PMT readout for PandaX liquid xenon detectors

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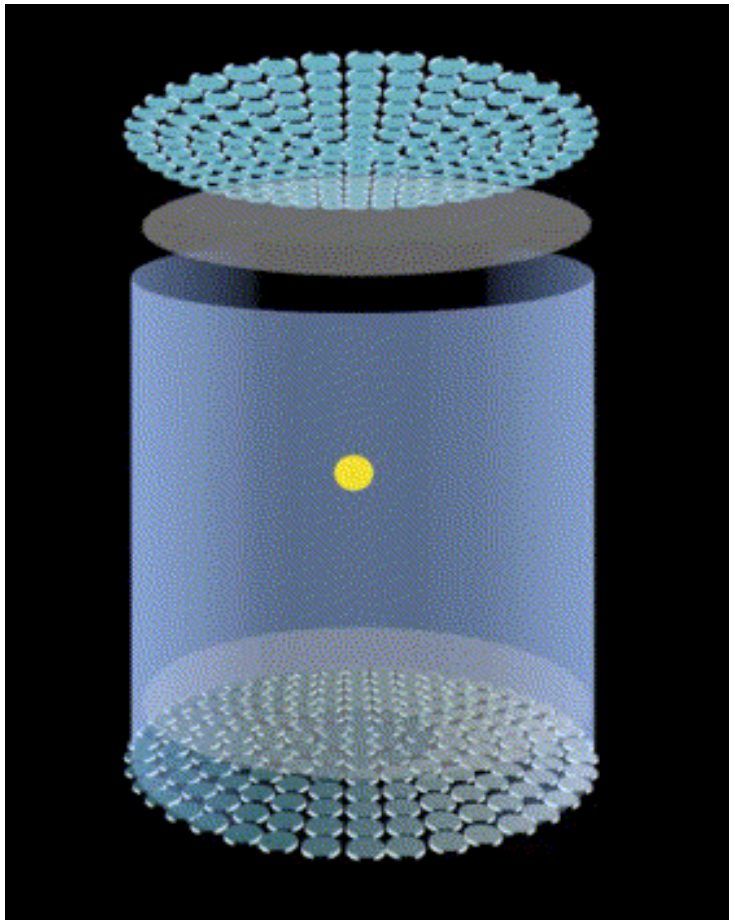
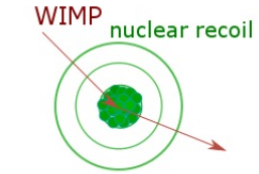
On behalf of the PandaX Collaboration

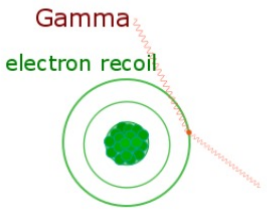
@Nagoya Workshop, Feb, 16, 2024

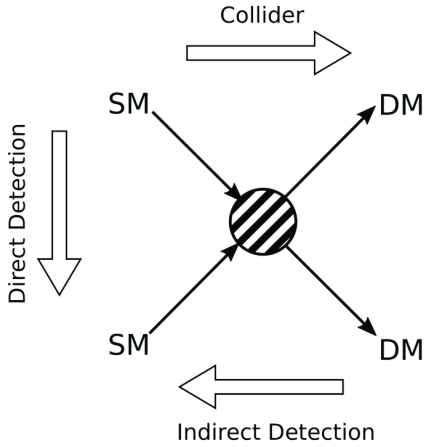
Contents

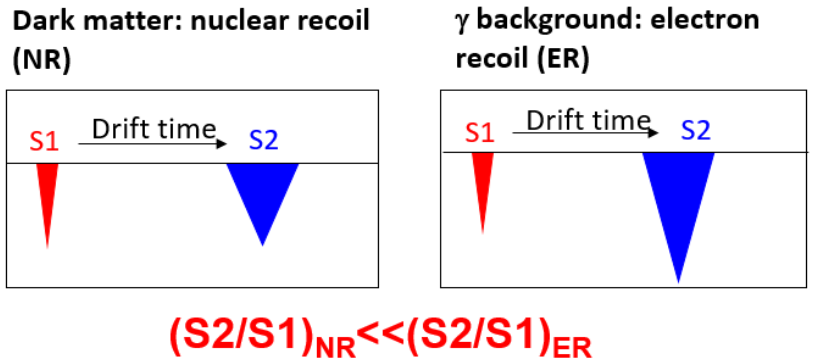
PandaX detector: Dual phase xenon TPC











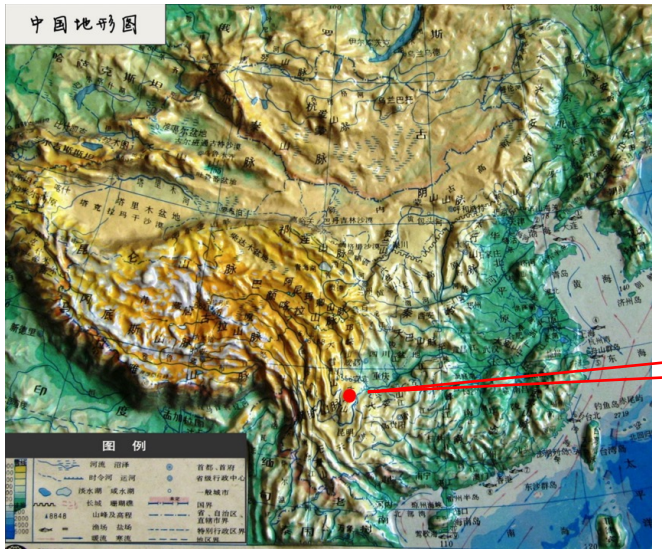
Dual phase xenon detector capability:

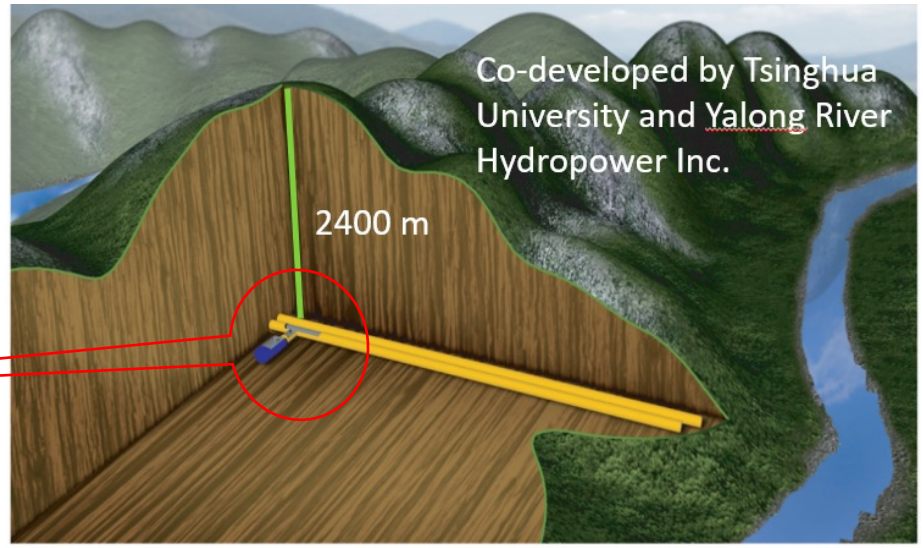
- S1: prompt scintillation signal
- S2: delayed ionization signal
- ER/NR identification
- 3D reconstruction and fiducialization
- Calorimeter from sub keV to MeV

PandaX Collaboration

- Particle and Astrophysical Xenon Experiment; started in 2009; now ~80 collaborators

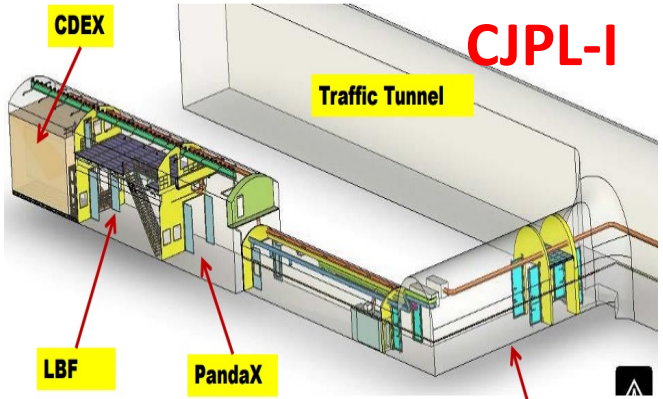
China JinPing Underground Laboratory – CJPL





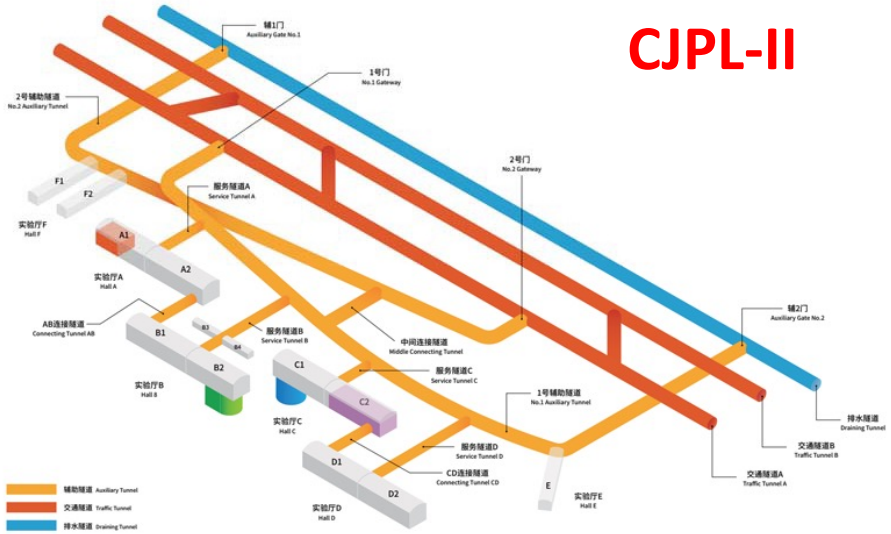
- Deepest (6800 m.w.e)
- Horizontal access
- Muon rate:

  1 count/week/m2



CJPL-I

- Total space: 4000 m³
- Main Lab Space: 6.5(W) x 6.5(H) x 42(L)



CJPL-II

PandaX road map

Collaboration formed

2009.3

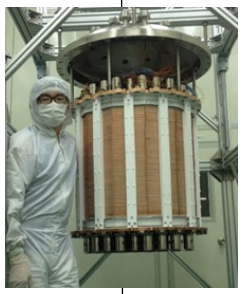
PandaX-I started

2012.7

2014.3

PandaX-I apparatus moved to Jinping

PandaX-II, 580 kg operation

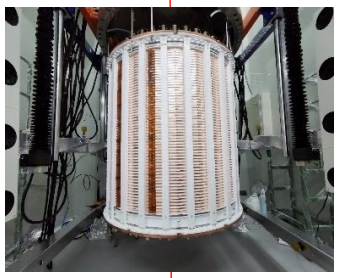


2014.5-10

2016.7-2019.7

PandaX-I, 120 kg operation

PandaX-4T, commissioning (run0)



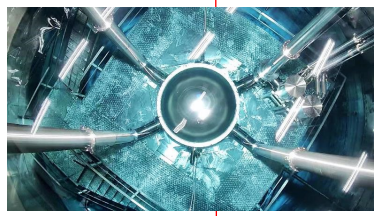
2019.8

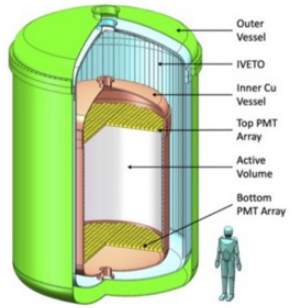
2020.11-2021.5

PandaX-4T, 3.7 ton moved to CJPL-II

2021.11

PandaX-4T run1

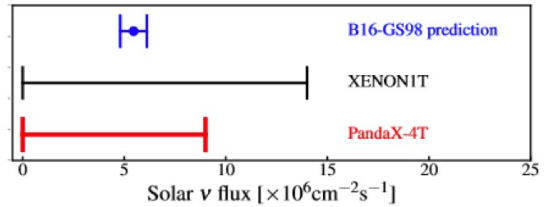




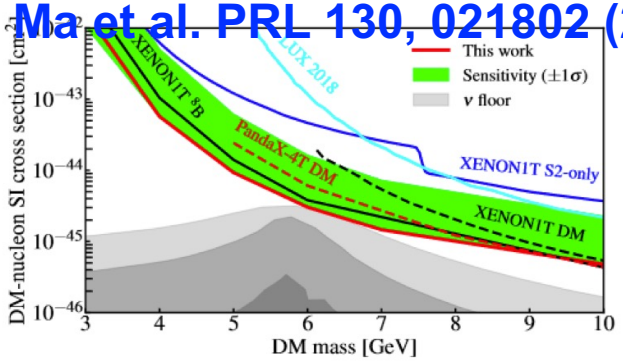
PandaX-xT

Ongoing

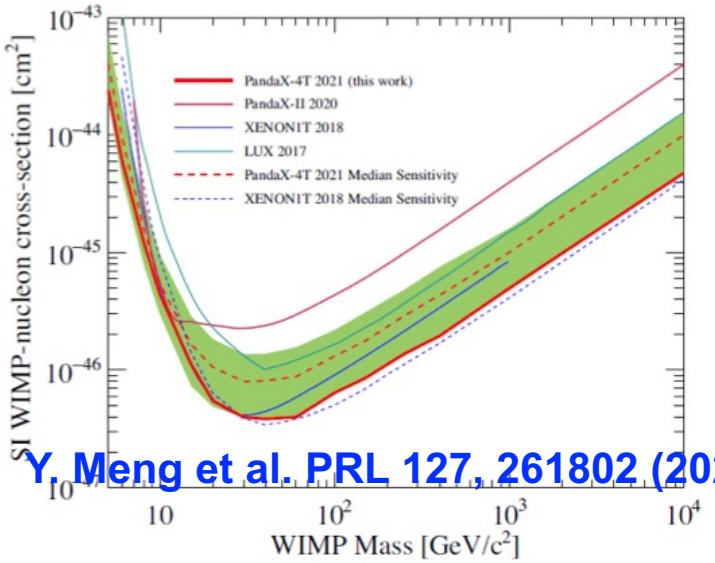
PandaX-4T multi physics results



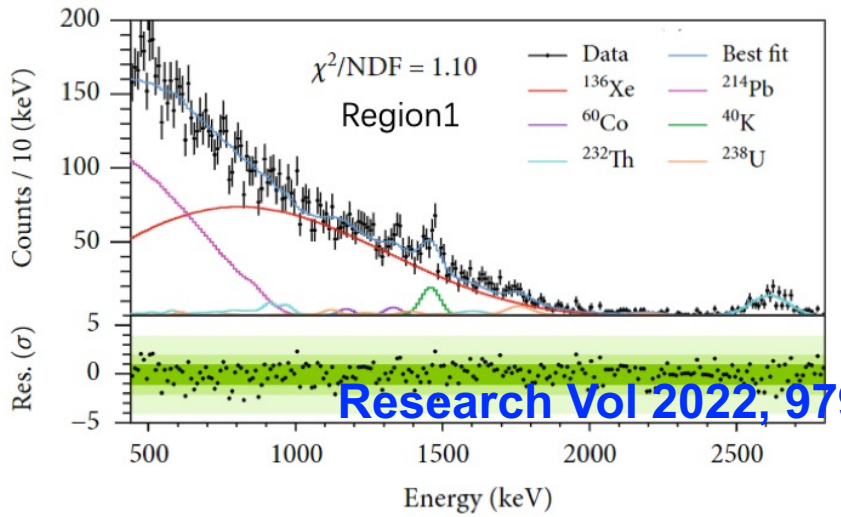
W. Ma et al. PRL 130, 021802 (2023)

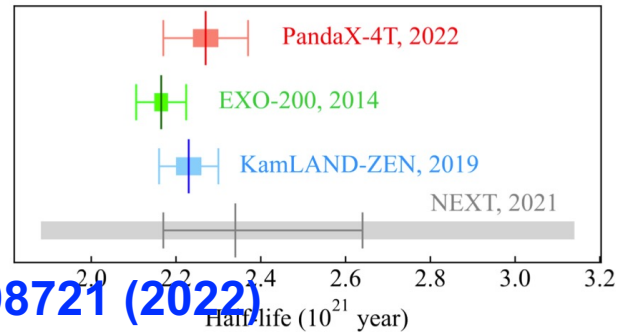


	Sub-keV	1 keV	10 keV	100 keV	1 MeV
Xe-136 (~9%)					$2\nu\beta\beta/0\nu\beta\beta$
Xe-134 (~10%)					$2\nu\beta\beta/0\nu\beta\beta$
Xe-124 (~0.1%)				2νECEC	
Xe all isotopes	Solar ^{8}B neutrino	WIMP and other DM models		Solar pp neutrino	



Y. Meng et al. PRL 127, 261802 (2021)

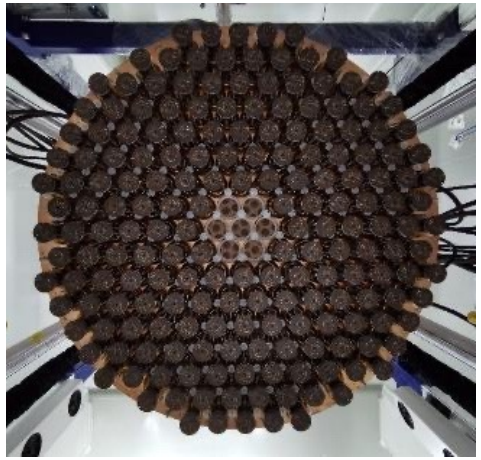




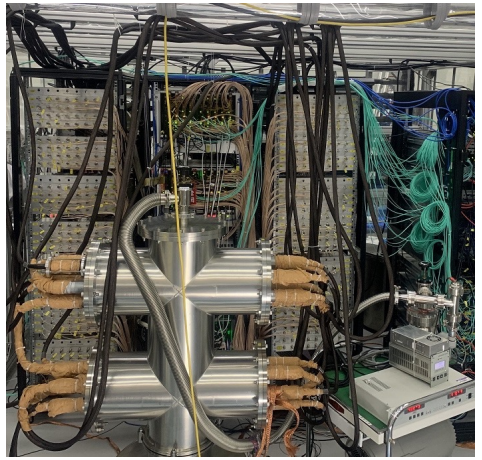
Research Vol 2022, 9798721 (2022)

PandaX-4T subsystems

TPC



PMT



Electronics

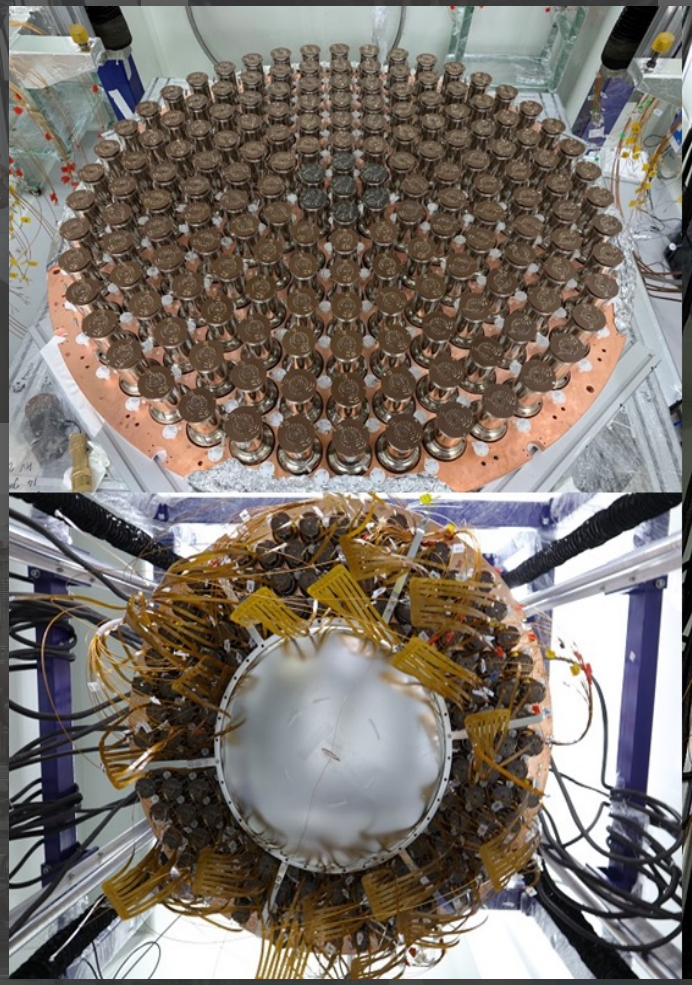
Distillation tower

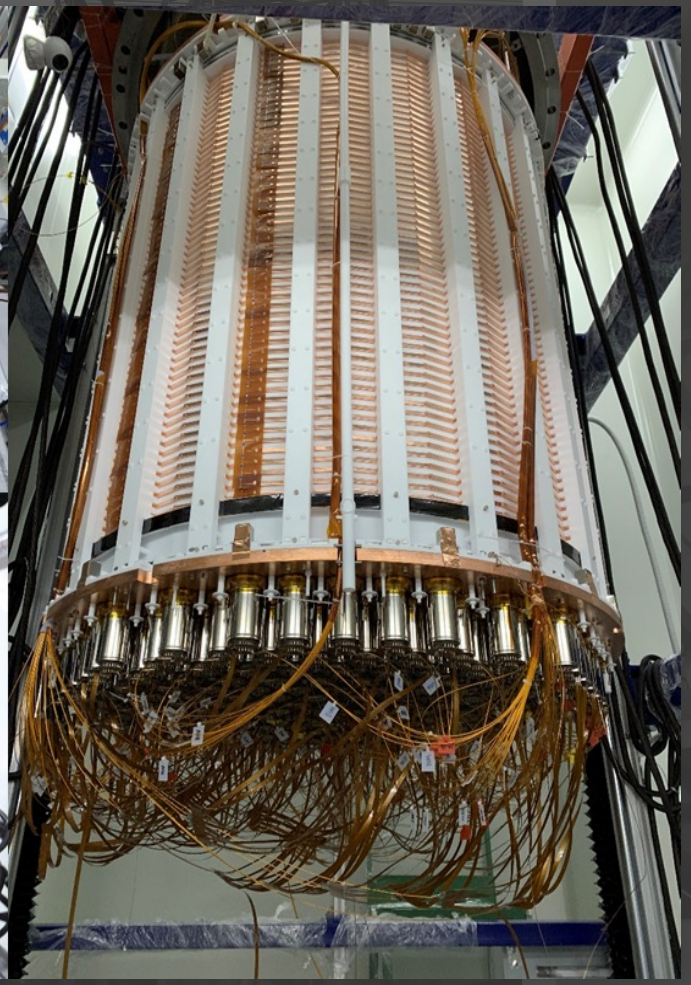
Cryogenics system

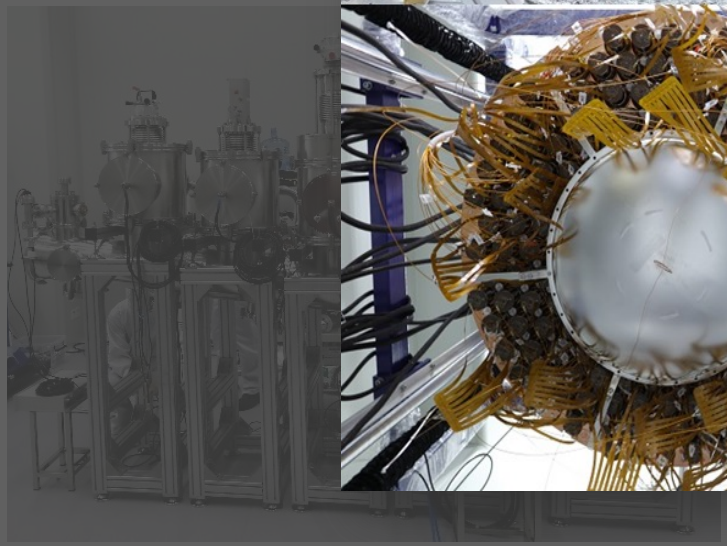
Gas storage system

PandaX-4T subsystems

TPC







Cryogenics system

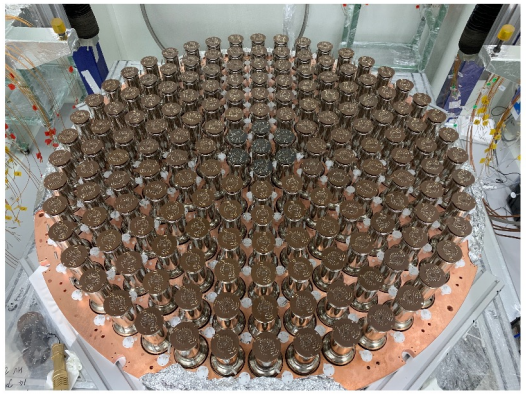
Gas storage system

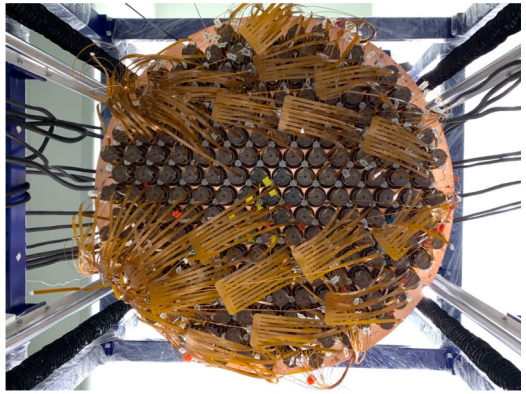
Distillation tower

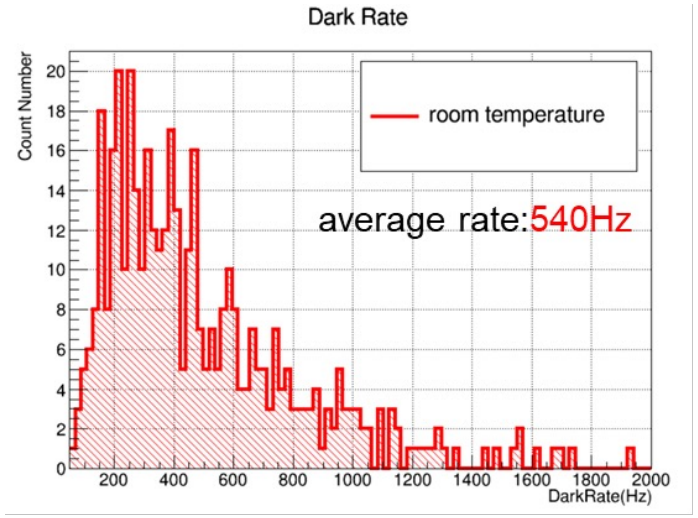
3-inch PMTs in PandaX-4T

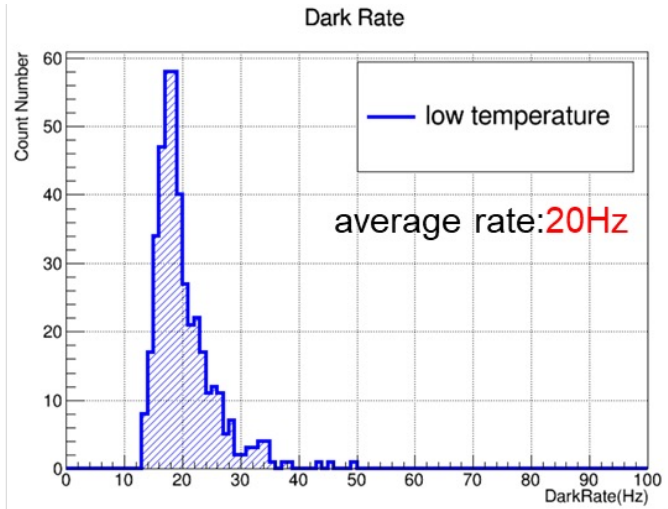
Key requirements:

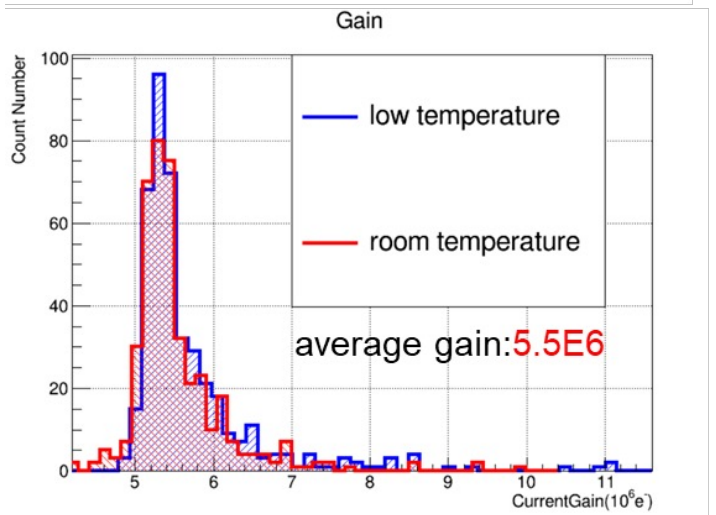
- High Quantum Efficiency ~34% at 178 nm
- High gain~5×10^6 @1500 V
- Low dark count rate
- Small after pulse probability (APP)
- Low radioactivity

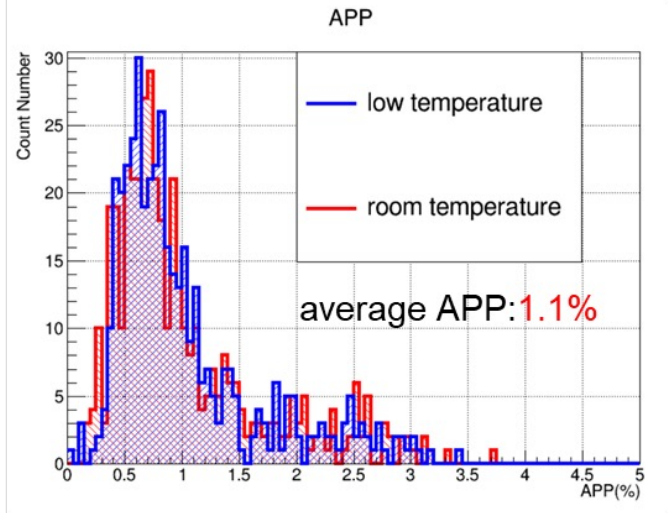










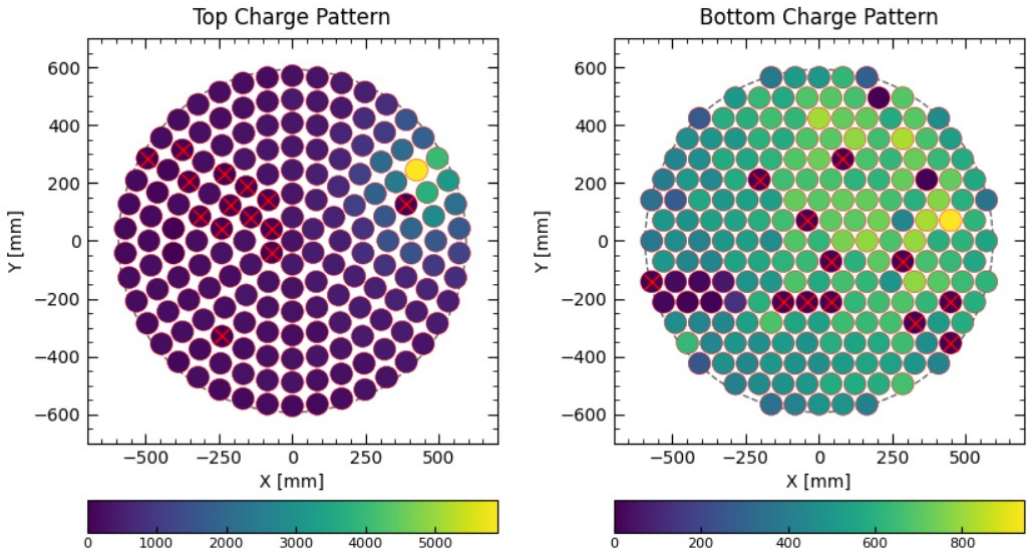


3-inch PMTs status at end of Run1

- 27 out of 368 were off at the end of Run1
- Fix these problems during PandaX-4T upgrade

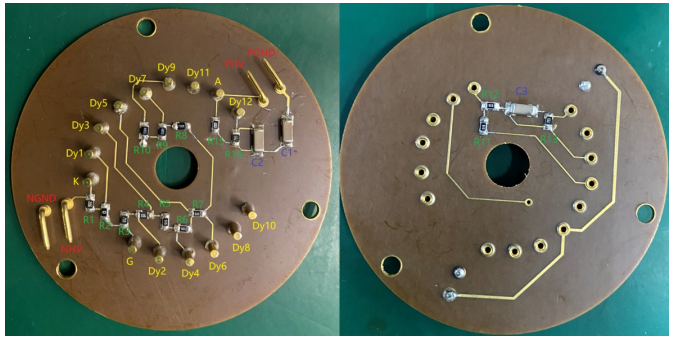
Off reason	quantity
Base broken	12
High app	7
Bad connection	8
sum	27

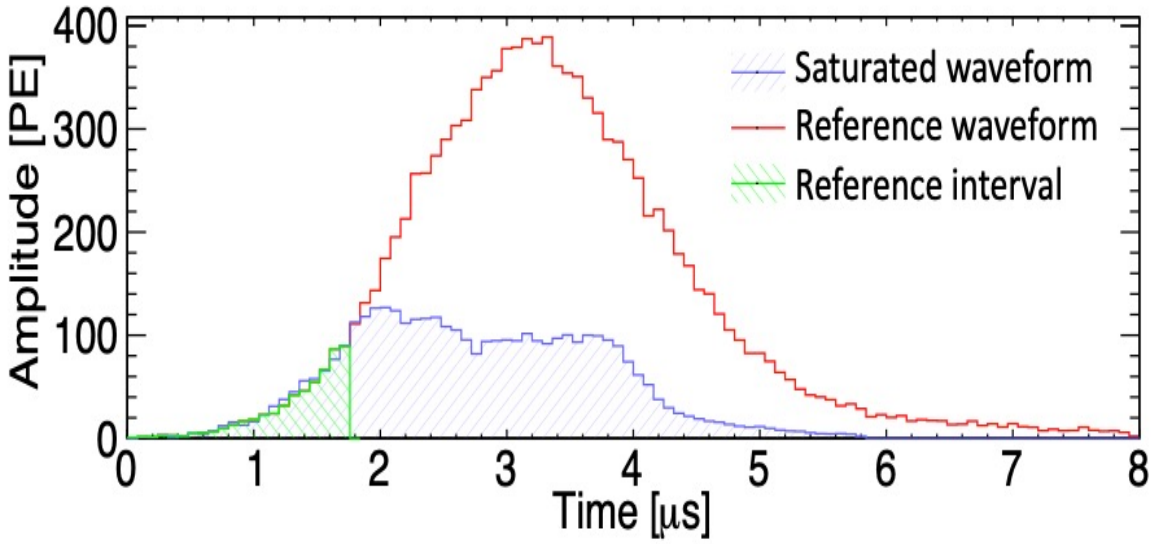
- Large signals suffer saturation and suppression
- Poor x-y position of multi-site events
- High radioactivity contribution

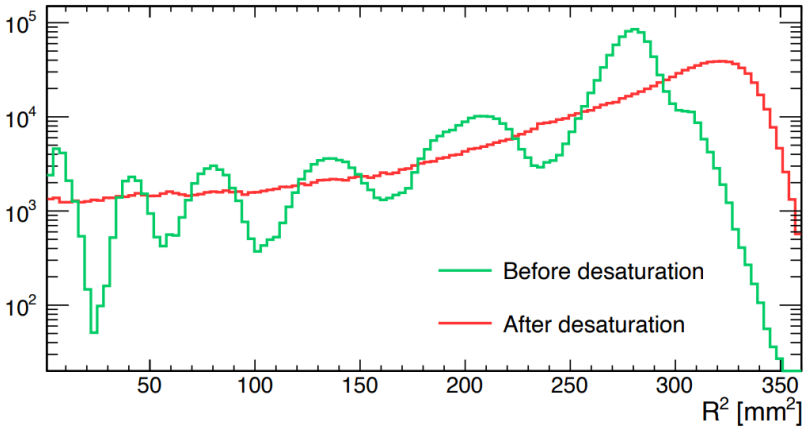


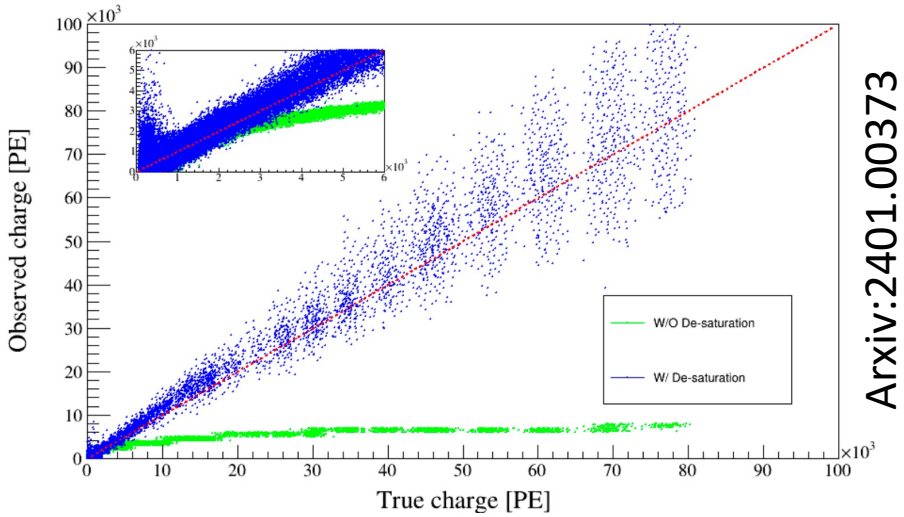
Challenge of PandaX-4T PMT: Saturation

- Baseline design base specially for DM search with few capacitors
- Develop a de-saturation algorithm and apply in data successfully





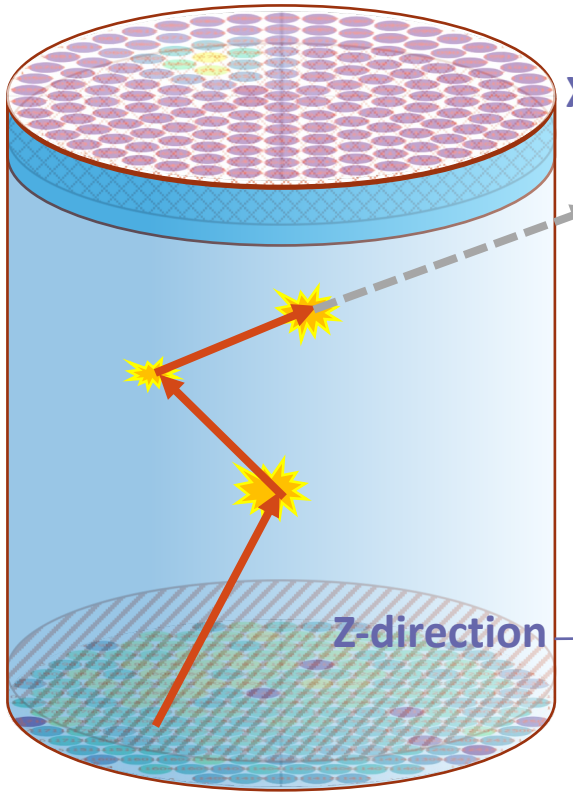


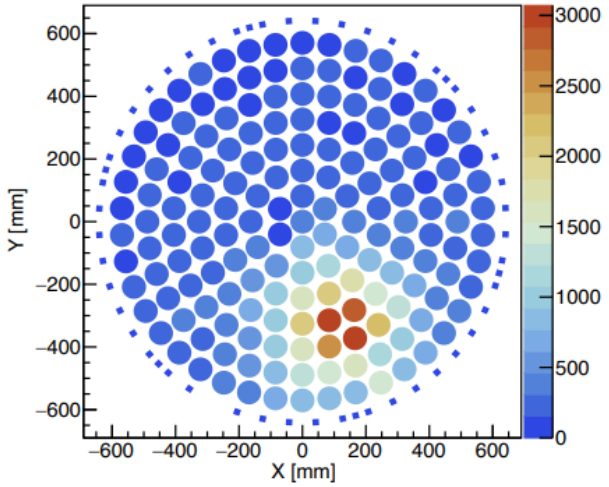


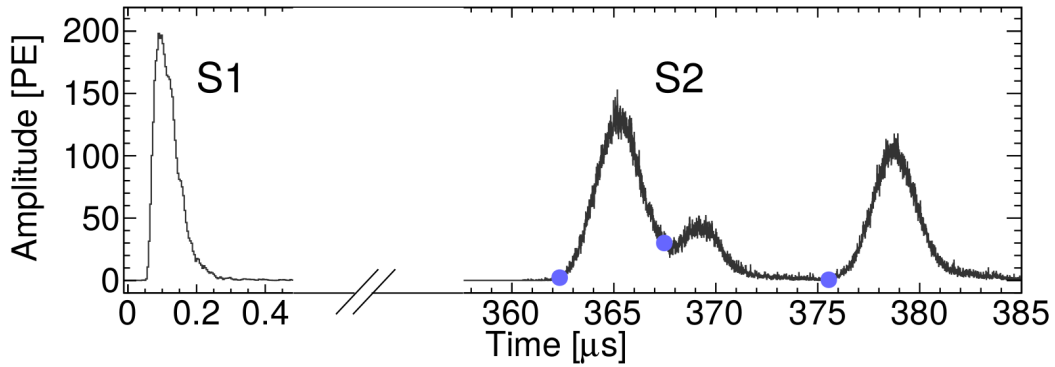
Arxiv:2401.00373

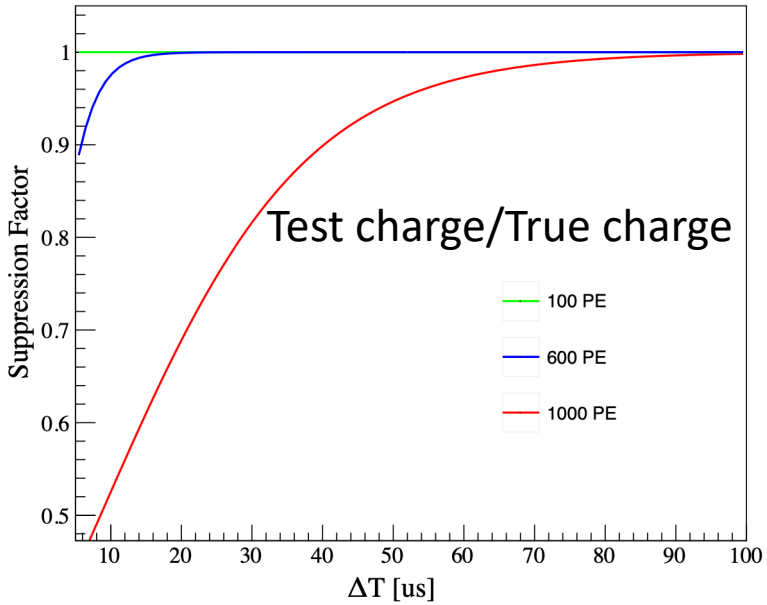
Challenge of PandaX-4T PMT: suppression effect of multi-site events

- Obvious suppression effect for baseline design base
- Identifying MS backgrounds with PMT waveforms



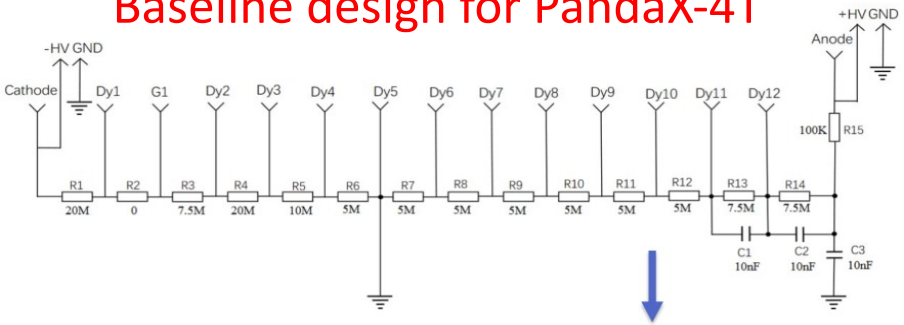




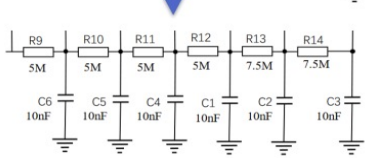


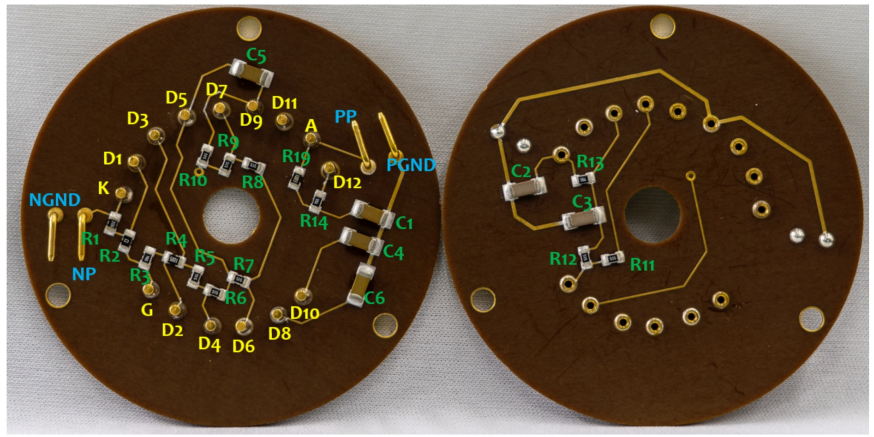
Updated base and bench test for 3-inch PMTs

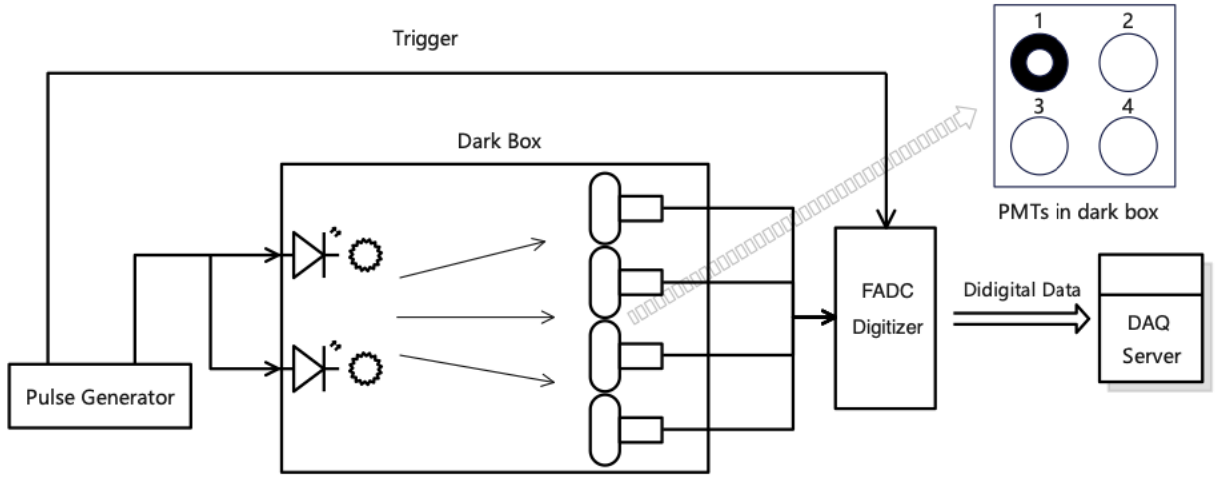
Baseline design for PandaX-4T



Updated design



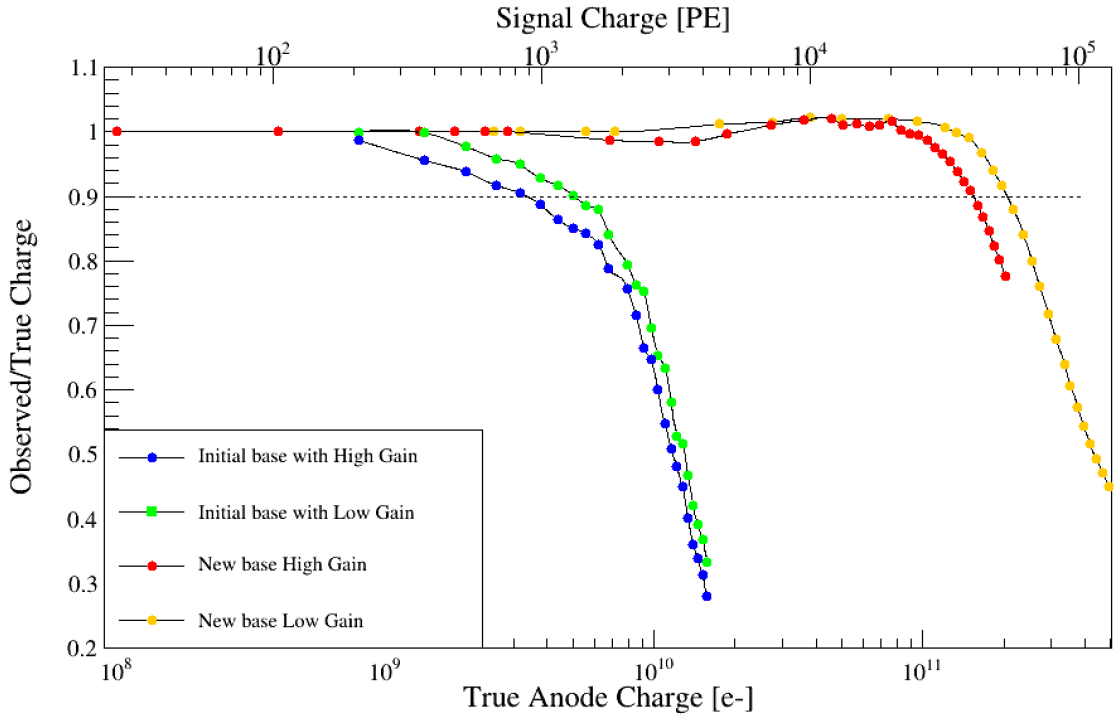


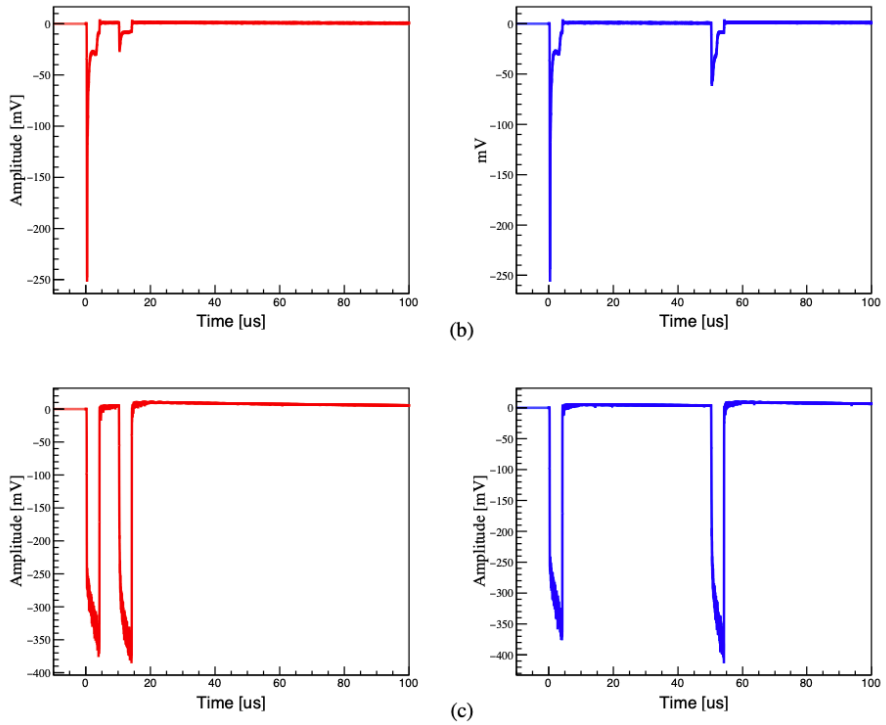


Unit: mDRU	ER	NR
PMT+BASE	$(5.1 \pm 1.2) \times 10^{-3}$	$(2.3 \pm 0.4) \times 10^{-4}$
PTFE	$(2.1 \pm 0.3) \times 10^{-5}$	$(8.4 \pm 1.3) \times 10^{-6}$
Copper	$(1.6 \pm 0.2) \times 10^{-6}$	$(7.2 \pm 0.5) \times 10^{-8}$
Inner vessel	$(1.8 \pm 0.8) \times 10^{-3}$	$(1.4 \pm 1.2) \times 10^{-4}$
Outer vessel	$(2.6 \pm 1.3) \times 10^{-3}$	$(5.2 \pm 1.9) \times 10^{-4}$
Total Material	$\mathbf{(9.5 \pm 1.9)} \times 10^{-3}$	$\mathbf{(9.1 \pm 2.2)} \times 10^{-4}$

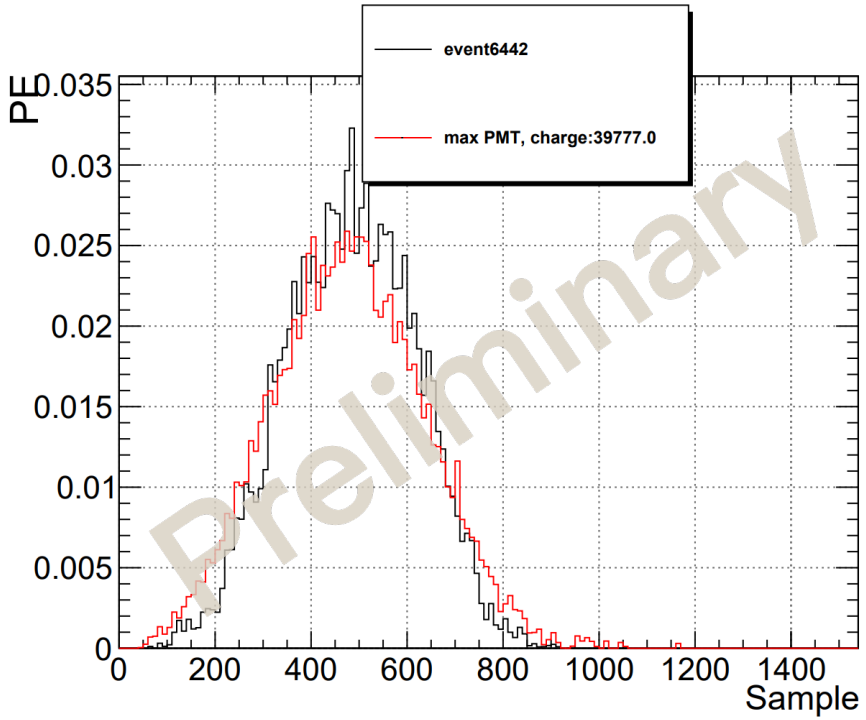
Bench test for 3-inch PMTs

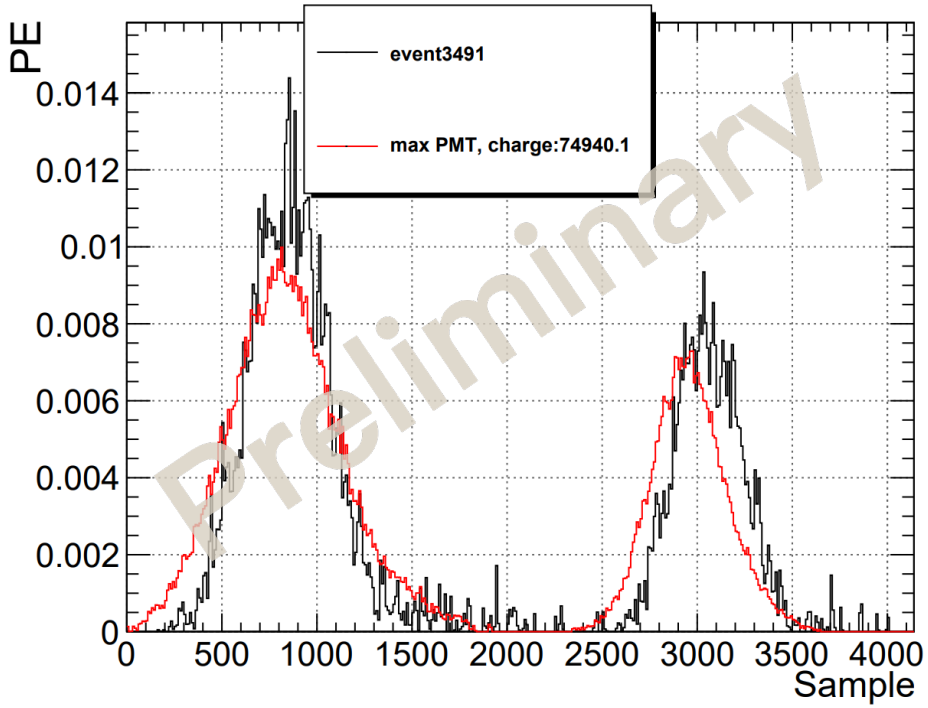
- Dynamic range increases significantly
- New designed base without suppression effect within 40 kPE
- Updated the configuration of de-saturation base for future PandaX-4T upgrade





3-inch PMTs performance in Run2

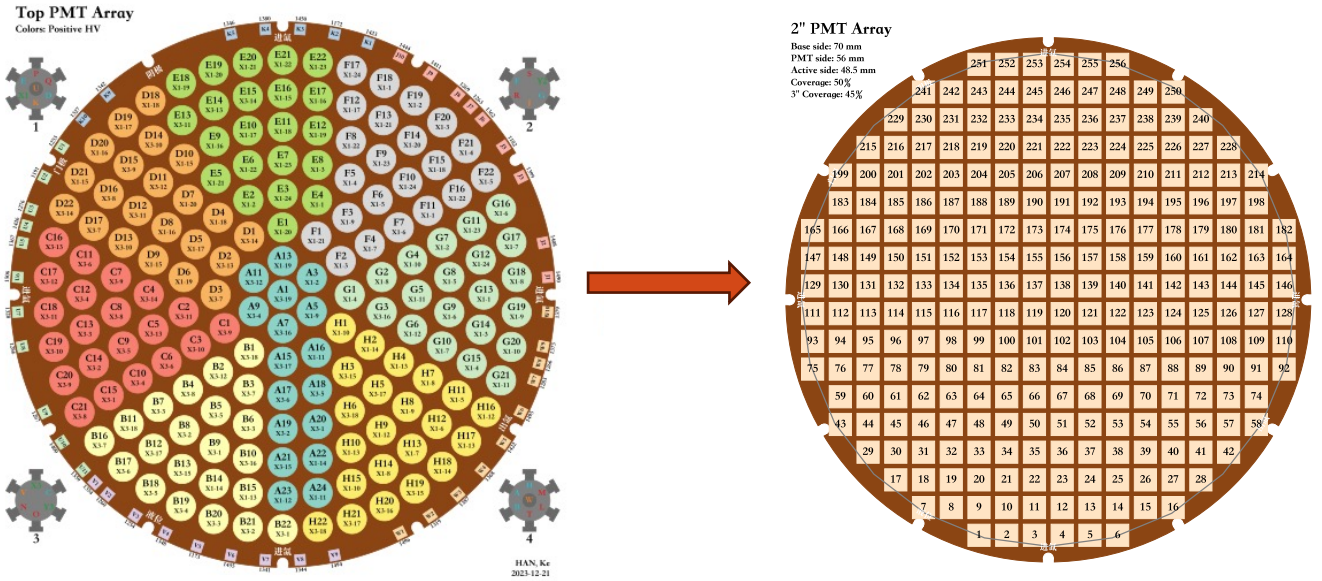




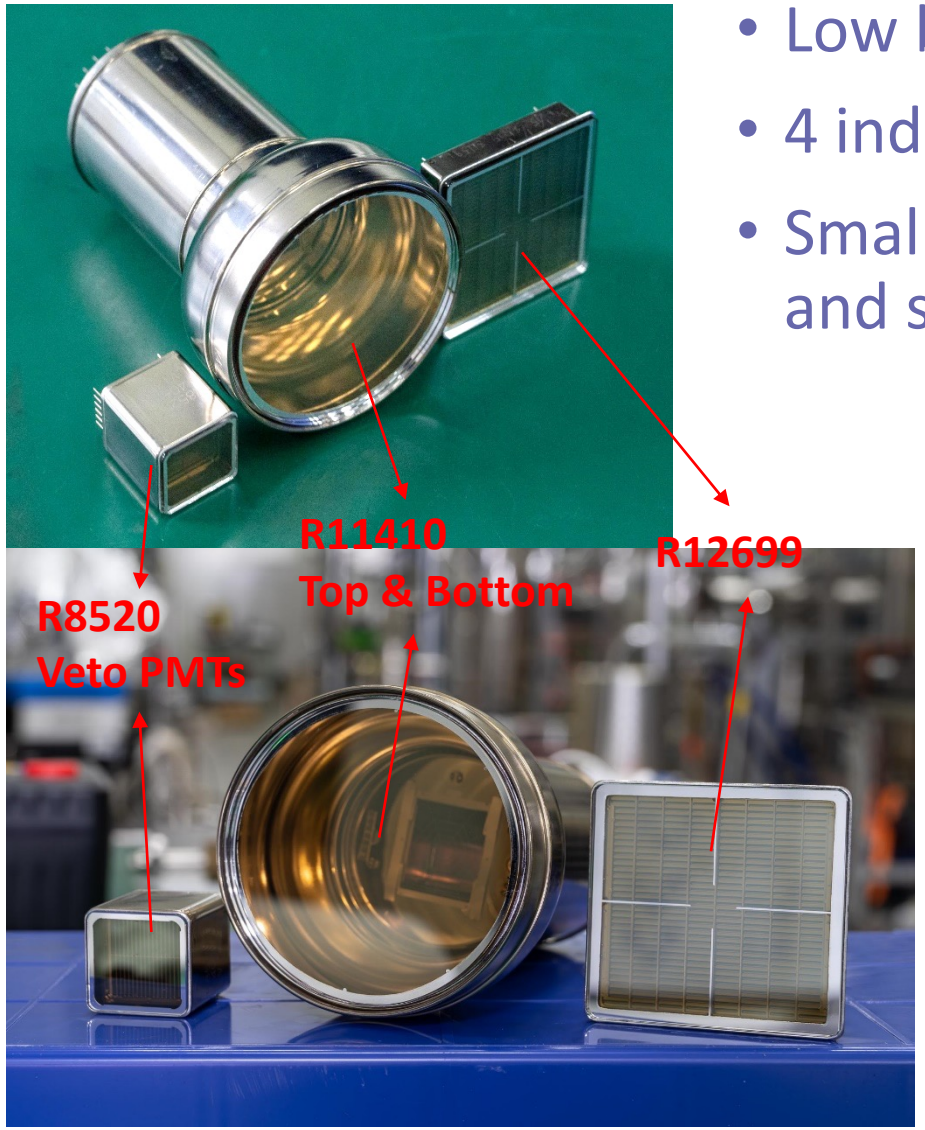
- Typical waveforms in Run2 demonstrates no obvious saturation/suppression with the new bases.

Requirements for PandaX upgrade: 3-inch to 2-inch PMT

- 3-inch PMTs perform very well, but we need :
  - Better performance from sub keV to MeV
  - Higher granularity position reconstruction
  - Lower radioactivity



New 2-inch PMT: R12699



- Low background, high granularity, fast timing performance
- 4 individual anodes
- Small size of effective photocathode is good for saturation and suppression effect

General

Parameter		R12699-406-M4	R11410-20	Unit
Spectral Response Range		160 to 650	160 to 650	nm
Wavelengh of Maximum Response		400	420	nm
Window Material / Thickness		Silica glass / 2.5	Silica glass / 3.5	- / mm
Photocathode	Material	Bialkali	Bialkali	-
	Minimum Effective Area	48.5 x 48.5	φ64	mm
Dynode Structure		Metal channel Dynode	Box & Linear-focused	-
Number of Stages		10	12	-
Number of Anode(s)		4	1	-
Weight		104	233	g
Operating Ambient Temperature		-110 to +50	-110 to +50	deg C
Storage Temperature		-110 to +50	-110 to +50	deg C

Maximum Ratings (Absolute Maximum Values)

Parameter	R12699-406-M4	R11410-20	Unit
Supply Voltage Between Anode and Cathode	1100	1750	V
Average Anode Output Current in Total	0.1	0.1	mA
Pressure-resistance (Guage)	0.5	0.3	Mpa

Test system for 2-inch PMTs

electronics

molecular pump

water

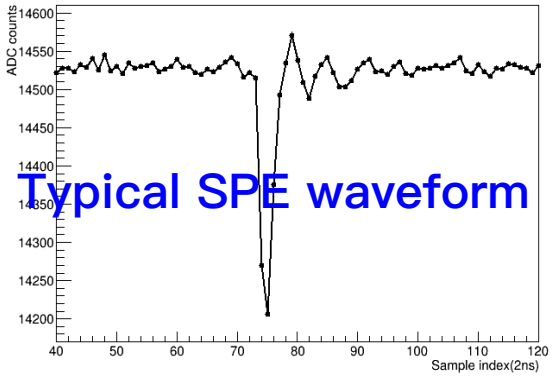
nitrogen

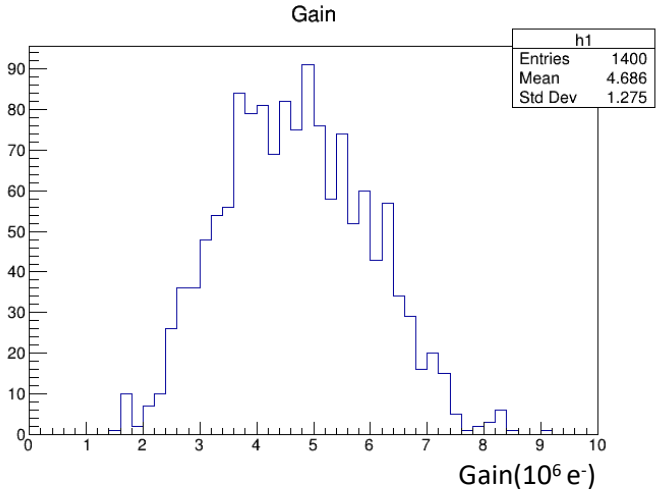
ethyl alcohol

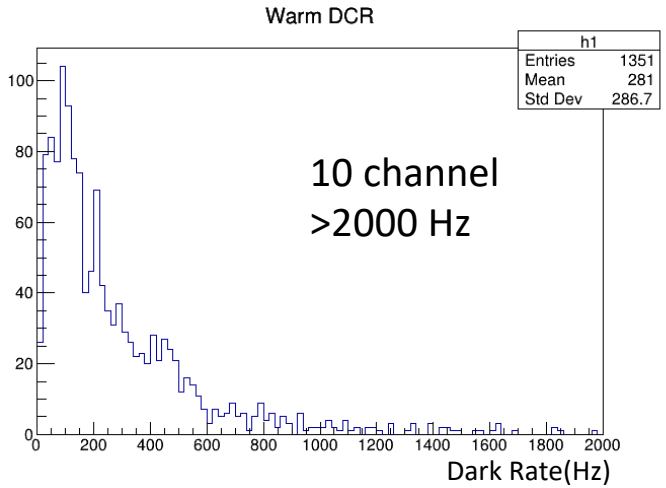
Cryogenic tank

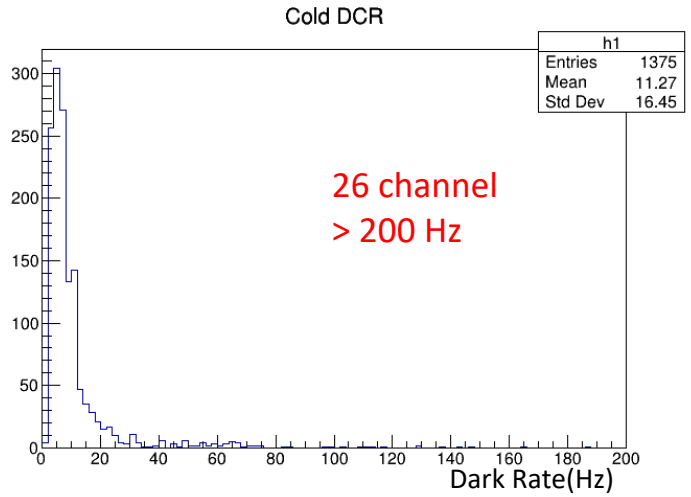
First batch test result

- 350 pcs PMTs test were finished.
- Gain of each channel is about 5×10^6 e$^-$ （>1.5e6）with 1000 V
- Dark rate at -100℃ is about 10 Hz per channel
- The basic parameters can meet the requirement of liquid Xenon TPC

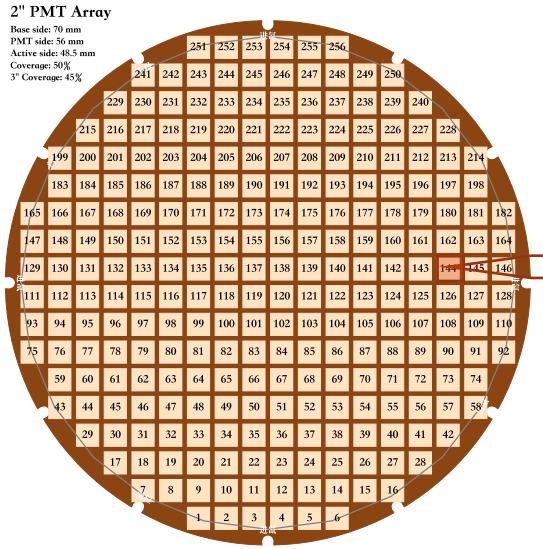




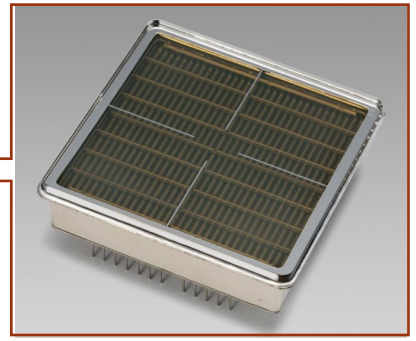


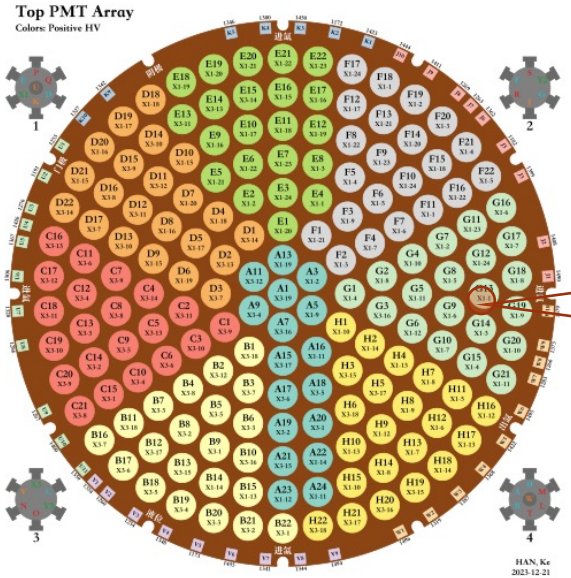


New 2-inch PMT: Advantage: position reconstruction

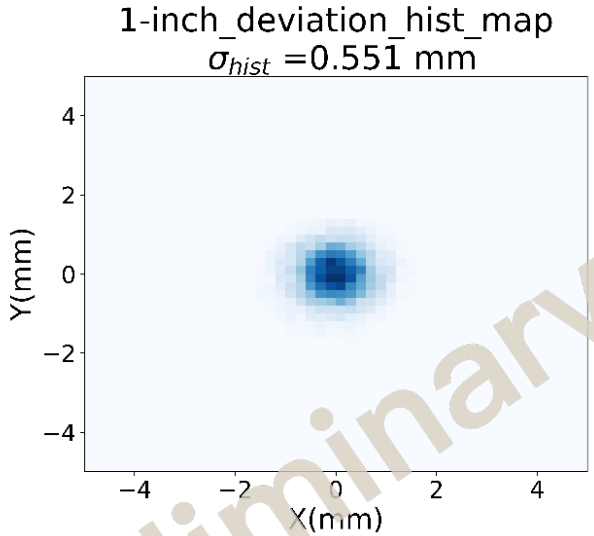


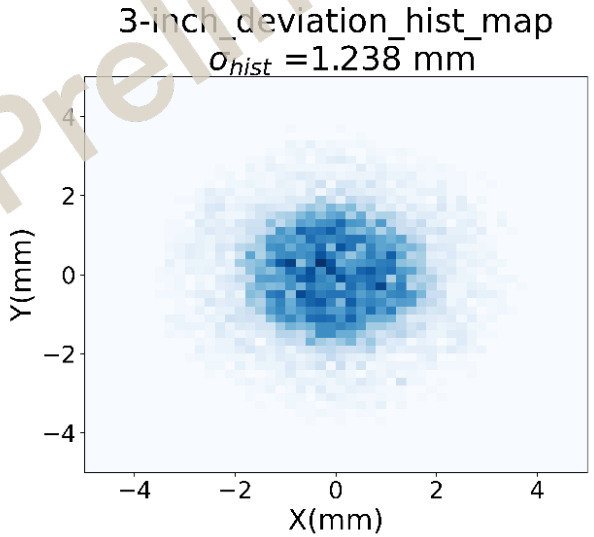
256pcs





169pcs





- Pixel density
  ×6 higher
- Position reconstruction
  ×2 better

Advantage: radioactivity

PMT Material Screening

Unit: mBq/pc	Co-60	Cs-137	K-40	Th-232 (early)	Th-232 (late)	U-235	U-238 (early)	U-238 (late)
Old Glass	0.00±0.00 <0.00	0.00±0.00 <0.00	0.20±0.02	0.07±0.01	0.04±0.00	0.02±0.03 <0.08	0.48±0.05	0.32±0.01
New Glass	0.00±0.00 <0.00	0.00±0.01 <0.01	0.57±0.18	0.00±0.02 <0.04	0.03±0.01 <0.05	0.02±0.02 <0.04	0.09±0.08 <0.21	0.06±0.01
2305ET0007	0.00±0.01 <0.02	0.08±0.05 <0.17	0.46±0.87 <1.89	0.19±0.14 <0.42	0.00±0.06 <0.10	0.00±0.10 <0.17	0.00±0.58 <0.95	0.00±0.09 <0.15
2305ET0003	0.00±0.03 <0.04	0.01±0.04 <0.08	0.03±0.84 <1.40	0.08±0.13 <0.30	0.00±0.06 <0.09	0.08±0.11 <0.26	0.27±0.54 <1.16	0.03±0.08 <0.16
2305ET0006	0.02±0.02 <0.05	0.00±0.01 <0.02	0.64±0.42 <1.33	0.03±0.07 <0.14	0.09±0.06 <0.20	0.00±0.08 <0.13	0.95±0.63 <1.99	0.04±0.05 <0.13
2305ET0009	0.02±0.02 <0.05	0.01±0.03 <0.06	0.41±0.41 <1.09	0.02±0.07 <0.14	0.11±0.07 <0.22	0.00±0.20 <0.34	0.26±0.76 <1.50	0.03±0.06 <0.13

- The result is scaled to mBq/pc by the mass. Has measured ~ 30 samples for the PMT background control.
- The newly screened 42alloy material passes the low-background test.

Advantage: radioactivity

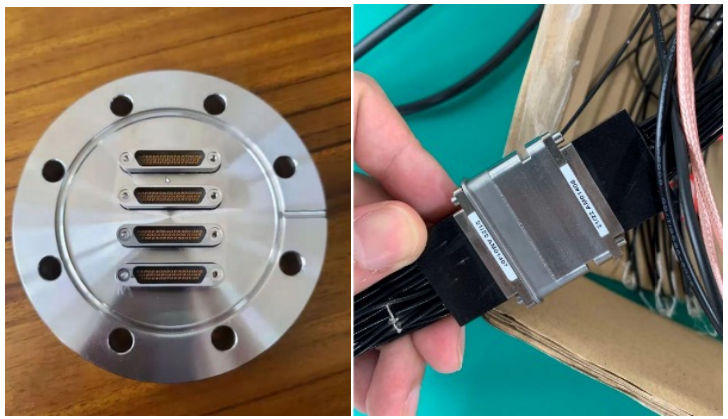
- The v2 R12699 PMT meets the requirements !

Unit: mBq/pc	Co-60	Cs-137	K-40	Th-232 (e)	Th-232(l)	U-235	U-238(e)	U-238(l)
PMT R11410	1.16±0.72 <2.34	0.52±0.81 <1.85	8.37±8.49 <22.34	4.29±2.14 <7.82	1.49±0.96 <3.06	13.56±8.96 <28.29	27.42±17.67 <56.48	2.05±1.18 <3.99
PMT R12699 v0	1.01±0.10	0.09±0.07 <0.20	31.54±2.17	0.00±0.16 <0.26	0.38±0.16 <0.64	0.30±0.23 <0.68	1.63±2.08 <5.05	0.61±0.15
PMT R12699 v1	0.00±0.04 <0.07	0.01±0.05 <0.09	30.83±2.14	0.13±0.17 <0.40	0.21±0.12 <0.40	0.13±0.21 <0.48	0.00±0.62 <1.03	0.47±0.11
PMT R12699 v2	0.13 ± 0.02	< 0.07 (0.05±0.02)	40.54 ± 4.92	< -0.07 (-0.11±0.03)	< 0.1 (0.02±0.05)	< 0.02 (-0.04±0.03)	< 1.16 (-0.06±0.74)	0.10 ± 0.03
Requirement	0.117	0.093	1.116	0.394	0.154	1.36	2.705	0.2

- v0->v1 replace high-Co60 kovar to 42alloy, v1->v2 replace high-U238 sealed glass
- K-40 didn't meet the requirement for the alkali-metal on the photocathode but it can be cut by fiducial volume in WIMP ROI.

Future work for R12699

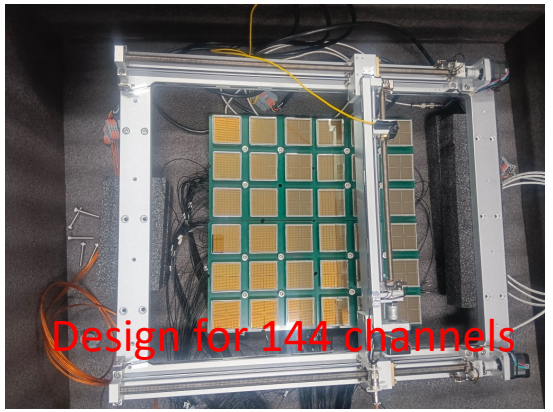
- Feedthrough design
- Electronics
- Prototype TPC
- Dedicated LED calibration setup
- Radioactivity is still go on



AXON Micro–D feedthrough

Triggerless 500MHz FADC

Prototype TPC for LXe test



Dark box for granularity test

Summary

- 3-inch R11410 PMTs perform well in PandaX-4T; Newly upgraded PMT base solves the saturation issue.
- 2-inch R12699 PMTs meet the light readout requirement from keV to MeV for liquid Xenon TPC.
- PandaX and Hamamatsu are co-developing a low background version of R12699.
- R&D for a high-granularity, low-background 2-inch PMT readout array for PandaX-xT is on-going.

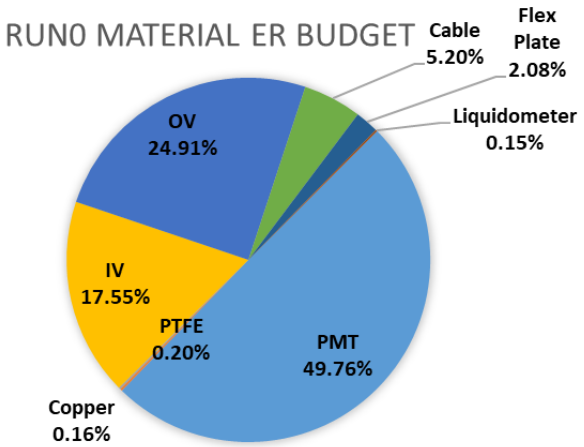
Stay tuned for multi-physics program with PandaX!

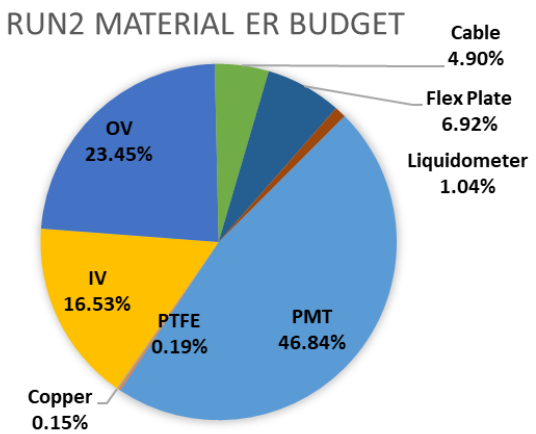
4T Run2 Part Screening

- Material ER background for Run2 increases ~6 % mainly for FlexPlate !

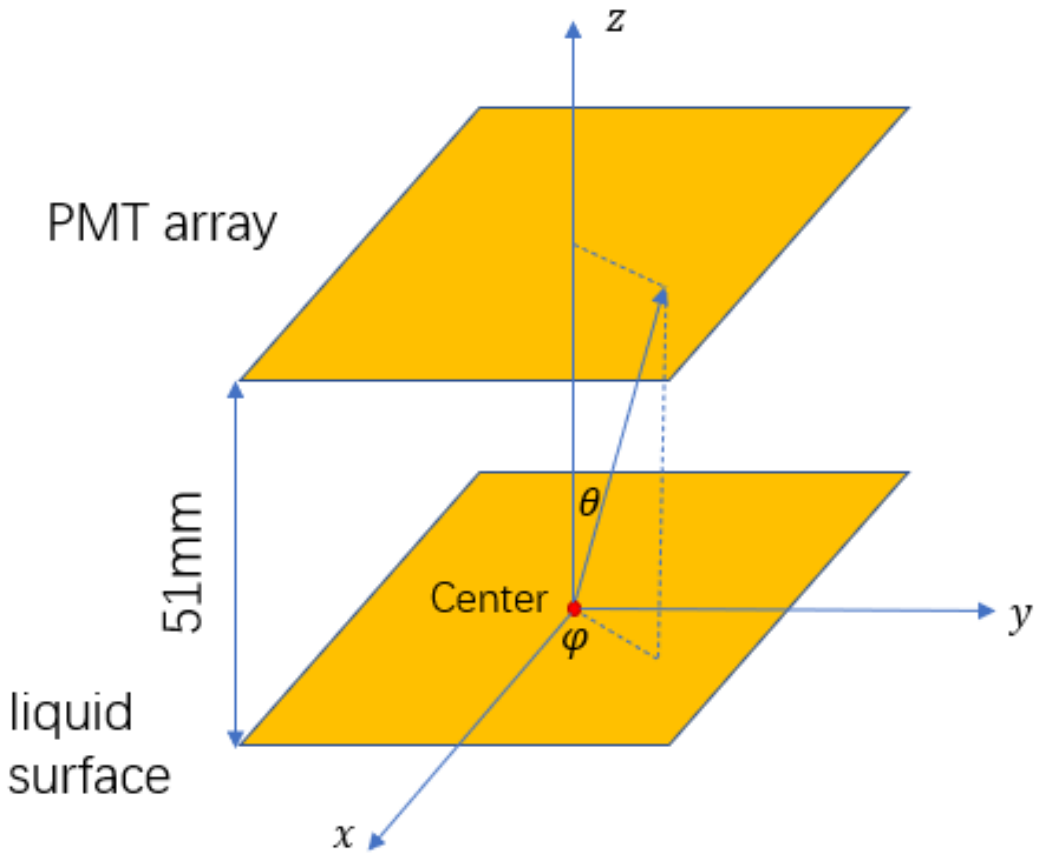
Unit: mBq/pc	Co-60	Cs-137	K-40	Th-232 (e)	Th-232(l)	U-235	U-238(e)	U-238(l)
KaptonBase (run2)	0.00±0.05 <0.08	0.12±0.10 <0.28	0.00±2.02 <3.31	0.35±0.28 <0.81	0.22±0.19 <0.54	0.03±0.29 <0.51	2.44±1.45 <4.83	1.07±0.19
KaptonBase (run0,run1)	<0.12	<0.46	<4.73	<1.30	<0.57	<2.45	6.97±1.94	0.84±0.22
FlexPlate (run2)	0.00±0.05 <0.08	0.00±0.14 <0.24	0.84±2.20 <4.46	0.00±0.59 <0.96	0.41±0.27 <0.84	0.00±0.57 <0.93	2.81±2.38 <6.73	5.05±0.41
FlexPlate (run0,run1)	0.00±0.31 <0.51	0.00±0.33 <0.54	1.43±3.37 <6.97	0.00±0.86 <1.41	1.58±0.53	0.00±0.42 <0.70	3.18±5.65 <12.48	1.50±0.50

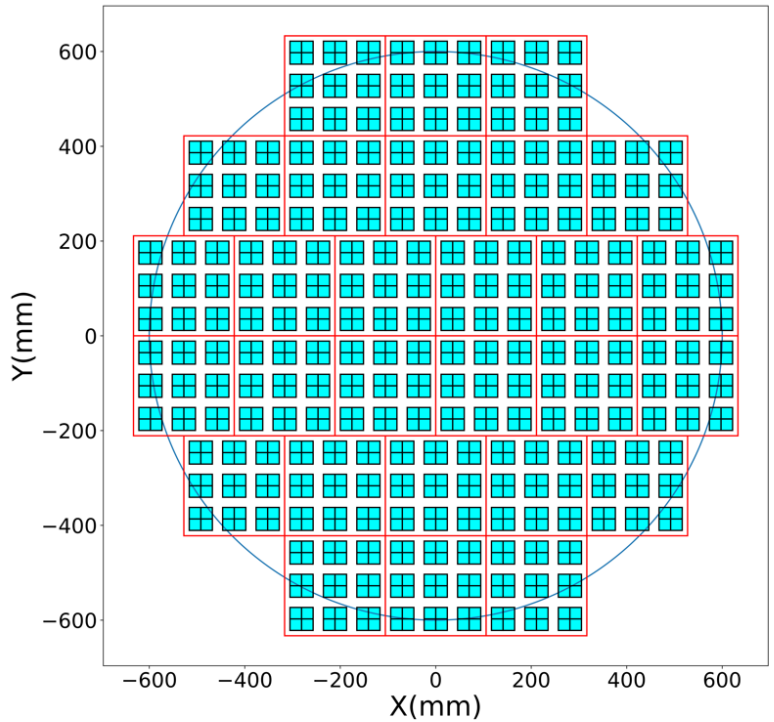
……





- The ER increases from 1.07e-2 mDRU to 1.14e-2 mDRU @[1,30] keV mainly for FlexPlate.


z
PMT array
51mm
θ
Center
φ
y
liquid
surface
x


600
400
200
0
−200
−400
−600
Y(mm)
−600
−400
−200
0
200
400
600
X(mm)

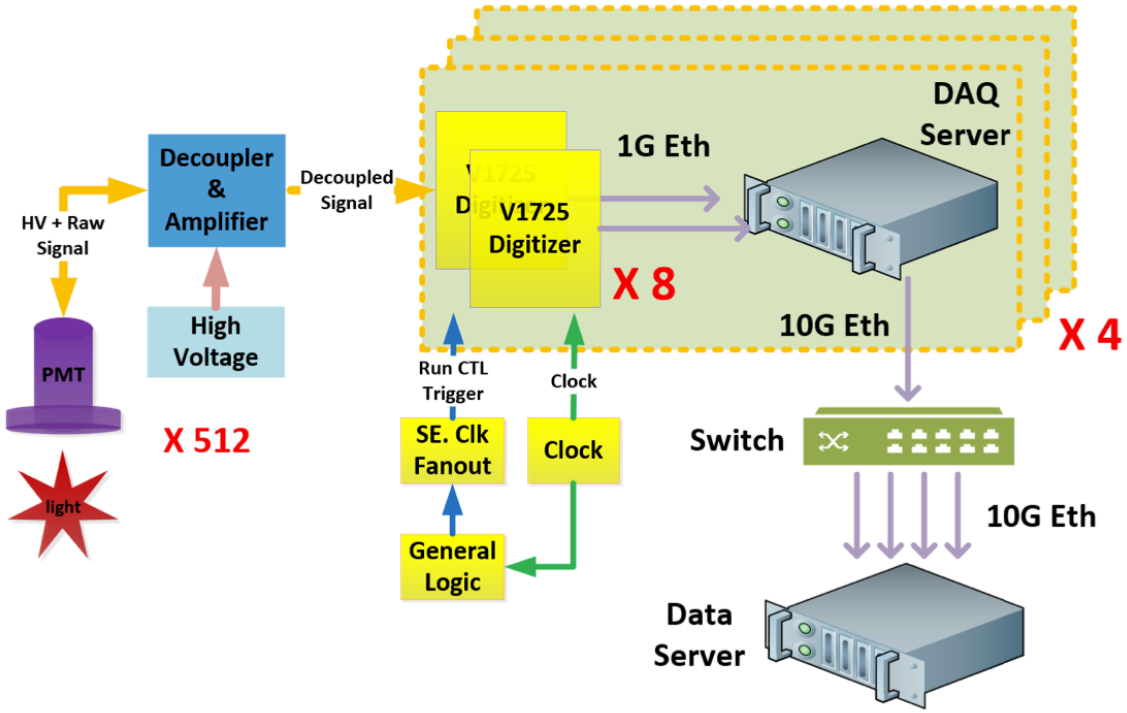
Advantage: time response

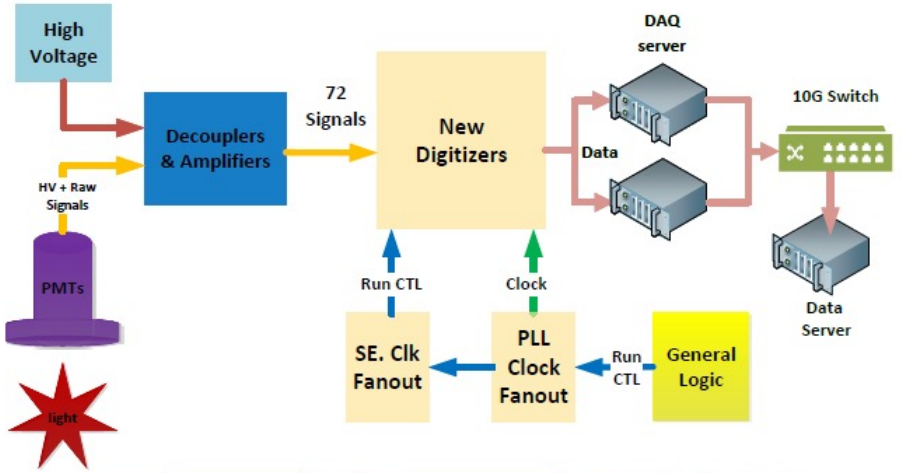
Characteristics at 25 deg C

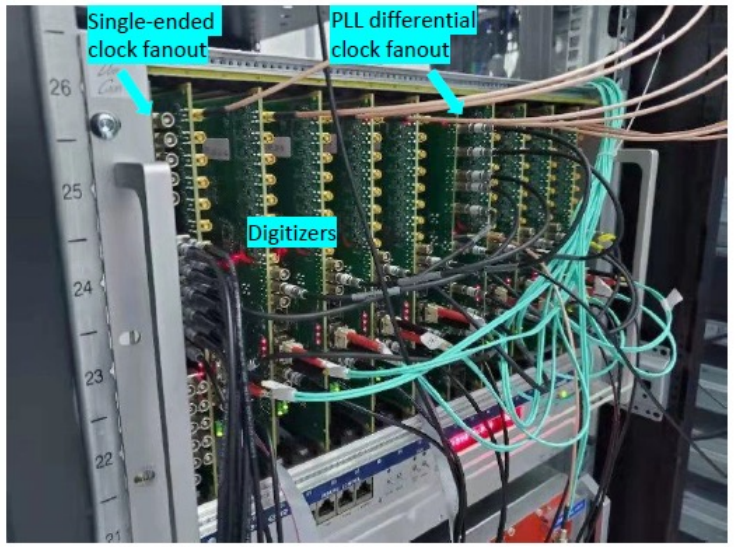
Parameter		R12699-406-M4	R11410-20	Unit
Cathode Sensitivity	Luminous (2856K)	**95**	**90**	uA/lm
	Blue Sensitivity Index	**10.0**	**10**	-
Anode Sensitivity	Luminous (2856K)	**140**	**315**	A/lm
Gain		**1.5×10^6**	**3.5×10^6**	-
Anode Dark Current (Each anode) (after 30min. storage in darkness)		**1.5**	**10**	nA
Time Response	Rise Time	**1.2**	**5.5**	ns
	Transit Time	**5.9**	**46**	ns
	Transit Time Spread (FWHM)	**0.41**	**9**	ns
Uniformity Between Each Anode		**1:1.5**	**-**	-
Pulse Linearity (Each Anode)	at ±2% Deviation	**8**	**20**	mA
	at ±5% Deviation	**20**	**-**	mA

Better time response may benefit pulse shape discrimination

Electronics







- From PMT to DAQ server;
- CERN V1725 Digitizer, 250 MS/s;
- Self-trigger mode: read out pulses above 20 ADC (~ 1/3 PE);

New digitizers: 14-bit, 500MS/s

Cable crosstalk test

Initial Check

Manual continuity checks,1/28 bad

Performance Test

24-PMT array with controlled voltage application and stability

Data Acquisition

Self-trigger mode at 20 ADC threshold for noise and signal analysis.

Key Metrics

Noise rms

Firing signs area >10PE, rms >5)

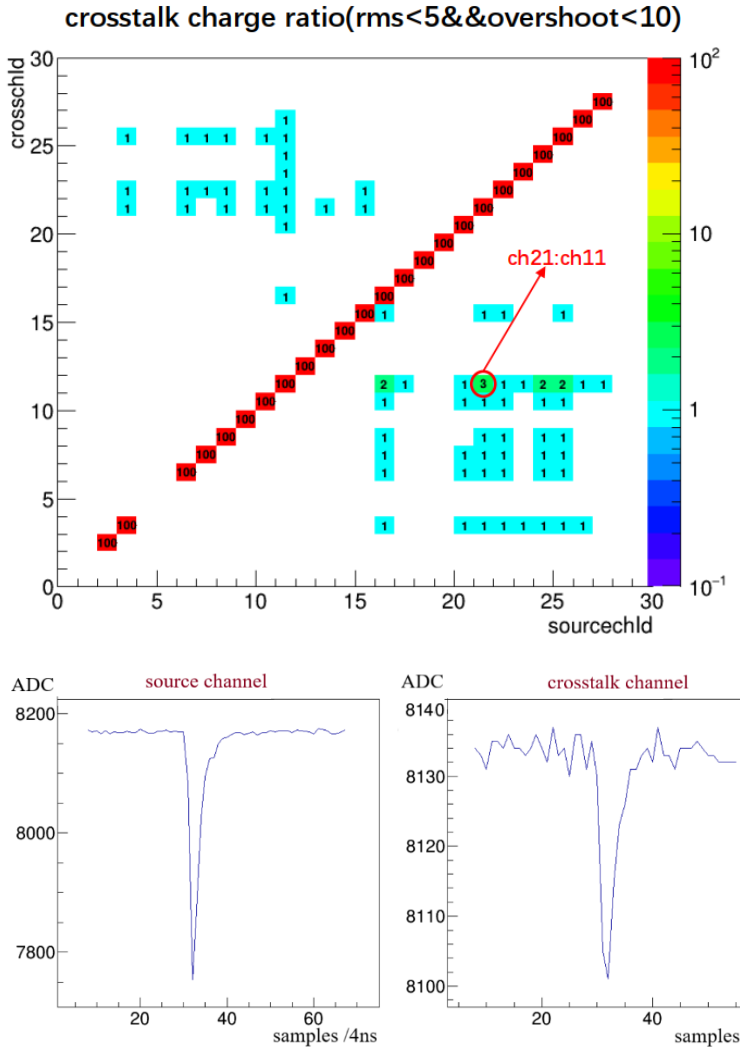
Crosstalk between channels

SPE consistency check

Dark count rate stability

Results

Majority of crosstalk <1%, with some exceptions (e.g., channel 21 to 11 at ~3%).



Suppression in Multi-Sites events

- A suppression waveform
- Suppression in run0 data