23rd International Workshop on NuINT 2022 , Oct 24st - 29th

Status of the KDAR neutrino search with JSNS^2 Experiment

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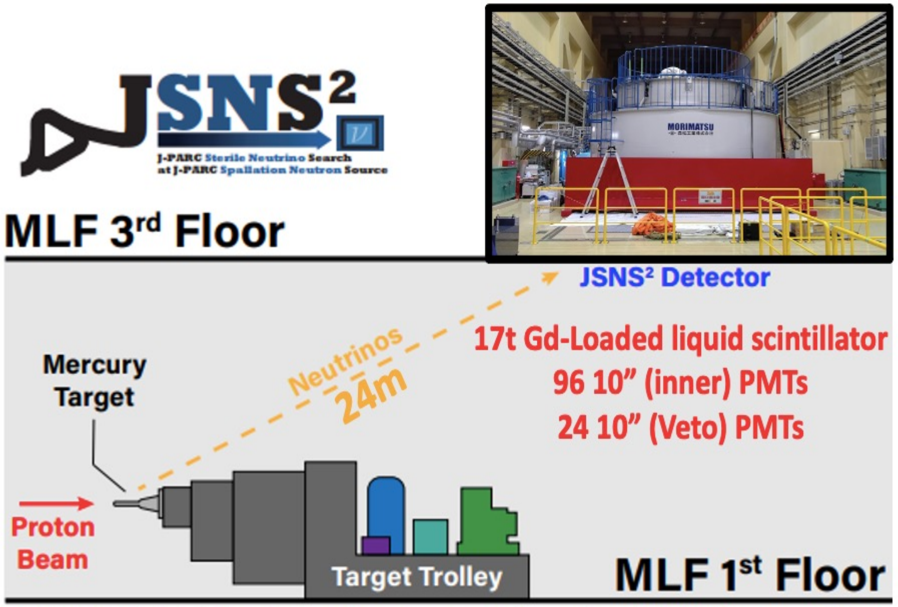
NuINT 2022

Introduction of JSNS^2 experiment


@ 10th JSNS^2 Collaboration meeting (7-9 Feb, 2020)

- The **J**-PARC **S**terile **N**eutrino **S**earch at the **J**-PARC **S**pallation **N**eutron **S**ource (JSNS^2) experiment has started a study of neutrino oscillations with $\Delta m^2 \sim 1\ eV^2$ from anti-muon neutrinos to anti-electron neutrinos detected via inverse beta decays(IBD) which are tagged via gammas from neutron captures on Gadolinium.

- JSNS^2 is the only experiment that can directly test the LSND anomaly without having to rely on theoretical scaling assumptions.



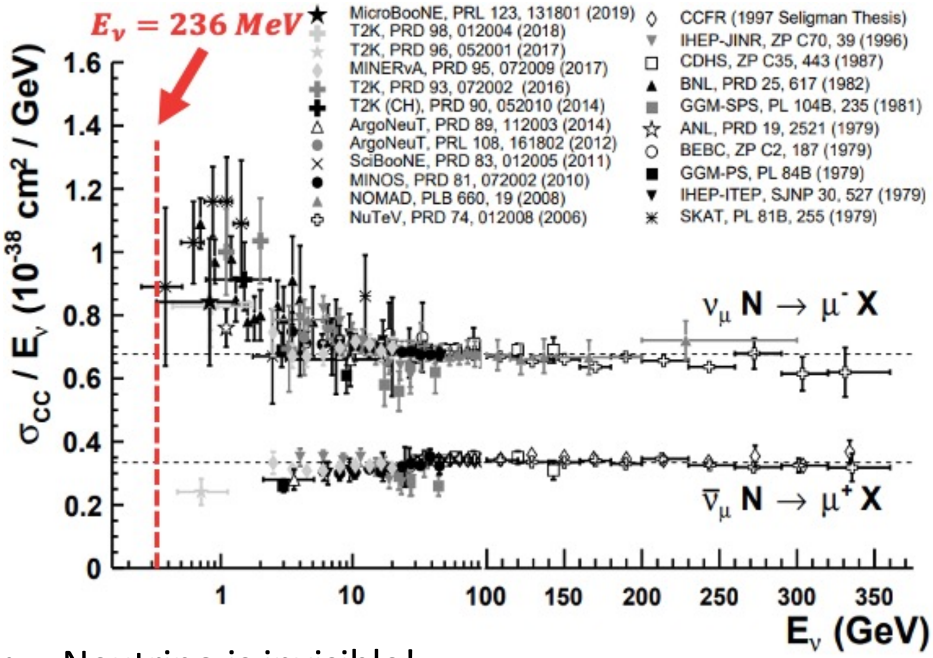
J-PARC MLF : Ideal environment for the JSNS^2 experiment

- The J-PARC MLF 3 GeV primary proton energy is sufficient to produce kaons efficiently. In consideration of the facility's beam intensity (eventually 1 MW, currently 0.7 - 0.8 MW), represents the best facility in the world to accomplish KDAR analysis.

- **We expect to make a more precise measurement of the Kaon Decay-At-Rest (KDAR) neutrino interaction cross-section.**

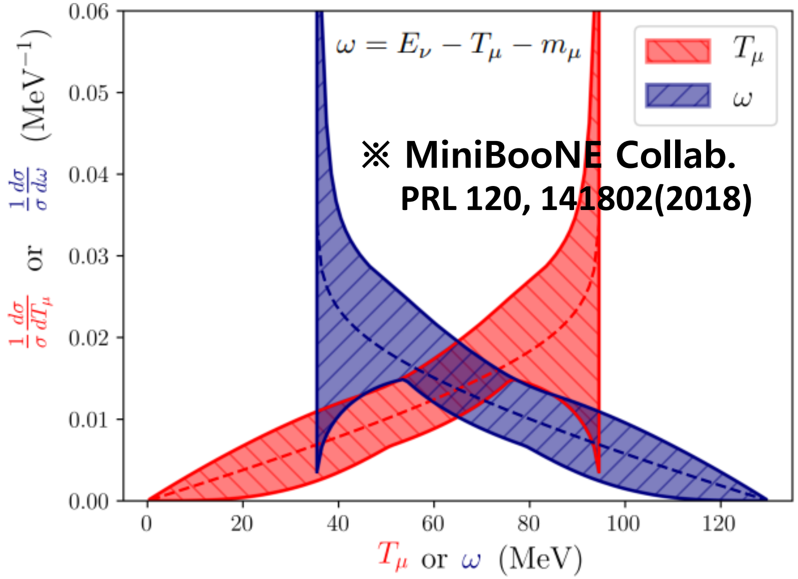
- **We will be able to measure the visible energy spectrum of KDAR primary event for the first time.**

Motivation



- Neutrino is invisible!
  → We can only detect when they interact.
- Neutrino cross section at low E is poorly known.
  1) Knowing neutrino energies is difficult.
  2) Hard to model and reconstruct.
- But the case of KDAR Neutrinos,
  1) Monoenergetic energy (236 MeV)
  2) CCQE : Relatively simple interaction process.

Shape-only differential cross sections in terms of T_μ and $\omega(\nu - n\ energy\ trasfer)$ with 1σ error bands.



※ MiniBooNE Collab.
PRL 120, 141802(2018)

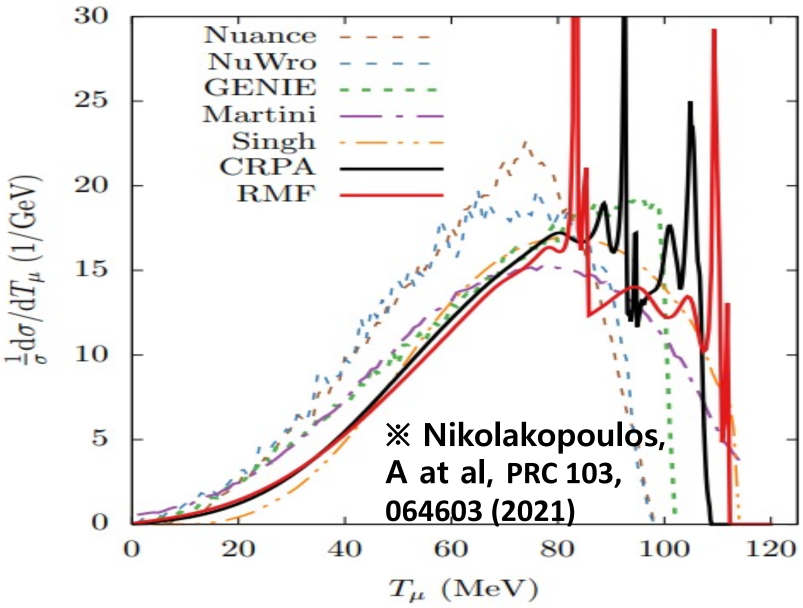
- Recently, MiniBooNE measured the KDAR neutrinos for the first time.

Total ν_μ CC cross section at $E_\nu = 236$ MeV:
$(2.7 \pm 0.9 \pm 0.8) \times 10^{-39}\mathrm{cm}^2/\mathrm{neutron}$

- Shape-only differential KDAR cross sections was measured in terms of energy.
  → Due to High Decay-In-Flight (DIF) backgrounds rate.
- JSNS^2 is expected make a better shape-only cross section measurement.

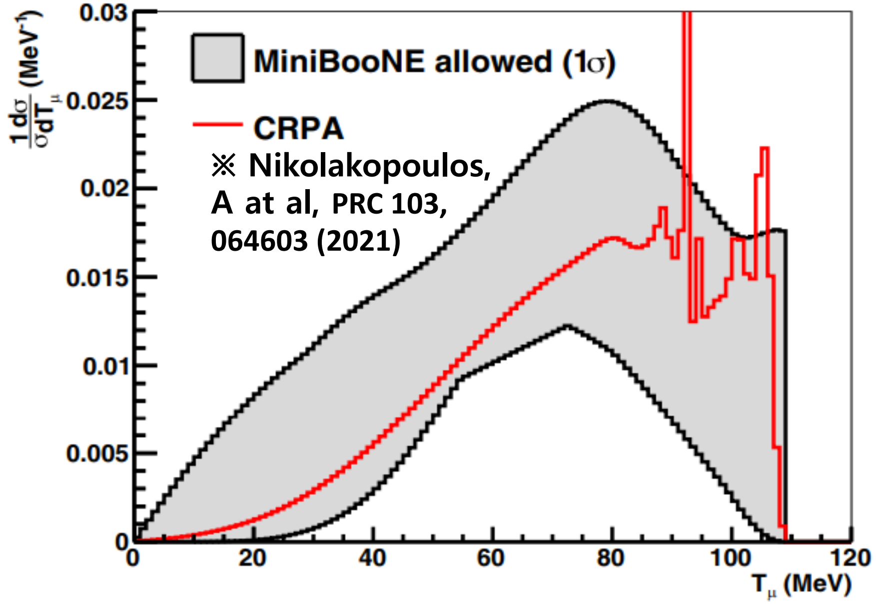
Motivation

KDAR for the various nuclear models



※ Nikolakopoulos, A at al, PRC 103, 064603 (2021)

MiniBooNE result with a prediction



※ Nikolakopoulos, A at al, PRC 103, 064603 (2021)

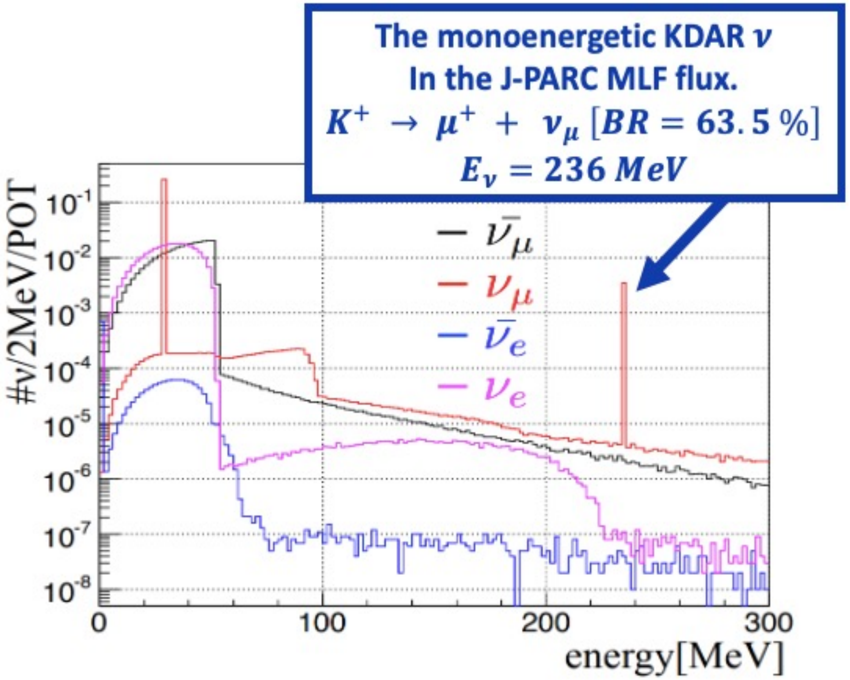
- Electron scattering has been the dominant tool for understanding the nucleus so far.
- We can probe the nucleus through neutrino.

- But the difficulty is,
  1) Knowing neutrino energies is difficult.
  2) The transition region between neutrino-nucleus and neutrino nucleon scattering are hard to model.

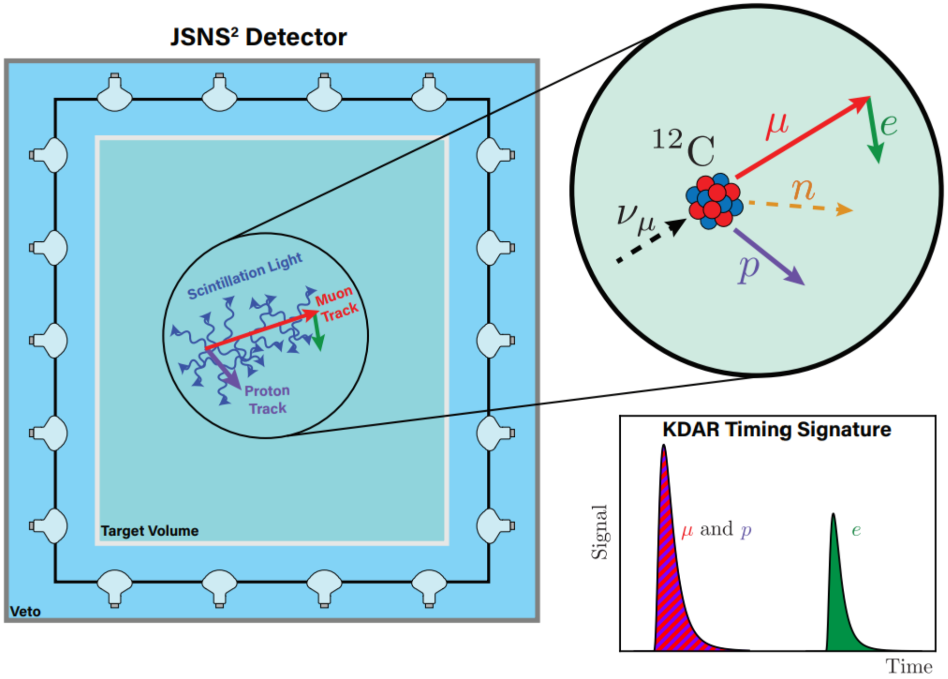
- One golden way: KDAR Neutrinos
  1) Known energy (Monoenergetic neutrino)
  2) Right at the transition between neutrino-nucleus and neutrino nucleon scattering

KDAR : What are we measuring?

※ **JSNS² TDR** arXiv:1705.08629



The monoenergetic KDAR ν
In the J-PARC MLF flux.
$K^+ \rightarrow \mu^+ + \nu_\mu\ [BR = 63.5\ \%]$
$E_\nu = 236\ MeV$



- When charged kaons decay at rest, they can produce monoenergetic neutrinos from the two-body decay.

$$K^+ \rightarrow \mu^+ + \nu_\mu\ [BR = 63.5\ \%]$$

- In the case that the kaon is at rest when it decays, the emitted muon neutrino is monoenergetic.

$$E_\nu = 236\ MeV, \qquad E_{vis} = E_\nu - m_\mu(106\ MeV)$$

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

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

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

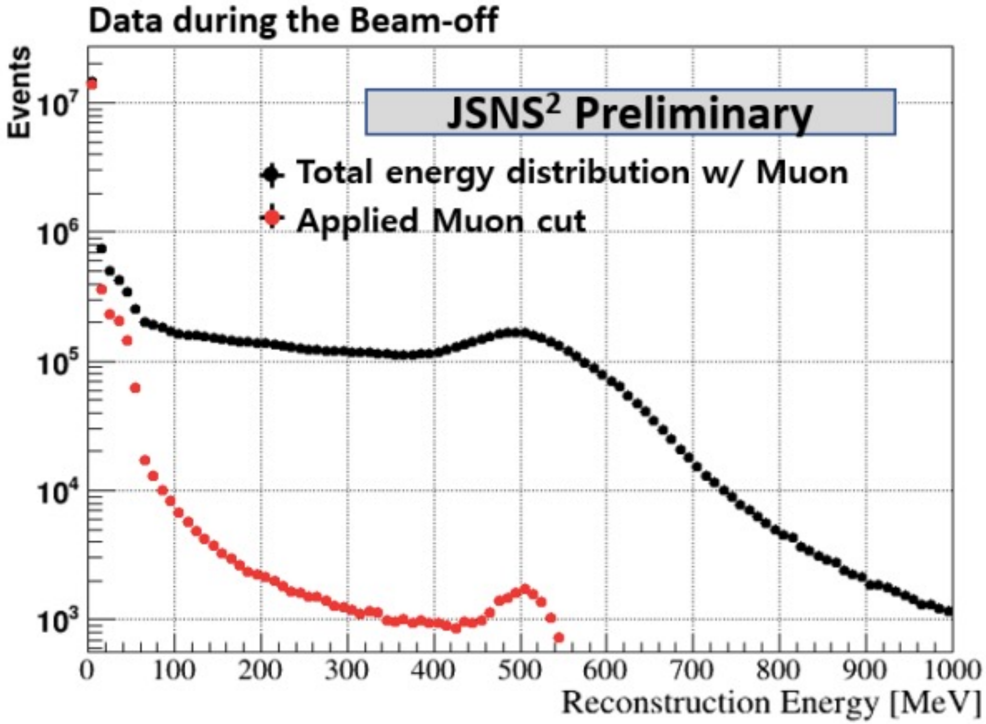
Backgrounds [Cosmic ray induced]

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

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

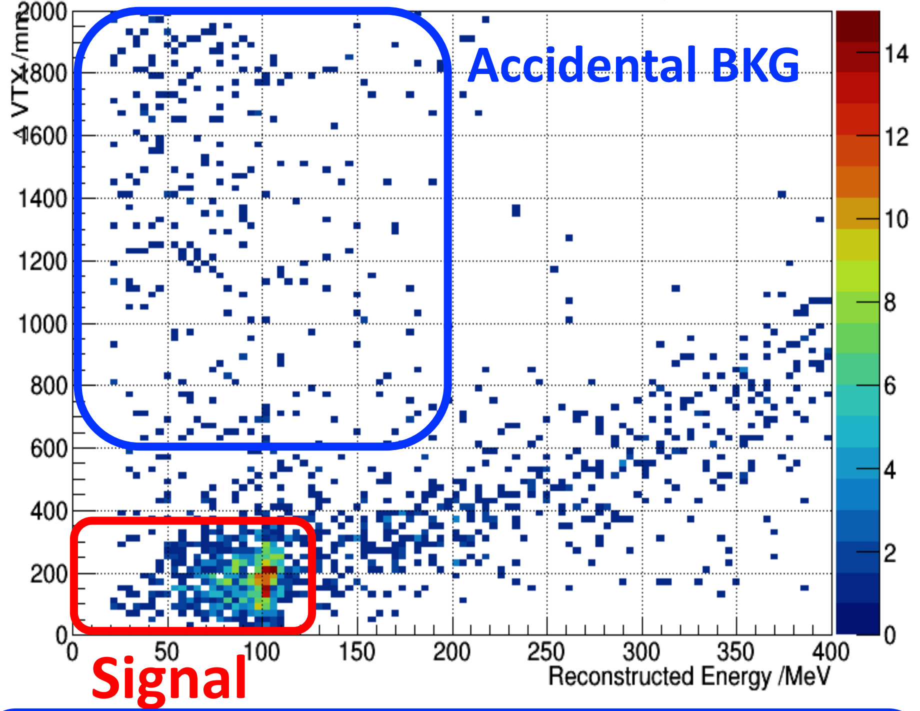
Delayed $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

$$\text{cosmic } \mu \xrightarrow{decay} \text{Michel } e$$

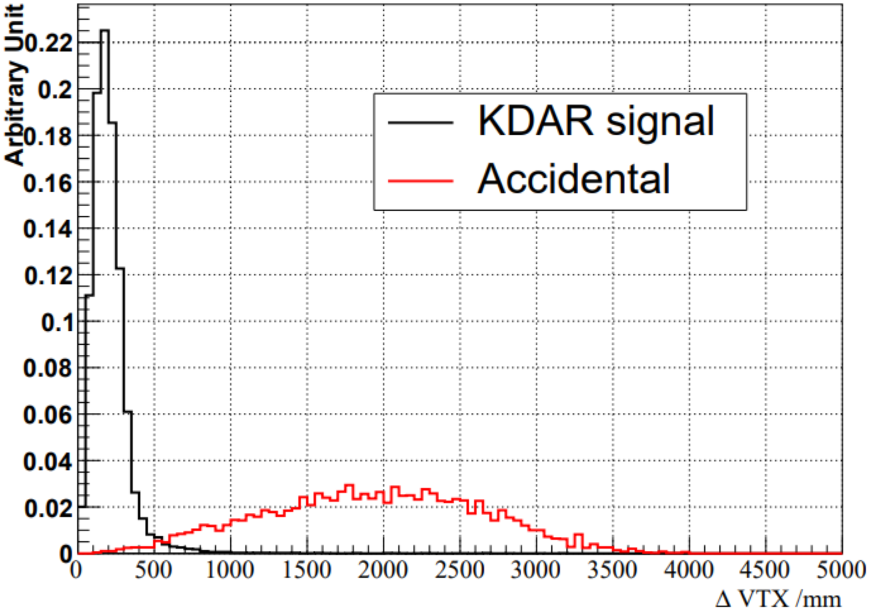


- As JSNS^2 is a surface based detector, we expect cosmic induced events to be the dominant source of backgrounds for this measurement.
- Cosmic muons can be produce a prompt & delayed event signature that is similar to that of KDAR neutrinos.
- We already measured the muon veto condition with no-beam data which means there is almost zero to muon interaction without cosmic induced muon.
  → Cosmic muon rejection with 99% efficiency.

Backgrounds [Accidental]


ΔVTX vs KDAR Prompt E_{vis}

$*$ **ΔVTX : Reconstructed vertex difference between prompt and delayed event of KDAR coincidence.**



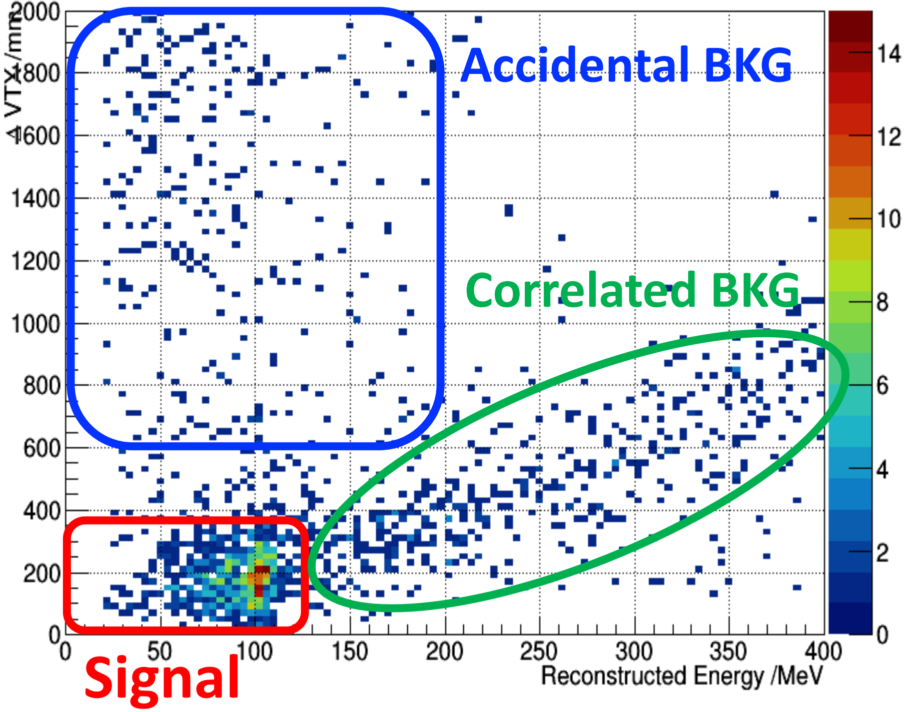
- **Accidental BKG** : Randomly paired as KDAR coincidence from single-particle events.

- **Correlated BKG** : Non-KDAR event have there own subsequence particle whose structure mimics KDAR event. (e.g. Cosmic ray induced muon and Michel e^-)

- Above showed the delta VTX (**ΔVTX**) template made by MC simulation.

- Clear difference distribution is shown. → Accidental (Randomly paired) event shoudn't have a correlation.

Backgrounds [Correlated]



ΔVTX vs KDAR Prompt E_{vis}

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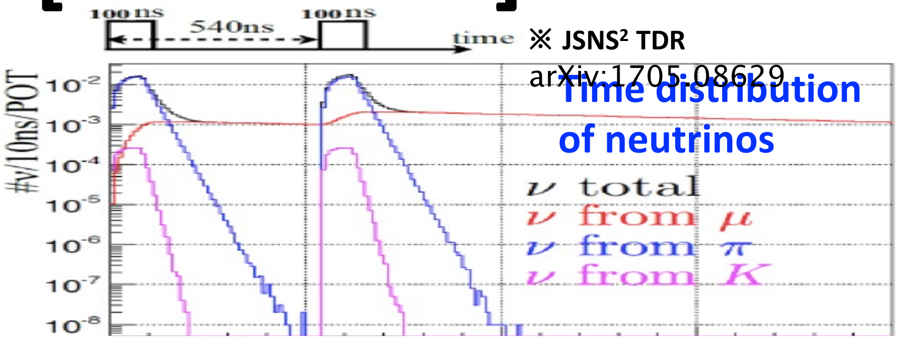
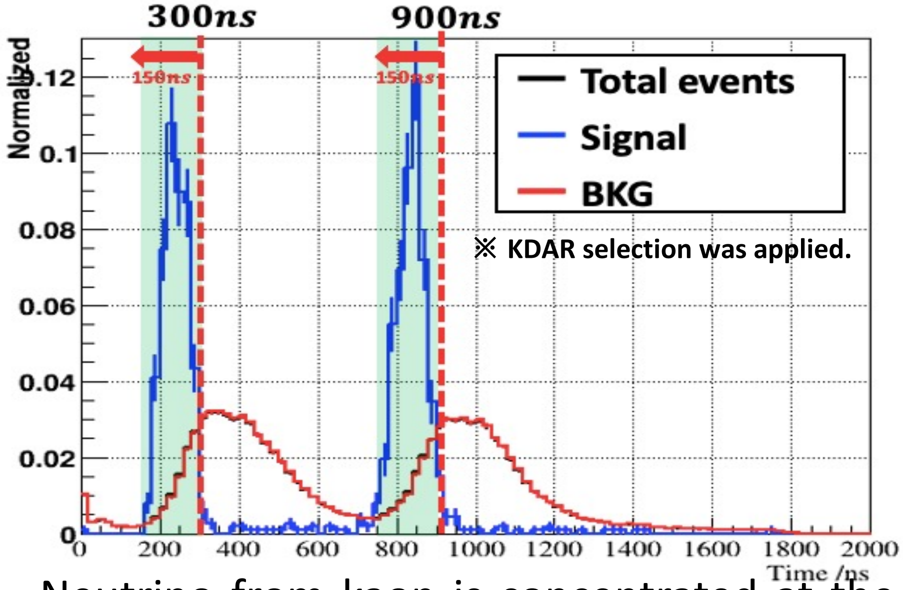


※ JSNS² TDR arXiv:1705.08629



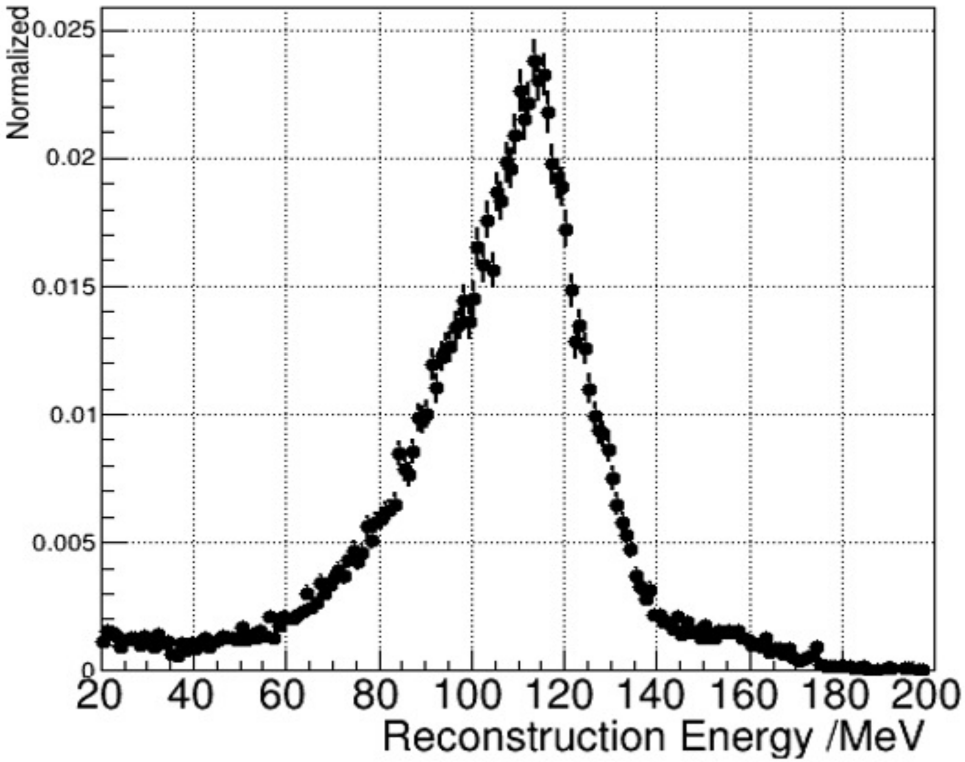
※ KDAR selection was applied.

- Neutrino from kaon is concentrated at the proton beam bunch timing.

- Reject events from most non-KDAR sources by selecting only events within a narrow timing window following the beam.

KDAR signal measurement in JSNS^2

MC : KDAR Prompt event ($\mu + X$)



Above shows the MC simulated KDAR energy spectrum as predicted by the NuWro simulation package.

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

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

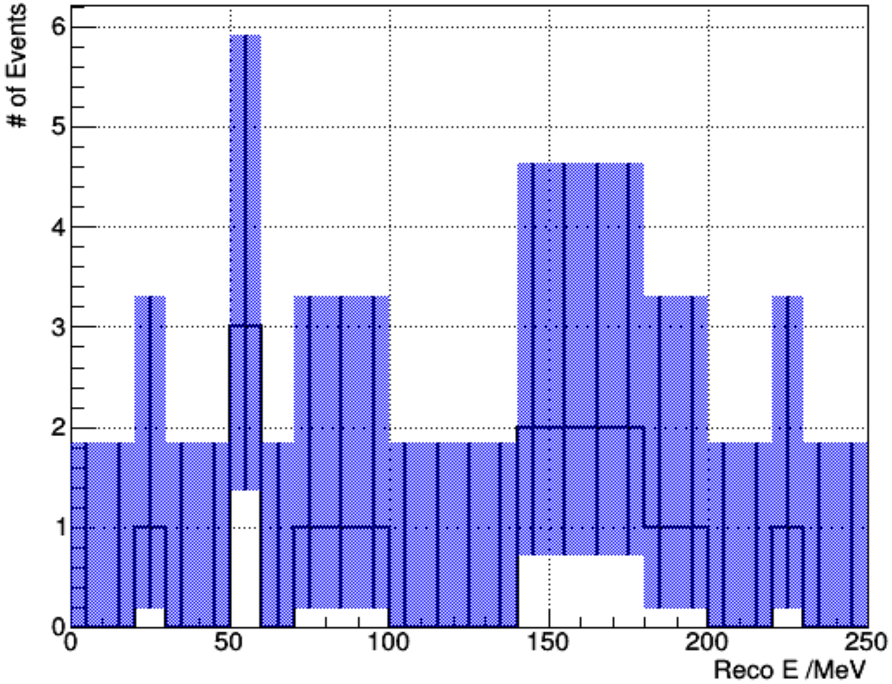
Delayed $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

- **KDAR Prompt E : 20 – 140 MeV**

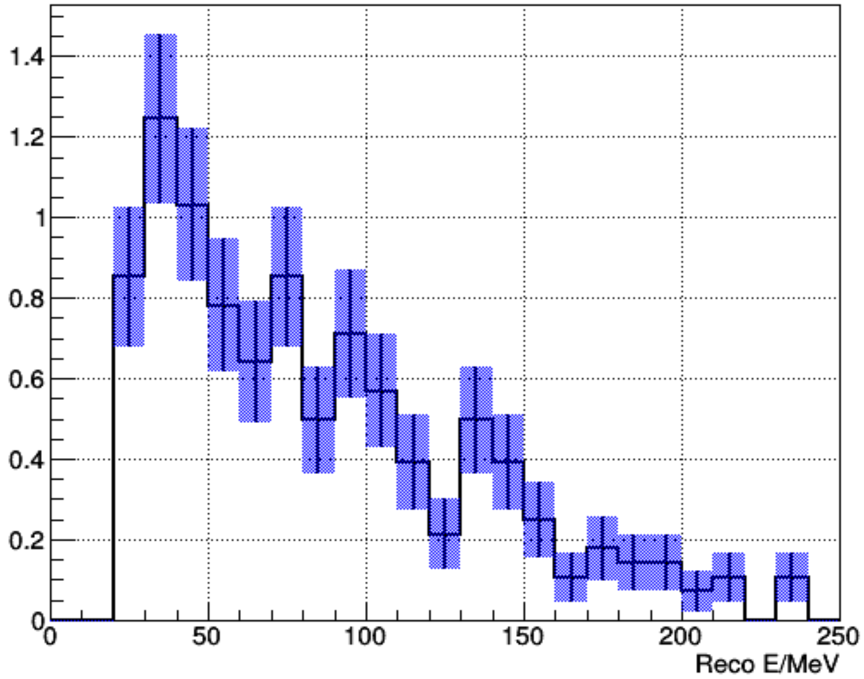
$$E_\nu = 236\ MeV$$
$$E_{vis} = E_\nu - m_\mu(106\ MeV) - T_X$$

- **KDAR delayed E : 20 – 60 MeV**
- **Time coincidence limit : < 10 us**
- **Beam-timing cut (150 ns each)**
- **Vertex difference criteria : 0.3 m**
- **Fiducial volume cut**

Backgrounds Estimation



Template of Correlated BKG

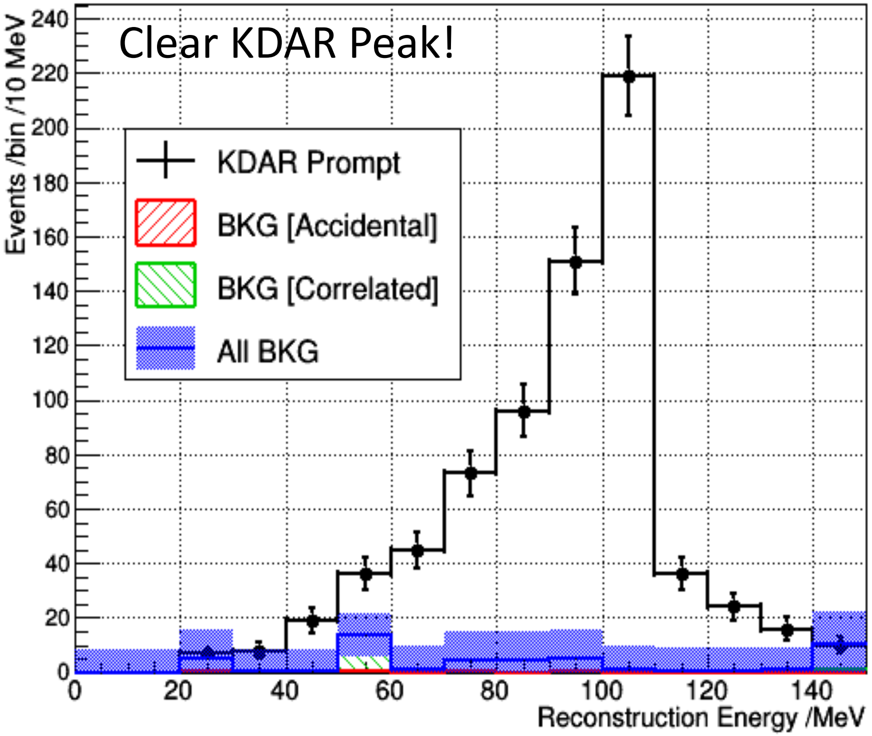


Template of Accidental BKG

- The correlated background energy spectrum was modeled via the sideband beam timing.
- The accidental background was obtained from random coincidence sample.
- The energy spectrum template was normalized by BKG dominant area, 140 – 250 MeV.
  → Expected no KDAR signal region.

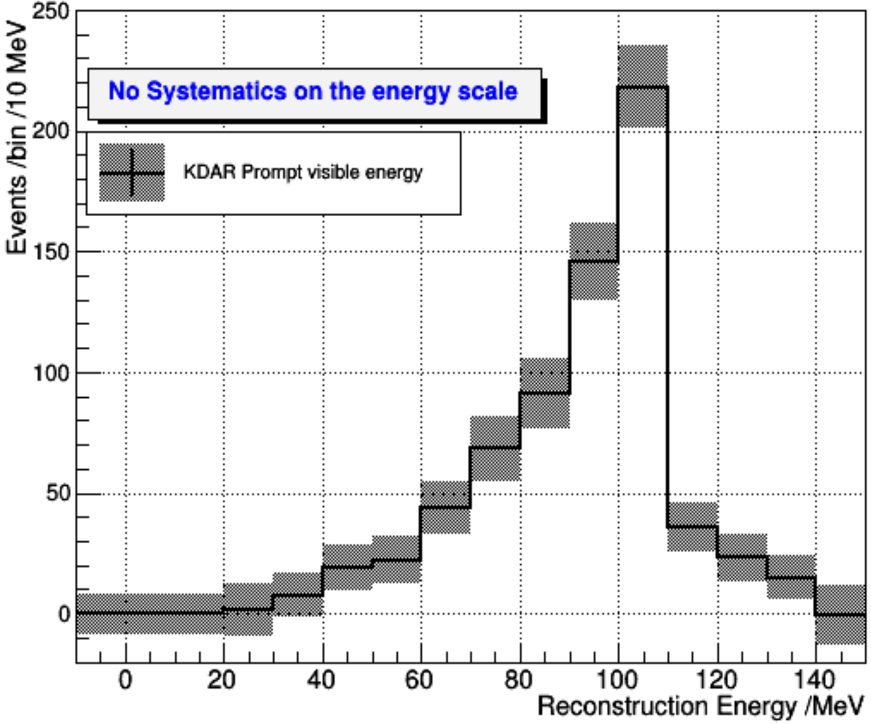
Analysis Result

KDAR Prompt visible spectrum with BKG



Clear KDAR Peak!

KDAR Prompt spectrum with BKG subtraction



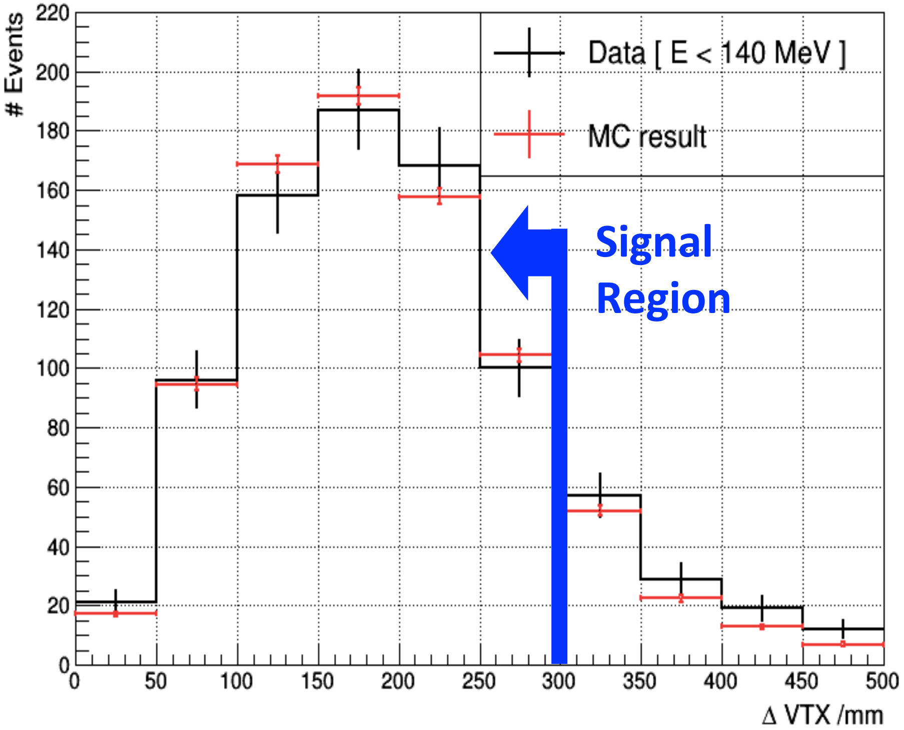
No Systematics on the energy scale

- The KDAR neutrino interaction is observed **691.9** $^{+46.9}_{-46.7}$ events (From total 730 events).
  → 38.1 $^{+38.4}_{-38.1}$ backgrounds (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 $^{+5.1}_{-5.0}$%
2	**Accidental**	**1.5 ± 0.1**	**0.2 ± 0.01%**
KDAR Candidate **730 events**		38.1 $^{+38.4}_{-38.1}$	5.2 $^{+5.3}_{-5.2}$%

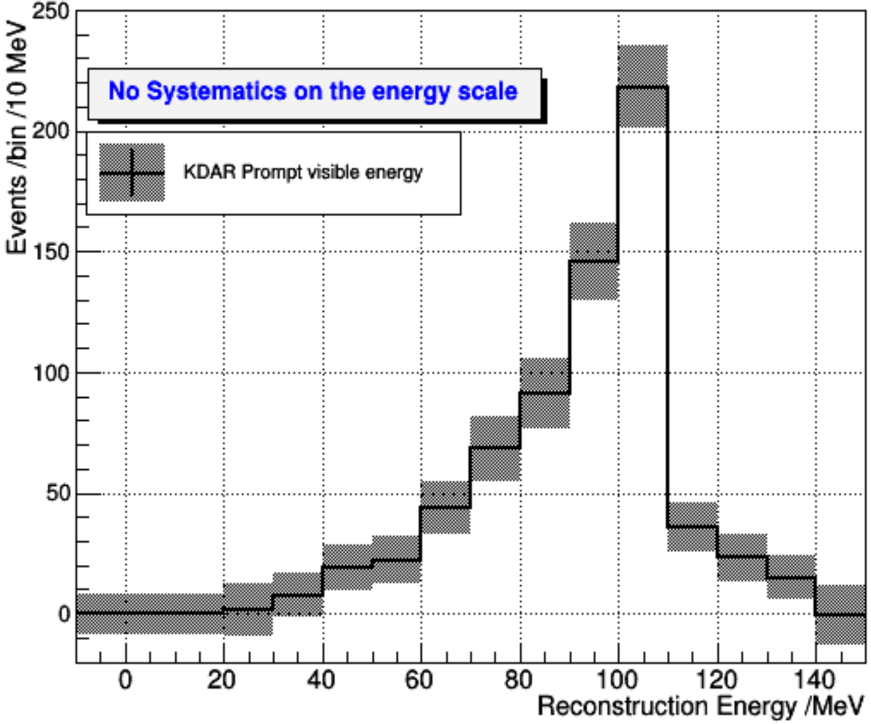
Analysis Result

∗ *ΔVTX* : Reconstructed vertex difference between prompt and delayed event of KDAR coincidence.



- The vertex difference distribution between data and MC shows the consistent within the error.
- It means that a high purity of KDAR signal is obtained in the signal region, 20 – 140 MeV.

KDAR Prompt spectrum with BKG subtraction



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Conclusion

- JSNS^2 has observed the neutrino interaction from KDAR through the visible energy spectrum using the first long-term physics data.

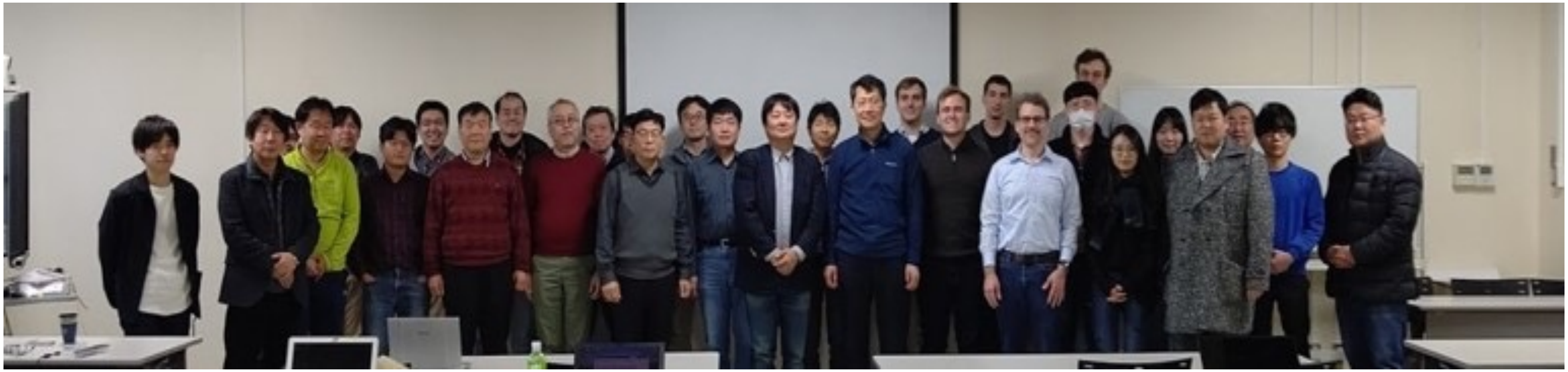
- This is the world first measurement of the visible energy from monoenergetic neutrino with a 5.2 % level of the backgrounds.

- The KDAR neutrino interaction is observed **691.9** $^{+46.9}_{-46.7}$ events with statistical error only.

- For the future analysis,
  → KDAR analysis from JSNS2 is not complete yet. More improvement and detailed analysis are actively ongoing.

  → Low-energy neutrino cross section measurement & Neutrino-nucleus interaction modeling

  → KDAR energy spectrum as a function of neutrons produced in the interaction, as measured via neutron capture.



Thank you!

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

► The spallation neutron source

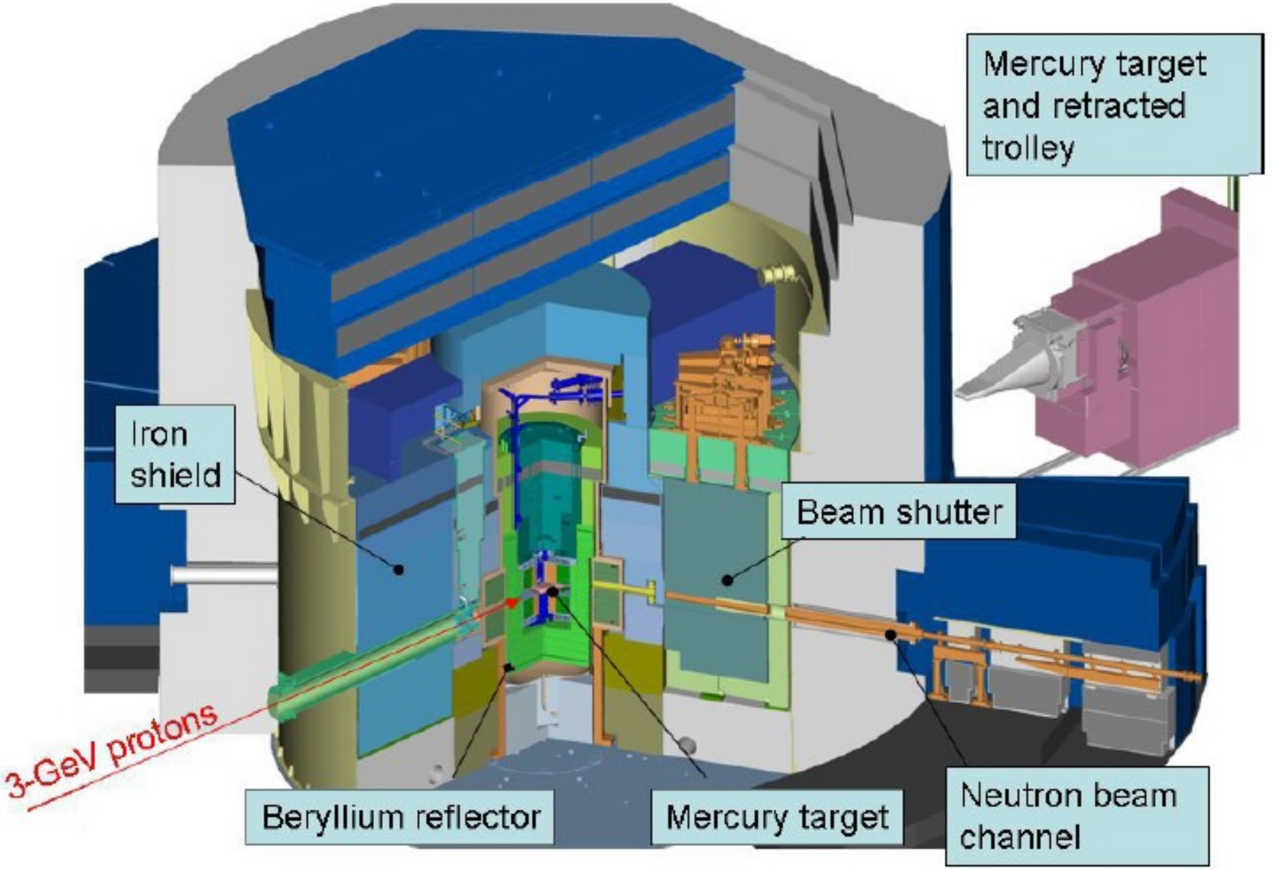
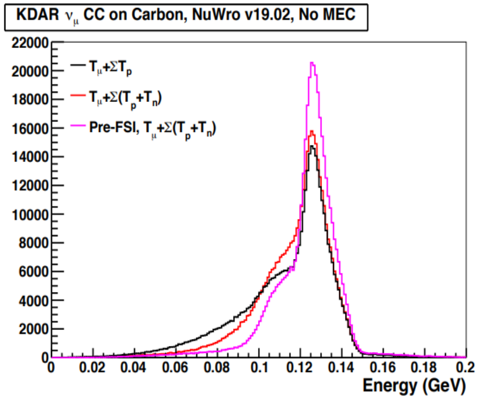


Figure 11: A schematic drawing of the J-PARC spallation neutron source.

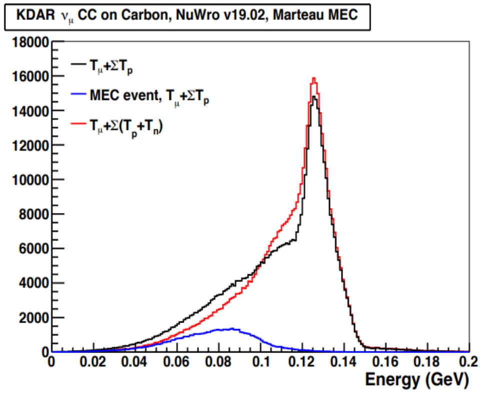
► Expected KDAR signal region & Background

KDAR for the various nuclear models in JSNS^2 detector simulation

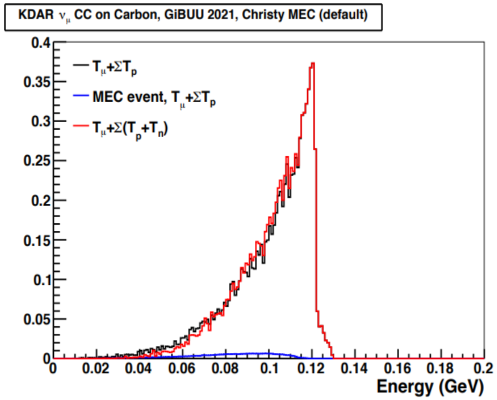
NuWro, including spectral function implementation (MEC neglected), before and after FSI



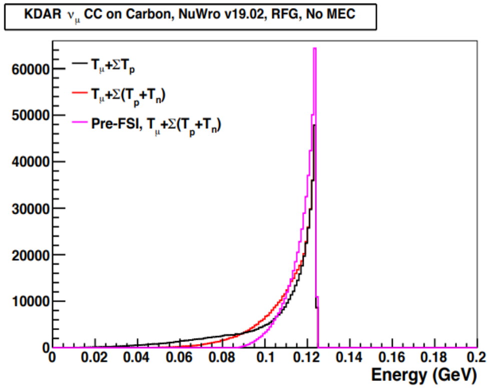
NuWro, including spectral function implementation and Marteau MEC, after FSI



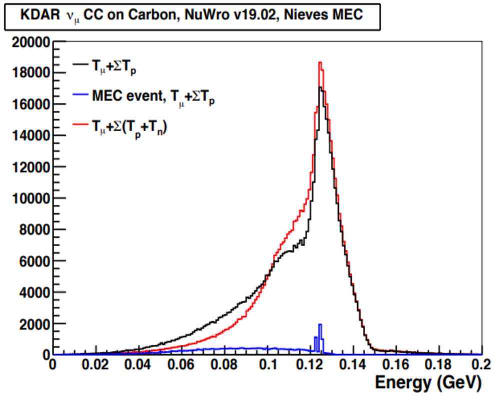
GiBUU, including spectral function implementation and Nieves MEC, after FSI



NuWro, including Relativistic Fermi Gas model implementation (MEC neglected).
Note, this is not the default! The default is the spectral function implementation



NuWro, including spectral function implementation and Nieves MEC, after FSI



- Even though various KDAR models exist, The observable KDAR prompt events have an end-point.

$$E_{vis} = E_\nu(236\text{ MeV}) - m_\mu(106\text{ MeV}) = 130\text{ MeV}$$

- For this analysis, roughly 140 MeV above is treated as a background.
  → Because the uncertainty of the energy scale is not fully studied yet.