Physics Opportunities with $JSNS^2$ / $JSNS^2$-II

Takasumi Maruyama (KEK) on behalf of $JSNS^2$ / $JSNS^2$-II collaboration

(you can also refer Matheus Hostert's nice introductions in his talk for $JSNS^2$/$JSNS^2$-II physics)

JSNS^2 / JSNS^2-II

Collaboration meeting @ CNU(Korea) (2025/July)

JAEA
KEK
Kitasato
Kyoto
Osaka
Tohoku
Tsukuba

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

BNL
Michigan
Utah

Sun Yat-sen (Zhongshan)

Direct test of LSND.

JSNS^2 / JSNS^2-II collaboration (58 collaborators)

- 7 Japanese institutions (25 members)
- 9 Korean institutions (24 members)
- 3 US institutions (5 members)
- 1 Chinese institution (3 members)

Spokesperson: T.Maruyama (KEK, Japan)
Co-spokesperson : M.Y.Pac (DSU, Korea)

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

- Anomalies, which cannot be explained by standard neutrino oscillations for ~20 years are shown;

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	
BEST (Ga)	e capture	$\nu_e \rightarrow \nu_x$	~4.0σ	<3,10
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ	3,10-100

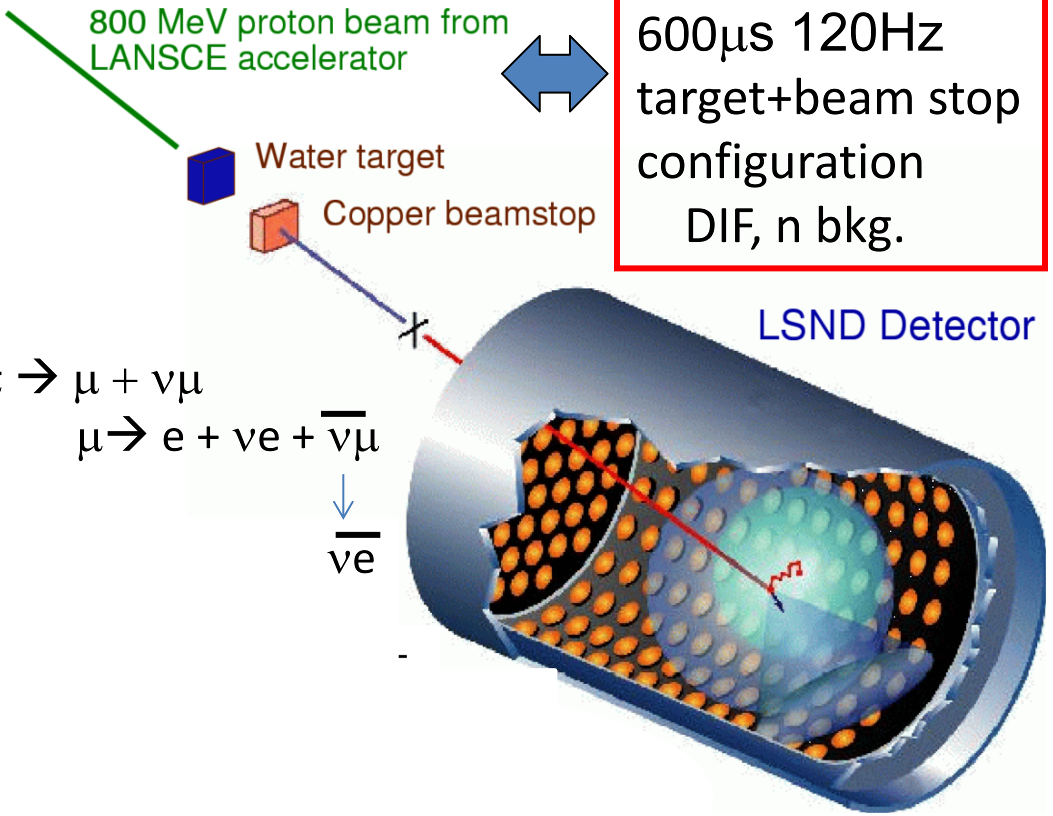
A direct test for this

- Excess or deficit really exists?
- JSNS^2(-II) is a **unique program in the world** to test LSND anomaly directly at present.
- using the same neutrino source (μ **Decay-At-Rest**), target (H) and detection principle (**IBD**) as LSND.
- A model (regardless of oscillation or not) independent test with 2 different baselines

LSND

LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Signal

1998 at LANL



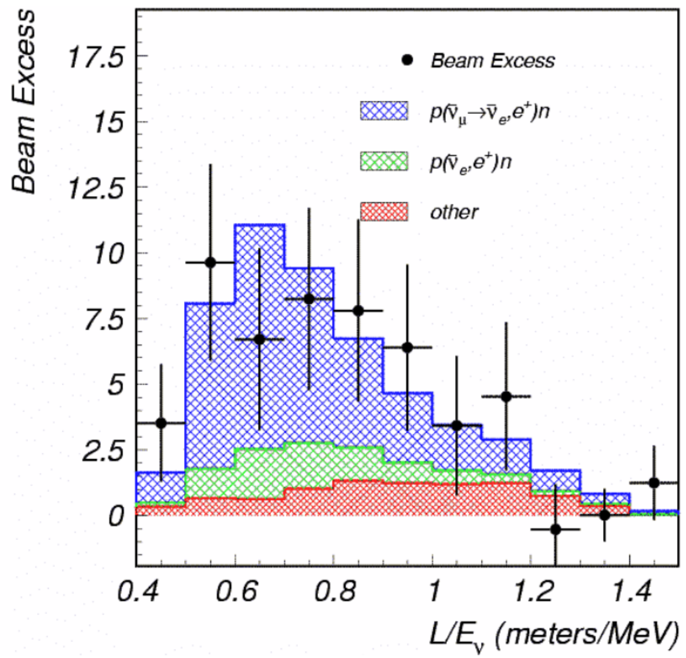
600μs 120Hz
target+beam stop
configuration
DIF, n bkg.

$\pi \rightarrow \mu + \nu_\mu$

$\mu \rightarrow e + \nu_e + \bar{\nu}_\mu$

$\downarrow$

$\bar{\nu}_e$



Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

π^-, μ^- absorbed before decay into ν's
there should not be $\bar{\nu}_e$ at the level of 7×10^{-4}

Signal : $\bar{\nu}_e\ p \rightarrow e^+ n \quad np \rightarrow d\ \gamma(2.2\text{MeV})$

Recent MicroBooNE results (2025/Dec)

- Published as Nature volume 648, pages 64–69 (2025)
- Beautiful results with 2 different neutrino beams.
- **<u>Their results do not explain the LSND anomaly</u>**. (they say it could be difficult to explain it by 3+1 oscillation model)
- Difference of numu->nue and numubar->nuebar ??

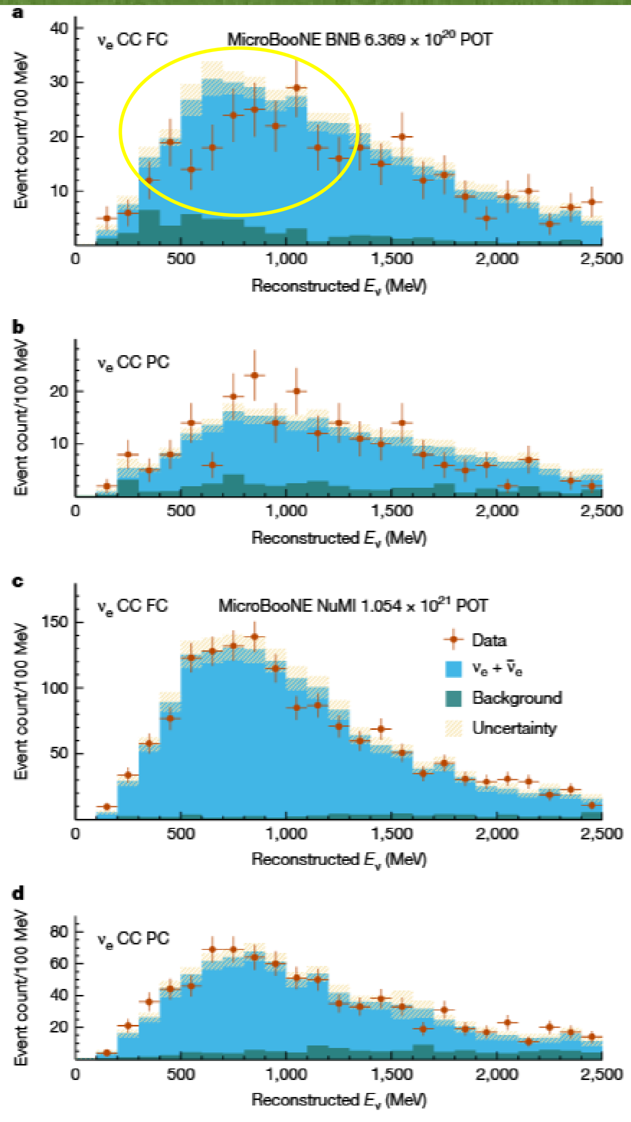


Fig. 2 | Observed CC ν_e candidate events. a–d, Reconstructed energy spectra of events selected as FC CC ν_e candidates in the BNB (a), PC CC ν_e candidates in the BNB (b), FC ν_e candidates in the NuMI beam (c) and PC ν_e candidates in the NuMI beam (d). The data points are shown with statistical error bars. The constrained predictions for each sample are shown for the 3ν hypothesis as the solid histograms, with the blue showing the true CC ν_e events and the green

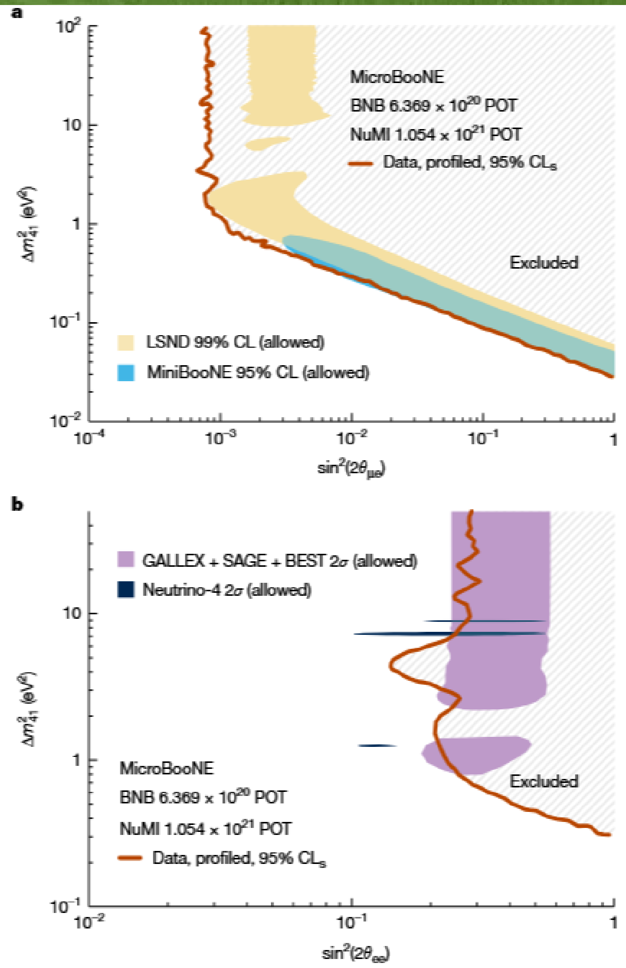
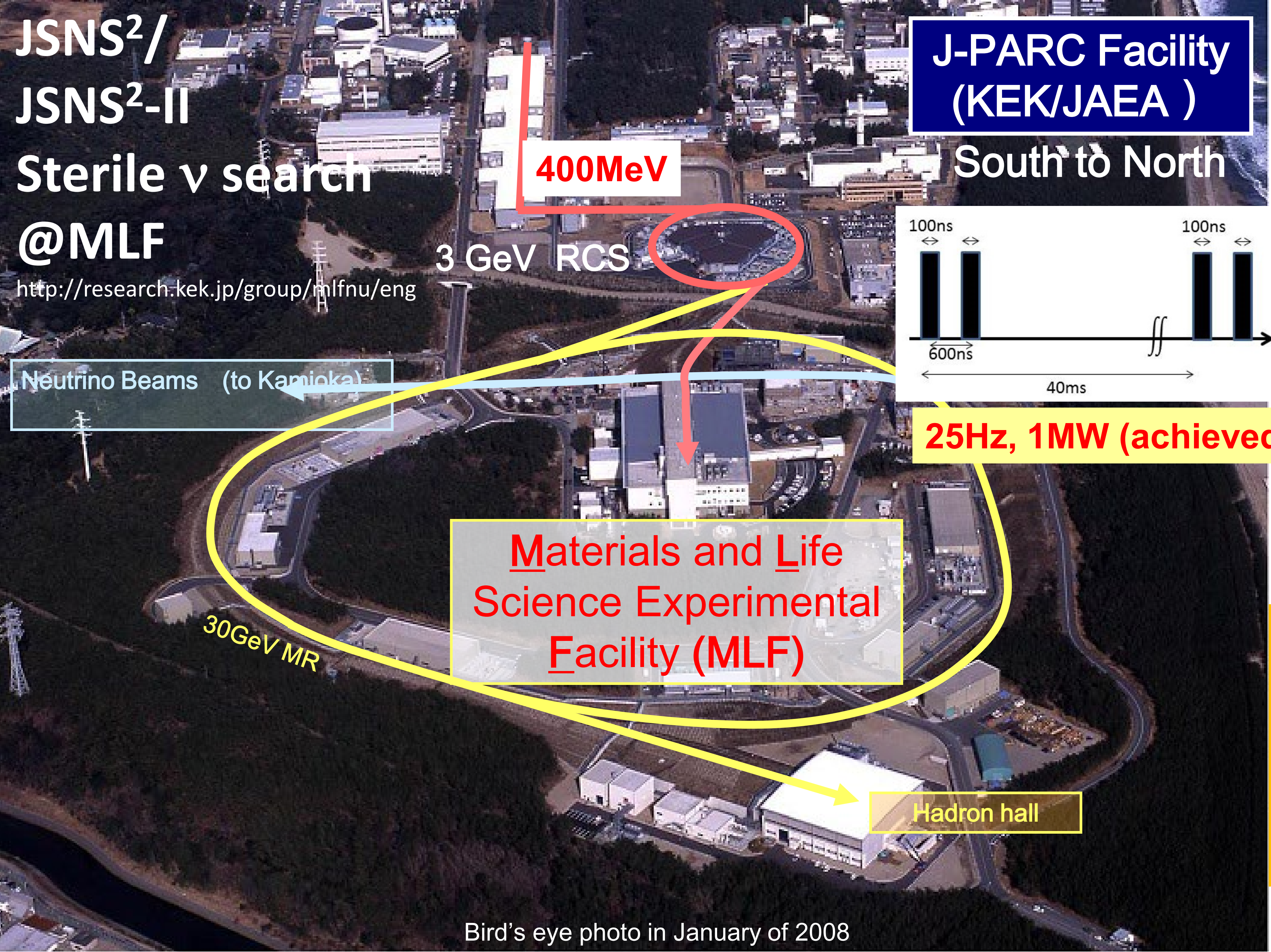


Fig. 3 | Constraints on parameters of the 4ν oscillation model. a, b, The red lines show exclusion limits at the 95% CL$_s$ level in the plane of Δm^2_{41} and $\sin^2(2\theta_{\mu e})$ (a) or $\sin^2(2\theta_{ee})$ (b). All the regions to the right of these lines are excluded by the MicroBooNE data. In a, the yellow shaded area is the LSND 99% CL allowed regions[3], which neglects the degeneracy between ν_e disappearance and appearance. The light blue area is the MiniBooNE 95% CL allowed region[38], considering both ν_e disappearance and appearance. In b, the purple shaded area is the 2σ allowed region of the gallium anomaly[39]. The dark blue shaded area is the 2σ allowed region from the Neutrino-4 experiment[9]. For context, note that the stronger-than-expected constraint on $\sin^2(2\theta_{\mu e})$, driven by the deficit observed in the BNB ν_e CC FC sample and the excess in the NuMI ν_μ CC sample, is discussed in detail in the Methods and Extended Data Fig. 2.

JSNS^2/ JSNS^2-II Sterile ν search @MLF

http://research.kek.jp/group/mlfnu/eng



Bird's eye photo in January of 2008

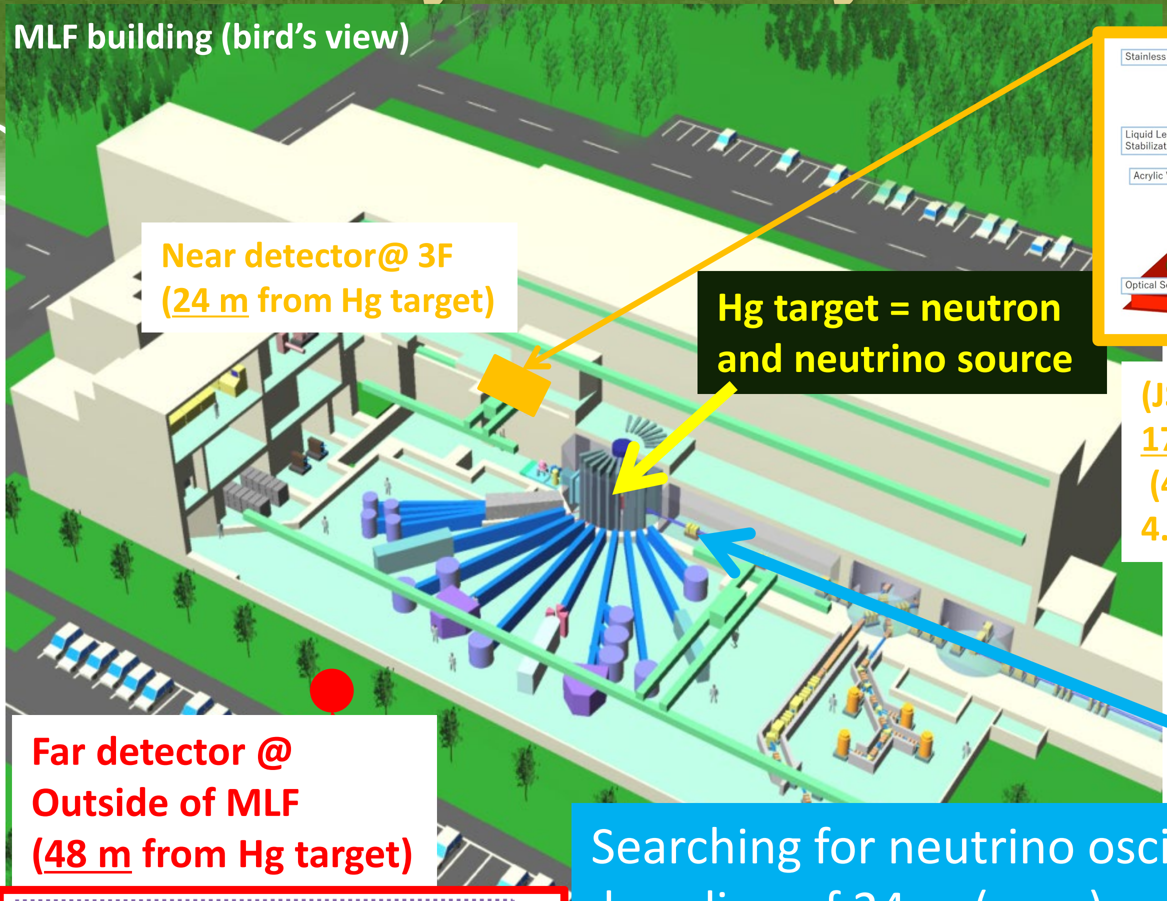
Low duty factor beam (short pulse + low repetition rate) gives excellent S/N ratio.

0.95 MW operation at MLF in 2024 April-May !
(design value was achieved!)

→ Thank you for the tireless efforts, J-PARC accelerator and MLF Hg target group!

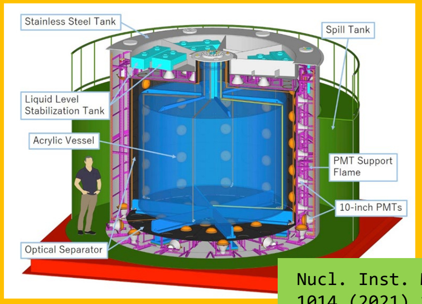
JSNS^2 and JSNS^2-II : Sterile Neutrino Search

MLF building (bird's view)



Near detector@ 3F
(24 m from Hg target)

Hg target = neutron and neutrino source



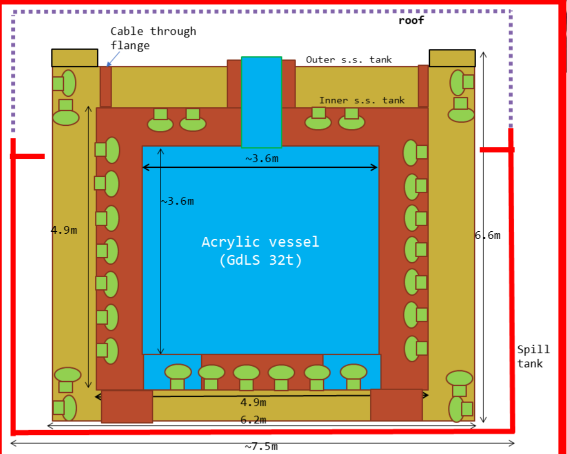
Nucl. Inst. Meth. A 1014 (2021) 165742

(JSNS2-I, JSNS^2-II near detector
17 t GdLS fiducial
(4.6 m diameter x
4.0 m height, 120 10" PMTs)

3GeV short pulsed beam

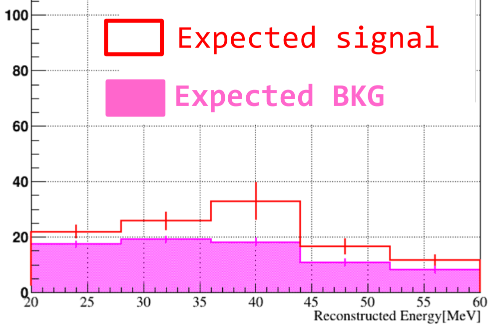
Far detector @
Outside of MLF
(48 m from Hg target)

Searching for neutrino oscillation : $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with baseline of 24 m (near), and 48 m (far detector)

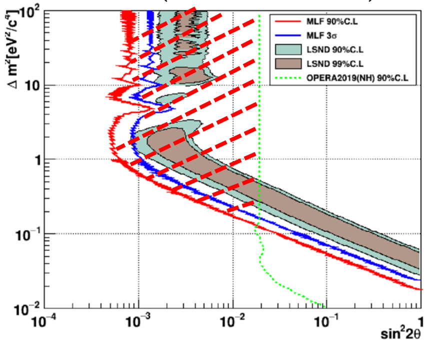


(JSNS^2-II:
Far detector)
32 t GdLS
(6.2 m dia x
6.2 m (h)
228 10"
PMTs)

JSNS^2(direct LSND excess case)



JSNS^2-II (oscillation case)



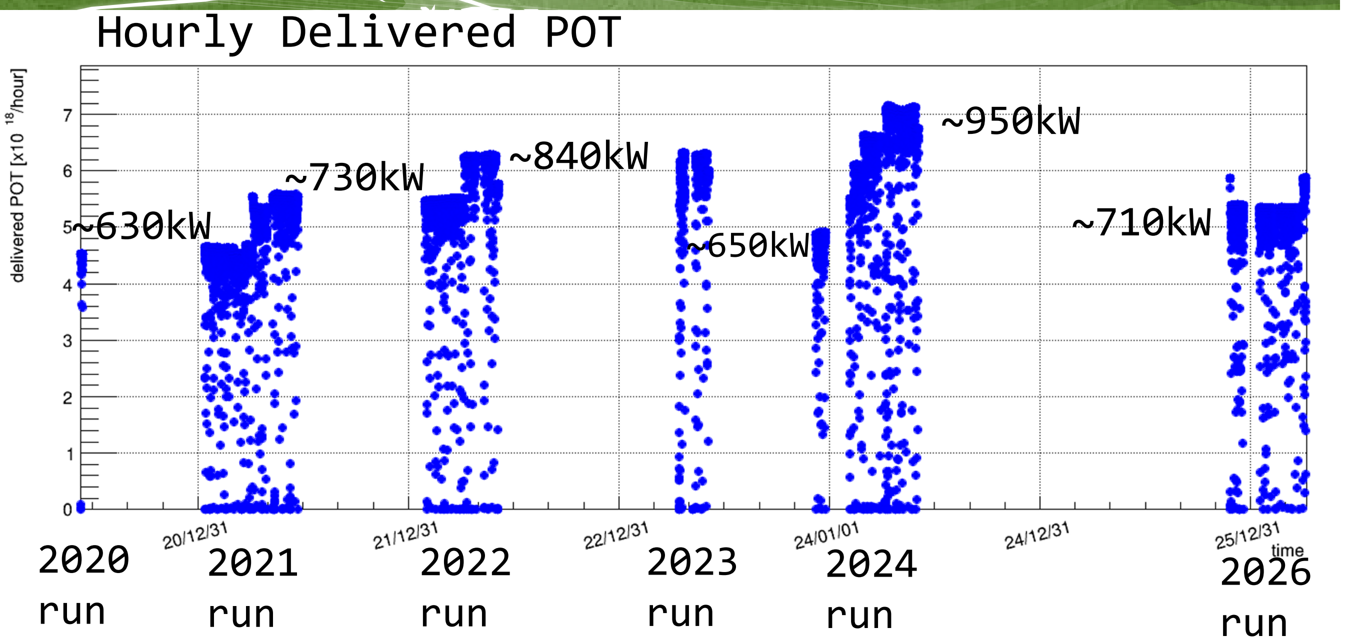
(JSNS^2):1 MW x 3 y(near only)

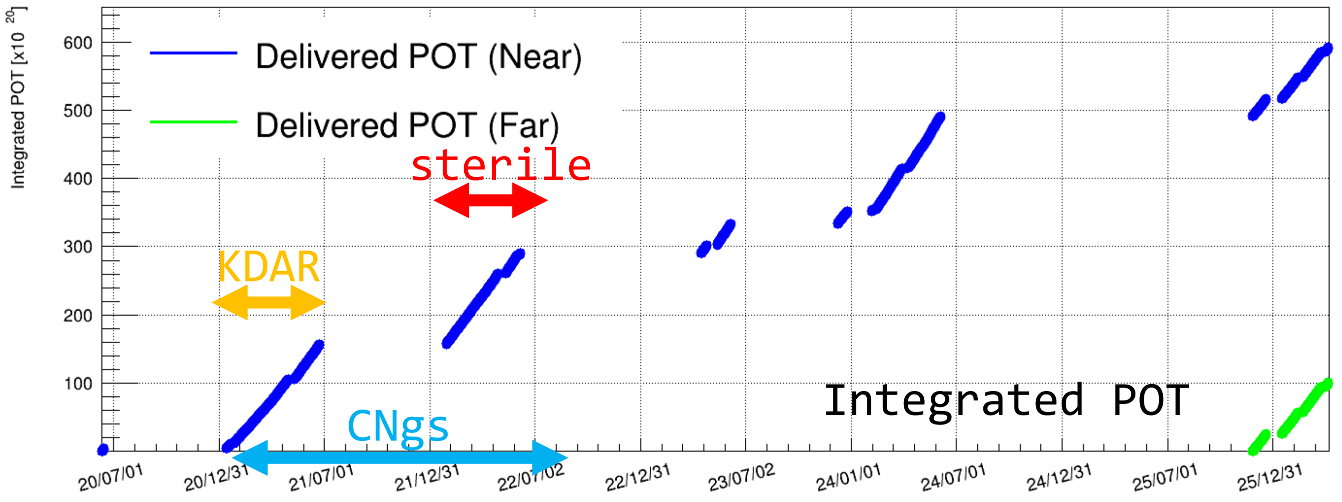
- Commissioning (2020)
- Five long term physics runs (2021-2026)
- New physics run (2025/Nov-)
- Analyses are on-going.
- The first result was published.
- New results with more than double POT will be shown at Neutrino 2026.

(JSNS^2-II):1 MW x 5 y

- Proposed in 2020
  - New far detector: fiducial 32 tons and 48 m location.
  - Two detectors with two different baselines -> a good access on LSND anomaly.
  - Good sensitivity on low Dm2 region. (oscillation case)
  - J-PARC/KEK granted the stage-2 approval in 2022.
  - LS was filled in Aug-2025.
  - Commissioning run with beam.

Current POT status





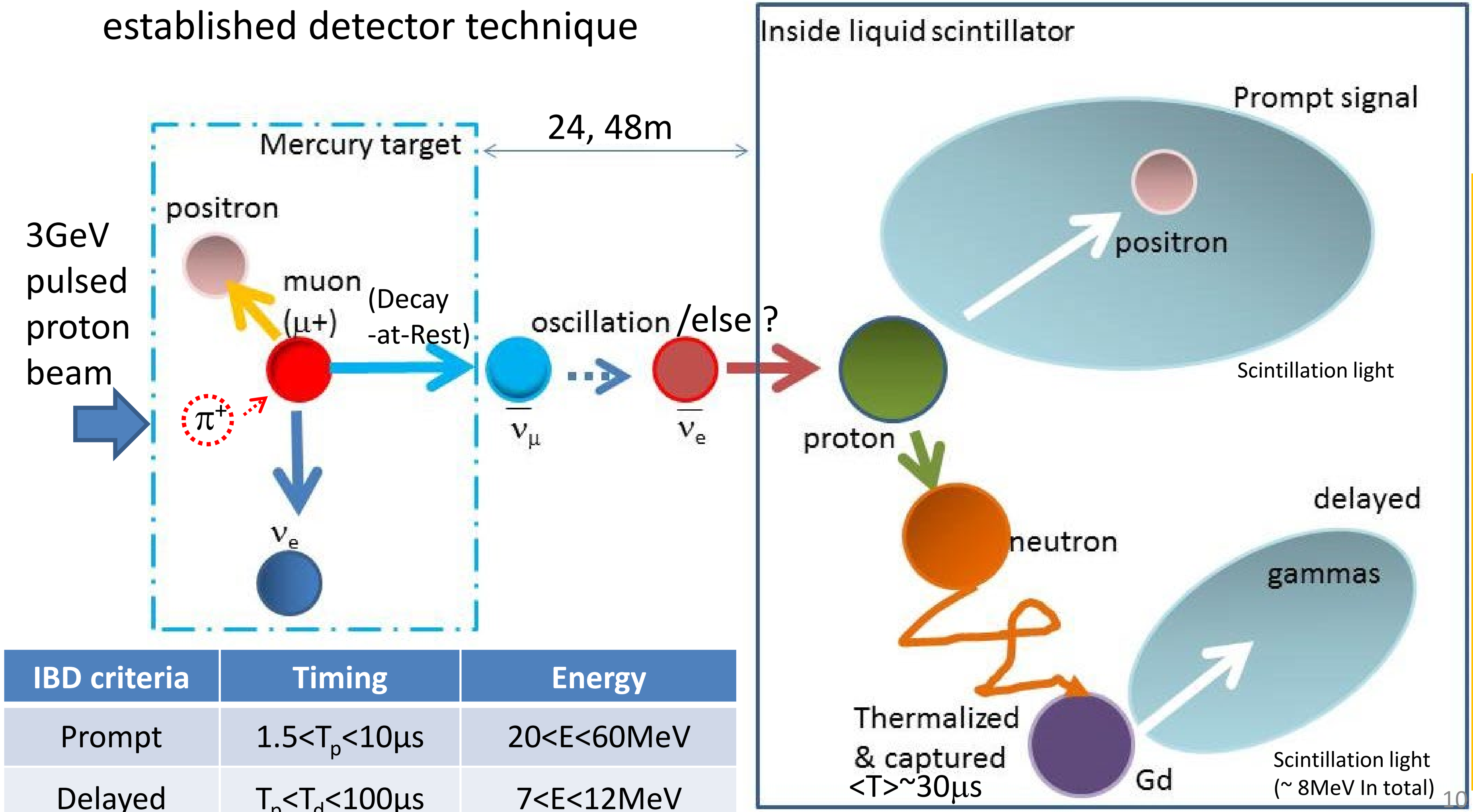
- Near detector :
  - The new physics run is on-going.
  - Accumulated delivered POT : 5.977 x 10^{22}
  - Publications using partial data were made. New results will be made with 2021-2024 data soon.
  - Light yield of liquid scintillator is kept within 6% for this 6 years.
- Far detector
  - We are performing the commissioning.
    - 1.127 x 10^{22} POT
  - Beam neutron background is larger than expected.
  - Currently, passive shields for this background is being optimized.

Near detector results

- Publications for physics
  - "First results from the search for an excess of nuebar events in JSNS2“, arXiv:2602.06274 [hep-ex] (also accepted by PRD)
  - The first JSNS^2 measurement of electron neutrino flux using $^{12}C(\nu_e,e^-)^{12}N_{g.s.}$ reaction : Phys. Rev. D 112, 032012 (2025)
  - "First Measurement of Missing Energy Due to Nuclear Effects in Monoenergetic Neutrino Charged Current Interactions“, Phys.Rev.Lett. 134 (2025) 8, 081801

Production / Detection for main search mode

- Large amount of parent $\mu+$ in Hg target → $\bar{\nu}_\mu$ are produced.
- If sterile ν exist, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation occurs with 24, 48m. Or other phenomena?
- Oscillated $\bar{\nu}_e$ is detected by Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$ w/ well established detector technique



IBD criteria	Timing	Energy
Prompt	$1.5<T_p<10\mu s$	20<E<60MeV
Delayed	$T_p<T_d<100\mu s$	7<E<12MeV

Most of them are same as the LSND.
→ Direct ultimate tests for LSND.

But use much better beam and Gd loaded LS.
→ Much better S/N
→ Much better systematics

Points of experiment / analyses

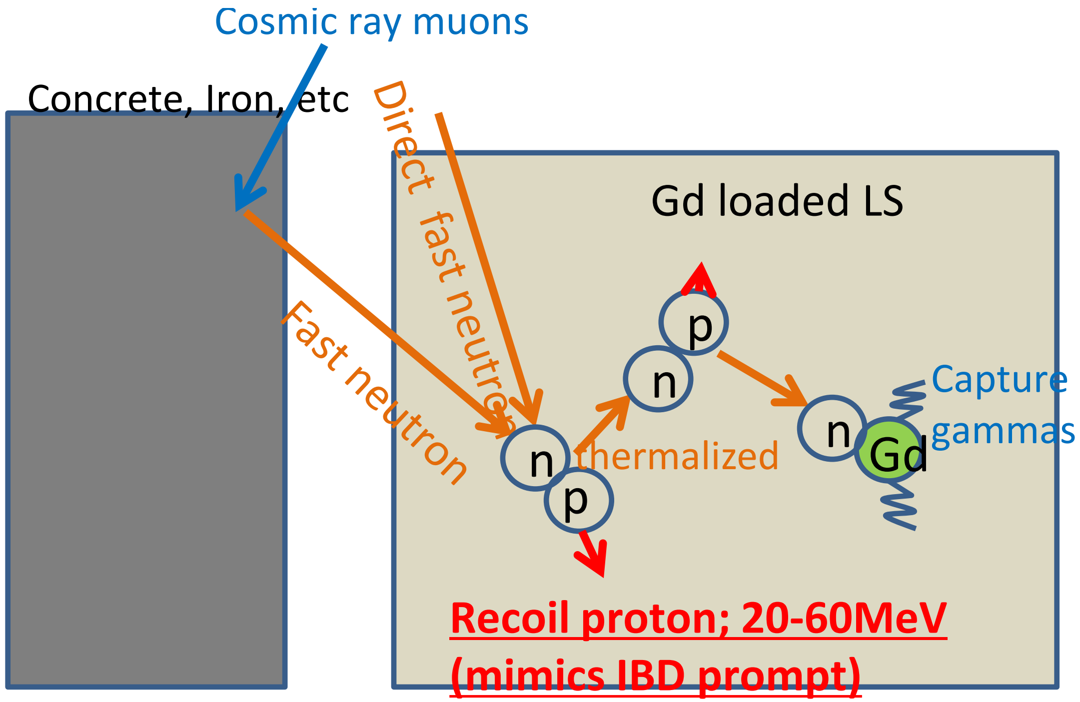
- The JSNS2 detector is located **above ground** → severe cosmogenic backgrounds. (rare opportunity to test "above-ground" neutrino experiment for a few 10 MeV neutrinos).
  - Main BKG1 : Accidental background:
    - Cosmogenic gamma (prompt) + gamma (delayed)
    - Control sample: Special calibration run (data, not MC)
  - Main BKG2 : Cosmogenic Neutron background:
    - Control sample : T_{beam} > 1ms (data)
- Even with a normal IBD selection, a typical signal-to-noise ratio is about 2-to-1000. (most of "1000" are due to neutrons).
  → how to reduce the neutron BKG is a key.
  → Pulse-Shape-Discrimination (PSD) + likelihood are essential.
  → **~1/1000 reduction was achieved.**

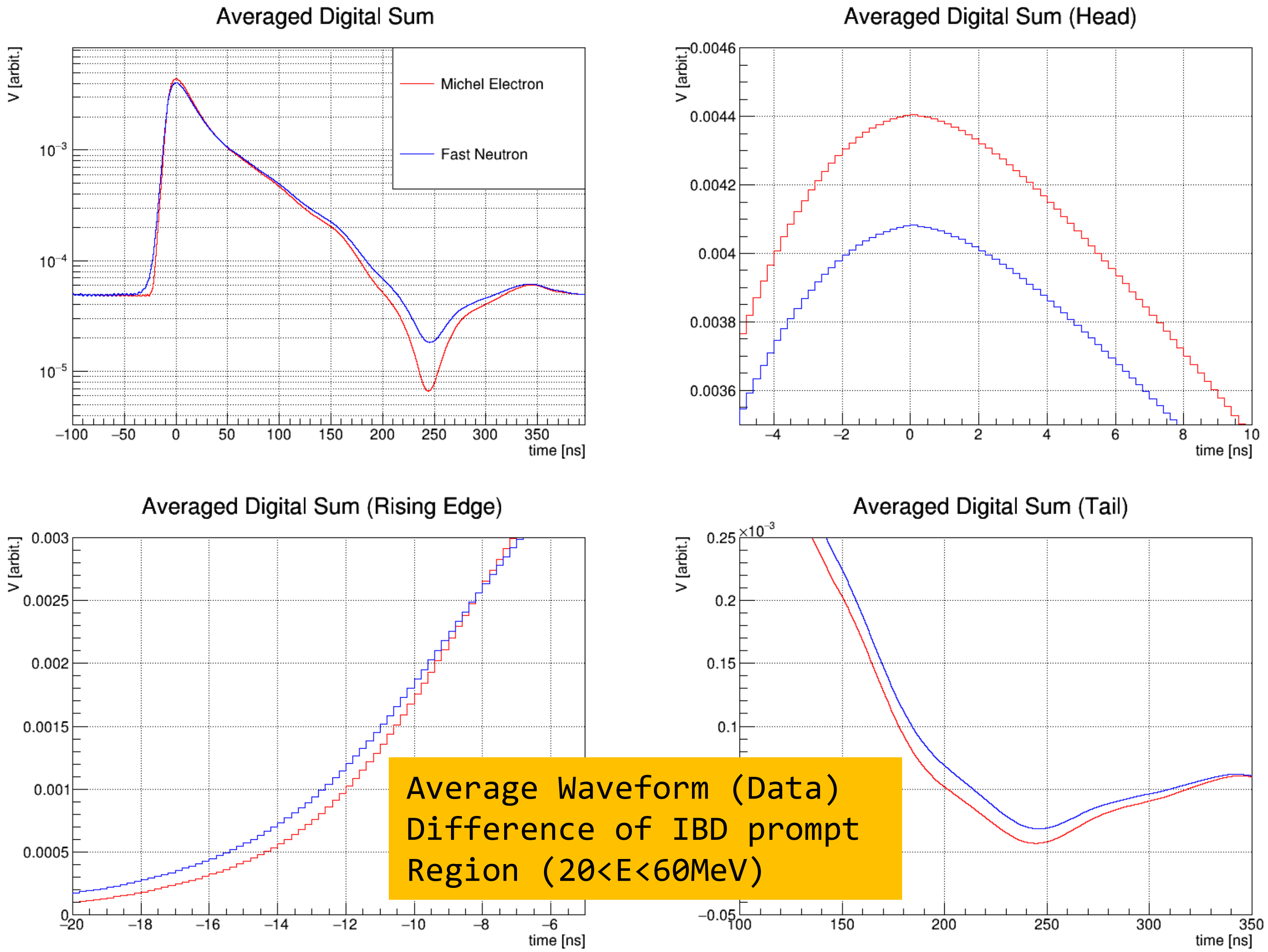
- Using energy **side-bands**, very careful analyses to understand backgrounds have been performed. (not shown in this talk though)
- To validate the methodologies, only **2022 data (0.8 x 10^{22} POT)** is used at first. → update with doubled data in Neutrino 2026.

PSD for neutron rejection (reminder)

Fast Neutrons are severe background because it is “correlated” BKG.

Pulse Shape Discrimination separates the IBD signals and fast neutrons.



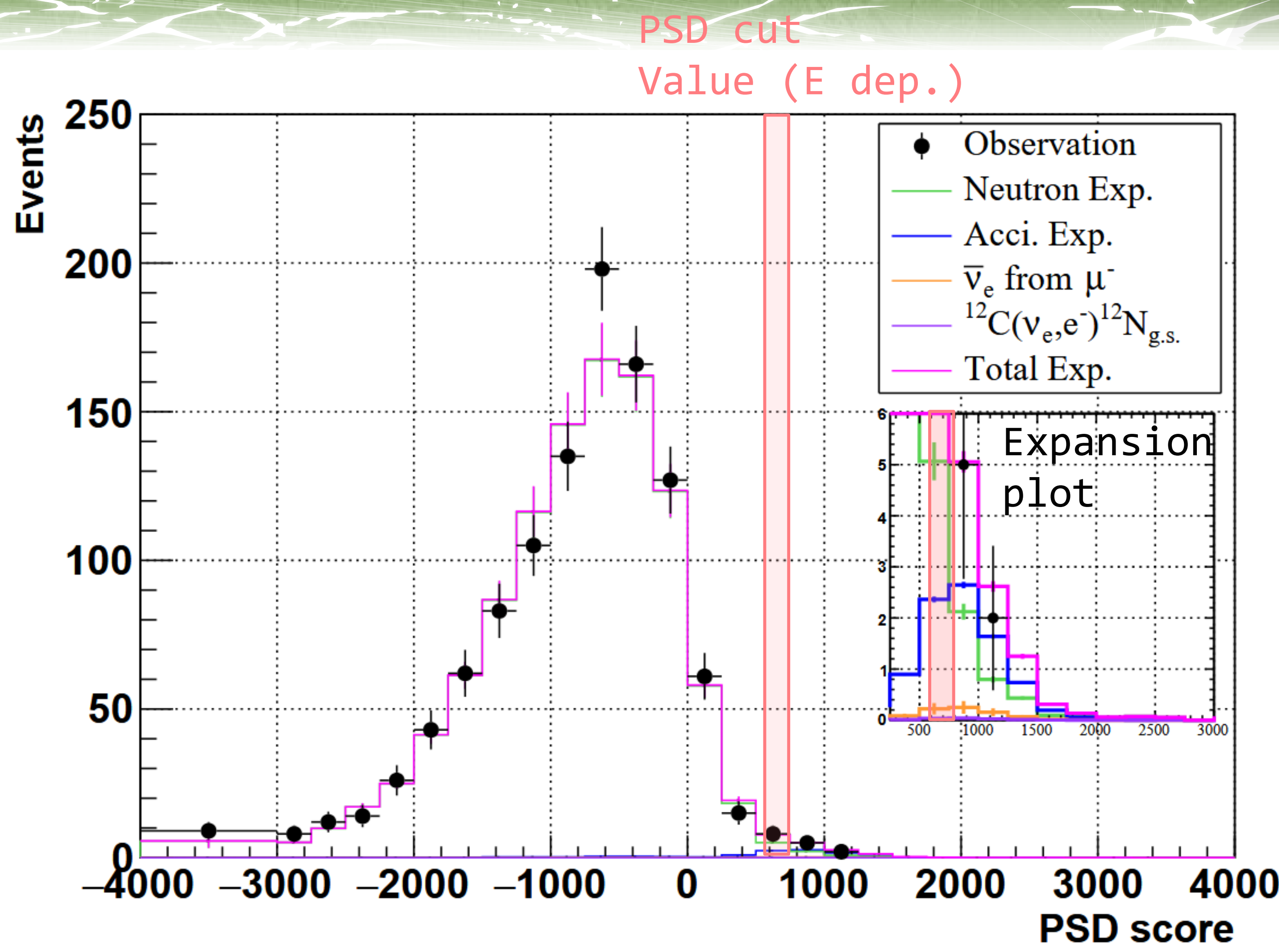


Average Waveform (Data)
Difference of IBD prompt
Region (20<E<60MeV)

- We have a few methods to distinguish these waveforms.
- Goal: factor 100 rejection of neutrons

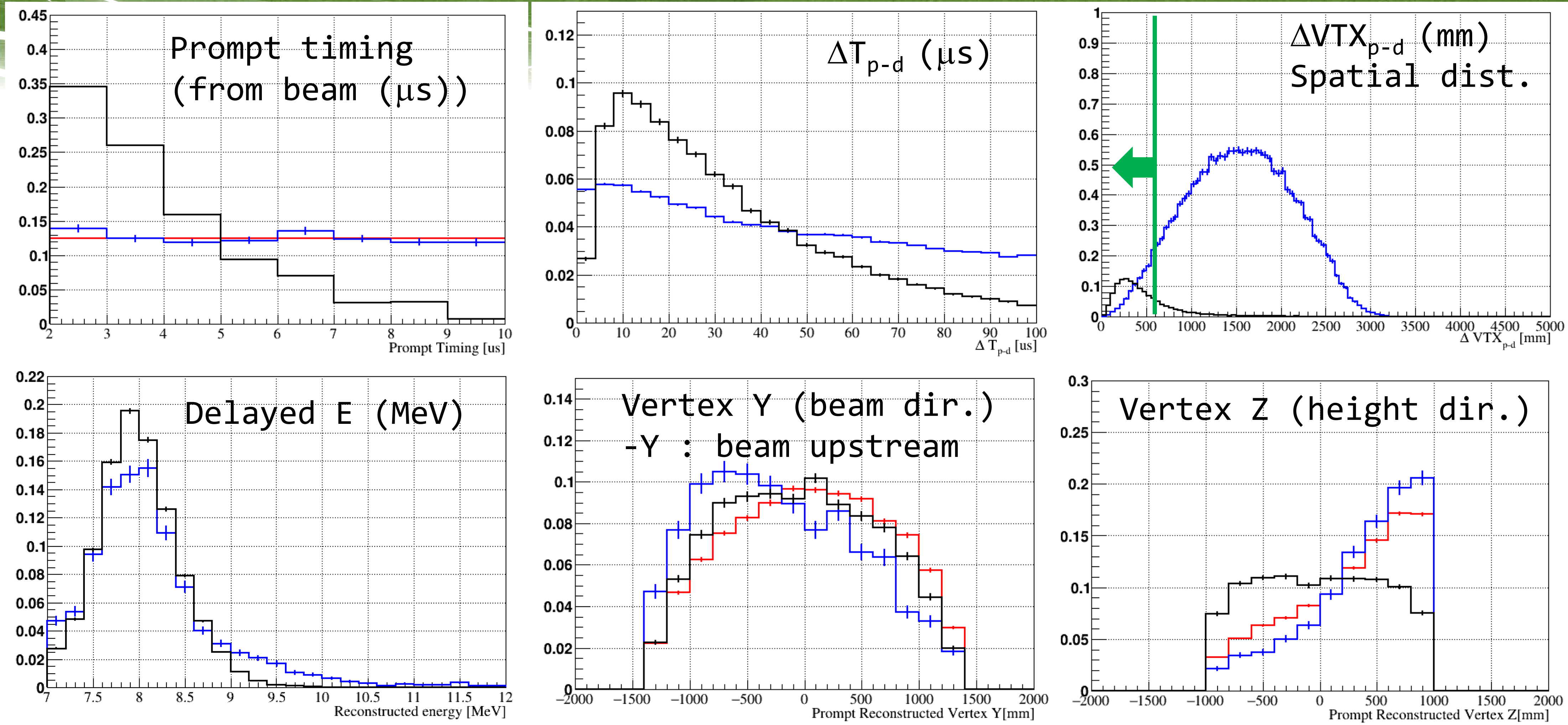
Application of PSD

- PSD
  - ~99.7% reduction of neutrons
  - 87.2+-9.1% efficiency for IBD
- Good agreements between observation and prediction in the entire score region
- Observed 10 events
- Prediction: 11.2+-0.7 ev.
  - Neutron: 3.0+-0.4
  - Accidental: 7.2+-0.1
  - Intrinsic: 0.9+-0.5
  - CNgs : 0.1+-0.04
- No excess is seen w/ this stat.!



Likelihood (timing/vertex/energy)

signal
Acc.BKG
neutron

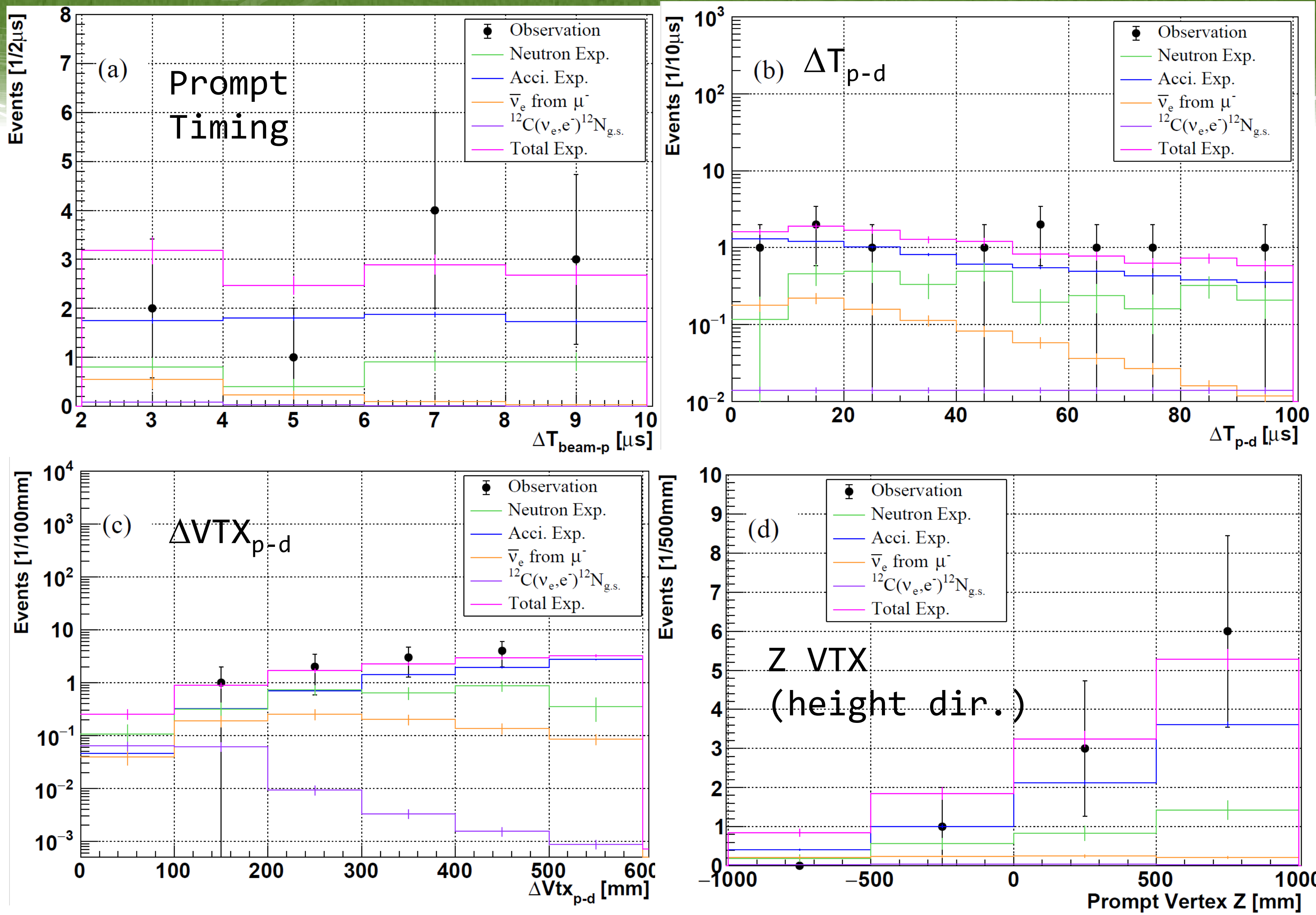


ΔT,ΔVTX,
Delayed E:
Neutron PDF
= signal PDF

- PDFs: Neutron (made by control sample), Accidental(control sample (data)), signal(MC)
- Backgrounds: neutrons (pure cosmogenic), accidental (prompt : pure cosmogenic, delayed : half beam n, half cosmogenic)
- Cosmogenic BKG:: timing; no correlation with beam. Vertex : from upward to downward.

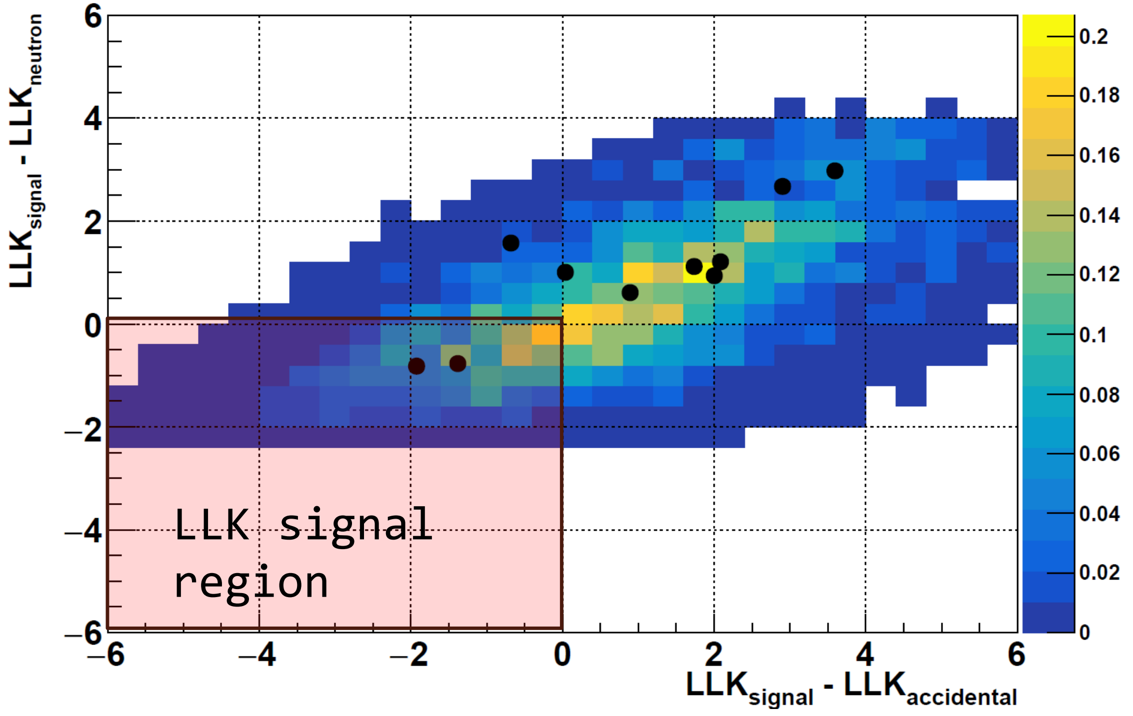
Variables after PSD

- 4 important variables are shown here.
  - Prompt timing (w.r.t. beam)
  - $\Delta T_{p\text{-}d}$
  - $\Delta VTX_{p\text{-}d}$
  - Z vertex
- Background only predictions explain the observations at this stage.



Application of LLK

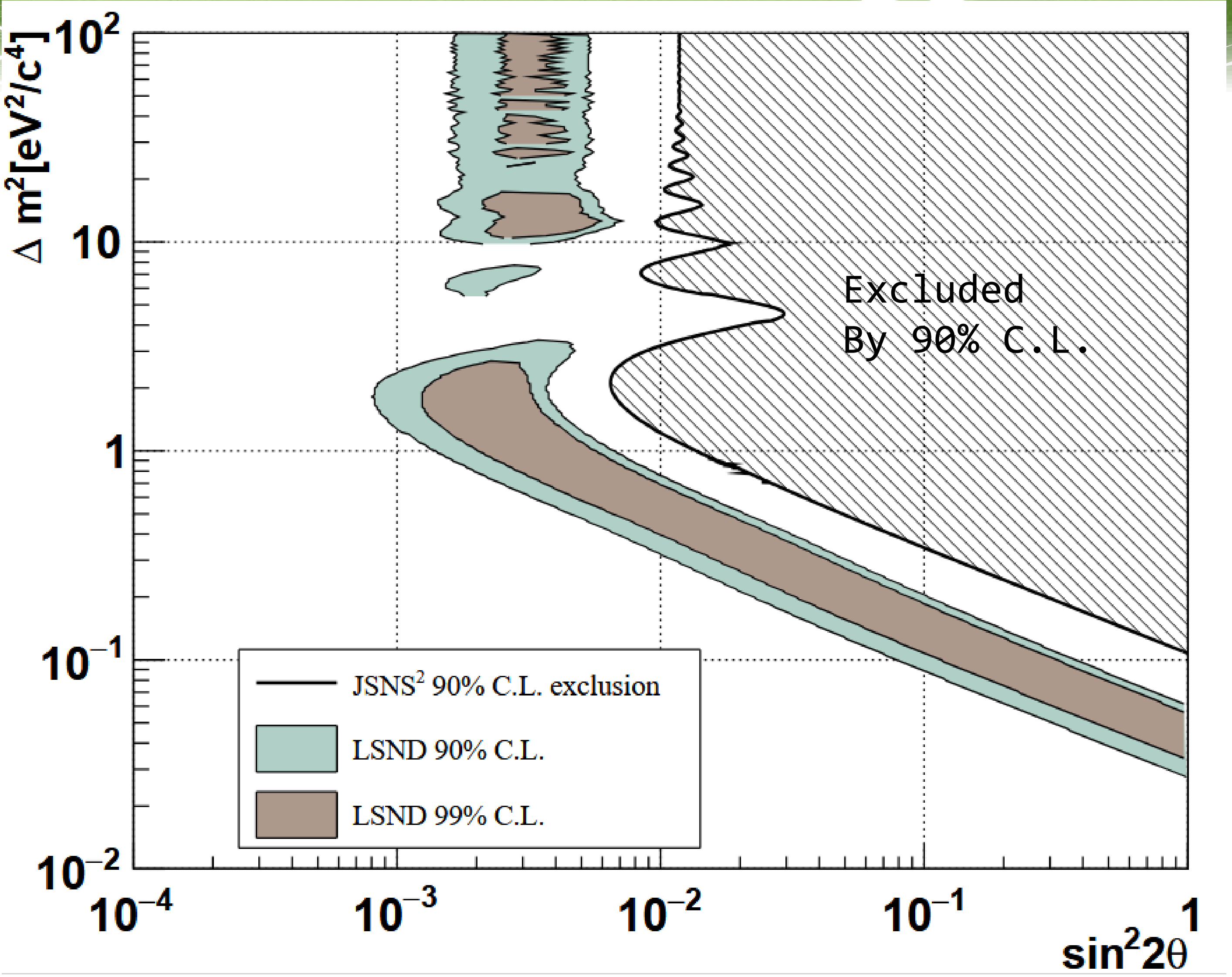
- LLK was applied after PSD
- 2 events are observed.
- 2.3±0.4 events are expected by background.
  - Neutron : 0.6+-0.2 events
  - Accidental : 1.0+-0.01
  - Intrinsic beam anti-nue: 0.6+-0.3
  - CNgs : 0.08+-0.02
- 2D distribution of data agrees the expectation with background only.
- Currently, it is difficult to discuss 1.1±0.5 events (LSND anomaly) statistically.
- However, **<u>this is a good starting point for future</u>**.



LLK:
84% rejection for accidental BKG.
70% rejection for neutron BKG.
71% efficiency for IBD signal.

Interpretation to neutrino oscillation

- Our results are worth while to compare to LSND in the $\nu_\mu \to \nu_e$ oscillation contour because of direct comparison.
- Excluded region is shown as shaded region.
  - Feldman-Cousin limit is used here.
- It does not reach to the LSND allowed region at this moment, but the nice starting point.



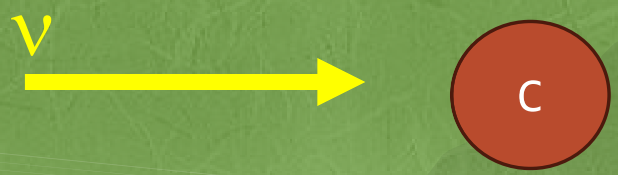
Future prospects

- Compared to LSND, ~6 times #ν/proton is available (due to proton energy) in JSNS².
  - On the other hand, a fiducial volume is 10 times smaller, a detection efficiency is 3 times smaller.
  - The JSNS2 fiducial volume will be extended. (by 1.7 times maximally) by analysis.
  - Efficiency : a few 10% can be improved. (trigger improvement (~20% increment) was already done)
  - Finally, statistics power / proton will be comparable to LSND.
- We already accumulated data, 7 times more than the current 2022 data analysis. (JSNS² phase 1 will accumulate the data 14 times compared to 2022 only)
- A new far detector will be used to check the distance dependence.

Cross section measurements using Mono-energetic neutrinos (~236 MeV)

→ 3 GeV (proton) exceeds the energy threshold to produce of Kaons. (MLF provides a unique opportunity)

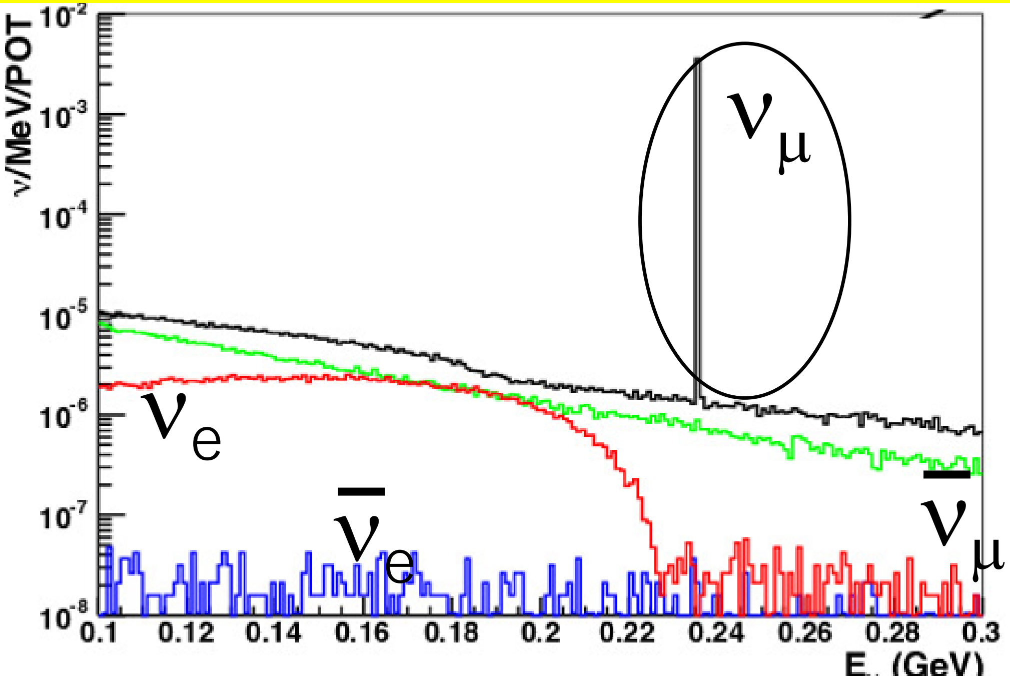
Phys. Rev. Lett. 134, 081801, 2025
(21 citations @ 2026/5/19)

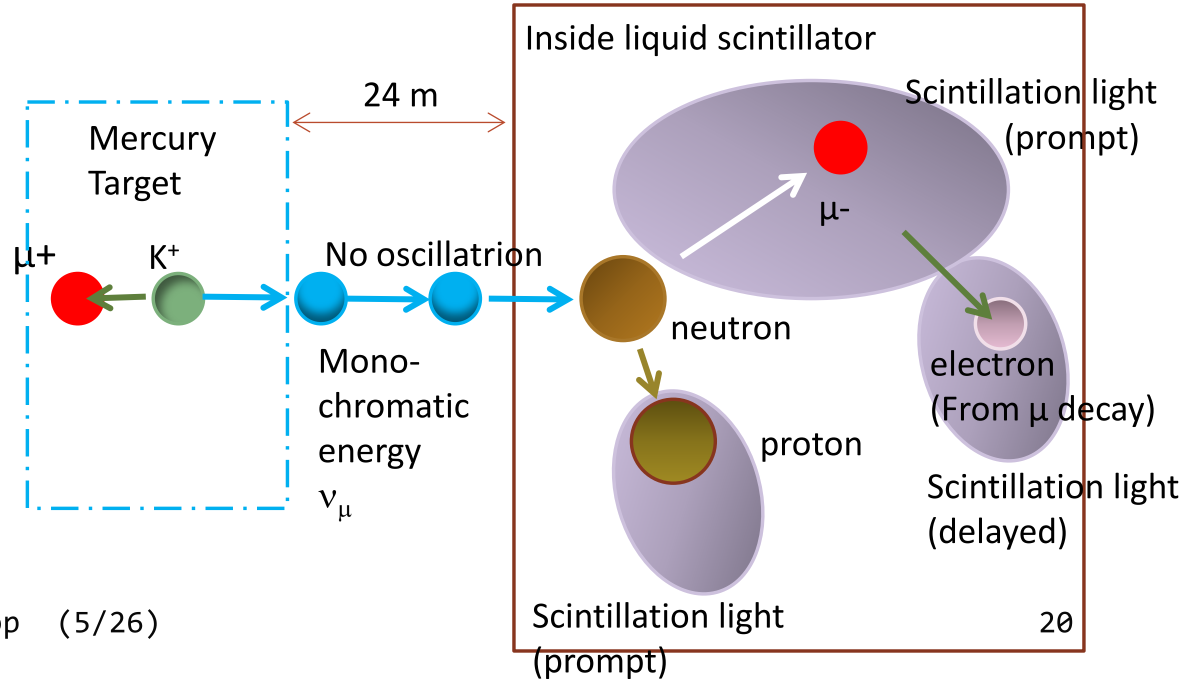


KDAR (Kaon Decay-At-Rest) ν

- Mono-energetic muon neutrinos from Kμ2 (decay-at-rest) gives a rare opportunity to investigate the quasi-elastic interactions and their effects from nucleus. (e.g.: FSI, etc..)
- In neutrino experiment, the horn focused beam provides wide neutrino energy, while JSNS^2-II has small DIF background.

ν energy from K$^+$ DAR (Kμ2): monochromatic

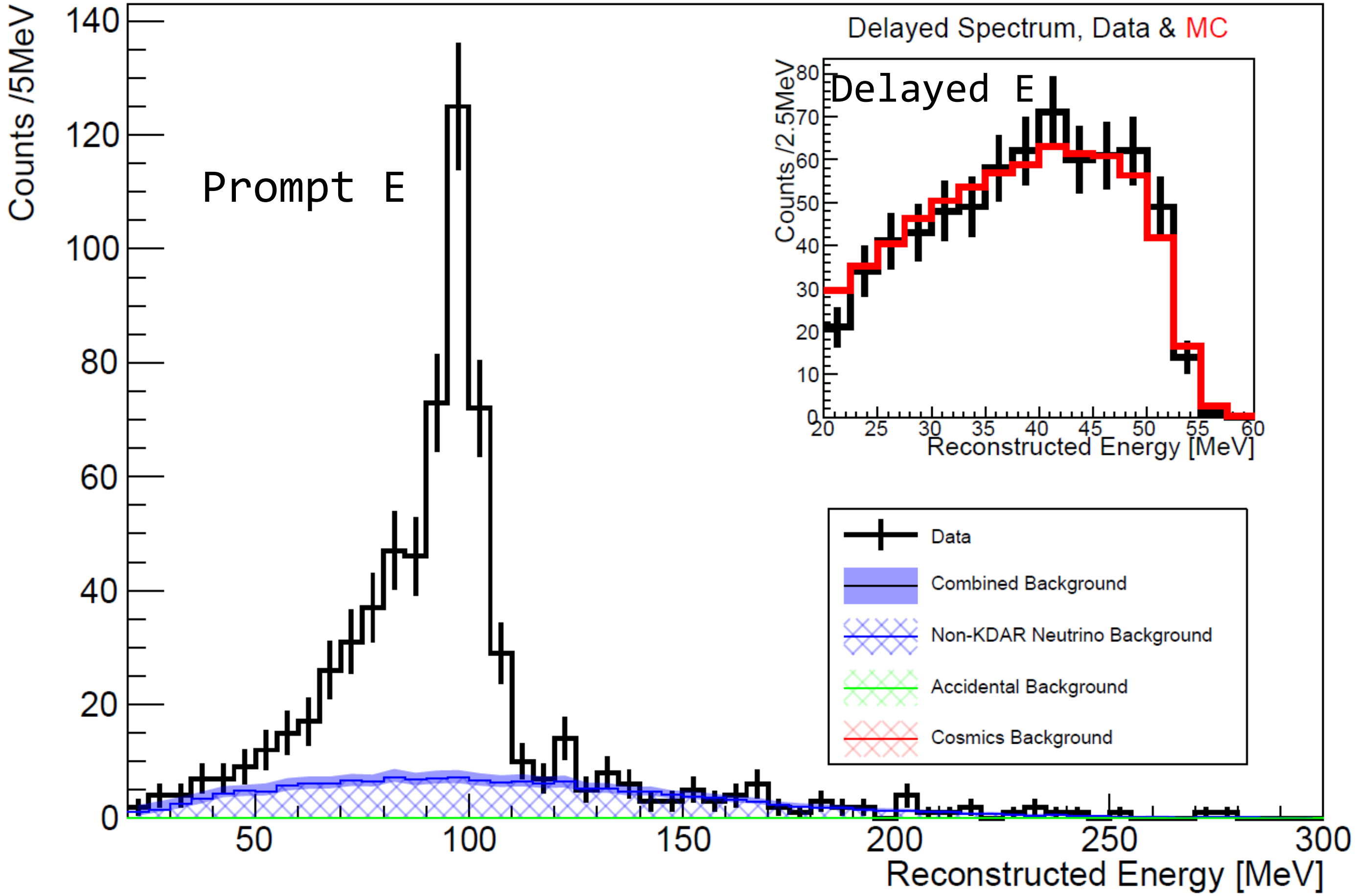




Selection / background

- Backgrounds are dominated by "non-"KDAR neutrinos. (DIF) => subtracted by MC and shape fit.

observed energy : 2021 data only 1.4 x 10^{22} POT

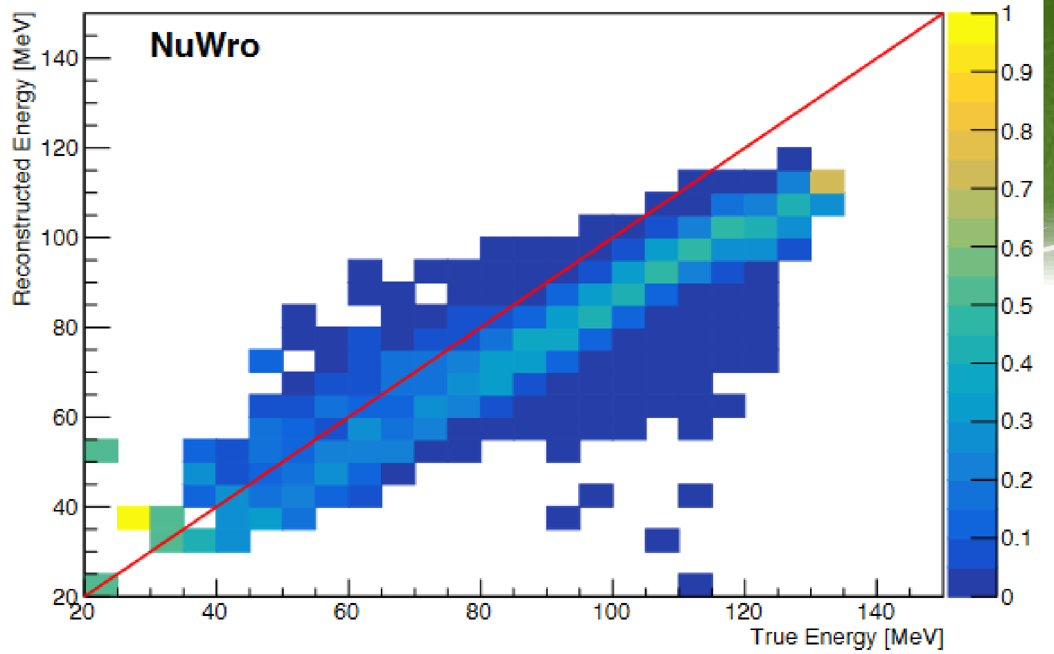


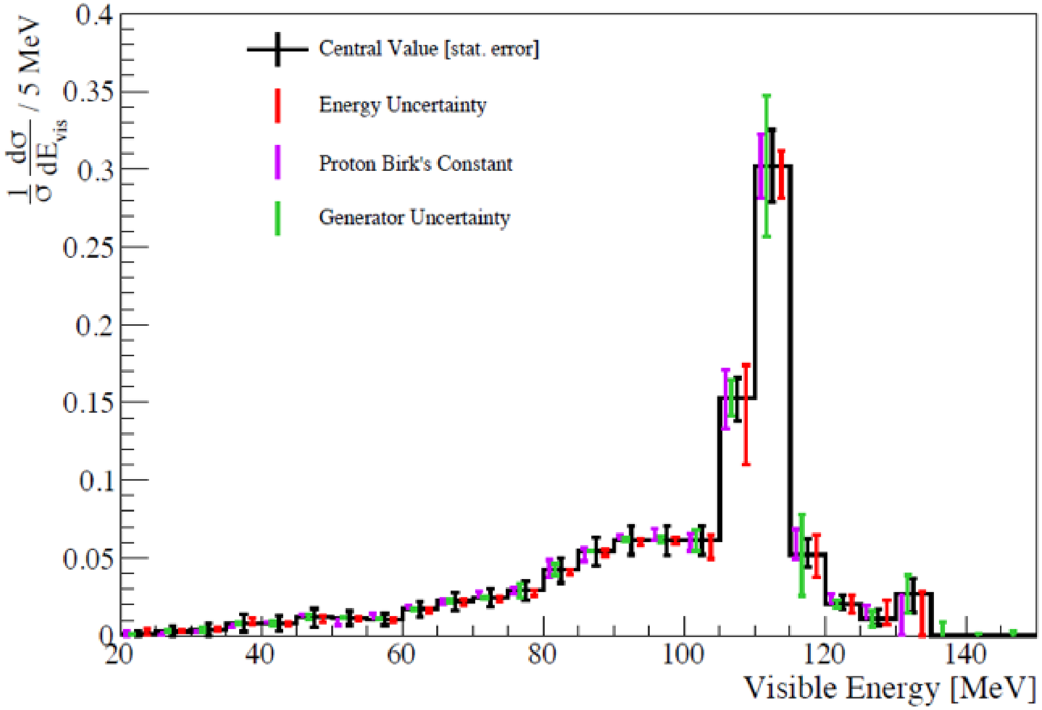
621 selected events
(144+-21 is BKG.)
(20-150MeV)

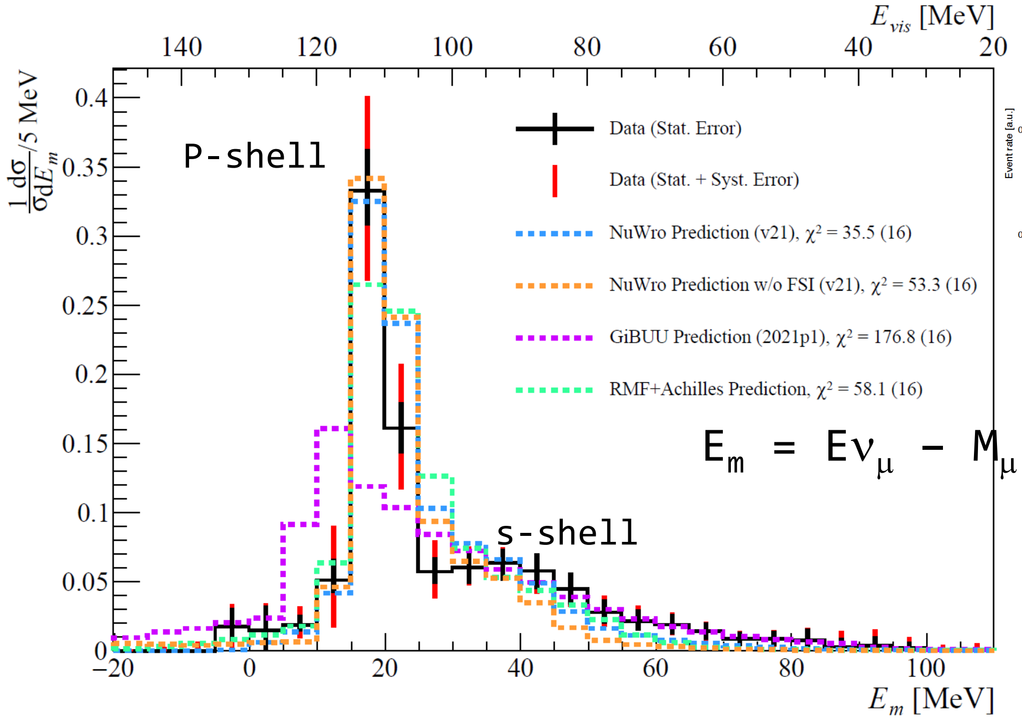
	Prompt	Delayed
Energy	20-150 MeV	20-60 MeV
Timing	2x150ns Beam centered windows	Δt < 10μs
Position	Fiducial Volume: R<1400mm -1000mm < z < 500mm	ΔVertex< 300mm

KDAR results

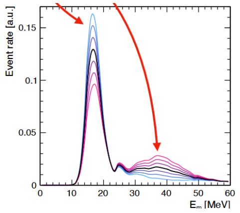
- Energy unfolding (removal of detector effects) was done by MC. (true E vs observed E matrix)
  - Iterative Bayes (D'Agostini) method was used.
  - Matrix on True Evis vs reconstructed energy was made by KDAR MC (top-right).
  - Shape only measurement. (K production rate is unknown in Hg-p (3GeV).
- The largest systematic uncertainty is coming from generator dependence.
  - **Balance of muon / proton energy** gives large difference. (proton gives different response from MIP like particles)







$E_m = E\nu_\mu - M_\mu - E_{vis}$



Prospects for KDAR

- Currently, analysis with 2021-2024 data is on-going. (better stat, improvements of techniques)
  - One US team (including one Ph.D student) is working for this.
- KDAR + neutron is also being discussed. (FSI, etc)
- Discussing with various groups on MC for neutrino interactions such as Nuwro.
  - Contacted to the person who is in charge to use NEUT.
  - Hopefully, $JSNS^2$ knowledge of KDAR can be useful for long baseline neutrino experiments also. (to reduce systematic uncertainties of ν interactions)

Summary

- A direct (model independent) test for the LSND anomaly is important in neutrino community.
  - JSNS^2-II is a unique program to test this with 2 detectors in the world.
  - Also complementary with other programs to test other short baseline anomalies.
- We opened the 2022 data.
  - 2 events are observed, while 2.3±0.4 background events are expected. (1.1+-0.5 LSND events are expected)
- Further improvements on the fiducial volume, efficiency and accumulated data will give crucial test very soon.
  - Also the new data is being accumulated now.
- The far detector : under commissioning phase.
  - The dependence of the baseline will be discussed.

Thank you for your attention !!

acknowledgements:

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

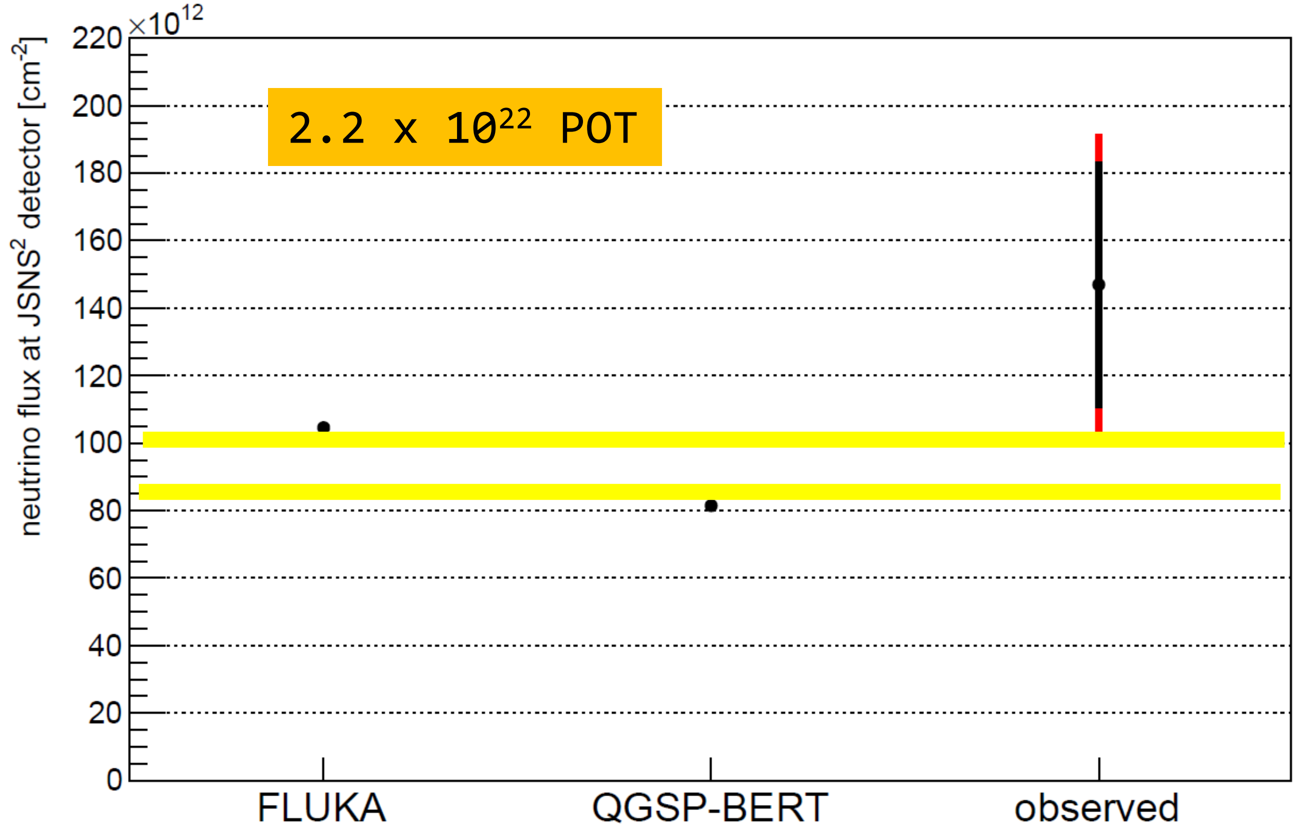
Also JSNS^2/JSNS^2-II deeply appreciate
→ Donation of GdLS / LS from Daya-Bay
→ Donation of PMTs / LS from RENO
→ Donation of PMTs / electronics from Double-Chooz

Backup

neutrino flux via $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$

- Cross section: σ
  - Averaged cross sections from KARMEN / LSND is used.
  - $(9.1 \pm 0.7)\times 10^{-42}$ cm^2
- Number of ^{12}C : N_{target}
  - 10.7 tonnes of GdLS+DIN in fiducial
  - DIN concentration is 10% (vol.)
  - $(4.68 \pm 0.37) \times 10^{29}$
  - Error is dominated by fiducial volume determination. (arXiv:2404.04153)
- Efficiency : ε
  - Averaged ε in 2021 and 2022 is 5.88+-0.21%

- **$(1.47 \pm 0.36(stat) \pm 0.26(syst)) \times 10^{14}$ /cm^2 (obs) vs 1.05×10^{14}(FLUKA), 0.82×10^{14}(QGSP-BERT)**
- Stat error is dominated. (~24%)
- Dominant systematic error is ~11% from methodology to estimate Nbkg.

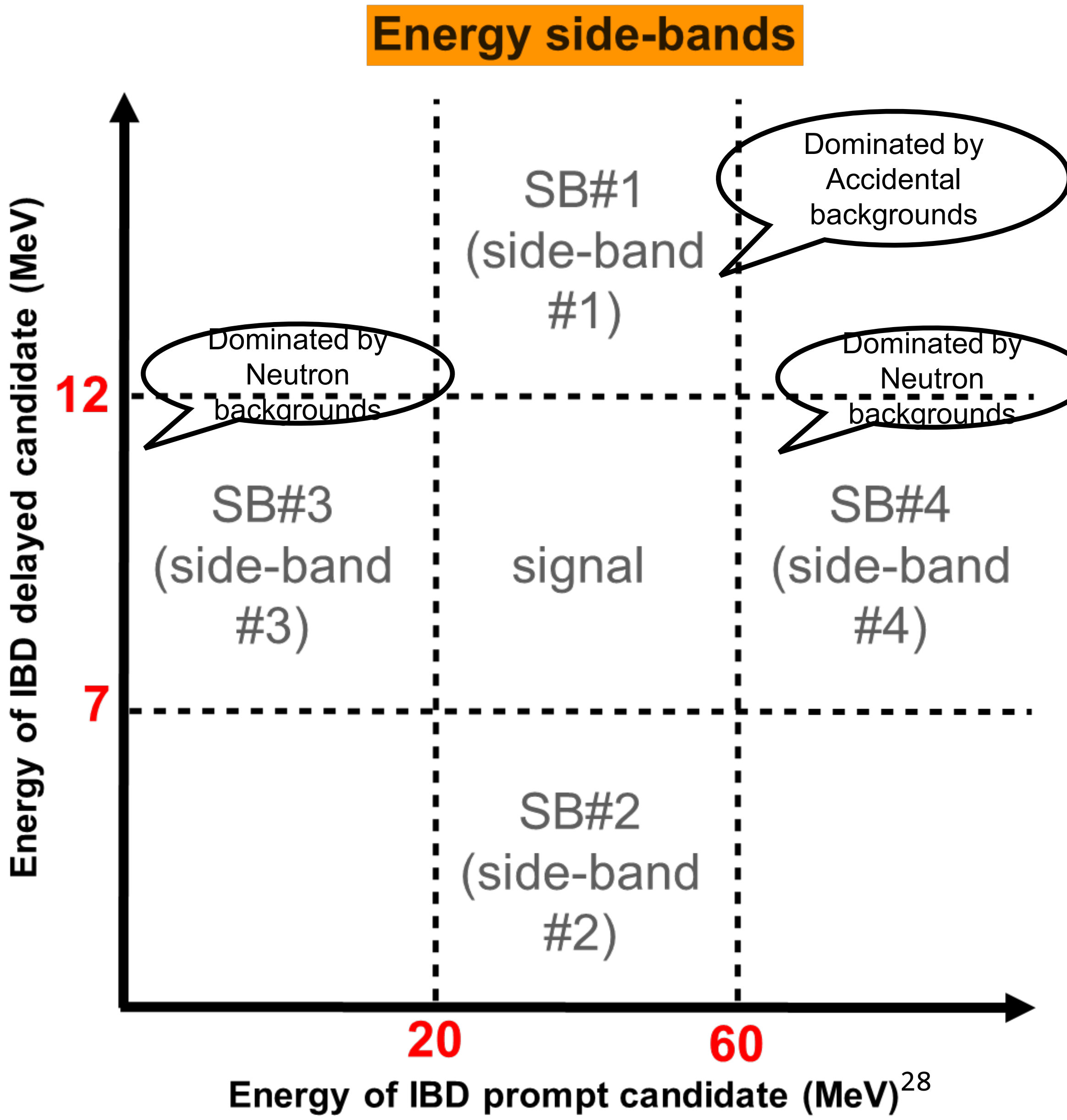


$$N_{eve} = Flux \times \sigma \times N_{target} \times \varepsilon$$

$$Flux = N_{eve} / (\sigma \times N_{target} \times \varepsilon)$$

The sterile neutrino search (Blind analysis)

- Only 2022 data (0.8 x 10^{22} POT) is used.
- Accidental background:
  - gamma (prompt) + gamma (delayed)
  - Control sample: Special calibration run (data, not MC)
- Correlated background:
  - Most of them are due to neutrons
  - Control sample : T_{beam} > 1ms (data)

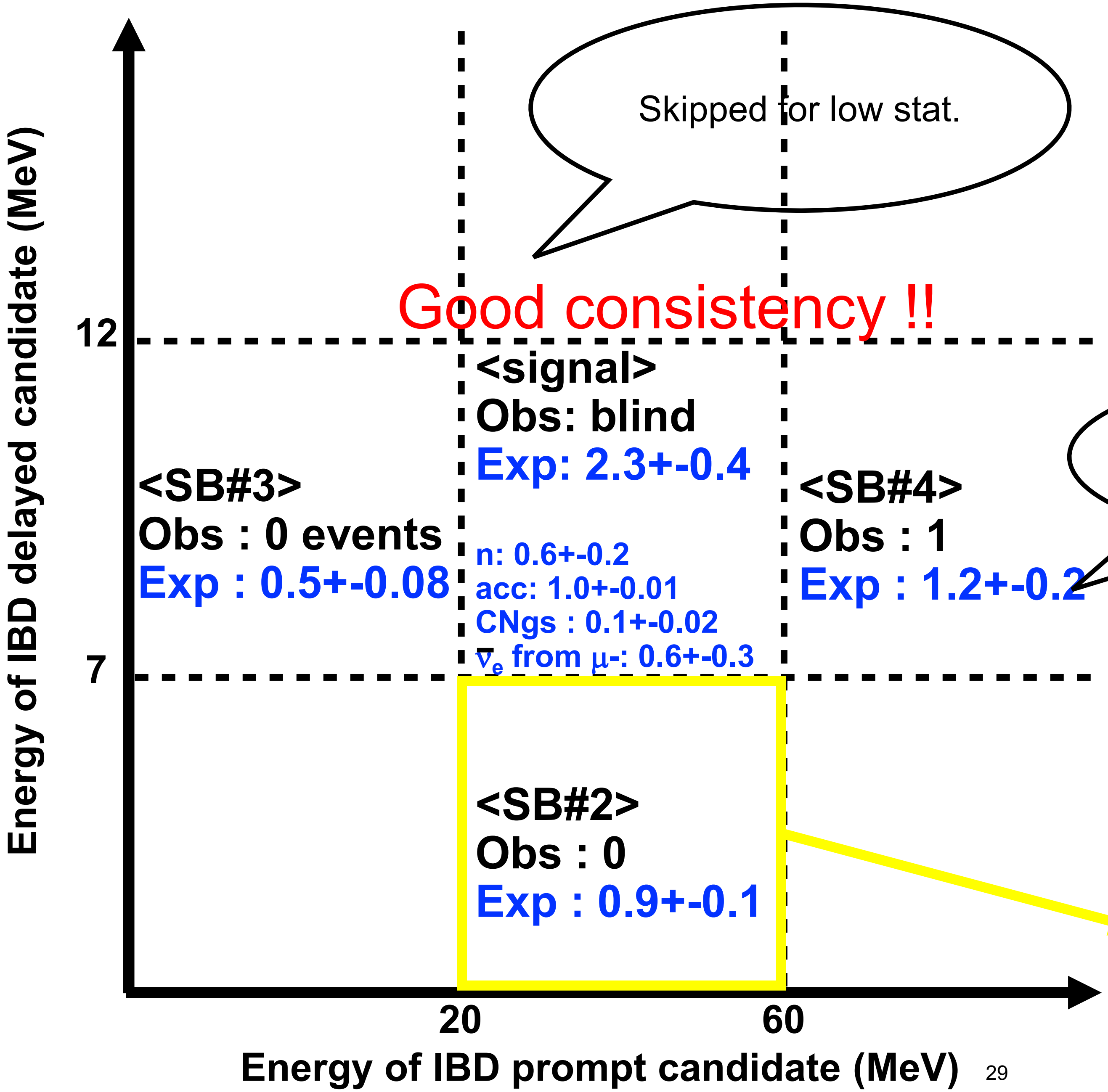


After spatial+PSD+LLK

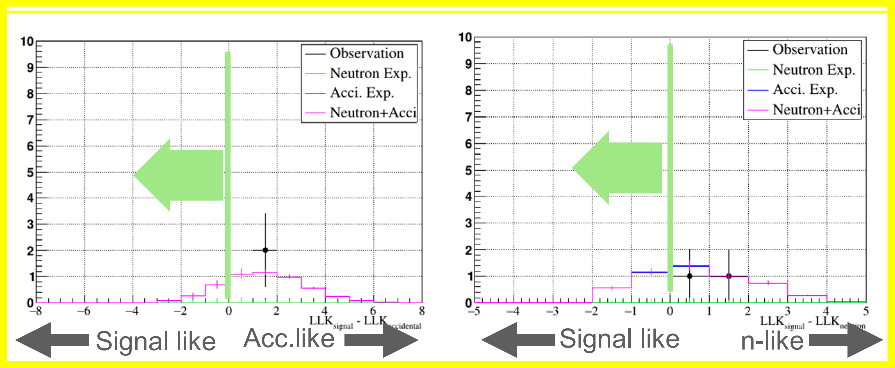
Energy side-bands

- 3 side-bands + signal region

Good consistency !!



Example of LLK score (SB#2 after PSD)

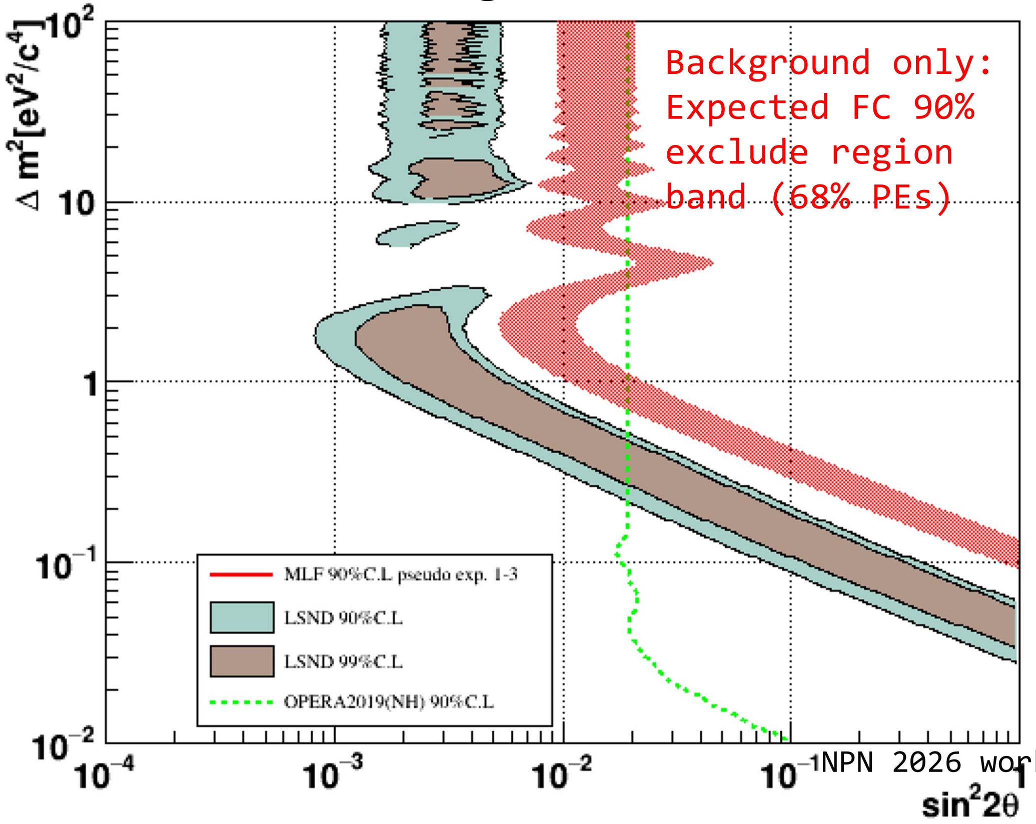


Expected exclusion region (2022) and future sensitivity

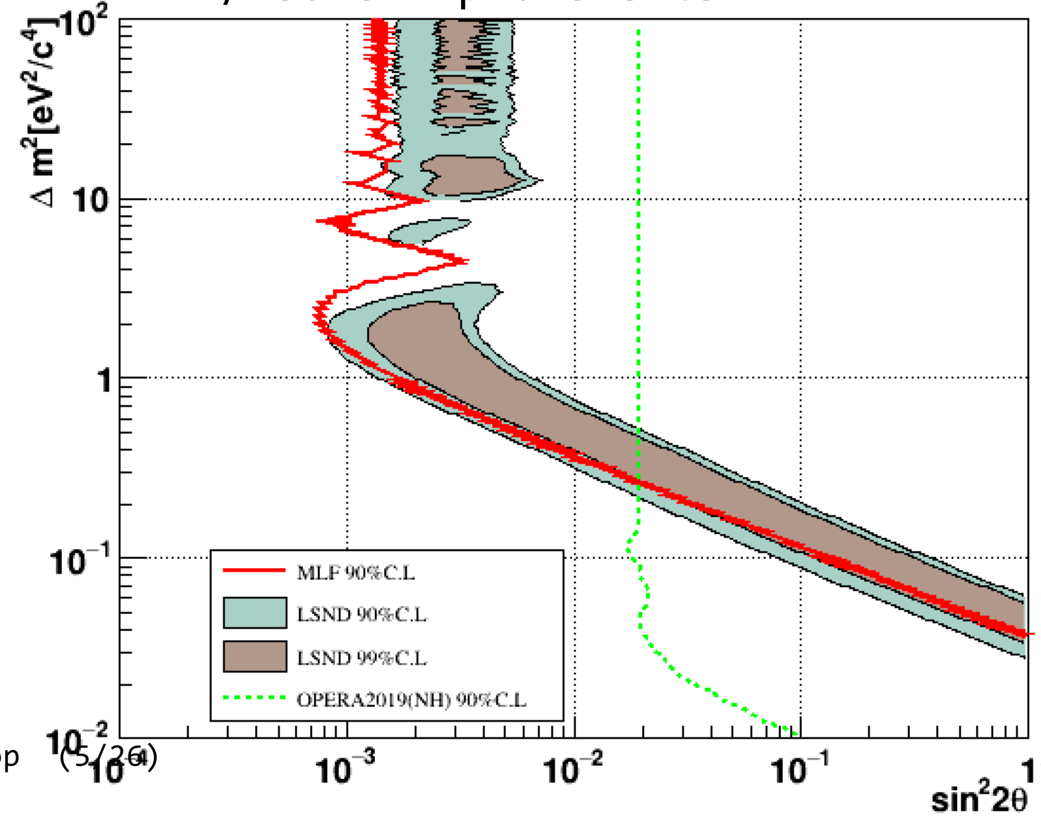
- bottom-left : expected 90% C.L. limit using Feldman-Cousin method (for 68% experiments)
  - Background only hypothesis.
- Full POT sensitivity (right) is comparable to JSNS2-I TDR after some more improvements.
  - Efficiencies, fiducial extension, π- production rate measurement

#Spill x beam power	POT	Signal(LSND best fit)	$\overline{\nu_e}$ from μ-	neutron	accidental
$1.35 \times 10^9 \times 1\mathrm{MW}$	1.14×10^{23}	39.5 ± 0.4	20.8 ± 2.1	15.6 ± 3.8	21.7 ± 0.2

2022 only expected 90% C.L. exclusion region



Full POT sensitivity for JSNS2-I w/ some improvements

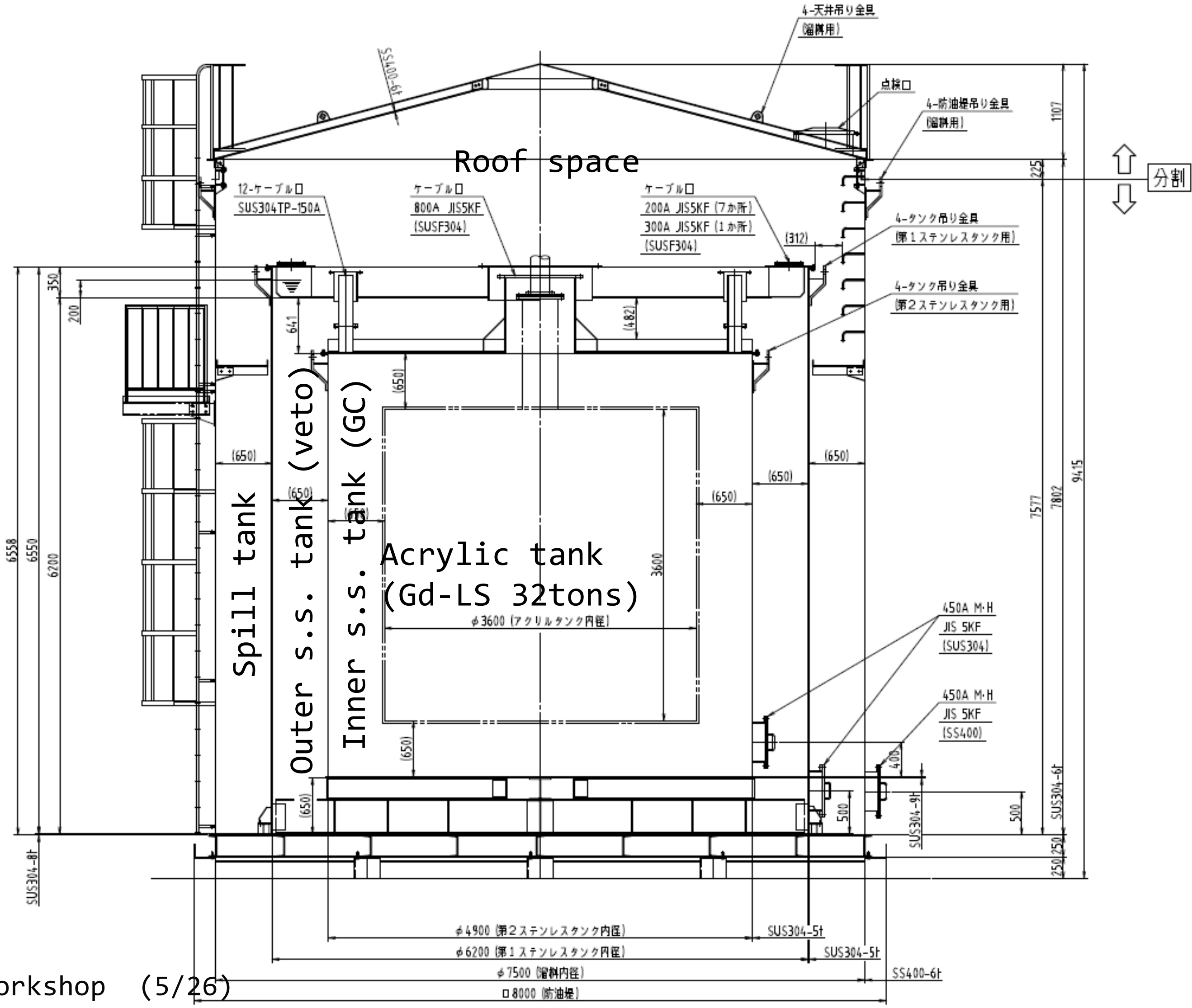


Far detector

- Publication to journal
  - PMT calibration for the $JSNS^2$-II far detector with an embedded LED system : JINST 20 T10003 (2025)

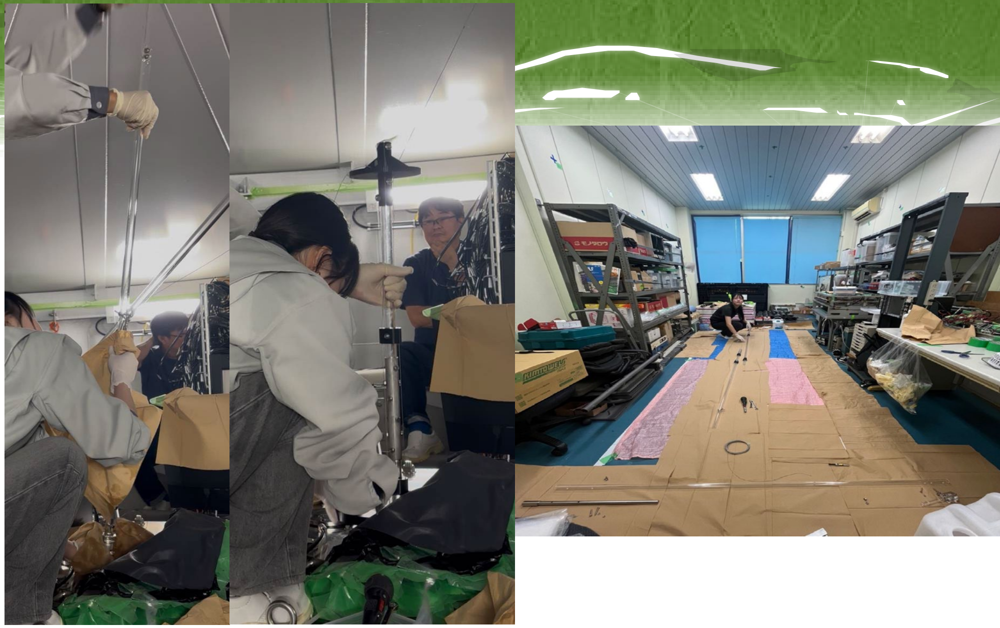
New far detector (reminder)

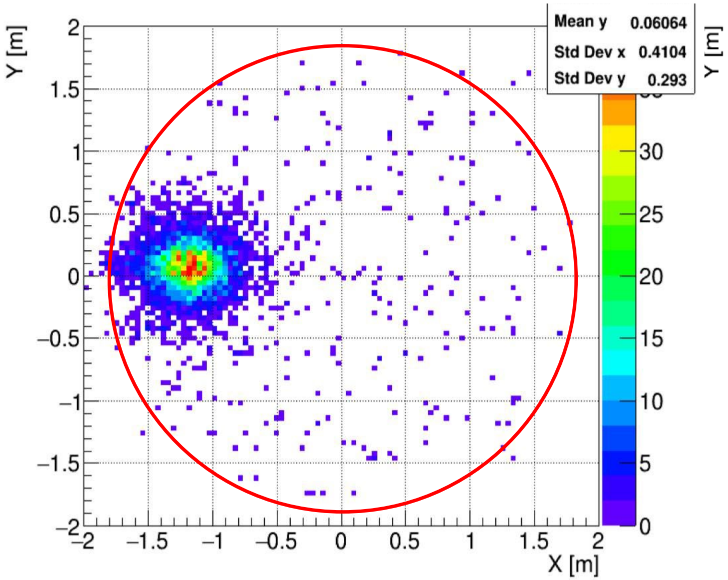
- Design: almost identical to the existing near detector.
  - 37 m^3 Gd-LS for the neutrino target
  - 150 m^3 no Gd-loaded LS for the veto and gamma catcher. Linear AlkylBenzene (LAB) based Liquid scintillator.
  - 228 PMTs will be used
- Electronics in the "roof space" with air conditioner to keep 18-28 C
- Construction Status:
  - Going well. See slides later.

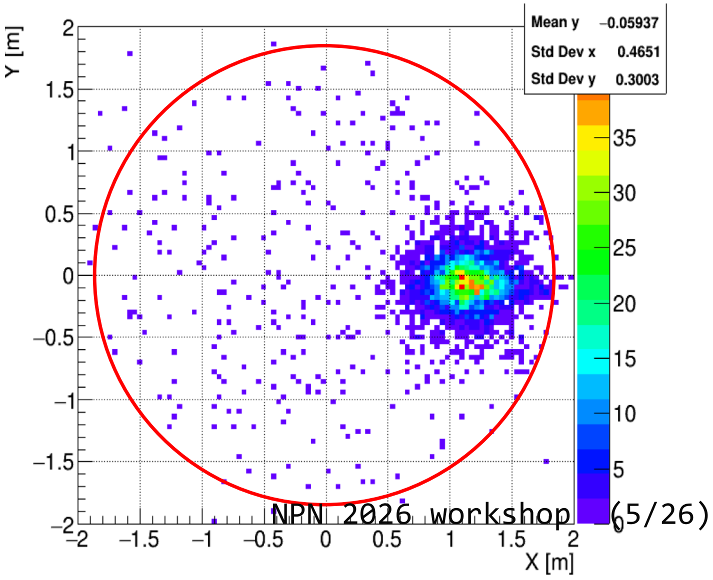


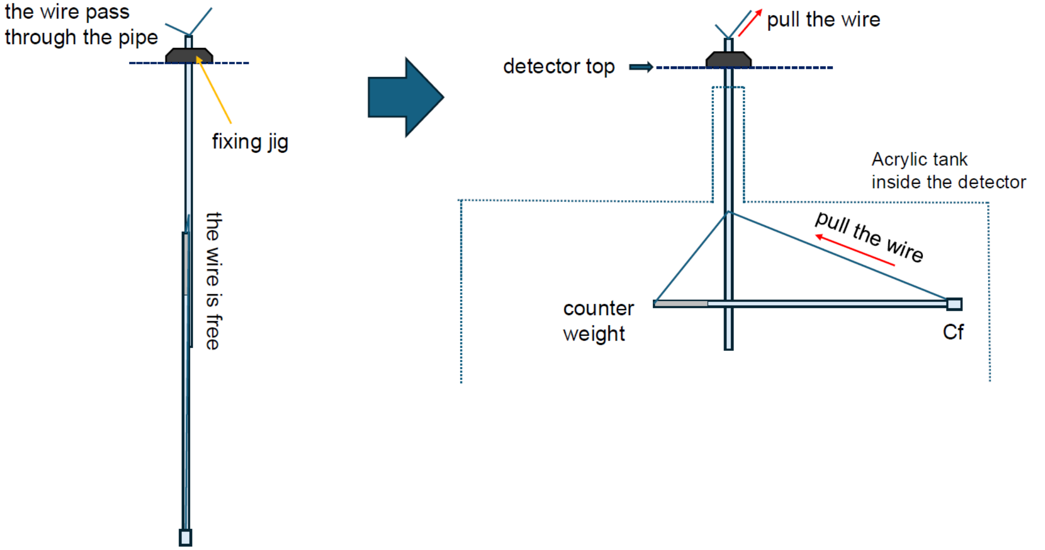
3D ^{252}Cf calibration at far detector

- R=1200mm (3 phi) positions were tried.
- The first results look good at the glance level.
- Quantitative Details are under investigation.
- (One master thesis was written on this topic.)









Beam neutron BKG (1)

- We saw beam neutrons more than expected.
  - One source is BL05. (one of neutron beamlines)
  - The other is from more downstream than muon target
  - Issue for the JSNS2-II neutrino physics program.