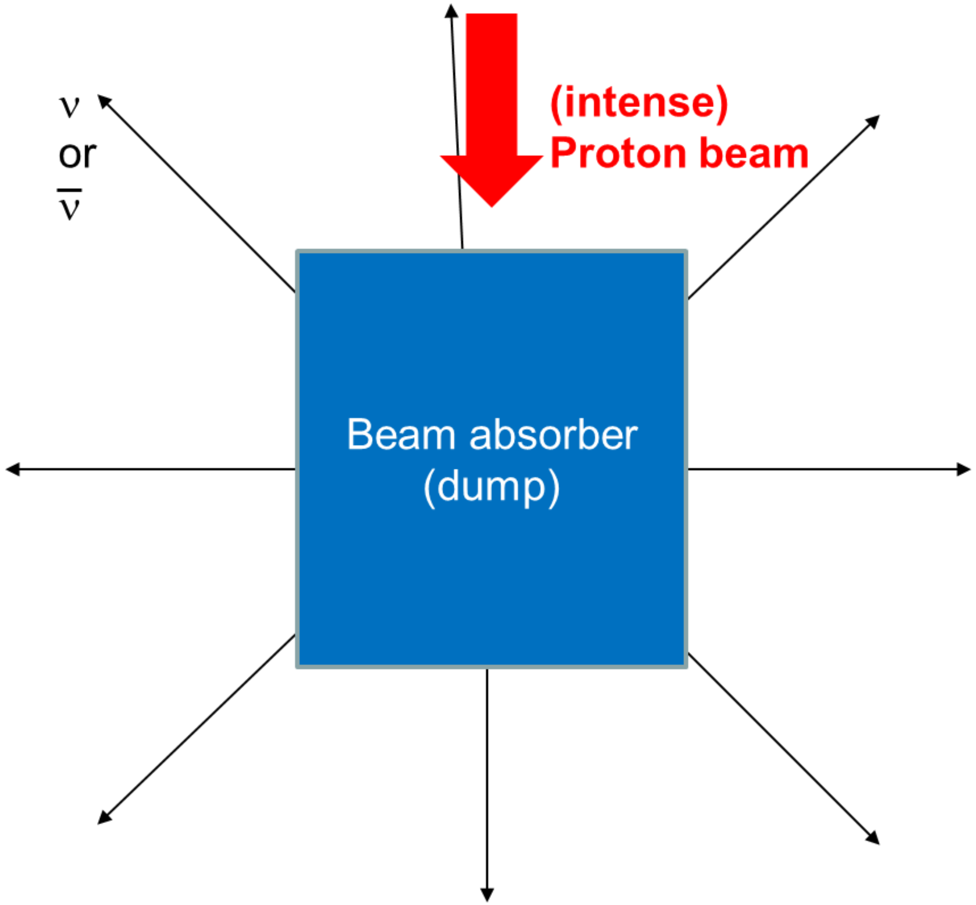
Measurements and searches with Decay-At-Rest neutrinos produced at J-PARC MLF

Takasumi Maruyama (KEK)

Introduction

- Neutrinos produced by Decay-At-Rest (of π, μ, K) are useful tool for the nuclear / particle physics.
  - O(10) MeV neutrinos are useful to understand the super-nova physics, for example.
  - O(100) MeV neutrinos are useful to understand the systematic uncertainties of neutrino interactions which are used for the neutrino oscillation measurement.
  - Also useful to search for the short baseline neutrino oscillations.
- They have well known energy due to 0 momentum of parent particles.
- They have well known $1/r^2$ dependence of neutrino fluxes due to isotopic decays.
- Minus charge parent particles such as π^- are absorbed by nucleus.

- (one disadvantage is the small neutrino flux compared to the horn focused beam).



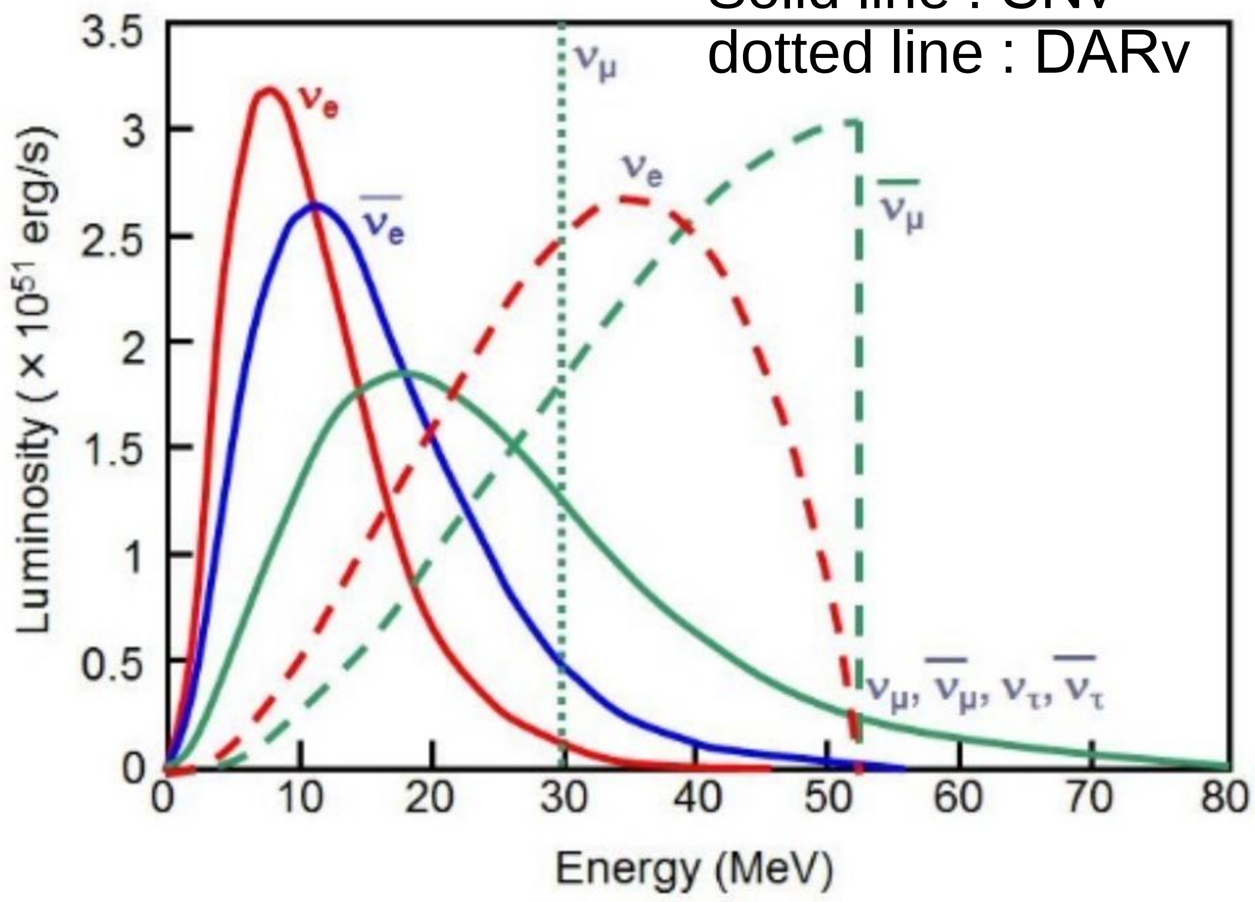
World DAR sources

Facility	country	Beam	Beam power	Beam energy	Time structure	target
ISIS	UK	Proton Syncrotron (PS)	0.16 MW (@ KARMEN)	0.8 MeV	50Hz (2 bunches)	Ta-D_2O
SNS	US	PS	~1.7 MW	~1.3 GeV	60Hz (1 bunch)	Liquid Hg
MLF(J-PARC)	Japan	PS	1.0 MW	3.0 GeV	25Hz (2)	Liquid Hg
CSNS	China	PS	0.1 MW	1.6 GeV	25Hz (2)	Ta cladded W
ESS	Europe (Sweden)	Linac	5.0 MW	2.0 GeV	--	W (Tungsten)
Los Alamos	US	Linac + dump	0.64 MW	0.8 GeV	--	H2O
Iso-DAR	?	cyclotron + dump				

→ Generally, facilities for neutron (not neutrino) spallation source also give the good DAR neutrinos.
→ DARs using other accelerators are also available, however duty factor of the Linac case is much worse than PS case. (typically more than 100)
→ SNS has a few results on cross sections of the coherent neutrino scattering.

Example of application : SuperNova(SN)ν and DARν

Solid line : SNν
dotted line : DARν



Neutrinos from μ-DAR have a few tens of MeV ;

-> similar range with SNν

-> Measurements of those DARν can also be useful for detection and evolution study of SNν

Example: Measurements of ν-A cross section

Reaction	Neutrino Source	Accuracy
$^{12}C(\nu_e,e^-)^{12}N_{gs}$	Accelerator DAR ν	~10%
$^{12}C(\nu_e,e^-)^{12}N^*$	Accelerator DAR ν	~15%
$^{12}C(\nu,\nu')^{12}C(1+1)$	Accelerator DAR ν	~20%
$^{12}C(\nu_e,e^-)^{13}N$	Accelerator DAR ν	76%
$^{56}Fe(\nu_e,e^-)^{56}Co$	Accelerator DAR ν	37%
$^{71}Ga(\nu_e,e^-)^{71}Ge$	RI (^{51}Cr)	11%
$^{127}I(\nu_e,e^-)^{127}Xe$	Accelerator DAR ν	33%

As seen here, DAR ν plays important role obviously.

For the SN physics, good measurements of “various ν-A interactions” are crucial.
-> There have been measurements for various ν-A cross-section
    -> **still uncertainties are large**

J-PARC neutrino experiments using Decay-At-Rest Neutrinos

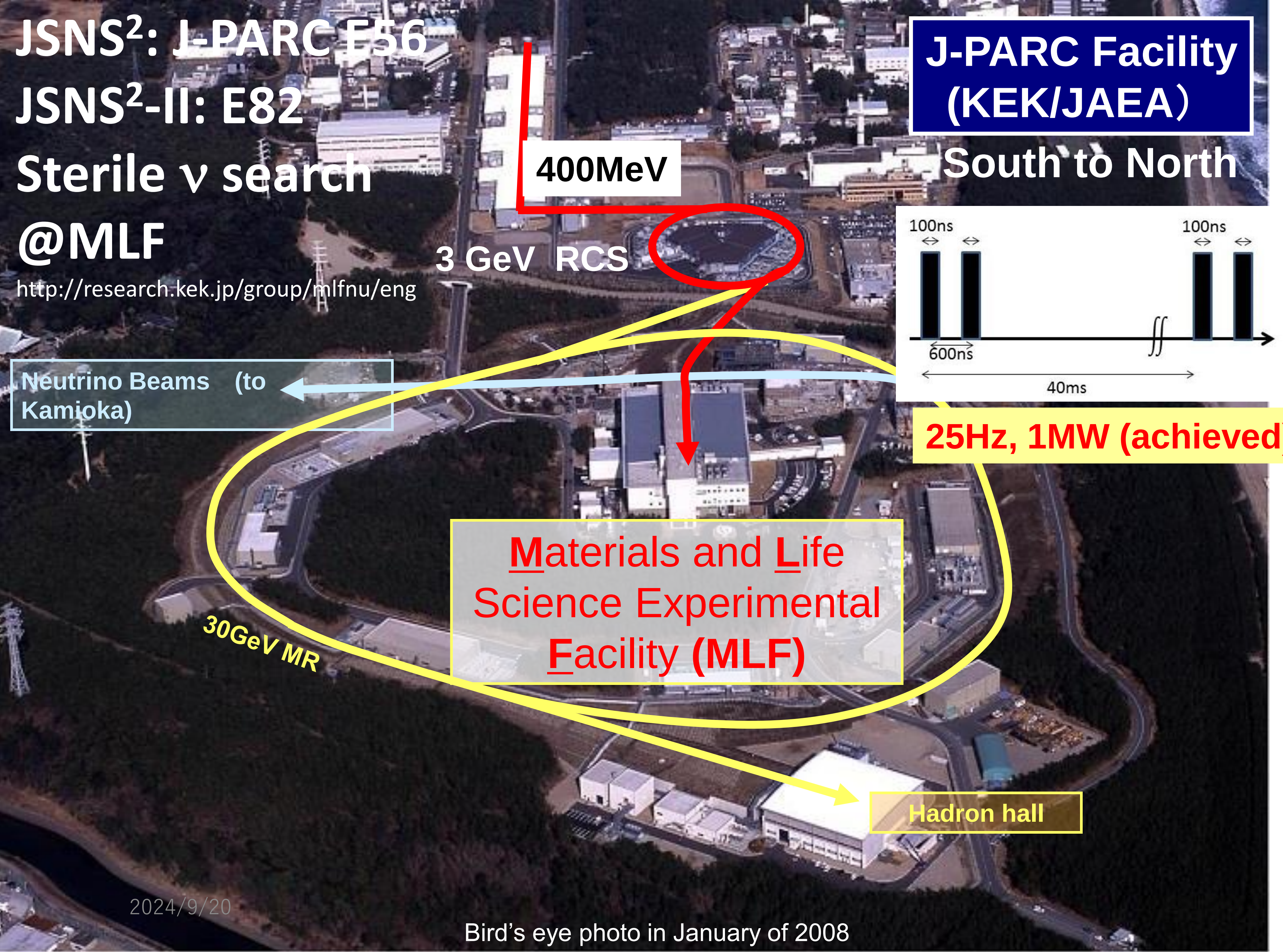
→ Generally, facilities for neutron spallation source also give the good DAR neutrinos.

→ J-PARC Material and Life science Facility (MLF,Japan) is one of the best facility to get such neutrinos.

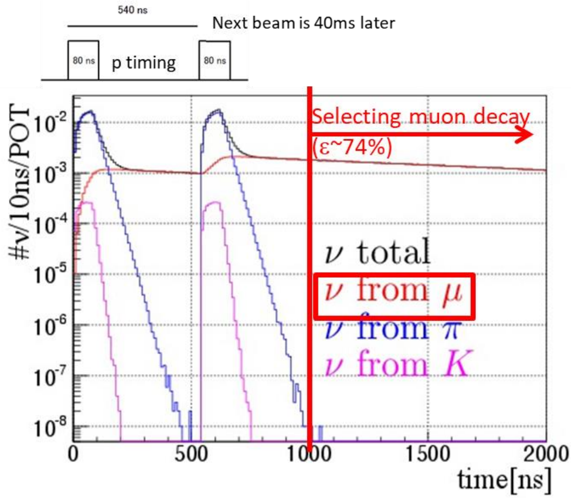
→ Sterile Neutrino Search (**JSNS^2, JSNS^2-II**)

→ Pb-ν cross section measurement (one test experiment)

→ Some coherent scattering measurements.. (under proposals)

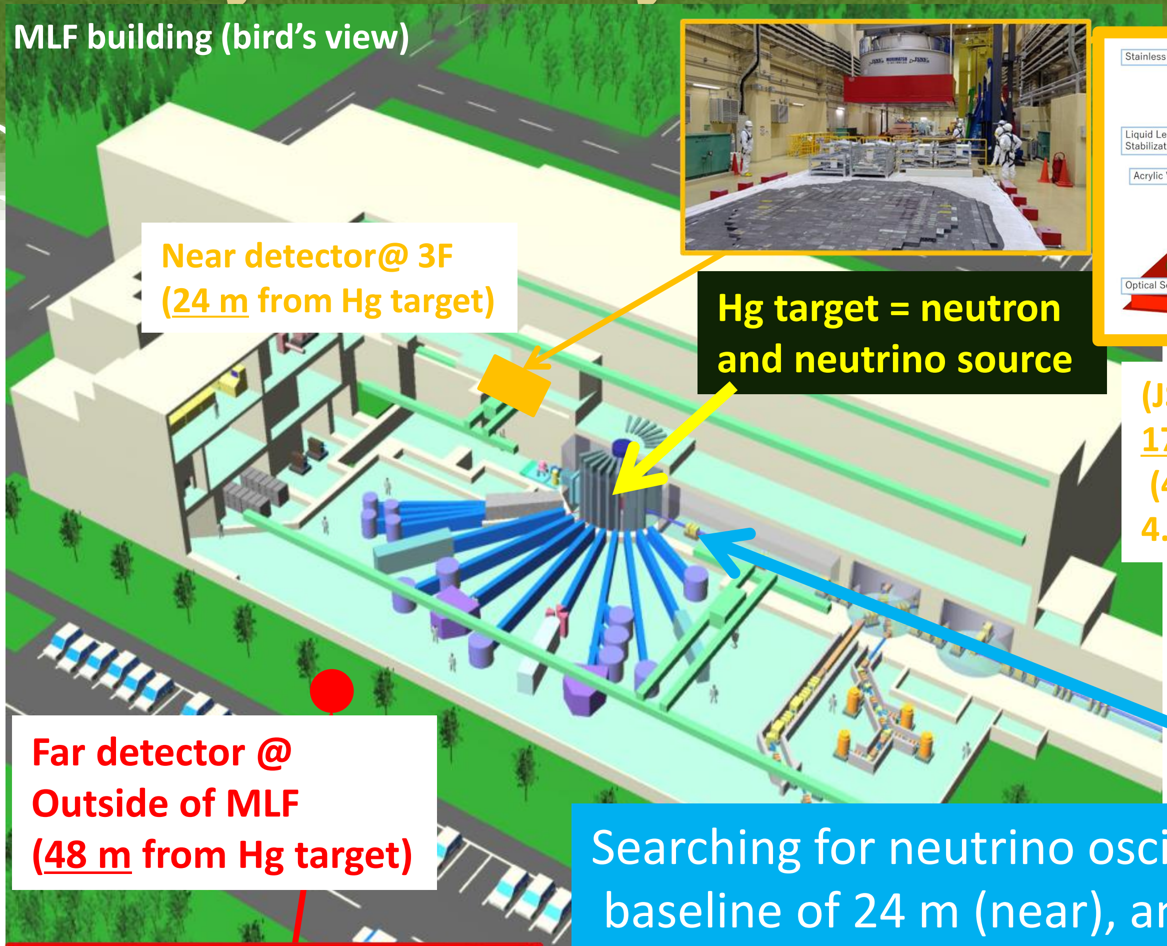


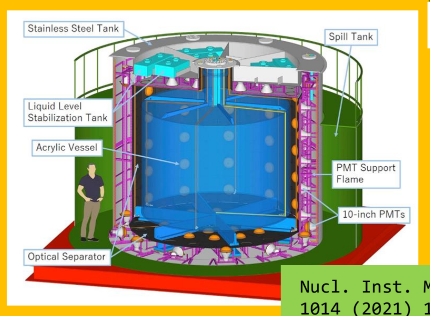
Low duty factor beam (short pulse + low repetition rate) gives excellent S/N ratio.



0.95 MW operation at MLF
(1.0 MW at RCS)
in 2024 April-May !

JSNS^2 and JSNS^2-II : Neutrino experiments using DAR



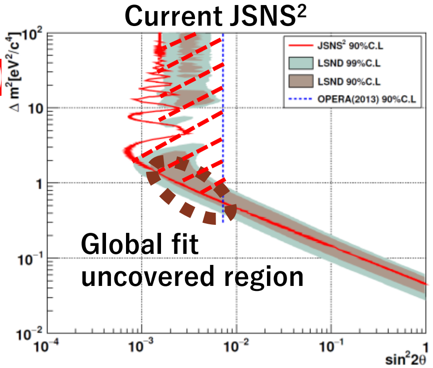


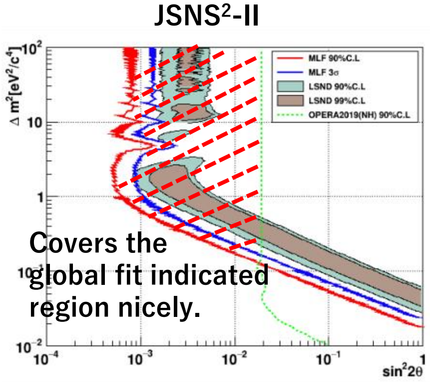
Nucl. Inst. Meth. A 1014 (2021) 165742

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

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)





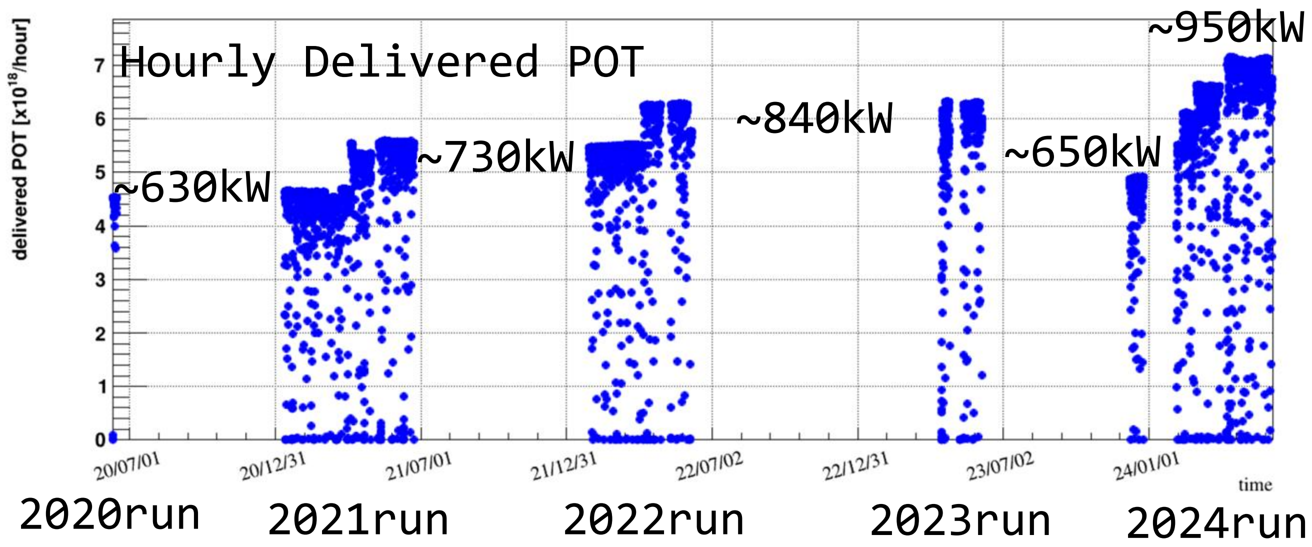
(JSNS^2):1 MW x 3 y(near only)

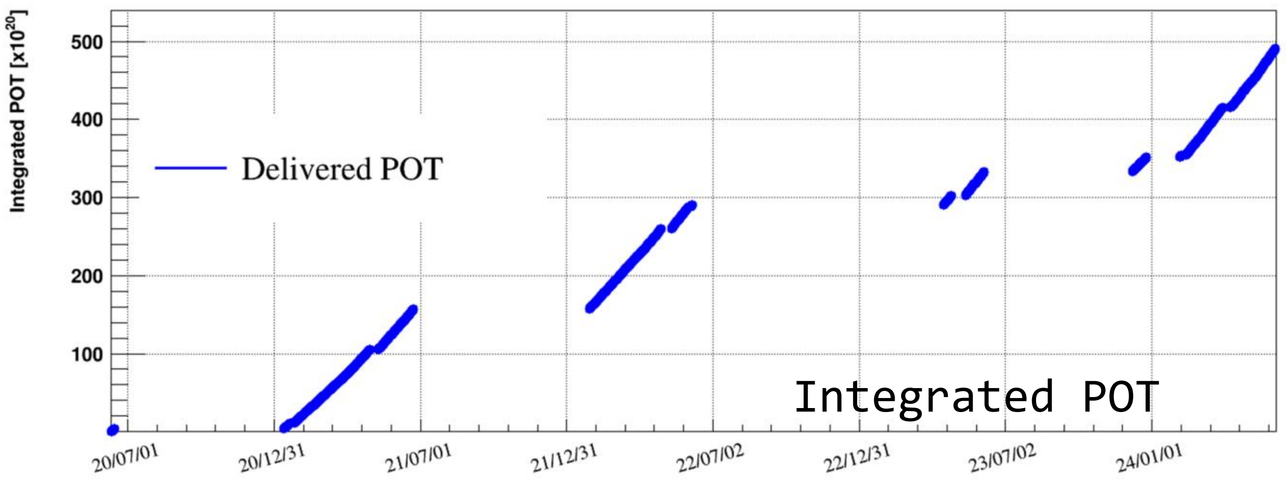
- Commissioning (2020) and four long term physics runs (2023-2024)
- Continue the physics runs
- Analyses are on-going.

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

- Proposed in 2020
  - New far detector: fiducial 32 tonnes and 48 m location.
  - Good sensitivity on low Δm^2 region.
  - Two detectors with two different baselines -> a solid conclusion on LSND anomaly.
  - J-PARC/KEK granted the stage-2 approval in 2022.
  - Construction is almost completed. (now LS was already filled in this summer.)
  - Data taking coming soon!

Beam power and Proton-On-Target (POT) (2020~2024) for JSNS²





- Beam power
  - Achieved the designed values. (1.0MW @ RCS)
  - Also 0.95 MW at MLF during 2024 April – May.
- POT
  - Total 4.85 x 10^{22} POT has been accumulated
  - 42.5% of approved POT for JSNS² (with single detector)

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

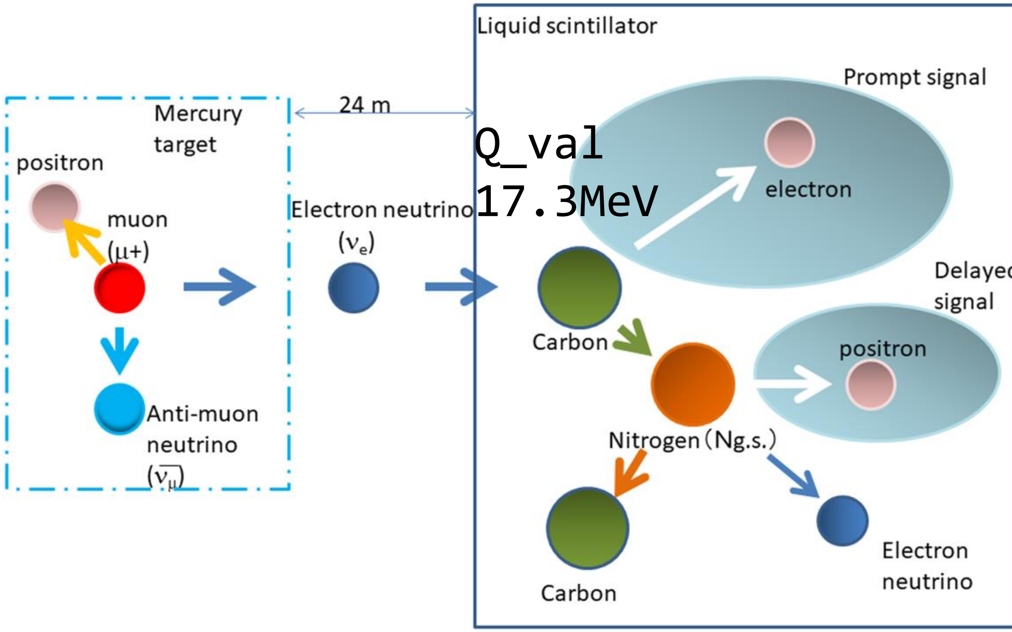
Motivation to measure $^{12}C(\nu_e,e^-)^{12}N_{g.s.}$ (CNgs) reaction

- **The number of μ^+ can be estimated by CNgs.**
  - parent particle: $\mu^+ \to e^+ + \boxed{\nu_e} + \boxed{\bar{\nu}_\mu}$

    CNgs   Sterile search
- No π/K production measurements on Hg+3GeV proton so far → in-situ measurement
- CNgs: $^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}_{g.s.}$

  $^{12}\mathrm{C} + \boxed{\nu_e} \to e^- + {}^{12}\mathrm{N}_{g.s.} \Longrightarrow {}^{12}\mathrm{N}_{g.s.} \to {}^{12}\mathrm{C} + \nu_e + e^+$ lifetime: ~16 ms, Emax=16.8MeV
  - prompt: electron, delayed: positron
  - reaction of ν_e (neutrino)

    * CNgs is useful to **understand neutrino flux**



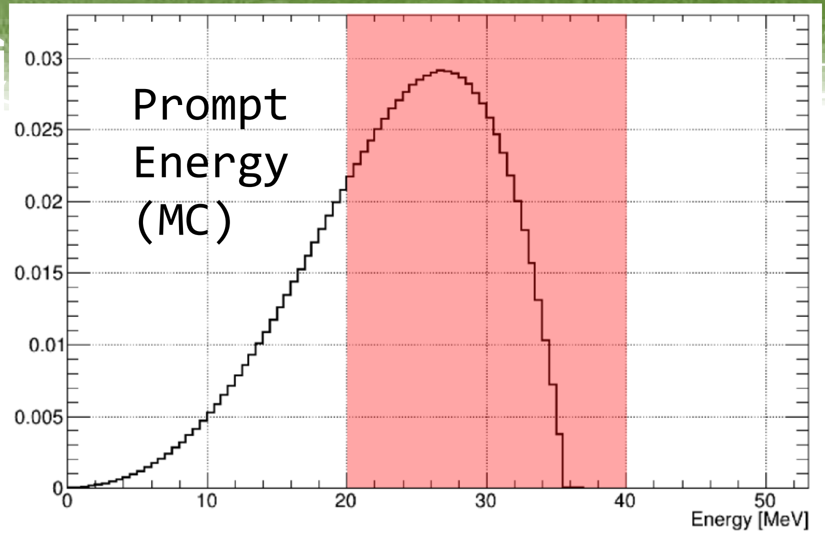
- If production rates of π are measured externally, we can also measure the cross section of this reaction
- From energy spectra, we could search for neutrino oscillations from CNgs

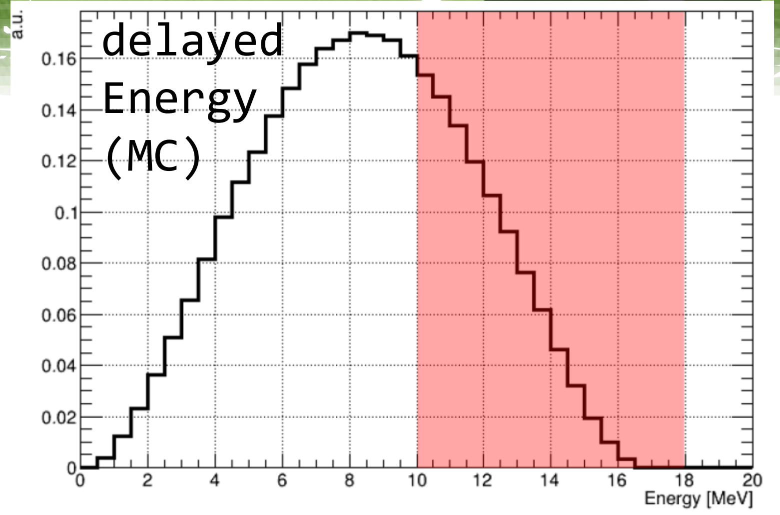
Selection criteria for CNgs

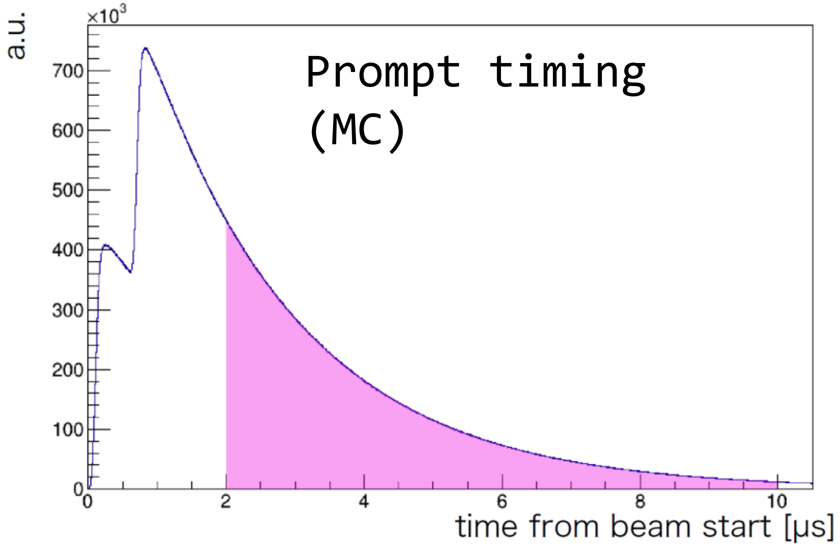
$$P_e E_e (E_{\text{max.}} - E_e)^2 \frac{2\pi\eta}{e^{2\pi\eta} - 1}$$

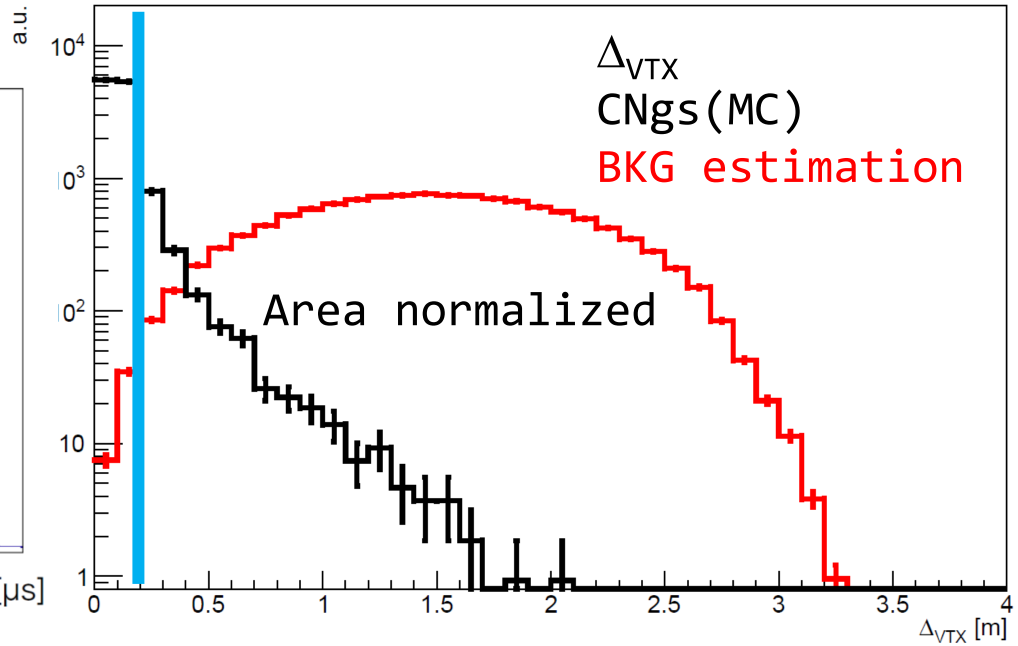
$$\eta = \frac{Z\alpha}{\beta_e}$$

- Energy
  - Prompt: 20<E<40 MeV
  - Delayed: 10<E<18 MeV
- Timing
  - Prompt: $2<T_{beam}<10$us
- Prompt vs delayed
  - Spatial correlation: Δ_{VTX} < 20cm (most crucial cut)
  - Timing: 0.2<ΔT<12,25ms (12ms : 2021 25ms : 2022 determined by trigger capability)
- Muon / Michel e veto
- Fiducial cut : |Z|<100 && R<140cm



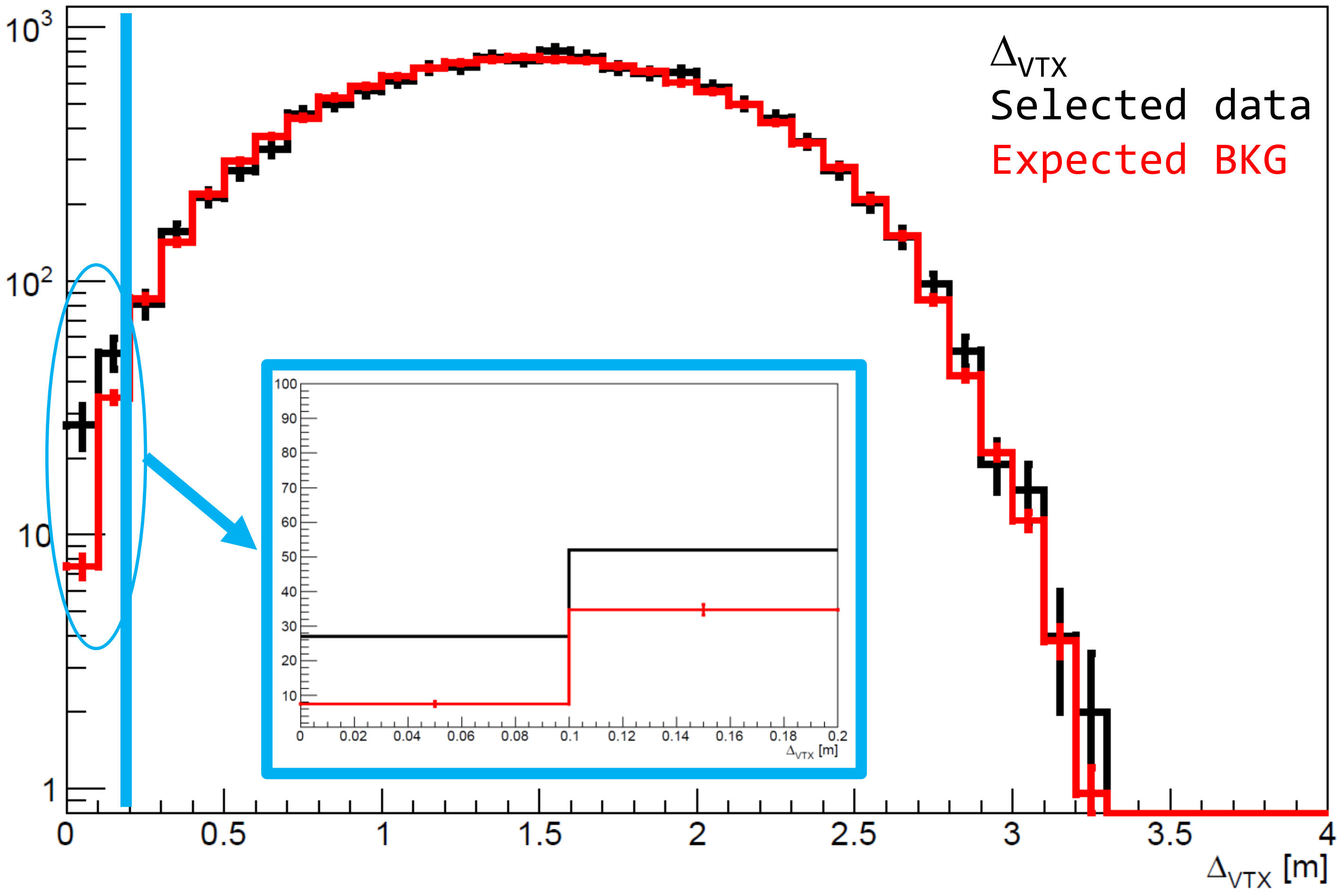






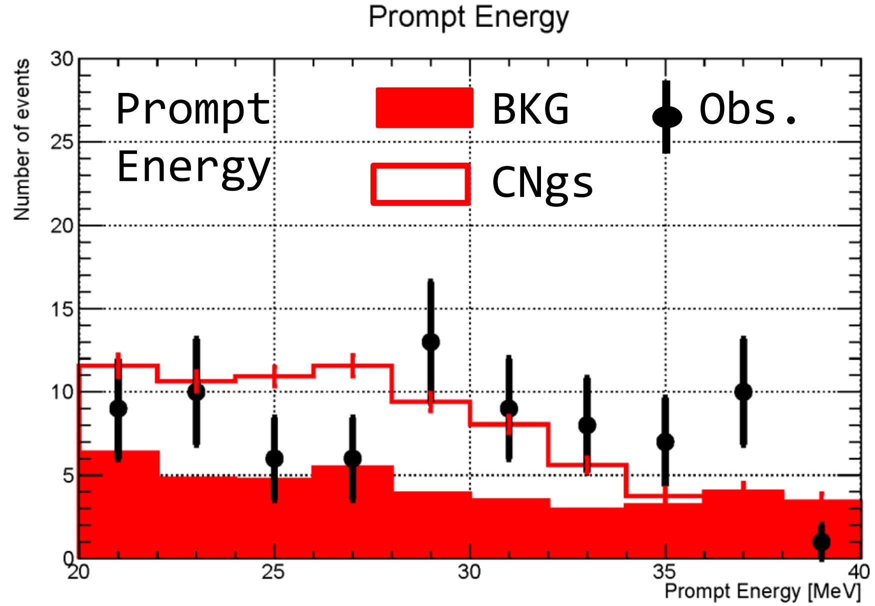
CNgs : selected data

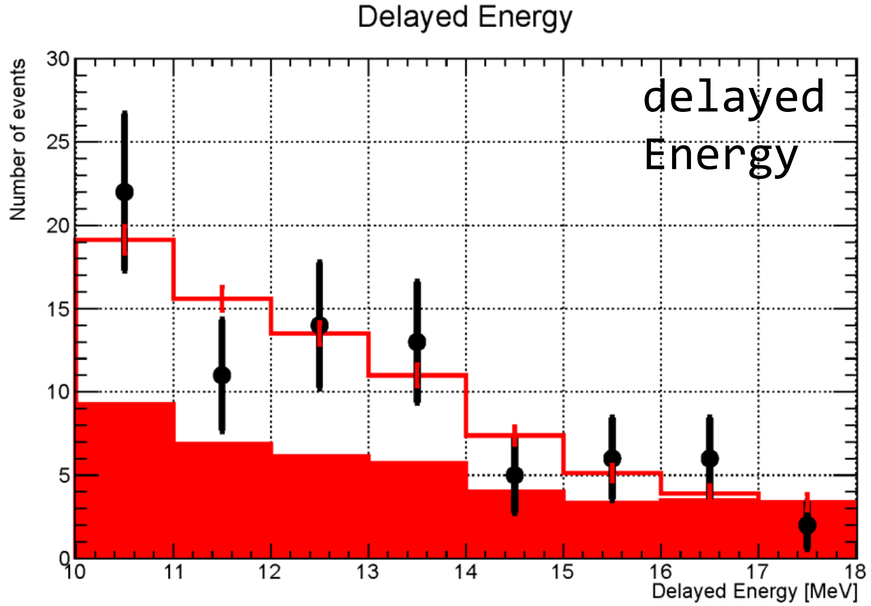
- 2021-2022 data
  - 2.20 x 10^{22} POT
- Clear excess is seen in signal region.
  - 79 events are observed.
  - 42.2+-4.8 (BKG, including syst.)
  - p-value: 2.9 x 10^{-7}
  - More than 6 sigmas

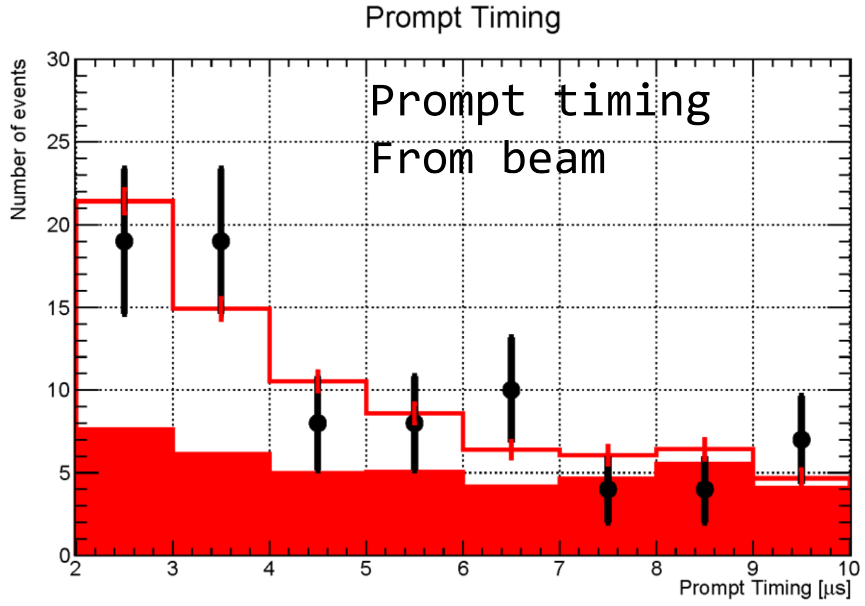


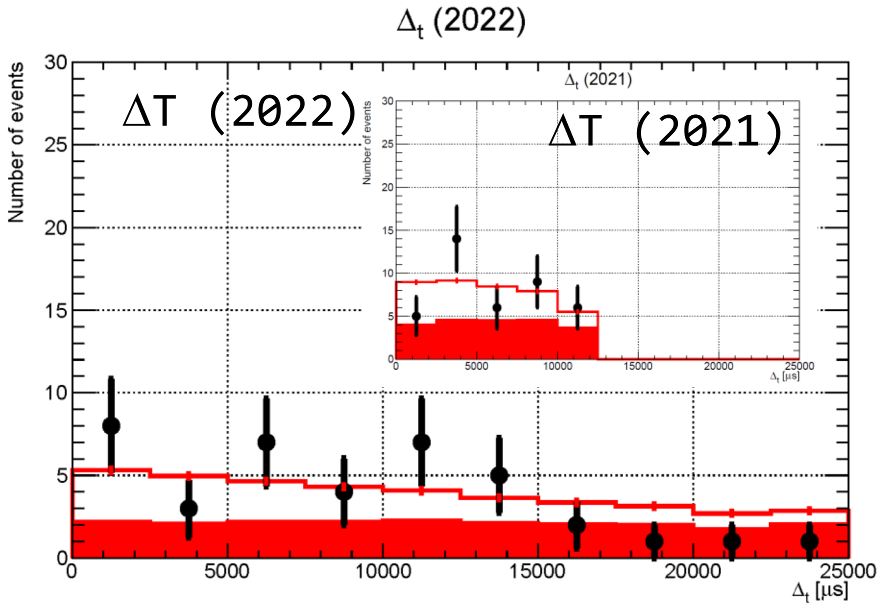
Variables

- All distributions for selected variables seem to be reasonable.
  - 36.8+-10.2 CNgs events
  - (42.2+-4.8 events for background).
- Successfully observed O(10MeV) neutrinos!!





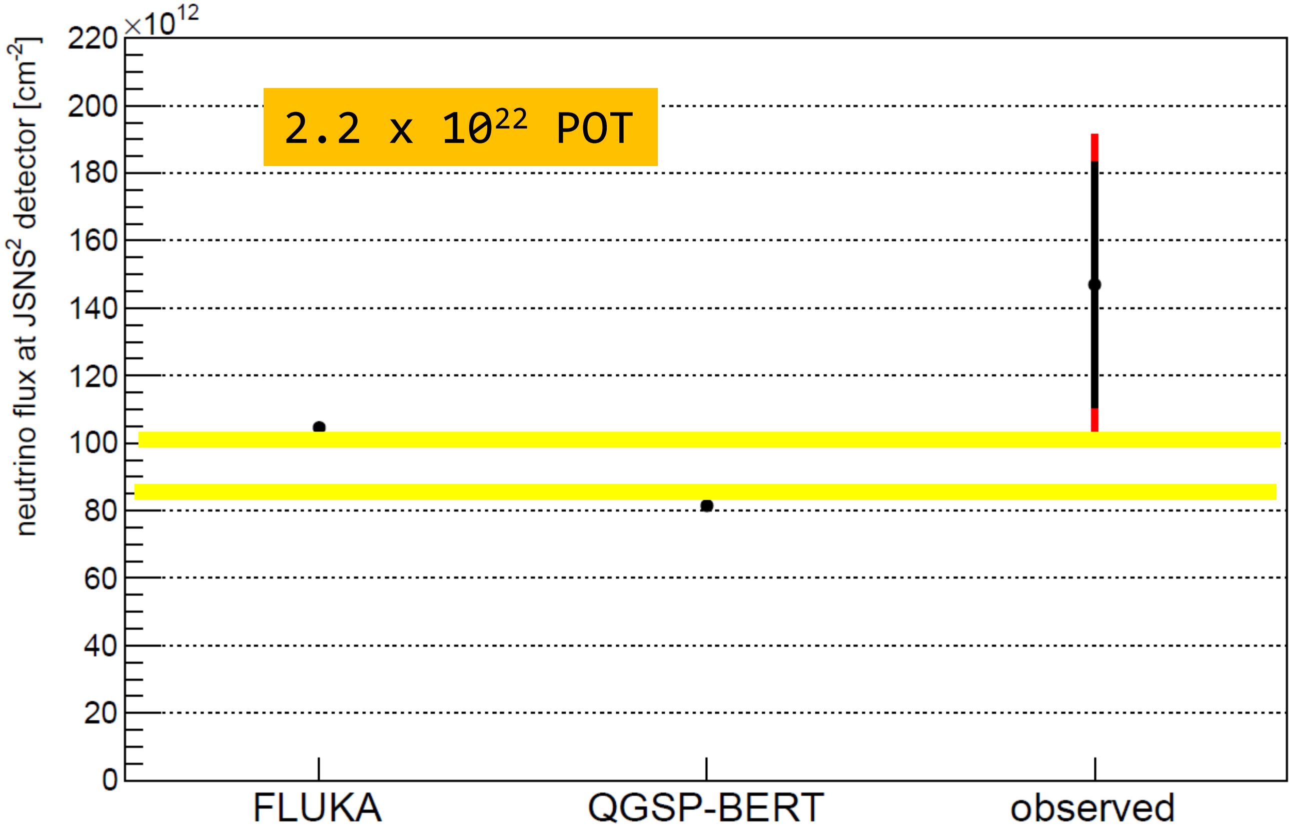




Interpretation to neutrino flux

- 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+-0.36(stat)+-0.26(syst)) x 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.



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

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

Interpretation to pions/proton and plan

- (0.48+-0.14)μ^+/proton from this measurement.
  - Much higher production rates compared to ISIS / LAMPH due to proton energy and target.
  - ISIS (KARMEN) : 0.0448+-0.0030 π^+ / proton
  - LAMPF (Los Alamos) : 0.084-0.090 μ^+ / proton

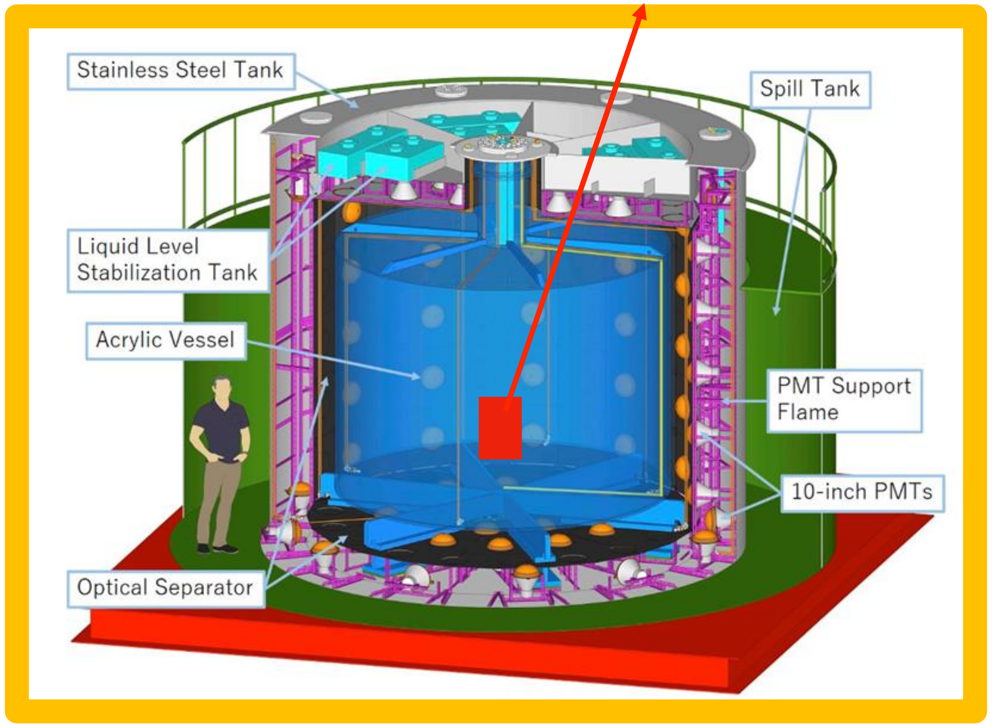
- Once the production rate measurements of π^+ production (between 3 GeV p and Hg) was done, a precise cross section measurement of CNgs can be done.
  - We have more than 10 times POT in JSNS^2 and JSNS^2-II.
    - 2 times data compared to this results in our hand already.
    - Additional POTs (6.7 times of current one) are approved by KEK/J-PARC.
- (Maybe we can also feed back to the electron neutrino disappearance oscillation)

JSNS2 can be nu-A factories?

Just private consideration now

A nu-A interaction also can be measured by putting **material block** at the center of the detector.

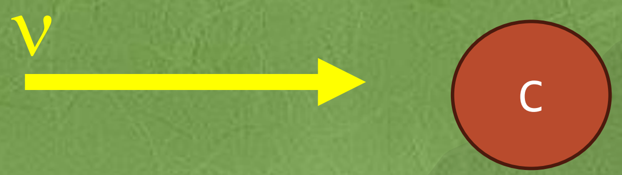
Any materials



JSNS^2 can be ν-A measurement factory ?

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

- → 3 GeV (of proton) is very close to open the production channels of Kaons. (MLF provides a unique opportunity)

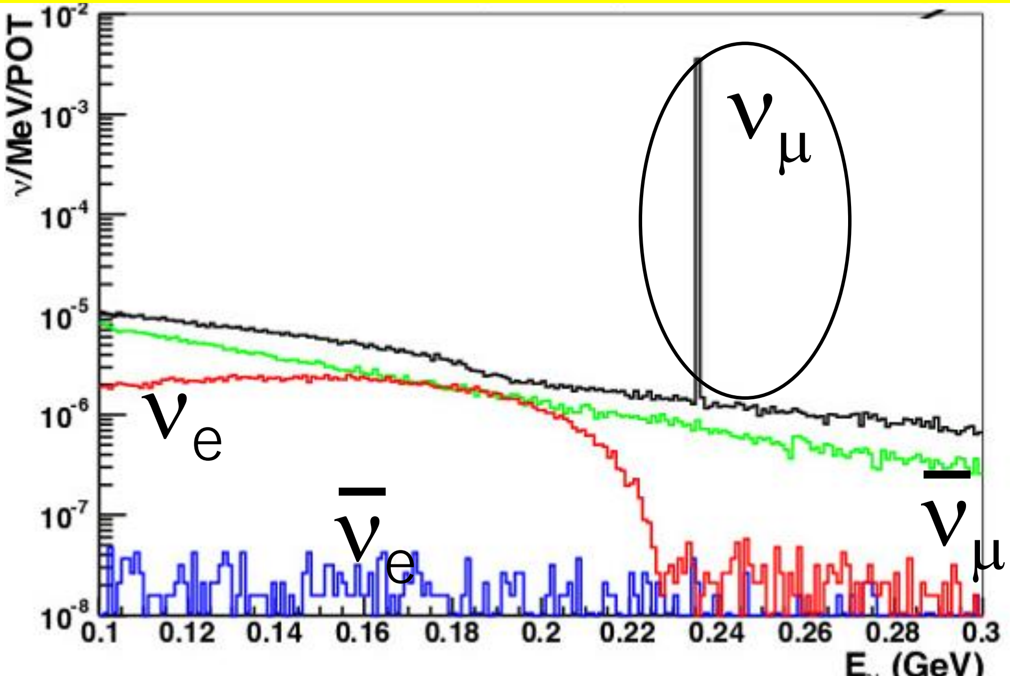


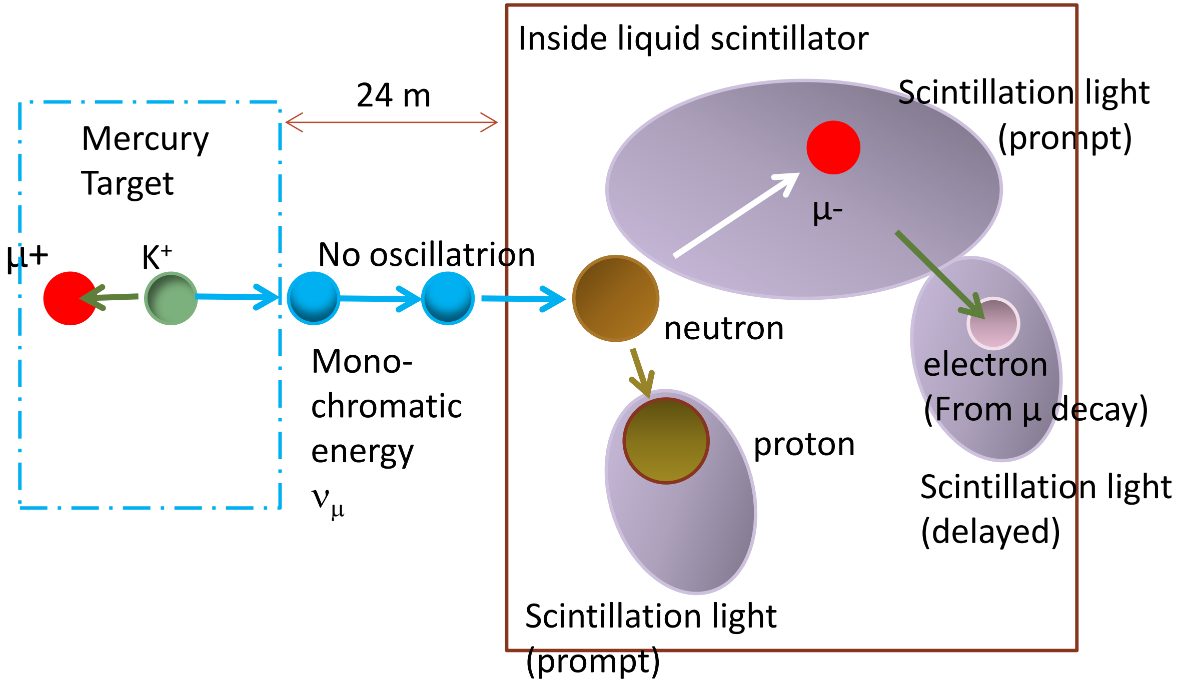
arXiv:2409.01383
(also submitted to PRL)

KDAR (Kaon Decay-At-Rest) ν

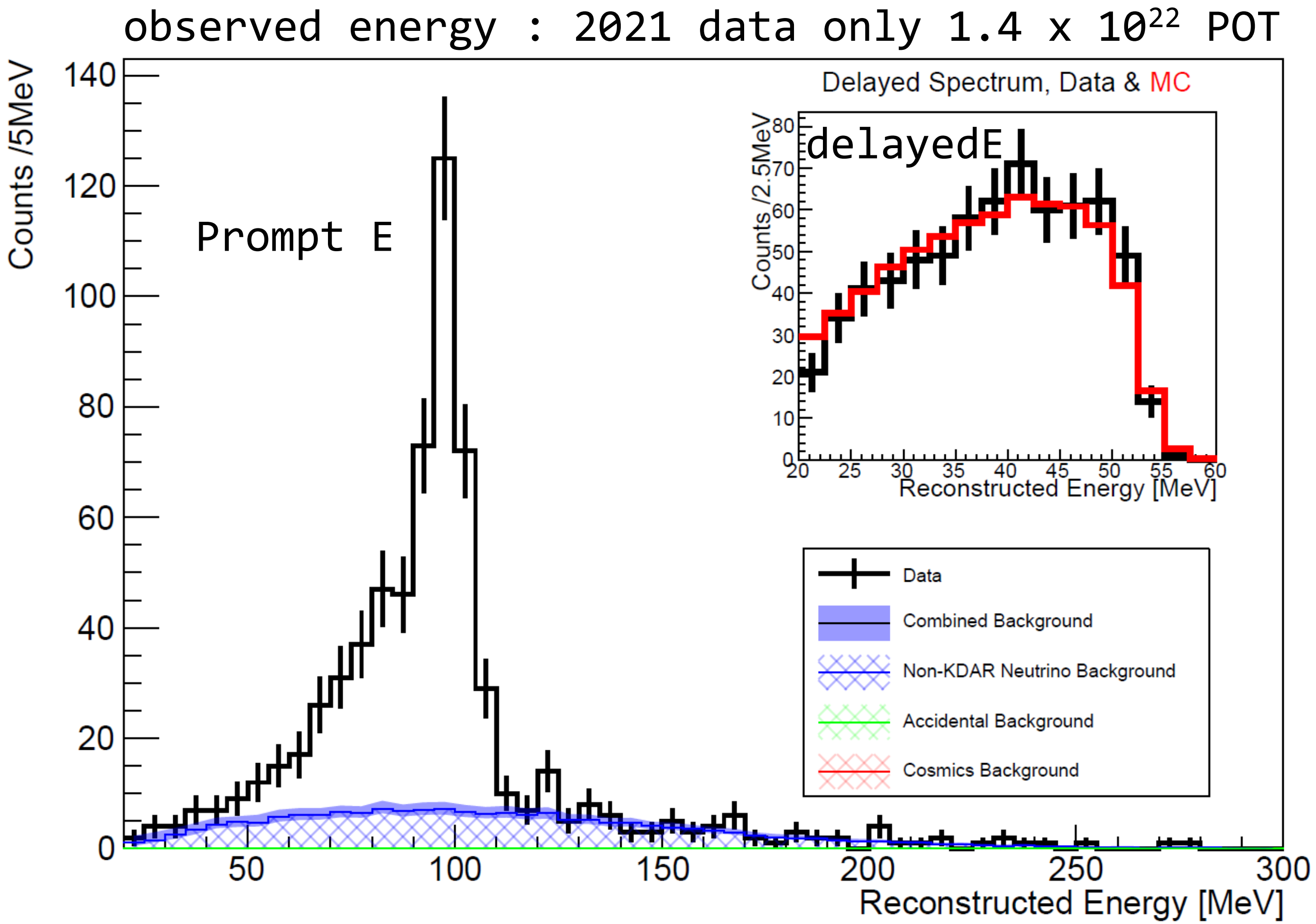
- Mono-energetic muon neutrinos from Kμ2 (decay-at-rest) gives a rare opportunity to investigate the quasi-elastic interactions and their regarding effects from nucleus. (e.g.: Fermi gas model, FSI, etc..)
- In neutrino experiment, the horn focused beam provides wide neutrino energy.

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





Selection / background

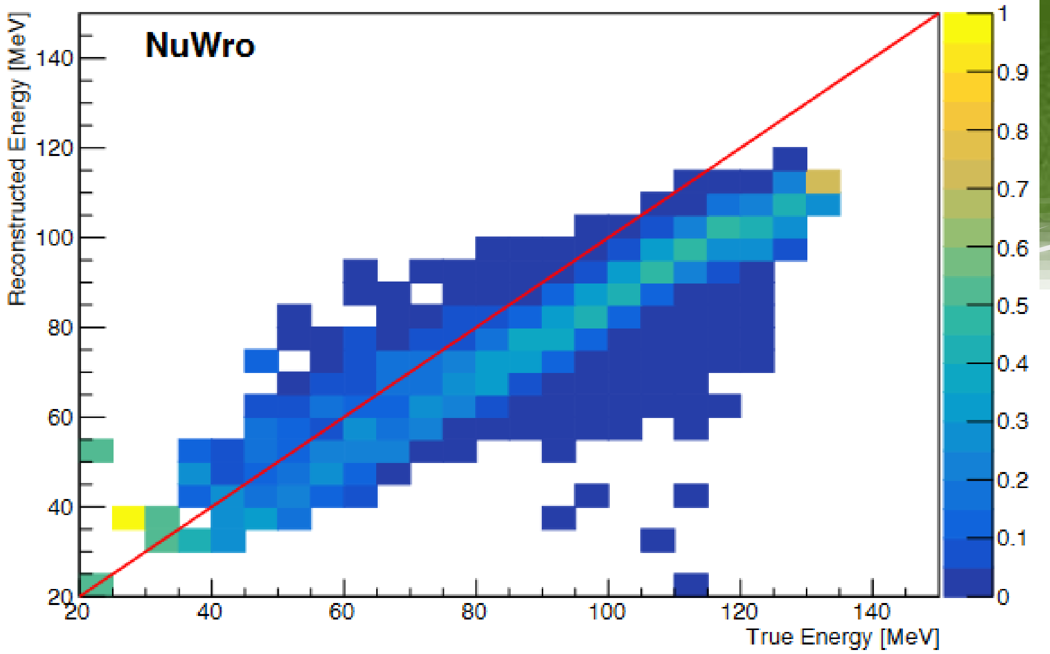


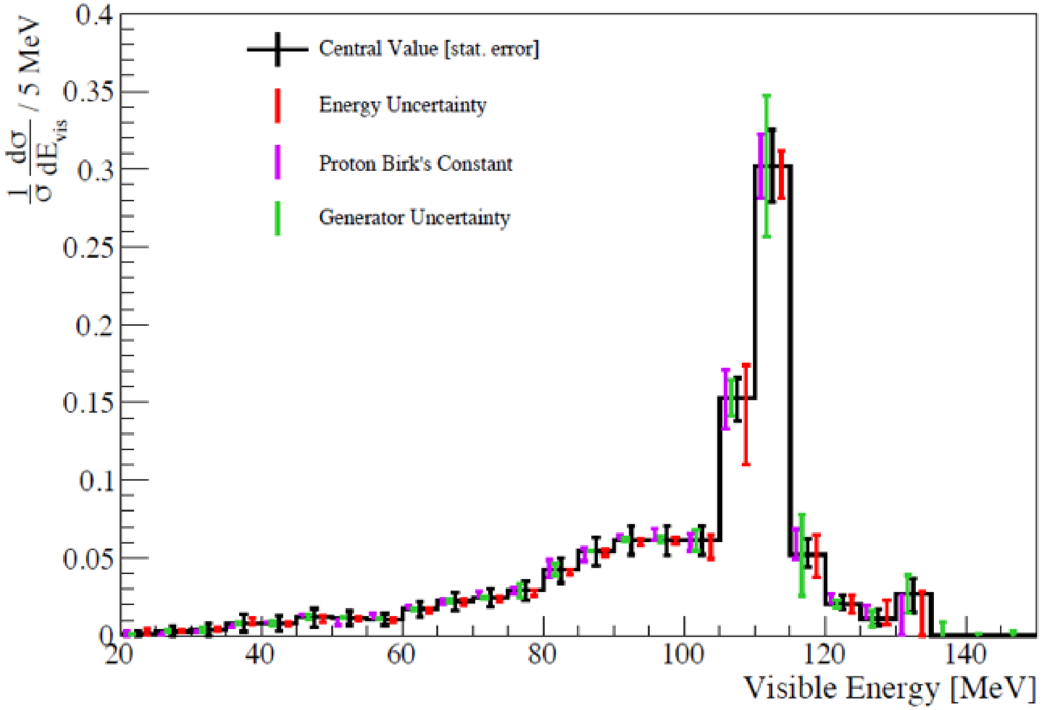
621 selected events
(144+-21 is BKG.)
(20-150MeV)

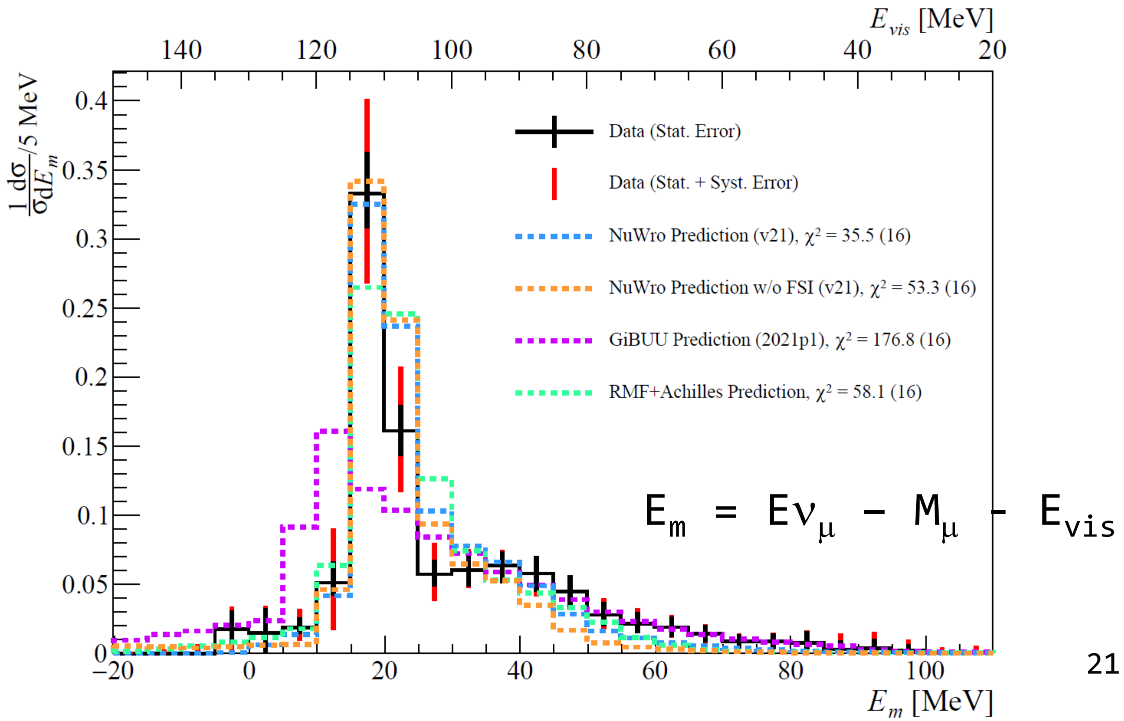
	Prompt	Delayed
Energy	20-150 MeV	20-60 MeV
Timing	2x150ns Beam centered windows	Δt < 10μs
Position	Fiducial Volume: R<1400mm -1000mm < z < 500mm	ΔVertex< 300mm

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)







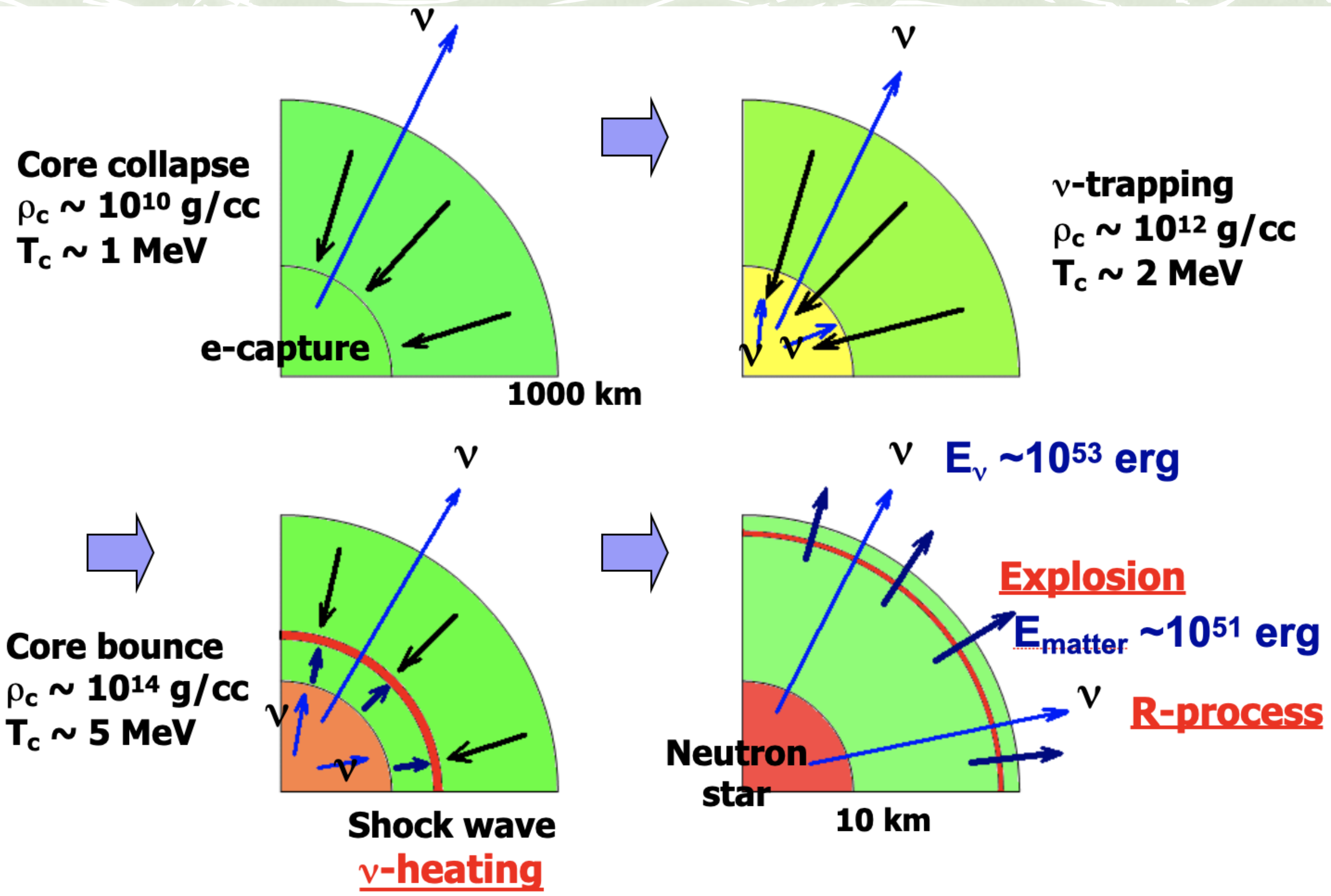
Summary

- Decay-At-Rest neutrinos are useful tool for various physics.
  - Cross section measurements of neutrinos with O(10 MeV) and O(100 MeV) energies.
  - Search for neutrino oscillation with short baseline
- Facilities for the neutron spallation source is potentially good DAR ν sources at the same time.
  - ISIS (UK), SNS (US, ORNL), MLF (Japan, J-PARC), CSNS (China), ESS (Europe), …

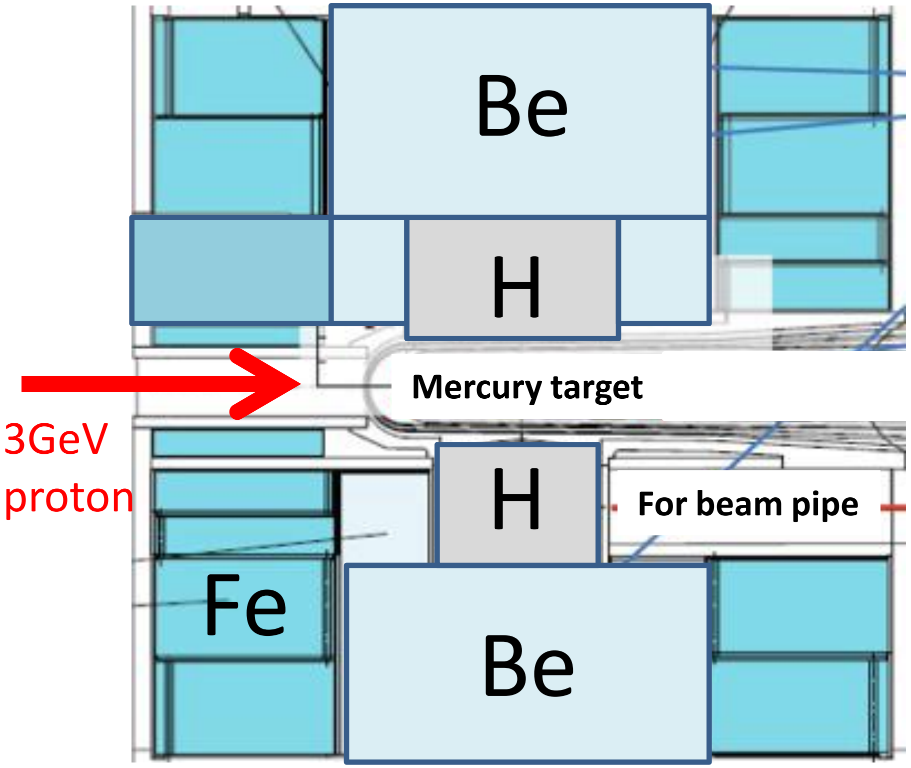
- JSNS^2 (J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source) just began to observe the neutrinos produced by DAR.
- We are taking data. Also a new 48m detector have been built recently. Exciting time continued !!

backup

Core collapse of Supernova



MLF mercury target and Intrinsic $\overline{\nu}_e$ BKG estimation

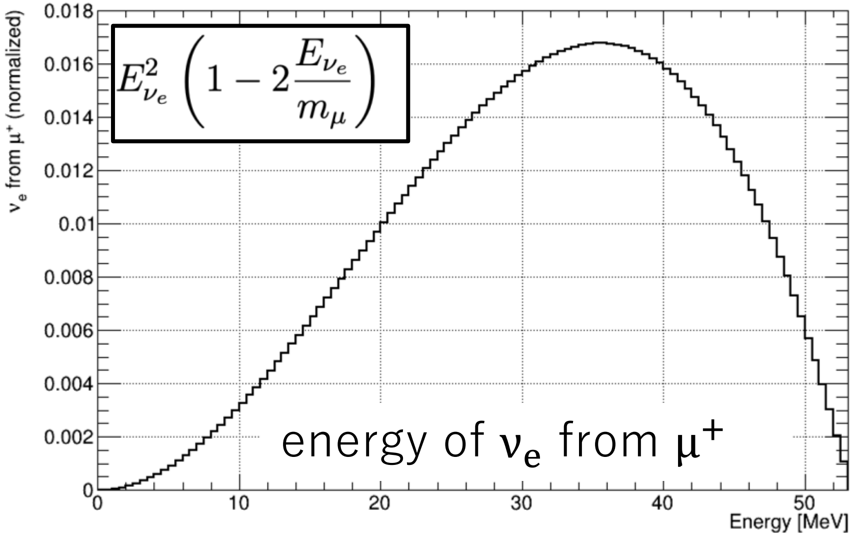


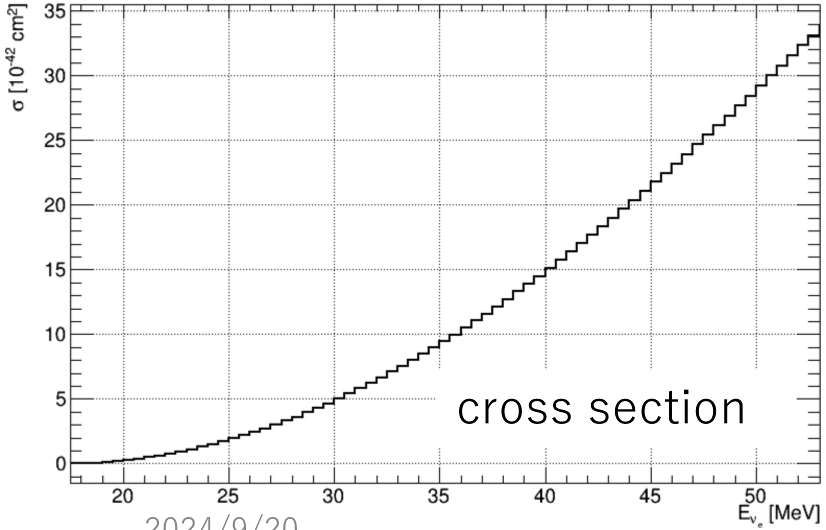
	Target	π^- absorb	μ^- capture	suppression	x	π^-/π^+
LSND	H2O	96%	88%	5×10^{-3}	x	0.13
J-PARC	Hg(+Fe+Be)	99%	~80%	1.7×10^{-3}	x	1.

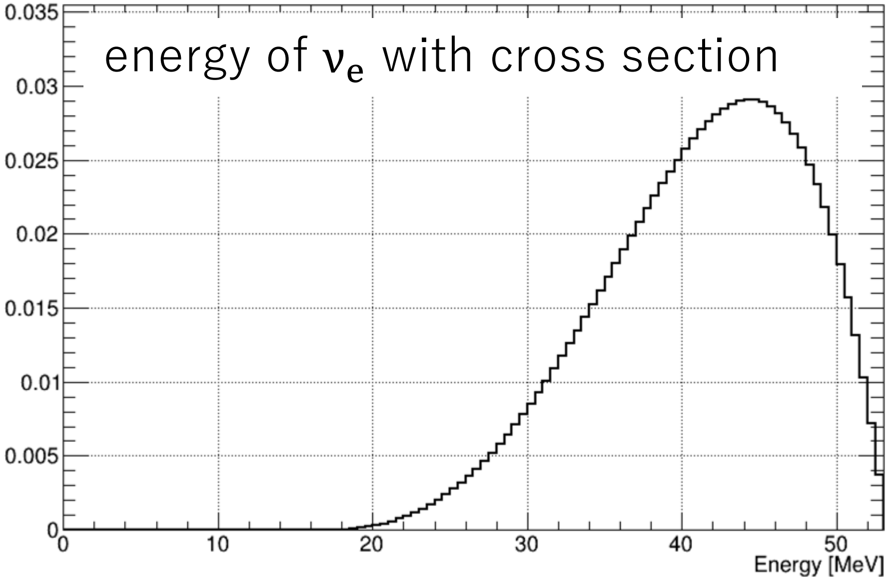
We will assume ~ 1.7×10^{-3} Intrinsic background hereafter.

Prompt energy

- Prompt energy for CNgs is determined by energy of ν_e from μ^+ and cross section.



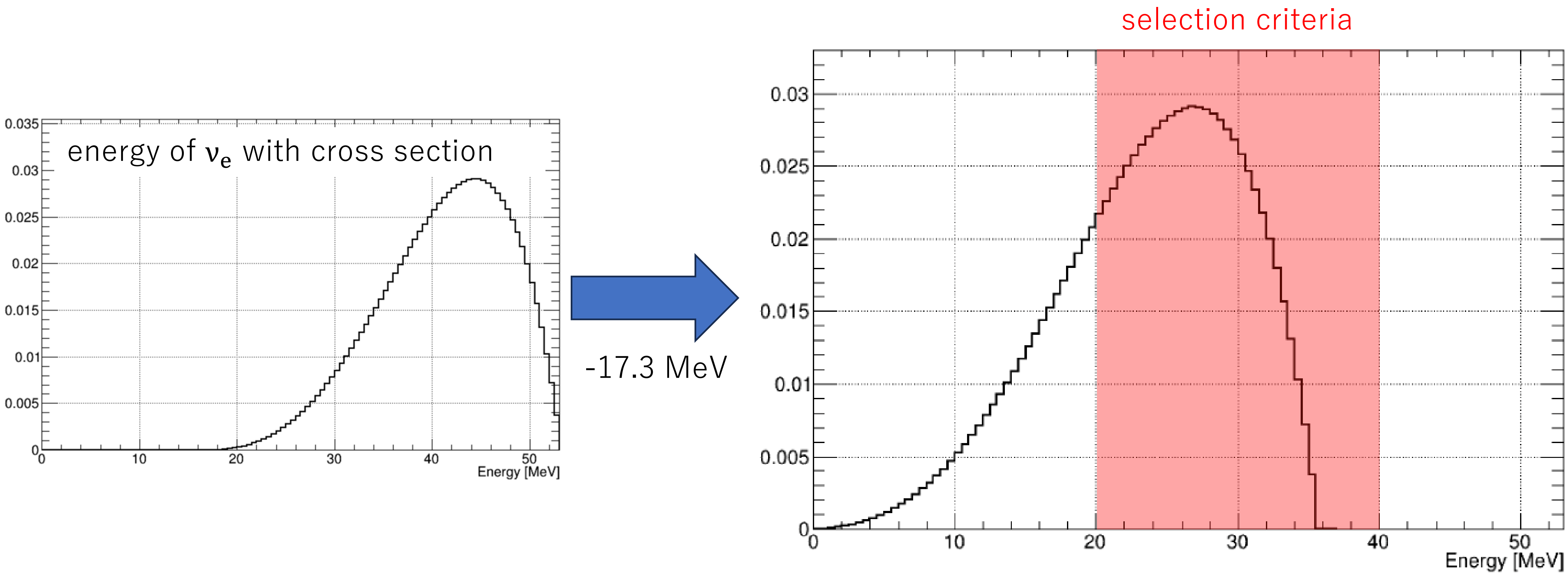




M. Fukugita, Y. Kohyama, and K. Kubodera, "Neutrino Reaction Cross Sections on ^{12}C Target", Phys. Lett. B 212 (1988) 139–144

Prompt energy

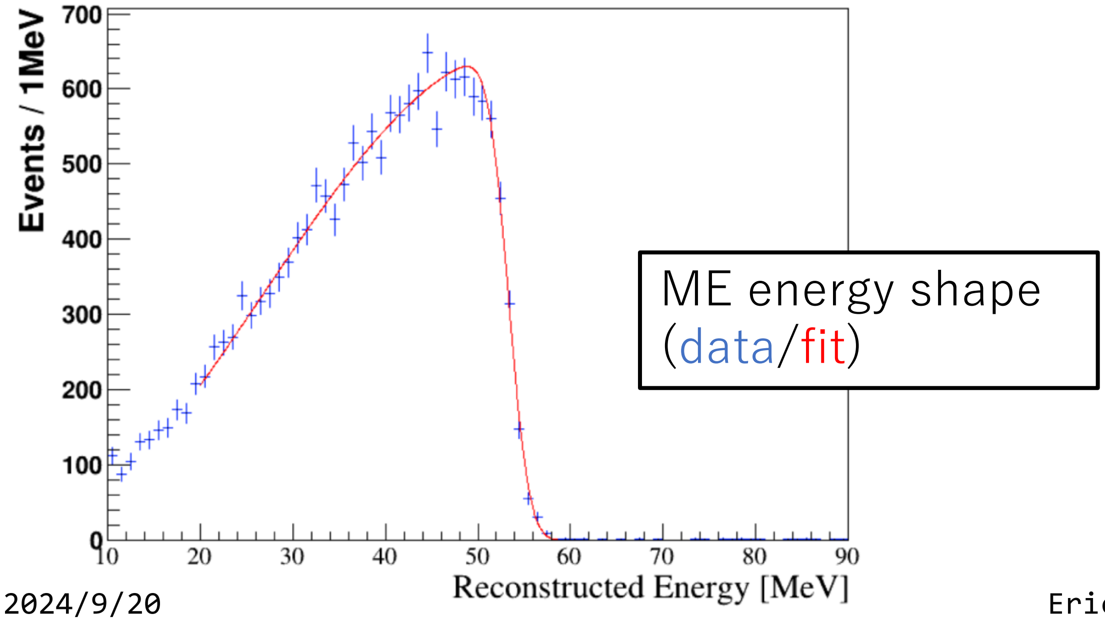
- Q-value of the ν_e-^{12}C reaction is 17.3 MeV.
- Right plot shows the prompt energy from the theoretical formula.

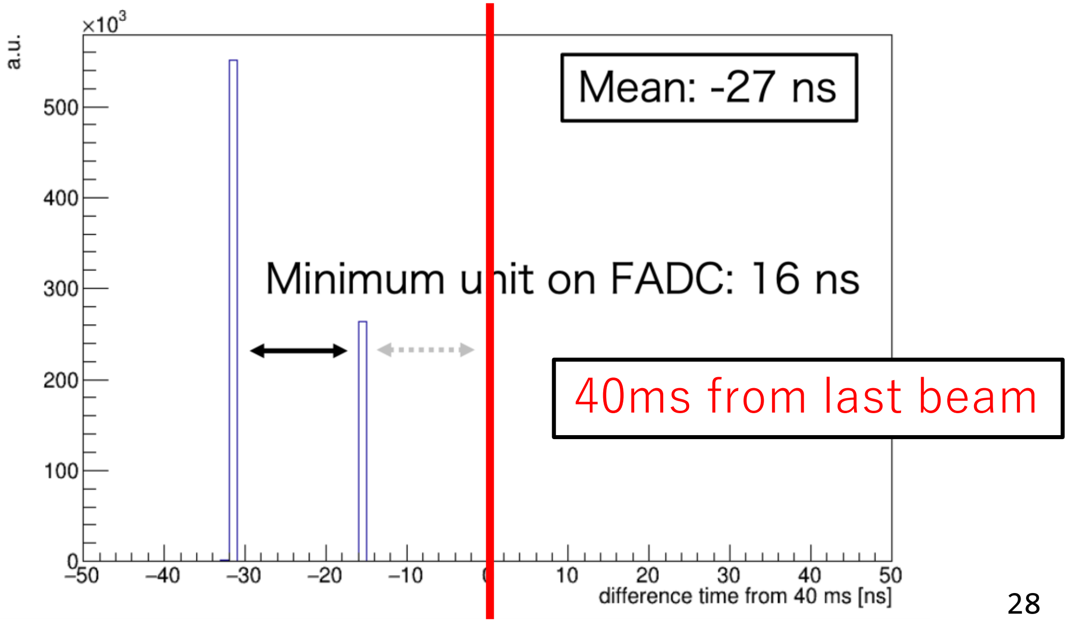


Precise energy and timing calibrations

- We can use n-Gd captured events (~8 MeV) and Michel electrons from μ (~53 MeV)
  - Careful energy calibration can be done for CNgs prompt (20-40 MeV) and delayed (10-18 MeV) events.
- The sources of the systematic uncertainties
  - Time variation, spatial dependence, quenching factor of LS (mainly)
  - Scale error is less than 1%.

- Timing of FADC was calibrated by accelerator RF timing. (every 40ms). → negligible error.





Efficiencies with systematic uncertainties

item		efficiency	error (%)
bkg estimation (MST vs SS)		-	10.7 %
Energy		2021: 0.255 2022: 0.255	2021: 4.6 % 2022: 5.0 %
(FADC) Timing	prompt	2021: 0.498 2022: 0.468	2021: 0.4 % 2021: 0.2 %
	Δ_t	2021: 0.5180 2022: 0.7805	2021: 0.08 % 2022: 0.05 %
muon veto		2021: 0.885 2022: 0.901	2021: 0.4 % 2022: 0.3 %
Michel electron veto	prompt	0.9930	0.01 %
	delayed	0.9768	0.03 %
Δ_{VTX}		0.881	0.8 %
fiducial		- (related to the number of ^{12}C)	8 %

item	value and error
The number of ^{12}C	$(4.68 \pm 0.37) \times 10^{29}$ (PSD fiducial volume)
Cross section	$(9.1 \pm 0.7) \times 10^{-42}$ cm^2

Total selection eff.
2021: 4.97+-0.24%
2022: 7.17+-0.37%

Average: 5.88+-0.21%