Features Analysis of Particle Tracks and Sensitivity Estimation in PandaX-III Experiment[1,2]

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[1] Li, T. *et al.* *JHEP* **06,** 106 (2021).
[2] Li, T. *et al.* *JHEP* **05,** 200 (2023).

Search for neutrinoless double beta decay

Experimental sensitivity to the half-life of $0\nu\beta\beta$

$$T^{0\nu}_{1/2} = \frac{ln2}{3} \cdot \frac{N_A \epsilon a}{W} \sqrt{\frac{M \cdot t}{b \cdot dE}}$$

- N_A: the Avogadro's number;
- ϵ: the signal detection efficiency in the ROI;
- a: the isotopic abundance of the parent isotope;
- W: molar mass of the source;
- M: the source mass;
- t: the measurement time;
- b: the background index;
- dE: the detector energy resolution;

Design criteria

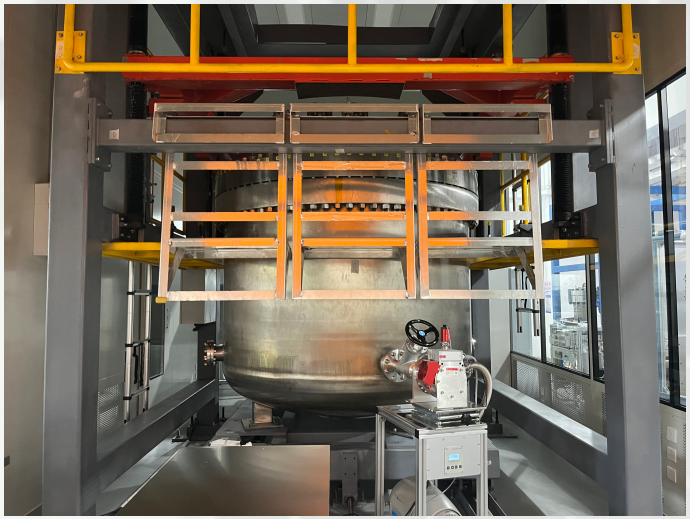
- isotope choices;
- Backgrounds control;
- Detector strategies;

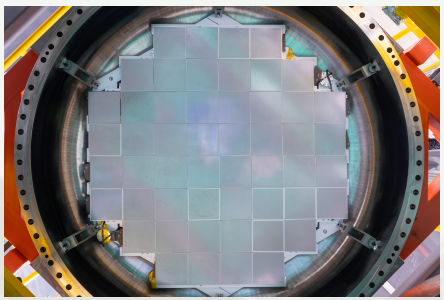
Candidate isotopes	Natural abundance(%)	$Q_{\beta\beta}$ (MeV)
^{48}Ca	0.187	4.2737
^{76}Ge	7.8	2.0391
^{82}Se	9.2	2.9551
^{100}Mo	9.6	3.0350
^{130}Te	34.5	2.5303
^{136}Xe	8.9	2.4578
^{150}Nd	5.6	3.3673

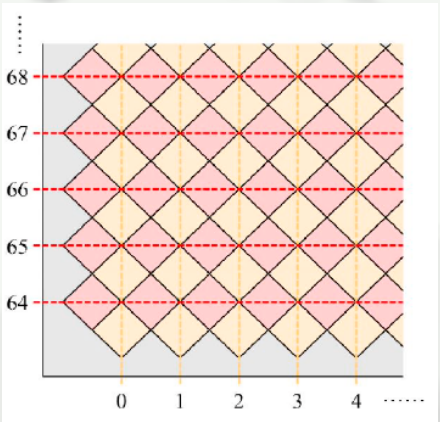
PandaX-III experiment

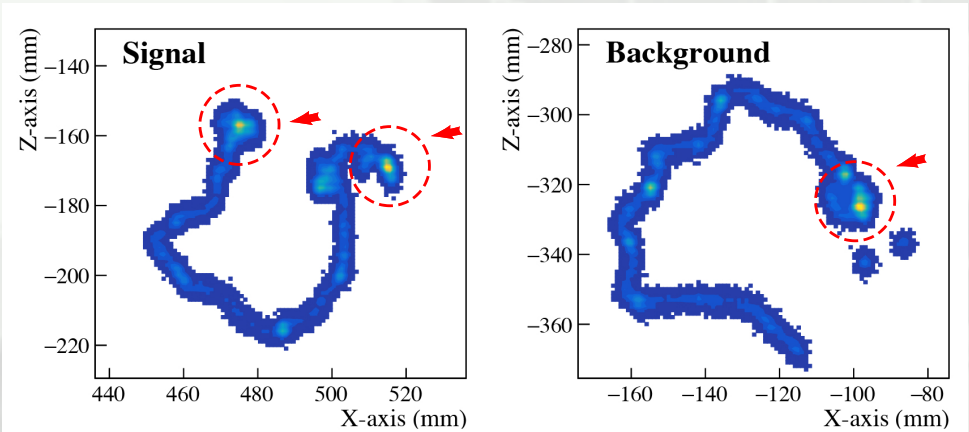
High-pressure gas-phase TPC

- 3 % FWHM @$Q_{\beta\beta}$=2.458 MeV;
- Active volume: 1.6 m in diameter and 1.2 m high;
- 137 kg of enriched xenon gas(1% TMA) in 10 bar;
- Readout: 52 modules of 20 cm $\times$ 20 cm (3 mm strips).









1. t_0 **(or the event vertex z_0) is not directly available due to the loss of scintillation light signal.**
2. **Track features can be extracted more effectively for signal identification.**

Motivation

Focus on the track features:

- **Signal identification based on Kalman filter:** $b \downarrow$;

Track reconstruction → **Topological analysis** → **Signal identification**

- z_0 **reconstruction based on CNN:** $b \downarrow$ and $dE \downarrow$;

Z_0 reconstruction → **Electron lifetime estimation** → **Spectrum correction; FV selection;**

Sensitivity of $0\nu\beta\beta$ half-life:

$$T^{0\nu}_{1/2} = \frac{ln2}{3} \cdot \frac{N_A \epsilon a}{W} \sqrt{\frac{M \cdot t}{b \cdot dE}}$$

b: the background index;

dE: the detector energy resolution;

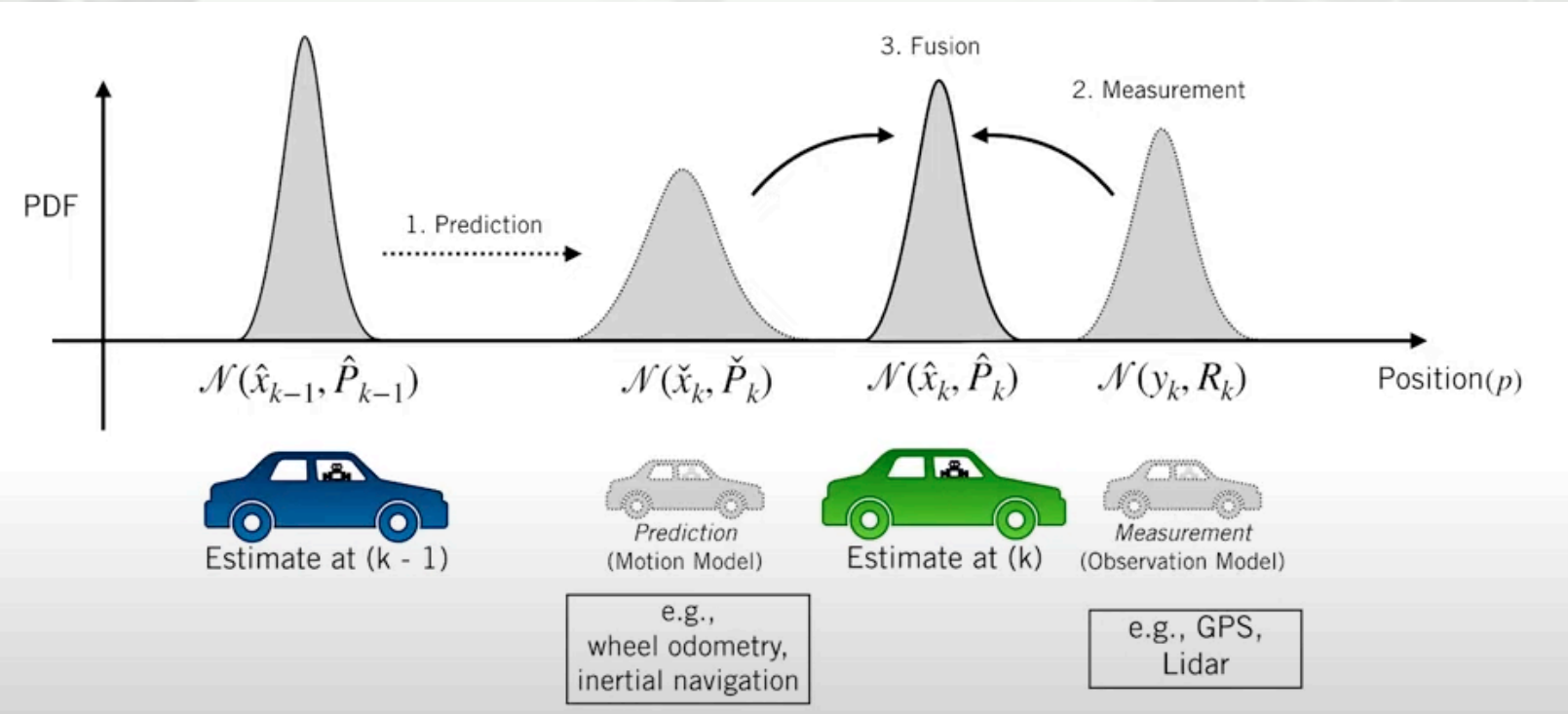
- **Finally improvement on experimental sensitivity to the half-life of $0\nu\beta\beta$!**

What is the Kalman filter?

An optimal linear estimator.

- Prediction and correction;
- minimum variance estimation;

$$\begin{cases} x_k = Fx_{k-1} + \omega_k \\ y_k = Hx_k + \delta_k \end{cases}$$



Kalman filter in a Bayesian formalism (KFBF)

6D Kalman filter model in our method:

Coulomb scattering: $\theta_{space}^{rms} = \frac{19.2\,\mathrm{MeV}}{pv}\sqrt{\lambda_0}[1 + 0.038\ln\lambda_0]$

State equation: $x_k = Fx_{k-1} + \omega_k$

Measurement equation: $y_k = Hx_k + \delta_k$

State vector

Process noise

Bayesian formula

Measurement vector

Measurement noise

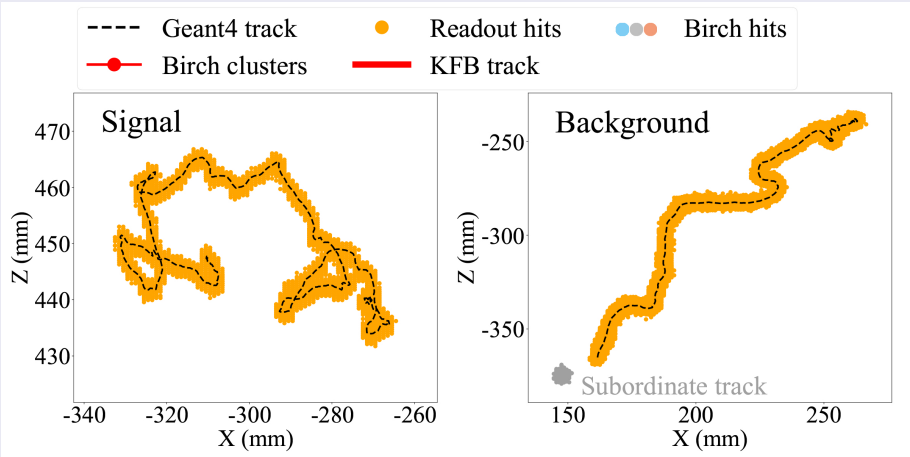
Bayesian formula:

The most likely value for both the noise items.

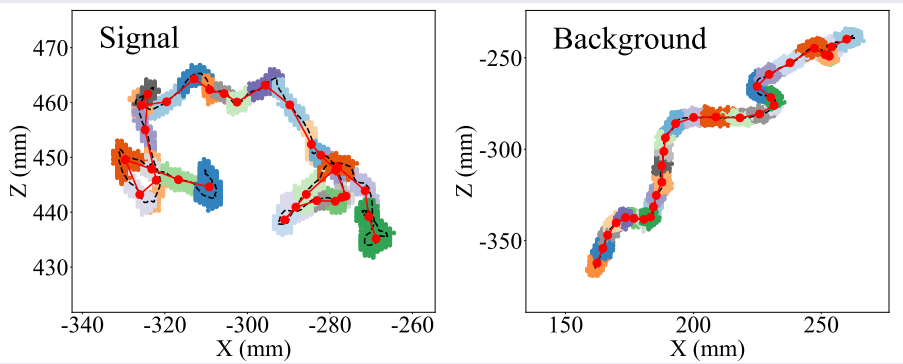
$$[Q_k,\ R_k] = \underset{Q_i\in\mathbb{Q},R_j\in\mathbb{R}}{\arg\max}\ (P(Q_i,\ R_j\,|\,\mathcal{M}^k)).$$

Track reconstruction

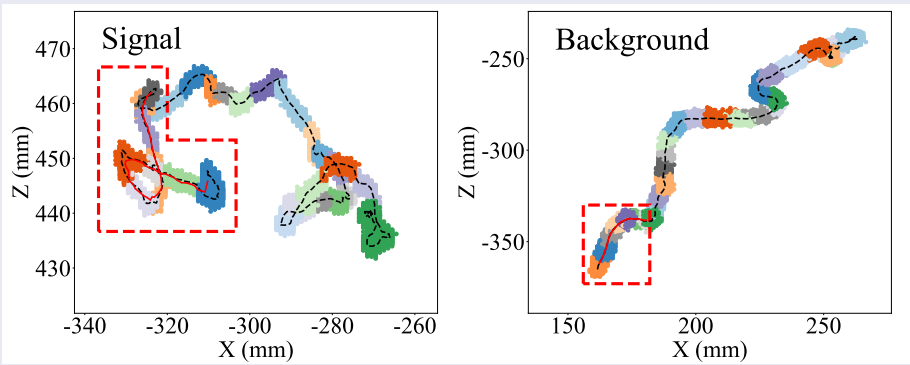
I: identification of the principle track:



II: Rough reconstruction:



III: Fine reconstruction (KFBF):



E_{Space}: The energy in a unit volume (57 mm) around the energy-weighted center of the event;

E_p: The total deposited energy of the principal track.

N_{Tracks}: The total number of the event track;

E_{BB}: The deposited energy in Bragg blob with radius 12 mm;

dE_{dx}: The energy loss per unit travel length.

$\hat{P}$: The momenta at the ends of the reconstructed track;

Estimation of $0\nu\beta\beta$ Sensitivity

The estimation of background level is 152 CPY. After the BDT cut, the background rate is 0.48 CPY. An improvement on sensitivity by a factor of 2.7 (2.4).

Comparation	Overall efficiency	background counts in 5 yr	significance	Sensitivity (90% C.L.)
This work	34.7%	2.4	**8.8**	**2.7×10^{26} yr**
Design target[3]	35.0%	25.3	2.8	9.8×10^{25} yr
Work before[4]	23.2%	7.6	3.3	1.1×10^{26} yr

Table: The $0\nu\beta\beta$ half-life sensitivity estimation of PandaX-III based on MC data.

Assuming 1 t Xenon and (3 mm, 1%), the background rate is 0.11 CPY, pushing the search towards background-free regime.

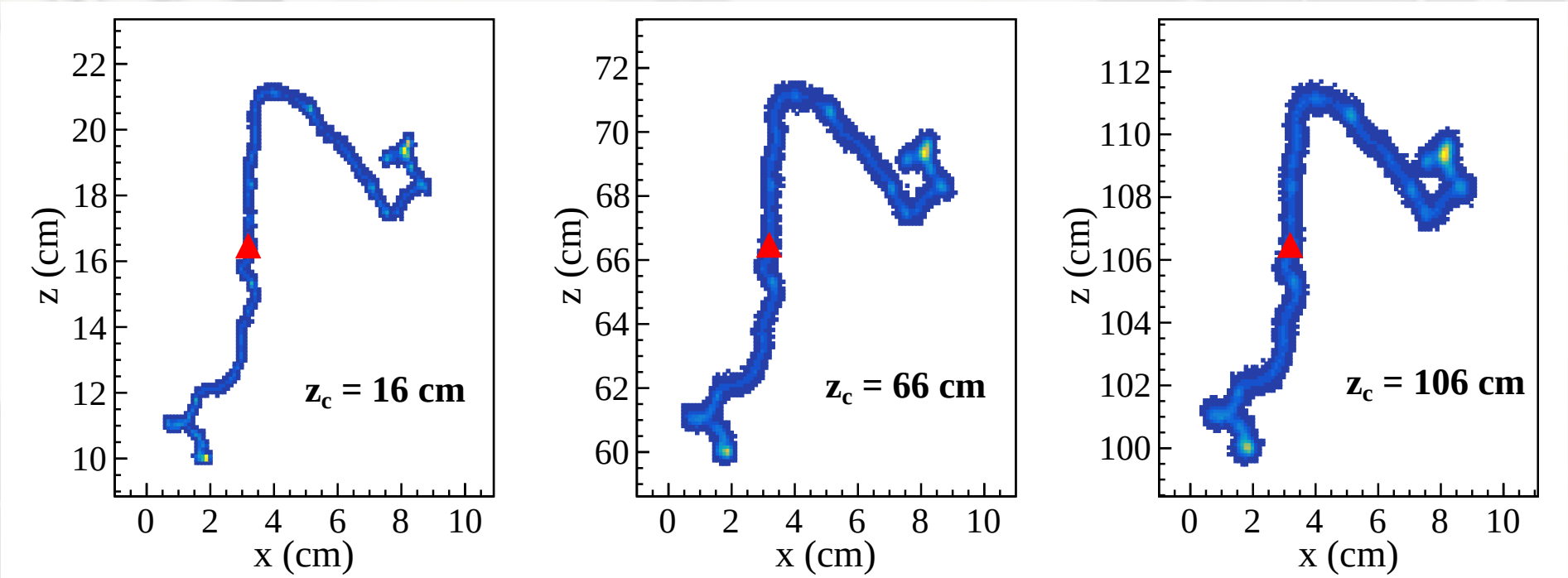
[3] Chen, X. *et al.* PandaX-III: Searching for neutrinoless double beta decay with high pressure 136 Xe gas time projection chambers. *Science China Physics, Mechanics & Astronomy* **60,** 1–40 (2017).

[4] Galan, J. *et al.* Topological background discrimination in the PandaX-III neutrinoless double beta decay experiment. *Journal of Physics G: Nuclear and Particle Physics* **47,** 045108 (2020).

Event vertex reconstruction in PandaX-III

t_0/z_0 loss

- Distortion of energy spectrum due to electron attachment effect;
- Events near the readout plane and cathode can't be identified (Radon degassing).
- Electron diffusion effect: z_0 is revealed in the degree of trajectory dispersion.

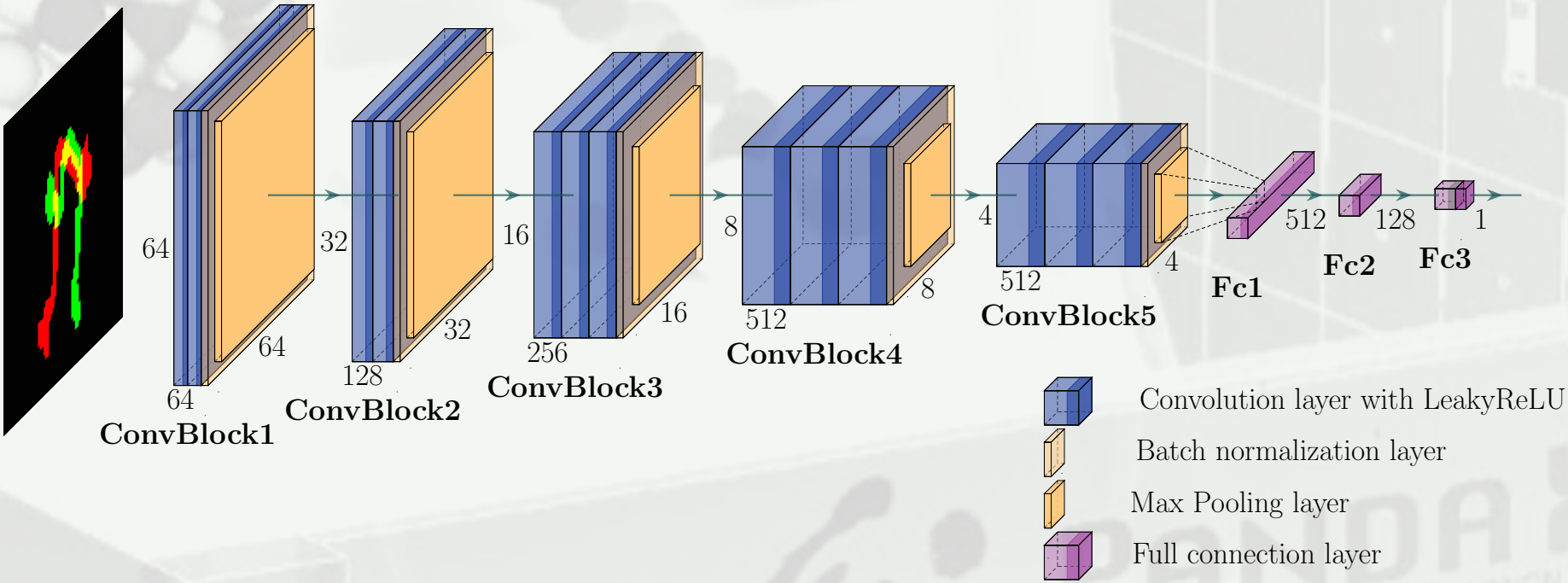


The simulated tracks for the same $0\nu\beta\beta$ event with different z_c of 16 cm, 66 cm, and 106 cm.

VGGZ0net

A customized *VGG16* model for z_c regression.

- Input: RGB Images consisting of 64×64 pixels (only the principle tracks);
- Label: The Z position of event charge center z_c;

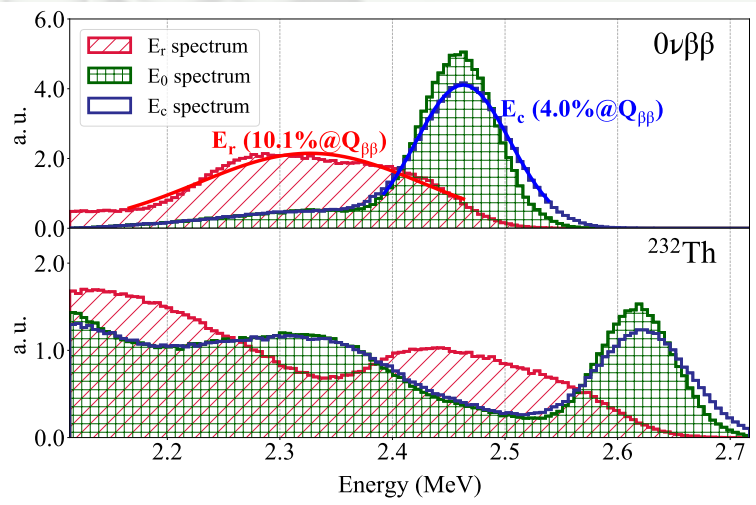


The Structure of VGGZ0net based on VGG16 classification model.

Correction on energy spectrum

Energy correction:

$$E_c = E_r / e^{-\hat{l}_e/\hat{z}_c}$$



The energy spectrum under 1200 cm hypothetical electron lifetime.

Table: The performance of vertex reconstruction and energy correction based on VGGZ0net in different electron lifetime scenarios. The corrected energy resolution at $Q_{\beta\beta}$ is presented.

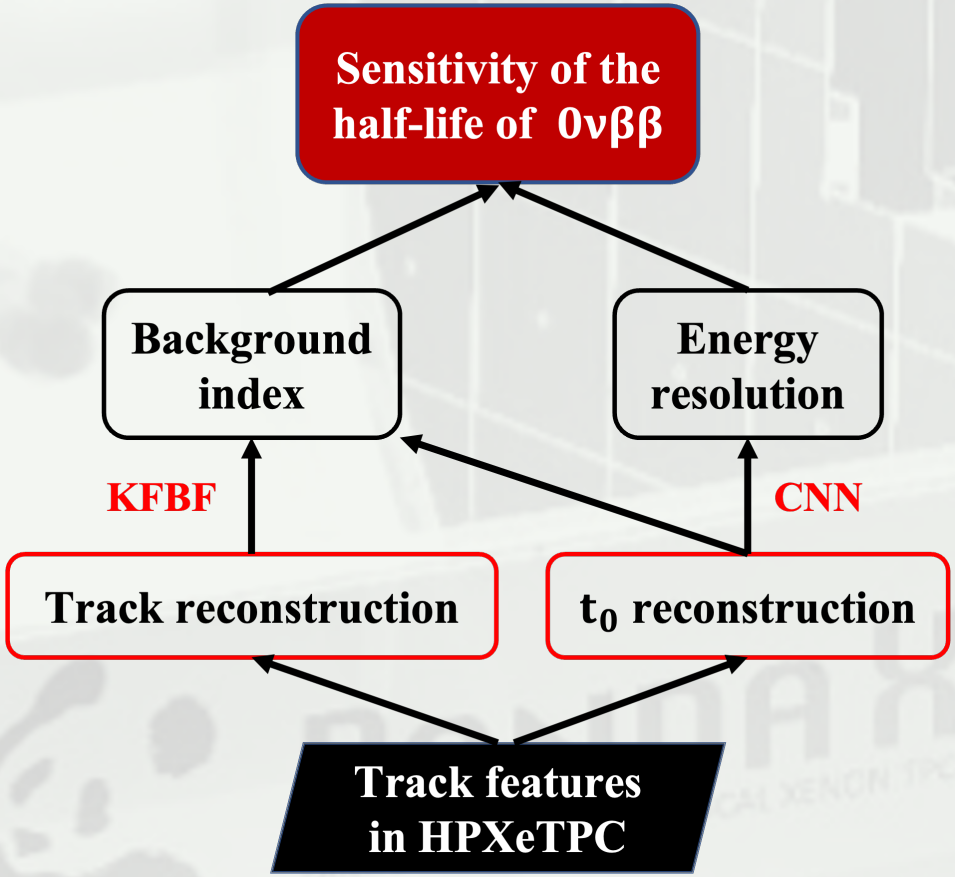
l_e (cm)	$\sigma(\Delta z)$ (cm)	$\hat{l}_e$ (cm)	Corrected FWHM
Infinity	11	-	3.3 %
2000	11	2015 ± 55	3.4 %
1800	11	1815 ± 53	3.5 %
1600	11	1614 ± 42	3.6 %
1400	11	1408 ± 33	3.7 %
1200	11	1217 ± 30	4.0 %
1000	11	1008 ± 25	4.2 %
800	11	809 ± 20	4.6 %

Summary

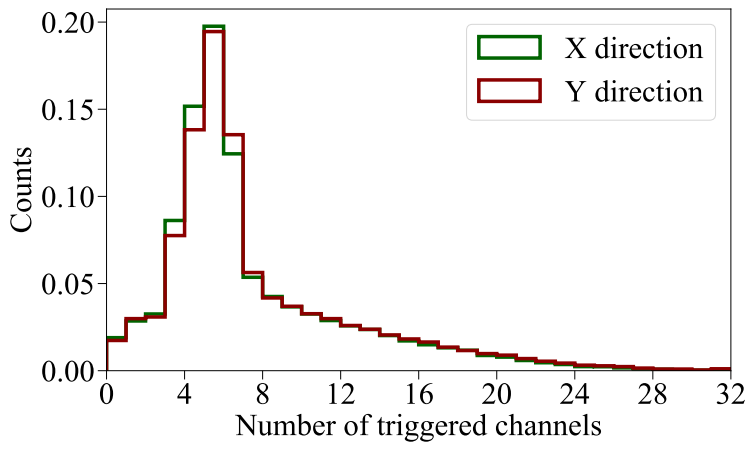
The PandaX-III experiment has great advantage to search for $0\nu\beta\beta$ due to its excellent ability of track measurement.

Focusing on the particle track features:

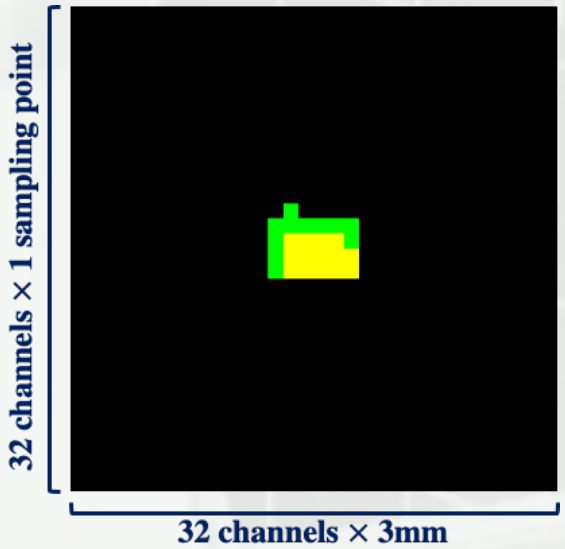
- Improve the sensitivity of PandaX-III experiment in the search for $0\nu\beta\beta$ by nearly 3 times;
- Build a CNN regression model VGGZ0net to reconstruct event vertex;
- Push the search towards background-free regime;



Data preparation

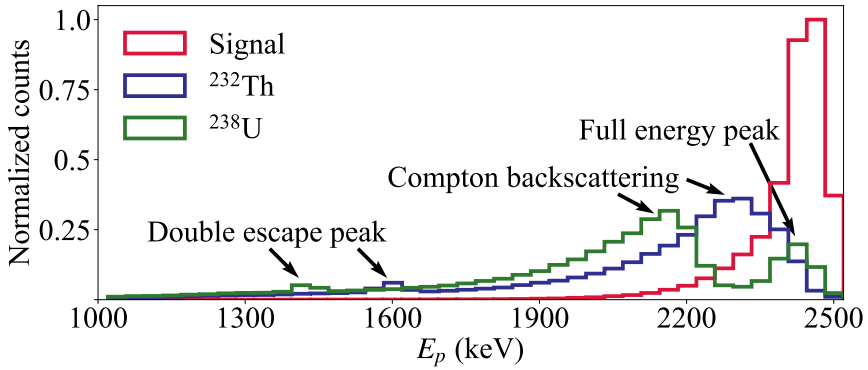


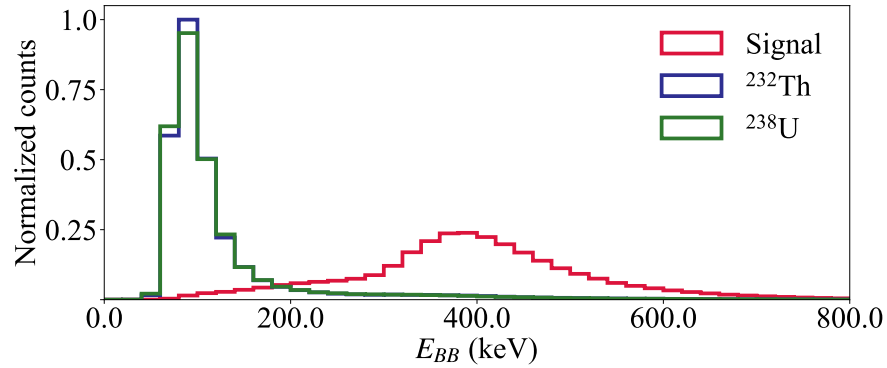
The distribution of triggered channels on XZ and YZ plane.

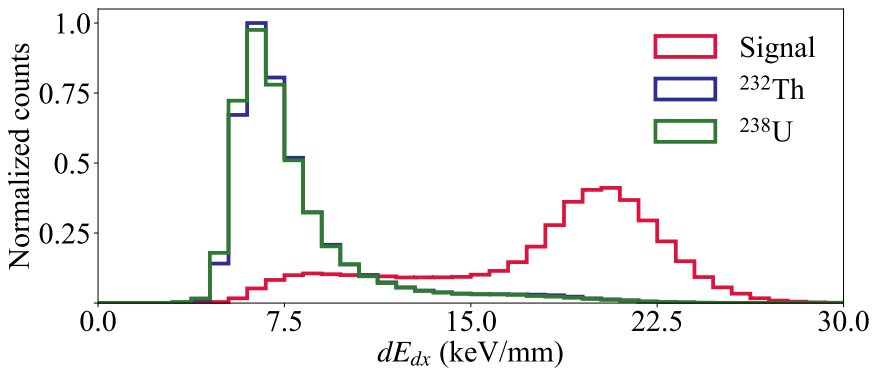


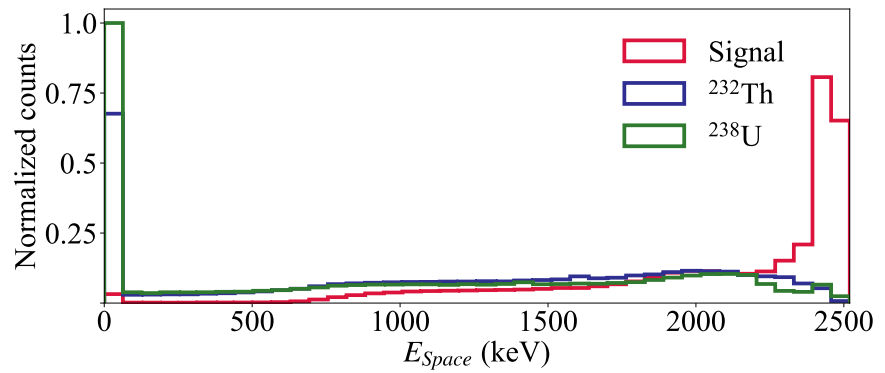
an example of RGB image conversion. the RGB image size is arranged to 32×32.

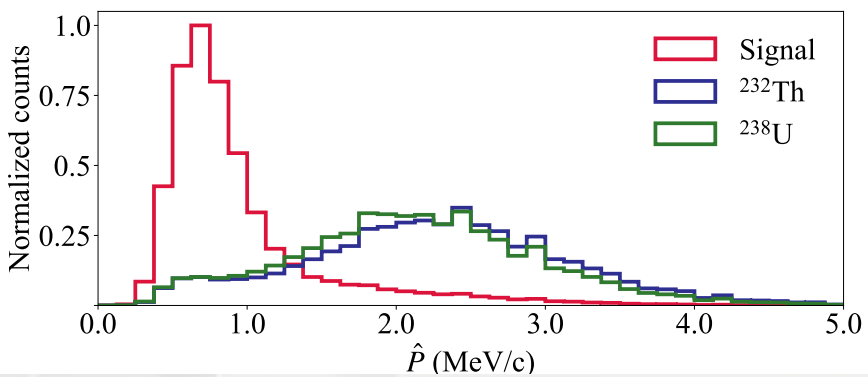
Distribution of track feature parameters

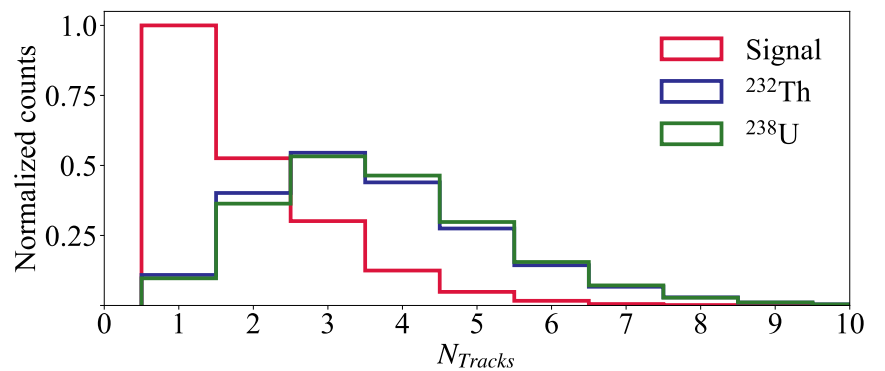












Identification of signal and background

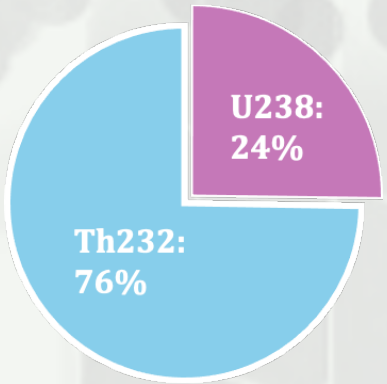
ϵ_s: the signal efficiency; ϵ_b: the background efficiency;

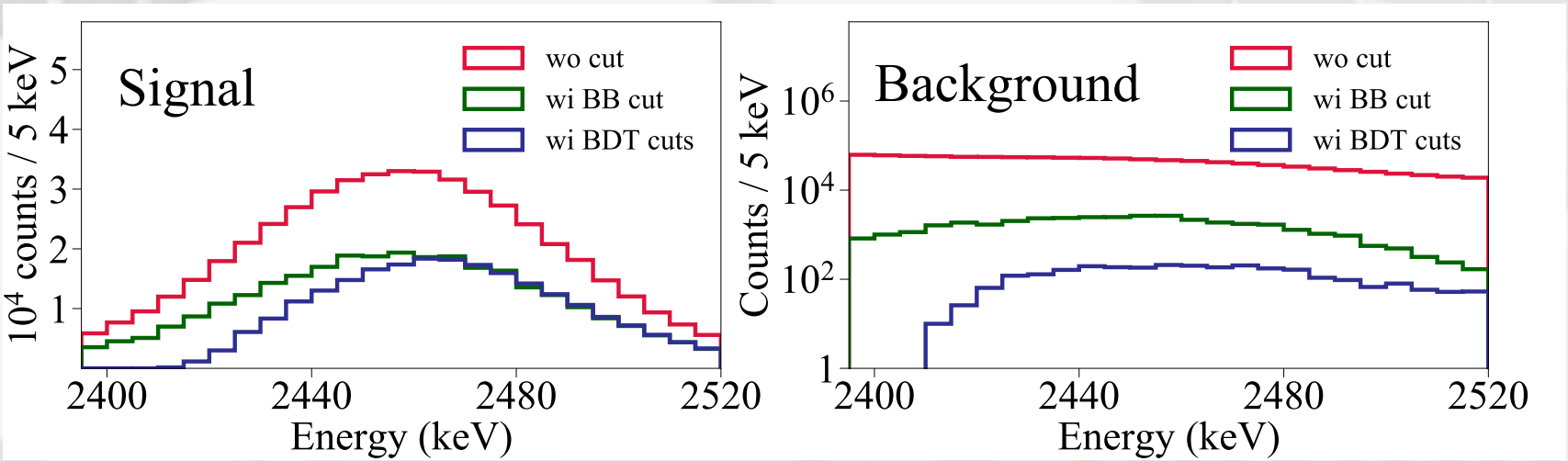
Ξ: the signal significance, $\Xi = \epsilon_s/\sqrt{\epsilon_b}$;

Configurations	BDT Cuts					
	^{232}Th			^{238}U		
	ϵ_s	ϵ_b	Ξ	ϵ_s	ϵ_b	Ξ
(1 mm, 3%)	0.34	4.7×10^{-4}	15.7	0.49	2.8×10^{-3}	9.3
(1 mm, 6%)	0.35	1.2×10^{-3}	10.1	0.57	4.2×10^{-3}	8.8
(3 mm, 3%)	0.39	6.7×10^{-4}	15.1	0.51	3.4×10^{-3}	8.7
(3 mm, 1%)	0.50	8.2×10^{-4}	17.5	0.40	1.5×10^{-3}	10.3
(3 mm strip, 3%)	0.32	8.3×10^{-4}	11.1	0.46	4.6×10^{-3}	6.8

Background estimation

- **The background level is 152 CPY;**
- **The majorities of the background are from the acrylic field cage, the copper liner, and the stainless vessel.**



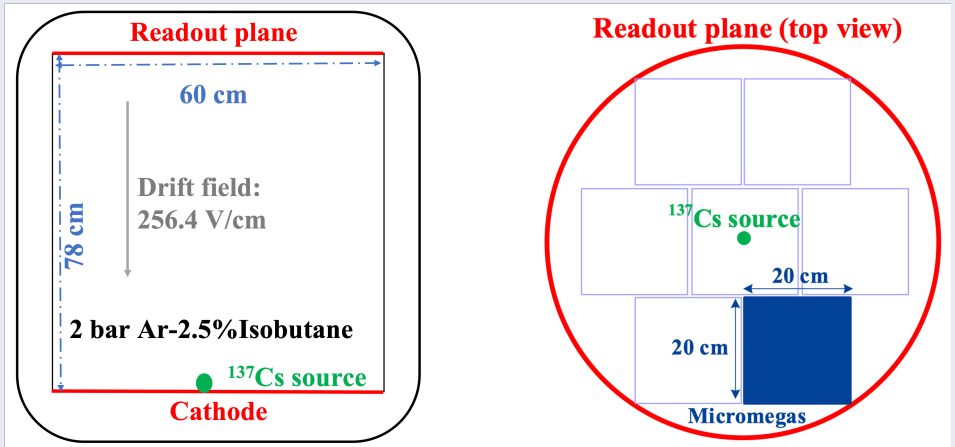


Effects of BB cut and BDT cuts for the signal (left) and background (right).

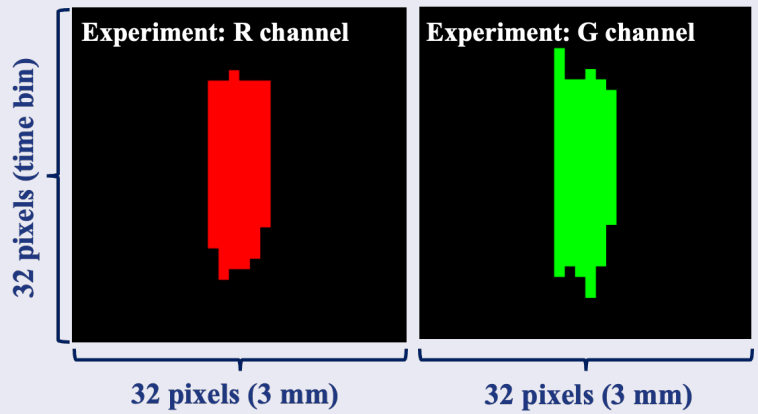
The background count after BDT cuts obviously goes down by about an order of magnitude compared with that after BB cut.

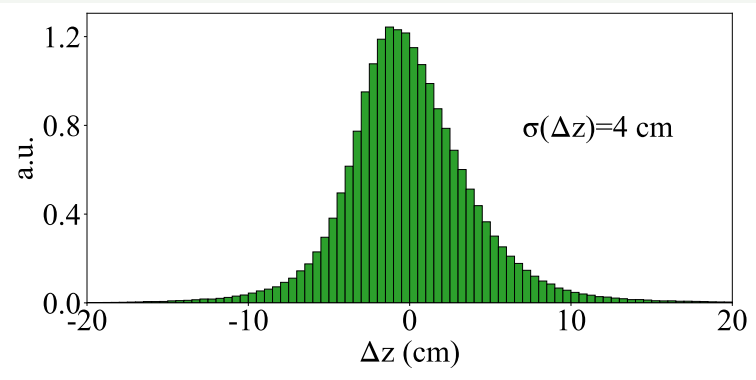
Validation through experimental data in prototype

Prototype installation:

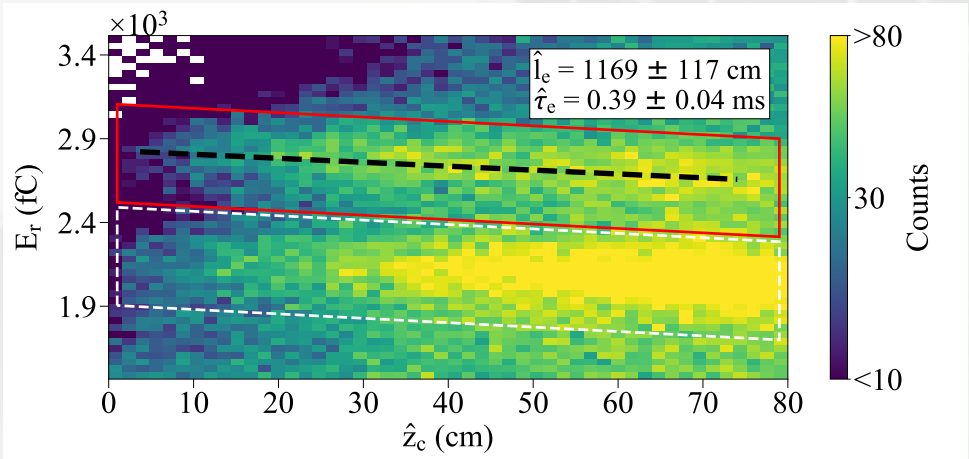


Input RGB images of ^{83m}Kr:





The prediction performance of VGGZ0net.



The distribution of E_r along $\hat{z}_c$ of experimental data.