A Search for Sterile Neutrinos at J-PARC Materials and Life science experimental Facility (the presentation at PAC)

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for MLF nu working group

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Proposal: A Search for Sterile Neutrino at J-PARC Materials and Life Science Experimental Facility

September 2, 2013

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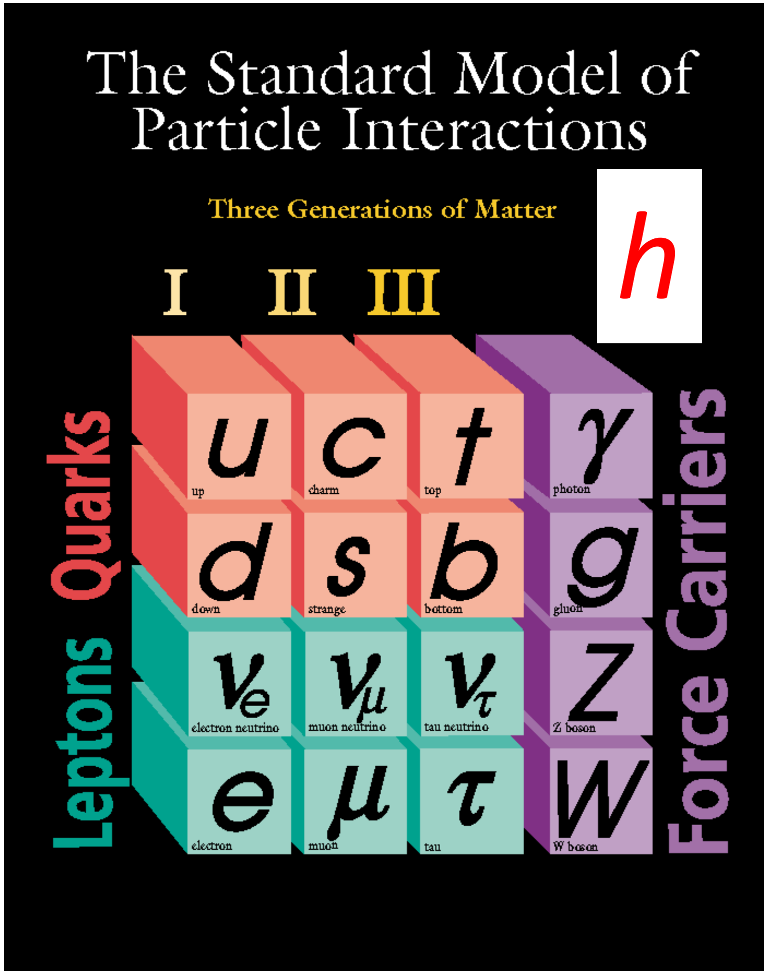
A fundamental questions in flavor physics even after Higgs discovery

- How many generations exists?
  - Only 3 active (weak interactive) neutrinos existed below Mz/2.

- No more elementary fermion in three generations?

$$\binom{u_L}{d_L},\ u_{R,}\ d_R,\ \cdots$$

$$\binom{\nu_{e_L}}{e_L}, e_R, \ldots$$



Sterile neutrinos

- Sterile neutrinos could give an insight for the questions beyond the standard model;

  (E.g.; PLB 631, 151 (2005))

  - No strong, electro-magnetic, weak interactions
  - Observed by only neutrino oscillations (also indicated by some experiments)
  - Could be ν_R (even see-saw partner) or new particle
  - Beyond PMNS matrix

- Sterile neutrino can be one of the Dark Matter candidate.

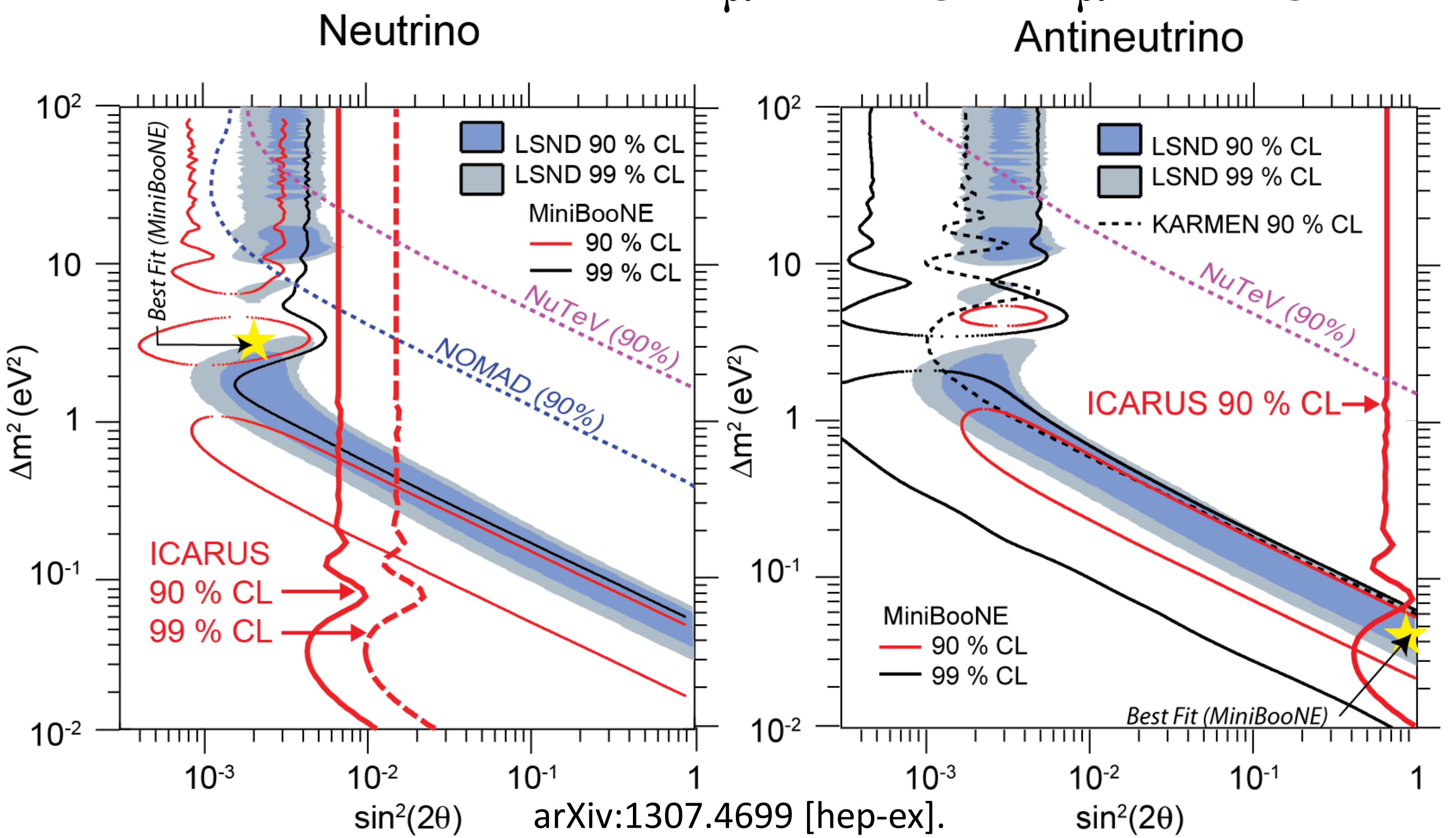
Status of the sterile neutrino search

- 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?

Excess are due to $\nu_\mu \rightarrow \nu_e$ / $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$?

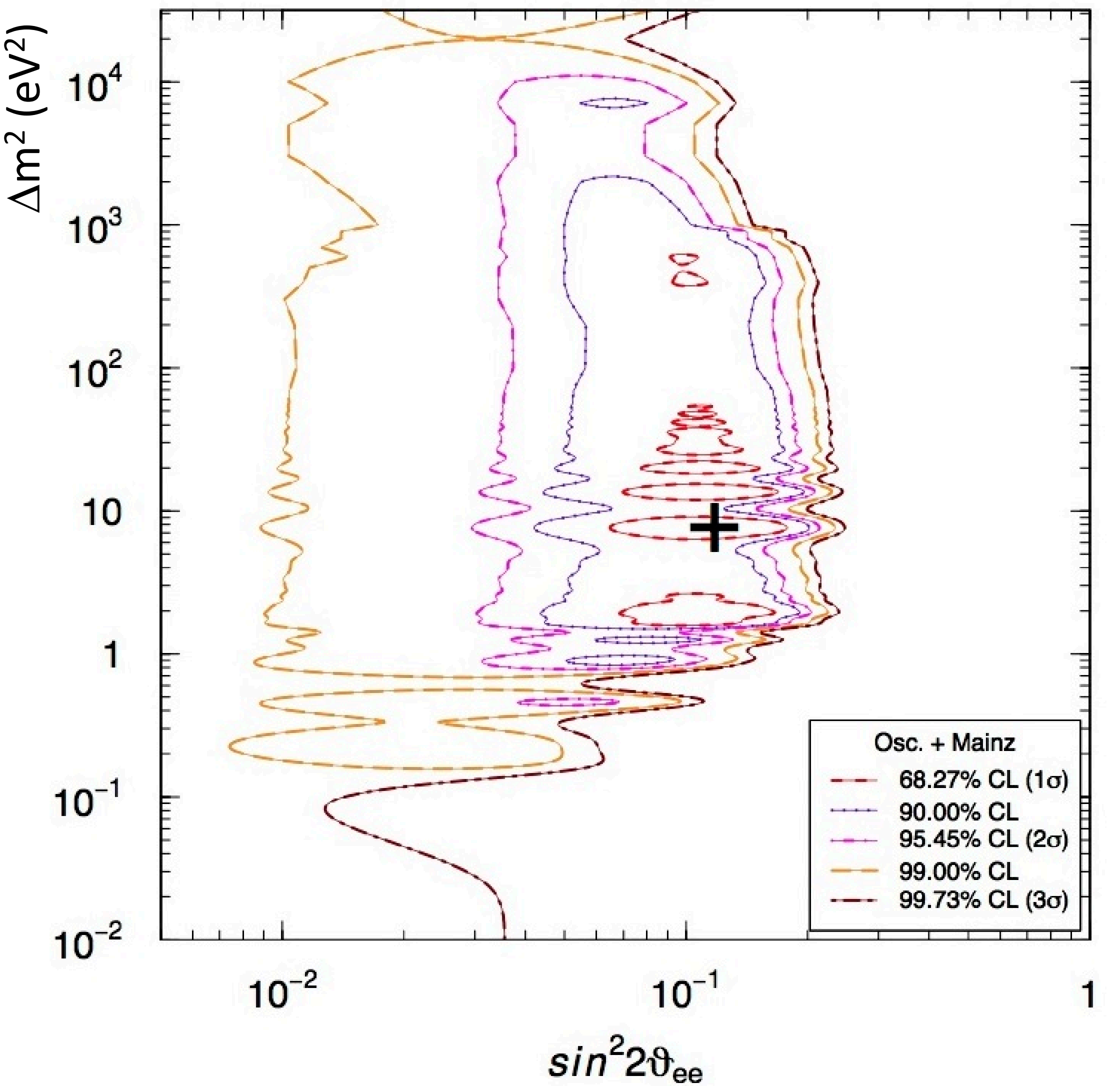


- LSND and MiniBooNE saw the excess.
- 3 generation model cannot explain oscillation with Δm^2>~1.0eV^2
- Z measurements conclude 3 active ν → sterile

ν_e disappearance in reactor and β–source

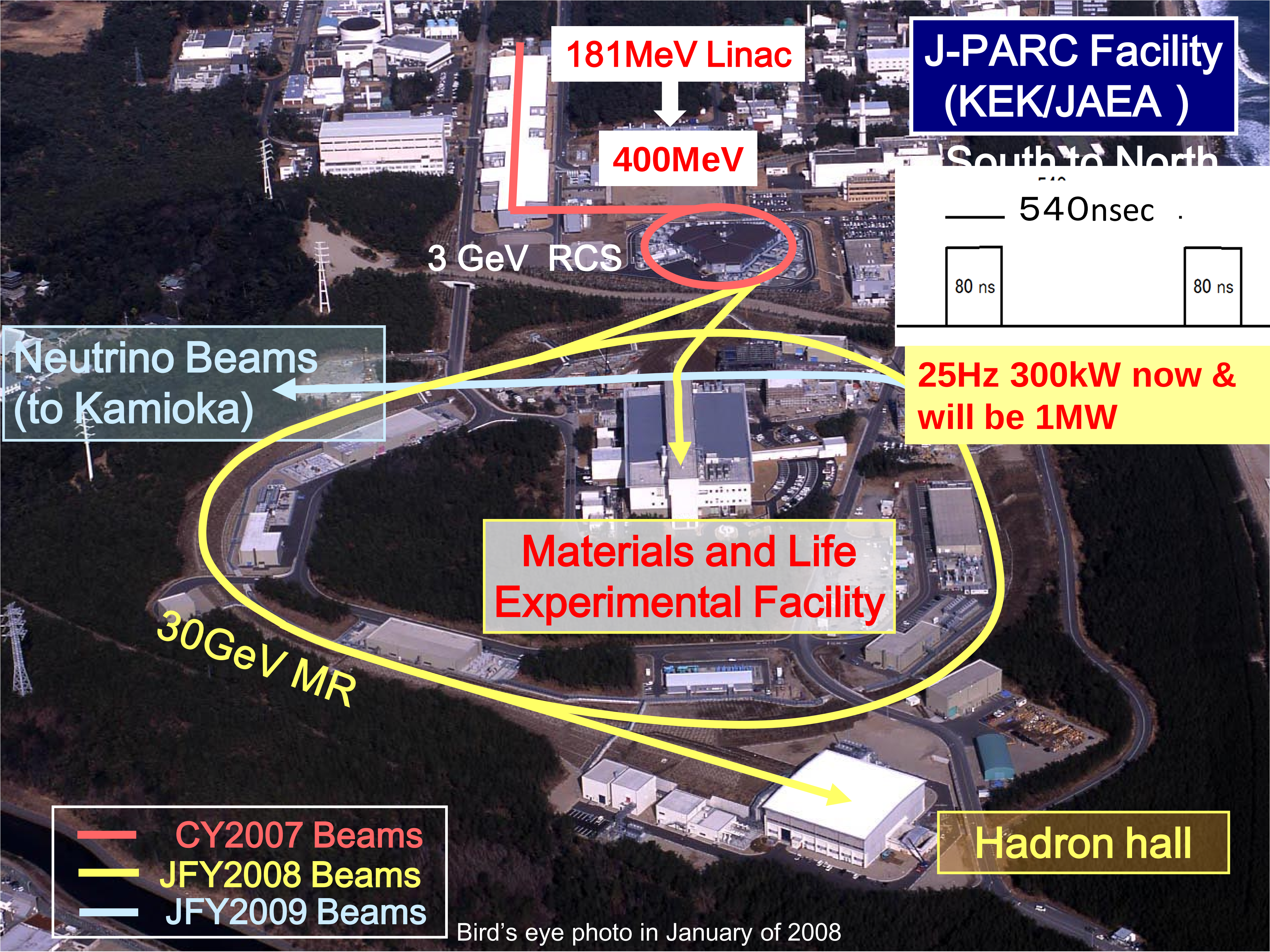
- Allowed region for disappearance (Reactor and beta source anomalies)

- High Δm^2 could be possible.

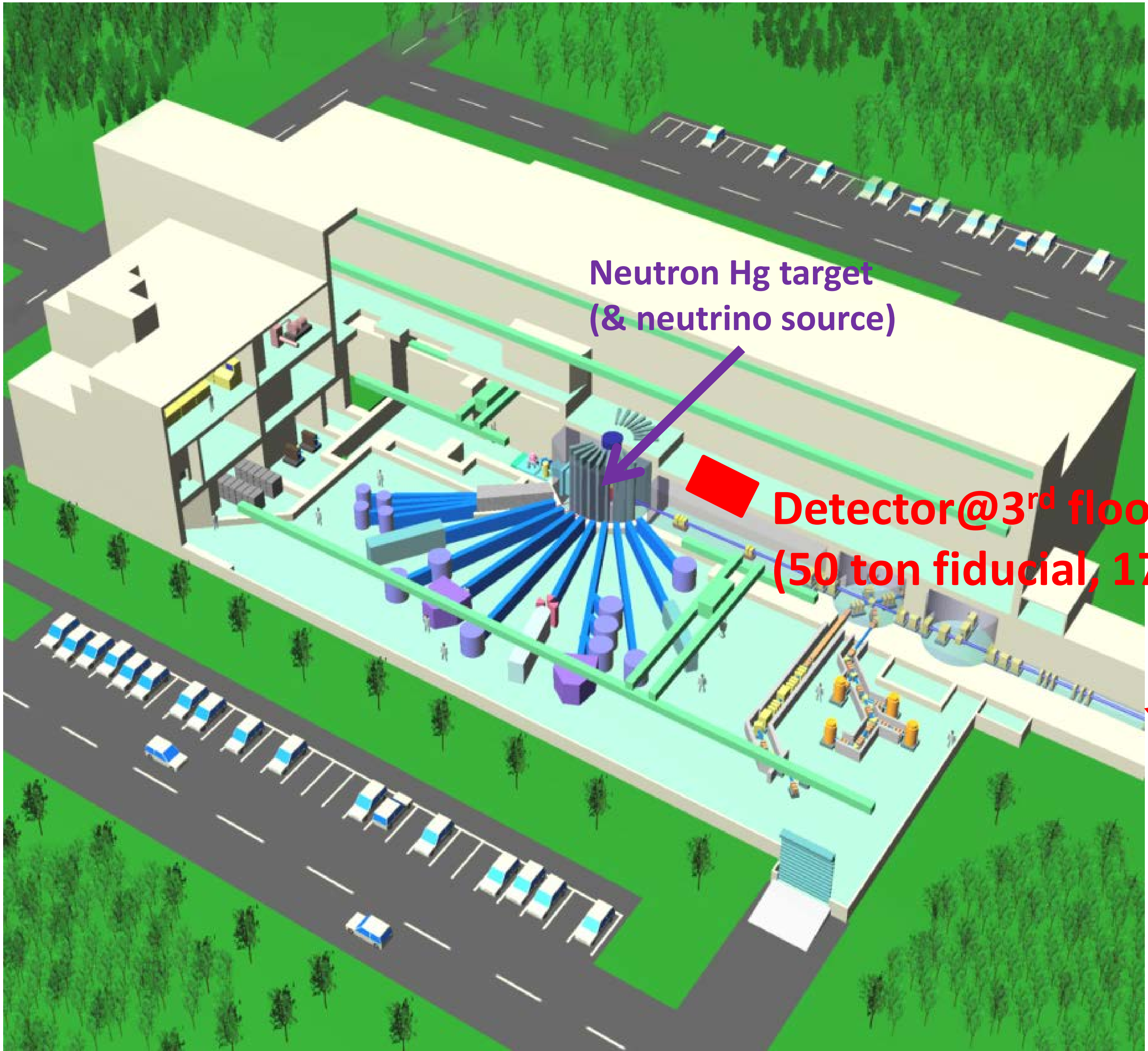


C. Giunti et al., Phys.Rev. D86 (2012) 113014.

New experiment using J-PARC Materials and Life science experimental Facility (MLF)


J-PARC Facility
(KEK/JAEA)
181MeV Linac
400MeV
South to North
540nsec
80 ns
80 ns
3 GeV RCS
Neutrino Beams
(to Kamioka)
25Hz 300kW now &
will be 1MW
Materials and Life
Experimental Facility
30GeV MR
Hadron hall
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in January of 2008

Neutrino production and detector site (3F)



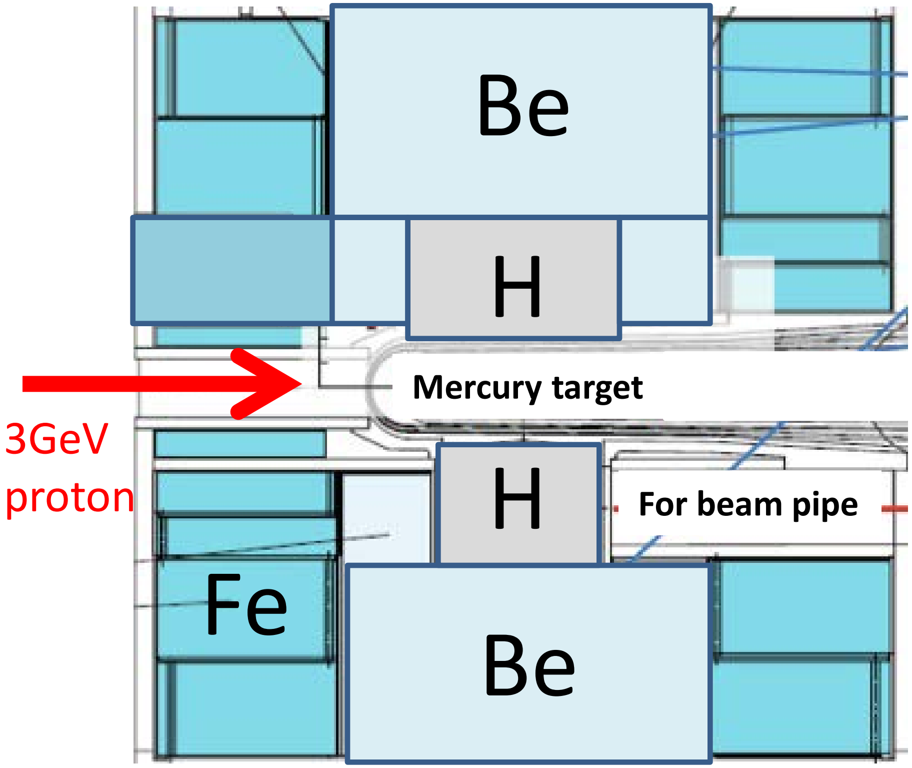
3GeV proton

Strategy and site of the experiment

- The candidate site is best.
  - ~17m; Large # of νs → **good sensitivity for high Δm^2 (>~$2eV^2$) with a 50 ton** (true Δm^2 can be almost anywhere)
  - Low BKG rate (good radiation shield)
  - No new detector building
  - If no definite signal → Will try sub-eV^2 search using a larger detector and a longer baseline.

- 3^{rd} floor of MLF -> maintenance area for the Hg target.
  - Maintenance works (one/year) → need to avoid interference.
  - Discussion to avoid the interference was started.
  - The design of the detector is based on the discussions.

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

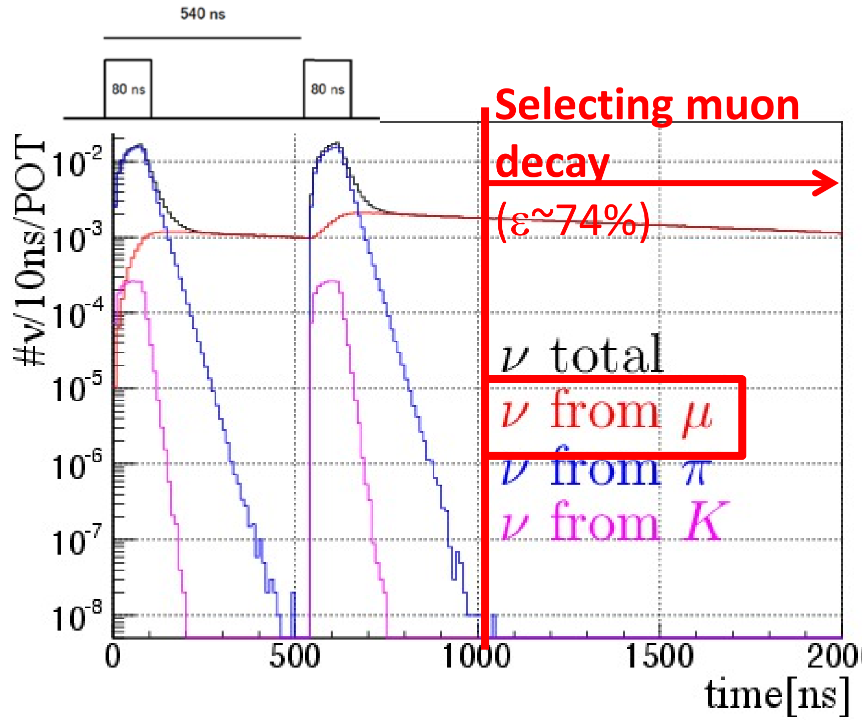


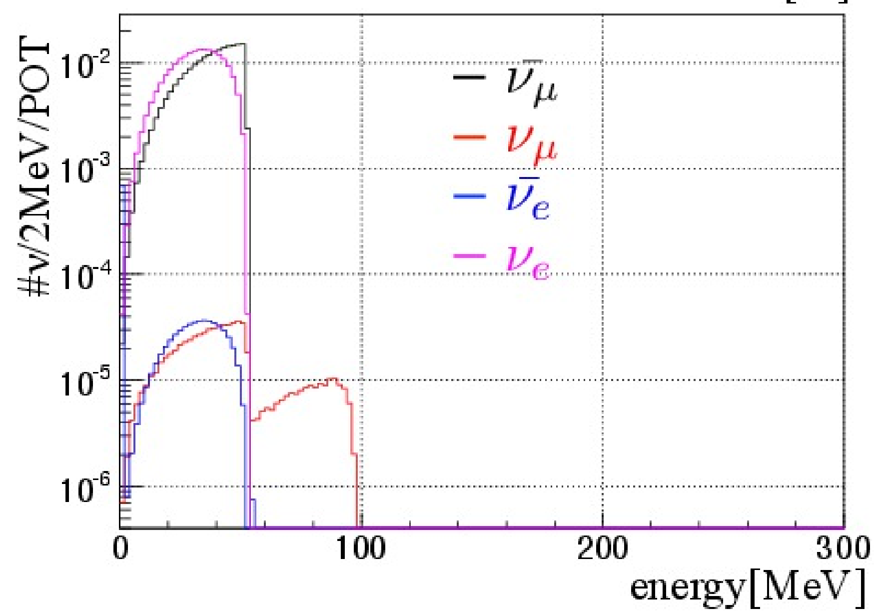
	Target	π^- absorb	μ^- capture	suppression	x	π^-/π^+
LSND	H2O	96%	88%	5×10^{-3}	x	0.13
J-PARC	Hg(+Fe+Be)	99%	~80%	1.7×10^{-3}	x	1.

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

Using neutrinos from only μ^+ decay at rest

- Neutrinos from only μ^+ decays are used. (μ^+ has long lifetime). (top)
- Energy spectrum of $\mu^+ \rightarrow e^+ \overline{\nu_\mu} \nu_e$ decay is well known (bottom)
  - Useful to examine the excess of $\overline{\nu_e}$.
  - $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillation is searched.
- $\pi^- \rightarrow \mu^-$ decay chain is highly suppressed (10^{-3} compared to μ^+)
- Proton energy of J-PARC is 3GeV, thus π^+/p ratio is higher than LSND / KARMEN (0.8GeV) by 5-10 times

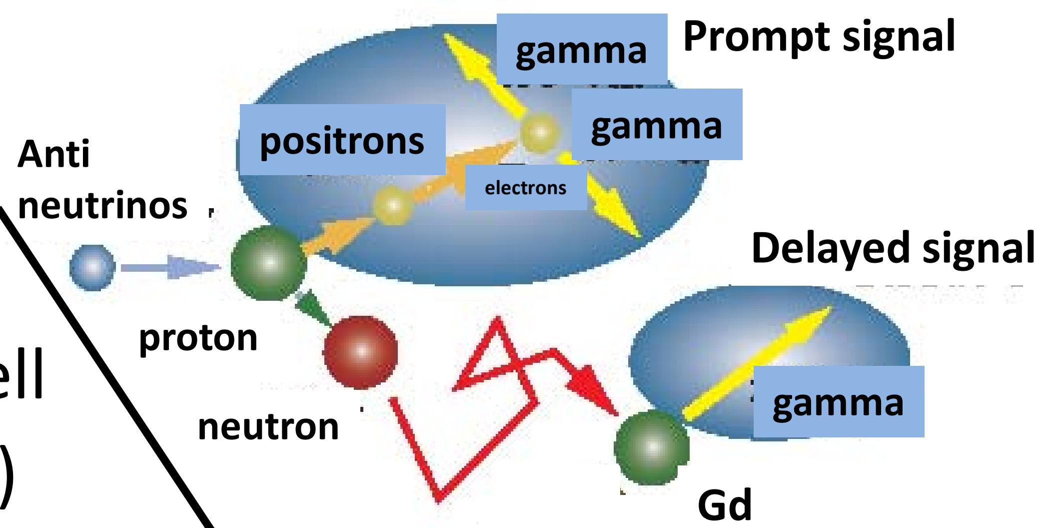




Detector; Liquid scintillator

- Coincidence between positron and neutron signal ($\overline{\nu_e}$ + p → e^+ + n; Inverse Beta Decay; IBD).
- Neutrons are captured by Gd, and emit gammas (totalE = 8MeV, lifetime; a few 10 μs.)

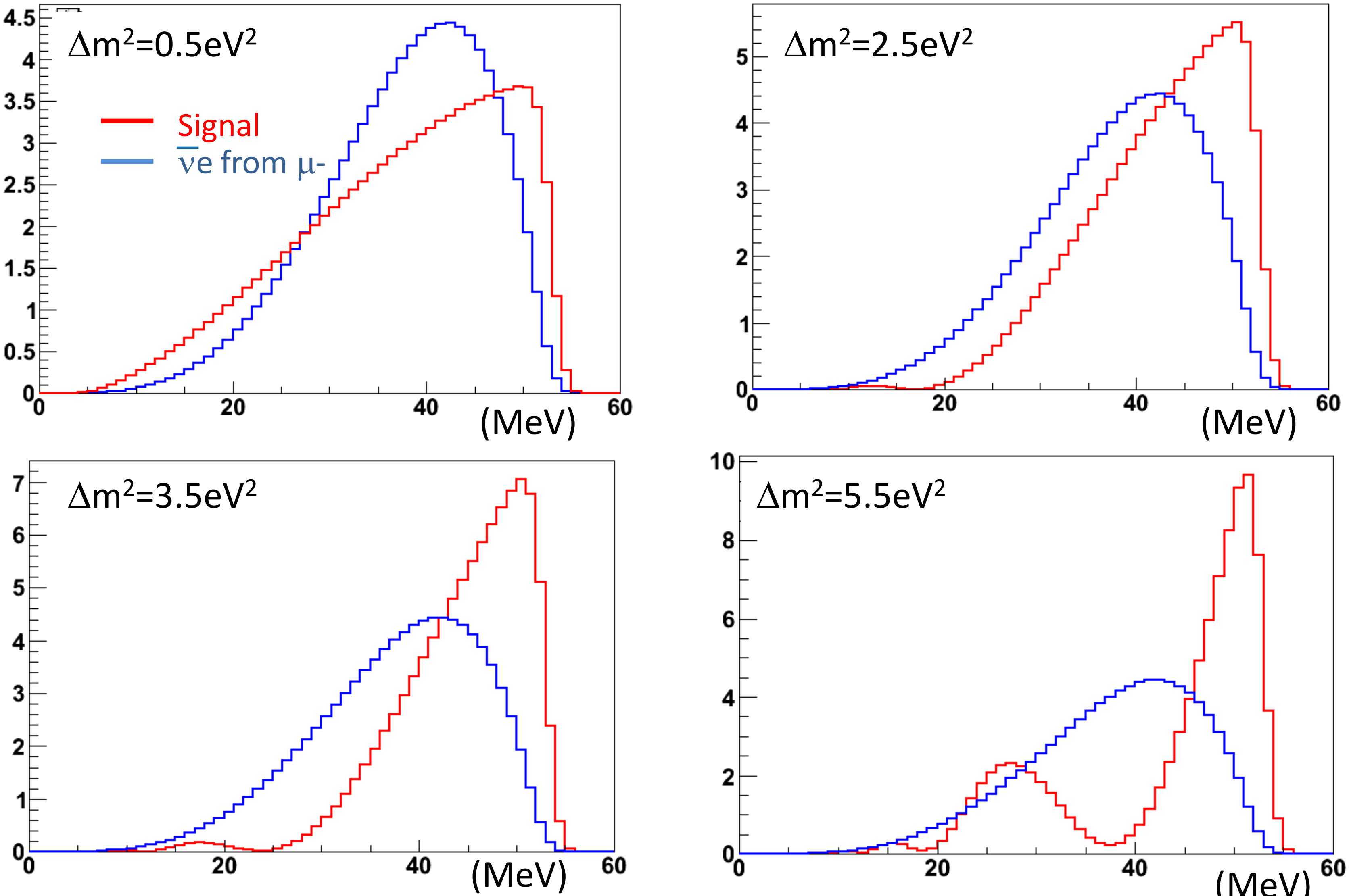
- Positrons → "prompt" signal (Eν = Evis+0.8MeV)
- Neutrons → "delayed" signal



- Cross section of IBD is well known. (~2% uncertainty) ($\sigma = 9.3 \times E_\nu^2 \times 10^{-44}$ cm^2)

- Energy spectrum of anti-neutrino is also well known. → event energy shape is also well known for signal and BKG

Energy distribution of events (L=17m)



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

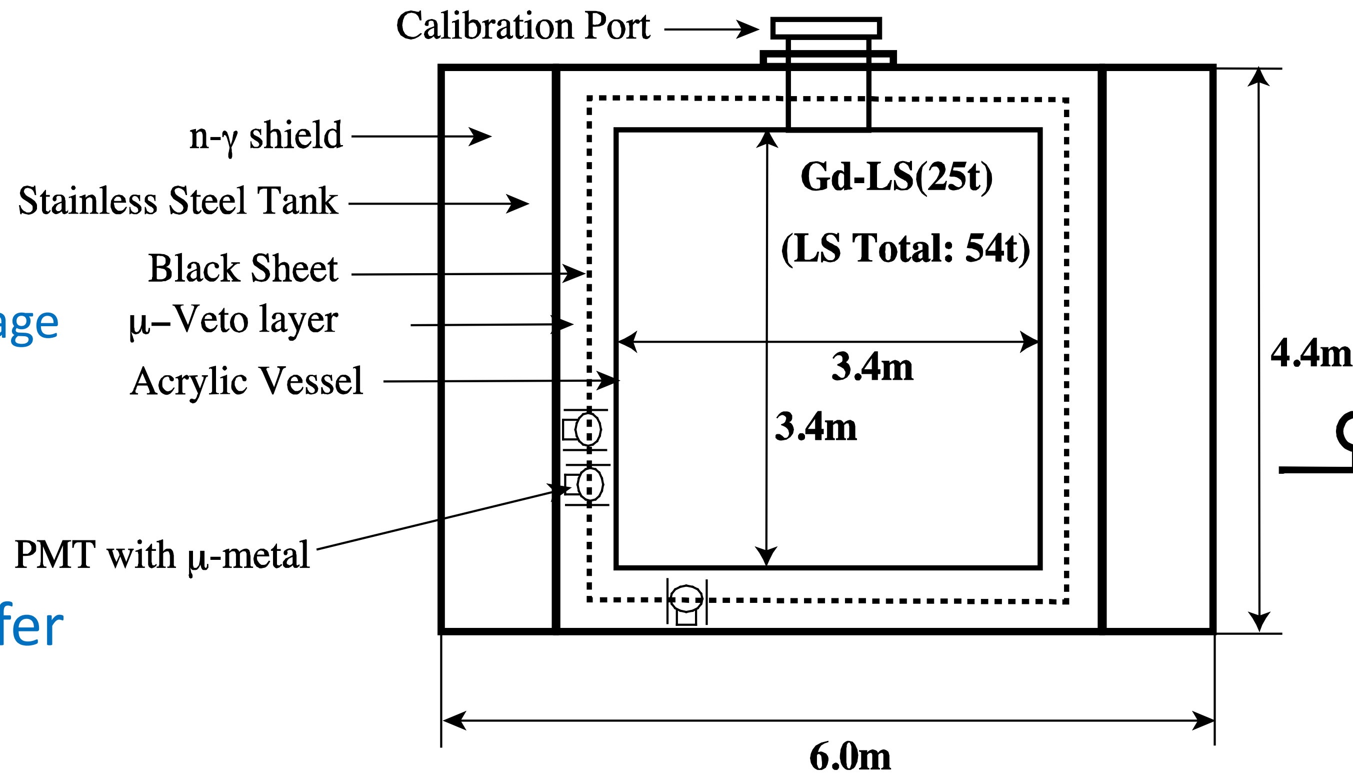
- Energy is smeared by 15%/sqrt(E) (detector E resolution)

Detector considerations

- Type, size, fiducial mass, constraints;
  - Double-Chooz type
  - Diameter 6m, height 4.4m; fiducial is 25 ton
  - Two identical detectors. (from MLF constraints)
  - Movable detectors.

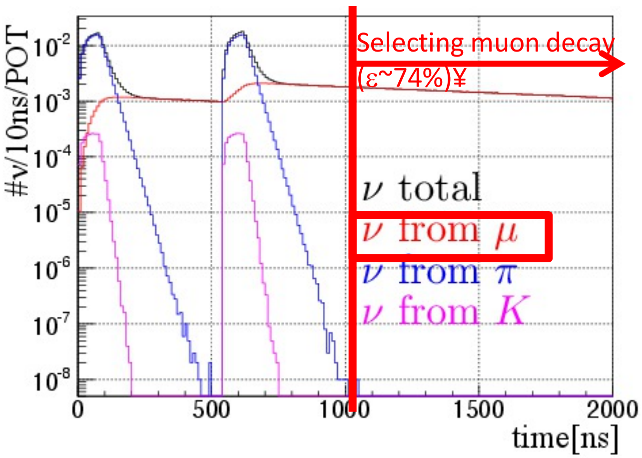
- 150 10" PMTs
  - good photo-coverage → <15%/sqrt(E).

- 50cm noGd-LS buffer region → veto and self-shield

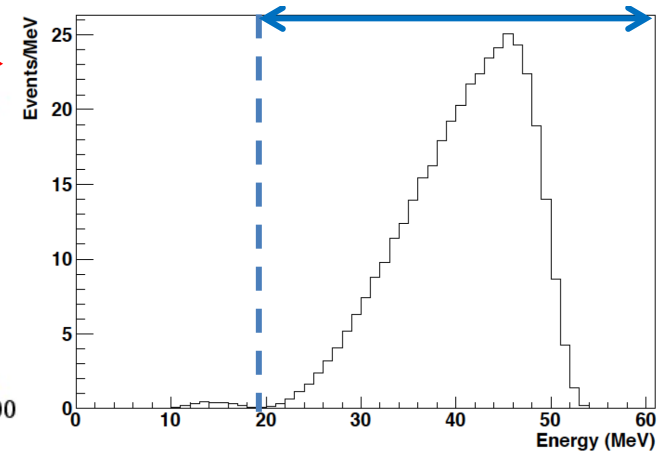


IBD event selection for signal

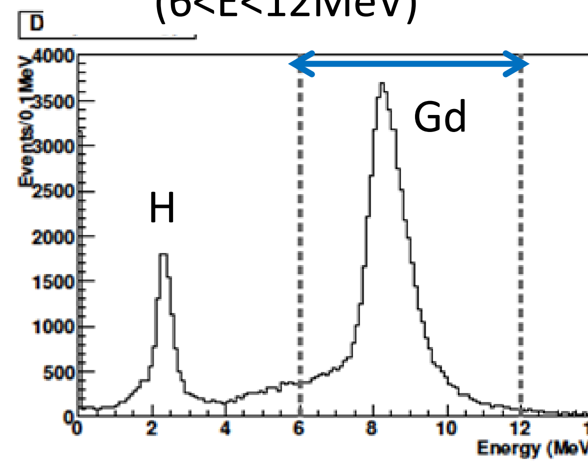
1. Prompt timing cut (1<Δt<10μs)

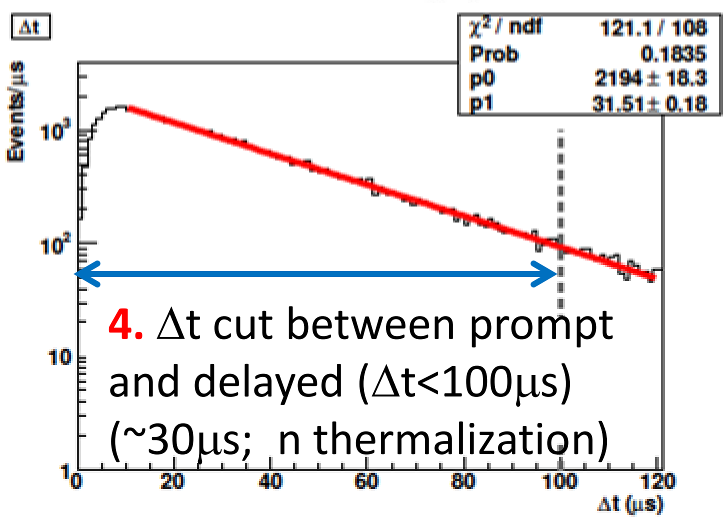


2. Prompt energy cut (20<E<60MeV)

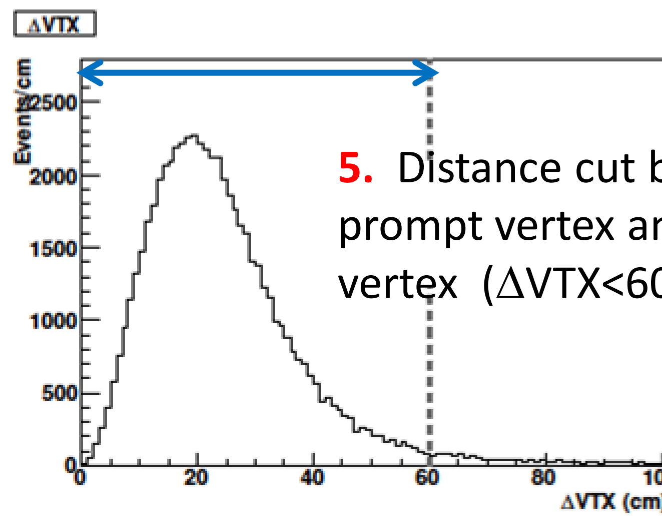


3. Delayed energy cut (6<E<12MeV)





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

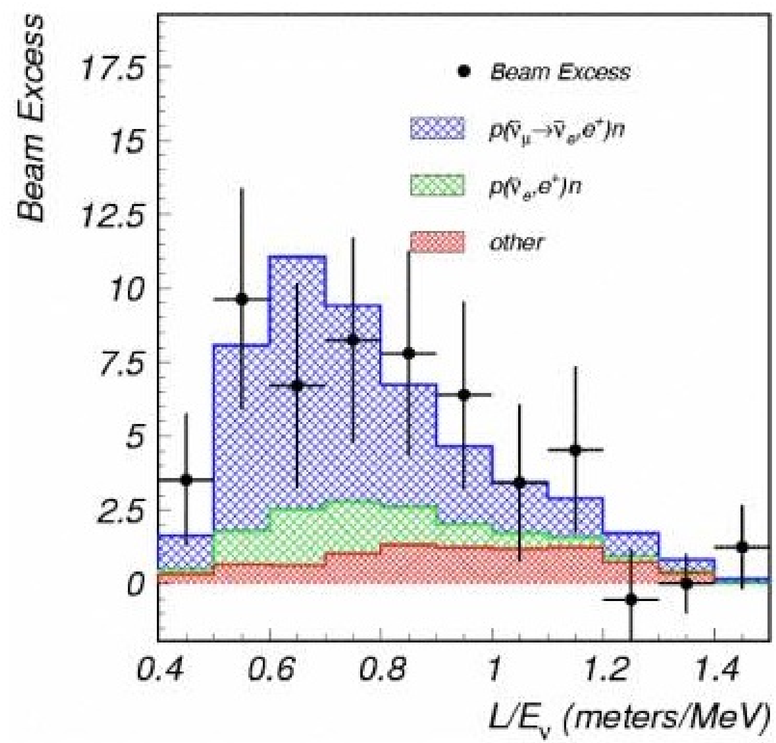


5. Distance cut between prompt vertex and delayed vertex (ΔVTX<60cm)

Total Selection ε ~ 48%

Pros compared to prior experiments

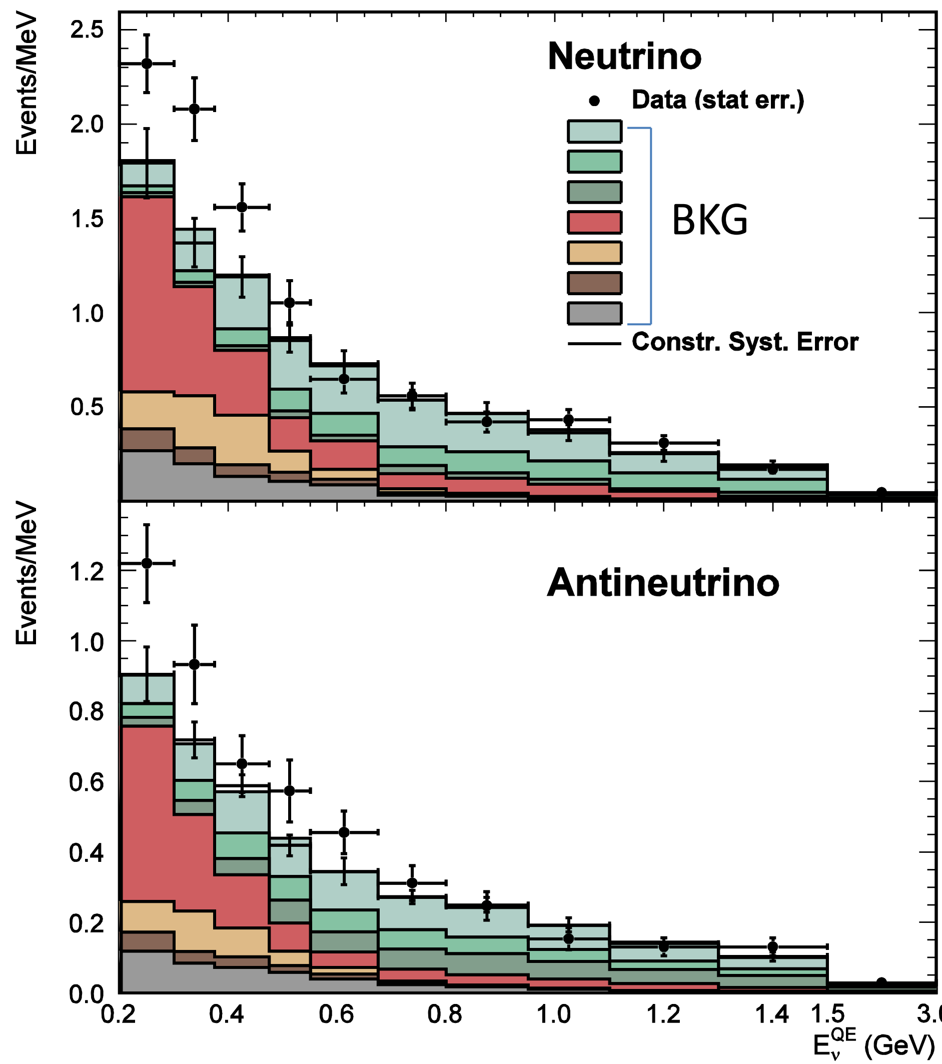
- Compared to LSND;
  - Narrow pulsed beam at MLF → timing cut.
    - LSND has no beam timing cut (Linac → ~ DC beam)
    - Pure muon decay at rest at MLF.
    - No Decay-In-Flight source in MLF
    - No beam fast neutrons BKG at MLF.
  - Detector has a lot of points to be improved;
    - Gd-LS improves S/N ratio.
    - Faster sampling rate of electronics and improved LS make PID easy.



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

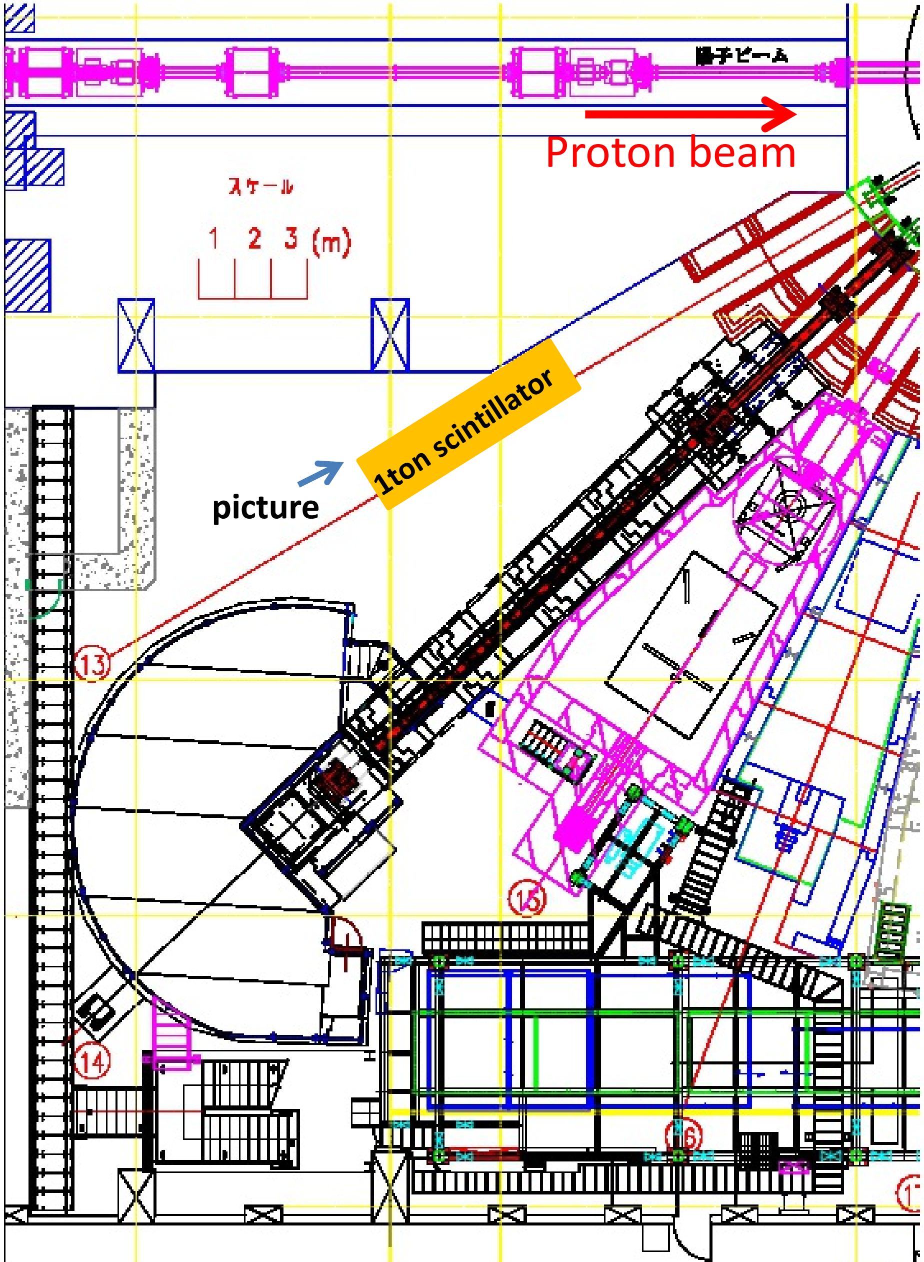
Pros compared to prior experiments

- Compared to MiniBooNE (conventional horn focused beam);
  - Background rates is small at MLF. (suppression of π^-, μ^-).
  - $E\nu$ reconstruction of IBD is clear.
  - Signal normalization ~10% level.



A background measurement at BL13 (Experimental area at the 1st floor) and expectation at the detector site

Measurement at BL13 with 1 ton detector



- A 50x50x450cm^3 detector made by 10.5 or 21(w) x 4(t) x 450(l)cm^3 plastic scintillators.
- BKG made by neutrons was measured at BL13.
- It is extrapolated to a detector site (MLF 3F) using a simulation.

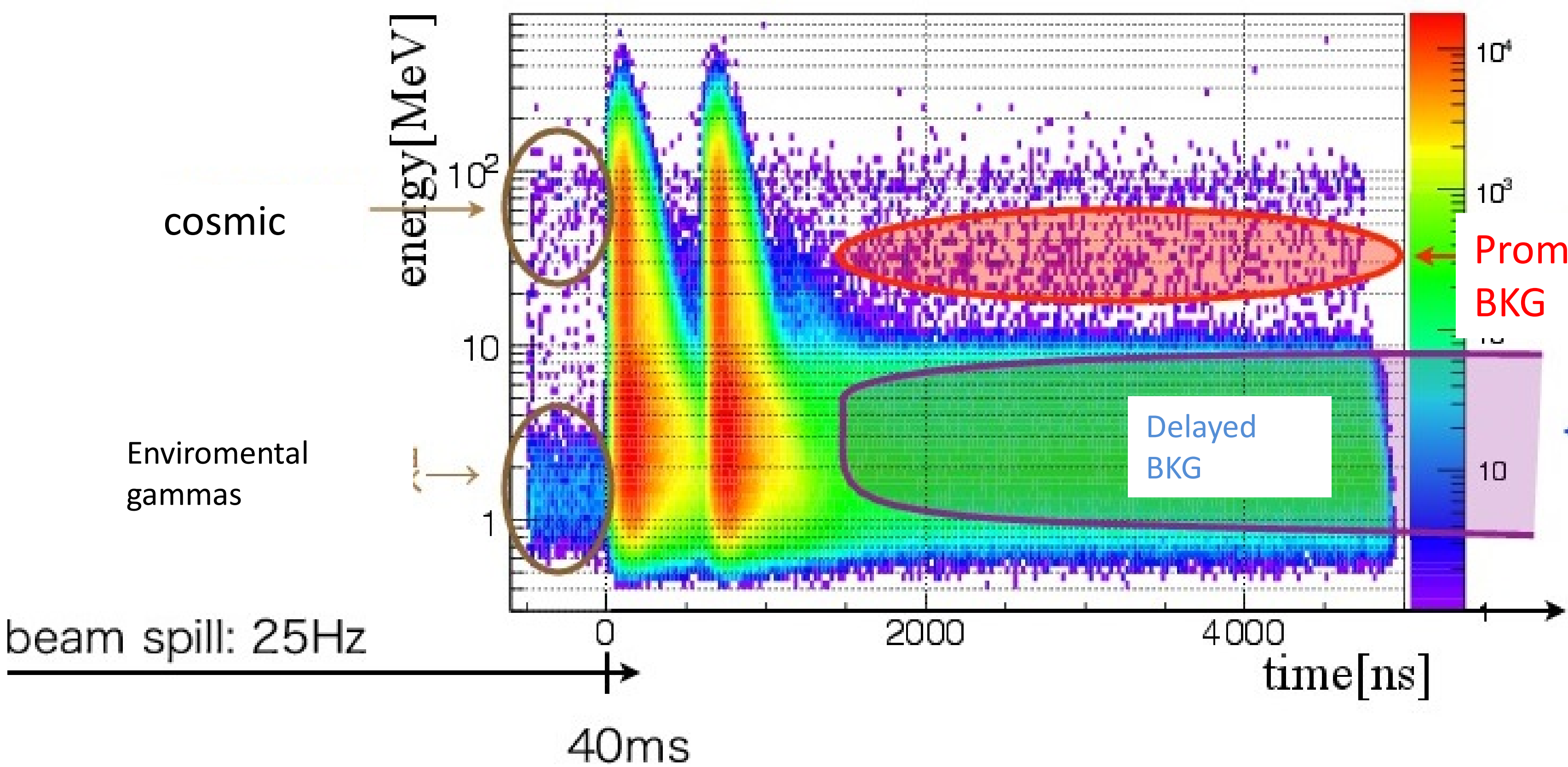
Strategy to extrapolate

- Checked the consistency between data and MC (PHITS simulation) → good agreement
- MC ratio MC_{3F}/MC_{BL13} is used to extrapolate.

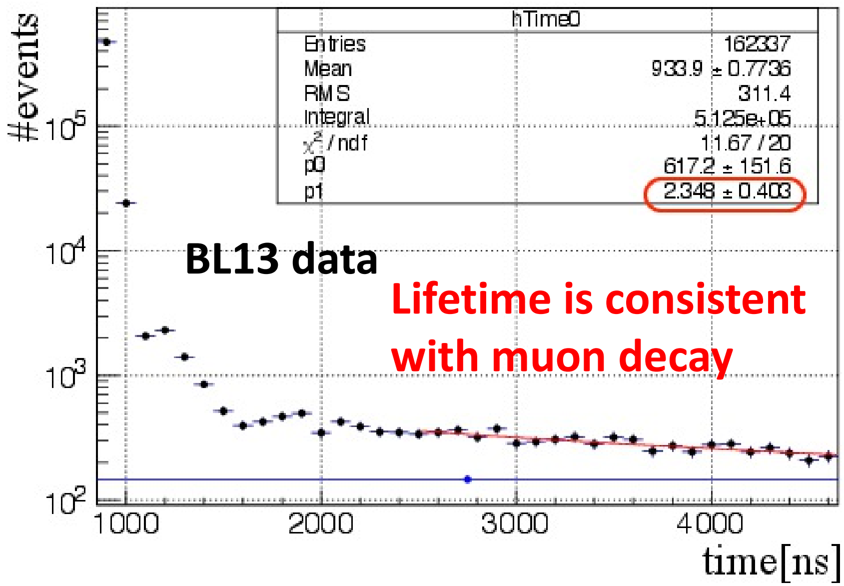
$$BKG(3F)_{exp} = \frac{BKG(3F)_{MC}}{BKG(BL13)_{MC}} \times BKG(BL13)_{data}$$

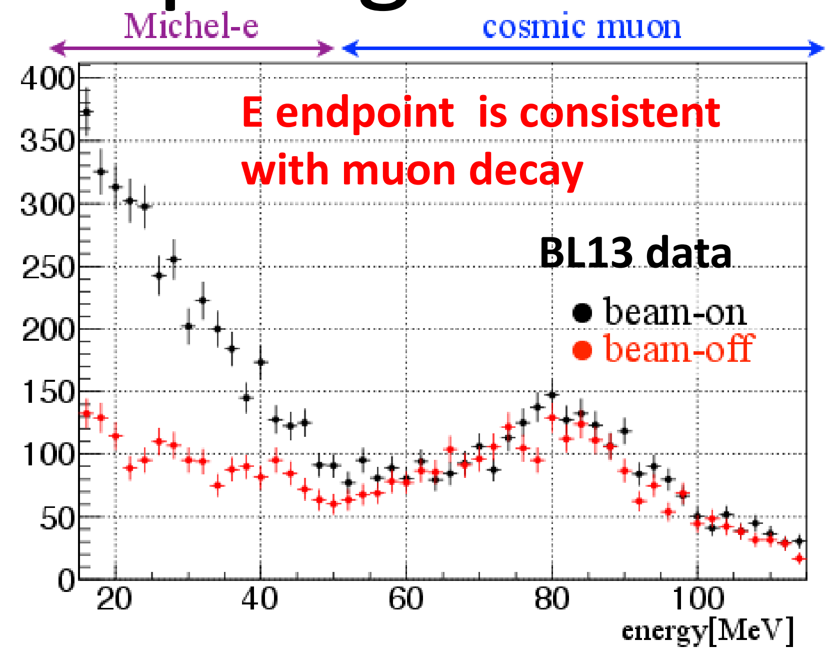
- PHITS simulation has been used to calculate radiation at MLF widely
- Taking ratio of MC predictions cancels the uncertainty on absolute numbers.

1 ton observation

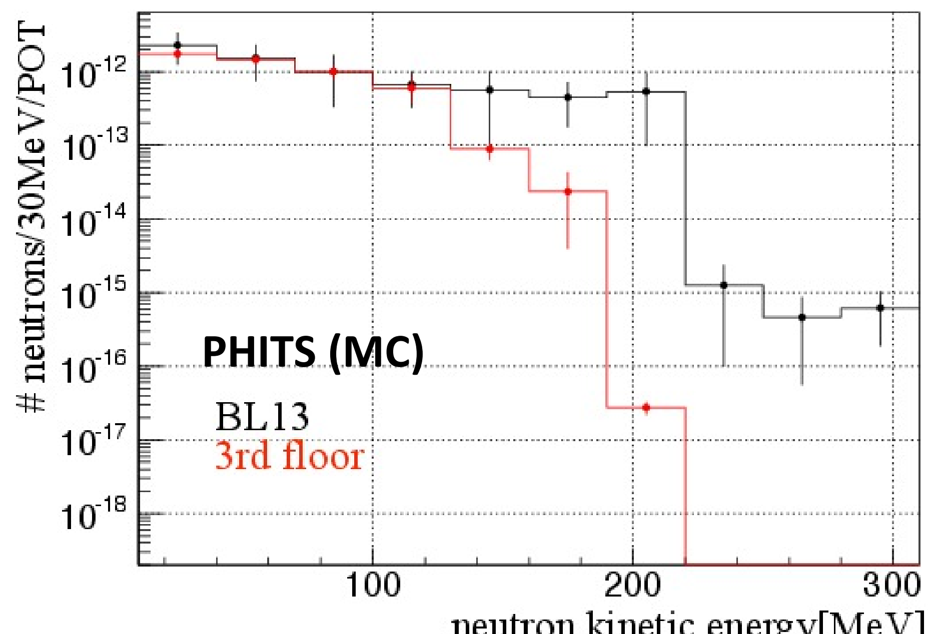


BKG for IBD prompt signal





- n+p->π+X; π->μ->e decay chain can cause this BKG (top 2 plots)

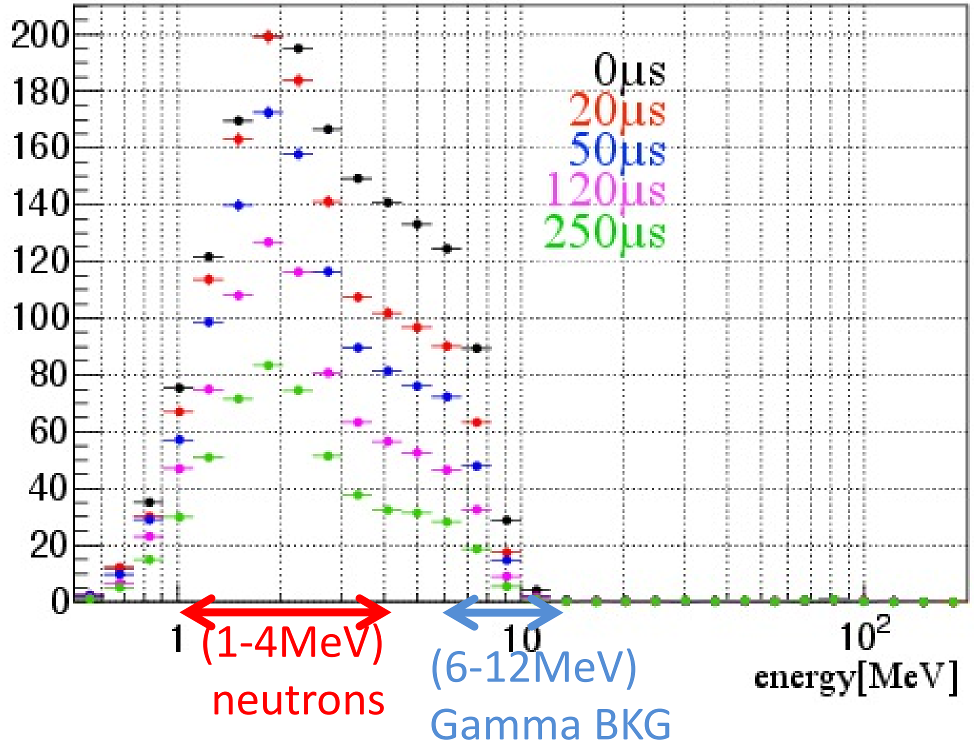


Measured BKG rate at BL13 is 5.6×10^{-4}/spill

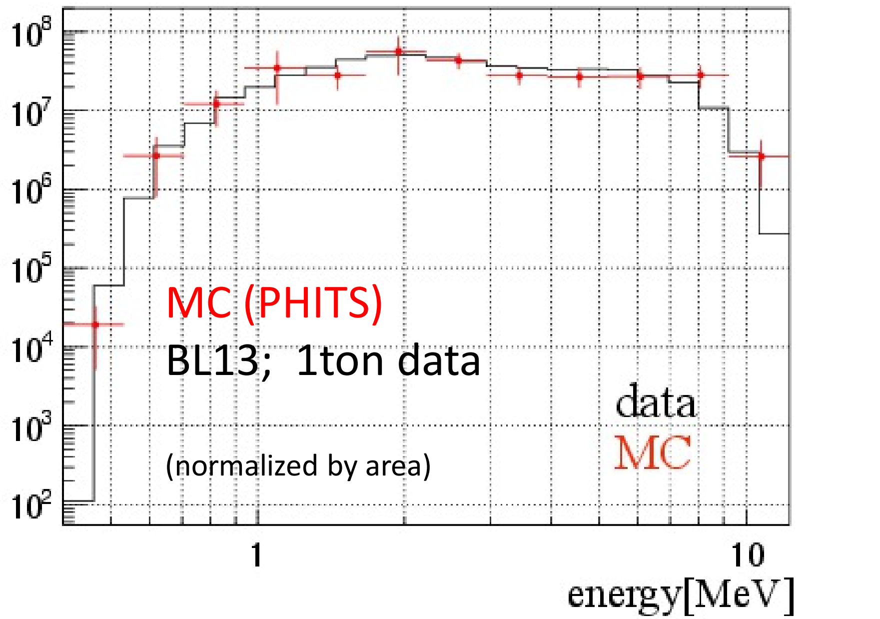
Right plot; #n @ BL13 and 3F (MC). n+p->π+X; π->μ->e decay chain@3F is reduced by 4 order of magnitude.

BKG for IBD delayed

- 1 ton observation;
  - Measured BKG neutrons rate (1-4MeV; from 2.2 MeV capture γ) → **14/spill**
  - Measured BKG gamma rate (6-12 MeV)→ **0.9/spill**



- Agreement between data and MC (bottom right plot) → Excellent.

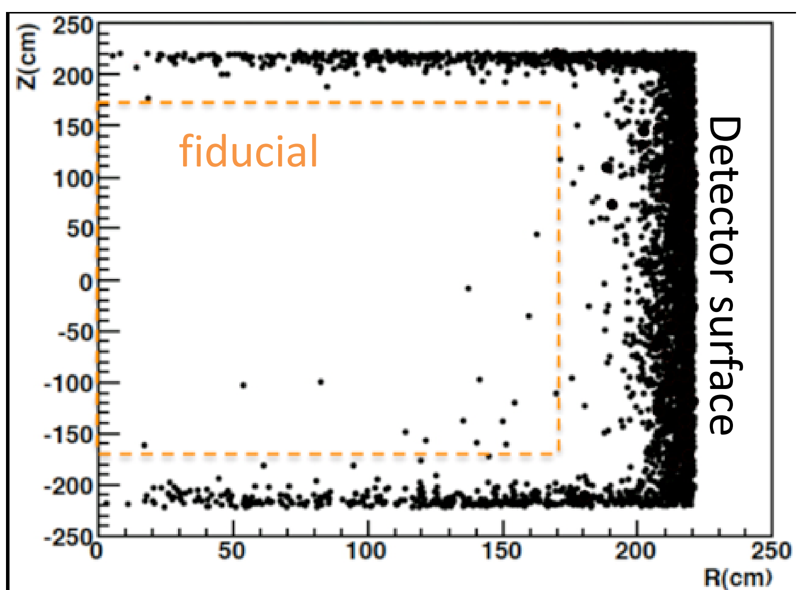


Summary of beam background at 3F

	BL13 (/spill/300kW/ton)	3^{rd} floor (/spill/MW/det.)	Detector fiducial volume (/spill/det./MW)	comment
#Fast neutron (for Michel e)	5.6×10^{-4}	**2×10^{-7}**		
LowE neutron	14 (captured by 1 ton)	40 (# of neutrons)	**2.4×10^{-3}**	Buffer region is effective
gamma	0.9 ($6<E<12$ MeV)	14 (all energy range)	**4.7×10^{-2}**	Buffer region is effective

- LowE neutrons → captured in the buffer region. (right plot)
- Energy of most of gammas is low ($E<100$keV), and interacted in the buffer region.

- **Beam BKG rate @ 3F is manageable!!**



Summary for all BKGs and signal @ 3F

Source	contents	#ev./50tons/4years	comments
background	$\overline{\nu}_e$ from μ-	377	
	$^{12}C(\nu_e,e-)^{12}N_{g.s.}$	38	IBD ε is 0.2%
	Beam fast neutrons	0.3	
	Fast neutrons (cosmic)	42	
	Accidental	37	See below
signal		881	Δm^2=3.0, $\sin^2 2\theta$=0.003
		377	Δm^2=1.2, $\sin^2 2\theta$=0.003

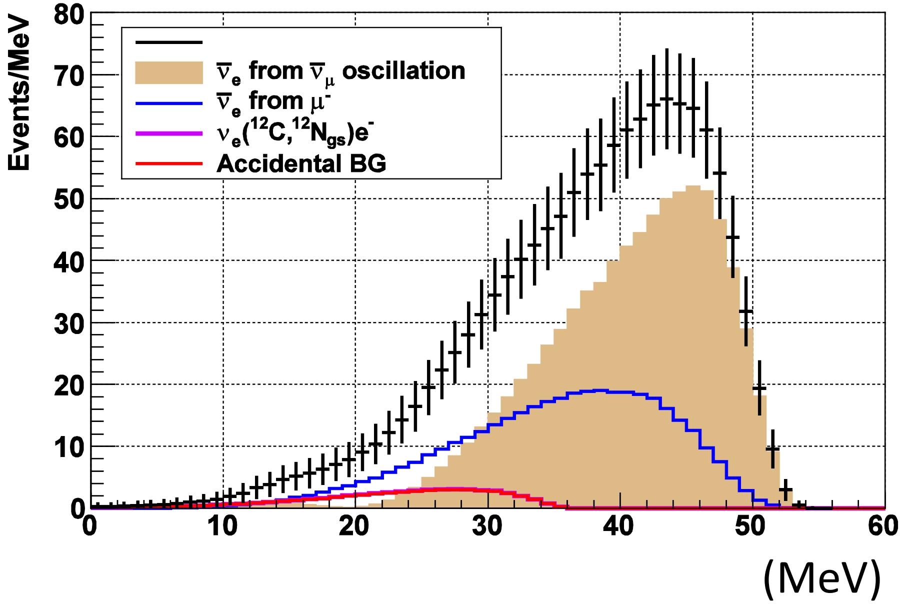
Accidental BKG is calculated by

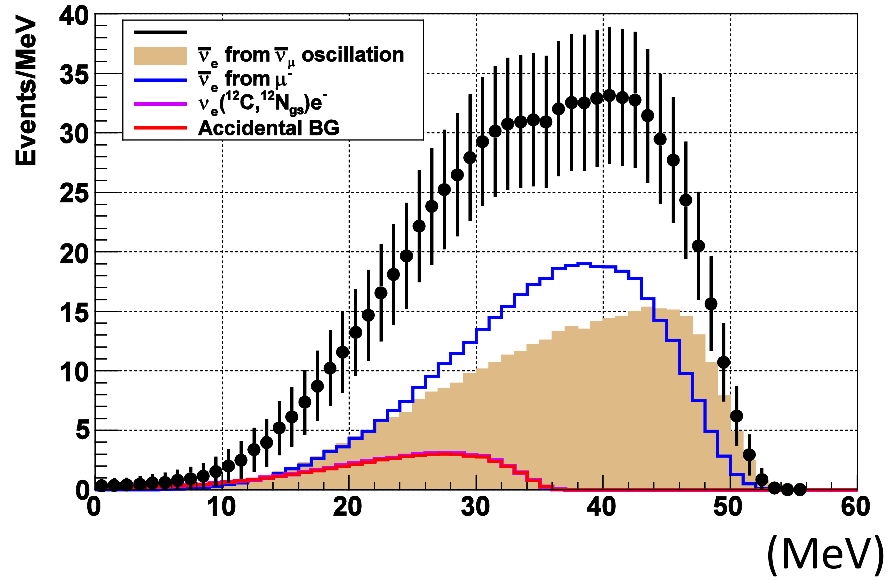
$$R\ acc = \Sigma R_{prompt} \times \Sigma R_{delay} \times \Delta_{VTX} \times N_{spill}$$

- ΣR_{prompt}, ΣR_{delay} are probability of accidental BKG for prompt and delayed signal.
- Δ_{VTX} ; BKG rejection factor of **50**.
- N_{spill}(#spills / 4 years) = 1.2×10^9

Fit and sensitivity

How to fit

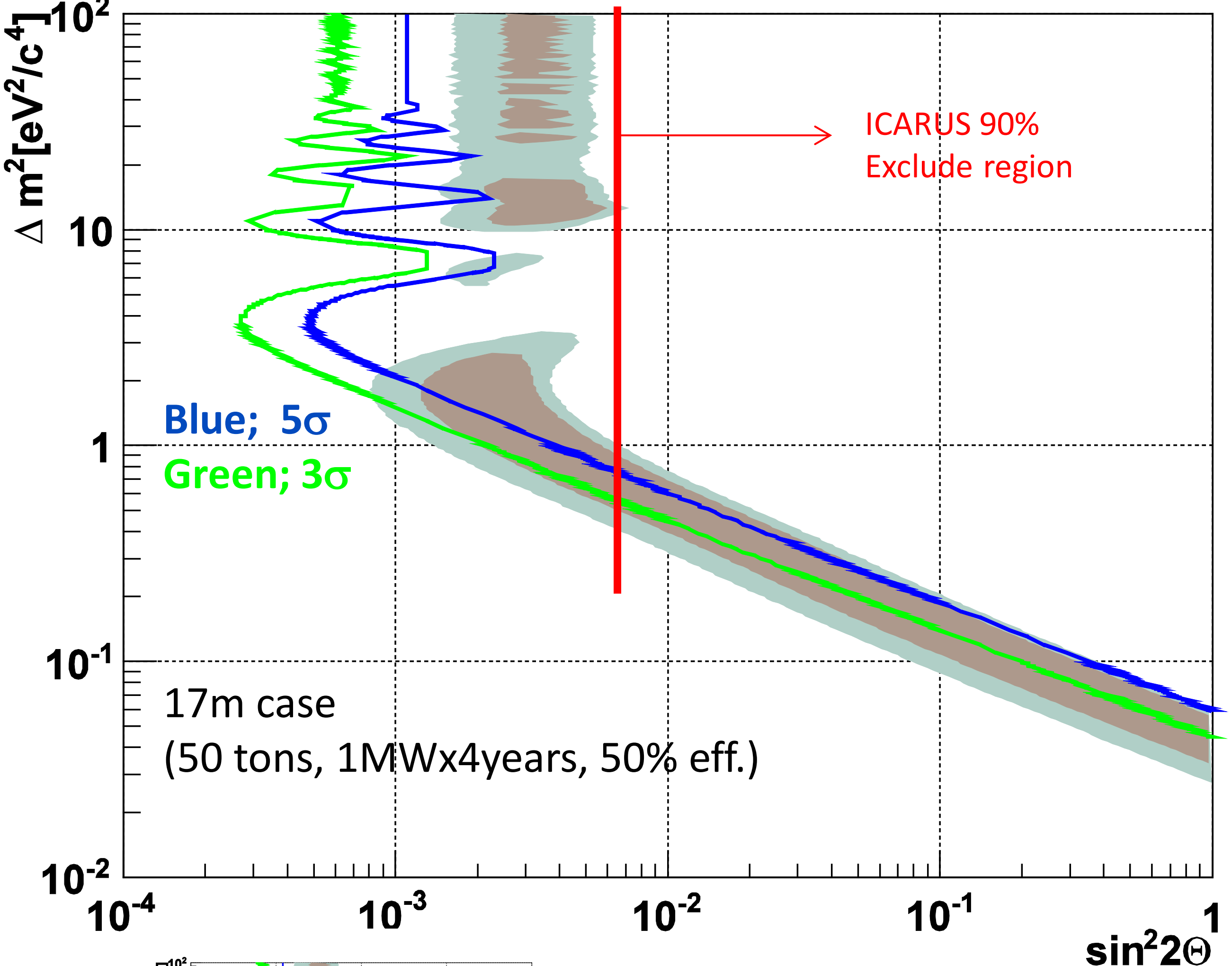




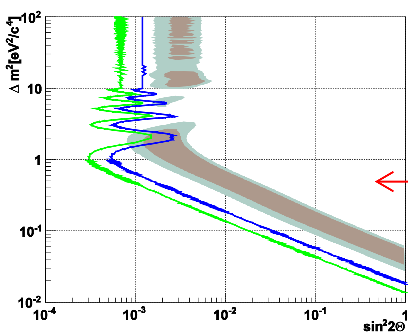
- Left; Δm^2=3.0eV^2 (best Δm^2 for MLF) , right; Δm^2=1.2 (LSND best) $\sin^2 2\theta$=0.003
- Simultaneous fit with maximum likelihood with 1MeV bin is used (20-60MeV).
- We use only signal and $\overline{\nu_e}$ from μ^- (Other components are small).
- Uncertainties on the overall normalization is 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.

Sensitivity

- Top plot;
  - 1MW x 4 years
  - 4000h / year
  - 50 tons fiducial
  - ~50% detection ε
- a definite conclusion above $2eV^2$ is obtained



- Bottom plot;
  - Example configuration;
  - 1kt detector with 60 m baseline. (future option)



60m, 1 kt, 1MW x 2 years, 50% eff.

Milestone and cost

Milestone

- The background rate at the 3rd floor of MLF will be checked with real data.
- Efficiencies and cut rejection factors based on pure MC should be proved by data.
- Detector configuration → optimized further.
- Electronics / DAQ
- Movable detector design (e.g.; mechanical design)

- We would start the experiment within 2 years with performing the R&D above.

Cost estimation for 2 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
Grand total			500Myen

Summary

- The definitive conclusion on the existence or the non-existence of the sterile neutrinos should be obtained.
- J-PARC MLF provides a unique opportunity to search for sterile neutrinos.
- Strategy; higher Δm^2 region search with short baseline (~17m, 3rd floor of MLF) at first.
- No signals → will try sub-eV^2 search using larger detector + longer baseline
- Collaborators are eager to search for sterile neutrinos ASAP.

Technical feasibility on detector

- Same type detectors have been worked stably → Double-Chooz, Daya-Bay, Reno, ..
- Many experts on detector inside collaboration → experiences from Double-Chooz, Daya-Bay, KamLAND, experts on Gd-LS, electronics, PMT, PID …

→Basic principles on detector are established already.

→Expertise on the detector are existed inside the collaboration.

Backup slide