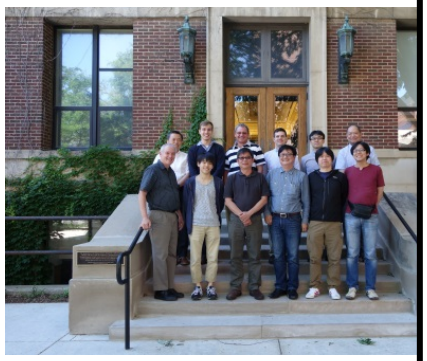
Searching for a Sterile Neutrino at J-PARC MLF (JSNS^2 / J-PARC E56)

JSNS^2: J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source (E56)

Takasumi Maruyama (KEK)
for JSNS^2 collaboration



Collaboration meeting on 28,29-Jun-2016@UMichigan

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Searching for a Sterile Neutrino at J-PARC MLF (E56, JSNS^2)

July 29, 2016

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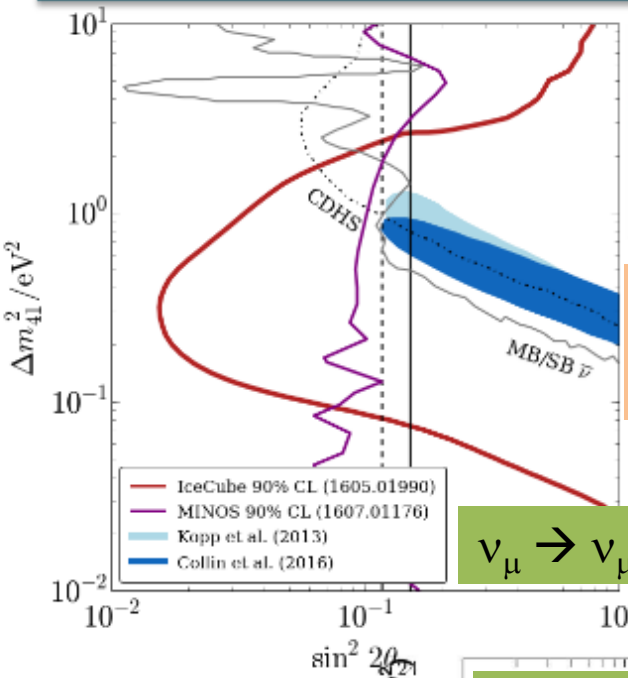
Status of the sterile neutrino search

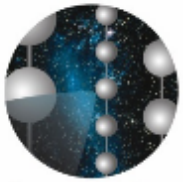
- Anomalies, which cannot be explained by standard neutrino oscillations for 15 years are shown;

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?

No positive results on steriles





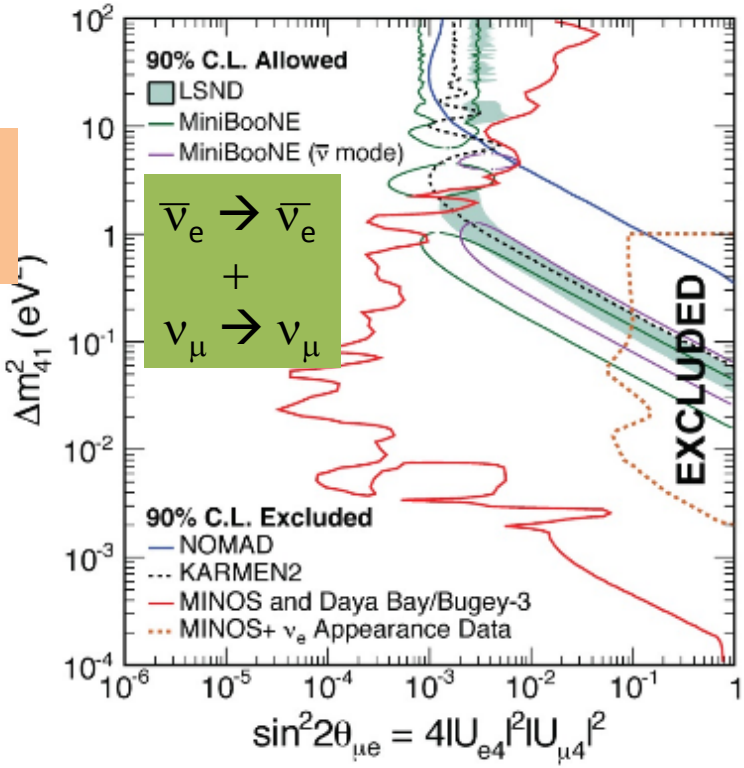
IceCube

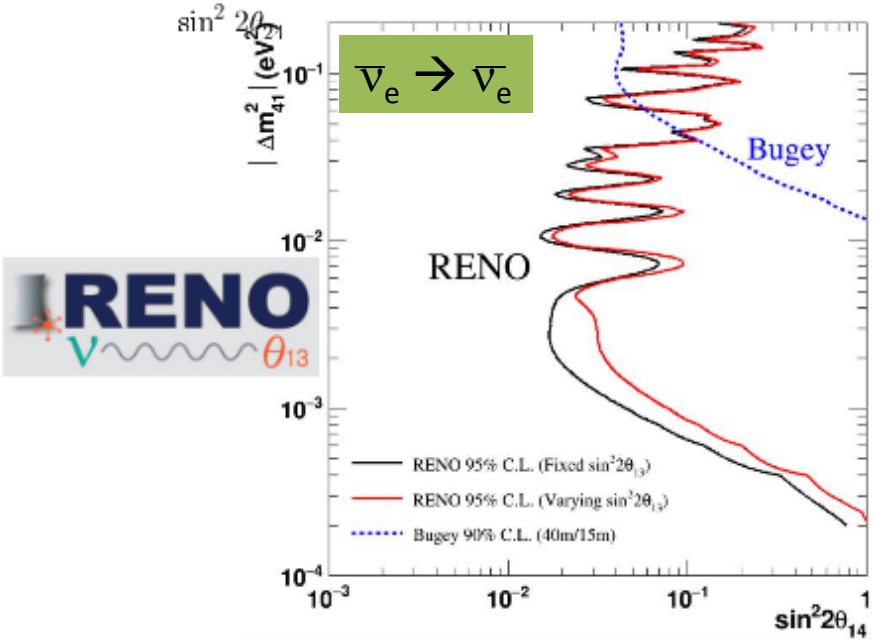
Mauro Mezzetto's (experimental summary) talk in Neutrino2016

$\nu_\mu \rightarrow \nu_\mu$

3+1 model checking

Daya Bay, Minos and Bugey 3 combined

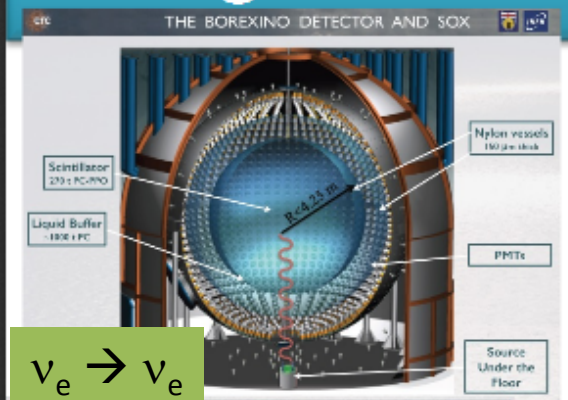




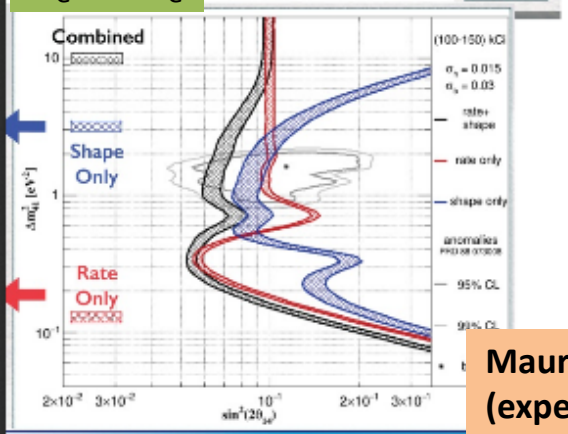
→ Is it time to check the LSND result directly without any excuses?

→ JSNS²

Next generation sterile experiments are almost ready



$\nu_e \rightarrow \nu_e$



$\bar{\nu}_e \rightarrow \bar{\nu}_e$

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea)	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA)	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia)	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA)	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US)	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA)	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France)	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Mauro Mezzetto's (experimental summary) talk in Neutrino2016

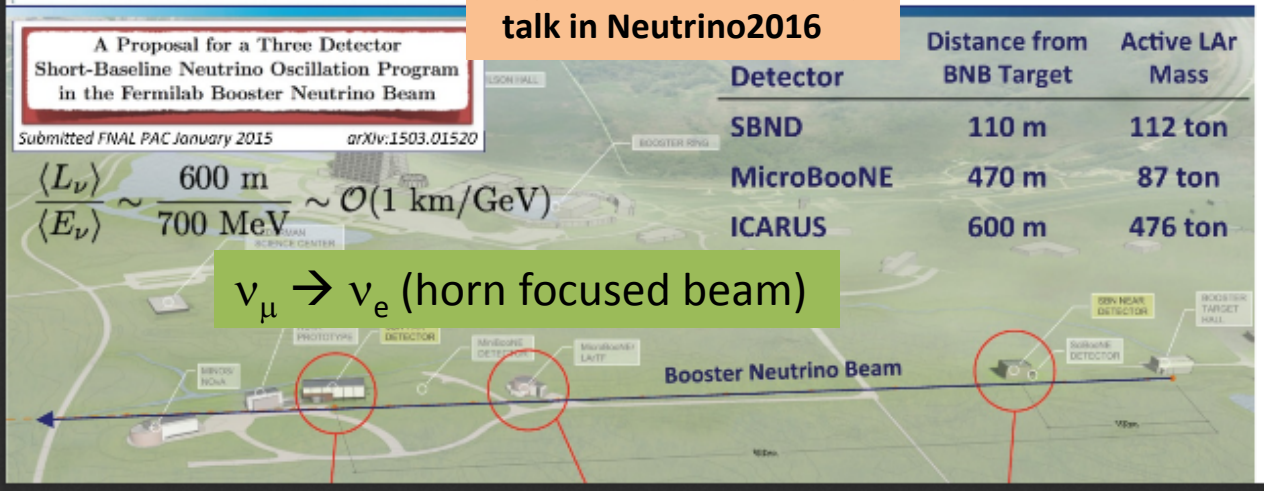
A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

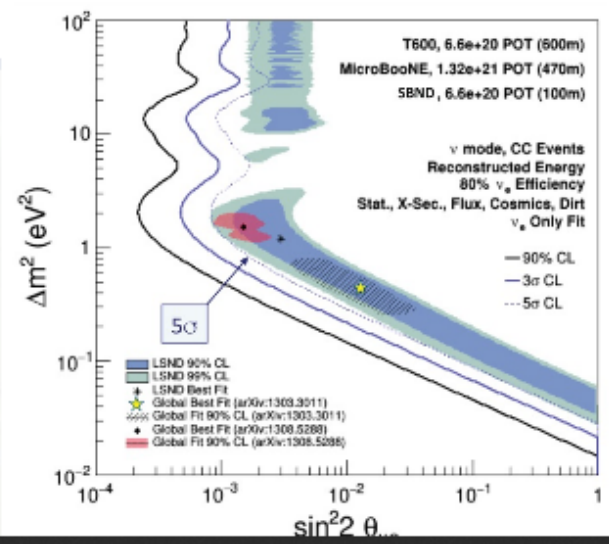
Submitted FNAL PAC January 2015 *arXiv:1503.01520*

$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \text{m}}{700\ \text{MeV}} \sim \mathcal{O}(1\ \text{km/GeV})$$

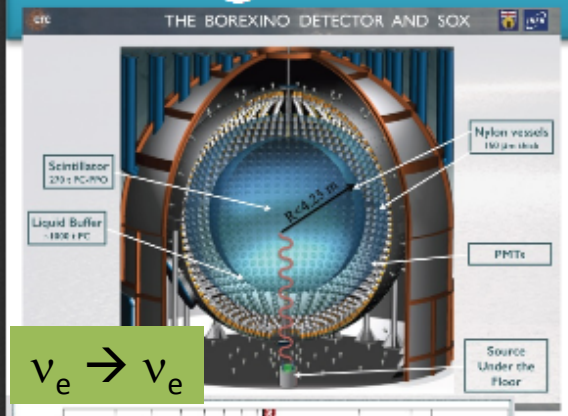
Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

$\nu_\mu \rightarrow \nu_e$ (horn focused beam)

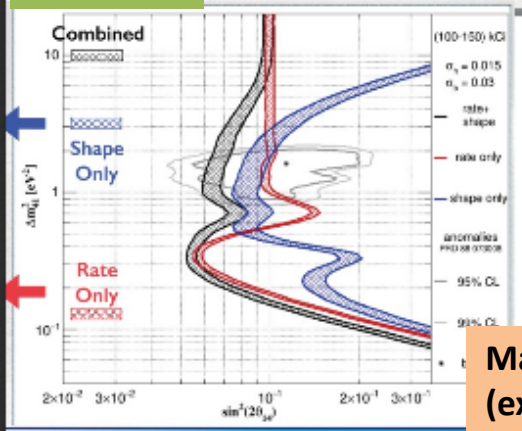




Next generation sterile experiments are almost ready



$\nu_e \rightarrow \nu_e$



$\bar{\nu}_e \rightarrow \bar{\nu}_e$

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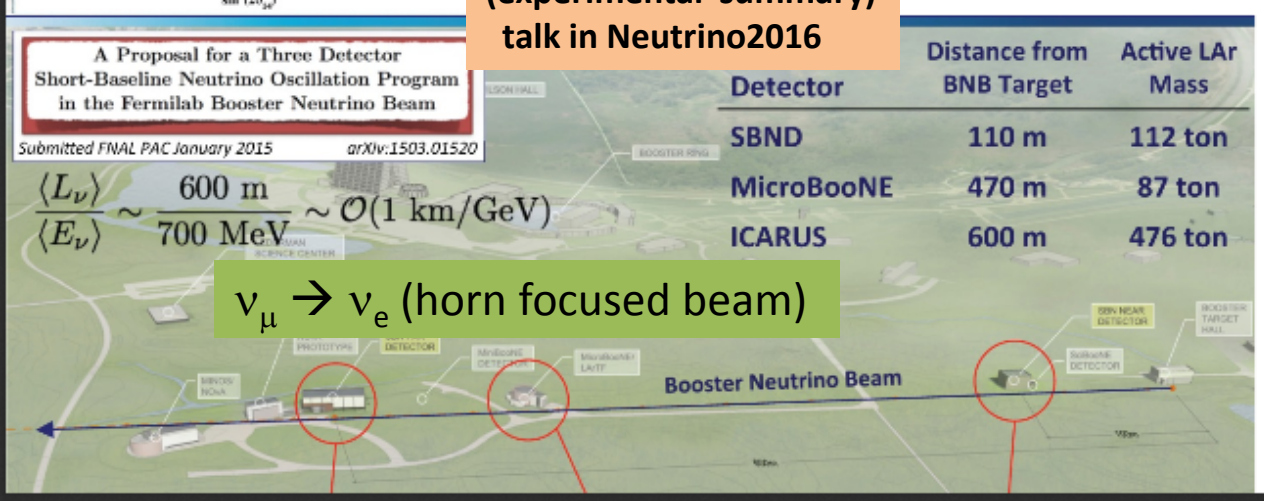
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]0cm	Direct single ended PMT	Topology only
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]cm	Direct double ended PMT	Topology, recoil & capture PSD
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]3D, 5cm [illegible]lex	WLS fibers	topology, capture PSD
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]3D, 5cm, [illegible] Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
(France)	[illegible] U fuel		Gd-doped LS	[illegible]cm	Direct single ended PMT	recoil PSD

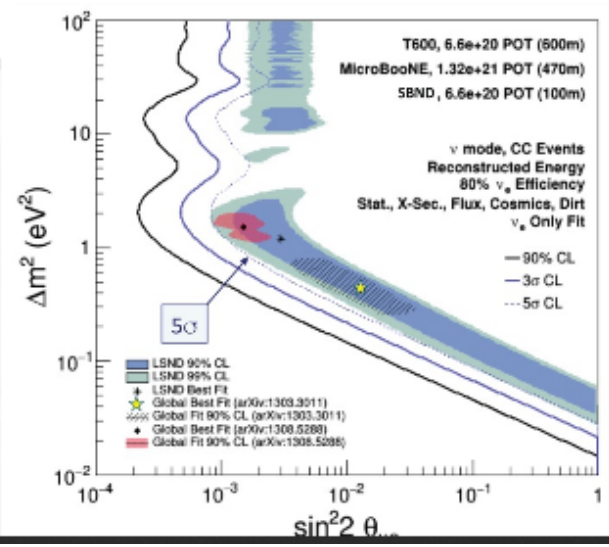
→ Is it time to check the LSND result directly without any excuses?

→ JSNS²

Mauro Mezzetto's (experimental summary) talk in Neutrino2016

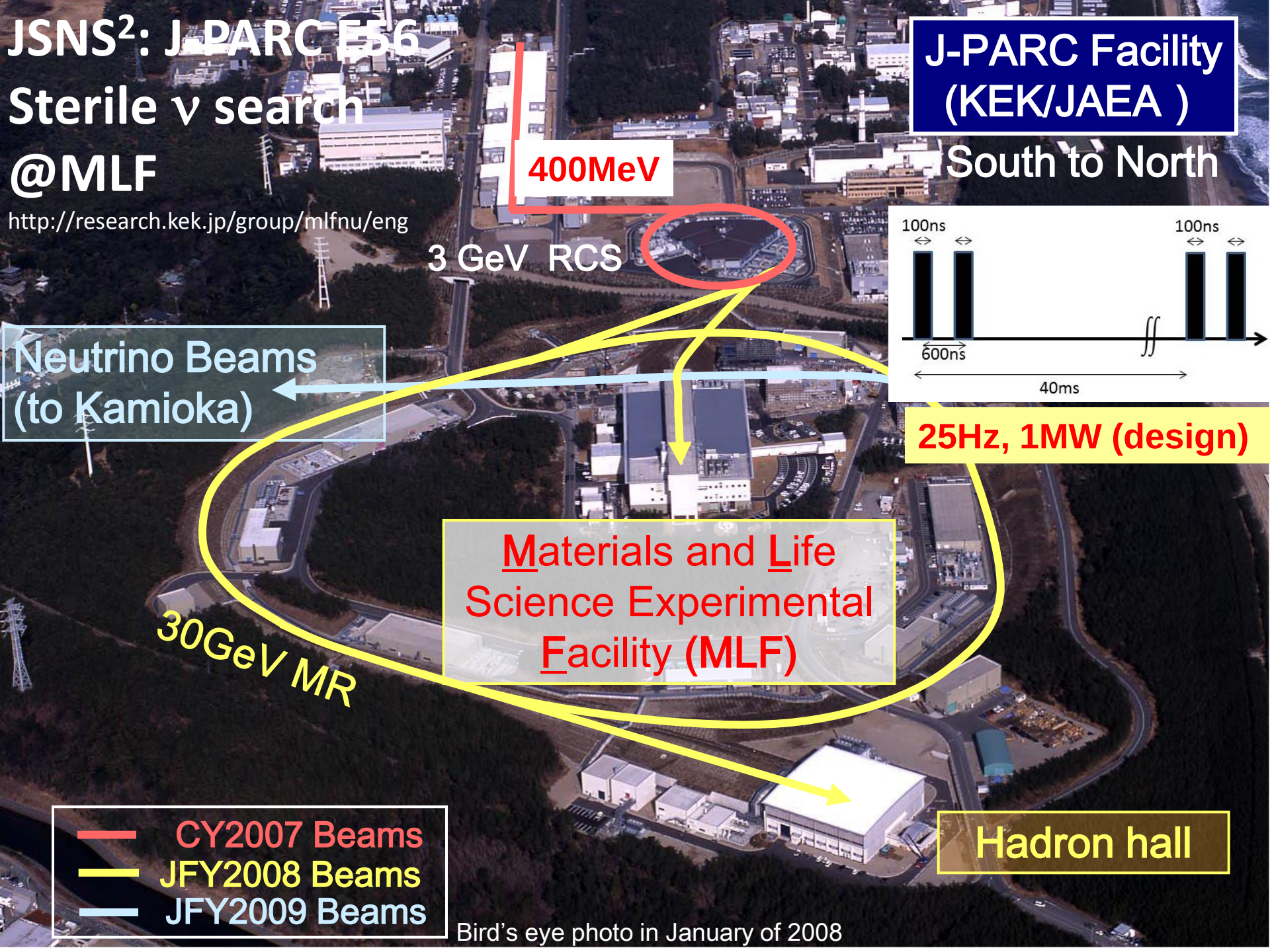


$\nu_\mu \rightarrow \nu_e$ (horn focused beam)



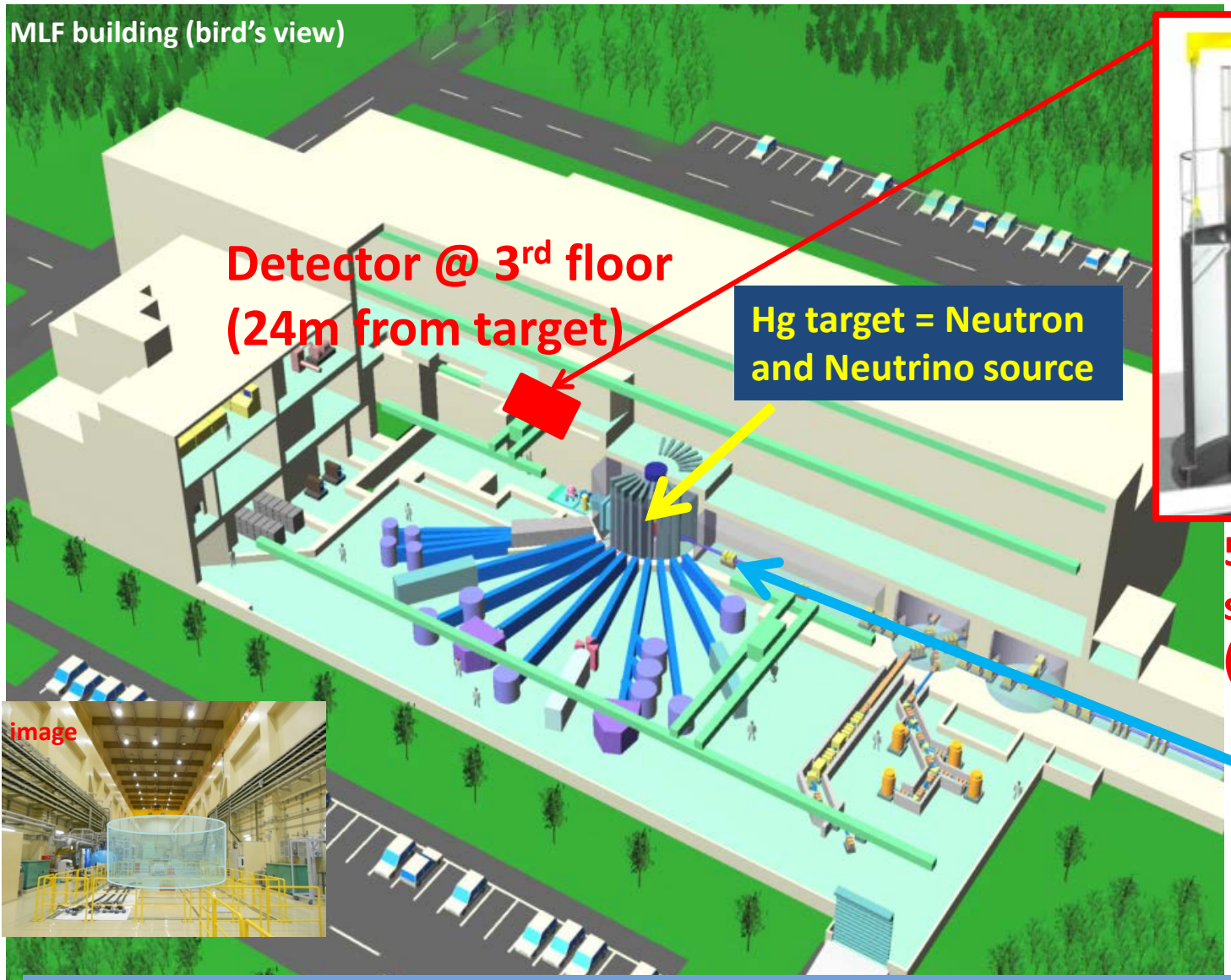
JSNS^2: J-PARC E56 Sterile ν search @MLF

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



Bird's eye photo in January of 2008

J-PARC MLF : World best environment



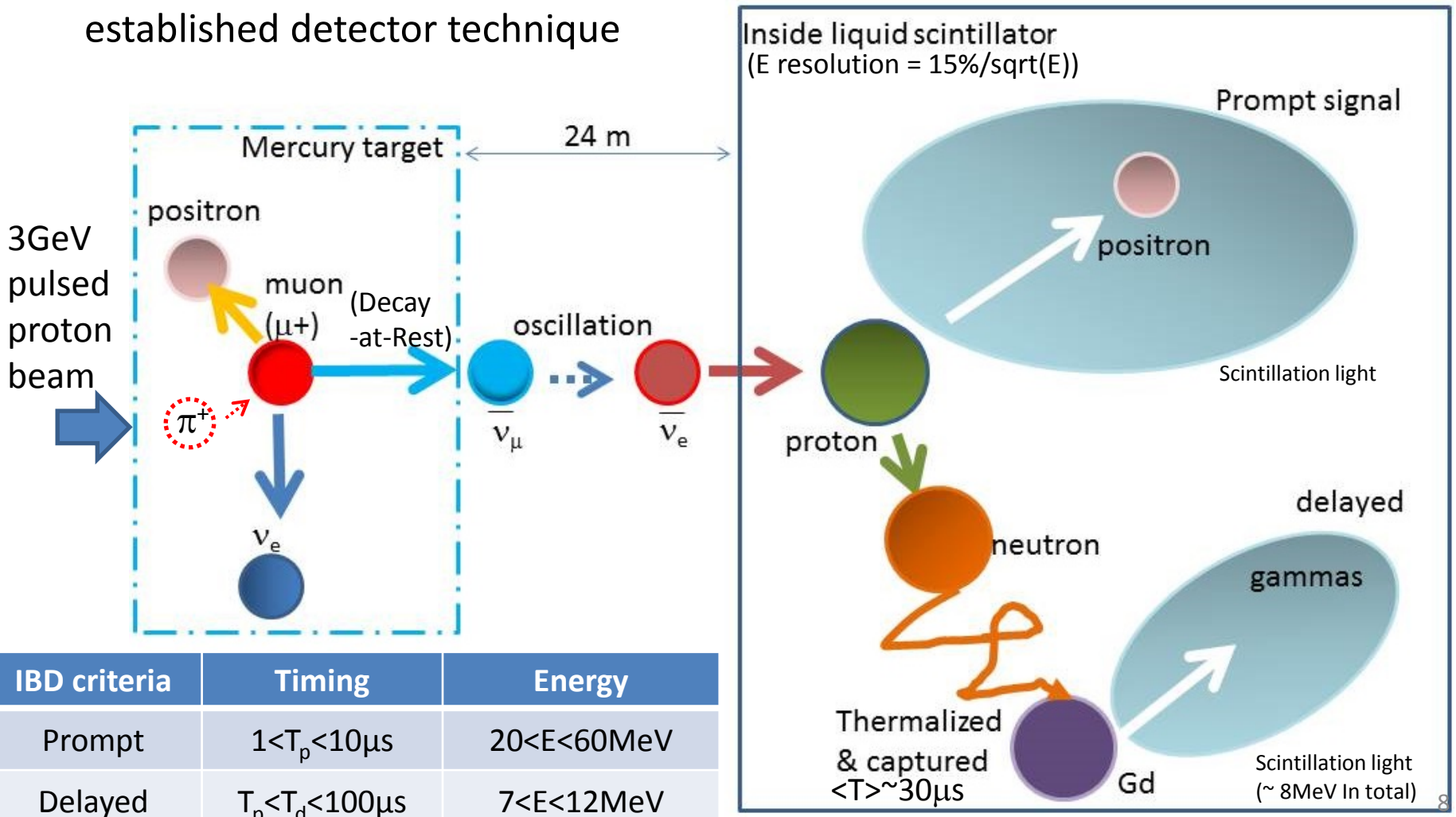
50t Gd-loaded liquid scintillator detector (4.4m diameter x 4.4m height) 150PMTs

3GeV pulsed proton beam

Searching for neutrino oscillation : $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up

Production / Detection

- Large amount of parent μ+ in Hg target → $\bar{\nu}_\mu$ are produced.
- If sterile ν exist, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation is happened with 24m.
- Oscillated $\bar{\nu}_e$ is detected by Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$ w/ well established detector technique



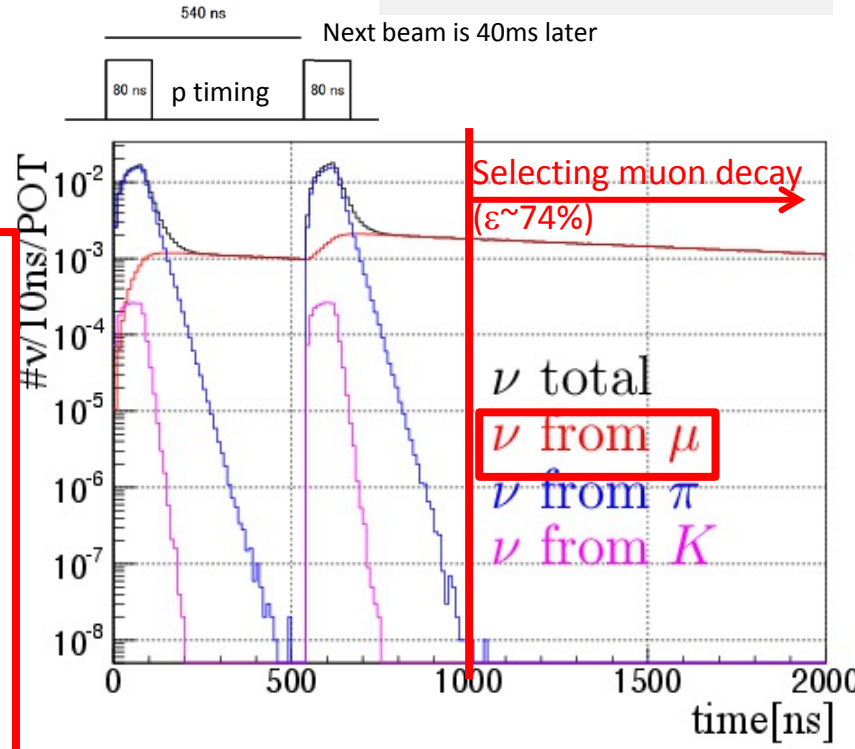
IBD criteria	Timing	Energy
Prompt	$1<T_p<10\mu s$	20<E<60MeV
Delayed	$T_p<T_d<100\mu s$	7<E<12MeV

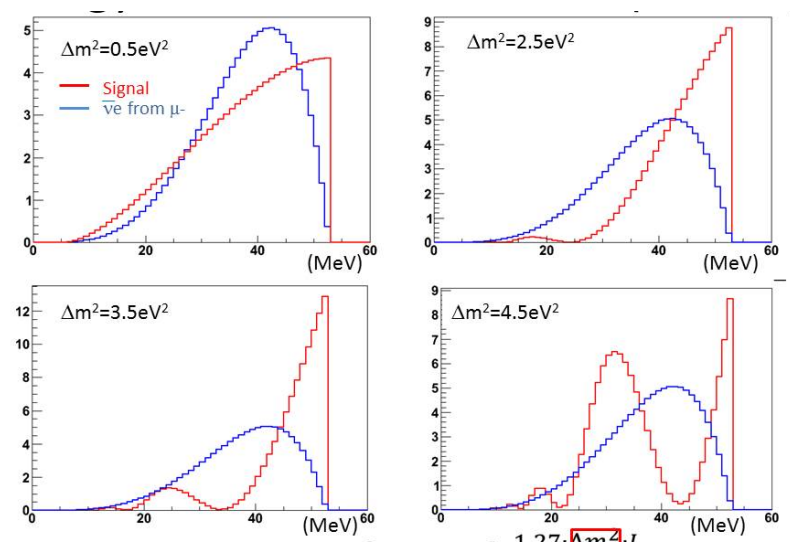
Timing and Energy

M. Harada *et al*, arXiv:1310.1437

Timing and Energy are friends of JSNS²

- Timing: Ultra-pure ν from μ^+ Decay-at-Rest
  - ν from π and K -> removed with timing
  - Beam Fast neutrons -> removed w/ time
  - Cosmic ray BKG -> reduced by 9μs time window.
- Energy: signals / BKG separation by energy.
  - ν from μ has well-known spectrum.
  - Energy reconstruction is very easy at the IBD. (Eν ~ Evis + 0.8MeV)
  - ν from μ- is high suppressed.

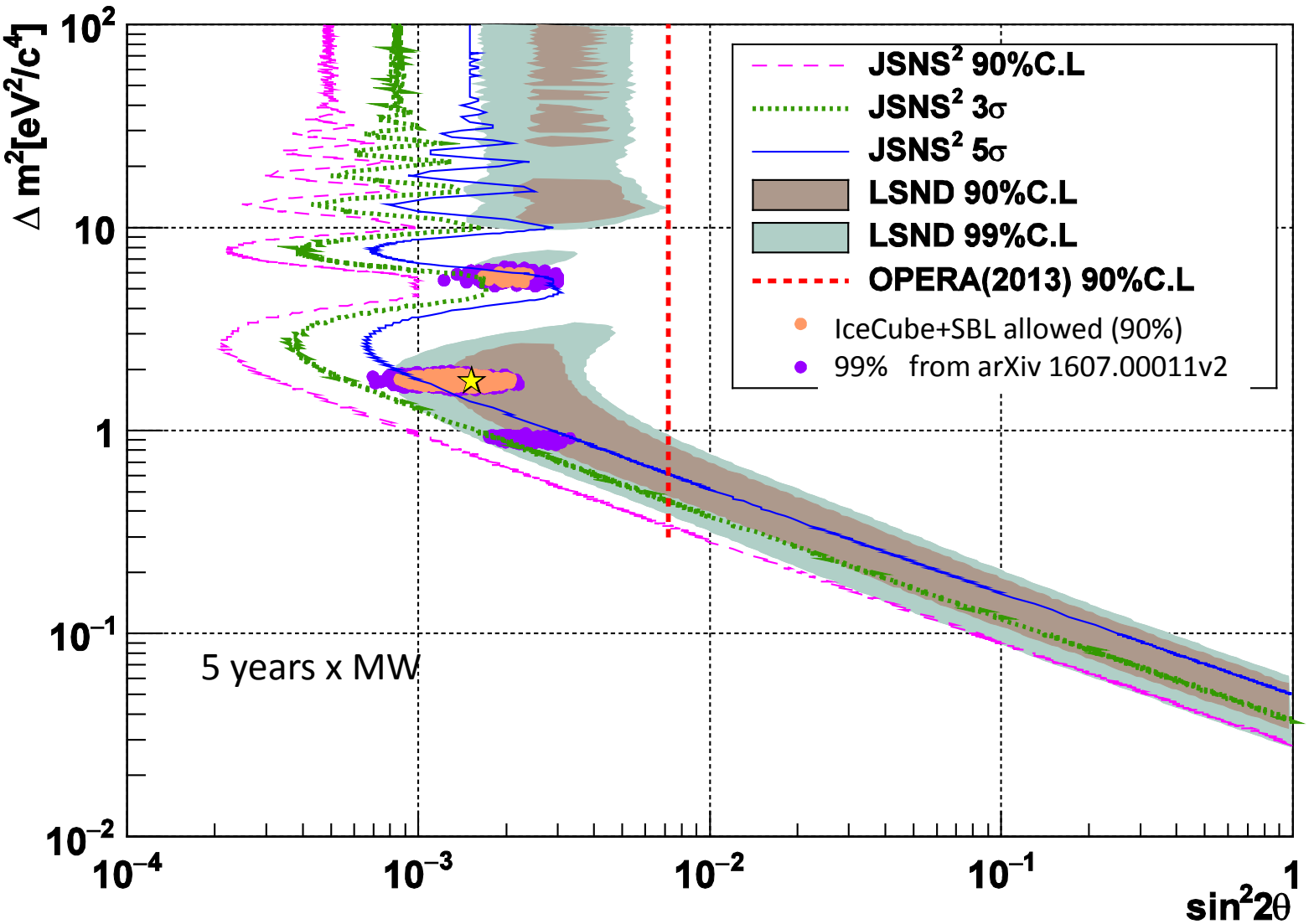




$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

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

Sensitivity of JSNS^2



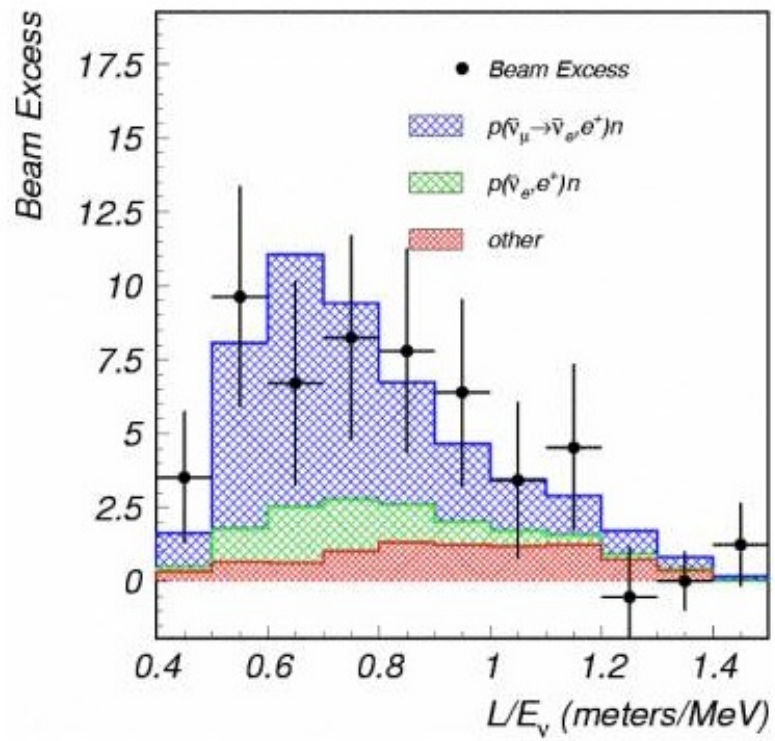
If we could see the hints ~ 3σ, we consider the phase2 experiment (w/ a bigger detector)

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
    - 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 at MLF.

As mentioned before

  - Detector has many improvements;
    - Gd-LS improves S/N ratio at MLF → time window of coincidence (factor 6) and delayed Energy. (2.2 → 8MeV)
    - Faster sampling rate of electronics and improved LS make PID easy at MLF.

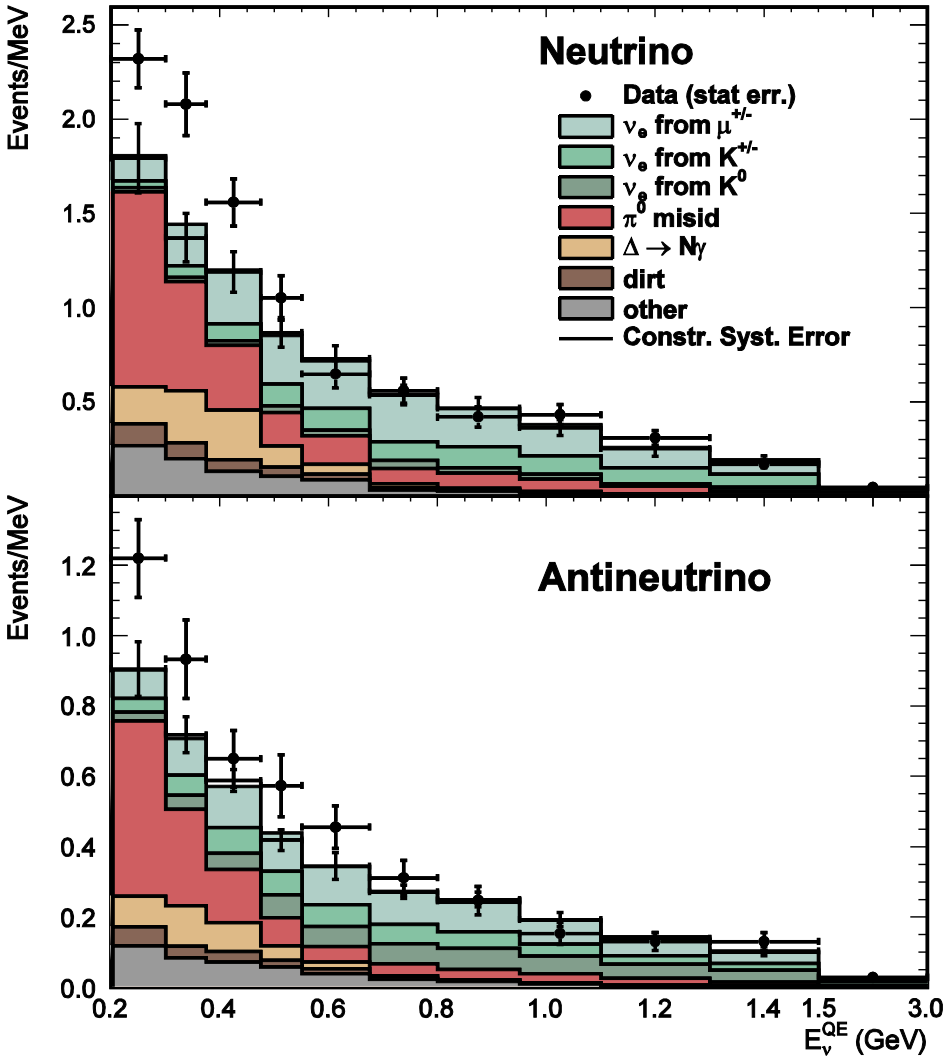


- vs KARMEN → JSNS^2 has more intense ν flux by >10 times + Gd-LS

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 at MLF (Eν ~ Evis + 0.8MeV in IBD)
  - Signal normalization ~10% level at MLF.

As mentioned before

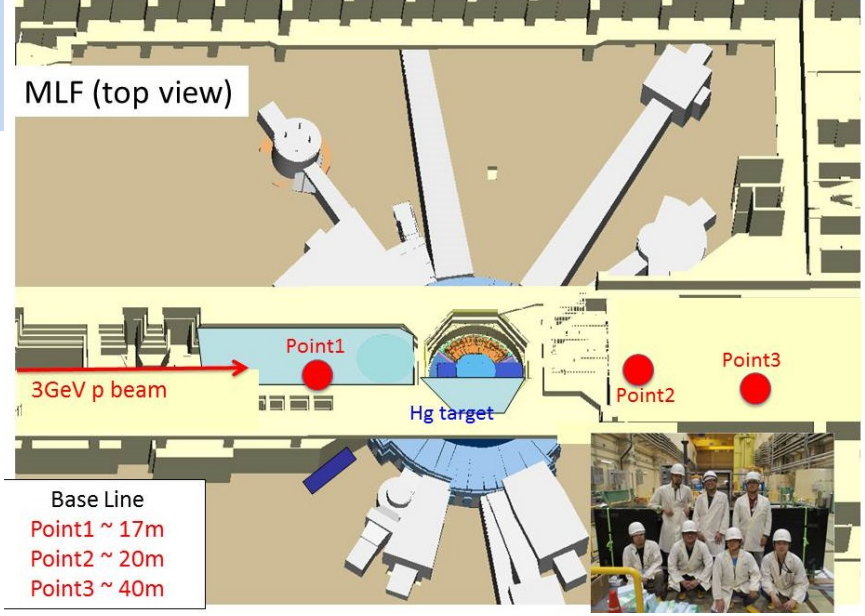


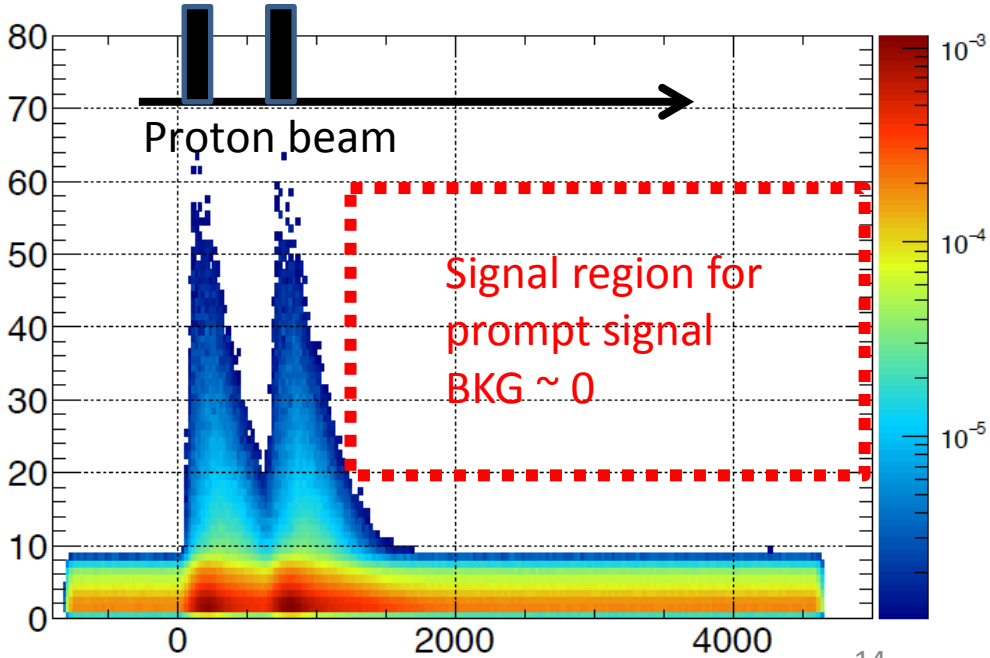
Complementarity

- to reactor / radiation source experiments
  - Disappearance measurement vs appearance (JSNS^2)
- to ν_μ disappearance
  - Disappearance vs appearance
- to FNAL SBN programs (LAr TPCs + horn focused beam)
  - $\nu_\mu \rightarrow \nu_e$ oscillation vs $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation (JSNS^2)
  - JSNS^2 aims 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. ($E\nu$ ~ Evis + 0.8MeV in IBD) : similar to MiniBooNE case.

Achievements so far

- 2013 Sep; A proposal was submitted to the J-PARC PAC
- 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; The result was reported to J-PARC PAC. → the stage-1 status was obtained from J-PARC /KEK
- The performance check of detector and safety discussions are being performed.
- **2016-June: The grant-in-aid is approved for one detector construction (140Myen)**
  → aim to start JSNS^2 in JFY2018





Energy (MeV, vertical) vs timing (ns, horizontal)

#events (1MW x 5 years x 2 detectors)

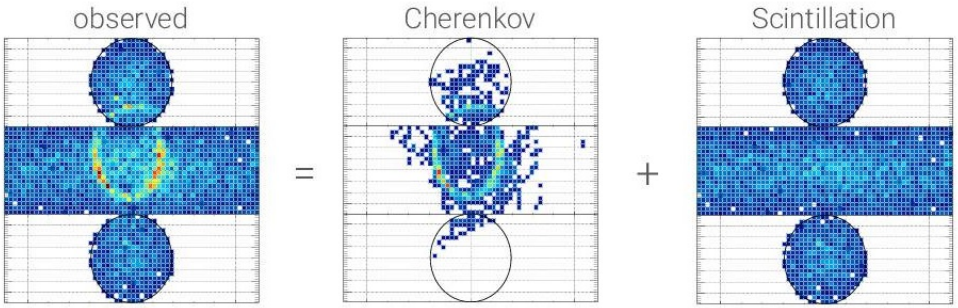
Source	contents	#ev./50tons/5years	comments
background	$\overline{\nu}_e$ from μ-	237	Dominant BKG
	$^{12}C(\nu_e,e-)^{12}N_{g.s.}$	16	
	Beam fast neutrons	**Consistent with 0 < 13 (90%CL UL)**	**Based on real data**
	Fast neutrons (cosmic)	37	
	Accidental	**32**	**Based on real data**
signal		480	Δm^2=2.5,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

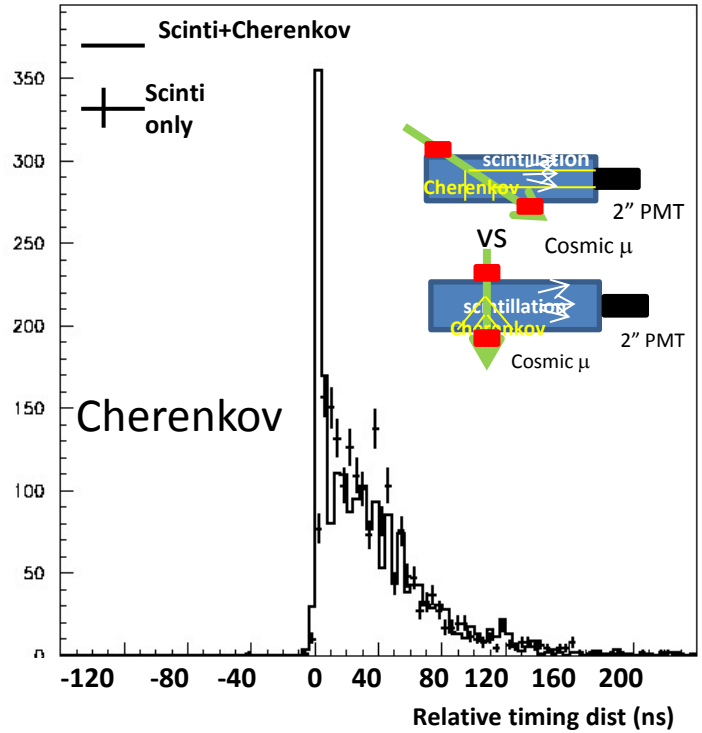
Accidental BKG is calculated by; $R_{acc} = \Sigma R_{prompt} \times \Sigma R_{delay} \times \Delta_{VTX} \times N_{spill}$

- 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 for detector

M. Harada et al, arXiv:1601.01046
M. Harada et al, arXiv:1507.07076

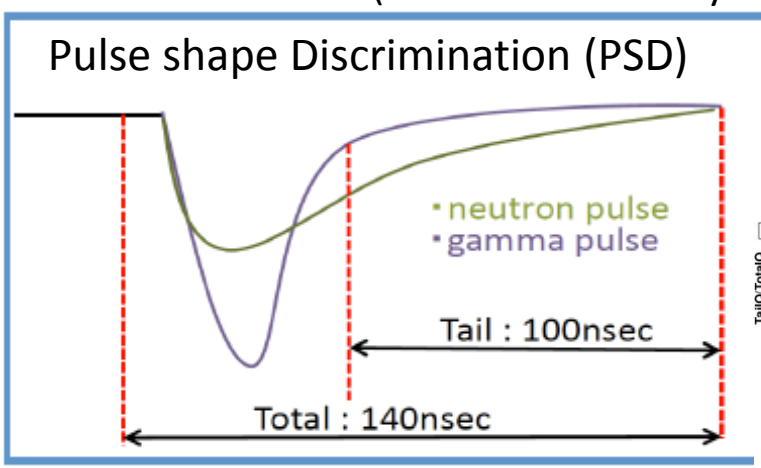




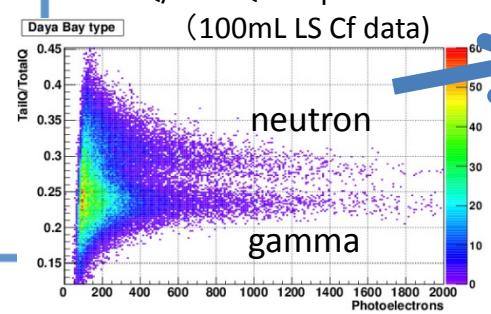
We aim to have

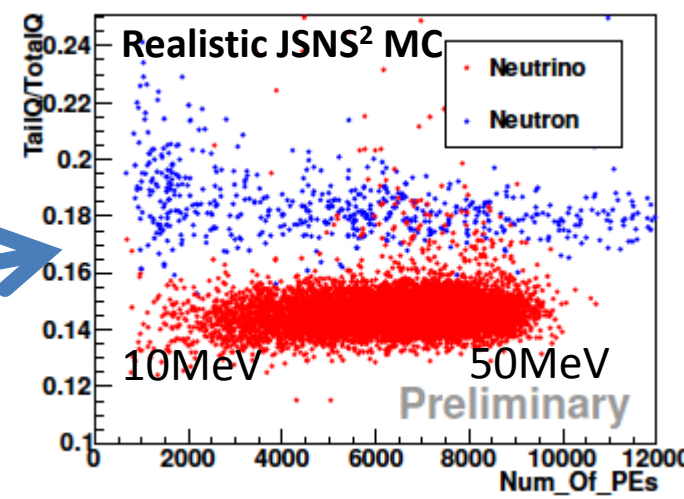
Good energy resolution and
Good fast neutron rejection
at the same time.

- With Cherenkov technique → recoil protons do not have but signal (IBD positrons) have Cherenkov. They have faster timing than scintillation.
- With Pulse Shape Discrimination (PSD) → a concept is shown below. (Full likelihood analysis will also be used)



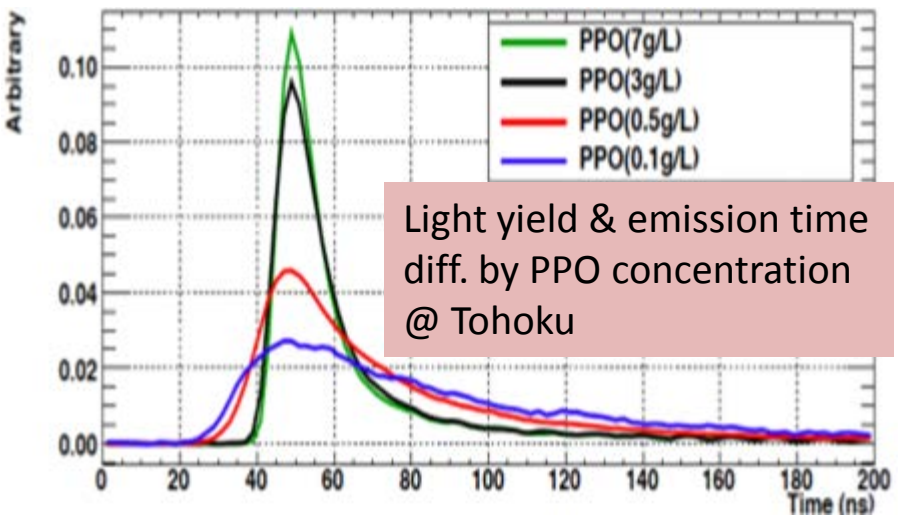
tailQ/totalQ vs #p.e.
(100mL LS Cf data)



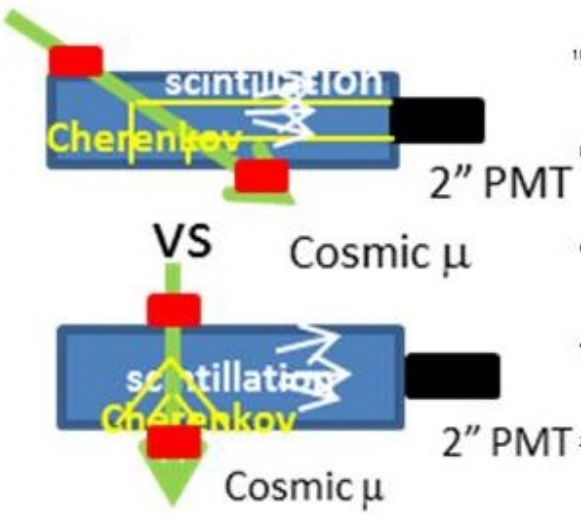


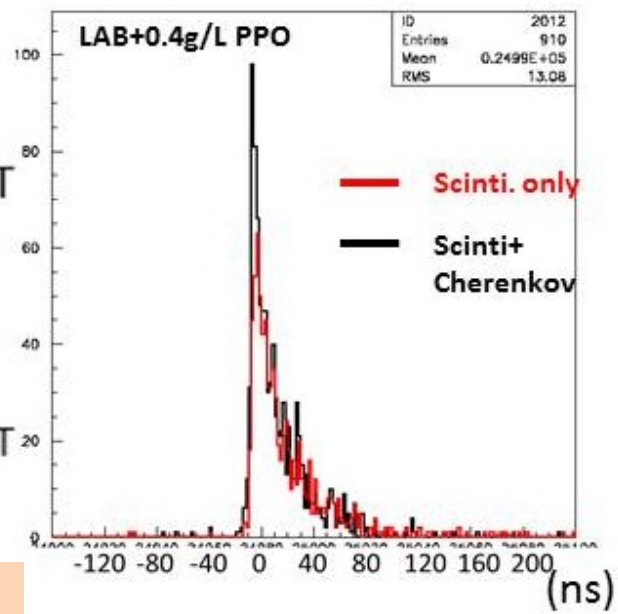
PSD + Cherenkov (LAB+0.5g/L PPO)

- Top-right: PPO (2nd light emission material) density dependence of light yield and emission time.
- The LAB + 0.5g/L PPO → good candidate to use both PSD (bottom-right) and Cherenkov (bottom-left) at the same time.
- Now we are checking the capability with these combination using a MC.

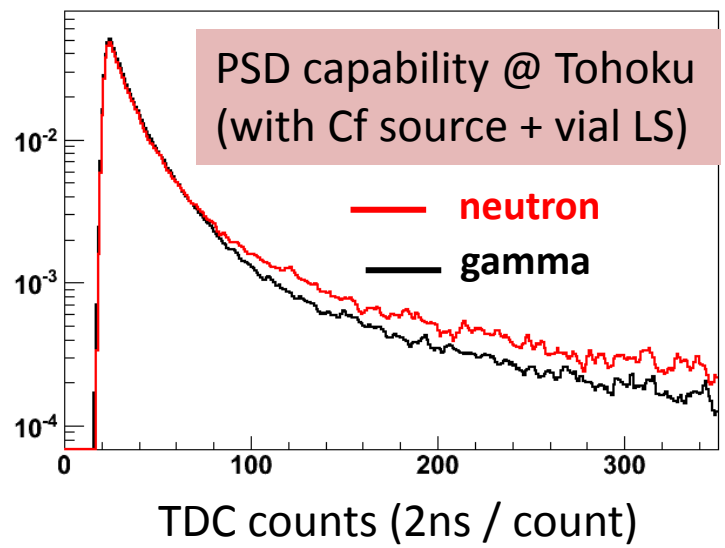


Light yield & emission time diff. by PPO concentration @ Tohoku





Cherenkov capability@KEK

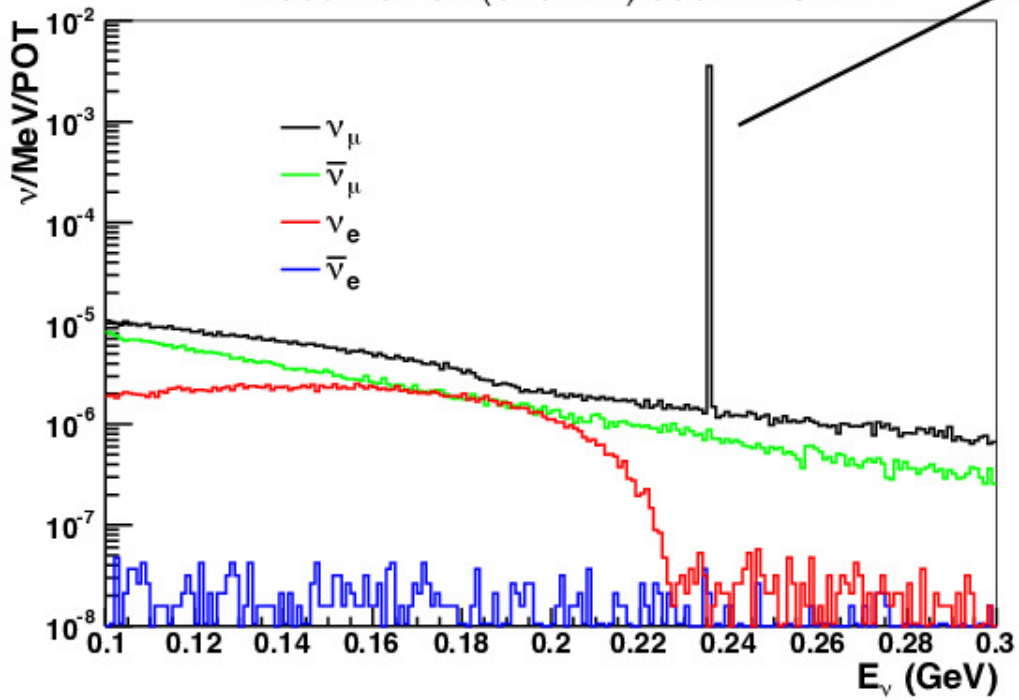


PSD capability @ Tohoku (with Cf source + vial LS)

JSNS^2 physics: Cross section measurements with monoenergetic muon neutrinos

236 MeV ν_μ from $K^+ \to \mu^+\nu_\mu$ (BR=63.6%) decay at rest

Neutrino flux (over 4π) at JPARC-MLF

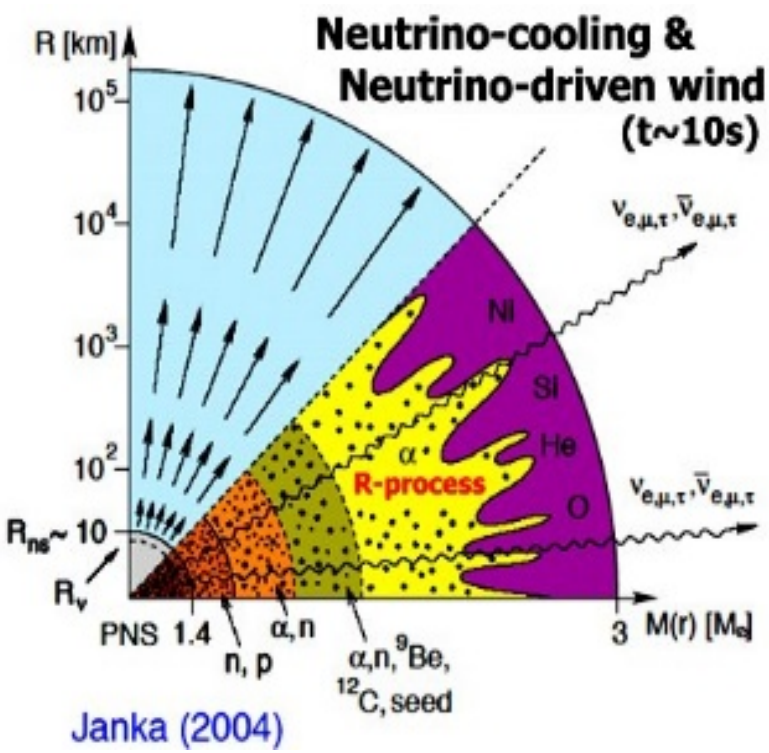


- Use this neutrino as a probe of the nucleus and as a standard candle for xsec and energy reconstruction near 236 MeV.
- For the first time ever:
  - 1. probe the nucleus with a known-energy, weak-interaction-only particle.
  - 2. measure ω (energy transfer) with neutrinos as a test of the underlying nuclear model.

Event rate expectation

Detector (source)	Target (mass)	Exposure	Distance from source	236 MeV ν_μ CC events
JSNS^2 (JPARC-MLF)	Gd-LS (50 ton)	1.875×10^{23} POT (5 years)	24 m	152000

Neutrino-nucleus interaction in Type-II SN



Janka (2004)

ν-A interactions are important in

- core-cooling by ν-emission
- ν-heating on shock wave
- ν-process of nucleosynthesis
- efficiency of neutrino detectors

Reaction rates are to be known with accuracy better than ~10%!

Experiment	$\sigma(^{12}C(\nu_e,e^-)^{12}N_{g.s.})$ (10^{-42} cm^2)
KARMEN (PLB332, 251 (1994))	9.1±0.5±0.8 (10.4%)
LSND (PRC64, 065501 (2001))	8.9±0.3±0.9 (10.7%)
JSNS^2 (arXiv:1601.01046)	(~3%(stat.) expected in 5yrs)

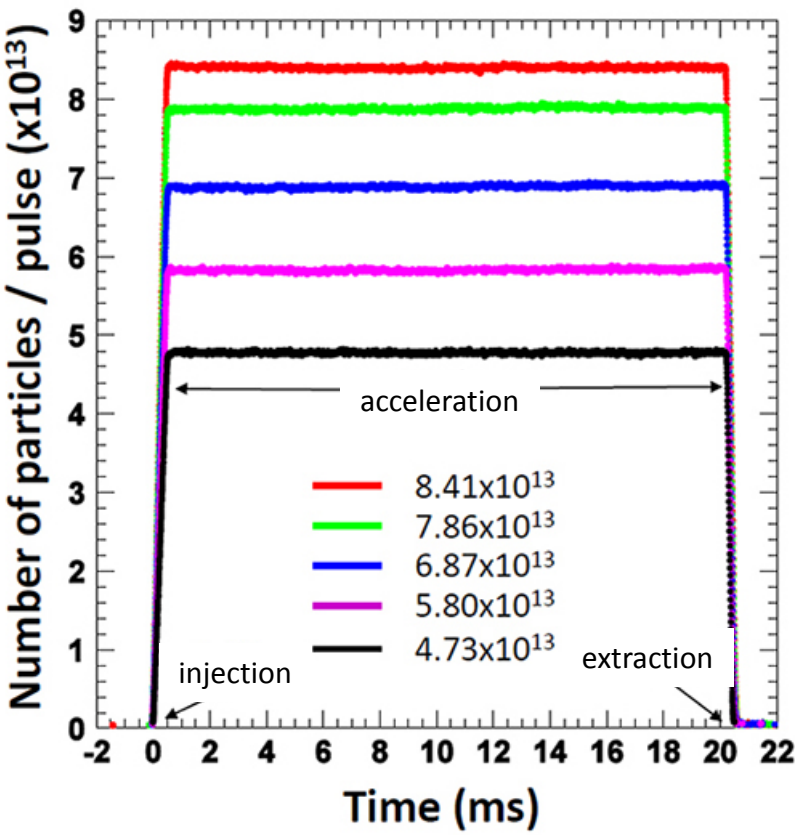
Summary and Prospects

- 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-ν_μ → anti-ν_e 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 status and **the grant-in-aid**
  - 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 aim to start the JSNS^2 in **JFY2018 w/ stage2**

backup

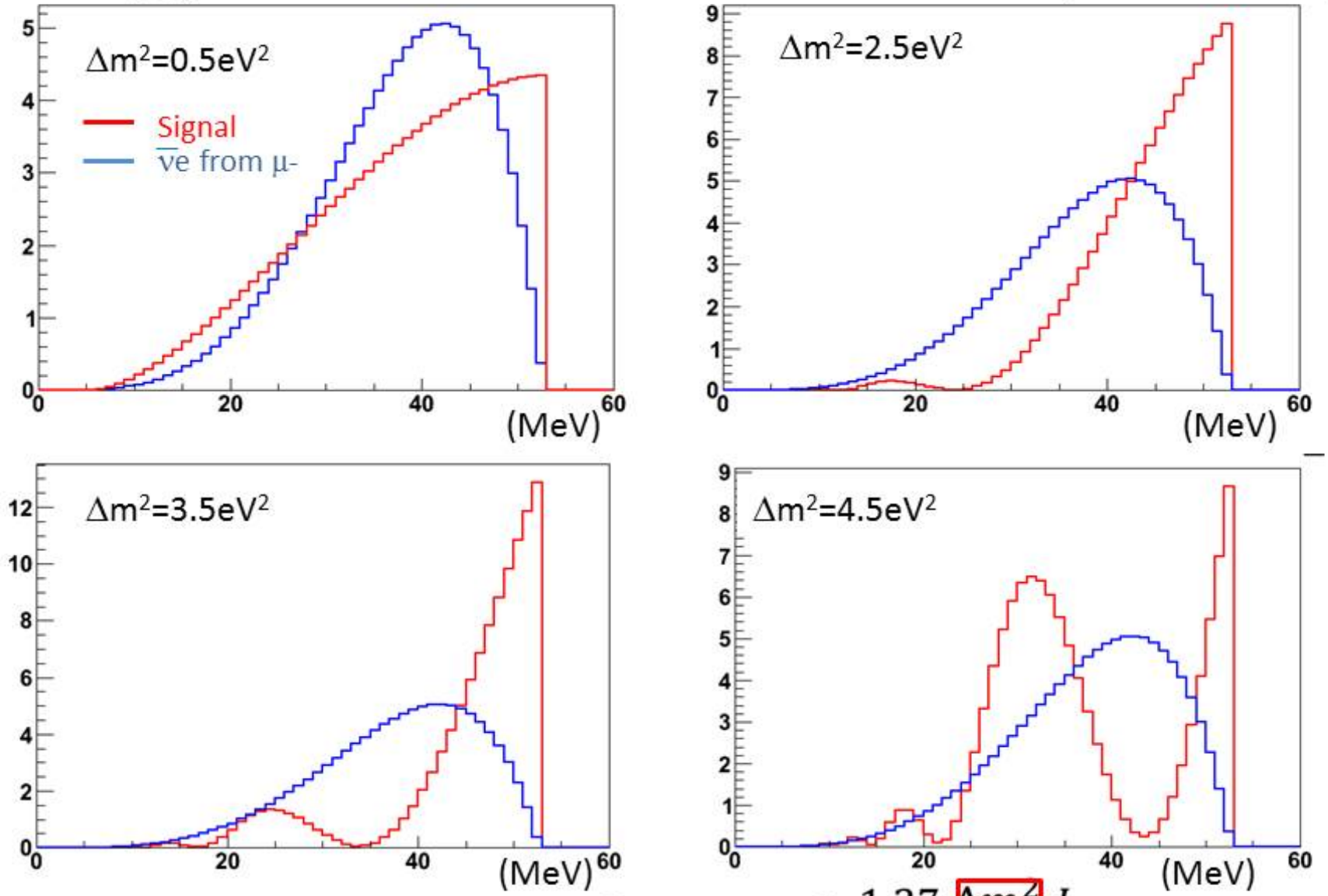
RCS/MLF beam

- 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
	8.41×10^{13}	1010 kW
	7.86×10^{13}	944 kW
	6.87×10^{13}	825 kW
	5.80×10^{13}	696 kW
	4.73×10^{13}	568 kW

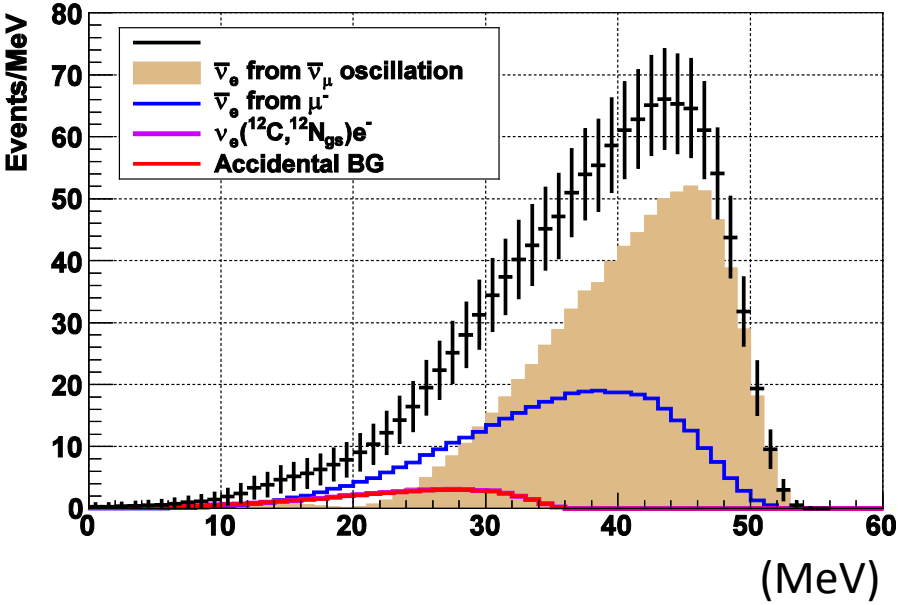
Energy distribution of events (L=24m)

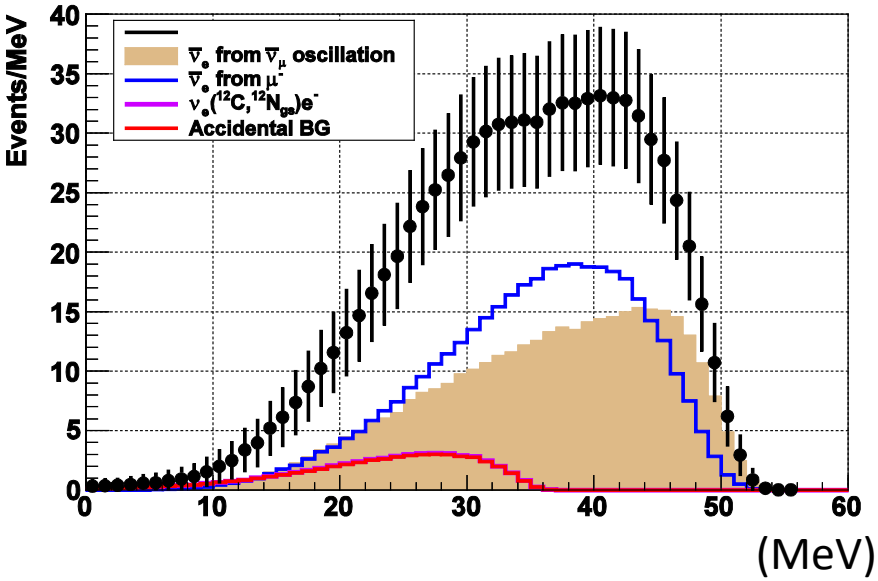


$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

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

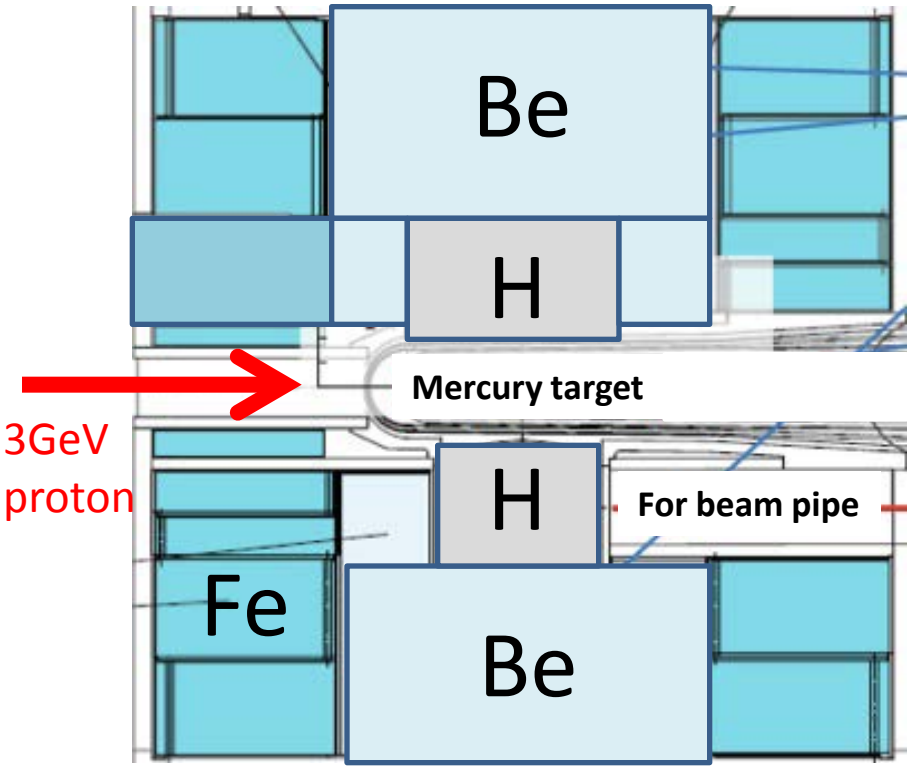
How to fit





- 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

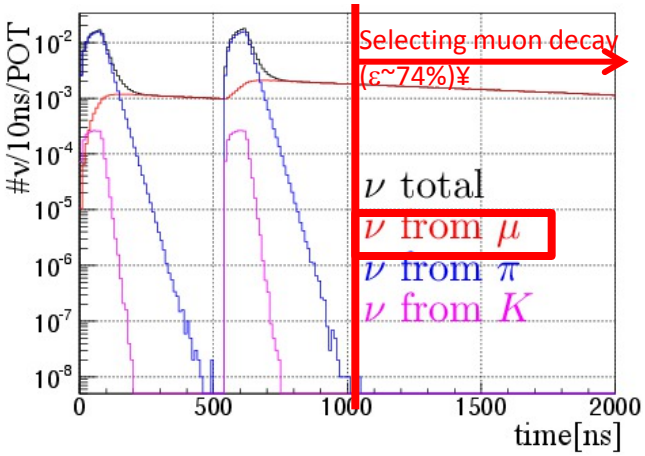


	Target	π^- absorb	μ^- capture	suppression	x	π^-/π^+
LSND	H2O	96%	88%	5×10^{-3}	x	0.13
J-PARC	Hg(+Fe+Be)	99%	~80%	1.7×10^{-3}	x	1.

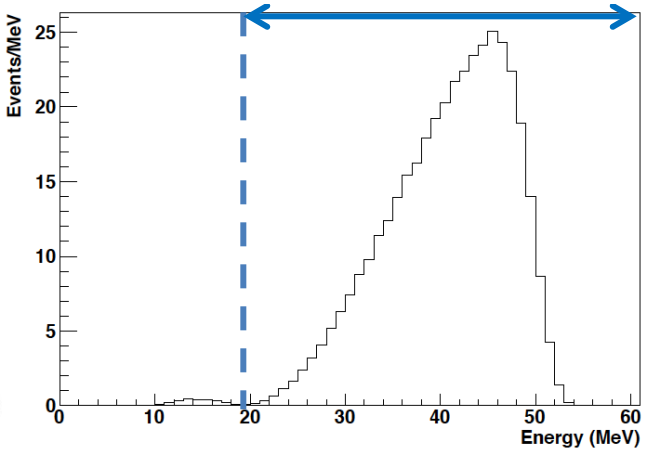
We will assume ~ 1.7×10^{-3} Intrinsic background hereafter.

IBD event selection for signal

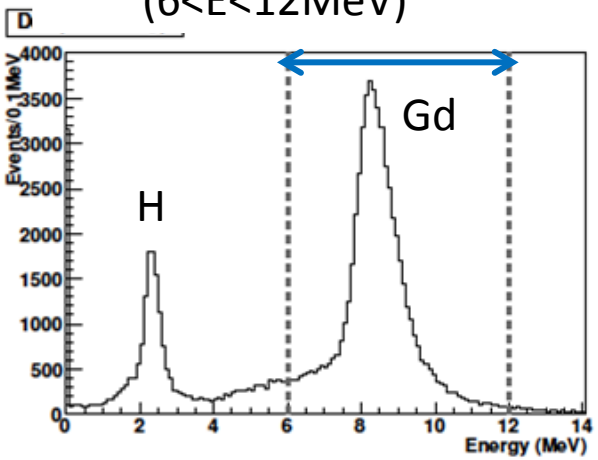
1. Prompt timing cut
(1<Δt<10μs)

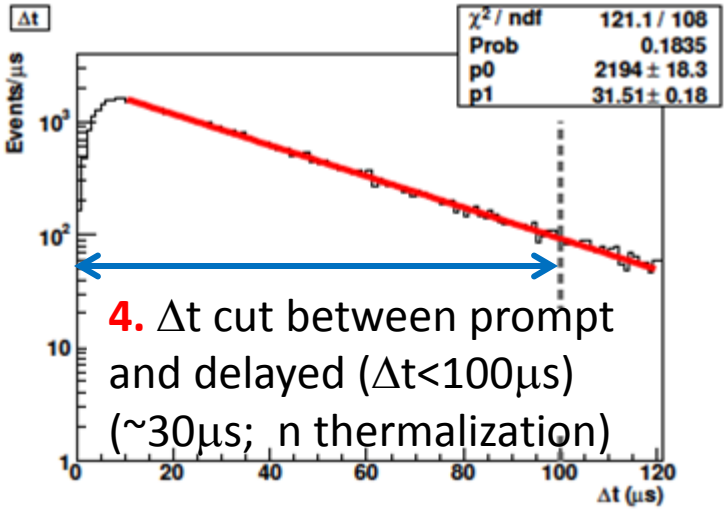


2. Prompt energy cut
(20<E<60MeV)

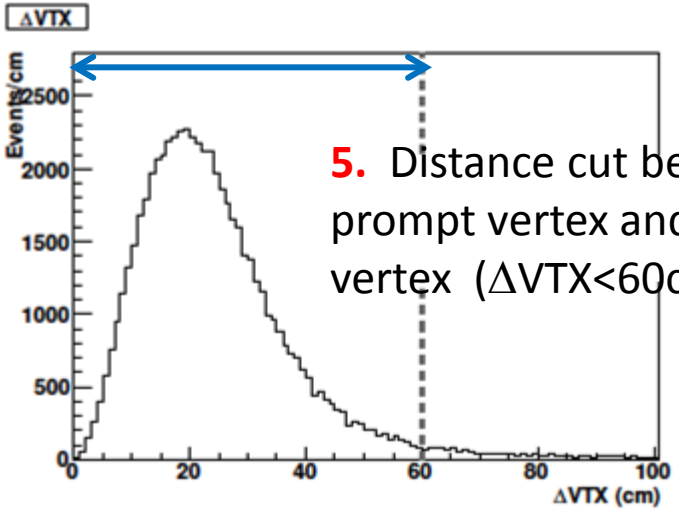


3. Delayed energy cut
(6<E<12MeV)





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)

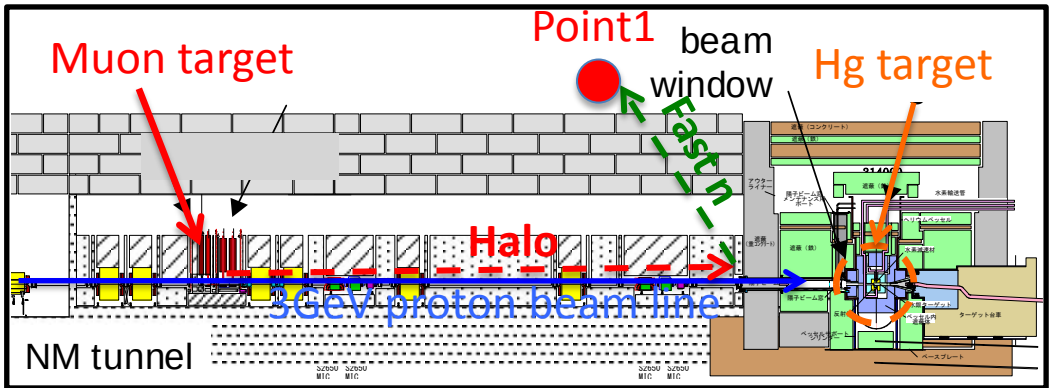
Point1 has large number of activities with high energy. → we measured **with** and **without muon target** for 6mins (~10000spills) at Point1.

Without muon target (special run for test experiment)

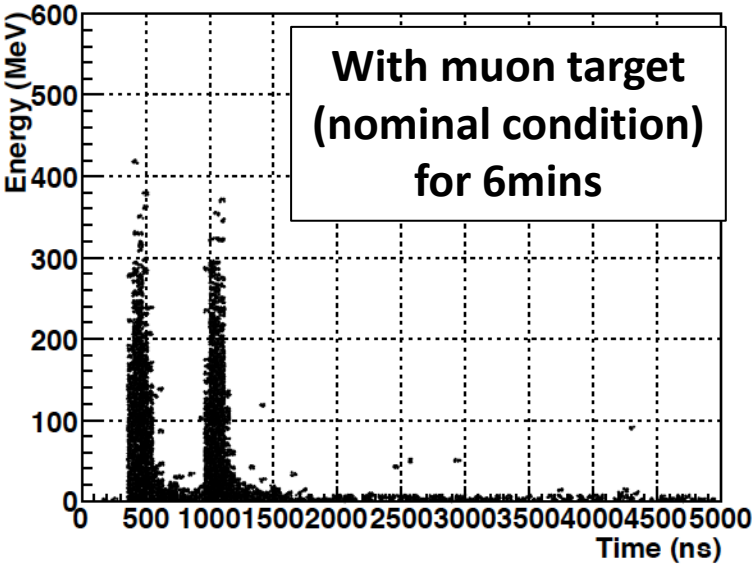
There is no on bunch event above 200MeV.

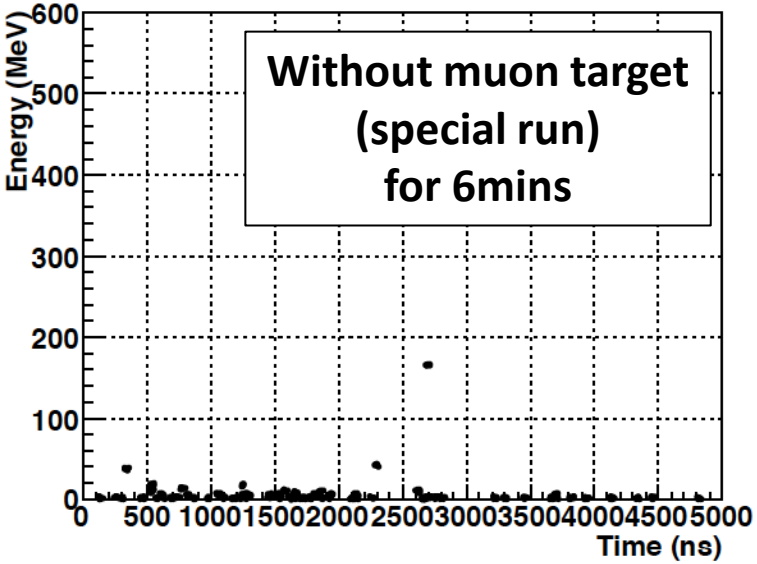
Guess

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

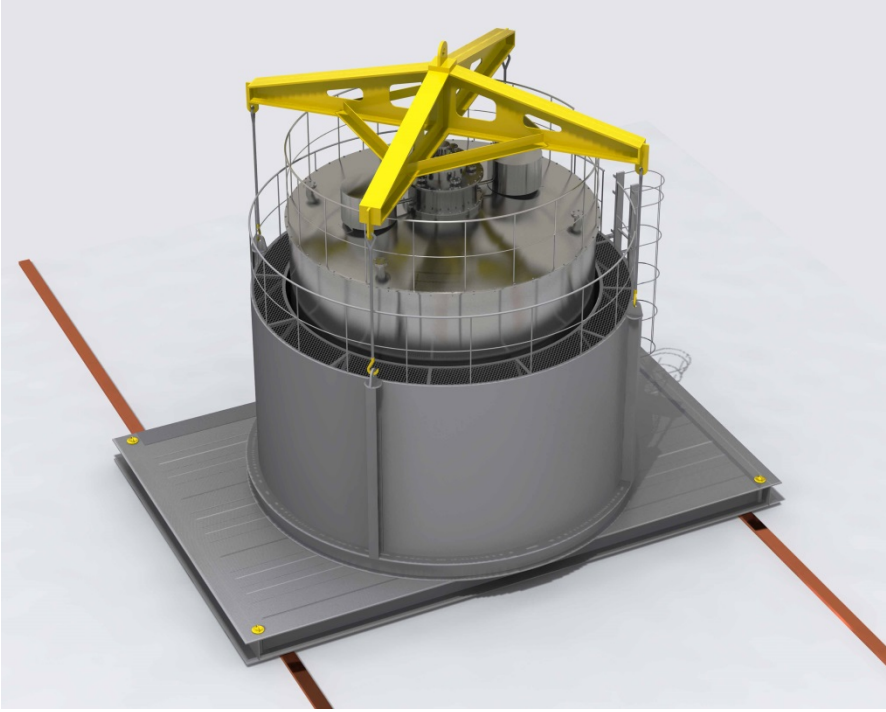


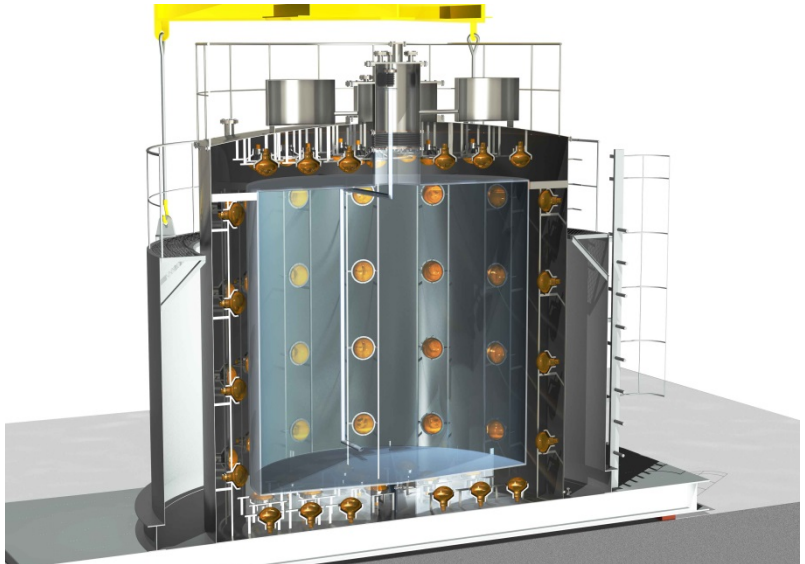


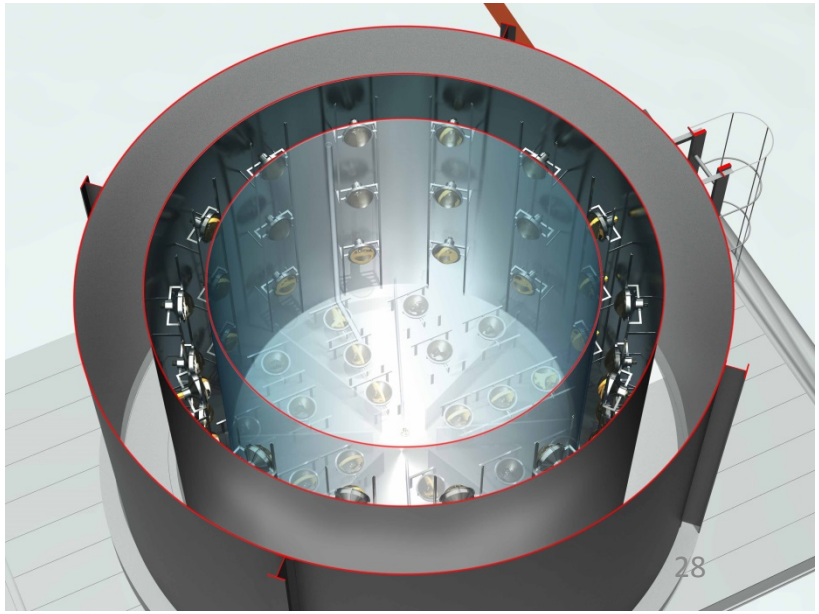
Detector design

- 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.**







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

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

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 $U_{e4}, U_{\mu 4} \sim 0.1$ $U_{s4} \sim 1$ $m_4 \sim 1\ eV >> m_{1,2,3}$

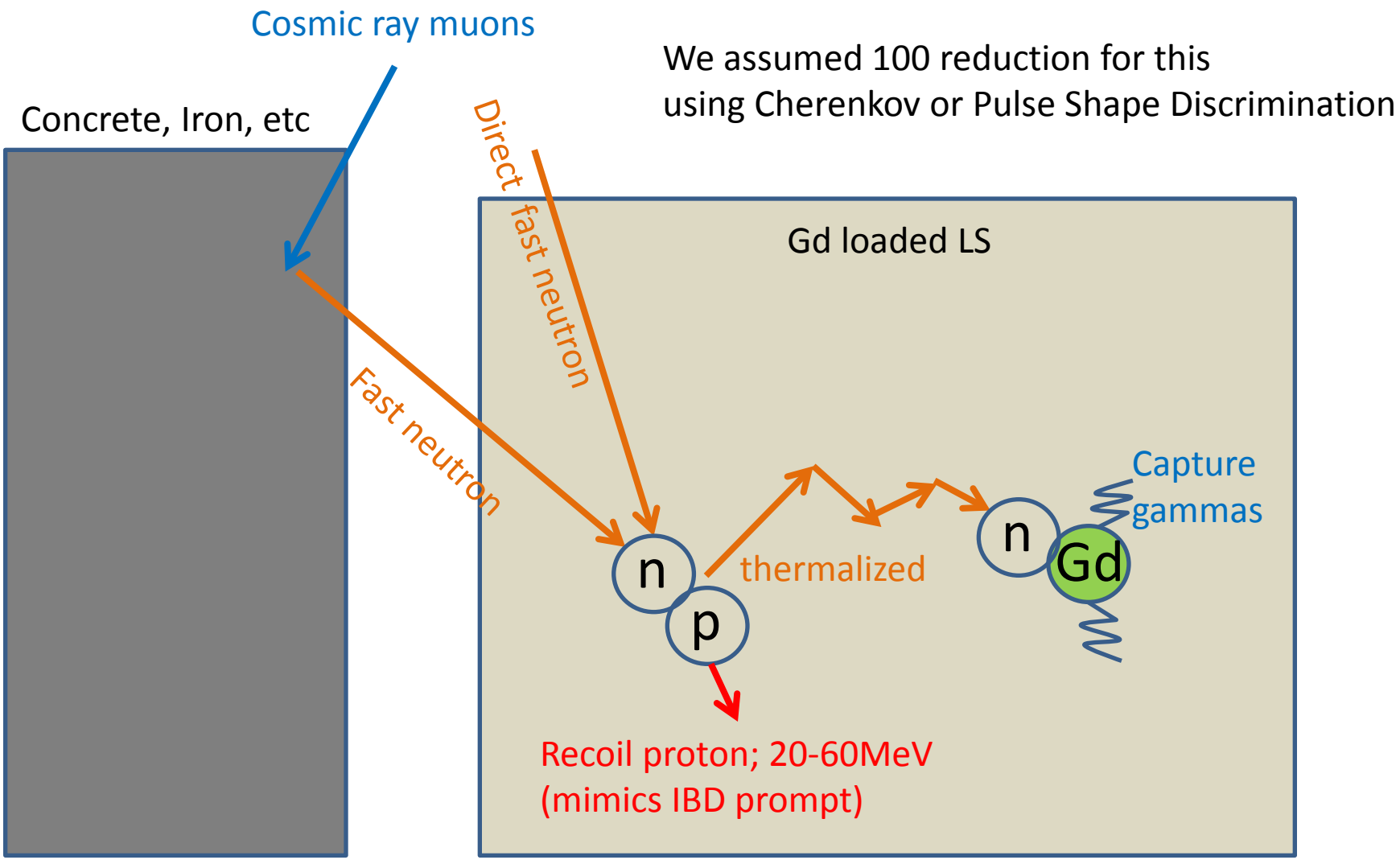
$$P_{e\mu} = -4 \sum_{i=1,3} (U^*_{e4} U_{\mu 4} U_{ei} U^*_{\mu i}) \sin^2 \frac{(m_4^2 - m_i^2)L}{4E_\nu} \sim 4 |U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \frac{\Delta m_4^2}{4} \frac{L}{E}$$

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

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

(3+1) model

Fast Neutrons from Cosmic Rays



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