Latest results of JSNS^2 and status of JSNS^2-II

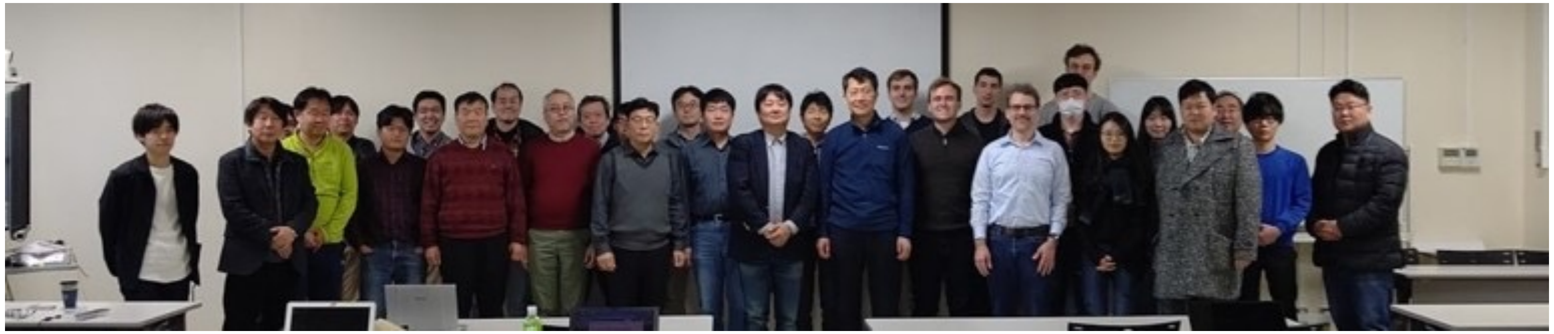
Ryeonggyoon Park (Chonnam National University)
On behalf of the JSNS^2/JSNS^2-II collaboration

J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source

JSNS^2/JSNS^2-II Collaboration

J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source

Collaboration meeting @ J-PARC (2020/Feb)



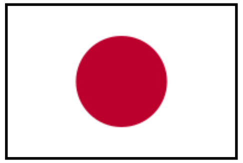
JSNS^2/JSNS^2-II collaboration
(61 collaborators)

- 6 Japanese institutions (29 members)

- 10 Korean institutions (24 members)

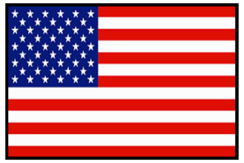
- 1 UK institution (1 member)

- 4 US institutions (7 members)



JAEA
KEK
Kitasato
Kyoto
Osaka
Tohoku

Chonnam National
Jeonbuk National
Dongshin
GIST
Kyungbook
Kyung Hee
Seoyeong
Soongsil
Sungkyunkwan
Seoul National of sci and tech



BNL
Florida
Michigan
Utah

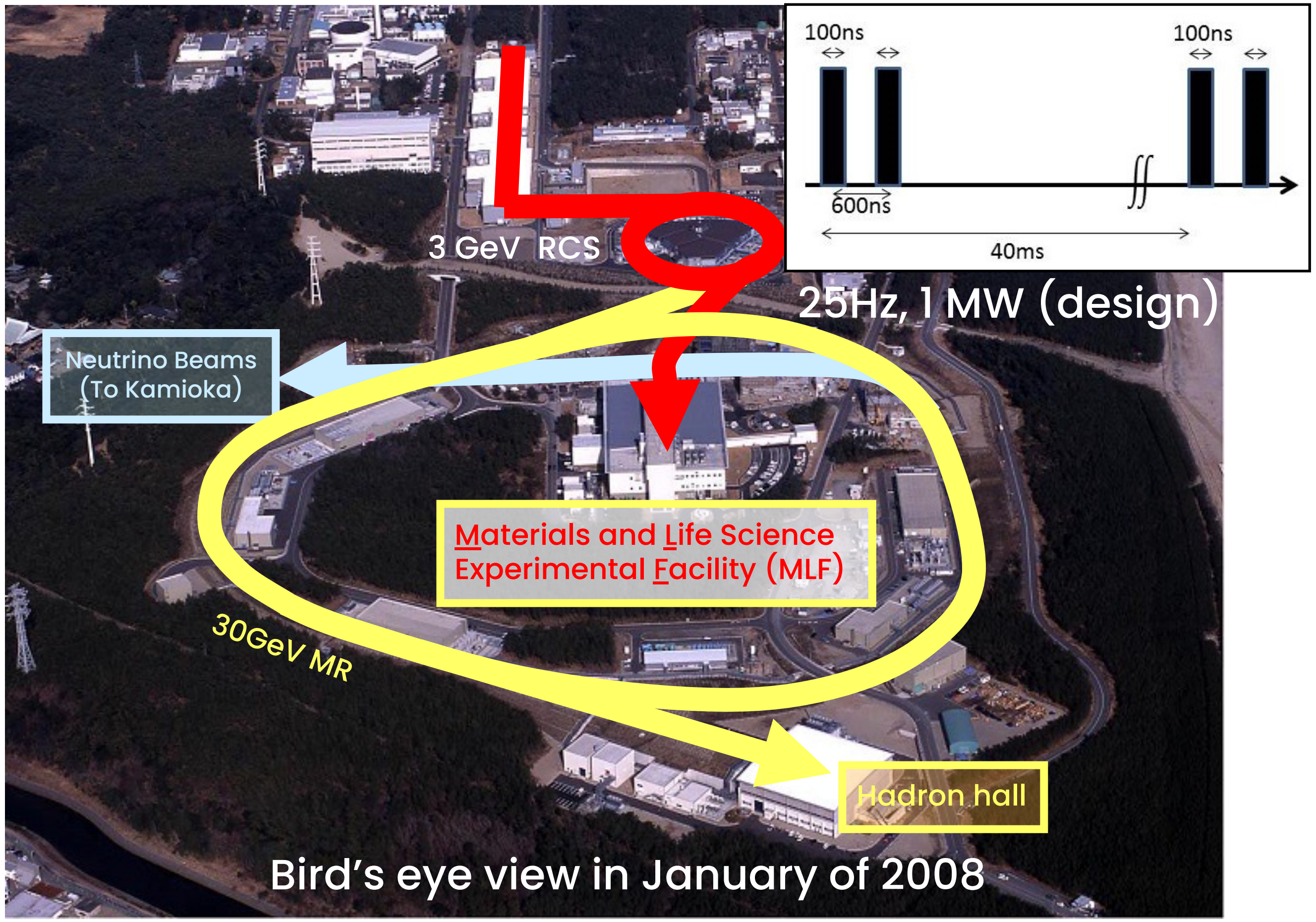
Sussex

Indication of a sterile neutrino ($\Delta m^2 \sim 1 eV^2$)

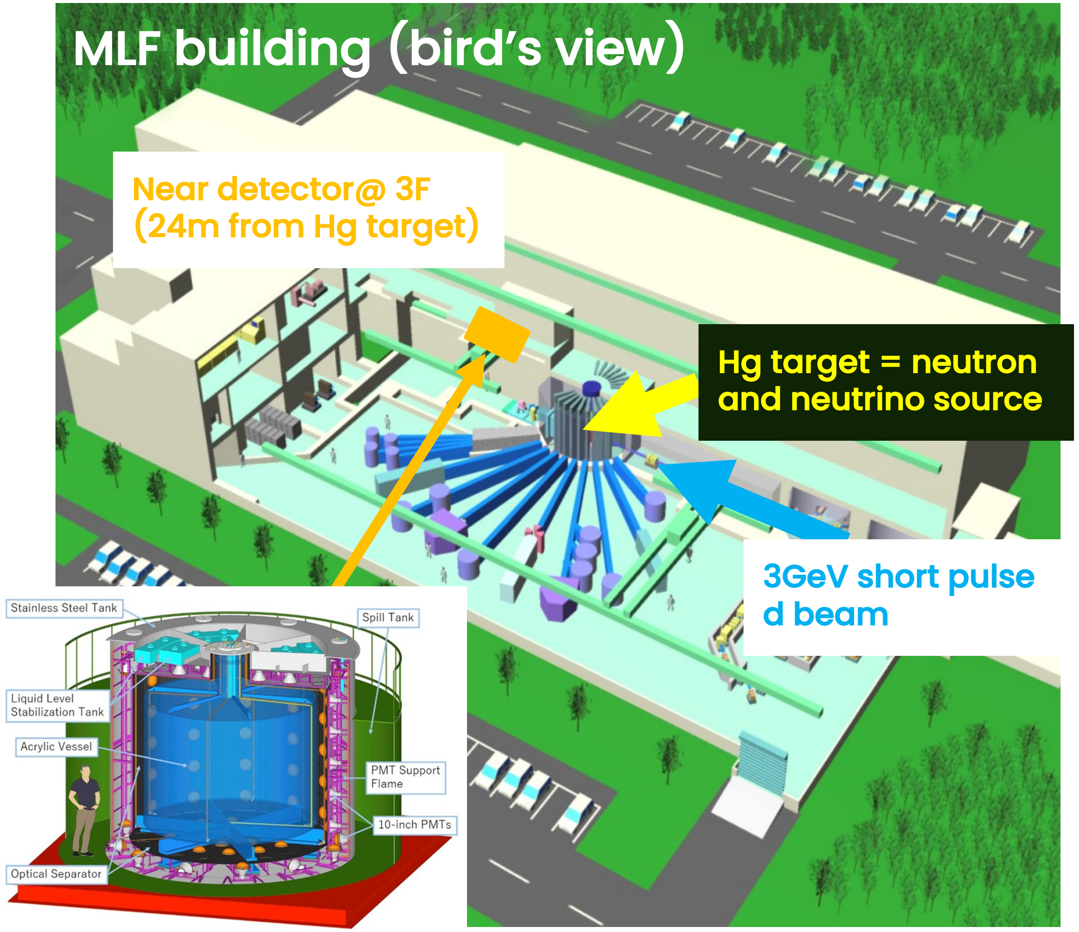
Experiments	Neutrino source	signal	significance	E(MeV),L(m)
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ	40,30
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	4.5σ	800,600
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8σ	
		combined	4.7σ	
Ga/BEST	e capture	$\nu_e \rightarrow \nu_x$	>4.2σ	<3,10
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ	3,10-100

- Direct test of the LSND
- JSNS^2 uses the same neutrino source (μ), target (H) and detection principle (IBD) as the LSND.
  → Even if the excess is not due to the oscillation, JSNS^2 can catch this directly.
- JSNS^2 is more sensitivity than LSND due to the use of Gd loaded LS and short pulsed beam.

J-PARC Facility & JSNS^2 detector



- Low duty factor beam (short pulse + small repetition rate) gives an excellent signal to noise ratio.



17 tons target, Gd-LS + 10% DIN
120 10'' PMTs

Operation

First physics run (2021)
- 0.6 MW (2021/Jan - Apr/5)
- 0.7 MW (2021/Apr/5 - June/24)

Second physics run (2022)
- 0.7 MW (2022/Jan/28 - Apr/6)
- 0.8 MW (2022/Apr/7 - June/6)

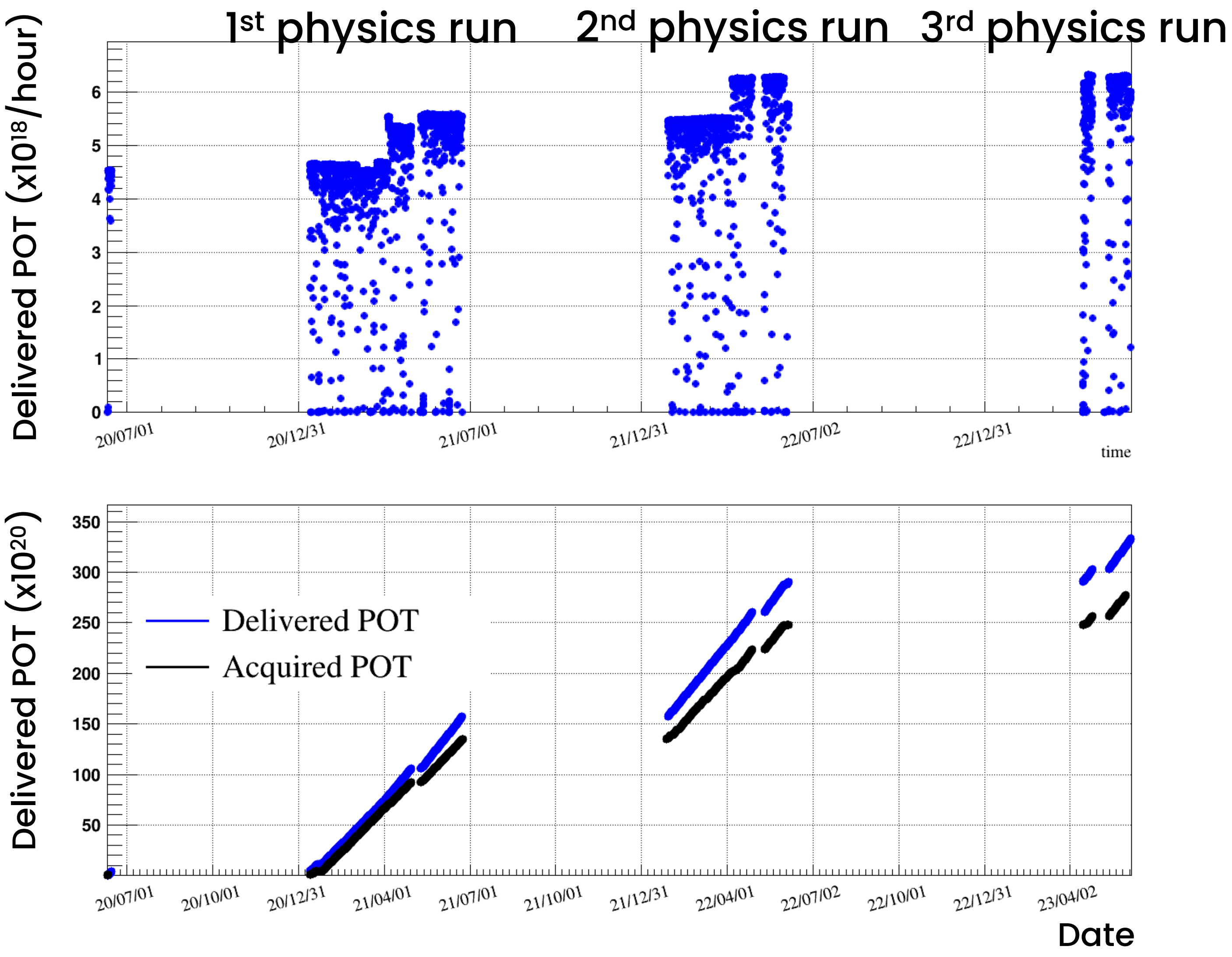
Third physics run (2023)
- 0.84 MW (2023/Apr/15 – June/2)

Beam power at RCS : 0.95 MW (2023)
→ A part of beam is passed to the main ring

Beam power was increased rapidly.
(now almost the same as design)

There is an accelerator maintenance period every year.

Delivered POT : 3.28×10^{22}
(28.7% of approved POT for $JSNS^2$)

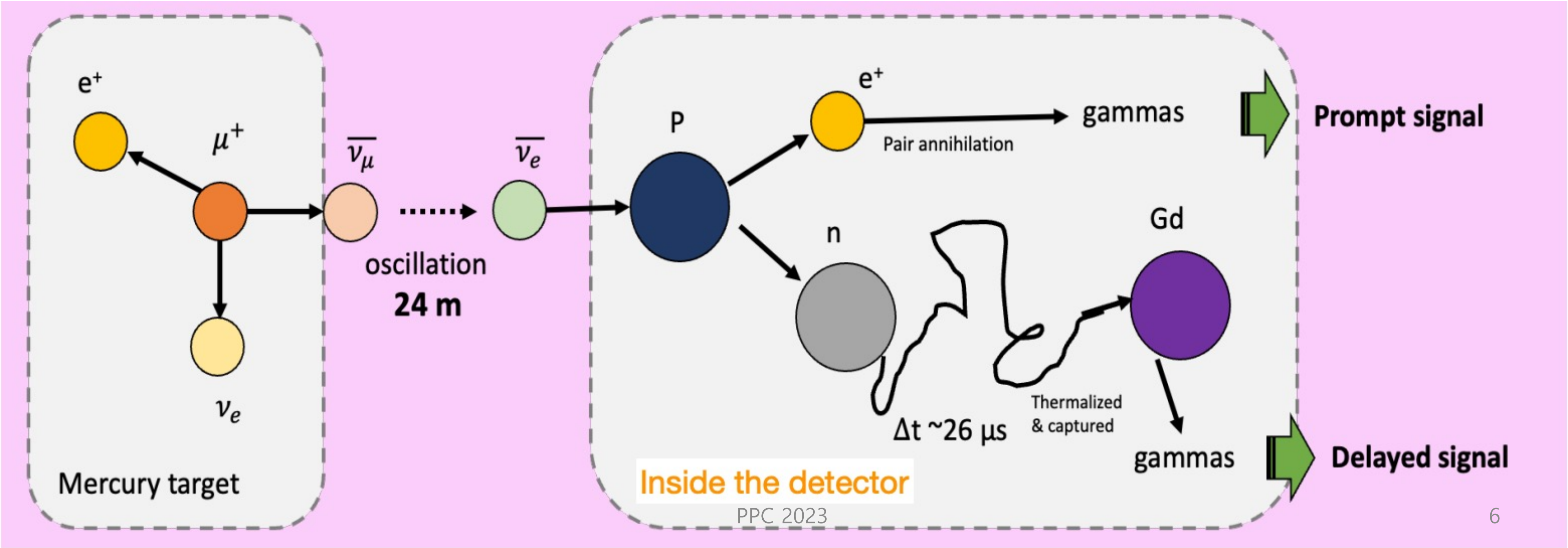


Sterile neutrino : searching signal

Coincidence of IBD (Inverse Beta Decay)

- Prompt : e+ annihilation
- Delayed : gammas from neutron capture on gadolinium (Gd)

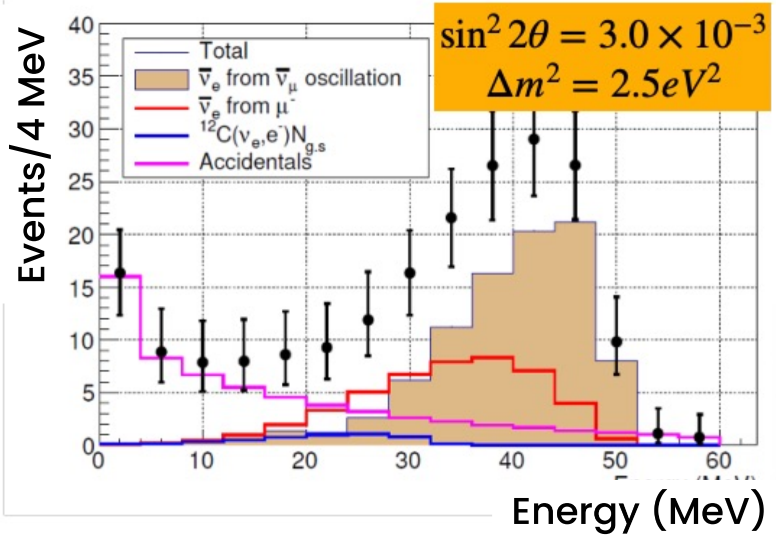
	Timing	Energy
Prompt	1.5 ~10μs from beam	20~60 MeV
Delayed	$\Delta T_{p\text{-}d}$ <100μs	7~12 MeV

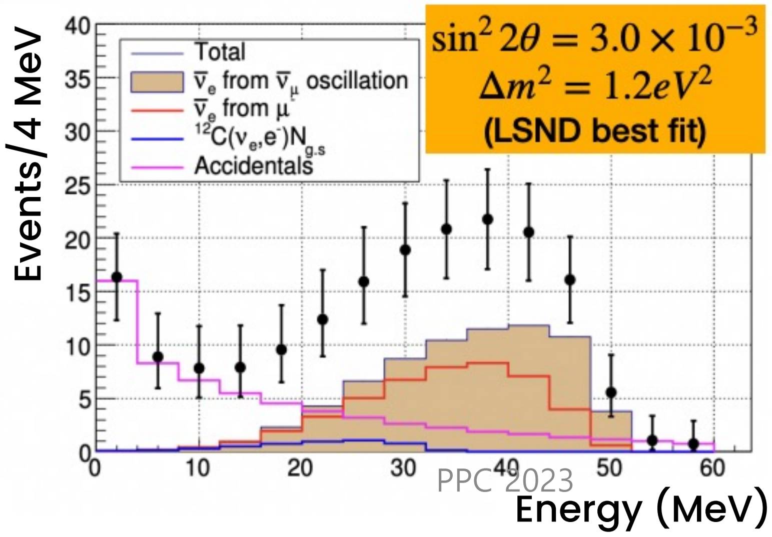


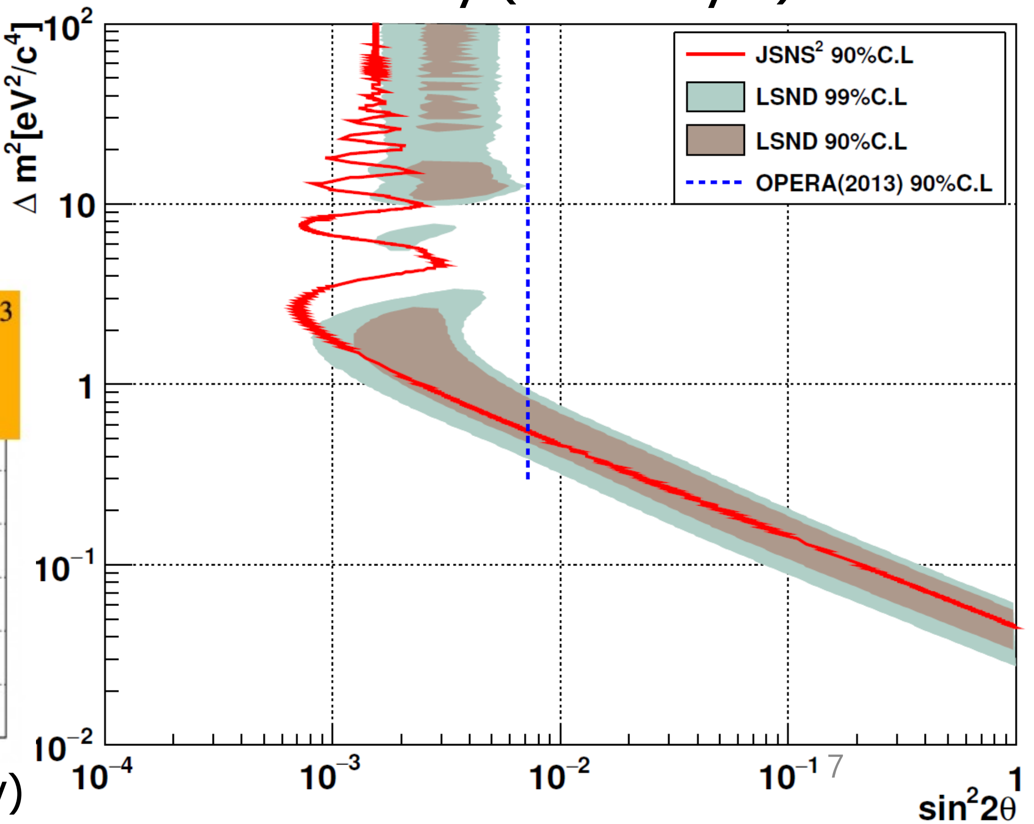
Expected visible energy and sensitivity
(JSNS^2 TDR, arXiv:1705.08629)

- $\overline{\nu}_e$ follows decay-at-rest $\overline{\nu}_\mu$ energy distribution
- Prompt background candidate : ~3.9 x 10^{-4} per spill
- Delayed background candidate : ~4.8 x 10^{-3} per spill
- Spectral fit is sensitive to the difference of energy spectrum.

Sensitivity (1MW x 3yrs)



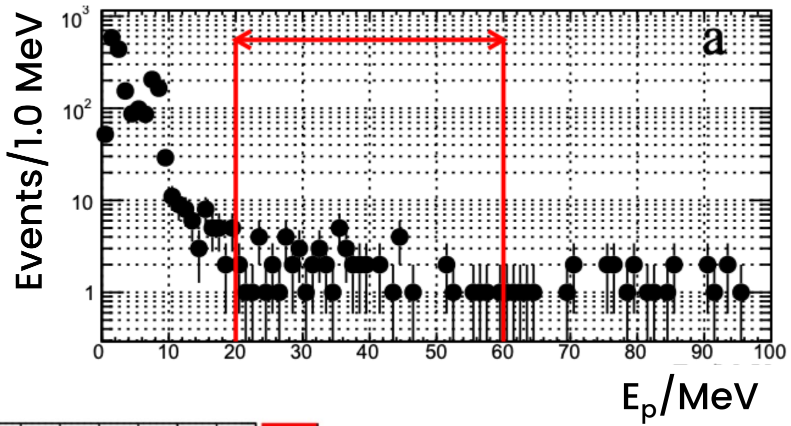




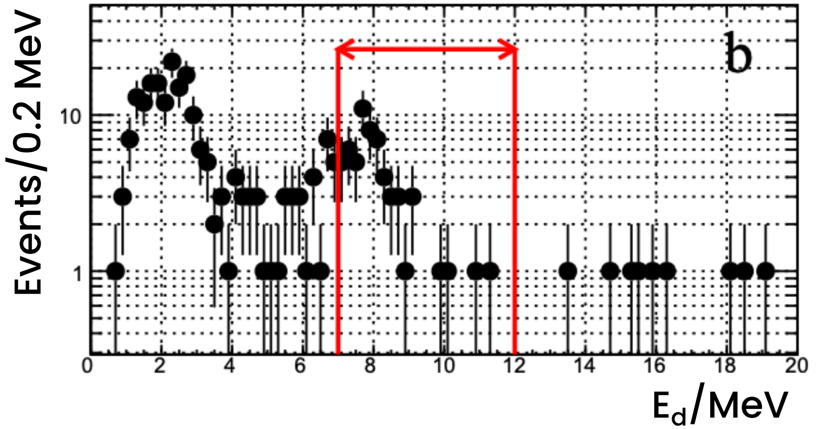
Commissioning run
(Eur. Phys. J. C (2022) 82:331)

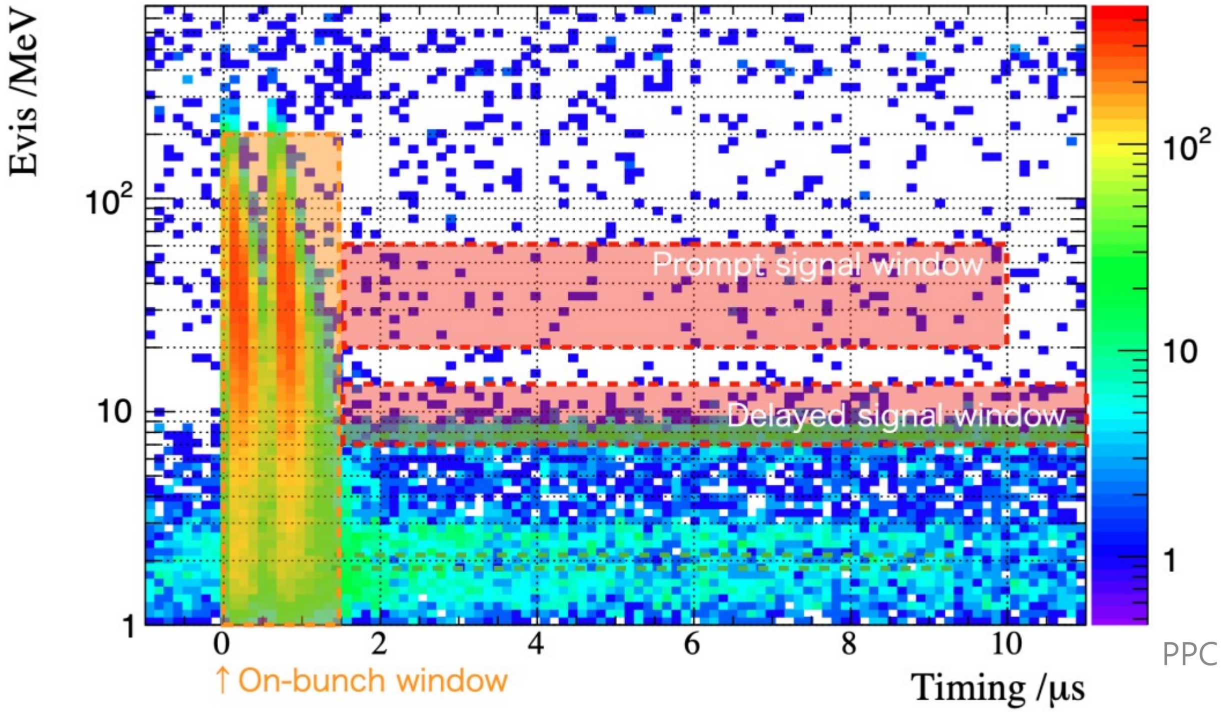
- June/5-15, 2020
- Integrated POT : 8.9 x 10^{20} (< 1% of required POT)
- Expected IBD signal : ≪ 1 event
- Beam trigger with 25μs width

Prompt



Delayed



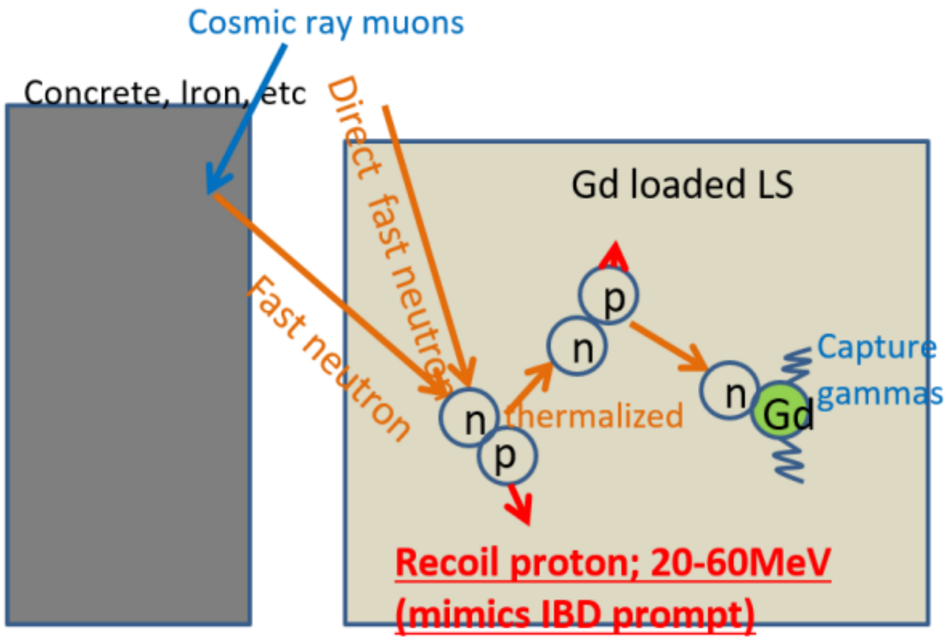


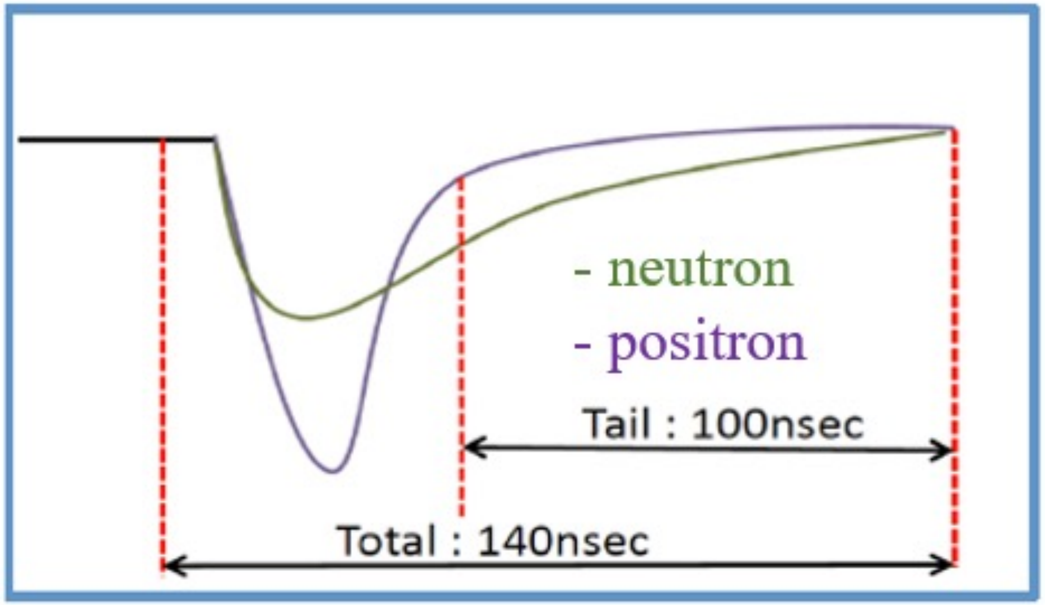
- Observed correlated event candidates : 59 ± 8 IBD events
- Expected cosmic-induced fast neutron from no beam data : 55.9 ± 4.3 events
- Cosmic-induced fast neutrons are the dominant background
- Pulse shape discrimination (PSD) would reject them.

Pulse Shape Discrimination (PSD)

- Fast neutrons can mimic IBD signals from electron anti-neutrino.
  → correlated background

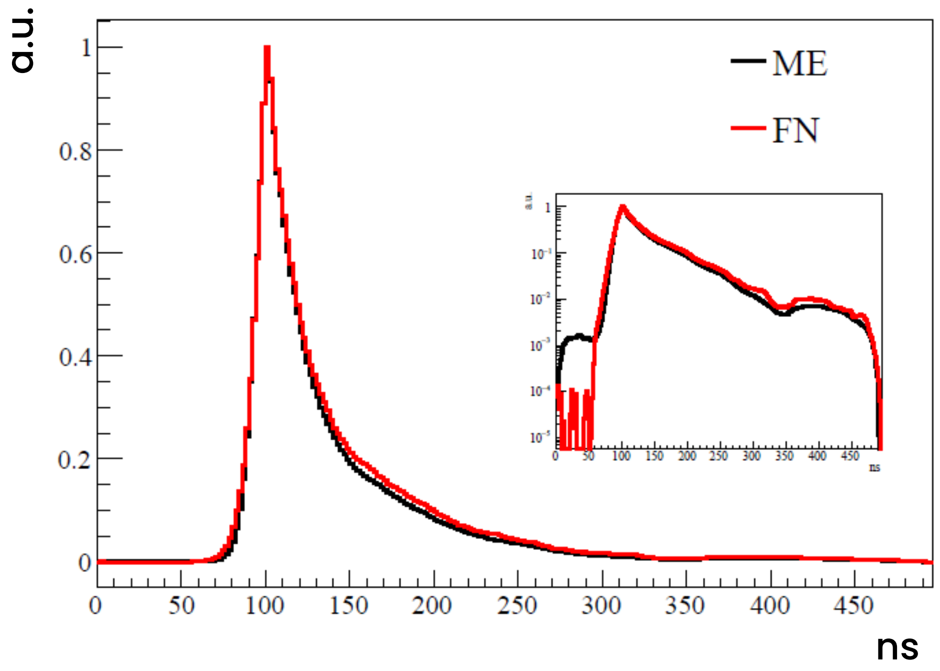
- PSD can separate the IBD signals and fast neutrons.
  → the goal is to remove 99% of fast neutrons.

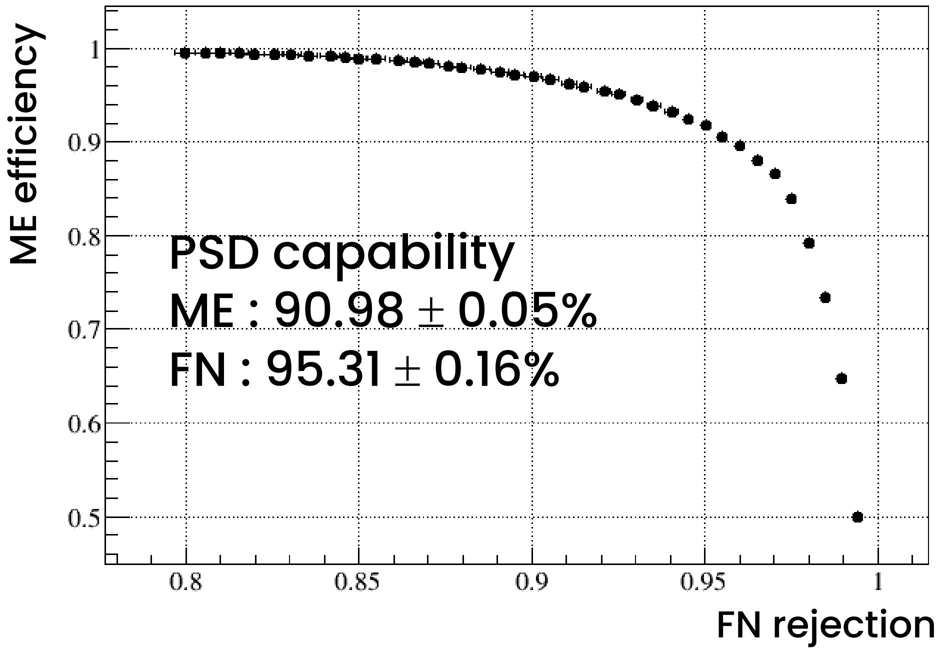




PSD : 2D likelihood method

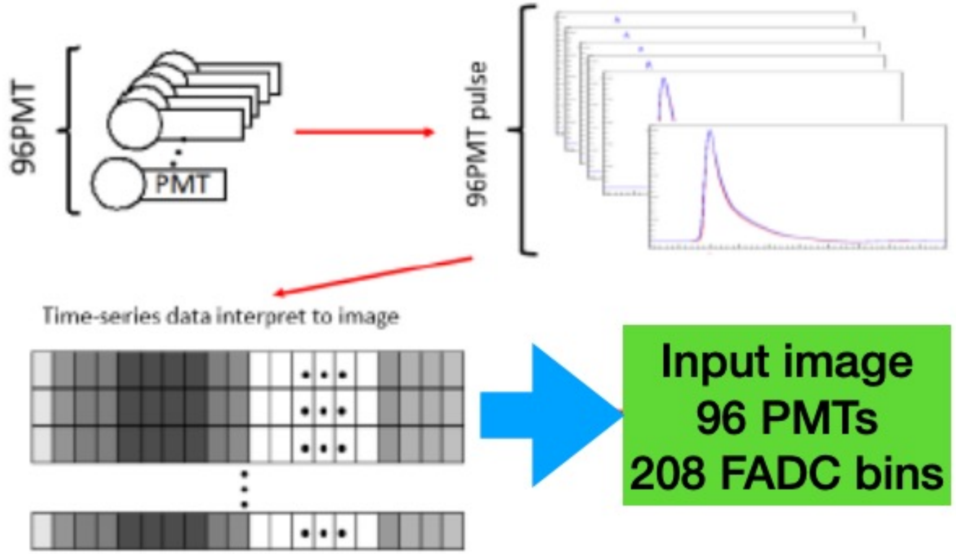
- It has been developed based on the real data of JSNS^2.
- The likelihood judges that all other points look like “neutron”-like or “electron”-like.
- Using control sample of Michel electrons (ME) and Fast neutron (FN)

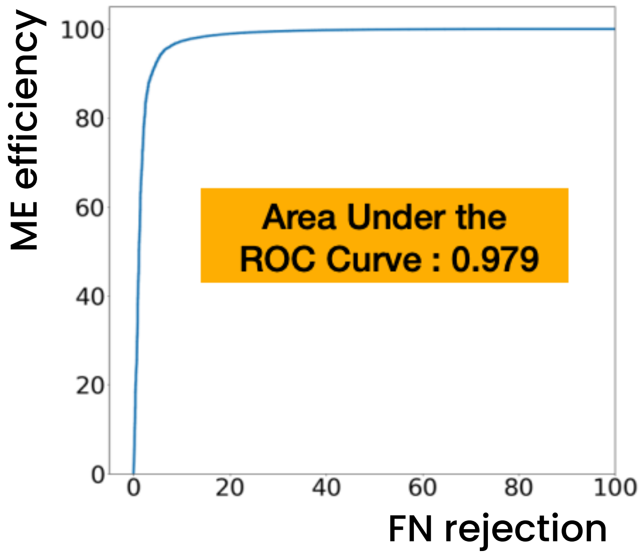


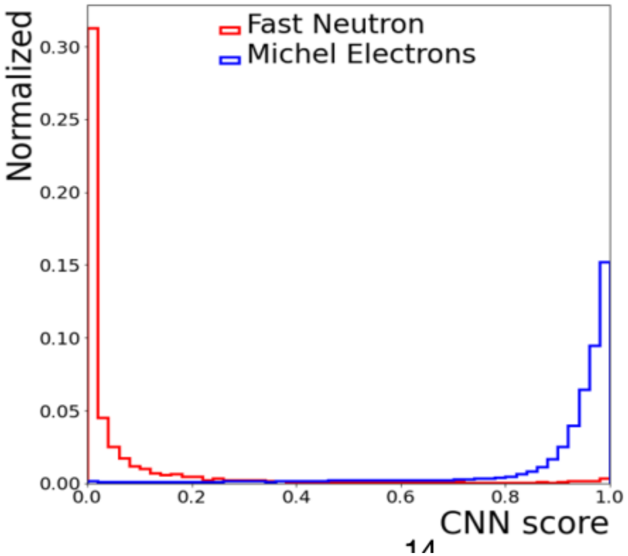


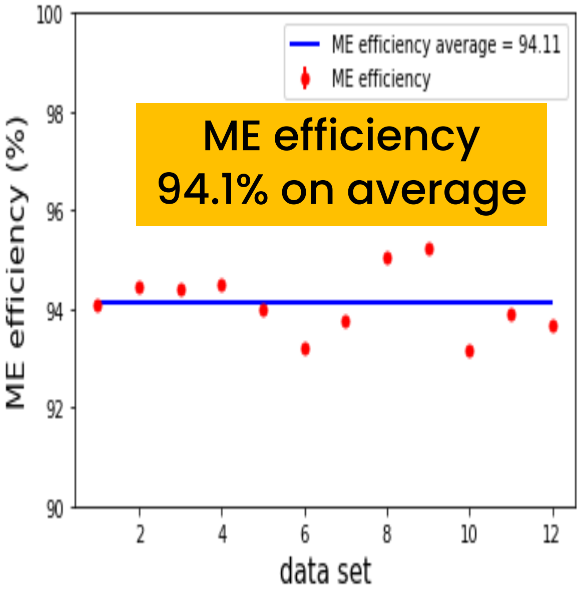
PSD : Convolutional Neural Network, CNN

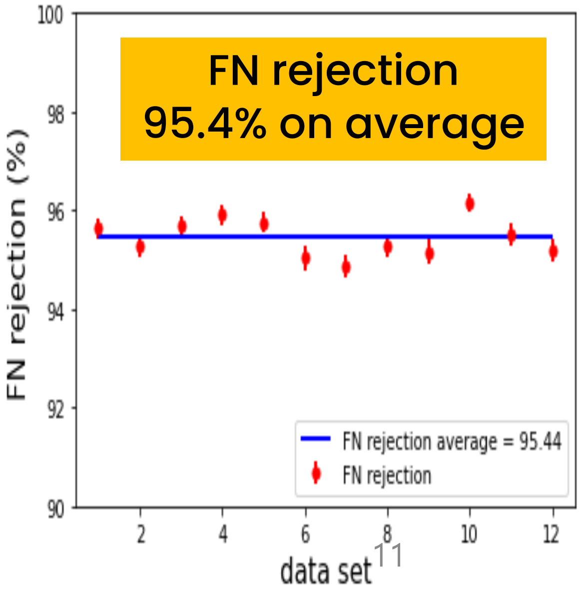
- Treated time-series data from a PMT with image data
- Data: Training (37.5%), validation (12.5%) and evaluation (50%)
- Two independent efforts show consistent FN-rejection result.



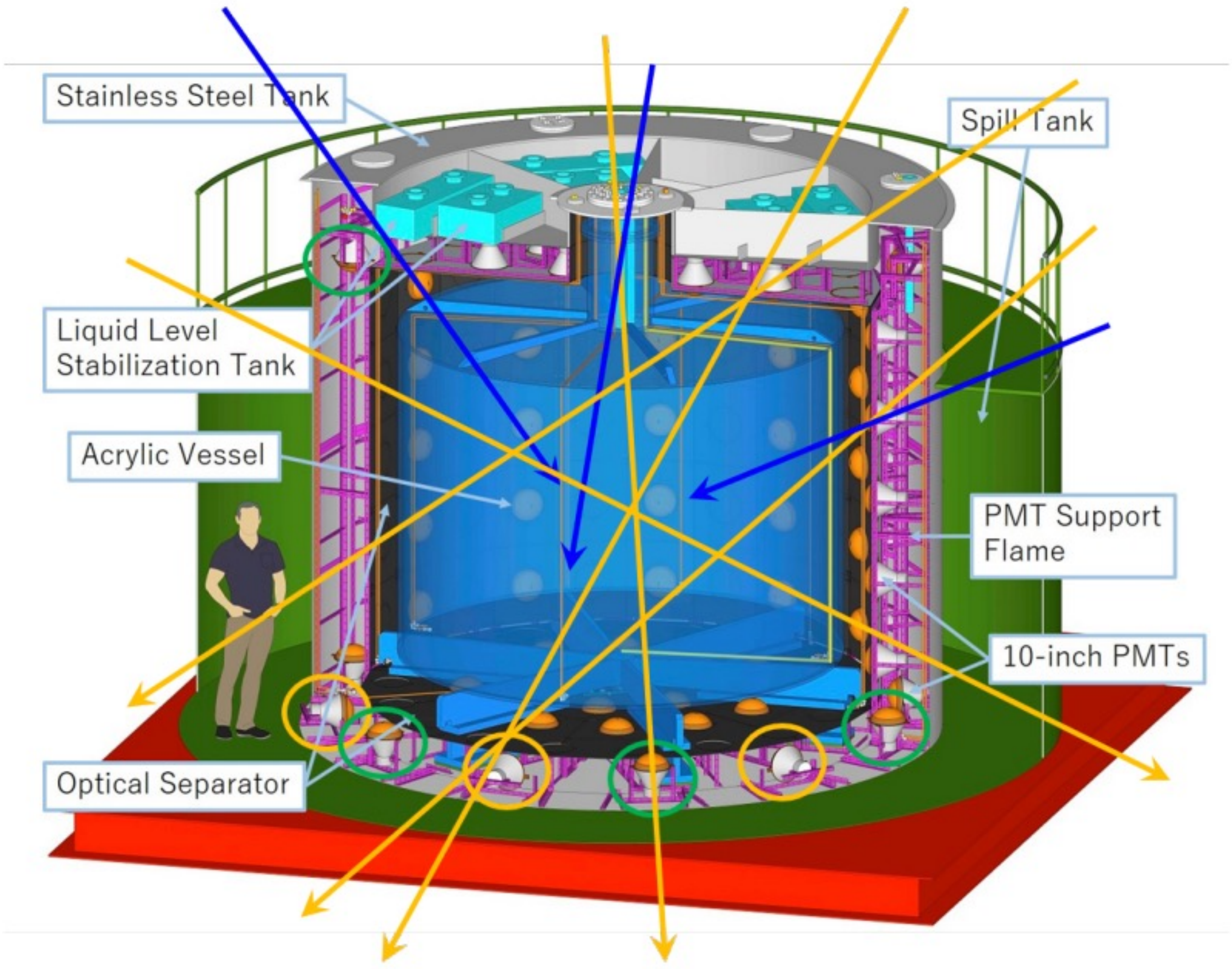








Cosmic muons & veto



- By using Top/Bottom Veto PMTs (vertical, side face), we can tag cosmic muons well. (Stopping muons ~1.5kHz, Through-going muon ~0.6kHz)

- ~1% of the fake rate from Michel electron by stopping muons.

Muon	Muon rate (Hz)
Stopping+Thru-going	2245.7 ± 0.7
Stopping	1487.8 ± 0.6
Thru-going	605.4 ± 0.4

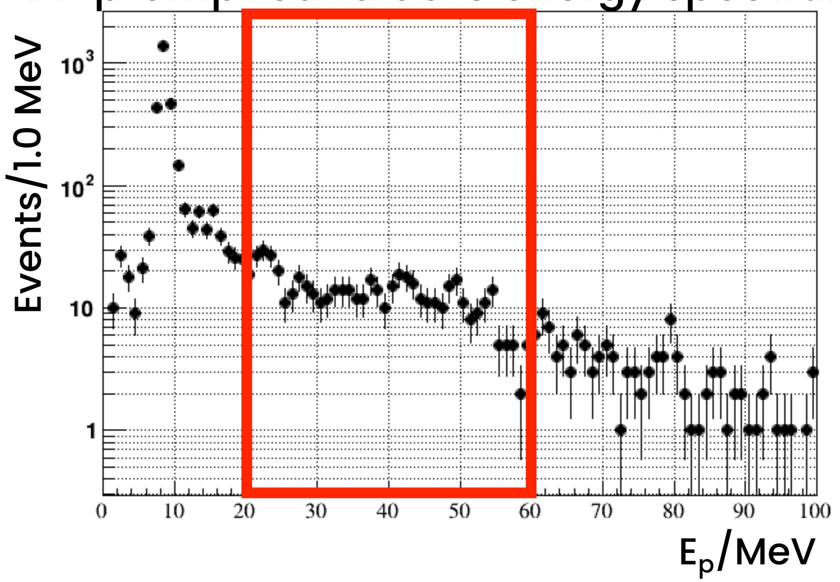
Accidental single rate of IBD prompt/delayed

- Special calibration using beam timing with 125μs time window data is used.
- External particle rejection using veto PMTs
- ME rejection : 10μs veto after a stopping muon
- Fiducial cut (R < 1400mm, |Z| < 1000mm)

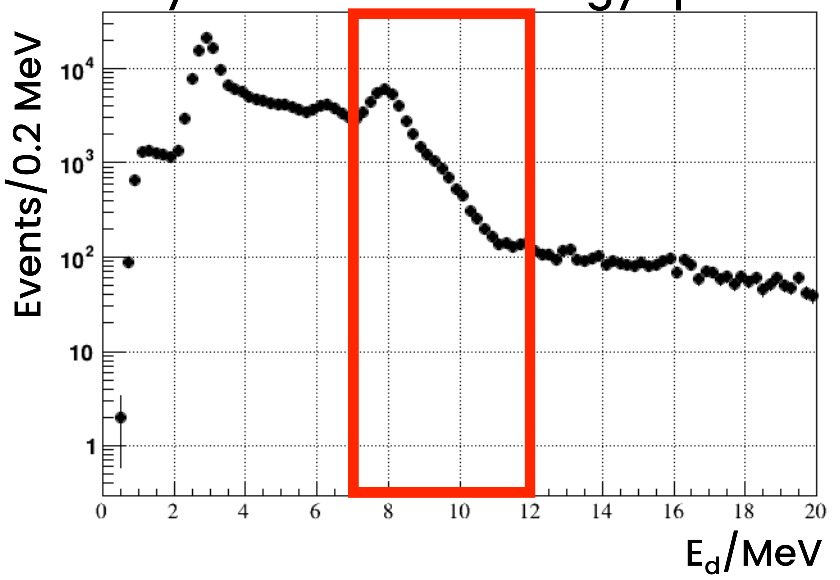
Observed
- prompt single rate : $(2.20 \pm 0.09) \times 10^{-4}$ /spill
- delayed single rate : $(1.80 \pm 0.01) \times 10^{-2}$ /spill

Reference : JSNS² TDR
- prompt single rate : 3.9×10^{-4} /spill
- delayed single rate : 4.8×10^{-3} /spill

IBD prompt candidate energy spectrum



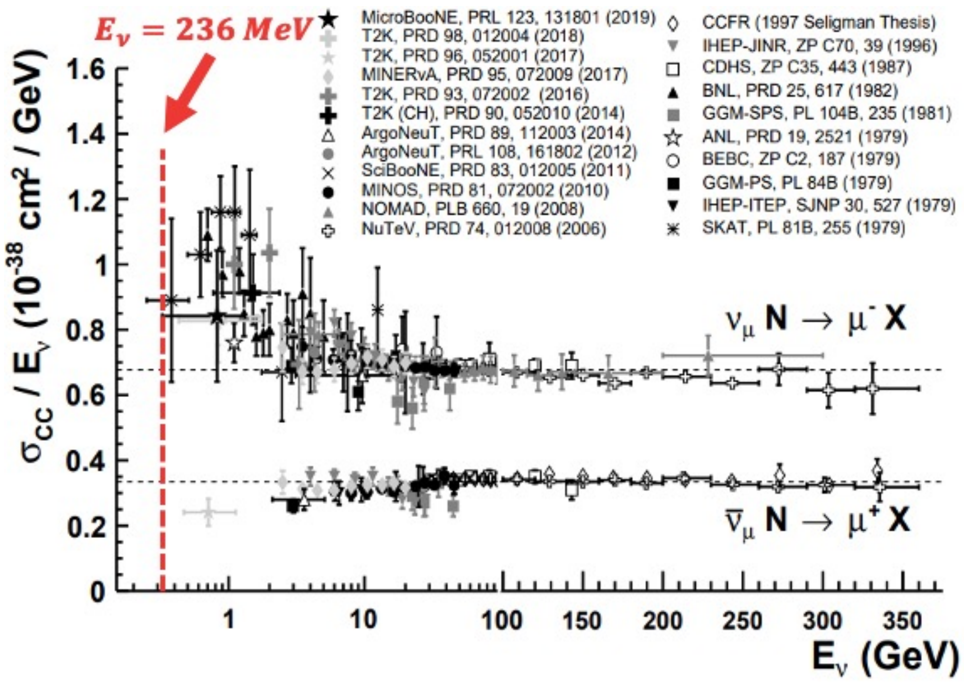
IBD delayed candidate energy spectrum

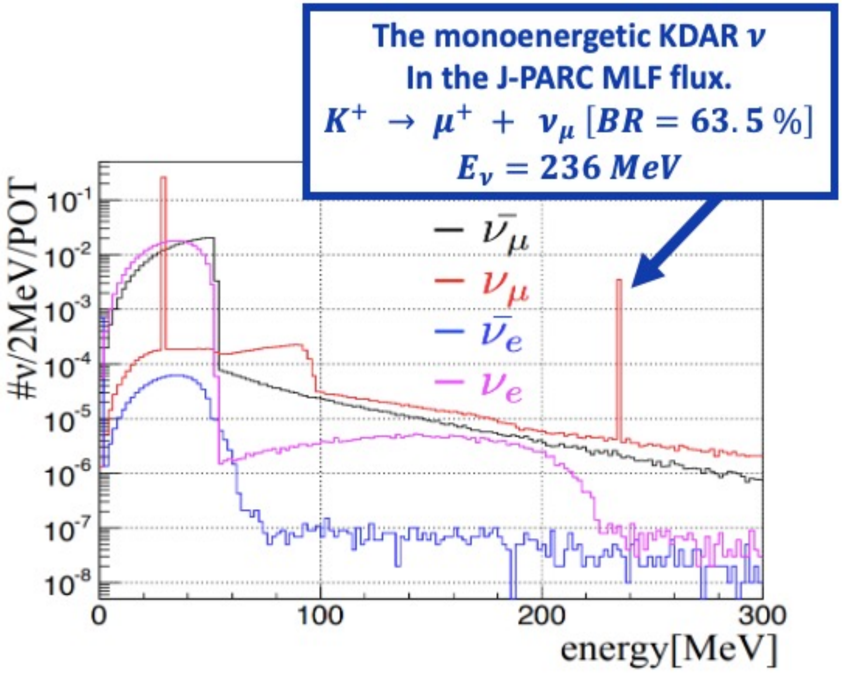


Kaon Decay-At-Rest neutrino measurement in JSNS^2

Kaon Decay-At-Rest neutrino measurement

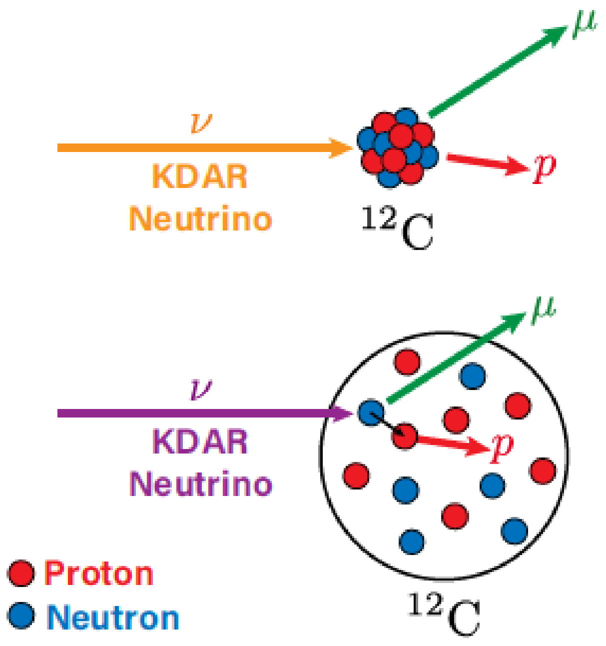
- Neutrino interaction models are a crucial part of neutrino physics, but poorly known at low energies.
- KDAR neutrinos is very good way for understanding the low energy neutrino interaction.
  → due to the well-known energy (Mono-Energetic neutrino at 236MeV)
- The JSNS^2 detector has the unique ability to measure the mono-energetic KDAR neutrino.
  (Note that horn focused beam can not make a decay-at-rest neutrino.)

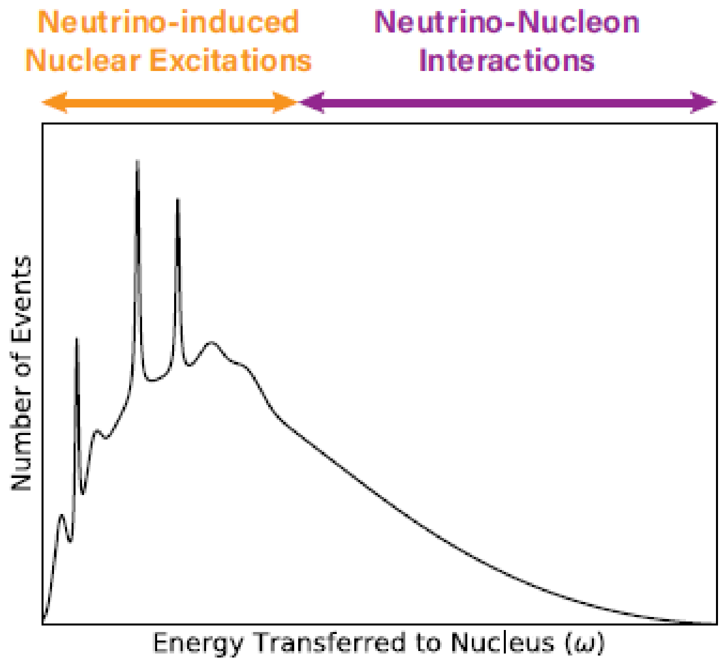




Nucleus with Kaon Decay-At-Rest neutrino

- KDAR neutrino energy exists a transition region between neutrino-on-nucleus and neutrino-on-nucleon scattering.
  → Make important contribution to KDAR neutrino scattering
  → Can be used to explore important aspects of nuclear physics models including short range correlations and final state interaction





KDAR signal measurement in JSNS^2

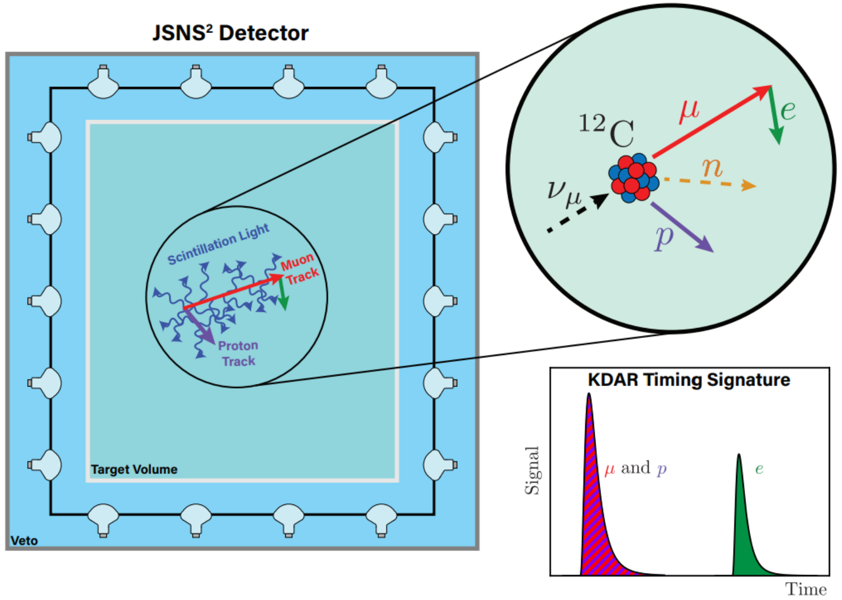
A double coincidence from KDAR signal

- Prompt : The initial neutrino interaction products
- Delayed : Michel electron

KDAR (In the Hg target) $K^+ \rightarrow \mu^+ + \nu_\mu$

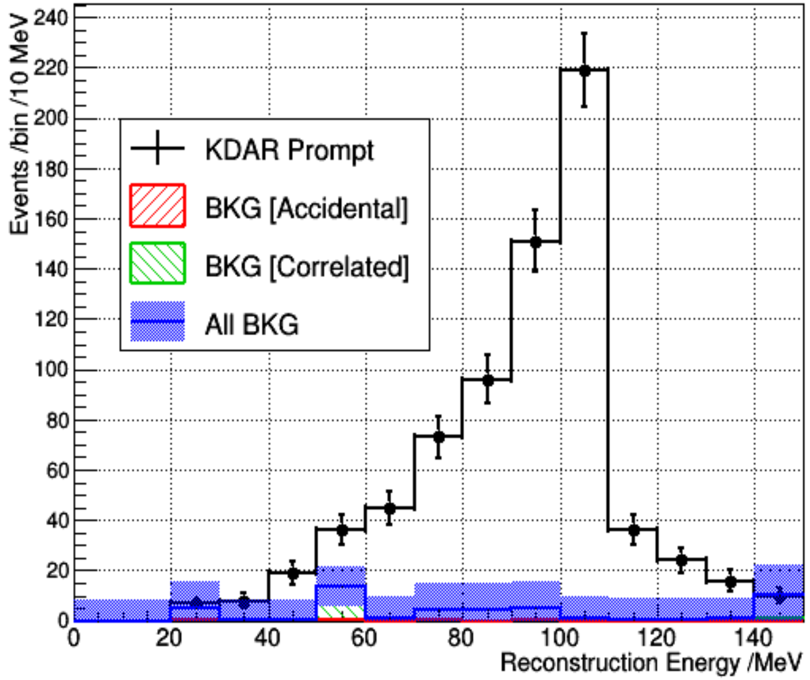
Prompt $\nu_\mu + {}^{12}C \rightarrow X + \mu^-$

Delayed $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$



KDAR event selection

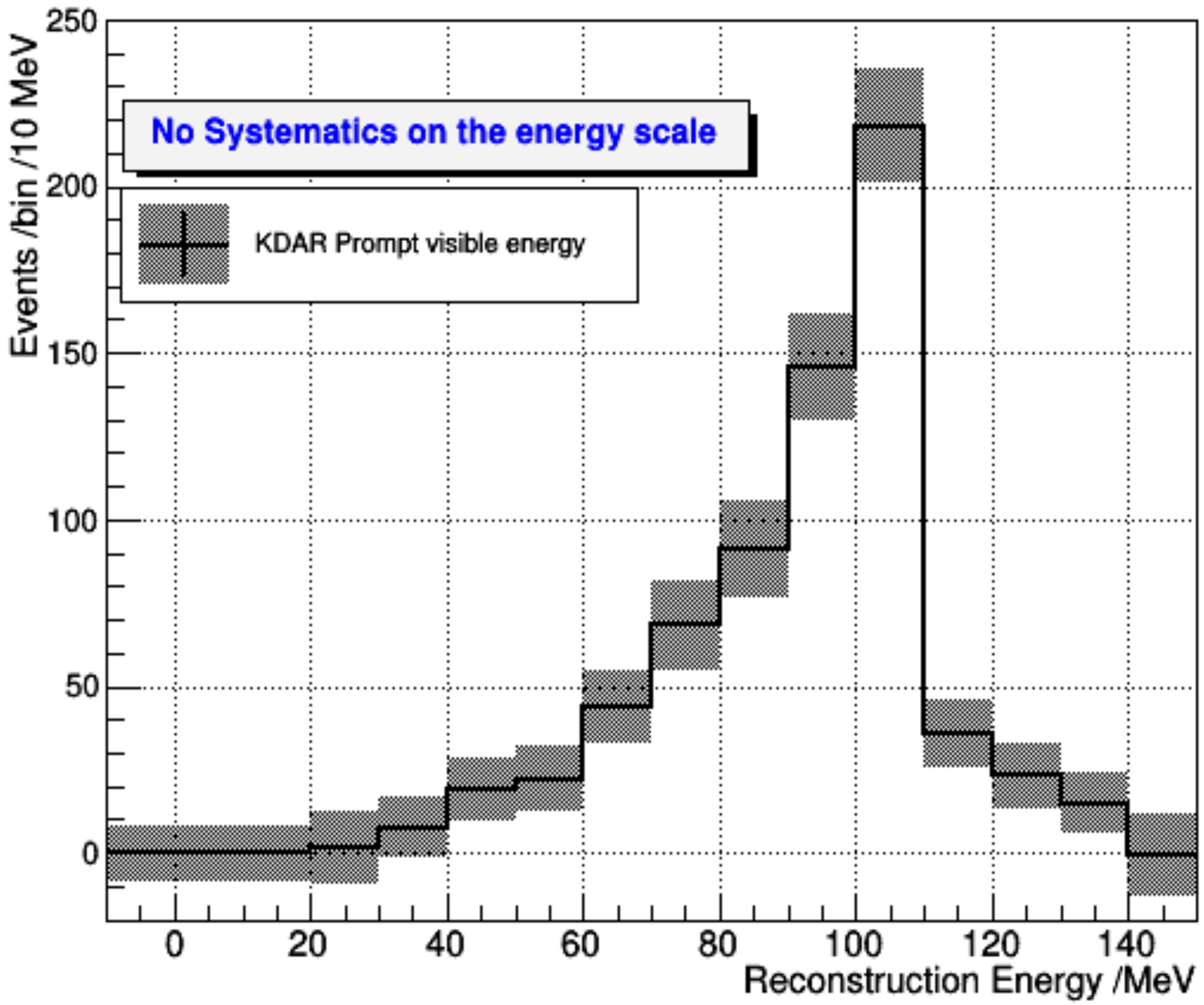
- Used data : 2021 physics run (11.9% of the approved POT)
- KDAR Prompt E : 20 – 140 MeV
- KDAR delayed E : 20 – 60 MeV
- Prompt : Within 150ns from Beam-timing
- Time coincidence between prompt and delayed : < 10 μs
- Vertex difference of prompt and delayed : < 0.3 m
- Fiducial volume cut applied (R < 1400mm, Z < +500mm, Z > -1000mm)



First clear KDAR signal

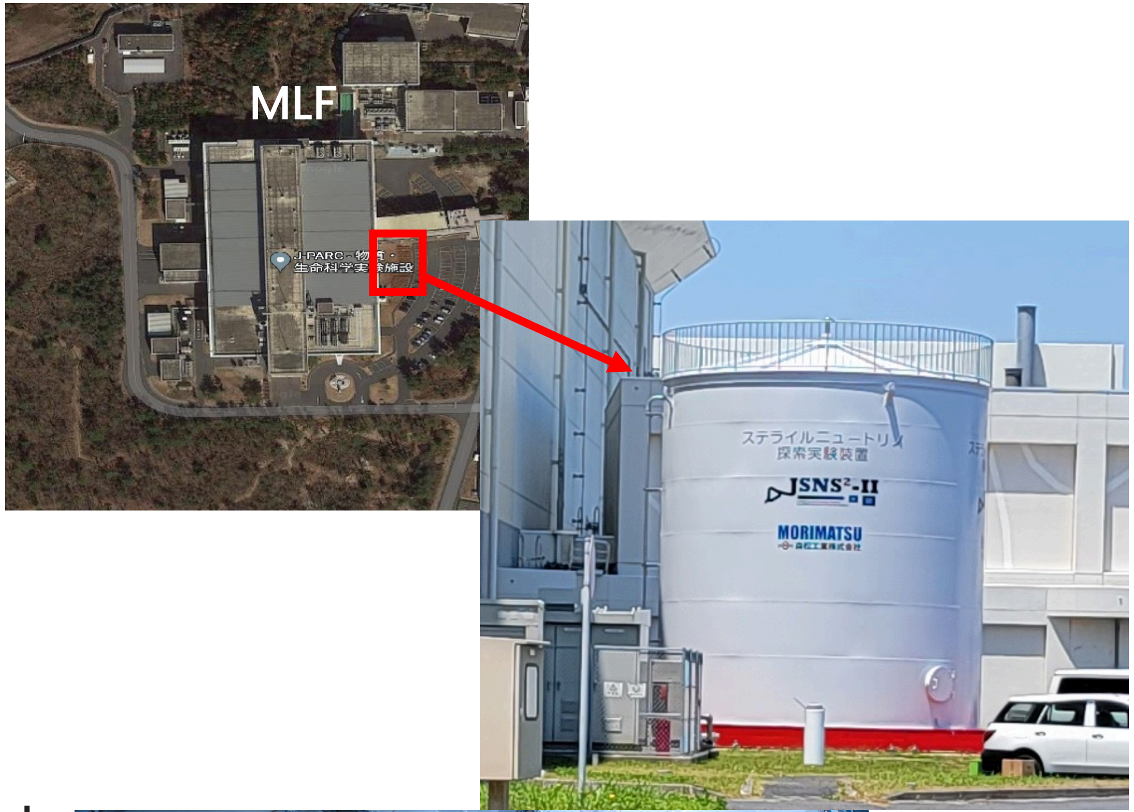
- KDAR peak is clearly seen.
- High purity (95%) KDAR signal. (Background: 5.2 %)
- Note that the systematics on the energy scale are not included yet.

BKG ID	Correlated/ Accidental	BKG (# of events)	
1	Correlated	36.6 +- 34.8	5.0 +- 4.7%
2	Accidental	1.5 +- 0.1	0.2 +- 0.01%
KDAR Candidates : 730 events		38.1 +- 36.8	5.2 +- 4.8%



JSNS^2–II
(arXiv:2012.10807)

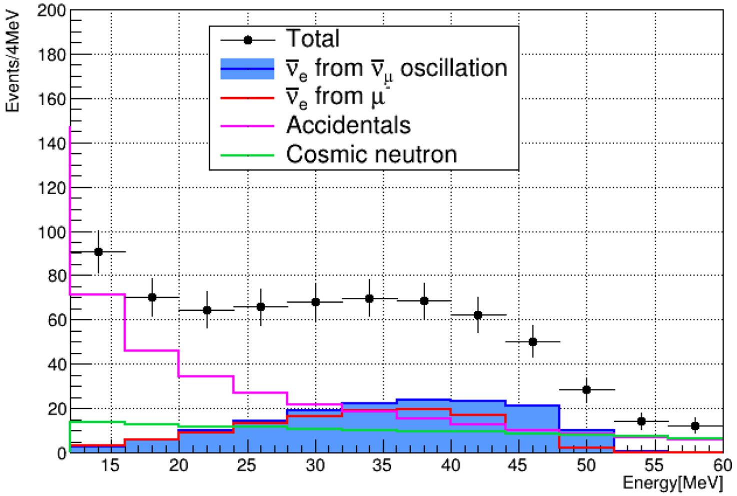
- Second phase of the JSNS^2 experiment with two detectors.
  → near (17 tons, 120 10-inch PMTs, 24 m) detector
  → far (32 tons, 228 10-inch PMTs, 48 m) detector
- Improve the sensitivity especially in the low Δm^2 region.
- J-PARC/KEK grants the stage 2 (2/2) approval.
- The stainless steel tank has been constructed.
- 142 PMTs were installed so far.
  (190 PMTs were donated by Double-Chooz, and they arrived in 2022)
- Acrylic vessel was made in Taiwan and shipped to Japan.
  (now in J-PARC)
- GdLS and LS were donated by Daya-Bay in 2021.
  (now in Japan)
- HV/splitters arrived at J-PARC in this May.



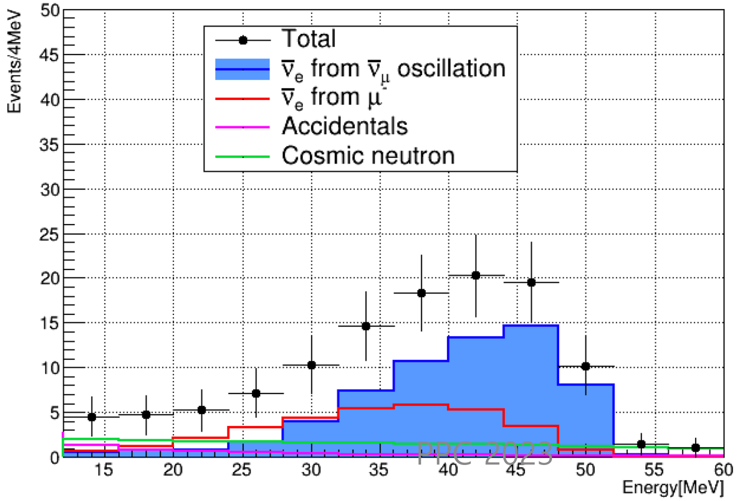
Sensitivity of JSNS^2-II

- Energy spectra (MC) are used for the fit to get the sensitivities.
- Fit methodology : We use likelihood instead of chi square for the low stat.
- 3 sigma further cover than LSND

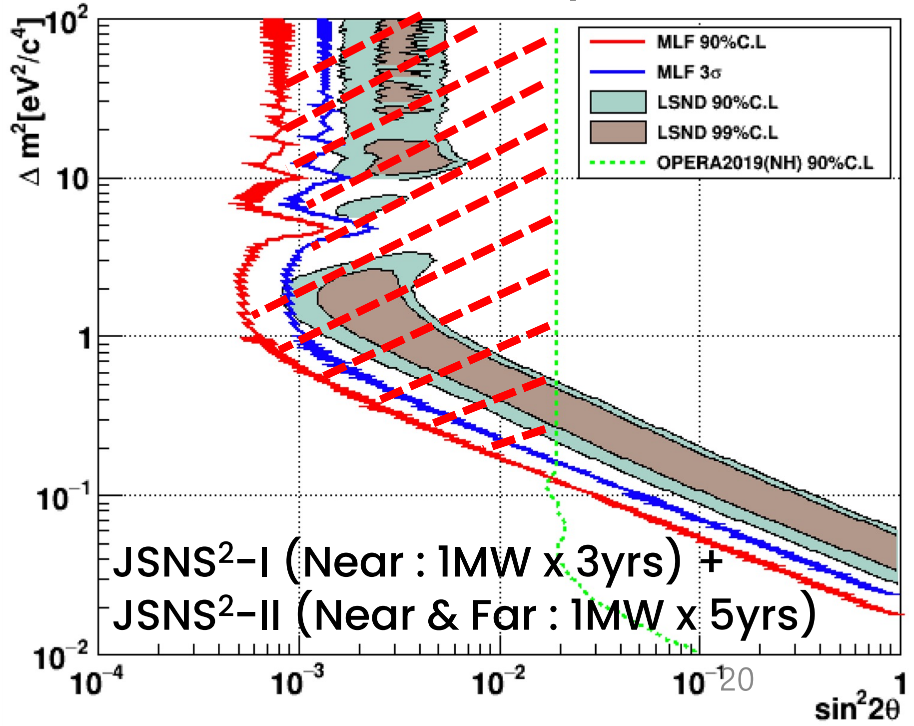
LSND best fit at near detector



LSND best fit at far detector



Sensitivity



JSNS^2-II : Schedule

	2021				2022				2023				2024			
	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12
s.s. tank			bid	construction												
Acrylic vessel						bid	construction		Transp.							
PMTs				Delivery/pre-calib					Installation							
		DC dismantle/shipping														
(Gd)LS	Donation					Storage/keep										
Electronics									Delivery							
Filling																
Data taking																

Summary

- There have been 1st (2021), 2nd (2022), 3rd (2023) physics run.

- JSNS^2 is working toward the first precise KDAR measurement.
  → We saw the clear KDAR signal

- Analysis are on-going with the data.
  → Has been developing two separate PSD tools.
  → ~95% of the fast neutron rejection by the both PSD tools.
  → Observed accidental single rate of IBD candidates.
    ▶ Prompt : $(2.20 \pm 0.09) \times 10^{-4}$ /spill
    ▶ Delayed : $(1.80 \pm 0.01) \times 10^{-2}$ /spill
  → Tagged cosmic muons using the veto PMTs.
    ▶ Stopping muon : ~1.5kHz
    ▶ Through-going muon : ~0.6kHz
  → Sterile neutrino search is on-going.

- JSNS^2-II was granted based on the JSNS^2 data.
  → Expects to start data taking at around the end of 2023.