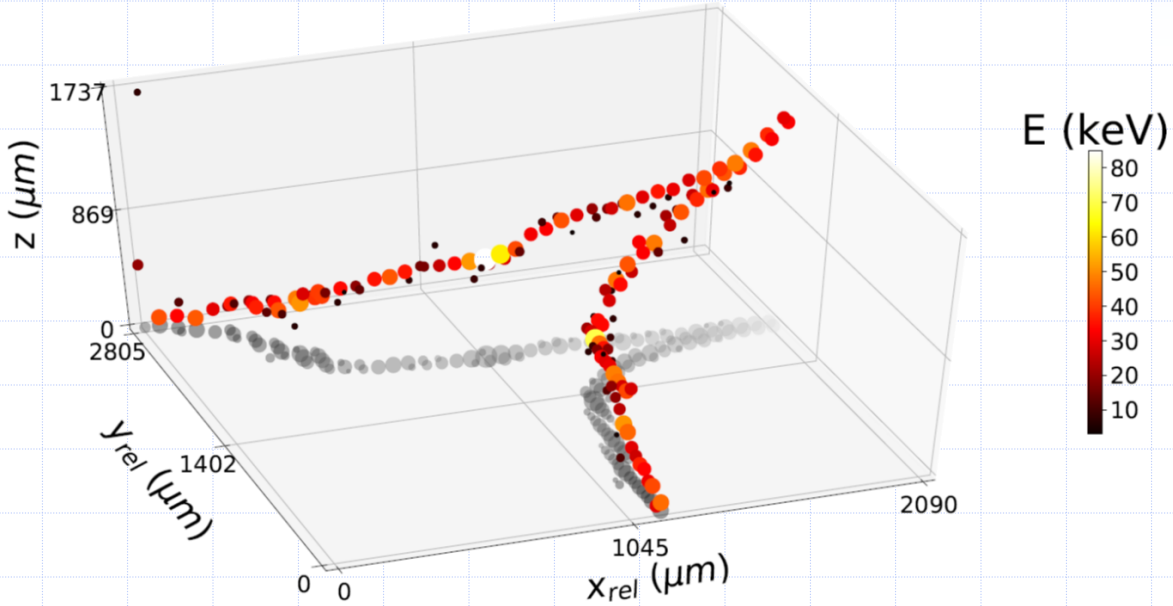


$E_{dep} = 1.56$ MeV



Pair-production (!?):

$E_{dep} = 3.96$ MeV



E_{dep}: Total energy deposition in the CdTe sensor layer.

Test beam measurement (40 GeV/c pion beam):
2 mm thick CdTe sensor – Fragmentation

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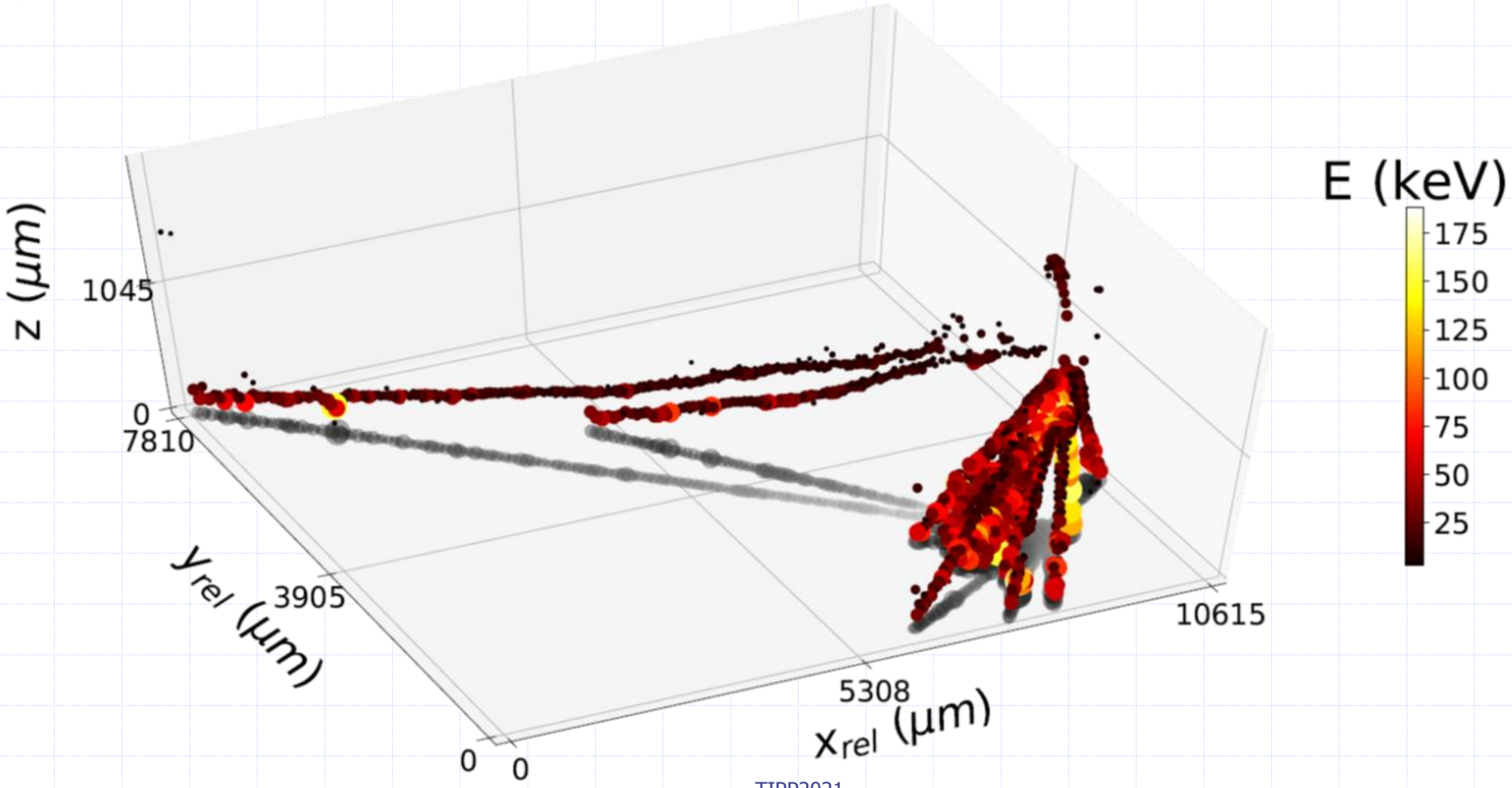
$E_{dep} = 37.06$ MeV



Impact and applications

- **Life-sciences:**
  - Single layer Compton camera (→ Search for γ radiation sources) [1]
  - Secondary particle tracking in hadron therapy
- **Space weather:**
  - Measurement and separation of e^-/p^+ (and their directions) in the Van-Allen Radiation belts [2]
  - Measurement of particles in Solar Particle Events
- **Applications in nuclear and particle physics**
  - Particle tracking and radiation field characterization (ATLAS, MoEDAL)
  - Vertex reconstruction and angular correlation measurements
  - Double beta decay experiments (?!) [3]

[1] D. Turecek et al., "Single layer Compton camera based on Timepix3 technology", JINST 15 C01014, 2020.
[2] St. Gohl et al., "Study of the radiation fields in LEO with the Space Application of Timepix Radiation Monitor (SATRAM)", Advances in Space Research, Volume 63, Issue 5, 2019.
[3] T. Michel et al., "The Potential of Hybrid Pixel Detectors in the Search for the Neutrinoless Double-Beta Decay of ^{116}Cd", Advances in High Energy Physics, Vol. 2013, Article ID 105318, 2013.