A Search for Sterile Neutrinos at J-PARC MLF (JSNS^2 / J-PARC E56)

JSNS^2: J-PARC Sterile Neutrino Search using νs from J-PARC Neutron Spallation Source

Takasumi Maruyama (KEK)

for JSNS^2 (E56) collaboration

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Many collaborators Related to MLF Operation

~10 institutions
~35 people now.
(if you are interested, Please contact)

Status Report:
A Search for Sterile Neutrino at J-PARC MLF (E56, JSNS^2)

June 27, 2015

M. Harada, S. Hasegawa, Y. Kasugai, S. Meigo, K. Sakai, S. Sakamoto, K. Suzuya
JAEA, Tokai, Japan

E. Iwai, T. Maruyama, S. Monjushiro, K. Nishikawa, M. Taira
KEK, Tsukuba, JAPAN

M. Niiyama
Department of Physics, Kyoto University, JAPAN

S. Ajimura, T. Hiraiwa, T. Nakano, M. Nomachi, T. Shima
RCNP, Osaka University, JAPAN

T. J. C. Bezerra, E. Chauveau, H. Furuta, F. Suekane
Research Center for Neutrino Science, Tohoku University, JAPAN

I. Stancu
University of Alabama, Tuscaloosa, AL 35487, USA

M. Yeh
Brookhaven National Laboratory, Upton, NY 11973-5000, USA

H. Ray
University of Florida, Gainesville, FL 32611, USA

G. T. Garvey, C. Mauger, W. C. Louis, G. B. Mills, R. Van de Water
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

J. Spitz
University of Michigan, Ann Arbor, MI 48109, USA

[1]

[1] Spokes person : Takasumi Maruyama (KEK) (takasumi.maruyama@kek.jp)

Status of the sterile neutrino search

- Anomalies, which cannot be explained by standard neutrino oscillations for 15 years are shown;

Experiments	Neutrino source	signal	significance
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	3.4σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8σ
		combined	3.8σ
Ga (calibration)	e capture	$\nu_e \rightarrow \nu_x$	2.7σ
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ

- Excess or deficit does really exist?
- The new oscillation between active and inactive (sterile) neutrinos?

Neutrino oscillations with $\Delta m^2 \sim 1 eV^2$ region

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \bullet \end{bmatrix} = \begin{bmatrix} \boxed{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}} & \begin{matrix} U_{e4} \\ U_{\mu 4} \\ U_{\tau 4} \end{matrix} & \begin{matrix} \bullet \\ \bullet \\ \bullet \end{matrix} \\ U_{s1} \quad U_{s2} \quad U_{s3} & U_{s4} & \bullet \\ \bullet \quad \bullet \quad \bullet & \bullet & \bullet \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \bullet \end{bmatrix}$$

Matrix elements, which are considered in 3x3 mixing framework.

$$\sum_{j=1,3} U^*_{ej} U_{\mu j} = -U^*_{e4} U_{\mu 4}$$

Small mixiture with active ν's $\quad U_{e4}, U_{\mu 4} \sim 0.1 \quad U_{s4} \sim 1 \quad m_4 \sim 1\,eV >> m_{1,2,3}$

$$P_{e\mu} = -4 \sum_{i=1,3} (U^*_{e4} U_{\mu 4} U_{ei} U^*_{\mu i}) \sin^2 \frac{(m_4^2 - m_i^2)L}{4E_\nu} \sim 4 \boxed{|U_{e4}|^2 |U_{\mu 4}|^2} \sin^2 \frac{\Delta m_4^2}{4} \frac{L}{E}$$

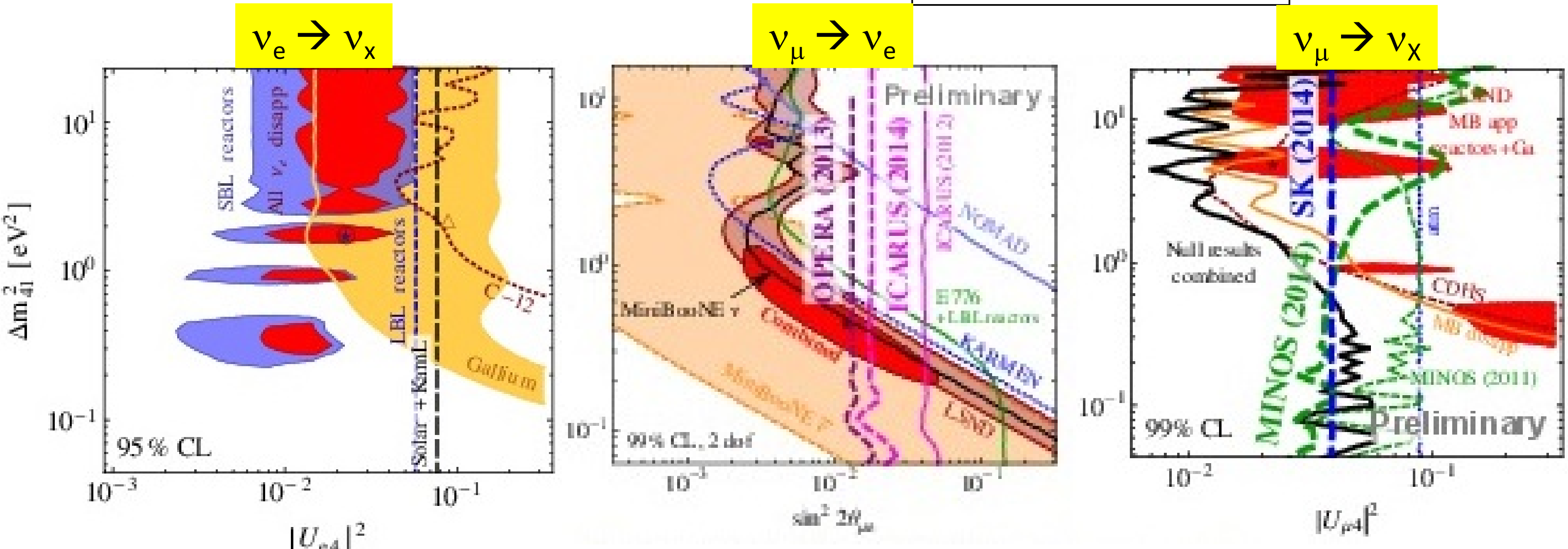
$$P_{es} = -4 \sum_{i=1,3} (U^*_{e4} U_{s4} U_{ei} U^*_{si}) \sin^2 \frac{(m_4^2 - m_i^2)L}{4E_\nu} \sim 4 |U_{e4}|^2 \boxed{|U_{s4}|^2} \sin^2 \frac{\Delta m_4^2}{4} \frac{L}{E}$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\Theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

(3+1) model

Status as of 2014

J. Kopp's
talk at Neutrino2014



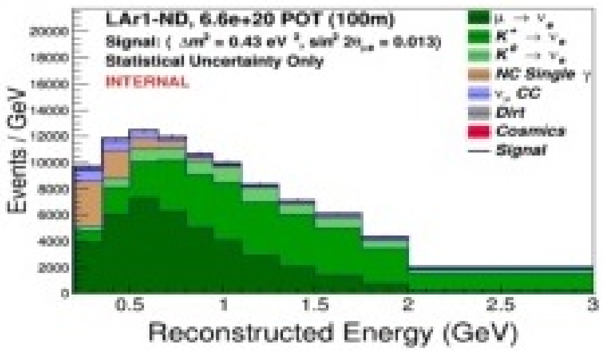
- ICARUS / OPERA experiments had new results in 2014 for appearance channel. And FNAL SBN programs are planned.
- SK / MINOS had new results in ν_μ disappearance channel. (FNAL SBN can do this search as well, IceCUBE is analyzing data.)
- Daya-Bay had the latest results on ν_e disappearance in 2014. There are many planned experiments w/ reactors and sources.

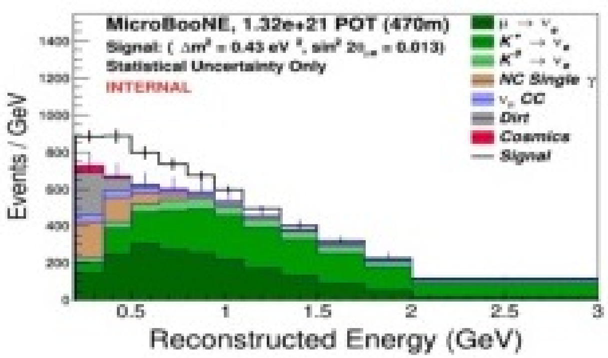
Discrepancy between ν_μ and others?

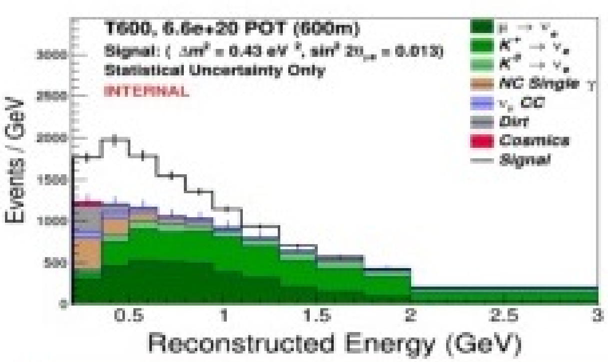
- Due to issue on theoretical model (3+1) ?
- **Confirming or refuting the anomalies with various E/L is first thing to do for experimentalists.**

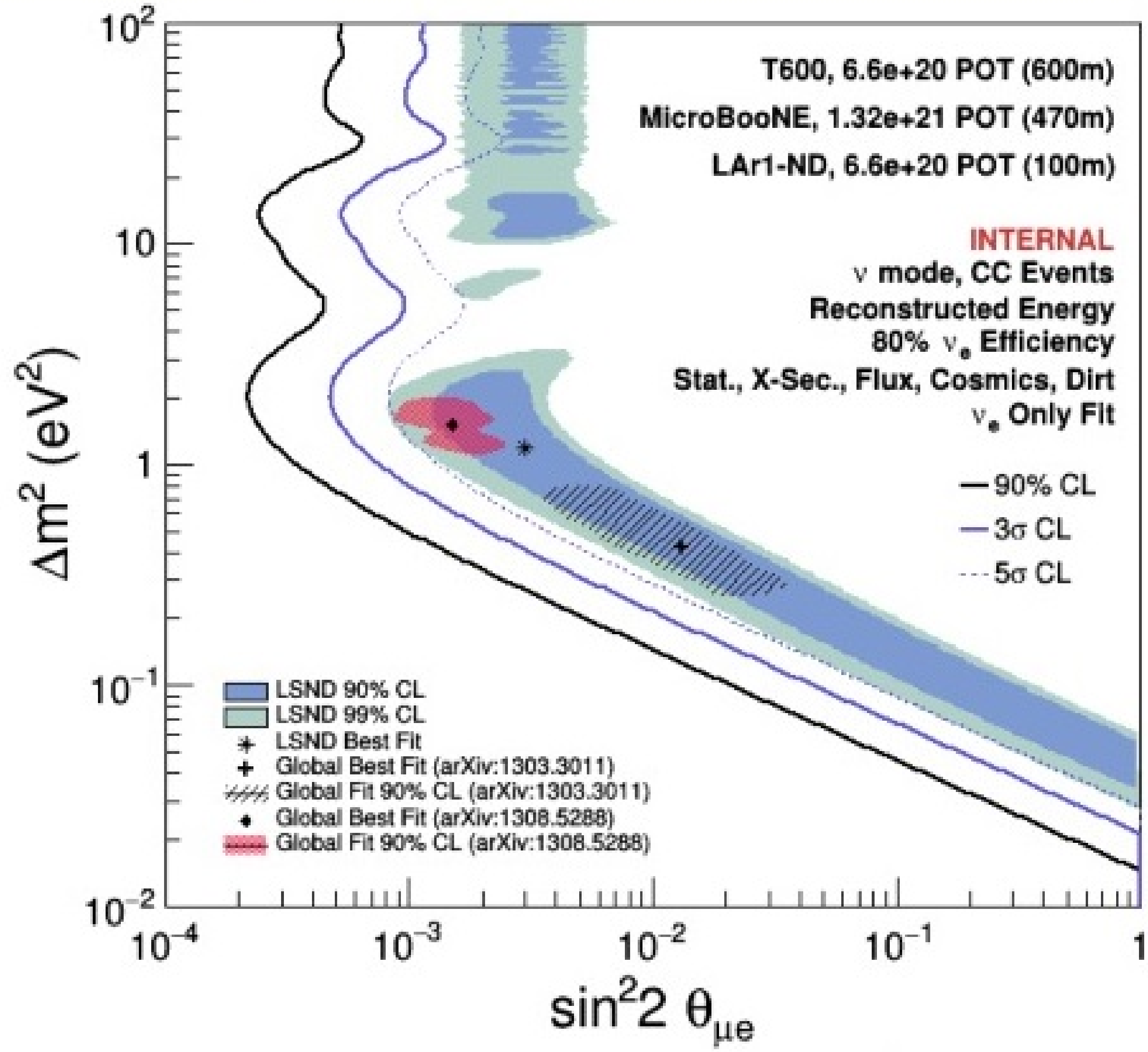
SBN ν_e Appearance Sensitivity

Peter Wilson's talk @ WINP workshop







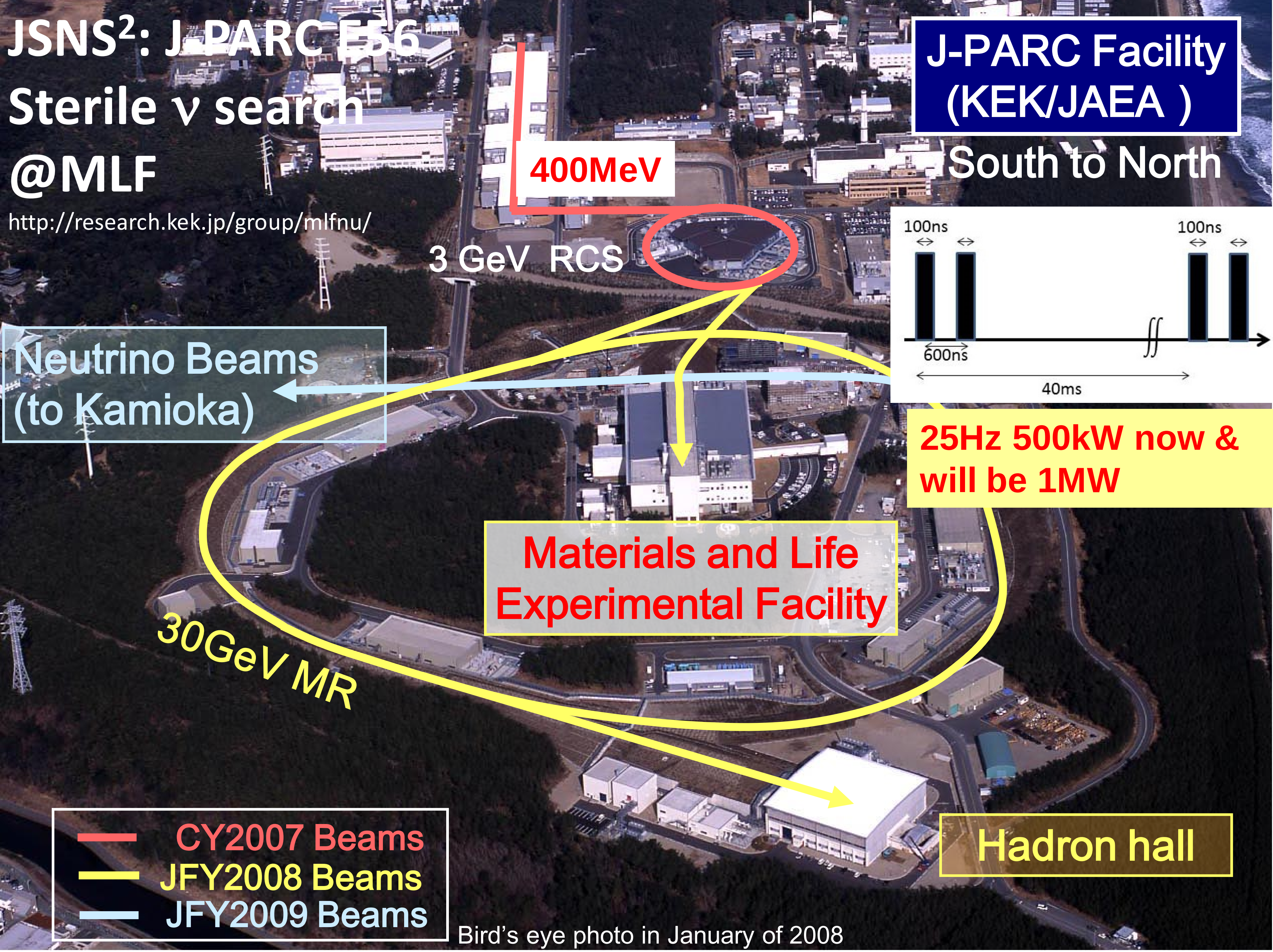


plan to start in 2018

JSNS^2 experiment

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

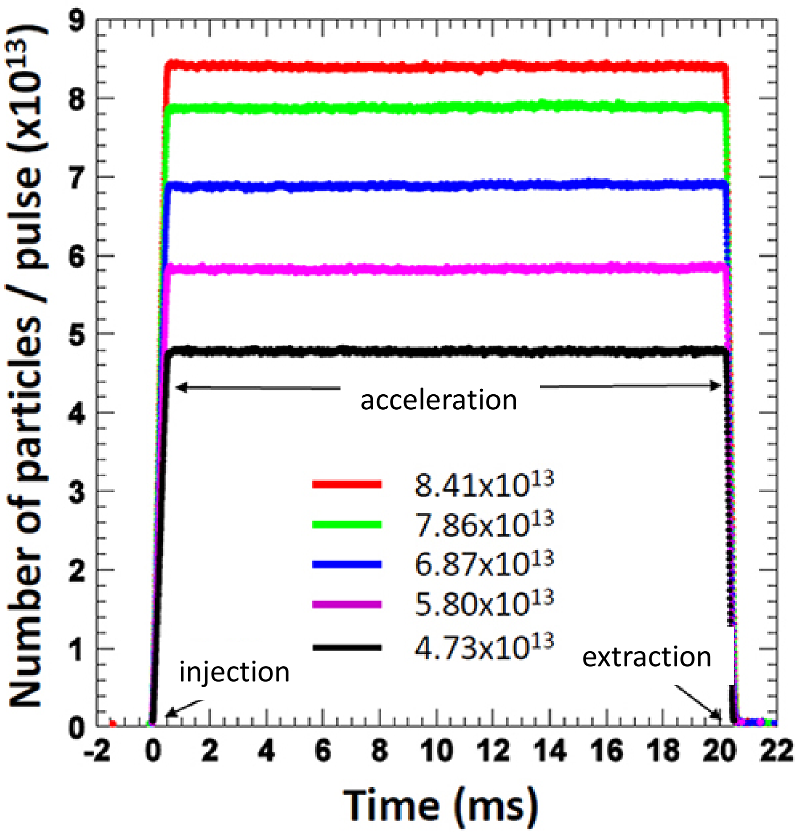
http://research.kek.jp/group/mlfnu/



Bird's eye photo in January of 2008

RCS/MLF beam

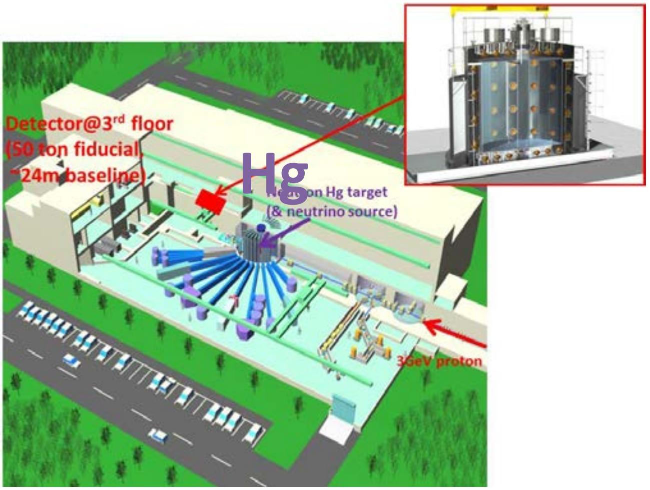
- Current nominal beam power is 500kW.
- 1MW trial during the very short period was succeeded. (bottom plot) http://j-parc.jp/ja/topics/2015/Pulse150206.html
- The nominal beam power will be slowly increased. (500kW -> 1MW)



	Number of Particles / pulse	Corresponding Power in 25 Hz
(red)	8.41x10^{13}	1010 kW
(green)	7.86x10^{13}	944 kW
(blue)	6.87x10^{13}	825 kW
(magenta)	5.80x10^{13}	696 kW
(black)	4.73x10^{13}	568 kW

Sterile neutrino search @MLF (JSNS^2;J-PARC E56)

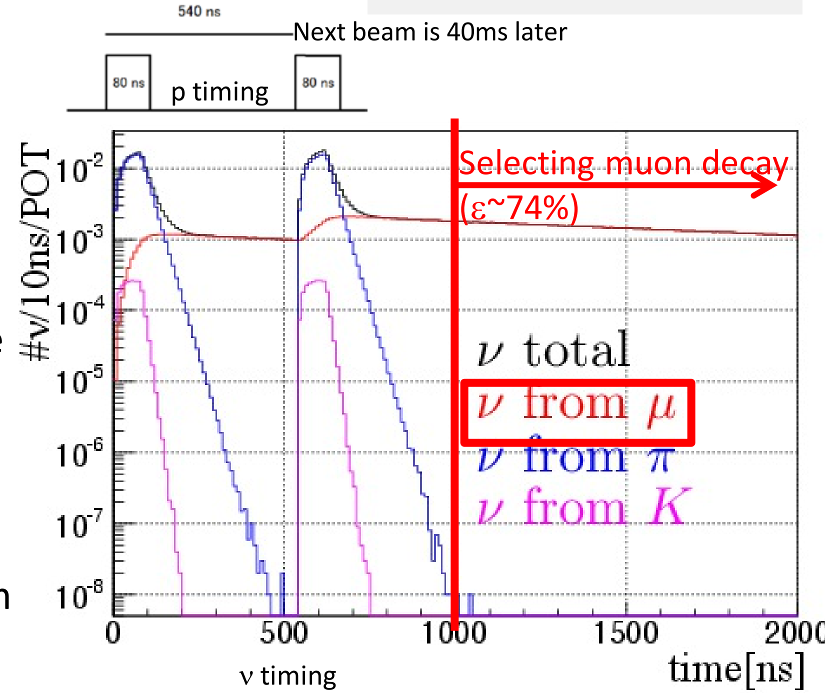
M. Harada *et al*, arXiv:1310.1437



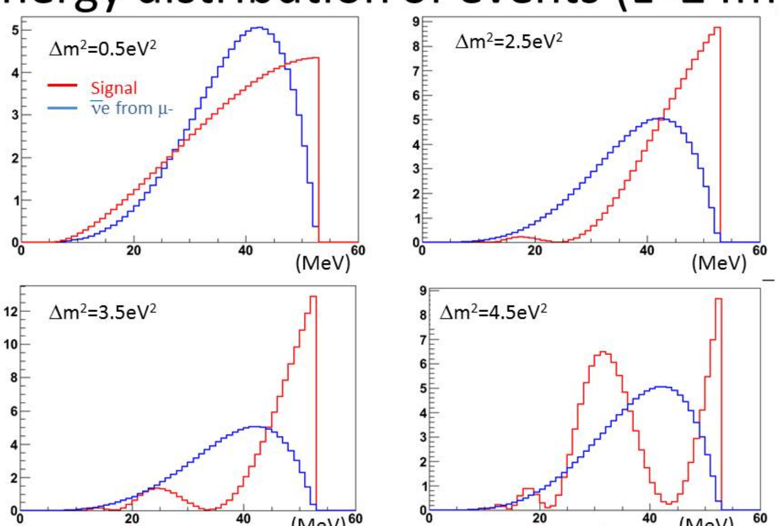
Note: Detector location is under discussion

JSNS^2

- confirms or refutes the neutrino oscillation with sterile neutrino($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$)
- uses ultra-pure neutrinos from stopping μ^+
- separates signals from BKG by measuring energy distortion

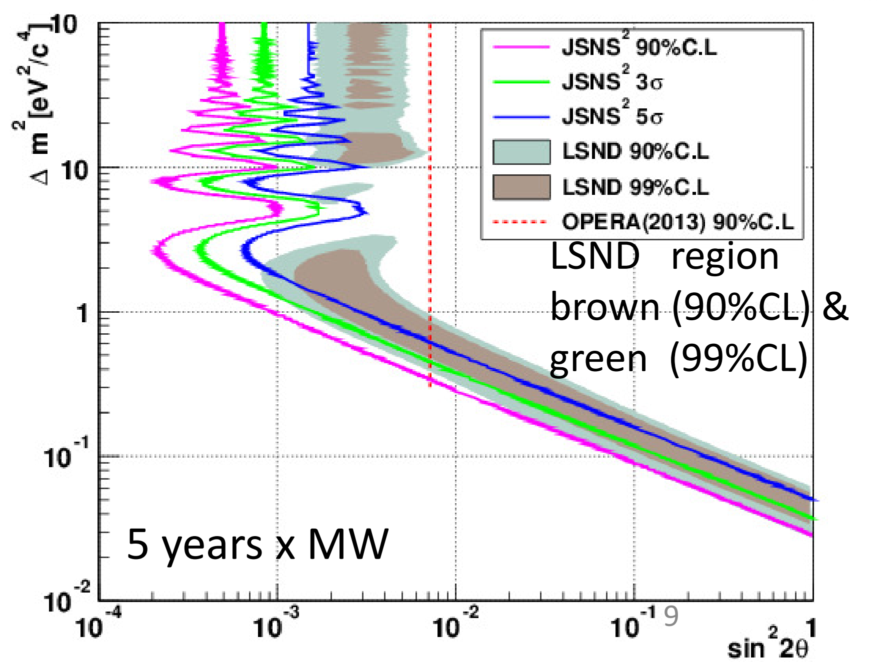


Energy distribution of events (L=24m)



$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \boxed{\Delta m^2} \cdot L}{E_\nu}\right)$$

- Energy is smeared by 15%/sqrt(E) (detector E resolution)

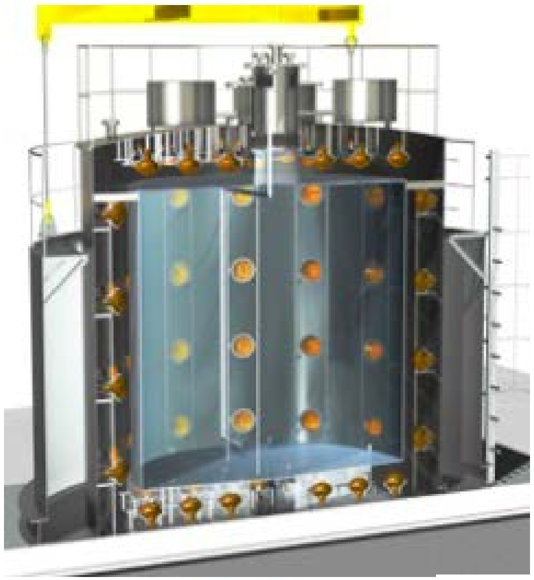


Detector and Detection Principle (reminder)

Detector

Target volume => **Gd-loaded LS**
(25tons x 2 detector ~ total 50tons)

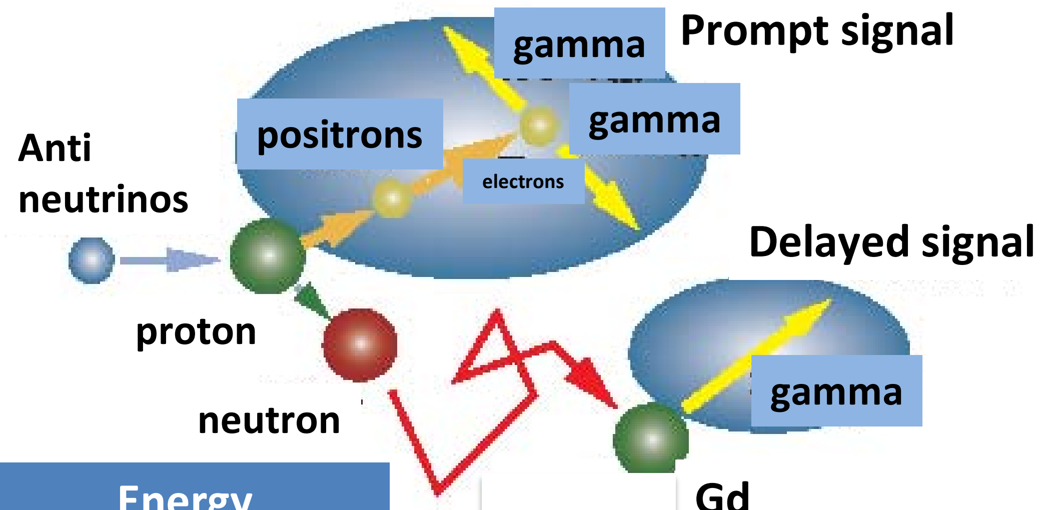
150 10” PMTs/detector
E resolution ~ 15%/√MeV



Delayed Coincidence (IBD)

$\nu_\mu \underset{\text{oscillation}}{=>} \bar{\nu}_e + p \rightarrow e^+ + n$

Identify ν with detecting
e^+ and γs from n capture on Gd.
=>Can reduce accidental BKG
(Gd~8MeV γs, capture time ~ 30 μs).



IBD Signal in the detector

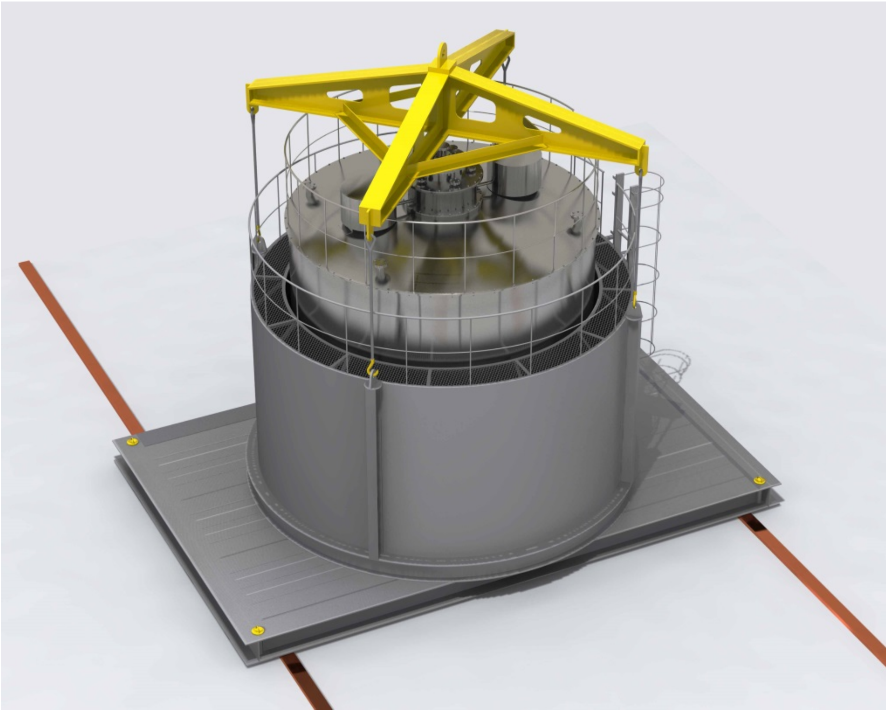
Selection criteria for IBD

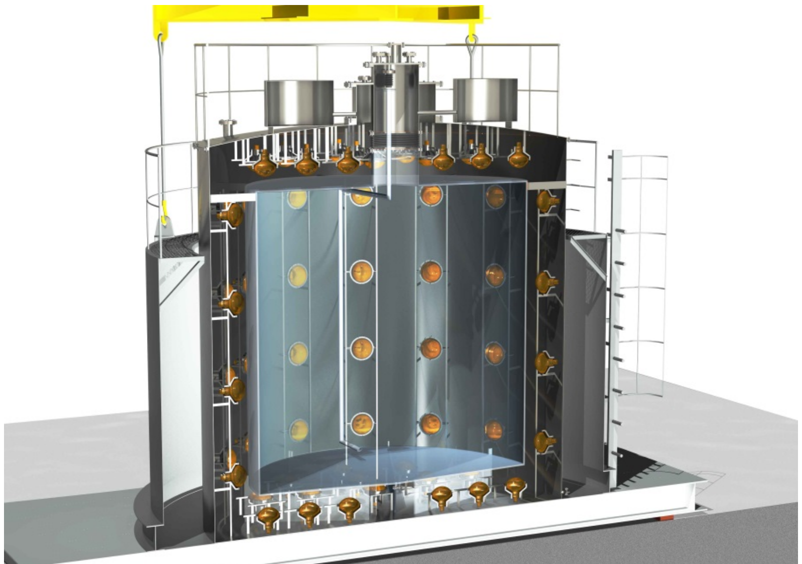
	Time from beam	Energy
Prompt signal	$1<T_p<10\mu s$	20<E<60MeV
Delayed signal	$T_p<T_d<100\mu s$	7<E<12MeV

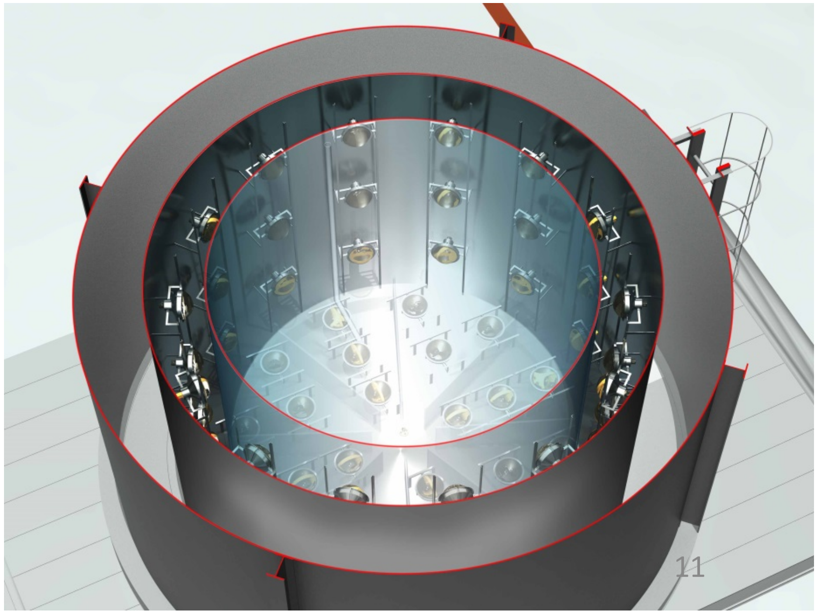
Detector design

- The design of the tank was done
- We calculated not only the static strength of the tank but also the endurance against the earthquake and movement of the detector.
- Well established technology(100ton / detector)
- E56 has Double Chooz / Daya-Bay collaborators

- MLF 3rd floor is the maintenance area to manage the mercury target or beam equipment.
- **The interference between facility and experiment should be considered. Also the law to operate the LS is to be considered.**







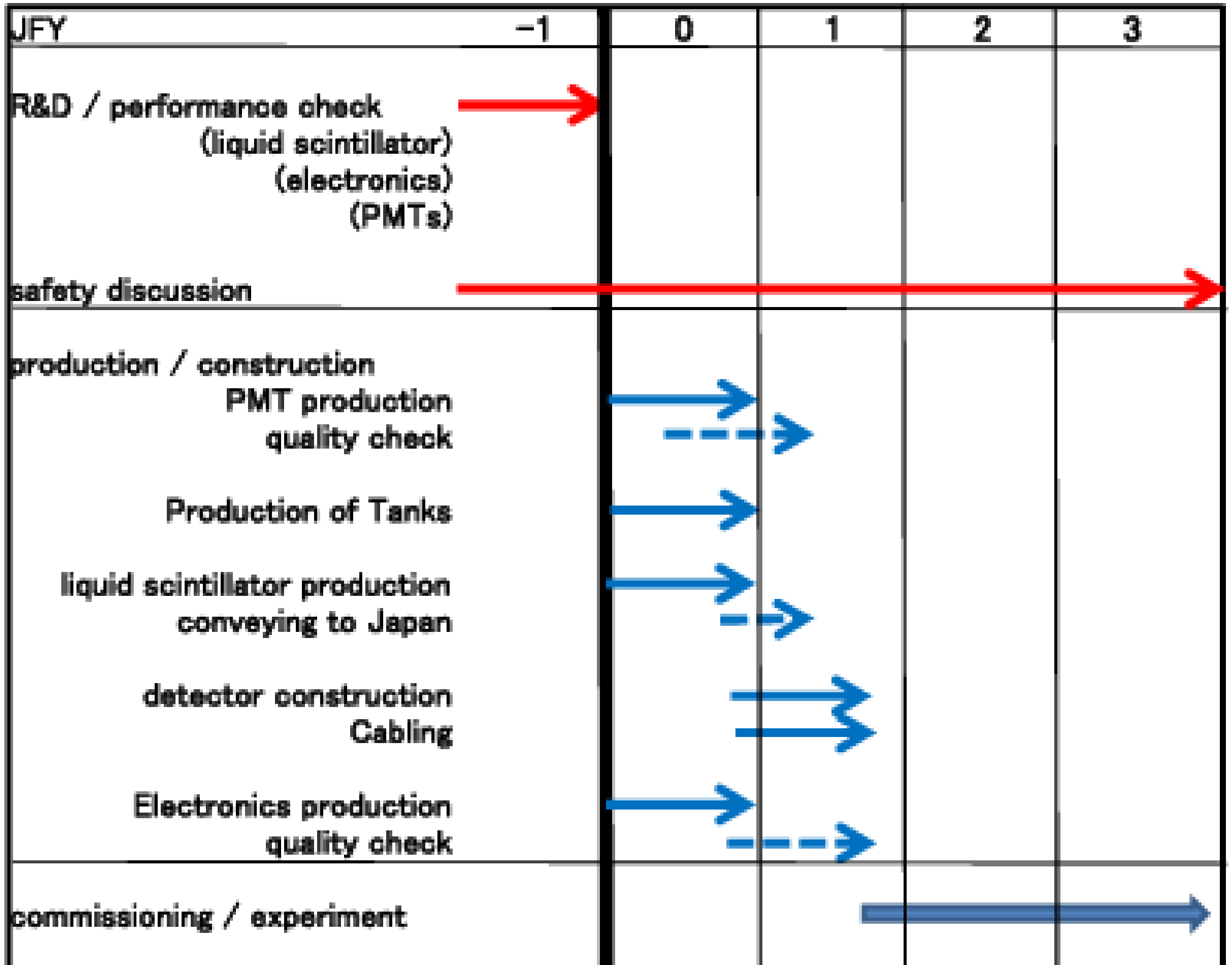
Cost estimation for detectors

items	Unit price	Quantities	Cost
PMTs & electronics	500kyen/ch	400 ch	200Myen
Tanks & Acrylic vessels	50Myen/set	2 sets	100Myen
GD-LS & buffer-LS			100Myen
Piping & infrastructure	50Myen/set	1 set	50Myen
Misc.			50Myen
New Beamline			**0**
New detector building			**0**
New detector hole			**0**
Grand total			500Myen(~4M$)

JSNS^2 does not need any new beamlines, detector buildings, holes
→ Very cost effective (within grant-in-aid) and timely results

Timescale

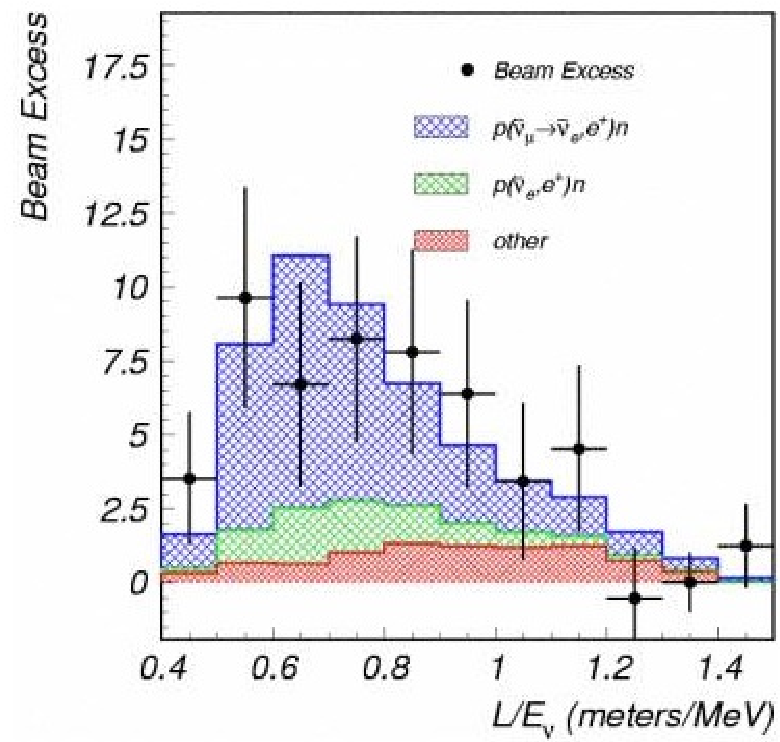
- **We don’t need any new beam-lines and detector holes or buildings.**
- Realistic time and cost estimation has been done with companies. → 1~2 years for the detector construction.
- Aim to start the experiment in 2018 at the earliest



“0”: obtaining budget

Pros compared to prior experiments

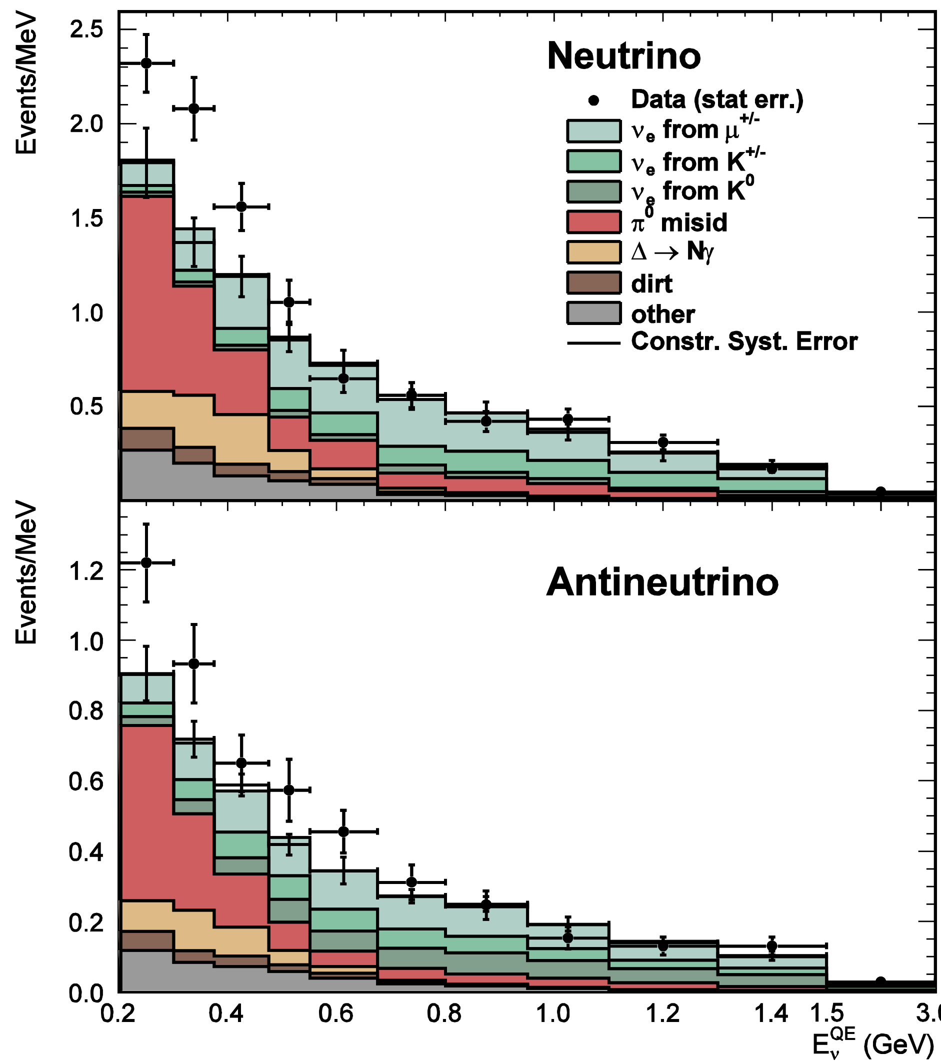
- vs LSND; → definite and direct test without any excuses (e.g.: ν type, Eν, detector target material) w/ better S/N
  - Narrow pulsed beam at MLF → timing cut.
    - LSND has no beam timing cut (Linac → large duty factor)
    - Pure muon decay at rest at MLF.
    - No Decay-In-Flight source in MLF
    - No beam fast neutrons BKG at MLF.
    - Tighter timing window (~9μs) for cosmic ray rejection.
  - Detector has many improvements;
    - Gd-LS improves S/N ratio. → time window of coincidence (factor 6) and delayed Energy. (2.2 → 8MeV)
    - Faster sampling rate of electronics and improved LS make PID easy.



Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

Pros compared to prior experiments

- to MiniBooNE (conventional horn focused beam) → much better S/N and Eν reconstruction;
  - Background rates is small at MLF. (suppression of π^-, μ^-).
  - Eν reconstruction of IBD is very clear.
  - Signal normalization ~10% level.

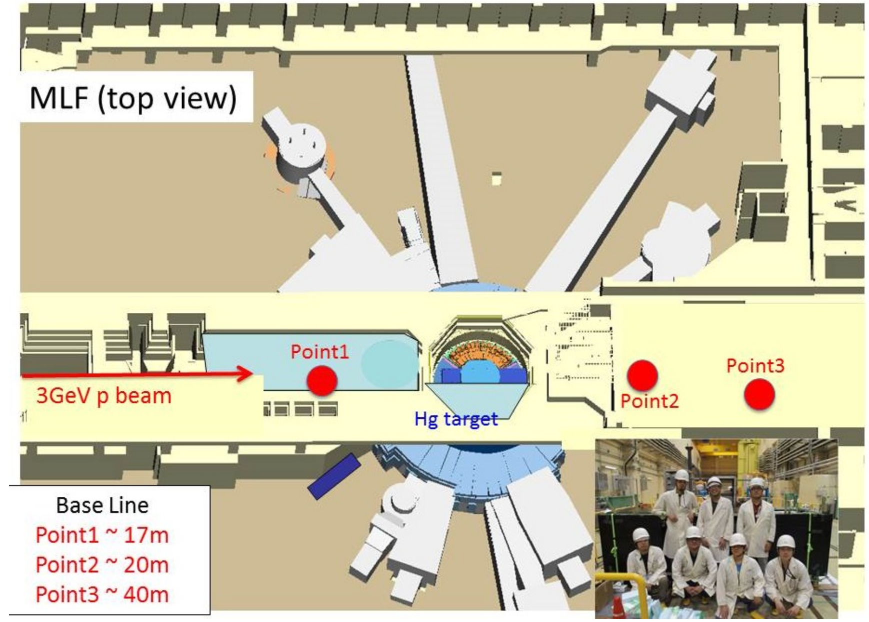


Complementarity

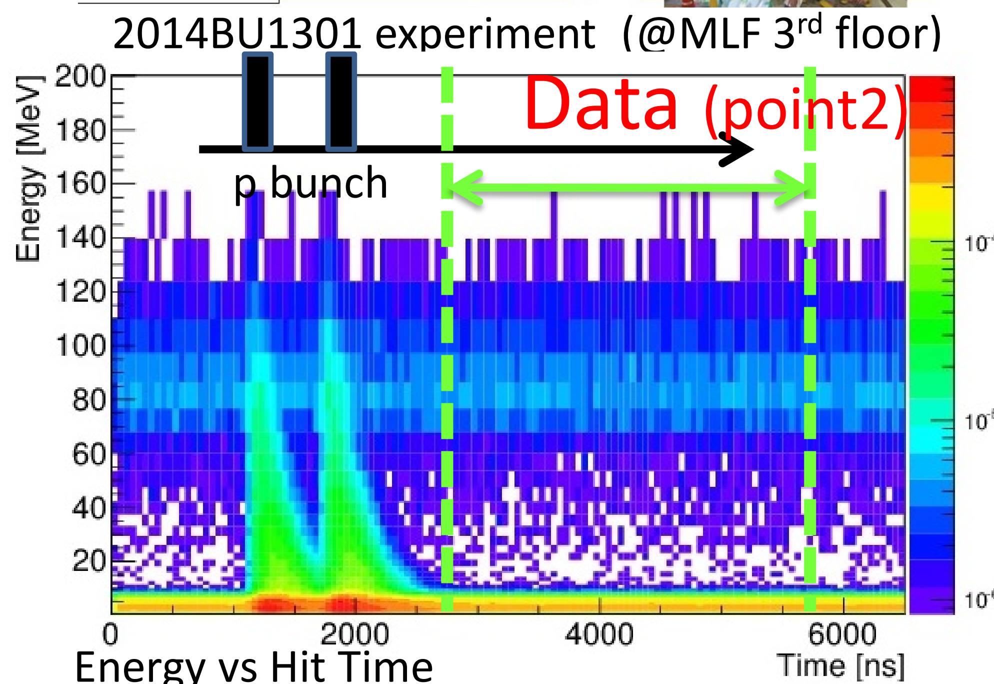
- to reactor / radiation source experiments
  - Disappearance measurement vs appearance ($JSNS^2$)
  - Reactor experiments suffers the high energy neutrons from the reactor → need PSD ($JSNS^2$ technique could be used?)
- to ν_μ disappearance
  - Disappearance vs appearance
  - $\nu_\mu \rightarrow \nu_\mu$ is also important to check models.
  - (IceCube is analyzing the data.)
- to FNAL SBN programs(LAr TPCs + horn focused beam)
  - $\nu_\mu \rightarrow \nu_e$ oscillation vs $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillation ($JSNS^2$)
  - $JSNS^2$ can have a complete test for the LSND anomaly with much better S/N and without any excuses.
  - Intrinsic background rate is smaller and energy reconstruction is much cleaner. ($E\nu \sim Evis + 0.8MeV$ in IBD)
  - Note; SBN can perform the $\nu_\mu \rightarrow \nu_\mu$ disappearance search.

Achievements so far

- 2013 Feb-May; A background measurement on the 1st floor
- 2013 Sep; A proposal was submitted to the J-PARC PAC
  - The PAC recommended to measure the background at the detector candidate site (3rd floor of MLF)



- 2014 Apr-Jul; We measured the BKG rate on 3rd floor. -> manageable beam / cosmic BKGs to perform JSNS^2
  PTEP 2015 6, 063C01 / arXiv:1502.02255
- 2014-Dec; A status report was submitted to J-PARC PAC. → the stage-1 approval was obtained from J-PARC /KEK



#events (1MW x 5 years) @ point2

Source	contents	#ev./50tons/5years	comments
background	$\overline{\nu}_e$ from μ-	237	Dominant BKG
	$^{12}C(\nu_e,e^-)^{12}N_{g.s.}$	16	
	Beam fast neutrons	**Consistent with 0 < 13 (90%CL UL)**	**Based on real data**
	Fast neutrons (cosmic)	37	
	Accidental	**32**	**Based on real data**
signal		480	$\Delta m^2=2.5$, $\sin^2 2\theta=0.003$
		342	$\Delta m^2=1.2$, $\sin^2 2\theta=0.003$

Accidental BKG is calculated by;R acc = $\Sigma R_{prompt} \times \Sigma R_{delay} \times \Delta_{VTX} \times N_{spill}$

- ΣR_{prompt}, ΣR_{delay} are probability of accidental BKG for prompt and delayed.
- Δ_{VTX} ; BKG rejection factor of **50**.
- N_{spill}(#spills / 5 years) = 1.9×10^9

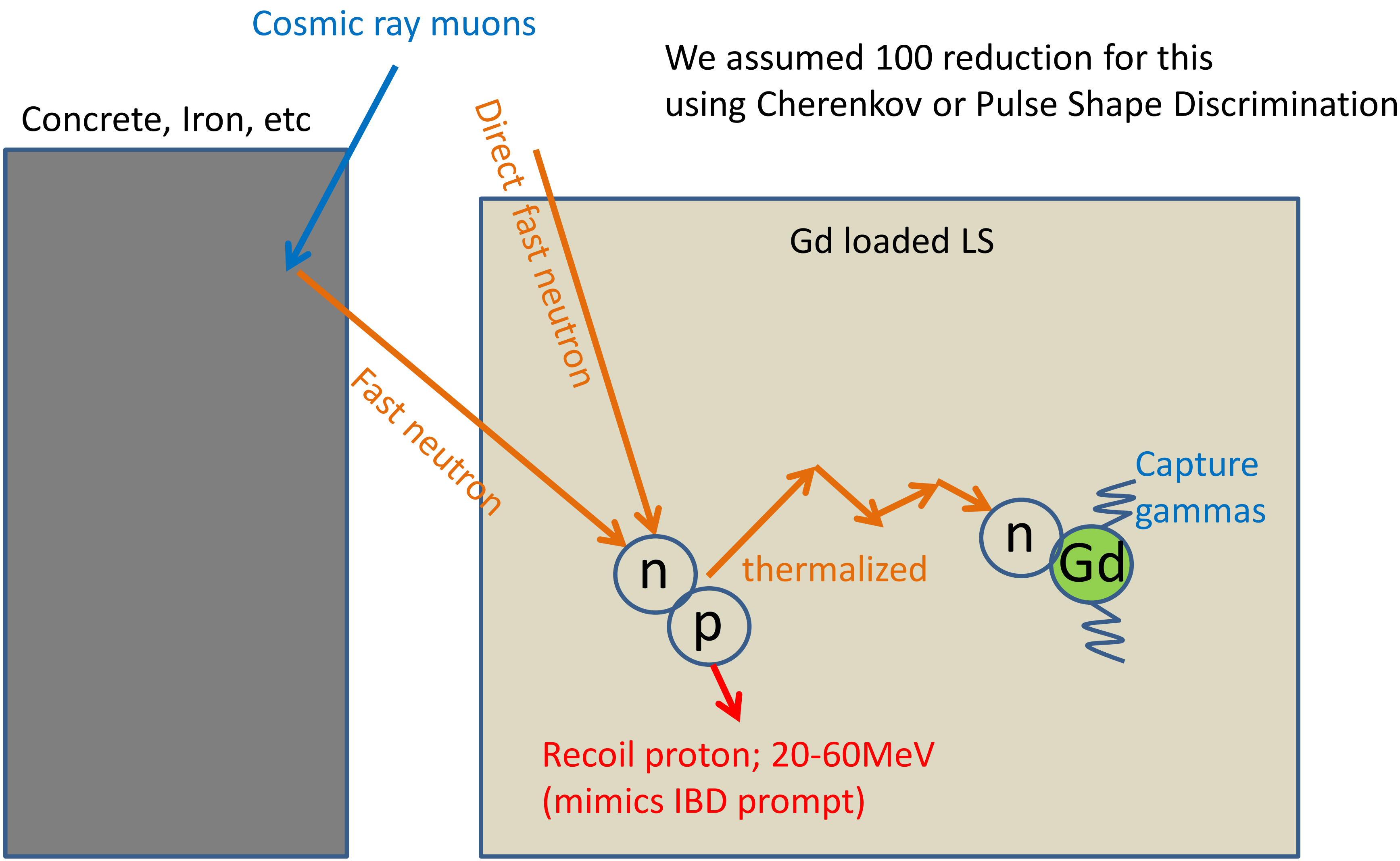
R&D status

(M. Harada et al, arXiv:1507.07076)

This R&D has been supported by

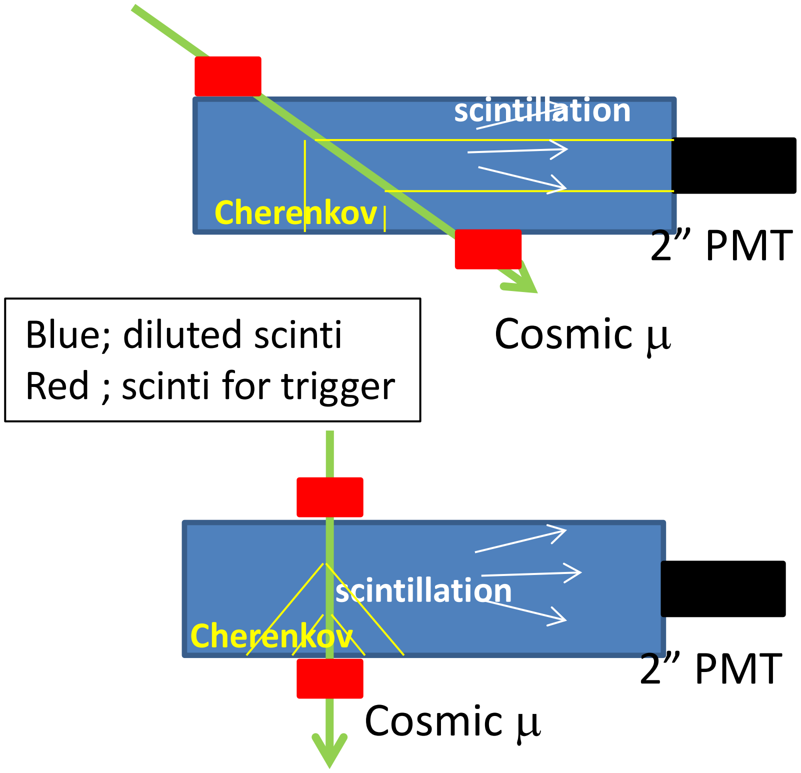
- J-PARC and KEK and
- US/Japan Corporation Program
  (We express warm appreciation)

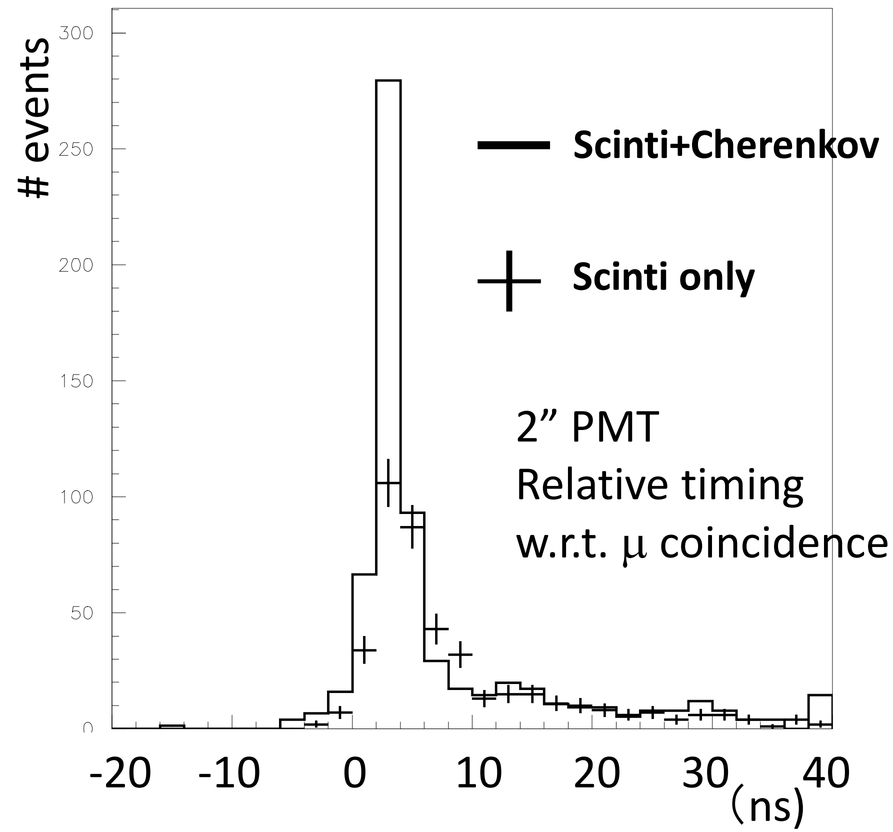
Fast Neutrons from Cosmic Rays



- If recoil protons enter the time window after the 1-10μs, these events can be the correlated background.

Cherenkov test using cosmic μ

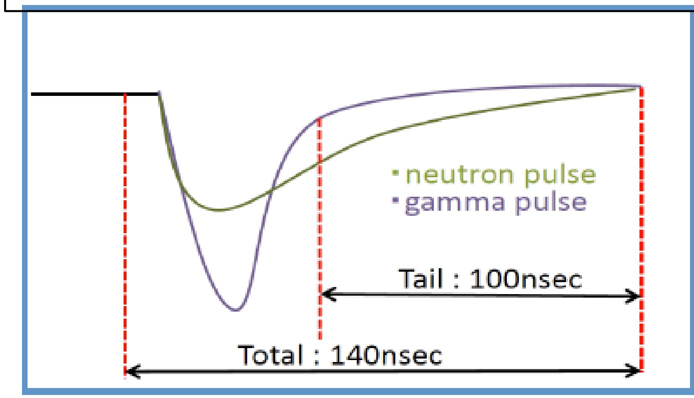




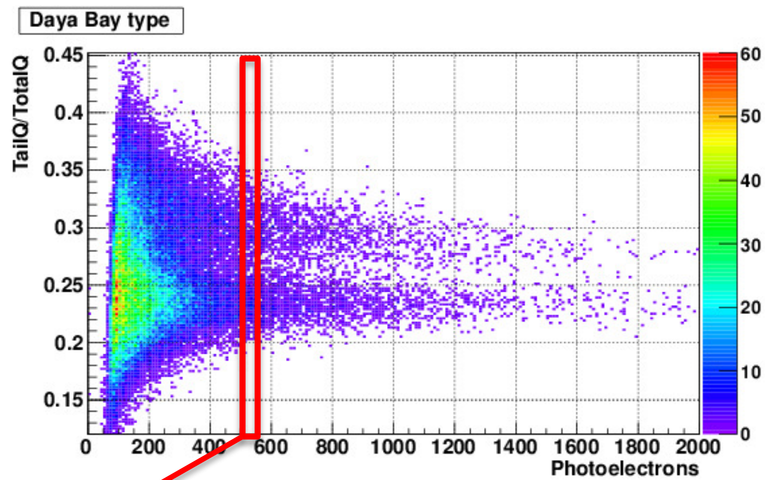
- Excess around fast timing from direct Cherenkov light.
- Amount of the Cherenkov light is similar to the scintillation light. (diluted scintillator → mineral oil + 0.03g/l b-PBD)

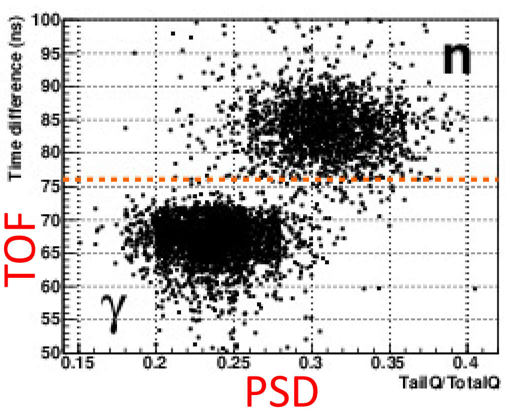
PSD capability test using 100mL LS sample and Cf

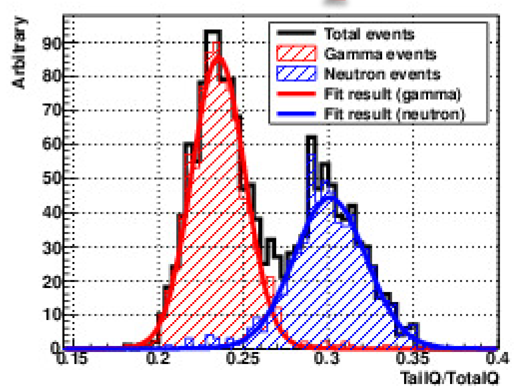
- **PSD → tailQ/totalQ ratio is used**

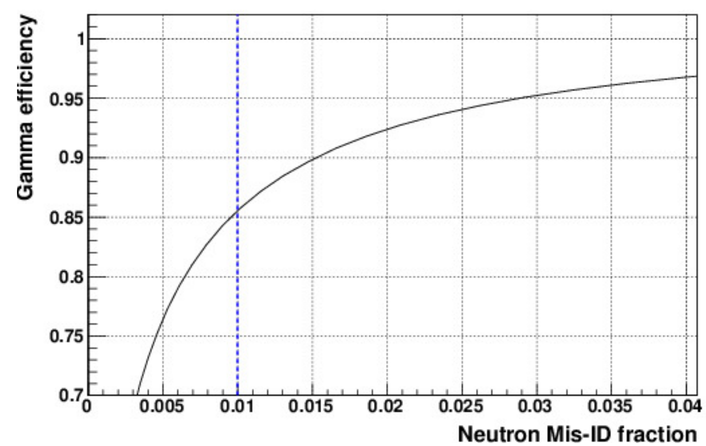


tailQ/totalQ ratio vs detected num of PEs







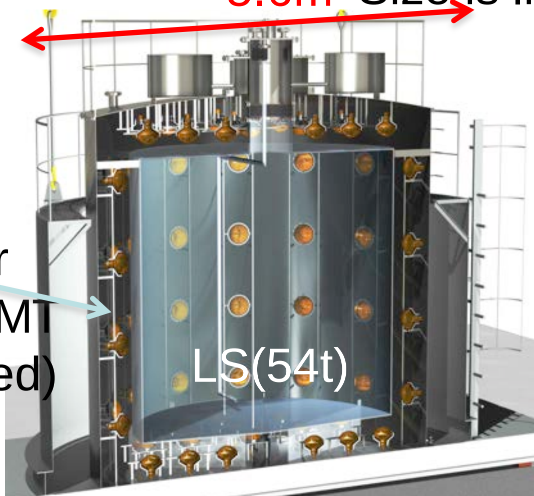


- Daya Bay type LS → good separation between n and γs
- 100 reduction of n vs 85% efficiency of IBD

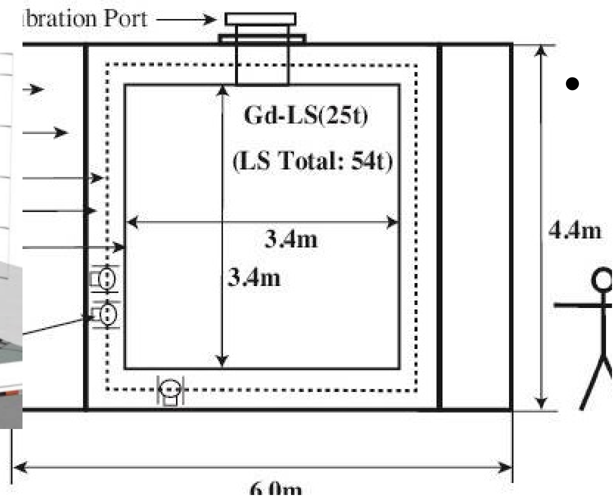
APD (SiPM)

- Motivation

5.6m Size is limited by MLF facility

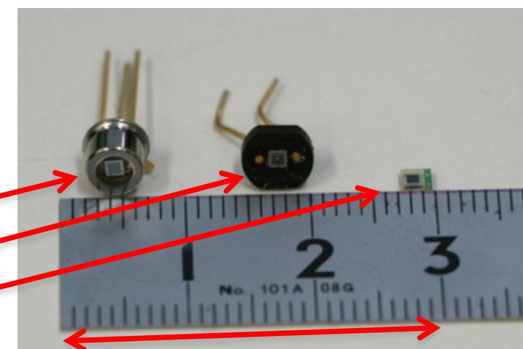


Veto Layer (5” PMT is used)



- 50 x 5” PMT is planned to use for veto region (25cm thick).
- Can the size of photo-detector be reduced?

APD (Avalanche photodiode)



- MPPC

Hamamatsu Photonics

model	Package Type	Pixel	Windows material
S-10362-11-025U	Metal	1600	borosilicate glass
S-10362-33-050U	Ceramic	400	Silicon
S-10362-11-100U	SMD	100	epoxy resin

- Test

Result

Ceramic (standard) type is damaged only one day

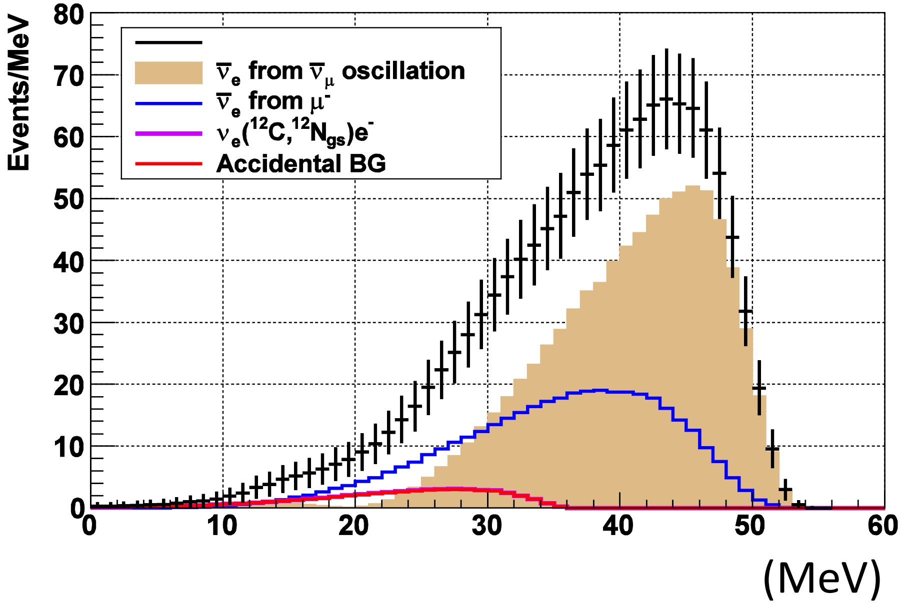
1 Day

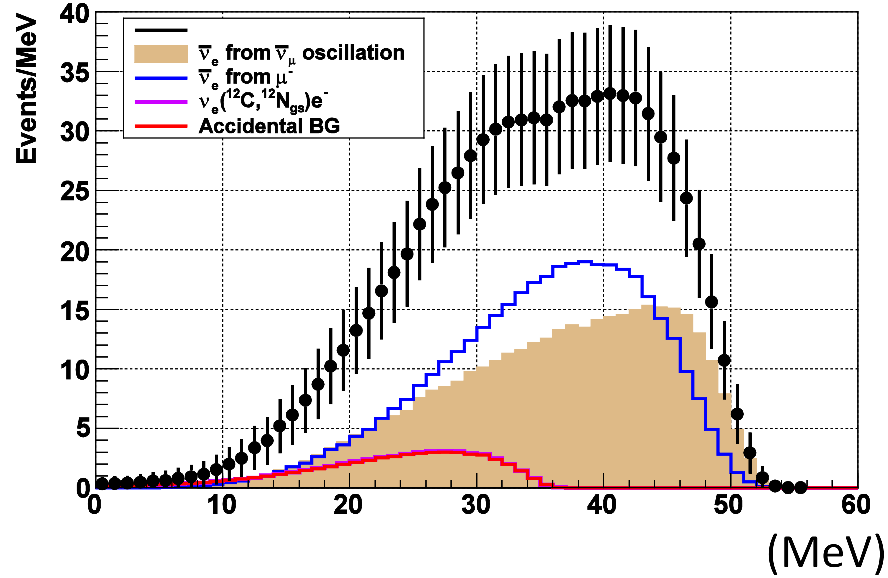
Summary and Prospects

- Searching for sterile neutrinos is one of the hottest topics in the neutrino community.
- JSNS^2 experiment stands at a good position to have a timely results on the anti-$\nu\mu$ → anti-νe appearance mode because
  - direct and complete test for LSND anomaly can be done with much better S/N, and without any excuses.
  - JSNS^2 does not need any new beamlines, detector buildings, detector holes.
  - Already obtained stage-1 approval
  - There are many collaborators who are related to MLF operation, and to construct other similar detectors for the reactor experiment. Welcome more.
  - JSNS^2 has a good complementarity / pros to other experiments
- Now we go forward to have results.

backup

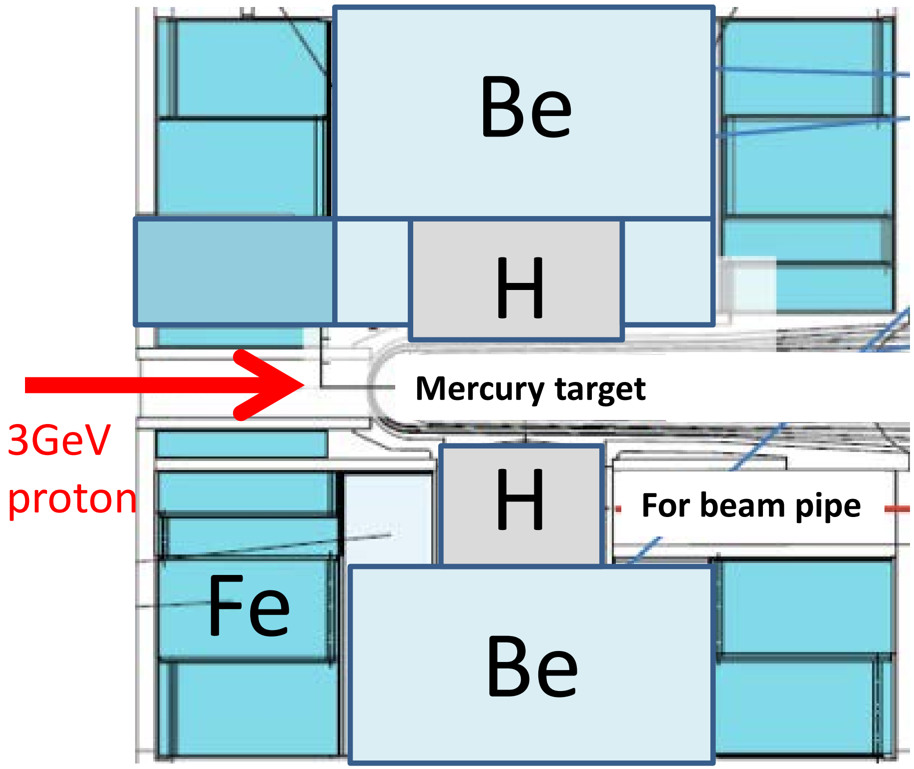
How to fit





- Left; Δm^2=3.0eV^2 (best Δm^2 for MLF) , right; Δm^2=1.2 (LSND best) $\sin^2 2\theta$=0.003
- Simultaneous fit with maximum likelihood with 1MeV bin is used (20-60MeV).
- We use only signal and $\overline{\nu_e}$ from μ^- (Other components are small).
- Uncertainties on the overall normalization is taken into account.
  - 10% for oscillated signal (since we monitor ν_e signal)
  - 50% for $\overline{\nu_e}$ from μ- since MC uncertainty is large.
- Background rate → can be estimated by fit.

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

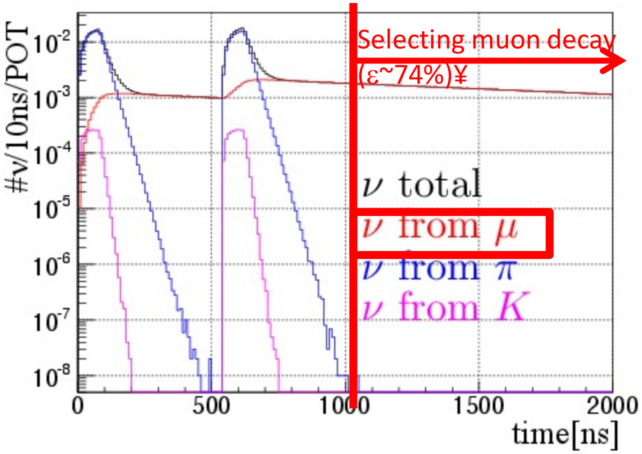


	Target	π^- absorb	μ^- capture	suppression	x	π^-/π^+
LSND	H2O	96%	88%	5×10^{-3}	x	0.13
J-PARC	Hg(+Fe+Be)	99%	~80%	1.7×10^{-3}	x	1.

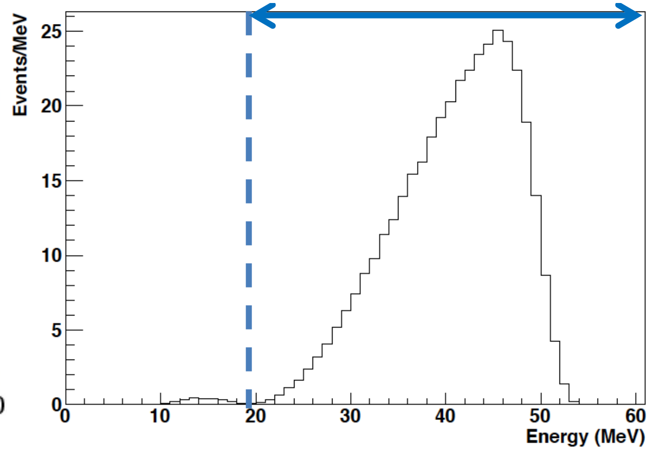
We will assume ~ 1.7×10^{-3} Intrinsic background hereafter.

IBD event selection for signal

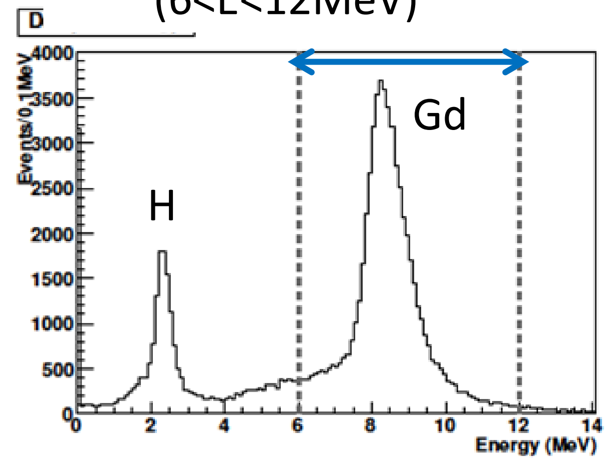
1. Prompt timing cut
(1<Δt<10μs)

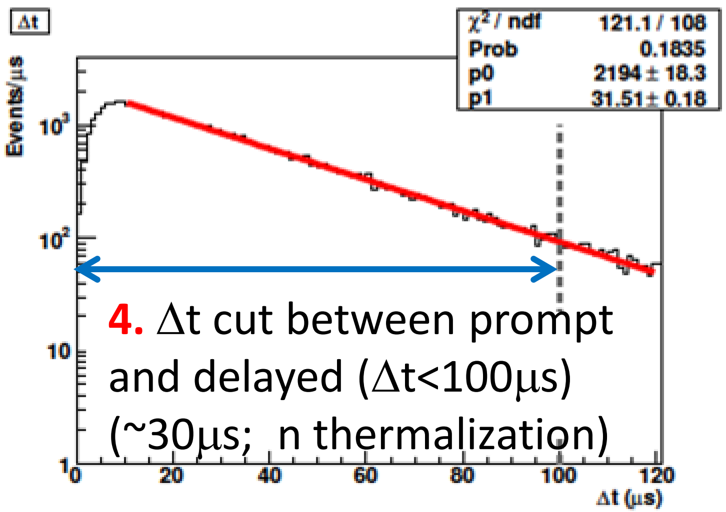


2. Prompt energy cut
(20<E<60MeV)

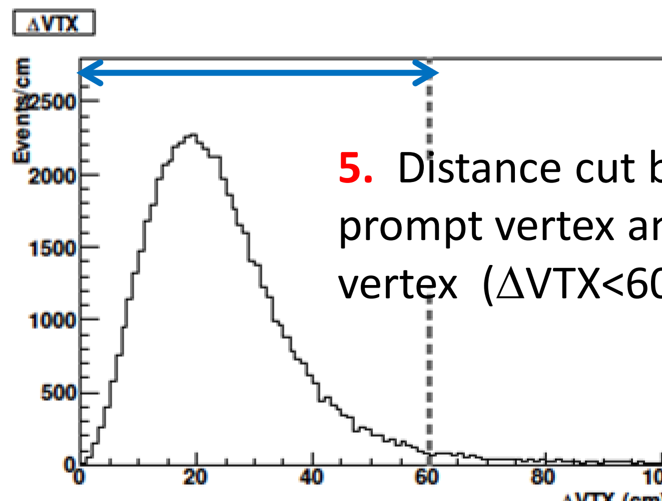


3. Delayed energy cut
(6<E<12MeV)





4. Δt cut between prompt and delayed (Δt<100μs)
(~30μs; n thermalization)



5. Distance cut between prompt vertex and delayed vertex (ΔVTX<60cm)

Total Selection ε ~ 48%

On-site Background measurement (MLF 3F)

Note: Point1 background (upstream)

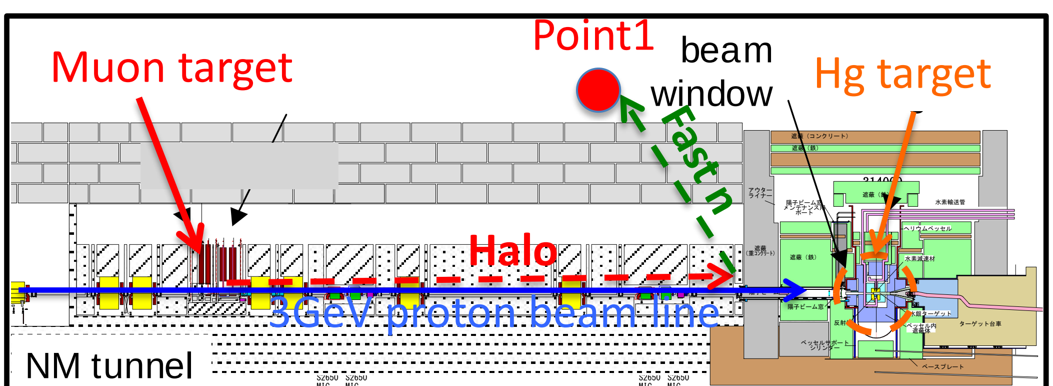
Point1 has large number of activities with high energy. → we measured **with** and **without muon target** for 6mins (~10000spills) at Point1.

Without muon target (special run for test experiment)

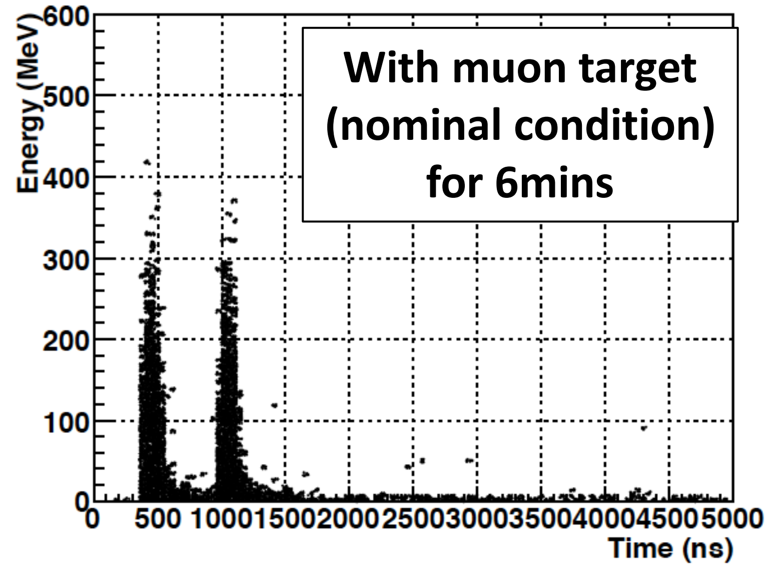
There is no on bunch event above 200MeV.

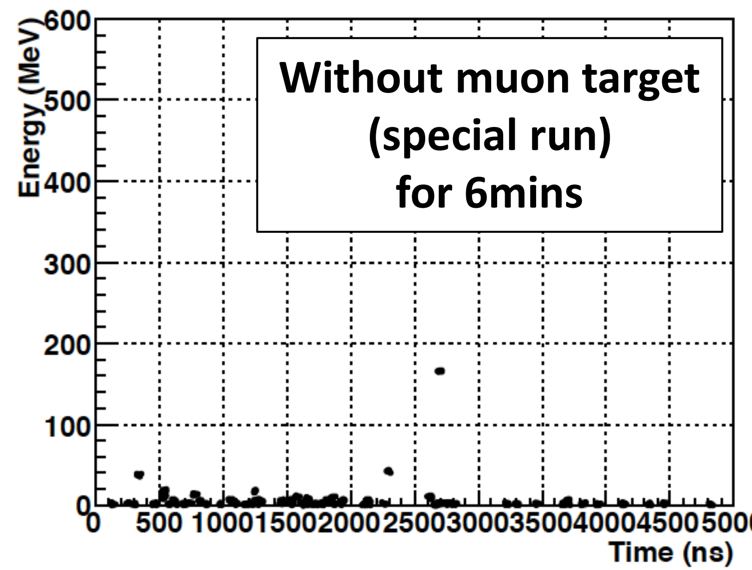
Guess

Proton multiple scattering at the muon target makes larger halo (red dashed line).
=>The halo makes fast n (green dashed line) at the shield around the Hg target.
=>To pass through until 3F is easier for the fast n.
(Not including iron shield inside the pass comparing to shields around Hg target.)



Energy vs Time at Poin1





Comments on phase2

- If we saw the signal, the phase-2 experiment will be performed with longer baseline and larger detector. (E.g.: 60m + ~1000 ton) to have a precision physics
  - Using $\nu_\mu \rightarrow \nu_e$ oscillation using the current detectors as near detectors.
  - Using ν_e disappearance (μDAR: $\mu^+ \rightarrow e^+ \nu_\mu \nu_e$) using current detectors as a near detectors.
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