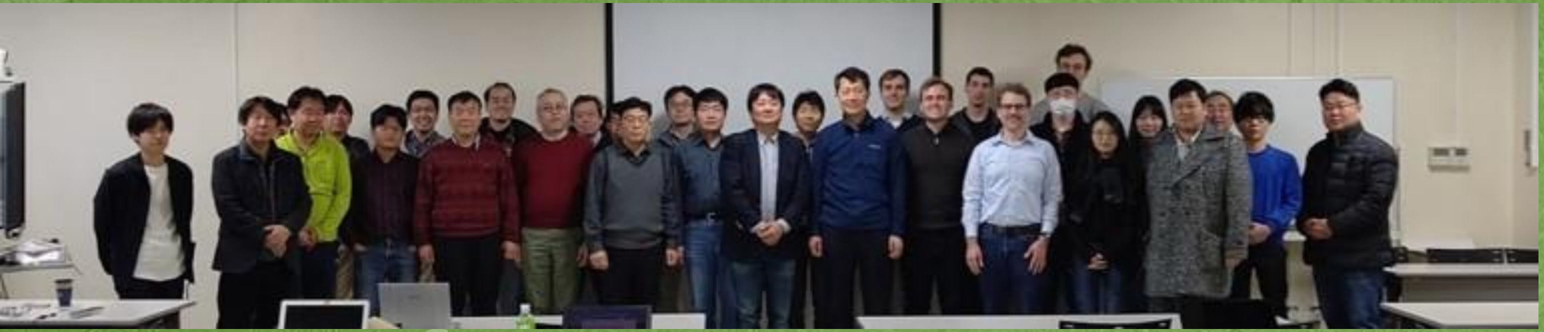
Status of JSNS^2 / JSNS^2-II

Takasumi Maruyama (KEK)

Direct test of LSND.

Collaboration meeting @ J-PARC (2020/Feb: before pandemic)



JSNS^2 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

Spokesperson: T.Maruyama (KEK)
Co-spokesperson: S.B.Kim (SKKU)

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;

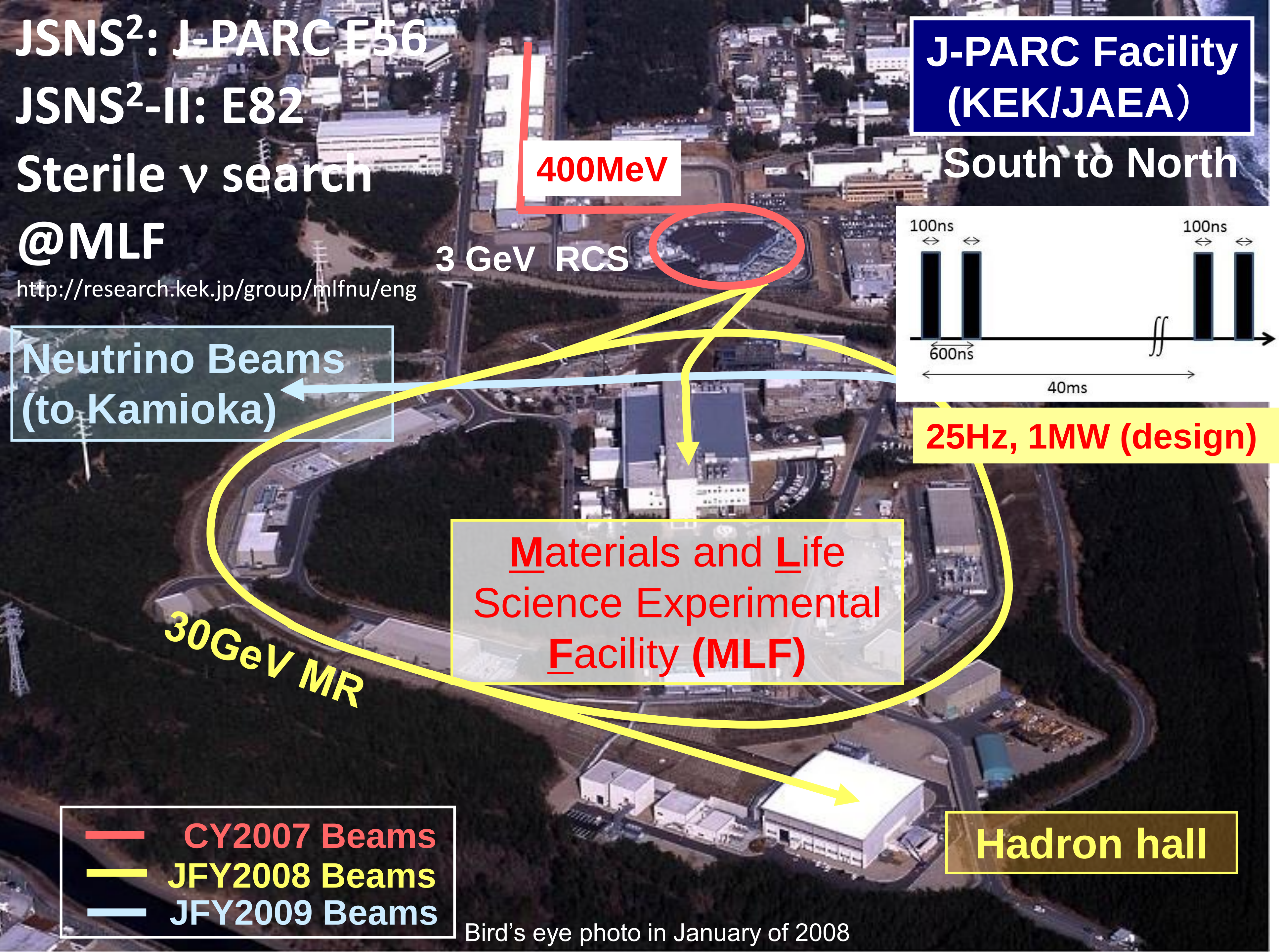
Experiments	Neutrino source	signal	significance	E(MeV),L(m)
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ	40,30
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	4.5σ	800,600
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8σ	
		combined	4.7σ	
Ga (calibration)	e capture	$\nu_e \rightarrow \nu_x$	2.7σ	<3,10
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ	3,10-100

We aim to have a direct test for this

- Excess or deficit do really exist?
- Note: JSNS^2 uses the same neutrino source (μ), target (H) and detection principle (IBD) as the LSND → even if this is not due to the oscillation, we can catch this directly

JSNS^2: J-PARC E56
JSNS^2-II: E82
Sterile ν search @MLF

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

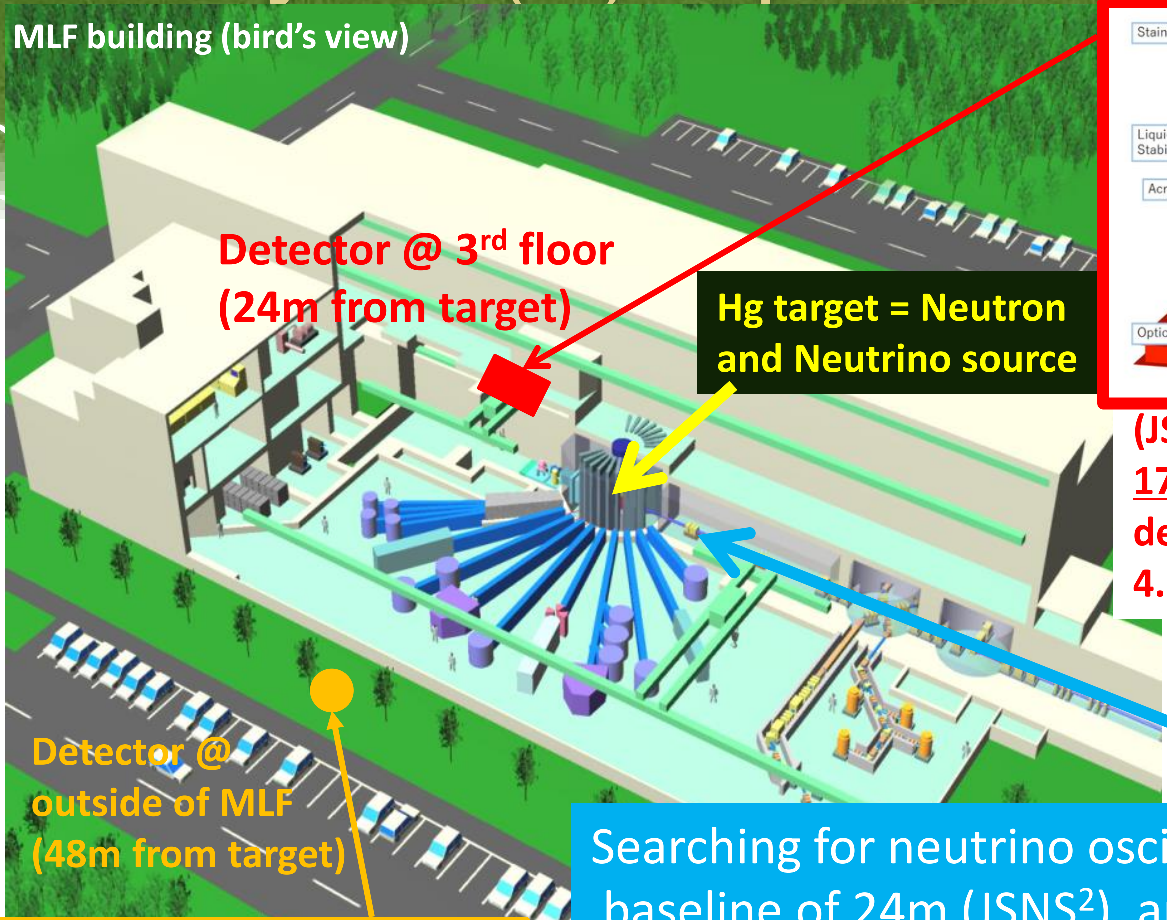


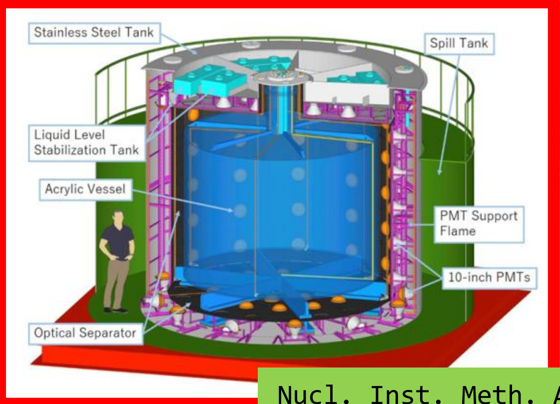
Bird's eye photo in January of 2008

Low duty factor beam (short pulse + small repetition rate) gives very nice S/N ratio.

0.6MW (Jan/12 – Apr/5)
0.7MW (Apr/5 – June/22)
beam was utilized for users.

JSNS^2(-II) experiments : Search for sterile neutrinos

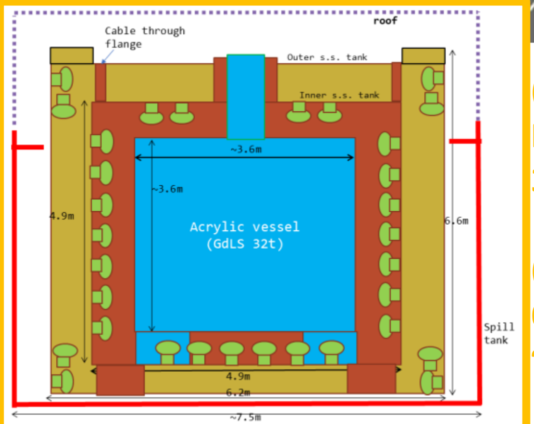




Nucl. Inst. Meth. A 1014 (2021) 165742

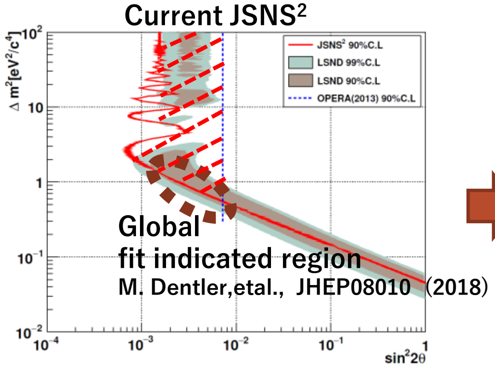
(JSNS^2)
17t GdLS fiducial (target) detector (4.6m dia. x 4.0m height, 120 10" PMTs)

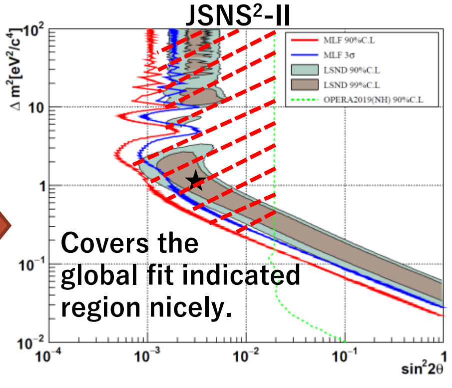
Searching for neutrino oscillation : $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ with baseline of 24m (JSNS^2), and 48m (JSNS^2-II)



(JSNS^2-II:
New detector)
32t GdLS fiducial

(6.2m dia. x 6.2m (h) ~220 10" PMTs)





(JSNS^2) : 1MW x 3 years

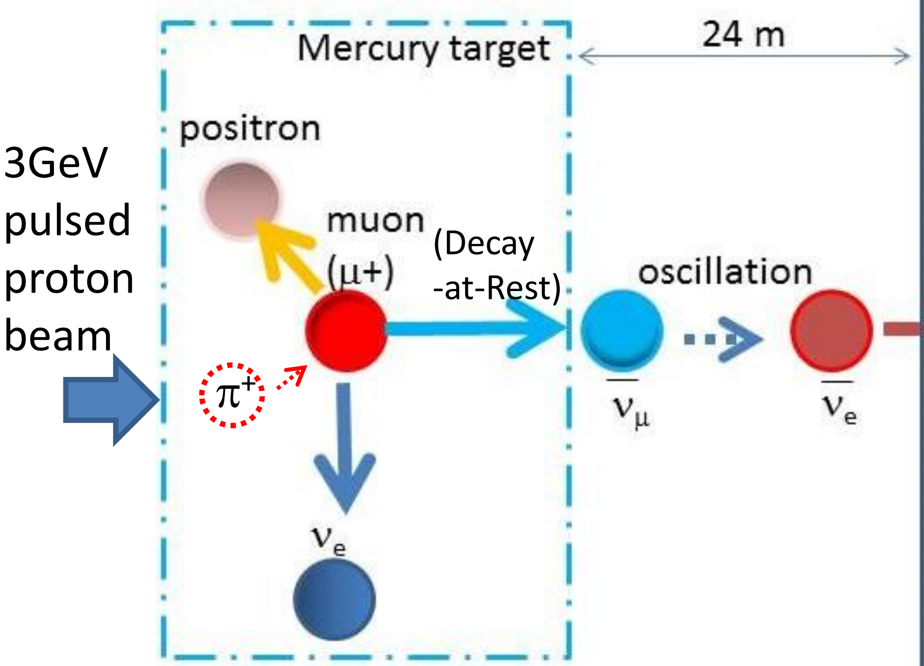
- Commissioning run in 2020.
- The first long physics run (2021) was finished (for ~0.5 years)
    - Smooth data taking.
    - Beam power is 600-700kW.
    - Extensive calibration / Data analyses are on-going.

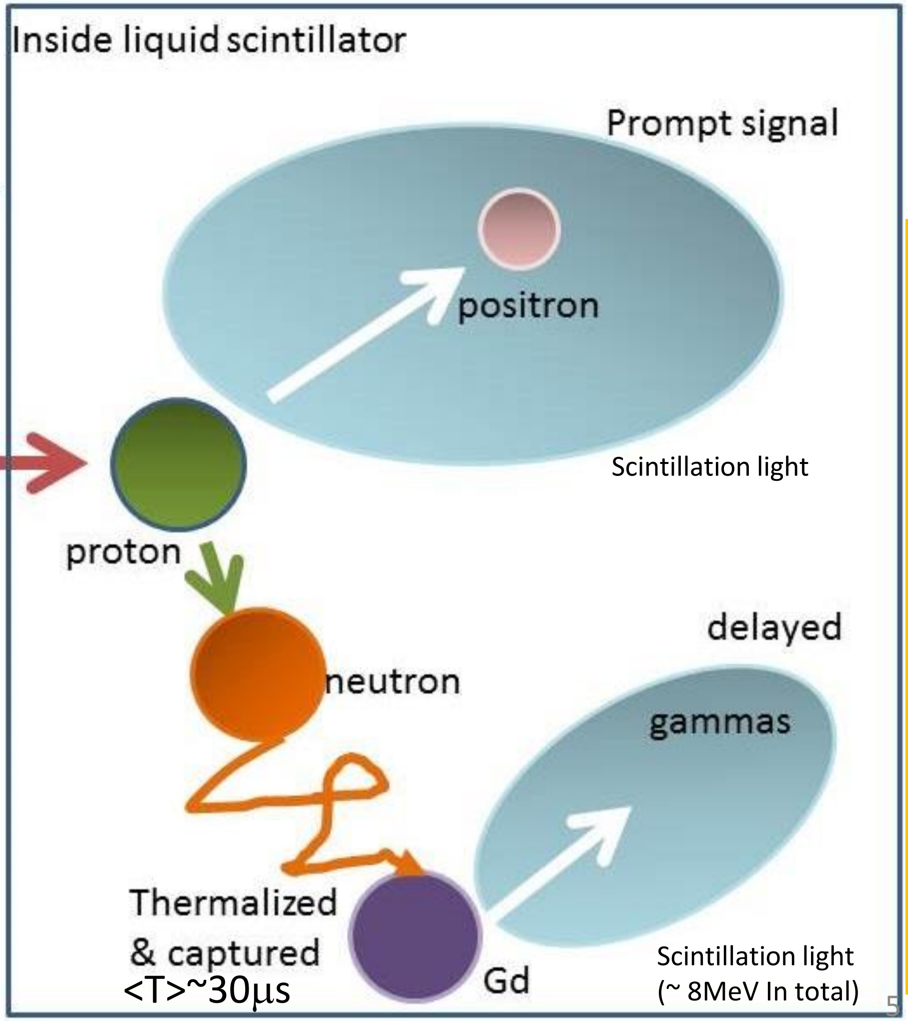
(JSNS^2-II): 1MW x 5 years

- Proposed in 2020. (arXiv:2012.10807)
    - One new detector : 32 tons fiducial in 48m baseline.
    - Improved the sensitivity, especially in low Δm^2.
    - Stage-1 status was granted by J-PARC/KEK

Production / Detection

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





IBD criteria	Timing	Energy
Prompt	$1<T_p<10\mu s$	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

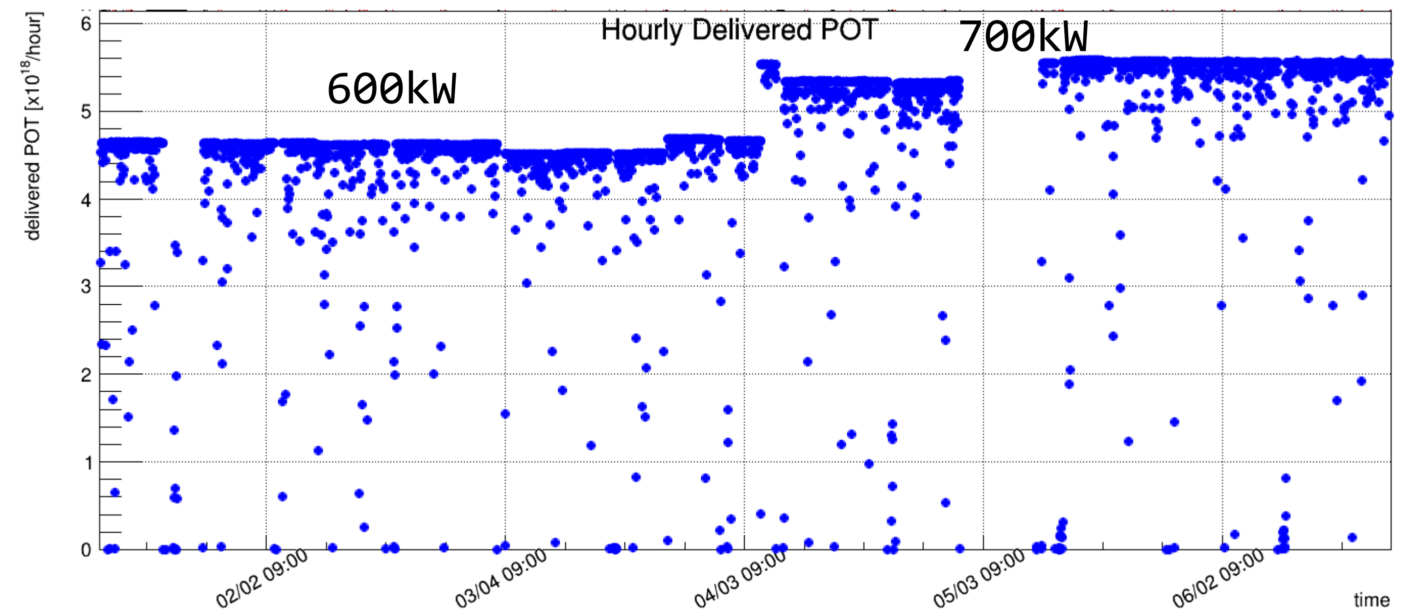
JSNS^2 vs LSND

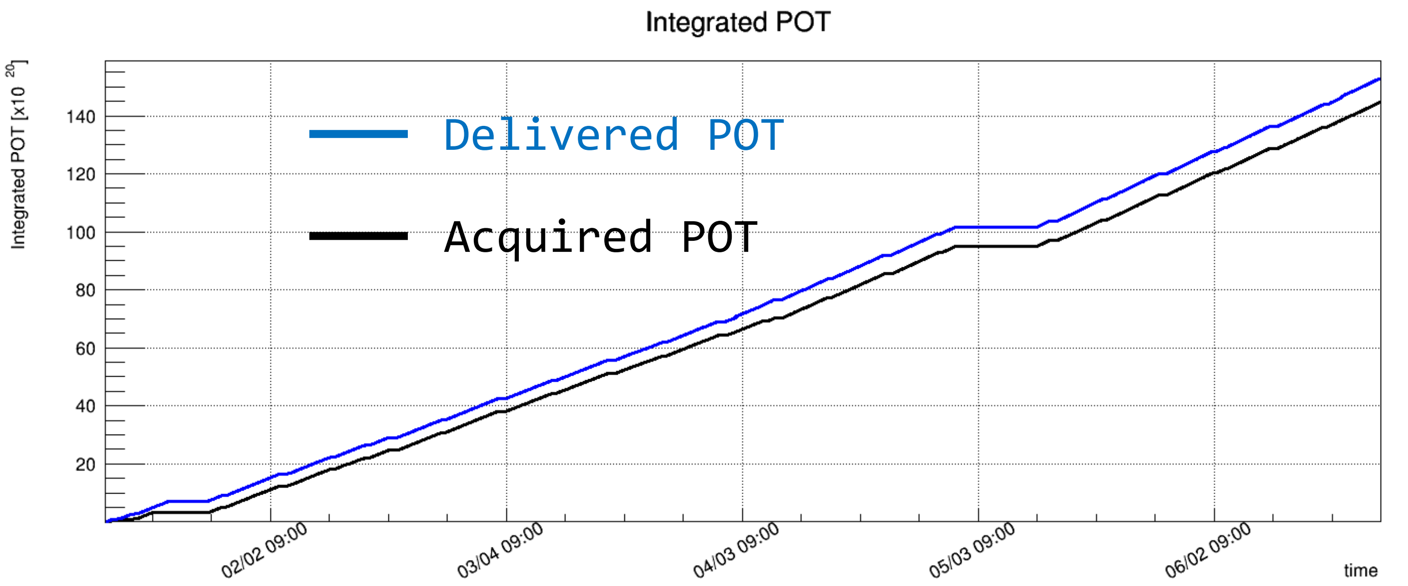
	JSNS^2	LSND
Target Mass	17 tons	167 tons
Baseline	24 meters	30 meters
Beam energy	3 GeV (larger # π^+ but also π^-)	0.8 GeV
Beam Duty Factor	**0.8/40000 (by Synchrotron)**	**1/14 (by Linac)**
Stopping μ^-/μ^+	1.7 x 10^{-3}	6.5 x 10^{-4}
Liquid Scintillator	**Gd-loaded** + large scint. light	Small #scinti. Light (to see Cherenkov), no Gd
Delayed signal	**Etot~8MeV, Δt~30μs**	**Etot~2.2MeV, Δt~200μs**
ΔE/E	2.4% @ 45MeV	7% @ 45MeV
Fast neutron rejection	Pulse Shape Discrimination	Cherenkov
# of IBD signal events (after offline cuts)	~20 events / year (LSND best fit (Δm^2=1.2eV^2, $\sin^2 2\theta$=0.003))	15 / year

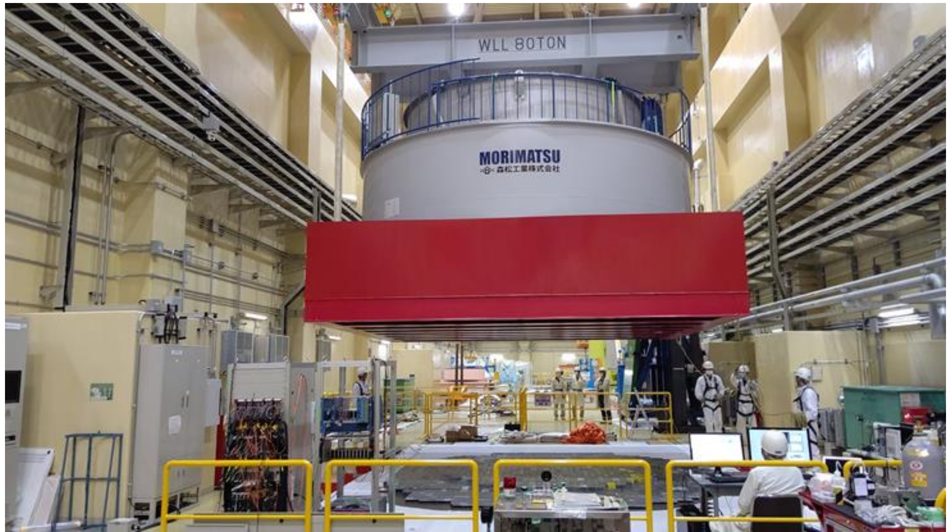
Beam power / Proton-On-Target

- ~600kW (1/12 ~ 4/5)
- ~700kW (4/5 ~ 6/23)

- 1.52 x 10^{22} POT (delivered)
- 1.45 x 10^{22} POT (JSNS^2 acquired: ~13% of TDR)

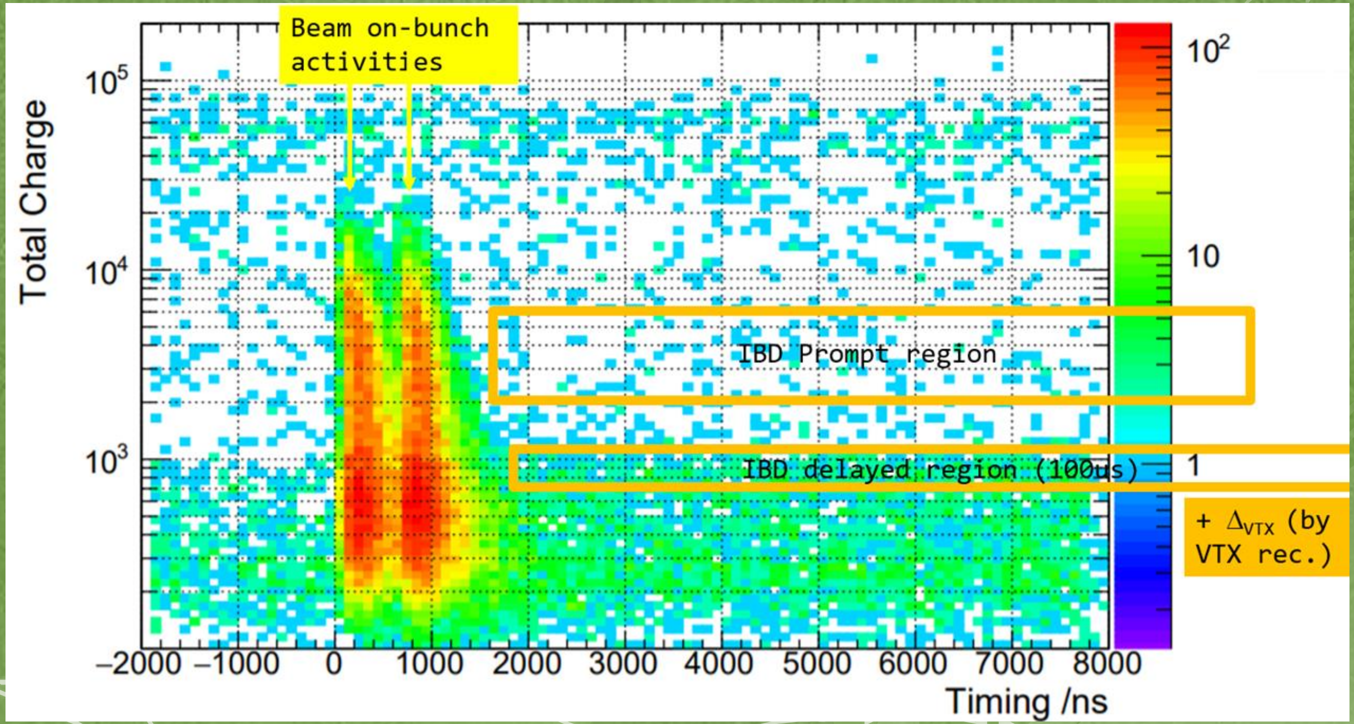




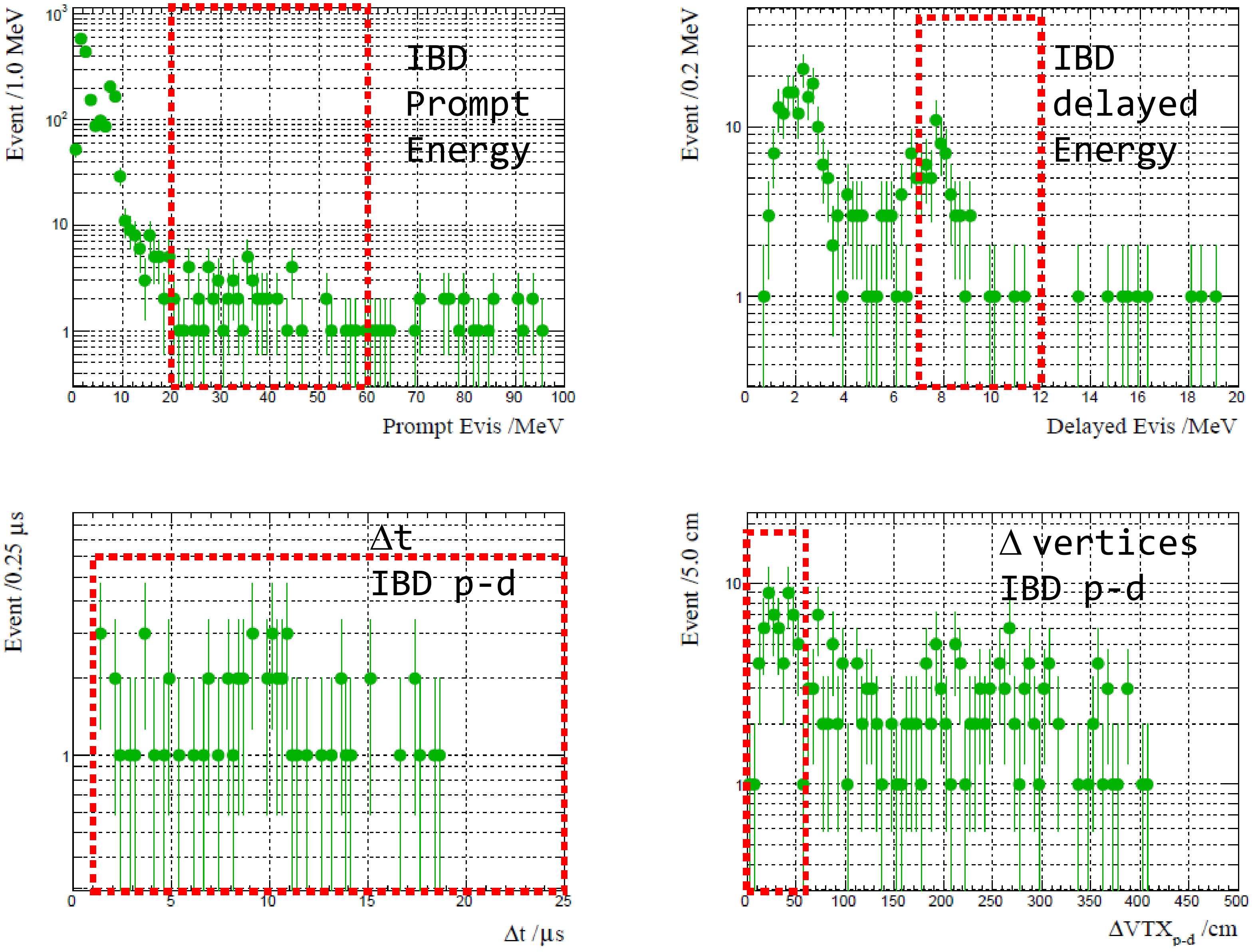


Analysis of commissioning run data (taken in 2020 June)

- 2020 June data : We have 25us time window data triggered by the accelerator scheduled timing. (~ 3 days: 8052903 beam spills)
- We analyzed data to estimate the number of background.



25us time window data



- Selection criteria
  - Energy and timing are shown in the bottom table.
  - Muon veto are applied.(ε_{veto}>99%)
  - Δ_{vtx}(prompt-delayed)<60cm

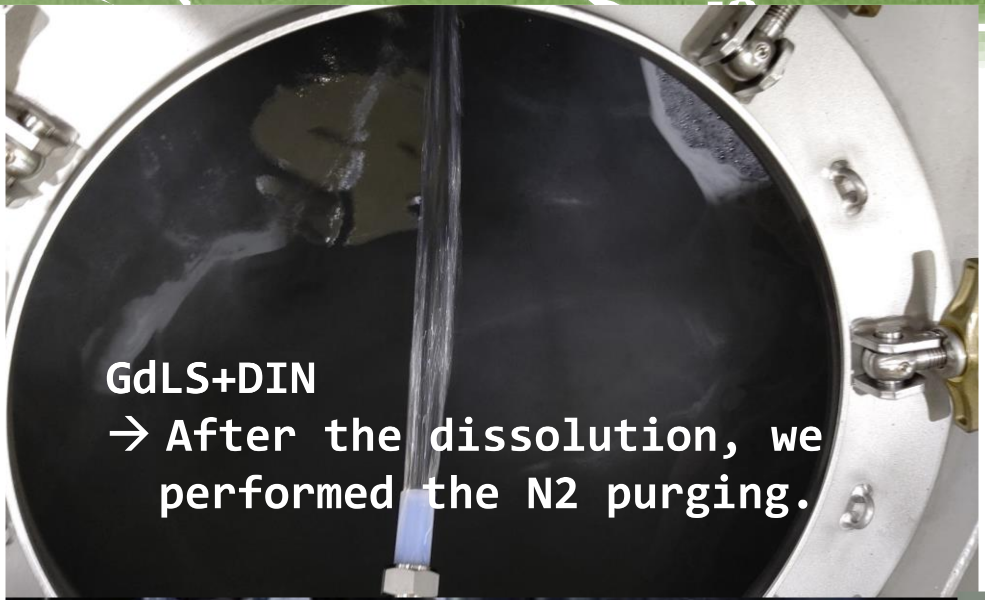
- Observed 59±8 events.
  - 55.9±2.7 events are expected from neutrons induced by cosmic rays.
    - Estimated by self-trigger data (during beam off time)

- Neutrons induced by cosmic rays are dominated.
- Beam induced background is much smaller background than neutrons.

IBD criteria	Timing	Energy
Prompt	$1.5<T_p<10\mu s$	20<E<60MeV
Delayed	$T_p<T_d<25\mu s$	7<E<12MeV

DIN dissolution (10%w inside Gd-LS) in 2020-2021

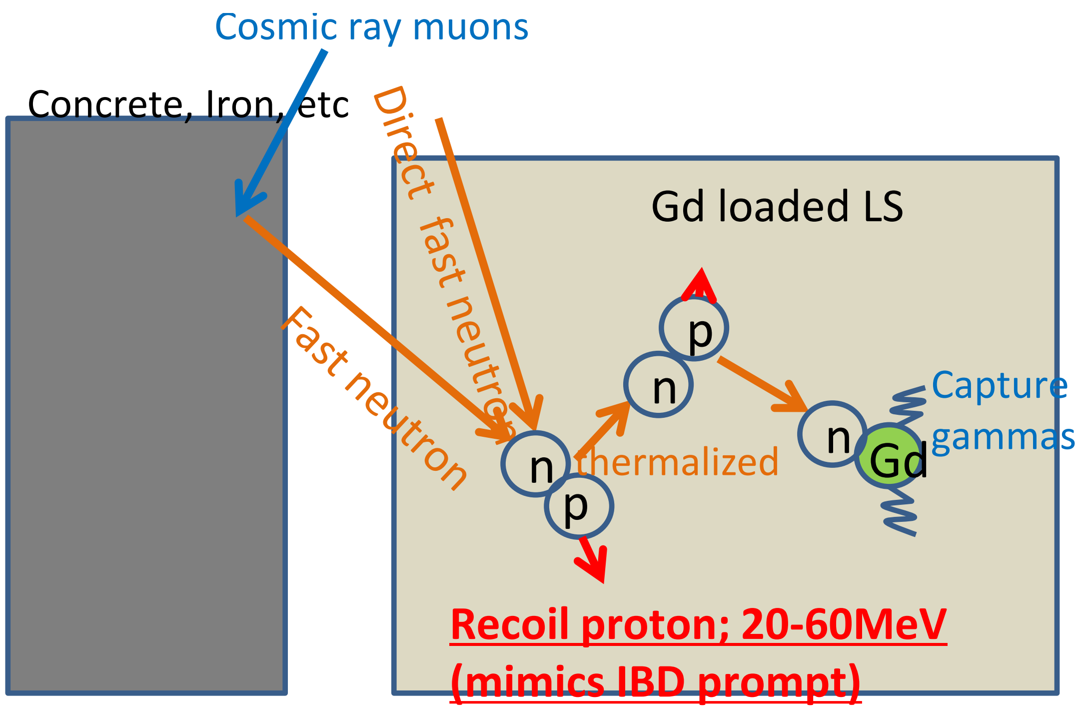
- 10%w: 2000L of DIN (di-isopropyl-naphthalene) was dissolved into Gd-LS in 2020-Dec/2021-July
- Immediately after the dissolution, the N_2 purging was done in the detector additionally.
- The Pulse Shape Discrimination power was drastically improved from the Gd-LS only.
- It is the first case to use DIN in 17tons scale detector in the world.

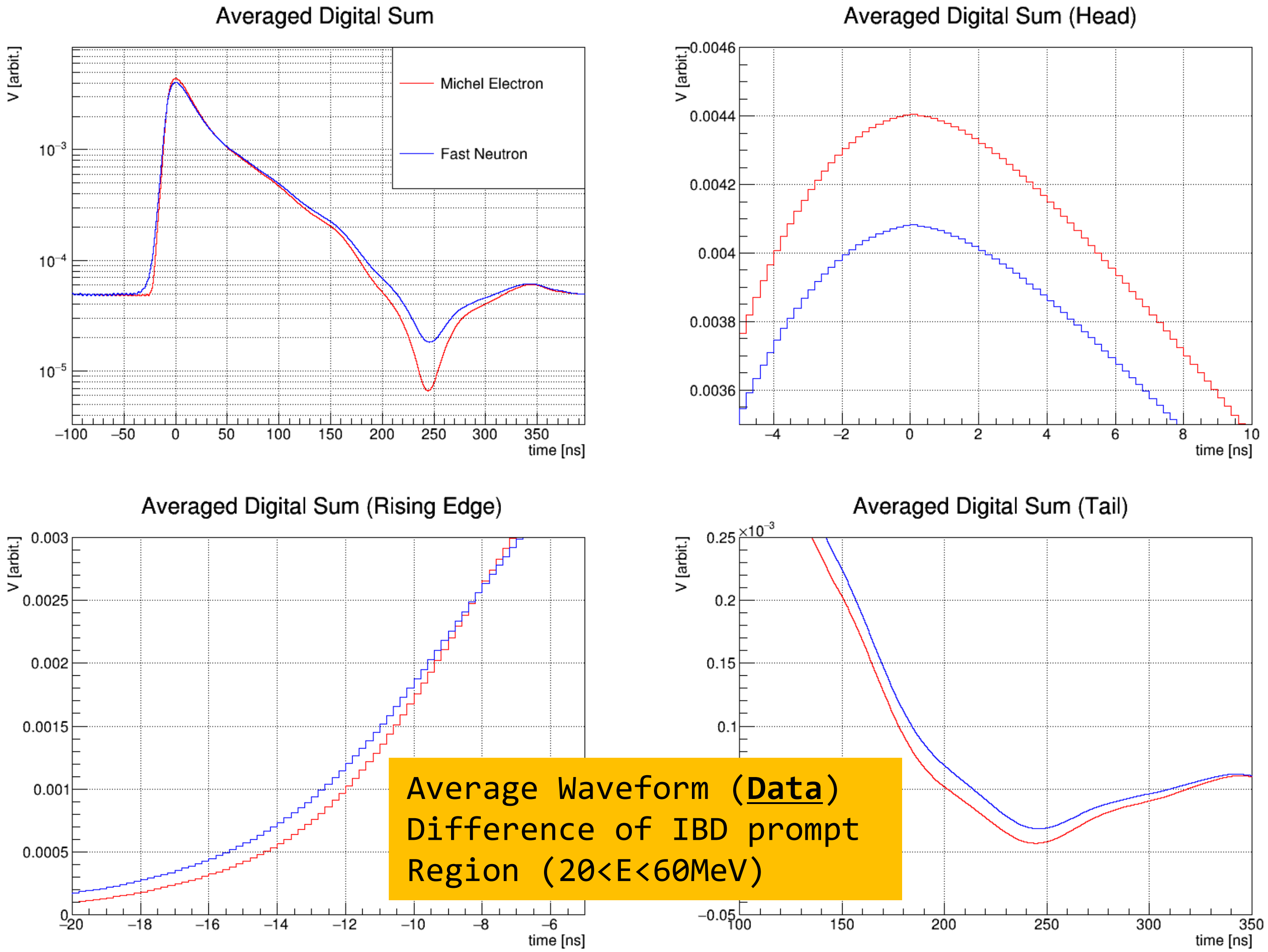


PSD capability for fast neutrons

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

Pulse Shape Discrimination separates the IBD signals and fast neutrons.





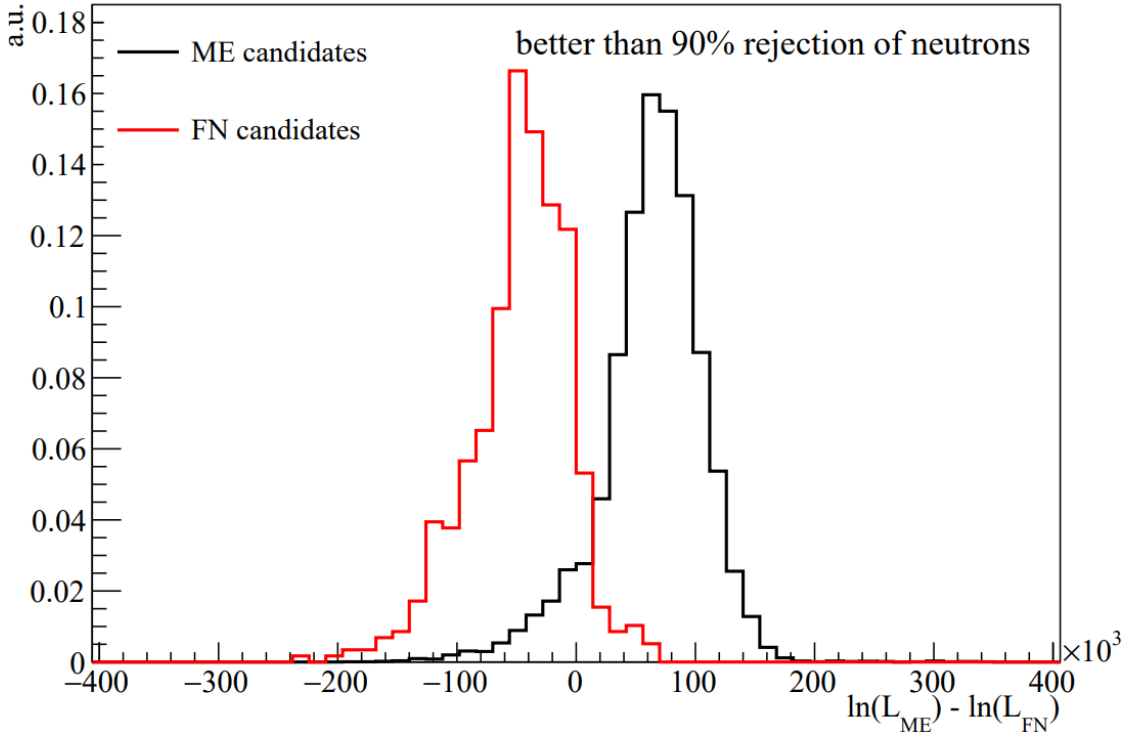
Average Waveform (**Data**)
Difference of IBD prompt
Region (20<E<60MeV)

- DIN was dissolved into Gd-LS as mentioned.
- We are trying a few methods to distinguish these waveforms.
- Likelihood / machine learning methods are under development.

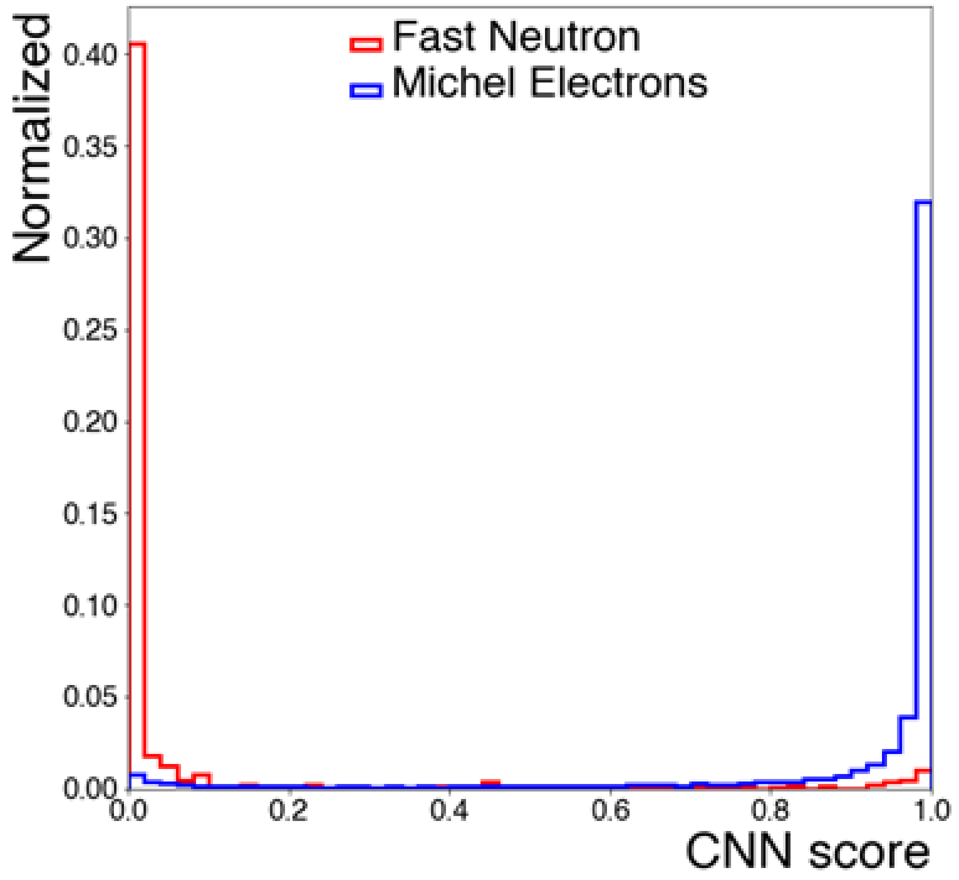
Pulse Shape Discrimination

Note:
Central region Only

Likelihood method

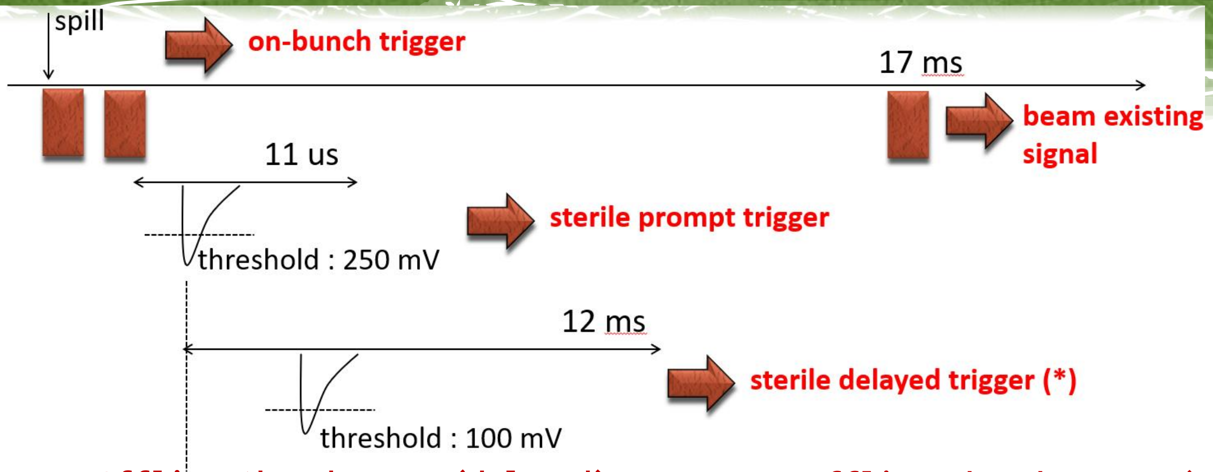


Convolutional Neural Network

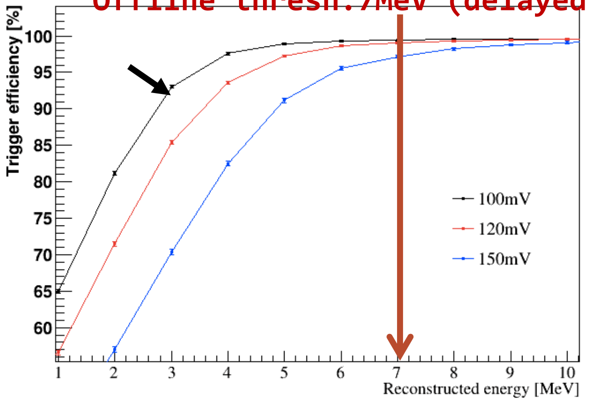


- Self-trigger data provide the control samples for Michel e and neutrons
- They are used for the training sample and to make scores.
- Impurities of control samples are under investigation, however the current point is to see the nice separation power. (more than 90% of rejection power, and additional improvements will be expected as well)

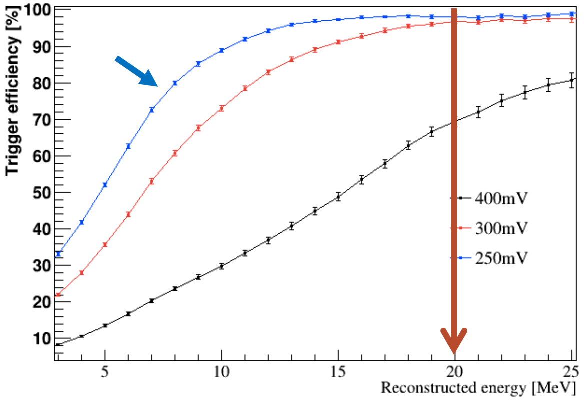
Other activities in 2021



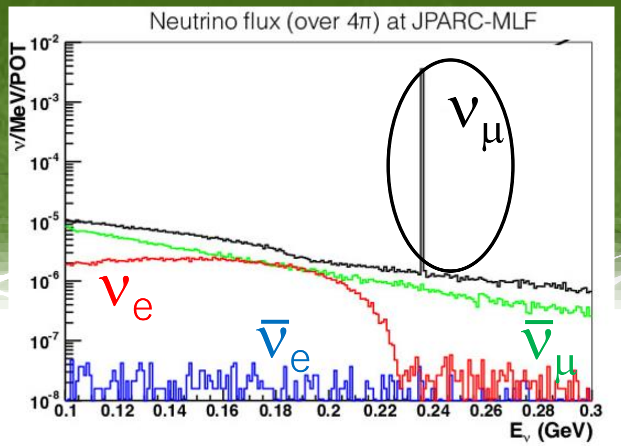
Offline thresh:7MeV (delayed)



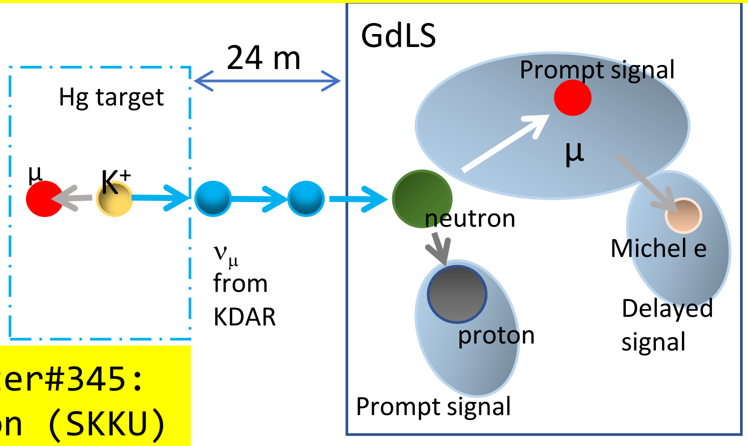
Offline thresh:20MeV (prompt)



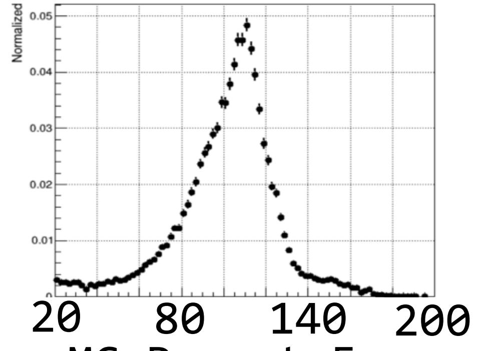
- New trigger with ~100% ε for the sterile neutrino search was implemented.
- Now blind analysis for the sterile neutrino search is on-going. Background rates/properties are being investigated by side-band / partially unblinded samples.
- Flux normalization (using $C(\nu_e,e)Ngs$) is being estimated.



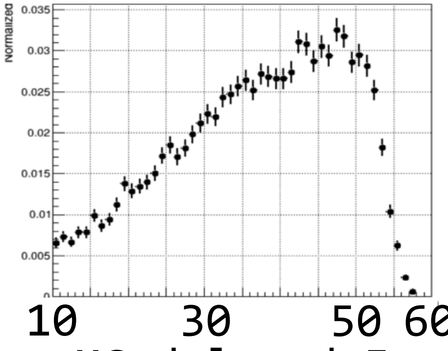
KDAR events: Analysis is on-going!!



See poster#345:
By H.Jeon (SKKU)



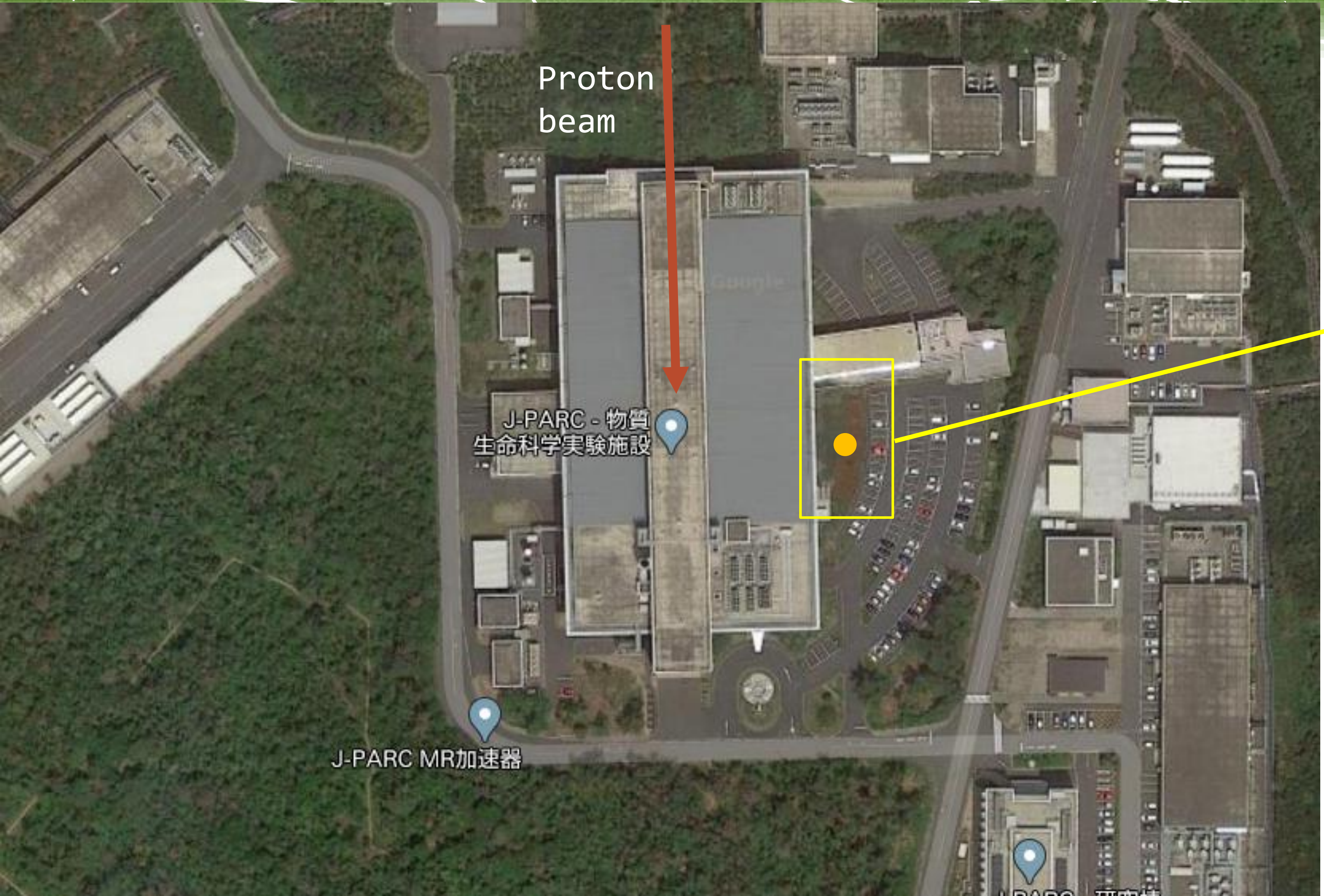
MC Prompt E (MeV)

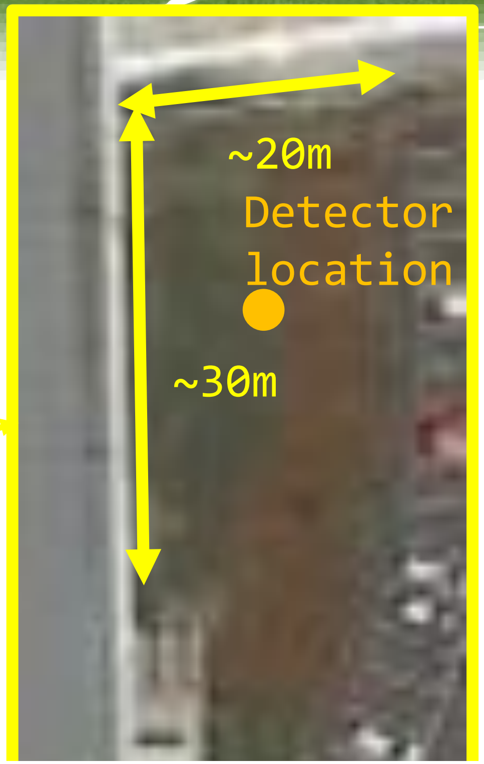


MC delayed E (MeV)

JSNS^2-II status / future

JSNS2-II : 2nd detector location (outside of MLF)





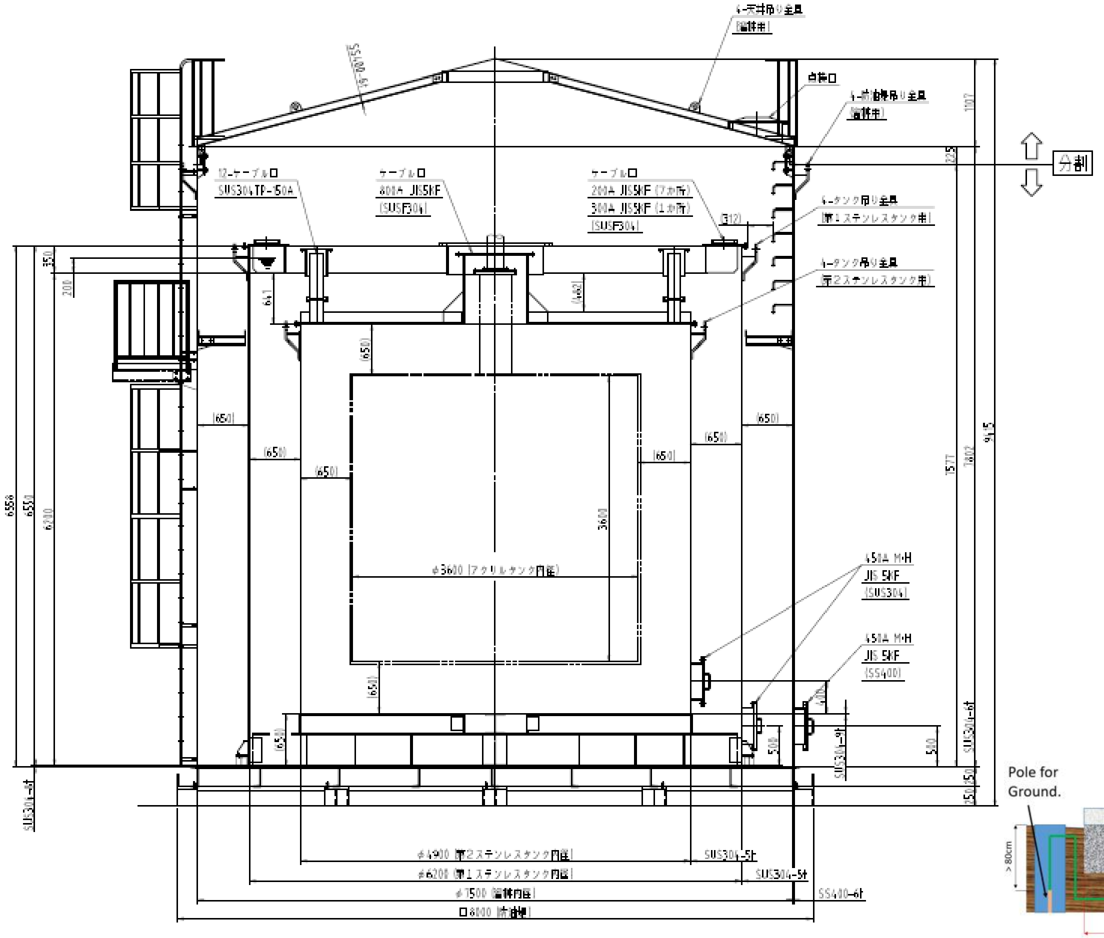
- Baseline is ~48m.
- Twice fiducial mass compared to 1st detector.
- No detector buildings.
- MLF approved to use this space.

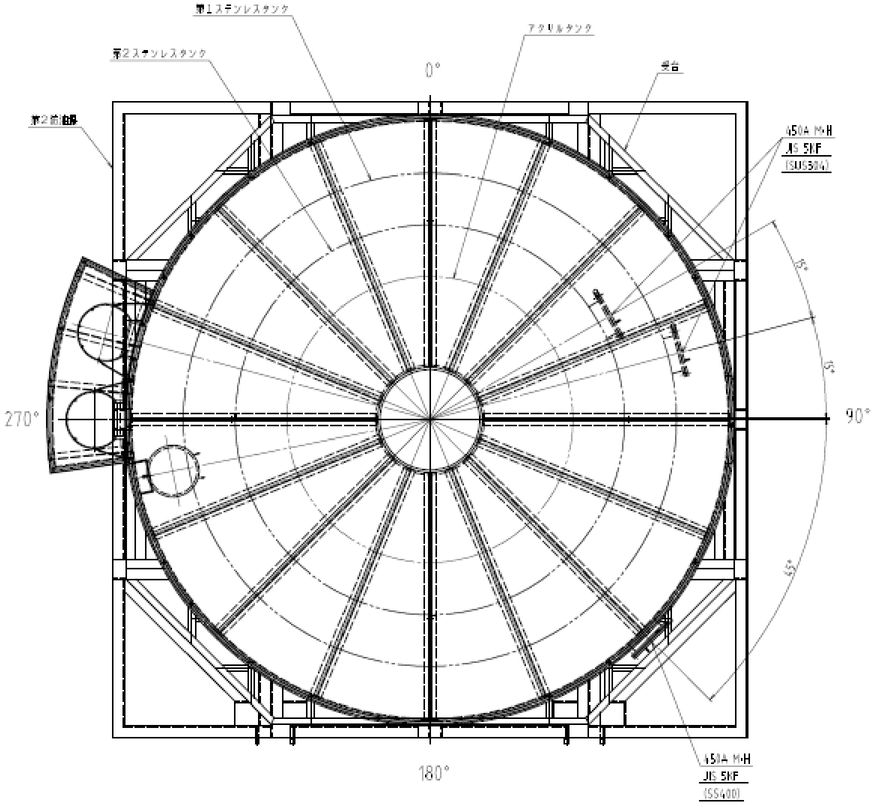
Recent progress

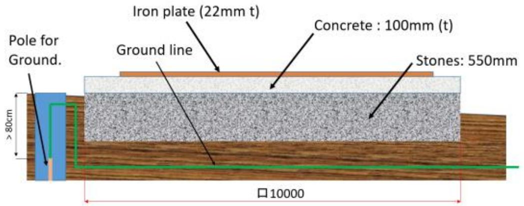
- Stage-1 status was granted by J-PARC/KEK officially on 2021-Apr. (P82 (proposal status) → E82 (experimental status))
- Daya-Bay already donated sufficient quantities/quality of Gd-LS and pure LS. Thank you.
  - these (Gd-)LS are already kept and monitored in Japan (near the Tokyo)
- The stainless steel tank is started to build. (will be completed by 2022-Mar)
- We are discussing the acrylic tank production with the company (in Taiwan). The construction will be done in 2022.
- The donation of 10” PMTs are discussed with Double-Chooz experiment.
  - 30 PMTs on the top-lid of Double-Chooz detector were already dismantled. We plan to transport them.
  - They are preparing for the dismantle of other PMTs.
  - If timescale is matched, the donation and transportation will be performed. (if not, we will purchase the PMTs)
- JSNS^2-II aims to start data taking in 2023.

Stainless steel tank for detector

- Drawings are made.
- We started to build the tank from this Sep.
- Construction will be completed by 2022-Mar.
- You can see the 2nd far detector tank when you visit the J-PARC.





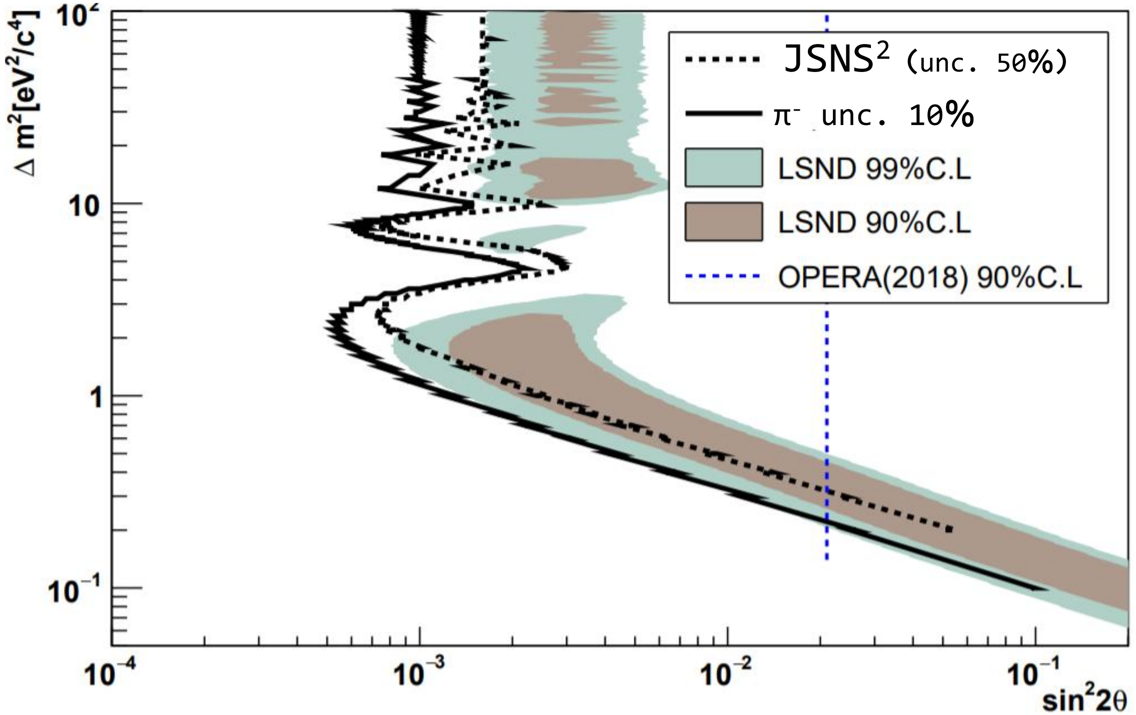


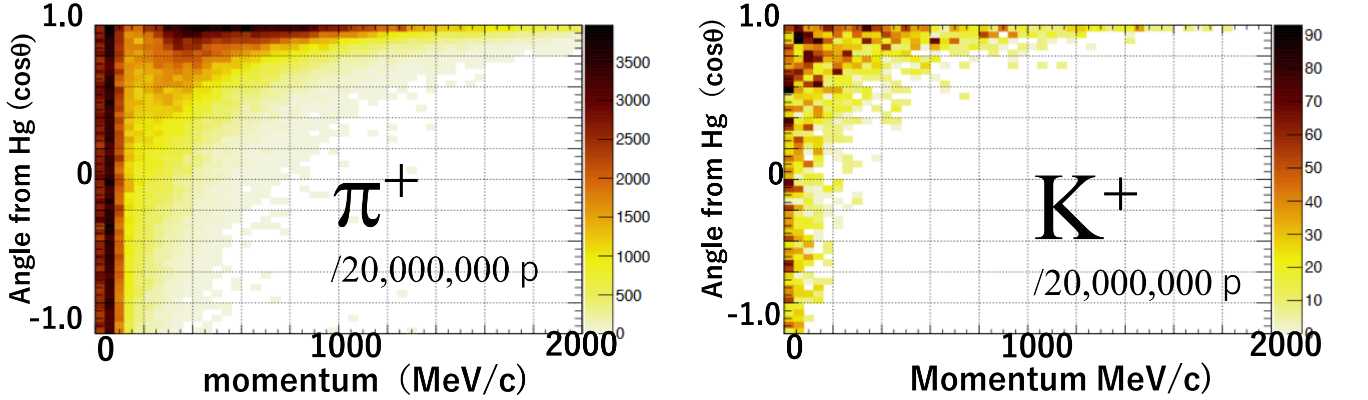
Timescale of JSNS^2-II

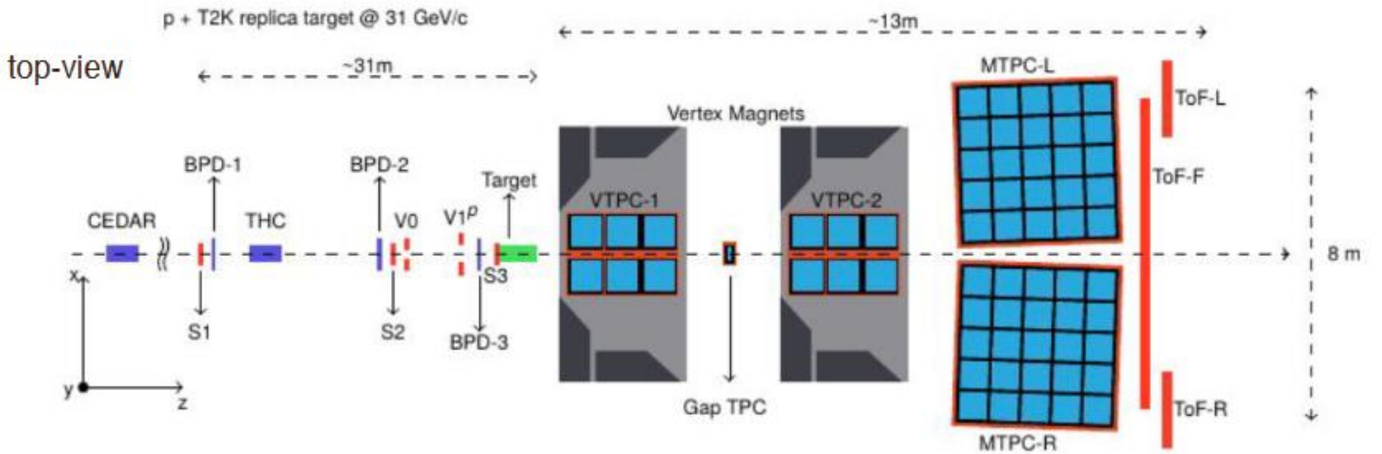
	2021				2022				2023				2024			
	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12
s.s.tank			bid	construction												
Acrylic vessel						bid	construction		Transp.	install						
PMTs				Delivery/ pre-calib		attachment										
		DC dismantle/ shipping?														
(Gd)LS	donation				Storage / keep											
electronics				R&D						Delivery						
Filling																
Data taking																

NA61 (@ CERN)

- There have been no measurements for the hadron (π/K) production between 3 GeV protons and mercury so far.→ large uncertainty for the amount of neutrinos is given, especially for π-→μ-→anti-electron neutrino. (we assigned 50% uncertainty for amount of anti-νe from this.)
- If we reduce the uncertainty, it is possible to improve the JSNS2 sensitivity. (left plot)
- We start to discuss the possibility to measure this using the low energy tertiary beam line at NA61, which could be build at CERN. The earliest possibility to take data is in 2024.
- Maybe other production measurements such as neutrons can be done.







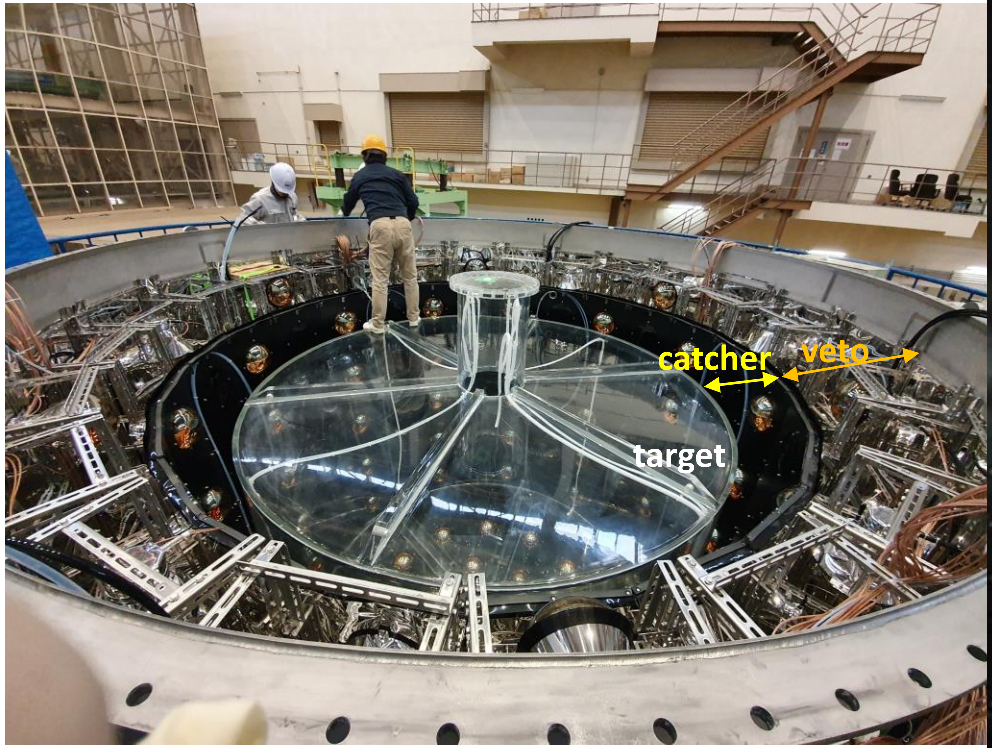
Summary

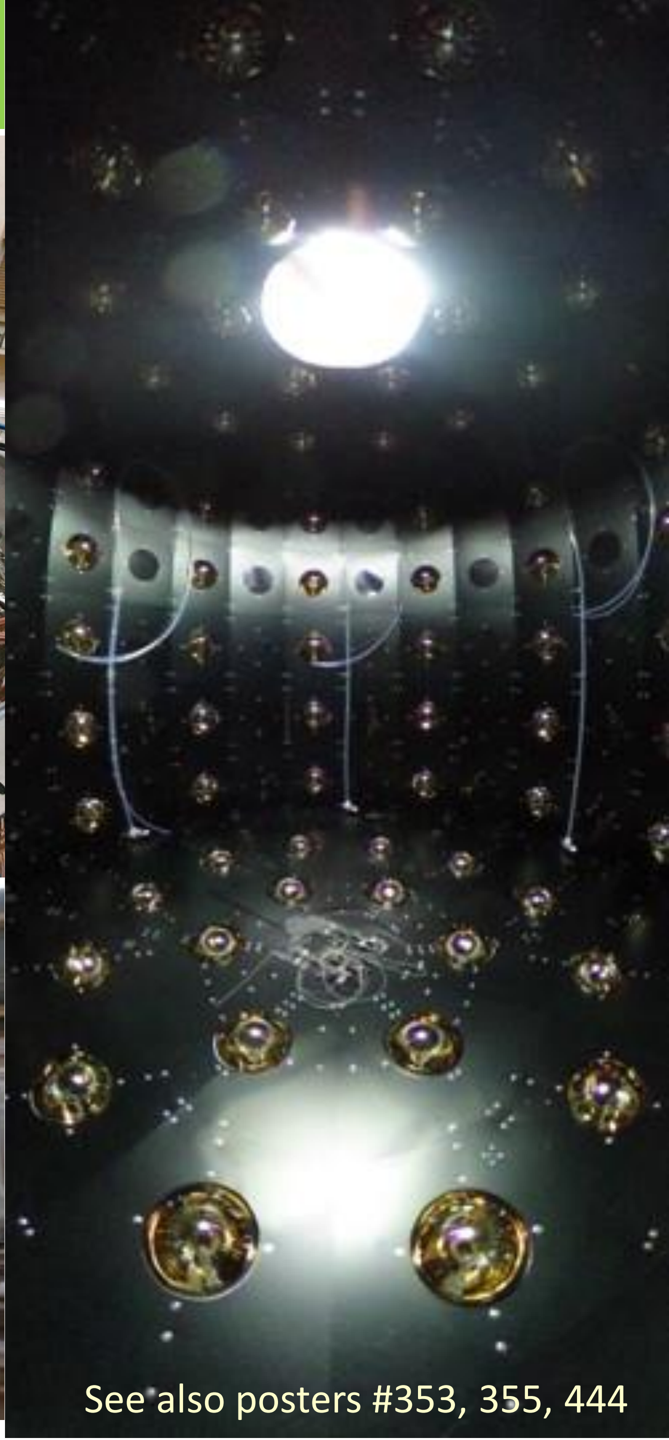
- JSNS^2 aims to test the LSND anomaly directly.
  - uses the same neutrino source (muon), target (H) and detection principle (IBD), but much smaller accidental background due to Gd-loaded LS and low duty factor J-PARC MLF beam.
- We started the first long physics data taking from 2021-Jan.
  - new and efficient trigger was implemented.
  - using the trigger, good sterile neutrino searches can be done.
  - smooth data taking with stable shifts crews for a half of year (1.45 x 10^{22} POT).
- Commissioning run data with 25us time window (~ 3 days) were analyzed.
  - The dominant background is coming from the fast neutrons induced by cosmic rays
  - To eliminate this background, the Pulse Shape Discrimination (PSD) methods are implemented. (currently they are in good shape.)
  - Beam related background rate (much smaller than fast neutrons) will be estimated with 2021 data.
- JSNS^2-II has good progress.
  - The sensitivity for the sterile neutrino search (especially, in the low Δm^2 region) are improved a lot.
  - Stage-1 status was granted by J-PARC / KEK officially.
  - Daya-Bay donated the GdLS / LS for JSNS^2-II. (now they are in Japan)
  - The stainless steel tank is being built.
  - Aim to start the JSNS^2-II from 2023. Welcome, new collaborators!

backup

Detector construction (2017–2020)

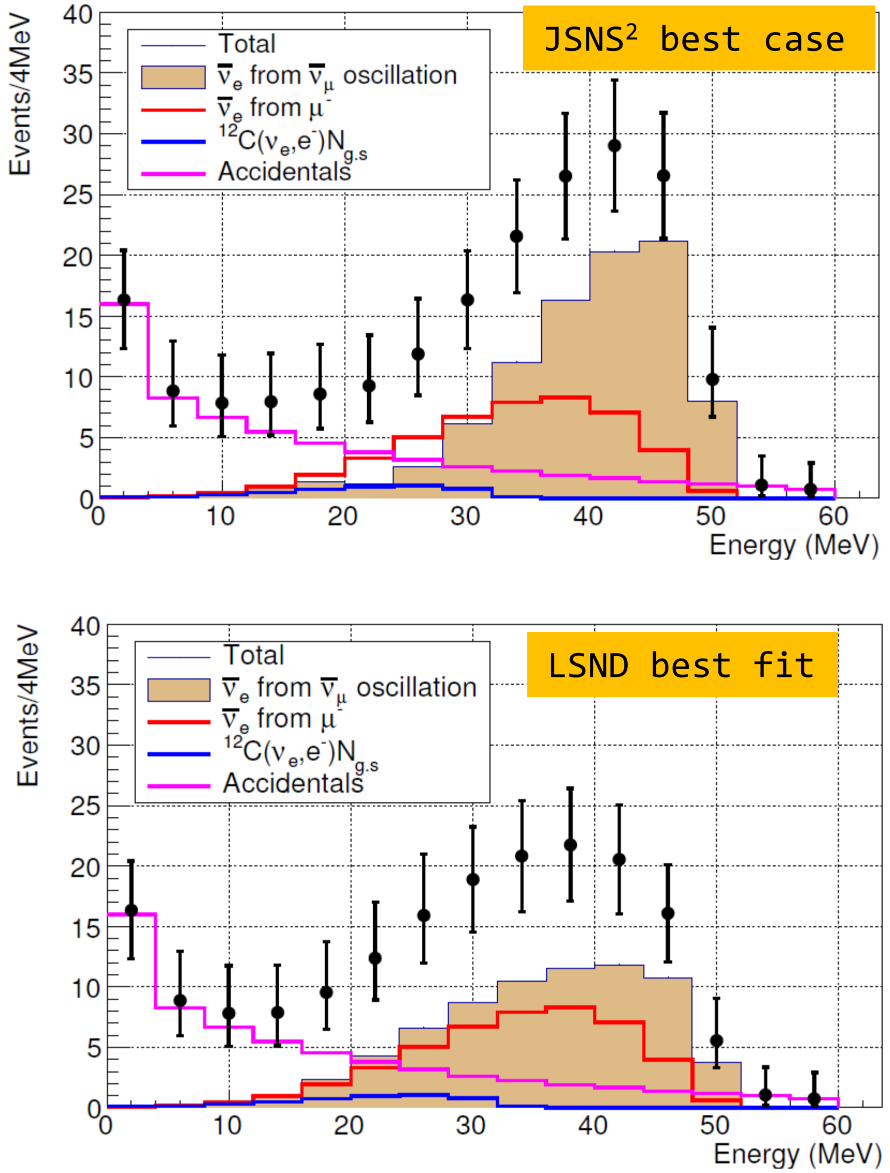
- The detector construction was finished 2020-Feb.
  - Stainless steel tank was produced by Japanese company (2017-2018: Morimatsu) JINST 14 (2019) no.09, T09001
  - Acrylic tank was produced by Taiwan company (2018-2019: Nakano).
  - 10” PMTs : arXiv:2005.01599 (also accepted by JINST)
    - ~53% is reused from RENO.
    - ~30% is newly purchased.
    - ~17% is reused from Double-Chooz.
  - 35 ton of pure liquid scintillator was produced by Korean collaborators at RENO site (2018) JINST 14 (2019) no.09, T09010
  - 17 tons Gd loaded liquid scintillator was donated by Daya-Bay (2019).
  - Electronics and DAQ system: arXiv:2006.00670
    - FADCs are donated by DC – Japan.
    - Front End Elec. are donated by DC.
    - HV are reused from DC.
    - Elec. upgrade will be done (See backup)
  - New Fast LED calibration system





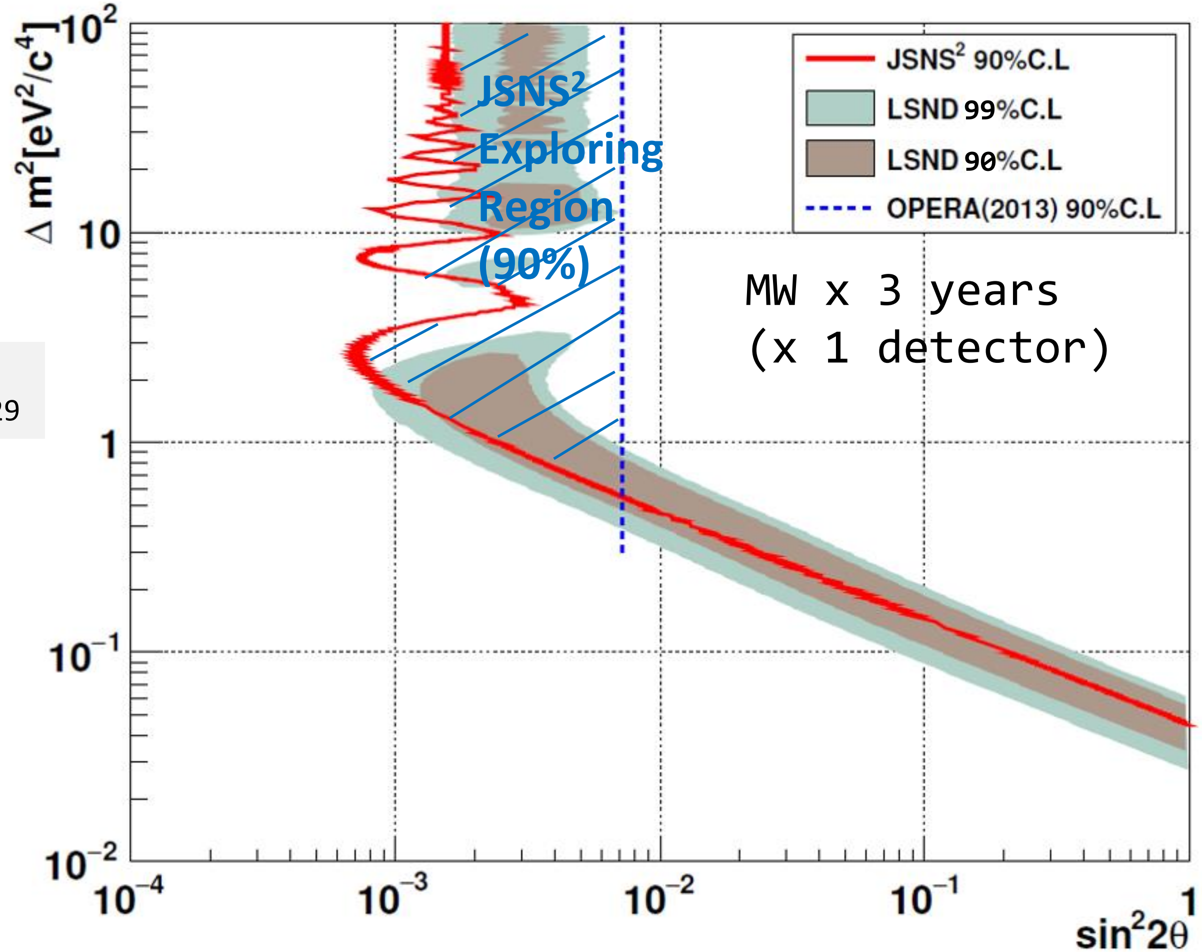
Very efficient experiment using reused or donated materials from various experiments. We do appreciate Daya-Bay, RENO and DC.

Energy Spectrum and Sensitivity (by MC simulation)

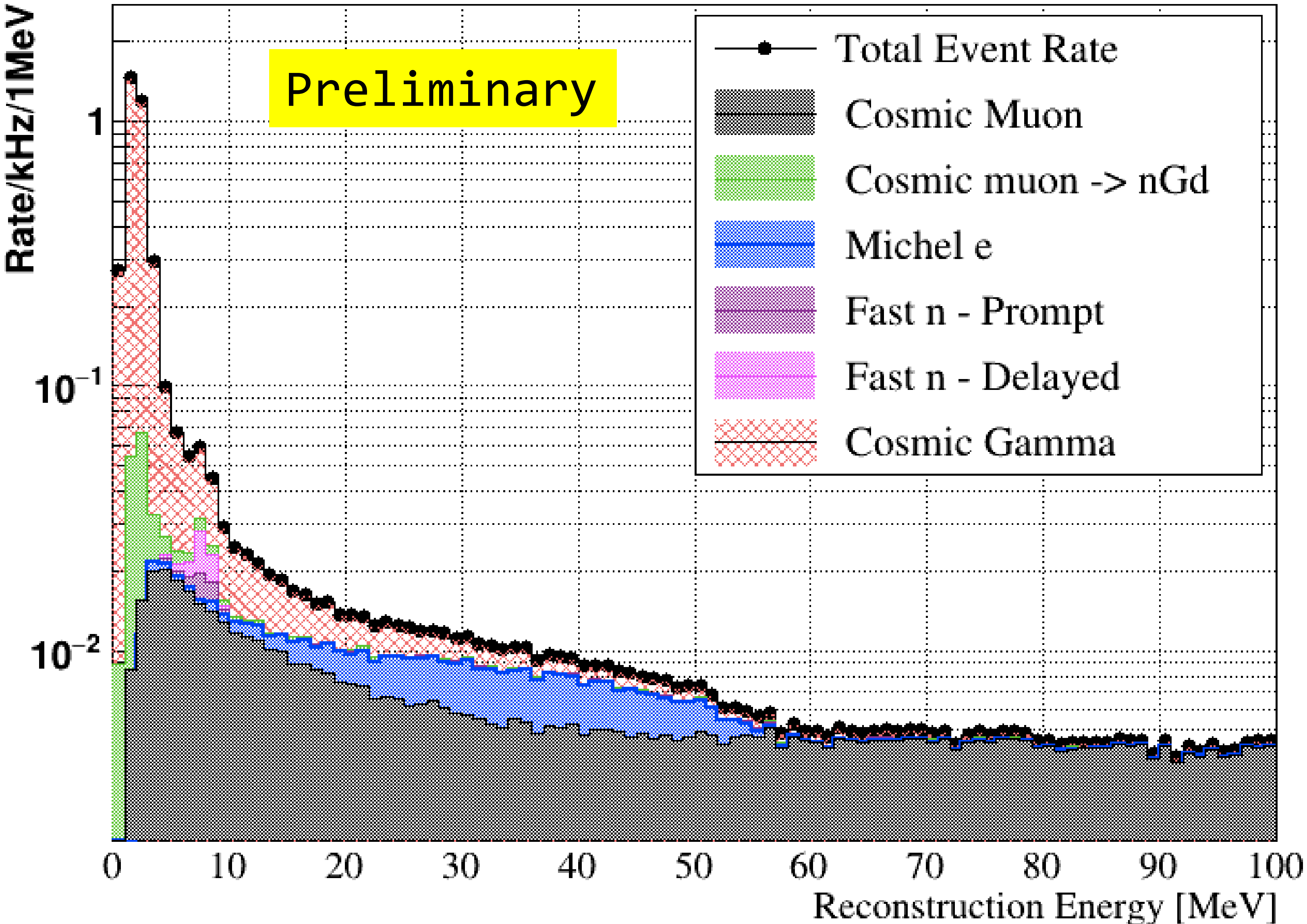


- Left: Energy spectrum; (Top: Δm^2=2.5eV², Bottom; 1.2eV² $\sin^2 2\theta$ = 0.003)
- Right: Sensitivity of 3 years physics running of JSNS² with one detector.

S. Ajimura *et al.*
arXiv:1705.08629



Data w/o beam (cosmic ray induced BKG)



- J-PARC has a day for the beam maintenance / week. (i.e. : no beam in the day)
- Left plot shows the preliminary plots for the background components taken by self-trigger. (2020/6/10)
  - Cosmic ray μ: ~2.3kHz (all energy range. Including >100MeV)
  - Michel e : ~85Hz (20-60MeV)
  - Fast neutrons: ~5.7Hz (20-60MeV)
  - Cosmic gamma: ~58Hz. (20-60MeV)
  - Cosmic gamma: ~100Hz (7-12MeV)

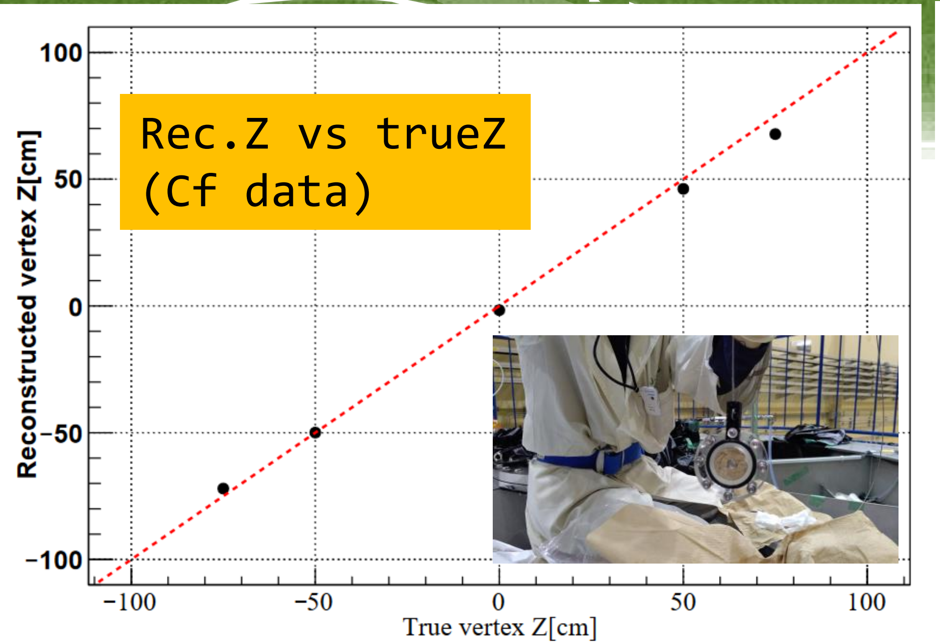
  (note1: uncertainties for all components are 20% level)

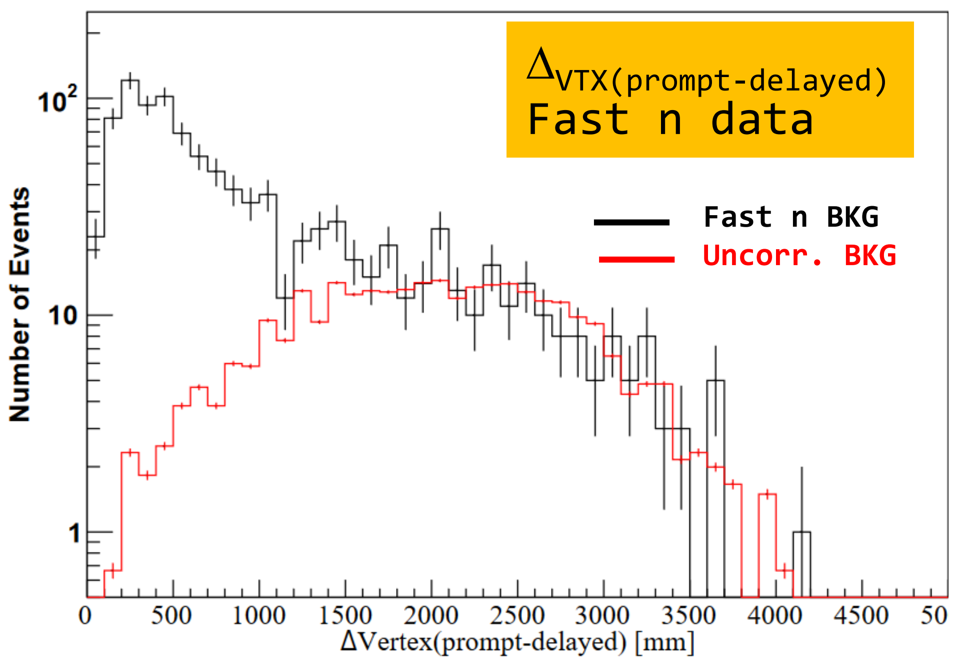
  (note2: these numbers have no fiducial volume cuts. BKG in the Catcher region are included in addition to target region. (target 20m^3 vs catcher 12.2m^3))

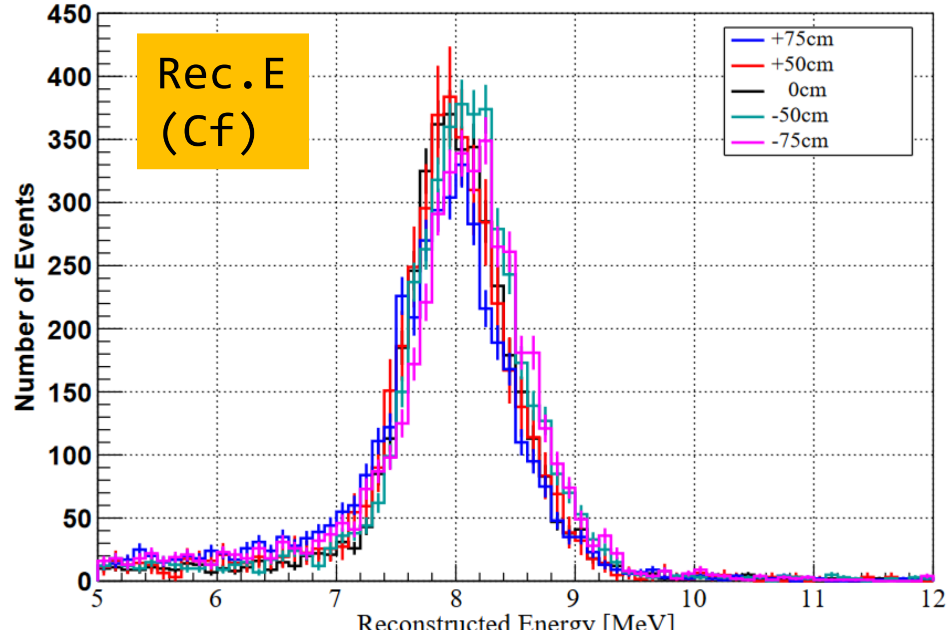
  (note3: fast neutrons and gammas rays are induced by cosmic muons)

  (note4: the efficiency to tag the cosmic muons in the veto: better than 99%)
- Time window to select IBD is powerful to reject these. (9μs = ~10^{-5} reduction for IBD prompt, 100us = 10^{-4} reduction for IBD delayed)

Vertex/Energy reconstruction performance







	Vtx Resolution (Cf)
data	92±3mm
MC	78±2mm

	E Resolution (Cf)
data	5.1±0.1%
MC	5.3±0.2%

- Top-left: almost no bias for vertex reconstruction for z-direction.
  - We are checking the bias for the R direction carefully.
- Bottom-left: no obvious bias for energy
- Top-right: Δ_{VTX} for prompt – delayed in fast neutrons. Spatial correlation is seen well.
- Bottom-right: energy and vertx resolutions comparison.

$\Delta T_{p\text{-}d}$ dist. for fast neutrons

- With self-triggered data.
- selection criteria is very similar to the IBD selection.
- still large uncertainty, but the capture time (n-Gd) is consistent with other experiments.