Search for light dark matter with PandaX-4T

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On behalf of PandaX collaboration

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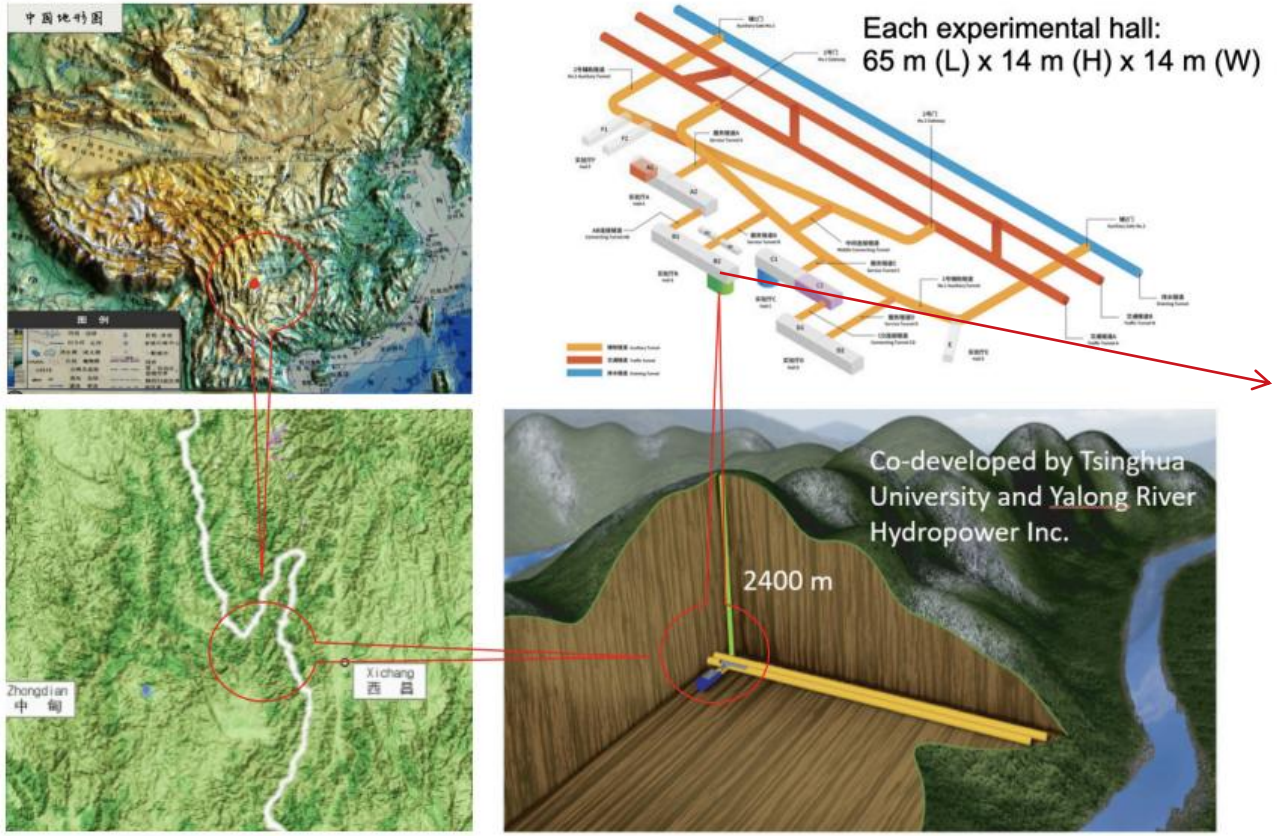
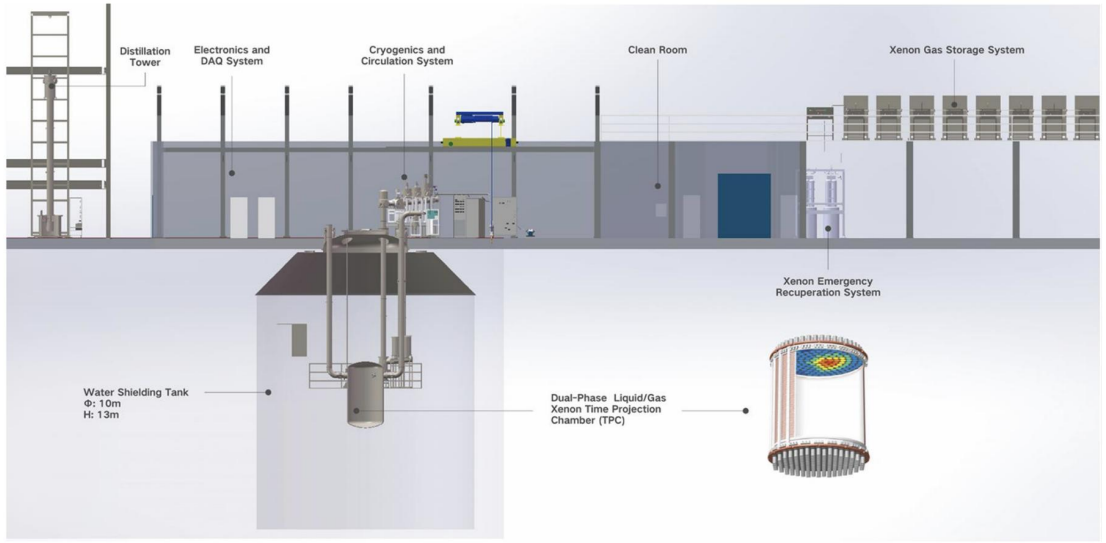
饮 水 思 源 • 爱 国 荣 校

PandaX-4T experiment

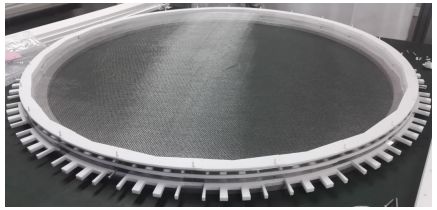
- A direct dark matter detection experiment located in China Jingping Underground Laboratory (CJPL)

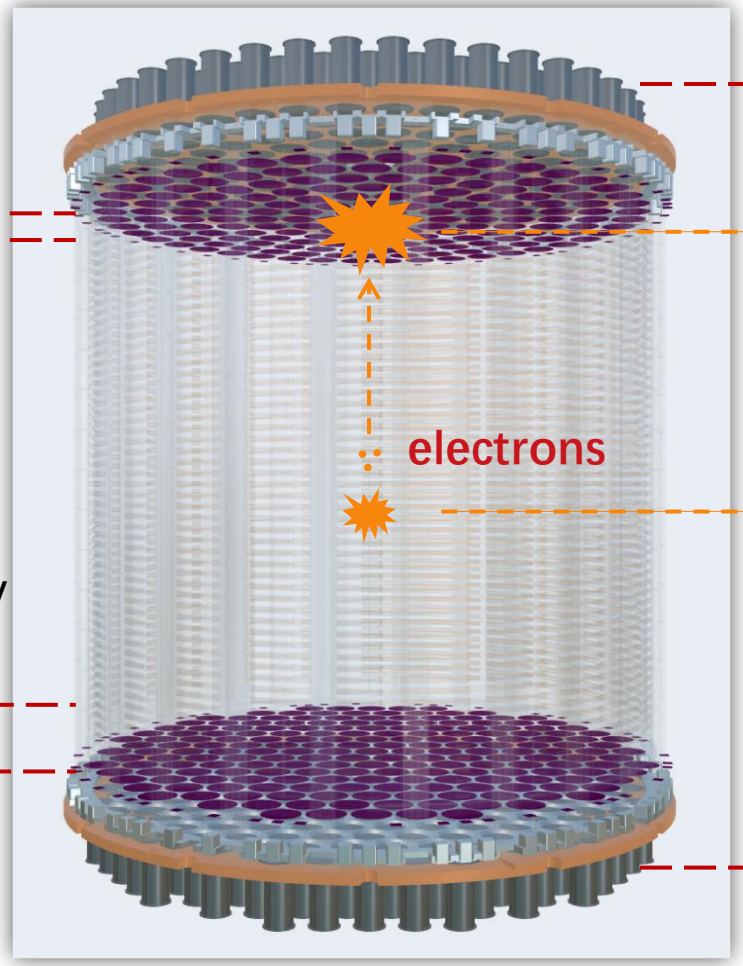




PandaX-4T experiment

Dual-phase Time Projection Chamber





- Energy measurement
- 3D position reconstruction
- Discrimination of nuclear recoil and electron recoil

PandaX-4T experiment

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

Physics runs

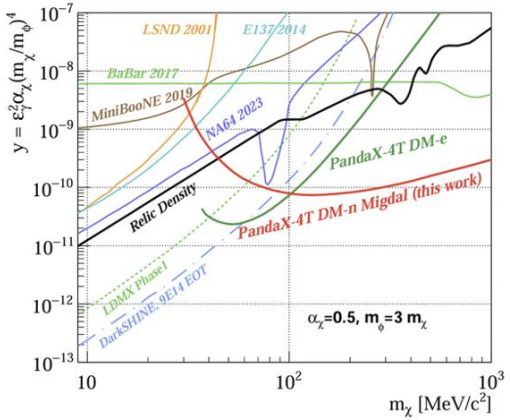
2020/11 – 2021/04	**Commissioning (Run0)** 95 days
2021/07 – 2021/10	**Tritium removal** xenon distillation, gas flushing, etc.
2021/11 – 2022/05	**Physics run (Run1)** 164 days
2022/09 – 2023/12	**CJPL B2 hall construction** xenon recuperation, detector upgrade
Current Status	**Physics run (Run2)**

Run0 and Run1 are both used in this analysis

Light Dark Matter search

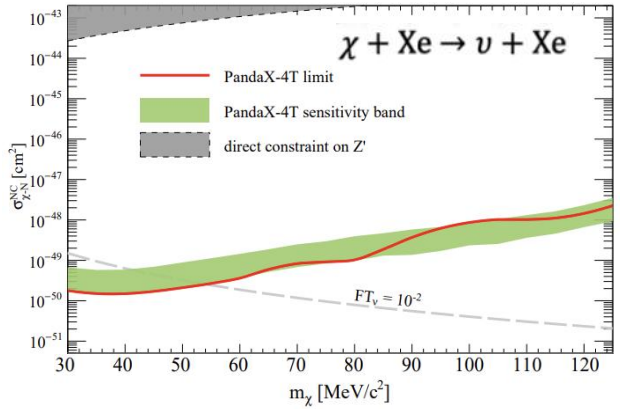
- PandaX has achieved progress in various light dark matter (LDM) interaction

DM-electron



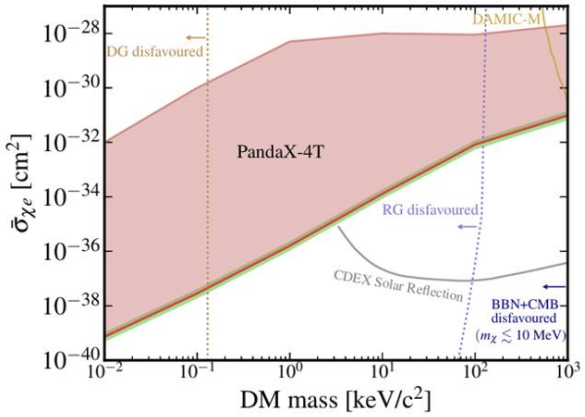
PRL 131,191002 (2023)

DM-neutrino



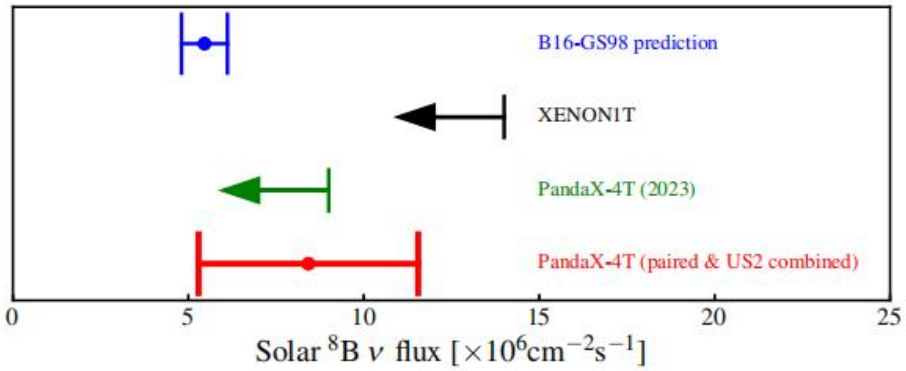
PRL 129,161803 (2022)

Boosted DM



PRL 133,101805 (2024)

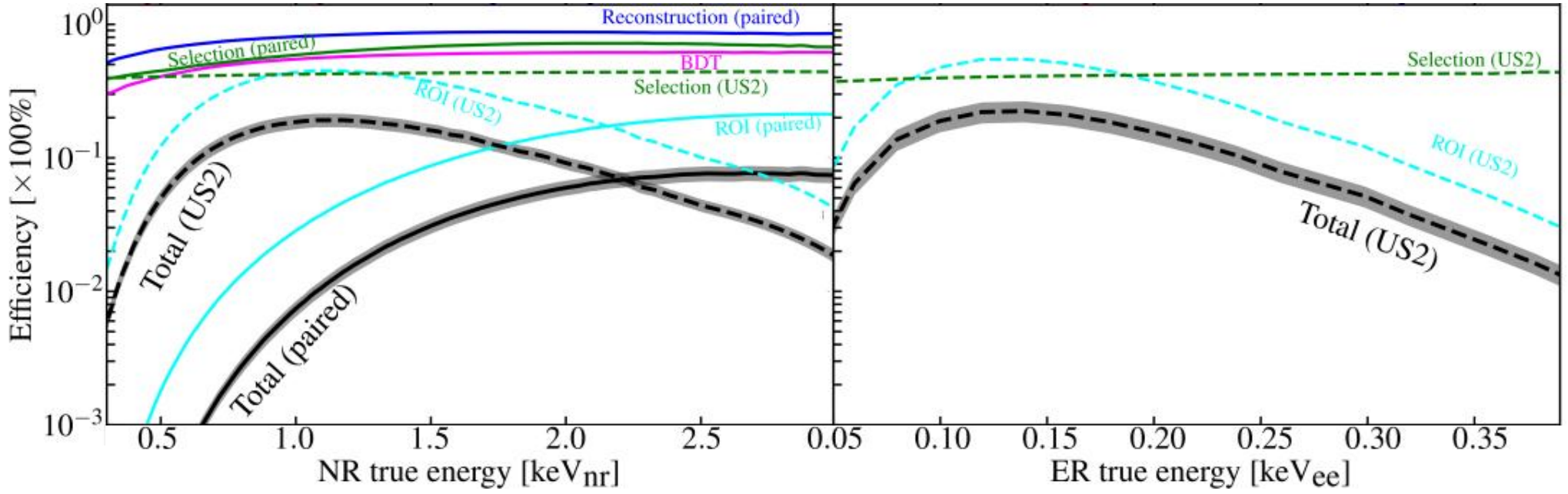
- To further improve sensitivity
  - Lower energy threshold



PRL133, 191001 (2024)

Low threshold channels

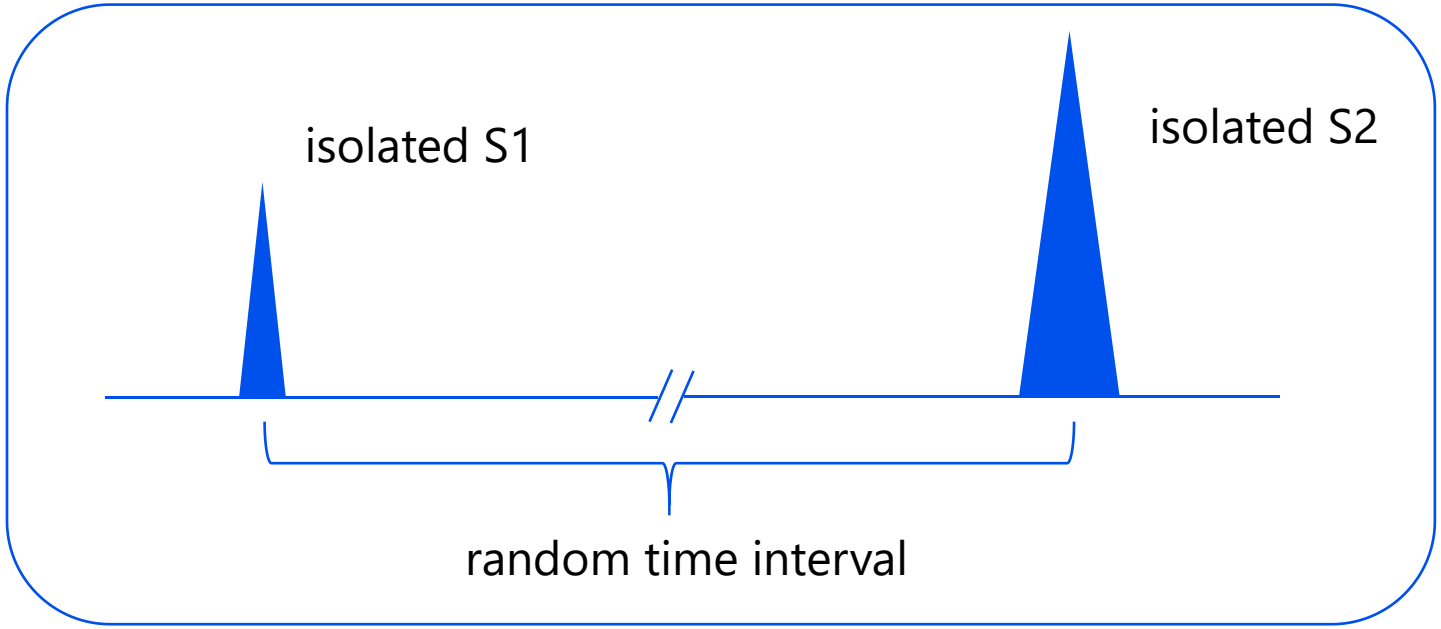
- Low threshold S1-S2 paired channel (Paired) ~1keVnr
- Unpaired S2 channel (US2) ~0.33keVnr ~0.04keVee



- Main challenges: Background and signal model

Paired channel

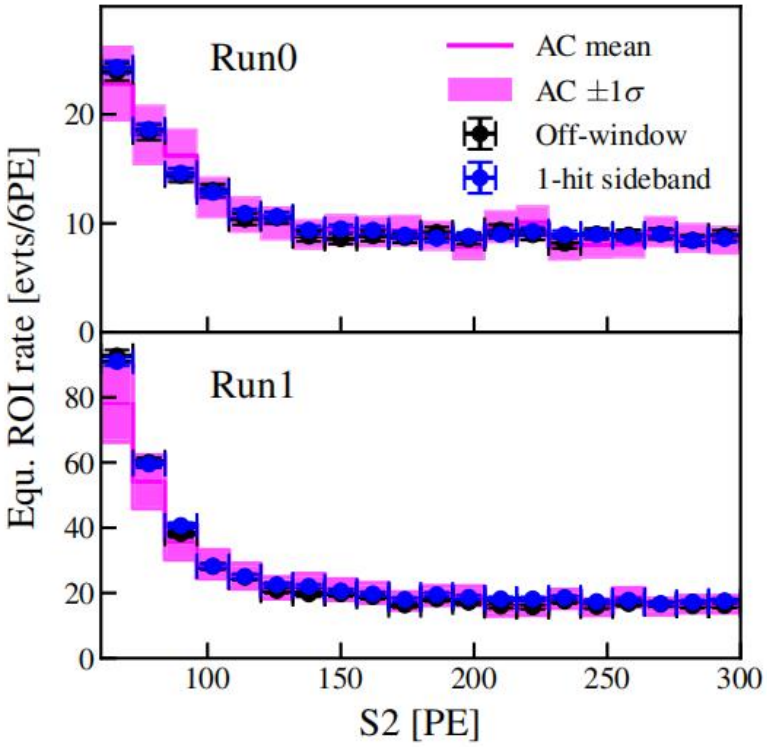
- Definition
  - S1 charge as low as 0.3 PE, requiring 2 or 3 hits
- Dominant background: Accidental events (AC)
  - Isolated S1 and S2 accidentally appear in a signal window



Paired channel

- AC Model
  - Pick isolated S1 and S2, and randomly pair them together
- Sideband to test model
  - Off-window: the interval between isolated S1 and S2 is larger than maximum drift time window
  - 1-hit: events with S1 only containing 1 hit
- Boosted decision tree (BDT)
  - Remove most AC backgrounds based on 23 variables related to waveform shape and position reconstruction

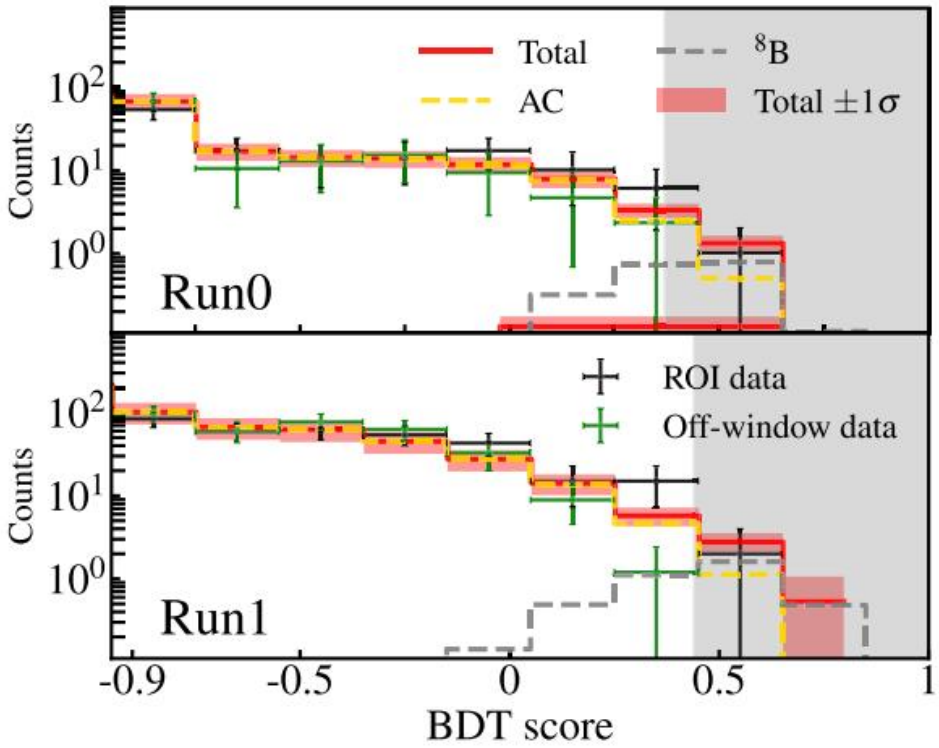
		Run0		Run1	
		W/O BDT	W/ BDT	W/O BDT	W/ BDT
Off-window	Prediction	180±27	0.9±0.2	417±63	1.2±0.4
	Data	205	1	404	0
10% data	Prediction	26±6	0.12±0.04	34±7	0.06±0.02
	Data	18	0	29	0
1-hit side-band	Prediction	17095±2564	14±4	27567±4135	15±5
	Data	17374	9	29359	17



Paired channel

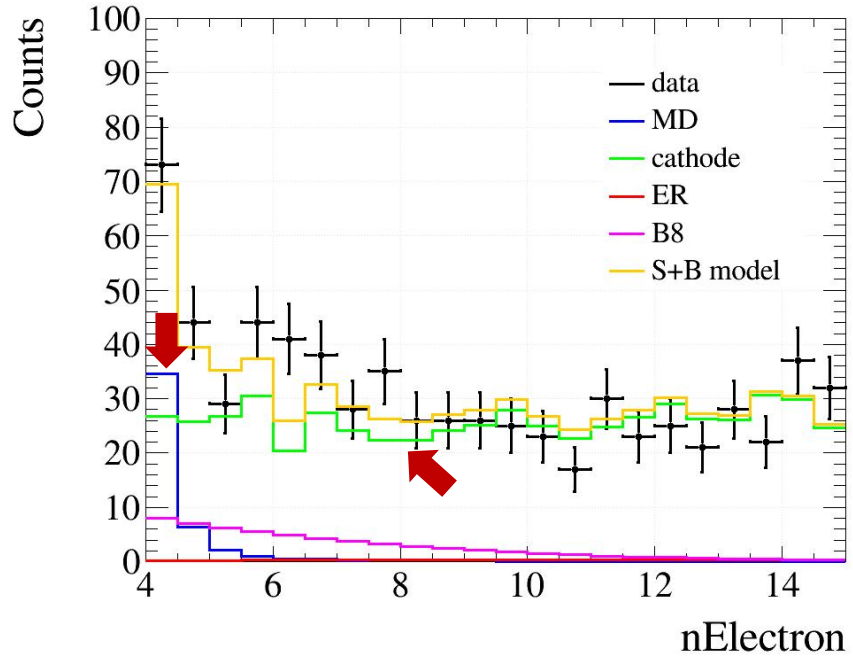
- Candidate events
  - Total exposure: 1.20 tonne·year
  - Some downward fluctuation

paired ROI	Run0 2-hit	Run0 3-hit	Run1 2-hit	Run1 3-hit
Surface	0.06±0.01	0.06±0.01	0.01±0.01	0.02±0.02
ER	0.01±0.00	0.00±0.00	0.01±0.01	0.01±0.01
Neutron	0.02±0.01	0.02±0.01	0.03±0.01	0.03±0.01
AC	1.08±0.28	0.07±0.02	1.15±0.35	0.24±0.08
Total bkg.	1.16±0.28	0.15±0.02	1.21±0.35	0.30±0.08
^{8}B CEνNS	1.00±0.24	0.24±0.09	1.76±0.50	0.40±0.18
Observed	1	0	2	0



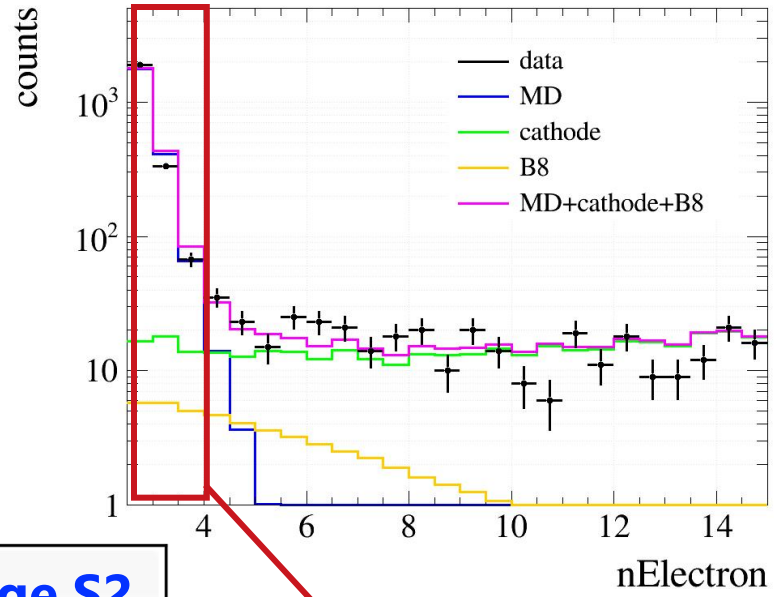
US2 Channel

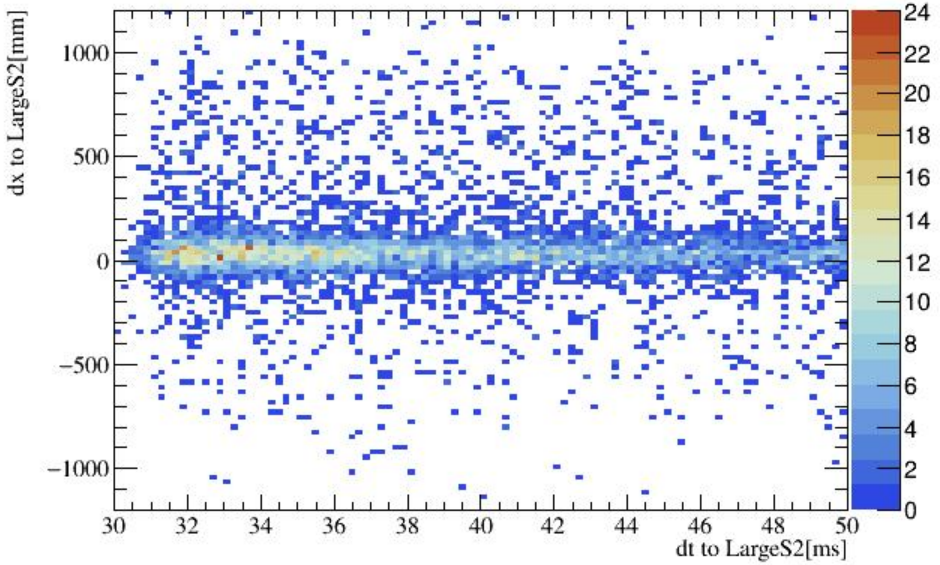
- Definition:
  - No paired S1 or paired S1 with only 1 hit
- Dominant backgrounds
  - Delayed electrons (MD)
    - Dominant in low energy region, drop sharply
  - Cathode
    - Dominant in relatively high energy region, flat spectrum

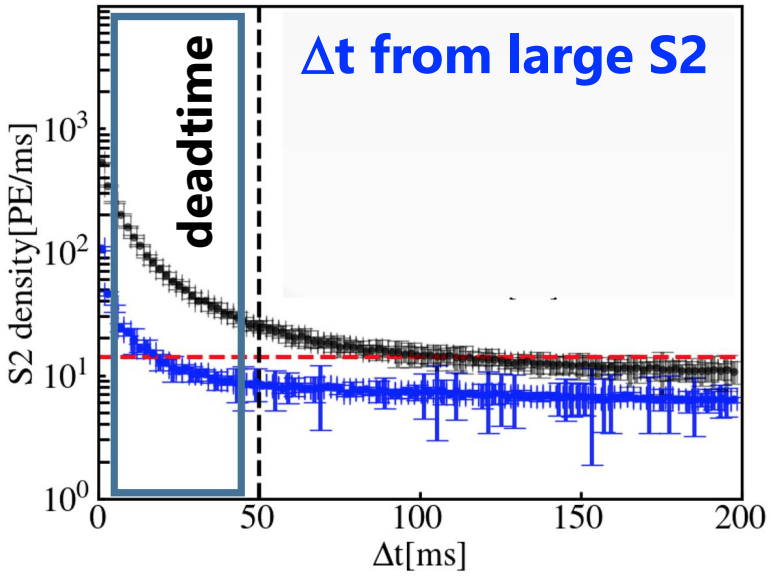


US2 channel

- Delayed electrons background:
  - Small charge
  - Related to single electron (SE) rate
  - Position relation with previous large S2
  - Spectrum get from deadtime region where SE rate is very high, use 2.5-4 nE as control region

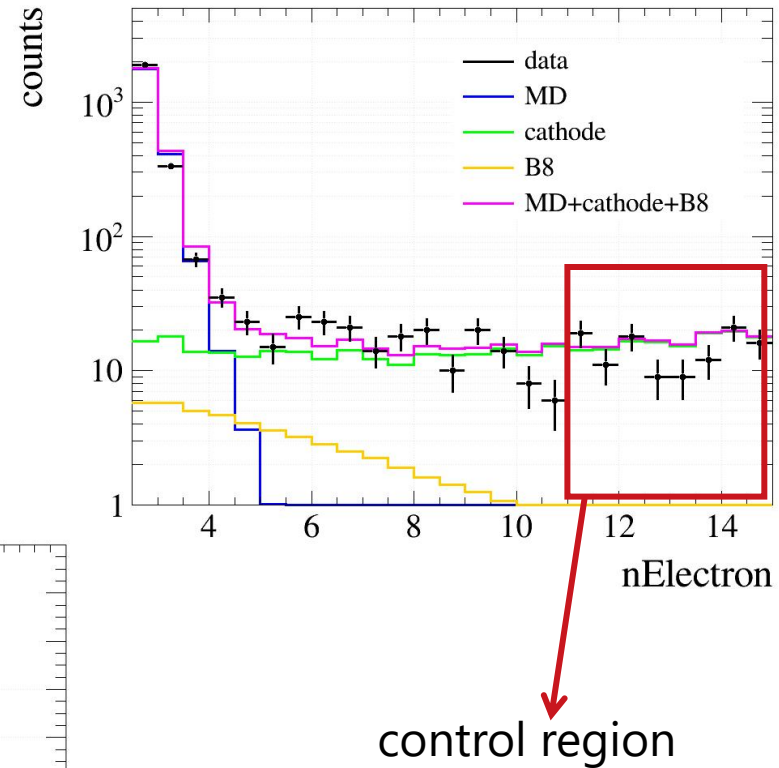


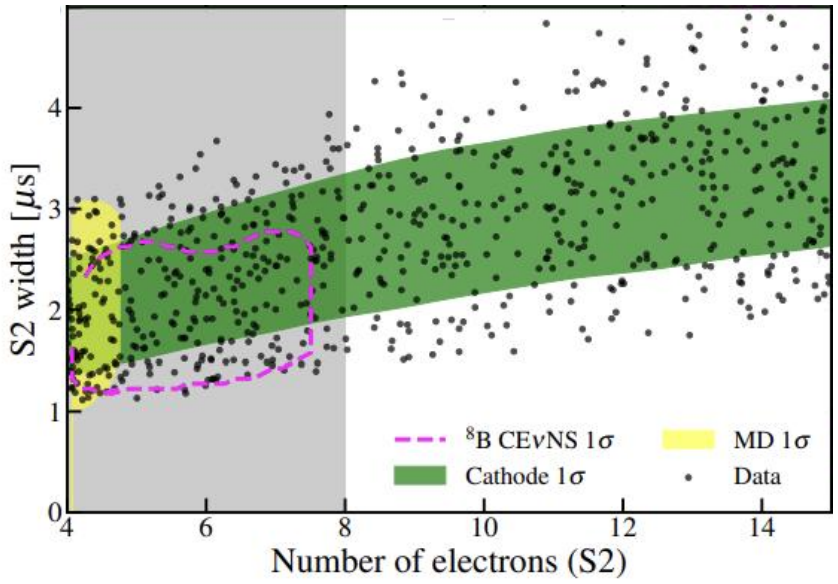


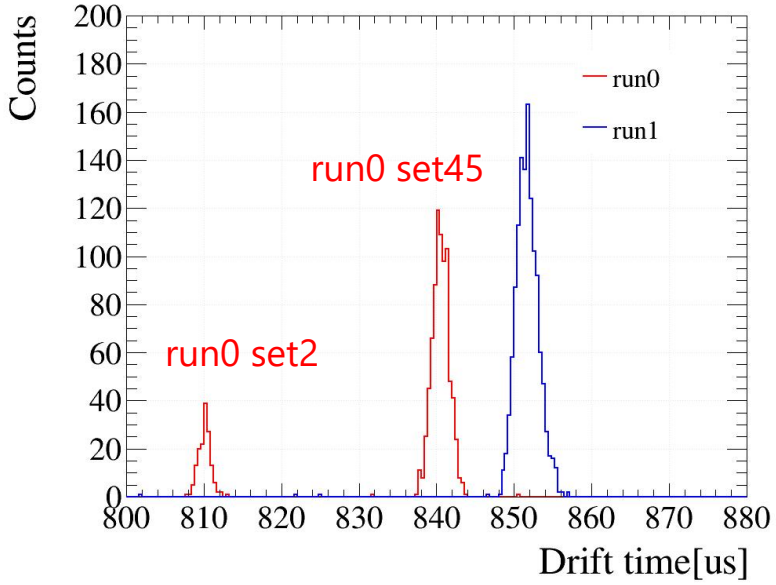


US2 channel

- Cathode background
  - Wide charge spectrum
  - Relatively large S2 width compared with physical events
  - Spectrum obtained from paired S1-S2 cathode events, using 11-15 nE as control region







US2 channel

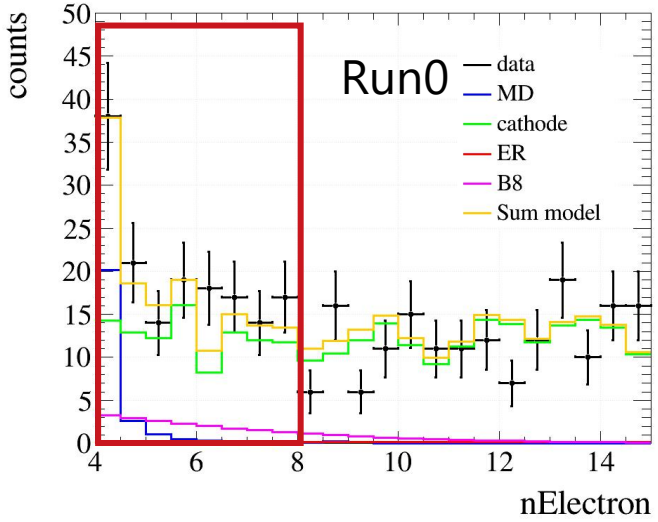
- Candidate events:
  - Total exposure: 1.04 tonne·year
  - Some upward fluctuation in high-energy region of ROI
  - MD uncertainty is greatly reduced compared with previous work

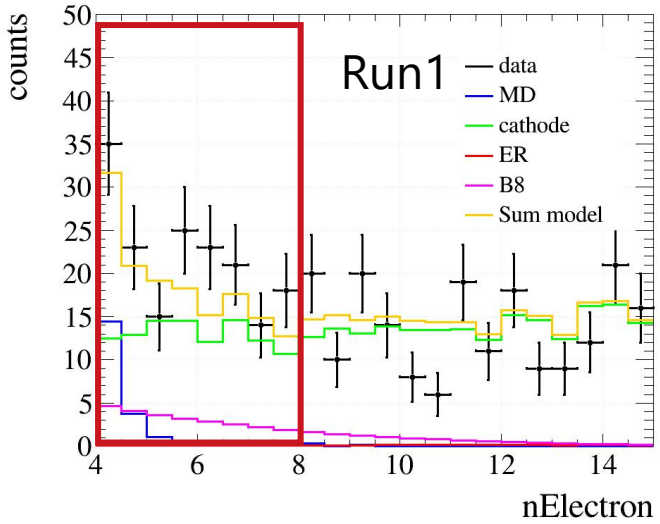
	Nominal
Cathode	41.6 ± 10.6
MD	$6.9^{+9.0}$
Solar ν	10.8 ± 3.7
ER	2.3 ± 0.6
Neutron	0.1 ± 0.1
Total	$61.7^{+14.4}_{-11.2}$

PRL 130, 261001 (2023)

US2 ROI	Run0	Run1
Cathode	100 ± 24	104 ± 21
MD	25 ± 3	20 ± 4
ERs	1.3 ± 0.1	0.9 ± 0.2
Total bkg.	126 ± 24	125 ± 21
^{8}B CEνNS	18 ± 4	25 ± 6
Observed	158	174

PRL133, 191001 (2024)

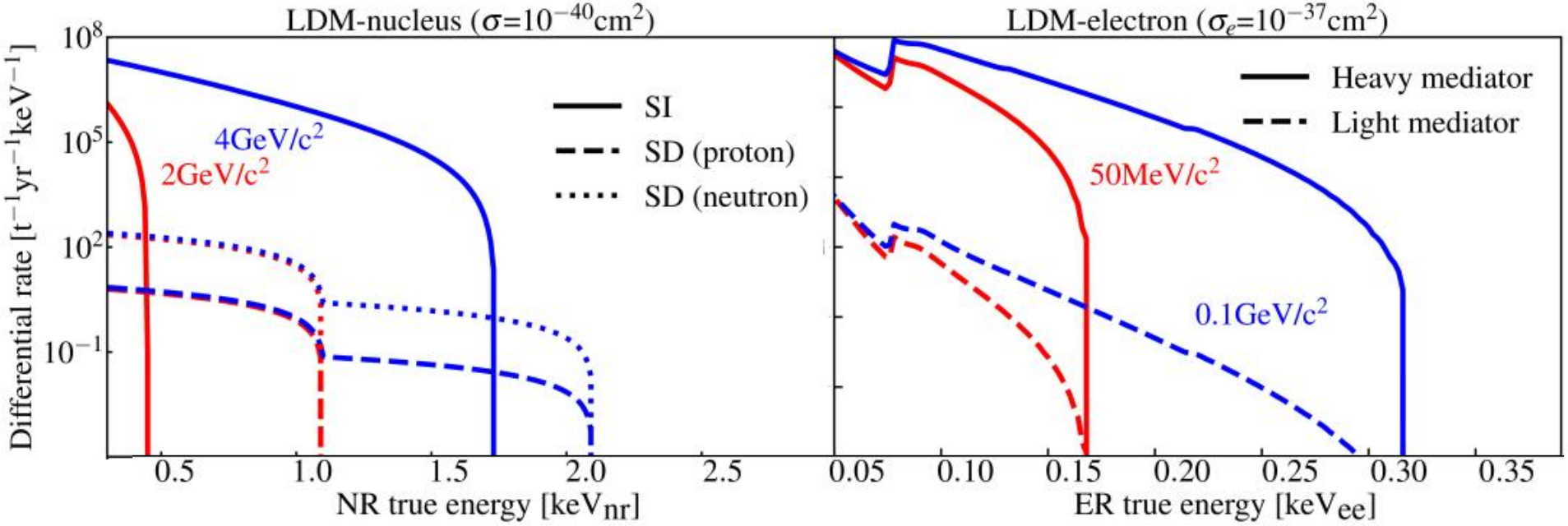




Signal model

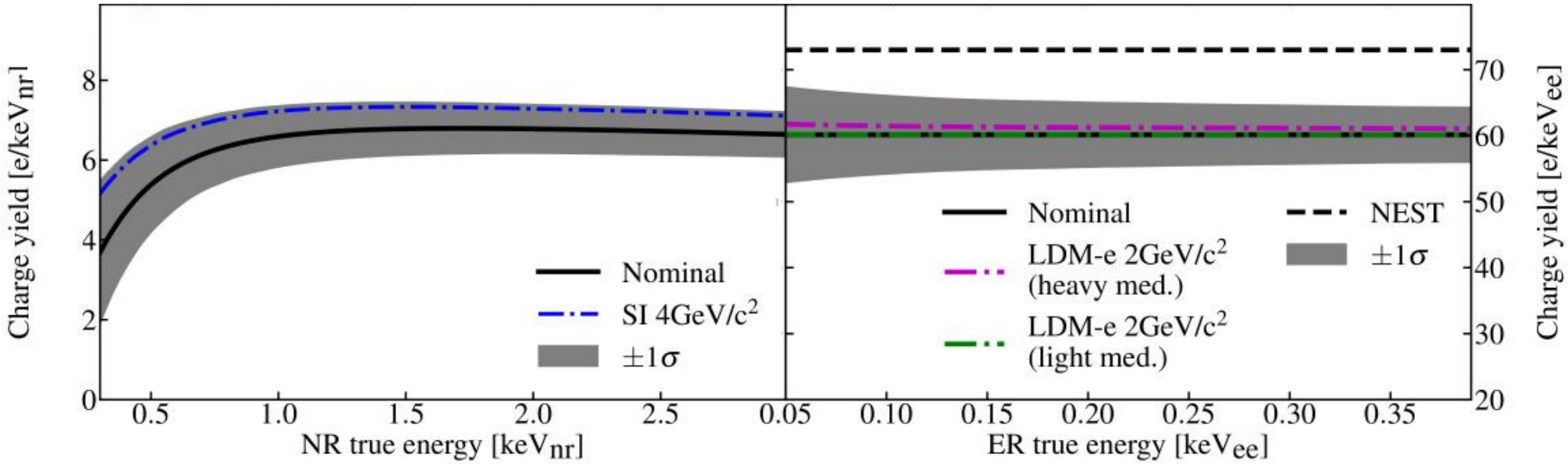
Models

- Spin-independent (SI) dark matter-nucleon interaction
- Spin-dependent (SD) neutron-only interaction and proton-only interaction
- Dark matter-electron interaction through heavy and light mediator



Signal model

- low energy response:

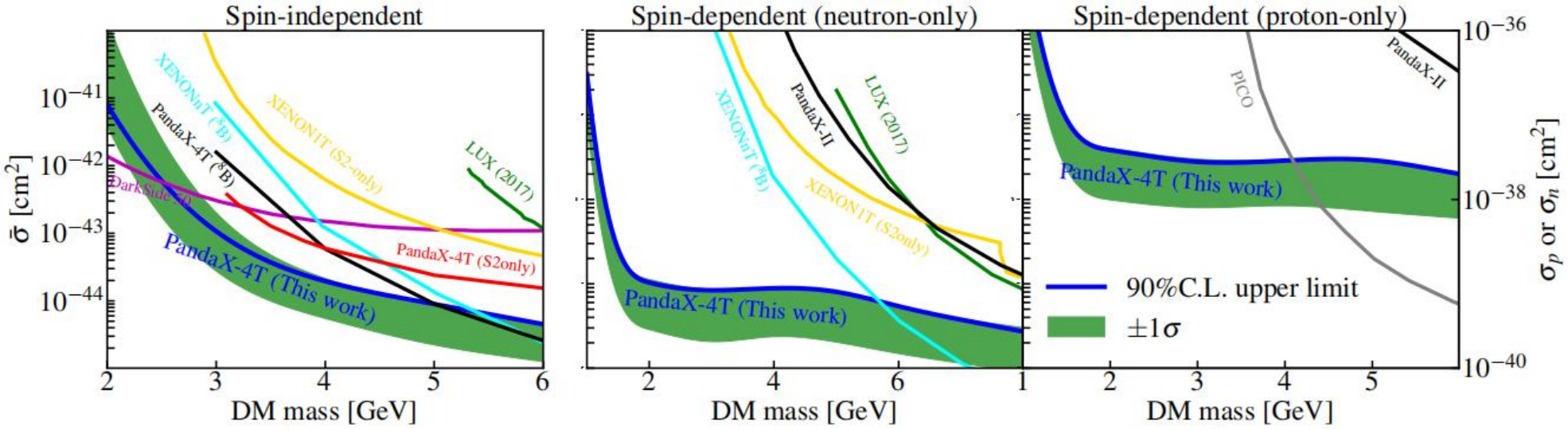


- LDM-nucleus
  - NEST model
  - Use Paired and US2 channels
  - Light yield and charge yield vary anti-correlatively in fitting
- LDM-electron
  - Conservative constant model
  - Only use US2 channel

Results

Dark matter-nucleon interaction

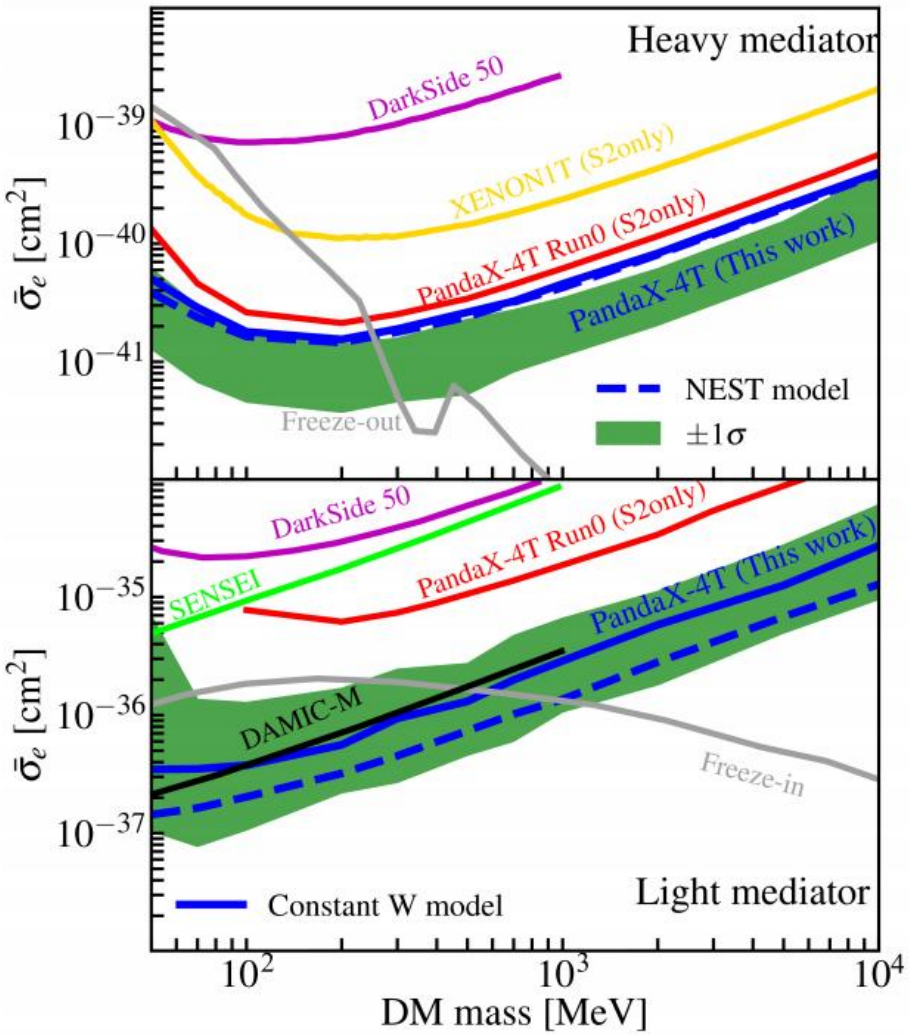
- Set the most stringent limits for SI interaction in [2.5, 5] GeV, SD neutron-only interaction in [1, 5.6] GeV, SD proton-only interaction in [1, 4.1] GeV
- Upward fluctuation due to excess in US2 channel high energy region
- Lowered energy threshold of US2 channel significantly improves SD interaction limits



arXiv: 2507.11930

Results

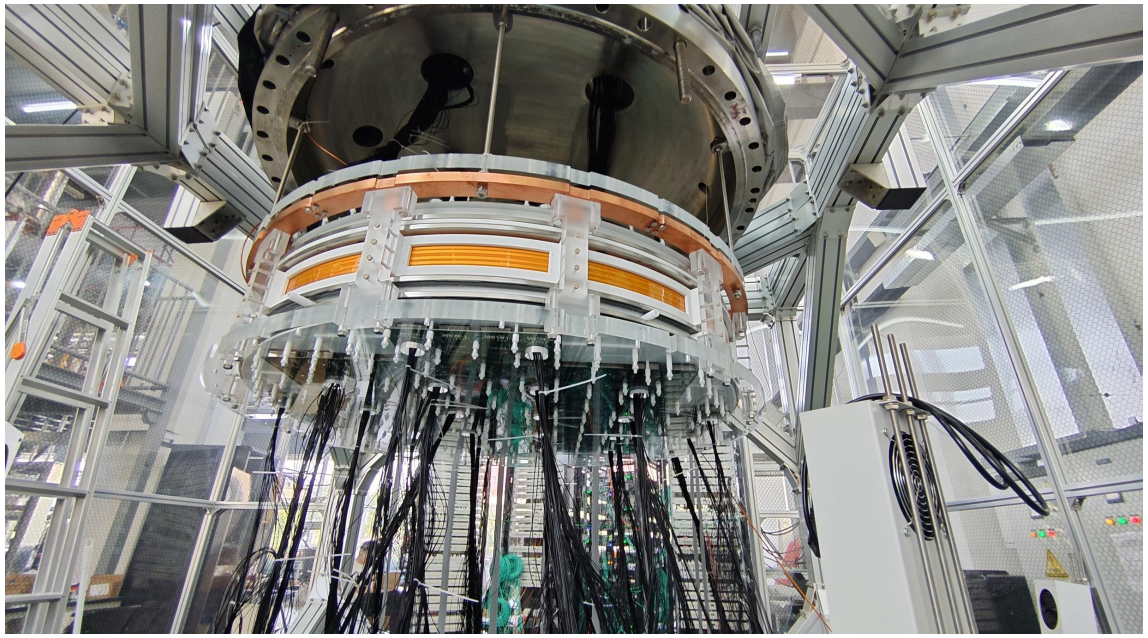
- Dark matter-electron interaction
  - Set the most stringent limit from 100MeV to 10GeV
  - Upward fluctuation in heavy mediator scenario is also because of excess in US2 channel high energy region
  - Due to different treatment in signal model and greatly reduced MD uncertainty, limit for light mediator scenario is significantly improved

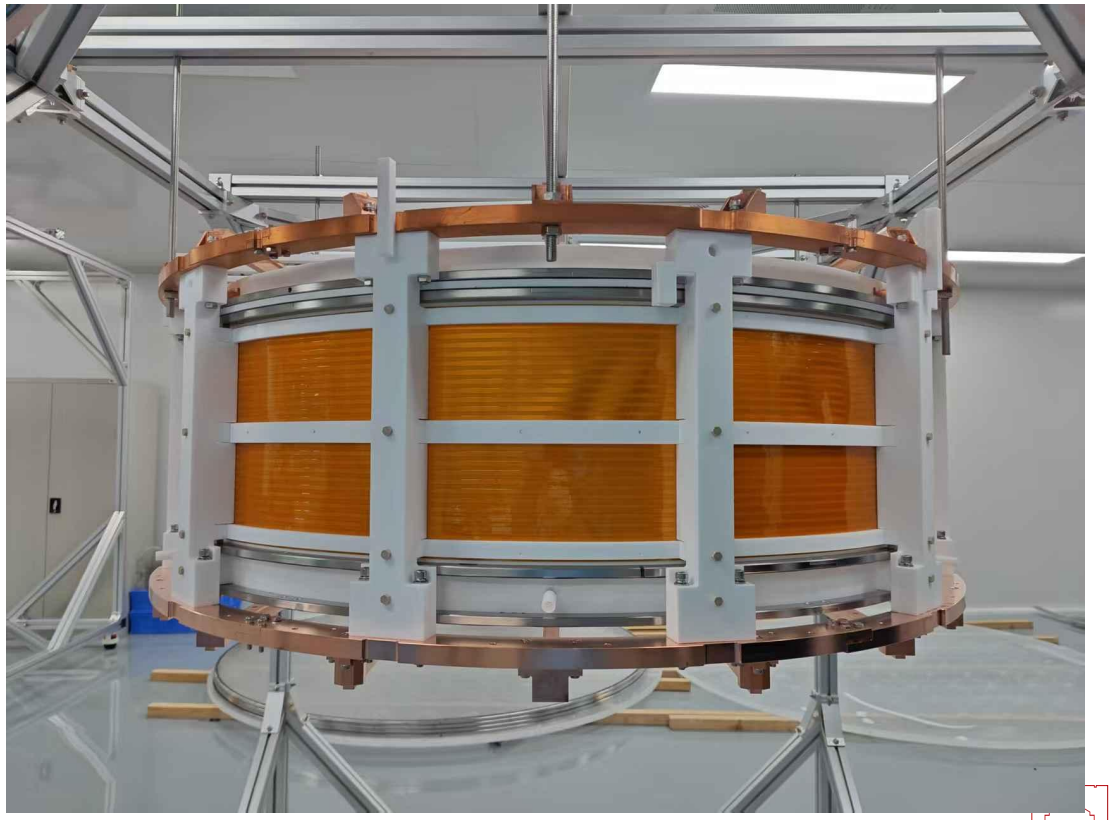


arXiv: 2507.11930

Future plan

- PandaX-4T Run2 will be finished this year
- PandaX-20T is under R&D
  - The prototype is being upgraded recently
  - 20T is expected to be online in 2027





Summary

- Model and suppress backgrounds of low threshold channels
- Give the most stringent limits for dark matter-nucleon and dark matter-electron interaction models
- In the near future, PandaX-4T Run2 data and PandaX-20T will further improve the sensitivity for light dark matter


PANDA X
Thank you
for your attention!
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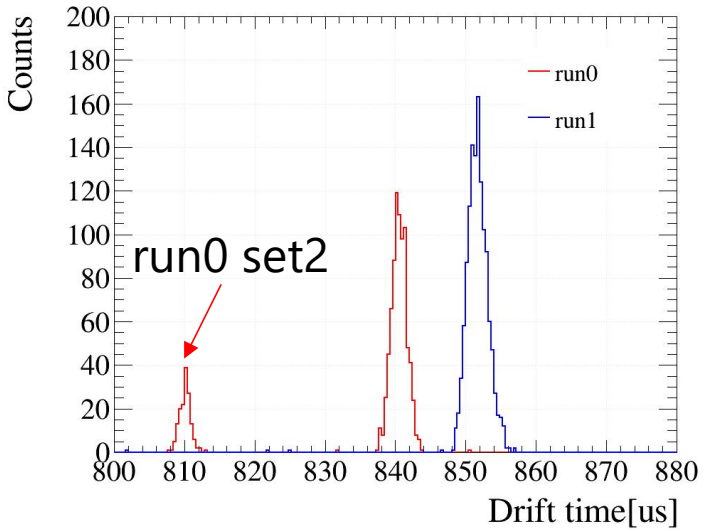
Cathode estimation

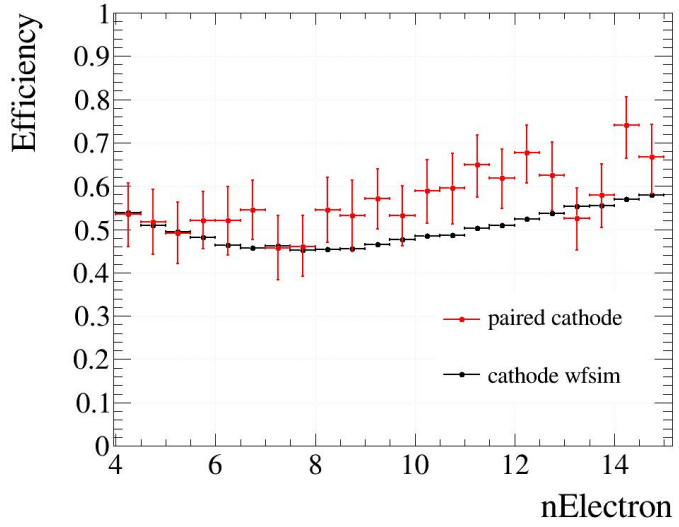
Cathode sample

$$\text{Efficiency: } \frac{selection\ cut}{selection\ cut\ with\ loose\ width\ cut}$$

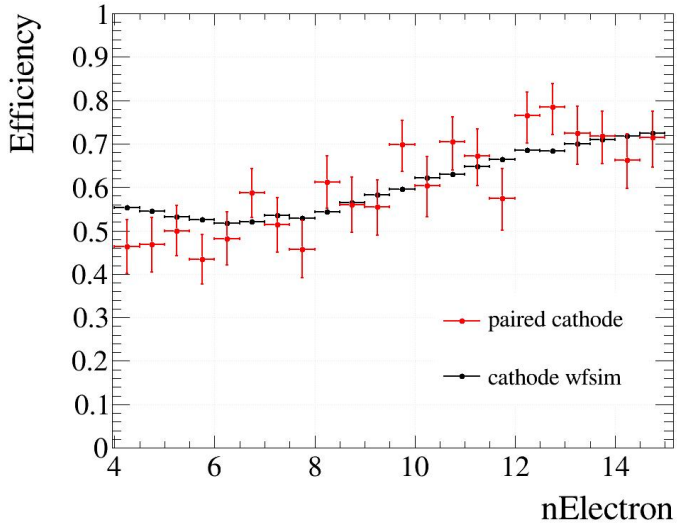
Cathode drift time distribution



Run0 efficiency



Run1 efficiency



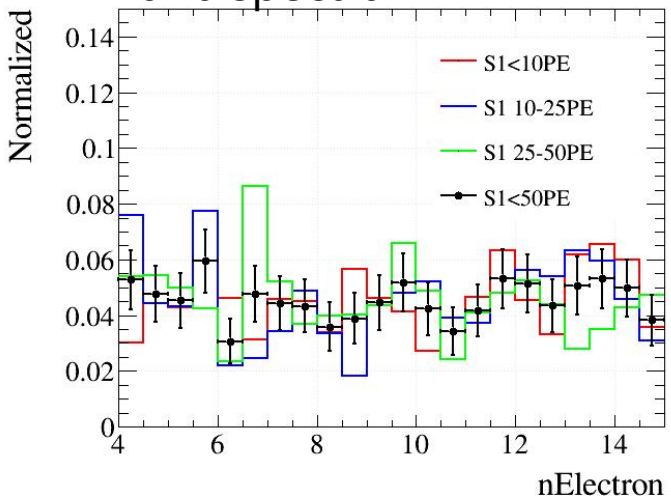
- Use paired cathode events as background sample
- Simulate events at the bottom of detector, these samples are consistent with paired cathode events
- To reduce spectrum statistical fluctuation, use the spectrum under a loose width cut, and then apply corresponding efficiency from waveform simulation to it

Cathode estimation

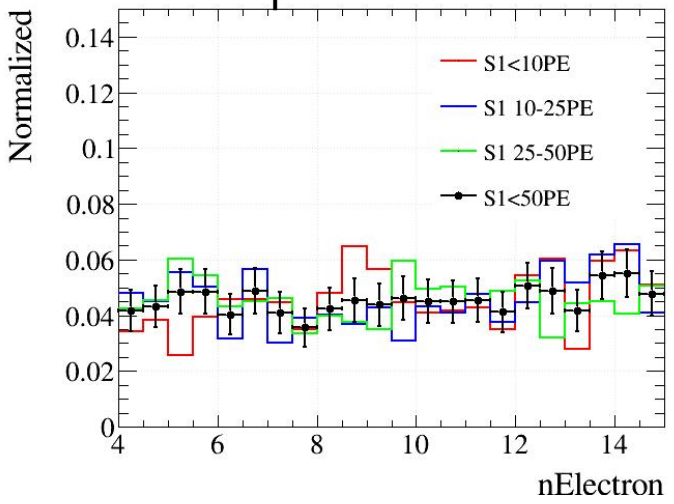
$$nominal = \frac{num\_sample\_in\_roi}{num\_sample\_in\_cr} \cdot num\_data\_in\_cr$$

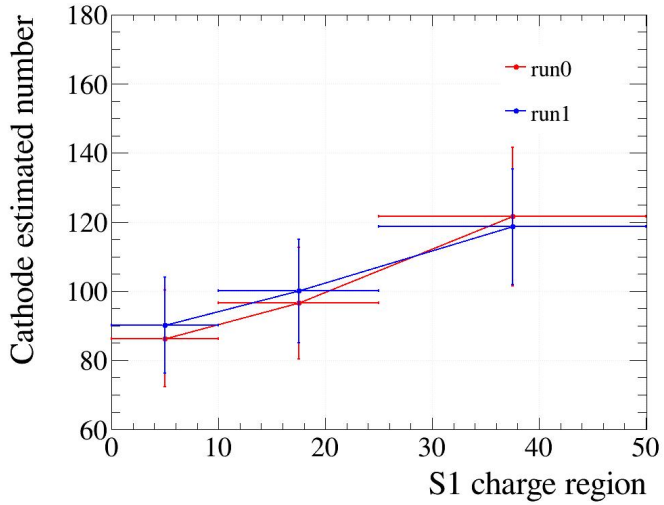
roi : 4-8nE cr : 11-15nE

Run0 spectrum



Run1 spectrum





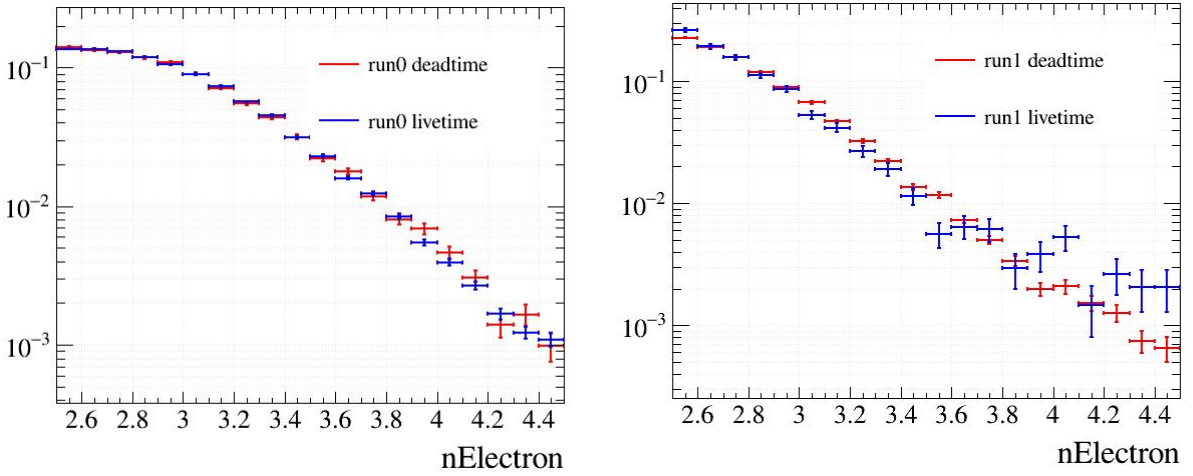
- Spectrum with different S1 range give systematic error
- Spectrum with total statistic give the nominal value and statistical error
- Difference of results given by efficiency from data and simulation give efficiency error

Estimation	run0	Run1
Result	100±24	104±21
Statistical error	12.4%	11.4%
Systematic error	18.1%	13.9%
Efficiency error	10.6%	9.4%

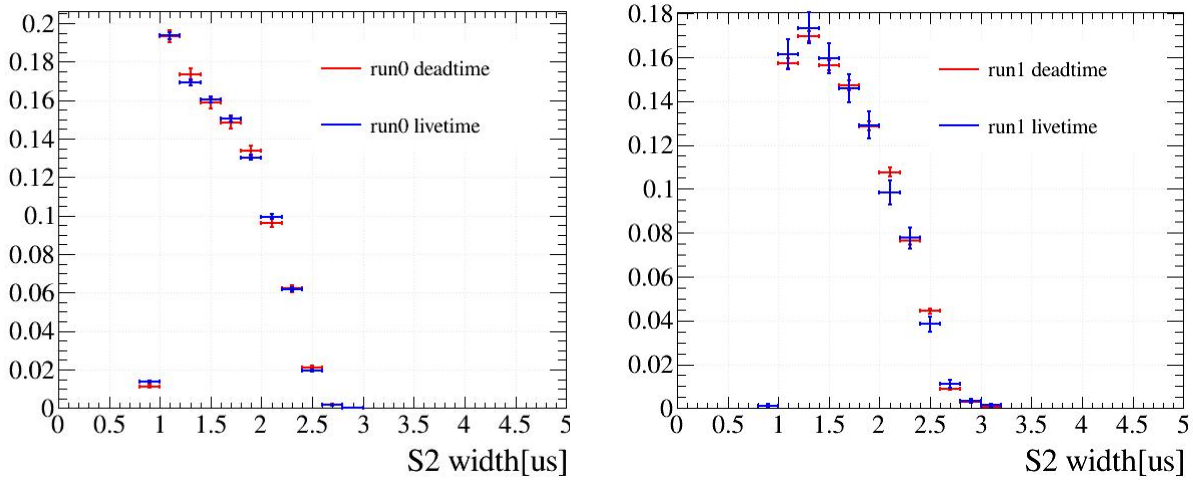
MD Estimation

MD sample

Charge distribution



Width distribution

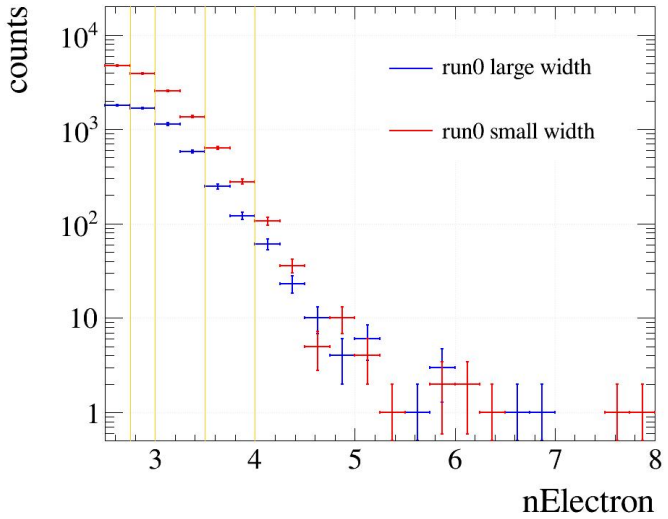


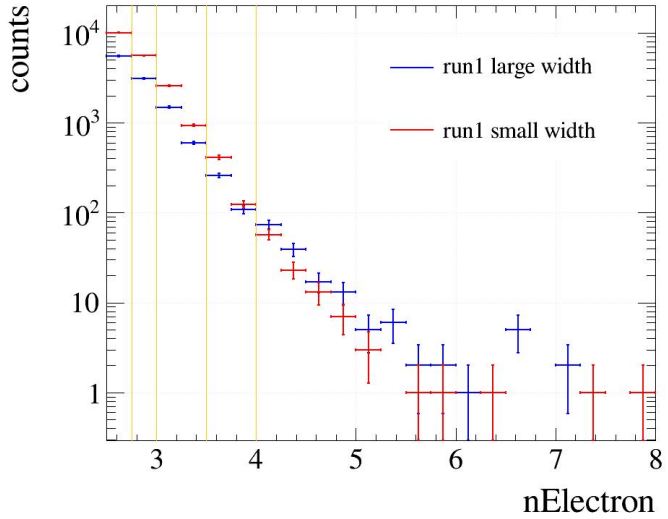
- We find that MD rate is related with single electron(SE) rate, so we get MD samples from deadtime region where SE rate is very high
- The sample in deadtime is consistent with the MD events in livetime
- MD events in livetime are from high US2(2.5-3nE) rate runs

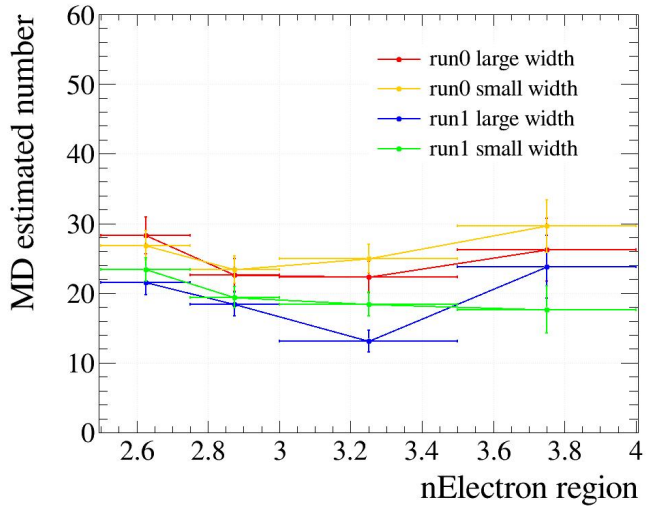
MD Estimation

$$nominal = \frac{num\_sample\_in\_roi}{num\_sample\_in\_cr} \cdot num\_data\_in\_cr$$

roi : 4-8nE cr : 2.5-4nE







- Different small control regions divided by S2 charge and width give systematic error
- Spectrum with total statistic give the nominal value and statistical error

Estimation	Run0	Run1
Result	25±3	20±4
Statistical error	6.5%	6.4%
Systematic error	10.6%	16.9%

Efficiency

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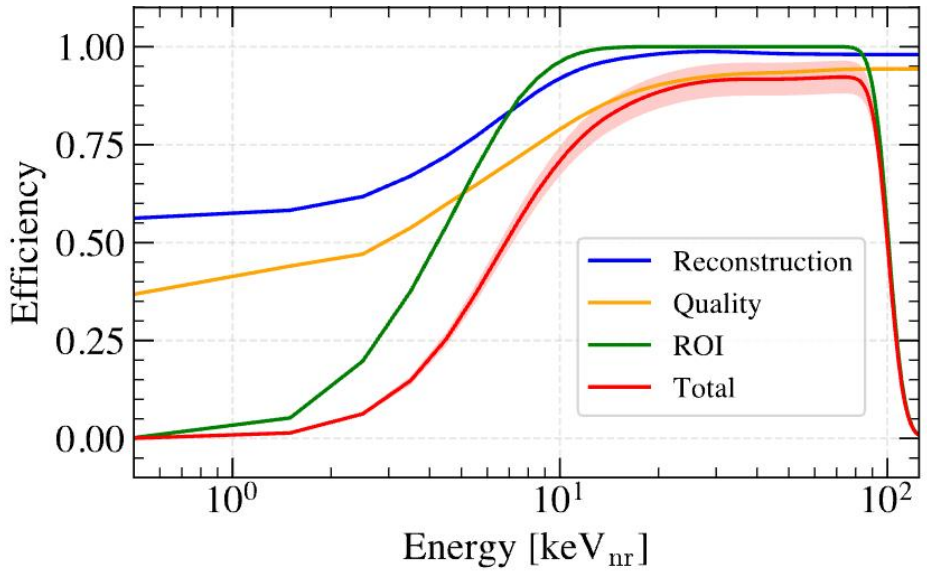
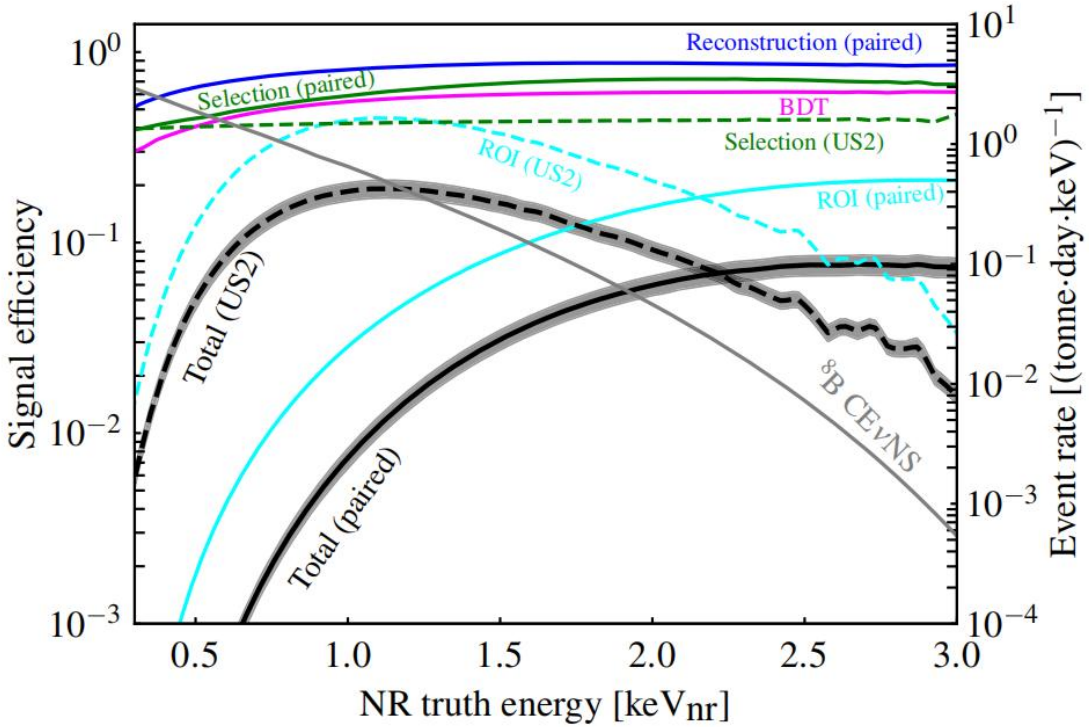
- wimp vs Paired&US2

traditional wimp analysis

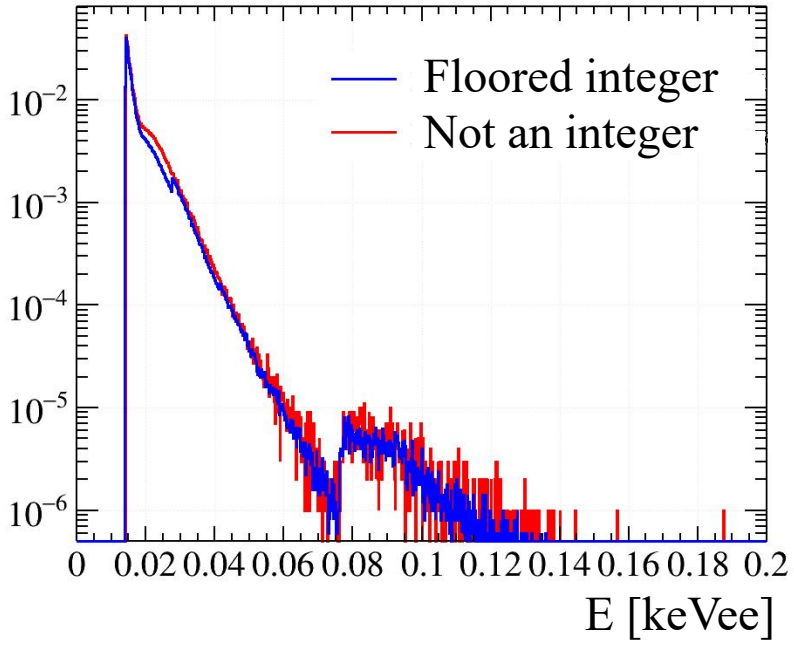


low threshold channels



Signal model

- A different treatment
  - In previous work(PRL 130, 261001 (2023)) searching for light dark matter with Run0 US2 data, the mean total number of created photons and electrons was conservatively set to a floored integer.



This effect can cause around 3 times difference in expected signal number of LDM–electron interactions mediated by a light mediator(underestimated in previous work)