Status of the JSNS^2 and JSNS^2-II

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On behalf of the JSNS^2 / JSNS^2-II collaboration

NPN 2024, June 3 - 5, 2024

JSNS^2 / JSNS^2-II Collaboration

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

Collaboration meeting @ J-PARC (2024/Feb)

JSNS^2 collaboration (61 collaborators)
- 7 Japanese institutions (27 members)
- 10 Korean institutions (25 members)
- 4 US institutions (5 members)
- 1 UK institution (1 member)
- 1 China Institution (3 members)

JAEA
KEK
Kitasato
Kyoto
Osaka
Tohoku
Tsukuba

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

BNL
Florida
Michigan
Utah

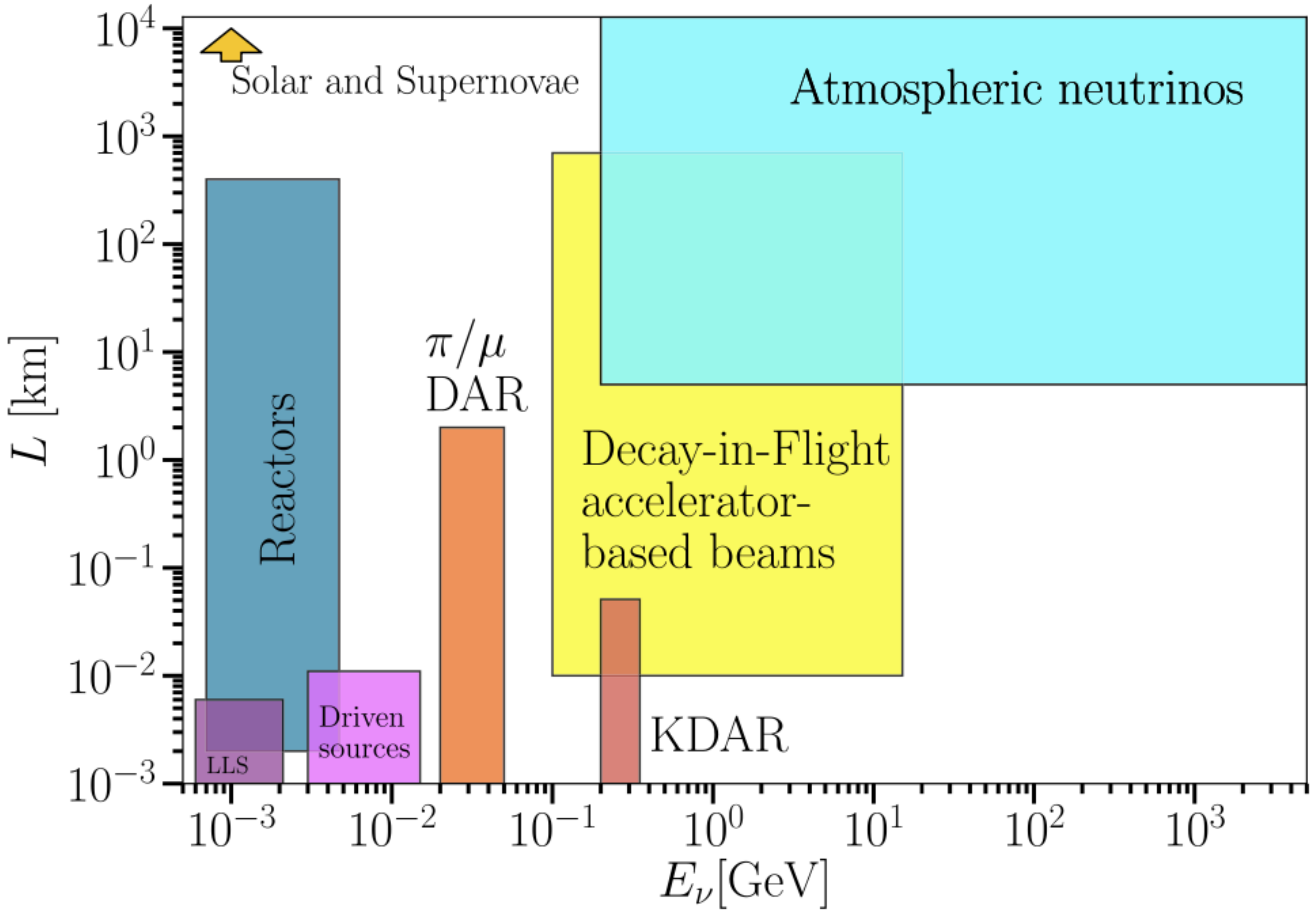
Sussex

Sun Yat-sen

Next-generation neutrino experiments and their capabilities

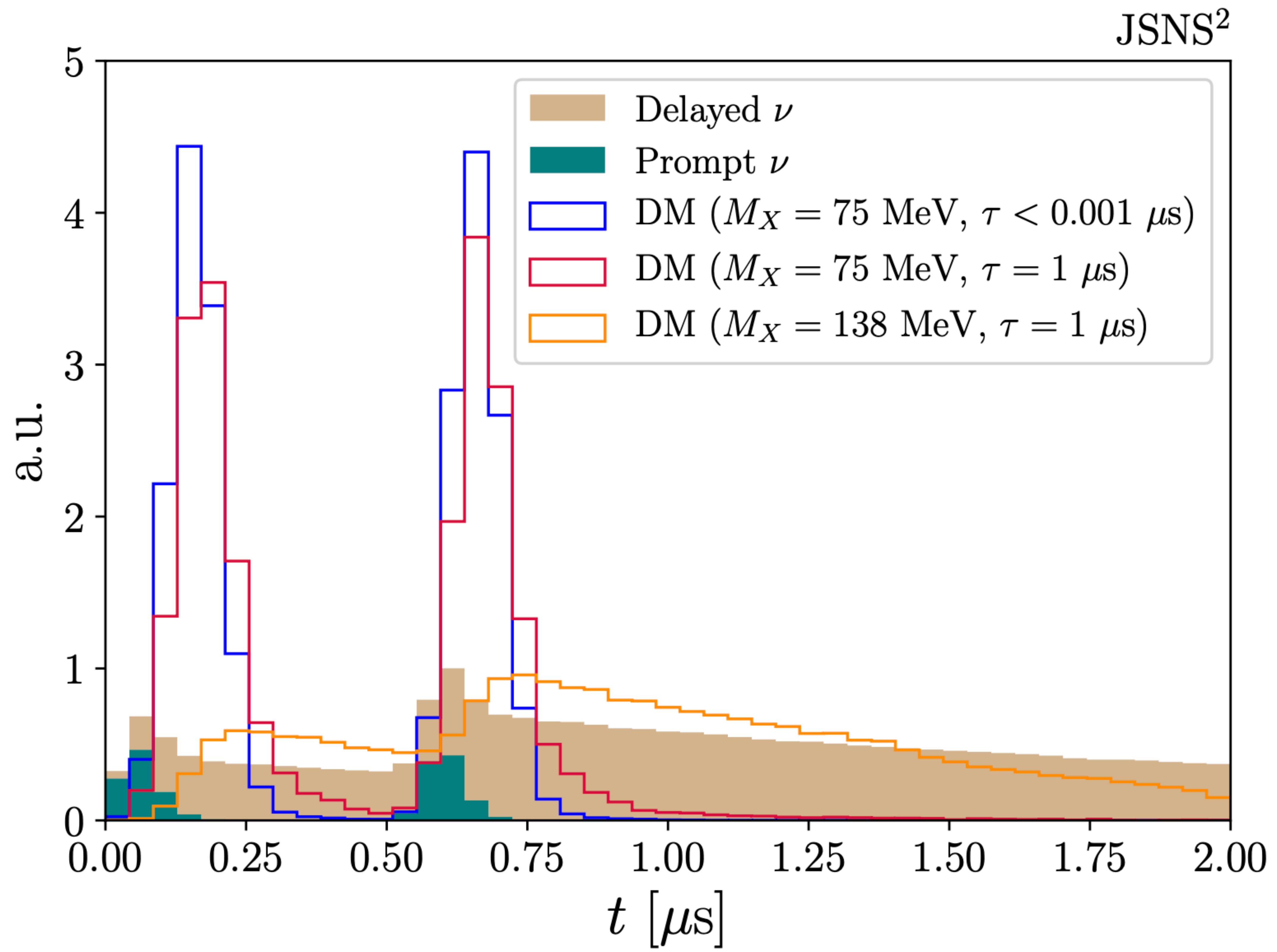
(Rep. Prog. Phys. 83, 124201)

- **Sterile neutrinos** using the accelerator sources
  - **Pion decay at rest in beam dumps**
  - Muon-type neutrinos in the range of a few tens of MeV
  - Studies and realizations of **muon decay-at-rest** and **kaon decay-at-rest** beams are under serious investigation
  - **Anti-electron neutrino appearance search**
  - Additionally, light dark matter (LDM) search can be carried out at JSNS[2] (JHEP 01 (2022) 144)

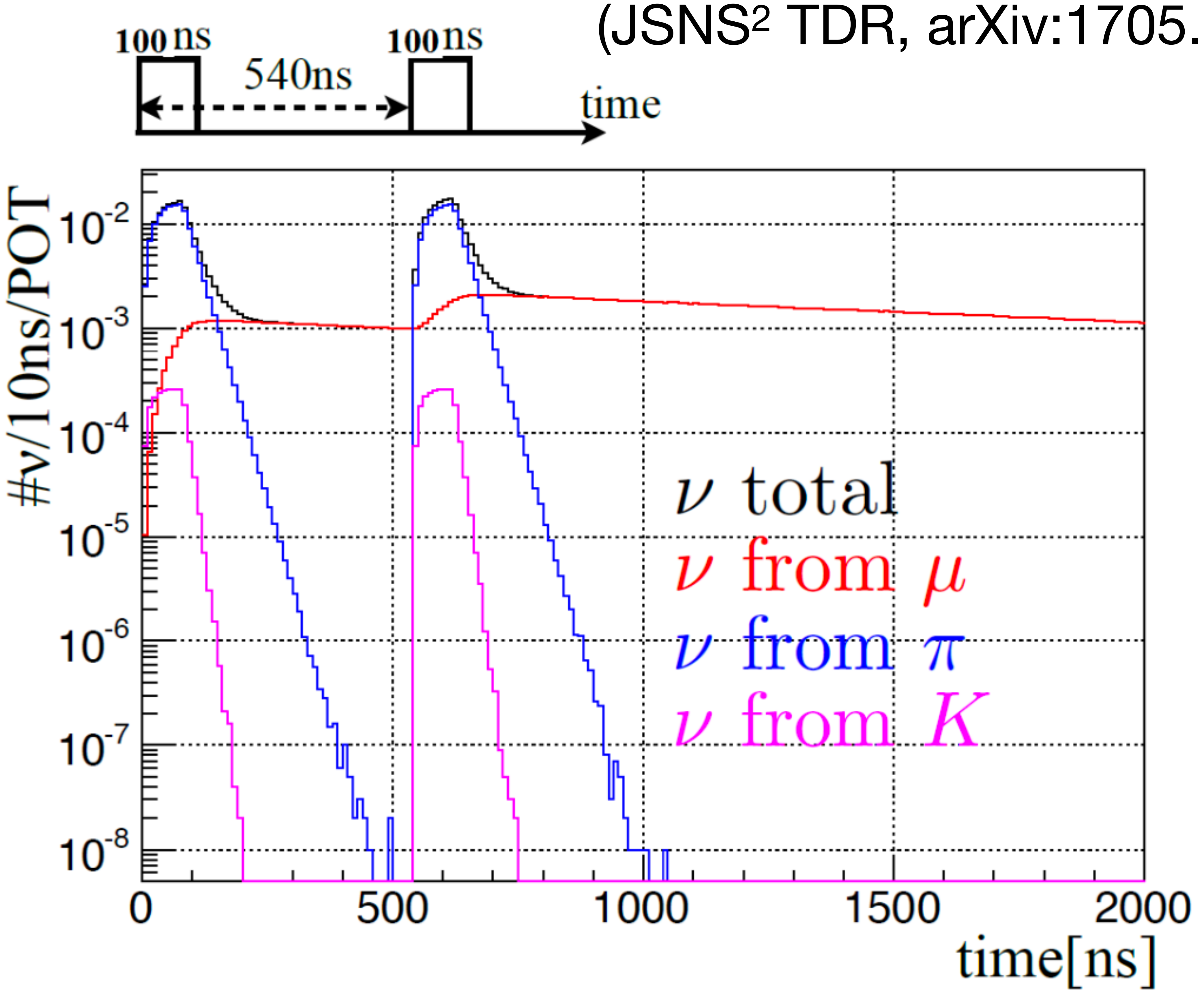


Light dark matter search

(JHEP 01 (2022) 144)



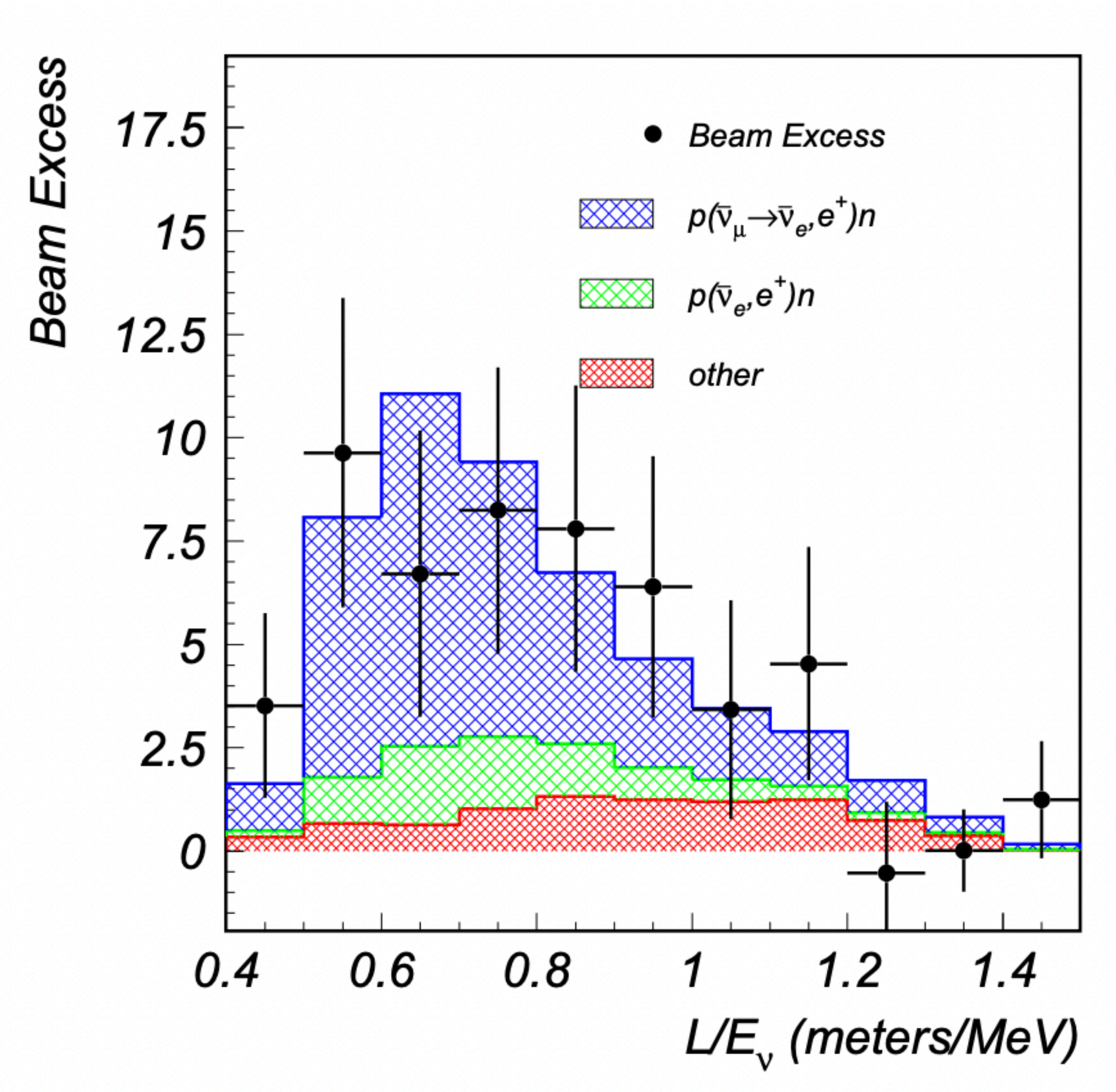
Time distribution of neutrinos
(JSNS² TDR, arXiv:1705.08629)



- A proper timing (and energy) selection may allow relatively pure neutrinos or dark matter data set.

LSND overview

(Nucl. Instrum. Meth. A 388 (1997) 149-172 and arXiv:1204.5379)



- 800 MeV proton beam and 30 m baseline
- Neutrinos from muon decay-at-rest
- $\bar{\nu}_e$ appearance signals were detected vis Inverse Beta Decay

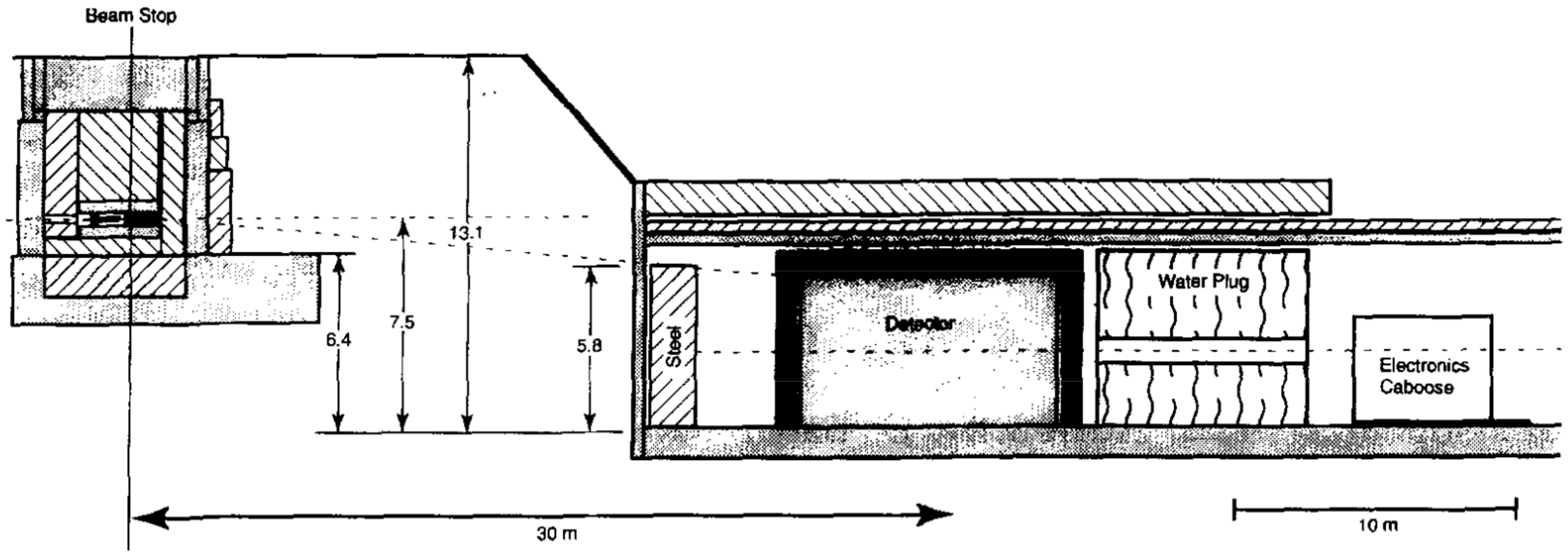


Fig. 1. Detector enclosure and target area configuration, elevation view.

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

Experiments (Neutrino source, signal, significance, energy, baseline)

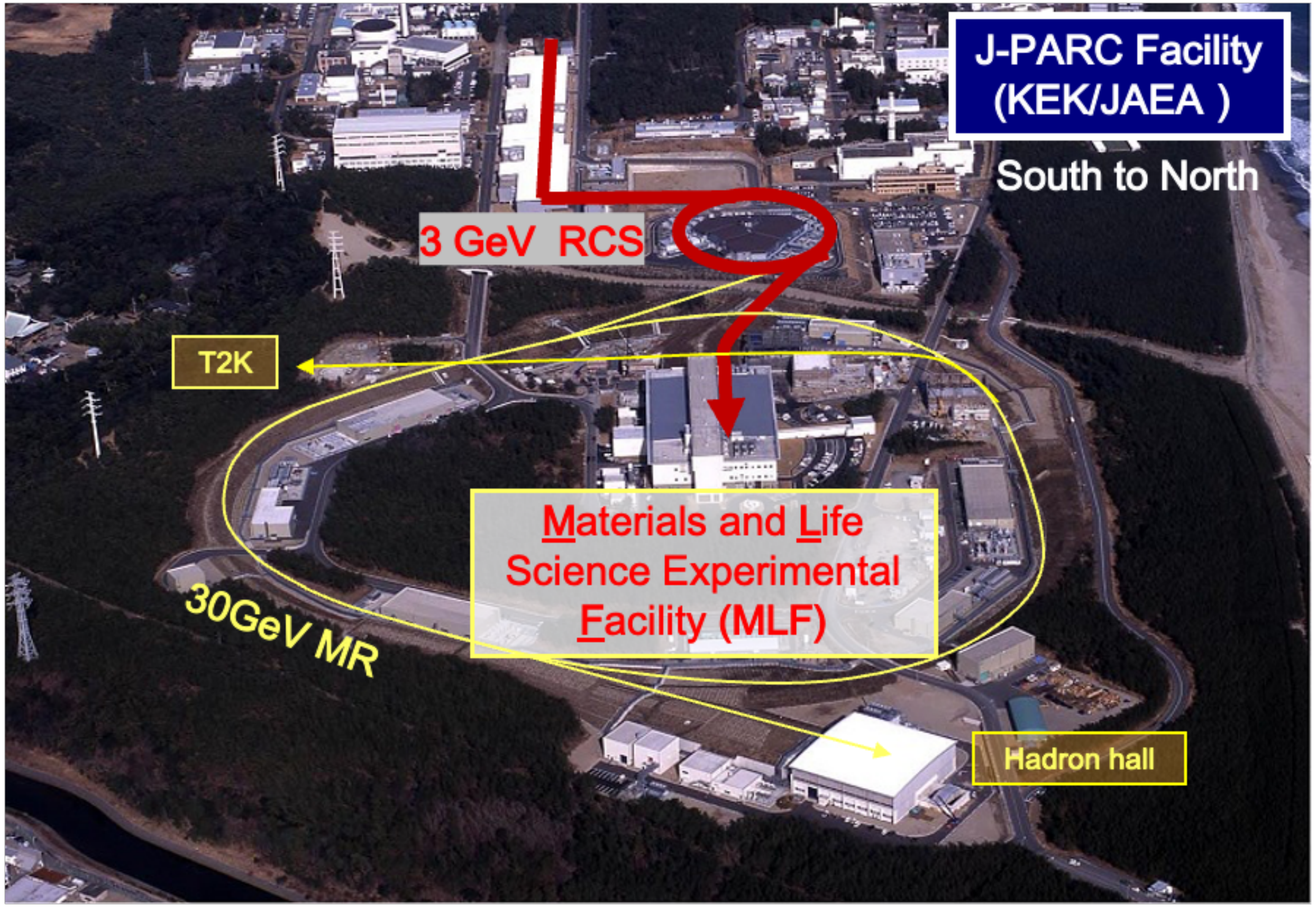
- **LSND** (μ Decay-At-Rest, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, 3.8 σ, 40 MeV, 30 m, LINAC (600 us), 120 Hz)
- **MiniBooNE** (π Decay-In-Flight, $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, 4.8 σ (combined), 800 MeV, 600 m)
- **BEST** (e capture, $\nu_e \rightarrow \nu_x$, ~4 σ, < 3 MeV, 10 m)
- **Reactors** (Beta decay, $\bar{\nu}_e \rightarrow \bar{\nu}_x$, significance varies, 1-8 MeV, 10 - 100 m)

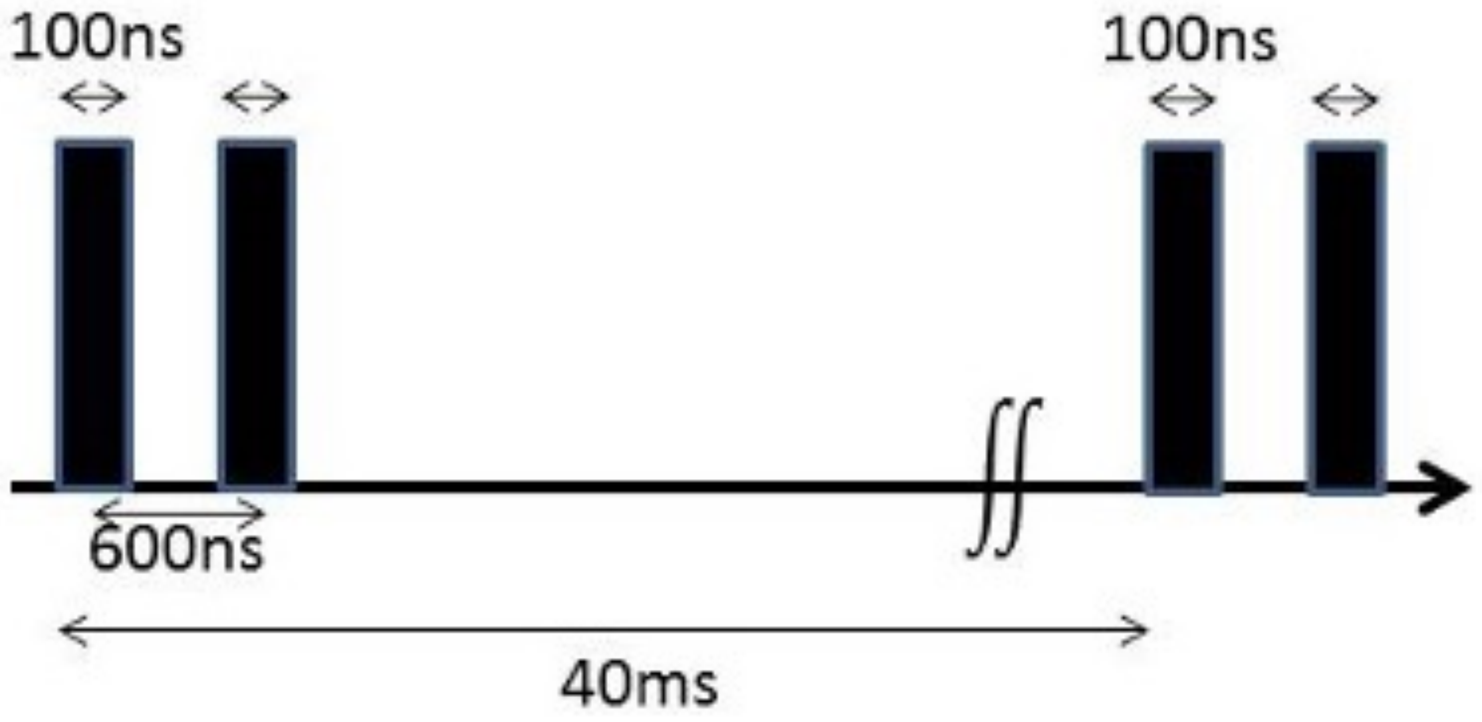
JSNS^2 uses the **same** neutrino source (μ), target (H), and detection principle (IBD) **as the LSND**

- Even if the excess is not due to the oscillation, JSNS^2 can catch this directly.

Two advantages: **short-pulsed beam (100 ns $\times$ 2, 25 Hz)** and **gadolinium(Gd)-loaded liquid scintillator**

J-PARC Facility





Low duty factor beam
(short-pulses + low repetition rate)
Gives an excellent signal to noise ratio

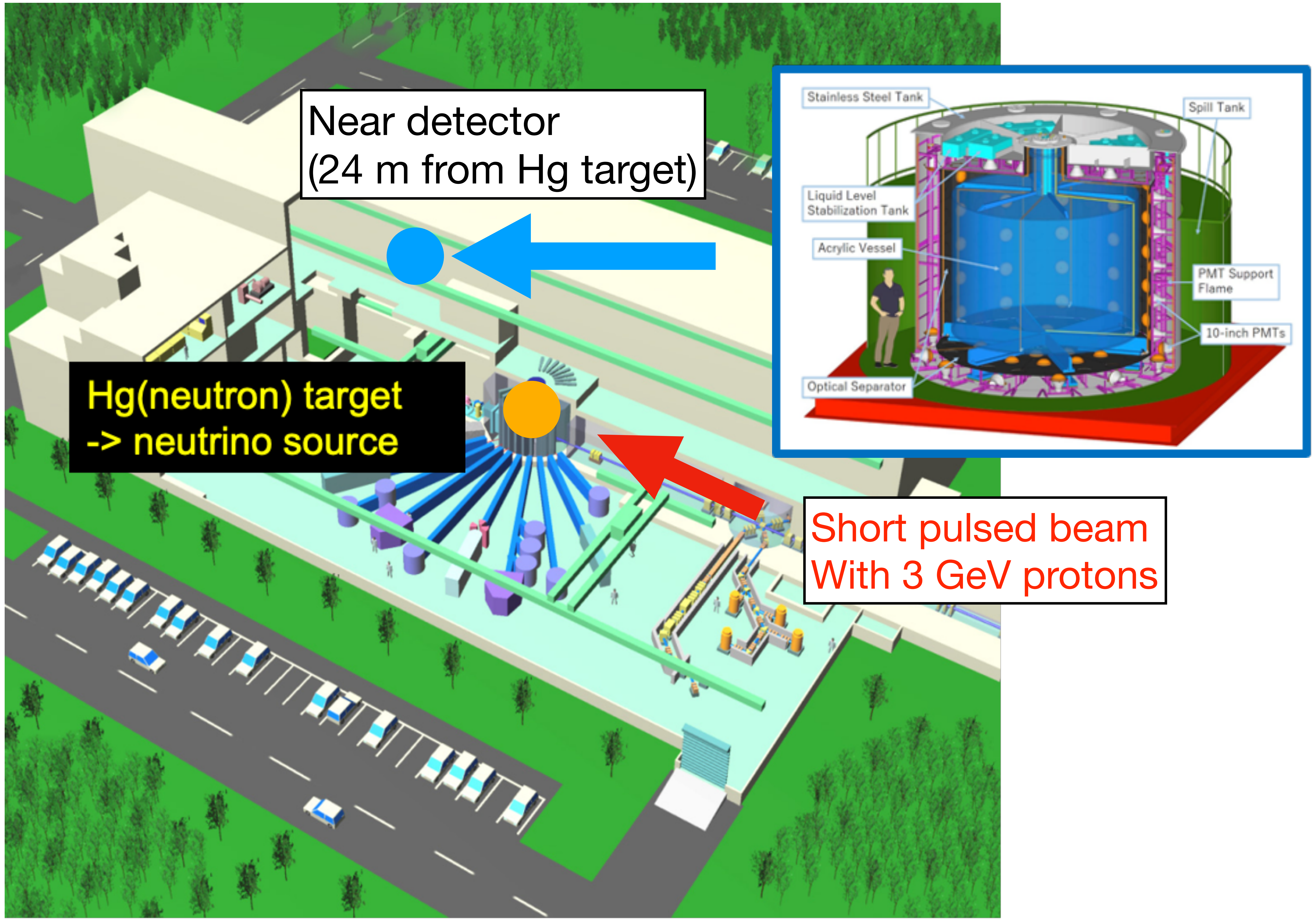
1 MW (design)

- 0.6-0.7 MW (2021)
- 0.7-0.8 MW (2022)
- 0.84 MW (2023) / 0.65 MW (2023 Dec)
- 0.88-0.95 MW (2024)

Beam power at RCS: 1 MW (2024)

- A part of the beam is passed to the main ring (for T2K or Hadron)

JSNS^2 detector
(Nucl. Instrum. Methods A 1014 (2021) 165742)



17 tons target, Gd-LS + 10% DIN
31 tons gamma-catcher and veto, LS
120, 10-inch PMTs

Commissioning (2020)

- Calibration
- Beam data with 25 us window
- Eur. Phys. J. C (2022) 82:331

Physics run (2021 - present)

- Eur. Phys. J. C (2024) 84:409
- More papers are under review and available on the arXiv also.

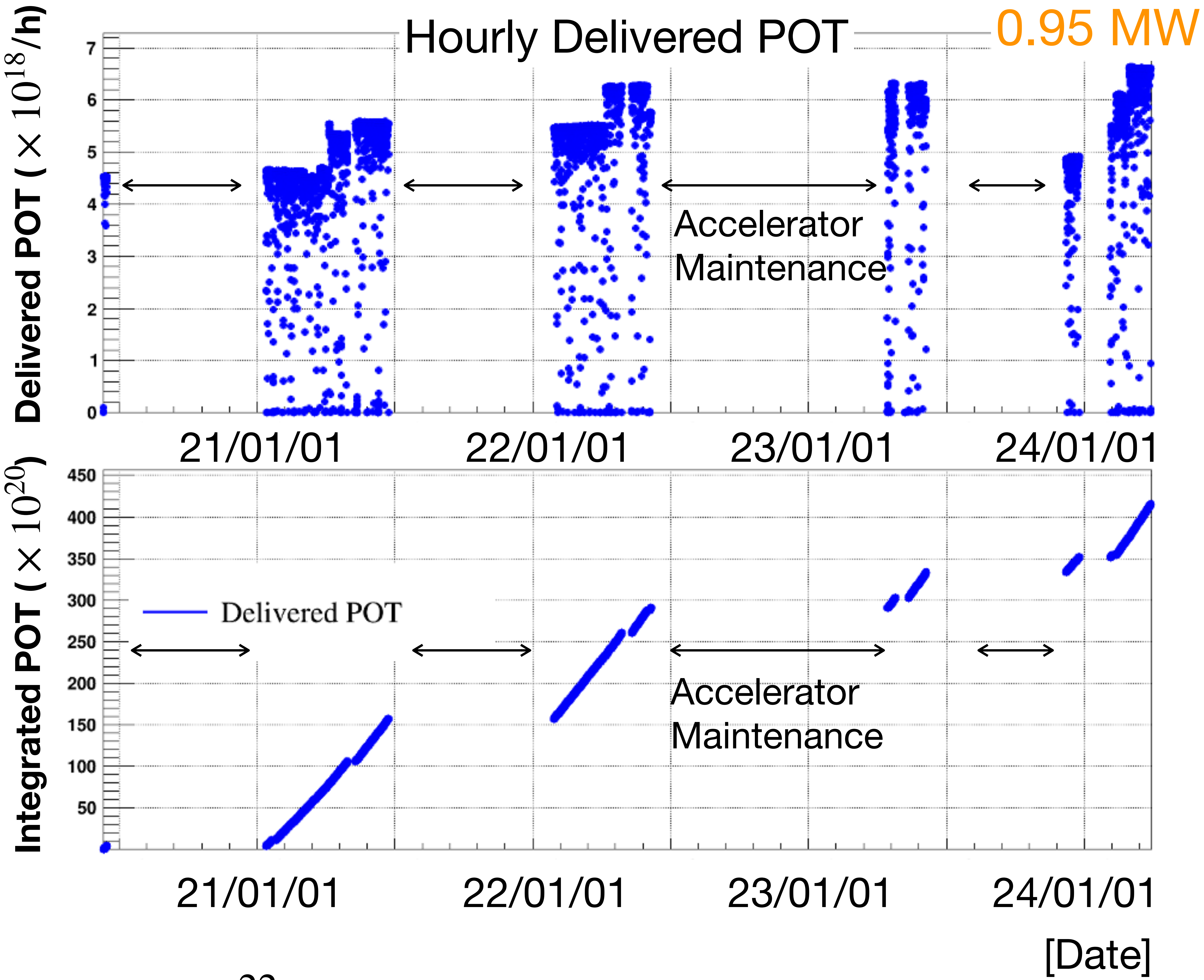
Operation

1st physics run
- 0.6 MW (2021/Jan - Apr/5)
- 0.7 MW (2021/Apr/5 - June/22)

2nd physics run
- 0.7 MW (2022/Jan/28 - Apr/6)
- 0.8 MW (2022/Apr/7 - Jun/6)

3rd physics run
- 0.84 MW (2023/Apr/15 - Jun/2)

4th physics run
- 0.65 MW (2023/Dec/7 - Dec/25)
- 0.88 MW (2024/Feb/6 - Apr/8)
- 0.95 MW (2024/Apr/8 -)



4.09×10^{22} POT has been delivered by end of March
(35.9 % of the approved POT of JSNS²)

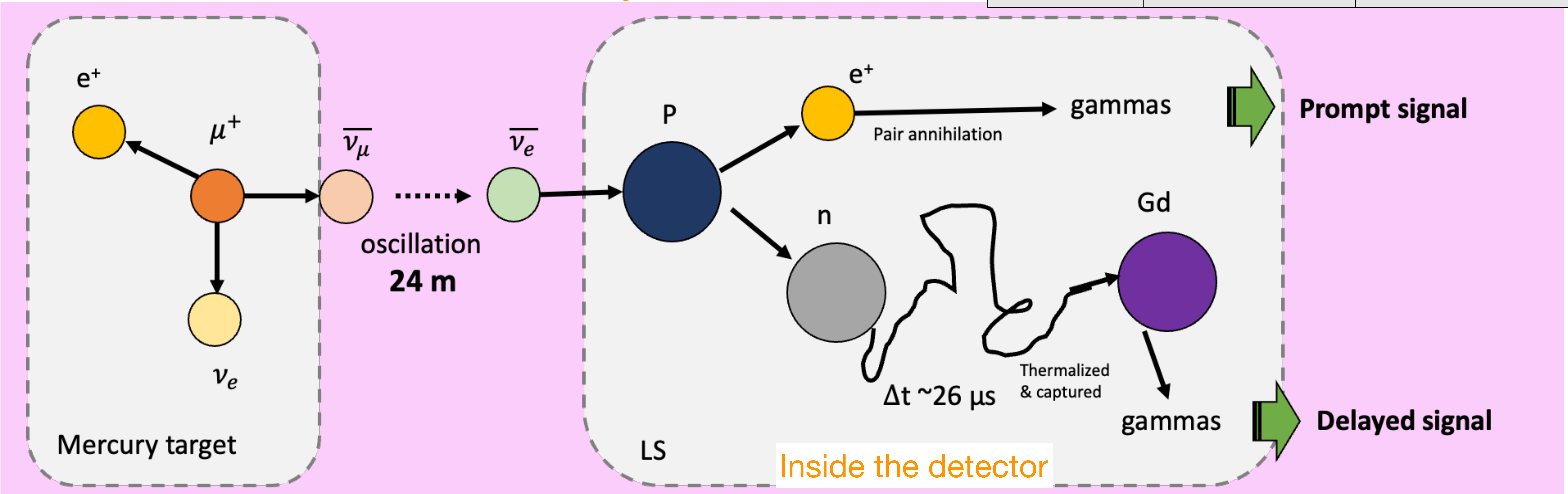
Production and detection

If sterile neutrinos exist, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation occurs with 24m

	Timing	Energy
prompt	$1.5 \leq T_p \leq 10\ \mu s$	$20 \leq E \leq 60$ MeV
delayed	$\Delta T_{p\text{-}d} < 100\ \mu s$	$7 \leq E \leq 12$ MeV

Coincidence of Inverse Beta Decay (IBD)

- The positron annihilation
- Gammas from neutron captured on gadolinium (Gd)

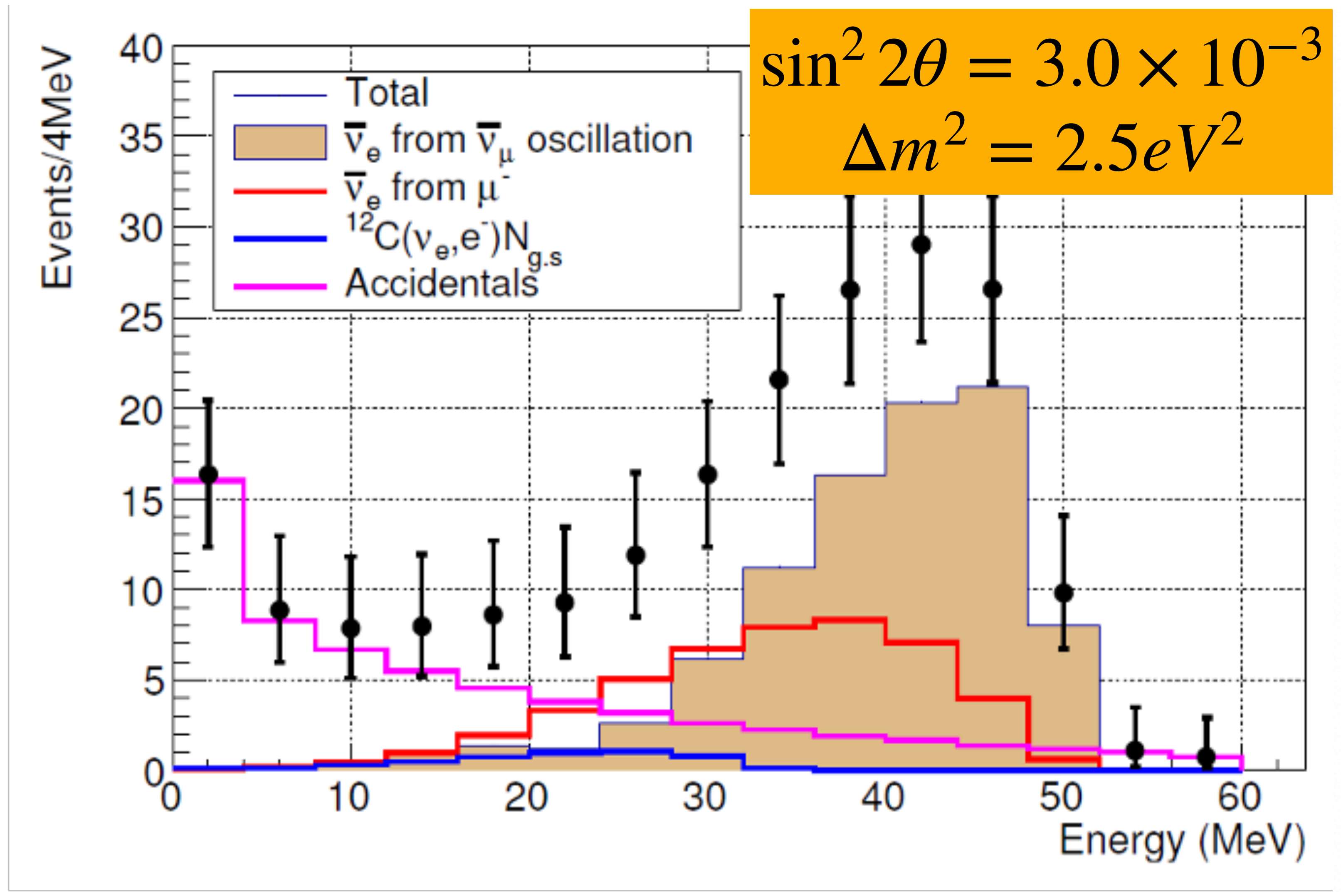


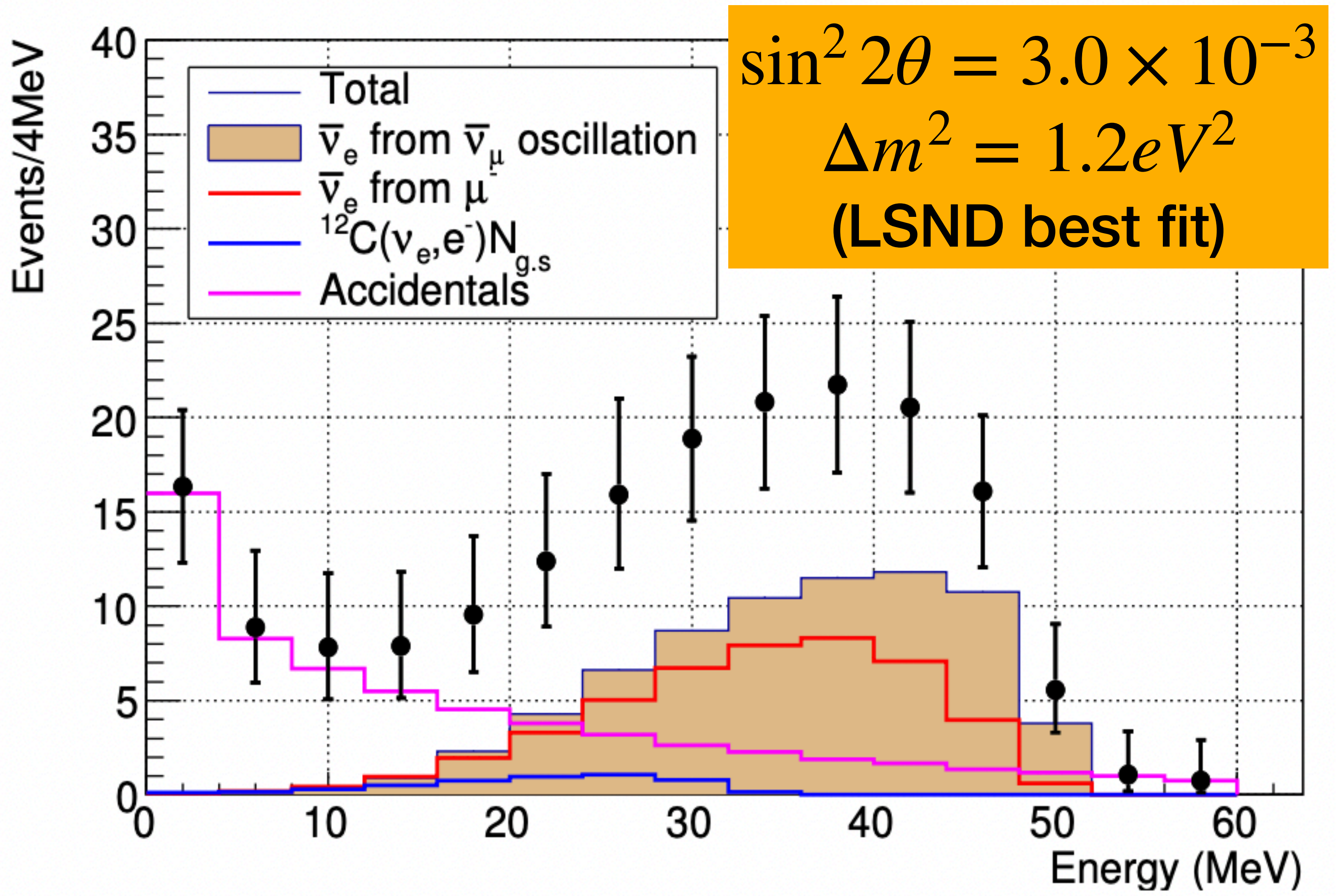
Expected energy spectrum and sensitivity

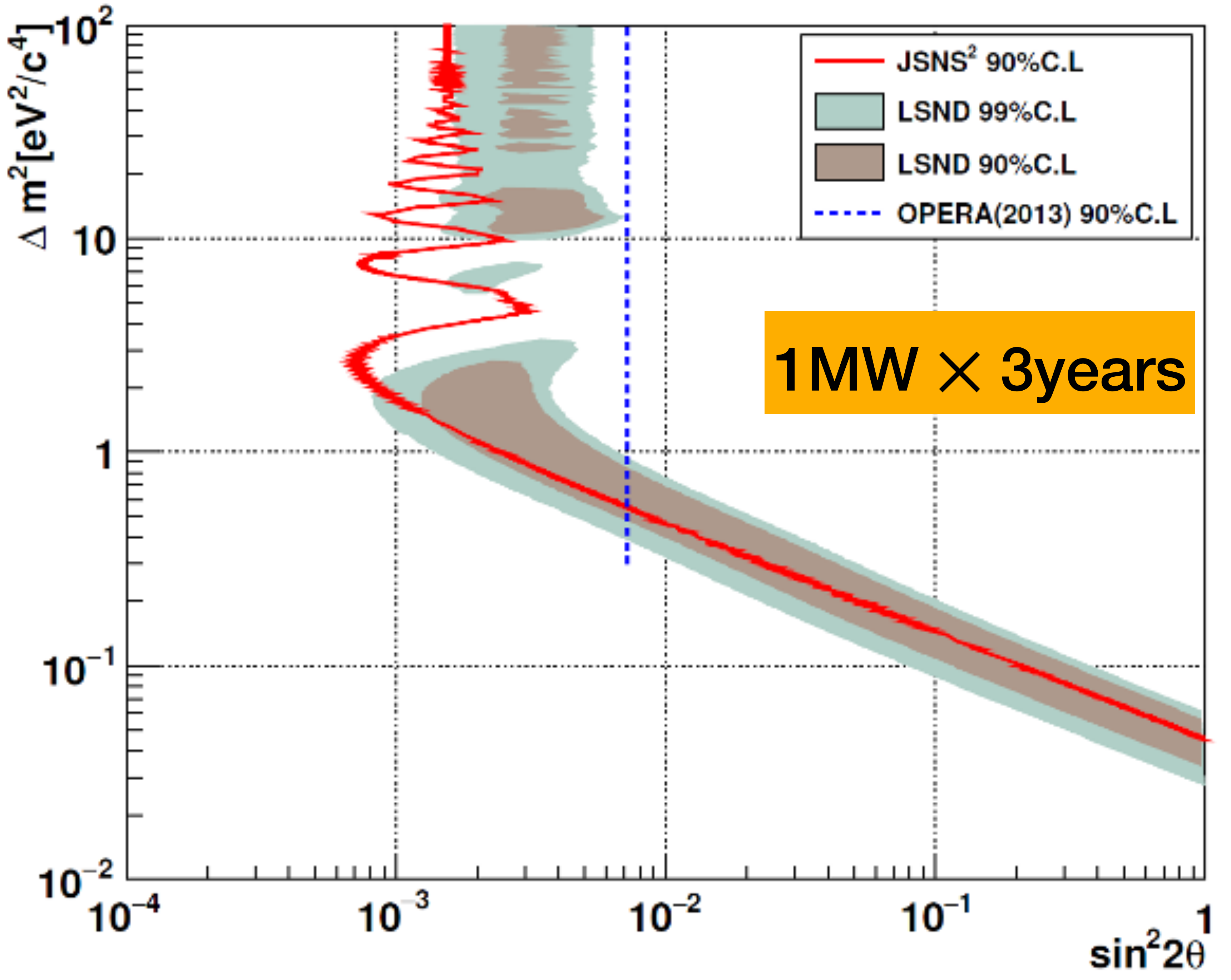
(JSNS² TDR, arXiv:1705.08629)

- $\bar{\nu}_e$ follows decay-at-rest $\bar{\nu}_\mu$ energy distribution
- Prompt single rate (background): ~3.9×10^{-4} per spill
- Delayed single rate (background): ~4.4×10^{-3} per spill
- Spectral fit is sensitive to the difference of energy spectrum

Signal	$sin^2 2\theta = 3.0 \times 10^{-3}$ $\Delta m^2 = 2.5eV^2$ (Best fit values of MLF)	87
	$sin^2 2\theta = 3.0 \times 10^{-3}$ $\Delta m^2 = 1.2eV^2$ (Best fit values of LSND)	62
background	$\bar{\nu}_e$ from μ^-	43
	$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	3
	beam-associated fast n	≤2
	Cosmic-induced fast n	negligible
	Total accidental events	20



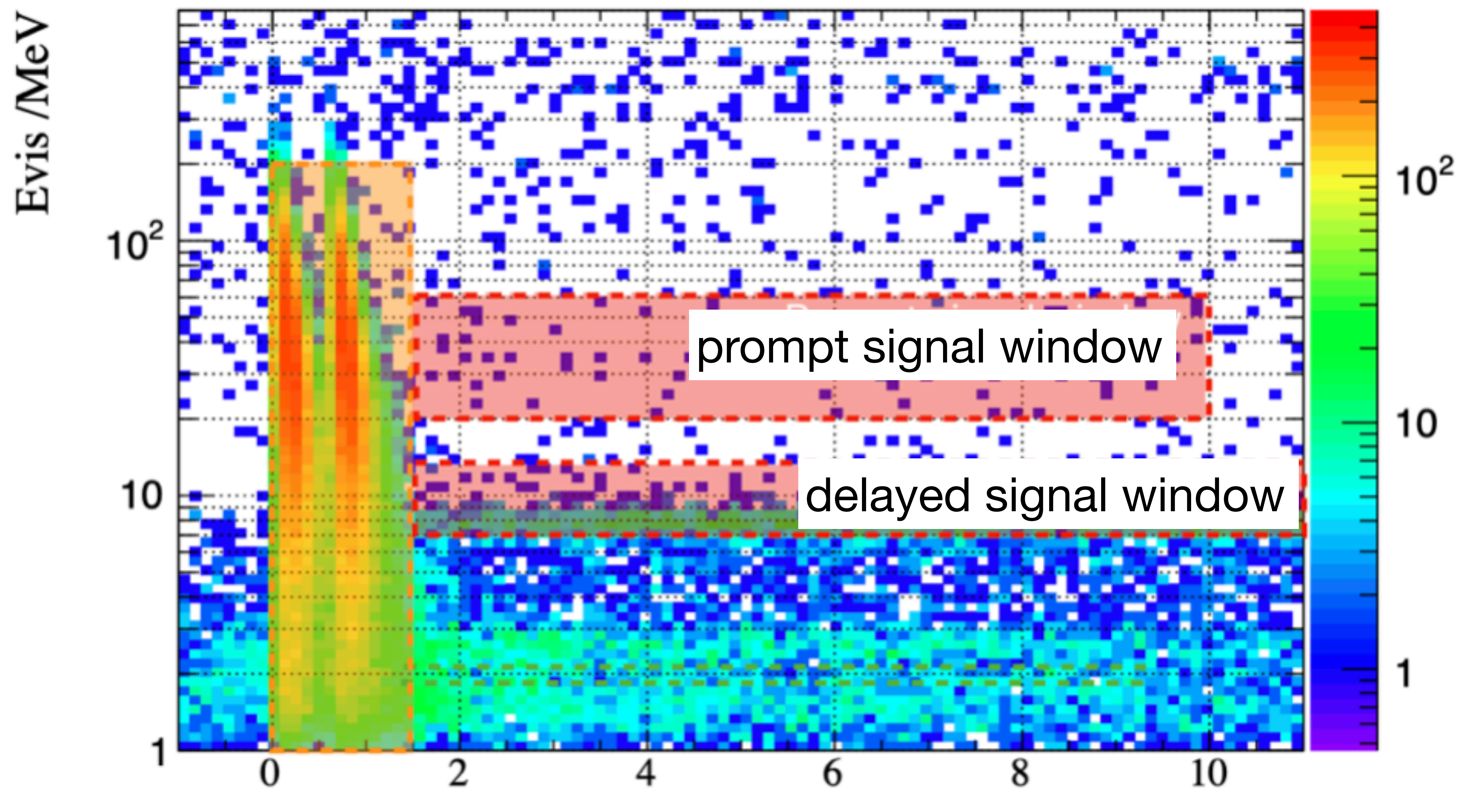


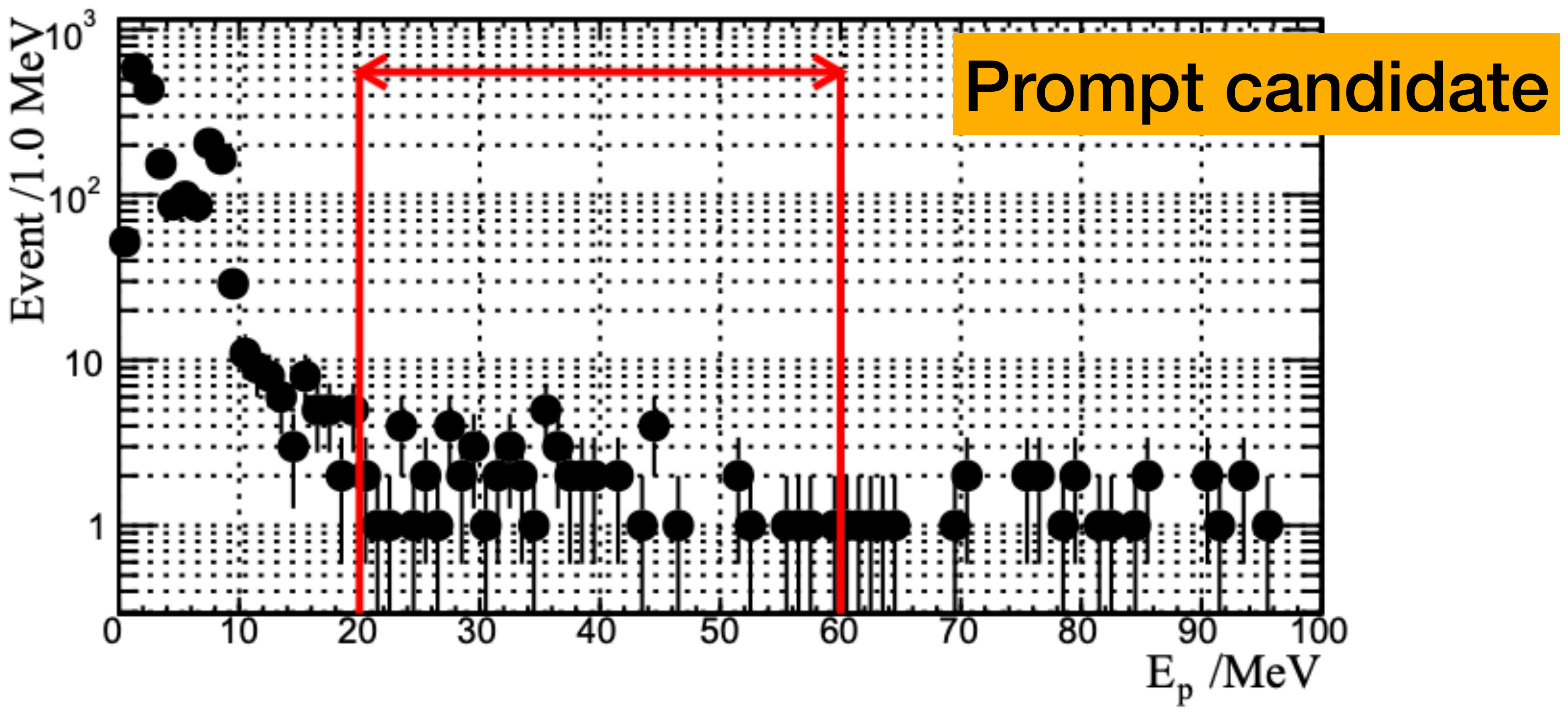


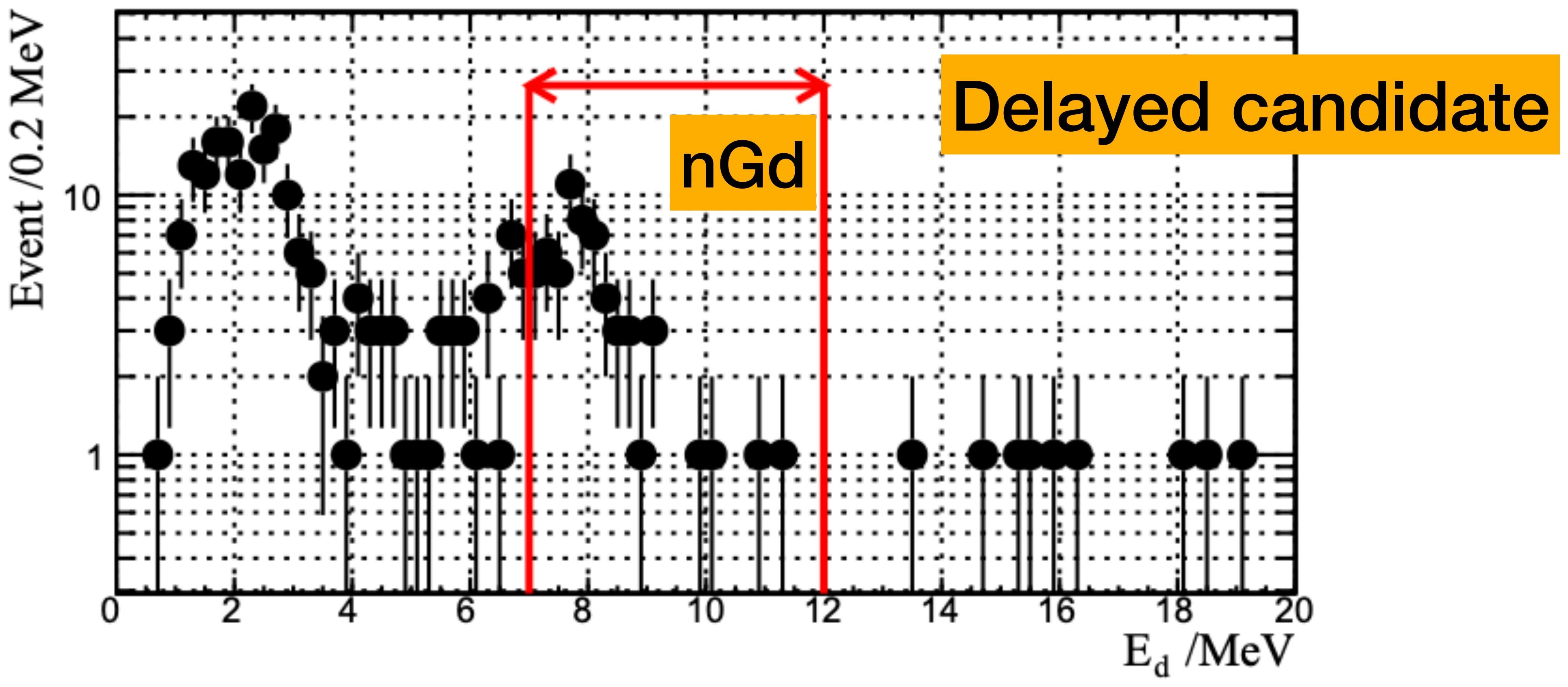
Sterile neutrino search

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

- June/5-15, 2020
- Integrated POT: 8.9×10^{20}
- Beam trigger with 25 μs width







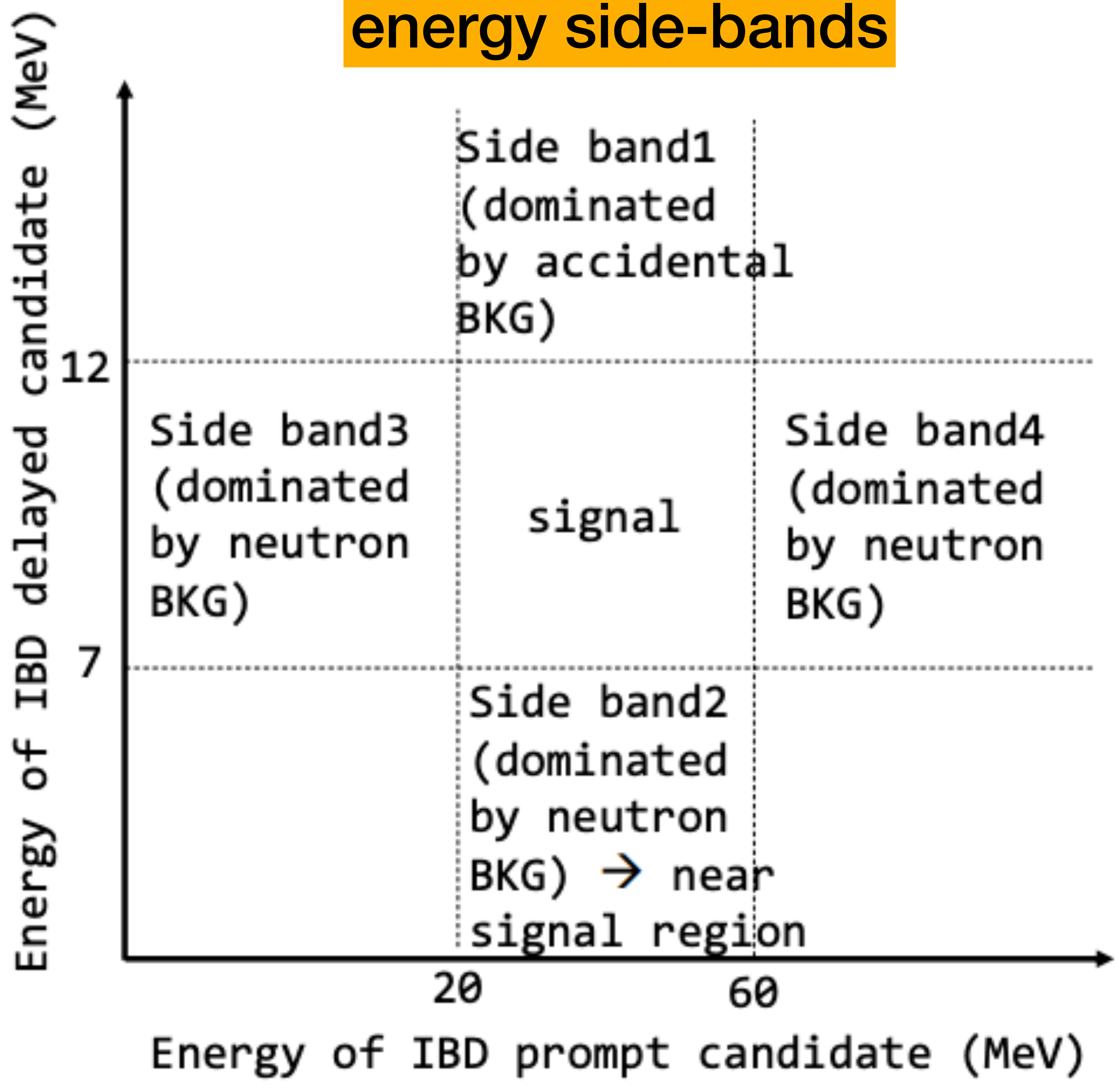
Observed correlated event candidates

- 59 ± 8 events / 8 M spills
- **Cosmic-induced fast neutrons** are the dominant background
  - **Correlated background:** 55.9 ± 4.3
  - **Pulse shape discrimination (PSD) would reject them.**
  - Two independent groups are working on it.

Toward the sterile neutrino search
(For the blind analysis)

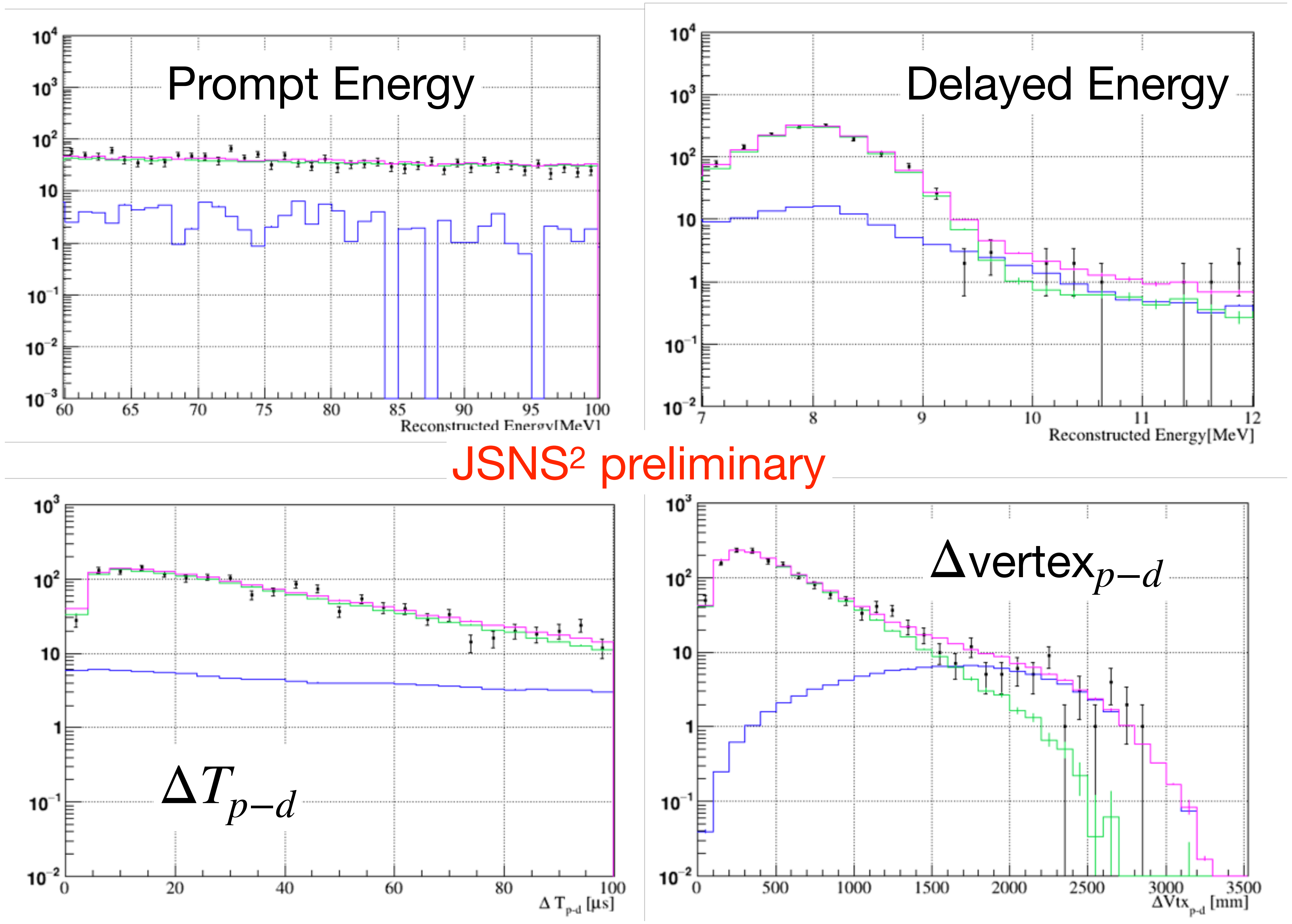
- **Energies define side-bands like a right plot.**
- All side-bands should be understood before Opening the signal region
- The rates in the side-band regions will be Predicted by the control samples driven by data
- Now, side-band 4 data are opened
  - Cosmic fast neutrons and accidentals are the main backgrounds in side-band 4

energy side-bands



The first comparison between the observation vs expectation

(Side-band 4, prompt 60-100 MeV)



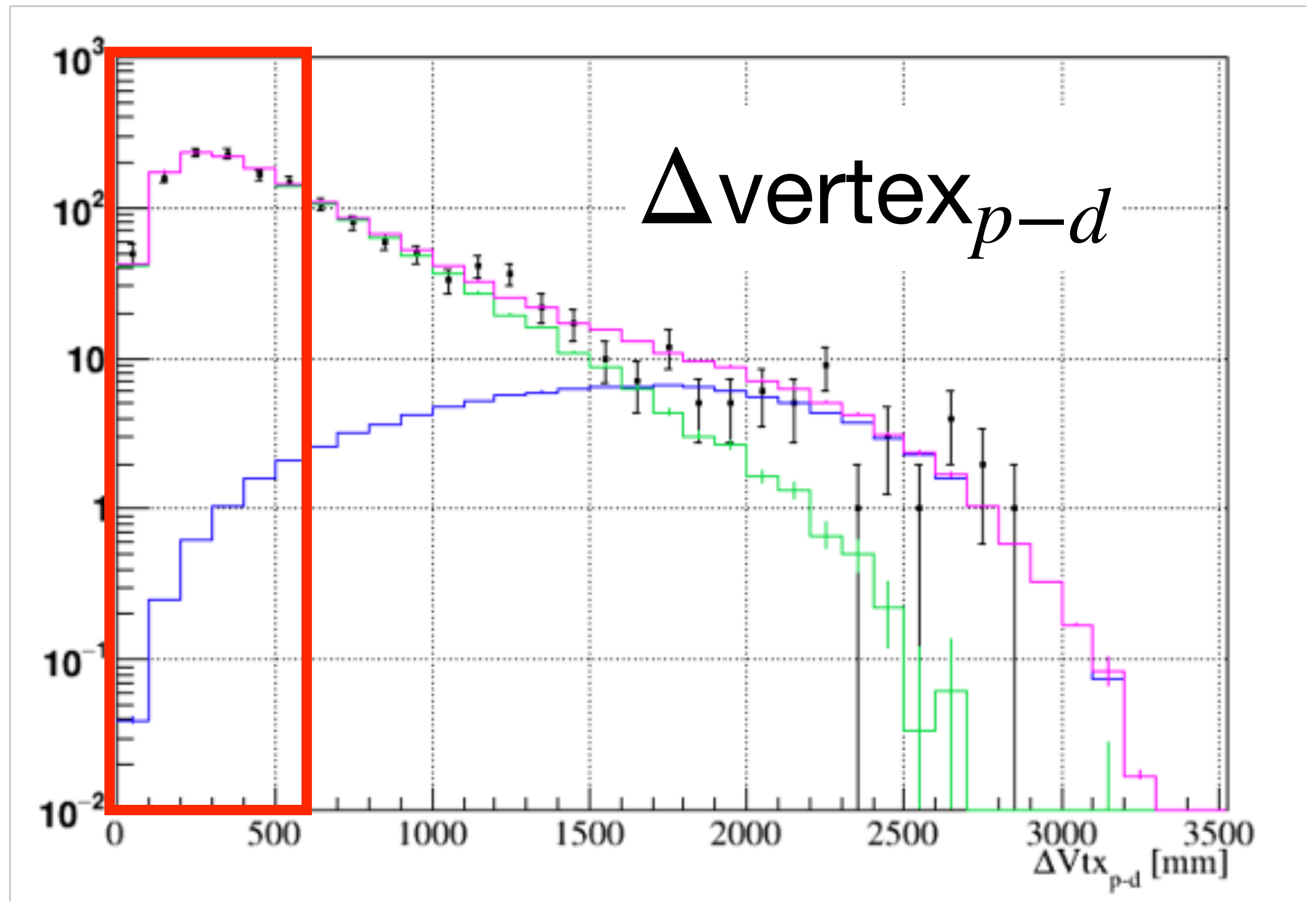
	Observed events	Expected Events
Total	1498 ± 38.7	1528.5 ± 5.9
Neutrons		1421.7 ± 5.7
Accidentals		106.8 ± 1.5

The observed events are compared with the background expectations
(Cosmic fast neutrons + Accidental)

- **They are well-agreed**
- Cosmic fast neutrons background is dominated

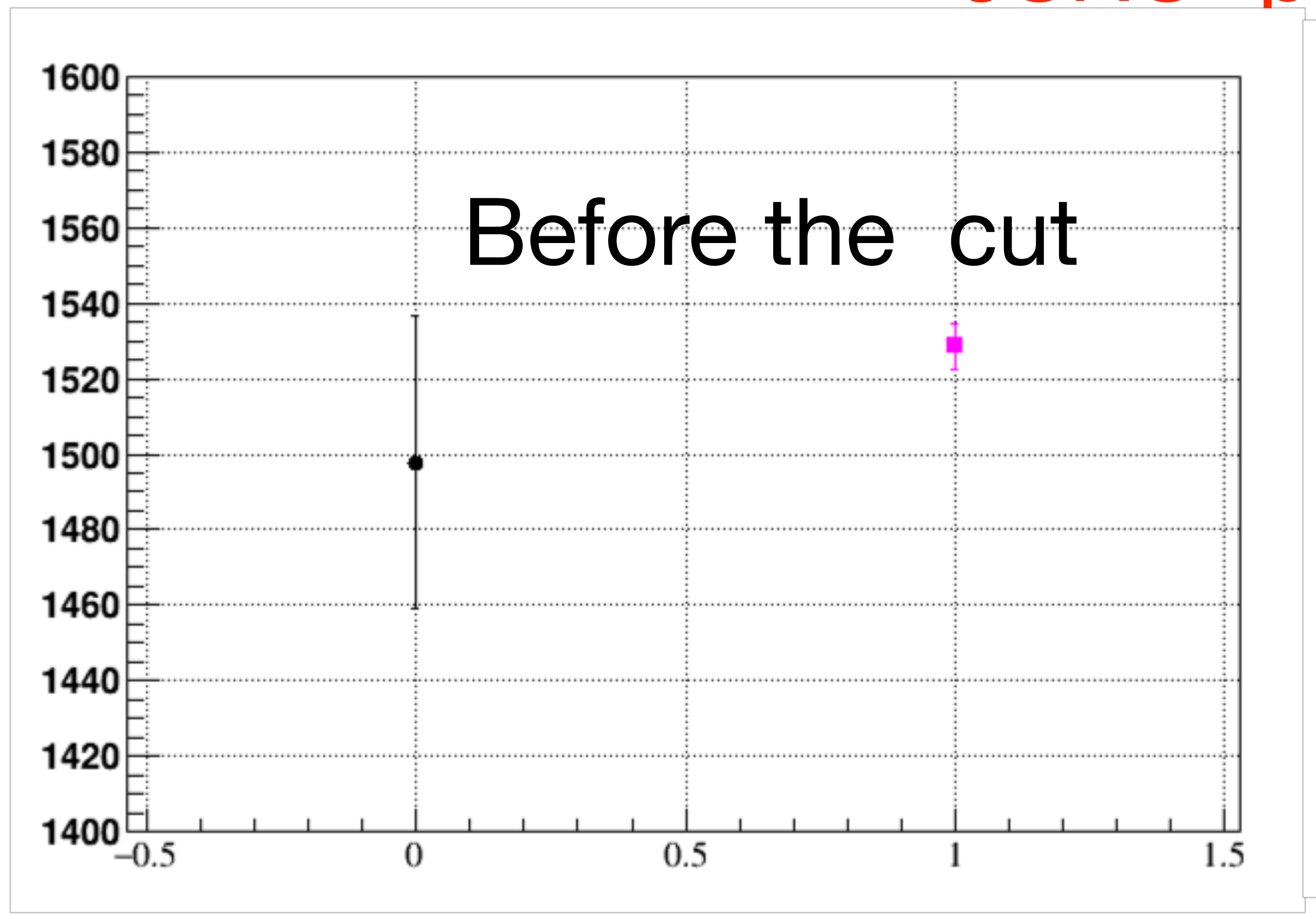
The first comparison between the observation vs expectation

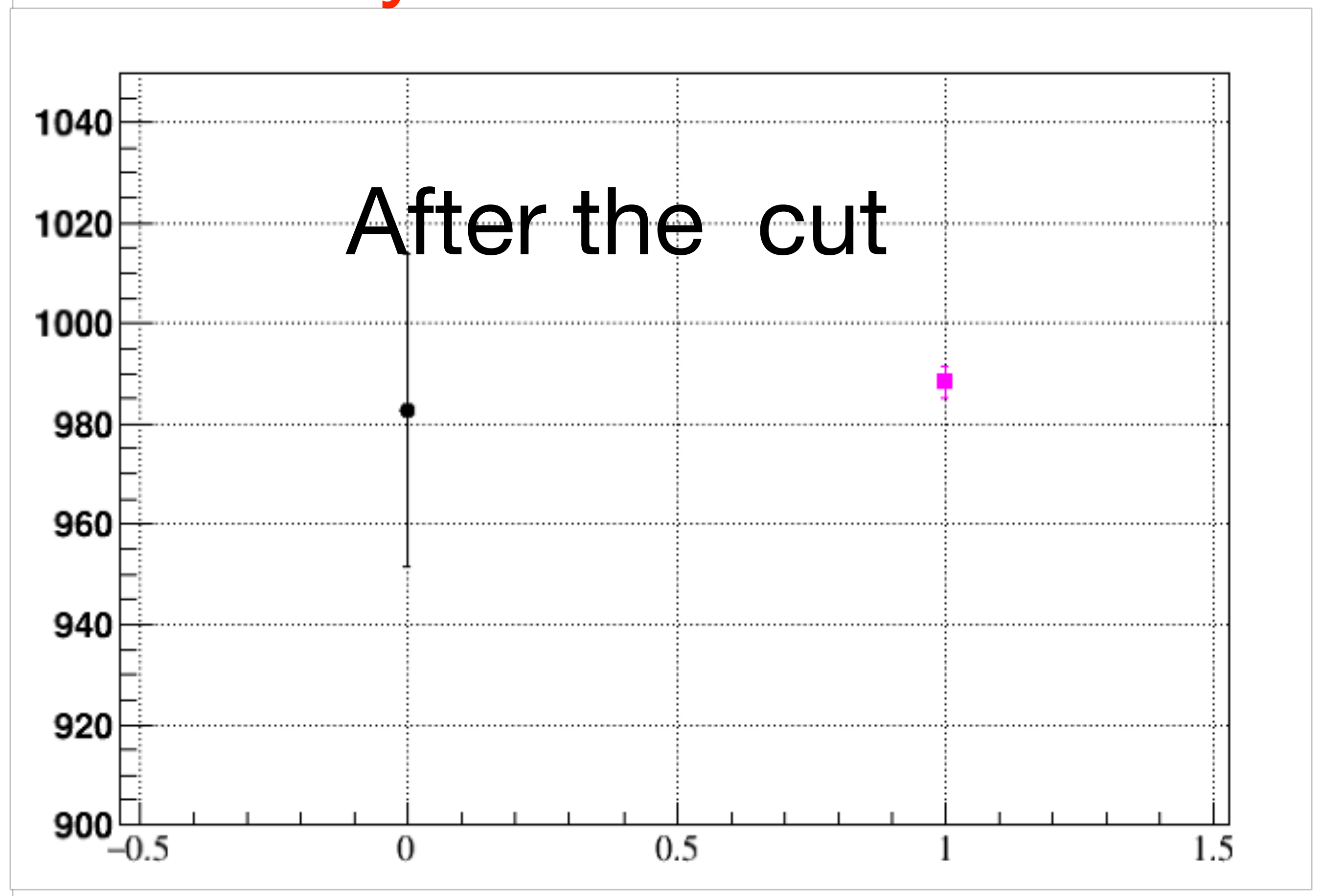
(Side-band 4, prompt 60-100 MeV)



	Observed events	Expected Events
Before the cut	1498 ± 38.7	1528.5 ± 5.9
After the cut	983 ± 31.4	988.4 ± 3.2

JSNS[2] preliminary



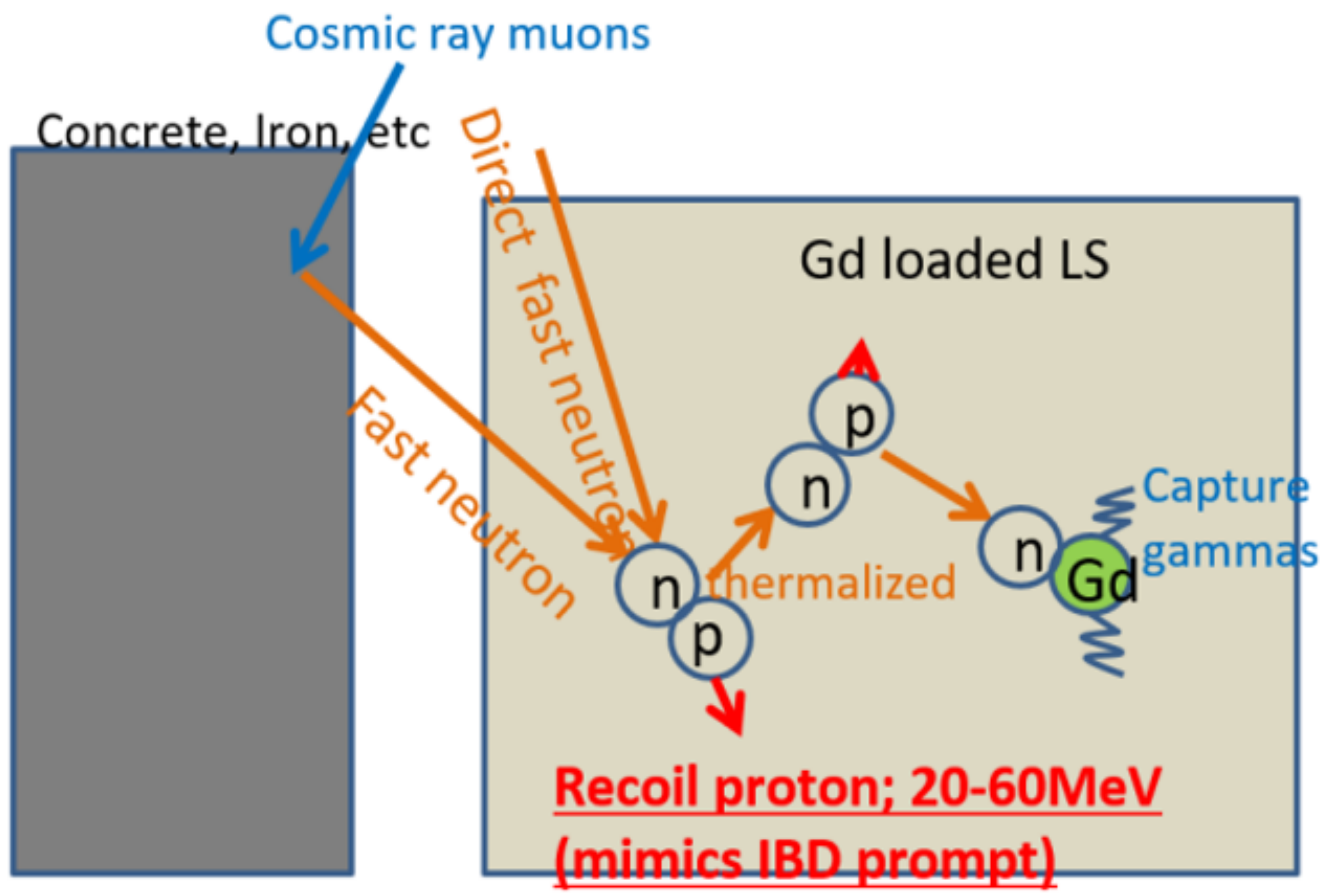


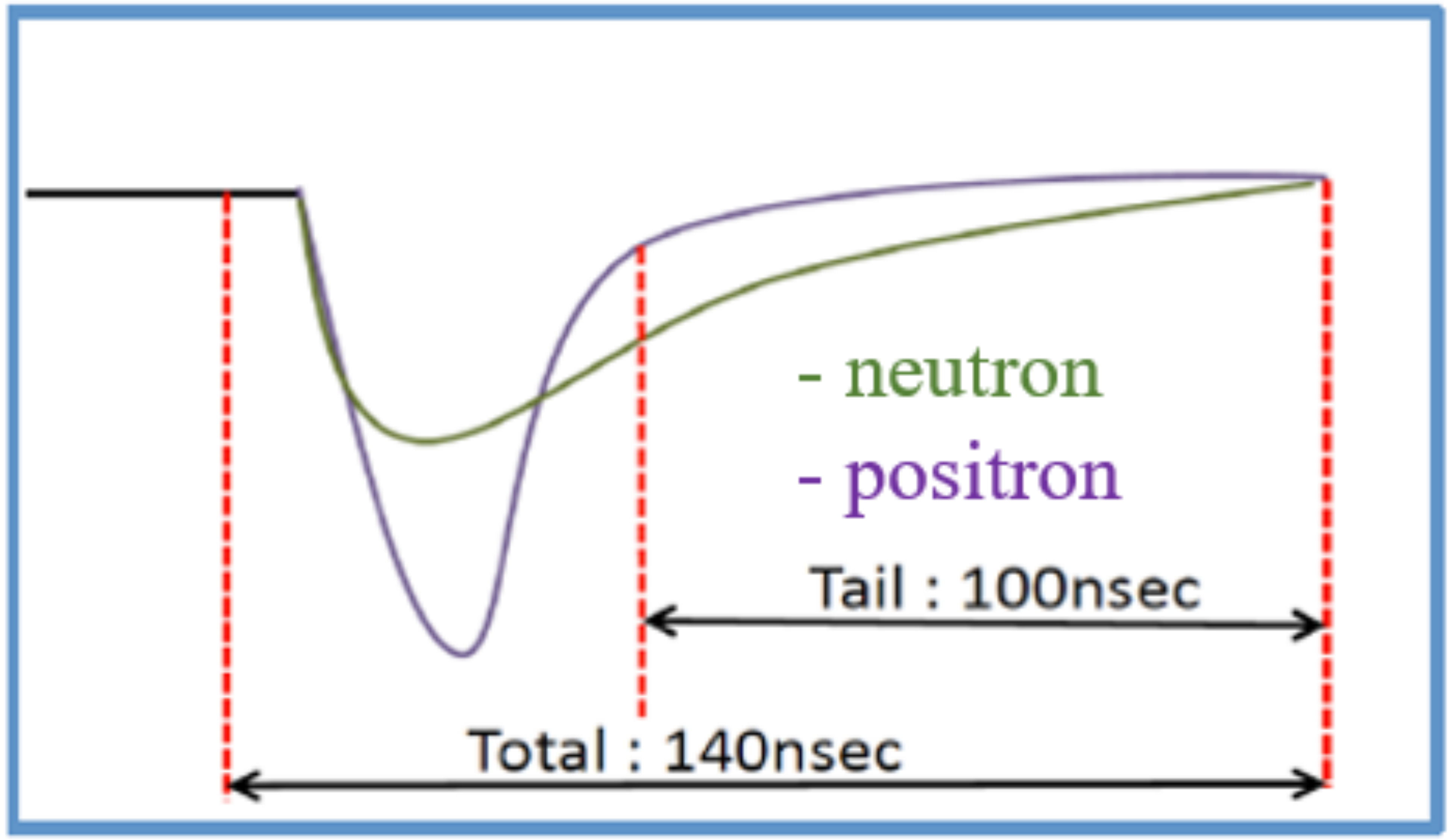
Δvertex$_{p-d} < 60\ cm$ cut would reject a large portion of the uncorrelated backgrounds

- They are well-agreed
- **Pulse Shape Discrimination (PSD) would reject them (arXiv:2404.03679)**
- After applying the PSD, the accidental will be dominated

Pulse Shape Discrimination (PSD)

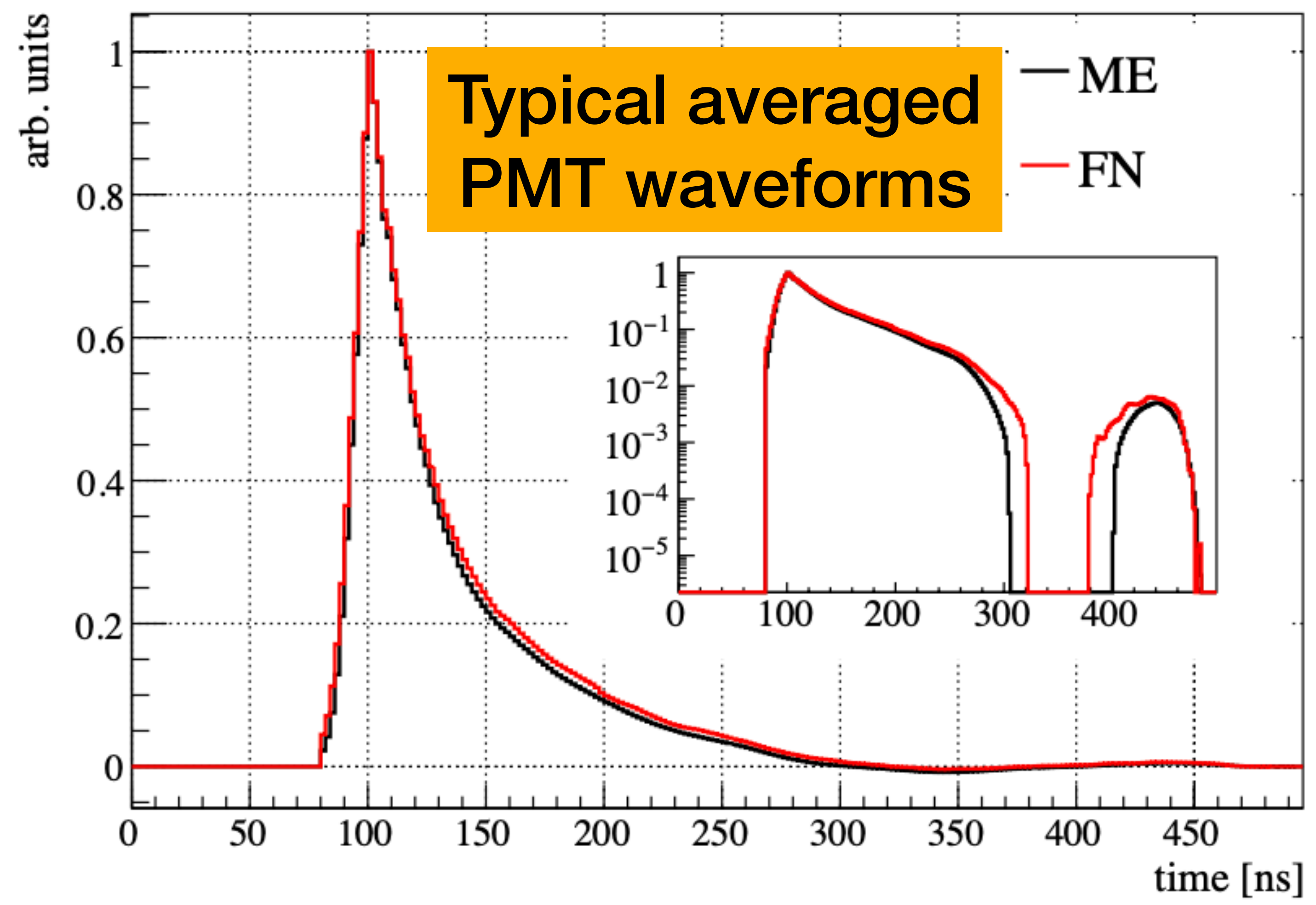
- Fast neutrons can mimic IBD signals from electron anti-neutrino (correlated background)
- PSD can separate the IBD signals and fast neutrons.
- **10% diisopropylnaphthalene (DIN —> EJ-309, 2000L)** has been added to improve the PSD power.
- The goal is to remove 99% of fast neutrons.

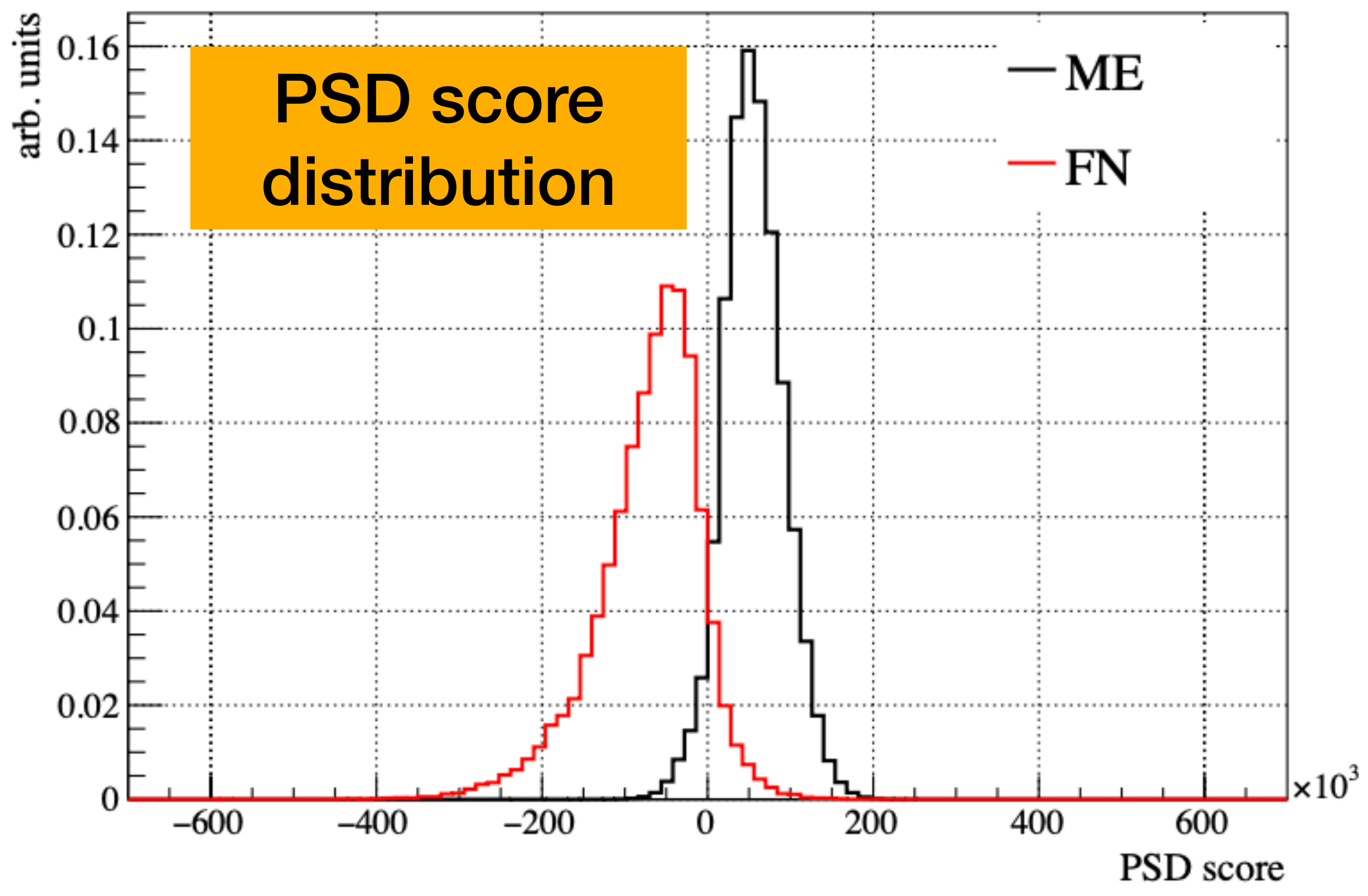


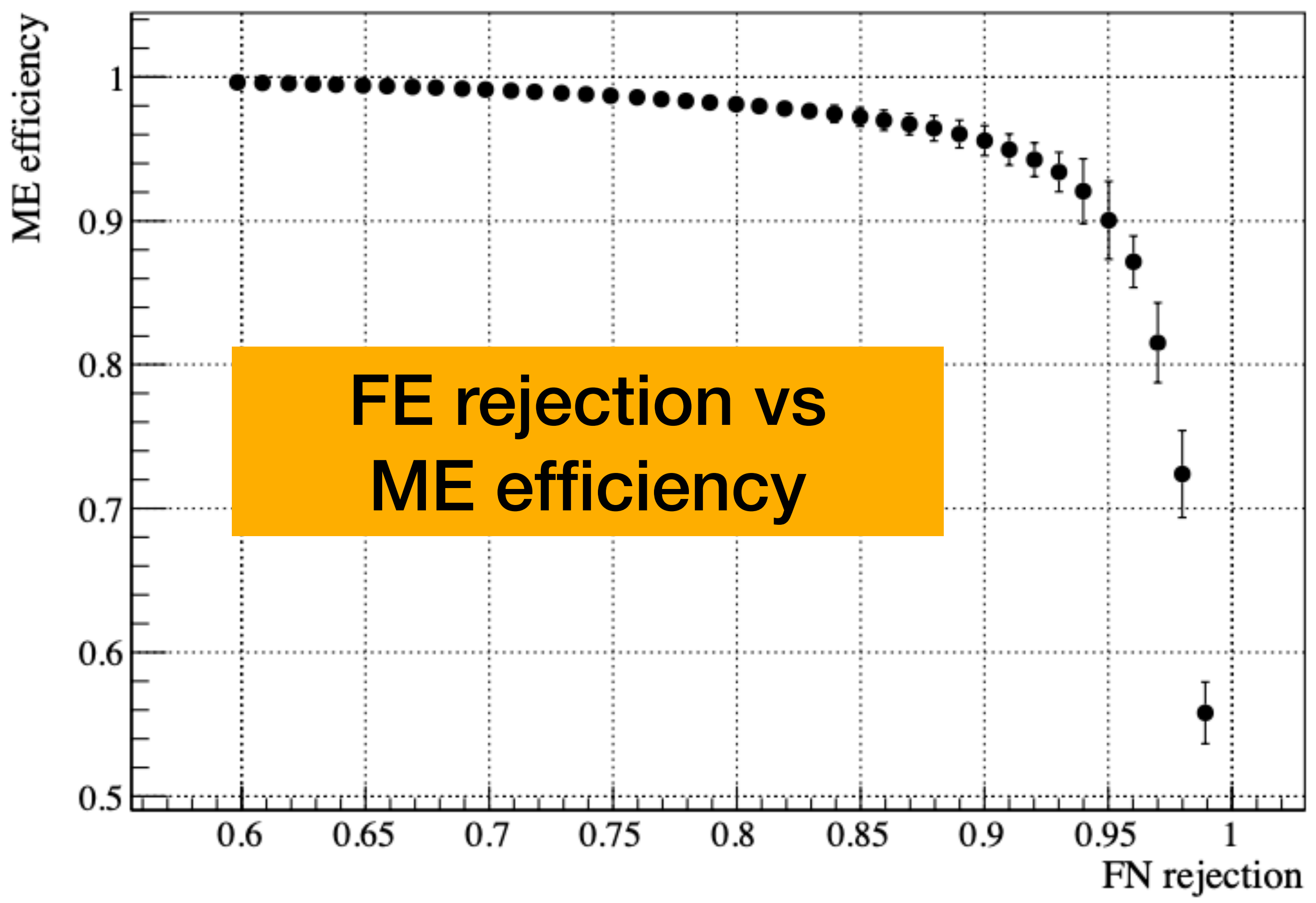


Likelihood method
(arXiv:2404.03679)

- The DAQ of JSNS² can measure a waveform every 2ns (500MHz sampling)
- The likelihood judges that each event looks like “a neutron” or “an electron”
- $L = \prod_{PMT}^{i<96} \prod_{bin}^{j<248} [P_{ij}(PH)]$, PH is the peak normalized pulse height of jth bin

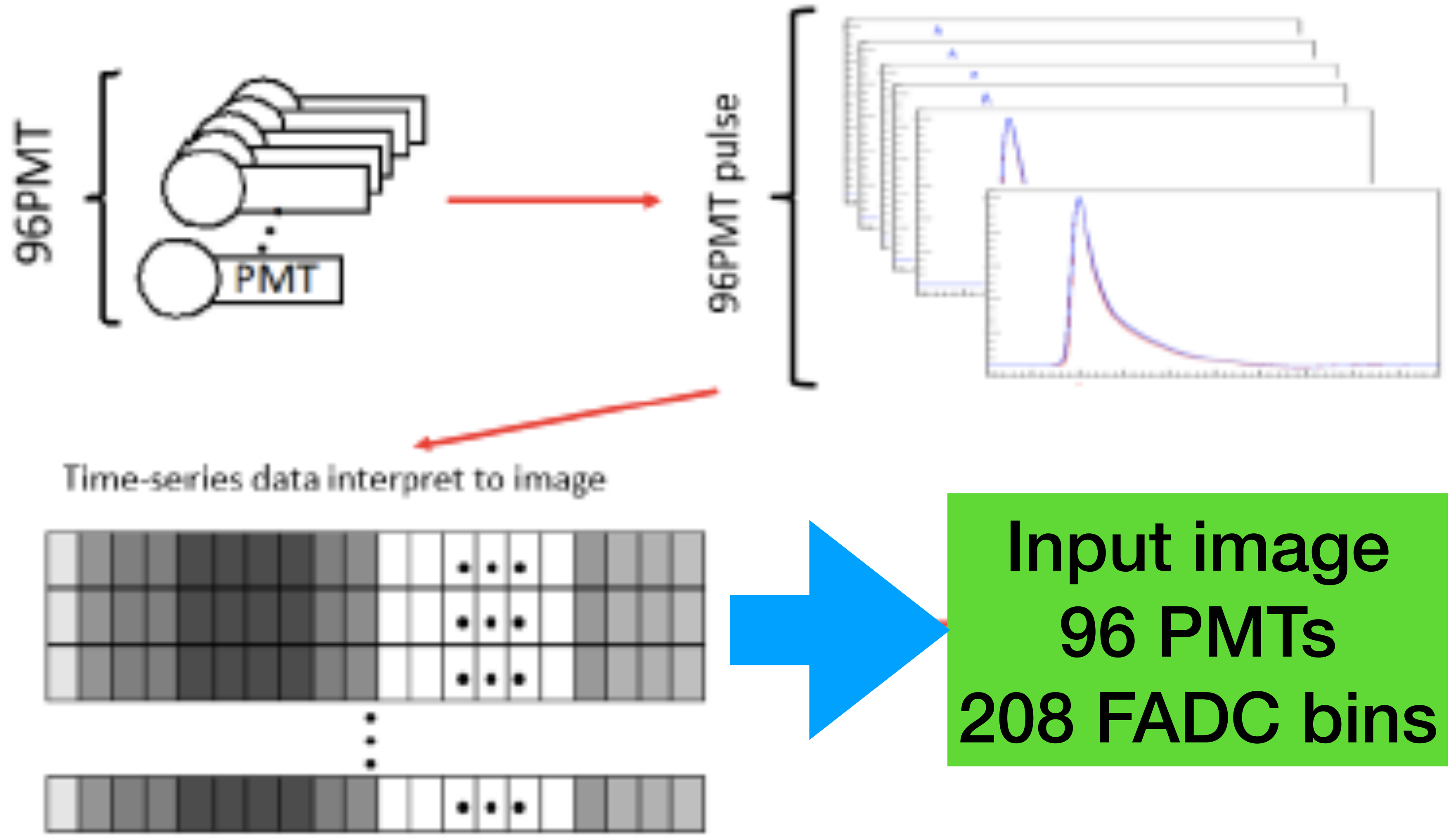


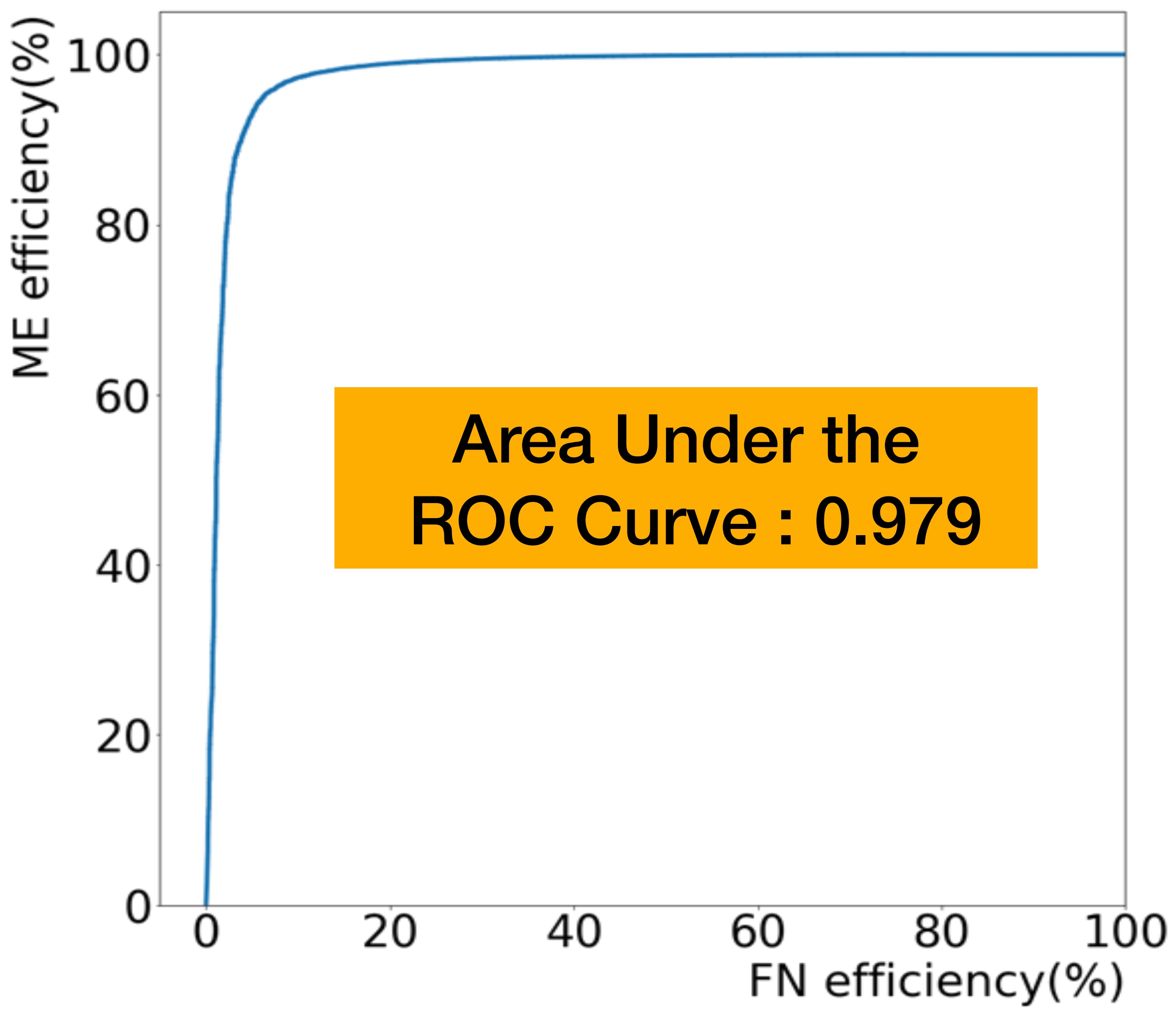


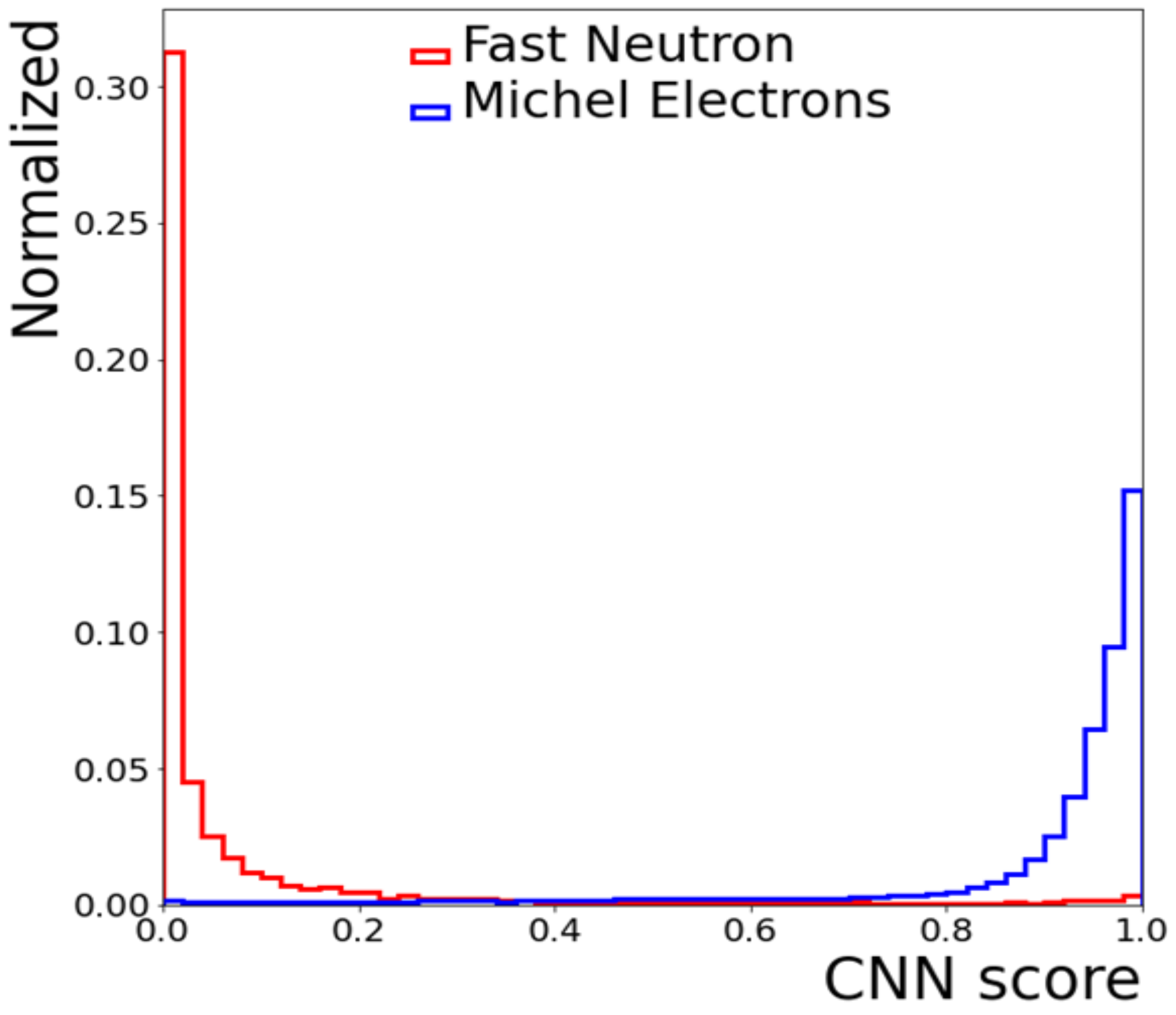


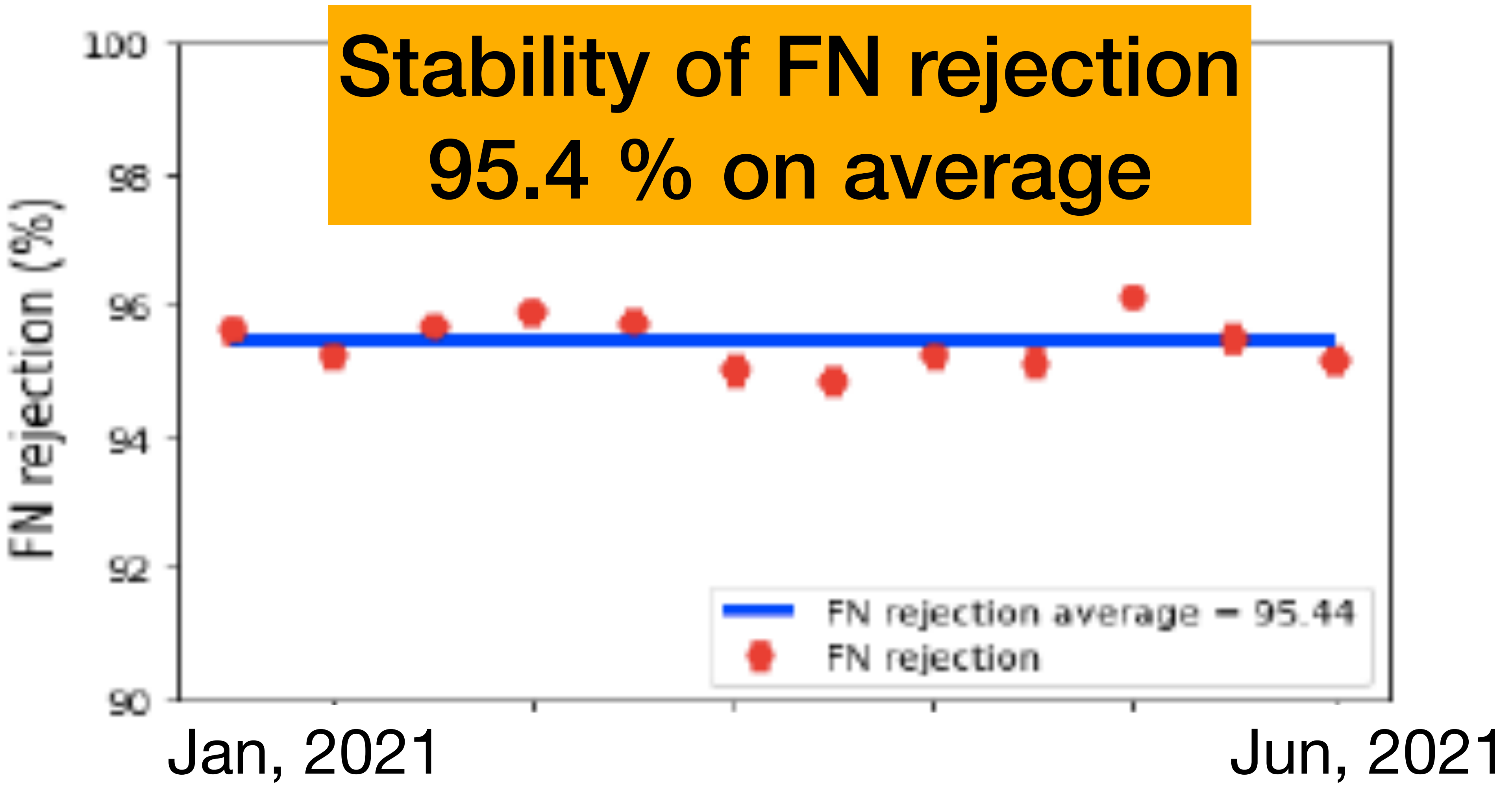
Convolutional Neutral Network (CNN)

- **Treated time-series data from a PMT with image data**
- **Two independent efforts show consistent FN-rejection results**



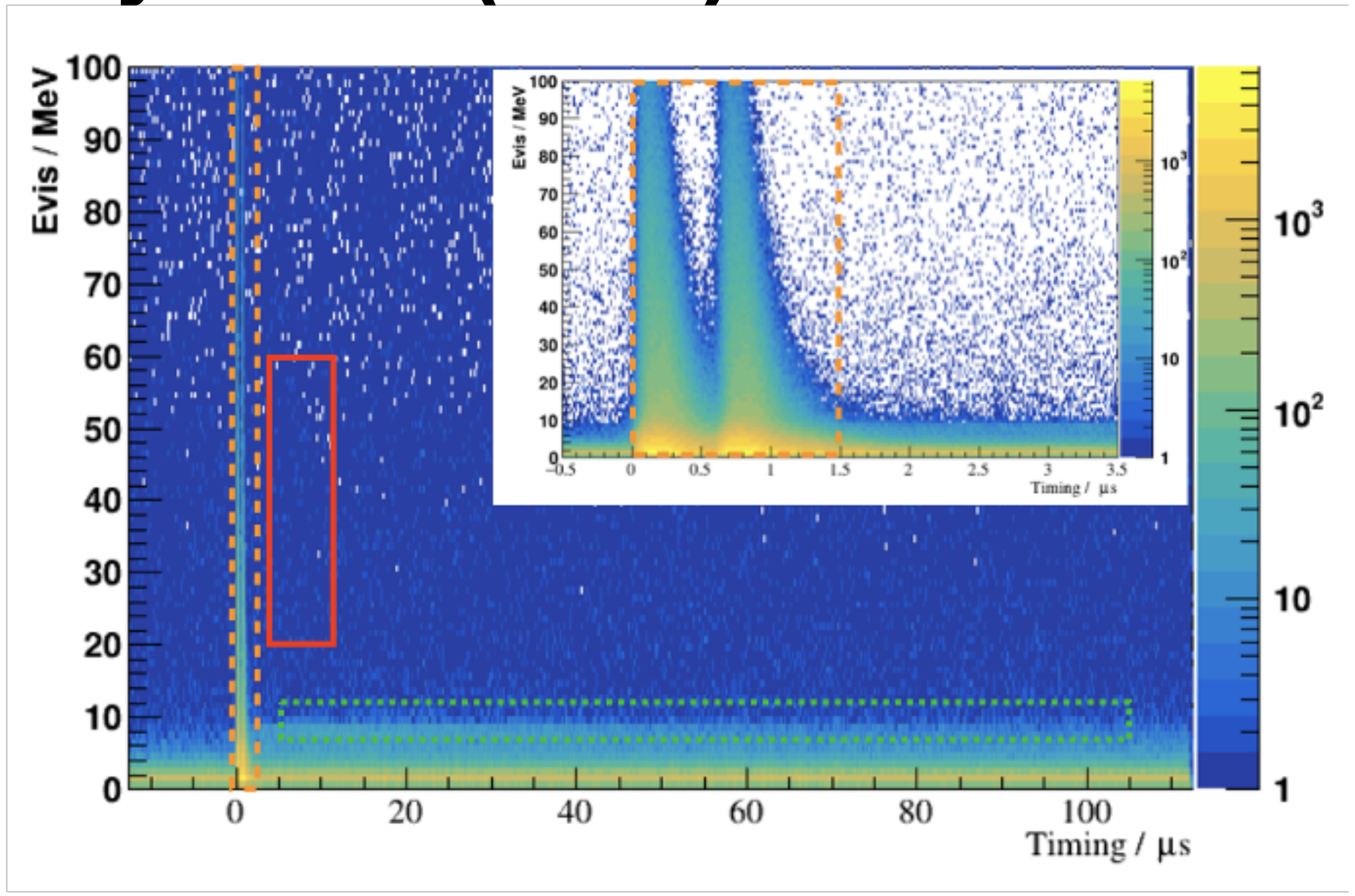




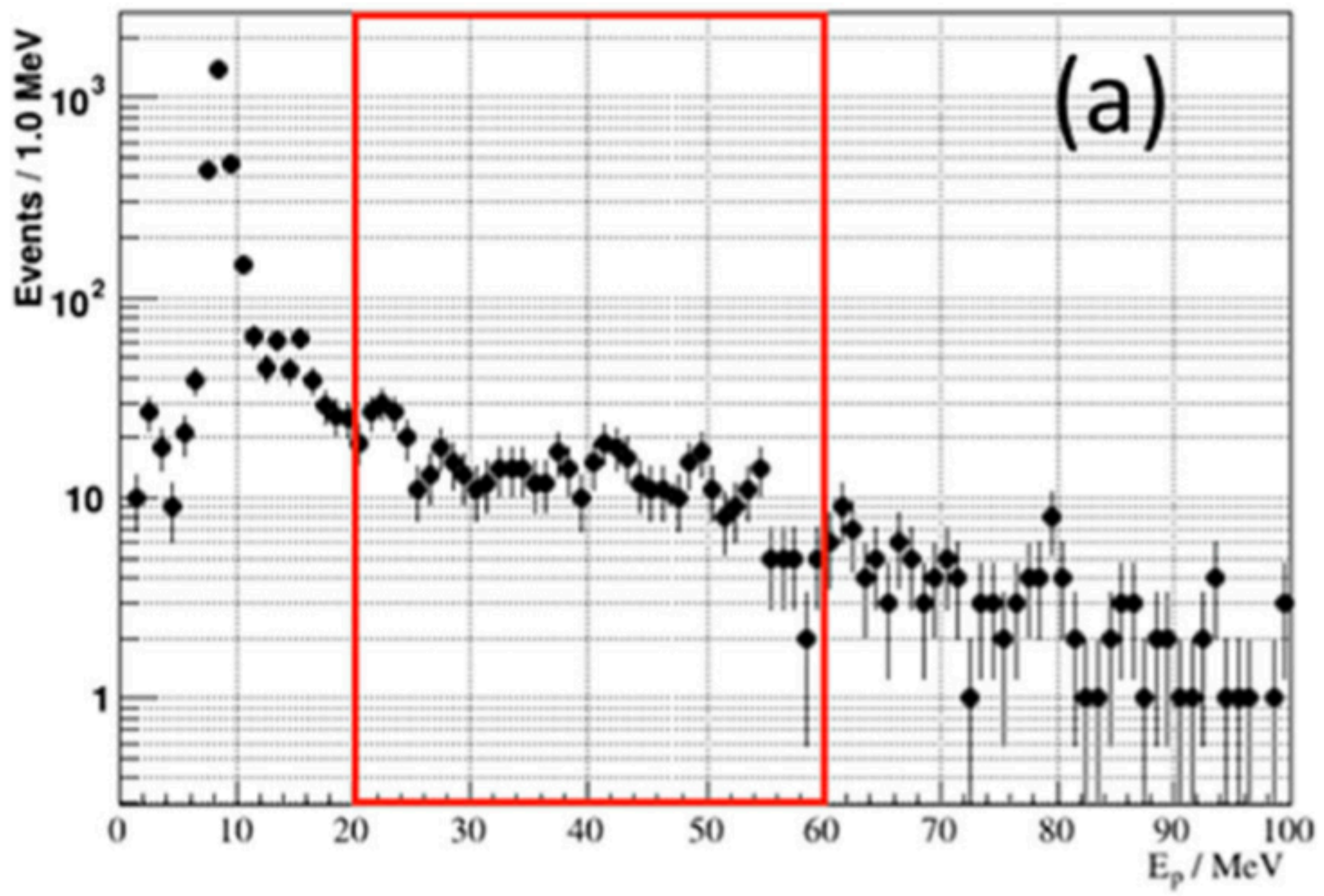


Accidental single rate of IBD prompt and delayed

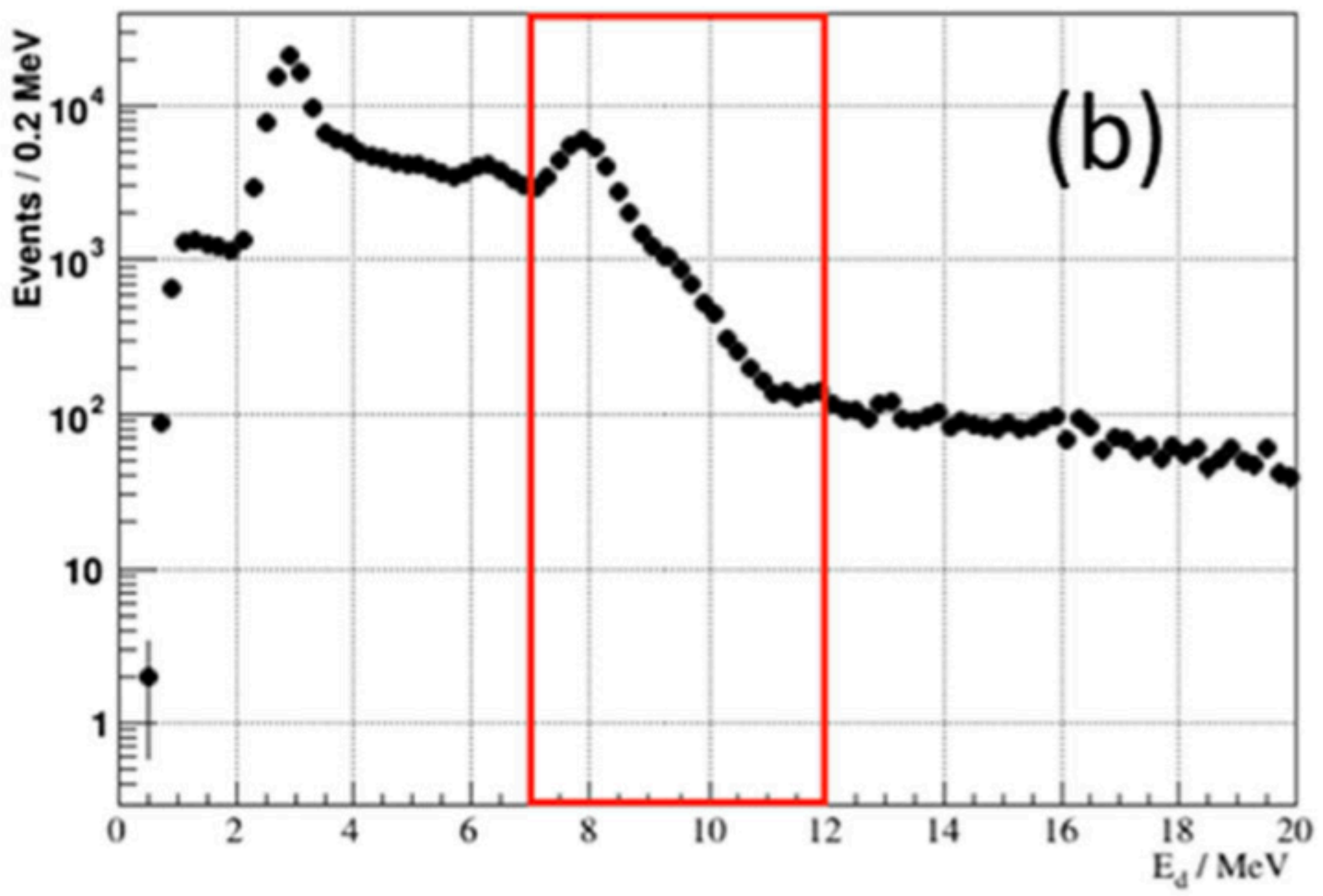
Eur. Phys. J. C (2024) 84:409



IBD prompt candidate



IBD delayed candidate

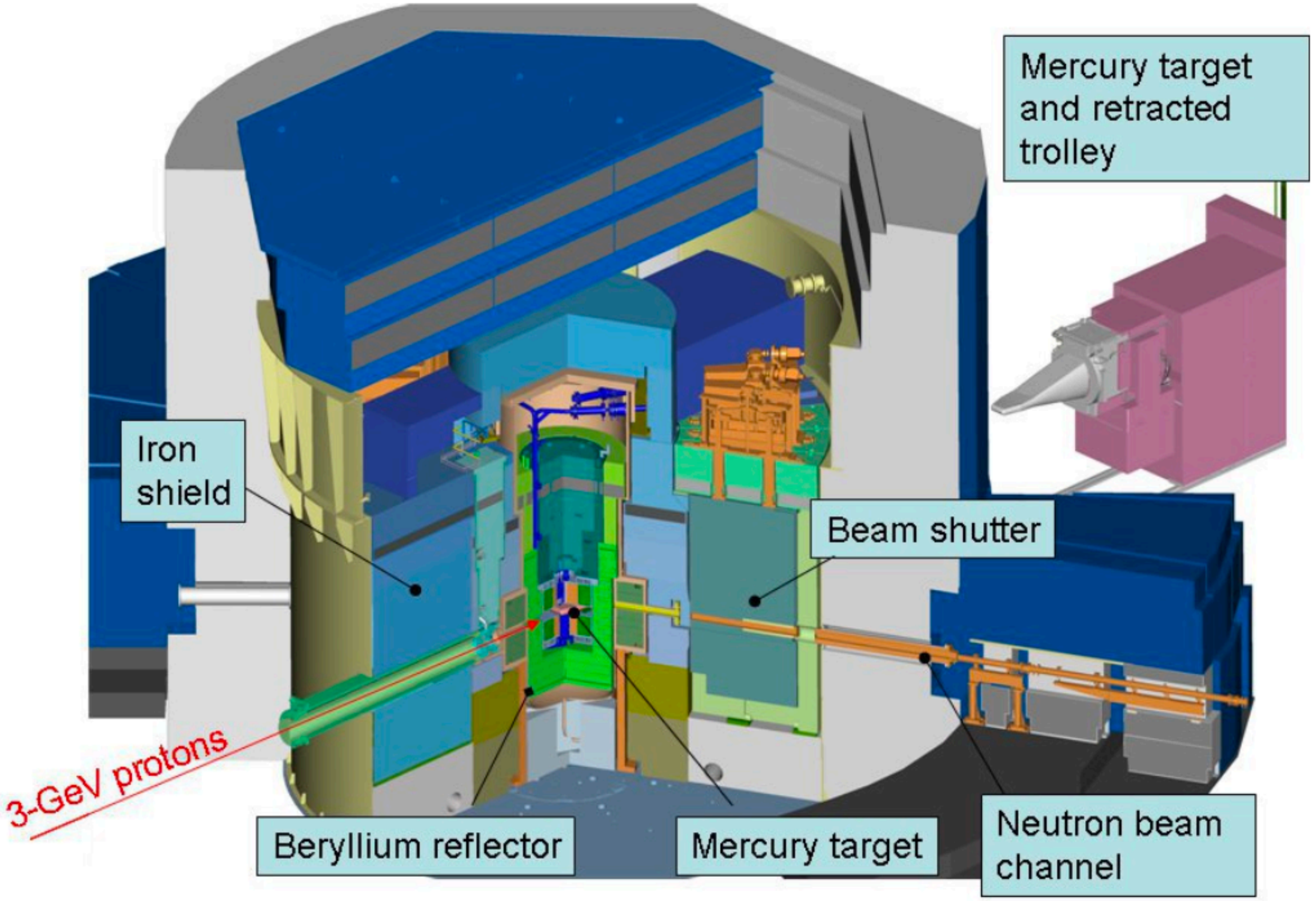


Special calibration run using beam timing with 125 μs time window

Observed (at 0.75 MW of averaged beam power)

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

Better understanding the neutrino beam
(JSNS² TDR, arXiv:1705.08629,)



- How to get the absolute $\bar{\nu}_\mu$ flux?
- Simulation may give a marginal number.
- μDAR neutrino production by 3 GeV protons
- However, there are Ambiguities in pion production
  - No measurement data of 3 GeV protons to a mercury target is available
  - Uncertainty in pion production from mercury
  - Target geometrical modeling
- Different simulation packages may help
- Or we can estimate from the data

Better understanding the neutrino beam
(JSNS² TDR, arXiv:1705.08629,)

- Simulated μDAR neutrino production by 3 GeV protons
  - Two different packages (FLUKA vs Geant4)
- **μDAR**: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- **CNgs**:
  - $^{12}C + \nu_e \rightarrow e^- + ^{12}N_{g.s.}$ (prompt: electron)
  - $^{12}N_{g.s.} \rightarrow ^{12}C + \nu_e + e^+$ (delayed: positron)
  - Lifetime: ~16 ms
  - Understand the neutrino flux from the data

FLUKA hadron simulation package (central value)

	$\pi^+ \rightarrow \mu^+ \rightarrow \bar{\nu}_\mu$	$\pi^- \rightarrow \mu^- \rightarrow \bar{\nu}_e$
π/p	6.49×10^{-1}	4.02×10^{-1}
μ/p	3.44×10^{-1}	3.20×10^{-3}
ν/p	3.44×10^{-1}	7.66×10^{-4}
ν after $1\mu s$	2.52×10^{-1}	4.43×10^{-4}

Geant4, QGSP-BERT package (cross-check)

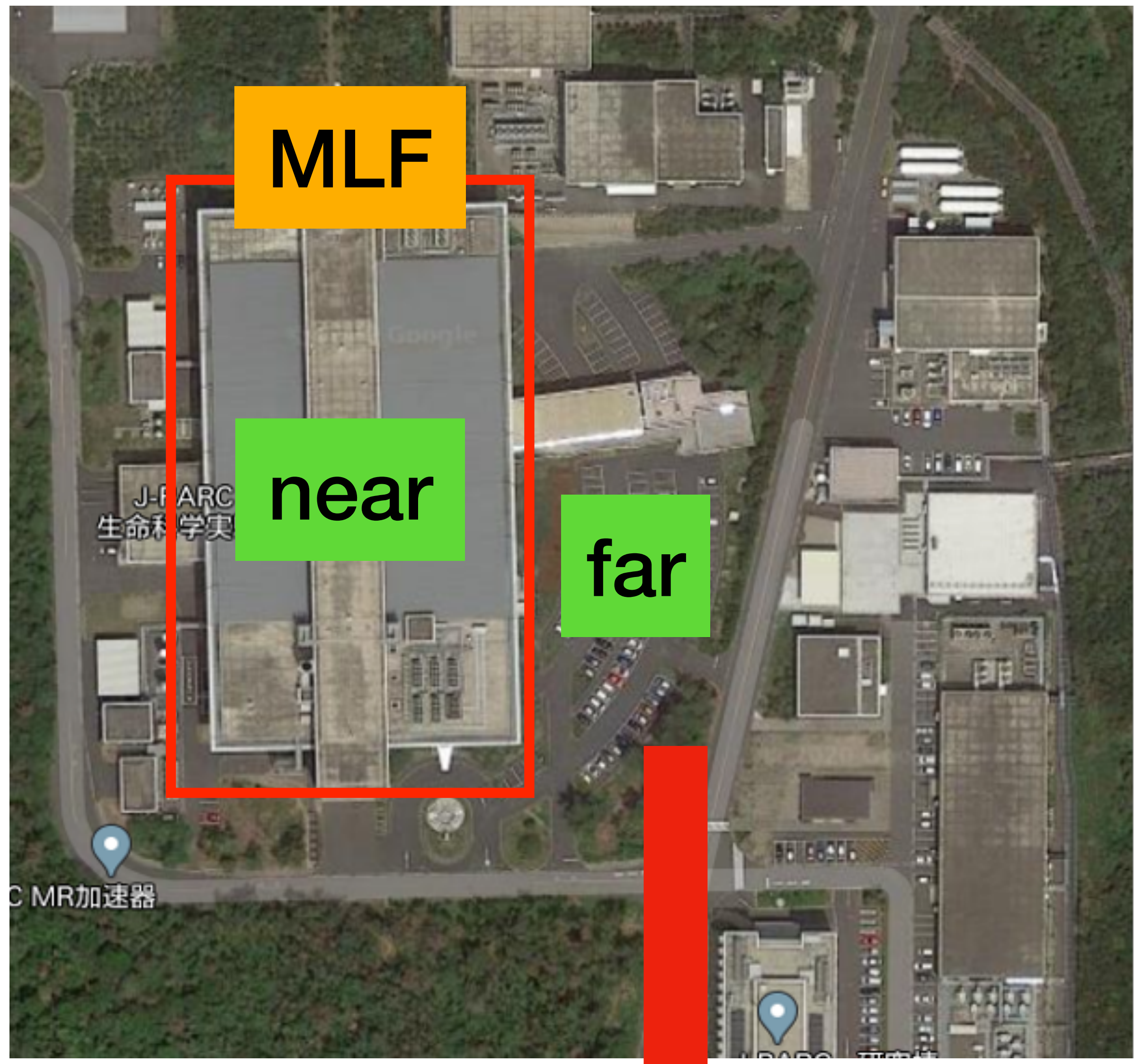
	$\pi^+ \rightarrow \mu^+ \rightarrow \bar{\nu}_\mu$	$\pi^- \rightarrow \mu^- \rightarrow \bar{\nu}_e$
π/p	5.41×10^{-1}	4.90×10^{-1}
μ/p	2.68×10^{-1}	3.90×10^{-3}
ν/p	2.68×10^{-1}	9.34×10^{-4}
ν after $1\mu s$	1.97×10^{-1}	5.41×10^{-4}

$JSNS^2$-II
(The second phase of the $JSNS^2$)

JSNS²-II
(arXiv:2012.10807)

New far detector

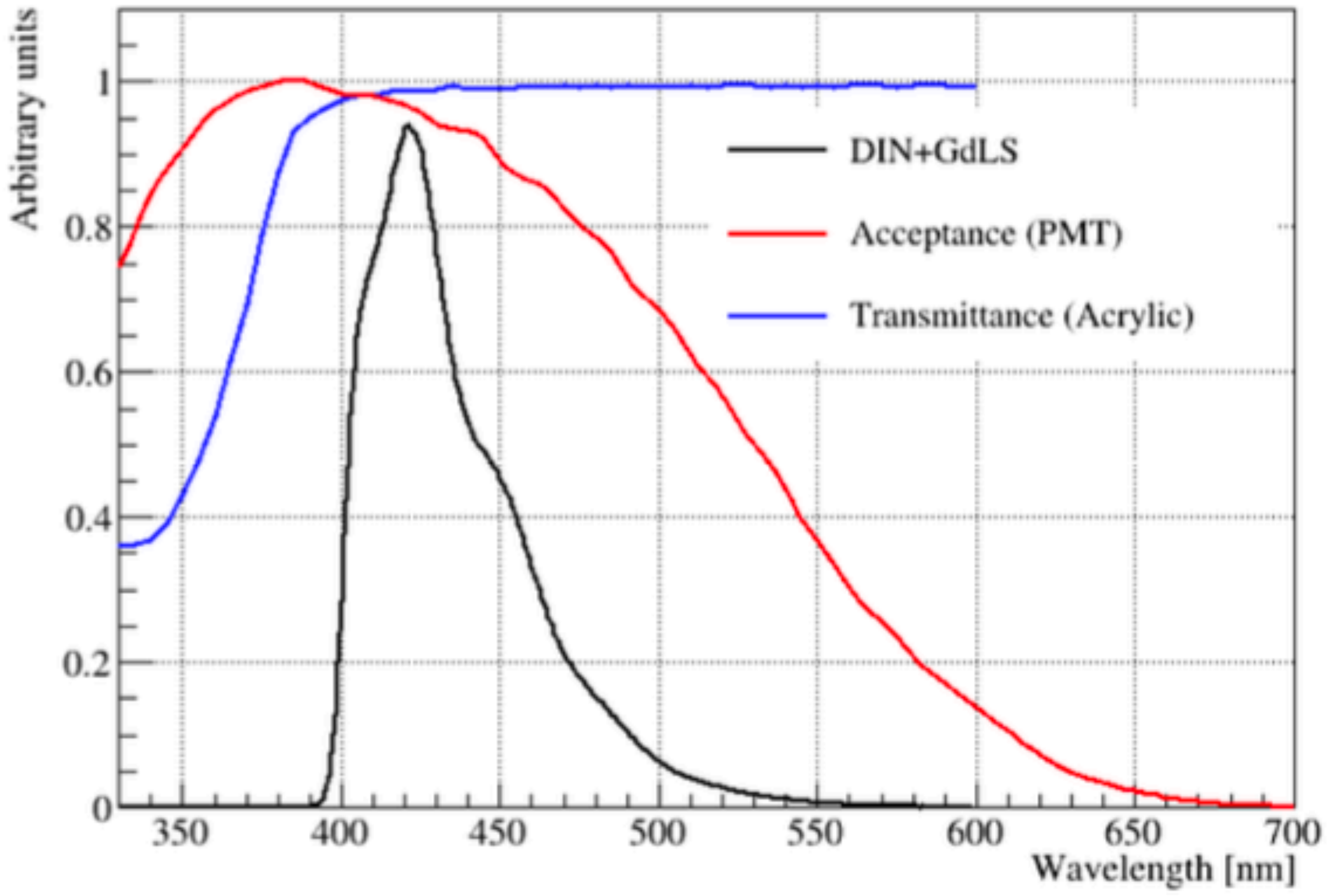
- Fiducial 32 tonnes and 48 m location)
- Two detectors with two different baseline
- A solid conclusion of LSND anomaly
- Improve the sensitivity
- Especially in the low Δm^2 region



New far detector

Almost identical to the near detector

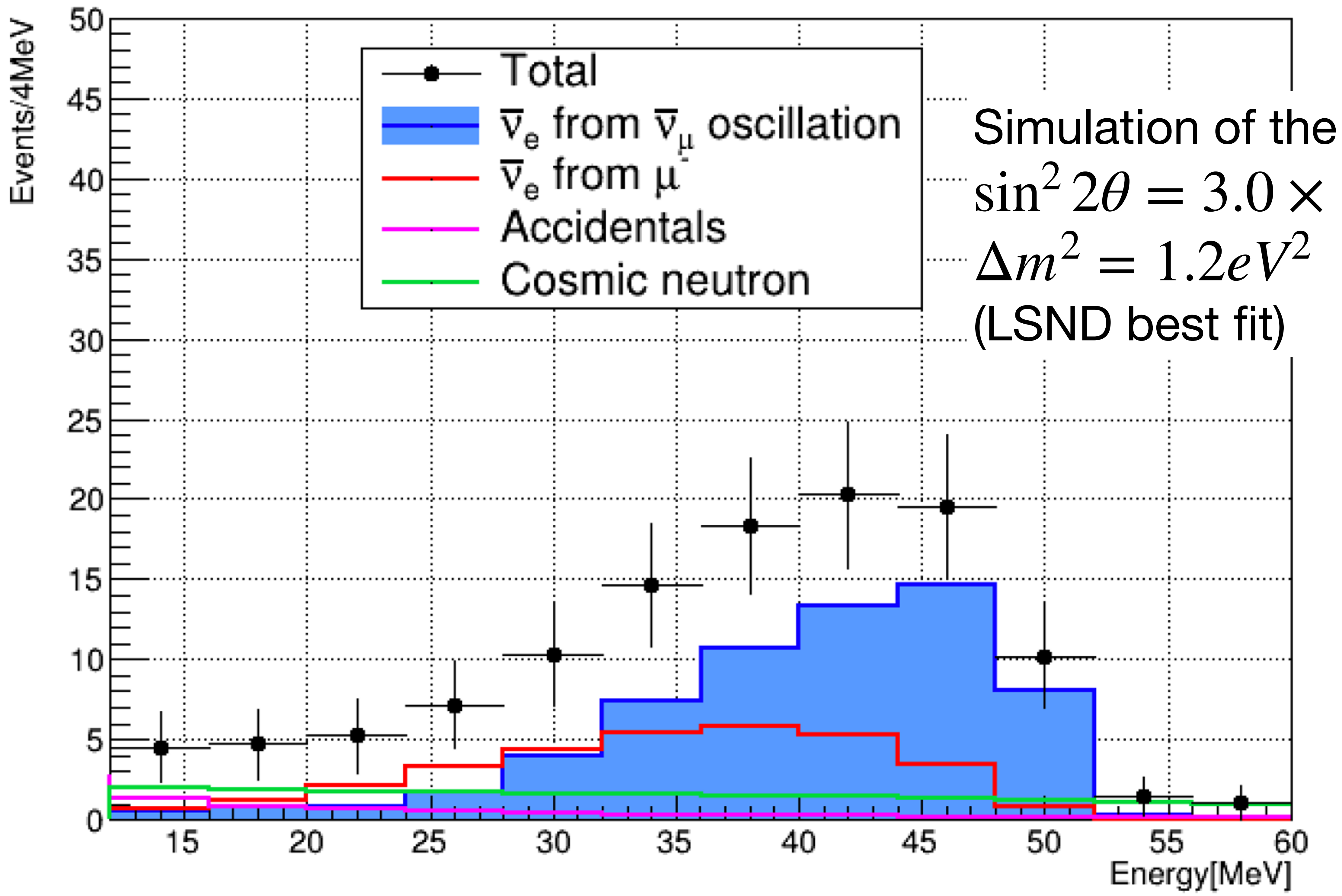
- The detector is placed outside of the building
- 37 m^3 Gd-LS for the neutrino target
- 150 m^3 pure LS for the gamma-catcher and veto
- 228, 10-inch PMTs were installed
- The acrylic vessel was made in Taiwan and installed
- GdLS and LS were donated by Daya-Bay in 2021 and are ready to fill
- An LED calibration system and temperature sensors were installed



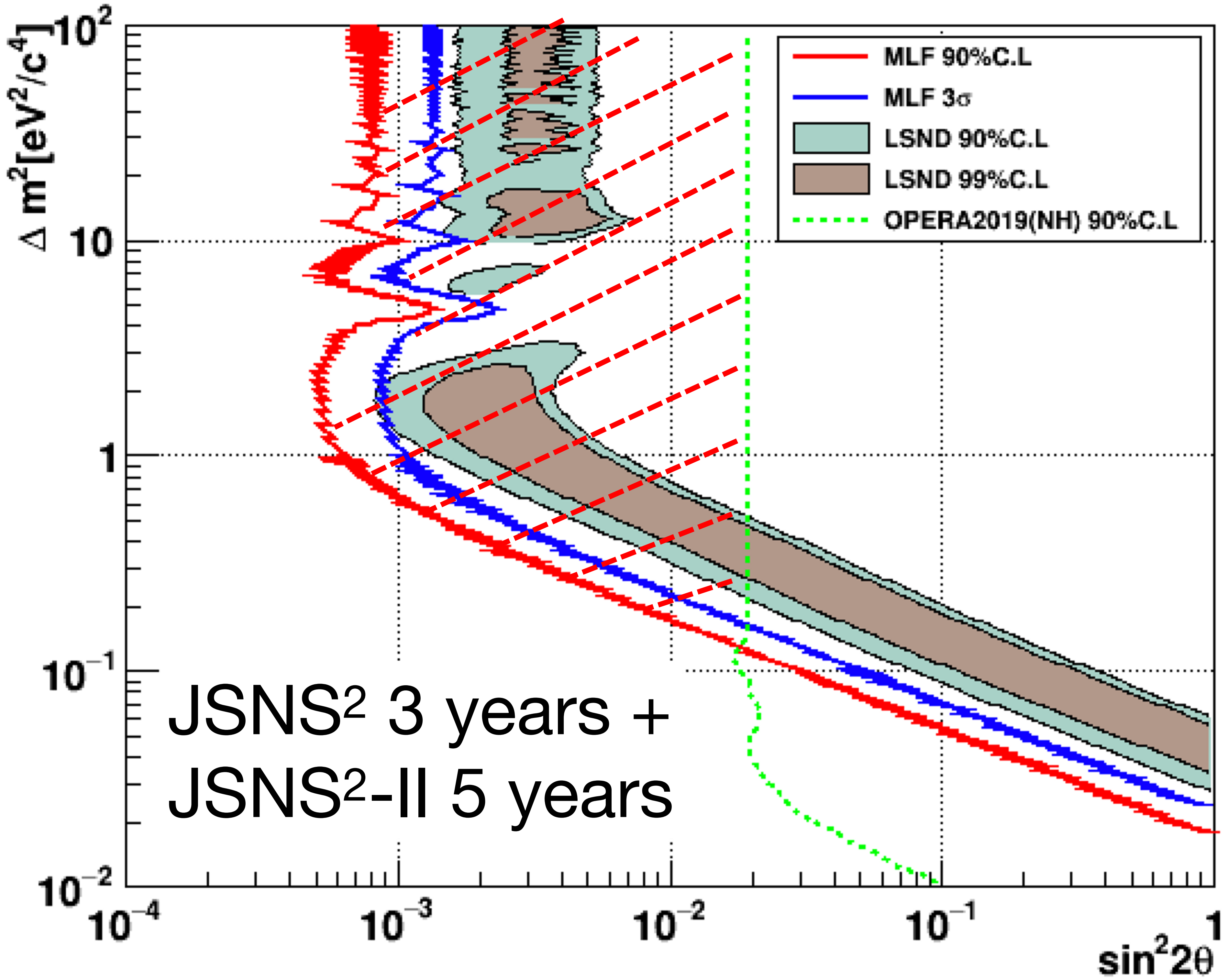
Sensitivity for the JSNS^2-II

(Based on the simulation)

- Each background simulation was done based on the JSNS^2 data
- Covering LSND by 3 sigma



Simulation of the far detector
$\sin^2 2\theta = 3.0 \times 10^{-3}$
$\Delta m^2 = 1.2 eV^2$
(LSND best fit)



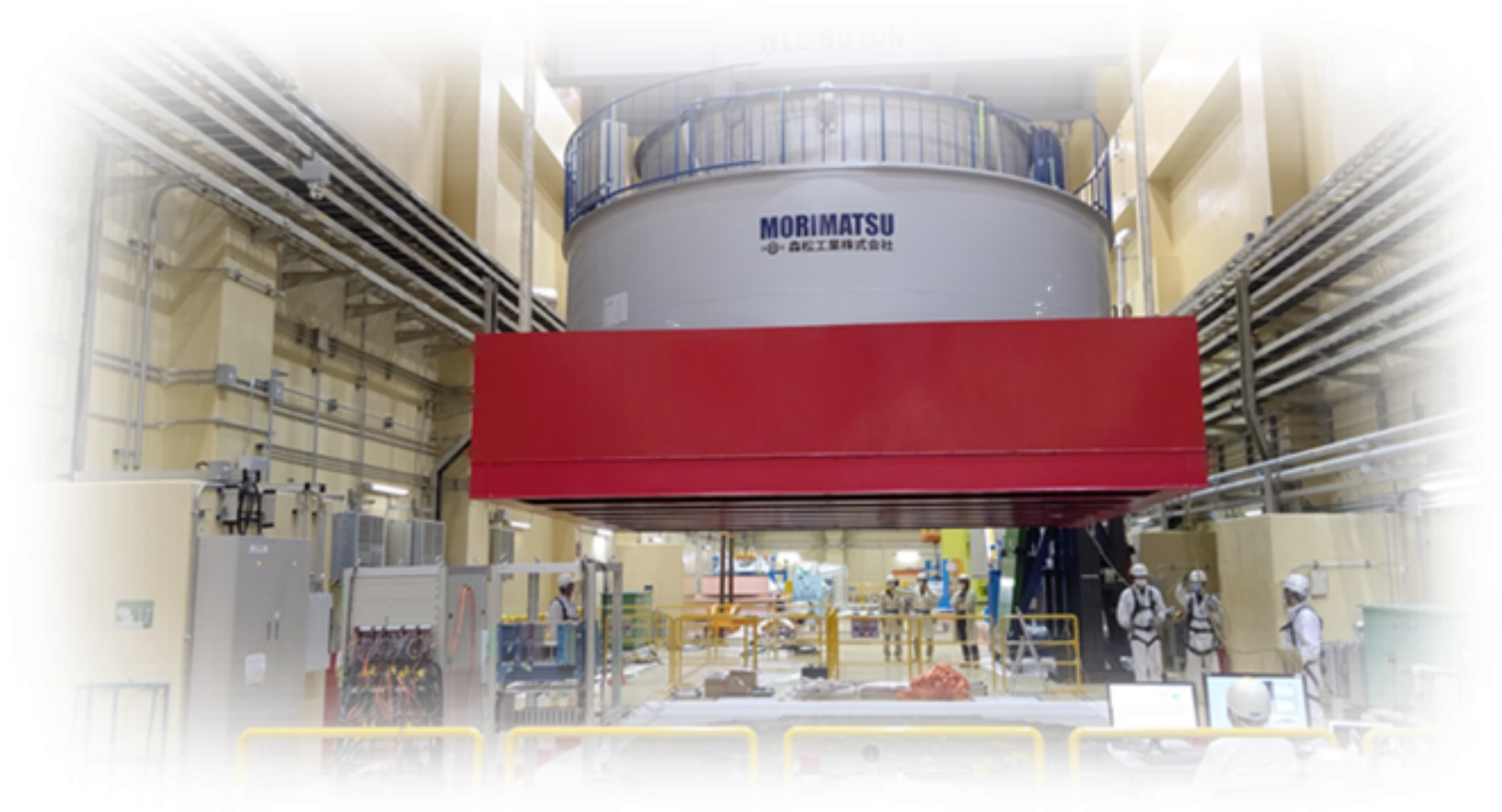
Construction schedule of the JSNS^2-II

	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		Trans.		Installation					
PMTs									Installation (near)				(Veto)			
		DC dismantle/ shipping (190 PMTs)											30 PMTs			
(Gd)LS	Donation		Storage/keep													
Filling																
Data taking																

Summary

- There have been 1st (2021), 2nd (2022), 3rd (2023) and 4th (2024) physics run.
- Side-band region 4 (prompt 60-100 MeV) data are opened
  - Good consistency between observation and expectation
- Has been studying fast neutron background (for PSD)
- Study on the accidental background using single rates
  - Published in Eur. Phys. J. C
- Based on the JSNS^2 data, JSNS^2-II has been granted.
- JSNS^2-II expects to start data taking at around the end of 2024.

Thank you for your attention



acknowledgements:
- MEXT, JSPS (Japan)
- Korea Ministry of Science, NRF (Korea)
- DOE, Heising-Simons Foundataion (US)
- Royal Society (UK)