Searching for Xe-136 Neutrinoless Double Beta Decay with PandaX-4T

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on behalf of PandaX Collaboration

TAUP @ Xichang

2025/08/25

PandaX: Particle and Astrophysical Xenon Experiment

PandaX Development

- Increasing the detector sensitive volume
- Lowering radioactive background

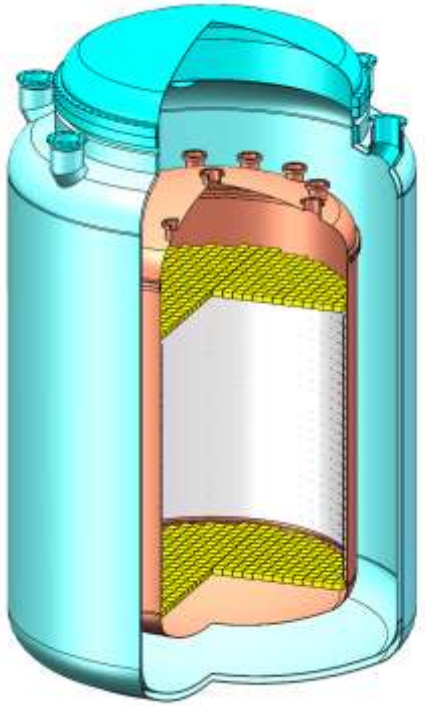
PandaX start

PandaX-I
120kg

PandaX-II
580kg

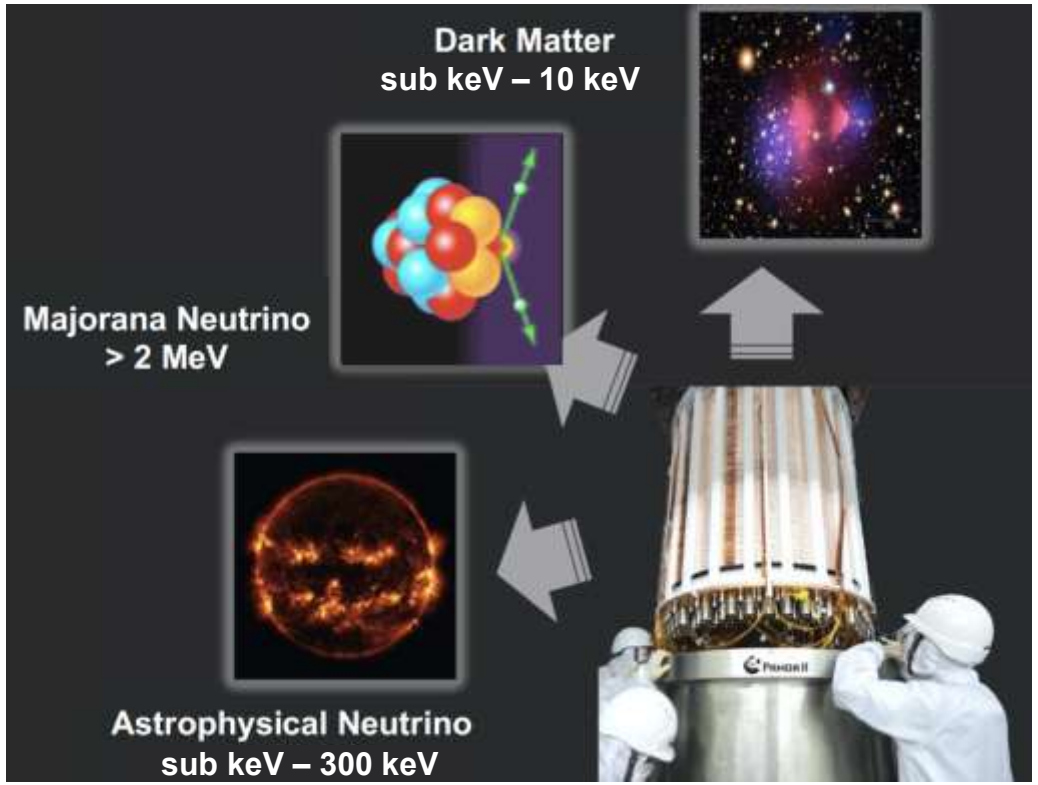
PandaX-4T
3.7 tonne

PandaX-xT



2009.3 | **2010 - 2014** | **2015 - 2019** | **2021 - Current** | **~ 2027**

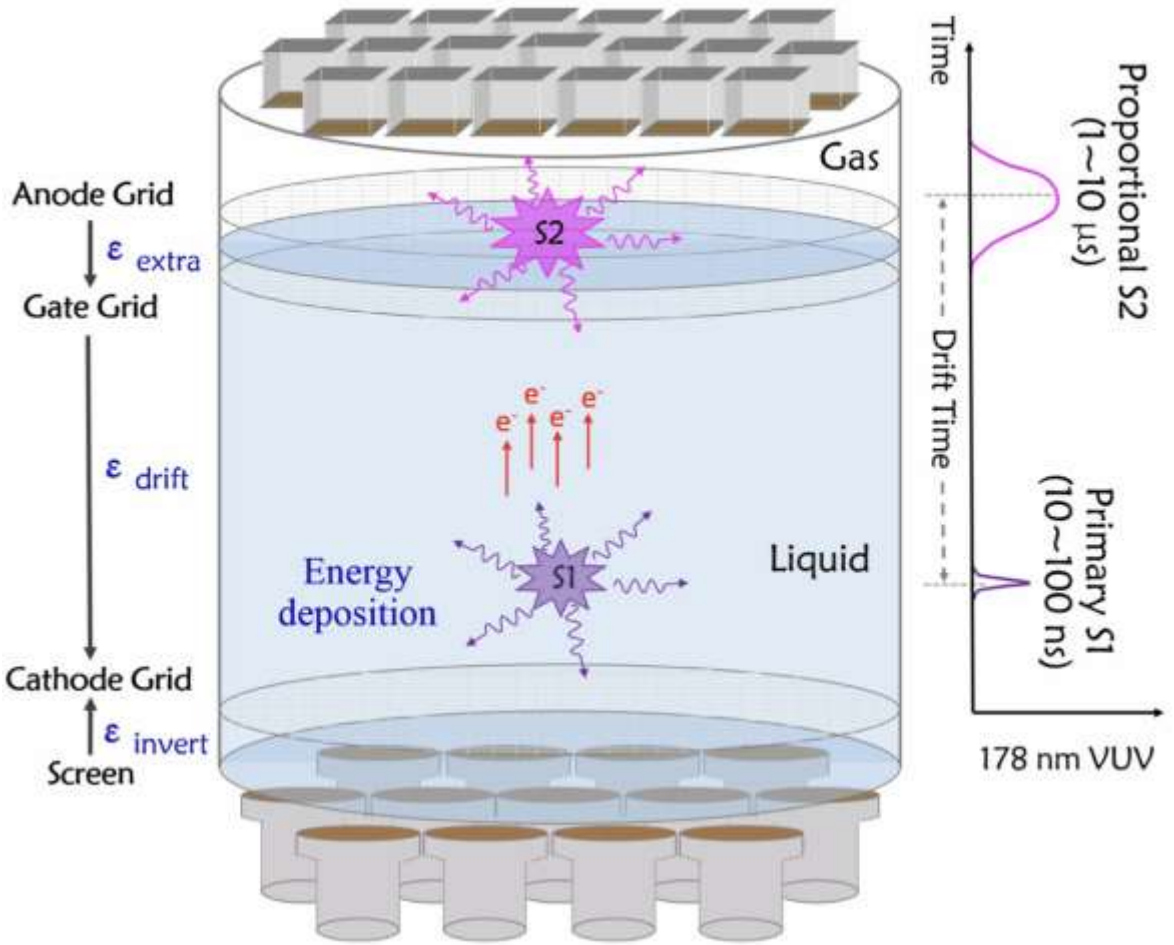
PandaX-4T

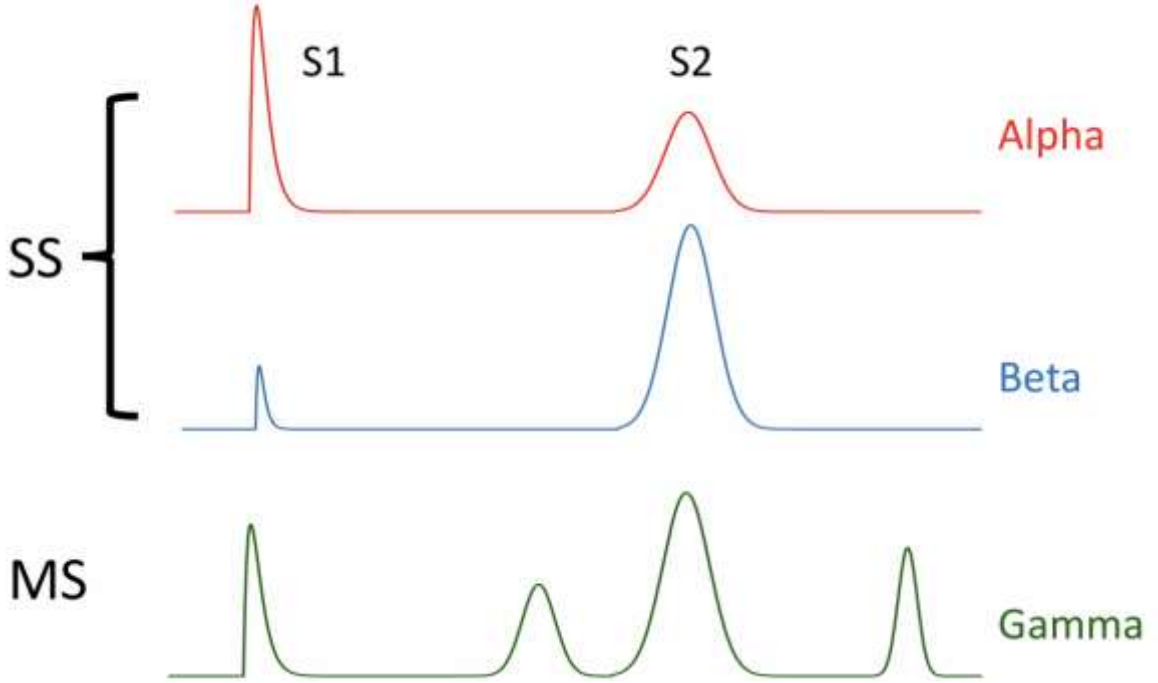


- CJPL: Deepest (2400 m rock, 6800 m.w.e);
- Extremely low cosmic-ray
- Calorimeter from sub keV to a few MeV
- Multi-physics targets

CJPL-II B2

Dual-phase Xenon Time Projection Chamber

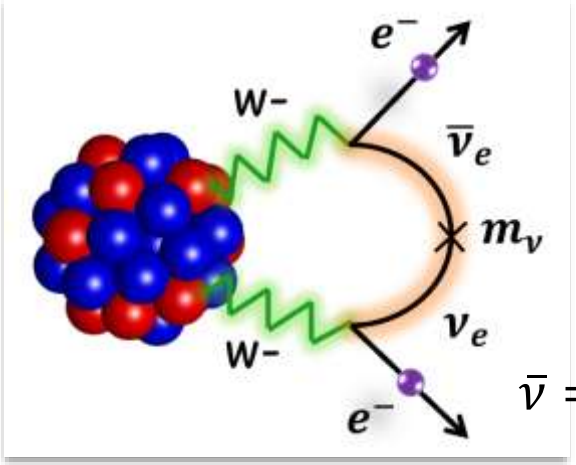




- Sensitive volume: 3.7t **natural Xenon**
- Dual-phase LXe TPC: 1.2 m (D) ×1.2 m (H)
- 3-inch PMTs: 169 top / 199 bottom
- 3D position reconstruction
- Single site (SS) / multiple site (MS) identification

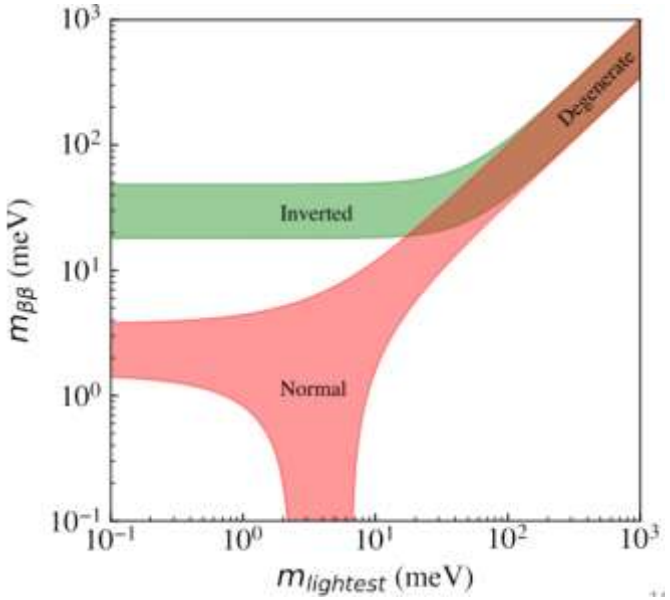
Neutrinoless Double Beta Decay (NLDBD)

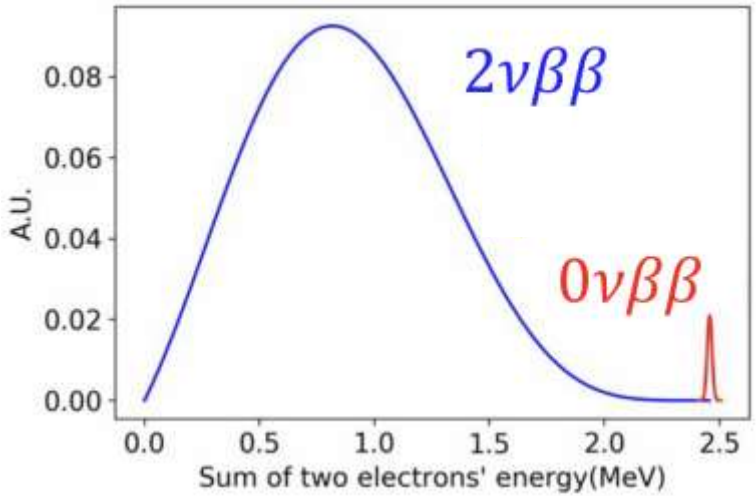
$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2\mathrm{e}^-$



$\bar{\nu} = \nu$

- Nature of neutrinos: Majorana or Dirac?
- Lepton number violation
- Neutrino mass and hierarchy
- Neutrino mass origin, matter-antimatter asymmetry ...

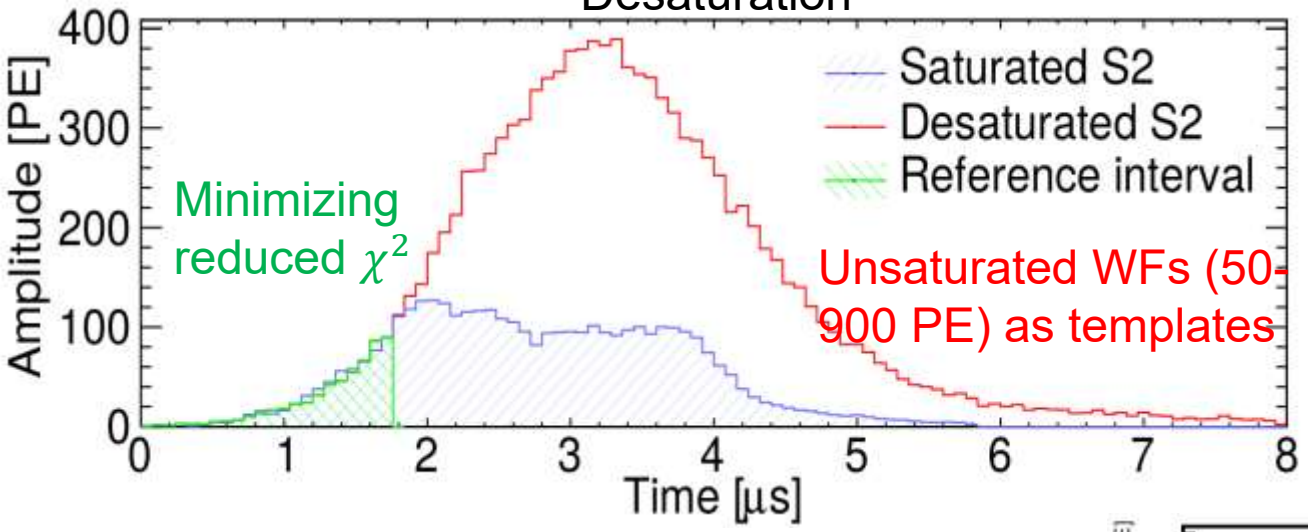




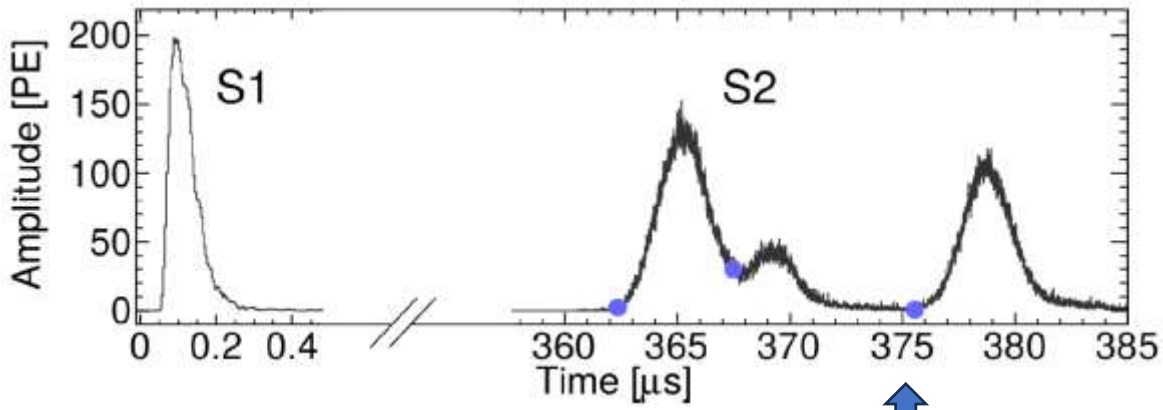
Imply new physics beyond the Standard Model

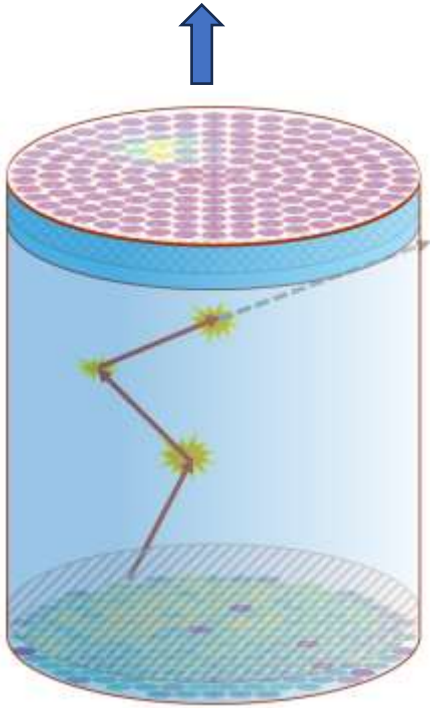
Extending energy from keV to MeV

Desaturation

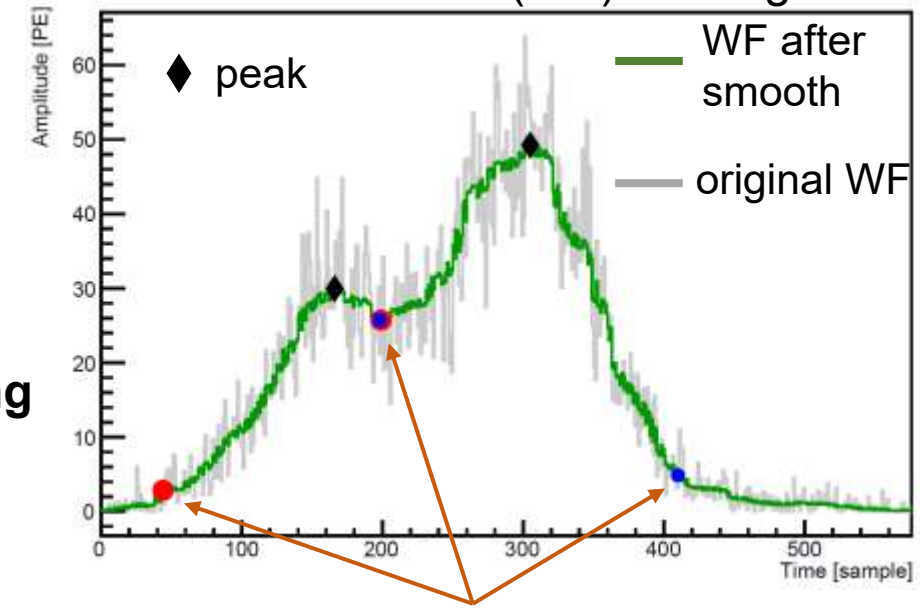


Multiple S2 waveforms connected end-to-end





waveform (WF) dividing



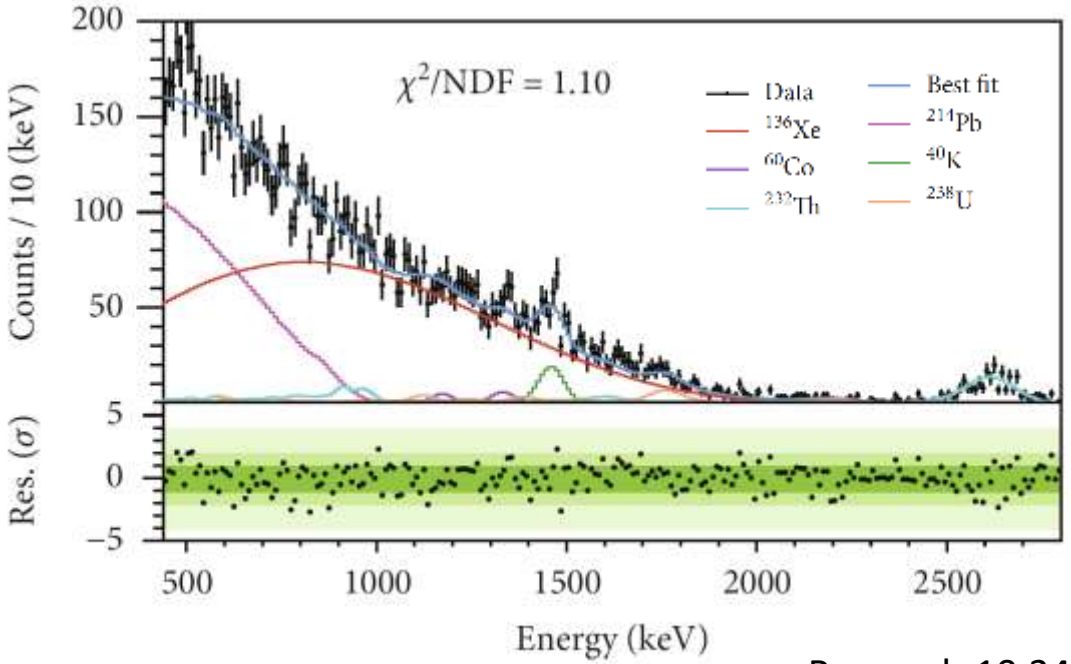
dividing position

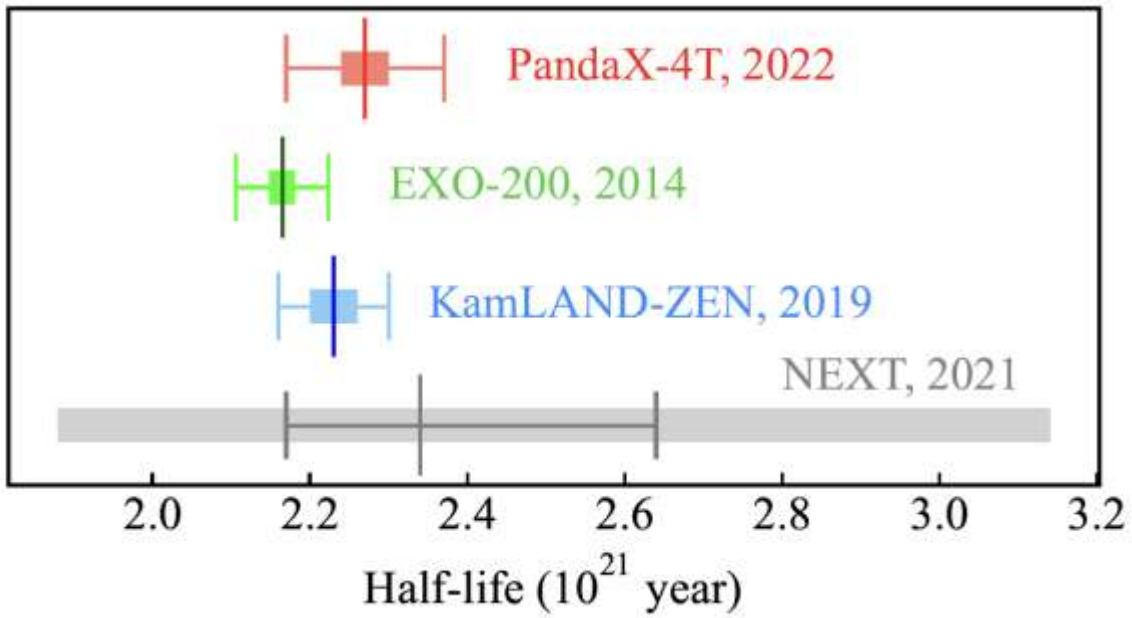
- There are 2 key challenges
  - PMT saturation → **S2 desaturation**
  - SS/MS identification → **S2 waveform dividing**

^{136}Xe Double Beta Decay (DBD) in PandaX-4T

- ^{136}Xe DBD has been measured with **commissioning run**.
- The first measurement result based on **natural xenon detector**.
- The widest decay energy spectrum range: **[440, 2800] keV**

Commissioning (Run 0)
2020/11/28 – 2021/04/16





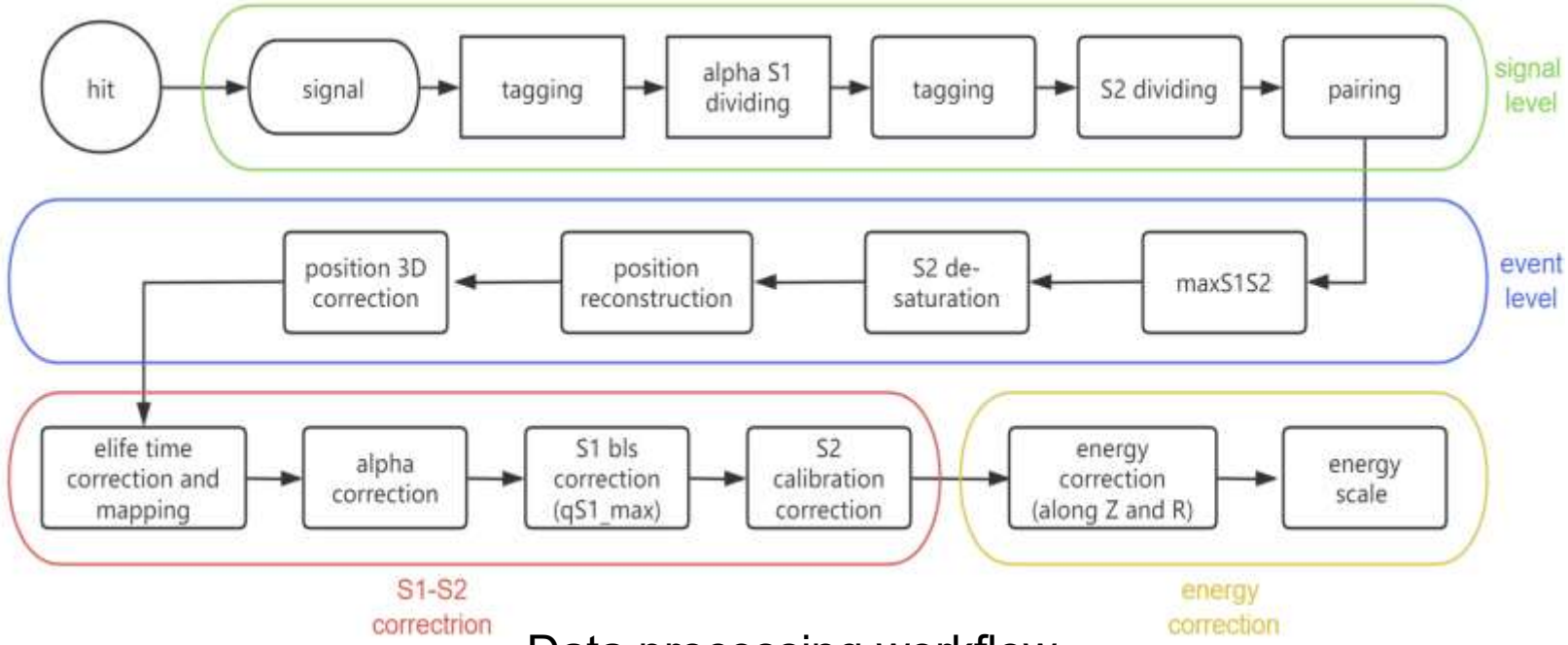
Research.10.34133/2022/979872

Optimized and Unified Data Reconstruction Pipeline

- Dedicated data analysis pipeline for **[40, 3000] keV.**
- Using Run 0 and Run 1 to search ^{136}Xe NLDBD with blind analysis.

  ROI = [2356, 2560] keV, only SS events used
- **Optimization** and **unification** of data processing for Run 0 and Run 1:
  - Recovered ~0.5% SS events by an improved time window cut;
  - S1 waveform dividing to improve alpha events reconstruction;
  - The misjudgment rate in S1/S2 tagging has decreased to 1%;
  - 3.5 ms dead-time cut before ^{214}Po events to remove isolated ^{214}Bi events: ~1% background reduction and negligible data loss;
  - And more...

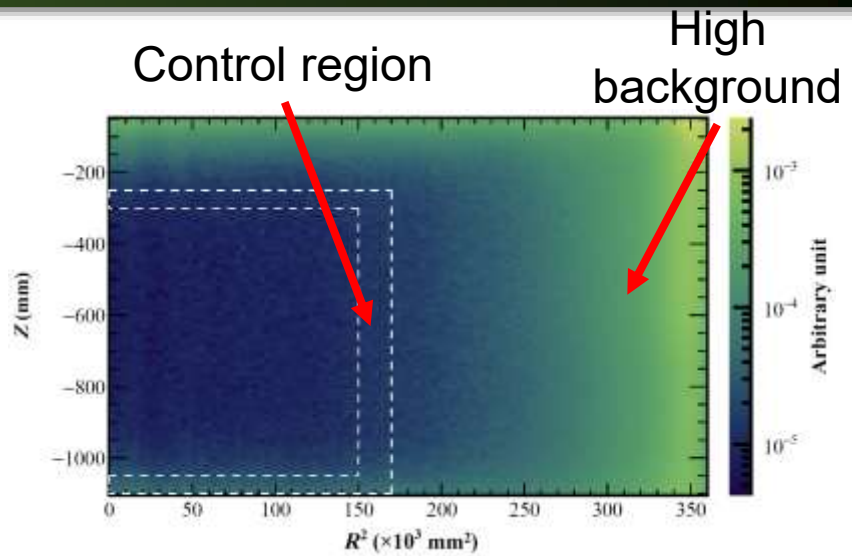
Commissioning (Run 0)	Physics Run (Run 1)
2020/11/28 – 2021/04/16	2021/11/15 – 2022/05/15



Data processing workflow

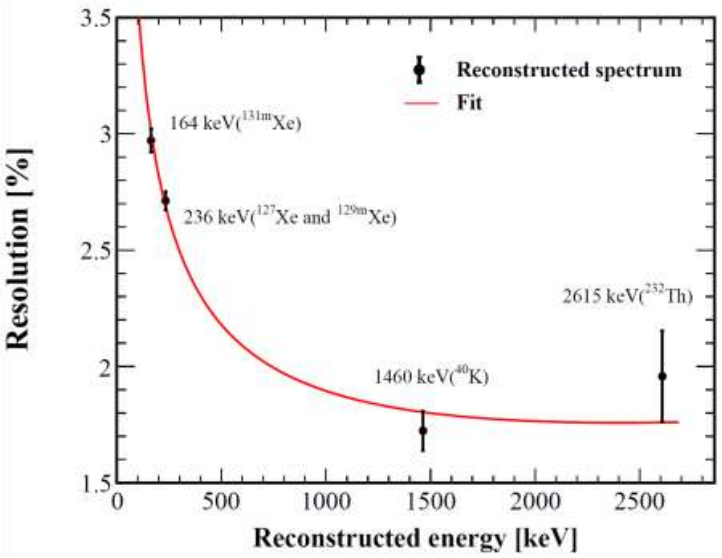
Energy Response Model

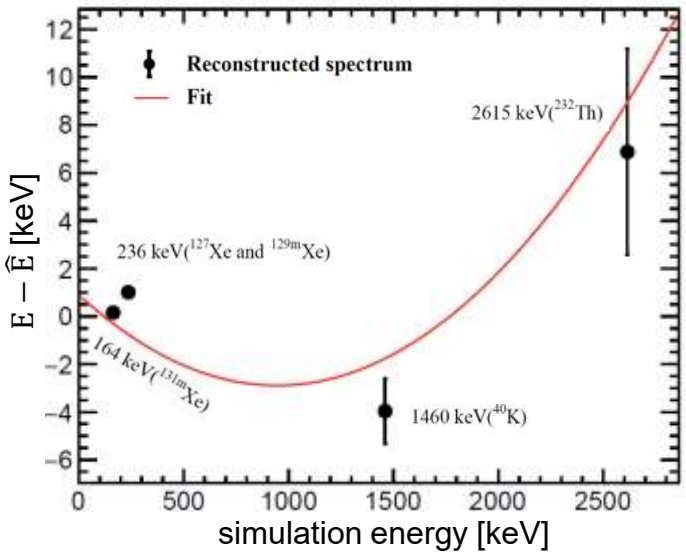
- **Energy resolution** vs. reconstructed energy
- **Energy bias** between simulated energy and reconstructed energy
- Physics data in **control regions** (white lines) used to obtain the nominal values and the covariance matrix of six parameters
- Original MC energy spectra convolved with the energy response model



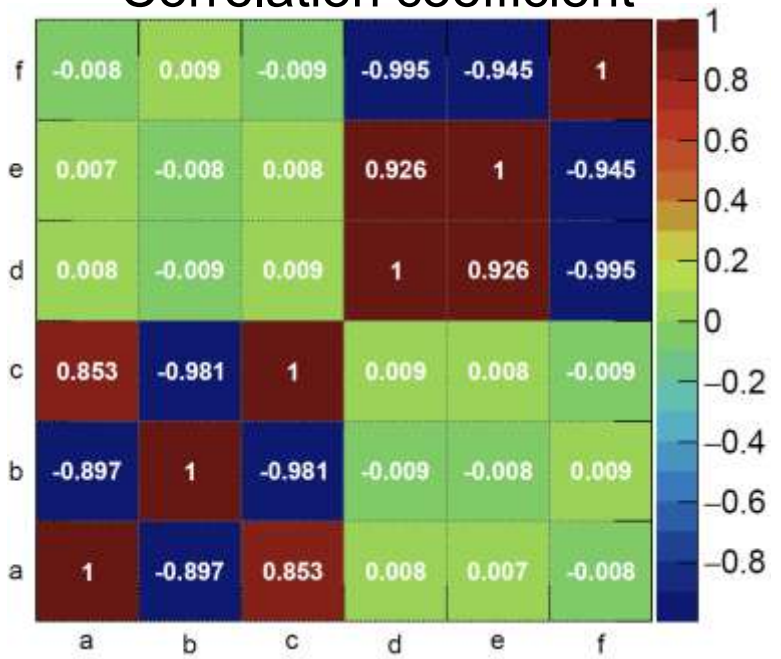
$$\frac{\sigma(E)}{E} = \frac{\boldsymbol{d}}{\sqrt{E}} + \boldsymbol{e} \cdot E + \boldsymbol{f}$$

$$E = \boldsymbol{a} \cdot \hat{E}^2 + \boldsymbol{b} \cdot \hat{E} + \boldsymbol{c}$$



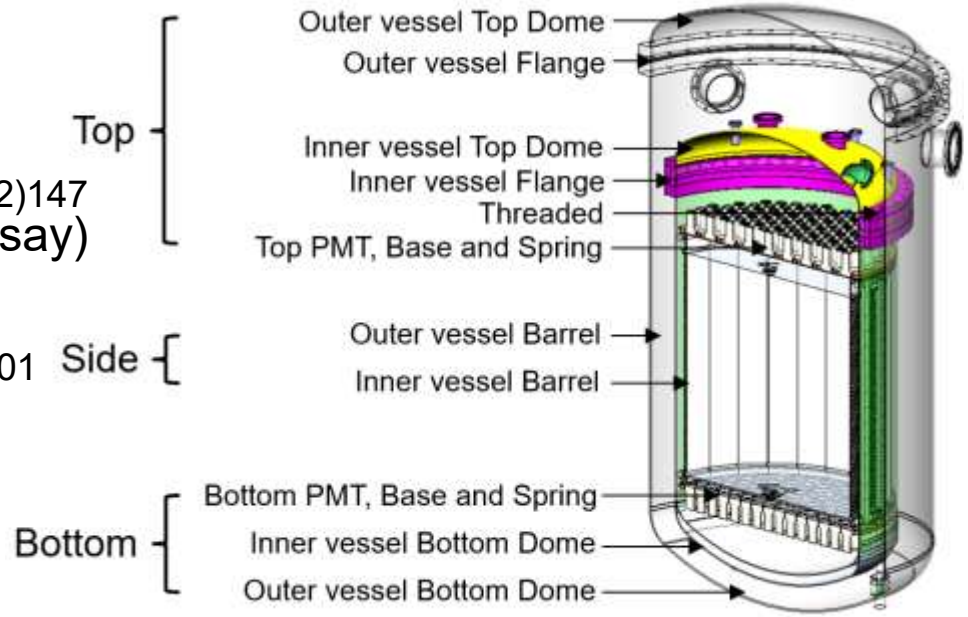


Correlation coefficient



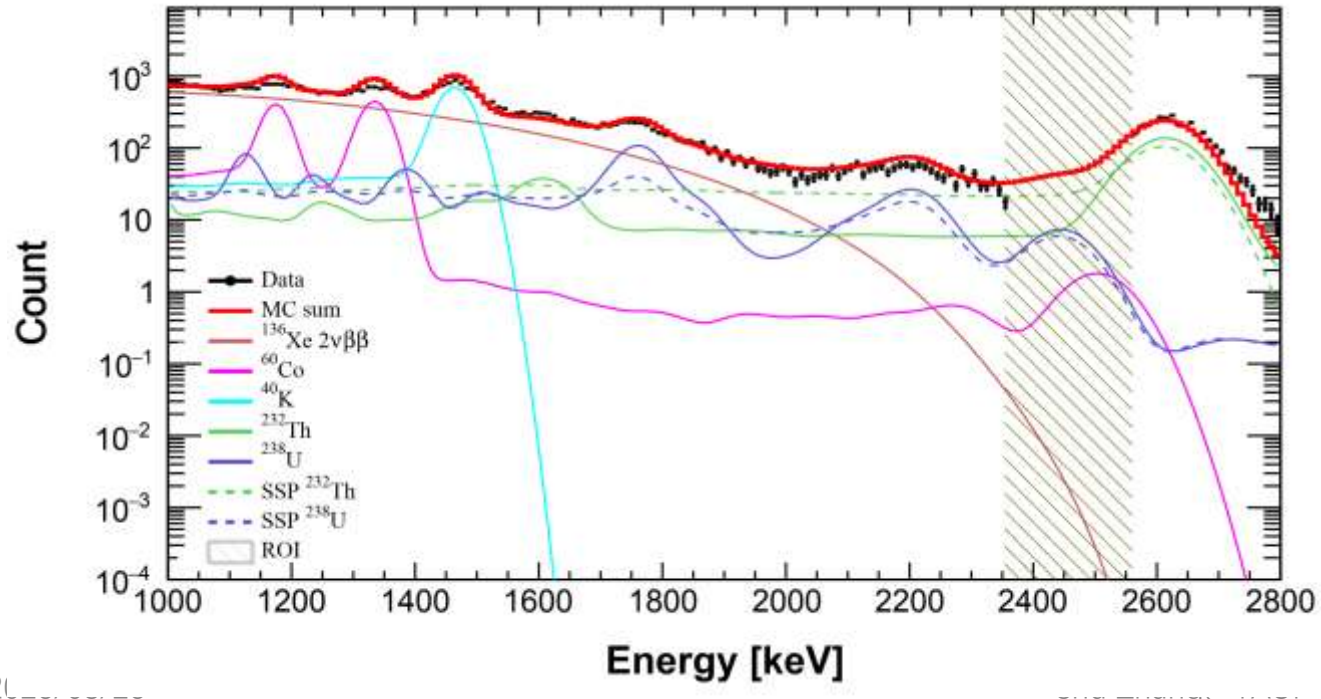
Background Model

- Background components:
  - **^{136}Xe DBD** (from ^{136}Xe DBD half-life measurement) Research.10.34133/2022/979872
  - **Detector material**: ^{60}Co, ^{40}K, ^{232}Th, ^{238}U (from HPGe material assay) 10.1007/JHEP06(2022)147
  - **Stainless steel platform** (SSP): ^{232}Th, ^{238}U (from MS fitting)
- Spectrum fitting range chosen as [1100, 2800] keV 10.1103/PhysRevC.93.035501



Detector material

Data vs background MC convolved with energy response model



- Other background components are checked:
  - Beta of ^{214}Bi in TPC (negligible)
  - Gammas of ^{214}Bi from LXe skin region (negligible)
  - 2.5 MeV peak from ^{60}Co cascade gammas (well modelled)

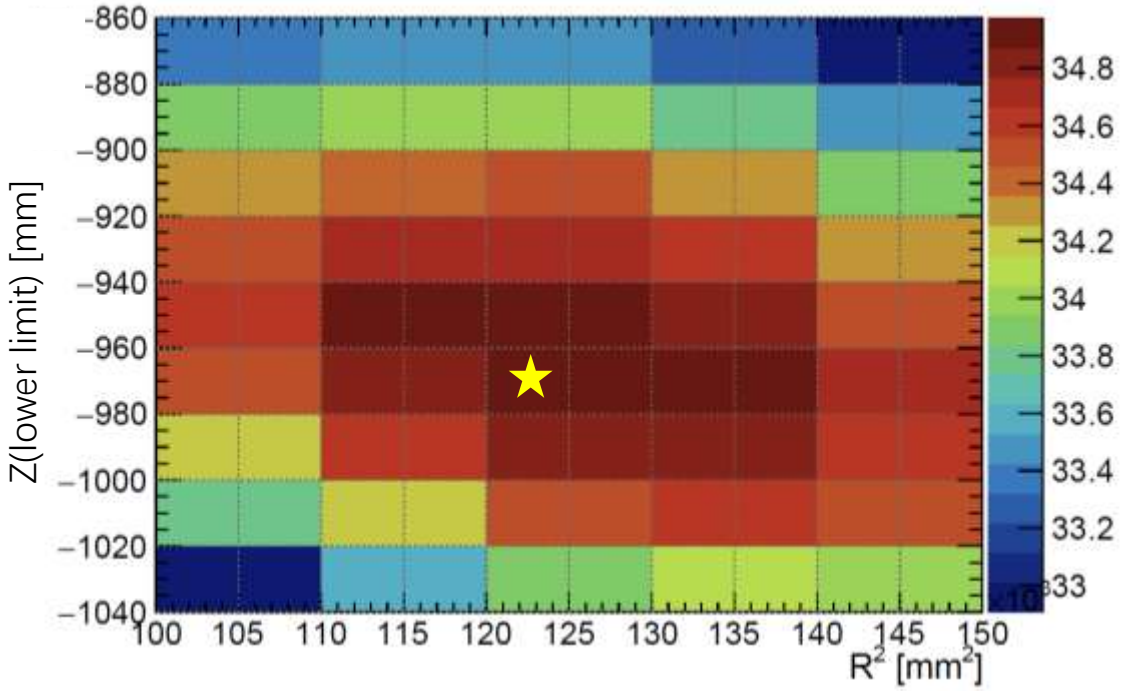
Fiducial Volume (FV)

$$FoM \propto \frac{m}{\sqrt{B}}$$

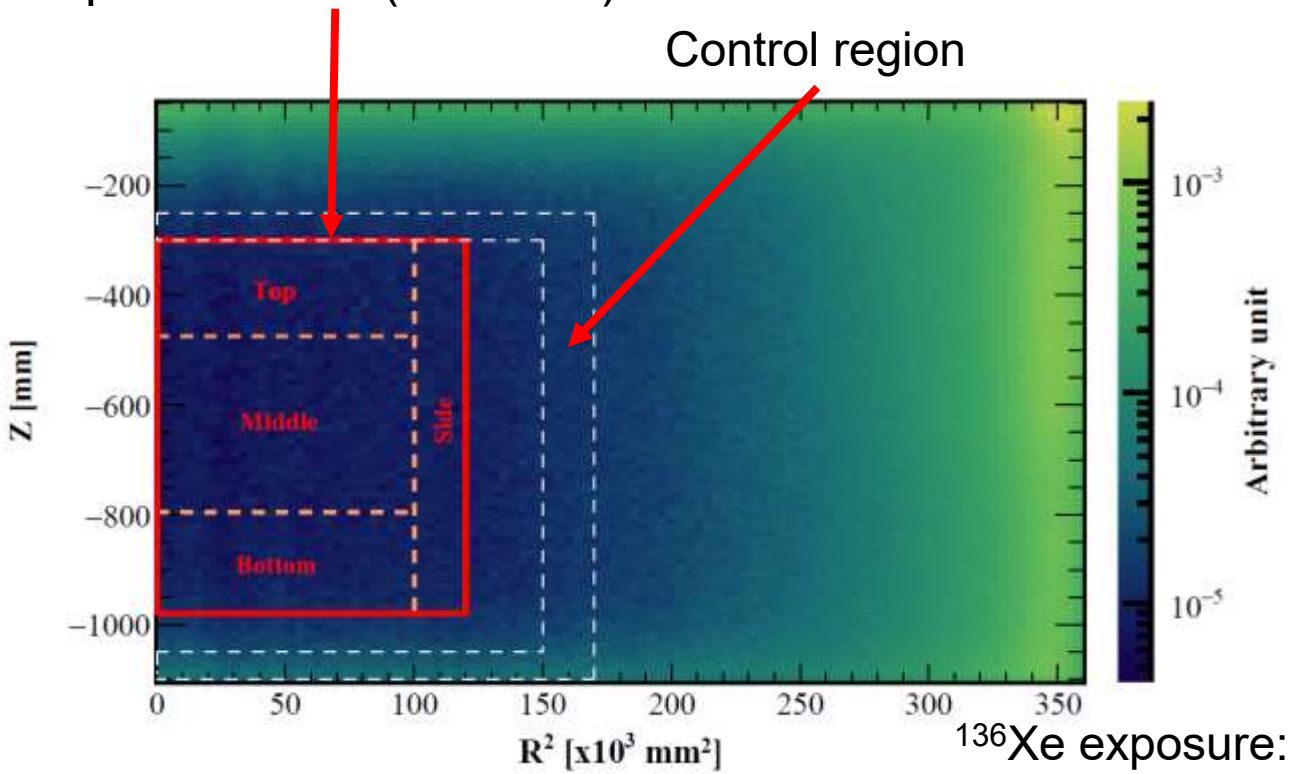
Xenon mass of FV

counts of background events

Figure of merit (FoM)



Optimized FV (red lines) for both Run 0 and Run 1:



^{136}Xe exposure:

44.6 kg·yr

FV is divided into four regions:

- Better constrain the detector material from different directions;
- Reduce degeneracy between detector material and SSP

Likelihood and Systematics

- Binned Poisson likelihood with Gaussian penalty terms to constrain nuisance parameters $(\boldsymbol{G}, \boldsymbol{\mathcal{G}})$.
- **Background model and systematics are included in likelihood fitting.**
- Systematics include three categories: energy response ($\boldsymbol{M}$), overall efficiency ($\boldsymbol{\eta_{eff}}$), ^{136}Xe mass ($\boldsymbol{\eta_s}$).

$$L = \prod_{r=0}^{N_{run}} \prod_{i=1}^{N_{region}} \prod_{j=1}^{N_{bins}} \frac{(N_{ijr})^{N_{ijr}^{obs}}}{N_{ijr}^{obs}!} e^{-N_{ijr}} \cdot \prod_{k=1}^{N_G} G(\eta_k; 0, \sigma_k) \cdot \mathcal{G}(\mathcal{M}; \mathcal{M}_0, \Sigma_m)$$

covariance matrix

$$N_{ijr} = (1+\eta_{eff}) \cdot [(1+\eta_s) \cdot n_s \cdot S_{ijr} + \sum_{b=1}^{N_{bkg}} (1+\eta_b) \cdot n_b \cdot B_{ijr}]$$

The simulated energy spectrum convolving the energy response model

Systematics

Sources		Values	
		Run0	Run1
Energy response	a [keV^{-1}]	$(4.2 \pm 1.0) \times 10^{-6}$	$(1.1 \pm 1.4) \times 10^{-6}$
	b	0.992 ± 0.002	0.997 ± 0.004
	c [keV]	0.90 ± 0.32	1.4 ± 1.5
	d [$\sqrt{\text{keV}}$]	0.259 ± 0.046	0.46 ± 0.25
	e [keV^{-1}]	$(1.1 \pm 1.5) \times 10^{-6}$	$(8.8 \pm 22.2) \times 10^{-7}$
	f	$(9.7 \pm 3.5) \times 10^{-3}$	$(7.4 \pm 10.0) \times 10^{-3}$
Overall efficiency	^{136}Xe $0\nu\beta\beta$ SS fraction	$(87.1 \pm 11.3)\%$	$(87.3 \pm 7.0)\%$
	Quality cut	$(99.89 \pm 0.10)\%$	$(99.97 \pm 0.02)\%$
^{136}Xe mass	^{136}Xe abundance	$(8.58 \pm 0.11)\%$	
	FV mass [kg]	735 ± 3	735 ± 14
Background model		Table. 2	

Fitting Results and Limit

- ^{136}Xe NLDBD event rate is fitted to be $\mathbf{14 \pm 55}\ t^{-1}yr^{-1}$, the upper limit of $\mathbf{111}\ t^{-1}yr^{-1}$ at 90% C.L. is derived

10.1016/j.scib.2025.03.009

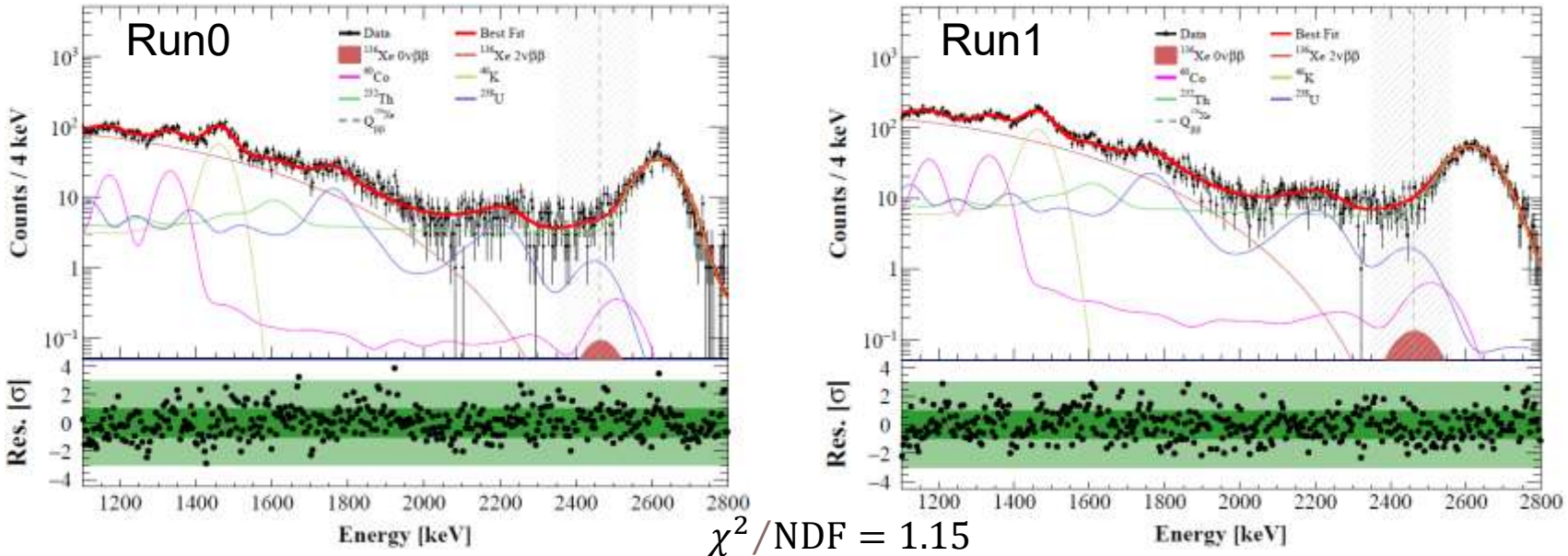
$$T_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{24}\ yr \text{ at } 90\%\ \text{C.L.}$$

Best results among natural xenon detectors so far

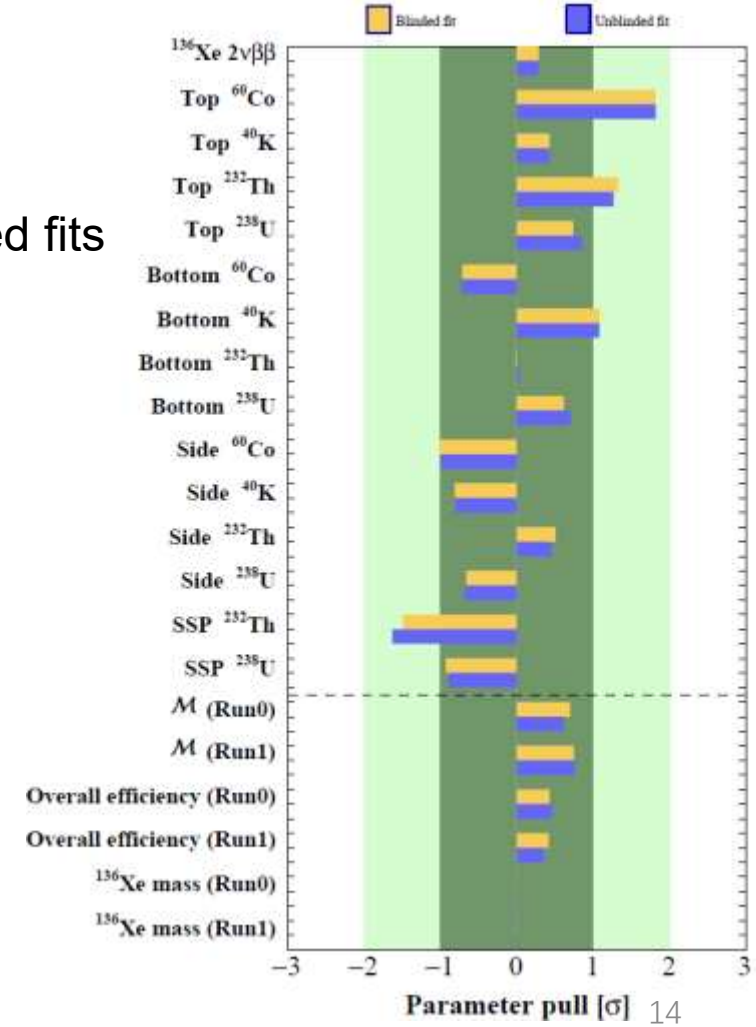
- Corresponding to the upper limit on effective Majorana neutrino mass:

$$< m_{\beta\beta} >= (0.4 - 1.6)\ eV/c^2$$

- All best-fit nuisance parameters are consistent between the blinded and unblinded fits
- The result is consistent with the median sensitivity within 1.1σ.



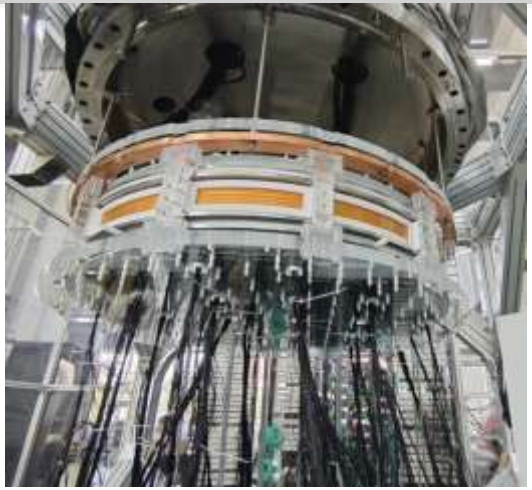
$\chi^2/\mathrm{NDF} = 1.15$



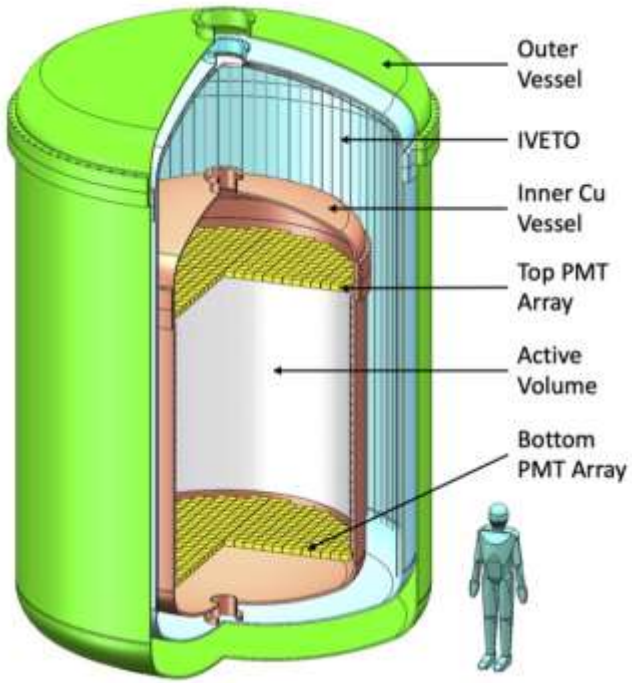
PandaX-xT

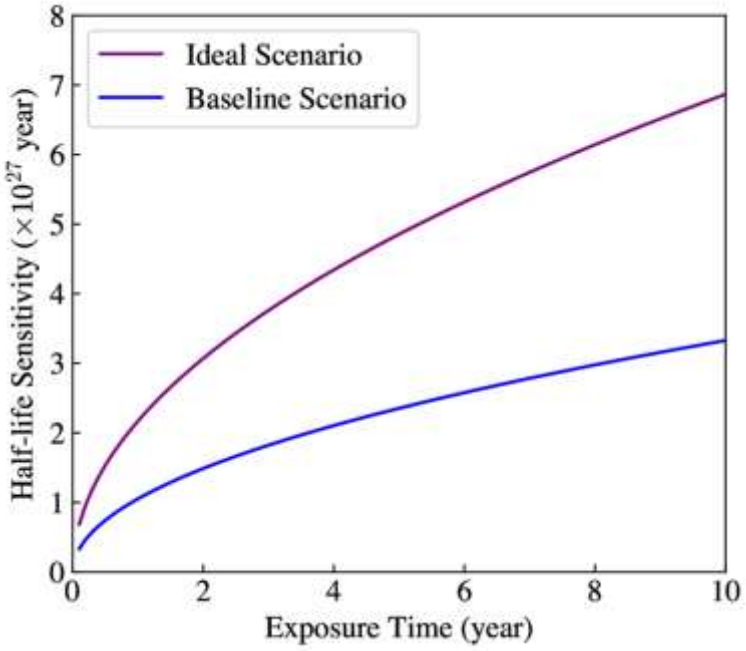
- Sensitive volume: ~40 tonne natural xenon.
- The effective Majorana neutrino mass sensitivity:

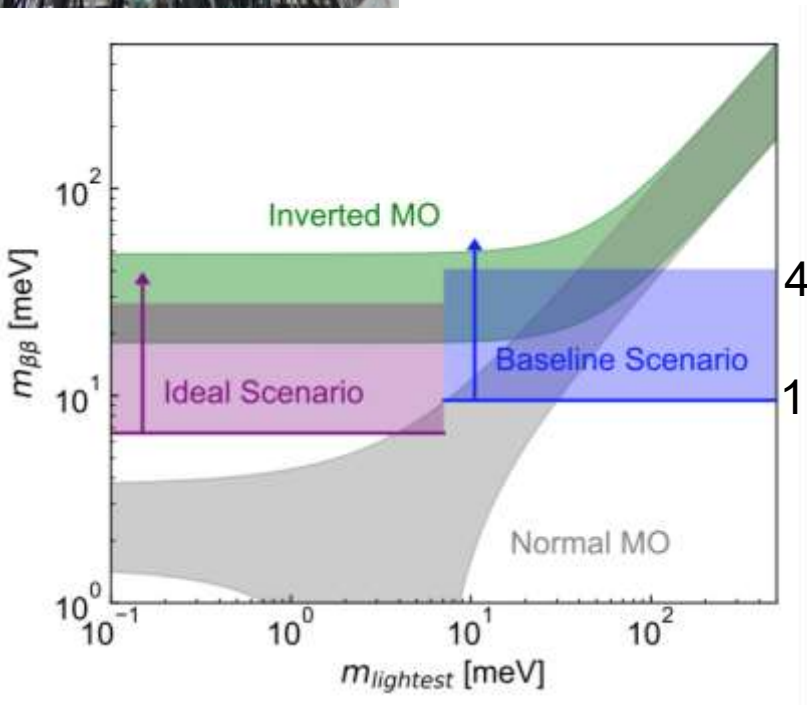
  [10, 41] meV



PandaX-20T will start commissioning run in 2027







SCPMA 68, 221011 (2025)

Summary

- We present a blind analysis to search for ^{136}Xe NLDBD with a combined dataset of PandaX-4T Run 0 and Run 1 with optimized and unified data processing.
- Background model and all systematics are included in the likelihood.
- Our results represents so far the most stringent constraint of ^{136}Xe NLDBD half-life from natural xenon detectors.

$$T_{1/2} > 2.1 \times 10^{24}\ yr \text{ at 90\% CL.}$$

- The proposed PandaX-xT experiment will mostly cover the allowed parameter space for inverted neutrino mass ordering.

Thank you !!

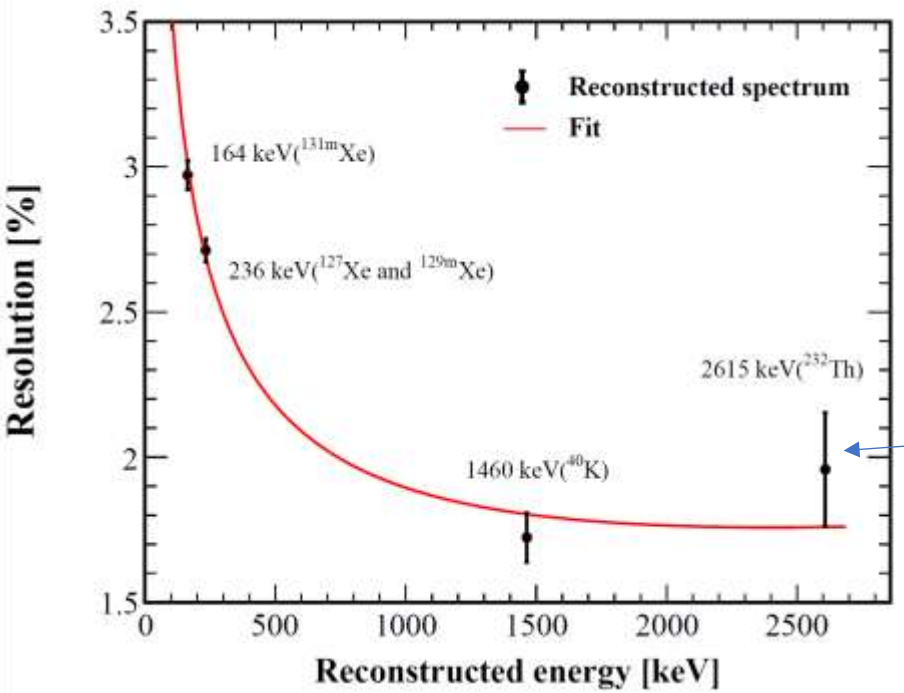
Backup

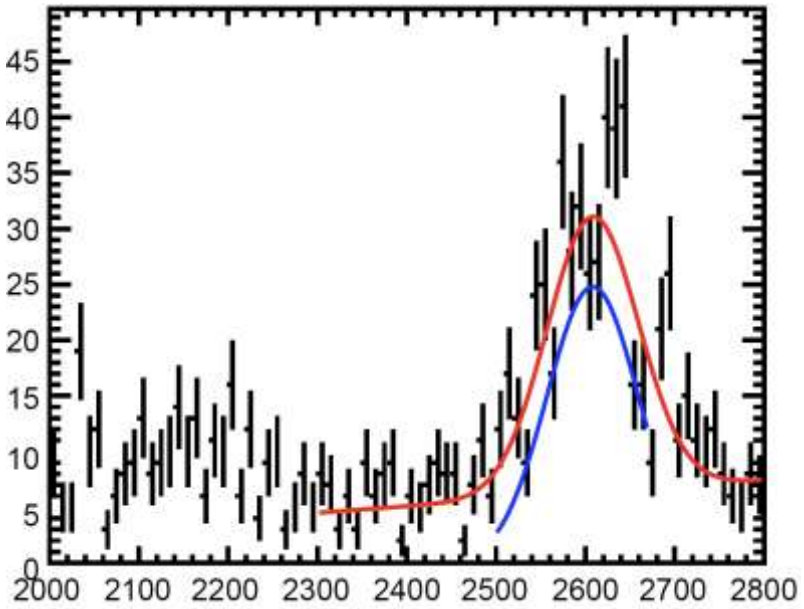
136Xe exposure: 44.6 kg-yr

Energy resolution @ 2615 keV in FV:

2.0% in Run0, 2.3% in Run1

Energy Response Model





Position reconstruction improvement with desaturation

- Position reconstruction based on PAF (photon acceptance function) methods devloped in DM analysis
- Reconstruction at HE is significantly improved with desaturation
- F
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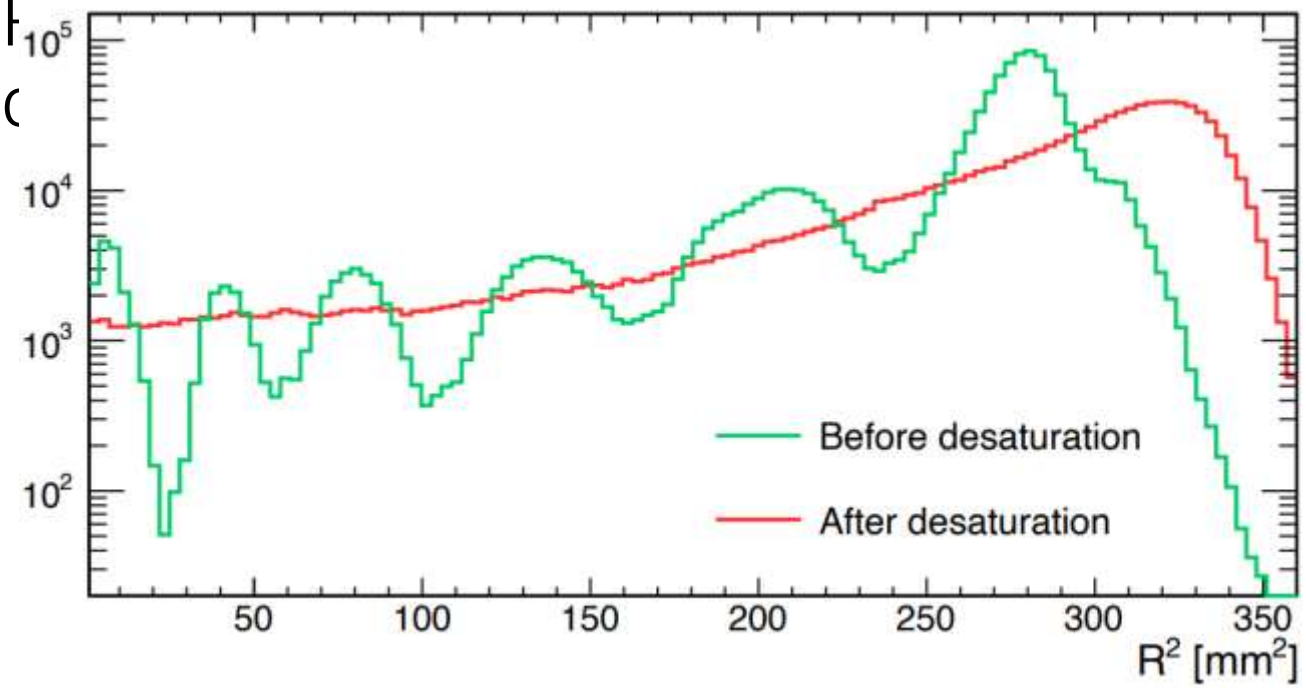
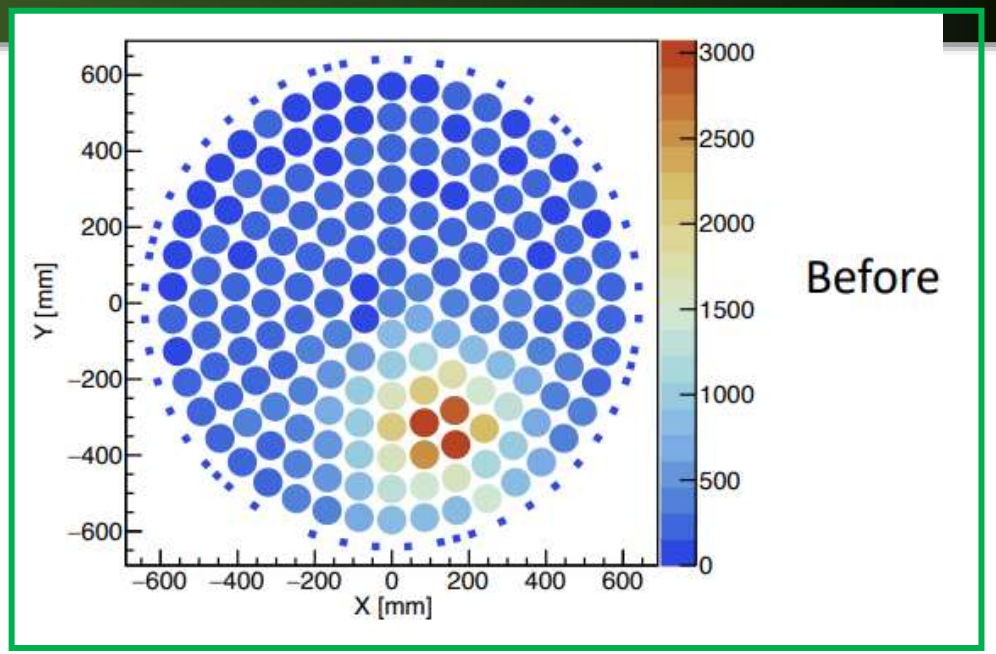
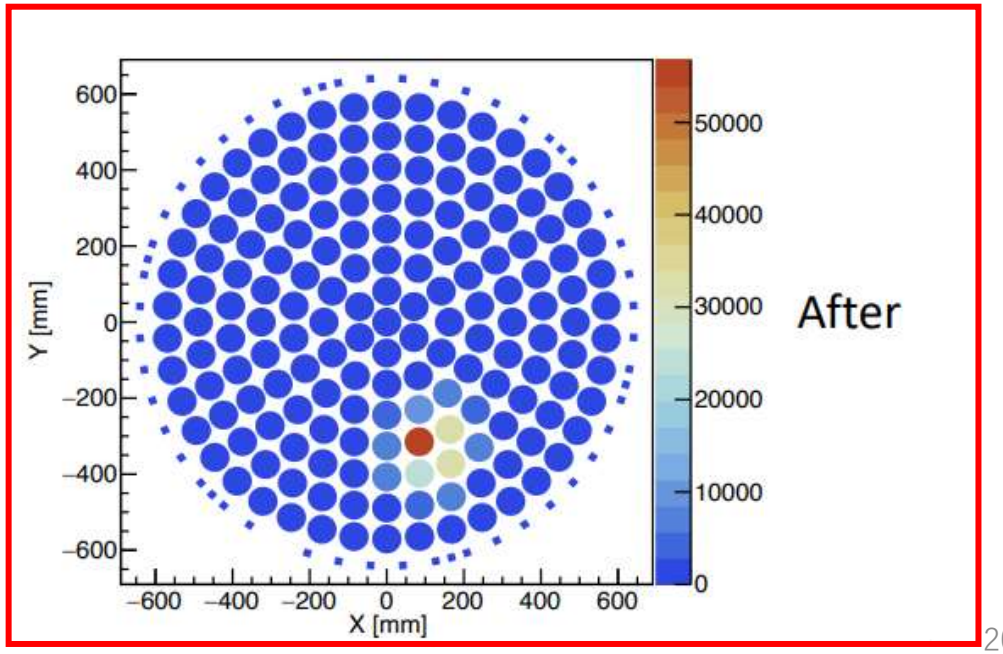
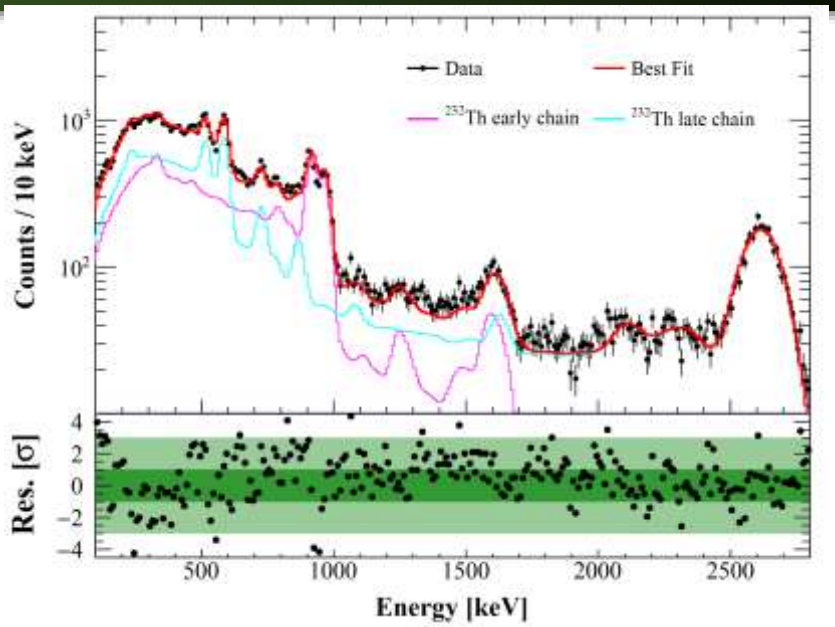


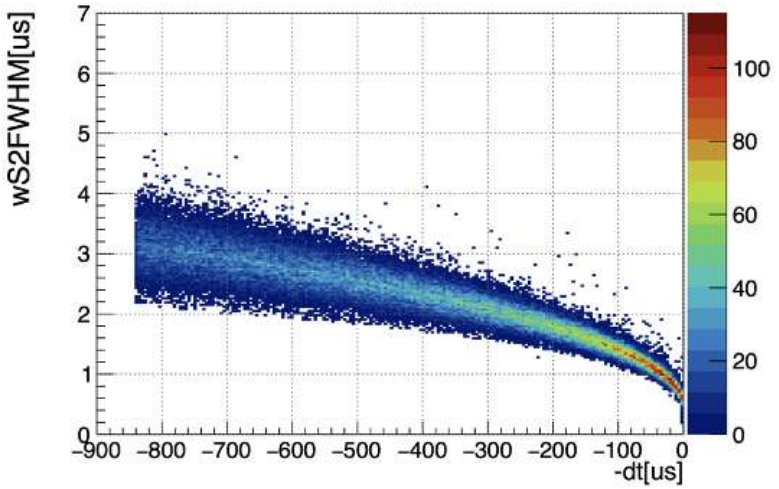


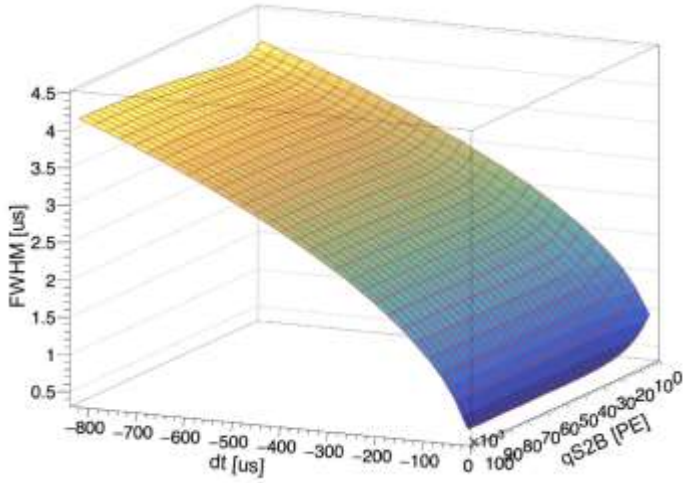


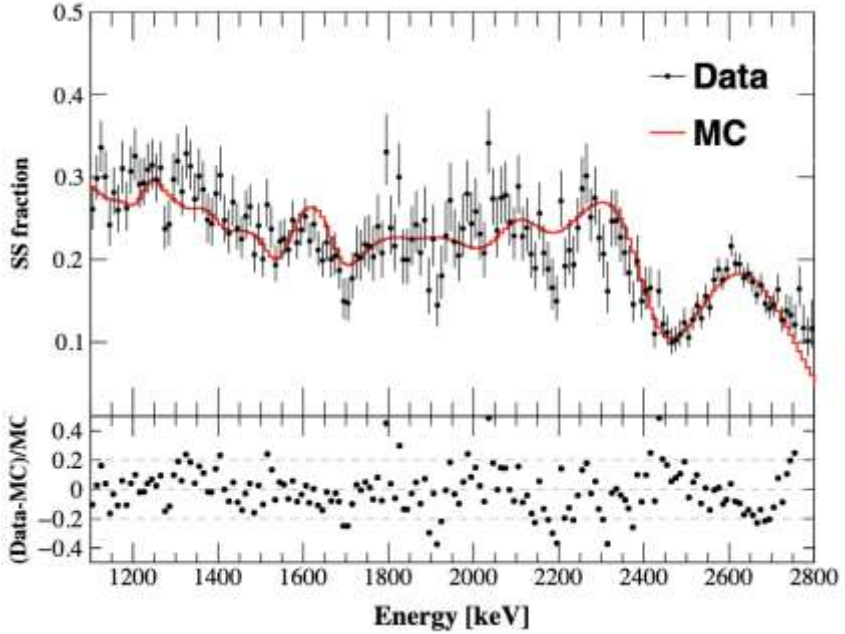
SS Fraction (SS/Total)

- Data-driven pseudo-S2 waveform simulation
- Processed through same data production pipeline to distinguish SS and MS events
- SS fraction uncertainty is estimated by comparison MC/data of ^{232}Th calibration
- Simultaneous fits to SS and MS spectra of ^{232}Th calibration data to determine the ratio of early/late chain
- Spectrum average of the absolute bin-by-bin deviation between data and MC taken as SS fraction uncertainty

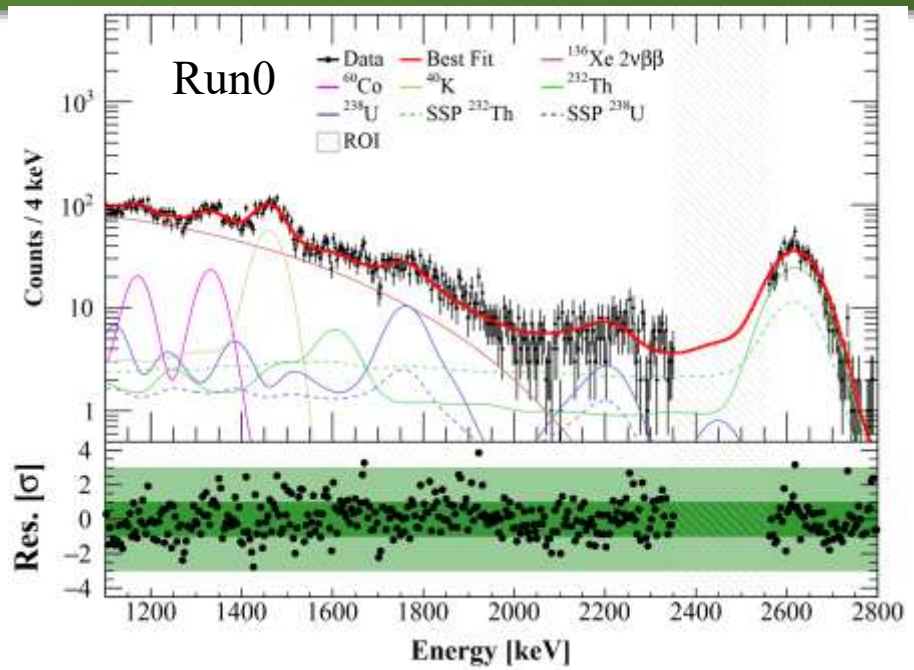


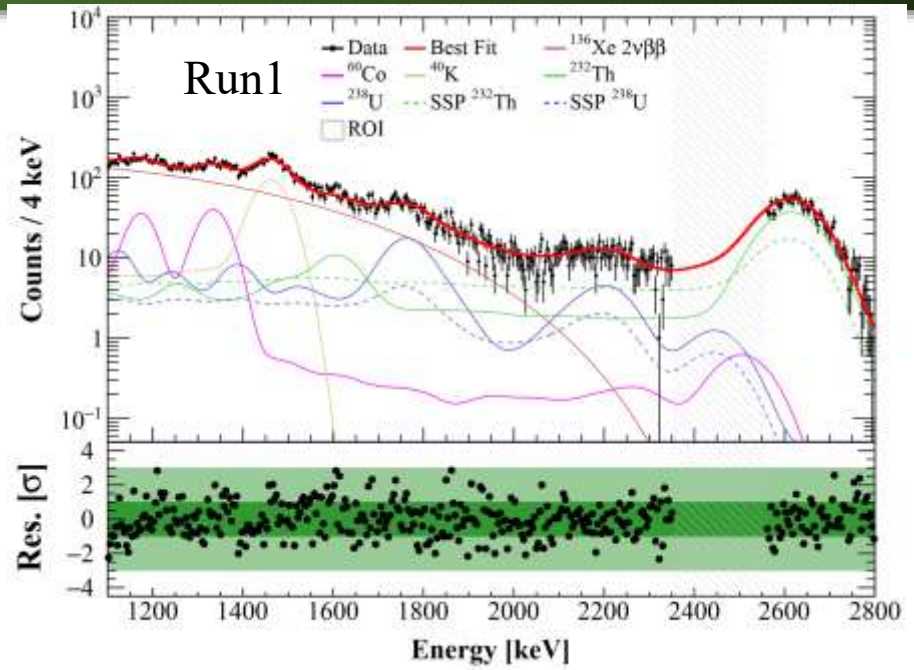






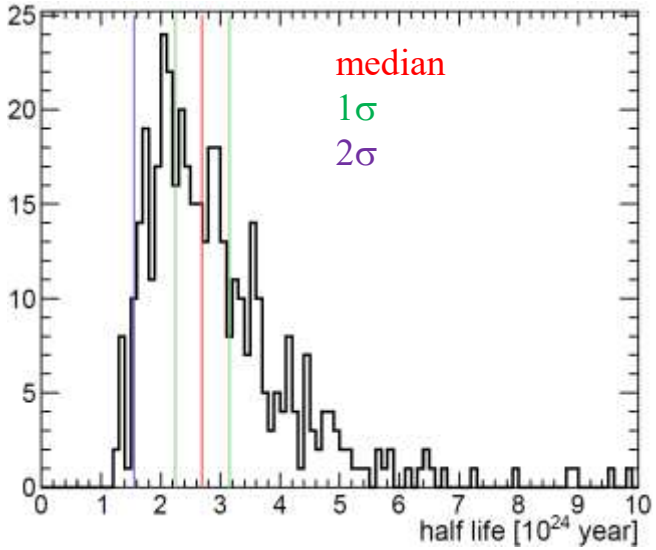
Blinded Fitting and Sensitivity





Goodness-of-fit:

χ^2/NDF = 1.14



Median sensitivity is estimated by fits to toy-data, which are generated from background-only fit to blind data spectra.

$$T^{0\nu\beta\beta}_{1/2,\,sensitivity} > 2.7 \times 10^{24}\ yr \text{ at } 90\%\text{ C.L.}$$

Background counts and parameter pulls

Background counts in the ROI

Background	Model expectation	Blinded fit	Unblinded fit
SSP ^{232}Th	527 ± 45	470 ± 34	458 ± 33
SSP ^{238}U	50 ± 15	38 ± 11	39 ± 11
^{232}Th	375 ± 224	510 ± 34	485 ± 31
^{238}U	78 ± 42	70 ± 9	72 ± 9
^{60}Co	18 ± 7	31 ± 3	31 ± 3
^{136}Xe	0.18 ± 0.01	0.19 ± 0.01	0.19 ± 0.01

- All pulls of nuisance parameters fall within the ±2σ range
- All best-fit nuisance parameters are consistent between the blinded and unblinded fits
- Pull of top ^{60}Co reaches 1.8σ, indicating that the model expectation from the HPGe material assay might be slightly underestimated