**The 29th International Workshop on Weak Interactions and Neutrinos, Zhuhai**
2023/07/07 Parallel talks 6: astro-particle physics & cosmology

# Search for solar neutrino and low–mass dark matter with PandaX–4T

W. Ma et al. PhysRevLett.130.021802
S. Li et al. PhysRevLett. 130.261001

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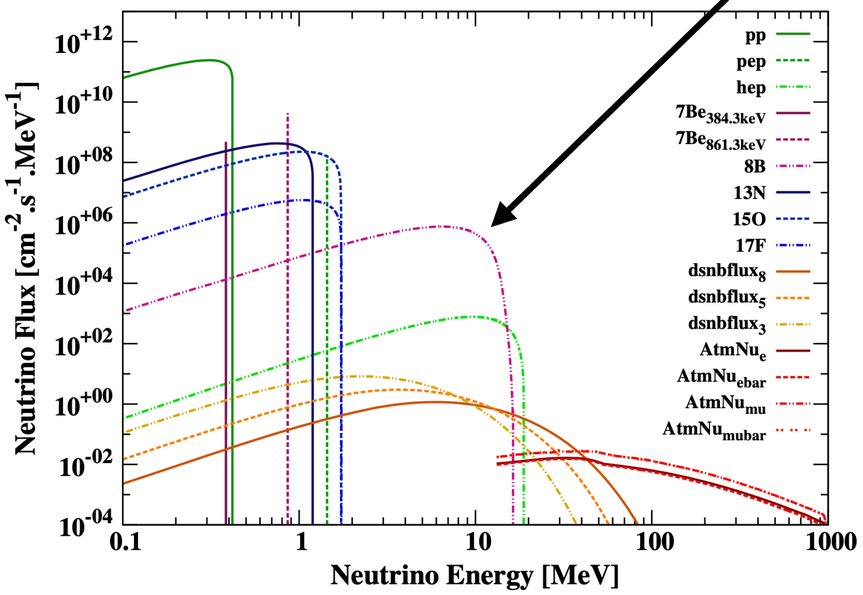
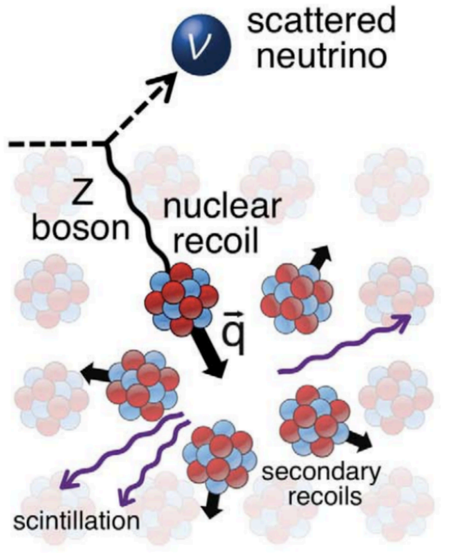
# Introduction

- solar fussion neutrino
- interact through CEvNS (coherent elastic neutrino-nucleus scattering)
- deposits several keVnr in LXe

solar $^{8}B$ $\nu$ $^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$

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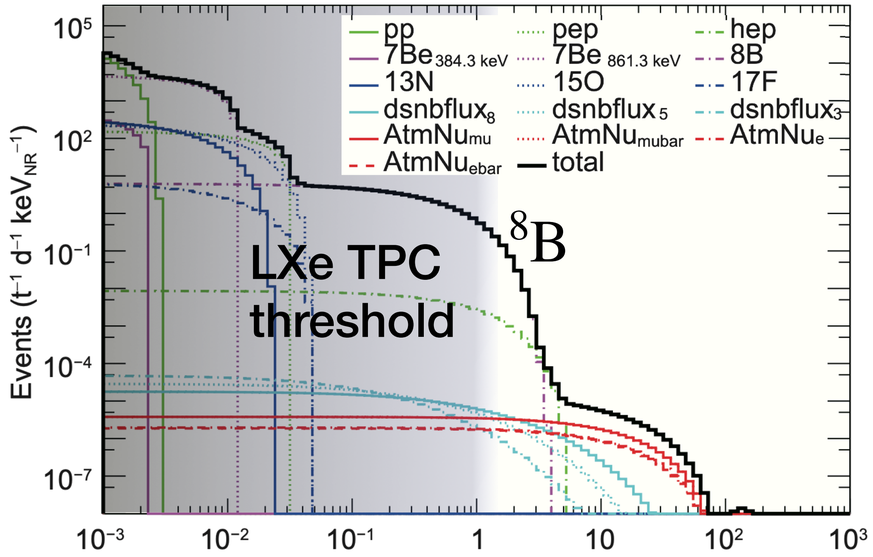
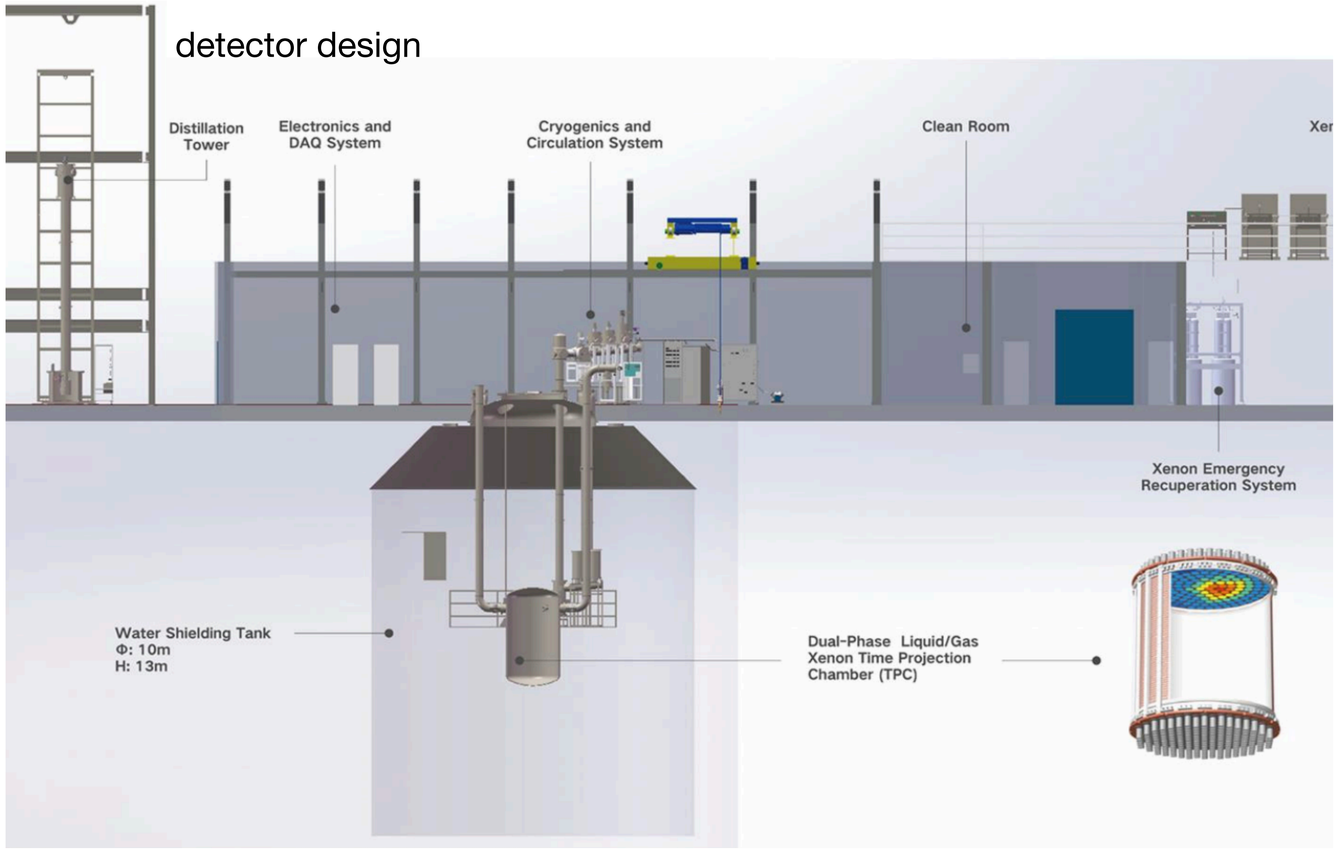
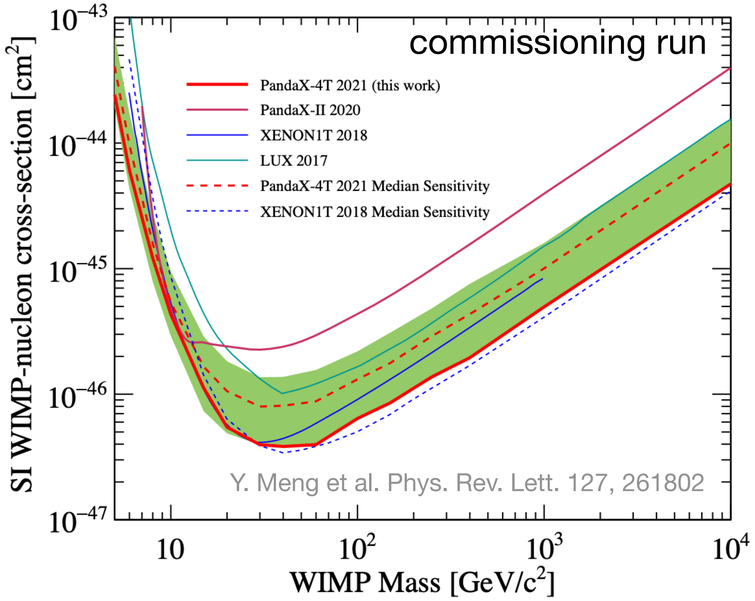


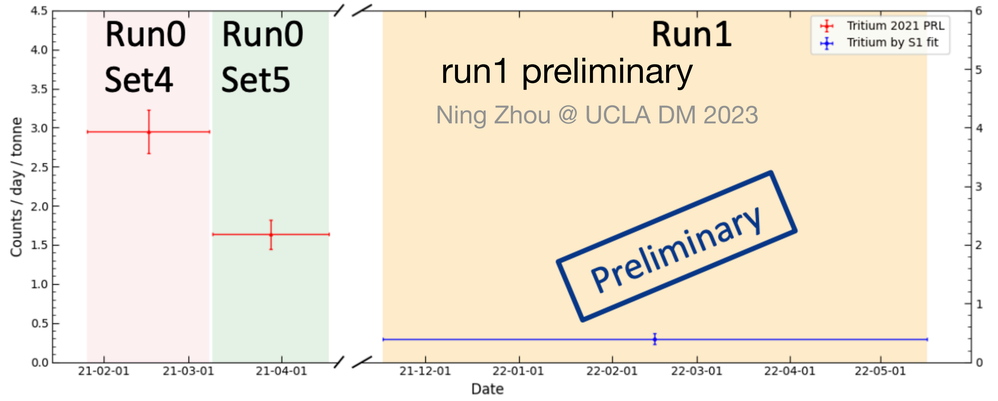

Recoil energy in liquid xenon

# PandaX–4T Experiment

- 5.6 tonne liquid xenon detector at CJPL-II
- 2020-2021: commissioning run0, 100 days
- 2021-2022: tritium removal and run1, 160 days

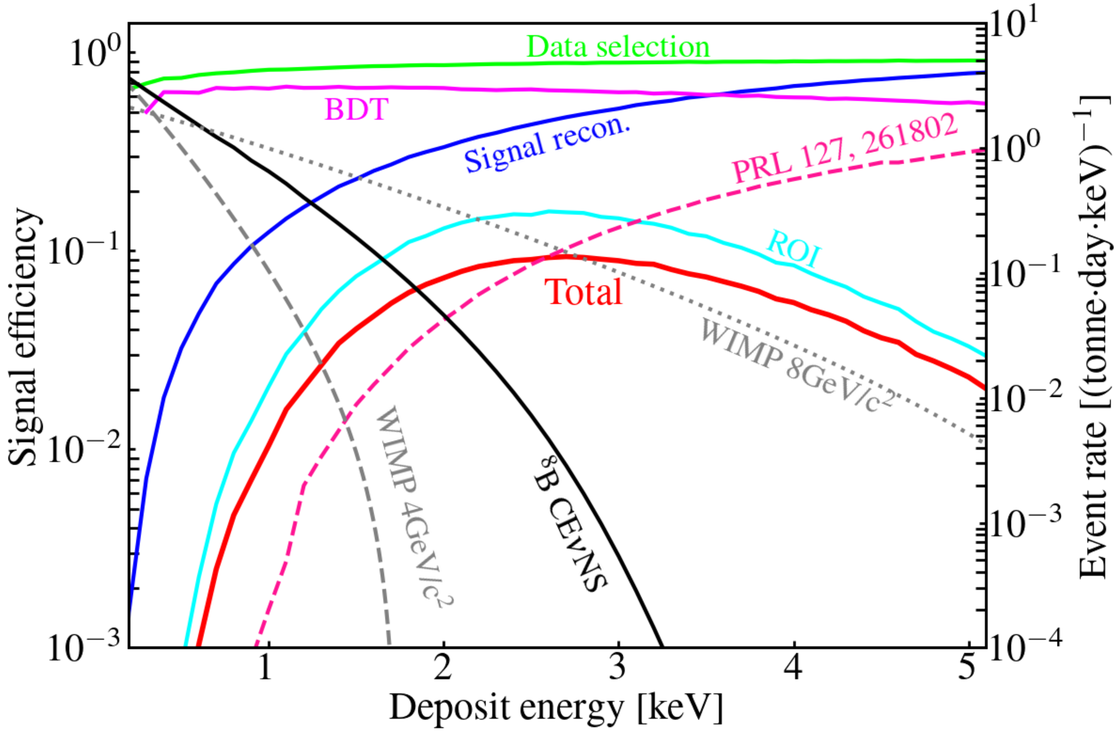


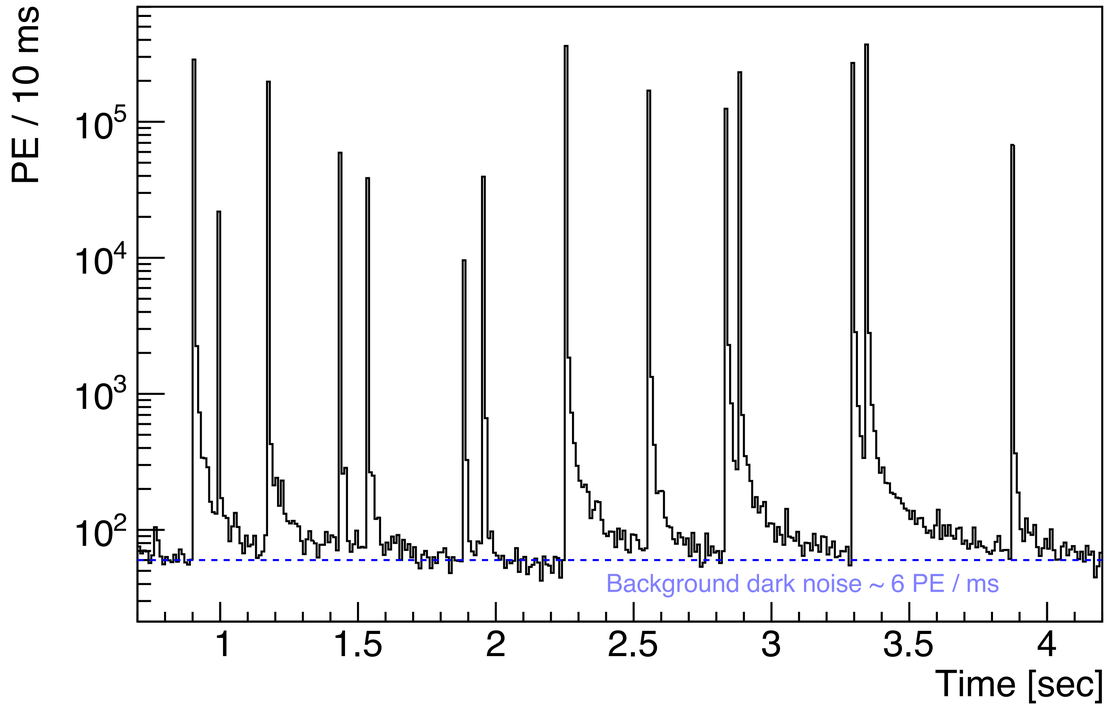



# Pushing threshold

- 2 or 3 hits among the entrie PMT array(169+199 PMTs)
- 65 PE of S2 (~3 electron)
- Improvement on deadtime monitoring, signal reconstruction, and quality cuts

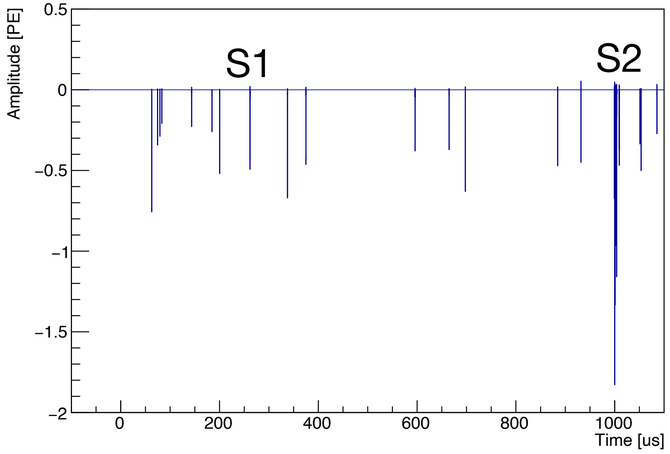


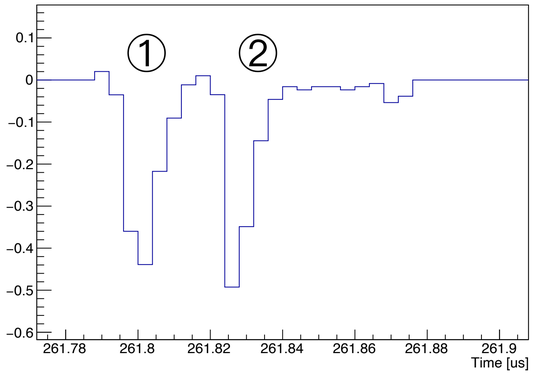
# Waveform simulation

- Precise calculation for detection efficiency at each energy bin
- Detector-specified simulation for S1, S2, delay ionization, dark noise, etc with data-driven method
- Integrated with the real

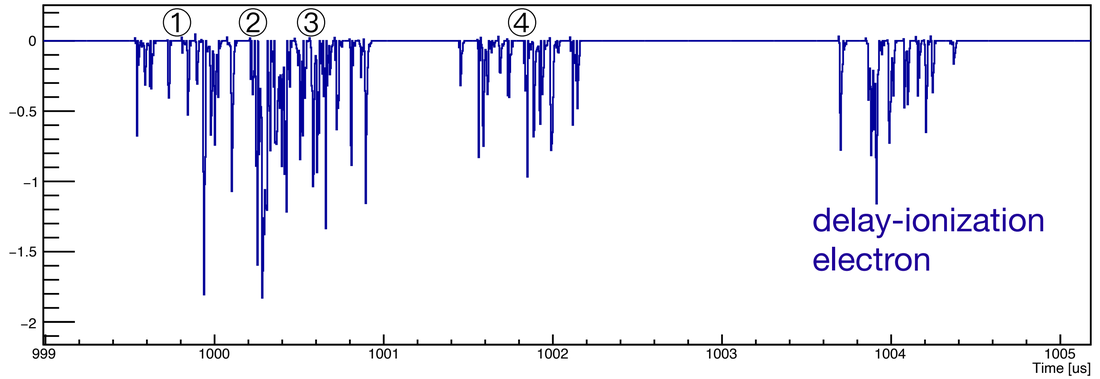
A complete simulation waveform



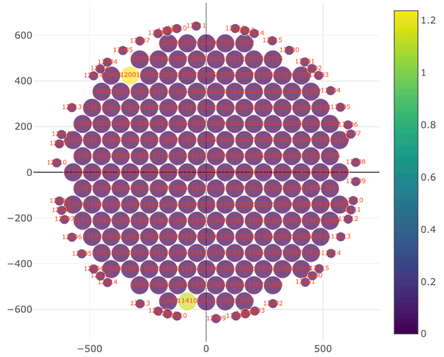

double-photon S1



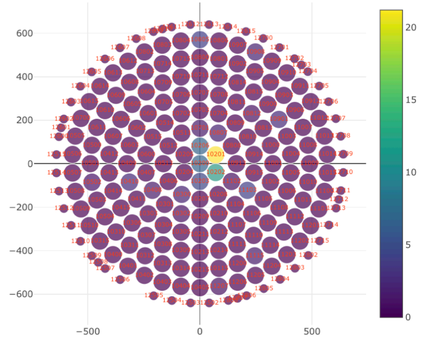

4-electron S2



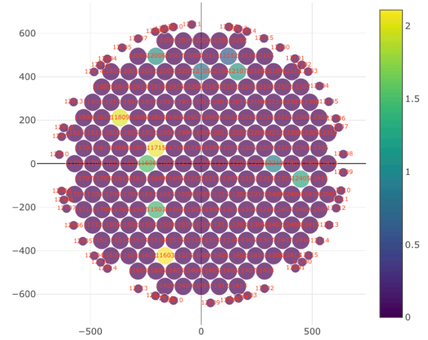

S1 pattern on the bottom array



S2 hit pattern on top

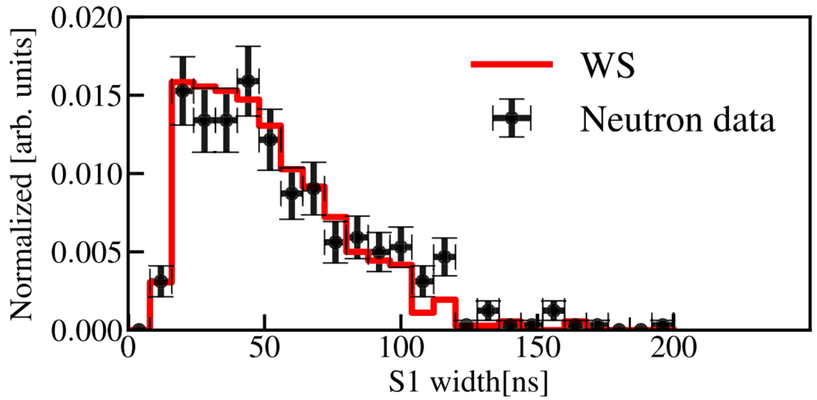


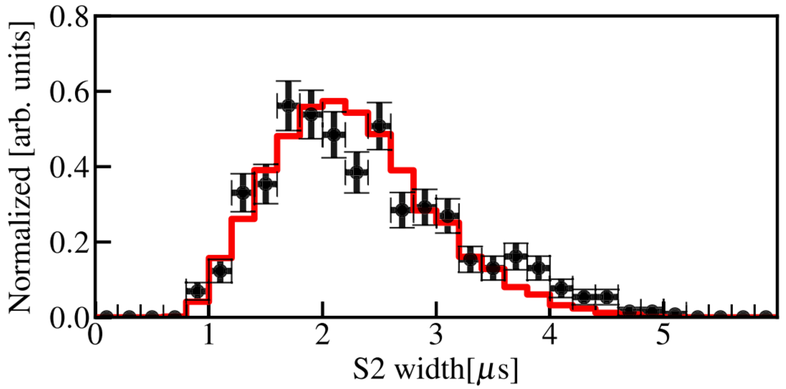
S2 hit pattern on bottom array

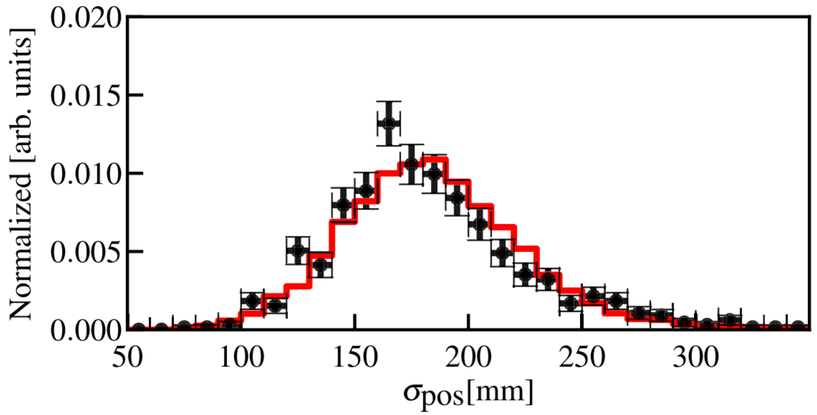


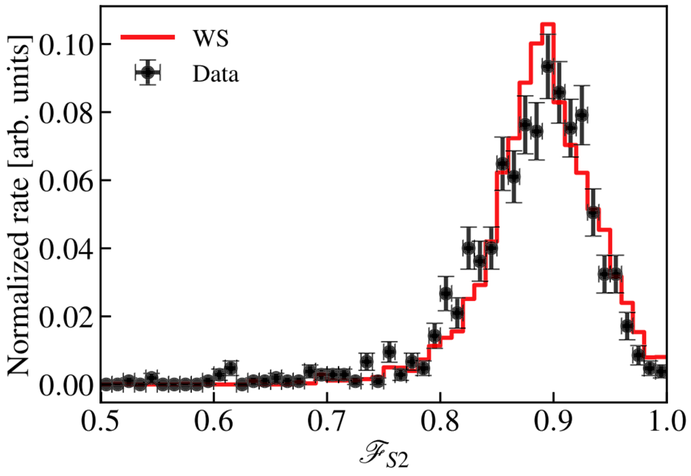
# Waveform simulation

- Consistent with data on S1/S2 width, pattern, RMS, and other complicated variables
- Reweighted, and consistent with low-energy neutron calibration
- Prediction for B8 is taken as nominal



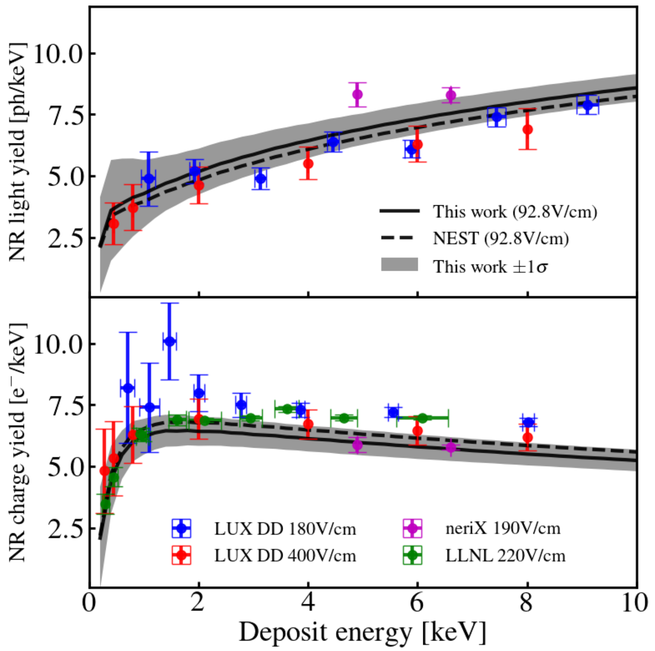



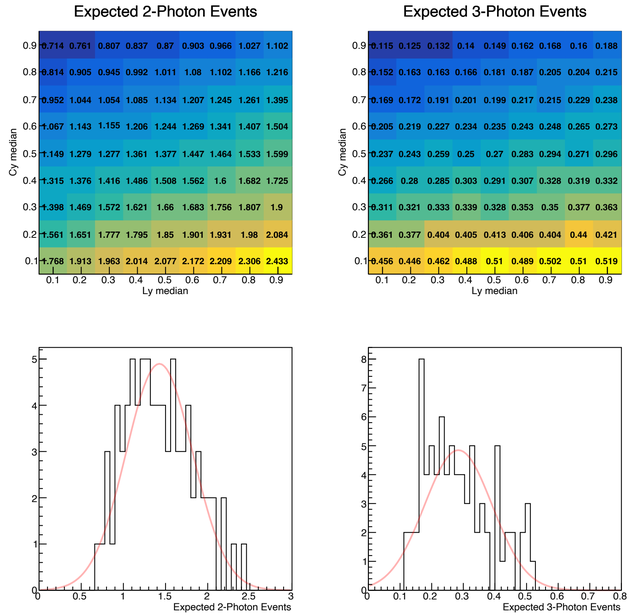
# LXe light and charge yield uncertainty

- Nominal value fitted from WIMP 2021
- Uncertainty band from other experiments (NEST v2.3.6)
- Convert to counting uncertainty

Light and charge yield band




Uncorrelated analysis



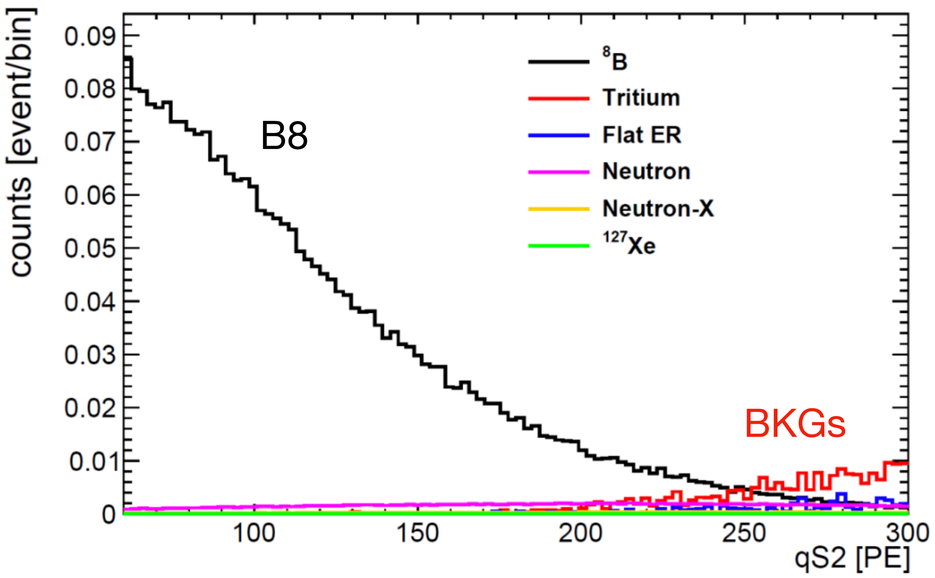

Counting uncertainty

| Particle | 2-hit uncertainty | 3-hit uncertainty |
|---|---|---|
| 4 GeV WIMP | 0.45 | 0.60 |
| B8 | 0.29 | 0.39 |
| 8 GeV WIMP | 0.16 | 0.24 |

# Background budget

- ER: LXe ER/NR discrimination
- NR: Different recoil energy spectrum
- Surface radioactivity: under control with the fiducial volume
- Accidental coincidence background is the real challenge

Two-hit channel S2 charge spectrum




Background budget

| N-hit | S2 ROI [PE] | ER | NR | Surface | Accidental coincidence | B8 |
|---|---|---|---|---|---|---|
| 2 | 65-230 | 0.04 | 0.10 | 0.14 | 62.43 | 2.32 |
| 3 | 65-190 | 0.01 | 0.05 | 0.08 | 0.79 | 0.42 |

# Accidental background

- Lower threshold → increase background
- Rate estimation + sample from data → prediction
- Check sideband prediction vs data, determine uncertainty

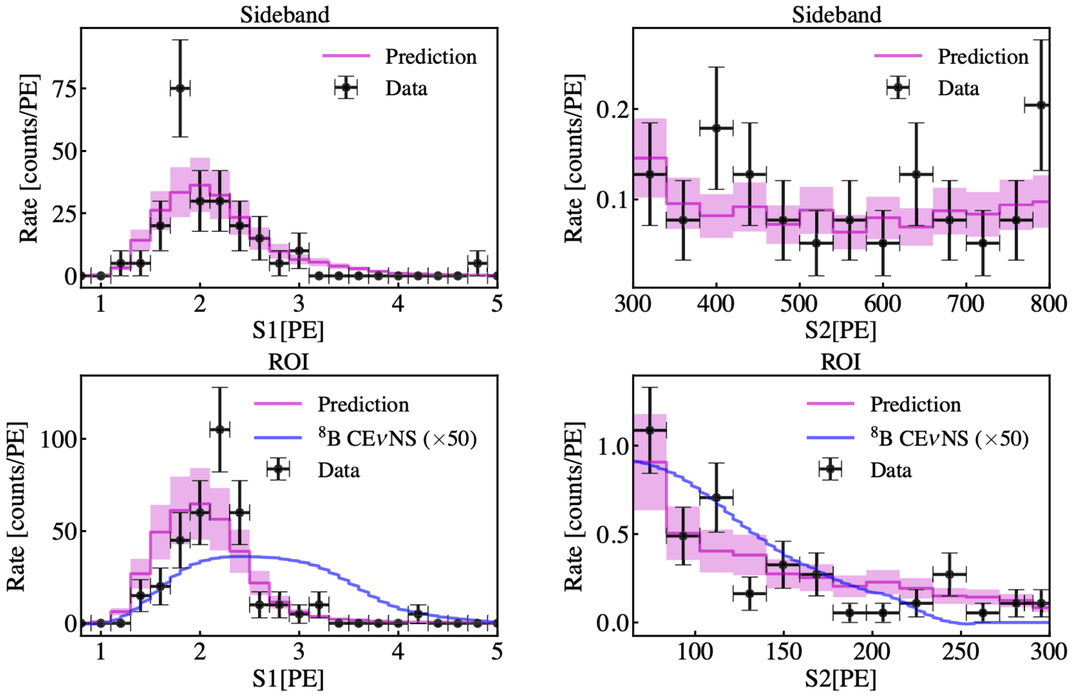
$$N_{\mathrm{AC}} = \epsilon_{\mathrm{cut}} R_{S1} R_{S2} T_{\mathrm{drift}} T_{\mathrm{livetime}}$$

Abdusalam Abdukerim et al 2022 Chinese Phys. C 46 103001

- R(S1): 6 kHz, picked from 1-ms-randomly-selected waveforms
- R(S2): ~ 1000 per day,  are selected from 0.9-1.5ms offwindow
- Drift window: 760us
- Livetime: 64 days after more stringent deadtime cut

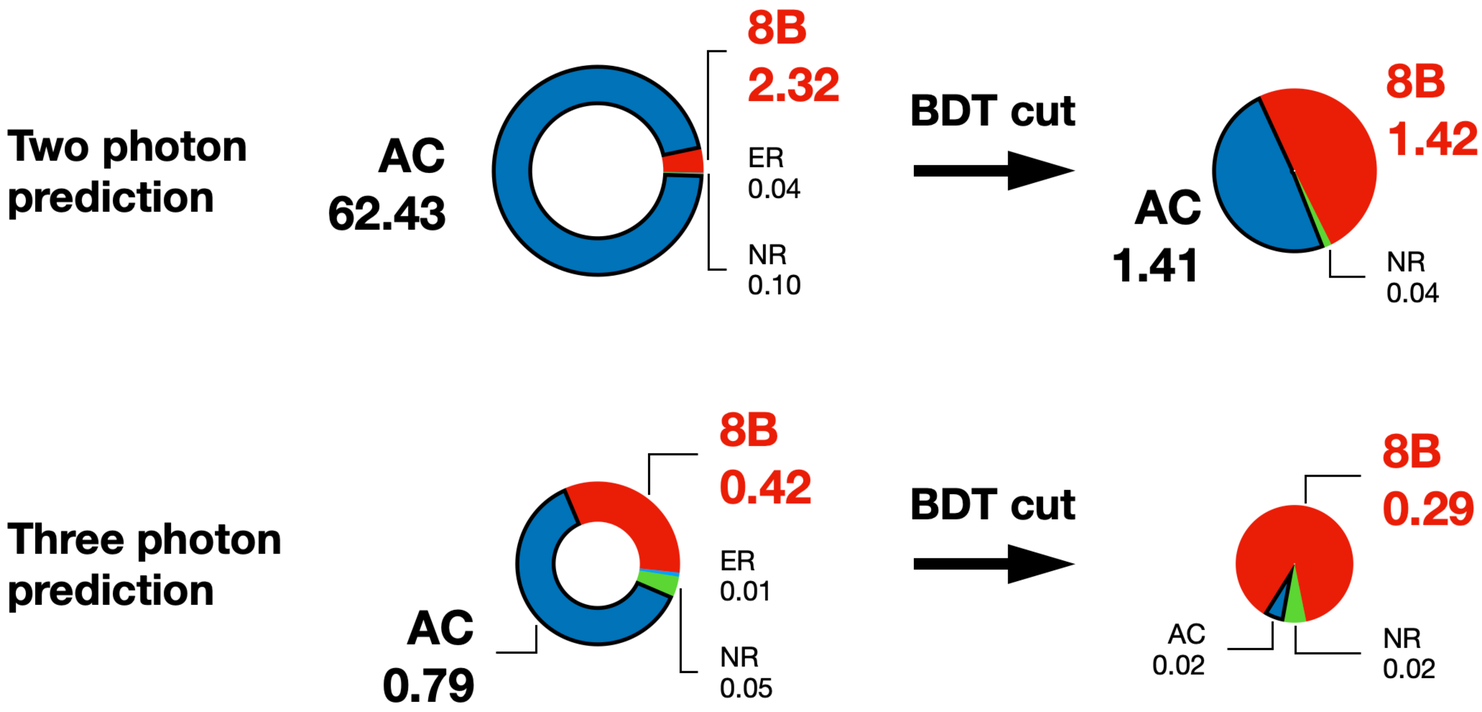
Sideband result

| Number of Photons | Physical Events | Accidental Events | Total Prediction | Data |
|---|---|---|---|---|
| **1** | 9.4 | 2060.5 | 2069.9 | 2043 |
| **2** | 10.1 | 33.8 | 43.9 | 47 |
| **3** | 6.9 | 2.2 | 9.1 | 7 |



# Accidental background

- Boosted decision tree (BDT): a classical machine-learning cut
- Input variables: related to charge, width, top-bottom asymmetry and PMT top pattern of S1 and S2s.
- Training s/b: $O(10^6)$ 8B event waveform simulation vs $O(10^6)$ data-driven accidental simulation

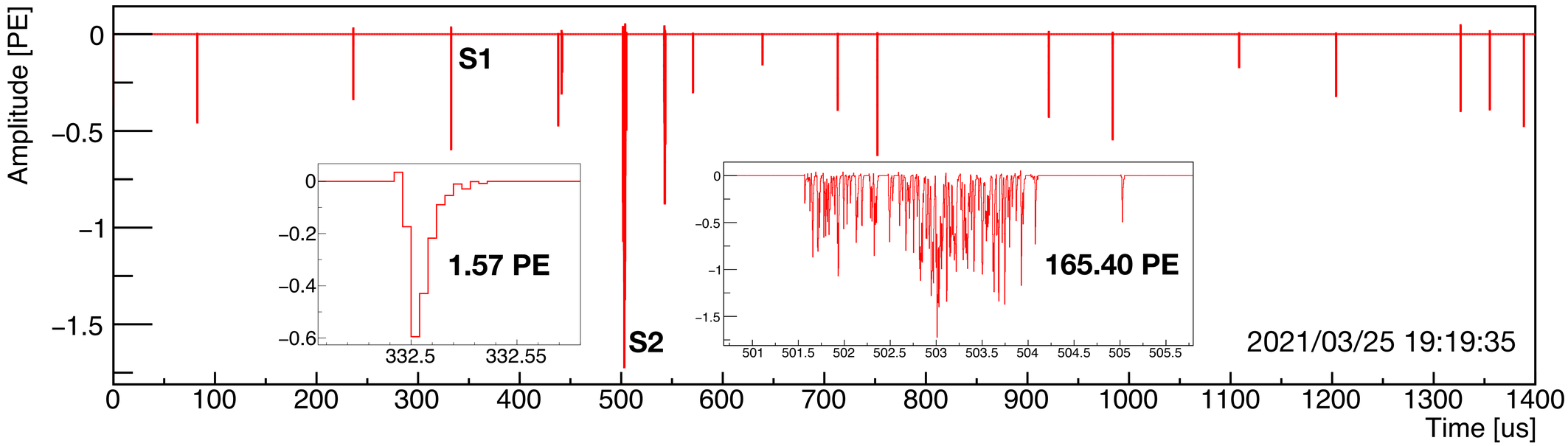


# Unblinding data

- Just one event was found
- 1-sigma downward fluctuation

Apply-BDT result

| N-hit | Total bkg | B8 | Data |
|---|---|---|---|
| 2 | 1.50 | 1.42 | 1 |
| 3 | 0.07 | 0.29 | 0 |



# Statistical interpretation

- Clear likelihood function with just two-bins: 2-hit, or 3-hit
- Uncertainty mainly drived by event rate, AC model, and BDT cut

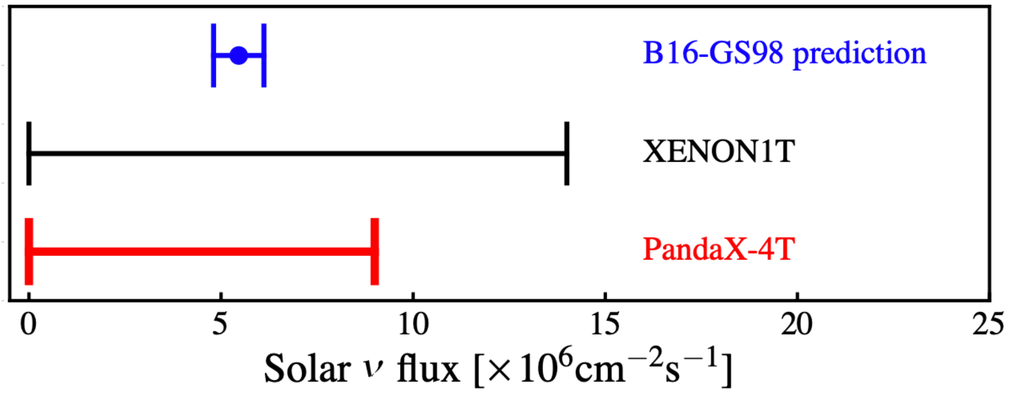
| Uncertainties | 2-hit bin | 3-hit bin |
|---|---|---|
| quality cuts | 0.14 | 0.14 |
| light and charge yield | **0.29** | **0.39** |
| accidental bkg | **0.30** | **0.30** |
| BDT cut for signal | **0.14** | **0.13** |
| BDT cut for bkg | **0.19** | **0.18** |
| solar B8-ν flux | 0.04 | 0.04 |

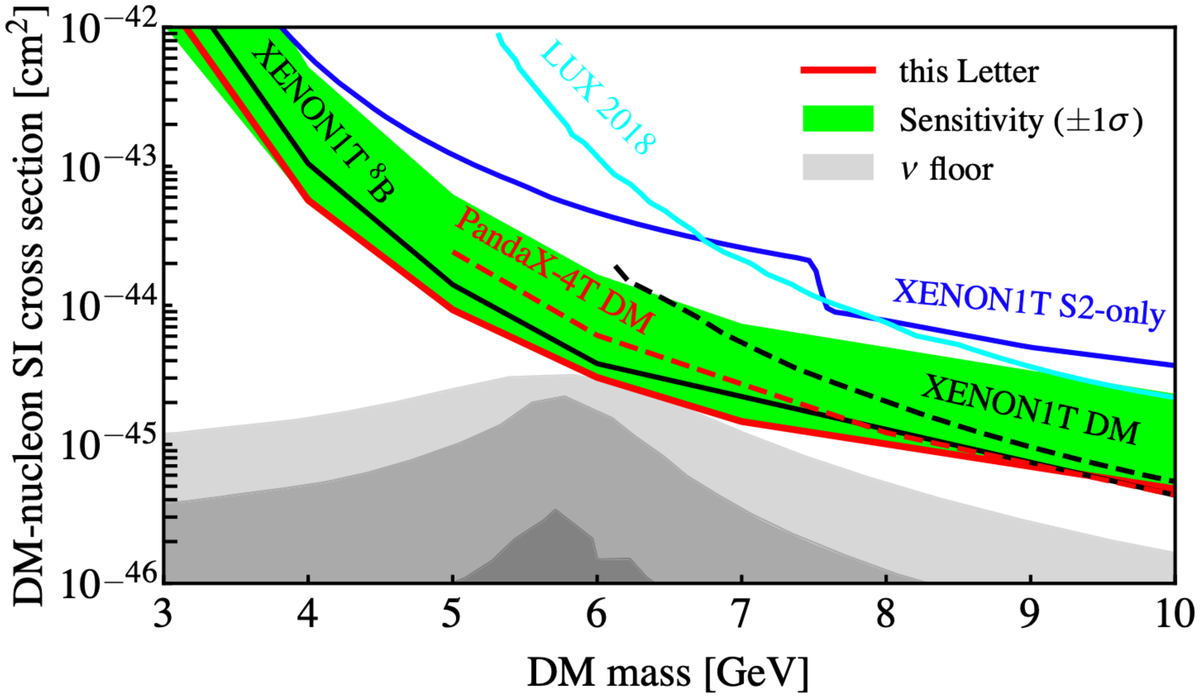
$$\mathcal{L} = G(\delta_\epsilon)G(\delta_s)G(\delta_b)G(\delta_\Phi) \times \left[\prod_i G(\delta^i_{\mathrm{BDT},s})G(\delta^i_{\mathrm{BDT},b})\frac{\lambda_i^{N_i}}{N_i!}e^{-\lambda_i}\right]$$

$$\begin{aligned}\lambda_i^\nu &= N_\nu(1+\delta_s f_i^\nu)(1+\delta_\epsilon)(1+\delta^i_{\mathrm{BDT},s}) \\ &\quad + N_{\mathrm{AC}}(1+\delta_b)(1+\delta_\epsilon)(1+\delta^i_{\mathrm{BDT},b}) + N_{\mathrm{other}}, \\ \lambda_i^\chi &= N_\chi(1+\delta_s f_i^\chi)(1+\delta_\epsilon)(1+\delta^i_{\mathrm{BDT},s}) \\ &\quad + N_\nu(1+\delta_s f_i^\nu)(1+\delta_\epsilon)(1+\delta^i_{\mathrm{BDT},s})(1+\delta_\Phi) \\ &\quad + N_{\mathrm{AC}}(1+\delta_b)(1+\delta_\epsilon)(1+\delta^i_{\mathrm{BDT},b}) + N_{\mathrm{other}},\end{aligned}$$

# Final Constraints

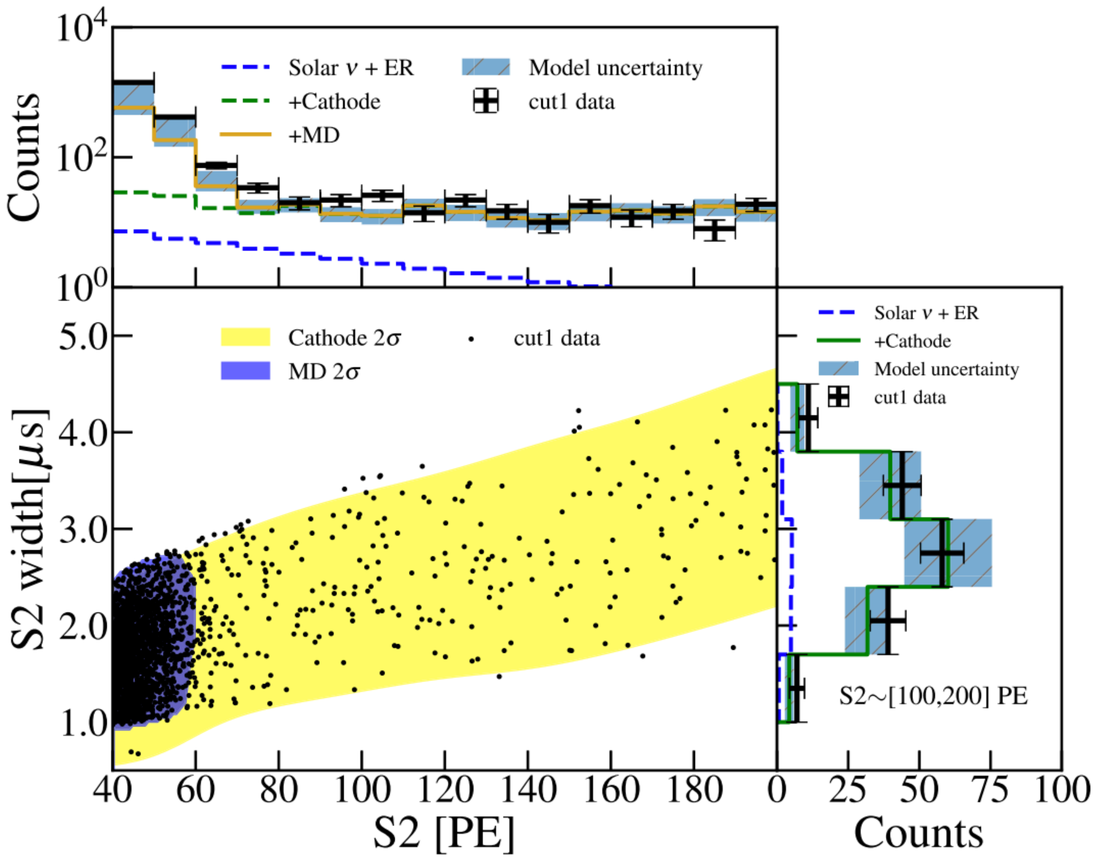
- Leading constraints on solar B8 CEvNS and 3-9 GeV WIMP

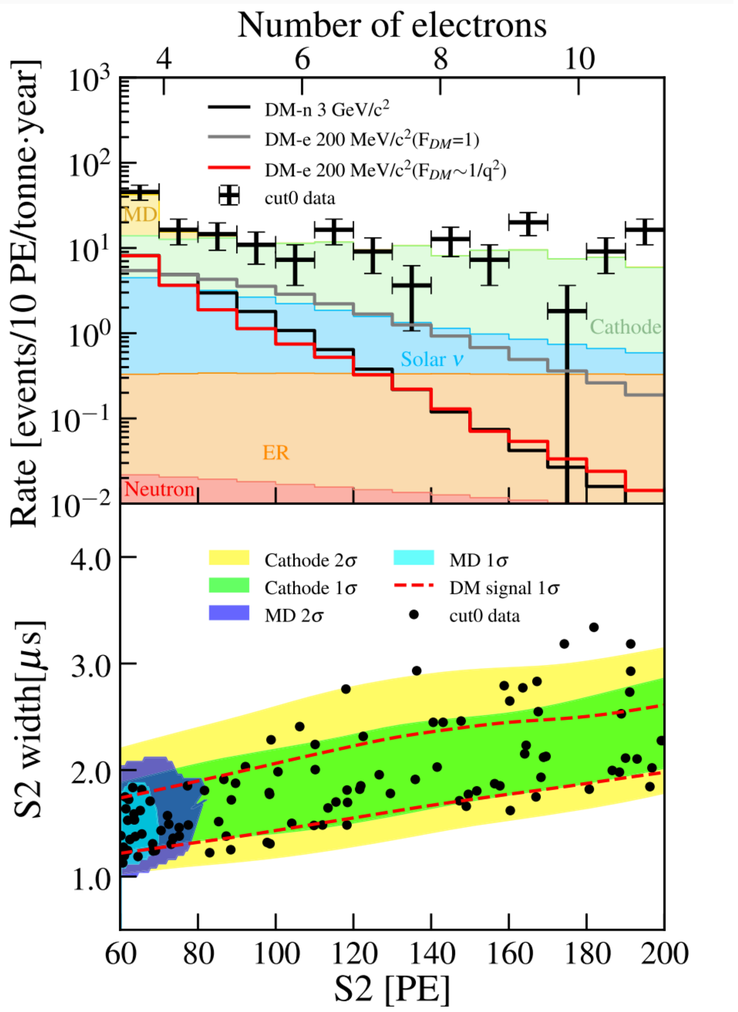


# S2–only analysis and constraints

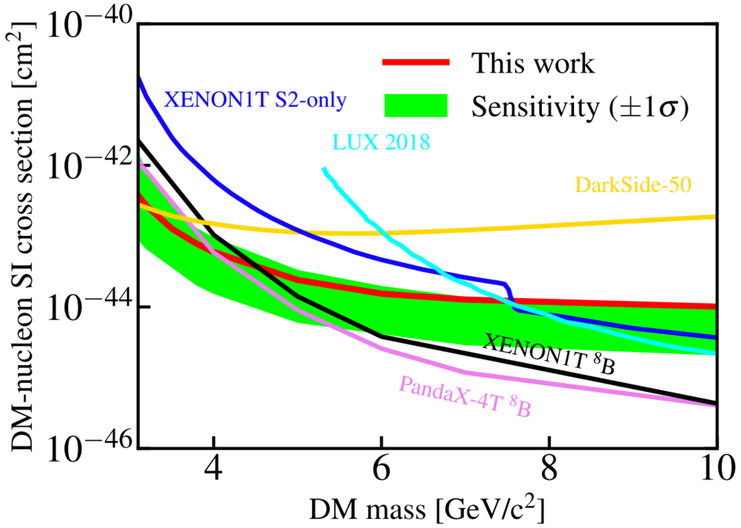
- Use consistent dataset and techniques, perform analysis on S2-only channel

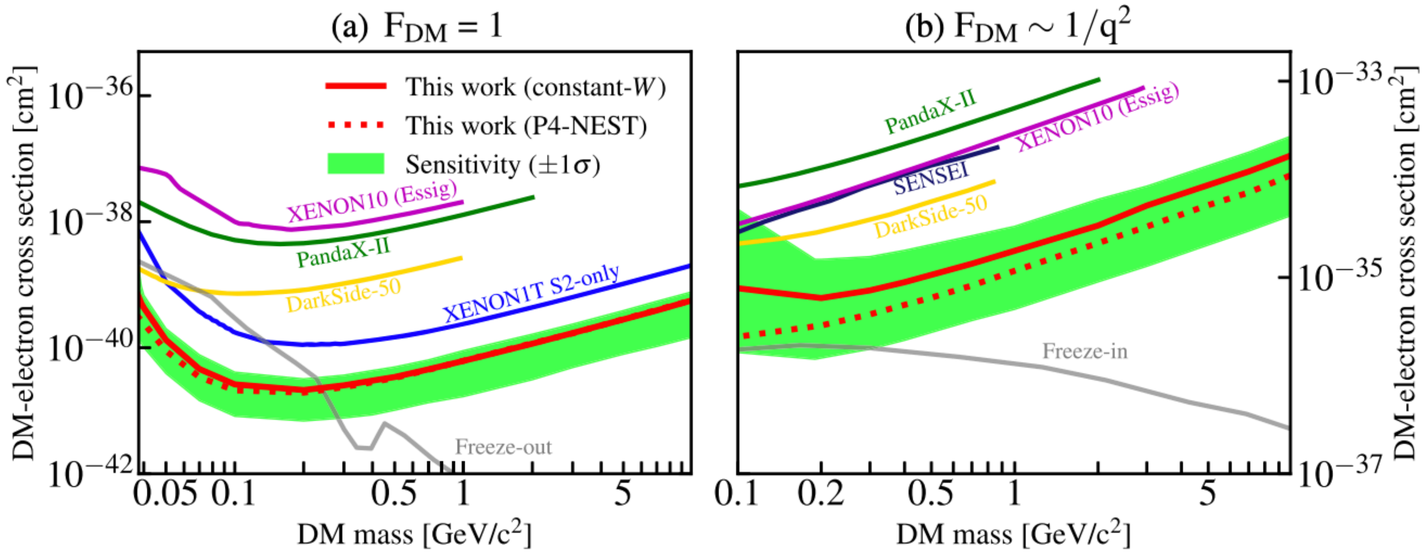


# S2–only analysis and constraints

- Use consistent dataset and techniques, perform analysis on S2-only channel
- Better DM-n and DM-e constraints at low-mass region



# Summary

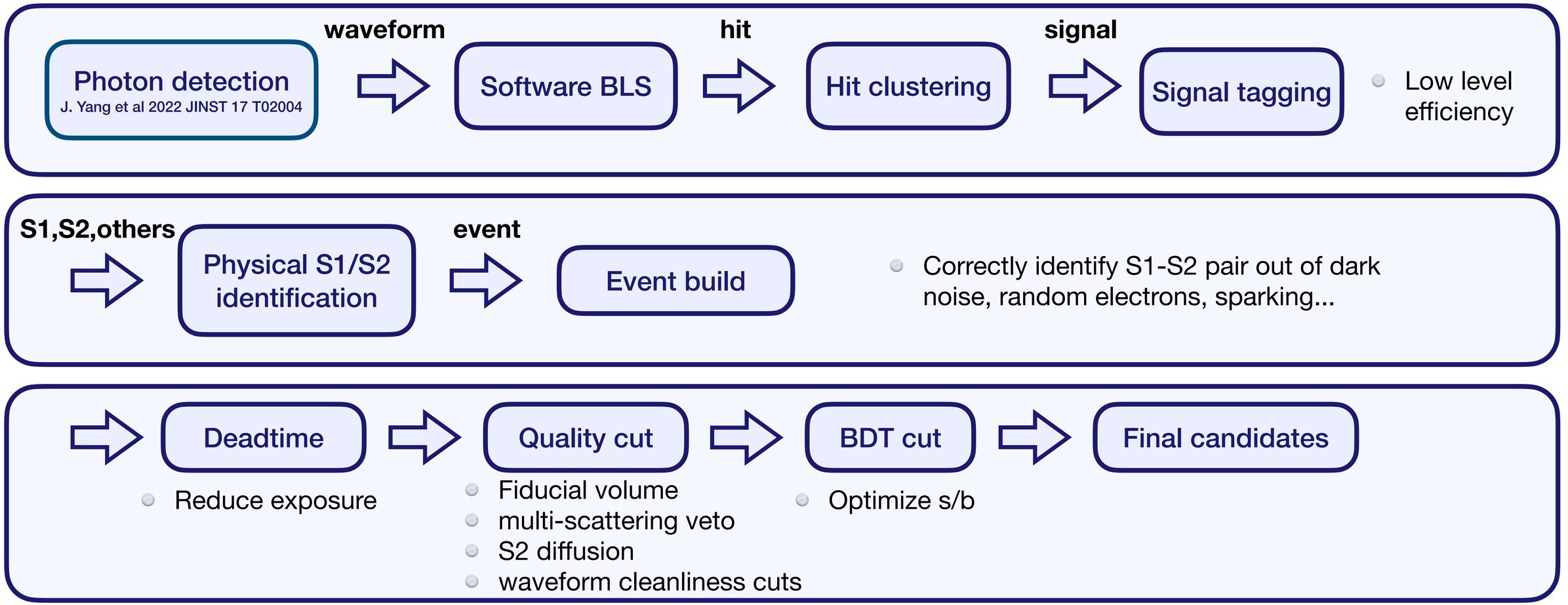
- PandaX-4T commissioning run low-energy analyses yield world-leading sensitivity for solar B8-ν CEvNS and low-mass dark matter.
- Low-threshold analyse techniques will be further employed in science run 1.
- Stay tuned.

# Questions

# Backup

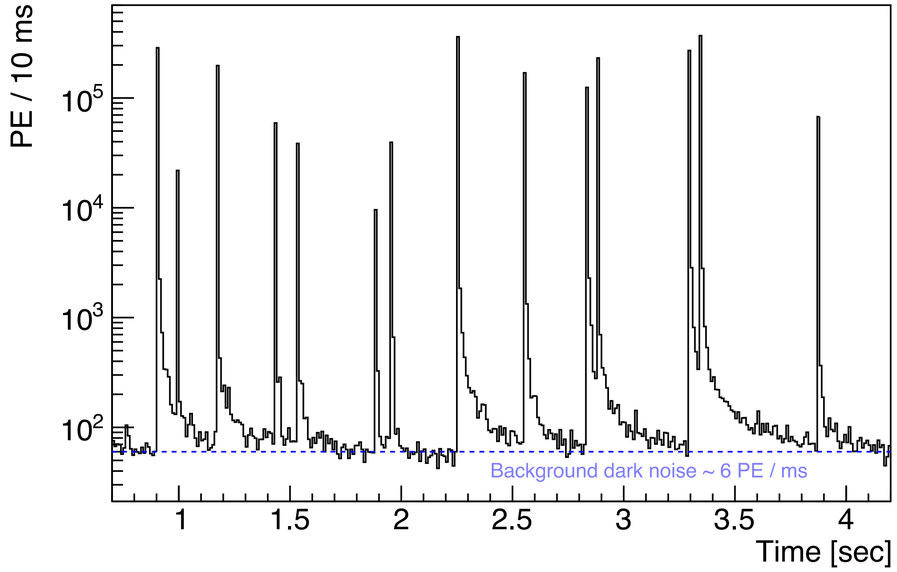
# Data processing

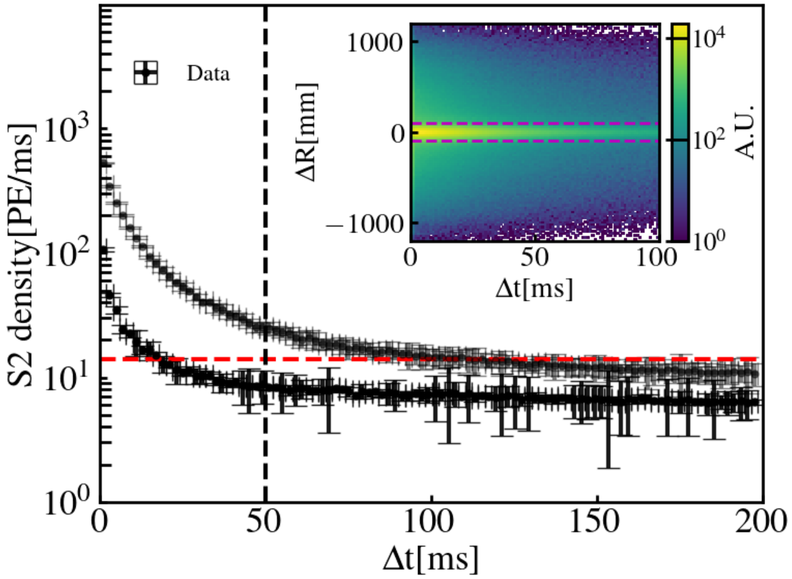
- Low-level detector response is crucial for searching 8B
- Discriminate physical events out of noise
- Cuts suppress background
- Validated the complete process using data-driven waveform simulation

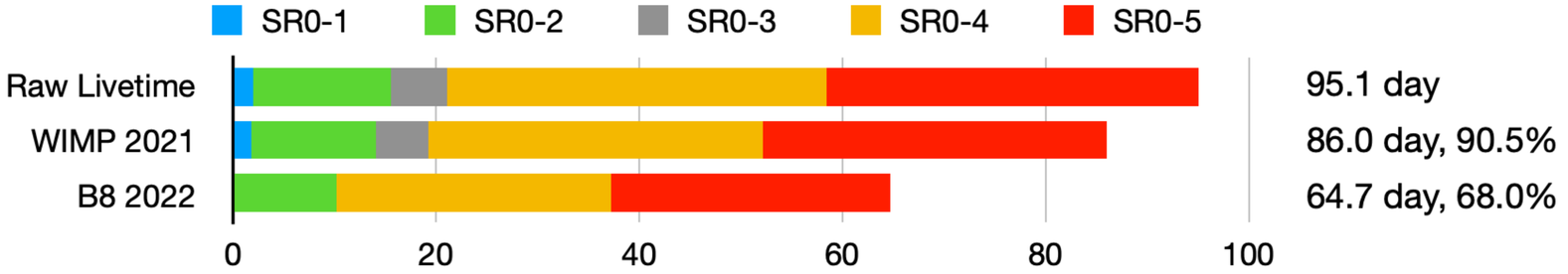


# Deadtime Effect

- ~ 3% Bad data files with excessive noise
- 7 live days with excessive micro-discharge
- High-charge period induced by tail of large signals



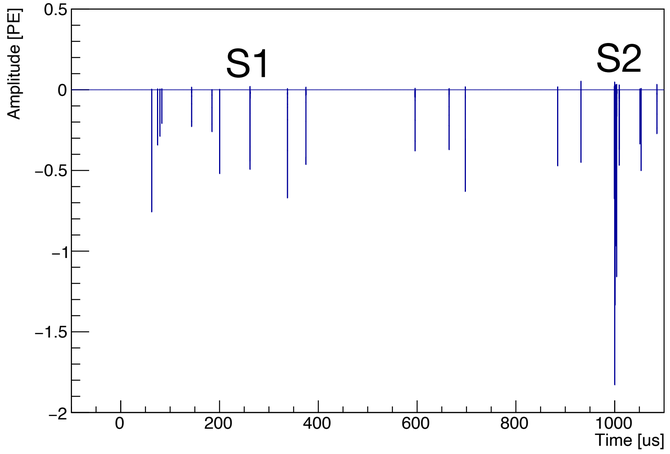



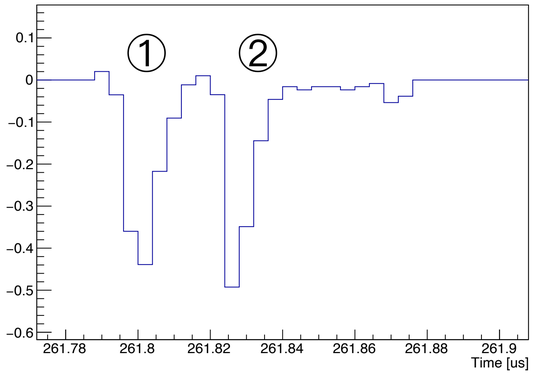
# Waveform simulation

- S1: sampled from neutron-calibration S1
- S2: formed by data-driven single electrons with proper diffusion width
- Data-driven delay ionization, noise, dark rate, and after pulse

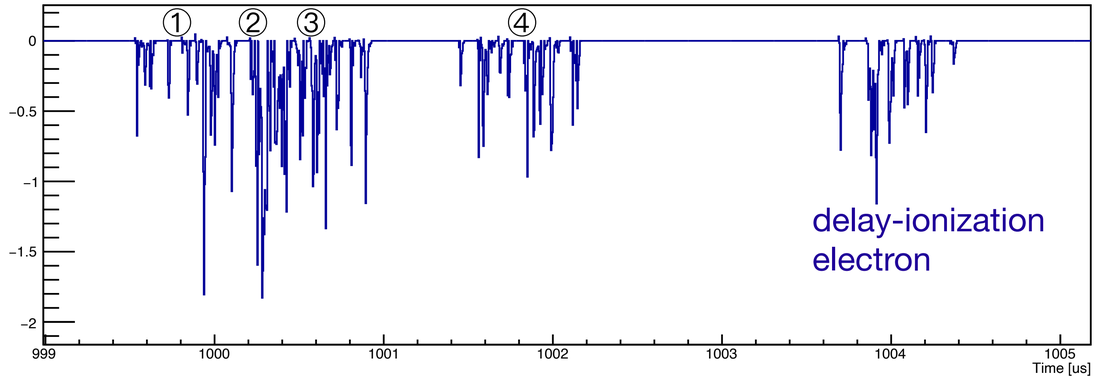
A complete simulation waveform



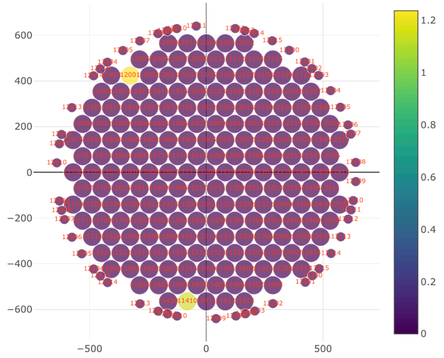

double-photon S1



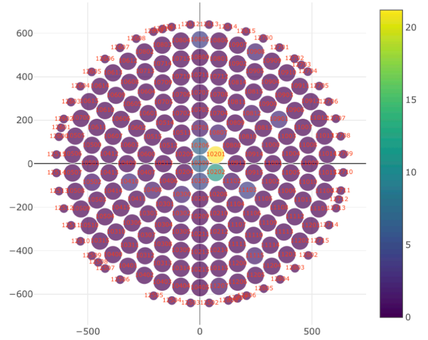

4-electron S2



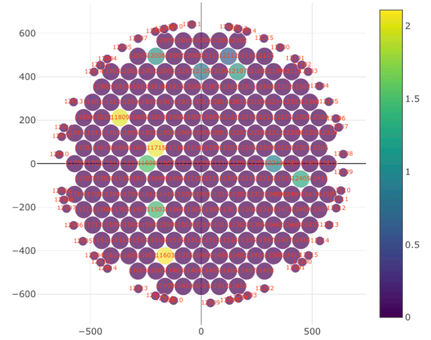

S1 pattern on the bottom array



S2 hit pattern on top

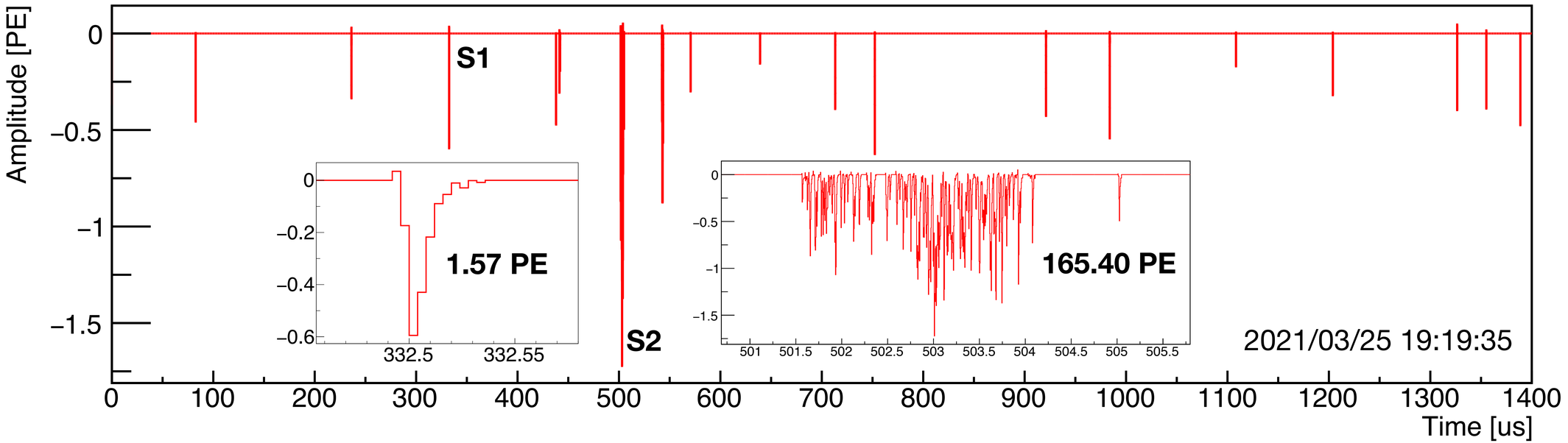


S2 hit pattern on bottom array



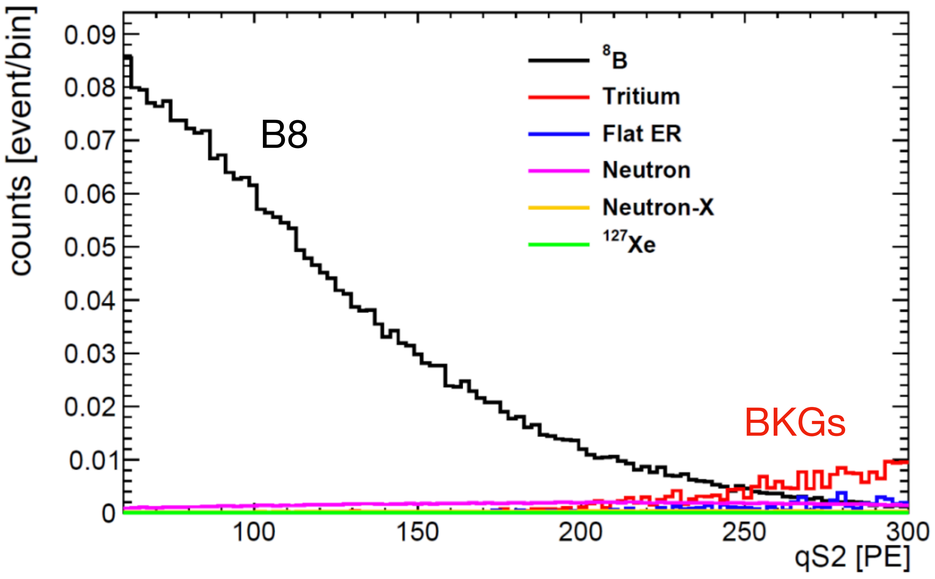
# Unblinded event

| $N_{hit}$ | $S2$ range (PE) | BDT | ER | NR | Surface | AC | Total prediction | $^8$B | Observation |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 65–230 | pre | 0.04 | 0.10 | 0.14 | 62.43 | 62.71 | 2.32 | **59** |
| | | post | 0.02 | 0.04 | 0.03 | 1.41 | 1.50 | 1.42 | **1** |
| 3 | 65–190 | pre | 0.01 | 0.05 | 0.08 | 0.79 | 0.93 | 0.42 | **2** |
| | | post | 0.00 | 0.02 | 0.03 | 0.02 | 0.07 | 0.29 | **0** |



# Physical background

Two-photon channel




Three-photon channel