New results and status of the JSNS^2 / JSNS^2-II

NuFact 2024
The 25th International Workshop on Neutrinos from Accelerators
Sep 16-21, 2024 Argonne National Laboratory

Dongha Lee (KEK)

JSNS^2
J-PARC Sterile Neutrino Search
at J-PARC Spallation Neutron Source

JSNS^2-II
J-PARC Sterile Neutrino Search
at J-PARC Spallation Neutron Source

JSNS^2 / JSNS^2-II Collaboration

(**J**-PARC **S**terile **N**eutrino **S**earch at **J**-PARC **S**pallation **N**eutron **S**ource)

JSNS^2 Collaboration - February 2024

KEK
JAEA
J-PARC
Tsukuba University
Osaka University
Tohoku University
Kitasato University
Kyoto Sangyo University

Soongsil University
Dongshin University
Seoyeong University
Kyung Hee University
Gwangju Institute of Science and Technology
Seoul National University of Science and Technology
Sungkyunkwan University
Chonnam National University
Jeonbuk National University
Kyungpook National University

Brookhaven National Laboratory
University of Michigan
University of Utah

Sun Yat-sen University

University of Sussex

5 countries
23 institutions
~60 collaborators

JSNS^2 / JSNS^2-II Papers in recent

- Y.Hino et al, “Characterization of the correlated background for a sterile neutrino search using the first dataset of the JSNS^2 experiment”, Eur. Phys. J. C (2022) 82: 331 (arXiv:2111.07482 [hep-ex]) (Commissioning runs)

Correlated Bkg

- C.D.Shin et al, “The acrylic vessel for JSNS^2-II neutrino target”, 2023 JINST 18 T12001 (arXiv:2309.01887 [hep-ex])

JSNS^2-II

- D.H.Lee et al, “Study on the accidental background of the JSNS^2 experiment”, Eur. Phys. J. C 84, 409 (2024) (arXiv:2308.02722 [hep-ex])

Accidental Bkg

- T.Dodo et al, "Pulse Shape Discrimination in JSNS^2”, arXiv:2404.03679 [physics.ins-det] (Under review @ PTEP)

PSD

- D.H.Lee et al, "Evaluation of the performance of the event reconstruction algorithms in the JSNS^2 experiment using a 252Cf calibration source”, arXiv:2404.04153 [hep-ex] (under review @ NIMA)

Calibration/ Reconstruction

- E.Marzec et al, "First Measurement of Missing Energy Due to Nuclear Effects in Monoenergetic Neutrino Charged Current Interactions” (arXiv:2409.01383 [hep-ex], submitted to PRL)

KDAR

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

- Anomalies, which cannot be explained by standard neutrino oscillations for a few tens 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	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	4.8σ	800	600
BEST	e capture	$\nu_\mu \rightarrow \nu_x$	4.2σ	<3	10
Reactors	Beta decay	$\bar{\nu}_\mu \rightarrow \bar{\nu}_x$	3.0σ	3	10-100

- JSNS^2 uses the same neutron source(μ), target(H) and the detection principle (IBD) as the LSND.

=> Even if the excess is not due to the oscillation, we can catch this directly.

=> Two advantages : short-pulsed beam / Gd-LS give excellent S/N ratio.

JSNS²: J-PARC E56

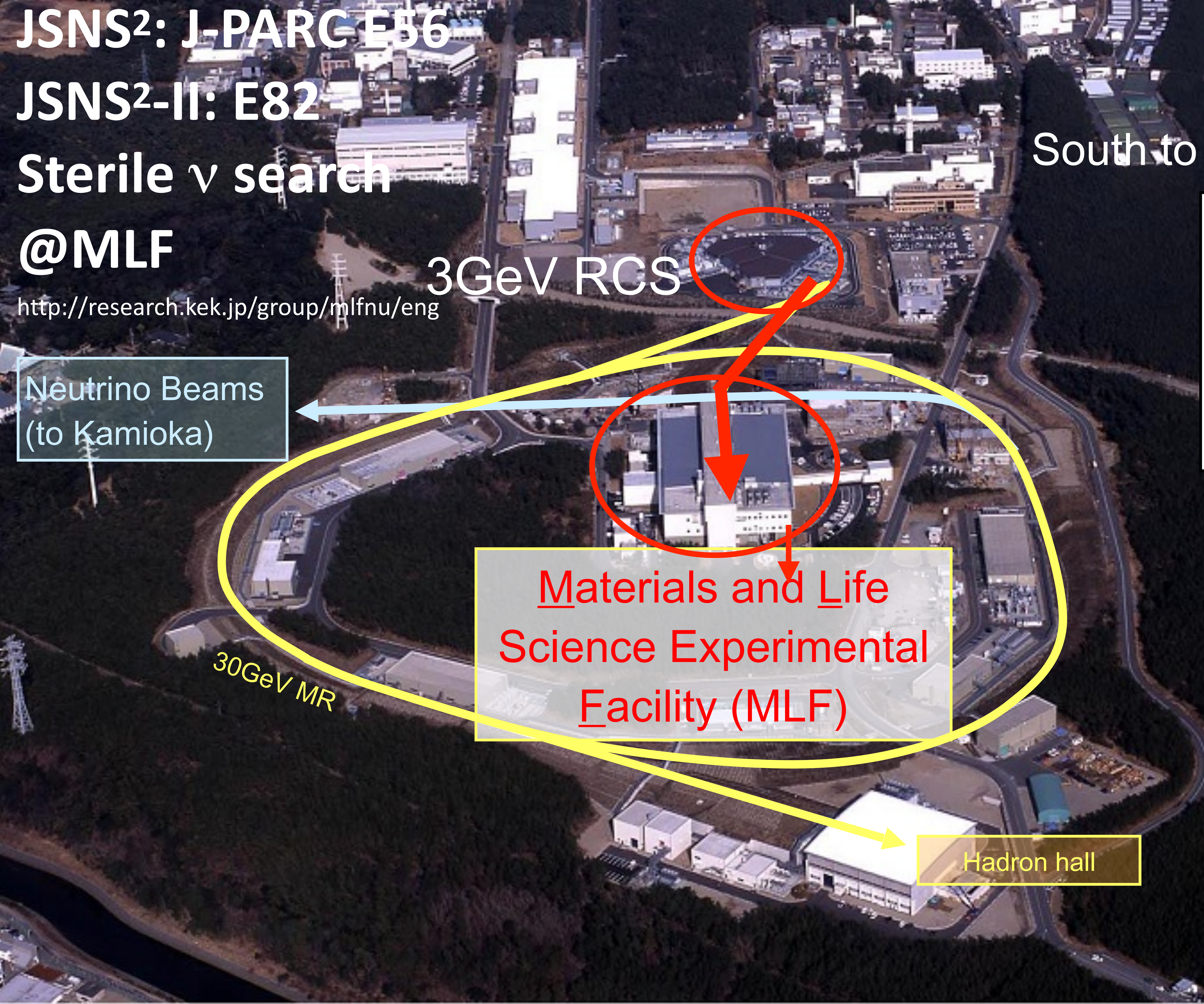
JSNS²-II: E82

Sterile ν search

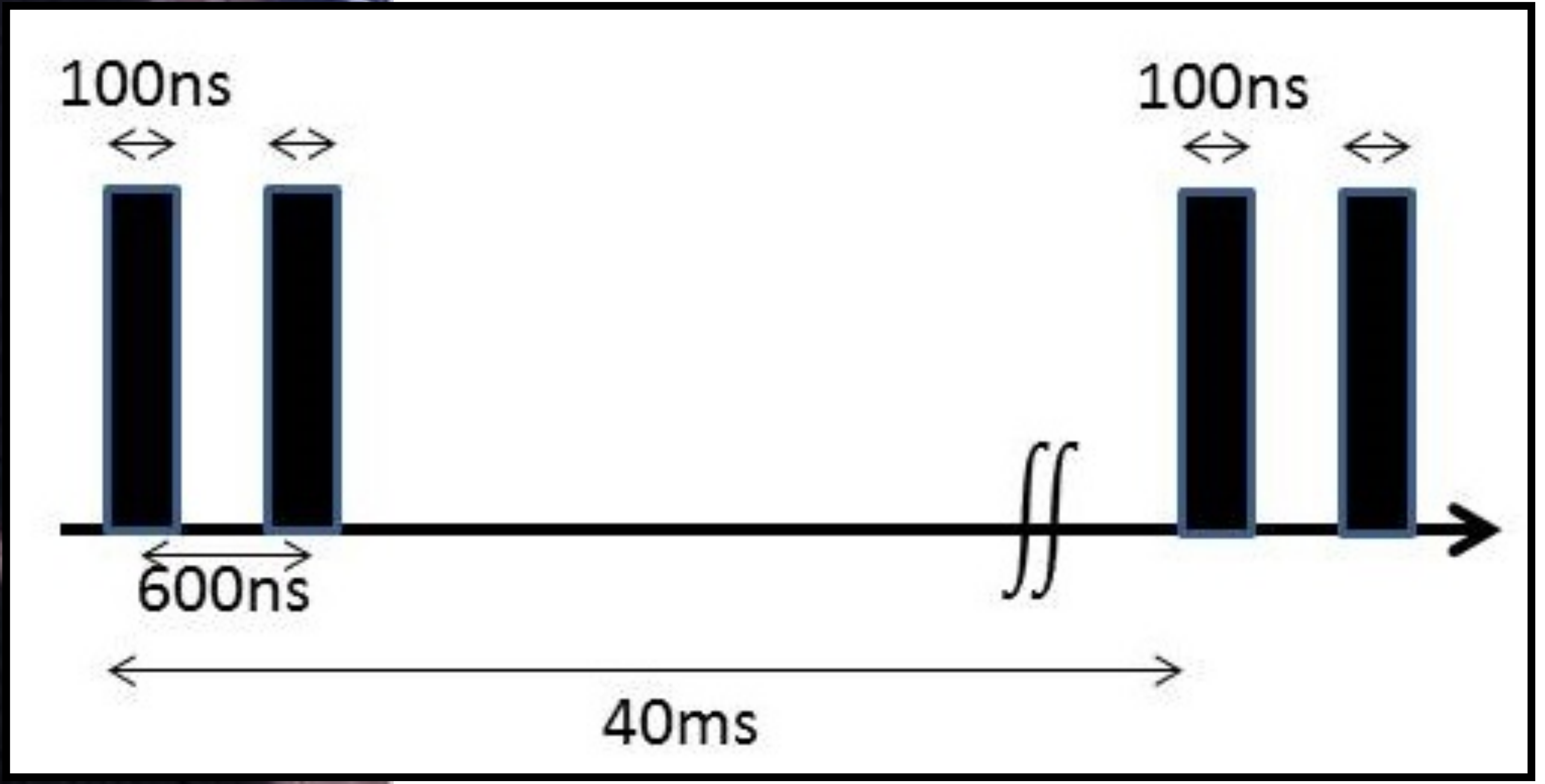
@MLF

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

J-PARC Facility (KEK/JAEA)



Materials and Life Science Experimental Facility (MLF)



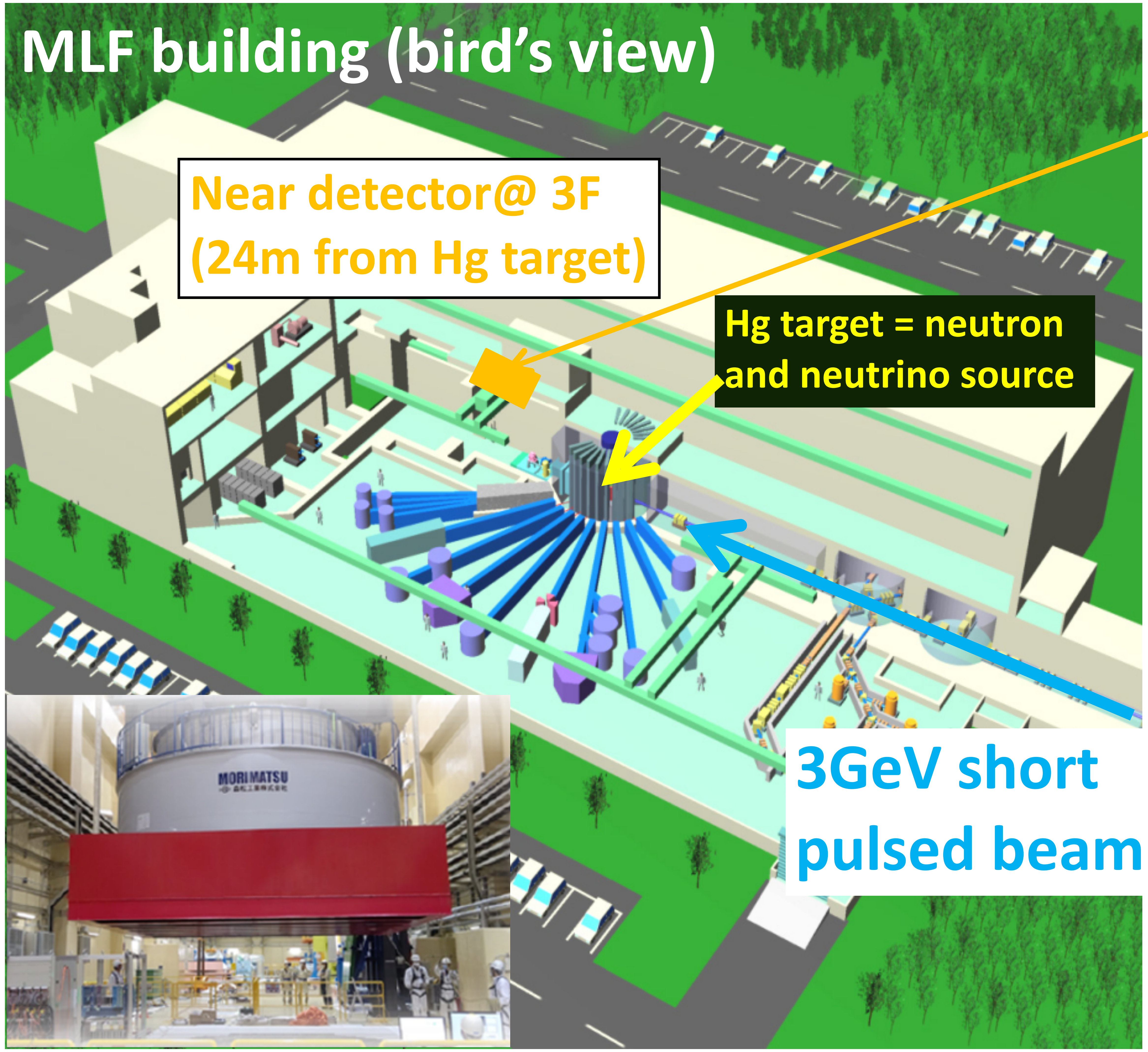
Low duty factor beam
(short pulse +
small repetition rate)
gives excellent S/N ratio.

25Hz, 1MW (design)

0.6-0.7MW (2021)
0.7-0.8MW (2022)
0.84MW (2023)
0.73-**0.95MW** (2024)

@MLF

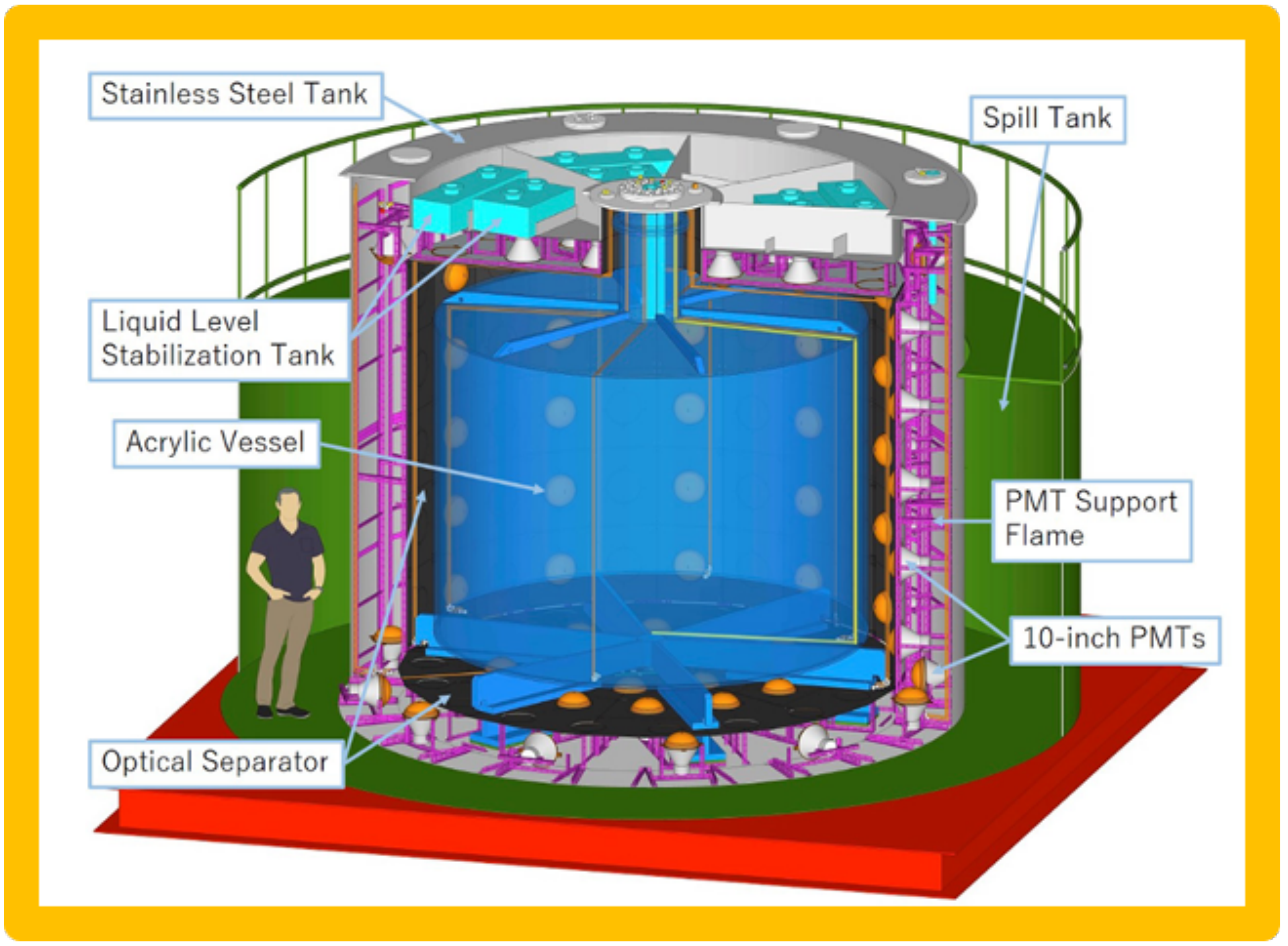
JSNS^2 detector


MLF building (bird's view)

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

Hg target = neutron
and neutrino source

3GeV short
pulsed beam



Nucl. Instrum. Methods A 1014 165742 (2021)

	Liquid	**Volume**
Target	Gd-LS + DIN(10%)	17 tons
Gamma-catcher & Veto	pure LS	31 tons

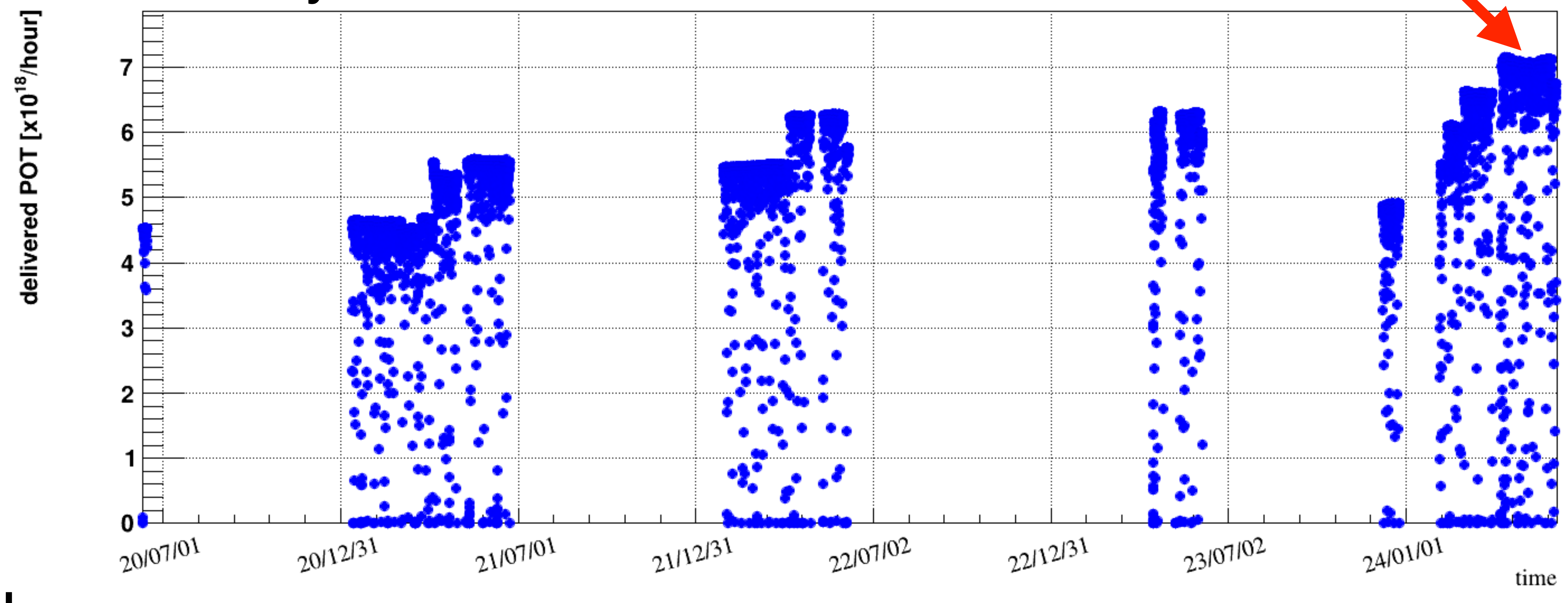
- 96 10” PMTs for the Inner Detector
- 24 10” PMTs for Veto

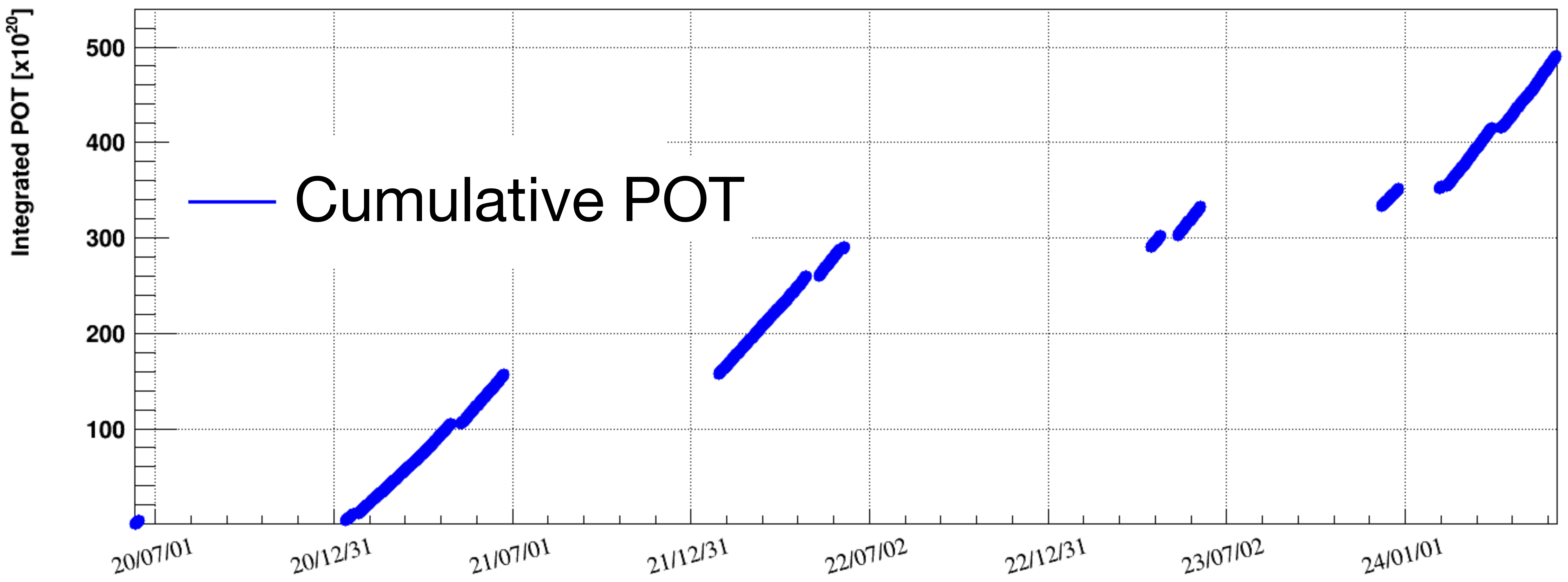
Operation of Near Detector

- Data taking
  - Commissioning (2020)
  - 4 long term physics run (2021-2024)
- 1MW beam power (Design)
  - Achieve 1MW @ RCS extraction point
  - 0.95MW @MLF
- 4.85×10^{22} POT so far
  - 43% of approved POT

0.95MW!!

Hourly POT





How to detect sterile neutrino signal

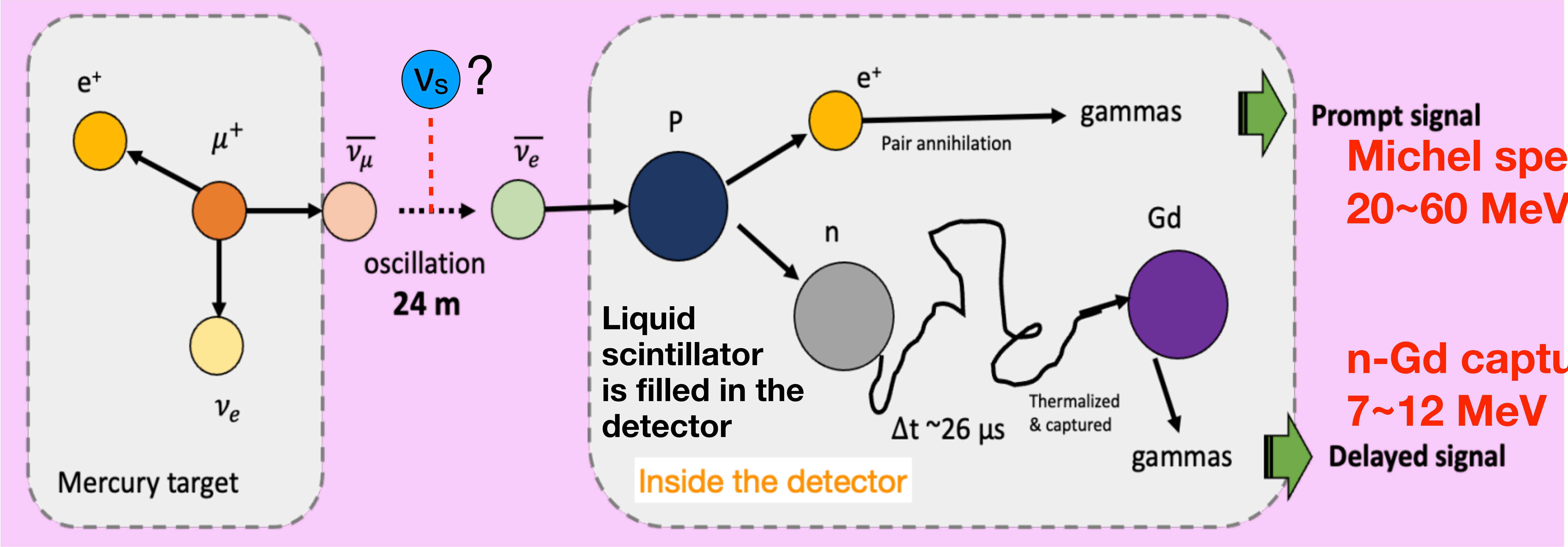
- **Sterile neutrino oscillation** during 24m baseline.

- Detection by coincidence of IBD (Inverse Beta Decay)

=> Prompt : e+ signal
=> Delayed : gammas from neutron capture on gadolinium (Gd)

	Timing	Energy
Prompt	$2<T_{beam}<10\mu s$	20~60 MeV
Delayed	$\Delta T_{p\text{-}d} <100\mu s$	7~12 MeV

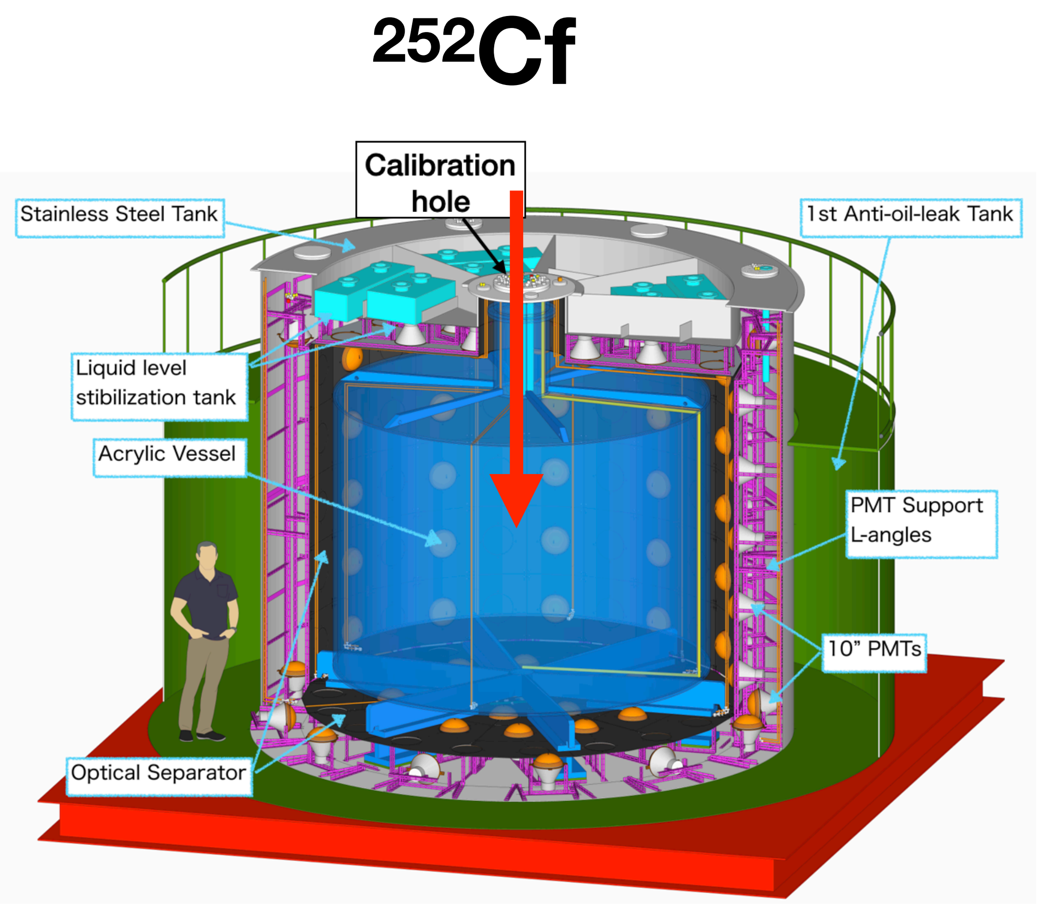
+ Spatial correlation cut
$\Delta VTX_{p\text{-}d} < 60cm$

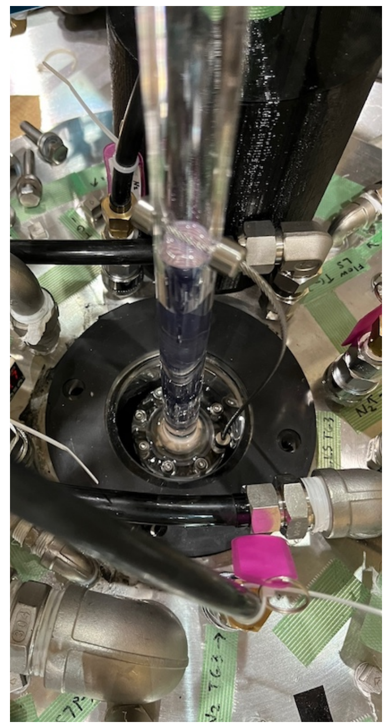


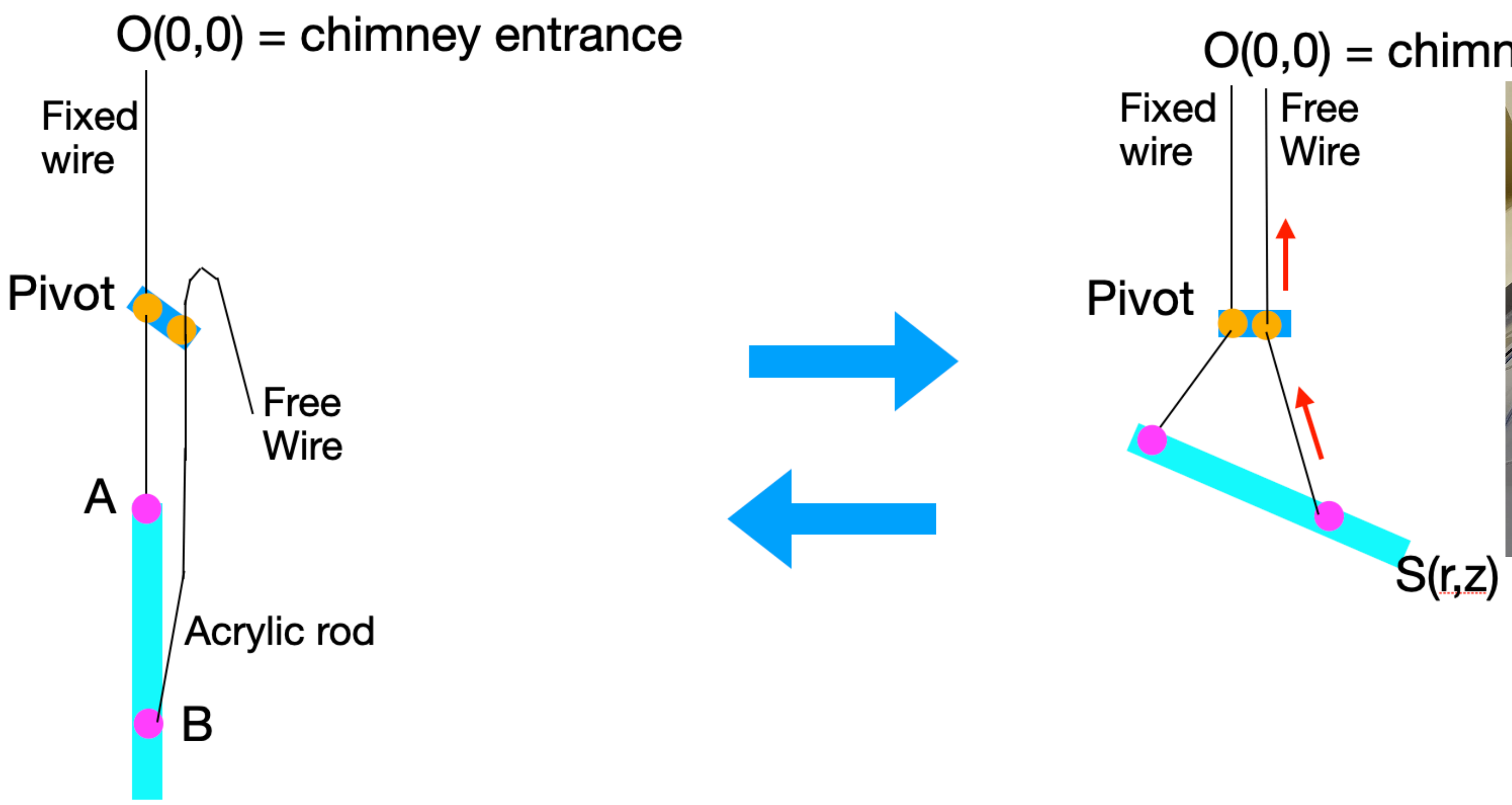
Michel spectrum
20~60 MeV

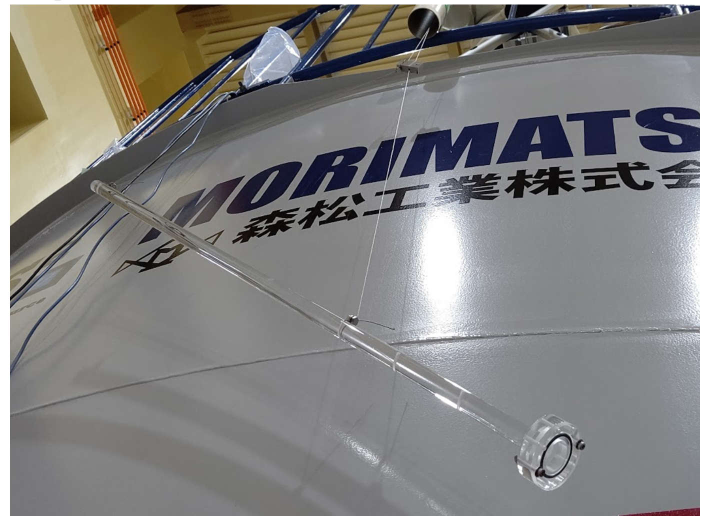
n-Gd capture
7~12 MeV

^{252}Cf 3D calibration : Energy/Vertex reconstruction









Installation / Dismantle

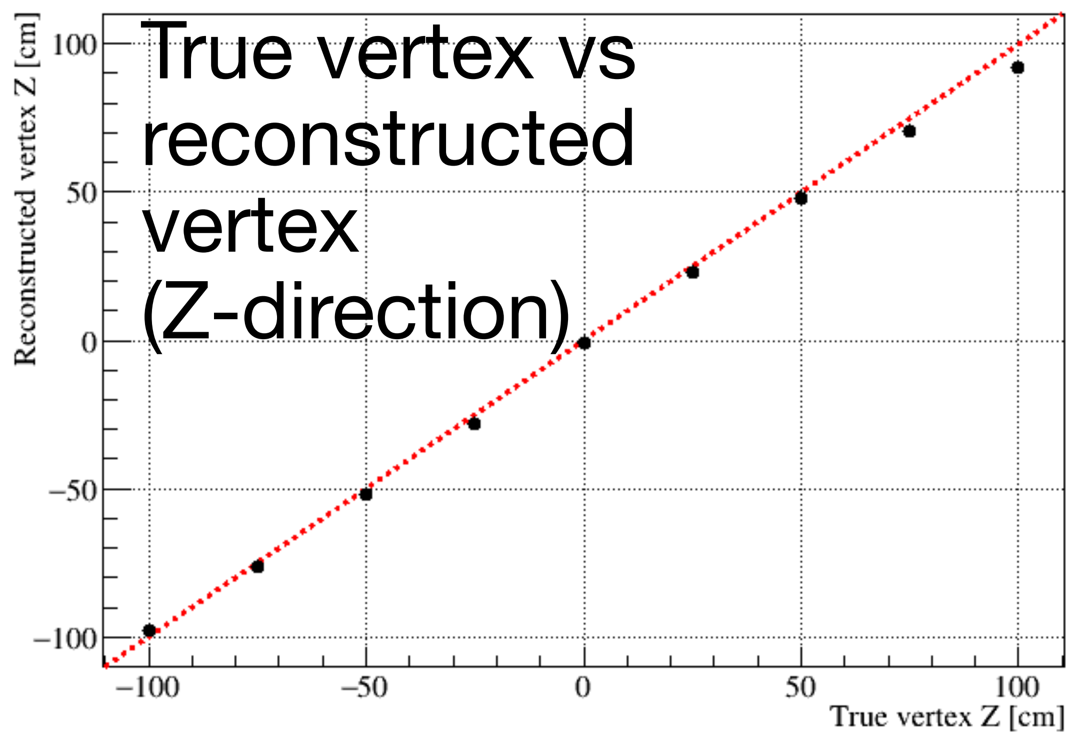
Manipulate the pipe

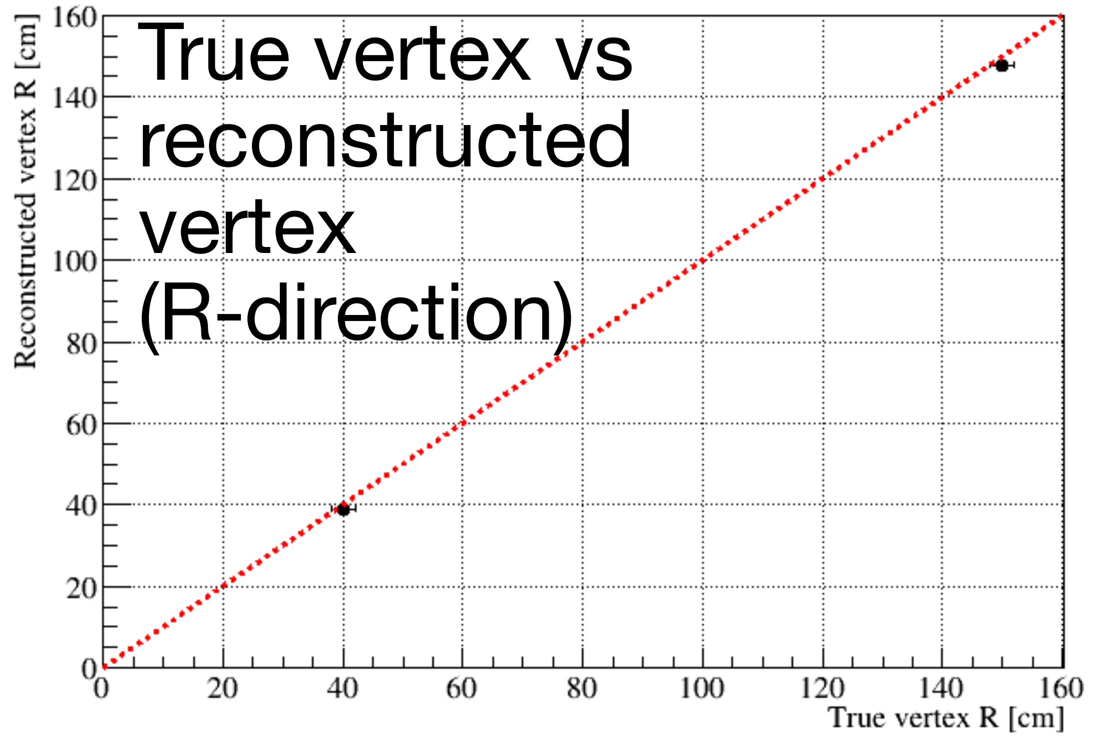
(NEW)
^{252}Cf 3D calibration system
-> **Any of position (R&Z)** can be covered!!!

arXiv:2404.04153 [hep-ex], under review @ NIMA

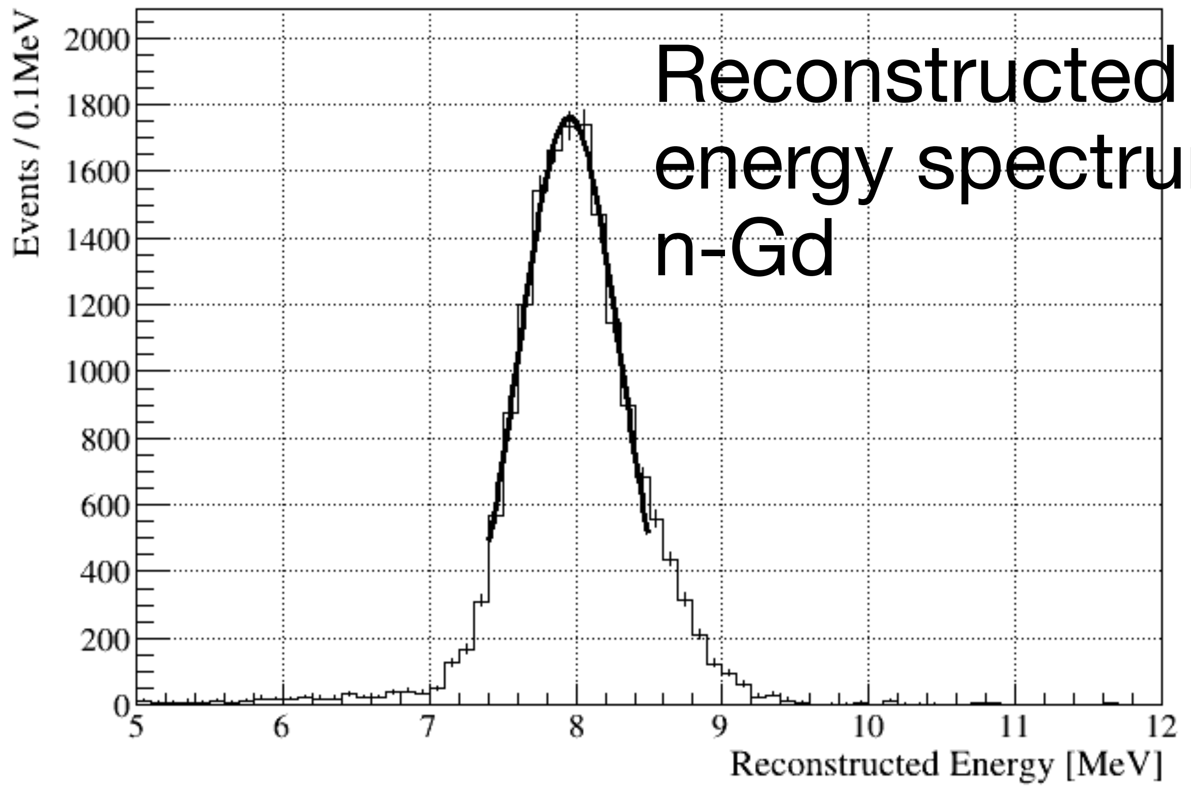
- Reconstruction Parameters were studied based on this calibration

=> Reconstruction performances were checked using ^{252}Cf and Michel electrons data sample

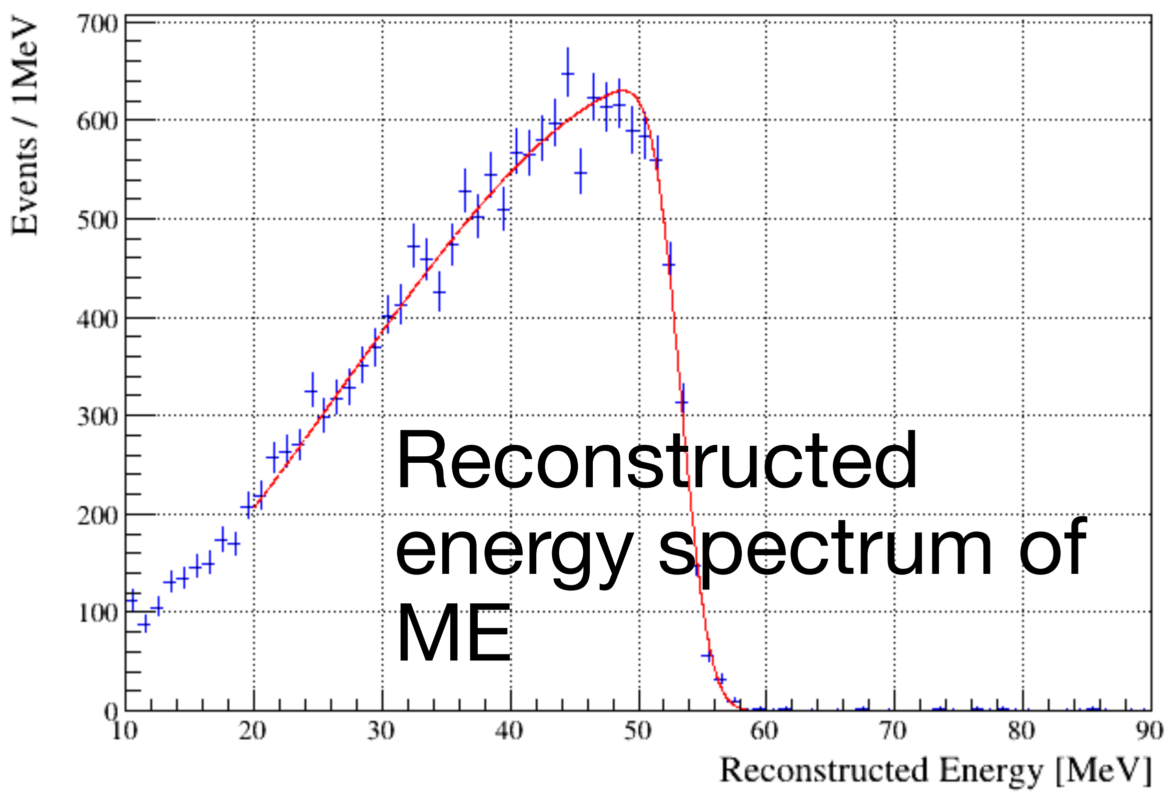




~10% fiducial volume uncertainty



~4% E resolution @ 8MeV of n-Gd



~3% E resolution @ ~53MeV of ME

Dongha Lee

Toward the sterile neutrino search (Blind analysis)

- PSD : arXiv:2404.03679 [physics.ins-det], under review @PTEP
- Accidental background : Eur. Phys. J. C 84, 409 (2024)

Toward the sterile neutrino search (Blind analysis)

- We are doing the blind analysis to search a sterile neutrino, by using the energy side-bands.
- The rates in the side-band regions will be predicted by the control samples driven by data
- **Now, side-band 4 (prompt 60-100MeV) data are opened!!!**
- Side-band 1&3 are being studied now.

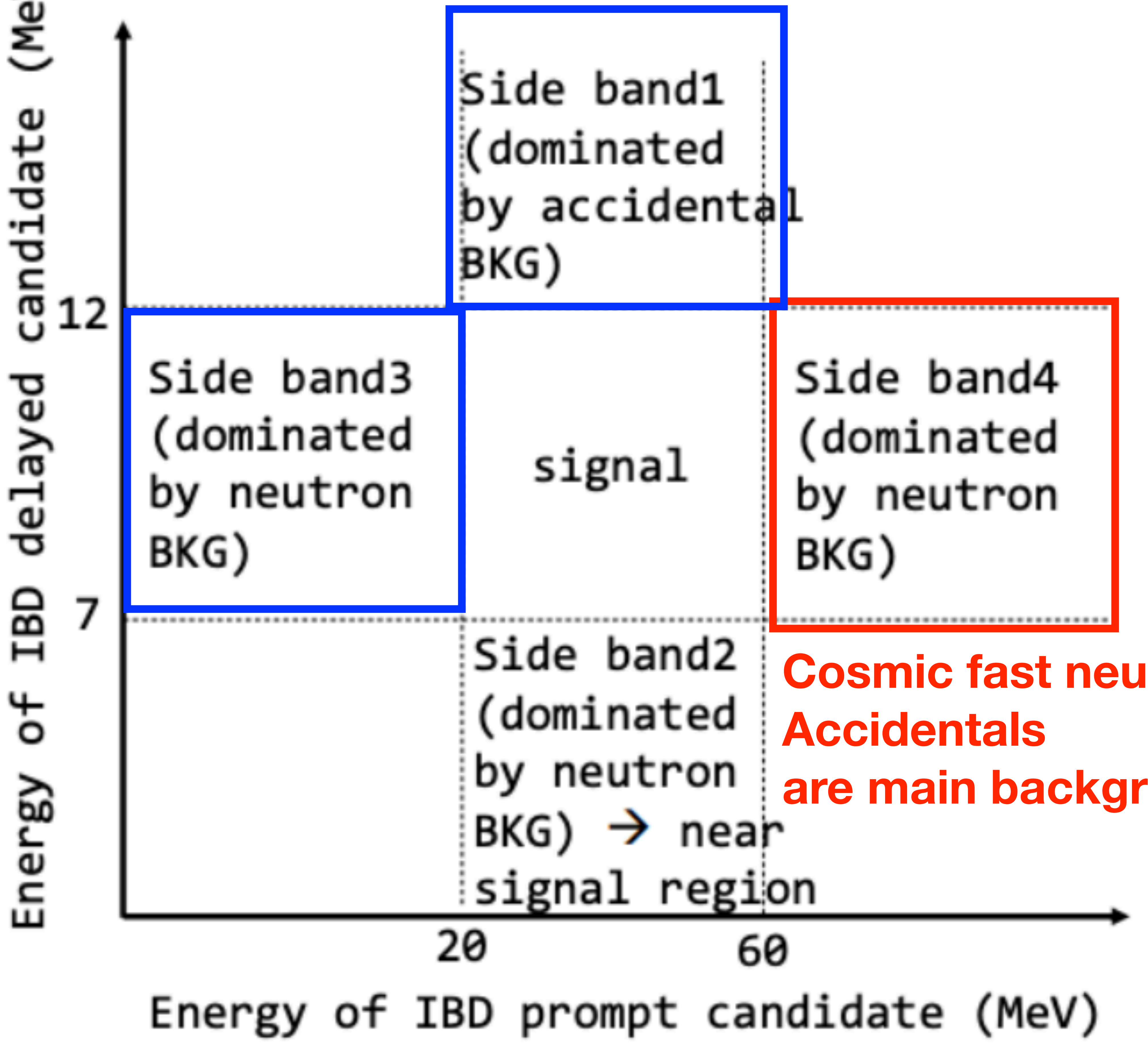
Observation **VS** **Expectation**

Physics data with criteria :
xx<E_p<yy MeV
zz<E_d<ww MeV
$\Delta T_{p\text{-}d}$ <100μs
$\Delta VTX_{p\text{-}d}$ < 60cm

Purely **data-driven** control sample

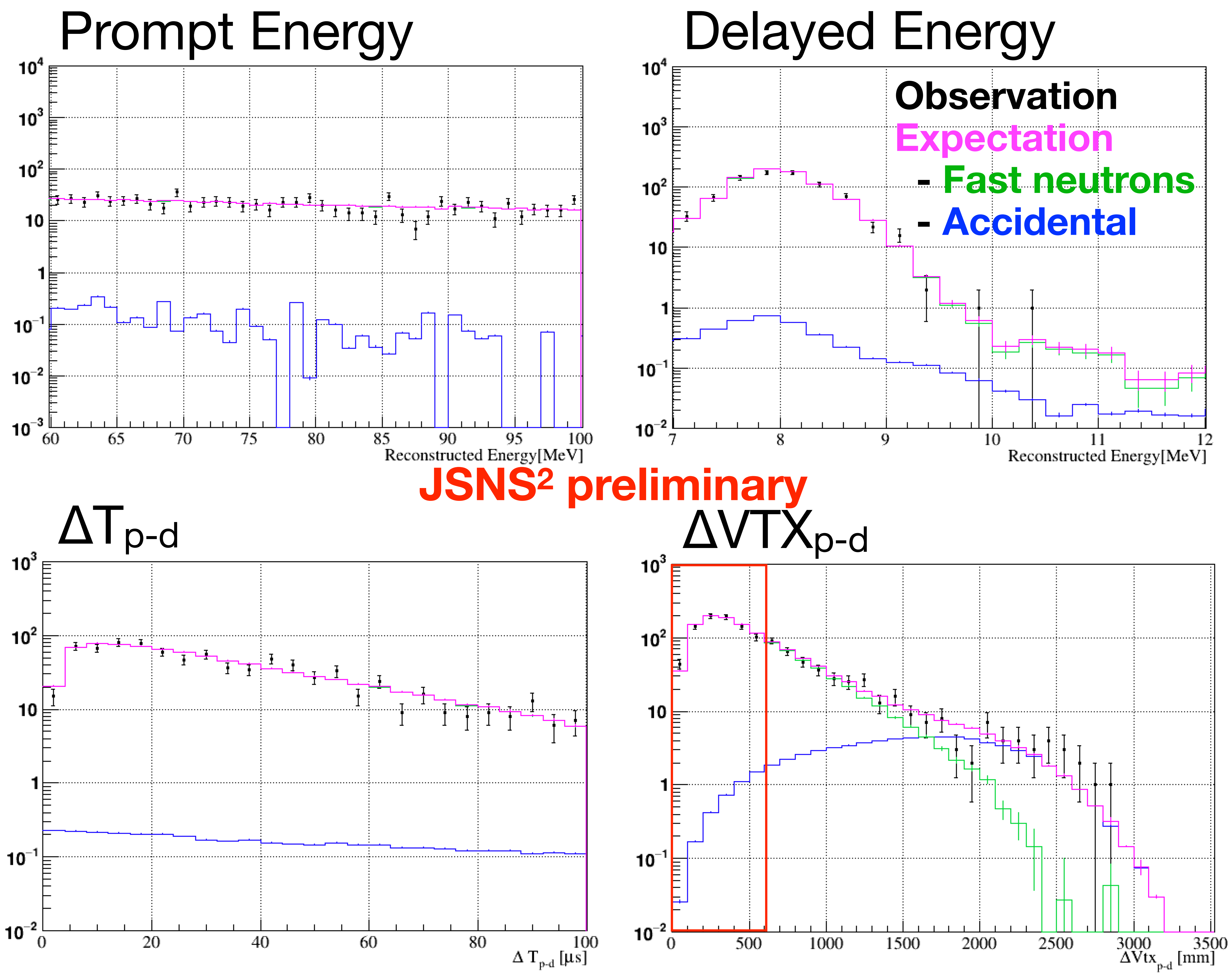
- **Fast neutrons**
  -> obtained at T_{beam} > 1ms
- **Accidental background**
  -> obtained with specific calibration runs

energy side-bands



Cosmic fast neutrons, Accidentals are main backgrounds

The comparison between the observation vs expectation for Side-band4 (prompt 60~100MeV)



Prompt Energy

Delayed Energy

ΔTp-d

ΔVTXp-d

JSNS² preliminary

*2022 physics data (0.8x10^{22} POT)

	# of Observation events	# of Expectation events
Total	818 +- 28.6 (stat) + 6.0 (sys)	839.3 +- 3.0 (stat) +- 2.6 (sys)
Fast neutrons		835.3 +- 3.0 (stat) +- 2.5 (sys)
Accidental		4.0 +- 0.1 (stat) +- 0.07 (sys)

- **Good consistency between Observation vs Expectation !!!**

- Cosmogenic fast neutrons are dominated
=> Aim to ~99% rejection
=> **Pulse Shape Discrimination (PSD)** would reject most of them
(**arXiv:2404.03679 [physics.ins-det]**)

- After applying PSD, **accidental bkg will be also crucial.** (**Eur. Phys. J. C 84, 409 (2024)**)

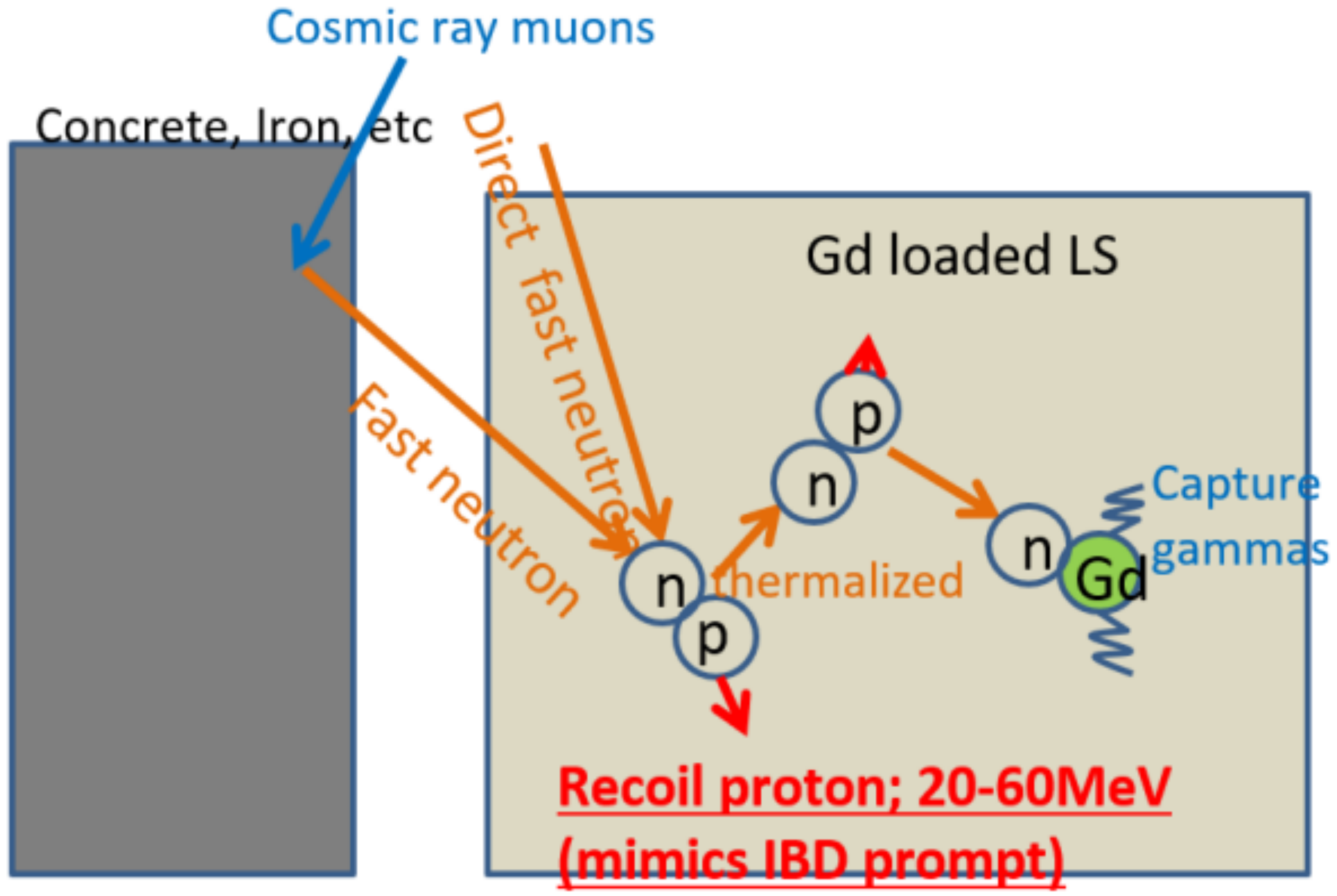
- (Preliminary) energy scale systematic uncertainties are much less than stat. error

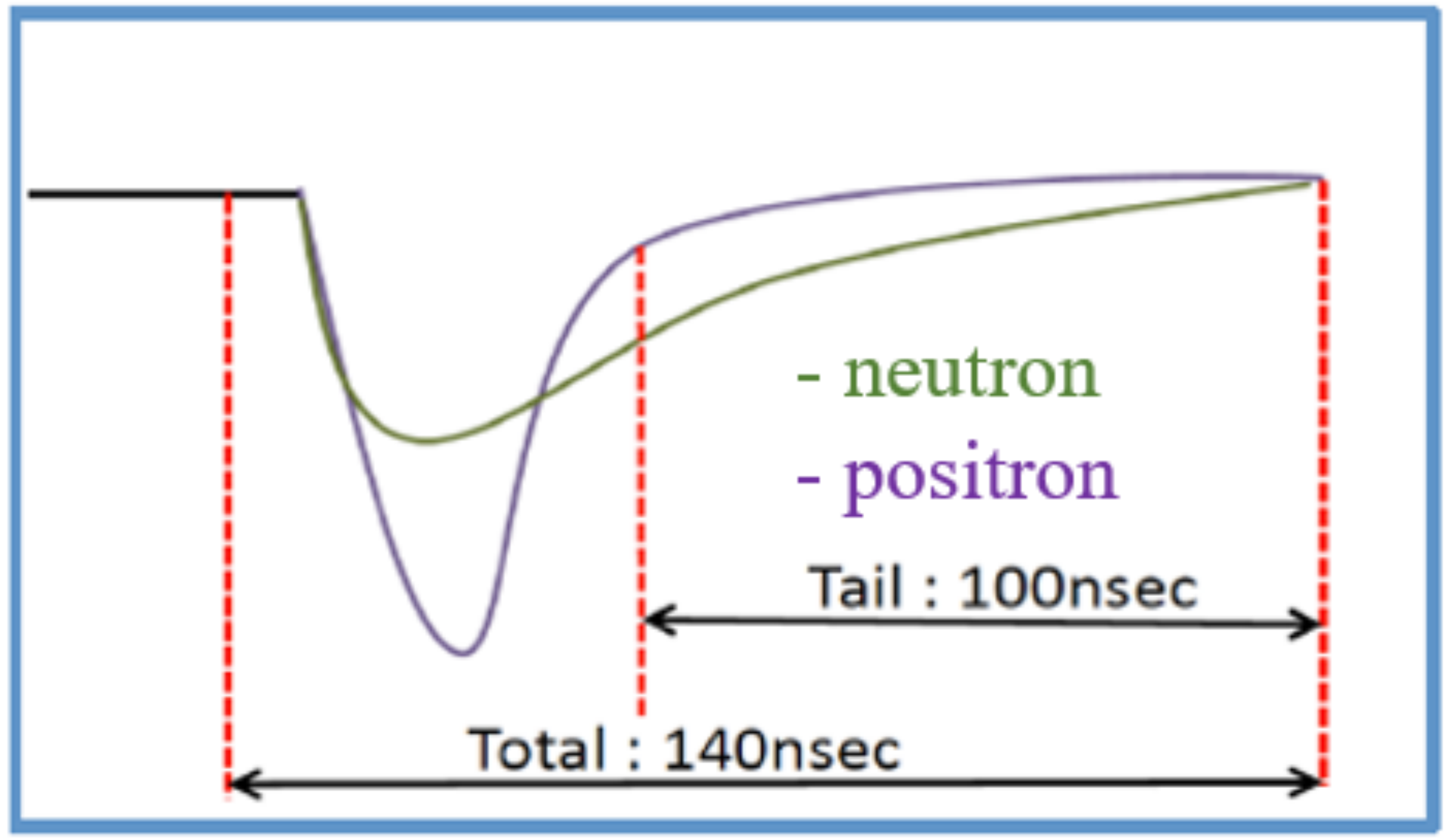
Pulse Shape Discrimination (PSD)

- **Fast neutrons** can mimic the IBD signals from electron anti-neutrino.

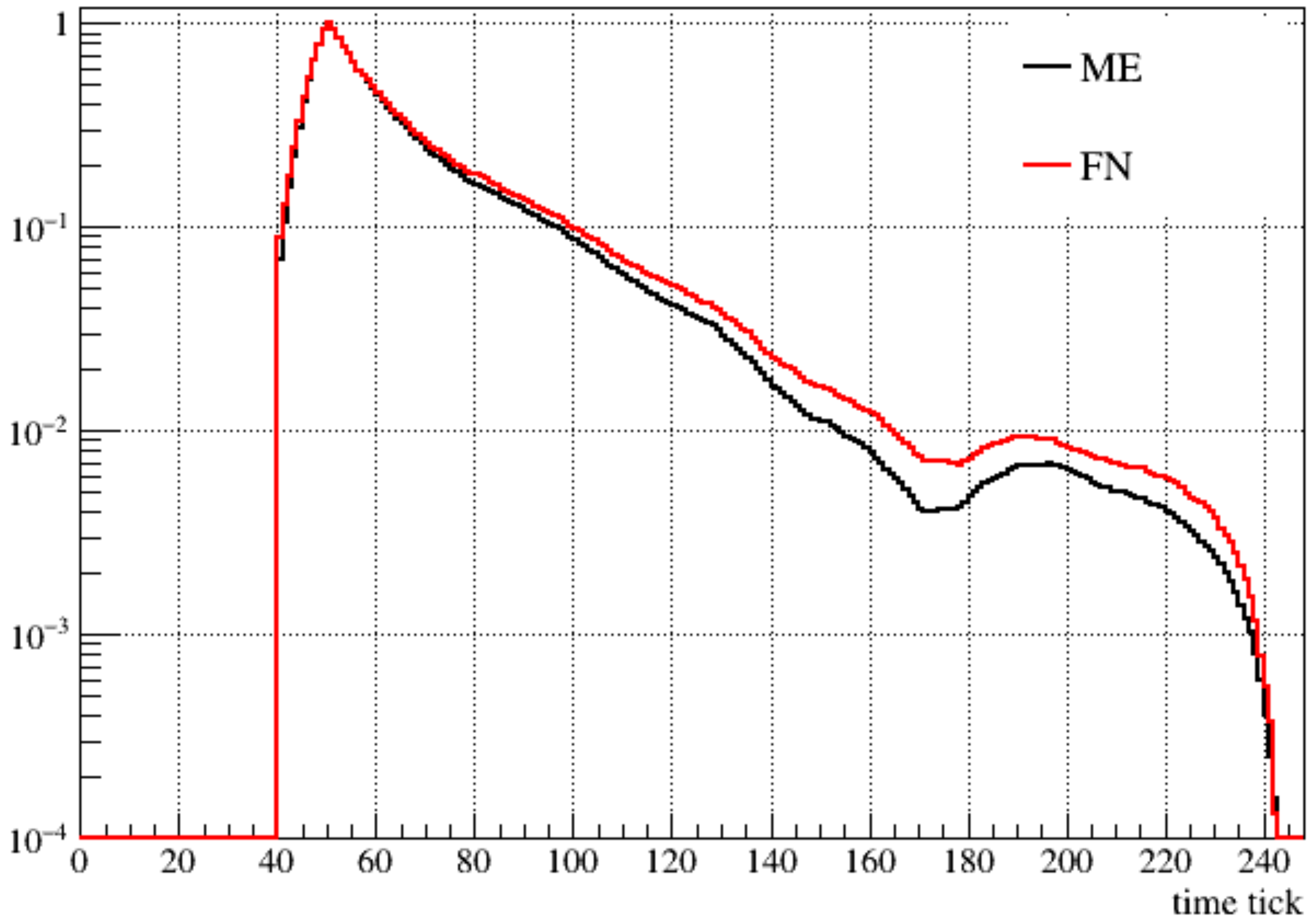
- **Pulse Shape Discrimination (PSD)** by using
the difference of waveforms between e-like and n-like.

- **Data-driven likelihood method**
(Control sample :
Michel electron / Fast neutron)
=> Full information of waveform height are used.
=> Each PMT has its own PDF and separation power.

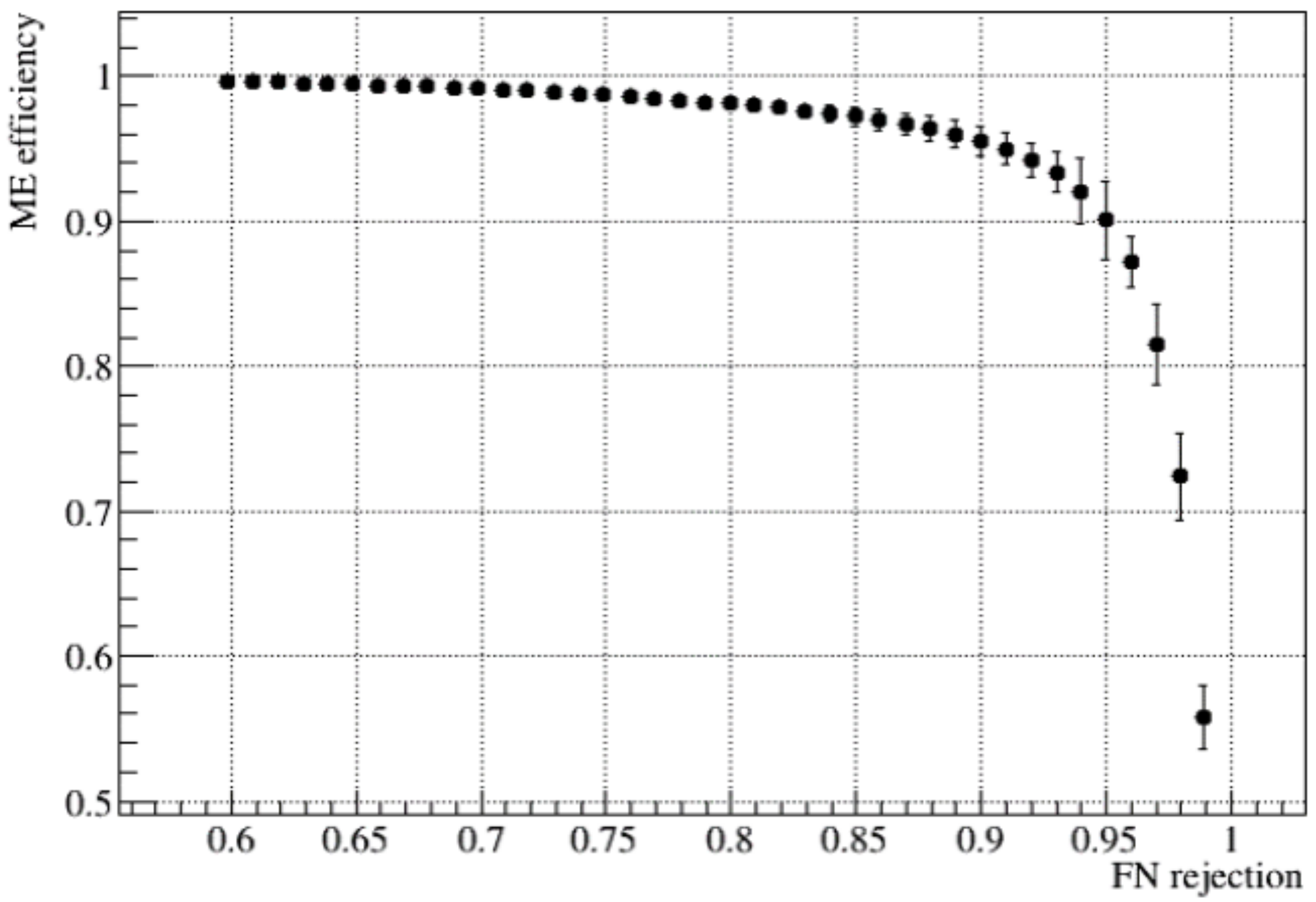




Average waveform (1 PMT)



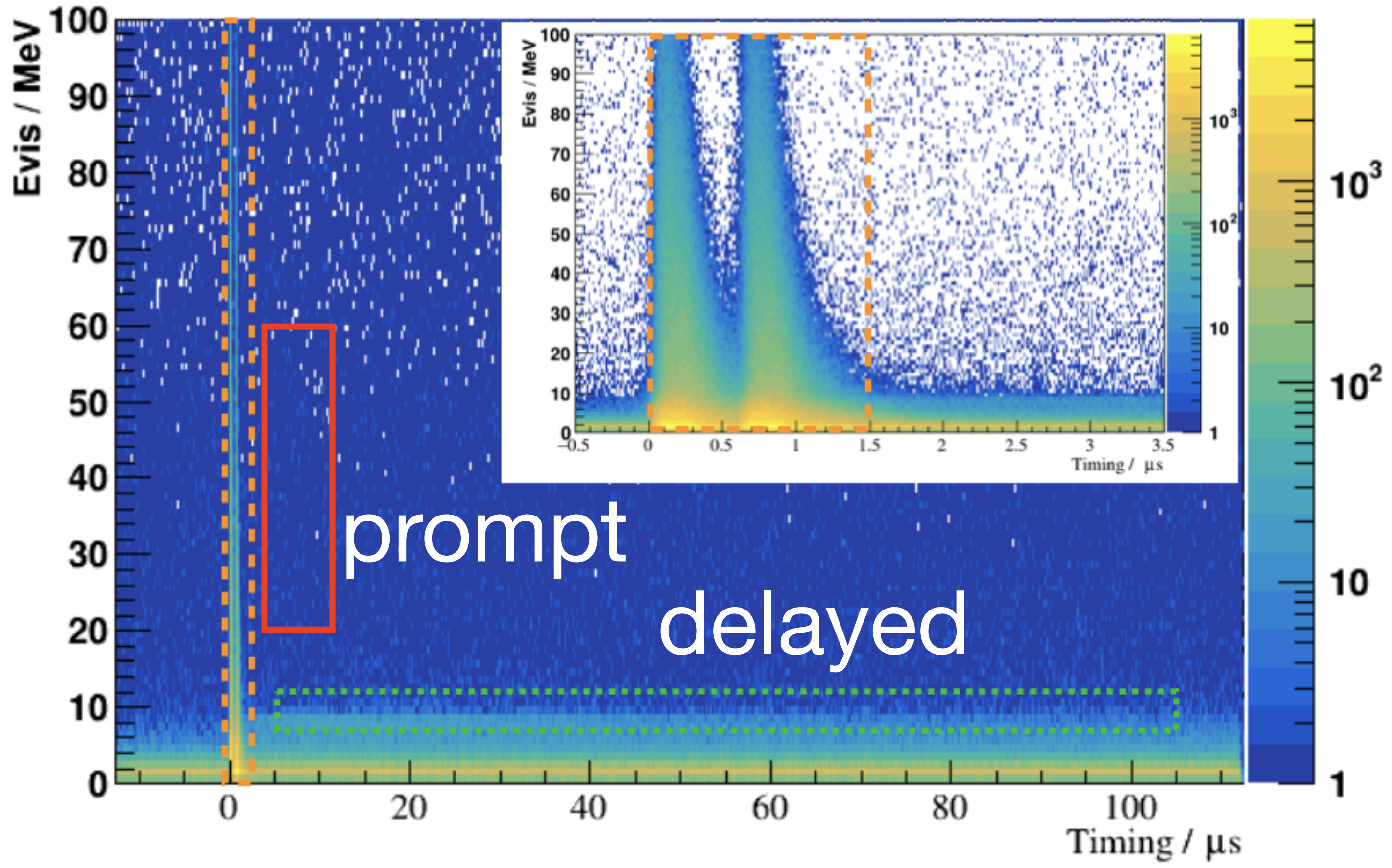
PSD capability



arXiv:2404.03679 [physics.ins-det], under review @PTEP

Study of the accidental background

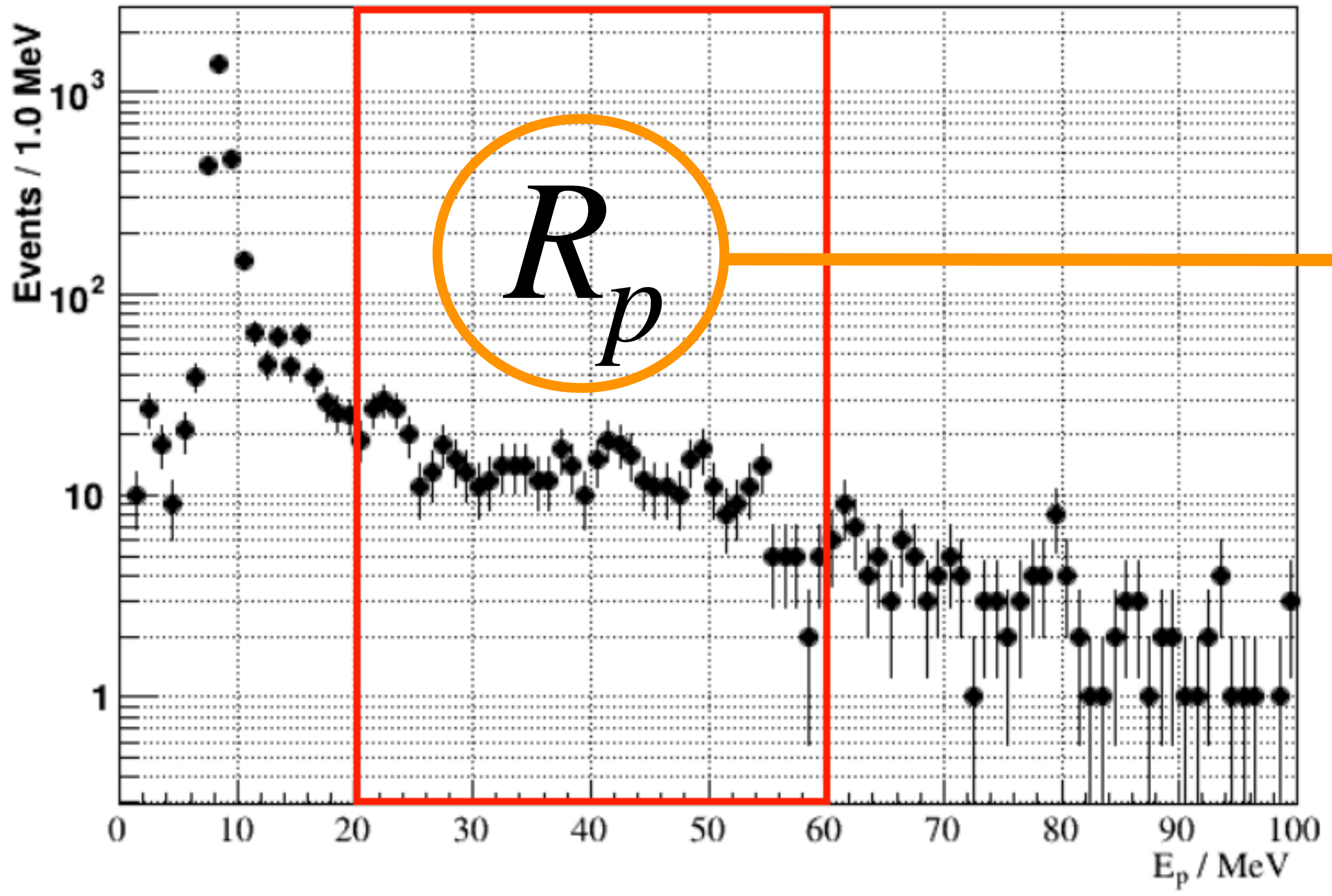
125μs time window triggered data
(special calibration run)

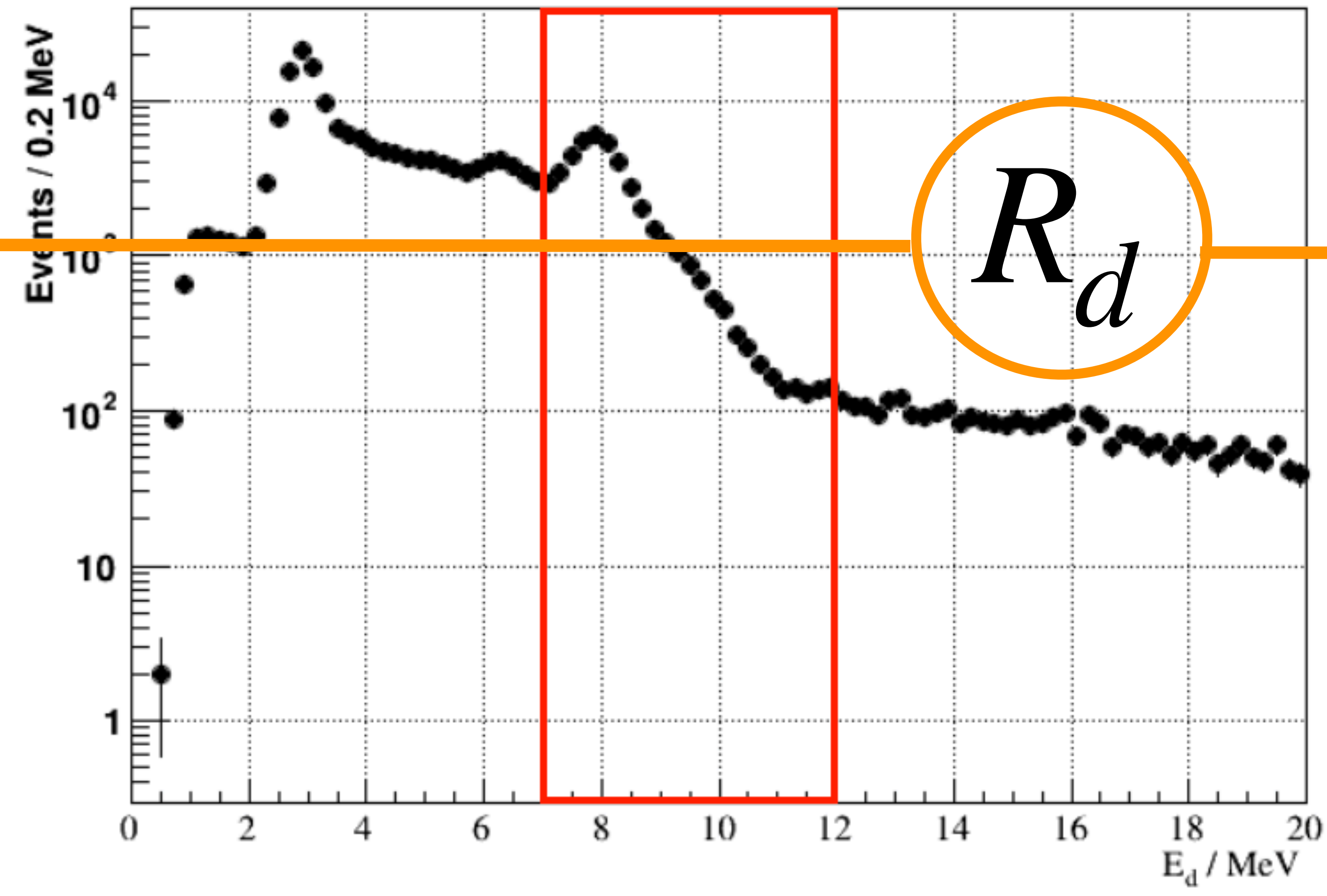


- Accidental background means just randomly paired events of the IBD signal coincidence selections.

- Accidental background can be estimated by the multiplication of the **Single Rates of Prompt/Delayed.**

Single Rates(/spill) of Prompt/Delayed events





$$R_{acci} = \boxed{R_p \times R_d} \times \varepsilon_{cut}$$

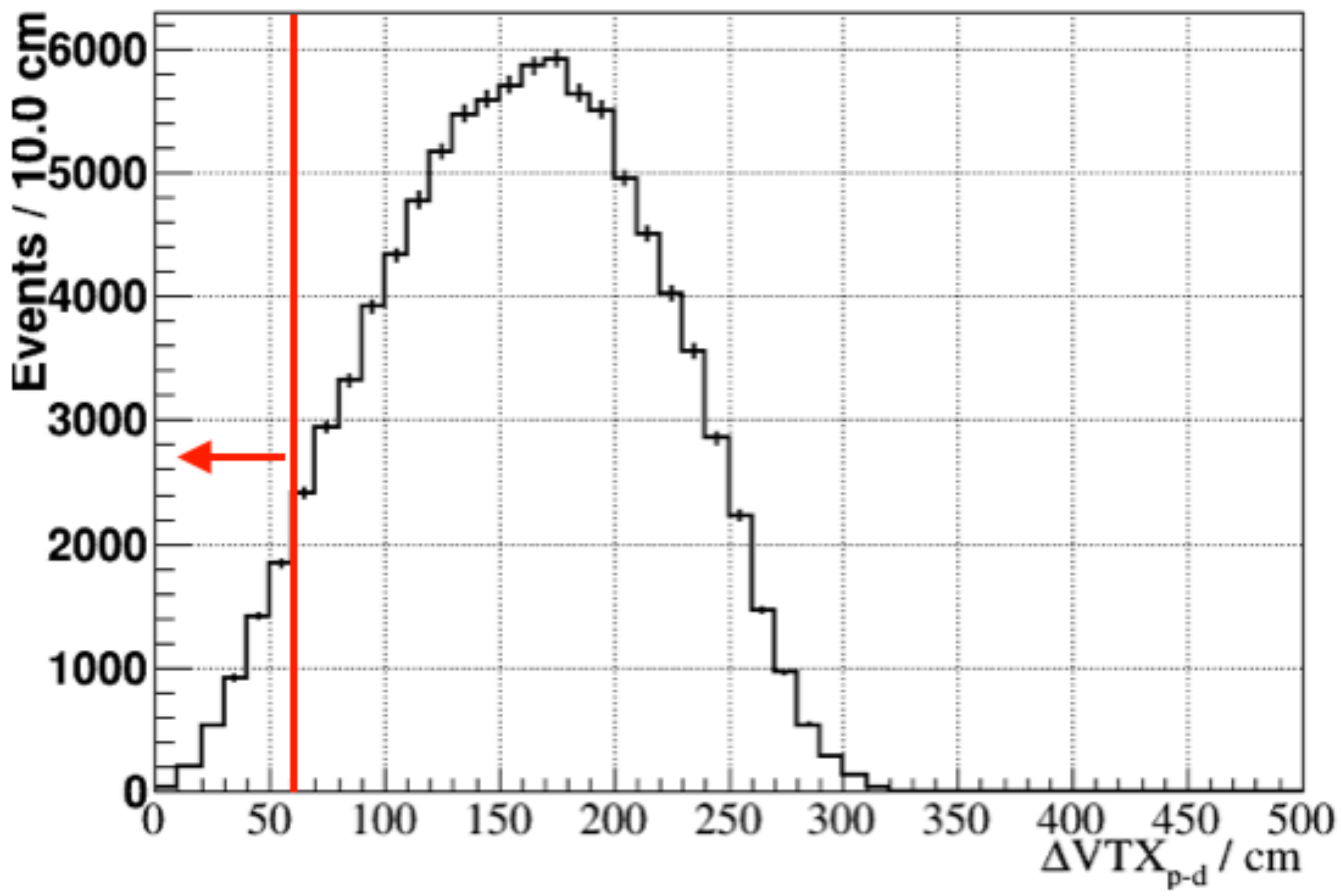
	Values
Prompt rate/spill	(2.20 +- 0.09) x 10^{-4}
Delayed rate/spill	(1.80 +- 0.01) x 10^{-2}

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

Study of the accidental background

- Not only the single rates, also any variable such as $\Delta VTX_{p\text{-}d}$ can be obtained from the data-driven control sample of random pairs.

$\Delta VTX_{p\text{-}d}$ Distribution



$$R_{acci} = R_p \times R_d \times \varepsilon_{cut}$$

	Values
Prompt rate/spill	$(2.20 \pm 0.09) \times 10^{-4}$
Delayed rate/spill	$(1.80 \pm 0.01) \times 10^{-2}$
ε ($\Delta VTX_{p\text{-}d}$ < 60cm)	5.1 +- 0.1%
ε (Timing Liklihood)	46%
Acci rate/spill/0.75MW	$(9.29 \pm 0.42) \times 10^{-8}$

Data
Data
Data
MC

- For reduction of accidental background, the events $\Delta VTX_{p\text{-}d} < 60$cm are selected.

- JSNS² has a comparable accidental rate as the expected IBD signal rate 4.59×10^{-8} /spill /1MW. (based on the LSND best fit oscillation parameters)

Still will be improved further !!!

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

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

- Preparing a paper now

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

- No π or K production rate measurements with Hg - p (3GeV) reaction, so far.

- $^{12}C(\nu_e,e^-)^{12}N_{g.s.}$ measurements can provide a normalization of IBD signals.

CNgs IBD/Sterile

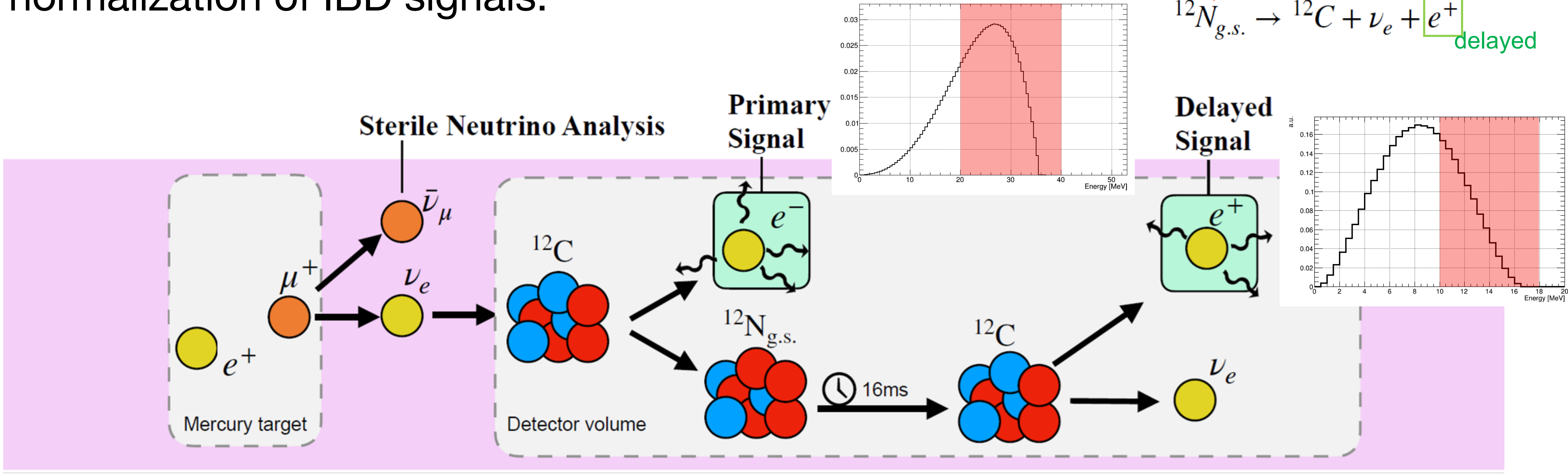
$$\mu^+ \to e^+ + \boxed{\nu_e} + \boxed{\overline{\nu}_\mu}$$

prompt

$$^{12}C + \nu_e \to {}^{12}N_{g.s.} + \boxed{e^-}$$

$$^{12}N_{g.s.} \to {}^{12}C + \nu_e + \boxed{e^+}$$

delayed

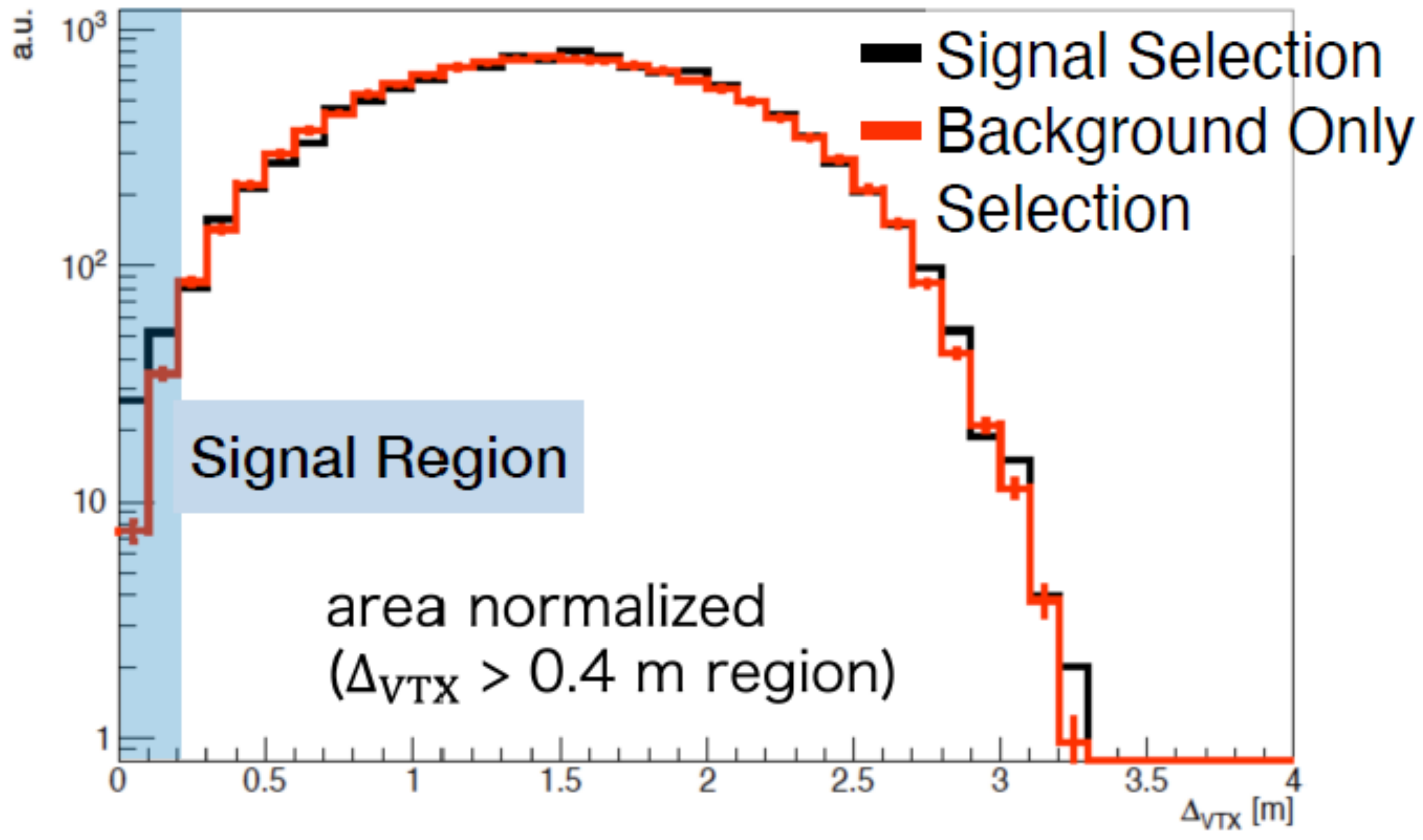


Observed events of $^{12}C(\nu_e,e^-)^{12}N_{g.s.}$

JSNS² preliminary

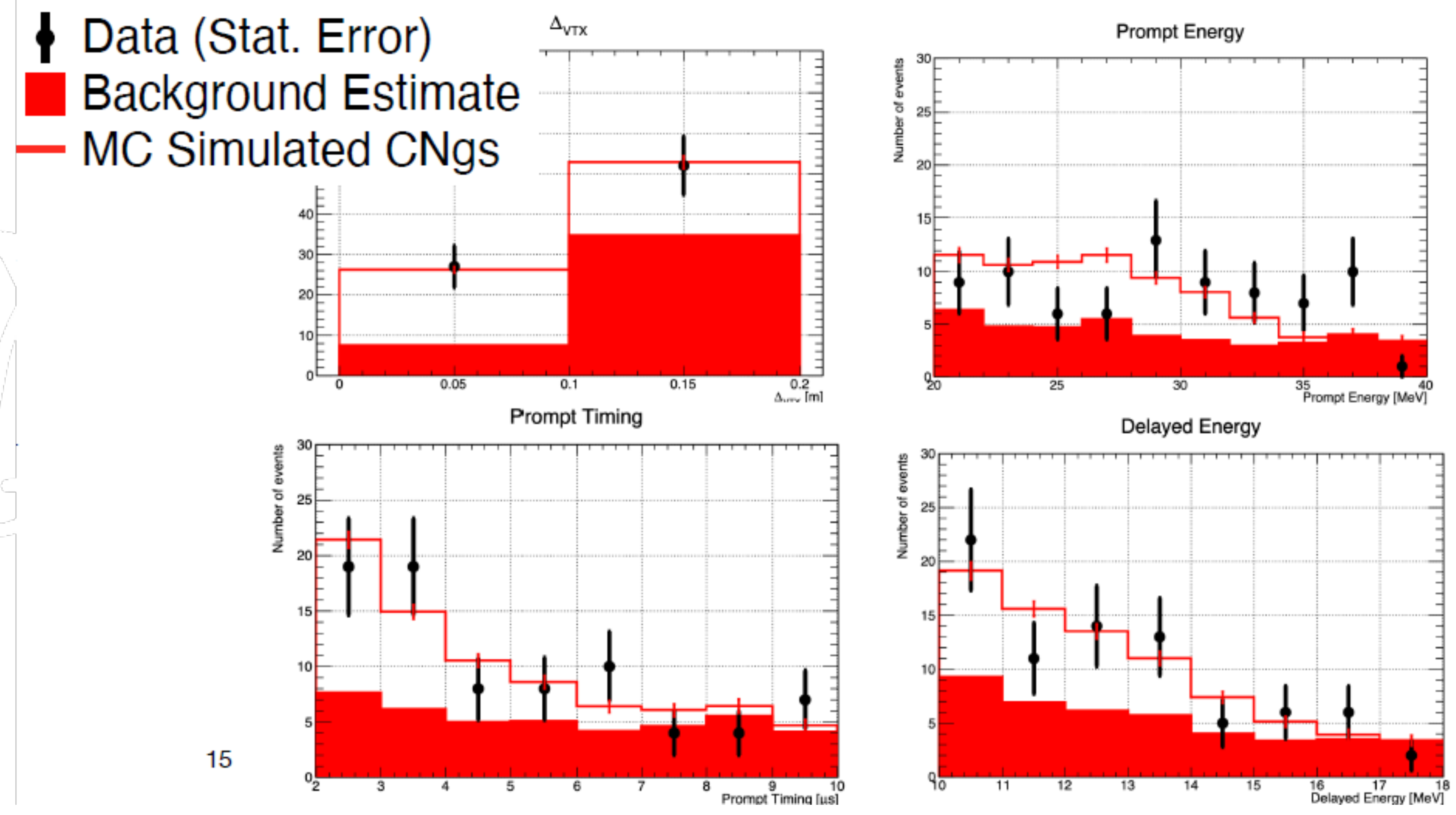
- 2021 & 2022 physics data (2.2×10^{22} POT)
- Observed CNgs candidates : 79 events
- Background events : 42.2 +- 6.5 (stat.) +- 1.7 (syst.)

<Event Selection>
$20 < E_p < 40$MeV
$10 < E_d < 18$MeV
$0.2 < \Delta T_{p\text{-}d} < 12$ms (2021)
<25ms (2022)
$\Delta VTX_{p\text{-}d} < 20$cm



- The accidental background is dominant.
=> estimated by normalization from large ΔVTX region.

- All distributions for selected variables seem to be reasonable.



Neutrino flux measurement

Observed Event Rate

Neutrino Flux

Selection Efficiency

Cross Section

$$N_{CNGS} = \frac{\boxed{\Phi_{\nu_e}} POT}{4\pi r^2} \epsilon \sigma N_C$$

Number of Carbons

- Neutrino flux can be obtained by above equation.

=> $\varepsilon_{detection}$ = 0.0588 +- 0.0021

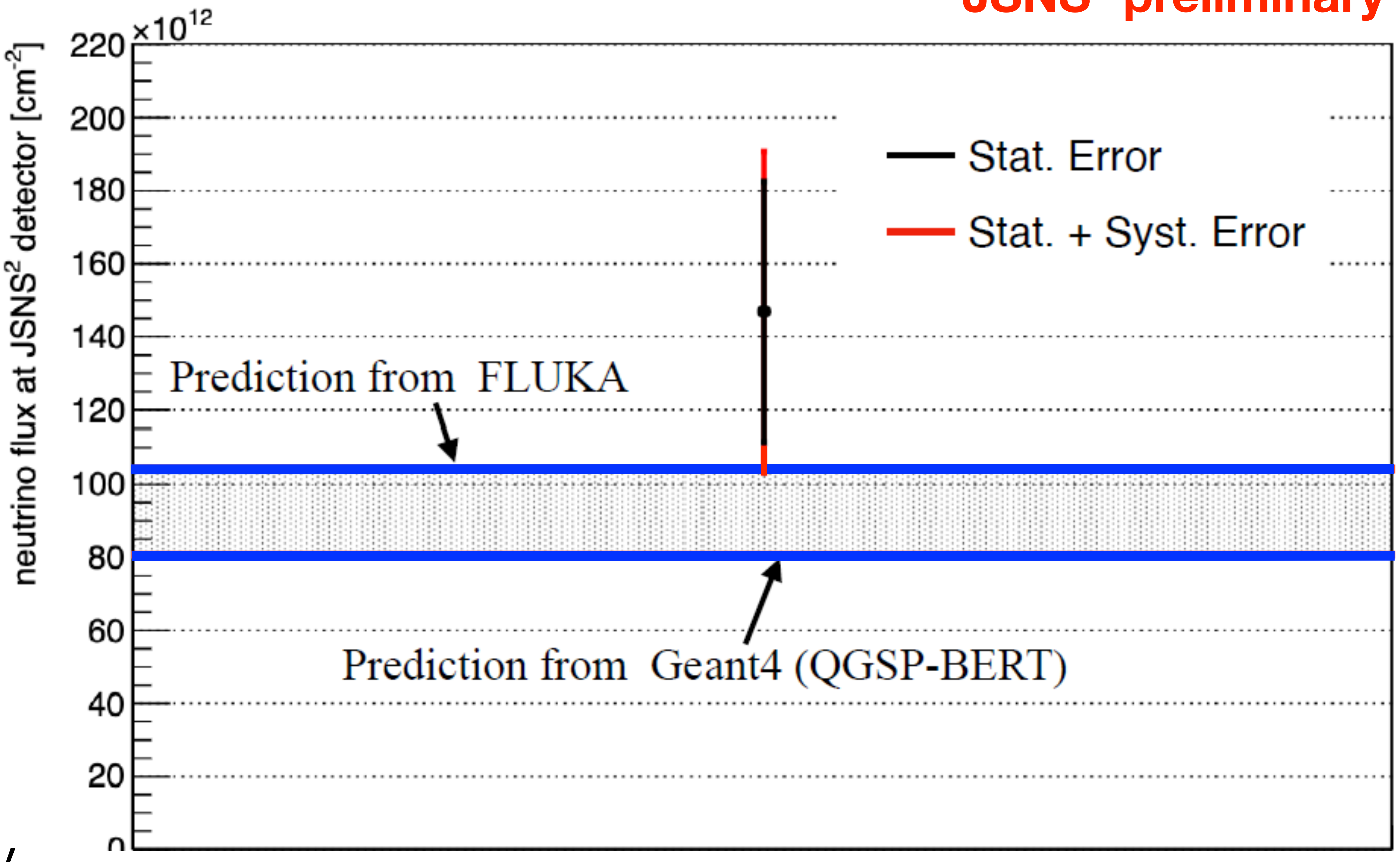
=> Cross section (LSND+KARMEN) = $(9.1 \pm 0.7) \times 10^{-42}$ cm^2

- Good consistency with the predictions.

- POT will be twice with full data of 2021-2024.

=> can achieve ~20% total uncertainty.

=> to normalization of IBD signals.



* For cross section,
the combined value of LSND (Phys. Rev. C 64:065501 (2001))
+KARMEN (Prog. Part. Nucl. Phys. 40, 183 (1998)) is used.

Dongha Lee

KDAR neutrino measurement

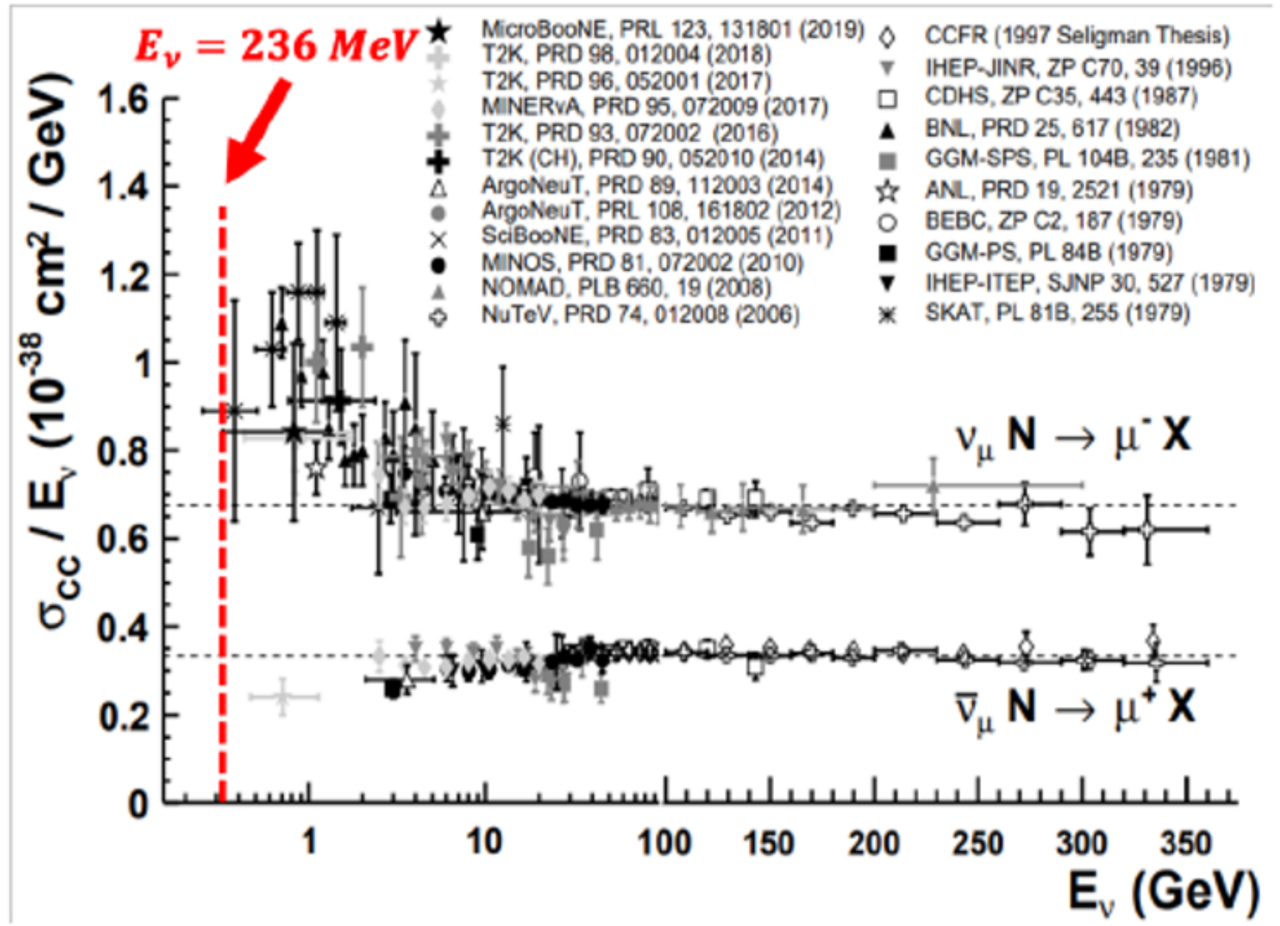
- arXiv:2409.01383 [hep-ex], submitted to PRL

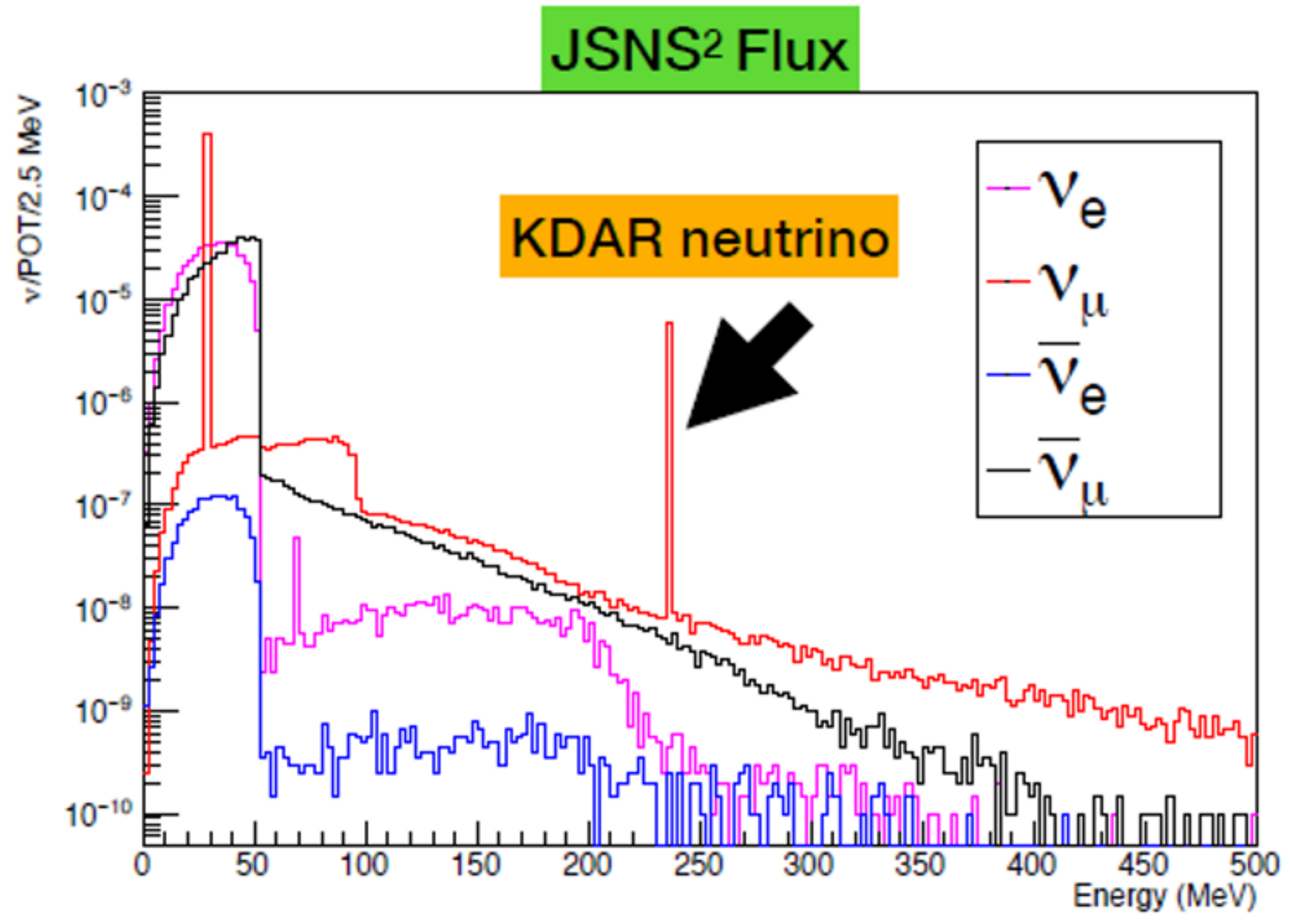
Kaon Decay-At-Rest neutrino measurement

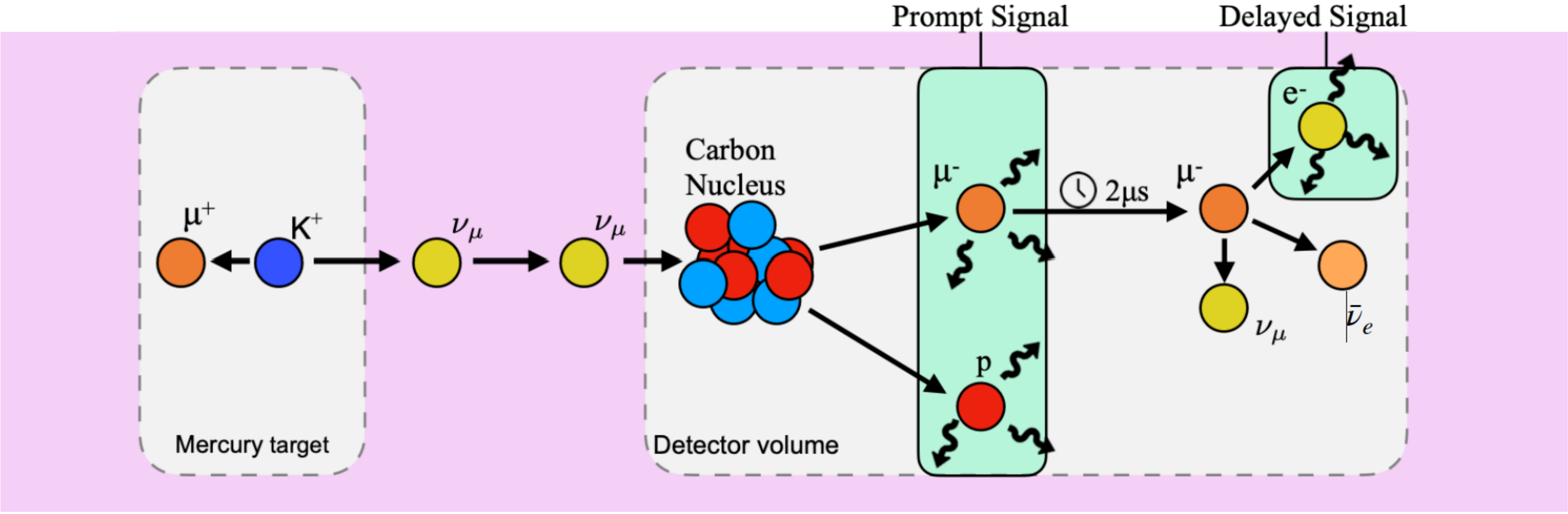
- KDAR neutrinos have a **KNOWN mono-energy (235.5MeV)**

- Few cross-section measurements below 1GeV so far.

- Nuclear effects measurements -> some progress in this study







KDAR $K^+ \to \mu^+ + \nu_\mu$

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

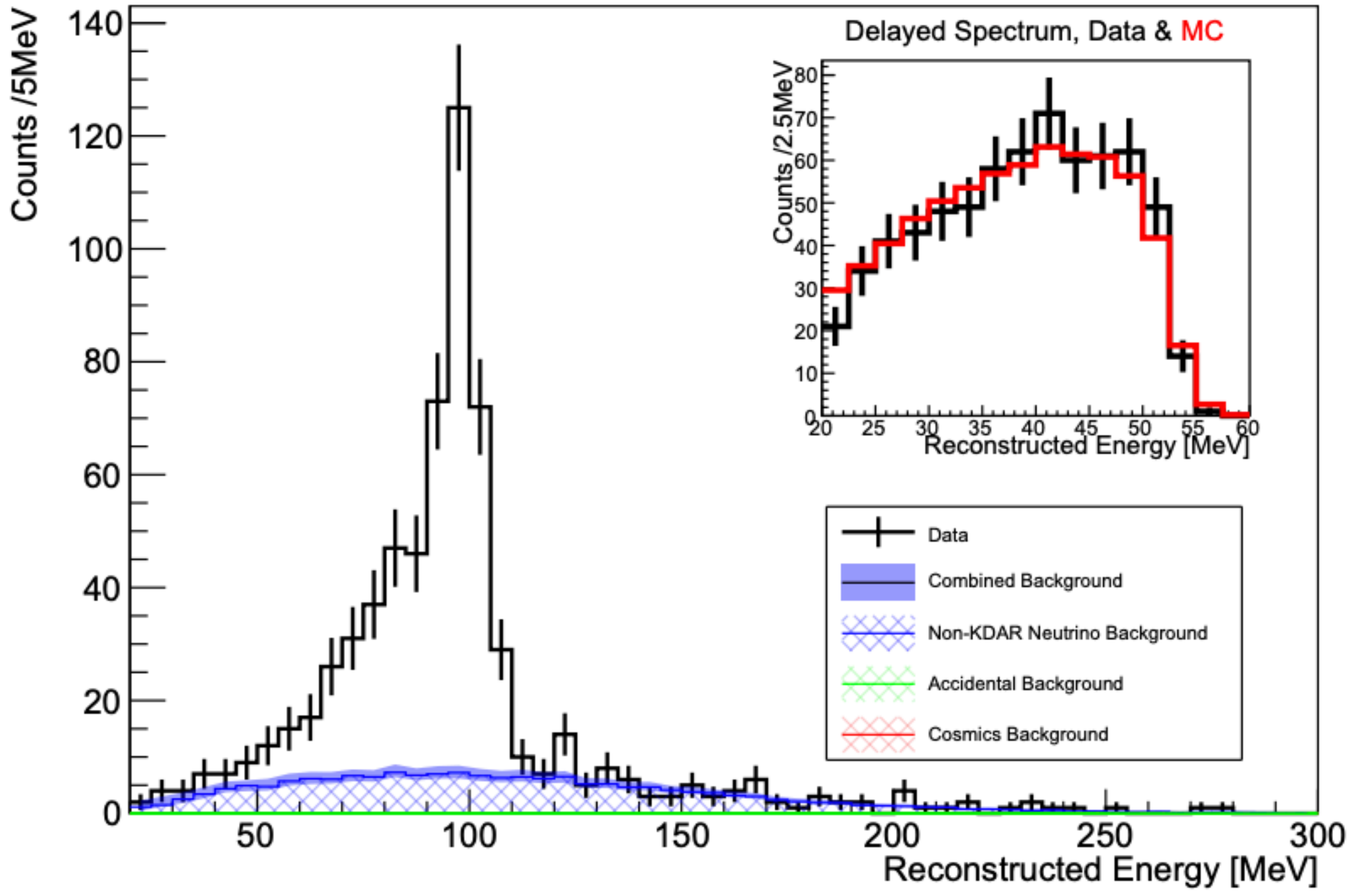
Delayed $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

- Detection by double coincidence
=> Prompt : muon and proton
=> Delayed :
electron from muon decay

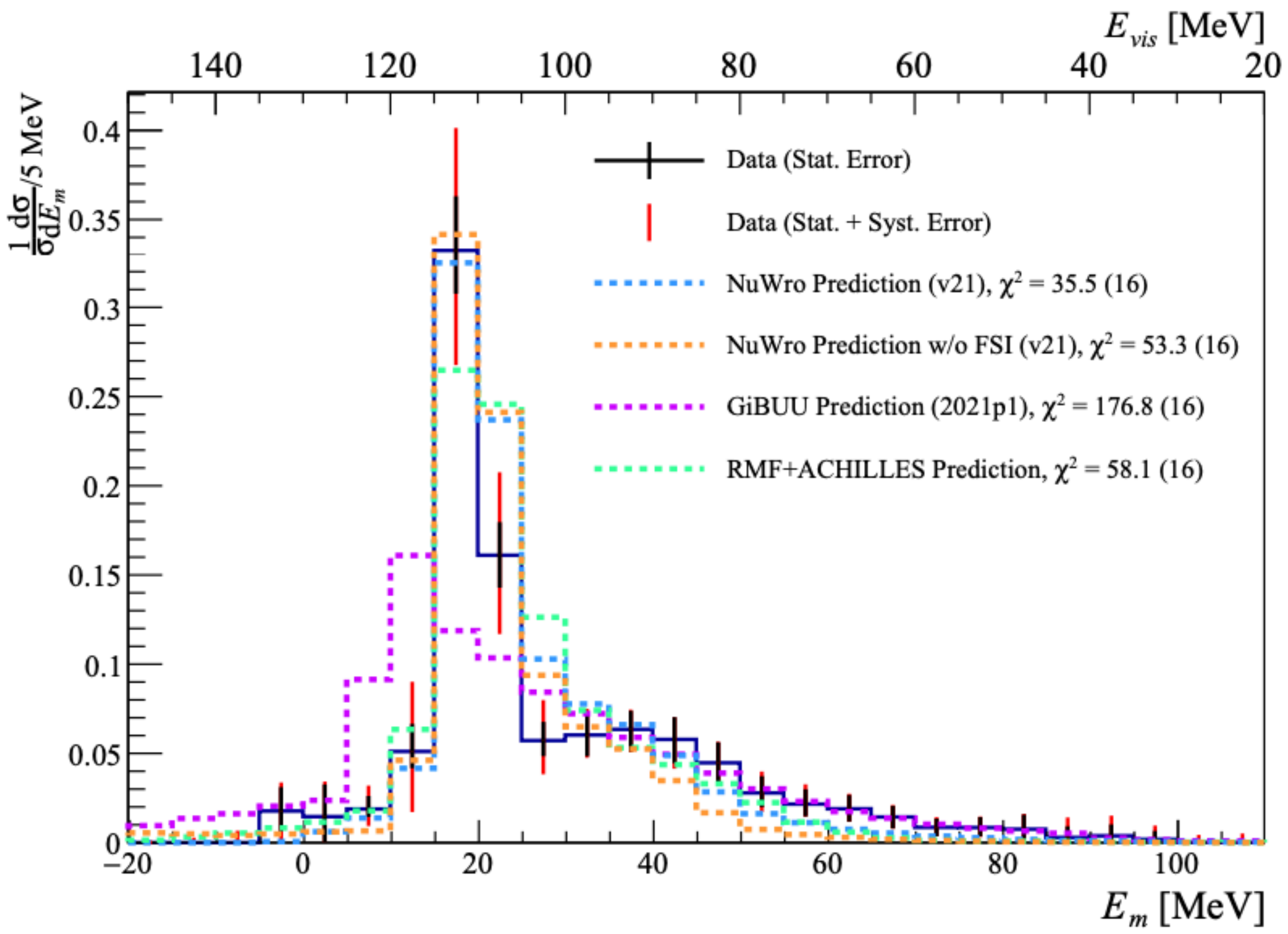
KDAR Results

- 2021 physics data is used. (1.4×10^{22} POT)
- KDAR candidates : 621 events
- Best Fit Bkg : $144.4^{+21.3}_{-21.1}$ events
  (πDIF ν dominant)

	Prompt	Delayed
Energy	20~150MeV	20~60MeV
Timing	2 x 150ns (Beam centered windows)	ΔT < 10μs
Position	R < 140cm -100cm < z < 50cm	ΔVTX < 30cm



- **The First measurement of Missing Energy** due to nuclear effects (shape-only analysis)
  => By using the KNOWN neutrino energy.
  (E_m (missing energy) $= E_\nu - m_\mu - E_{vis}$)
  => Unfolded E_{vis} is used.
- Standard candle for improving the understanding of the low energy neutrino-nucleus interaction.
- arXiv:2409.01383 [hep-ex], submitted to PRL



Status of JSNS^2-II

JSNS^2-II : the second phase of JSNS^2

- New Far Detector

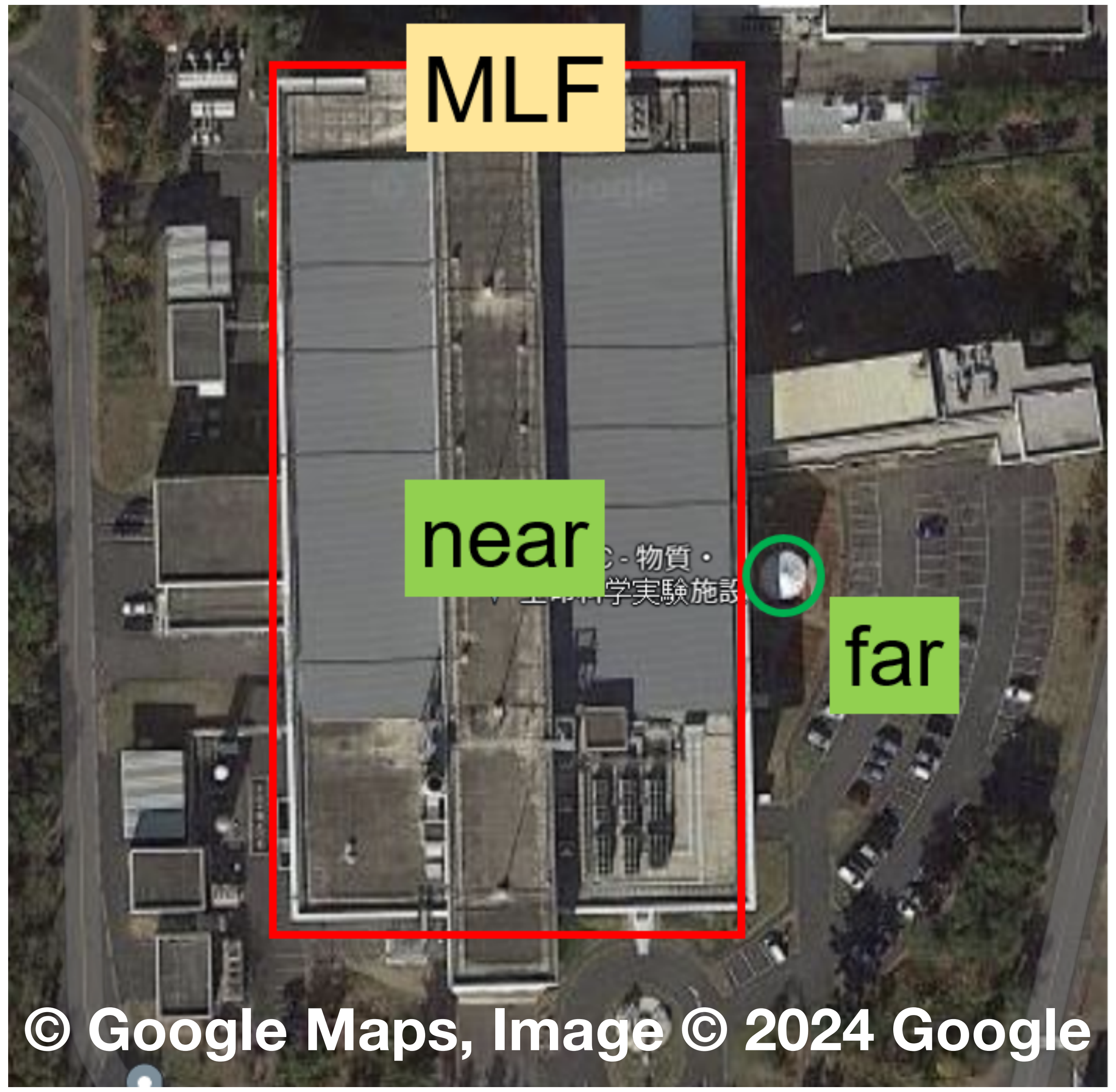
=> Almost identical structure with ND.
=> Target : 32tons of Gd-LS.
=> 48m baseline, outside of MLF building.

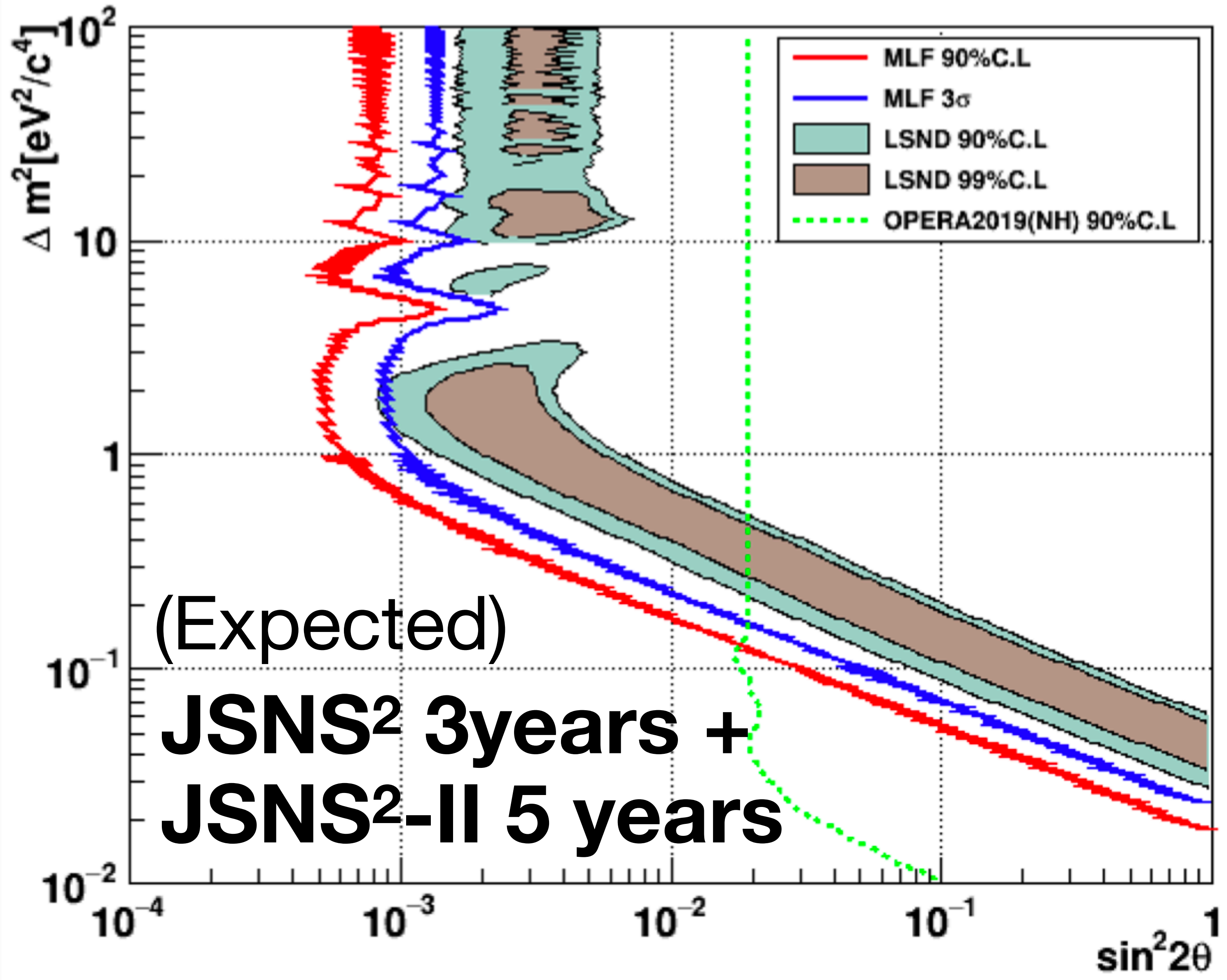
- Two detectors (ND+FD) with
two baselines (24m, 48m)

=> The sensitivity at low Δm^2 region
will be much improved.
=> A solid conclusion on LSND anomaly.

- FD construction since 2021.

=> Expected to begin data taking
in early 2025.





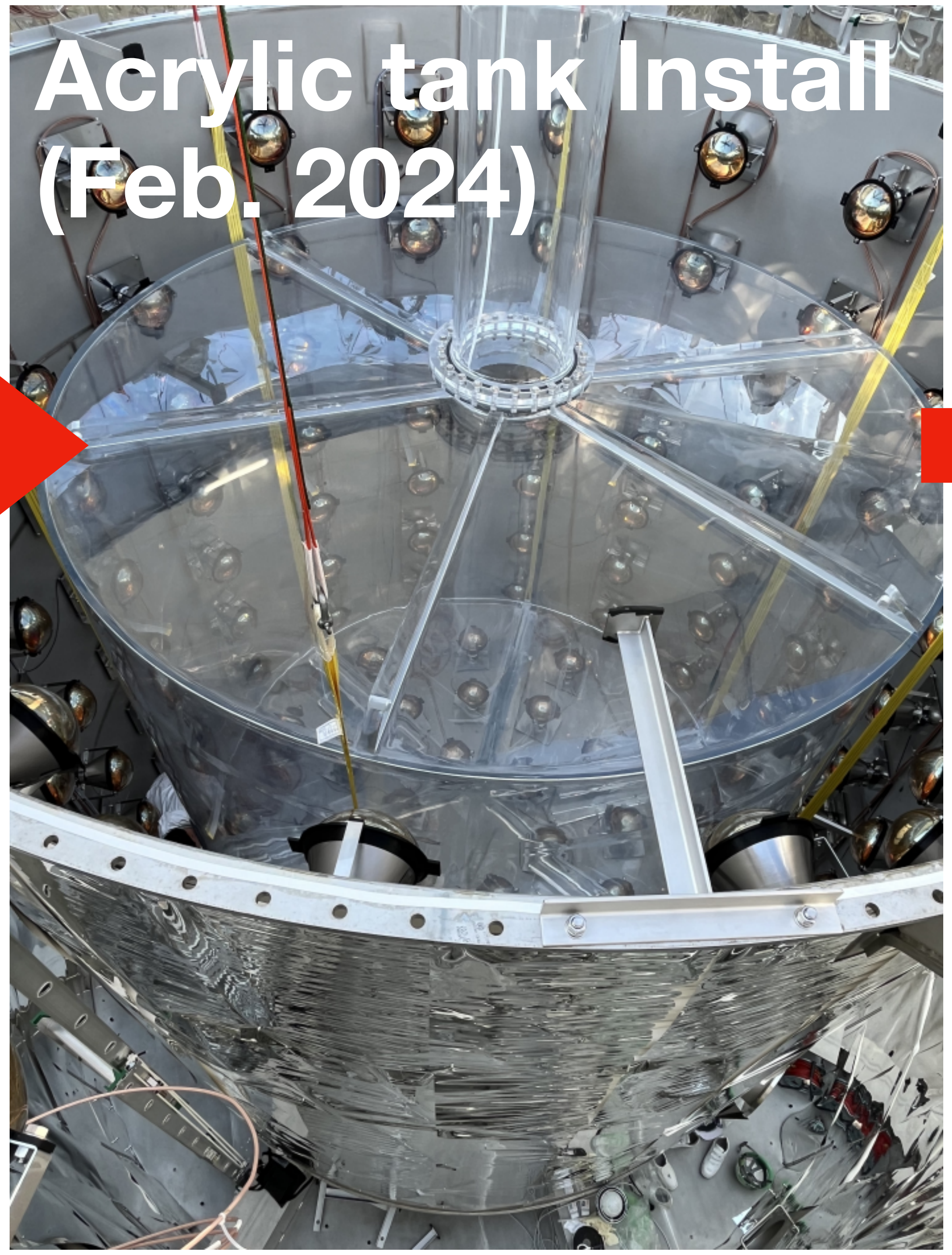
(Expected)
JSNS^2 3years +
JSNS^2-II 5 years

JSNS2-II Far detector construction

SUS tank
(Mar. 2022)

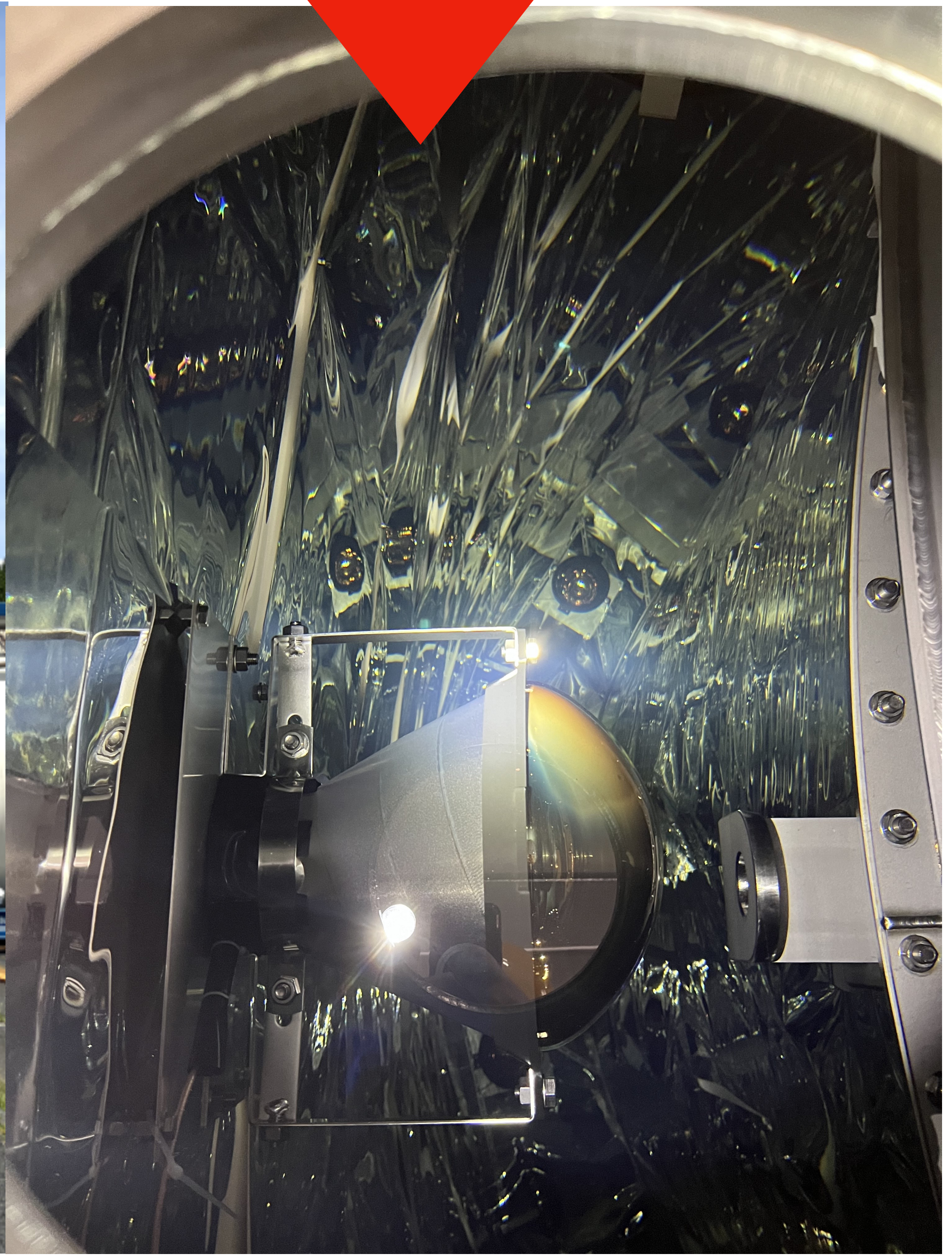
©KEK (IPNS)

Inner PMTs Install
(Aug. 2023)



Acrylic tank Install
(Feb. 2024)

Veto PMTs Install
(Apr. 2024)



LS filling
(Aug. 2024)

- Smooth progress so far.
- LED test soon.

Summary

- 4 long term physics run (2021-2024)
  => 950kW @MLF in 2024 (Design 1MW is achieved at RCS extraction point)

- Blind analysis (energy side-bands) for the sterile neutrino search
  => Good consistency between Observation vs Expectation for a side-band so far.

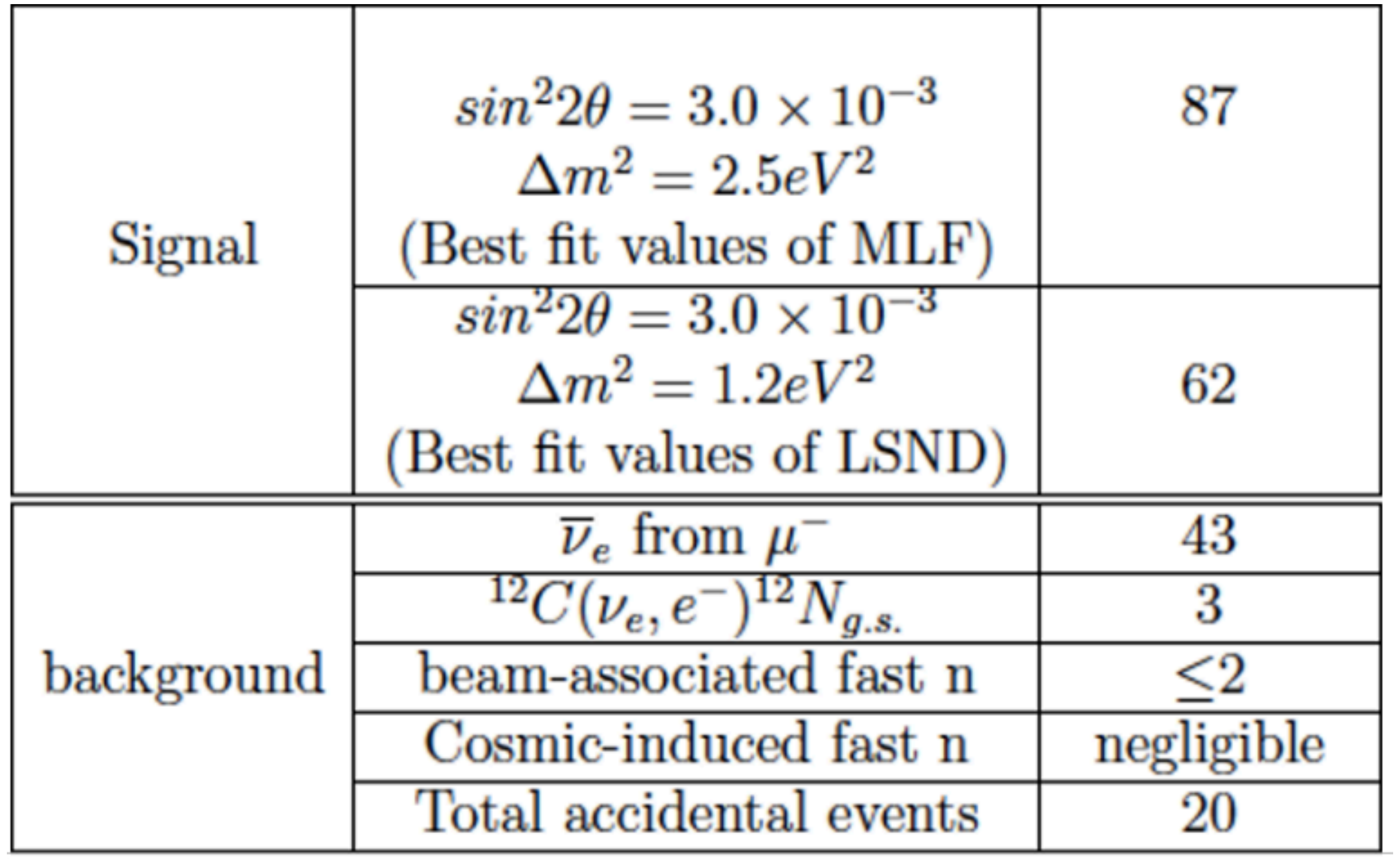
- CNgs measurement
  => Neutrino flux measurement has a good consistency with prediction.

- KDAR measurement
  => With known neutrino energy (235.5MeV), the first measurement of the missing energy.

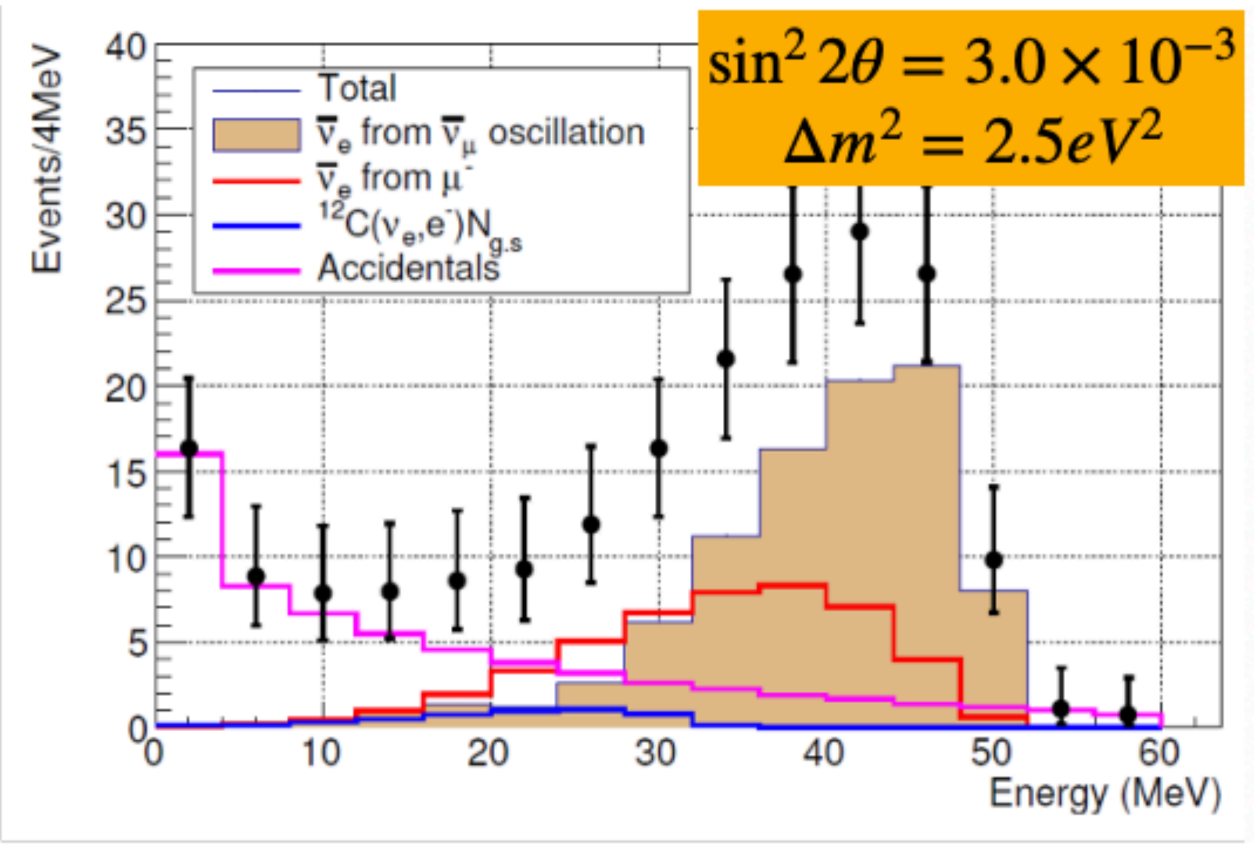
- JSNS^2-II : the second phase
  => Now climax of New Far Detector construction.

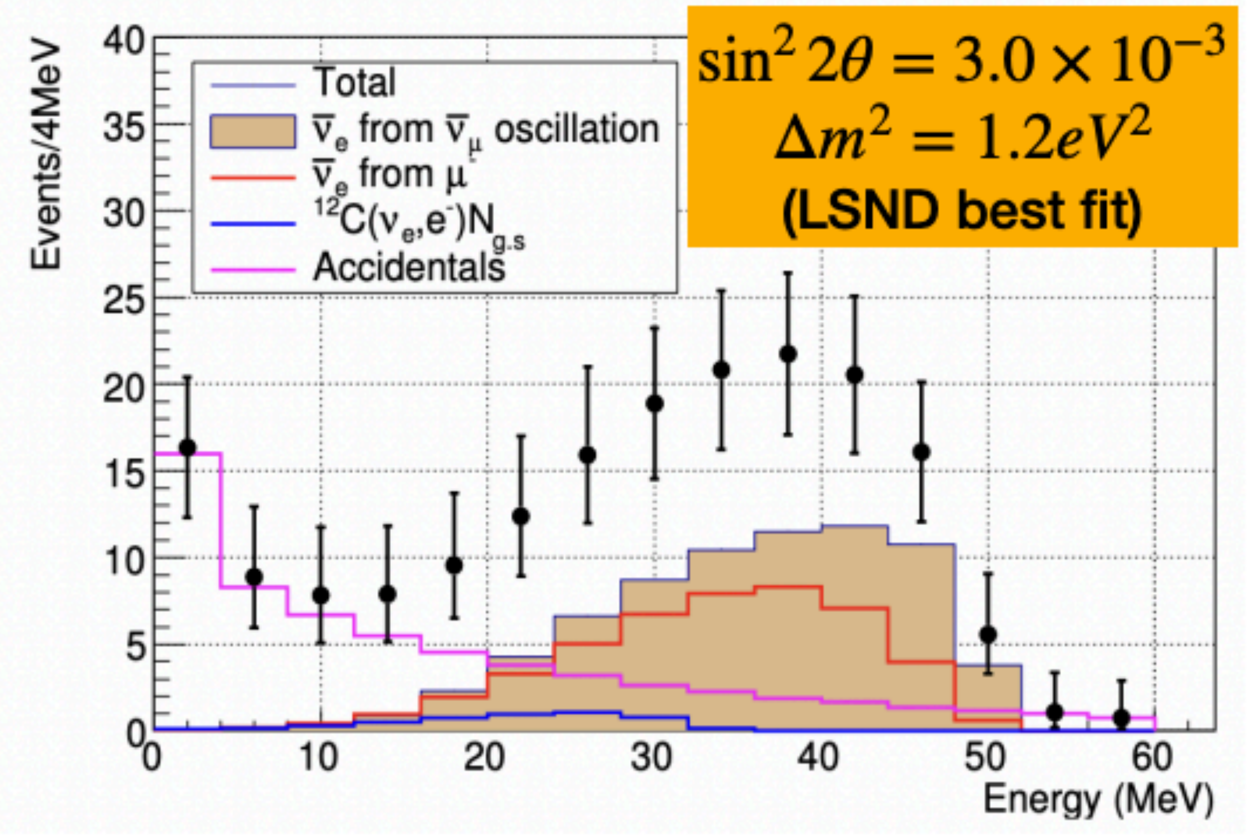
Backup

Expected Sterile neutrino sensitivity (JSNS^2)



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	$\overline{\nu}_e$ from μ^-	43
	$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$	3
	beam-associated fast n	$\lesssim$2
	Cosmic-induced fast n	negligible
	Total accidental events	20





1MW x 3years
(100% approved POT)