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

Tao Li / 李涛
(on behalf of the PandaX-III collaboration)

Sino-French Institute of Nuclear Engineering and Technology
Sun Yat-sen University

July 18, 2023

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

Outline

Neutrinoless double beta decay

Neutrinoless double beta decay ($0\nu\beta\beta$)

$${}^{N}_{Z}A \rightarrow {}^{N-2}_{Z+2}A + 2\beta^{-}$$

Half-life of $0\nu\beta\beta$

$$T^{0\nu}_{1/2} = (G_{0\nu}|\mathrm{M}^{0\nu}|^2 < m_{\beta\beta} >^2)^{-1}$$
$$\approx 10^{27-28}(\frac{0.01\ eV}{<m_{\beta\beta}>})^2 \text{ yr}$$

Ettore Majorana.

Search for $0\nu\beta\beta$

- Neutrino is Majorana particle;
- Lepton number violation and asymmetry of matter-antimatter;
- Origin of neutrino mass;

$0\nu\beta\beta$ experiment

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

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

- N_A: the Avogadro's number;
- ϵ: the signal detection efficiency in the ROI;
- a: the isotopic abundance of the 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

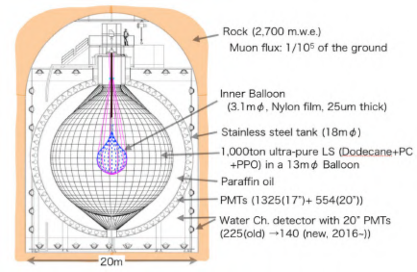
- isotope choices;
- Backgrounds control;
- Detector strategies;

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

$0\nu\beta\beta$ experiment

KamLAND-Zen(^{136}Xe)

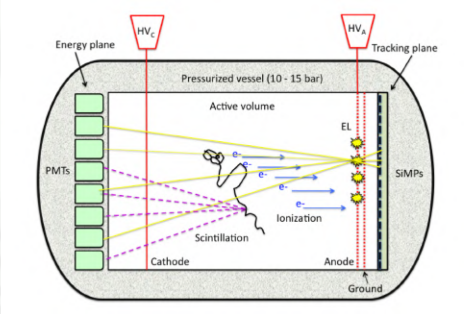
Xe-LS is contained in a 25 μm-thick nylon ”mini-balloon”.



KamLAND-Zen detector.
$T_{1/2} > 2.3 \times 10^{26}$ yr (90 % C.L.).

NEXT(^{136}Xe)

A planned high-pressure gas-phase xenon TPC that employs amplification via electroluminescence.

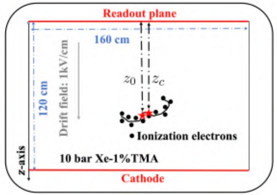


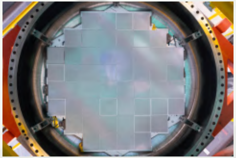
NEXT detector.

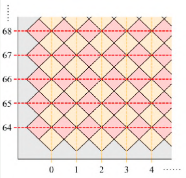
PandaX-III experiment

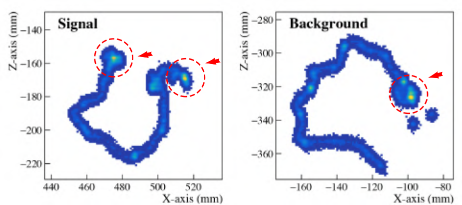
High-pressure gas-phase TPC

- 3 % FWHM @$Q_{\beta\beta}$=2.458 MeV;
- Active volume: 1.6 m in diameter and 1.2 m high;
- 140 kg of enriched xenon gas(1% TMA) in 10 bar;
- Readout: 52 modules of 20 cm × 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:** Suppress the background events in ROI ($b \downarrow$);

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

- z_0 **reconstruction based on CNN:** Correct spectrum due to electron lifetime ($dE \downarrow$);

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

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

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

b: the background index;

dE: the detector energy resolution;

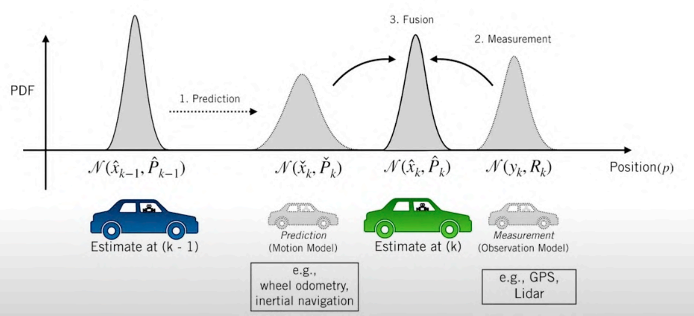
- **Finally improvement on experimental sensitivity to the half-life of $0\nu\beta\beta$!**

What is the Kalman filter?

An optimal linear estimator through iteration

$$\begin{cases} x_k = Fx_{k-1} + \omega_k & \text{(State equation)} \\ y_k = Hx_k + \delta_k & \text{(Measurement equation)} \end{cases}$$

- Prediction and correction;
- minimum variance estimation;



Kalman filter in a Bayesian formalism (KFBF)

6D Kalman filter model in our method:

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

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

Measurement equation: $y_k = Hx_k + \delta_k$

State vector: x_k; Process noise: ω_k; Measurement vector: y_k; Measurement noise: δ_k → Bayesian formula

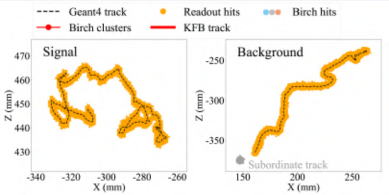
Bayesian formula:

The most likely value for both the noise items.

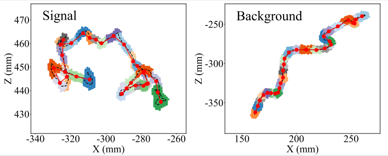
$$[\omega_k,\, \delta_k] = \underset{\omega_i \in \omega,\, R_j \in \delta}{\arg\max}\, (P(\omega_i, \delta_j \,|\, y^k)).$$

Track reconstruction

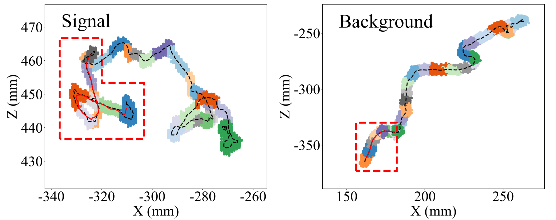
I: identification of the principle track:



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;

Identification of signal and background

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

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

(Readout granularity, Energy resolution)	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

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).

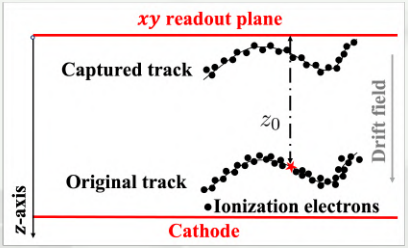
[4] Galan, J. *et al.* Topological background discrimination in the PandaX-III neutrinoless double beta decay experiment. *Journal of Physics G: Nuclear and Particle Physics* **47**, 045108 (2020).

Electron lifetime and energy resolution

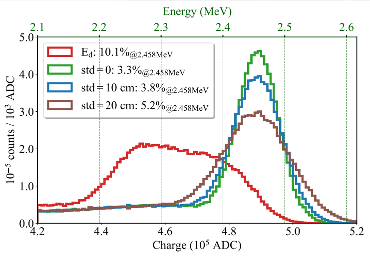
t_0/z_0 loss in PandaX-III

- Events near the readout plane and cathode can't be identified (Radon degassing).
- Distortion of energy spectrum due to electron attachment effect;
  Electron lifetime τ_e:

$$\tau_e = (\eta_a \nu_d)^{-1}; E_0 = E_r * e^{-z_0/\tau_e} = \mathbf{F}(E_r; z_0, \tau_e) \quad (1)$$



z_0 in PandaX-III TPC

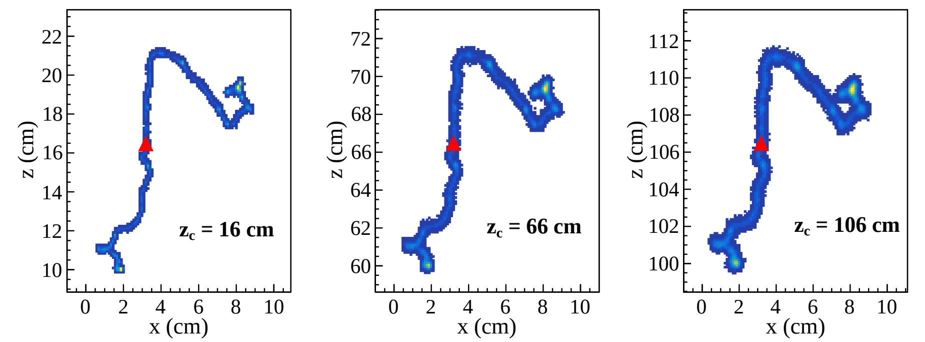


Spectrum correction from a toyMC assuming τ_e=1200 cm.

Electron diffusion effect

z_0 is revealed in the degree of trajectory dispersion.

$$\sigma^2_{L,T} = \sigma^2_{0L,T} + 2 \cdot D_{L,T} \cdot z_0, \tag{2}$$

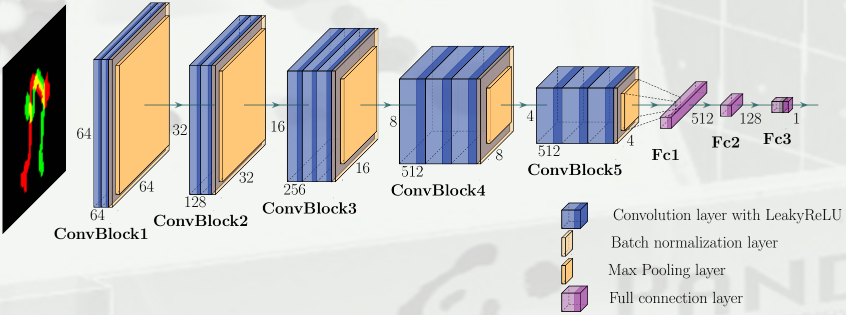


The simulated tracks (projection in xz plane) for the same $0\nu\beta\beta$ event with different z_c (red triangles) of 16 cm, 66 cm, and 106 cm.

Network architecture

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.

Performance on simulated validation dataset

Results under the $0\nu\beta\beta$ and ^{232}Th dataset of 1200 cm hypothetical electronic lifetime.

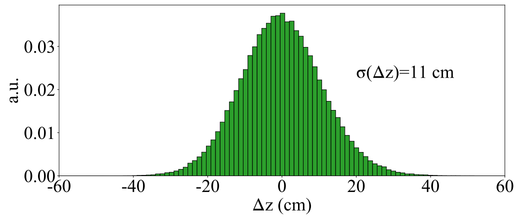
Energy correction:

$$E_c = E_r / e^{-\hat{l}_e/\hat{z}_c} \quad (3)$$

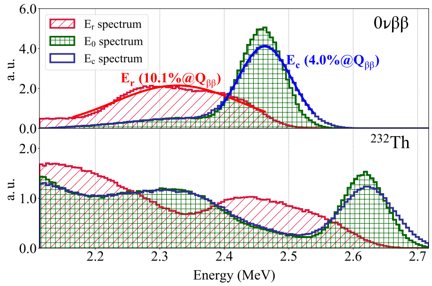
E_r: Raw energy affected by electron attachment;

E_c: Energy corrected by VGGZ0net;

E_0: Energy of the zero-attachment scenario;



The prediction performance of VGGZ0net model.



The energy spectra of simulated $0\nu\beta\beta$ (Top) and γ from ^{232}Th (Bottom) datasets.

Performance on simulated validation dataset

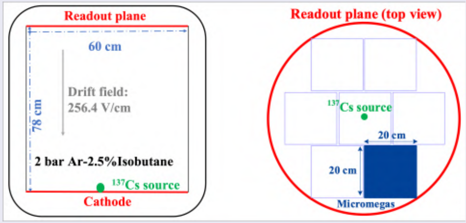
$\sigma(\Delta z)$: prediction error of VGGT0net; $\hat{l}_e, \hat{\tau}_e$: electron lifetime estimation;
l_e: Setting value of electron lifetime;

l_e (cm)	$\sigma(\Delta z)$ (cm)	$\hat{l}_e$ (cm)	$\hat{\tau}_e$ (ms)	Corrected energy resolution at $Q_{\beta\beta}$ (%) FWHM
Infinity	11	-	-	3.3
2000	11	2015 ± 55	10.83 ± 0.30	3.4
1800	11	1815 ± 53	9.76 ± 0.28	3.5
1600	11	1614 ± 42	8.68 ± 0.23	3.6
1400	11	1408 ± 33	7.57 ± 0.18	3.7
1200	11	1217 ± 30	6.54 ± 0.16	4.0
1000	11	1008 ± 25	5.42 ± 0.13	4.2
800	11	809 ± 20	4.35 ± 0.11	4.6

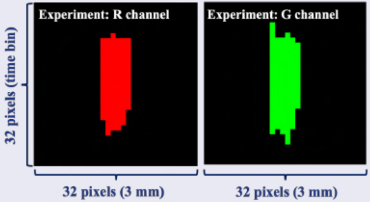
Table: The performance of vertex reconstruction and energy correction based on VGGZ0net in different electron lifetime scenarios. The corrected energy resolution at $Q_{\beta\beta}$ is presented.

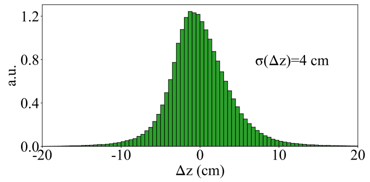
Validation through experimental data in prototype

Prototype installation:

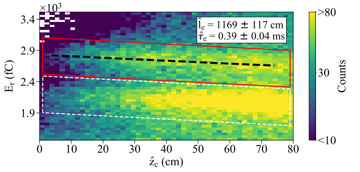


Input RGB images of ^{83m}Kr:





The prediction performance of VGGZ0net.



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

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;