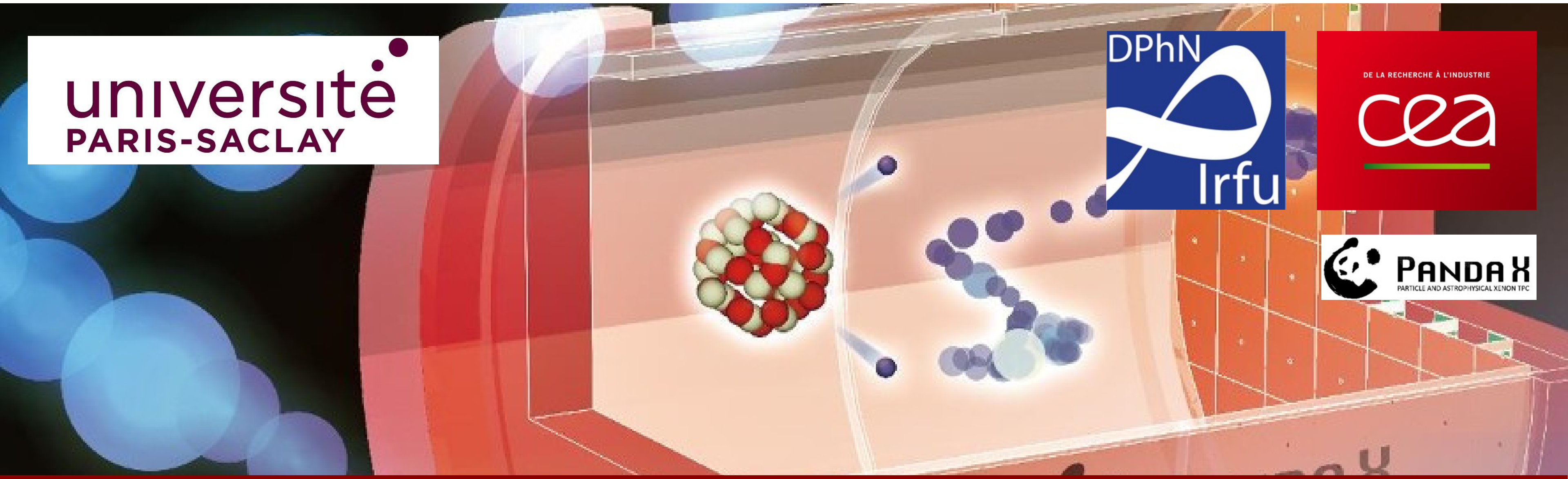


GDR Deep Underground Physics plenary meeting

Neutrinoless double-beta decay searches with Xe136-based PandaX-III experiment

Andrii Lobasenko

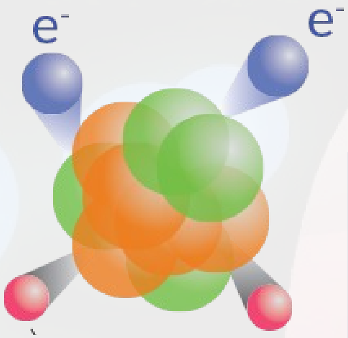
PandaX-III group, LSN, DPhN, IRFU, DRF, CEA
01.12.2021

Introduction

- $0\nu\beta\beta$ searches

➢ Neutrino is a Majorana particle? 0NDBD searches

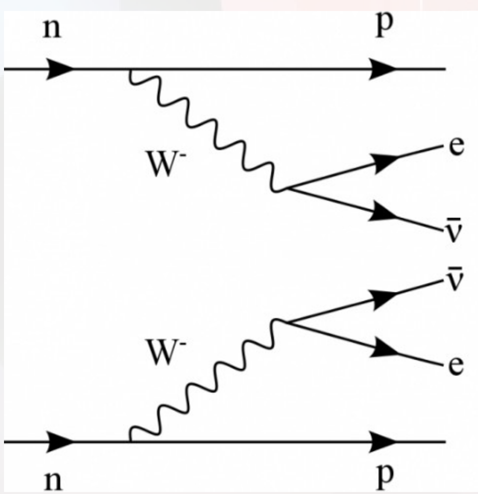
Double beta decay



$2\nu\beta\beta$

Experimentally observed in 11 isotopes

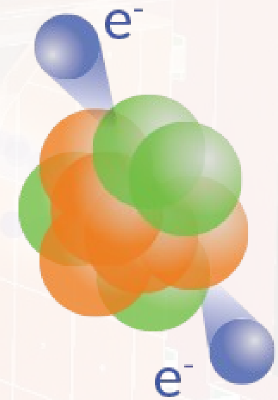
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$



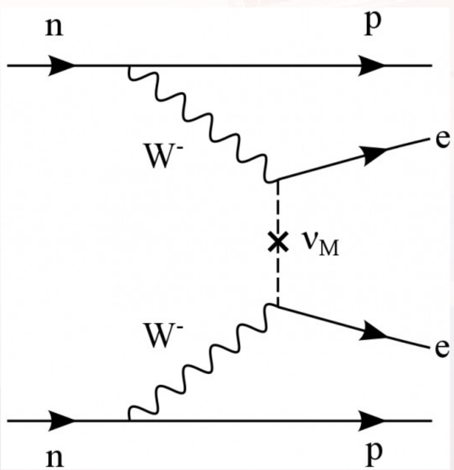
Neutrinoless double beta decay

$0\nu\beta\beta$

Never observed

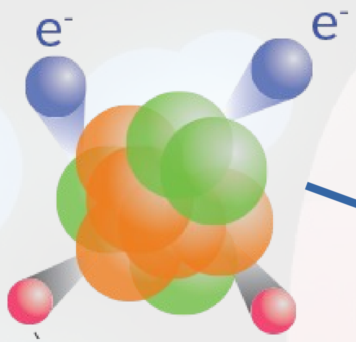


$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$



➢ Energy spectrum comparison

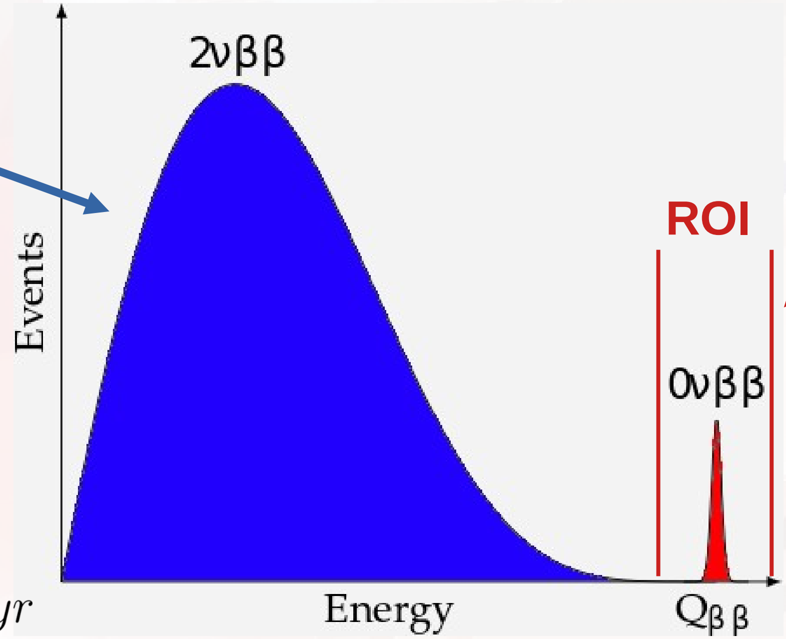
$2\nu\beta\beta$



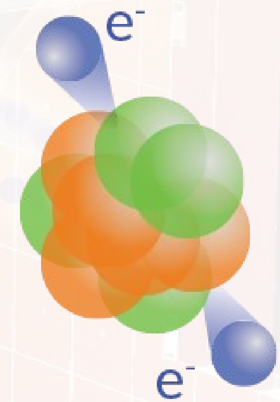
The rarest nuclear decay process!

$$T_{1/2}(2\nu\beta\beta) \sim 10^{18} - 10^{24}\ yr$$

Electron energy spectrum of $\beta\beta$ **decay**



$0\nu\beta\beta$



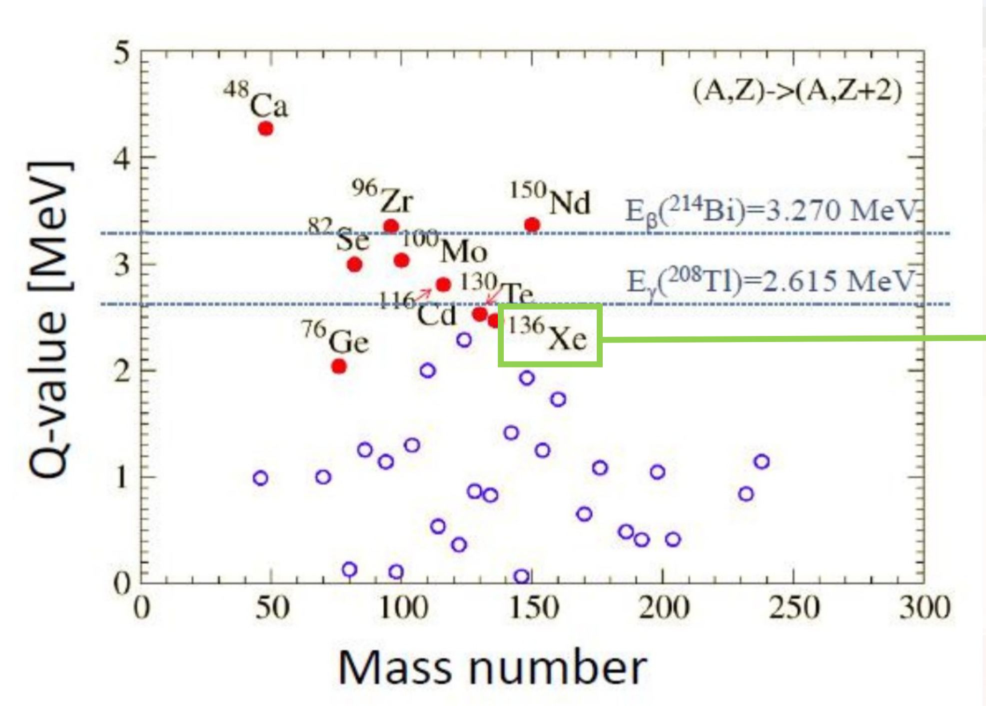
Expected half-life time of the $0\nu\beta\beta$ decay

$$T_{1/2} > 10^{25} yr$$

Decay rate for 1 ton-scale experiment: ~10 000 events/day

Decay rate for 1 ton-scale experiment: ~1 event/day

➢ Why we are using Xe136?



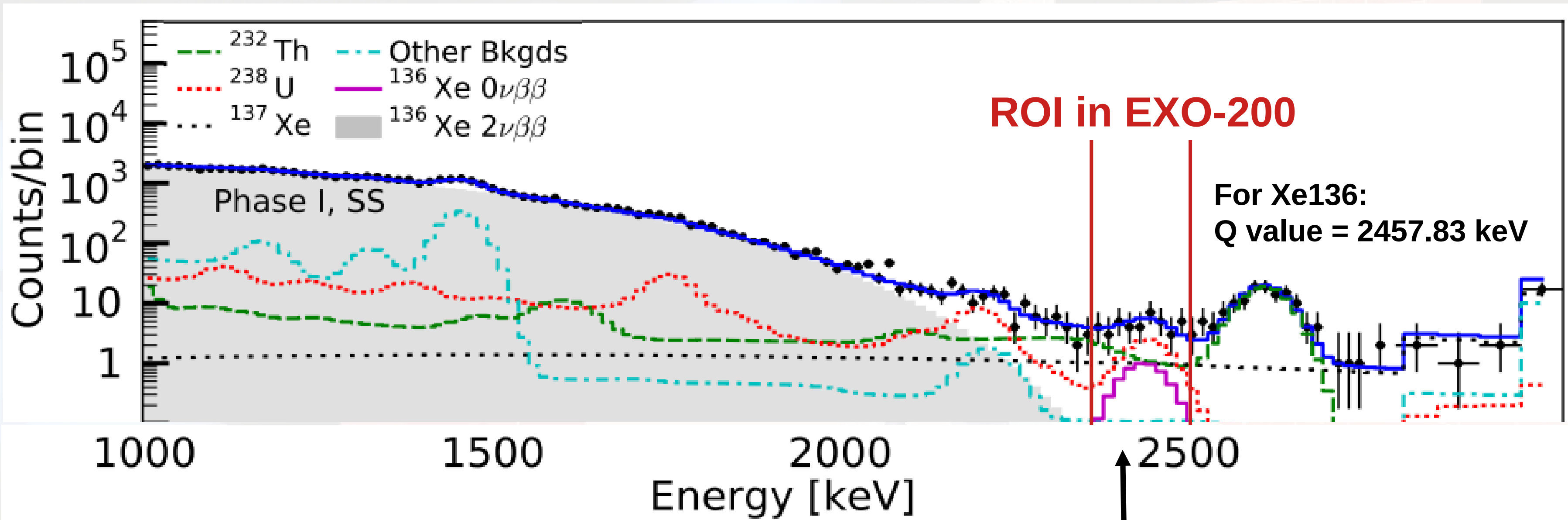
Xe-136:
Noble gas (gaseous amplification)
=> Can be used in TPCs

BUT!
Low Q-value:
Higher probability to have the bkg contamination

For Xe136:
Q value = 2457.83 keV

➢ Background contamination at Qbb value

EXO results (liquid Xenon detector)



PhysRevLett.123.161802, Search for $0\nu\beta\beta$ with the Complete EXO-200 Dataset

Discrimination of the bkg must be performed.

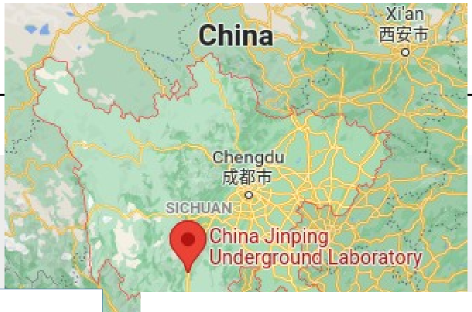
ROI is contaminated by the bkg:
U238 and **Th232** decay chains:

- 2448 keV gamma from **Bi214**
- 2615 keV gamma from **Tl208**

Introduction

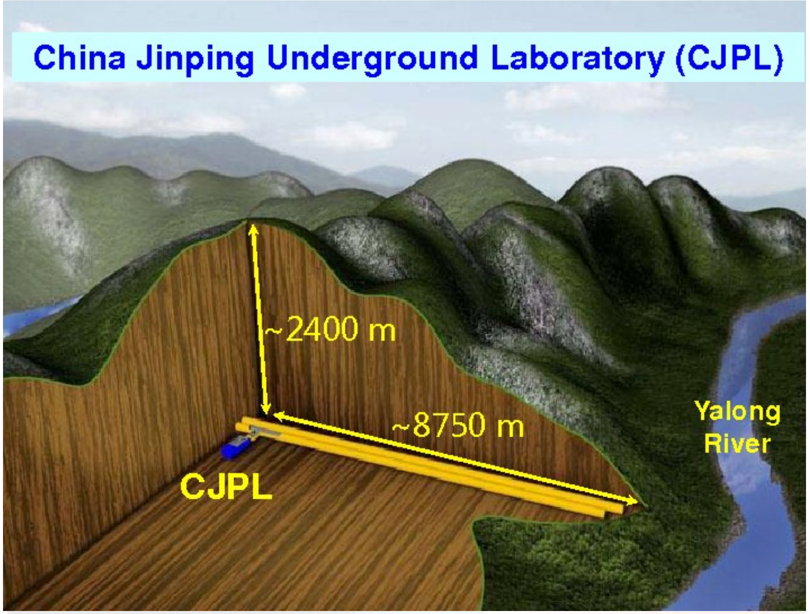
- PandaX-III experiment

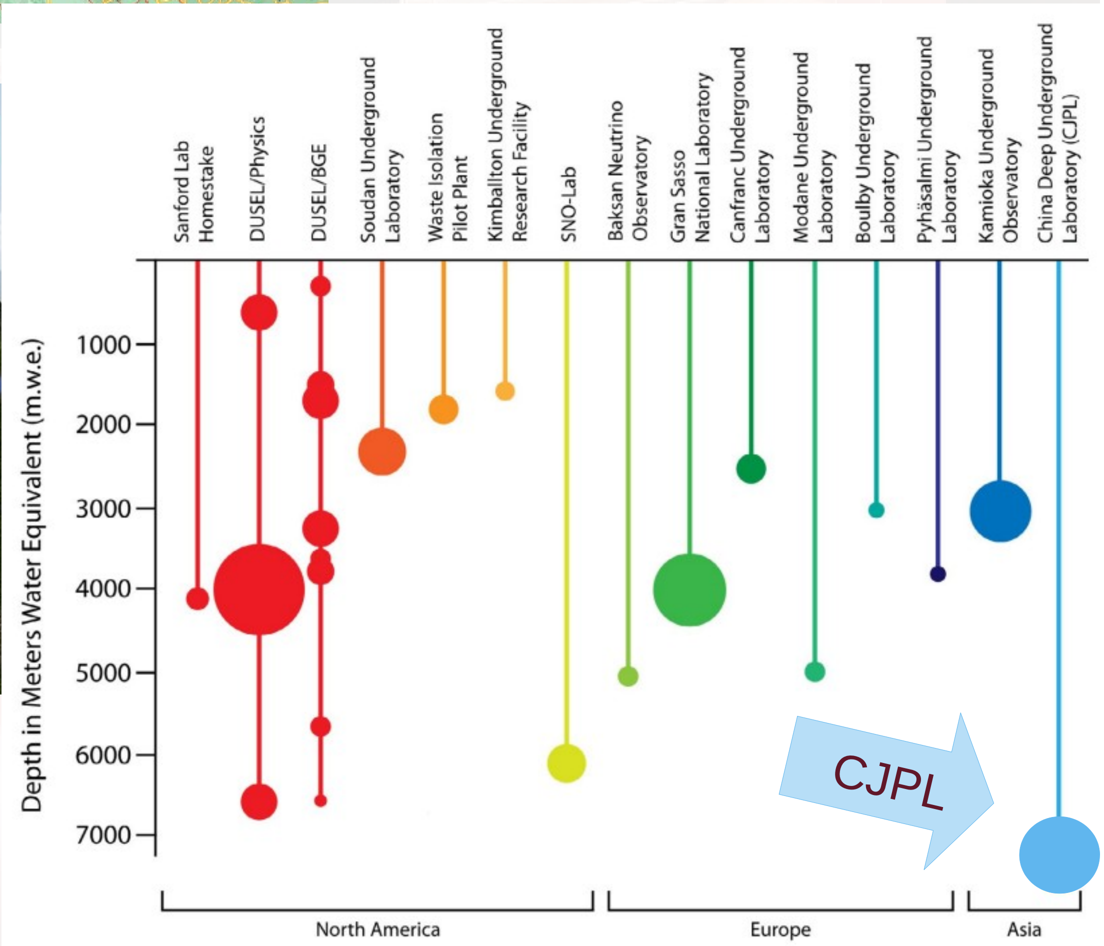
➢ CJPL laboratory



Reaching low bkg level:

Deepest underground laboratory

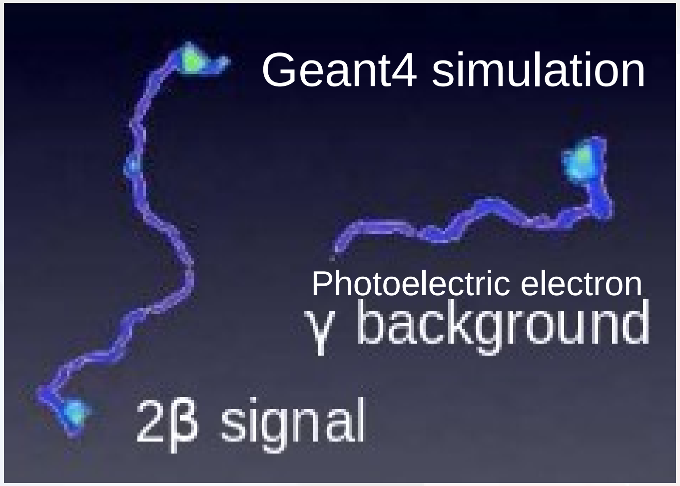




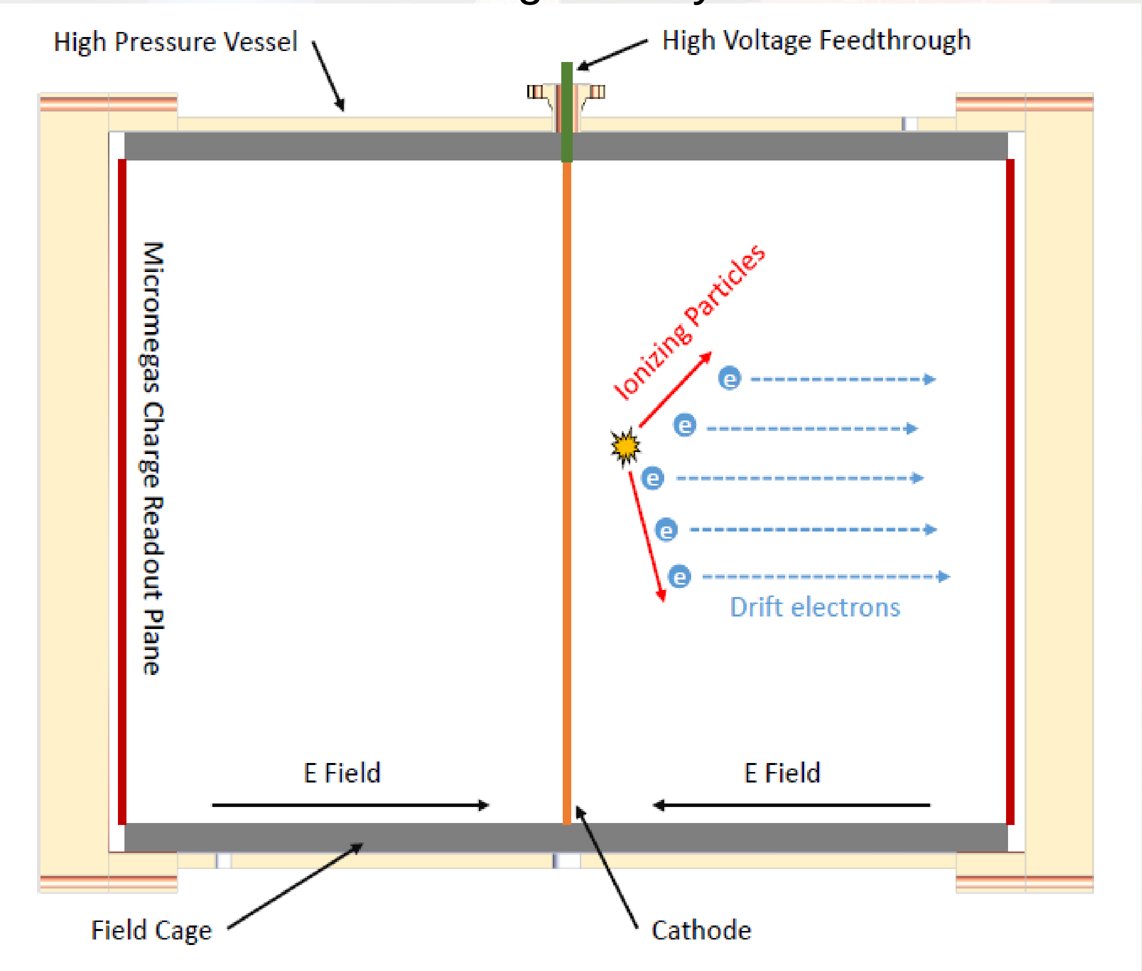
Reaching the cosmic **bkg level** to be **~1 cts/week/m^2**

An Assessment of the Deep Underground Science and Engineering Laboratory (DUSEL)

➢ TPC based experiment



Side view of the **Time projection chamber (TPC)** detector geometry



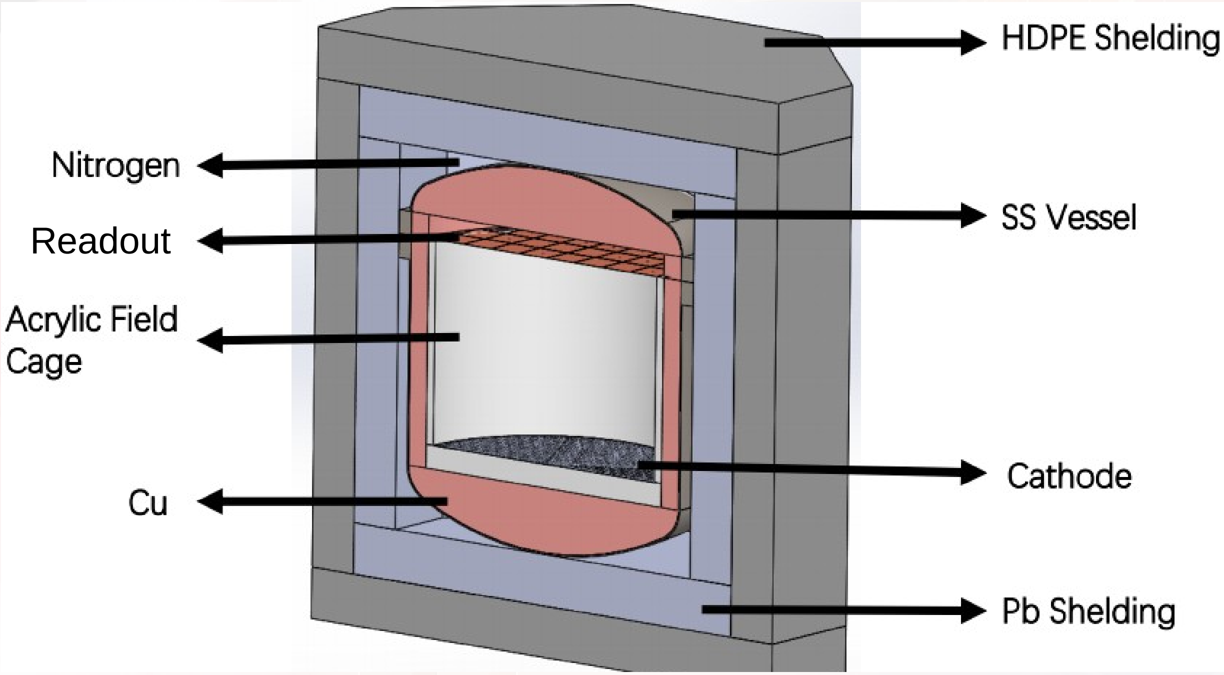
Output:
- **Reconstruction of the deposited energy**
- **Track topology reconstruction**

➢ PandaX-III 1-st Module setup

Reaching low bkg level, applying additional shielding

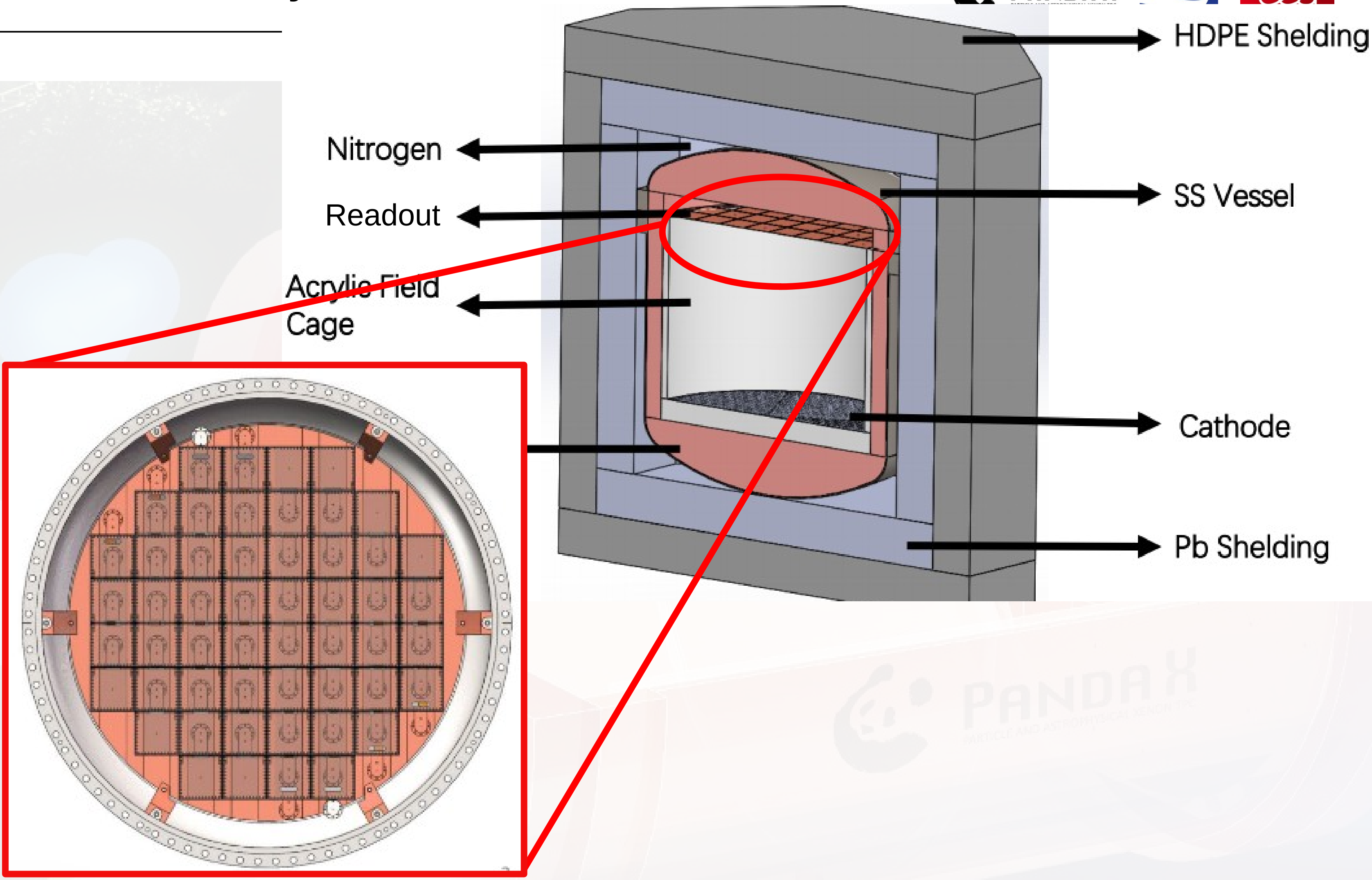
90% enriched Xe136 gas +1% TMA
Pressure: **10 bar**
Total gas mass: **140 kg**

PandaX-III TPC detector geometry



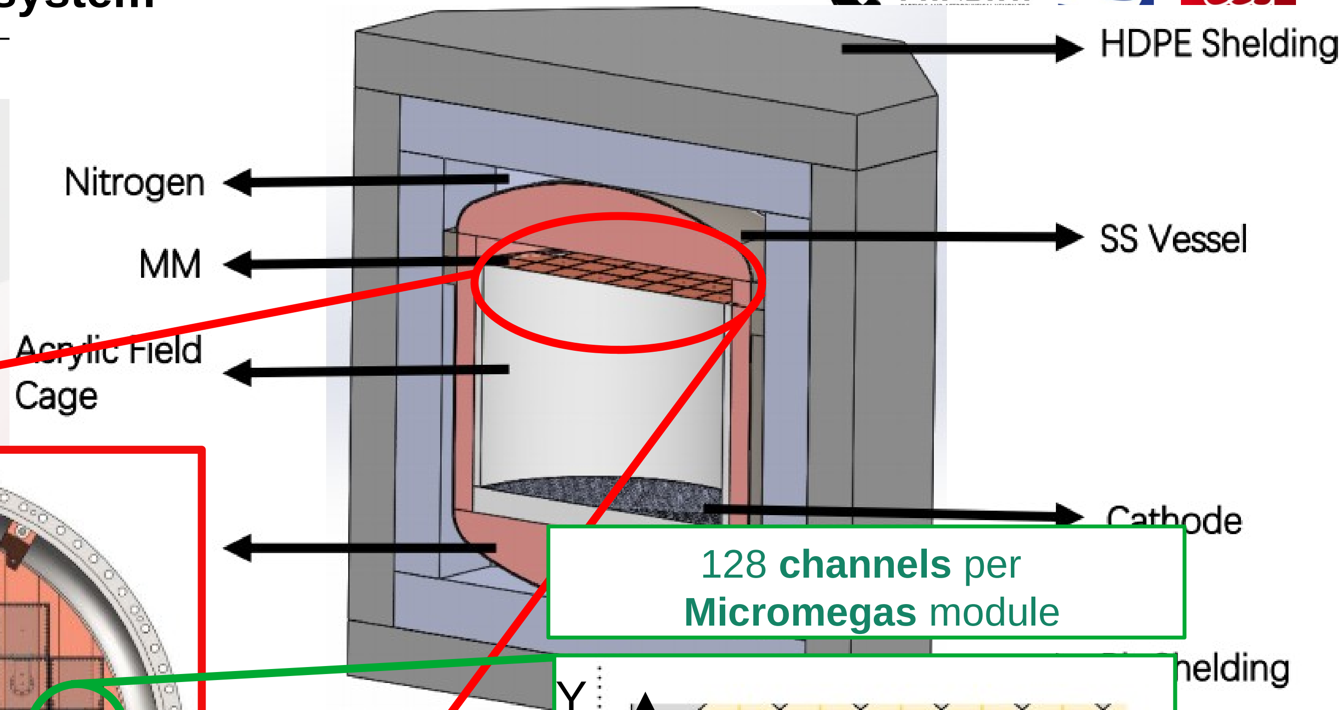
Bkg is suppressed from the surrounding contamination, leaving the irradiation from the electronics and Cu

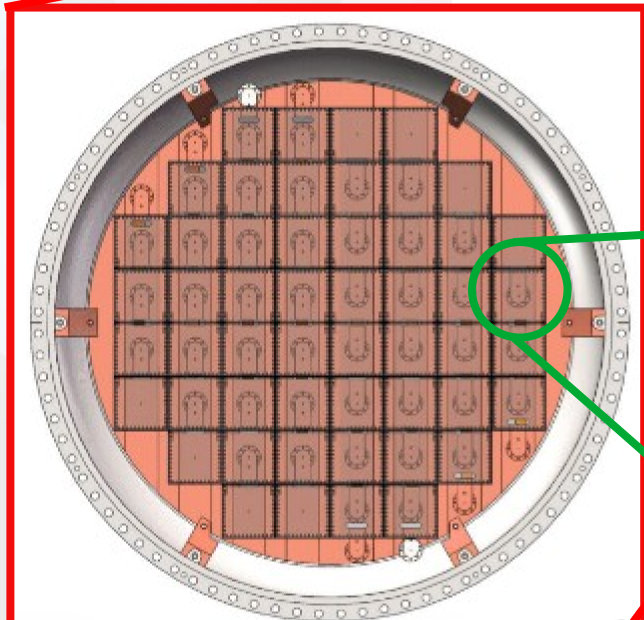
➢ PandaX-III Readout system



Readout Plane
(52 **Micromegas** modules)

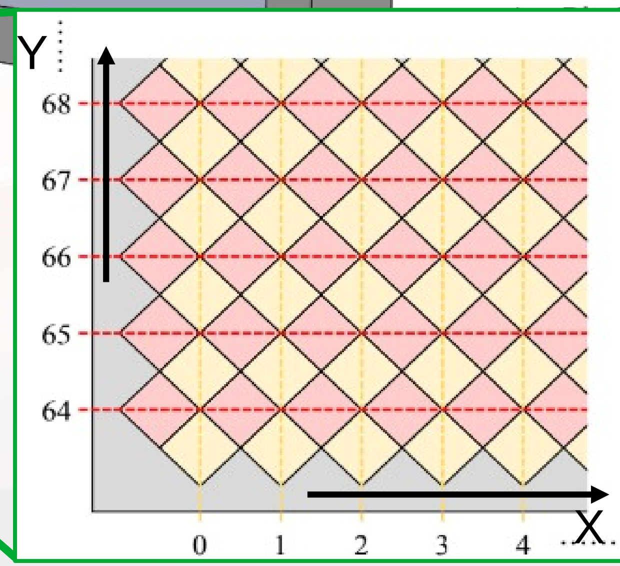
➢ PandaX-III Readout system





Readout Plane
(52 Micromegas modules)

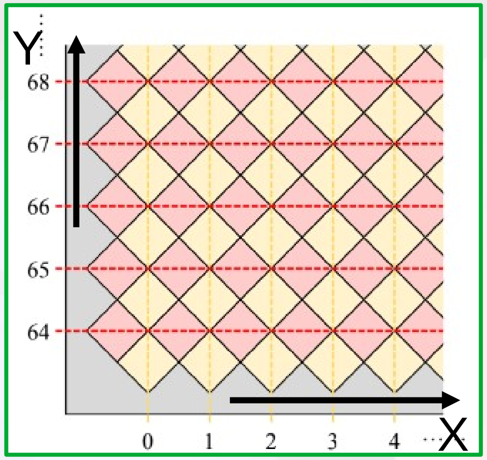
128 **channels** per
Micromegas module

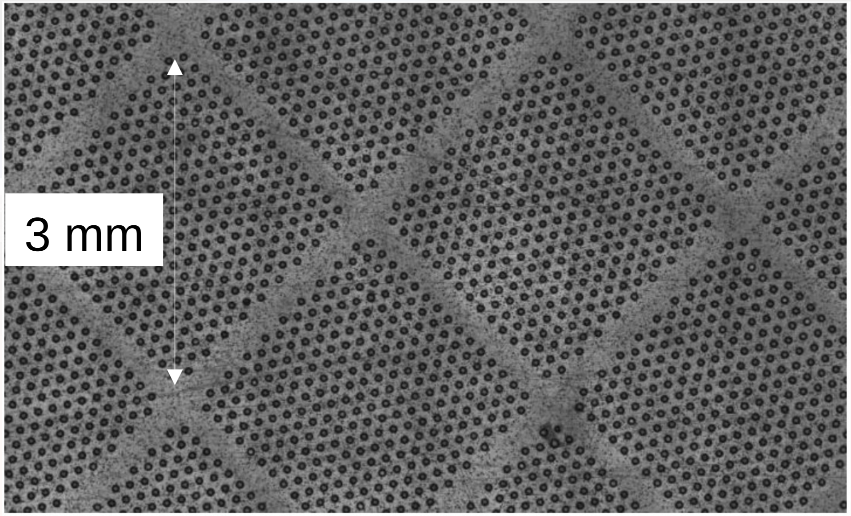


Dimentions: 20cm*20cm

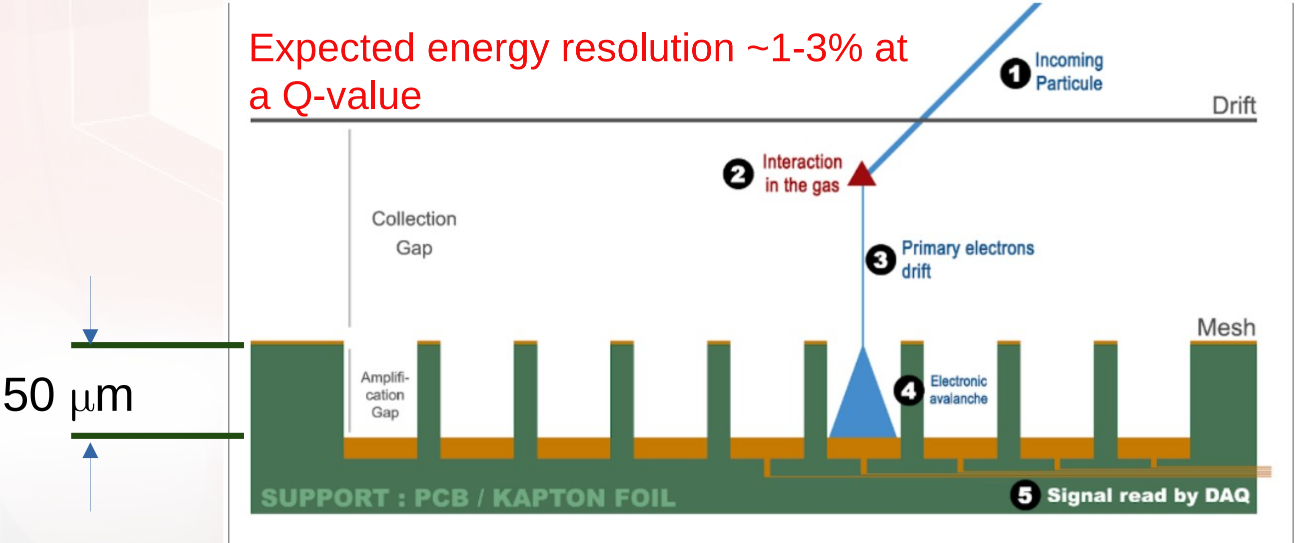
➢ Microbulk Micromegas work principle

128 **channels** per **Micromegas** module





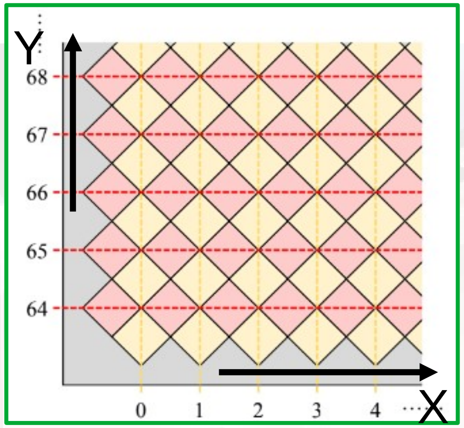
Expected energy resolution ~1-3% at a Q-value

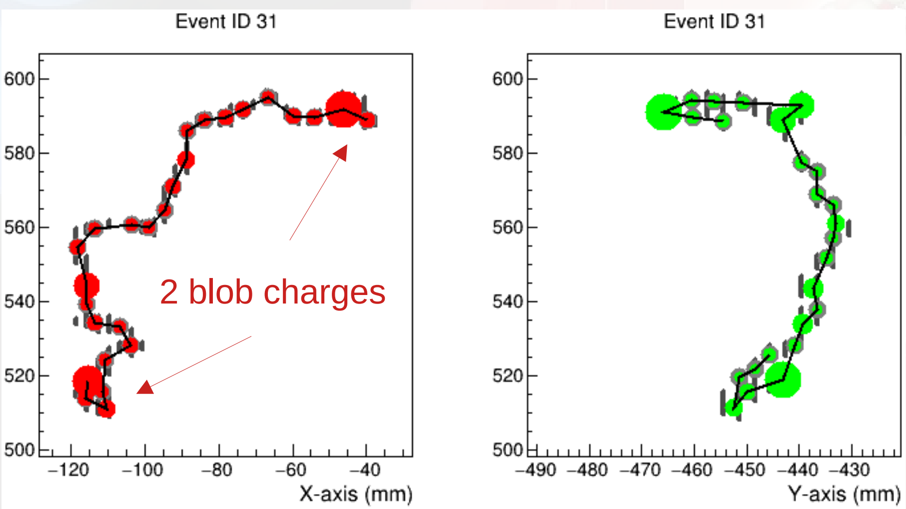


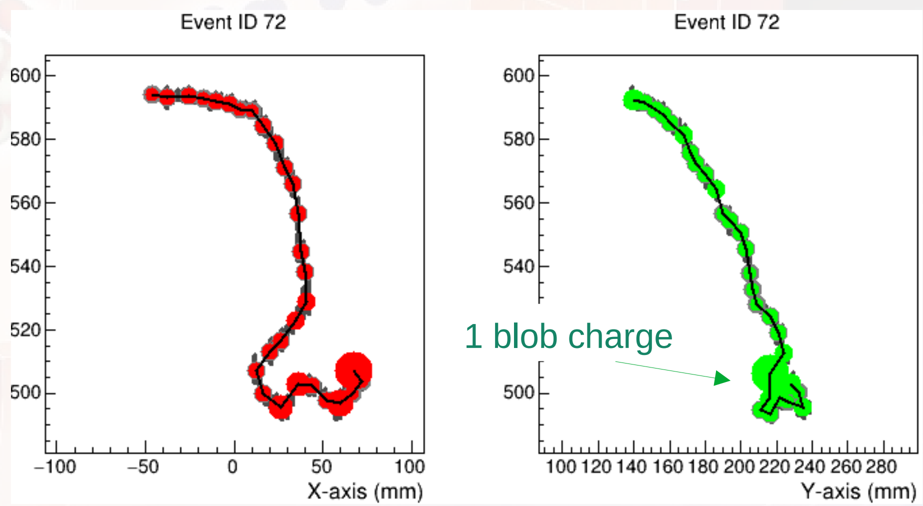
Schematic of a Microbulk Micromegas

Reconstruction output

From the reconstruction we obtain 2 projections: X/Y axis vs Time (Z axis)







$\beta\beta$ track

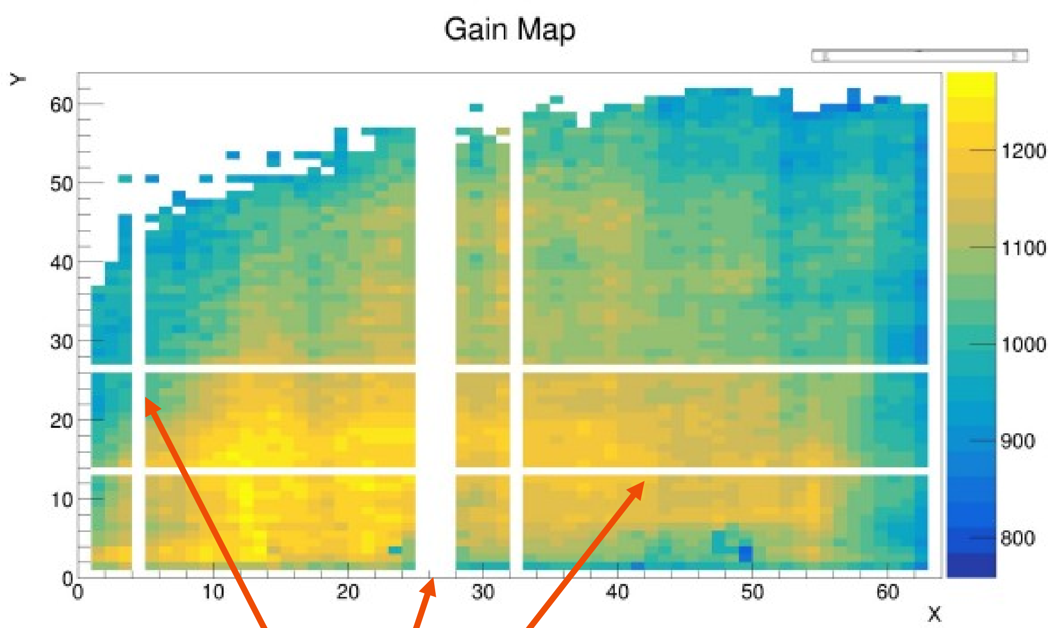
Gamma bkg
(of the same kinetic energy)

IMPORTANT TO RECONSTRUCT TRACK TOPOLOGY PROPERLY!

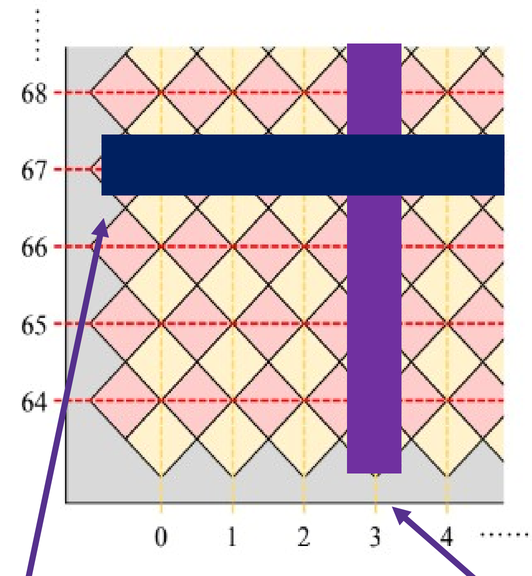
Missing Channels problem

➢ Missing channels problem

Gain map for one Micromegas module



Microbulk Micromegas module



Missing channels

Missing channels cause loss of information:

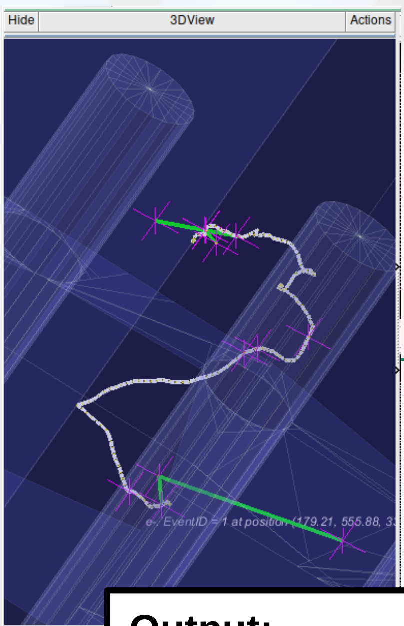
- Topology of the track
- Energy reconstruction loss

Missing Channels problem
-Simulations

➢ Simulations

Whole simulation and processing chain:

Monte-Carlo simulation
Done with **REST** environment

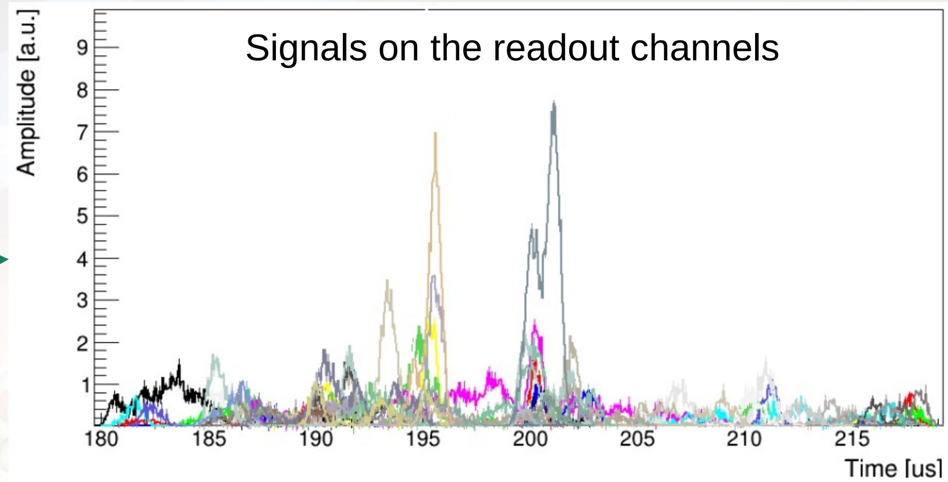


Simulation of the detector response

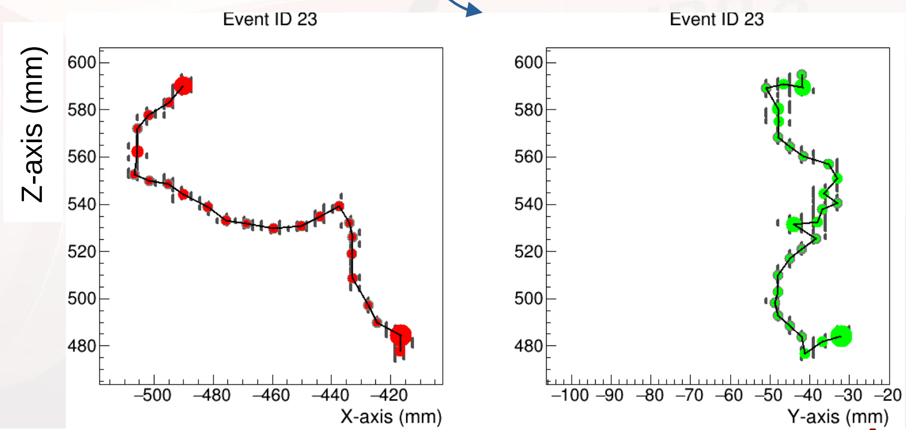
Electron diffusion, smearing, Signal shaping, etc.

Output:
- Total reconstructed energy of the track
- Track topology

Signal from the readout system



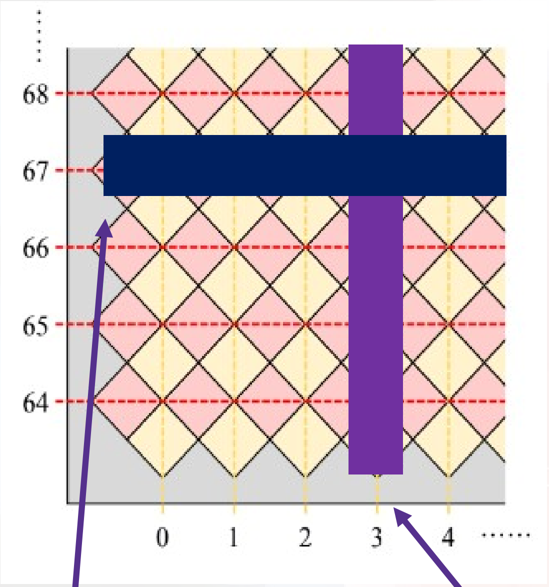
Track Reconstruction processing chain



Missing Channels problem
-Effect of missing channels

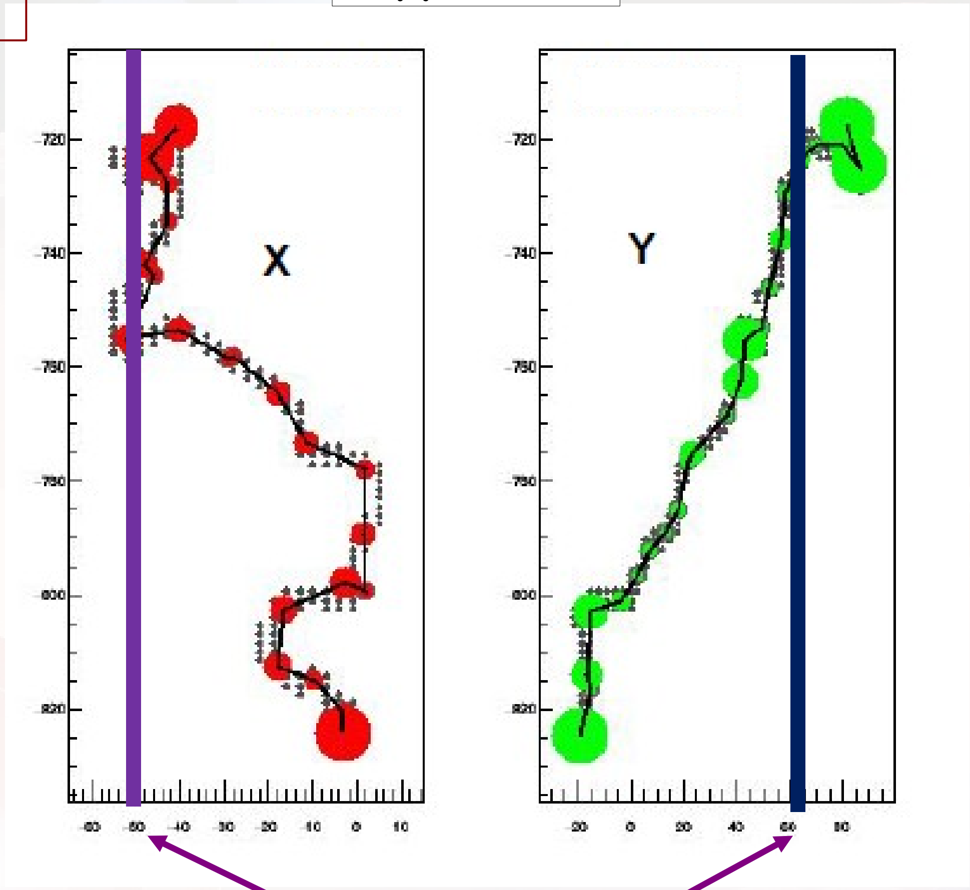
➢ Missing channels in the simulation

Microbulk Micromegas module



Missing channels

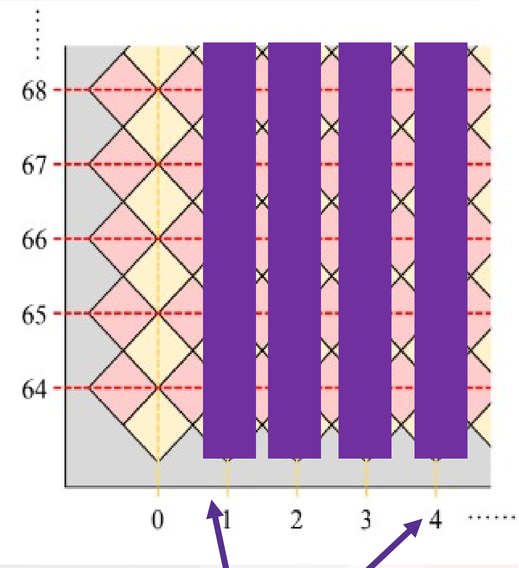
$0\nu\beta\beta$ event

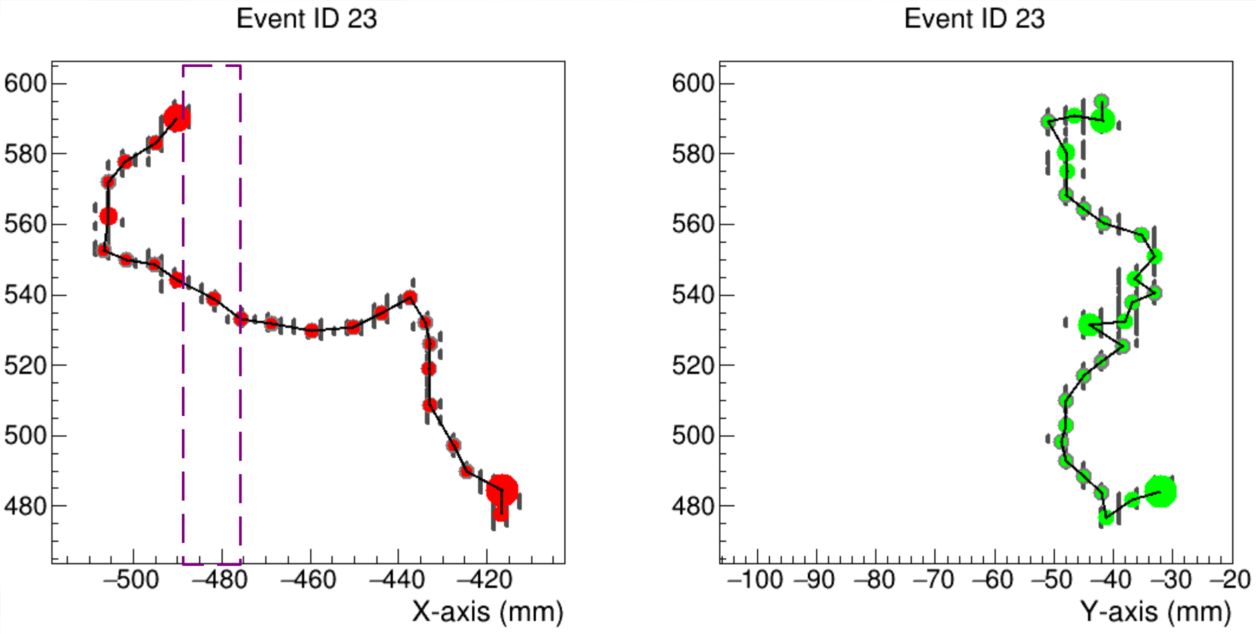


Due to missing channels
not all the energy of the event
would be measured

➢ Missing channels in the simulation

Microbulk Micromegas module



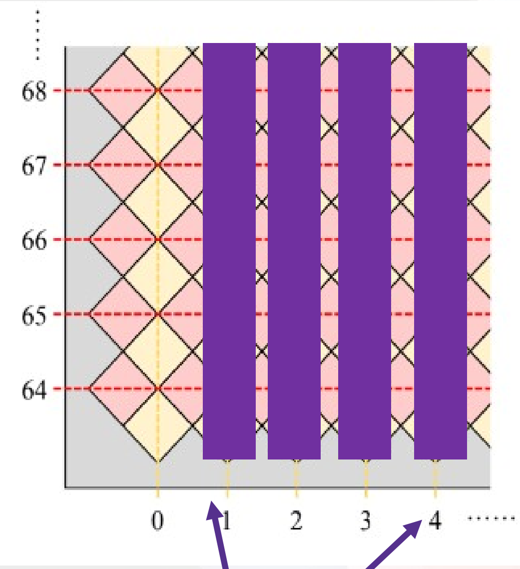


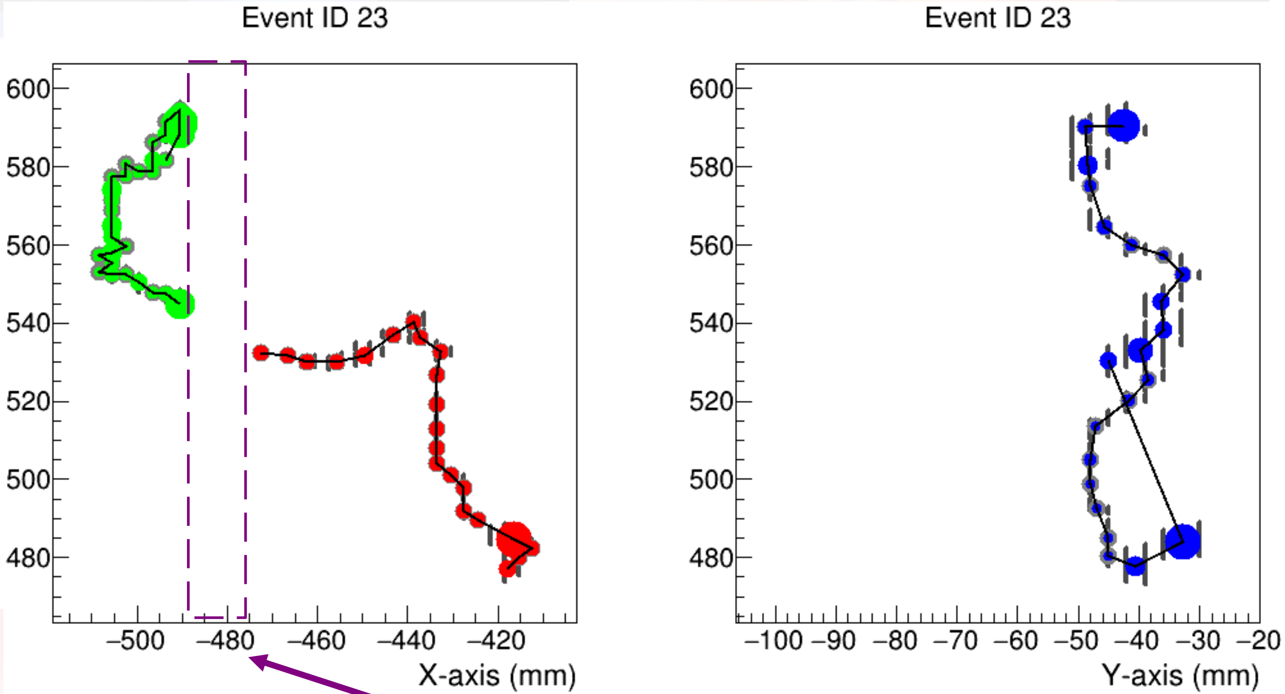
Consecutively missing channels

Reconstructed tracks without cut channels

Missing channels in the simulation

Microbulk Micromegas module





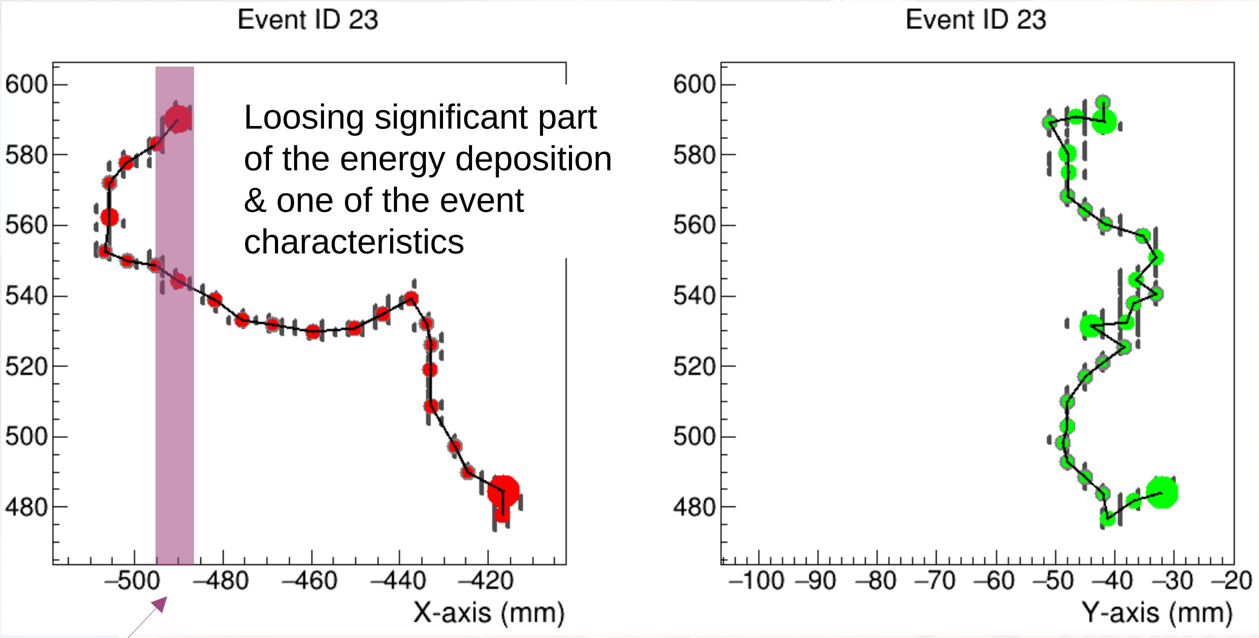
Consecutively missing channels

Consecutively cut strips may result in track separation

Impossible to analyze such Track event

Missing channels in the simulation

Missing channels resulting in loss of the Blob charge part



Due to consecutively missing channels

Correlation of Blob charges b/w XZ and YZ projections must be studied

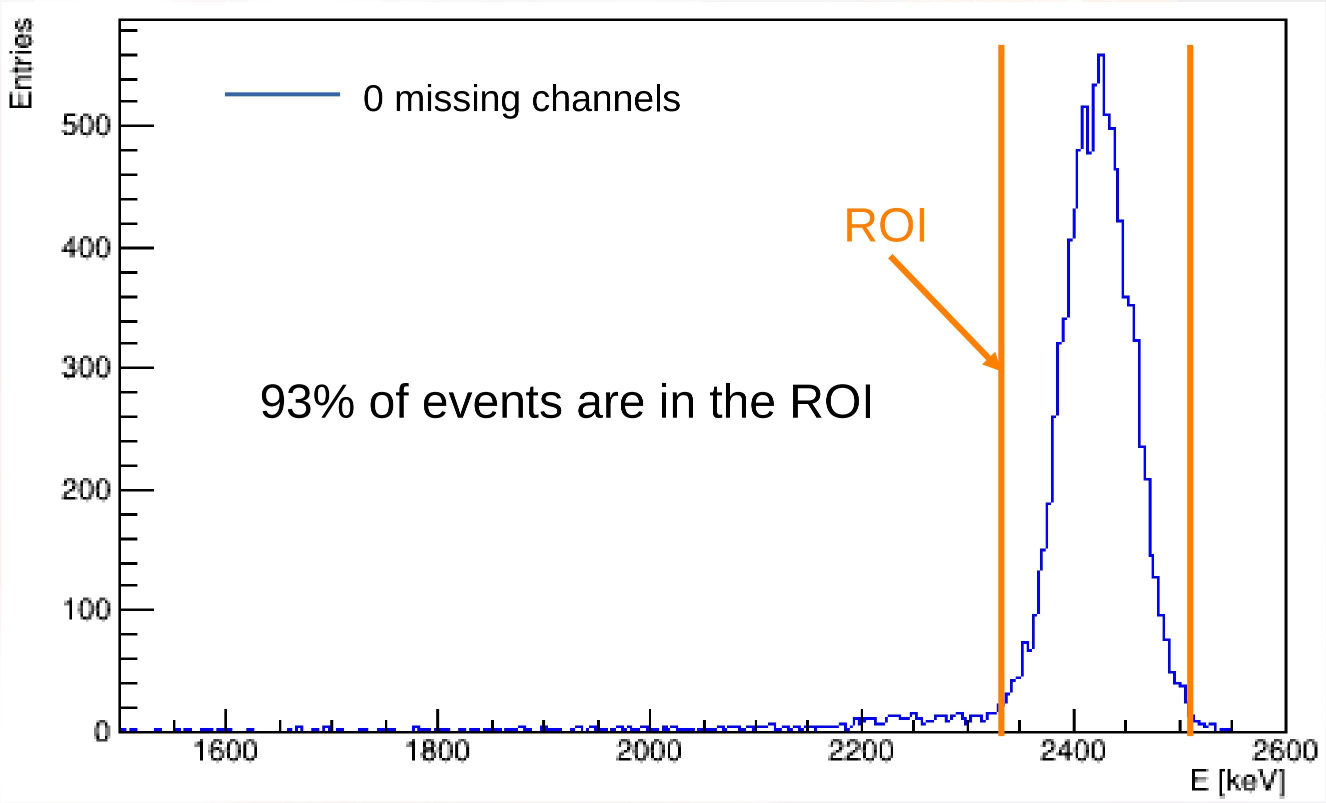
Effect of the missing channels on the energy spectrum

Without missing channels

Simulate:
~10 000 $0\nu\beta\beta$ events of Xe136.

Q value = 2454 keV
ROI : [2357, 2553] keV

Energy spectrum of the reconstructed $0\nu\beta\beta$ events



➢ Effect of the missing channels on the energy spectrum

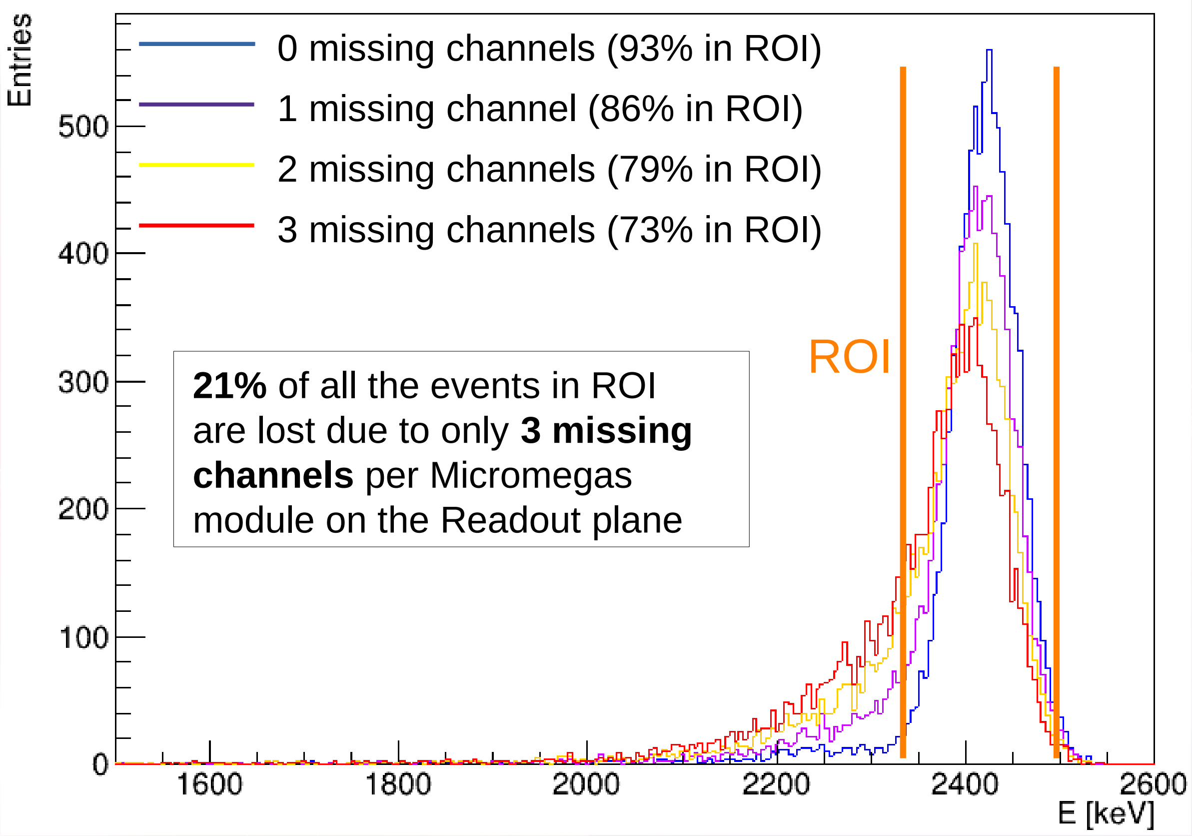
Without missing channels

Number of missing channels correspond to amount per Micromegas module!

Simulate:
~10 000 $0\nu\beta\beta$ events of Xe136.

Q value = 2454 keV
ROI : [2357, 2553] keV

Energy spectrum of the reconstructed $0\nu\beta\beta$ events

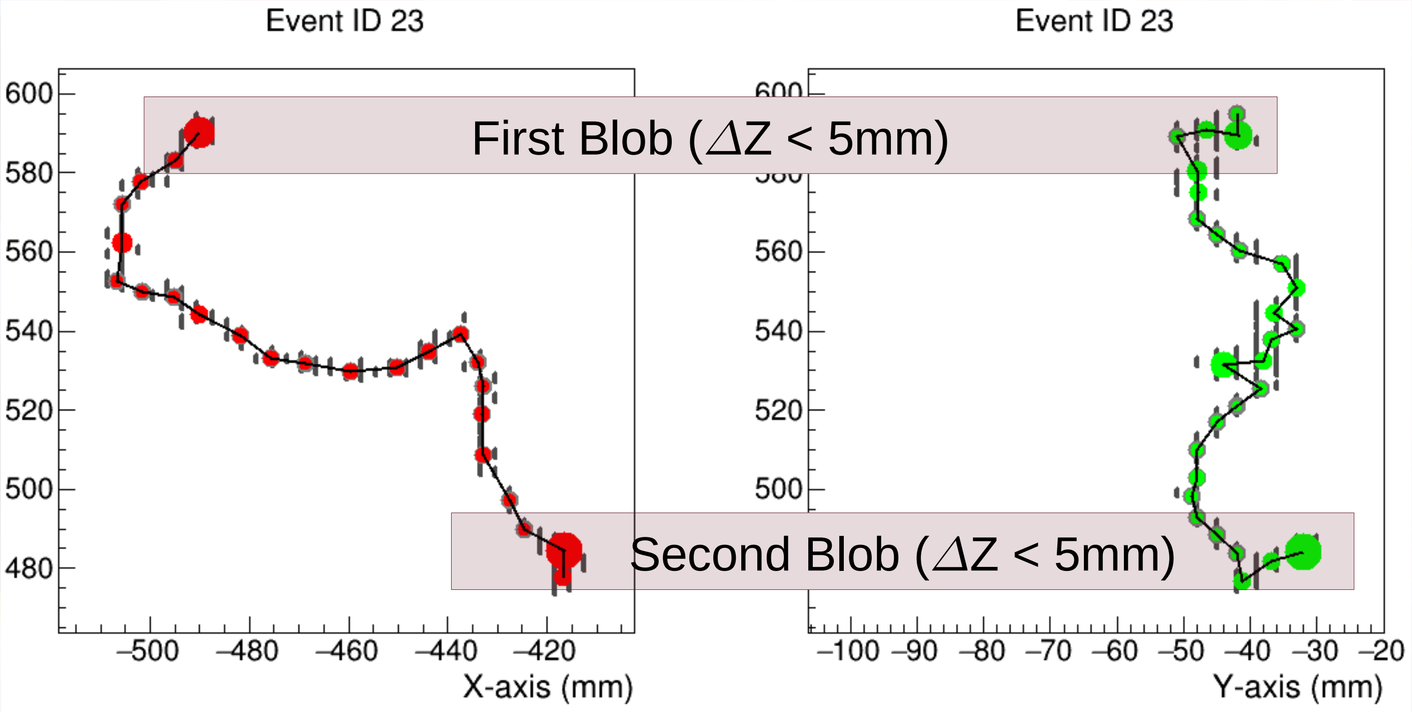


Missing Channels problem -Analysis

➢ Blob charge analysis

Approximation of the lost Blob charge information from the second projection → Study of the Blob charge energy correlation

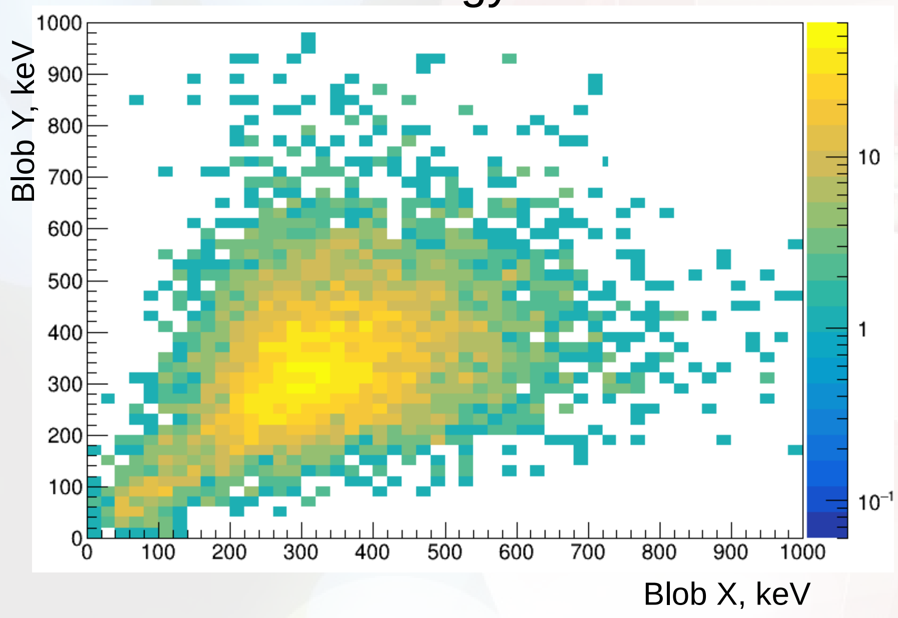
Looking for the 1st most energetic one at the end of the track and the 2d most energetic one on the other end of the track



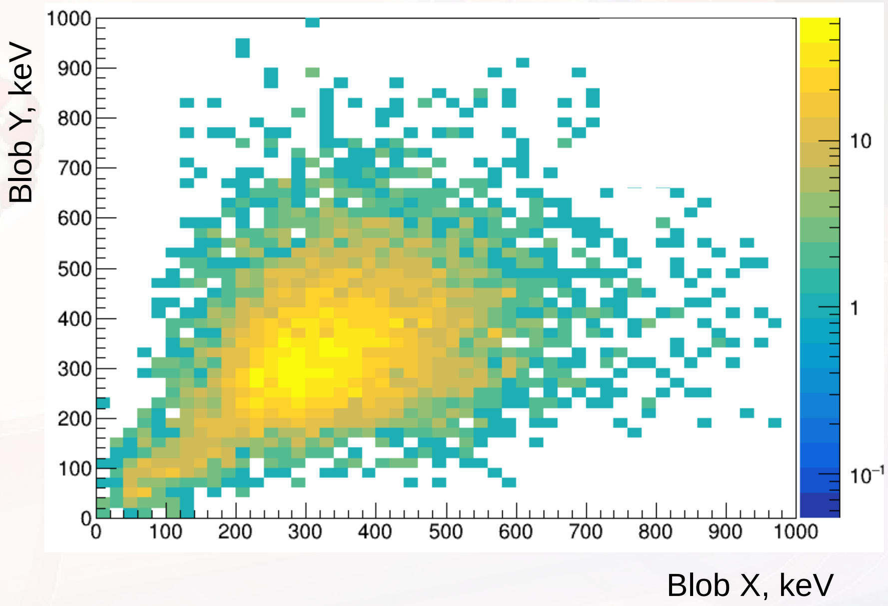
Blob charge analysis

Approximation of the lost Blob charge information from the second projection → Study of the Blob charge energy correlation

First Blob energy correlation

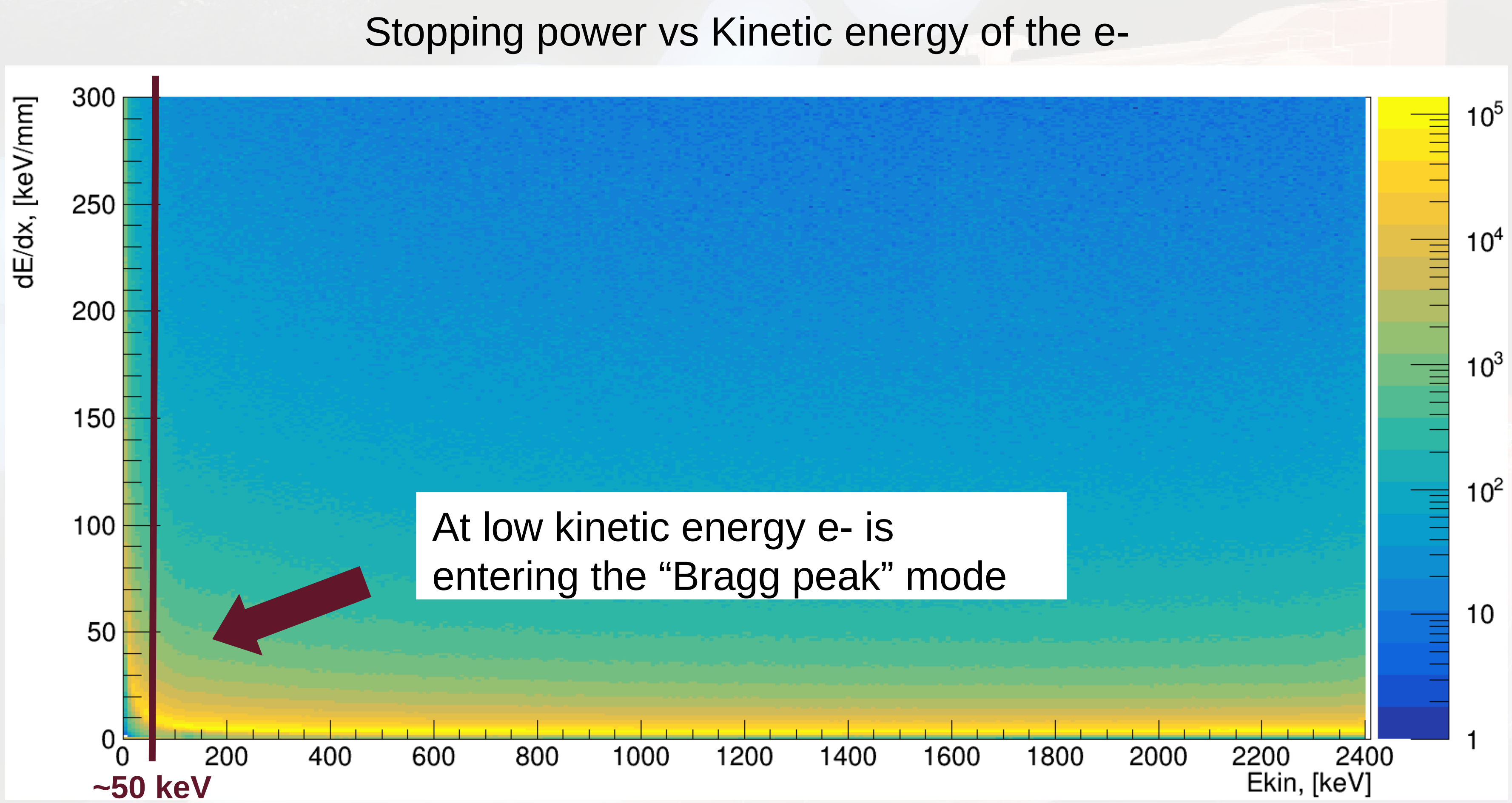


Second Blob energy correlation



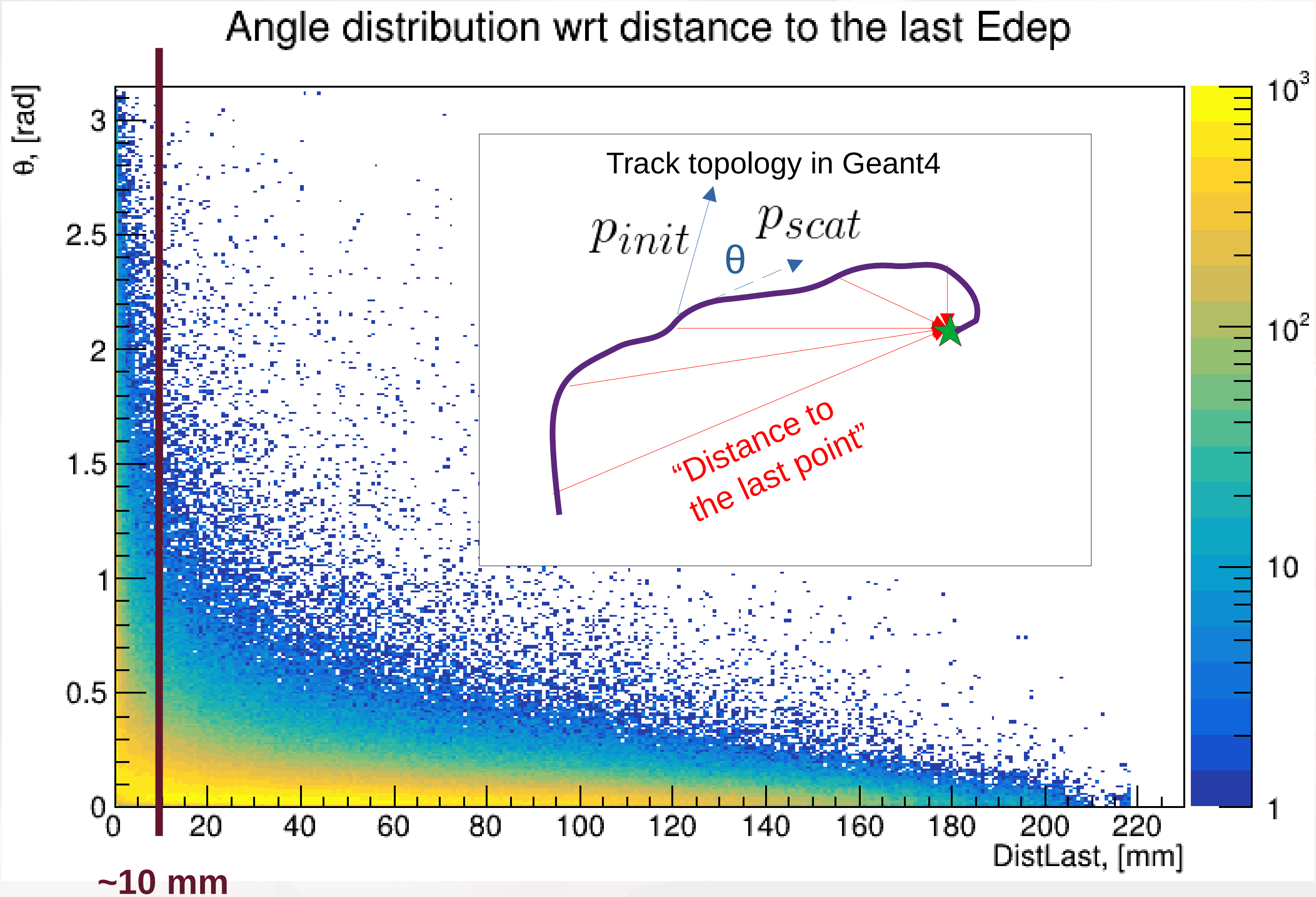
Better determination of the Blob charge deposition → Study of the correlation b/w E deposition and Scattering angle θ

➢ Relative energy deposition wrt Kinetic energy of the e-



➢ Study of the distribution of the scattering angle

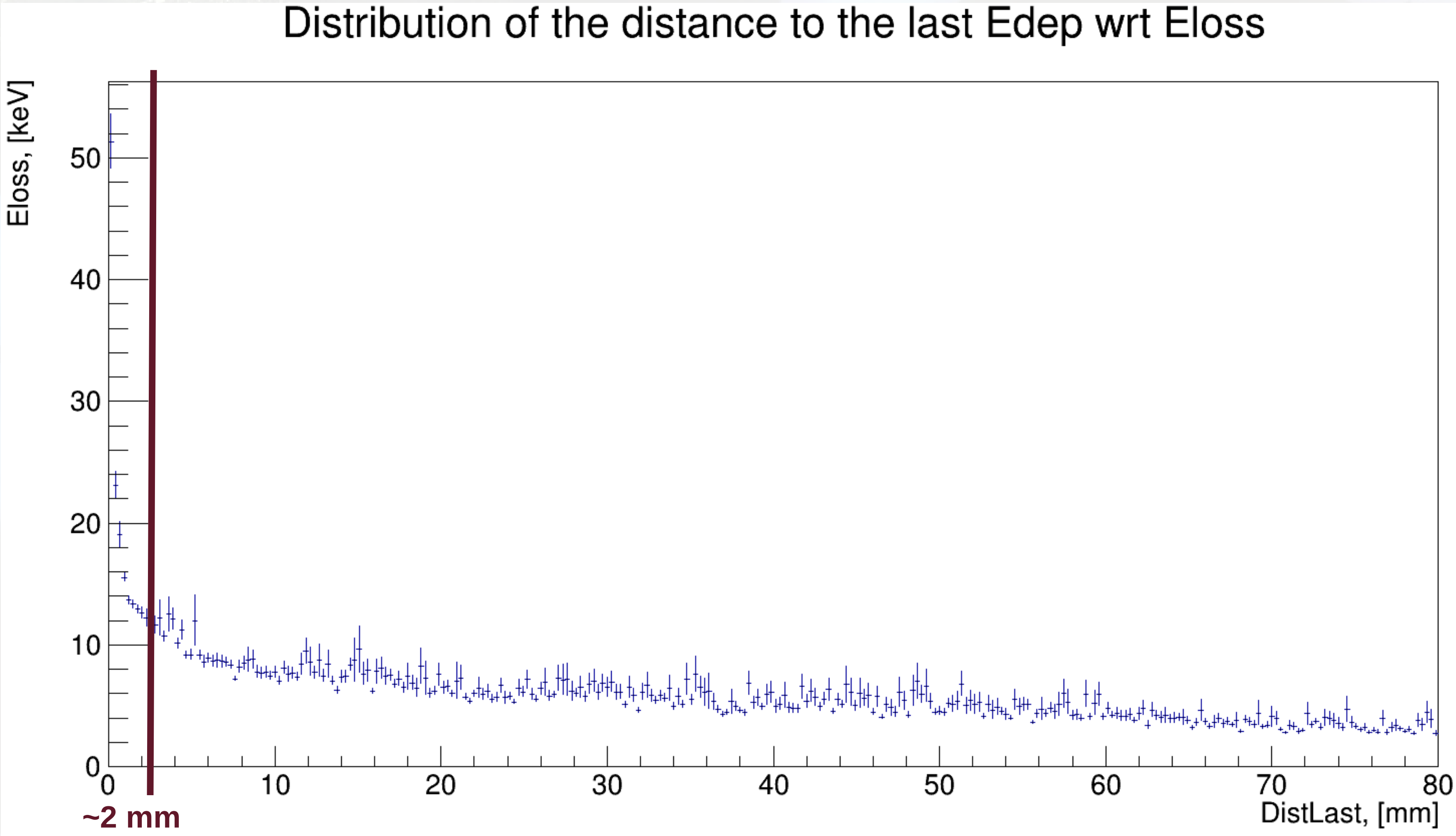
Distribution of the scattering angle θ of the e- wrt distance to the last point of the track topology



~10 mm

In range of ~10mm to the last point the angular distribution becomes wider

➢ Study of the distance to the last track point



Energy deposition drastically increases at ~2mm to the last point of the track

➢ Further prospects

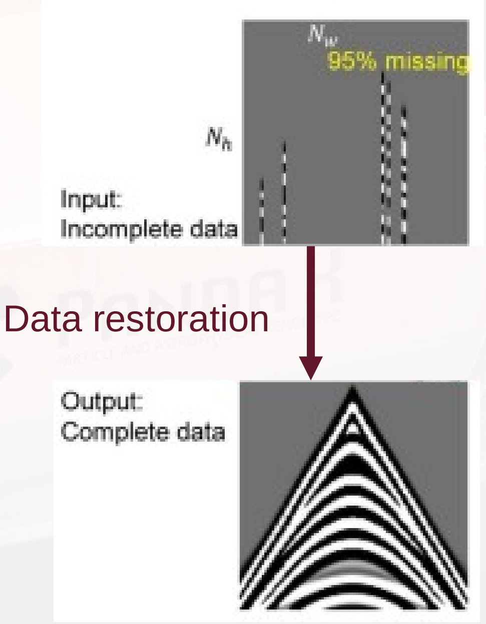
TO DO:

- Finish the study of the energy deposition correlation wrt scattering angle θ and distance to the last track point

- Implementation of the analytical approach to the lost data restoration

- **U-Net**
- (Convolutional Neural Network architecture)

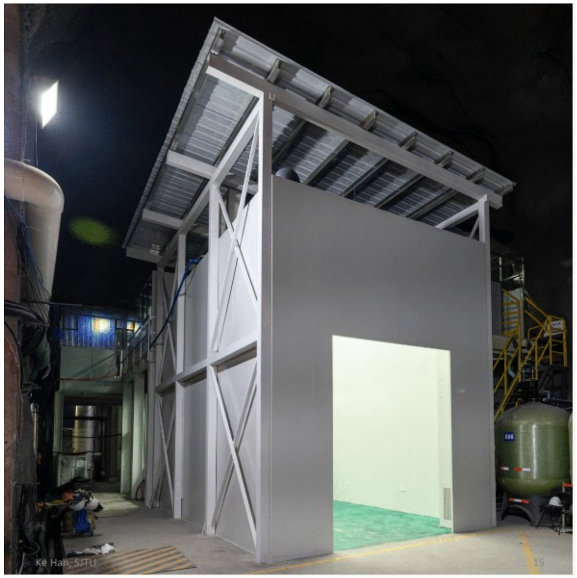
Deep learning for irregularly and regularly missing data reconstruction. Sci Rep 10, 3302 (2020)



➡ Data preprocessing is needed for treatment with ML techniques

➢ Further prospects

Full vessel: low background SS, 4 m^3 inner volume



Experimental hall at Jinping laboratory almost ready

TPC vessel produced, production of shielding ongoing

Commissioning of the first TPC module expected last trimester of 2022

Study ongoing on thermal-bonded Micromegas detectors to replace Microbulk ones

Conclusions

- **Main idea of 0NDBD searches**

- **Missing channels drastically decrease detection efficiency of the $0\nu\beta\beta$.**
- We could have 1-3 missing channels per module in the real experiment(worst case scenario → we can't accept detectors with higher number of missing channels):
- **20-25% of true events** would not be registered.

- Data analysis and preprocessing for further implementation of the reconstruction techniques is ongoing

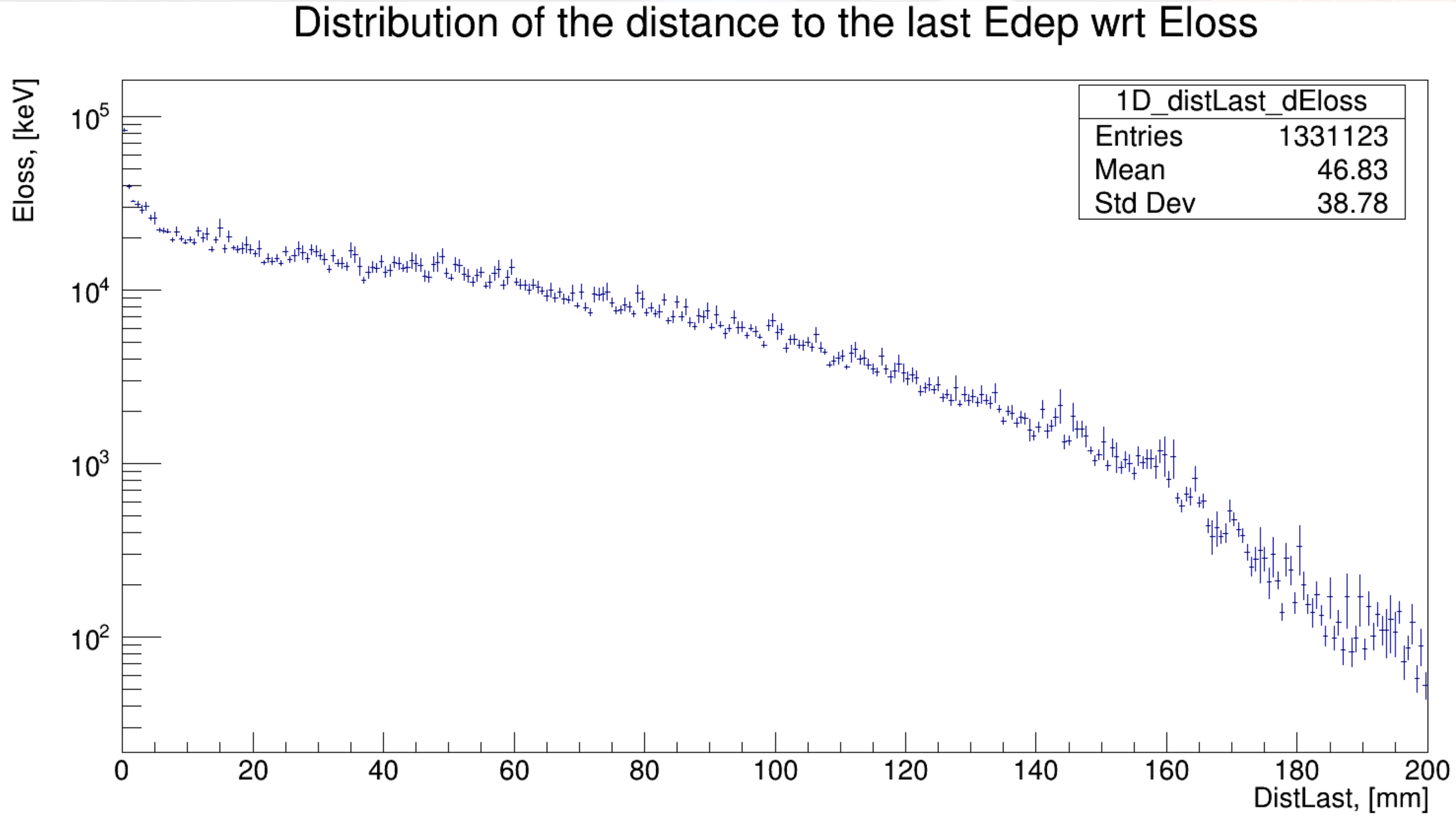
Prospects:

Further study on track topology

ML techniques will be studied to improve the data reconstruction

Thank you

1. Introduction
   1. 0??? searches
   2. PandaX-III experiment
2. Missing channels problem
   1. Simulation introduction
   2. Effect of missing channels
   3. Analysis
3. Conclusions


Distribution of the distance to the last Edep wrt Eloss
1D_distLast_dEloss
Entries 1331123
Mean 46.83
Std Dev 38.78
Eloss, [keV]
DistLast, [mm]
0
20
40
60
80
100
120
140
160
180
200

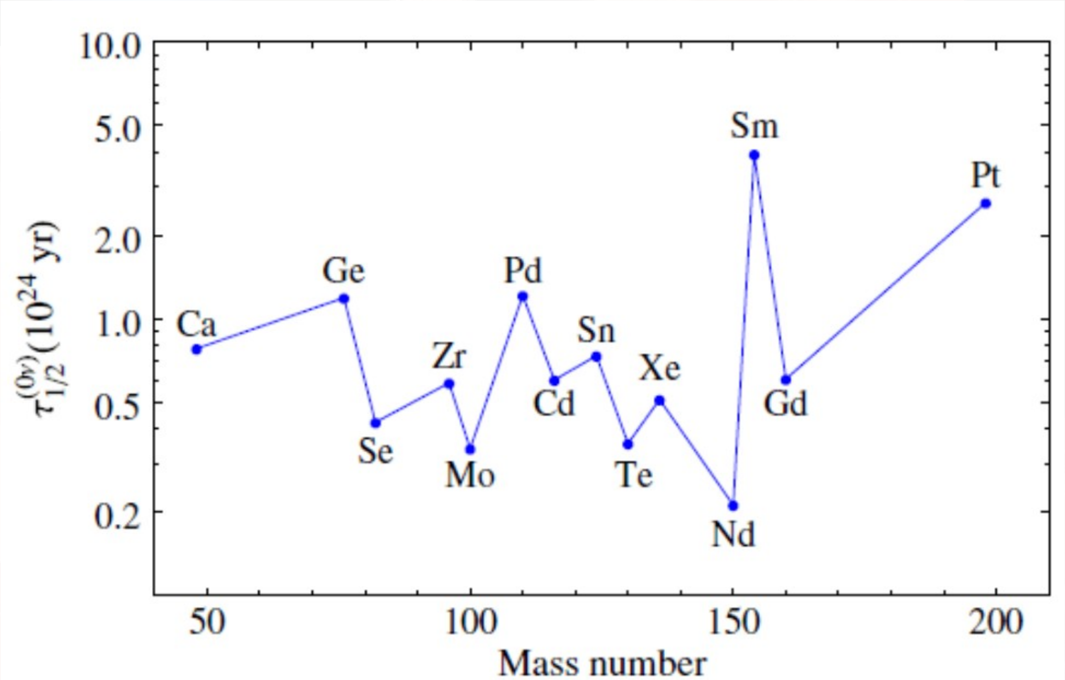
0NDBD searches

Why are we using Xe136?

Decays with 2nbb mode

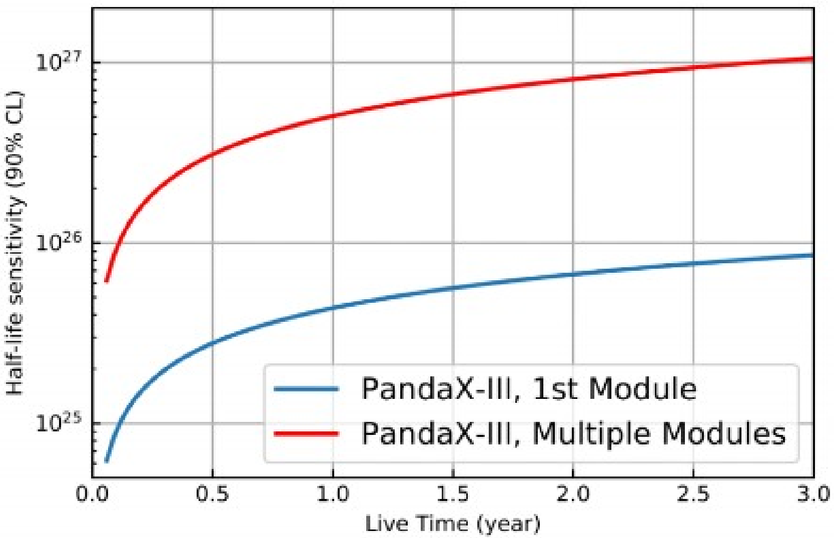
Noble gas → chemically inert

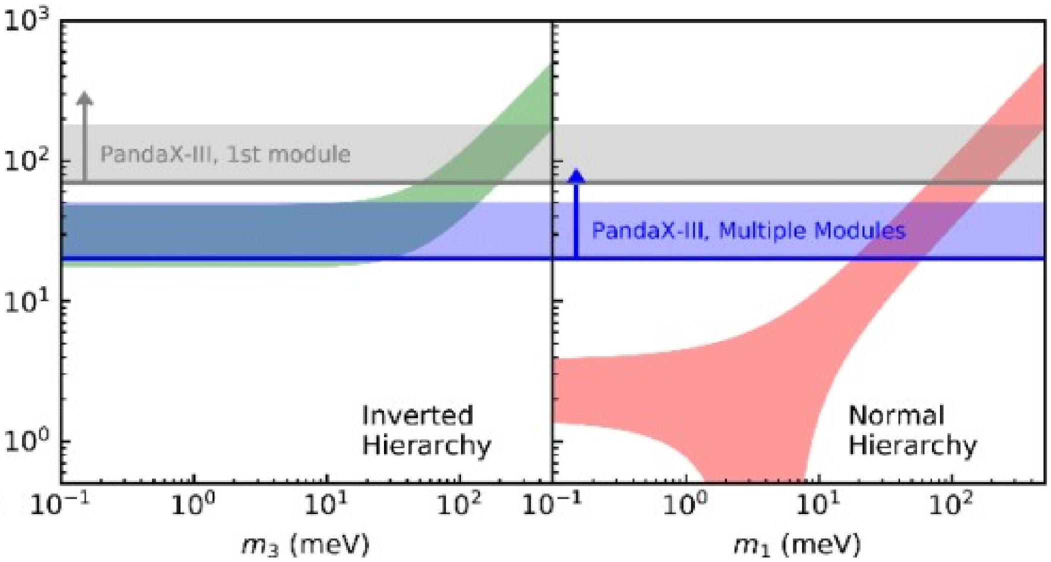
8.9% in natural xenon → easy to enrich



0NDBD searches

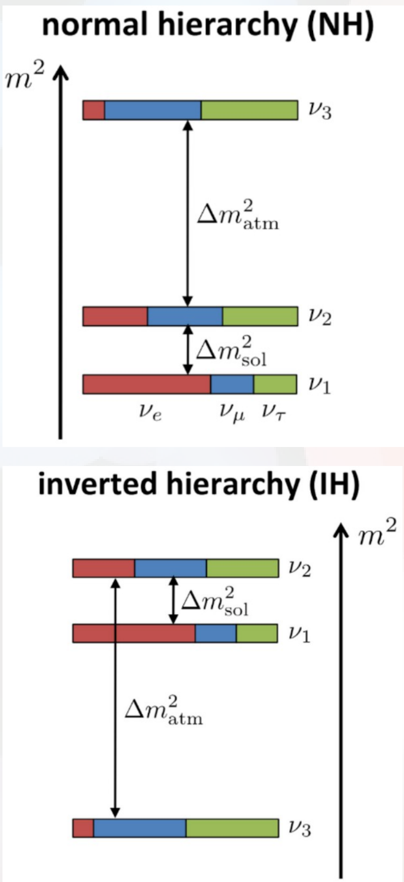
- PandaX-III 100-kg scale high pressure gas TPC module
  - Sub-systems move forward
  - Assembly starts soon
- Half-life sensitivity with 3 years of data: 9×10^{25} yr (90% CL)
  - Will fully exploit tracking feature to further improve the sensitivity

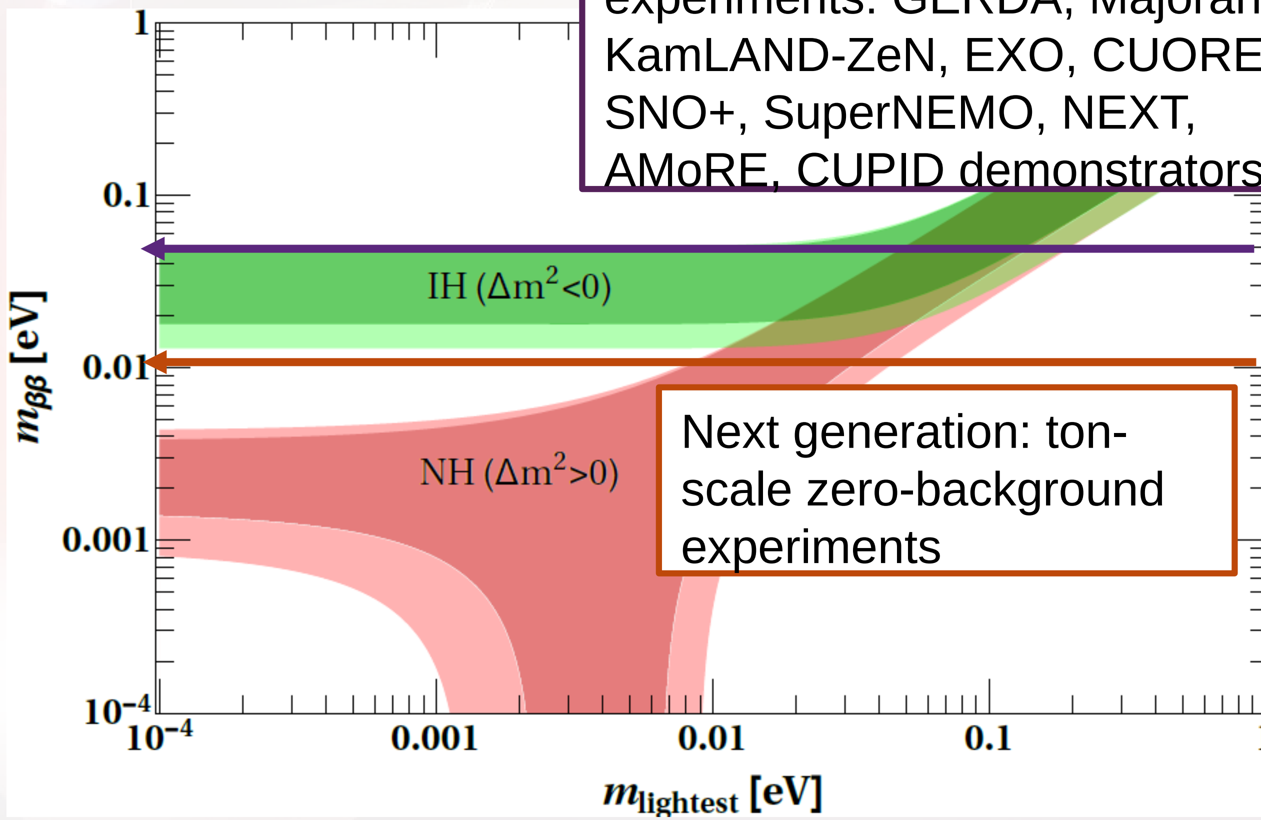




➢ 0NDBD searches

From solar&atmospheric neutrino studies;
Obtained constraints on neutrino mass differences and possible mass hierarchies.
(citation from Benjamin's thesis!!!)



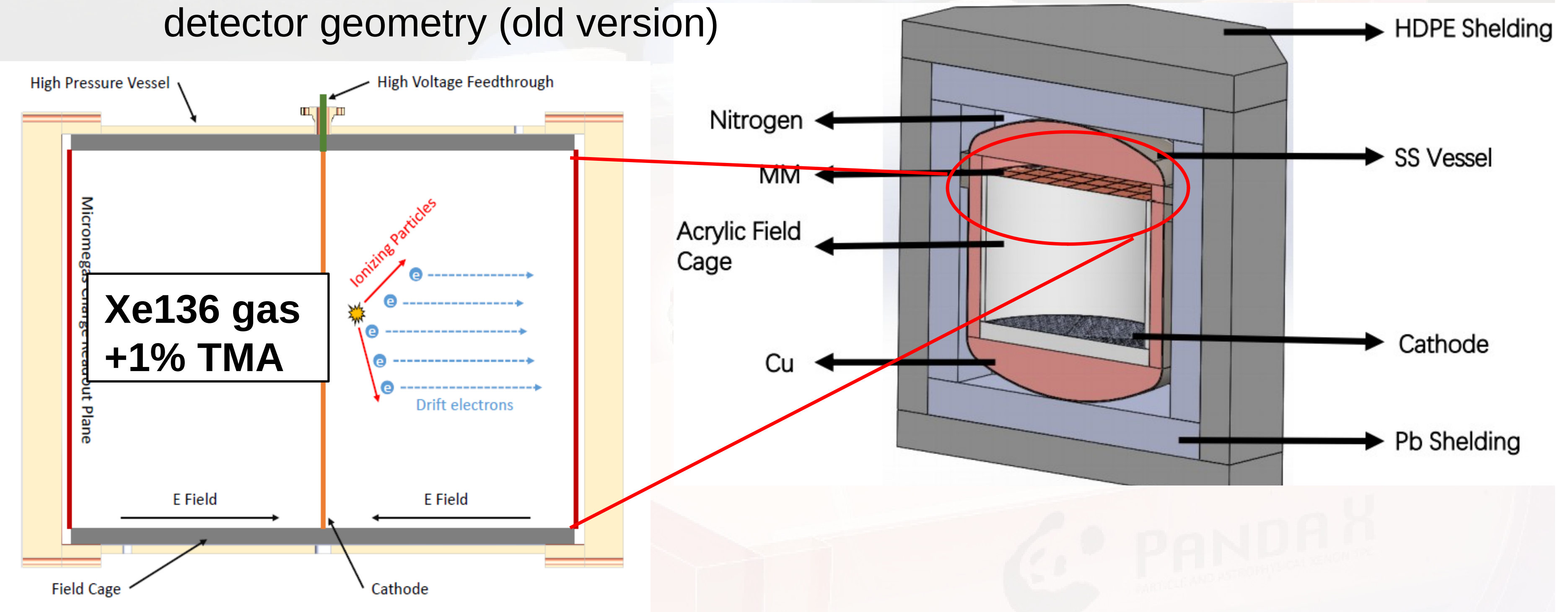


Current and near future experiments: GERDA, Majorana, KamLAND-ZeN, EXO, CUORE, SNO+, SuperNEMO, NEXT, AMoRE, CUPID demonstrators

Next generation: ton-scale zero-background experiments

➢ PandaX-III experiment

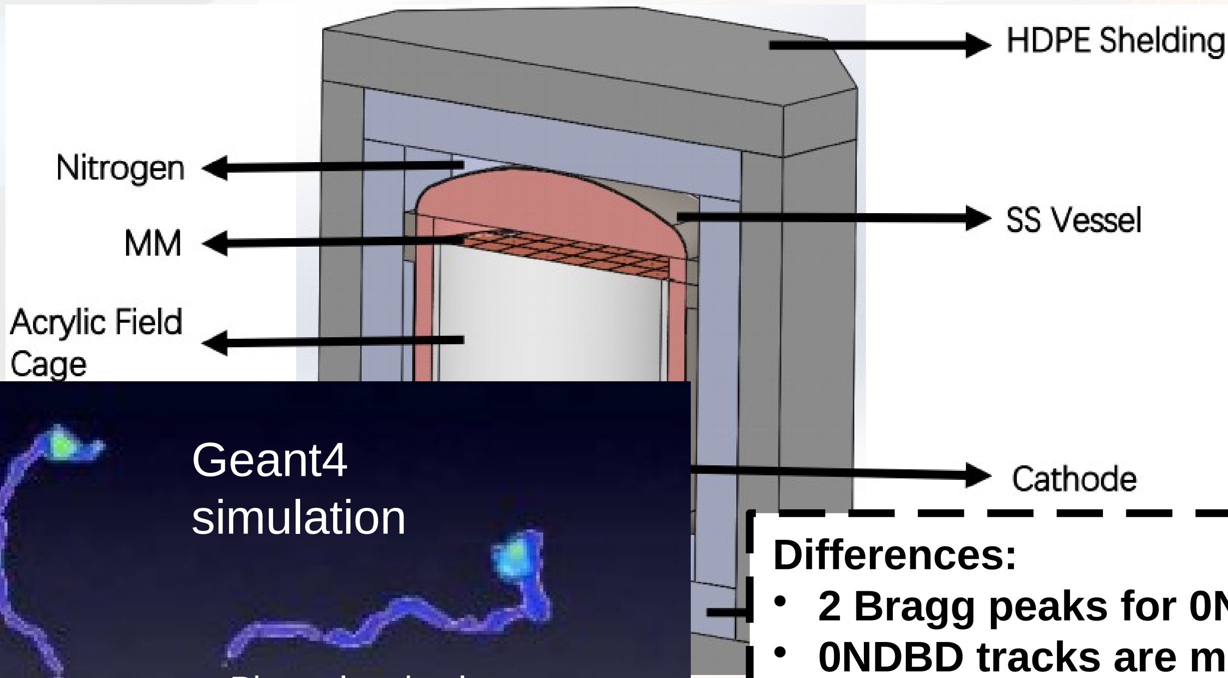
Side view of the **Time projection chamber (TPC)** detector geometry (old version)

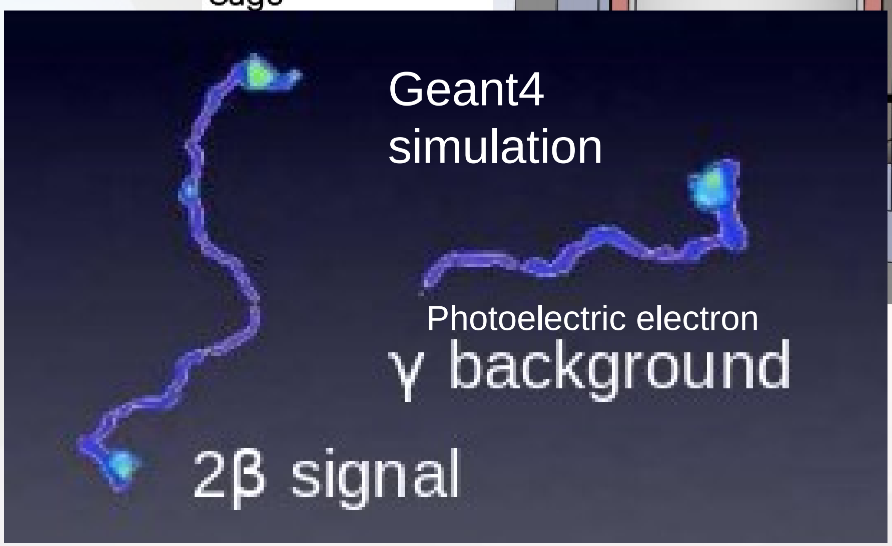


- Filled with Xe136 gas
- Good energy resolution (~3% FWHM)
- Low bkg level
- Scalability (possible to reach 1 ton scale)

Reaching low bkg level, applying additional shielding (HDPE, Pb Shelding, Nitrogen, Stainless Steel, purified Cu)

New **Time projection chamber** (**TPC**) detector geometry

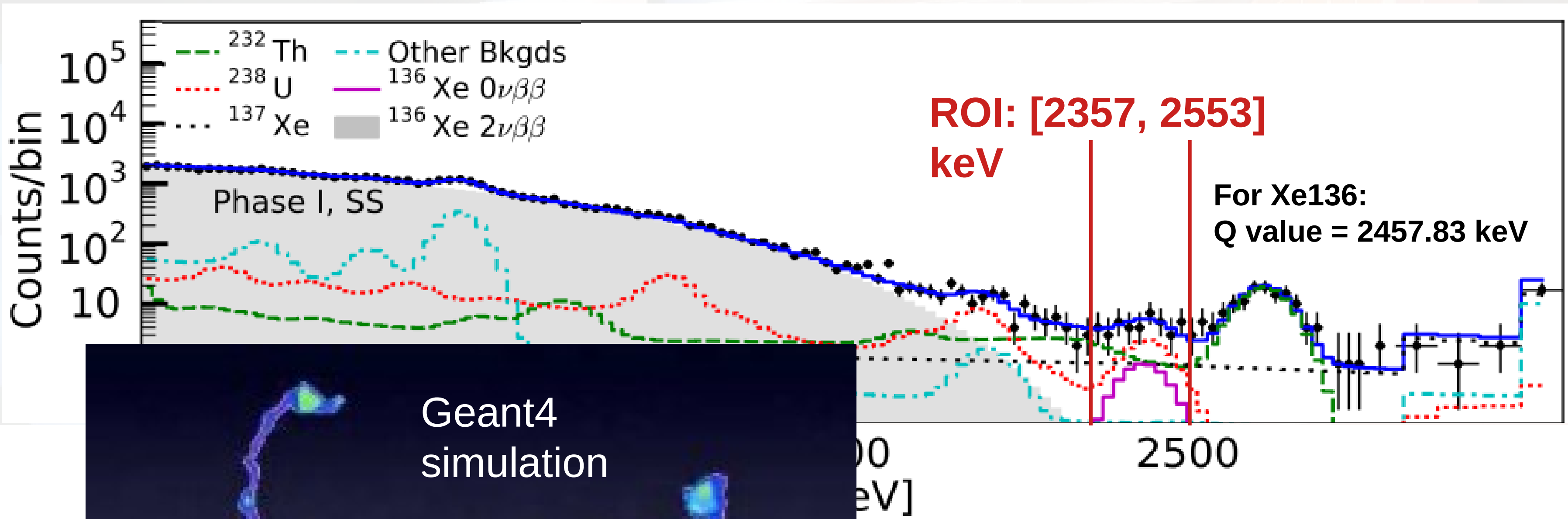




Differences:

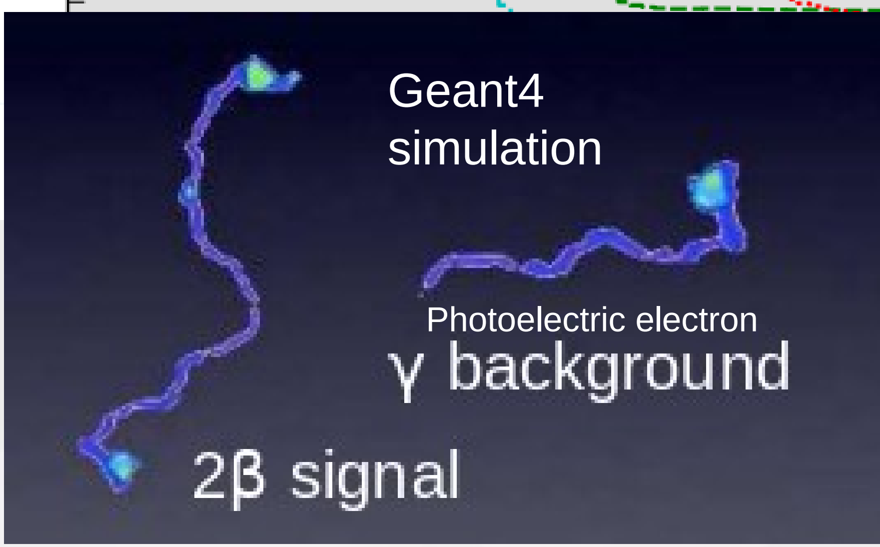
- **2 Bragg peaks for 0NDBD**
- **0NDBD tracks are more "twisted"**
- **The length of the 0NDBD tracks is shorter**

EXO results (liquid Xenon detector)



ROI: [2357, 2553] keV

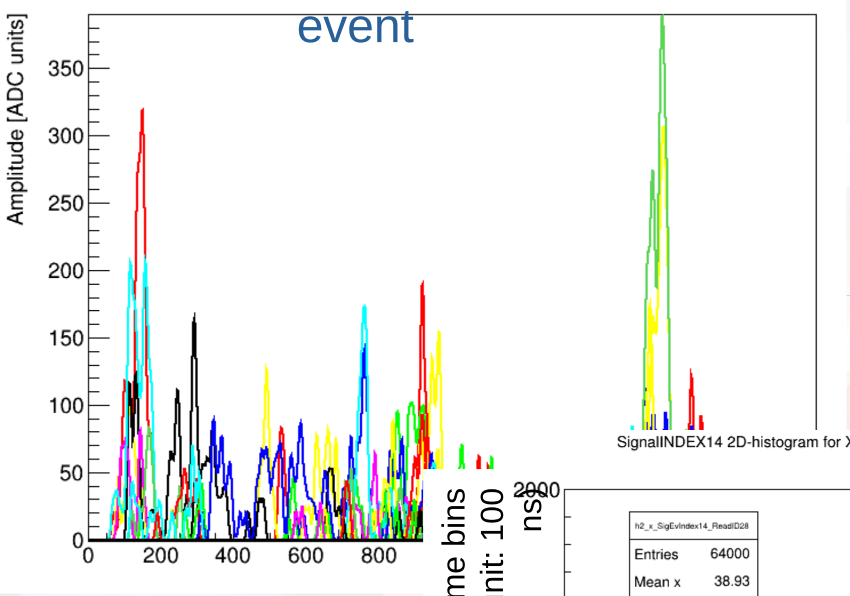
For Xe136:
Q value = 2457.83 keV



Differences:
- **2 Bragg peaks for 0NDBD**
- **0NDBD tracks are more "twisted"**
- **The length of the 0NDBD tracks is shorter**

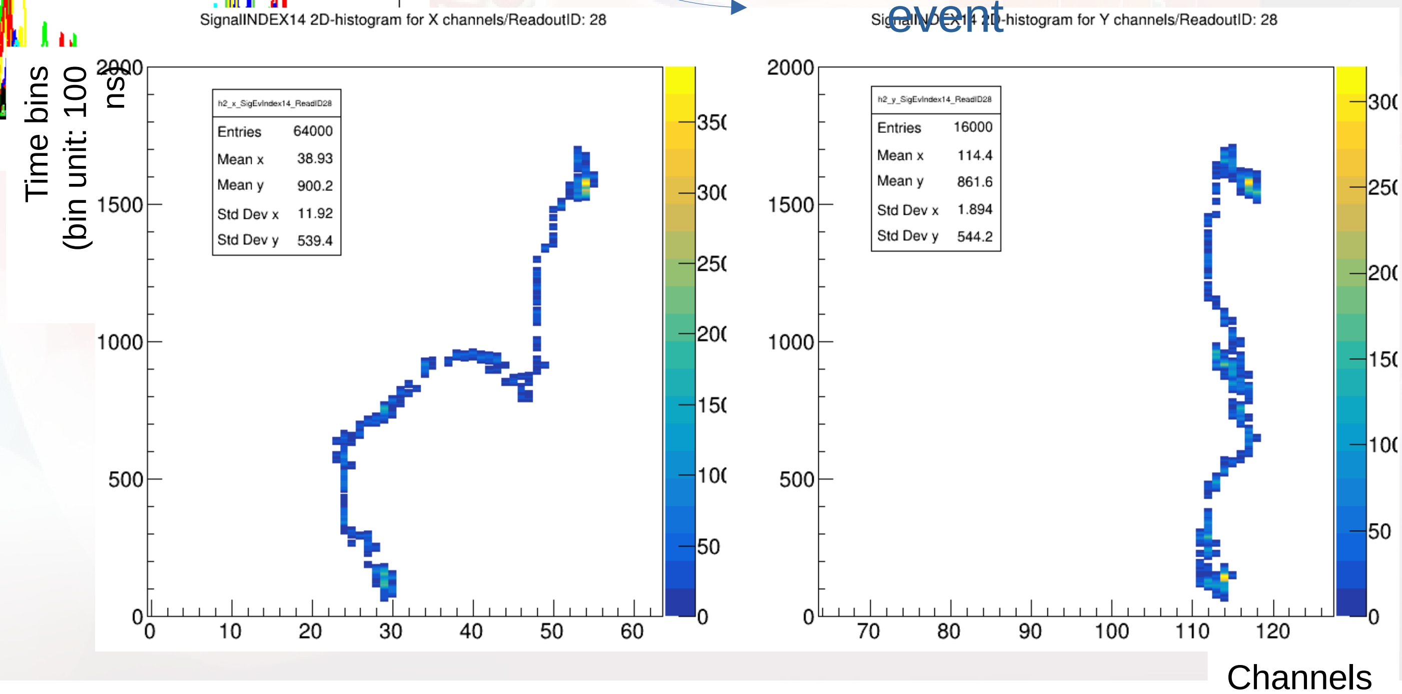
➢ Data processing

Signal event



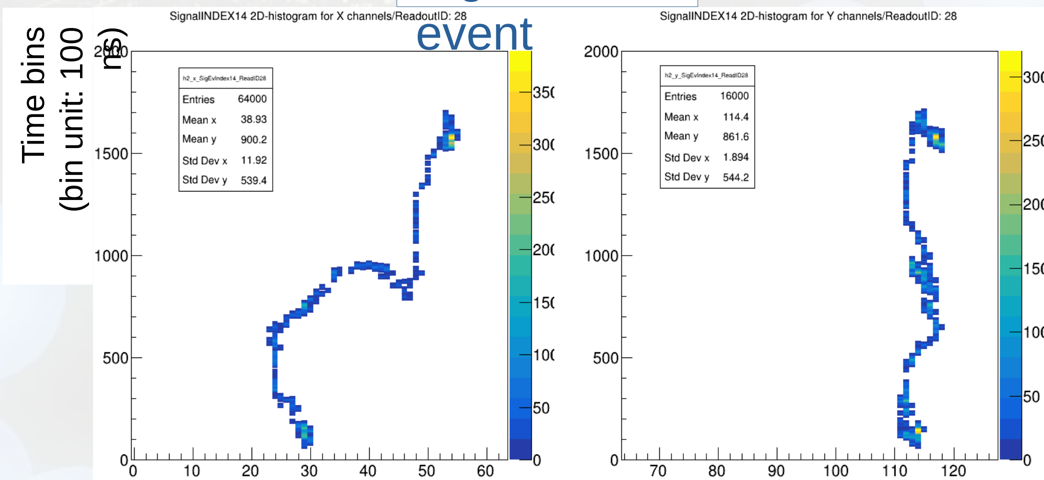
Another way to represent Signal Event as 2D histograms.
Color correspond to the signal amplitude (ADC units)

Signal event



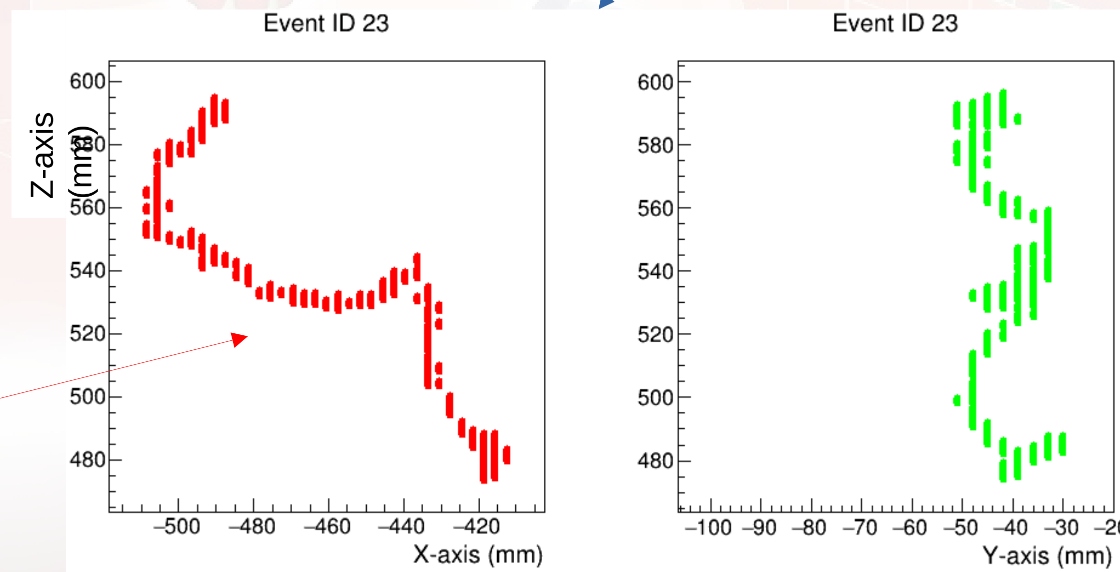
Data processing

Signal event



Inside the **Hits** an information about the position/time and deposited energy is being stored

Signal to Hits

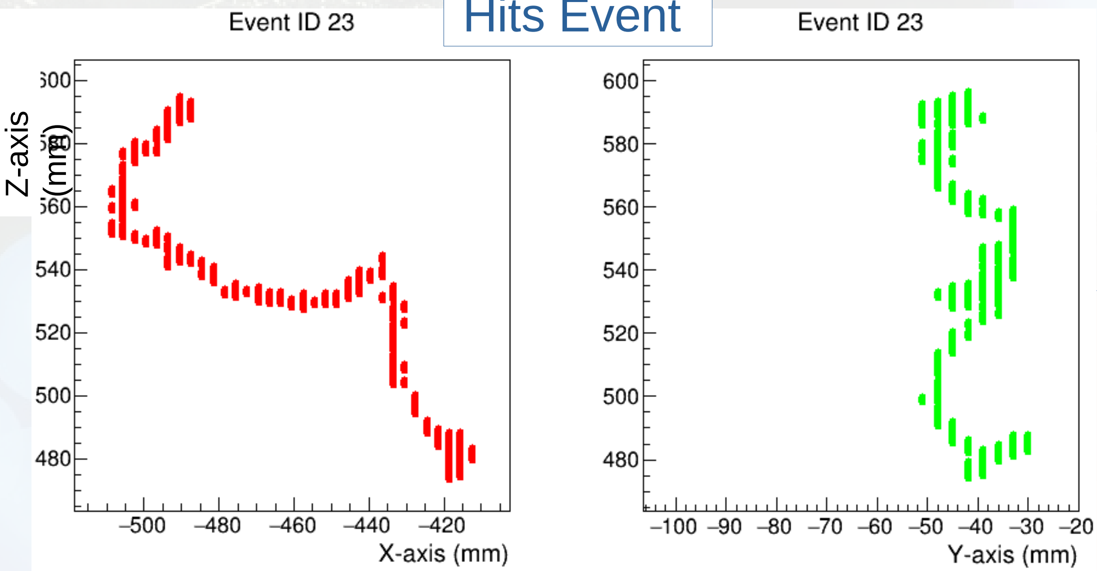


Track projection image is reversed due to the fact that Readout Plane position is at the Z = 600.5 mm

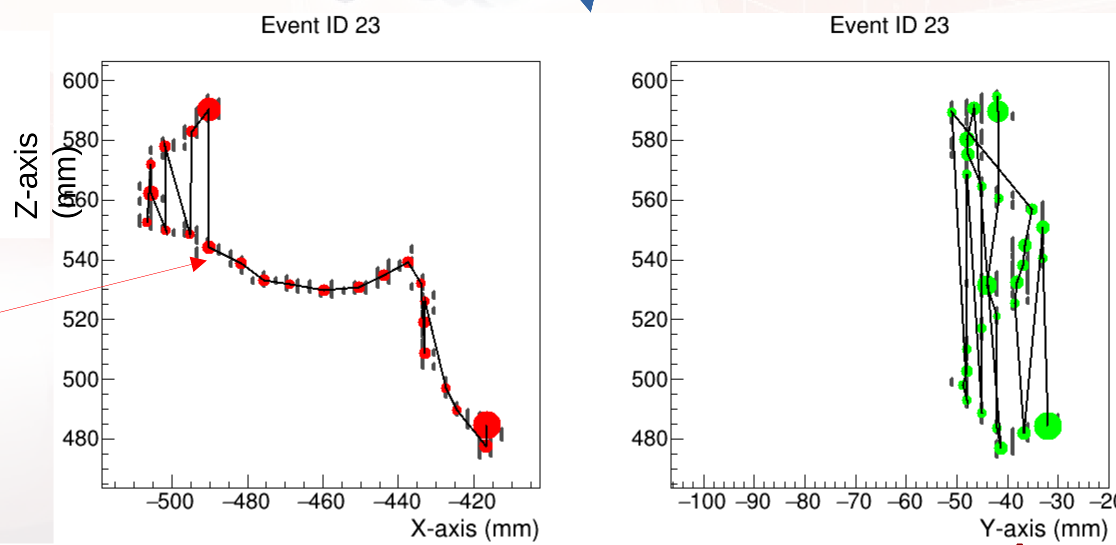
Clusterisation of Hits

➢ Data processing

Hits Event

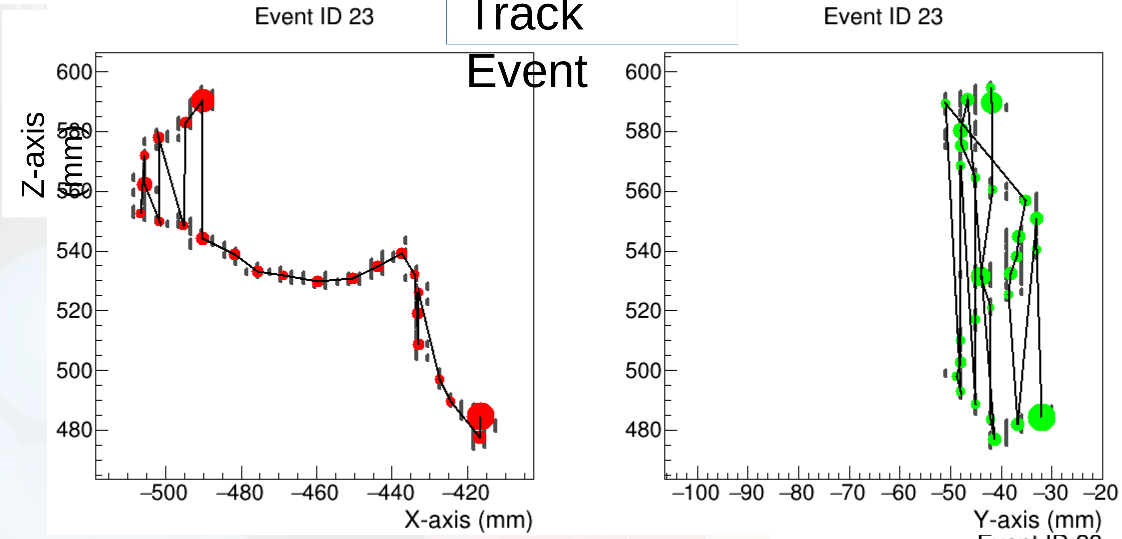


Hits to Track



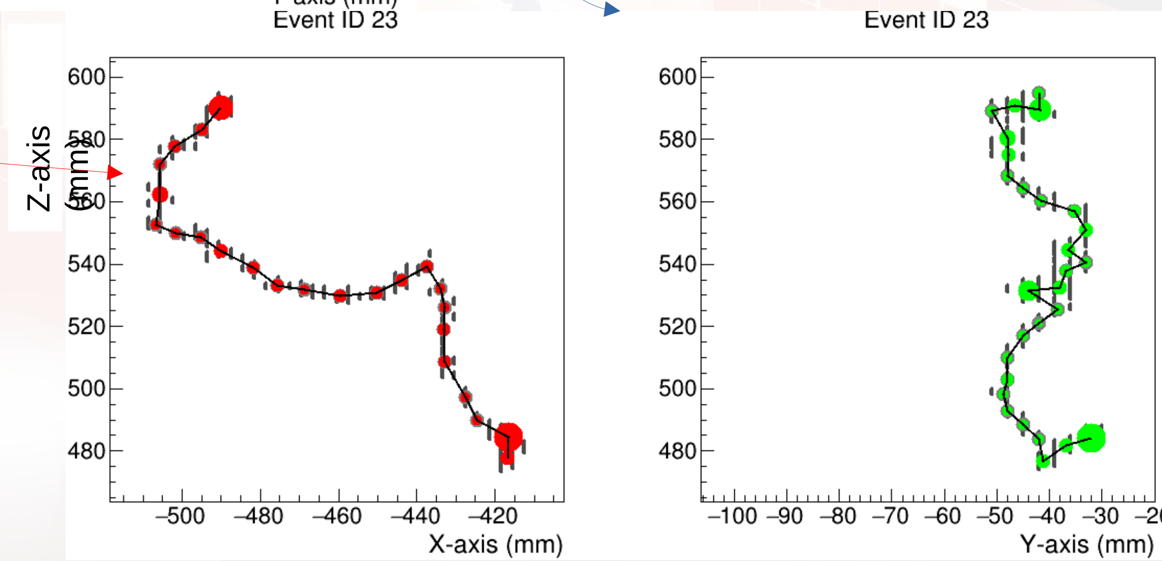
Now Hits inside the Track are being clustered.

Track Event



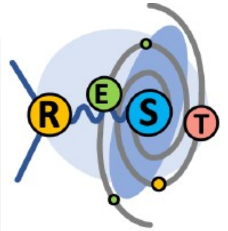
Track Minimisation
+
Track Reconnection

Reconnection of the track

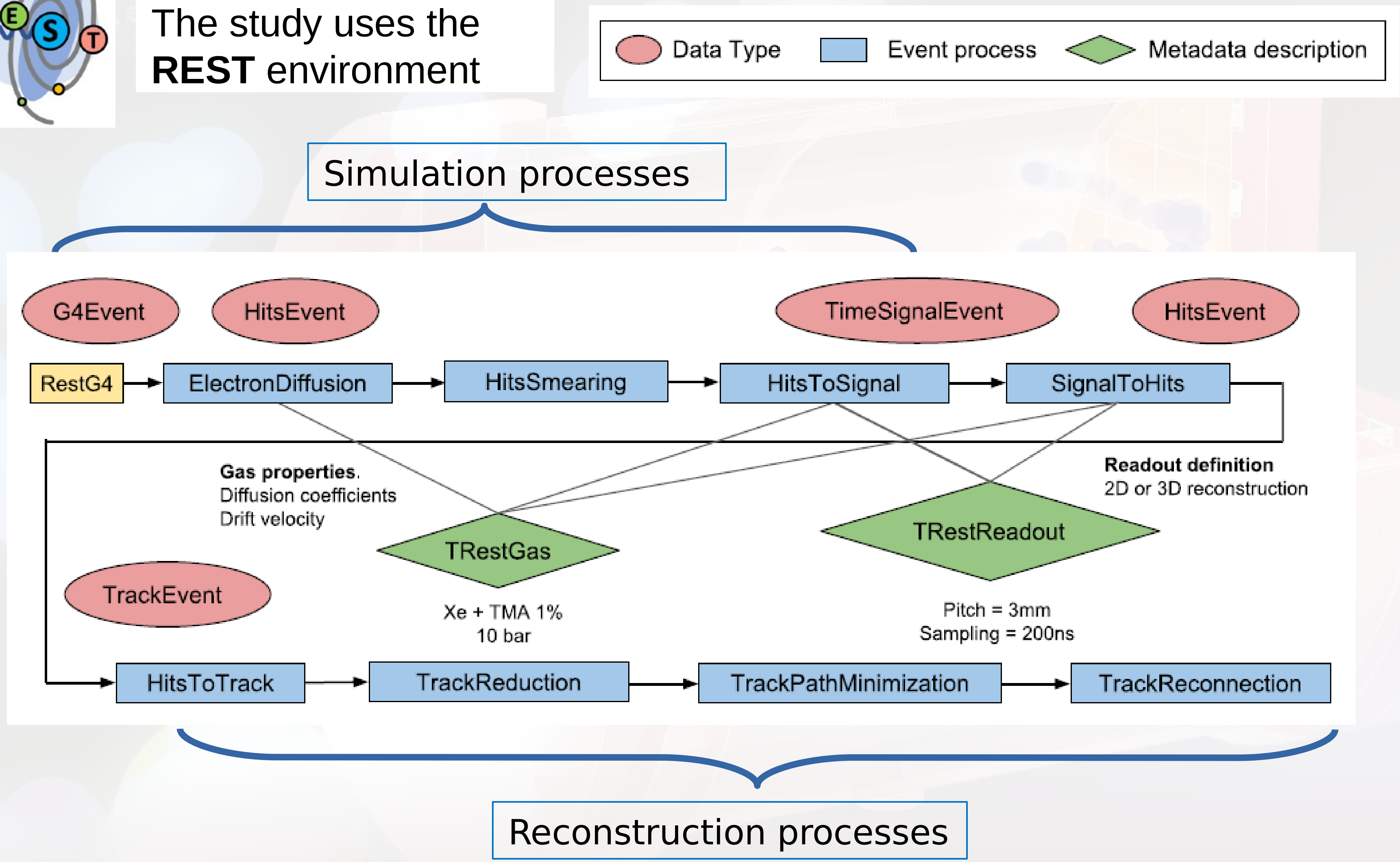


Output:
- Total reconstructed energy of the track
- Energy depositions on the track length
- Track topology

➢ Simulations



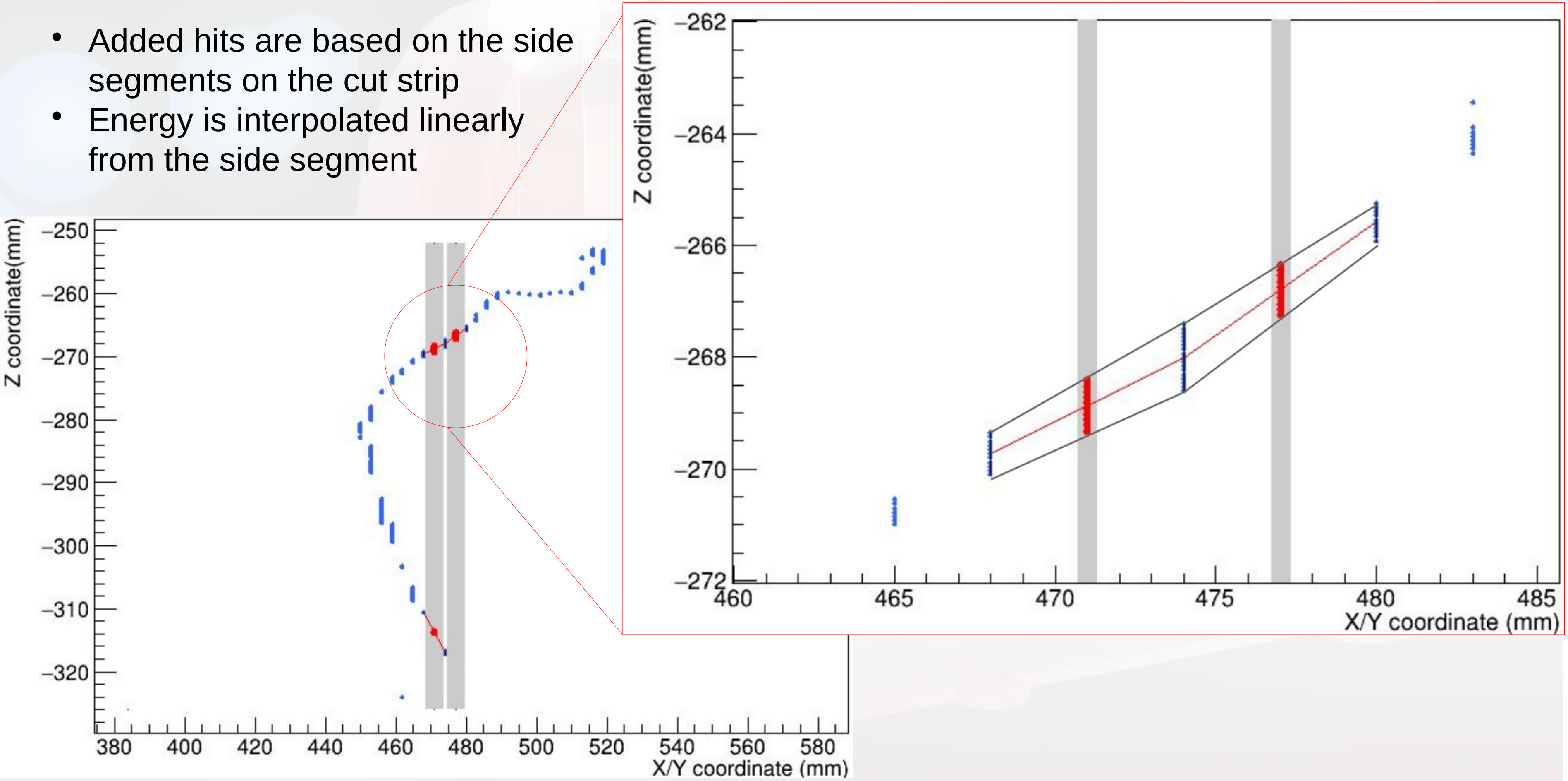
The study uses the **REST** environment



Missing channel repairing with linear interpolation (Benjamin Manier)

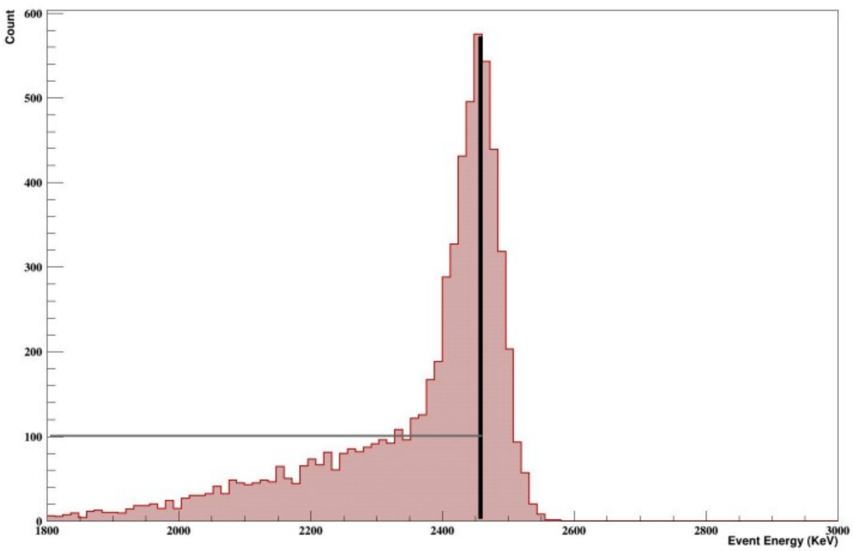
Hits Event

- Added hits are based on the side segments on the cut strip
- Energy is interpolated linearly from the side segment

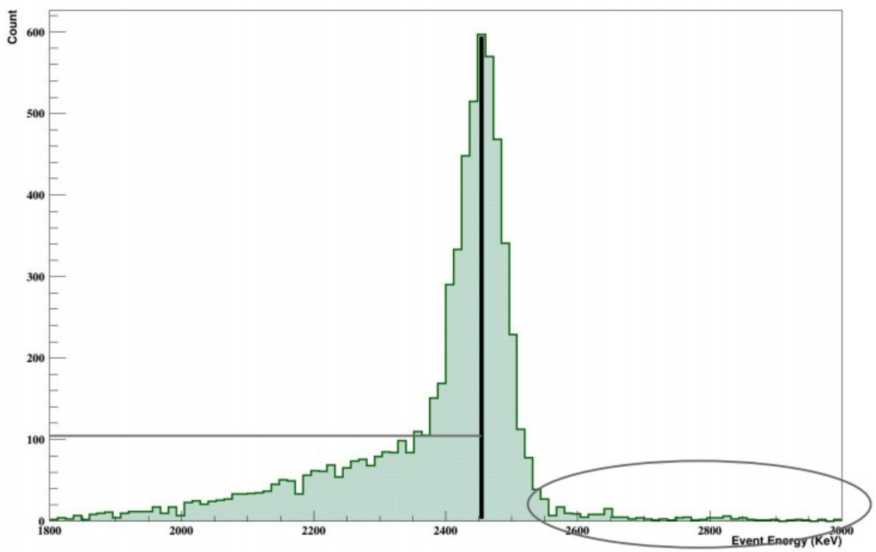


Missing channel repairing with linear interpolation (Benjamin Manier)

Energy Spectrum, Double beta decay, after cuts



Energy Spectrum, Double beta decay, after repair

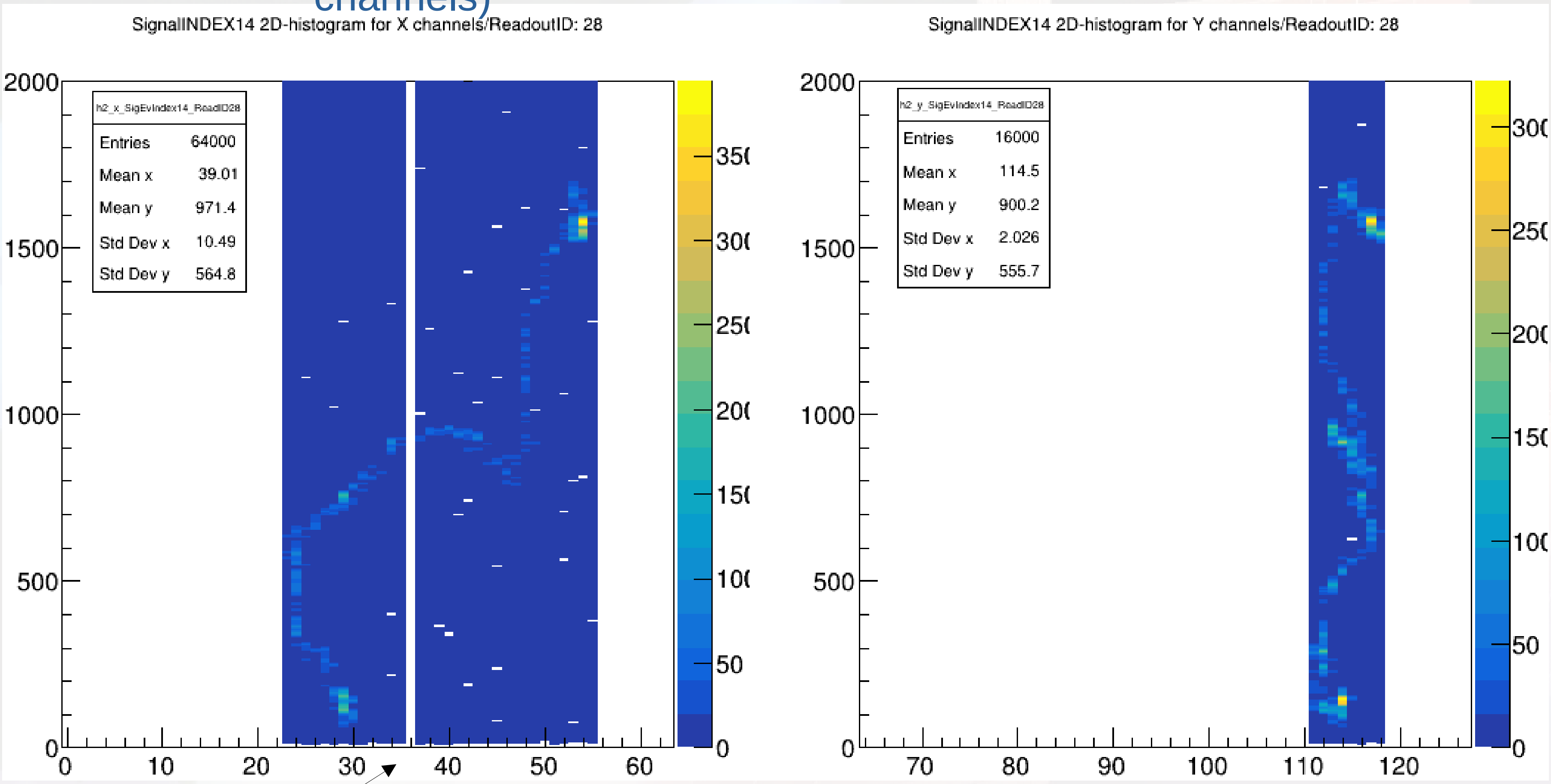


Simulation of **5 consecutively cut strips** per Readout Module.
After repair: a large over estimation of the energy loss is present.

No real change on the overall spectrum.
However, 71% track reconnection achieved. (for 5 consecutively cut strips)

➢ Missing channels problem

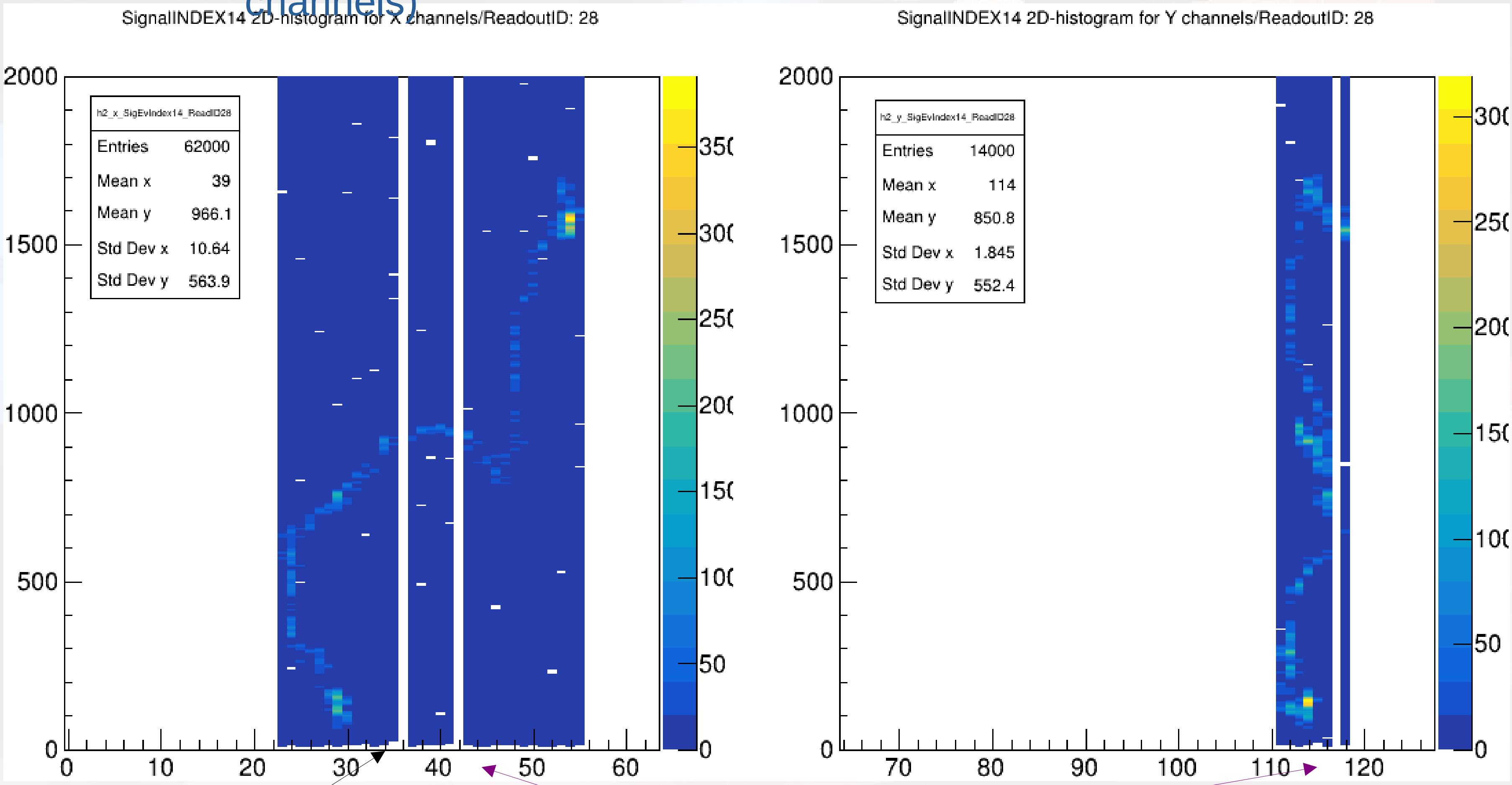
Signal Event with simulated noise (NO cut channels)



No signal at a first place

Missing channels problem

Signal Event with simulated noise (5 random cut channels)

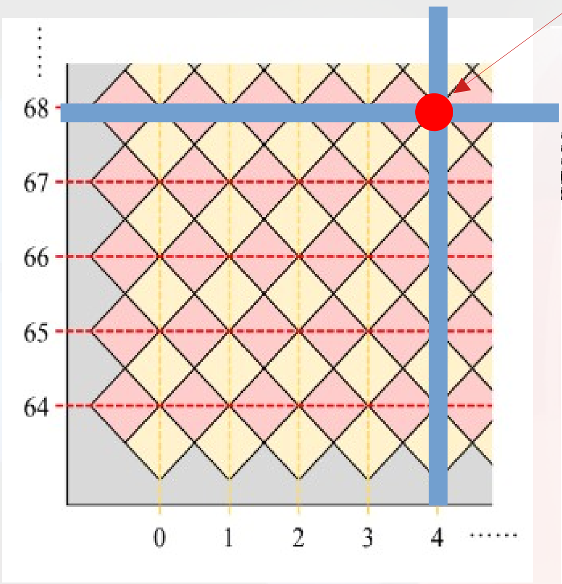


No signal at a first place

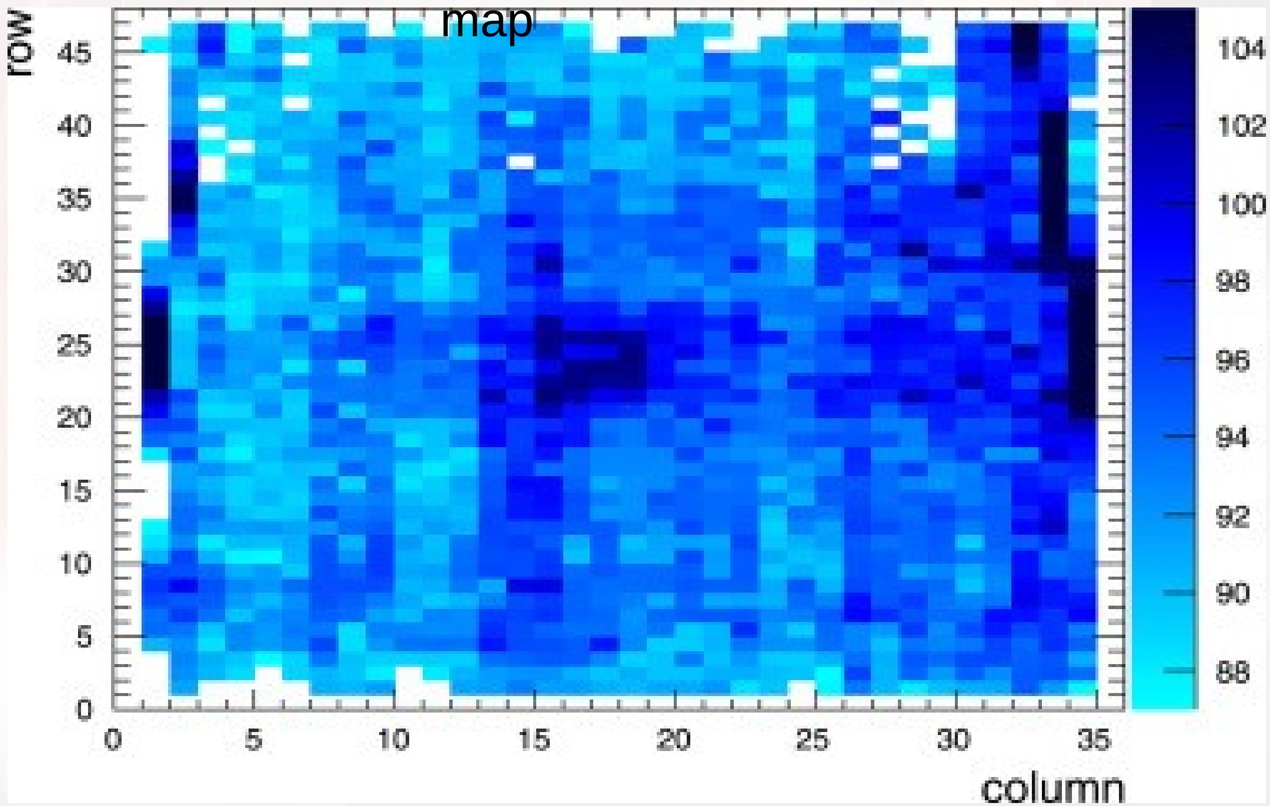
Cut channels

➢ Missing channels problem

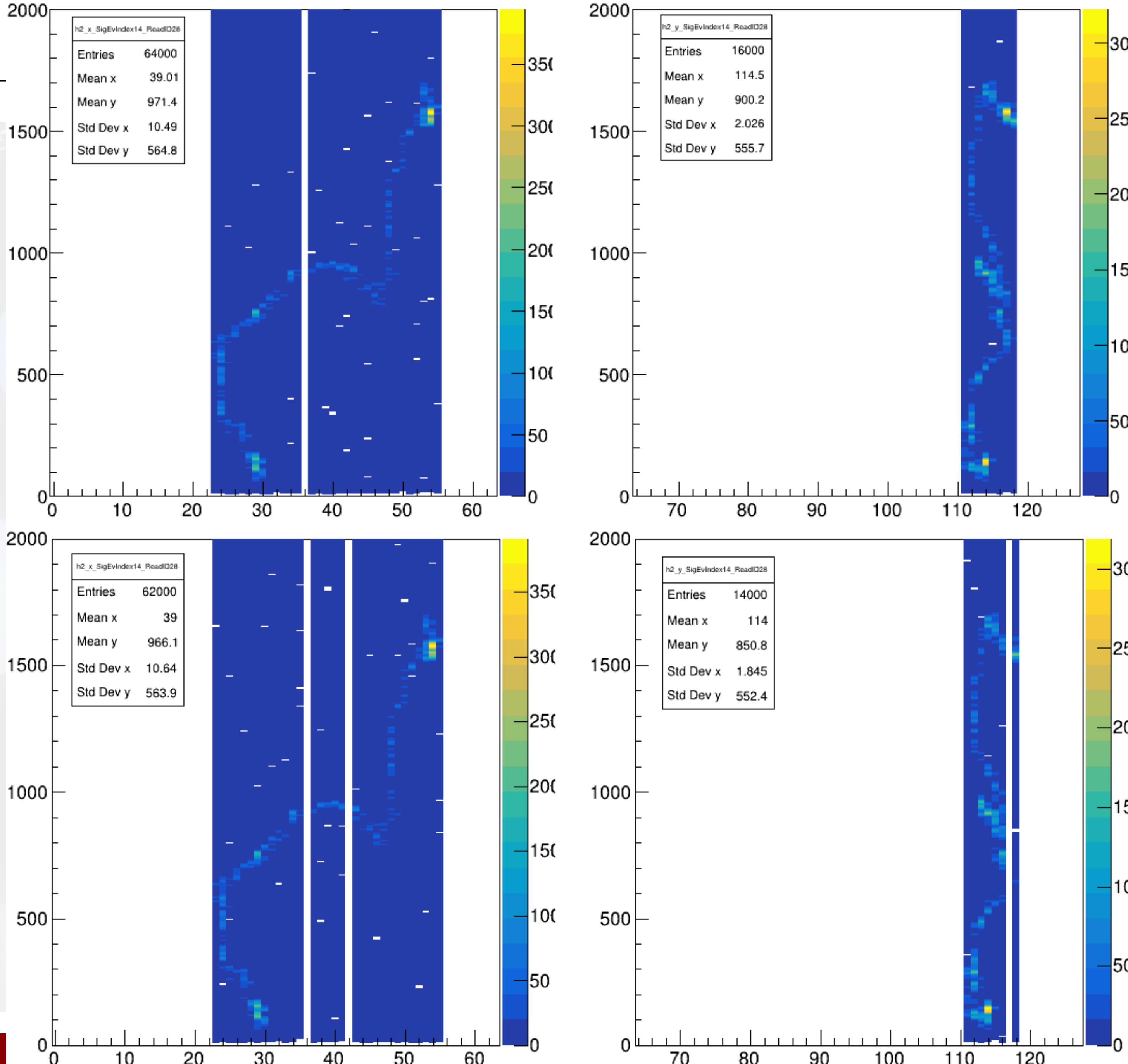
Inhomogeneous energy gain (other problem)

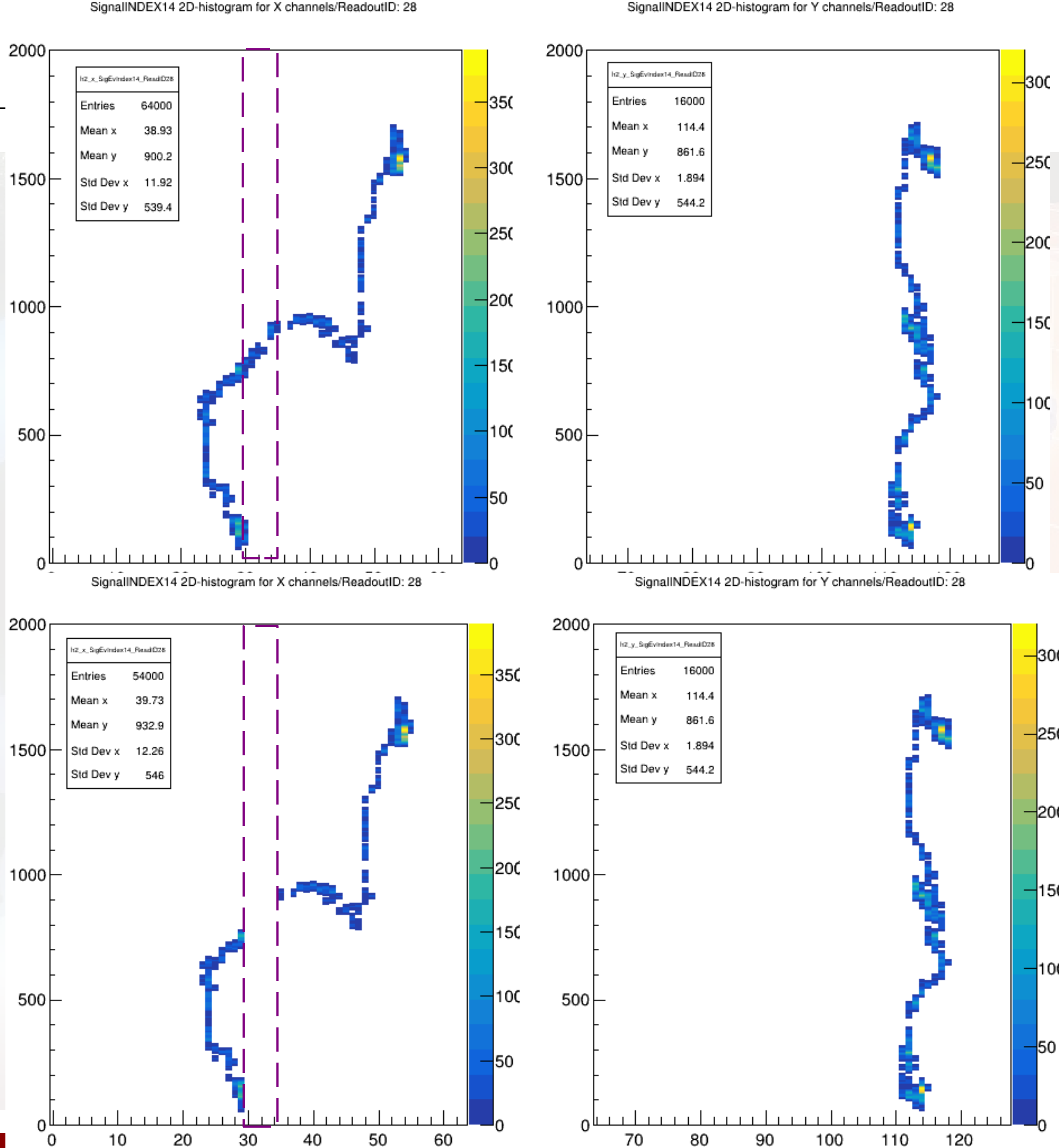


Energy gain map



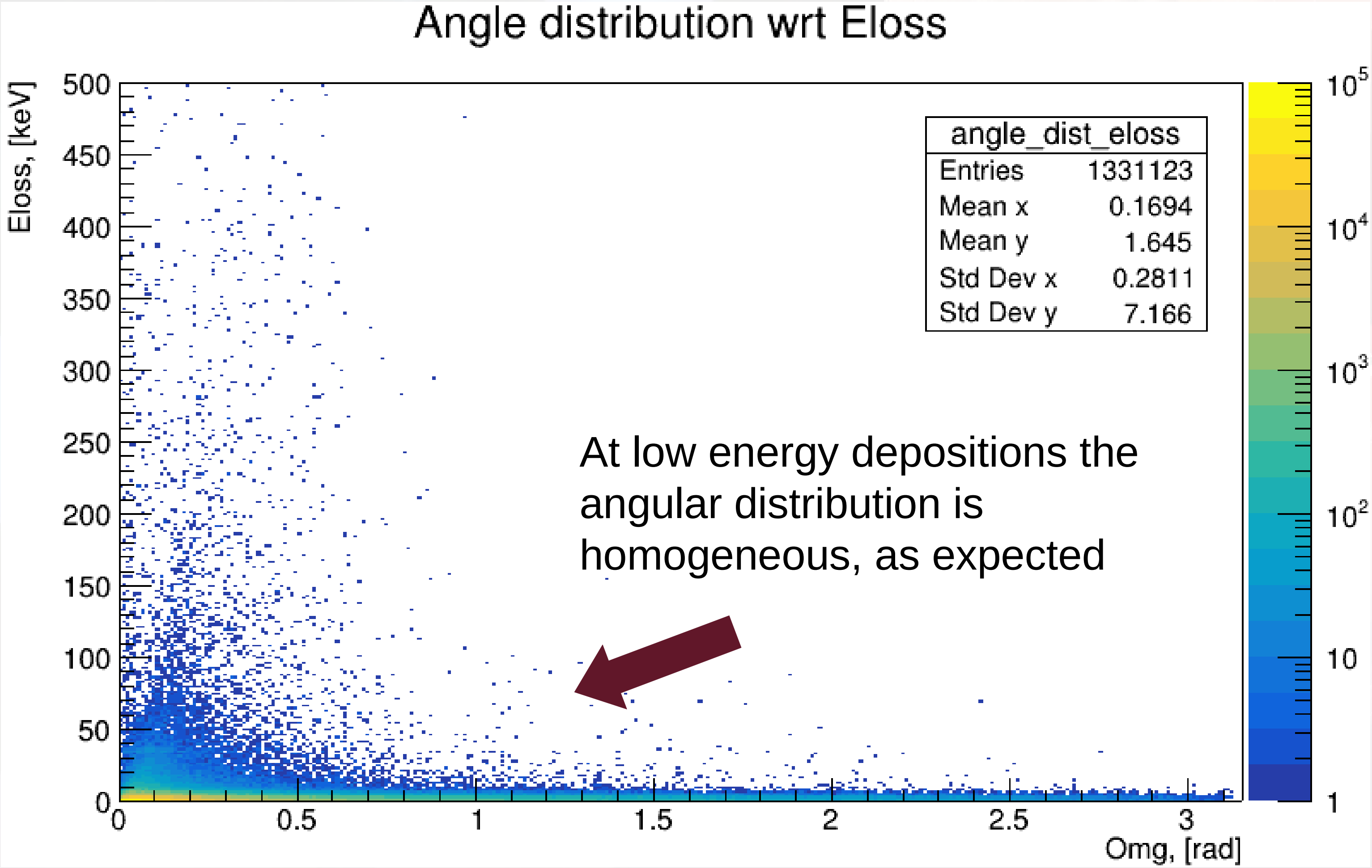
Each pixel corresponds to the gain index for one X and one Y strip on which signal was registered simultaneously.


h2_x_SigEvIndex14_ReadID28
Entries 64000
Mean x 39.01
Mean y 971.4
Std Dev x 10.49
Std Dev y 564.8
h2_y_SigEvIndex14_ReadID28
Entries 16000
Mean x 114.5
Mean y 900.2
Std Dev x 2.026
Std Dev y 555.7
h2_x_SigEvIndex14_ReadID28
Entries 62000
Mean x 39
Mean y 966.1
Std Dev x 10.64
Std Dev y 563.9
h2_y_SigEvIndex14_ReadID28
Entries 14000
Mean x 114
Mean y 850.8
Std Dev x 1.845
Std Dev y 552.4


SignalINDEX14 2D-histogram for X channels/ReadoutID: 28
h2_x_SigEvIndex14_ReadID28
Entries 64000
Mean x 38.93
Mean y 900.2
Std Dev x 11.92
Std Dev y 539.4
SignalINDEX14 2D-histogram for Y channels/ReadoutID: 28
h2_y_SigEvIndex14_ReadID28
Entries 16000
Mean x 114.4
Mean y 861.6
Std Dev x 1.894
Std Dev y 544.2
SignalINDEX14 2D-histogram for X channels/ReadoutID: 28
h2_x_SigEvIndex14_ReadID28
Entries 54000
Mean x 39.73
Mean y 932.9
Std Dev x 12.26
Std Dev y 546
SignalINDEX14 2D-histogram for Y channels/ReadoutID: 28
h2_y_SigEvIndex14_ReadID28
Entries 16000
Mean x 114.4
Mean y 861.6
Std Dev x 1.894
Std Dev y 544.2

Missing channels problem

Looking for the correlation b/w scattering angle and the total deposited energy of the e- inside the gas

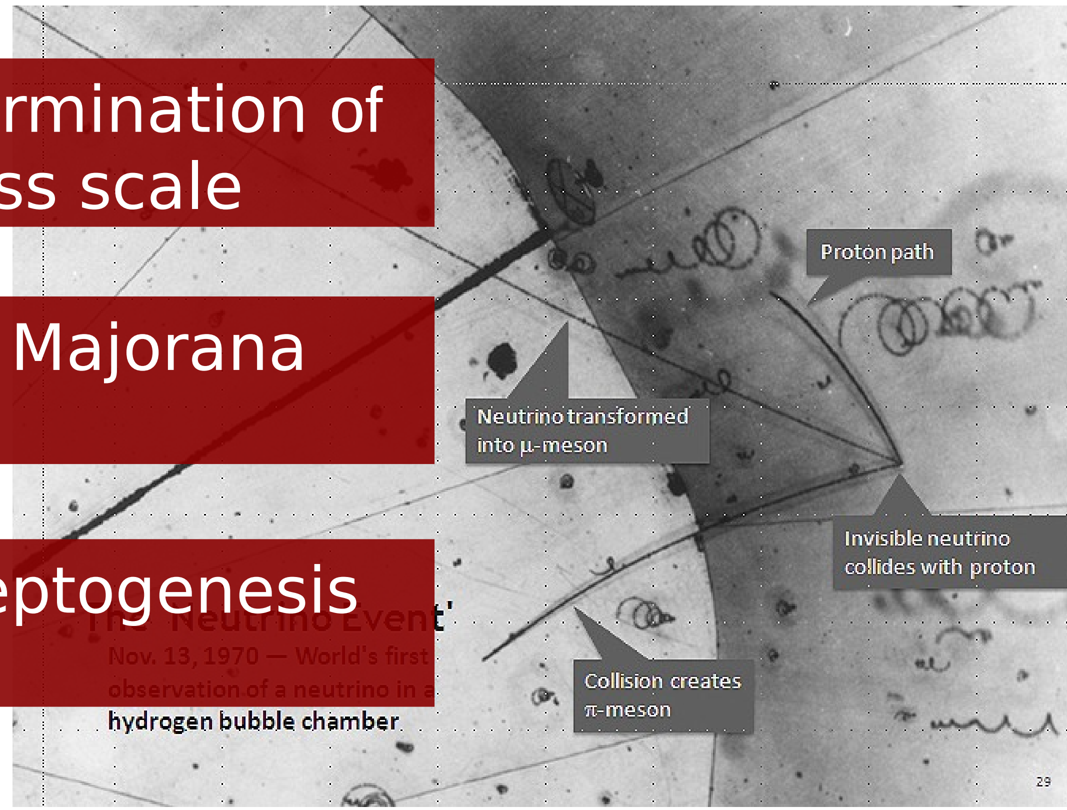


Why neutrinoless double-beta decay?

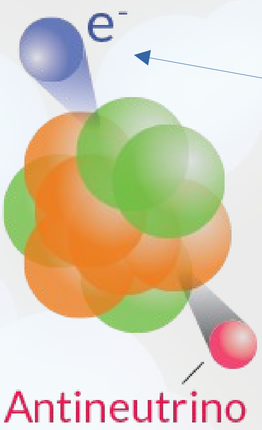
1. Absolute determination of the neutrino mass scale

2. Neutrinos are Majorana Particles

3. Proof of the Leptogenesis Process



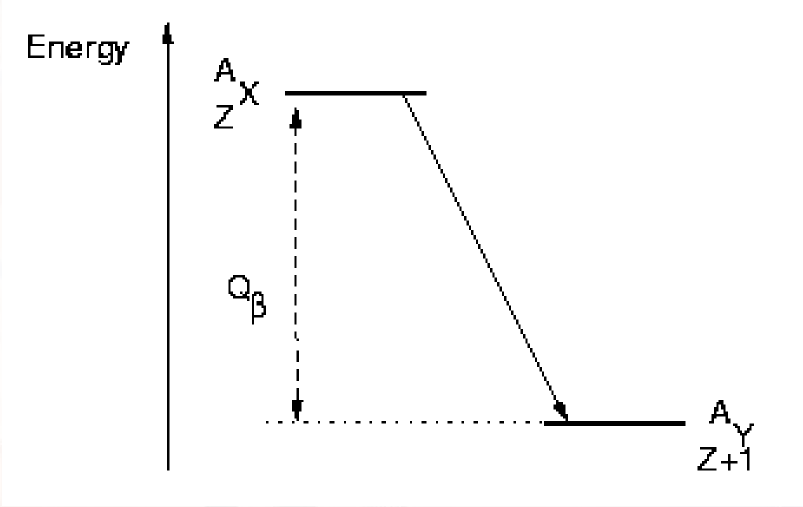
Beta decay



Energy of the decay **(Q value)** is distributed between two particles

$$(A, Z) \rightarrow (A, Z+1) + e^{-} + \overline{\nu}$$

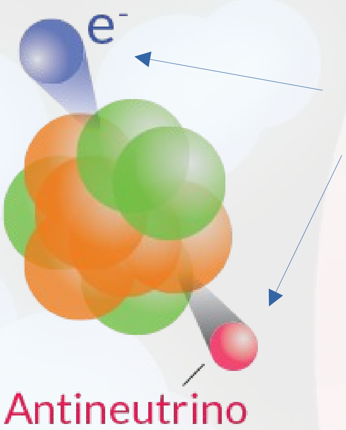
Energy scheme of beta decay



Q value – amount of energy released during the nuclear reaction

$$Q = (m_{\mathrm{n}} - m_{\mathrm{p}} - m_{\overline{\nu}} - m_{\mathrm{e}})c^2 = K_{\mathrm{p}} + K_{\mathrm{e}} + K_{\overline{\nu}}$$

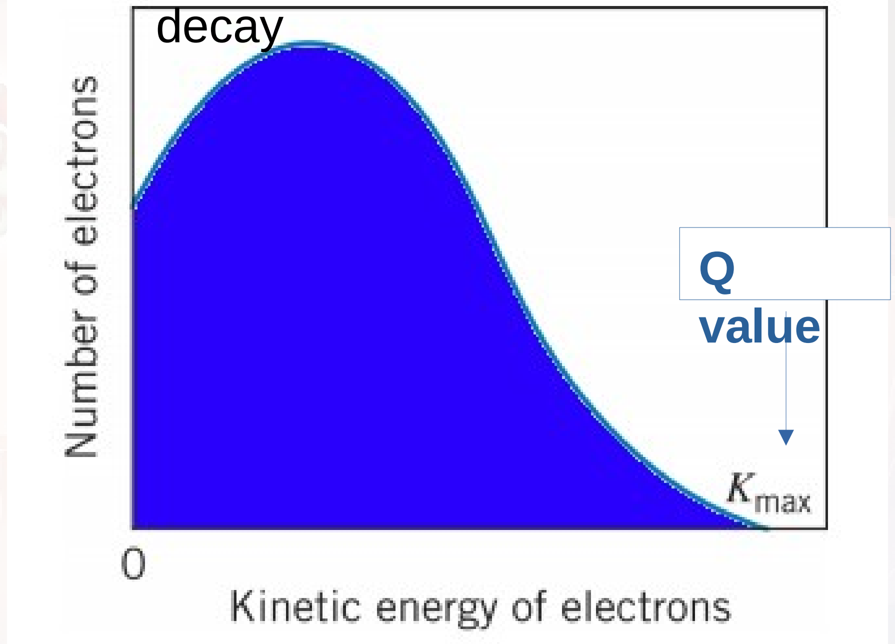
Beta decay



Energy of the decay **(Q value)** is distributed between two particles

$$(A, Z) \rightarrow (A, Z+1) + e^- + \overline{\nu}$$

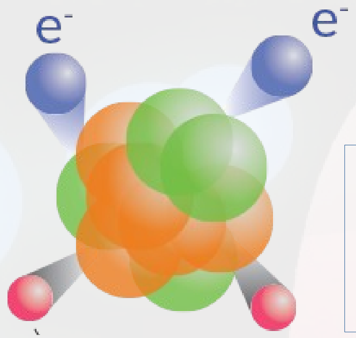
Energy spectrum of Beta decay



Q value – amount of energy released during the nuclear reaction

$$Q = (m_{\rm n} - m_{\rm p} - m_{\overline{\nu}} - m_{\rm e})c^2 = K_{\rm p} + K_{\rm e} + K_{\overline{\nu}}$$

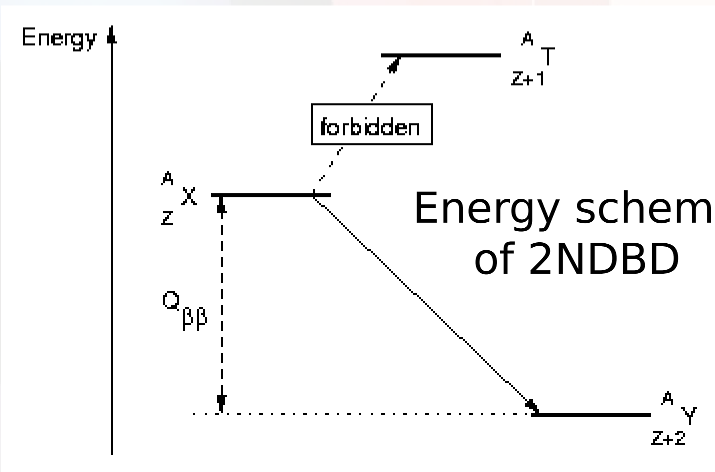
Double beta decay



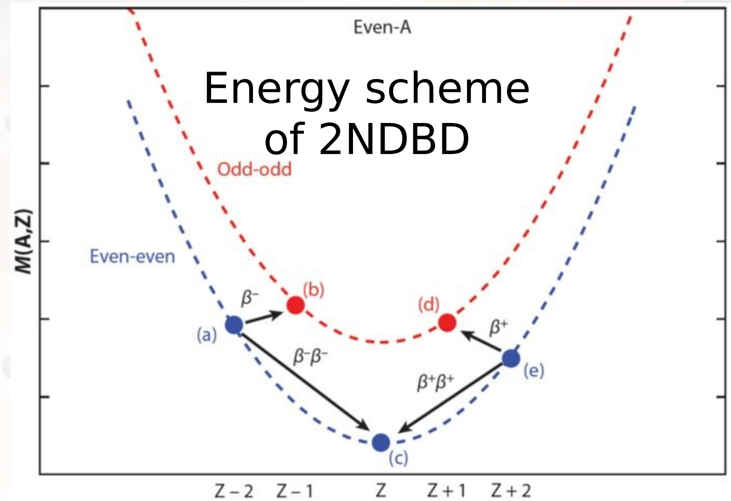
$$2\nu\beta\beta$$

Experimentally observed in 11 isotopes (out of ~300)

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$$

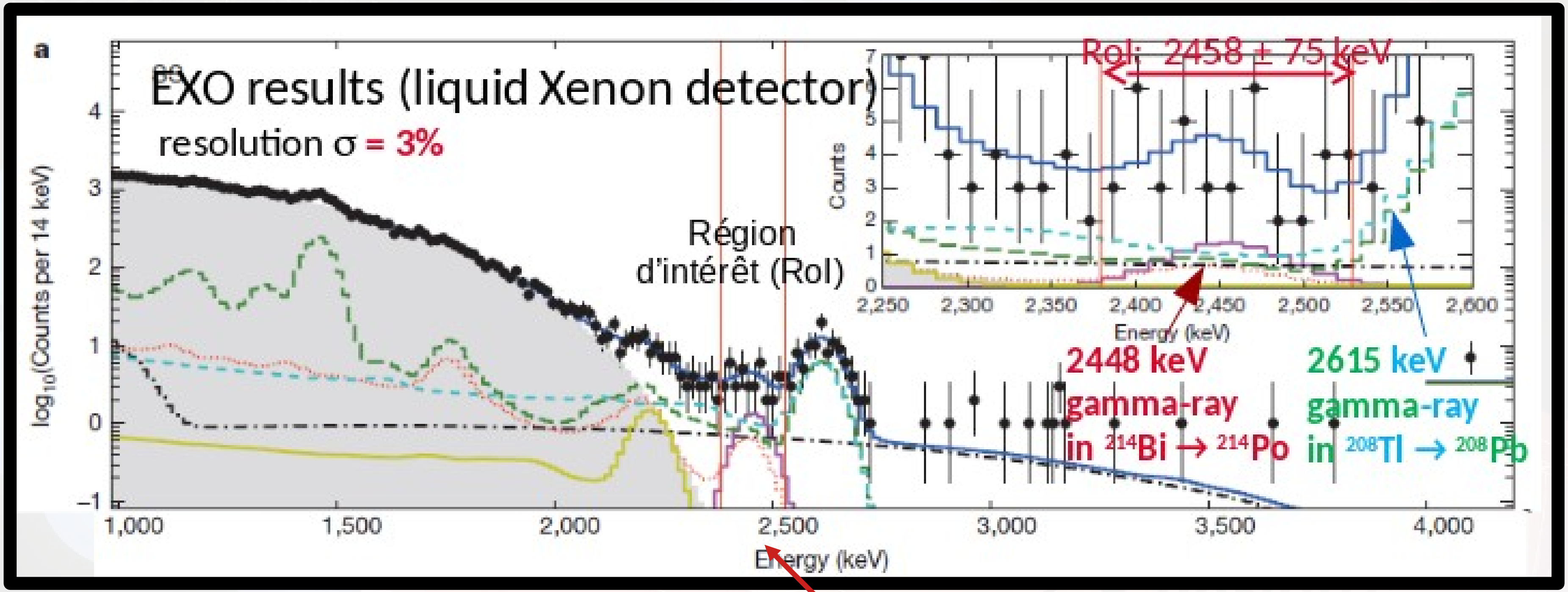


Energy scheme of 2NDBD



Energy scheme of 2NDBD

➢ PandaX-III experiment

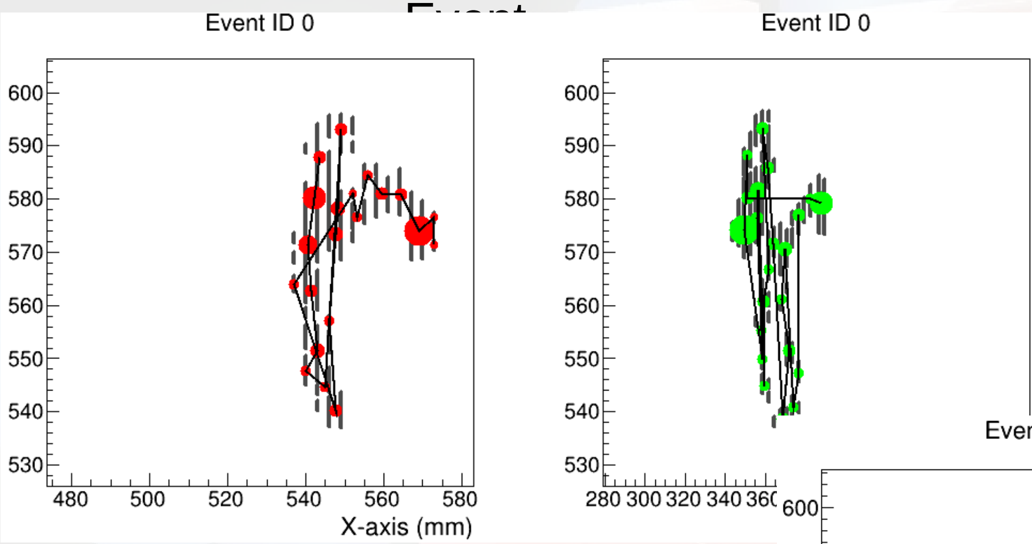


For Xe136:
Q value = 2457.83 keV
ROI : [2357, 2553] keV

ROI is highly contaminated by the bkg:
U238 and Th232 decay chains

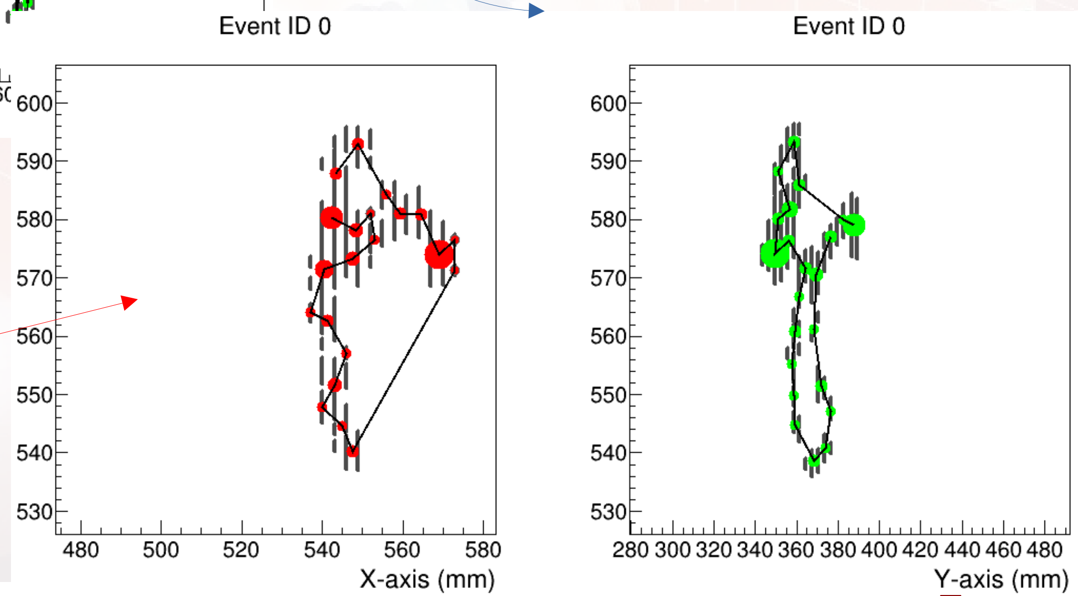
Data processing

Track



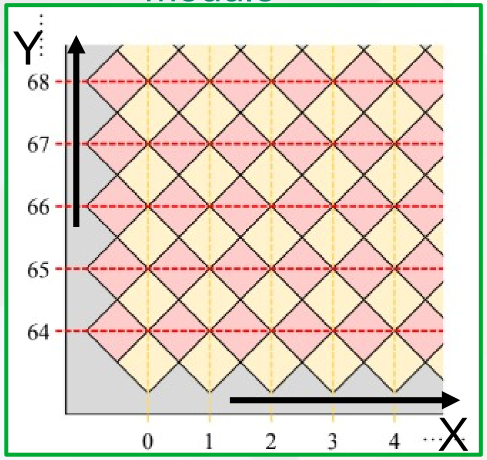
Track Minimization

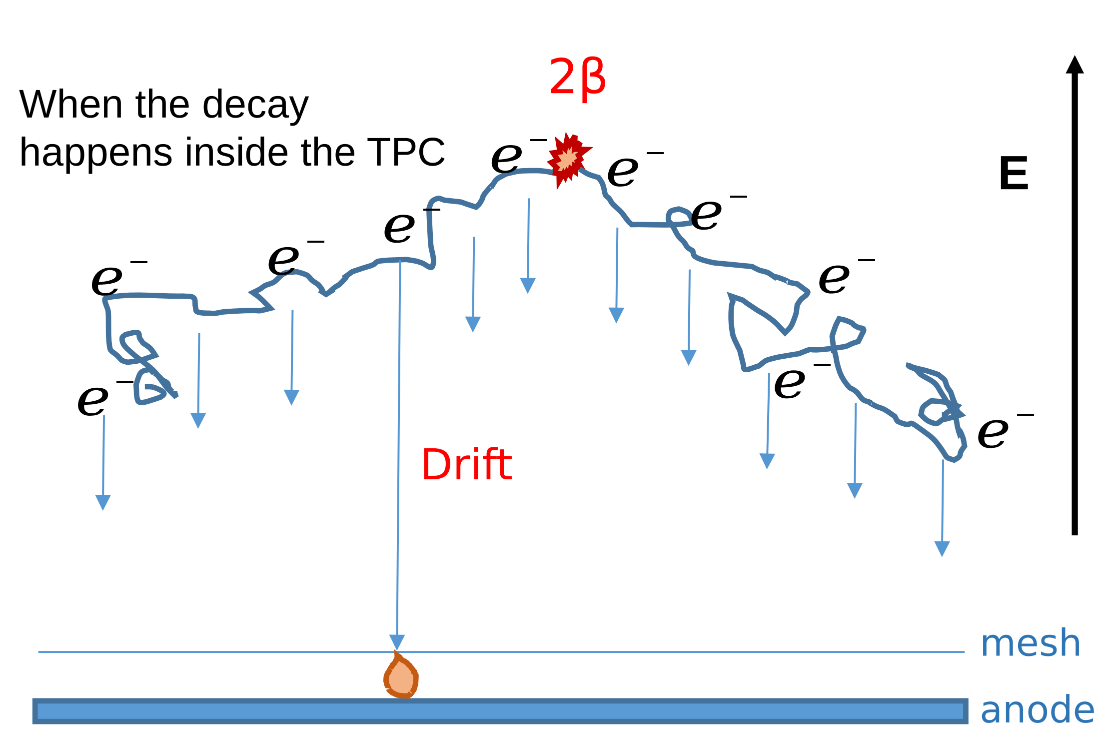
Track path minimization was applied



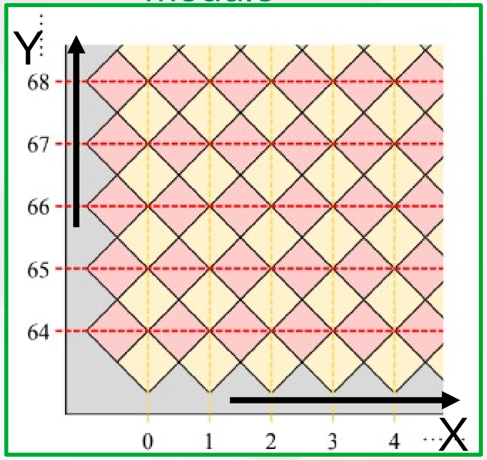
➤ PandaX-III experiment

128 **channels** per **Microbulk Micromegas** module

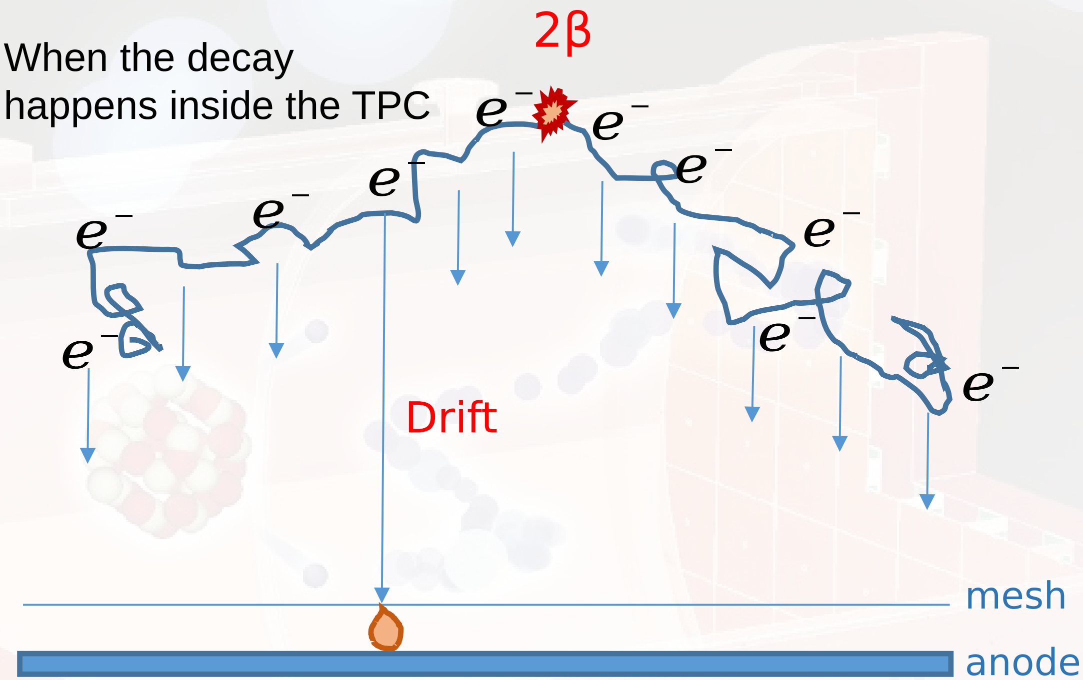


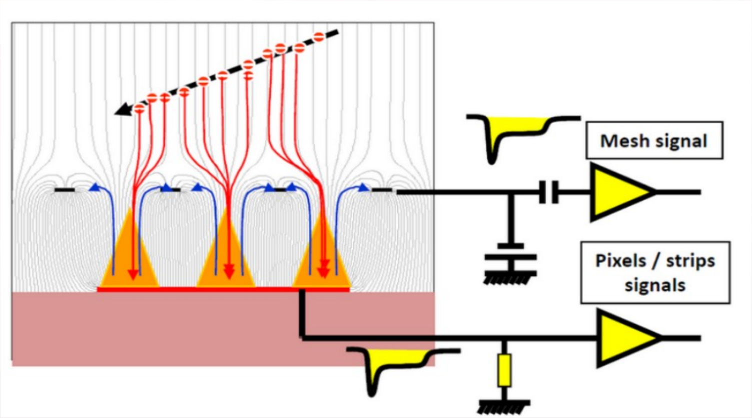


128 **channels** per
Microbulk Micromegas
module



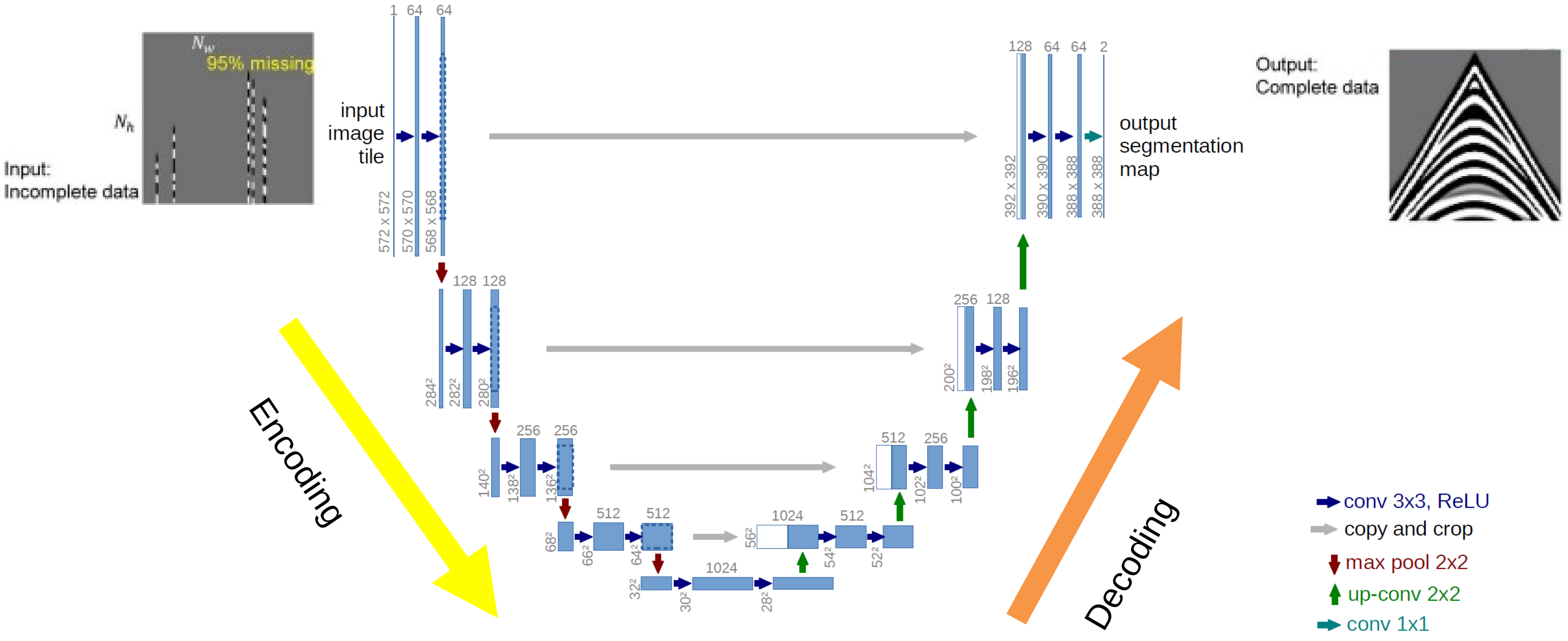
When the decay
happens inside the TPC





Possible approaches to resolve missing channels problem

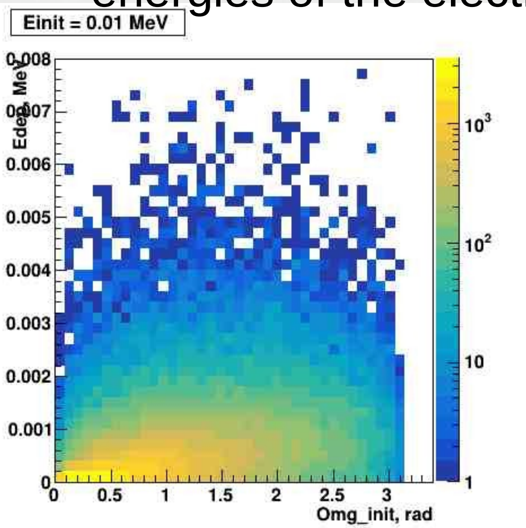
U-Net Convolutional Neural Network architecture

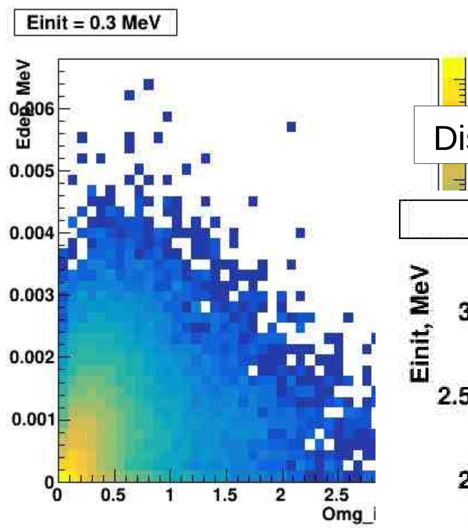


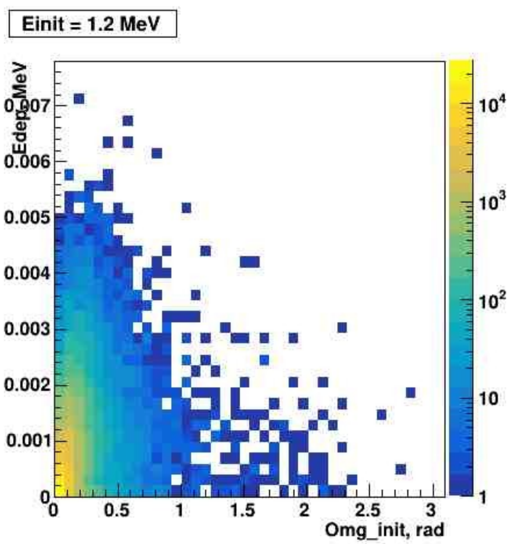
(2020) 10:3302 | https://doi.org/10.1038/s41598-020-59801-x

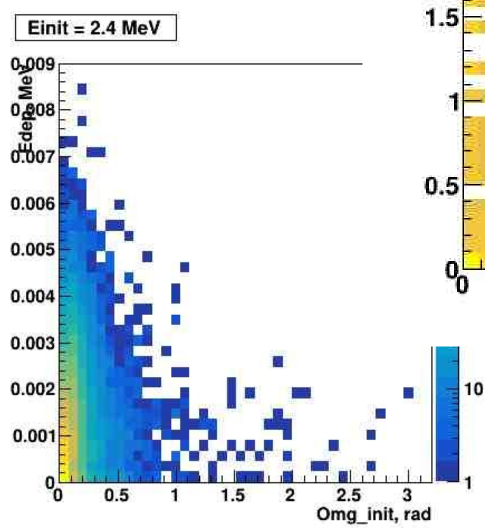
➢ Missing channels problem

Distribution of the scattered angle wrt energy deposition for different kinetic energies of the electron



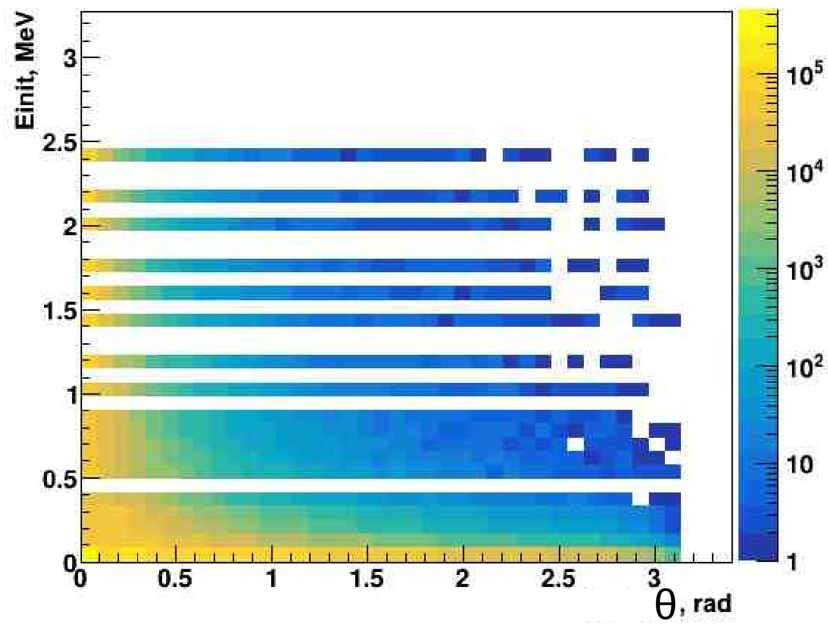


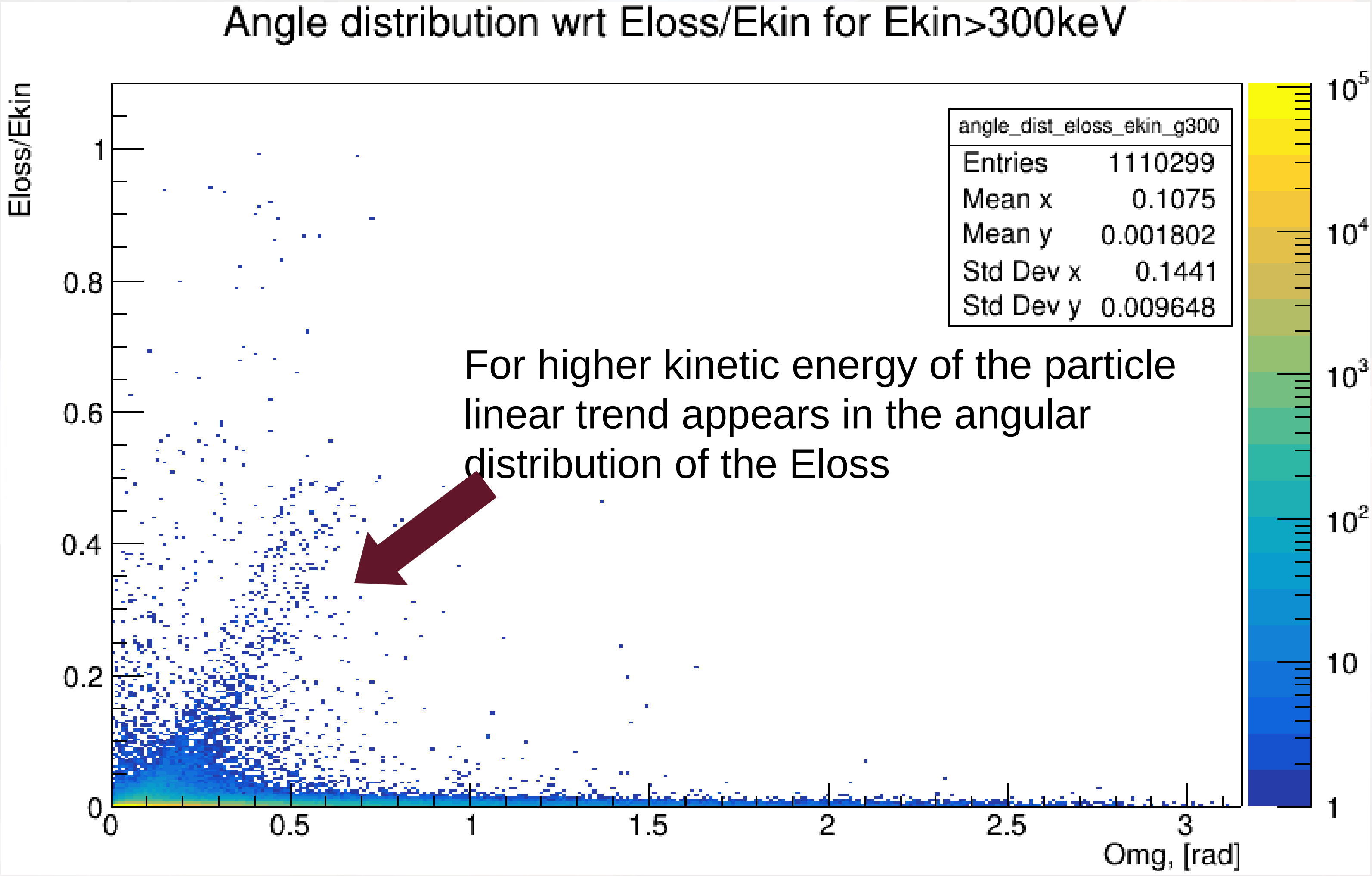




Distribution of θ wrt the Kinetic energy of the particle

θ variation for 200eV - 2.4MeV




Angle distribution wrt Eloss/Ekin for Ekin>300keV
Eloss/Ekin
Omg, [rad]
angle_dist_eloss_ekin_g300
Entries 1110299
Mean x 0.1075
Mean y 0.001802
Std Dev x 0.1441
Std Dev y 0.009648
For higher kinetic energy of the particle linear trend appears in the angular distribution of the Eloss