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

JSNS^2 new results

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

Neutrino 2022, May 30 - June 4, 2022

The 50th Anniversary
NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics
Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

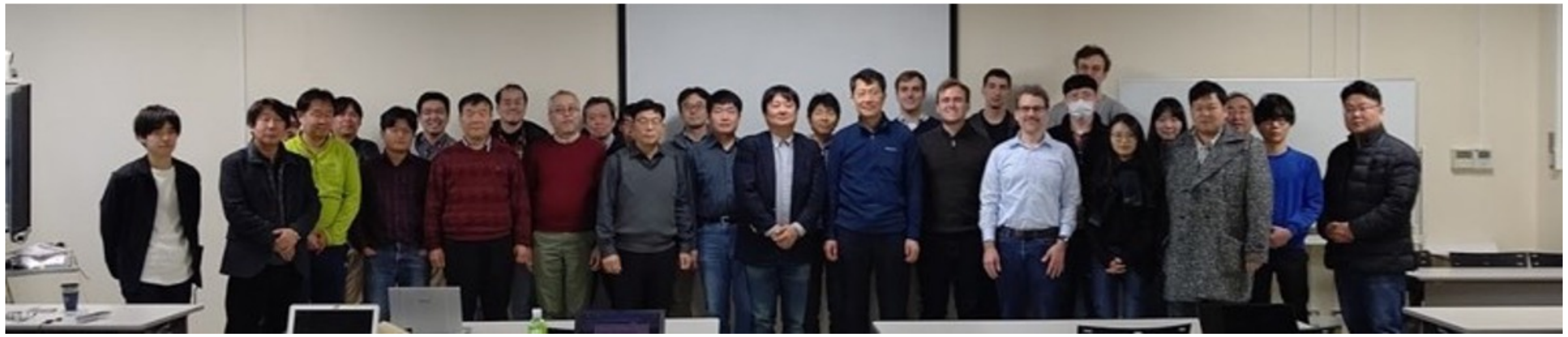
List of the $JSNS^2$ posters

- P0417, “Background studies for sterile neutrino search in the $JSNS^2$ experiment” by S. H. Jeon
- P0410, “Result of the first long physics run of $JSNS^2$ & study of $JSNS^2$-II” by D. H. Lee
- P0447, “Status of the KDAR neutrino measurement with $JSNS^2$” by H. K. Jeon
- P0415, “$JSNS^2$ trigger for a sterile neutrino search” by D. E. Jung
- P0570, “Development of pulse shape discrimination (PSD) for removing fast neutrons in the $JSNS^2$” by T. Dodo
- P0768, “Pulse Shape Discrimination with Machine learning at $JSNS^2$” by C. H. Yoo
- P0620, “An ATCA based DAQ system for the $JSNS^2$ experiment” by E. Marzec

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 collaboration (61 collaborators)

- 10 Korean institutions (24 members)
- 6 Japanese institutions (29 members)
- 4 US institutions (7 members)
- 1 UK institution (1 member)

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

JAEA
KEK
Kitasato
Kyoto
Osaka
Tohoku

BNL
Florida
Michigan
Utah

Sussex

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

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

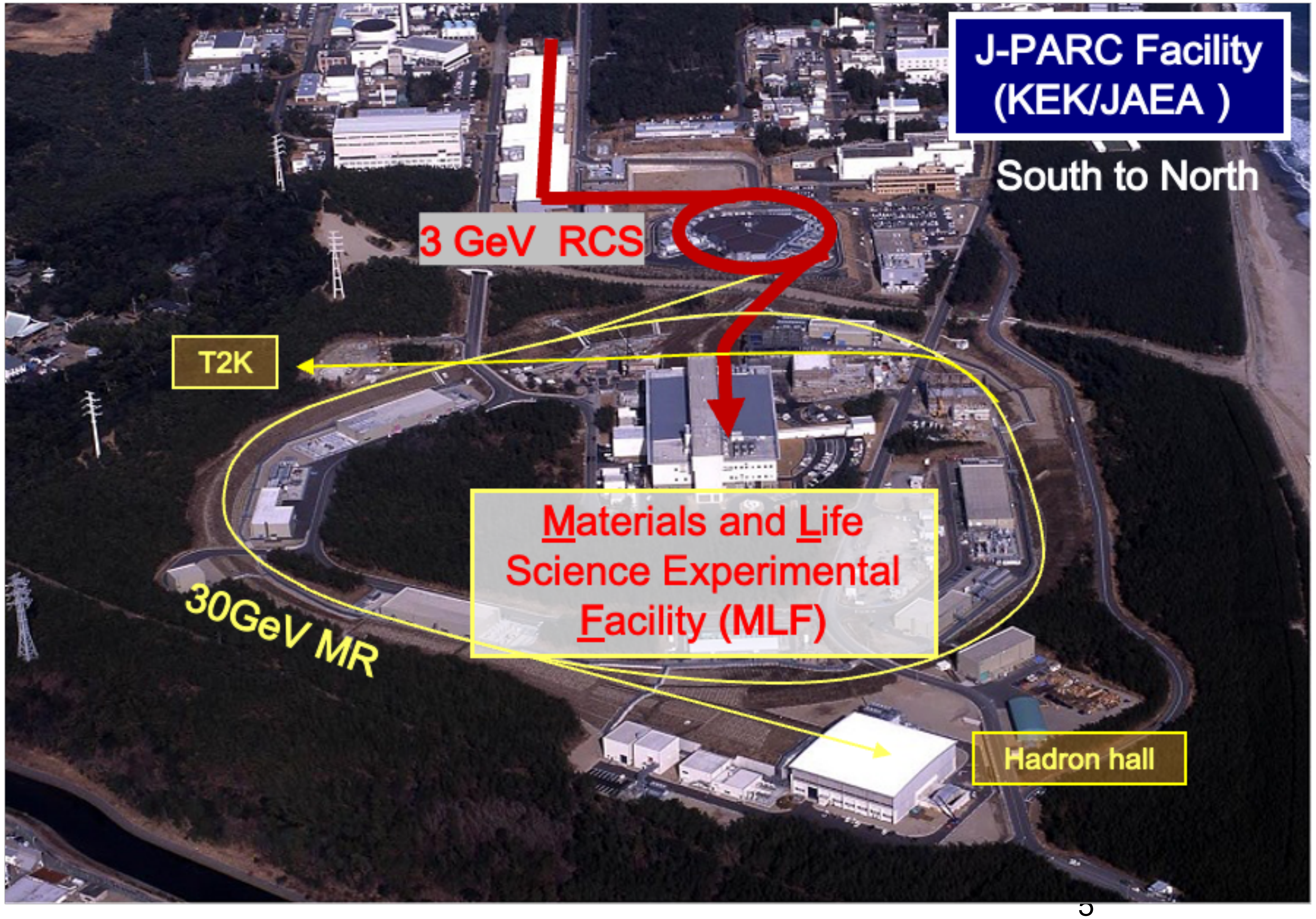
- **LSND** (μ Decay-At-Rest, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, 3.8 σ, 40 MeV, 30 m)
- **MiniBooNE** (π Decay-In-Flight, $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, 4.8 σ (combined), 800 MeV, 600 m)
- **BEST** (e capture, $\nu_e \rightarrow \nu_x$, ~4 σ, < 3 MeV, 10 m)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

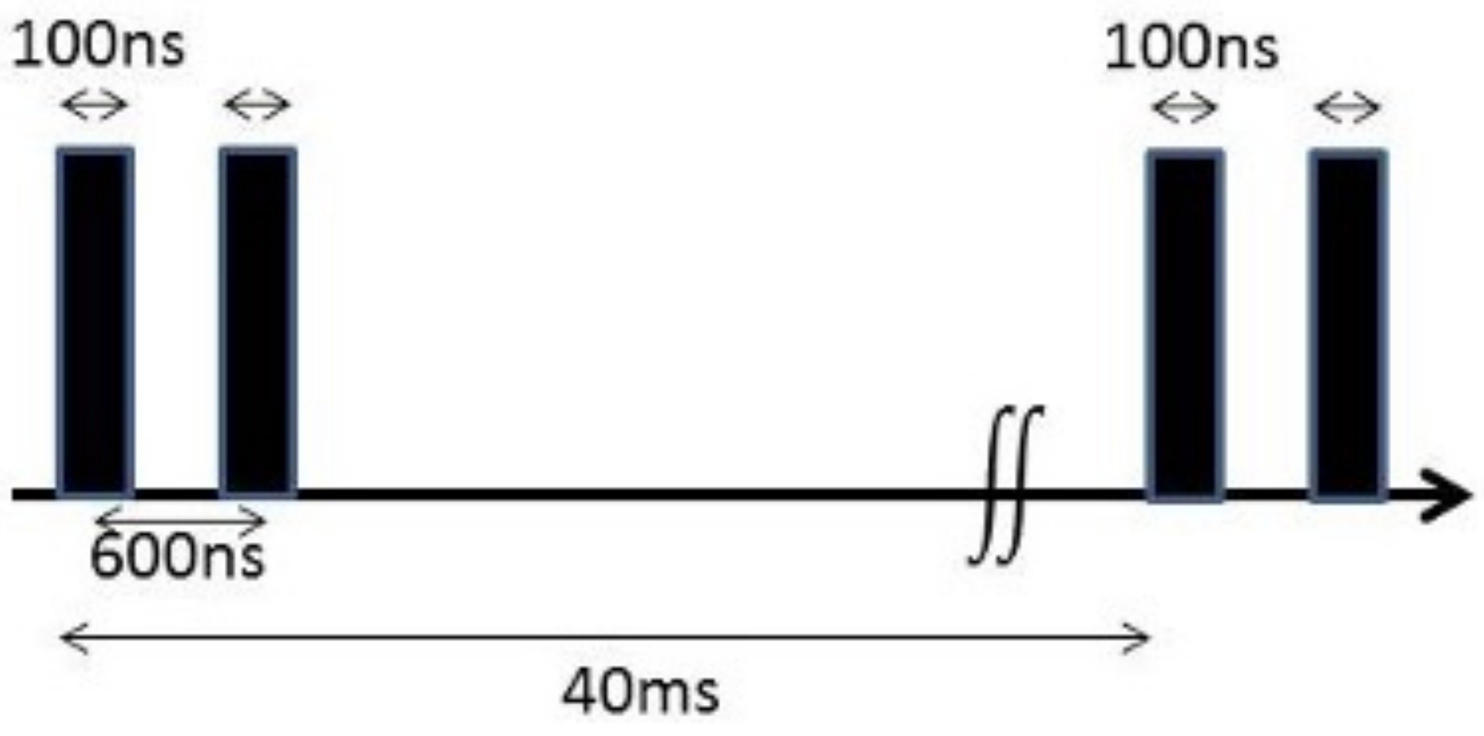
JSNS^2 uses the **same** neutrino source (μ), target (H), and detection principle (IBD) **as the LSND**

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

Two advantages: **short-pulsed beam** and **use of the gadolinium(Gd)-loaded liquid scintillator**

J-PARC Facility



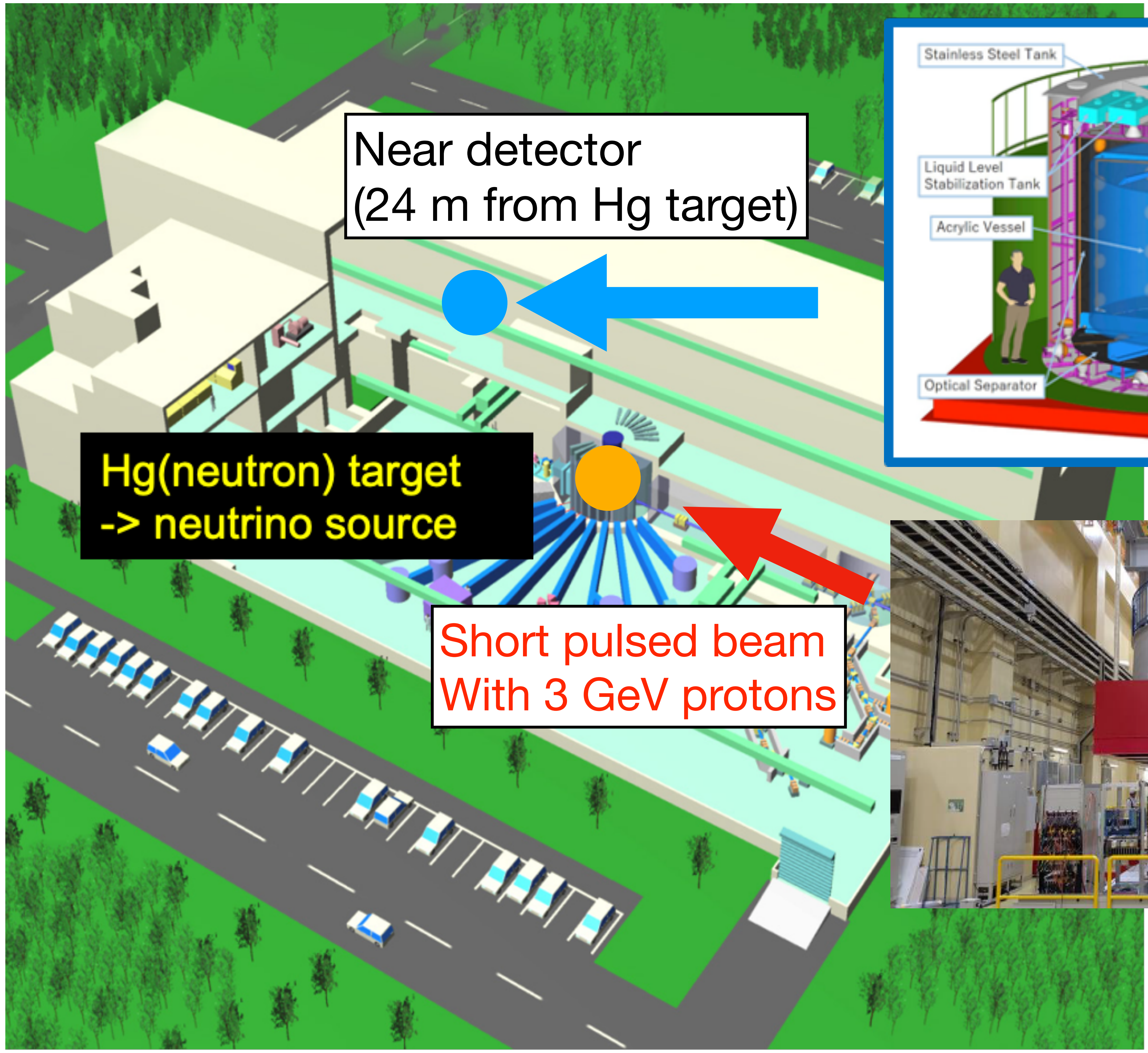


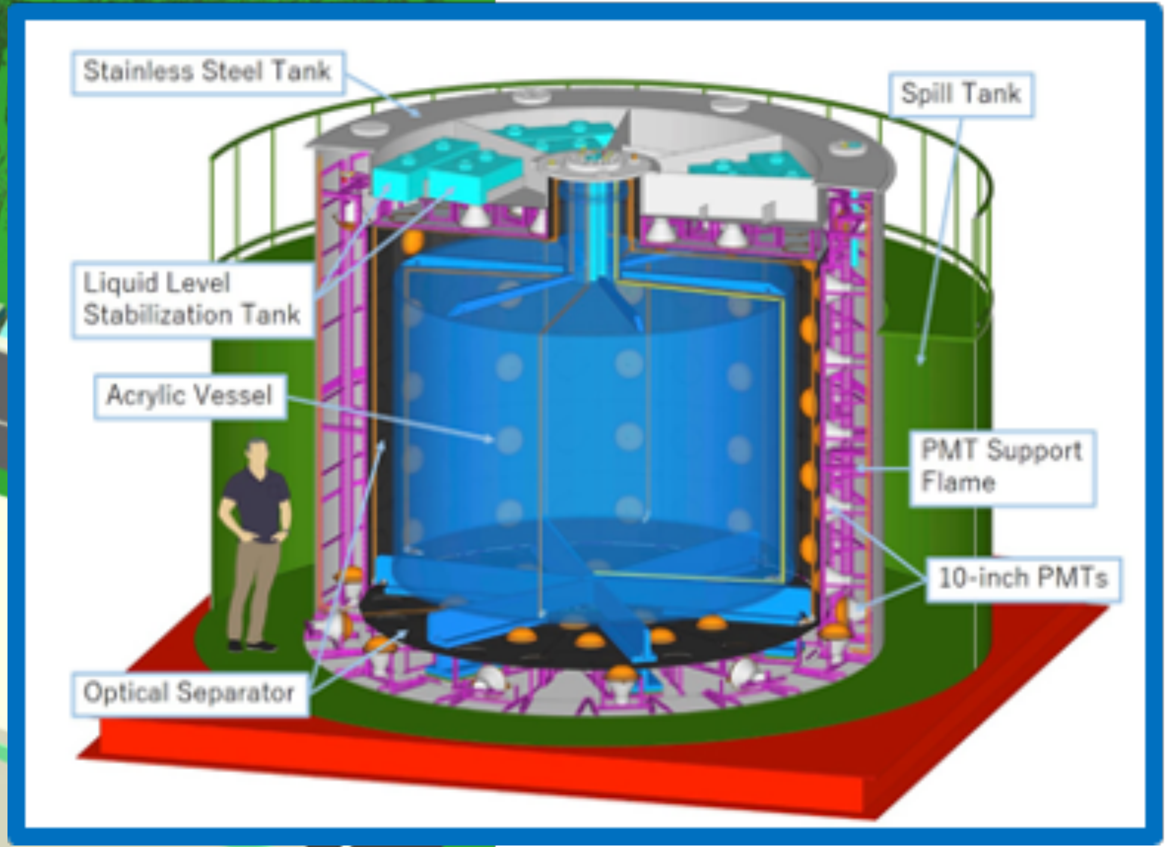
Low duty factor beam
(short-pulses + low repetition rate)
Gives an excellent signal to noise ratio

1 MW (design)

0.6 MW (2021/Jan - Apr/5)
0.7 MW (2021/Apr/5 - June/22)
0.7 MW (2022/Jan/28 - Apr/6)
0.8 MW (2022/Apr/7 -)

JSNS^2 detector and data taking





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

Commissioning (2020)
- Calibration
- Beam data with 25 us window
- Eur. Phys. J. C (2022) 82:331

First long physics run (2021)
- Smooth data taking (0.5 years)
- Beam power: 0.6 - 0.7 MW
- Analyses: in progress

Second long physics run (2022)
- Jan/28 - May/31
- Beam power: 0.7 - 0.8 MW

Operation

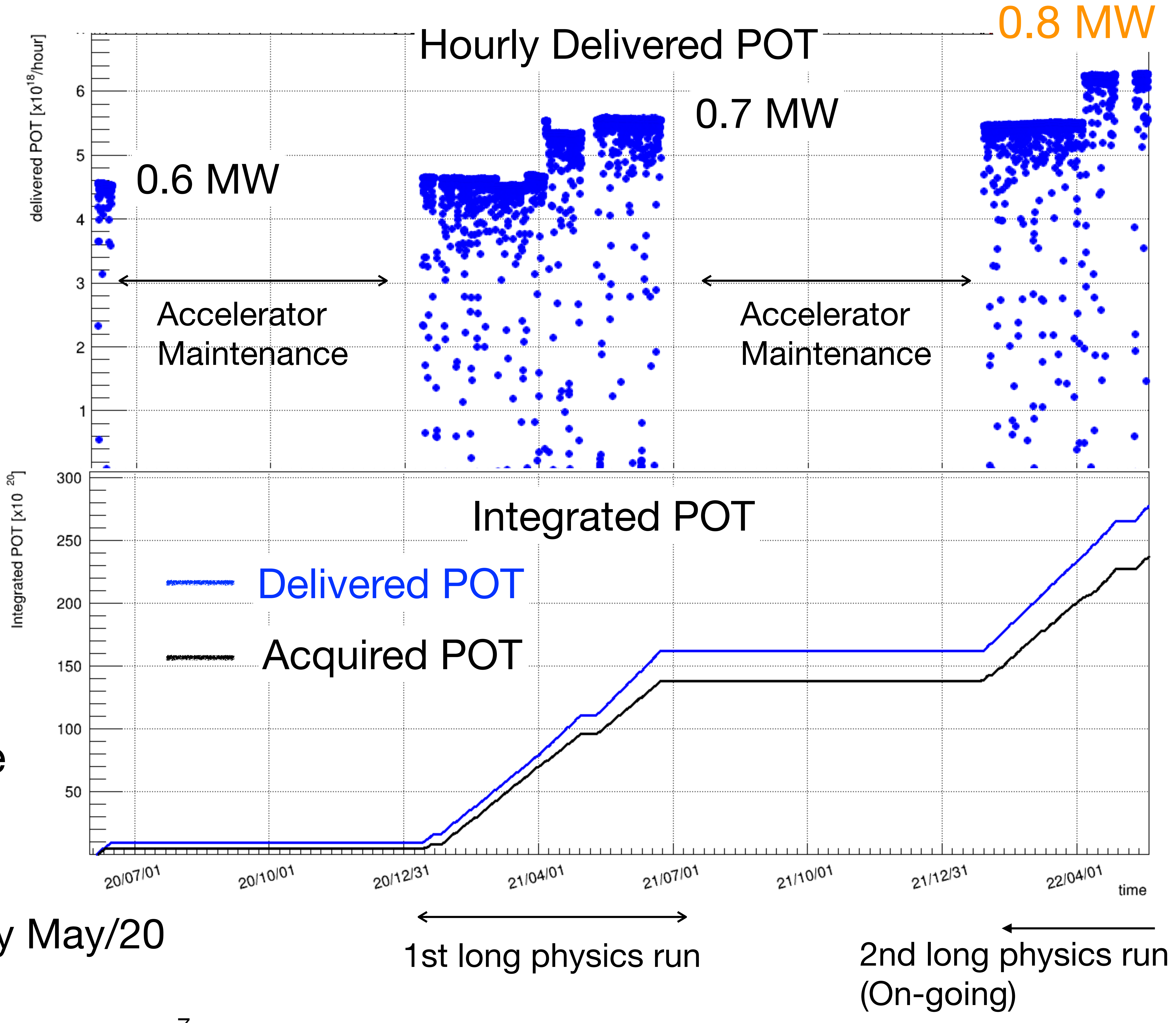
1st long physics run

- 0.6 MW (2021/Jan - Apr/5)
- 0.7 MW (2021/Apr/5 - June/22)

2nd long physics run

- 0.7 MW (2022/Jan/28 - Apr/6)
- 0.8 MW (2022/Apr/7 - May/31)

There is an accelerator maintenance period every year

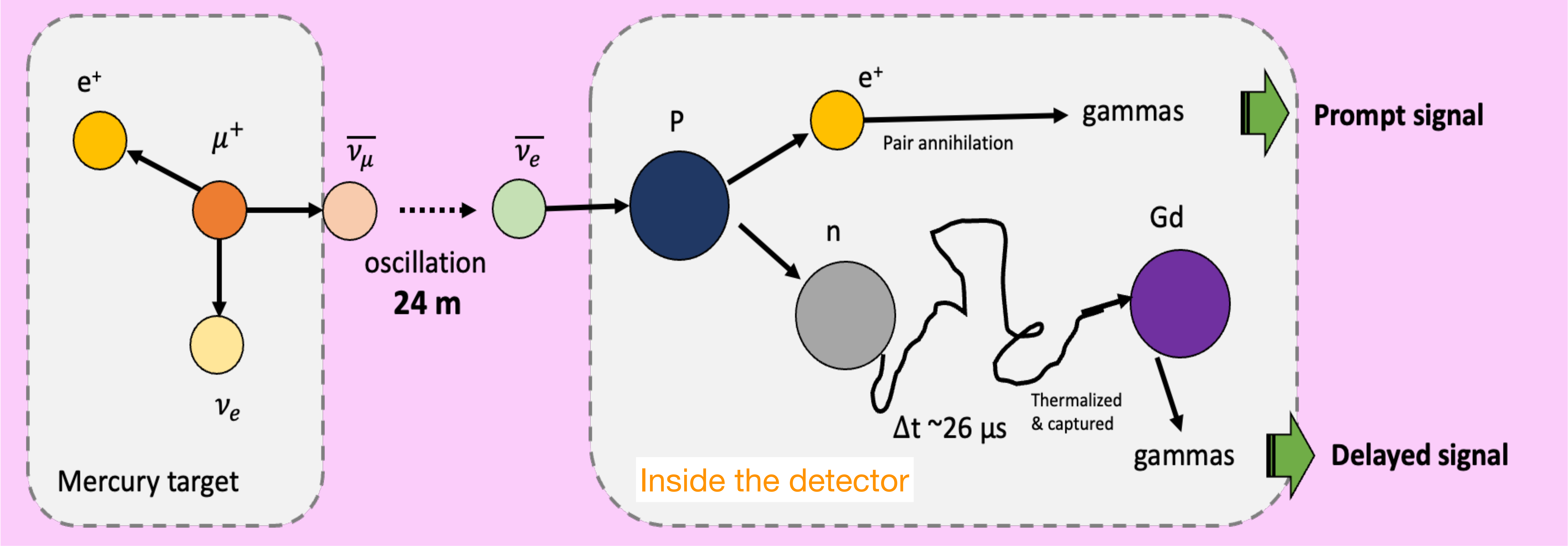


2.77×10^{22} POT has been delivered by May/20
(23 % of the approved POT of JSNS²)

Sterile neutrino
(Production and detection)

A double coincidence between
- The positron annihilation and
- Gammas from neutron captured on gadolinium (Gd)

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

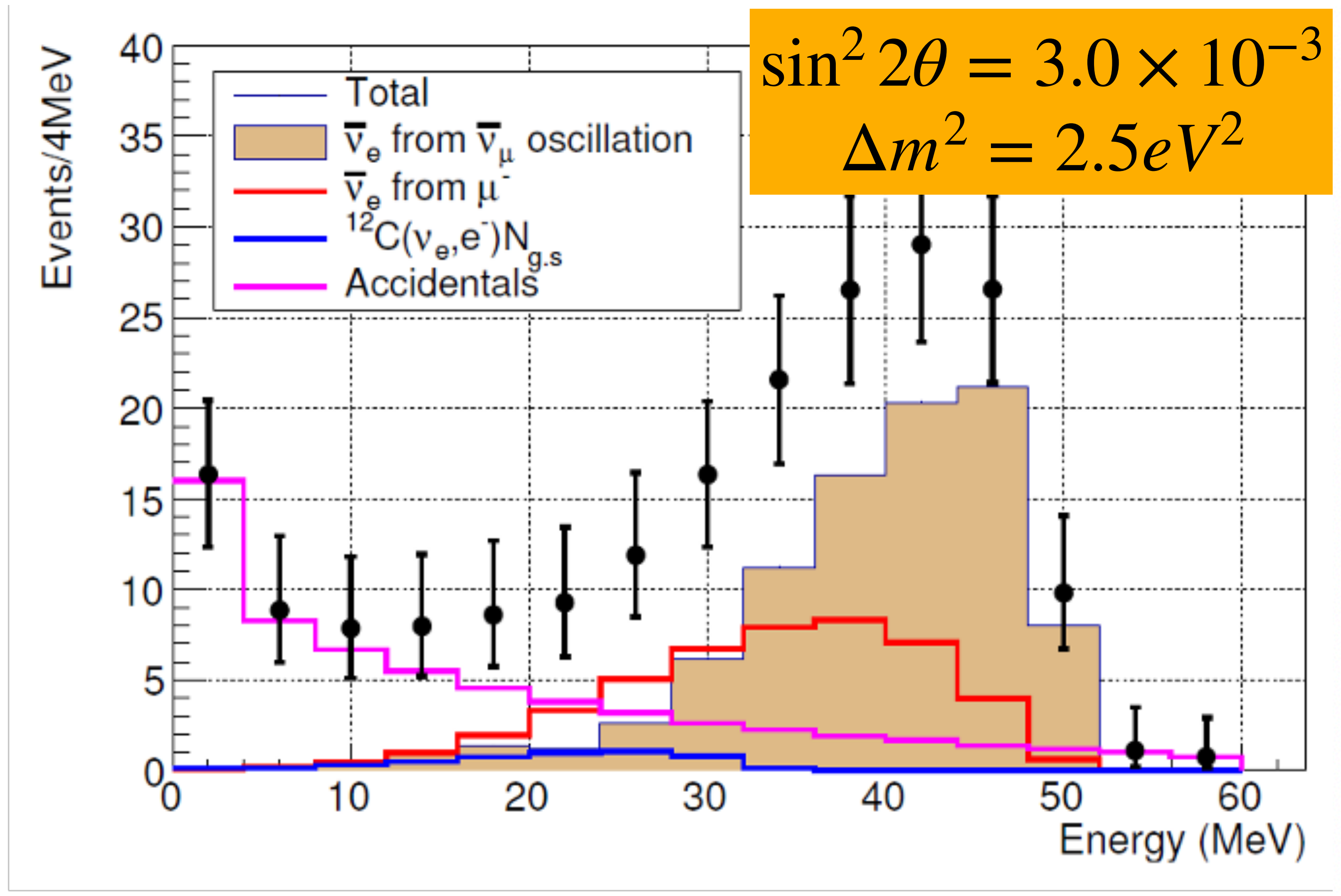


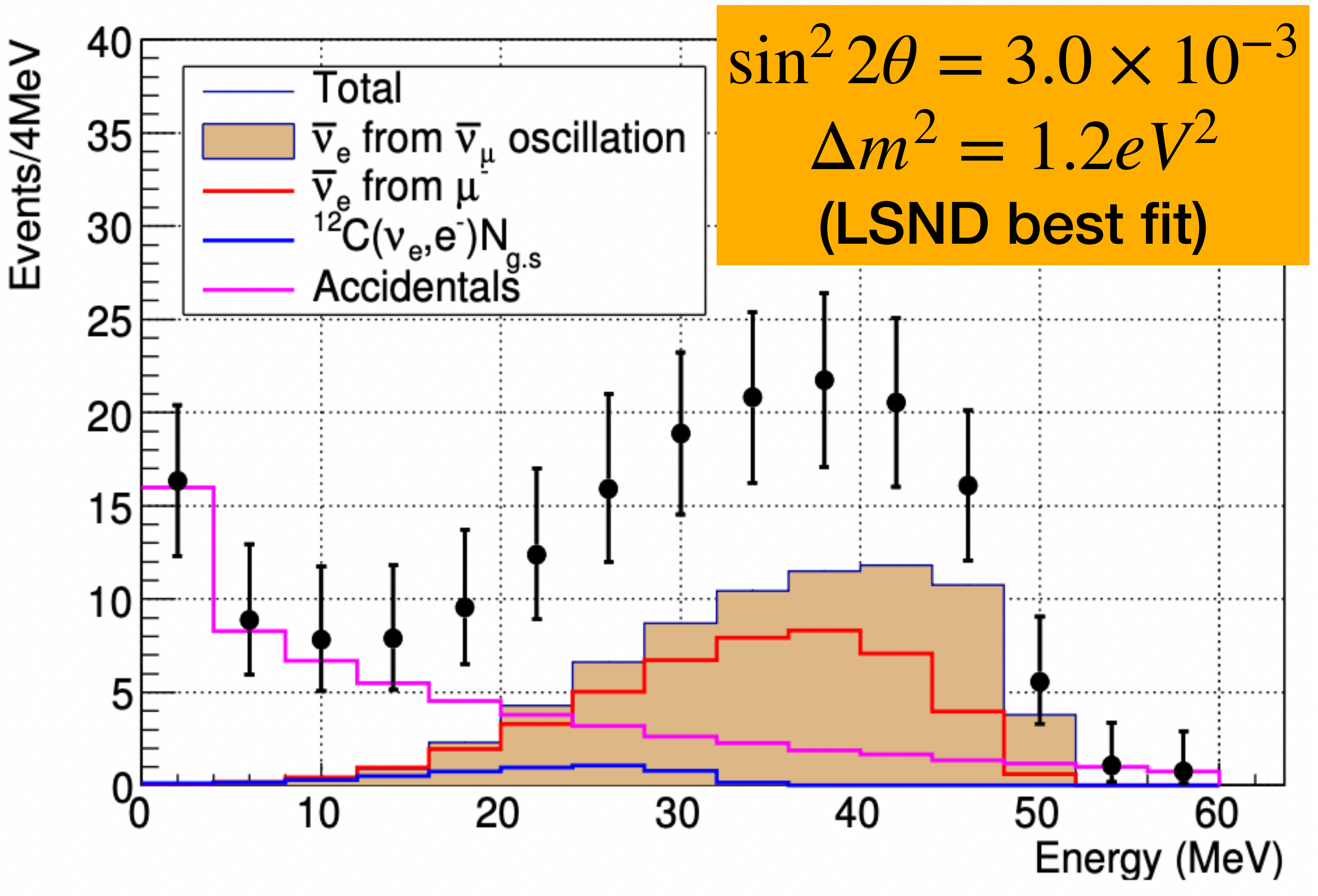
Expected visible energy and sensitivity

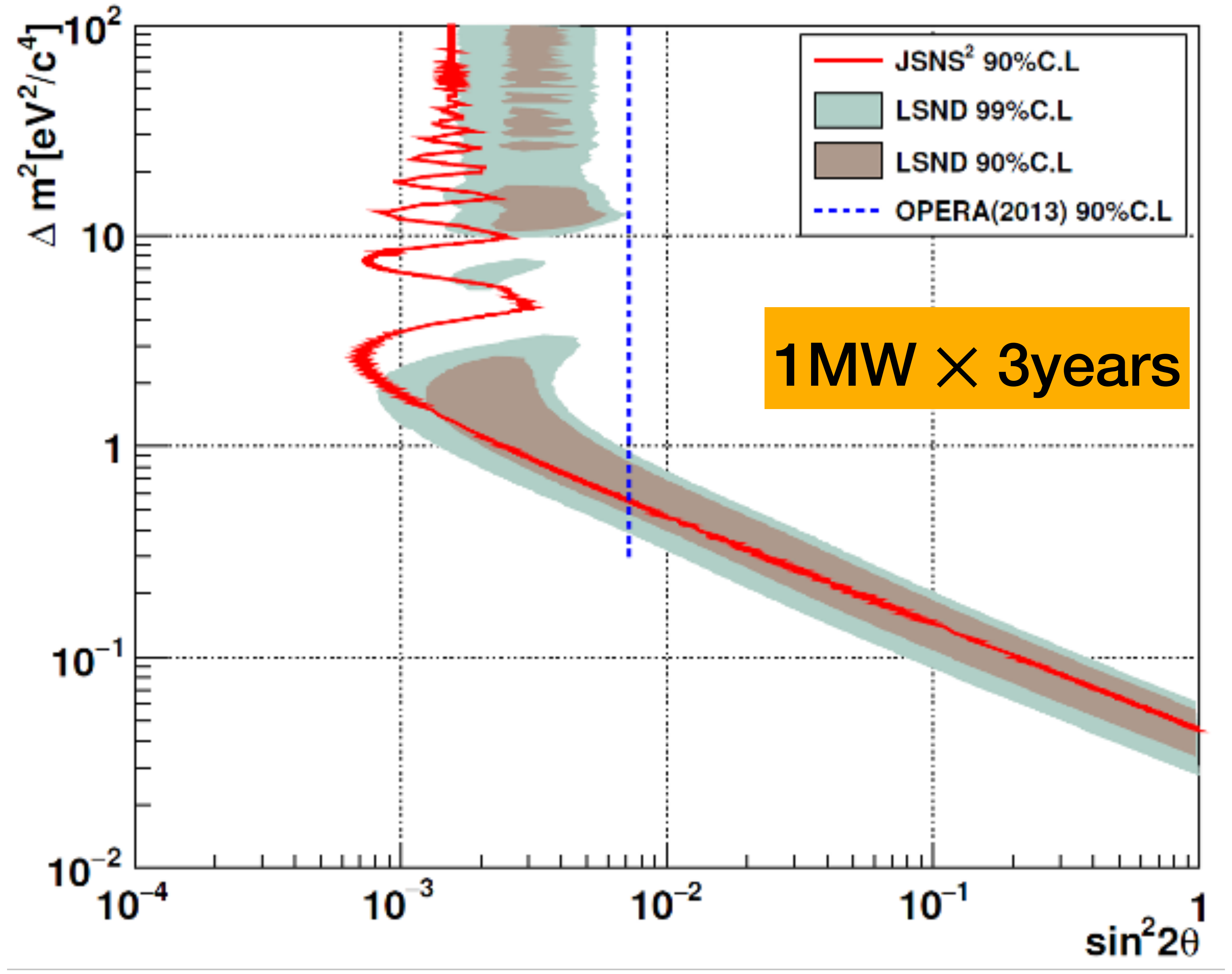
(From JSNS² TDR, arXiv:1705.08629)

Signal	$sin^2 2\theta = 3.0 \times 10^{-3}$ $\Delta m^2 = 2.5 eV^2$ (Best fit values of MLF)	87
	$sin^2 2\theta = 3.0 \times 10^{-3}$ $\Delta m^2 = 1.2 eV^2$ (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	$\leq$2
	Cosmic-induced fast n	negligible
	Total accidental events	20

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

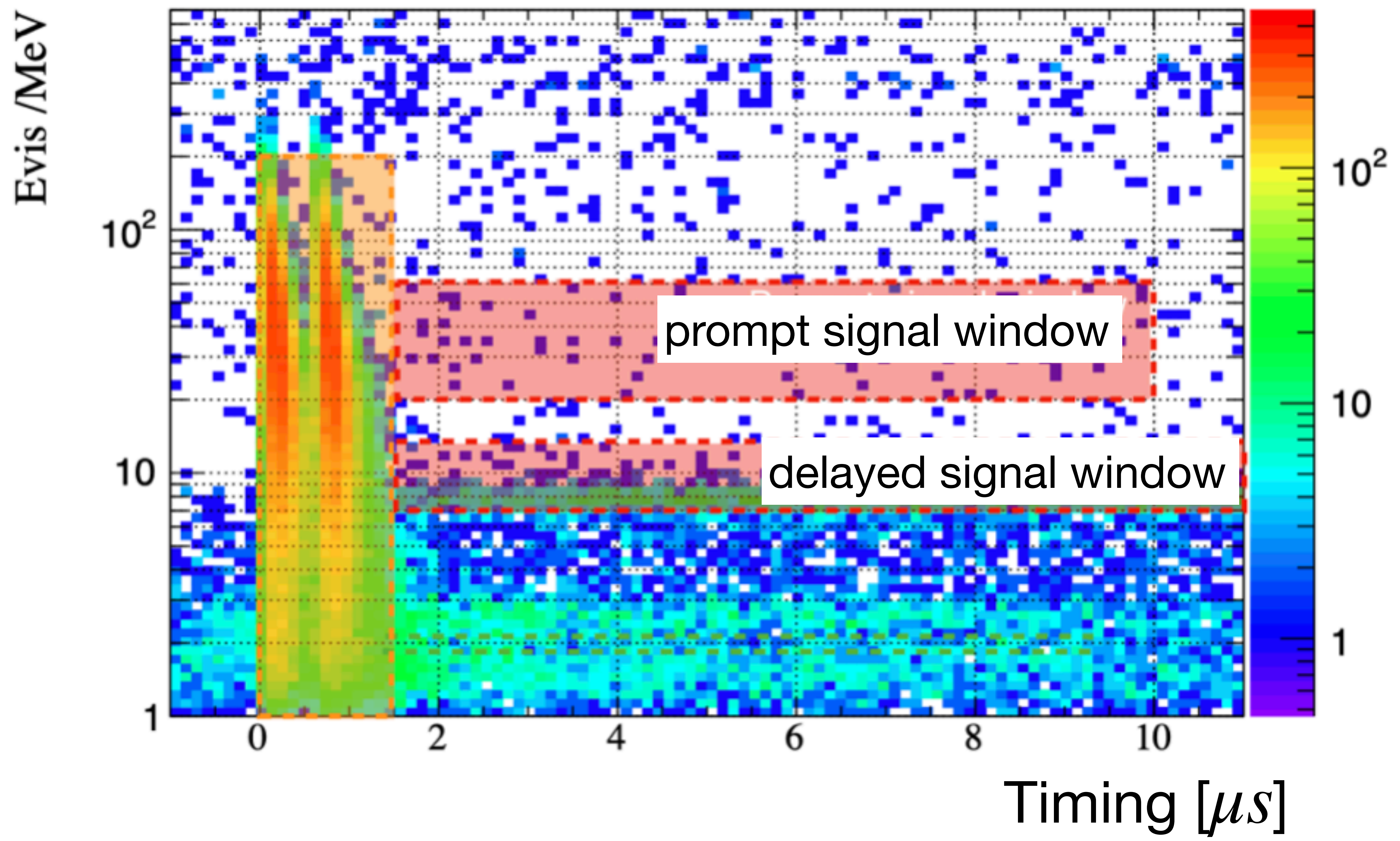


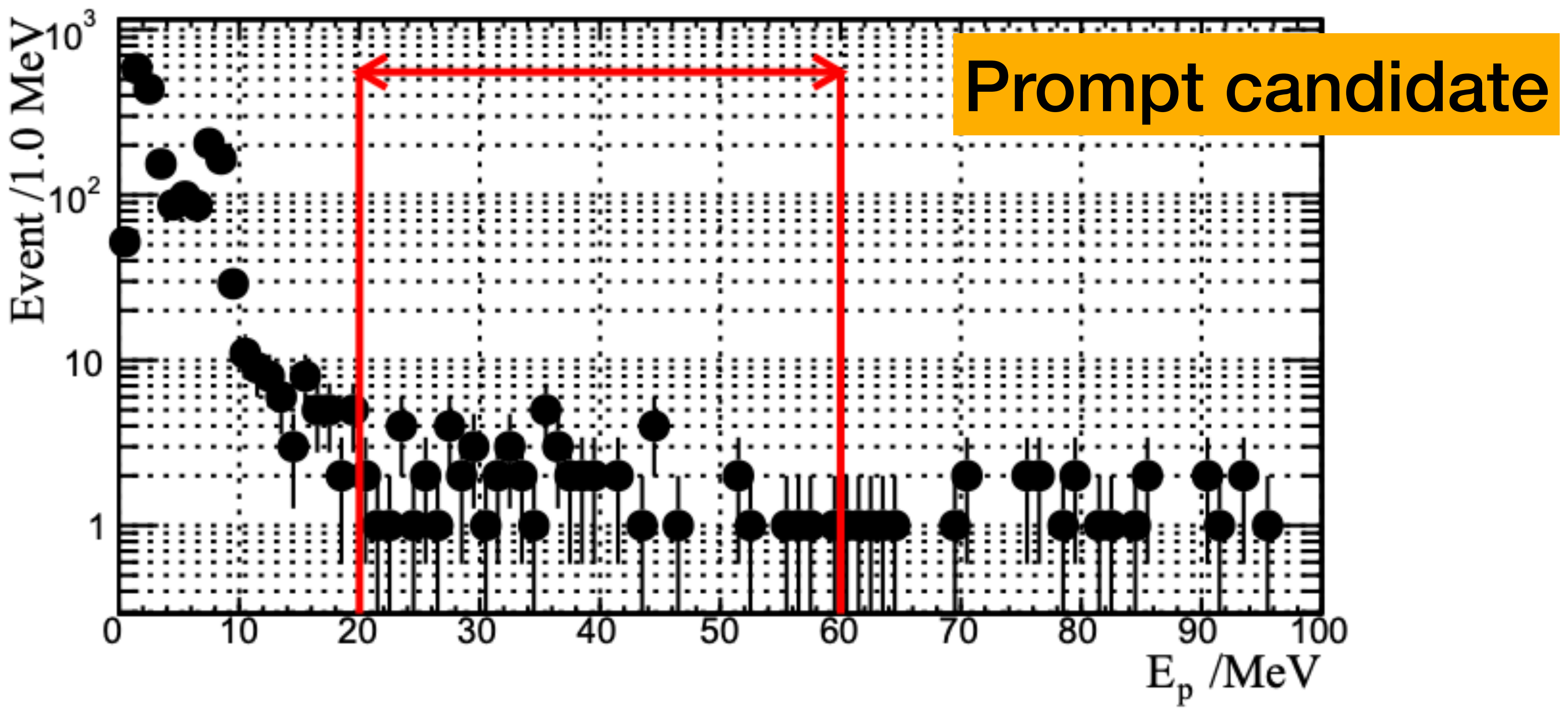


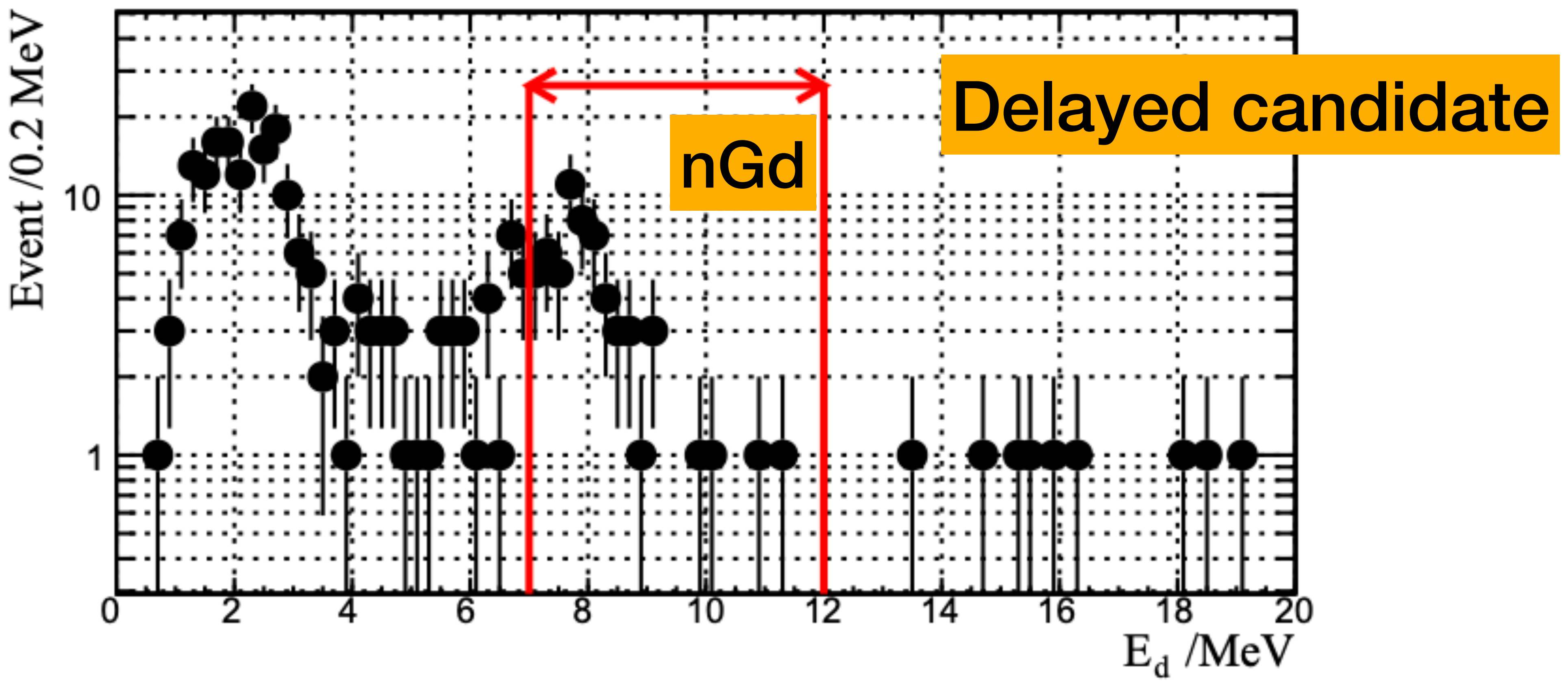


Commissioning run
(Eur. Phys. J. C (2022) 82:331)

- 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.

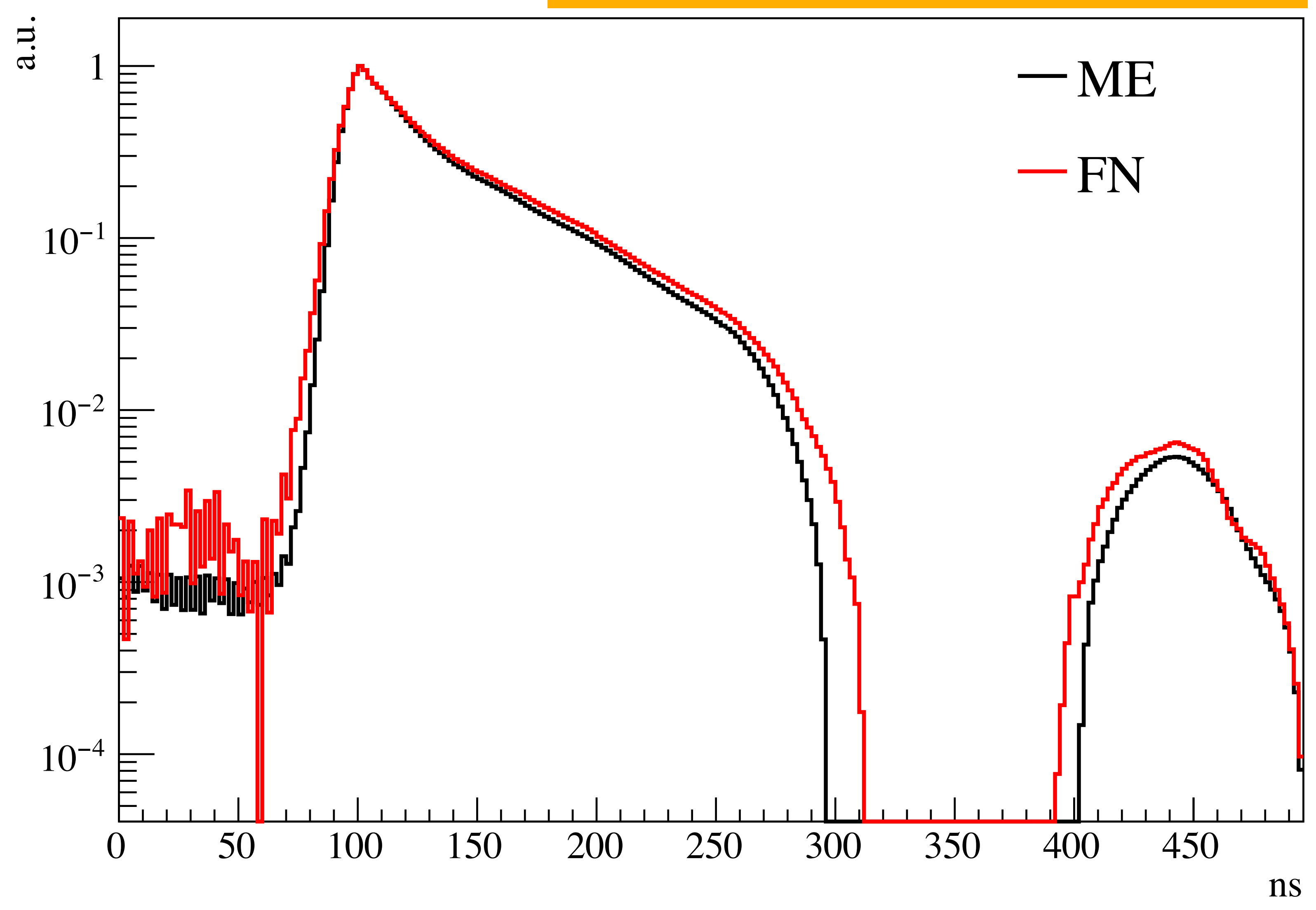
Analysis using 2021 data set

Pulse Shape Discrimination (PSD)
(2-dimensional likelihood method)

- It has been developed **based on the real data of JSNS²**.
- **10% DIN** (2000 L) has been added for improving the PSD power.
- Based on the charge ratio of each FADC bin (208 bins in total) divided by the peak of each waveform.
- **Using control samples of Michel electrons (ME) and Fast neutrons (FN)**
- PSD evaluation score: $\sum_{PMT} Q_{PMT}^{total}[ln(L_{ME} - ln(L_{FN})]$

  where $L = \prod_{bin} [P_{bin}(Q_{ratio}], \ Q_{ratio} = Q_{bin}/Q_{peak}$
- Note that there are two types of ME for considering afterpulse.

Example of waveforms

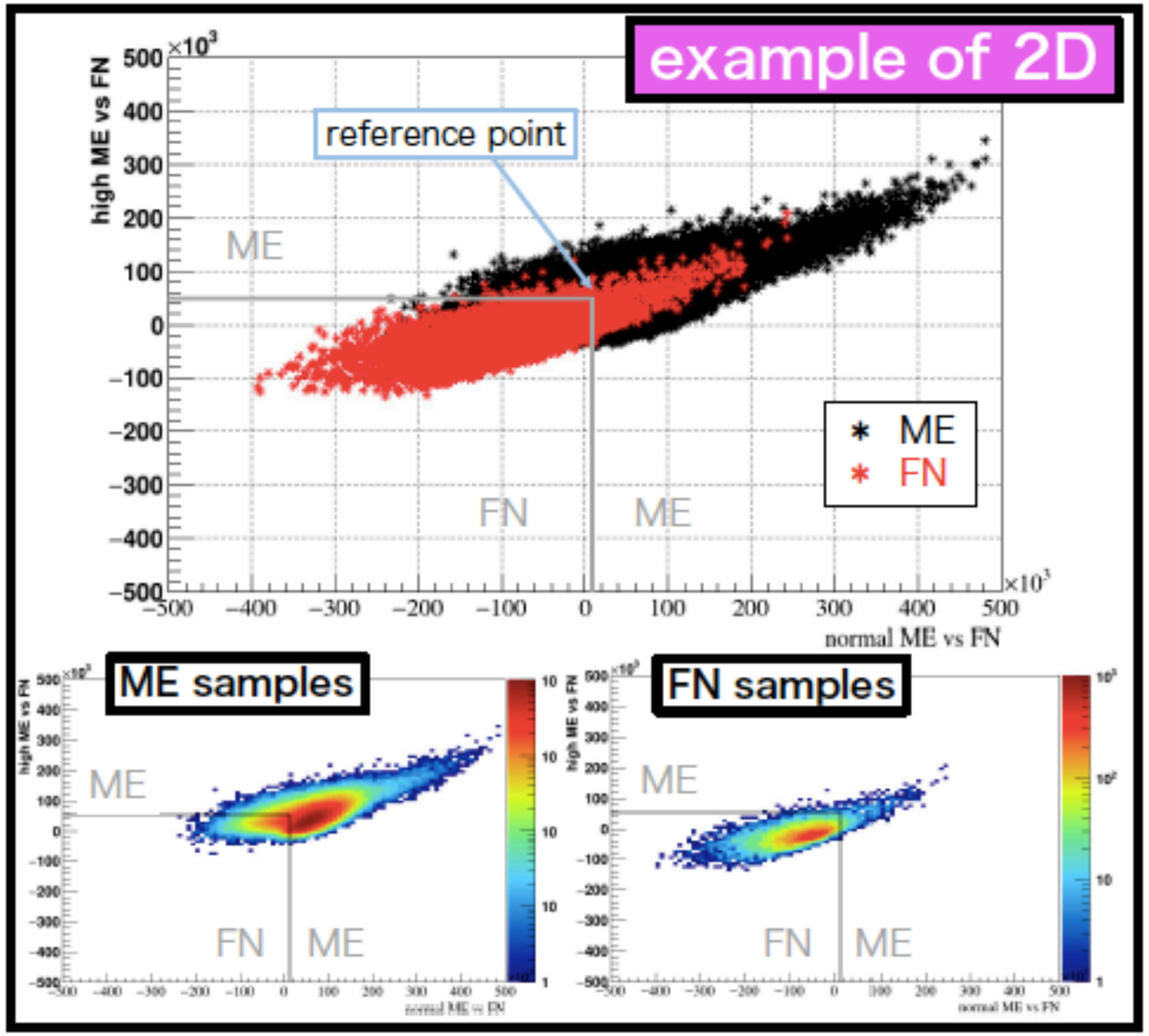


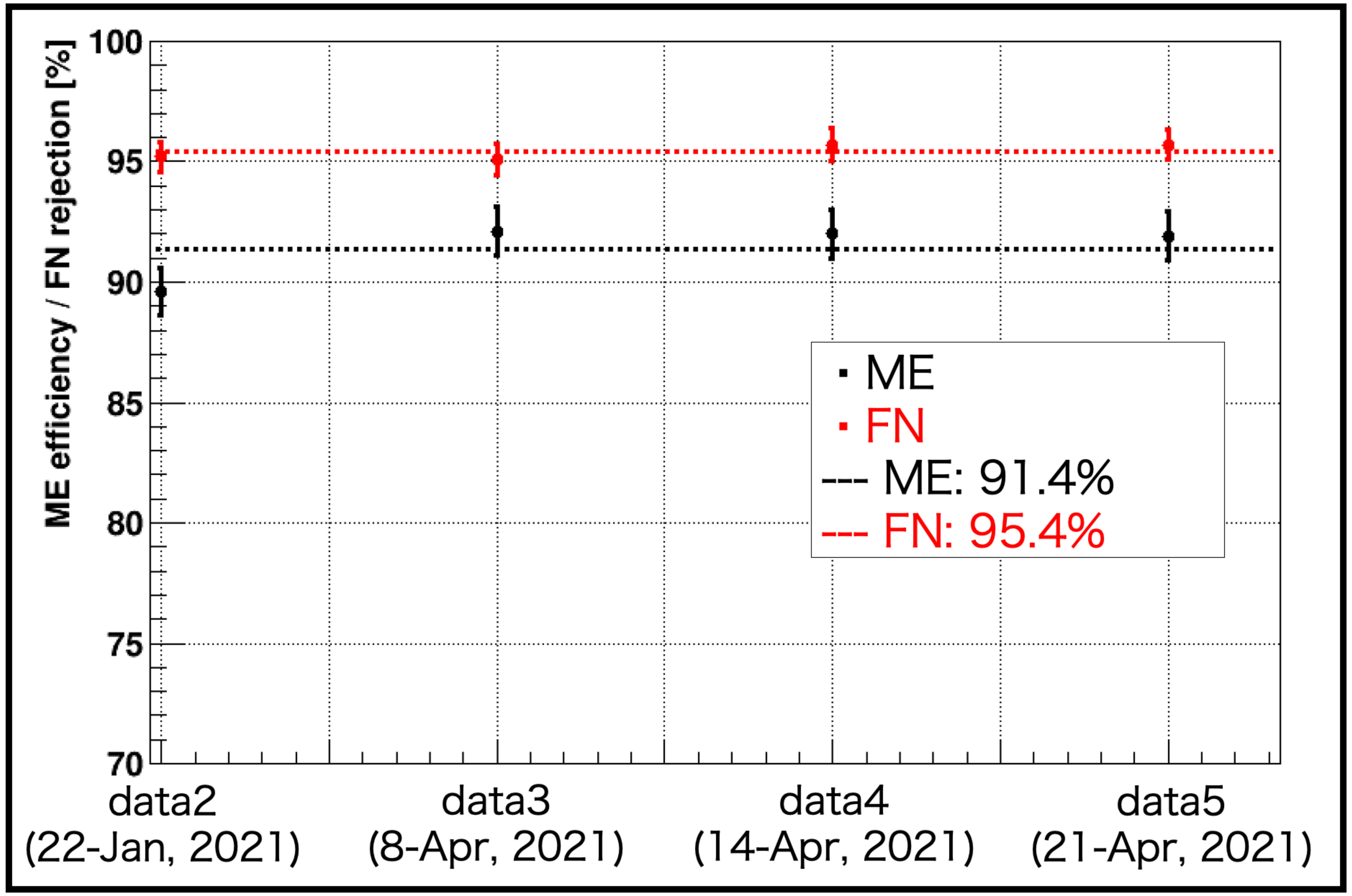
Pulse Shape Discrimination (PSD)

(2-dimensional likelihood method)

ME efficiency: 91.4 ± 0.5 %

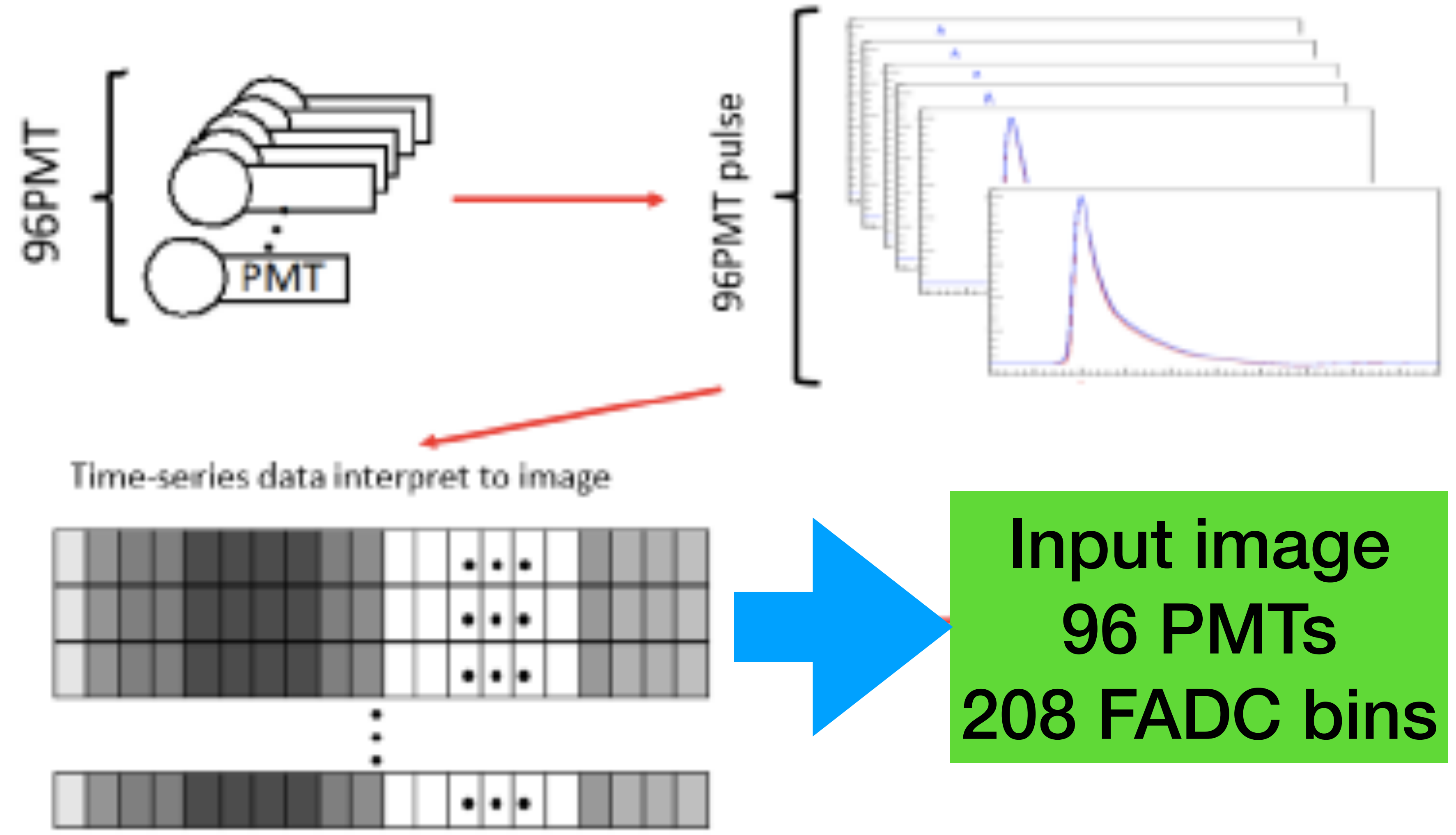
FN rejection: 95.4 ± 0.3 %

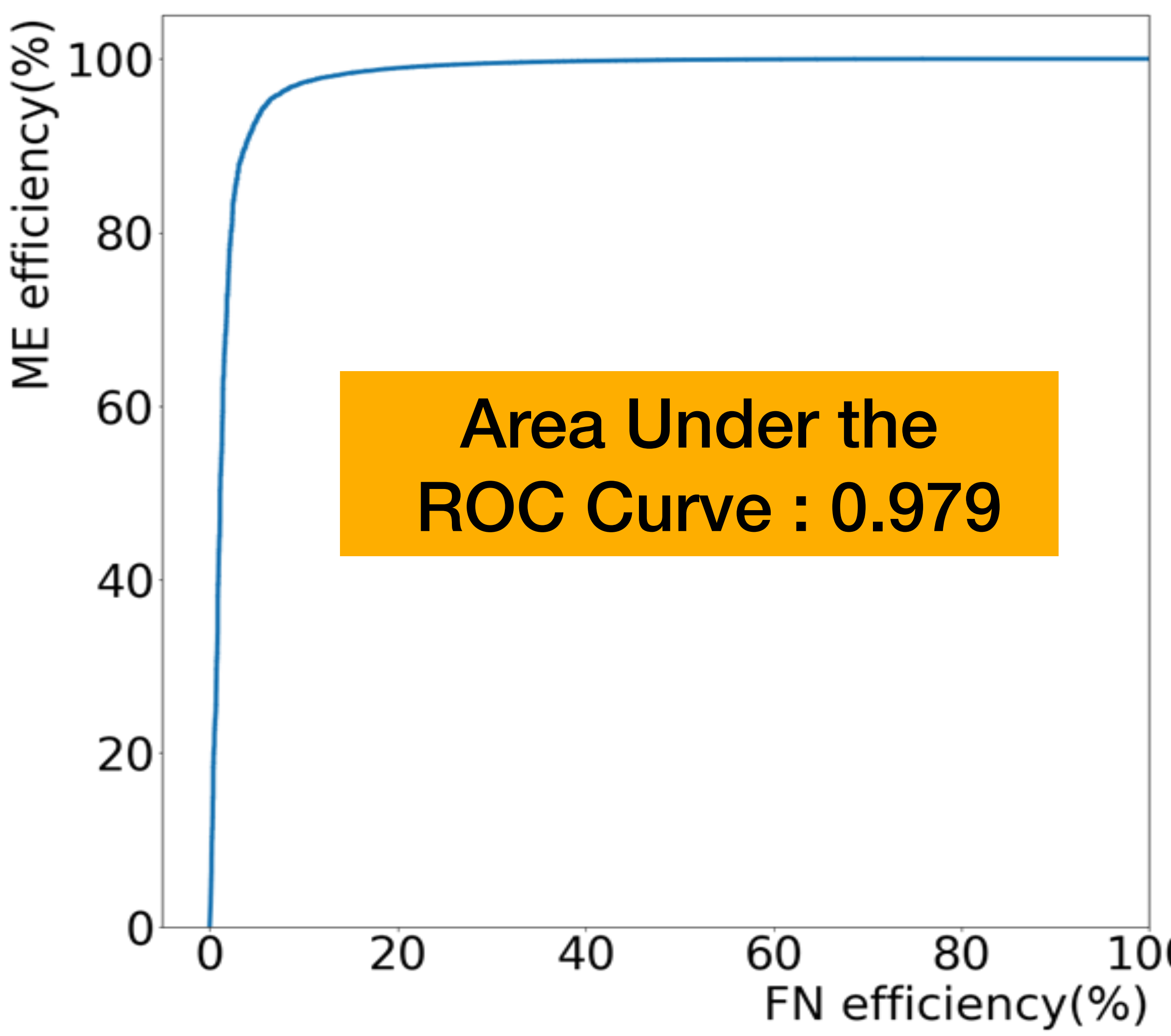


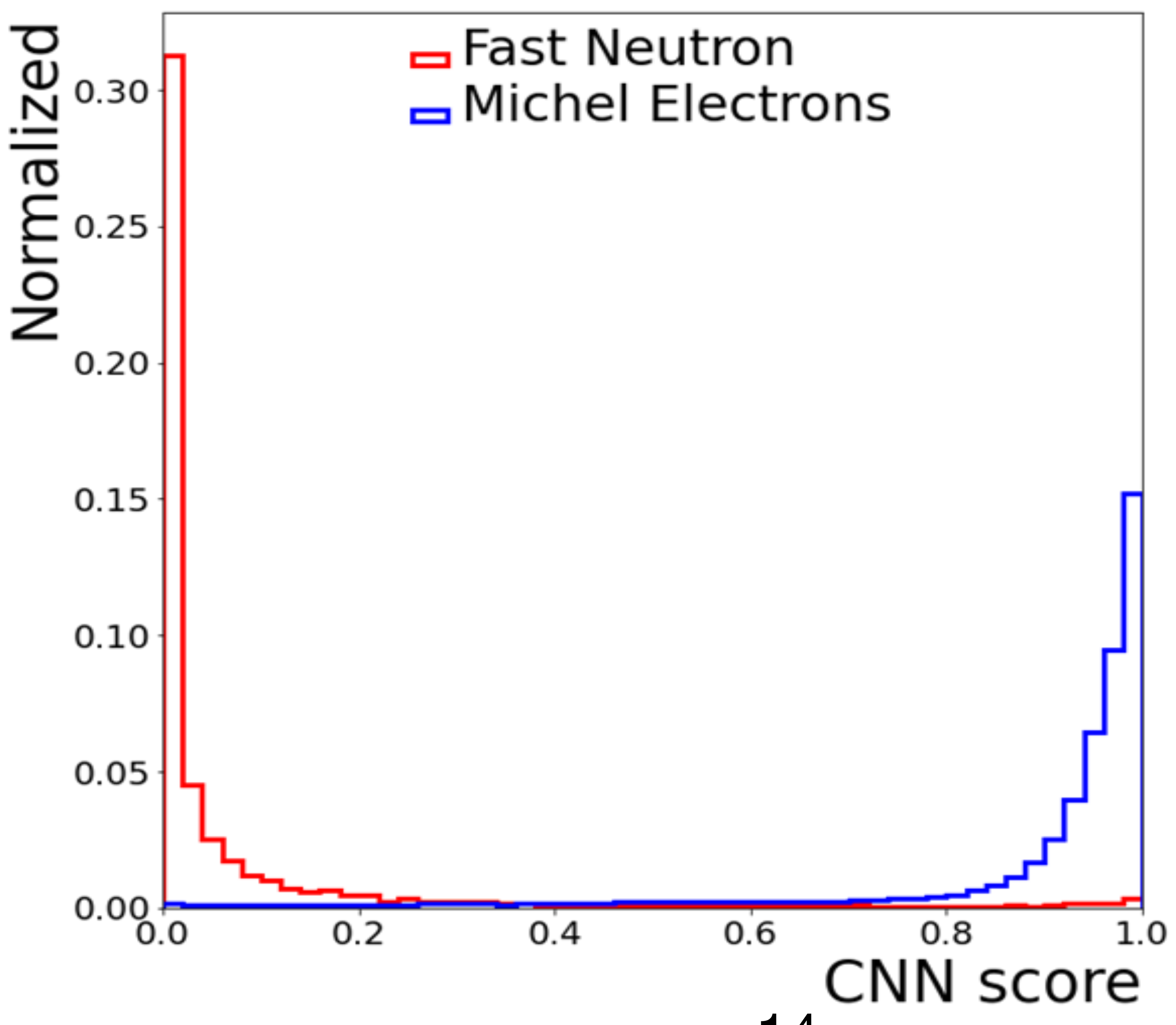


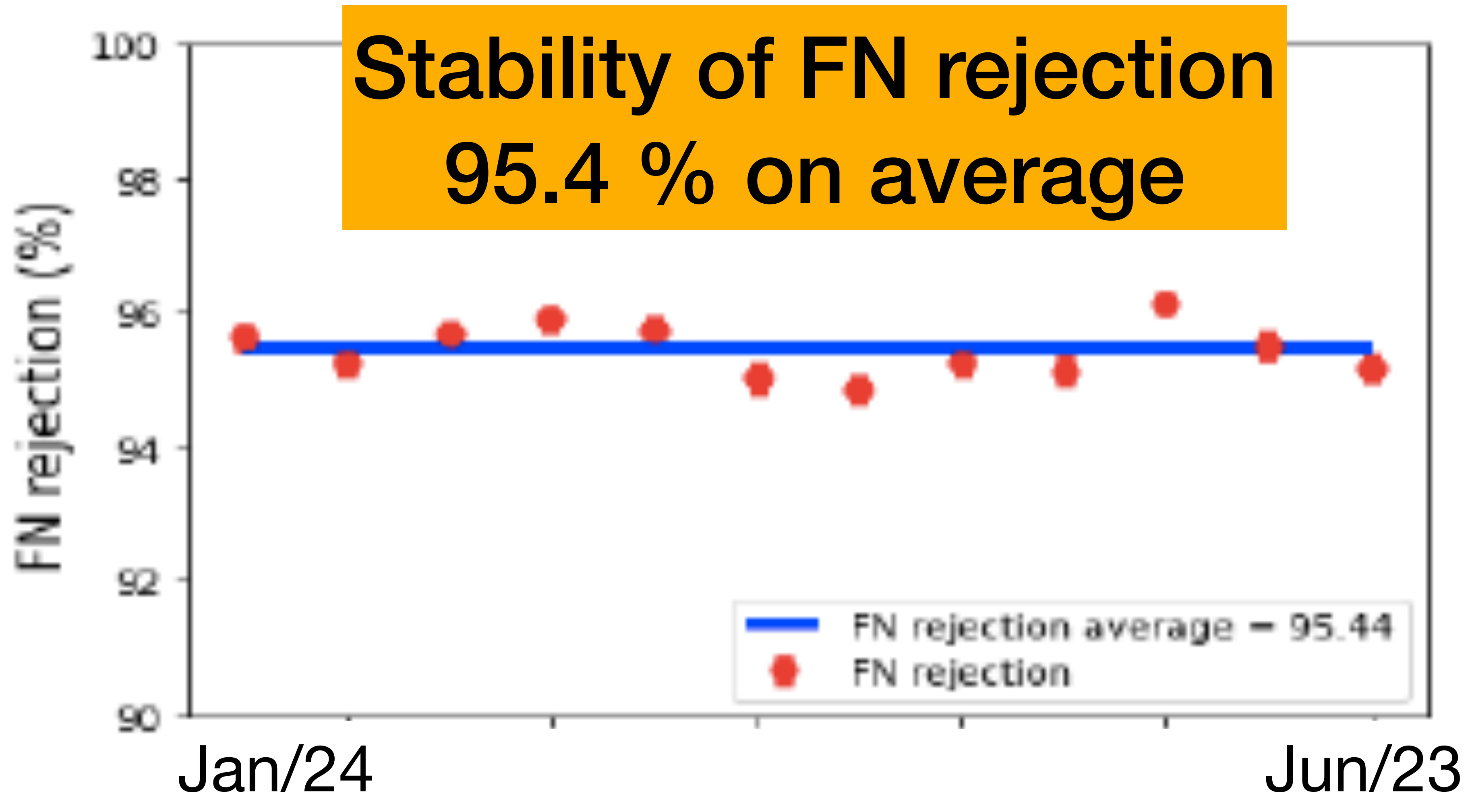
Pulse Shape Discrimination (PSD)
(Convolutional Neural Network, CNN)

- **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**









Roadmap
(sterile neutrino search)

Estimation of the background → **Blind analysis** → **Sensitivity**

JSNS² is here

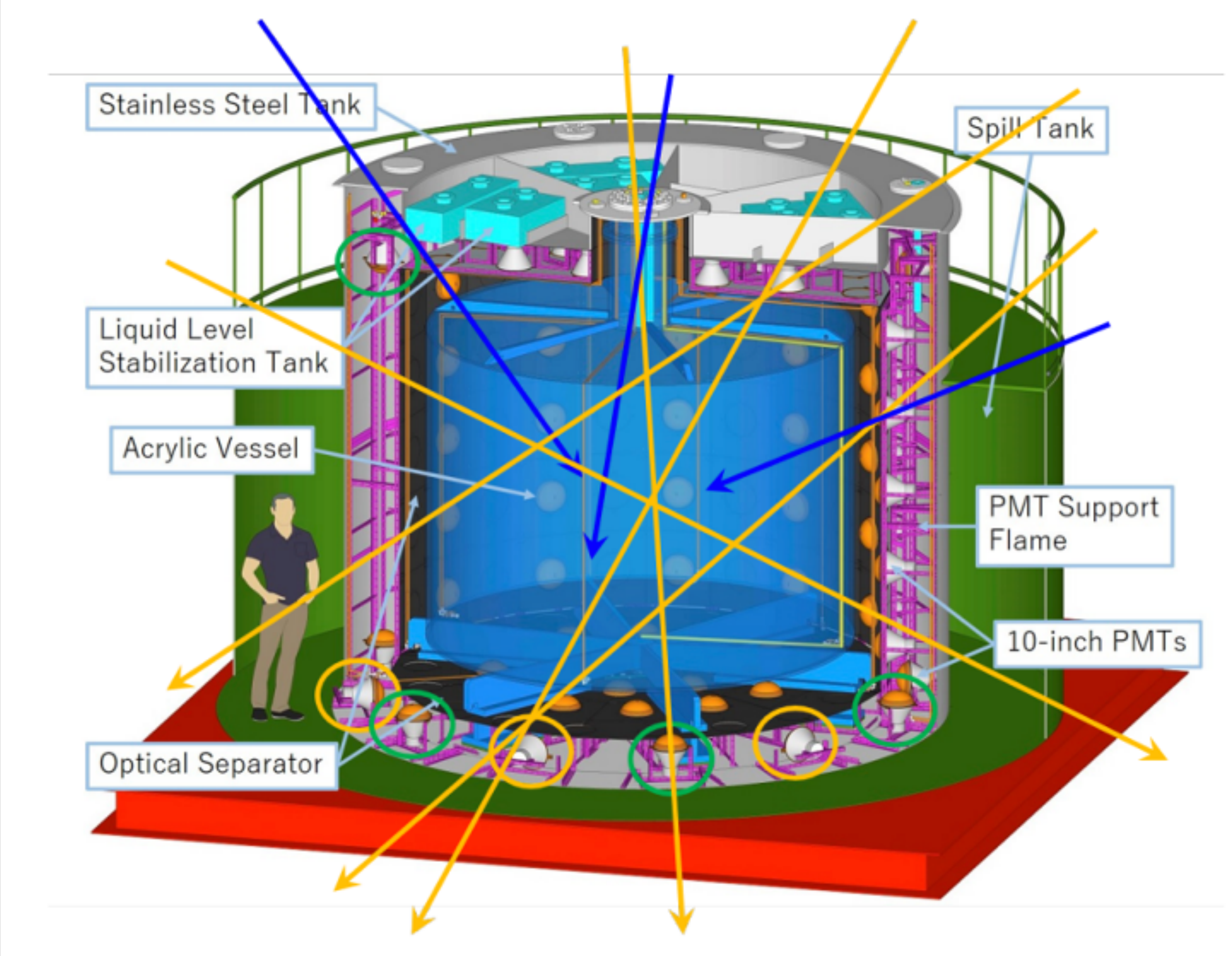
Estimation of the background
- Reduction
- Event selection
- **Compare single rate with TDR**
- Coincidence
  - Energy and timing
  - Delta vertex
  - Fiducial
  - More sophisticated method

Blind analysis
- Energy side-bands (and timing side-band)
- **Consistency check**
- self-trigger / beam trigger
- PSD
- More sophisticated method
- Toward a signal region

Sensitivity
- Uncertainties
  - Flux
  - Energy scale
  - Others

Cosmic muon identification

- Michel electron induced by cosmic muon and muon itself are one of the backgrounds.
- Tag muons passing through the detector & stopping at the detector using veto information.



JSNS^2 equips 24 Veto PMTs

- 12 PMTs on top / 12 PMTs on bottom
- 6 PMTs among 12 face radial direction
- Other half face vertical direction

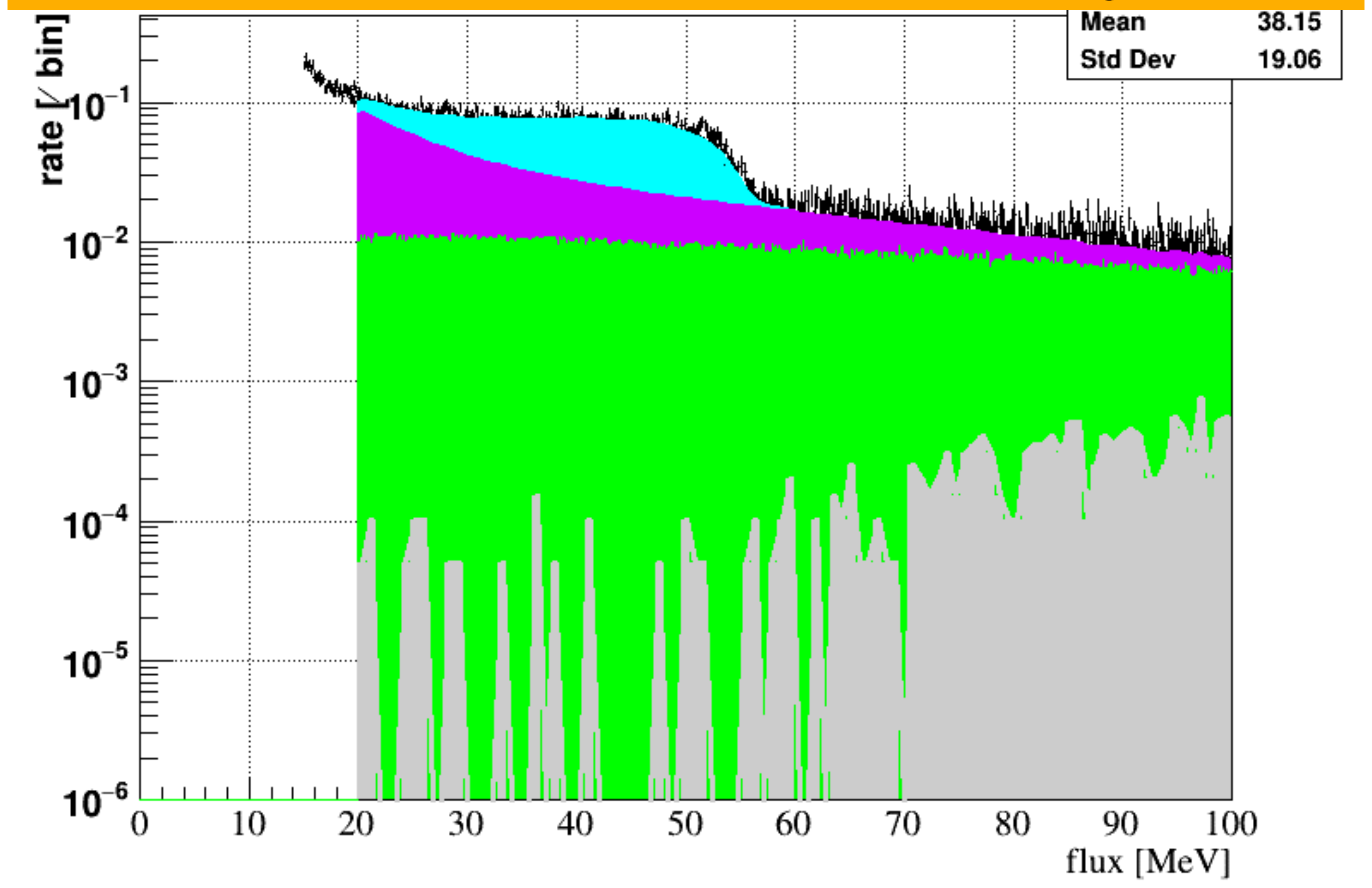
- Muon candidate rate [Hz]: 1487.8 ± 0.6
- Michel candidate rate [Hz]: 110.1 ± 0.2 ($>$ 10 MeV)

Single rate of the sterile prompt

(Background estimation effort)

- External particle rejection with Veto PMTs
- **ME rejection: 10 μs vetoing after a stopping-muon**
- Fiducial cut
- Decomposition have been performed
  - To estimate each component
  - correlated / accidental
  - **Spectrum is obtained from each control sample.**
- **Reference (JSNS² TDR): 3.8×10^{-4} per spill**

Prompt candidate after ME rejection



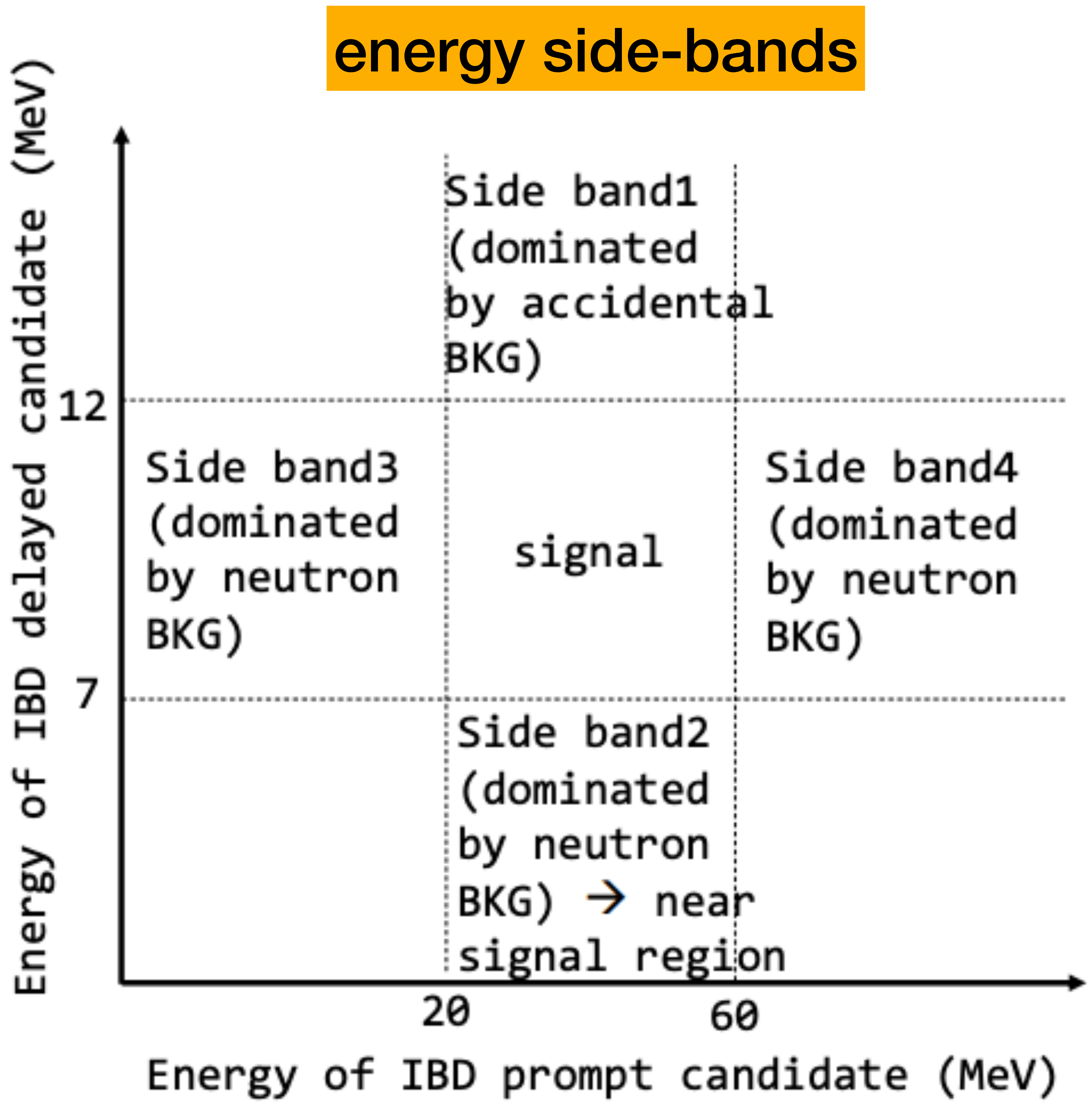
correlated, but PSD would reject it

IBD pairing (coincidence) would highly suppress them

component	rate [Hz]
cosmic fast neutron (green)	3.9±0.7
michel electron (cyan)	13.3±0.3
cosmic gamma (violet)	9.3±0.6
stopping muon (gray)	0.01±0.02
total (black)	26.8±0.1
rate per spill	$(2.144\pm0.010)\times10^{-4}$

Toward the sterile neutrino search
(For the blind analysis)

- **Side-bands are defined by energies**
- The rates in the side-band regions can be predicted by other data
  - self-trigger: cosmic-induced neutron
  - beam-trigger: accidental
- After application of PSD, all of side-band regions will be accidental dominated.
- JSNS^2 has been studying each side-band
- All side-bands should be understood thoroughly before opening the signal region



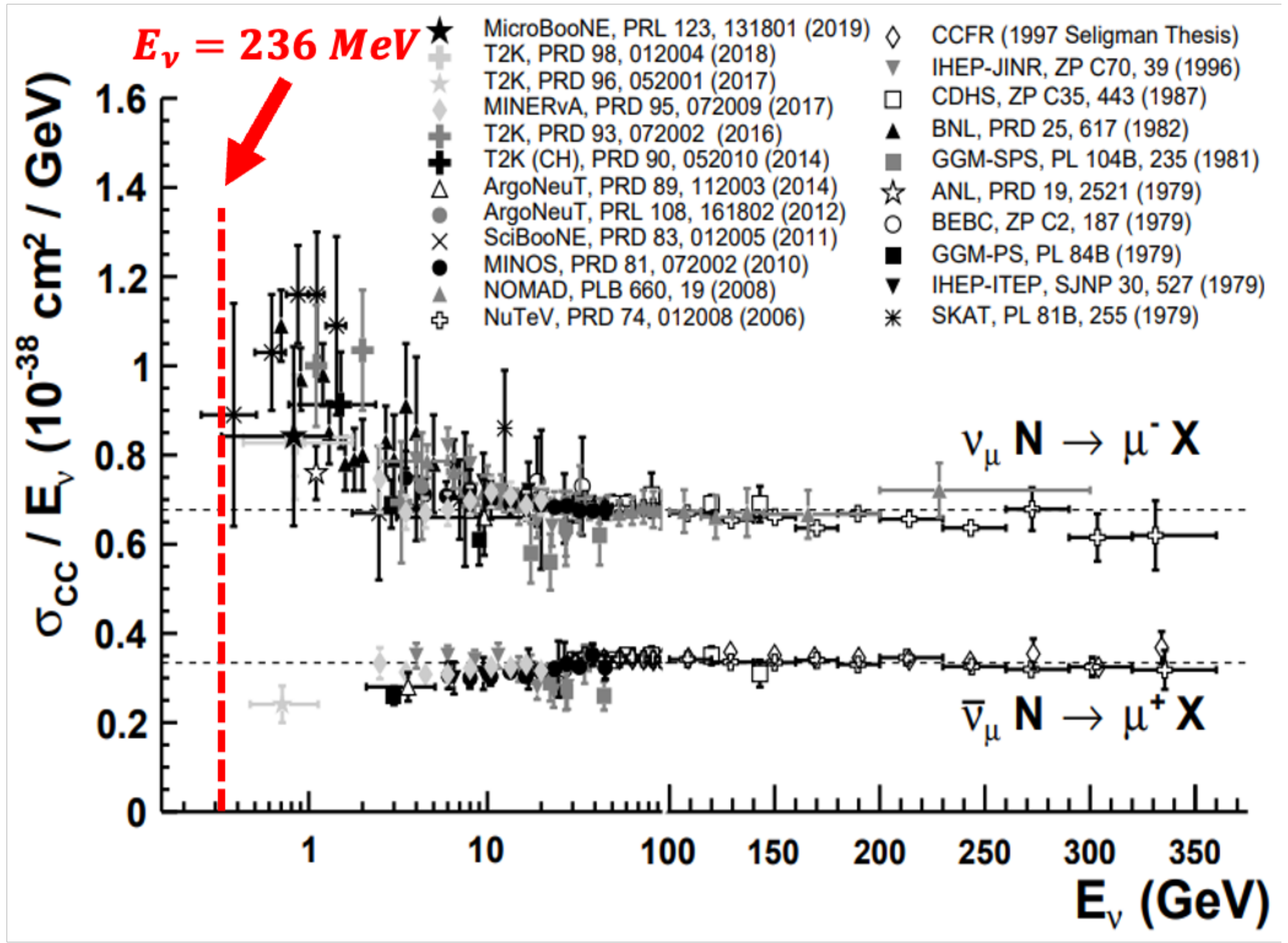
Kaon Decay-At-Rest (KDAR) Neutrino

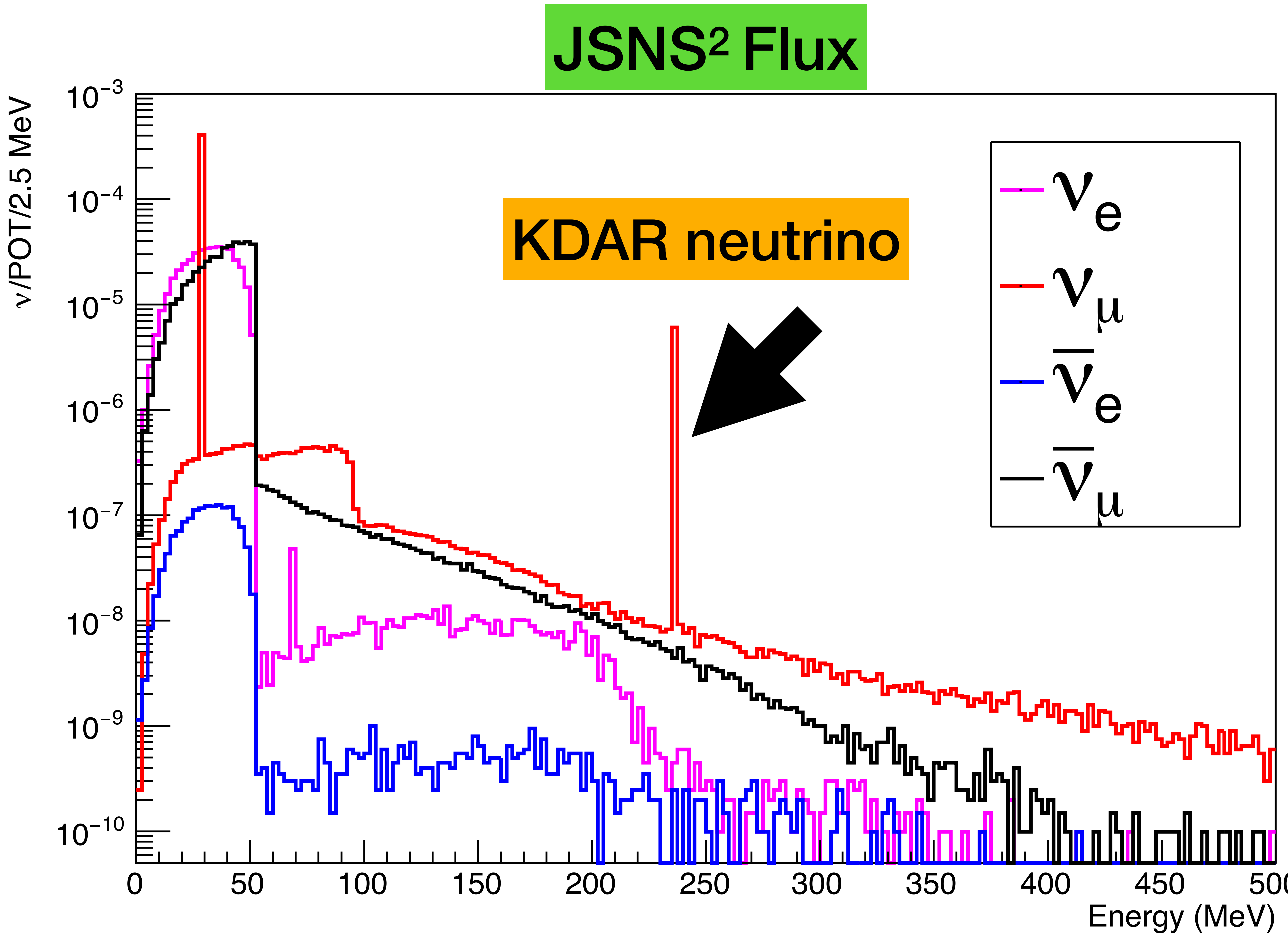
(Toward first KDAR precise measurement)

Kaon Decay-At-Rest neutrino measurement

(KDAR neutrino: 236 MeV mono-energetic)

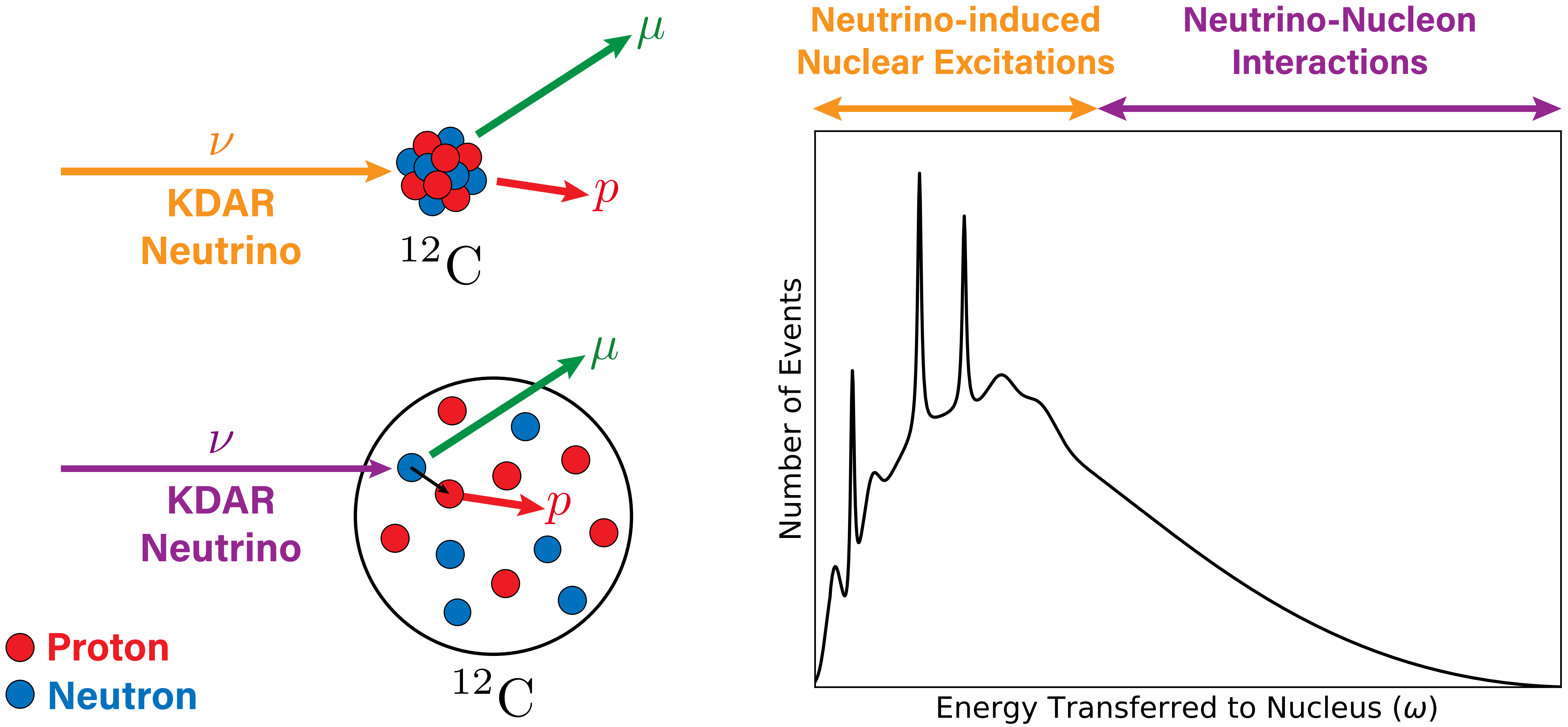
- Neutrino interaction models are a crucial part of neutrino physics, but poorly known at low energies.
- **The JSNS^2 detector has the unique ability to measure the mono-energetic KDAR neutrino.**
- Note that horn focused beam can not make a decay-at-rest neutrino.





Probing the nucleus with KDAR neutrinos

- KDAR neutrinos: a known-energy, weak-interaction-only probe of the nucleus, right at the transition between neutrino-nucleus and neutrino-nucleon scattering



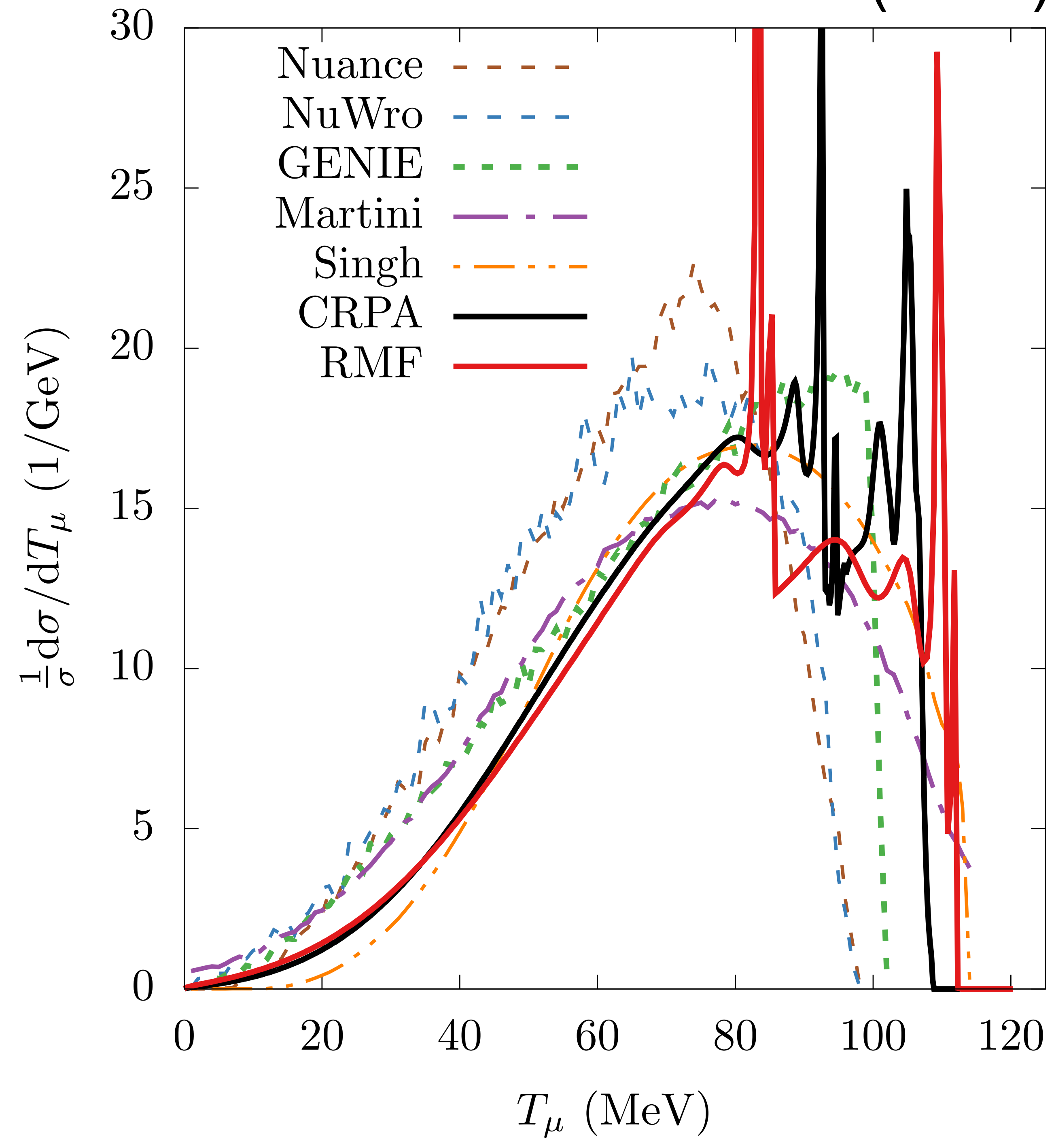
$K^+ \rightarrow \mu^+ \nu_\mu$ [BR = 63.6 %]

$E_\nu = 236\ MeV$ if K^+ is at rest

Why it is important

- The transition region between neutrino-nucleus and neutrino-nucleon scattering is very hard to model
- Models and generators strongly disagree.

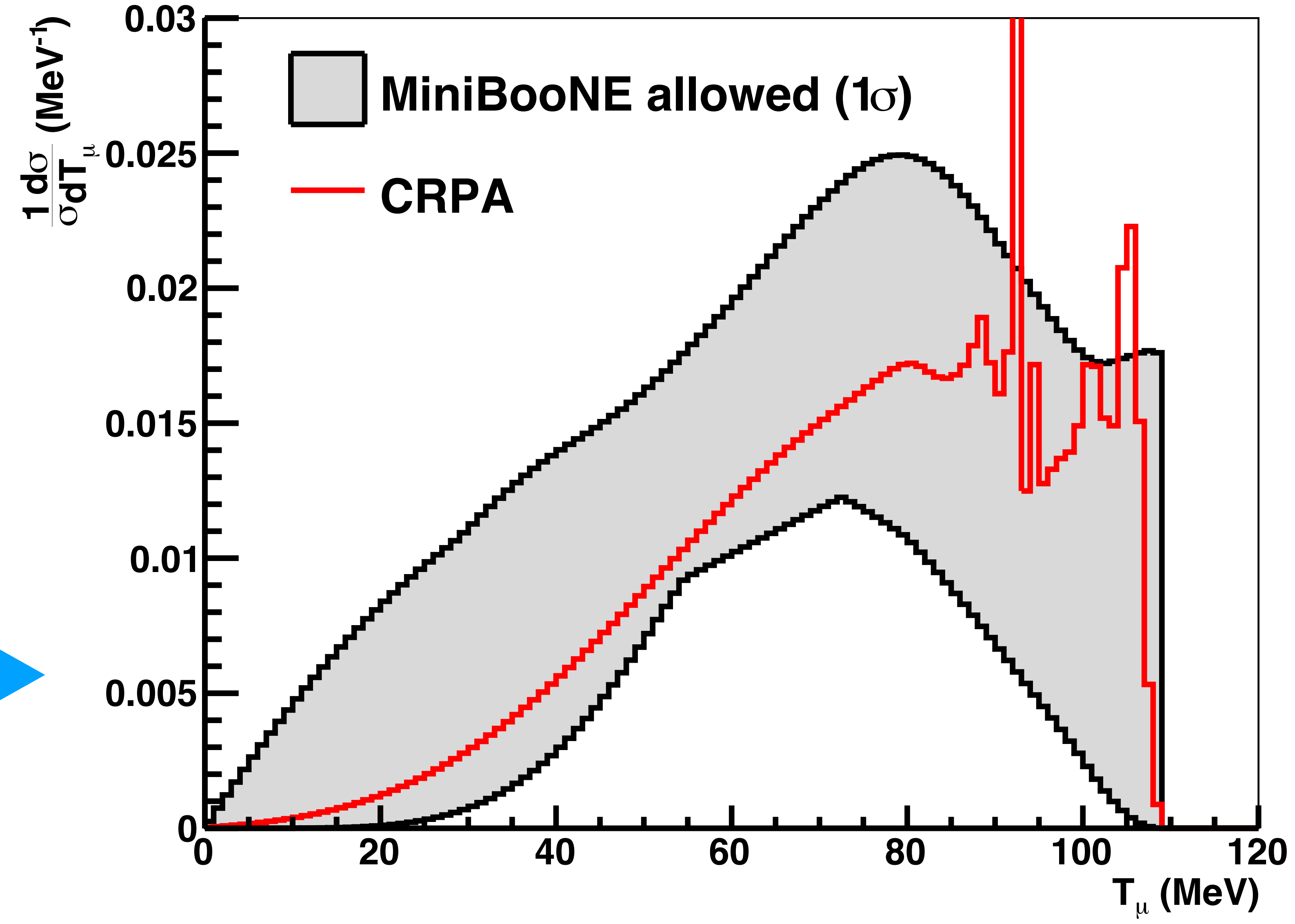
PRC 103 064603 (2021)



Relevant for:

- Long baseline exps and modeling of neutrino-nucleus interactions in the 100s-of-MeV region.
- Understanding MiniBooNE low-energy excess.
- Supernova neutrinos.
- Solar dark matter annihilation signatures.
- Future oscillation searches with KDAR (muon disappearance and electron appearance)

MiniBooNE, PRL 120 141802 (2018)



Only previous KDAR measurement (MiniBooNE) [3.9 σ first observation of KDAR neutrinos]

KDAR signal measurement in JSNS^2

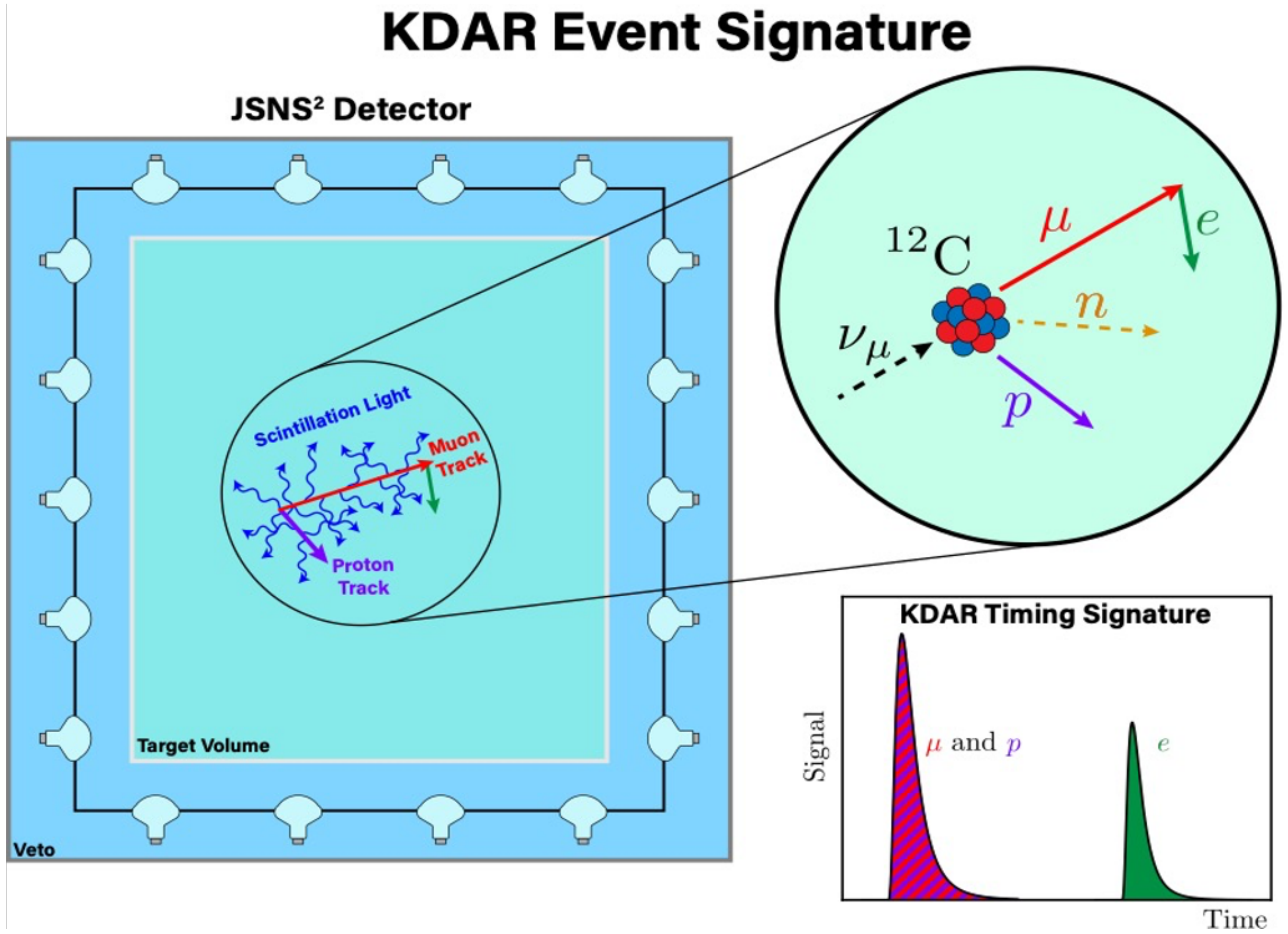
A double coincidence between

- The initial neutrino interaction products and the subsequent muon decay.

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

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

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



KDAR event selection

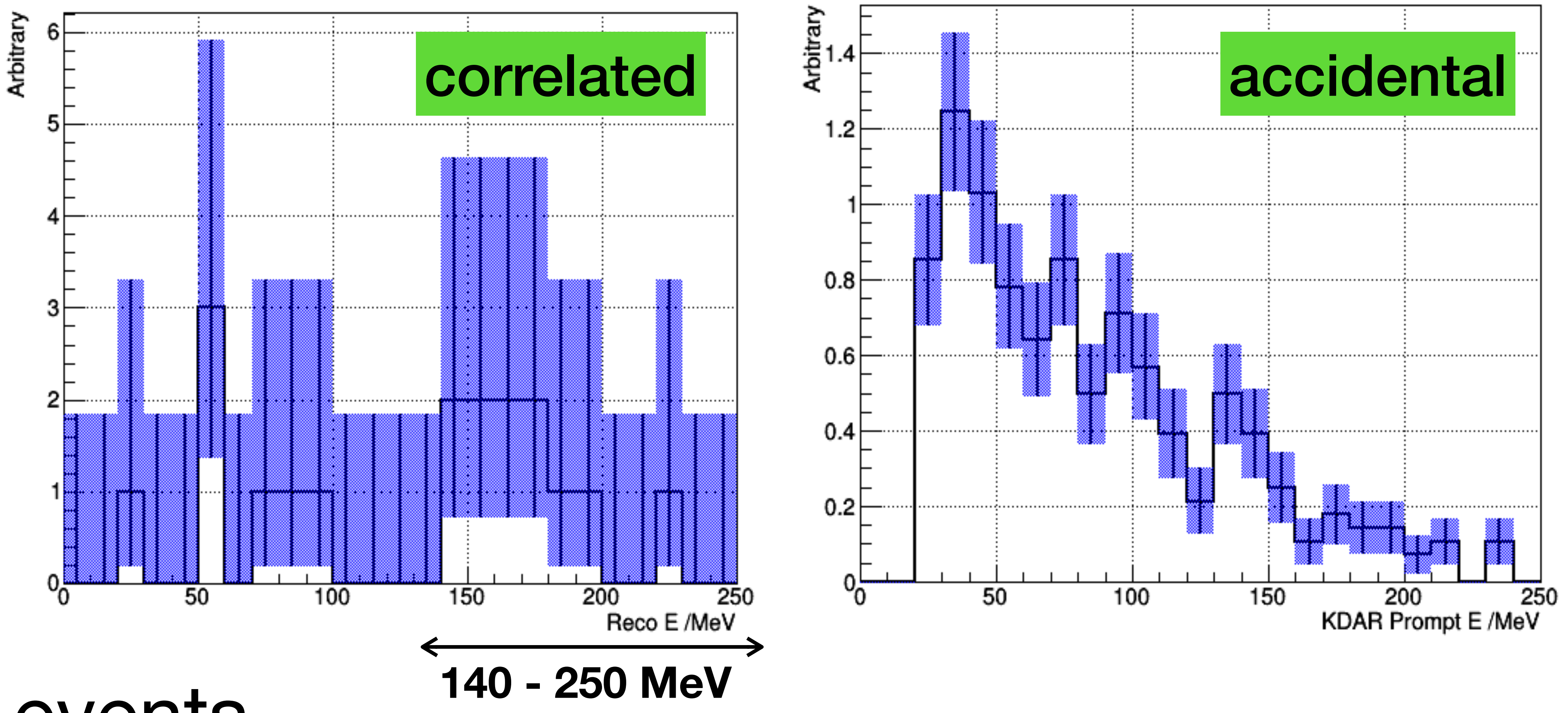
Used data: 2.256×10^8 spill

- 11.9% of the approved POT

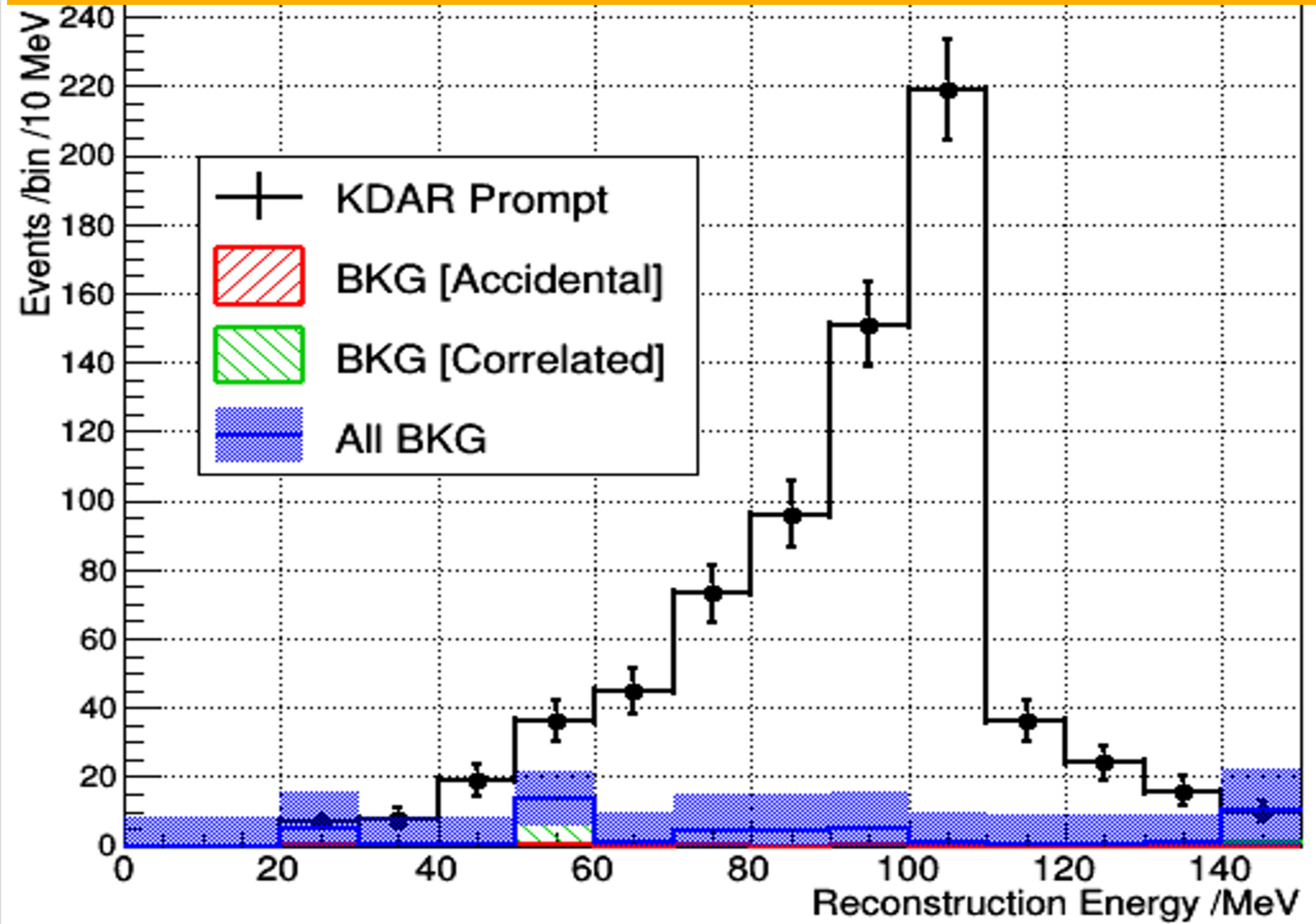
- Identify muon and remove proceeding 10 μs events
- Beam-timing cut (150 ns each)
- Prompt candidate: 20 - 140 MeV (μ^-)
- Delayed candidate: 20 - 60 MeV (e^-)
- Delta T: < 10 μs
- Delta vertex: < 300 mm
- Applied the Fiducial cut

- Background template: timing side-band
- Magnitude: area normalization b/w 140 - 250 MeV

Template of background energy



Visible energy spectrum w/ backgrounds



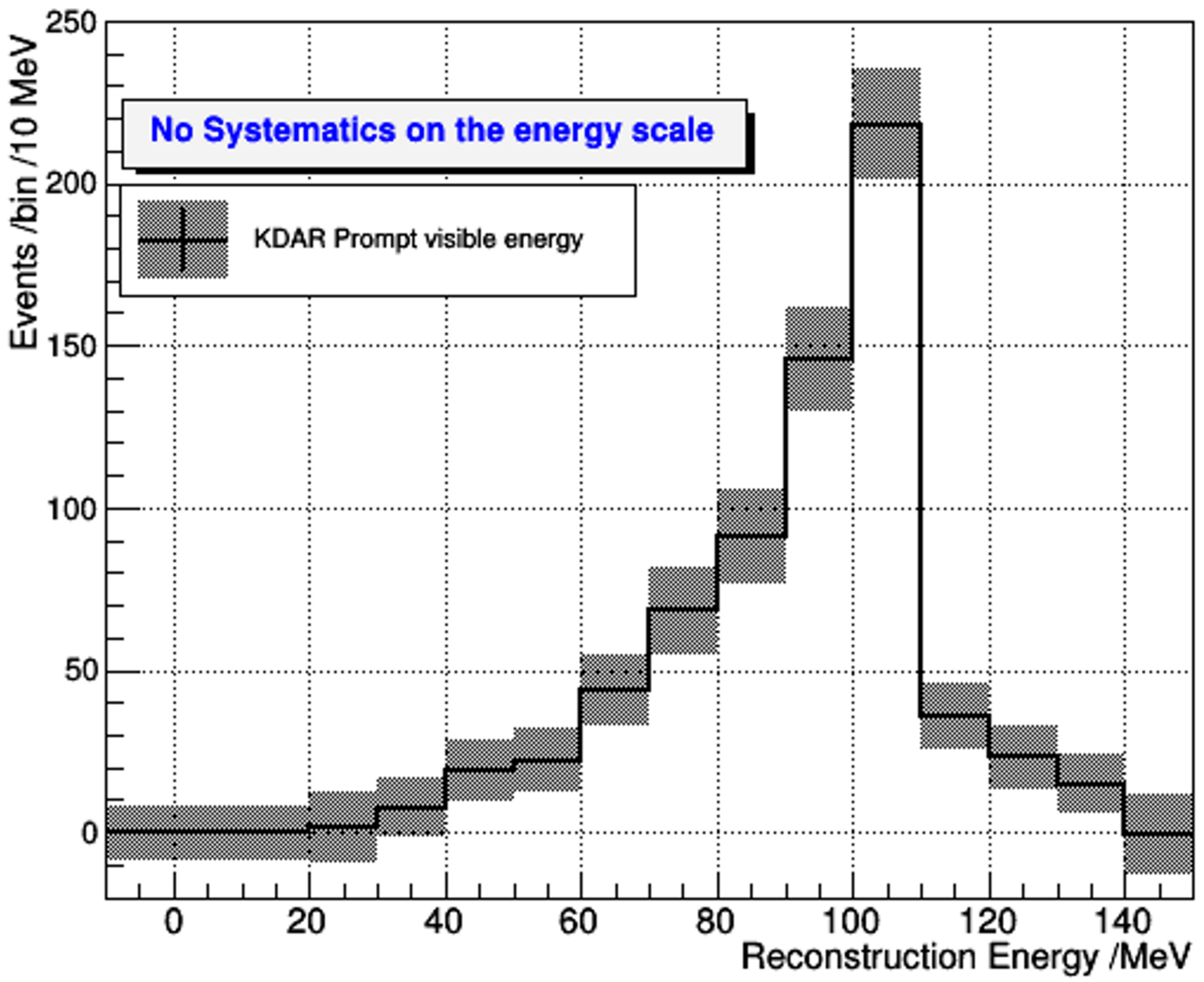
First clear KDAR signal

(Toward first precise KDAR measurement)

- **KDAR peak is clearly seen**
- **High purity (95%)** KDAR signal
  - Background: 5.2 %

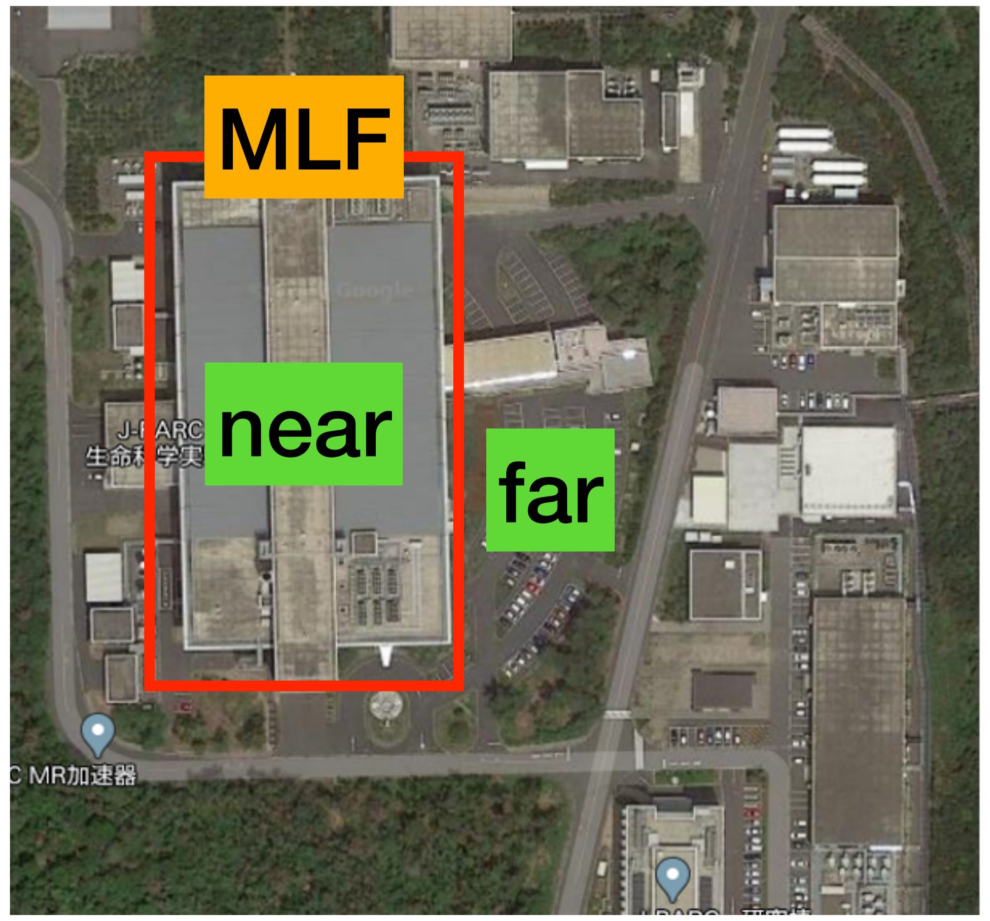
- Note that **the systematics on the energy scale are not included yet.**

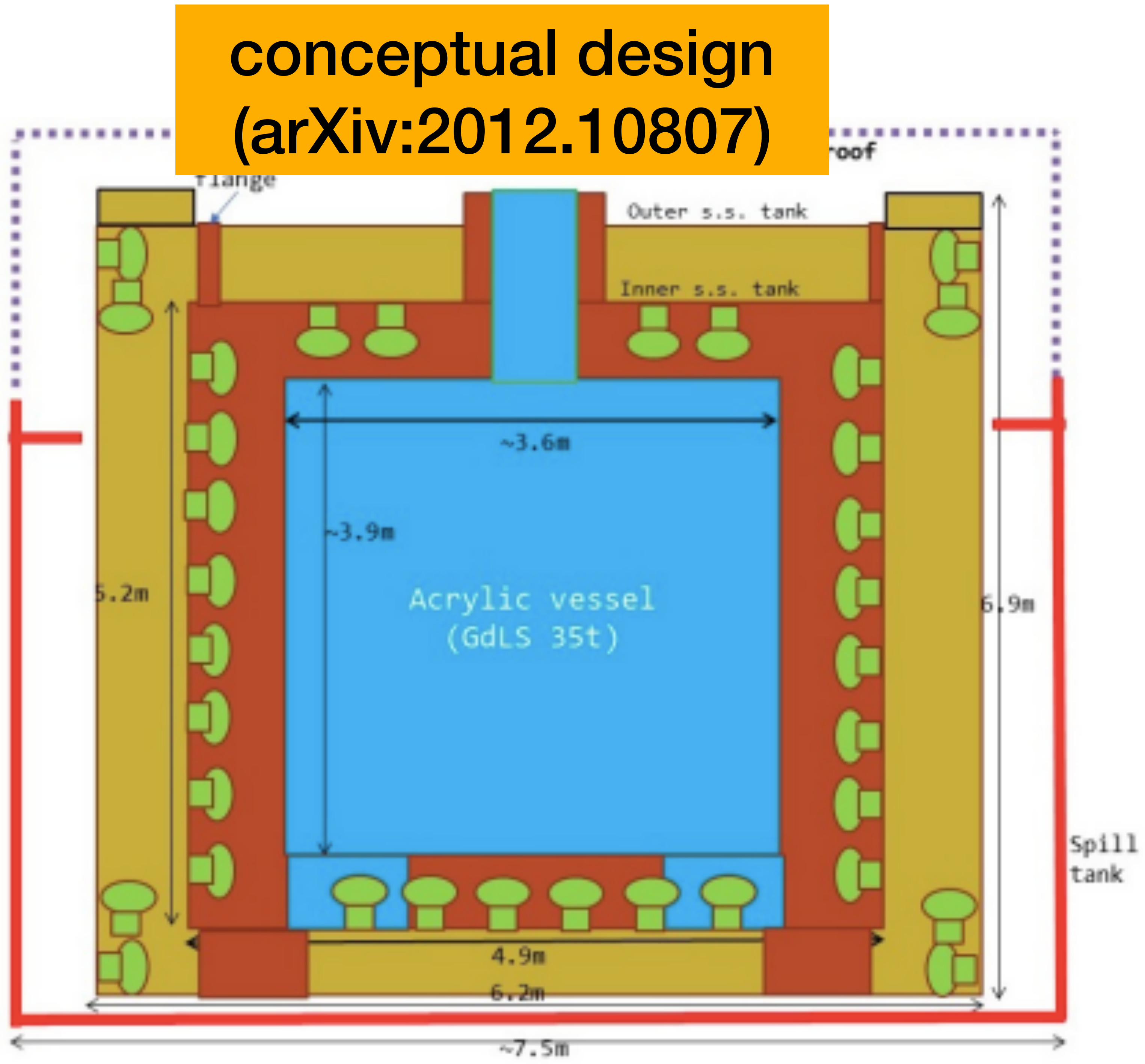
BKG ID	Correlated/ Accidental	BKG (# of events)	
1	Correlated	36.6 ± 34.8	$5.0 \pm 5.1\%$
2	Accidental	1.5 ± 0.1	$0.2 \pm 0.01\%$
KDAR Signal : 730 events		38.1 ± 38.4	$5.2 \pm 5.3\%$



Toward the second phase ($JSNS^2$-II)

JSNS²-II
(arXiv:2012.10807)



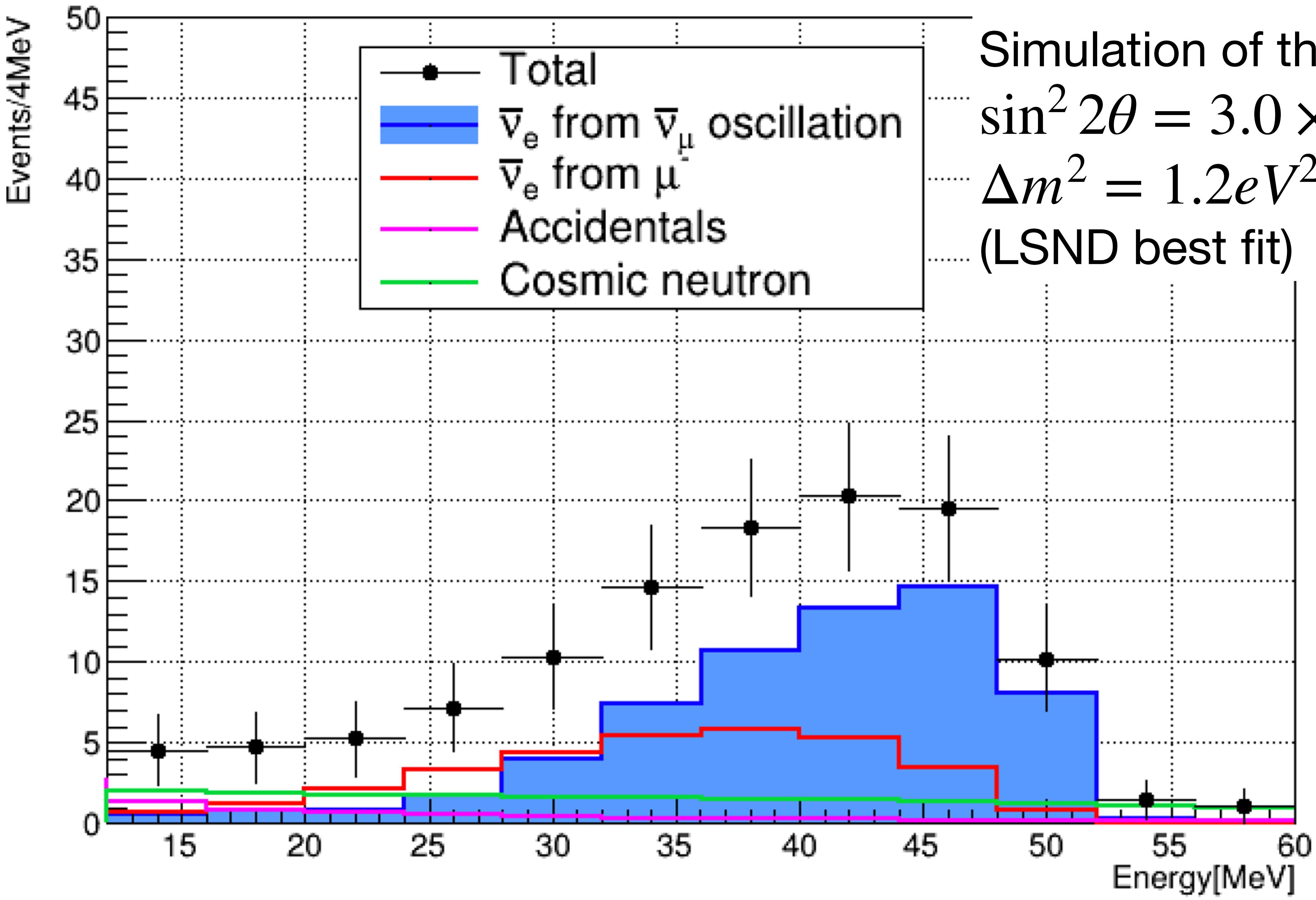


- Second phase of the JSNS² experiment with two detectors
  - near (17 tons, 120 10-inch PMTs, 24 m),
  - far (32 tons, 220 10-inch PMTs, 48 m) detector
  - Improve the sensitivity especially in the low Δm^2 region
  - J-PARC/KEK grants the stage 2 (2/2) approval
  - The stainless steel tank has been constructed
  - Other works are on-going

Sensitivity for the JSNS²-II

(Based on the simulation)

- Each background simulation was done based on the JSNS² data
- Covering LSND by 3 sigma

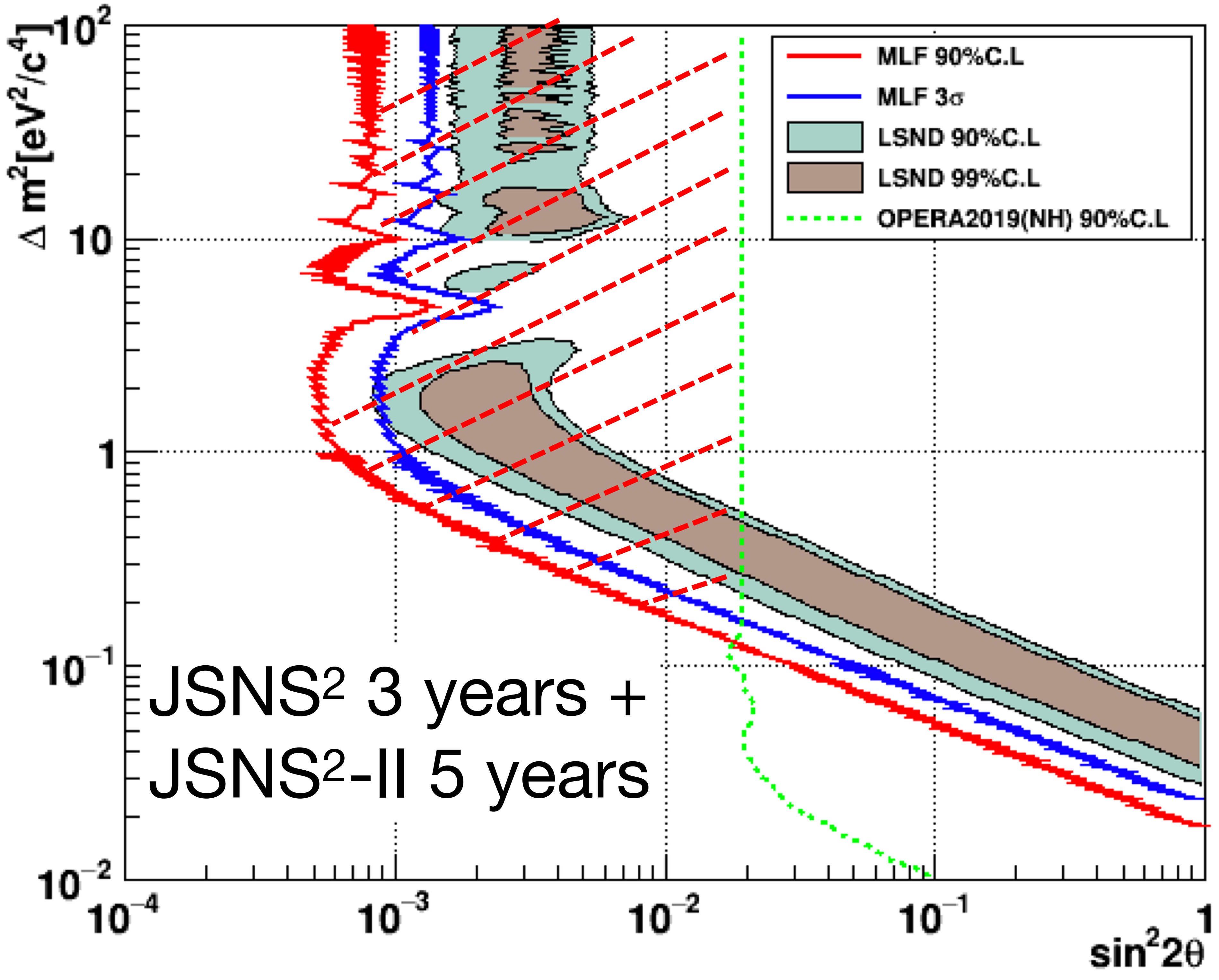


Simulation of the far detector

$\sin^2 2\theta = 3.0 \times 10^{-3}$

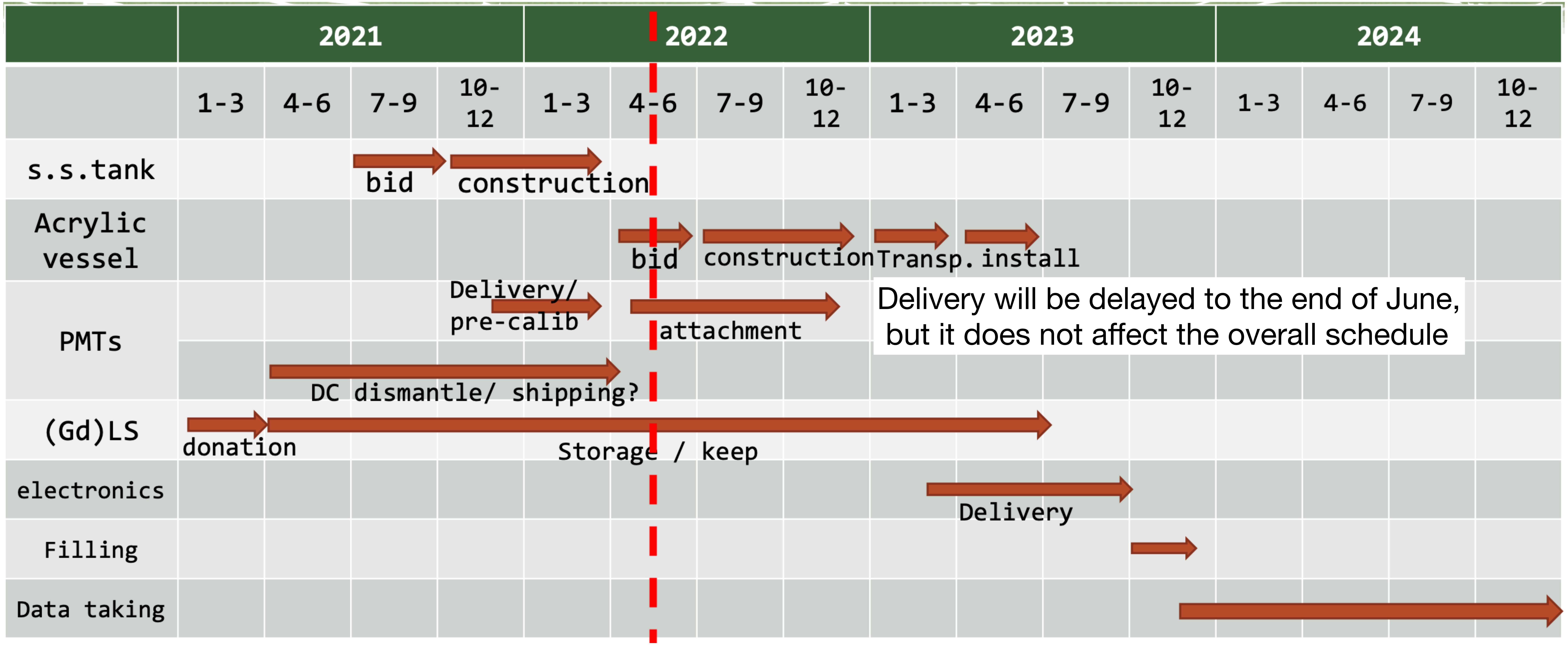
$\Delta m^2 = 1.2 eV^2$

(LSND best fit)



JSNS^2-II: Schedule

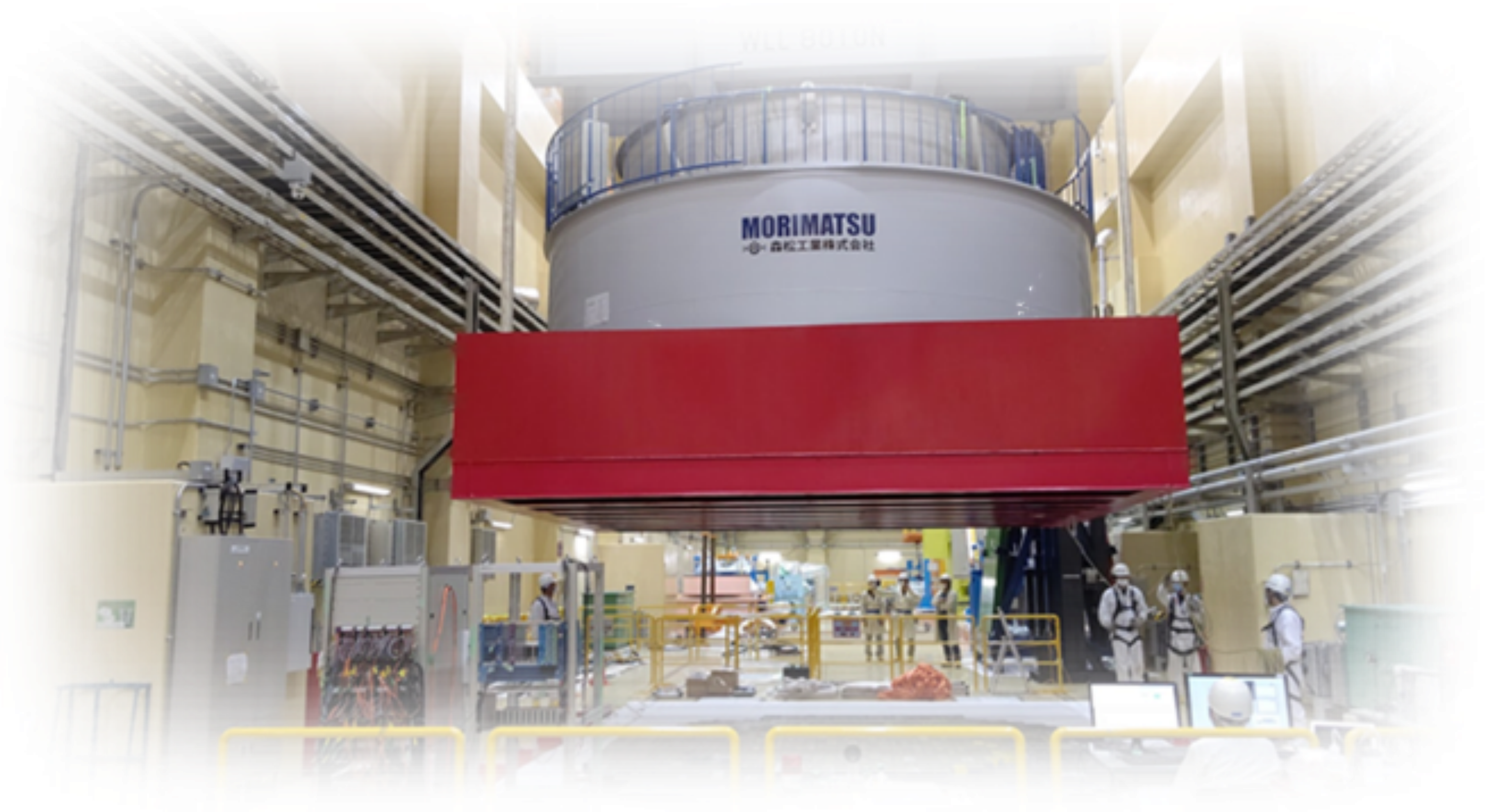
(Even under the COVID-19, the overall schedule was well followed from 2021's plan)



Summary

- **JSNS^2 is working toward first precise KDAR measurement**
  - **Clearly see the high purity KDAR signal**
- There have been 1st (2021) and 2nd (2022, ongoing) long physics runs in JSNS^2.
- Analyses are ongoing with the data.
  - Has been developing two separate PSD tools
  - Sterile neutrino search is on-going according to the roadmap
- Based on the JSNS^2 data, JSNS^2-II has been granted.
- Even under the COVID-19, the overall schedule was well followed from 2021's plan.
- JSNS^2-II expects to start data taking at around the end of 2023.

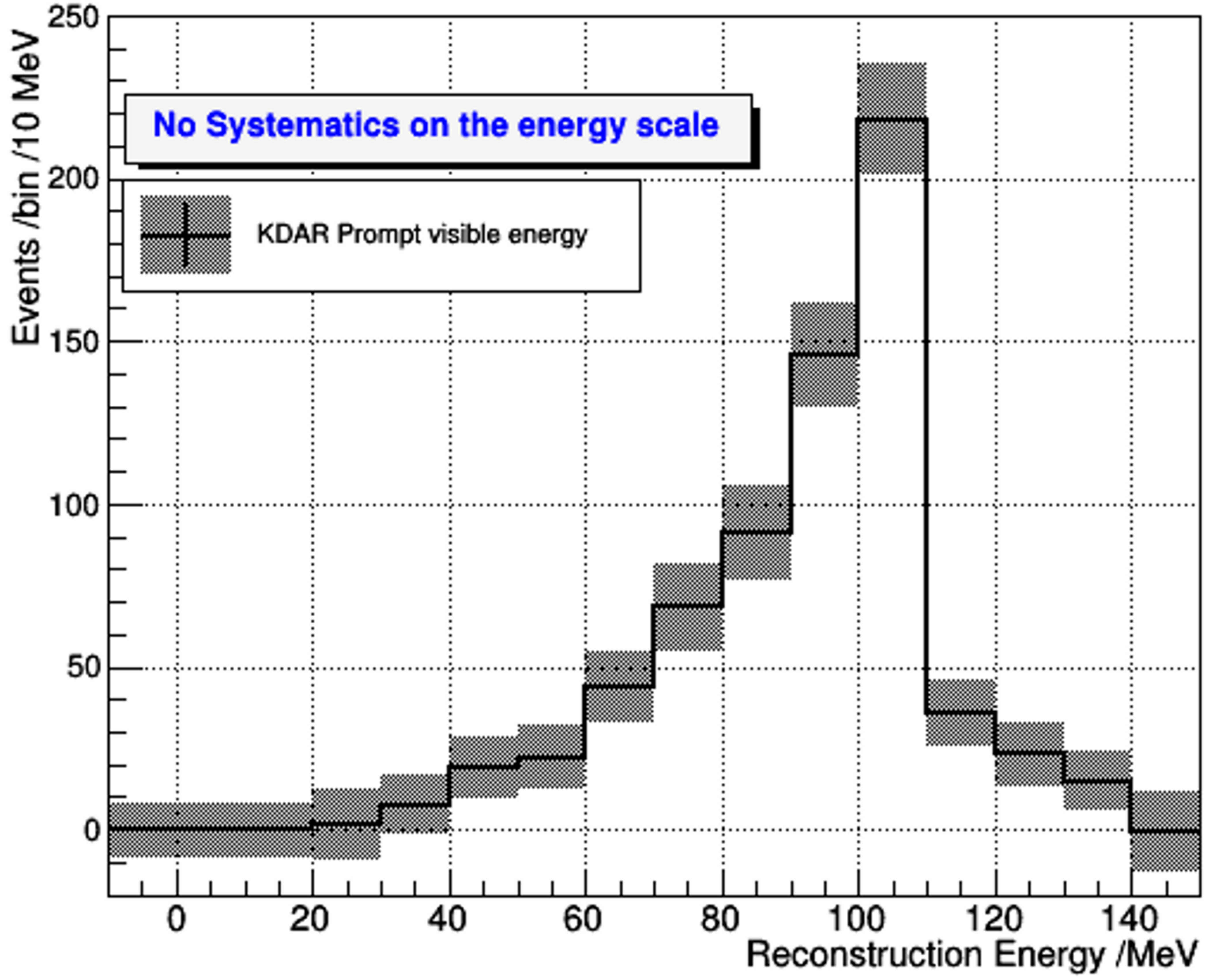
Thank you for your attention



acknowledgements:

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

KDAR summary slide

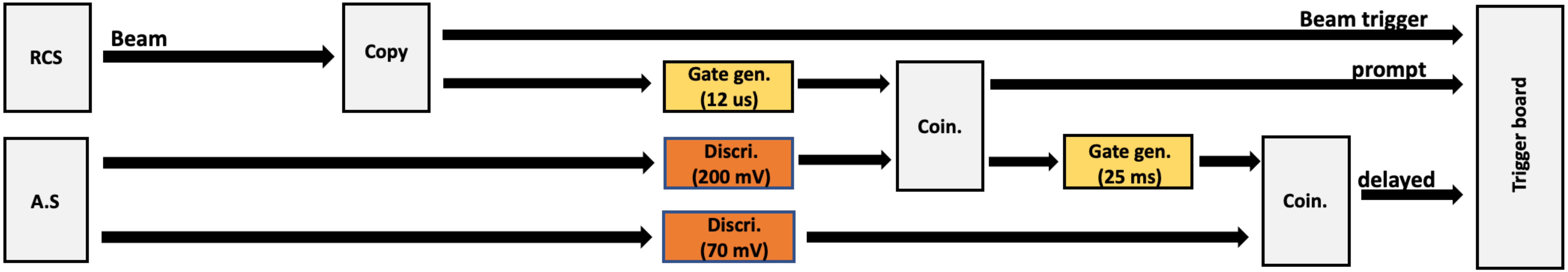


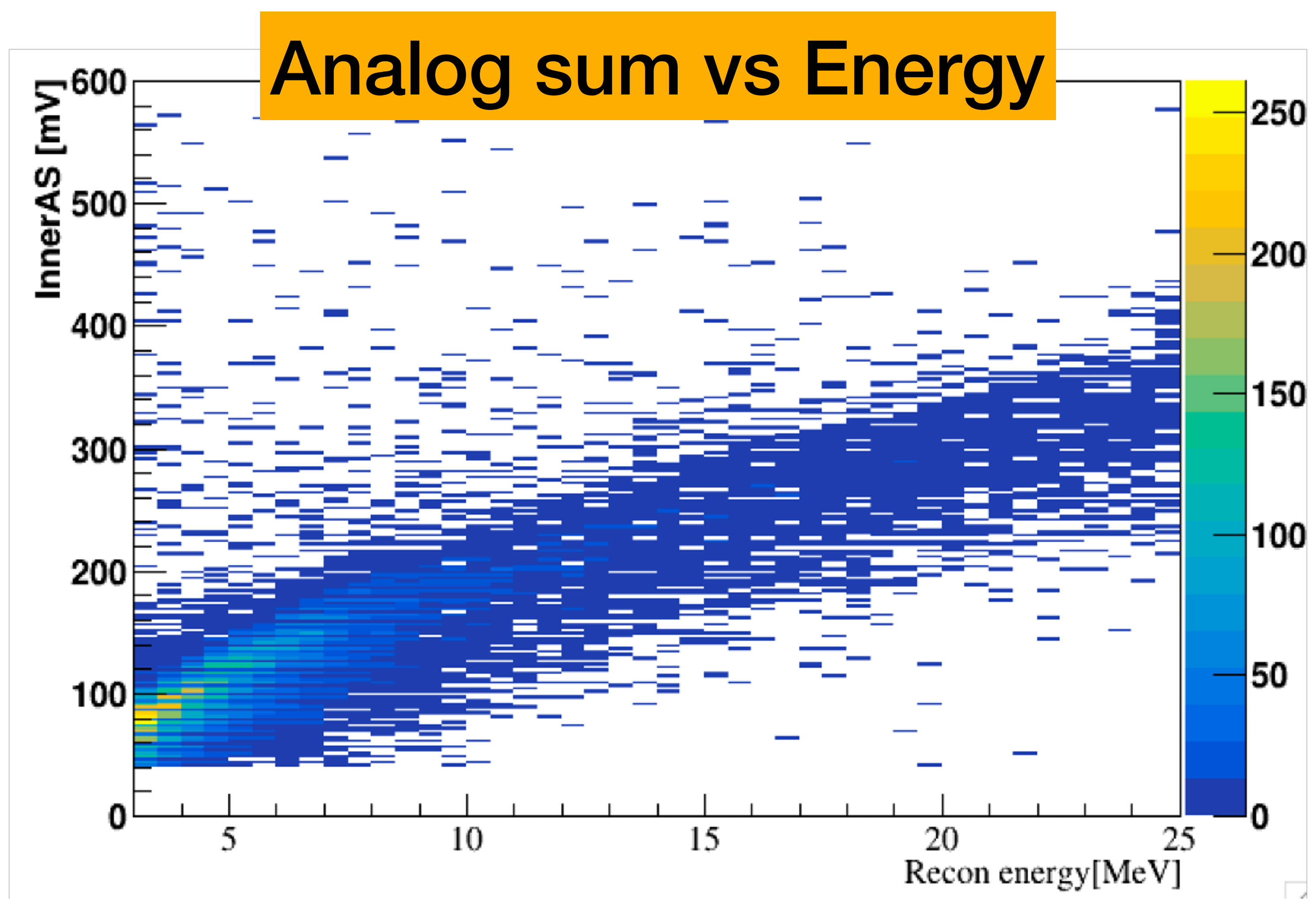
- JSNS2 clearly observes a high purity (95%) KDAR signal!
- This signal will provide the first precision measurement of KDAR neutrinos!
- Working towards finalizing visible energy $(T_\mu + \sum T_p)$ spectrum measurement and detailed model comparison.
    - Will elucidate the difficult to model neutrino-nucleon to neutrino-nucleus transition region, highly relevant across many aspects of neutrino physics

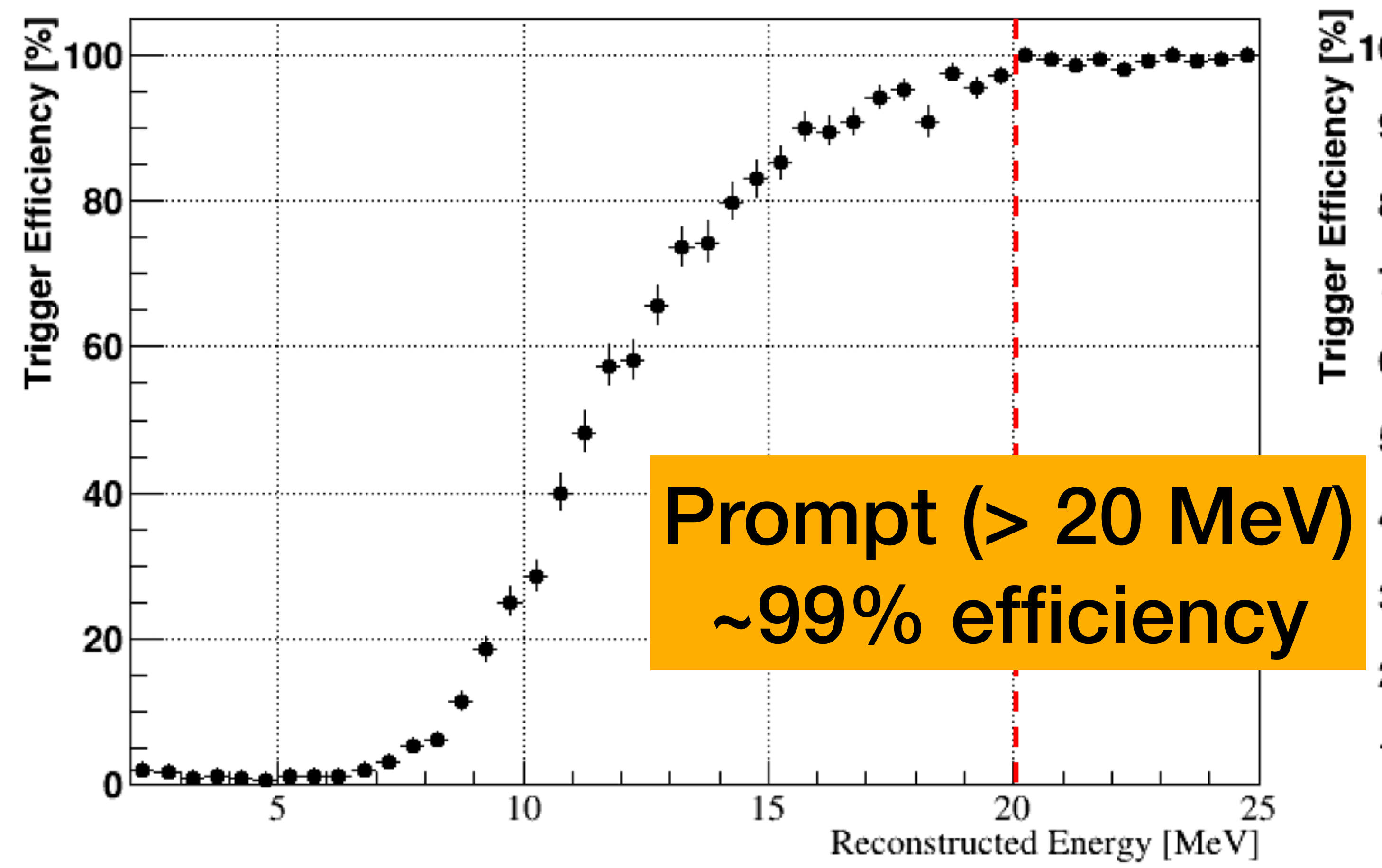
Backup

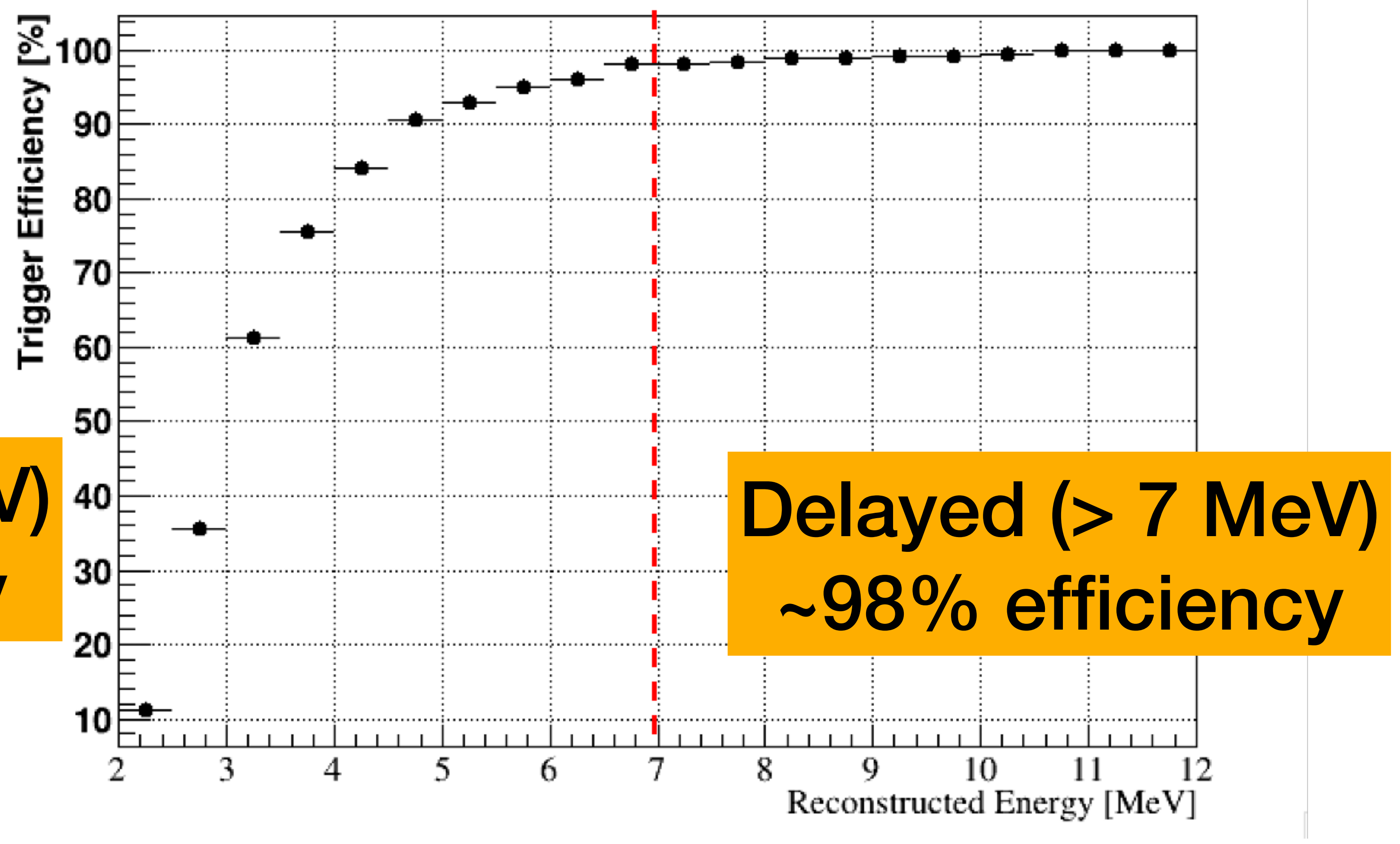
Dedicated sterile trigger

(Conditional and sequential of beam and self trigger)





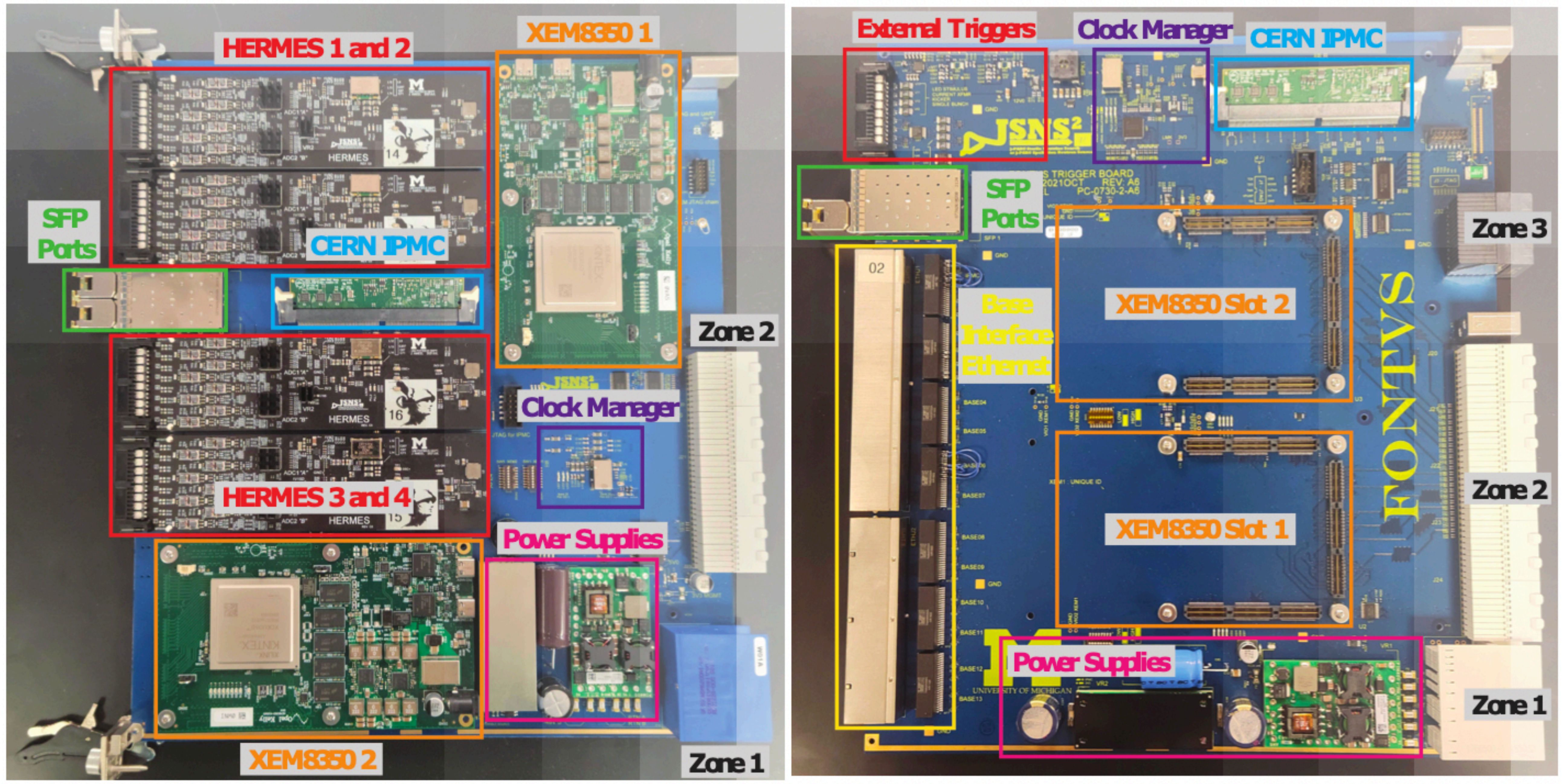


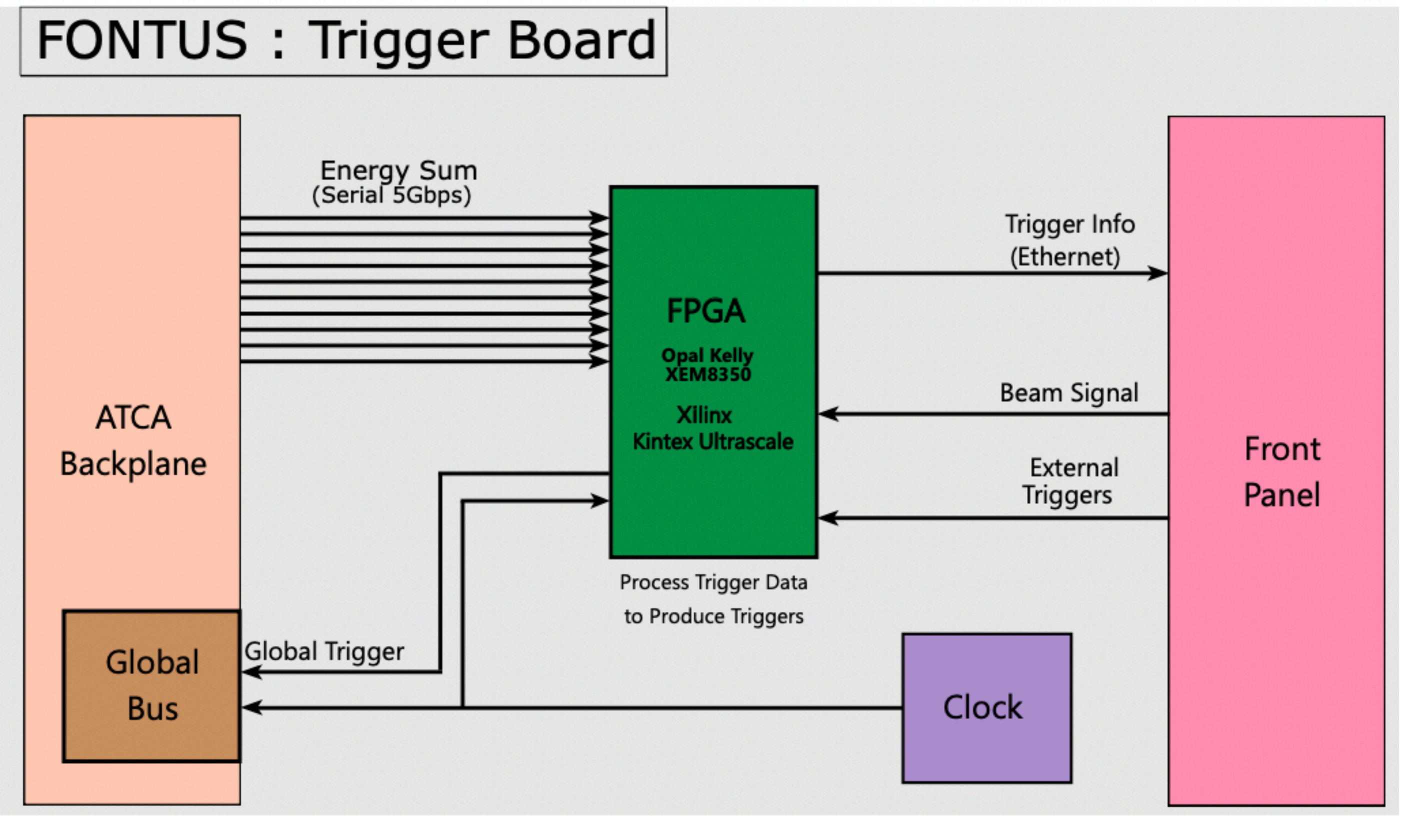


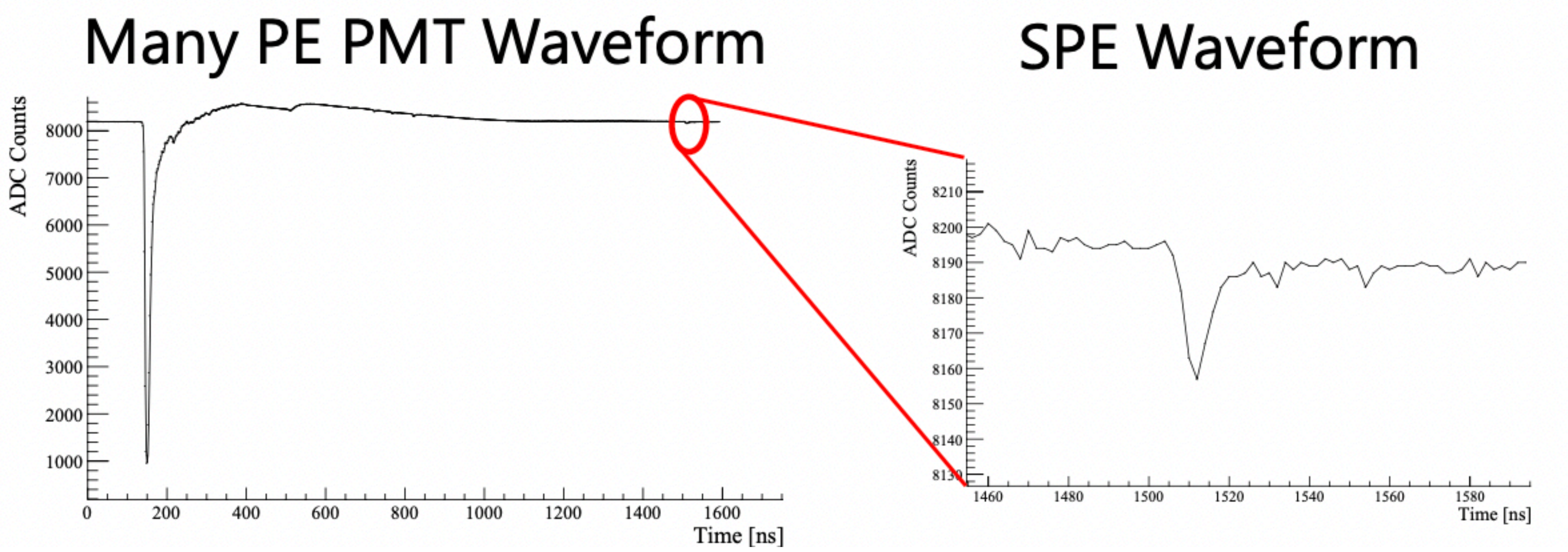
Electronics upgrade

(Under developing)

- The goal is to provide excellent efficiency and resolution over a wide energy range
- FPGA based trigger
- Hosted by an ATCA shelf
- A combined test has been done







JSNS^2 vs. LSND

	LSND	JSNS^2	Advantage of JSNS^2
Detector Mass	167 Tons	17 Tons	
Baseline	30 m	24 m	
Beam Kinetic Energy	0.8 GeV	3.0 GeV	**Allows for KDAR measurement / 10 times higher pion production**
Beam Power	0.8 MW	1.0 MW (designed)	**More intense beam**
Beam Pulse	600 us, 120 Hz	100 ns (x2), 25 Hz	**300 times less steady-state background for BID**
Capture Nucleus	H (2.2 MeV)	Gd (~8 MeV)	**Shorter capture time, higher signal to ratio**