Sterile Neutrino Searches at J-PARC MLF

Takasumi Maruyama (KEK)

Thanks to J.Spitz (U of Michigan)
for KPIPE experiment discussion

indication of the sterile neutrino (Δm^2~1eV^2) ?

- Anomalies, which cannot be explained by standard neutrino oscillations for ~20 years are shown;

Experiments	Neutrino source	signal	significance	E(MeV),L(m)
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8σ	40,30
MiniBooNE	π Decay-In-Flight	$\nu_\mu \rightarrow \nu_e$	3.4σ	800,600
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8σ	
		combined	3.8σ	
Ga (calibration)	e capture	$\nu_e \rightarrow \nu_x$	2.7σ	<3,10
Reactors	Beta decay	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3.0σ	3,10-100

- 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

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

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

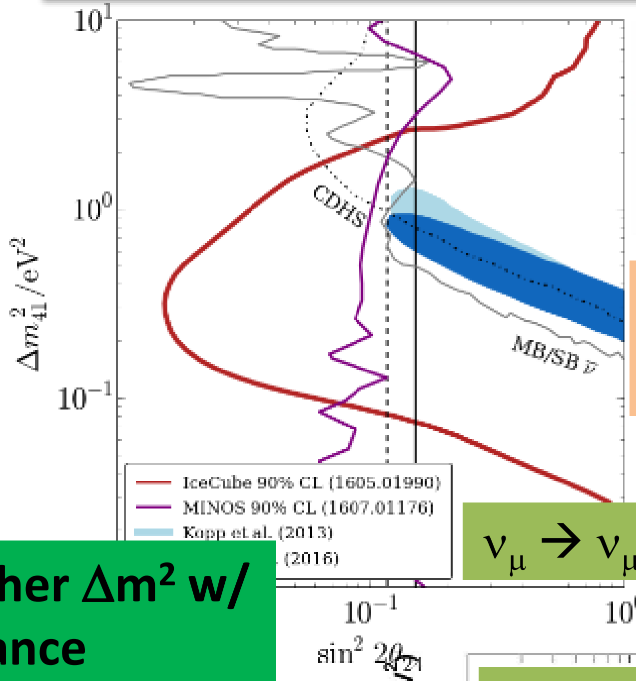
$$P_{e\mu} = -4 \sum_{i=1,3} (U^*_{e4} U_{\mu 4} U_{ei} U^*_{\mu i}) \sin^2 \frac{(m_4^2 - m_i^2)L}{4E_\nu} \sim 4 |U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \frac{\Delta m_4^2}{4} \frac{L}{E}$$

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

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

(3+1) model

No positive results on steriles



IceCube

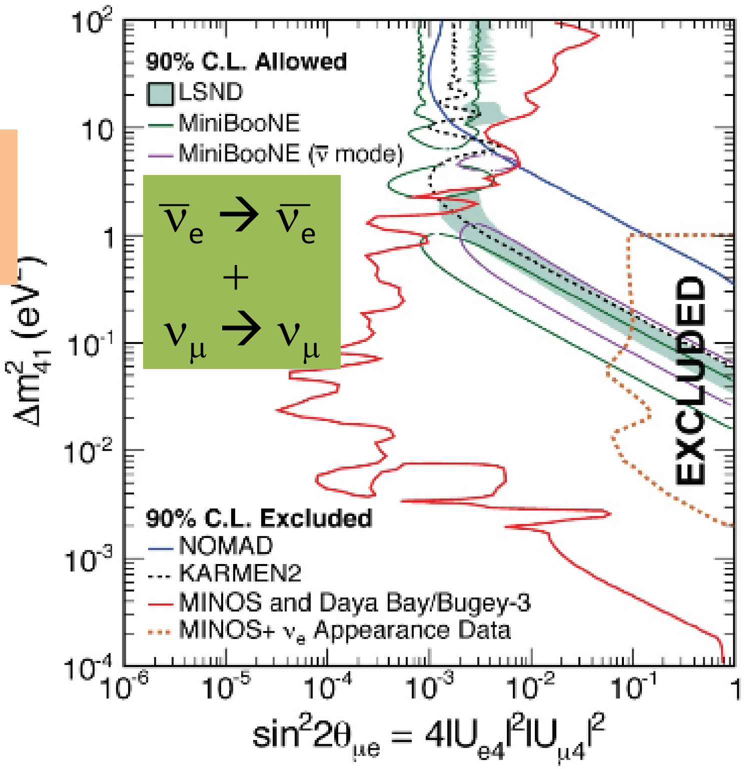
Mauro Mezzetto's (experimental summary) talk in Neutrino2016

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

3+1 model checking

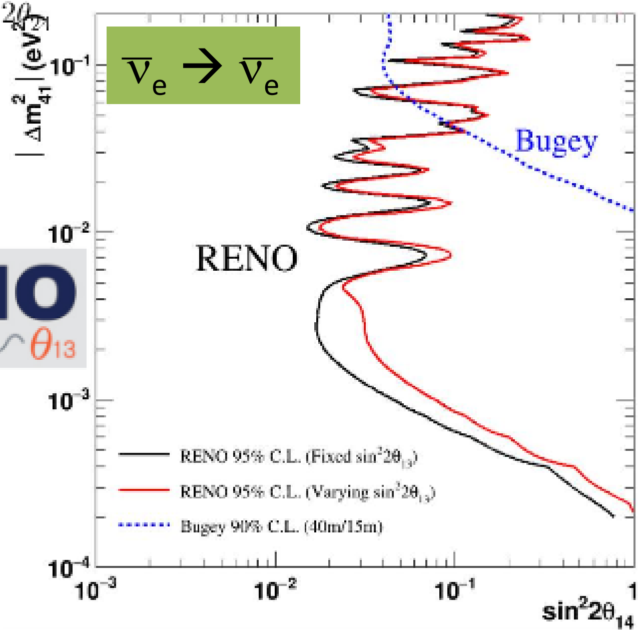
→ Checking higher Δm^2 w/ nm disappearance
→ KPIPE

Daya Bay, Minos and Bugey 3 combined



$\bar{\nu}_e \rightarrow \bar{\nu}_e$
+
$\nu_\mu \rightarrow \nu_\mu$

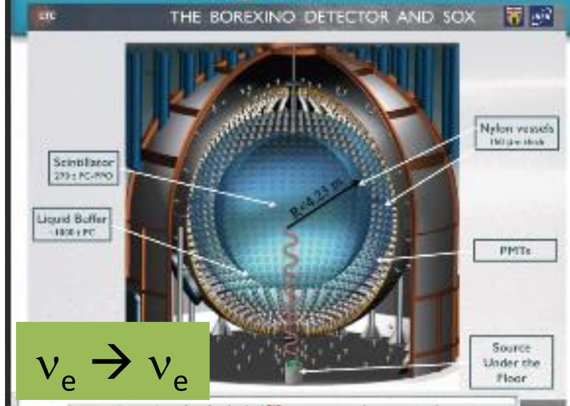
RENO



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

→ Is it time to check the LSND result directly w/o any excuses?
→ JSNS^2

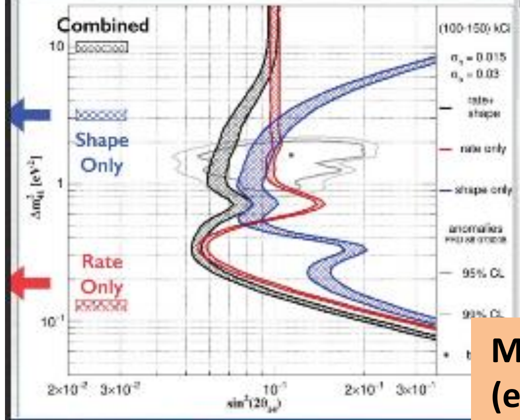
Next generation sterile experiments are almost ready



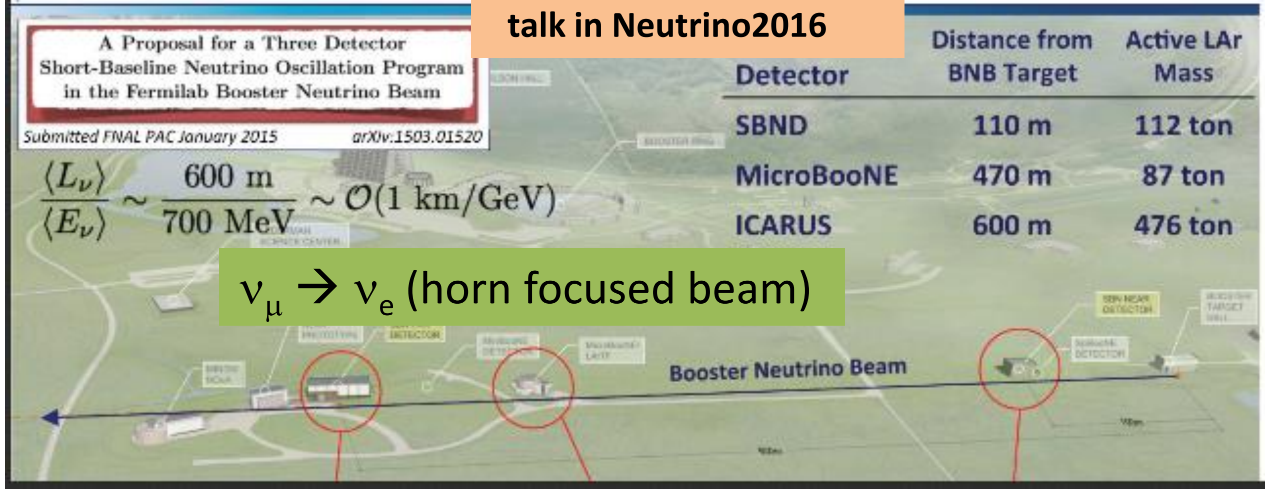
$\overline{\nu}_e \rightarrow \overline{\nu}_e$

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

$\nu_e \rightarrow \nu_e$



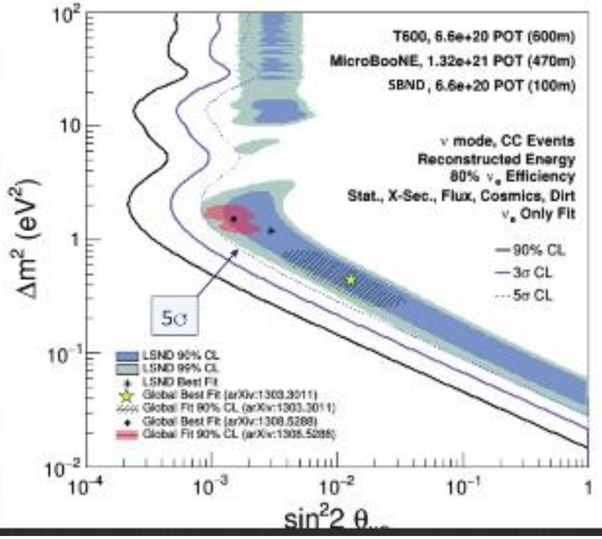
Mauro Mezzetto's (experimental summary) talk in Neutrino2016



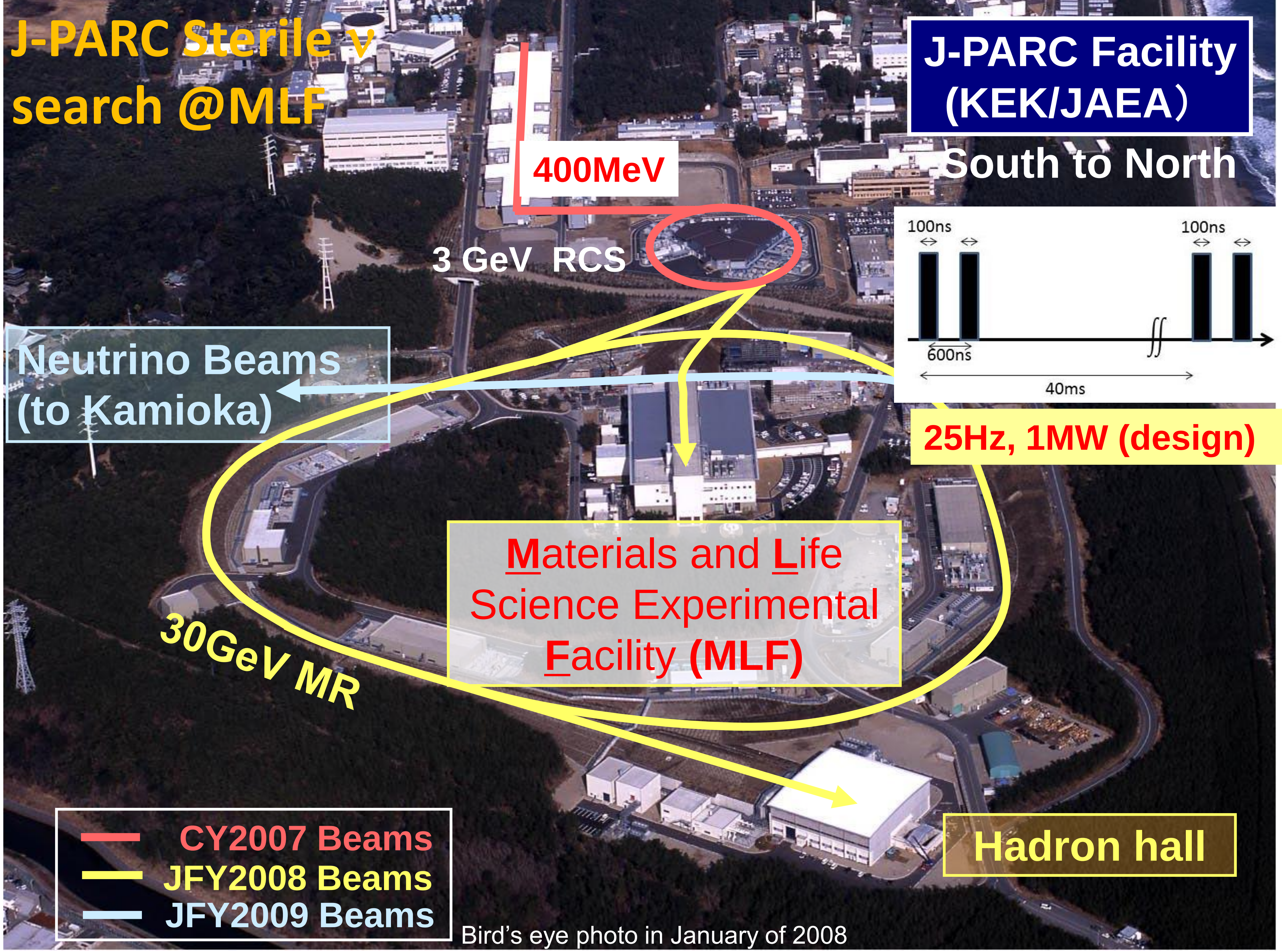
$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \mathrm{m}}{700\ \mathrm{MeV}} \sim \mathcal{O}(1\ \mathrm{km/GeV})$$

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)



J-PARC Sterile ν search @MLF



Bird's eye photo in January of 2008

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

Direct ultimate tests for LSND.

JSNS^2 collaboration (53 collaborators)

- 10 Korean institutions (18 members)
- 6 Japanese institutions (28 members)
- 5 US institutions (7 members)

Technical Design Report (TDR):
Searching for a Sterile Neutrino at J-PARC MLF
(E56, JSNS^2)

S. Ajimura[1], M. K. Cheoun[2], J. H. Choi[3], H. Furuta[4], M. Harada[5], S. Hasegawa[5], Y. Hino[4], T. Hiraiwa[1], E. Iwai[6], S. Iwata[7], J. S. Jang[8], H. I. Jang[9], K. K. Joo[10], J. Jordan[6], S. K. Kang[11], T. Kawasaki[7], Y. Kasugai[5], E. J. Kim[12], J. Y. Kim[10], S. B. Kim[13], W. Kim[14], K. Kuwata[4], E. Kwon[13], I. T. Lim[10], T. Maruyama[*15], T. Matsubara[4], S. Meigo[5], S. Monjushiro[15], D. H. Moon[10], T. Nakano[1], M. Niiyama[16], K. Nishikawa[15], M. Nomachi[1], M. Y. Pac[3], J. S. Park[15], H. Ray[17], C. Rott[18], K. Sakai[5], S. Sakamoto[5], H. Seo[13], S. H. Seo[13], A. Shibata[7], T. Shima[1], J. Spitz[6], I. Stancu[19], F. Suekane[4], Y. Sugaya[1], K. Suzuya[5], M. Taira[15], W. Toki[20], T. Torizawa[7], M. Yeh[21], and I. Yu[18]

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May 23, 2017

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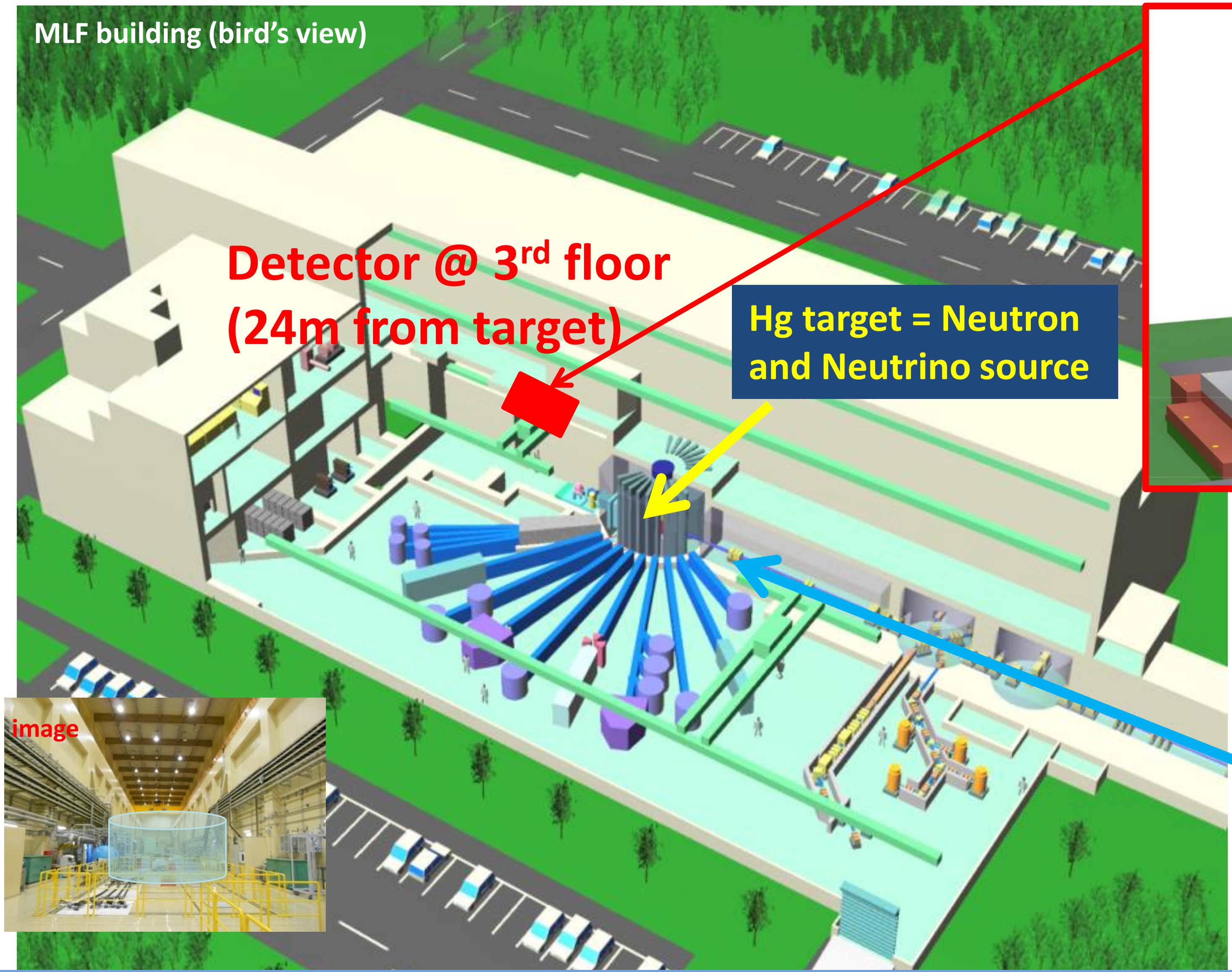
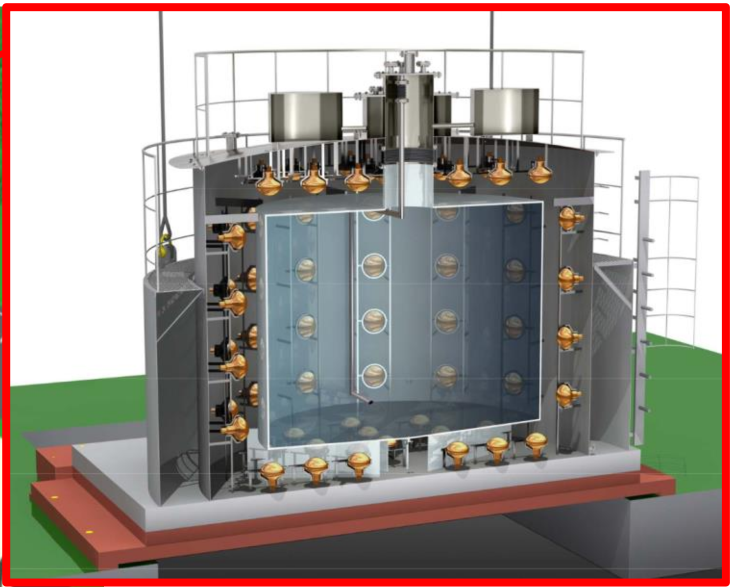
JSNS^2 setup at J-PARC MLF





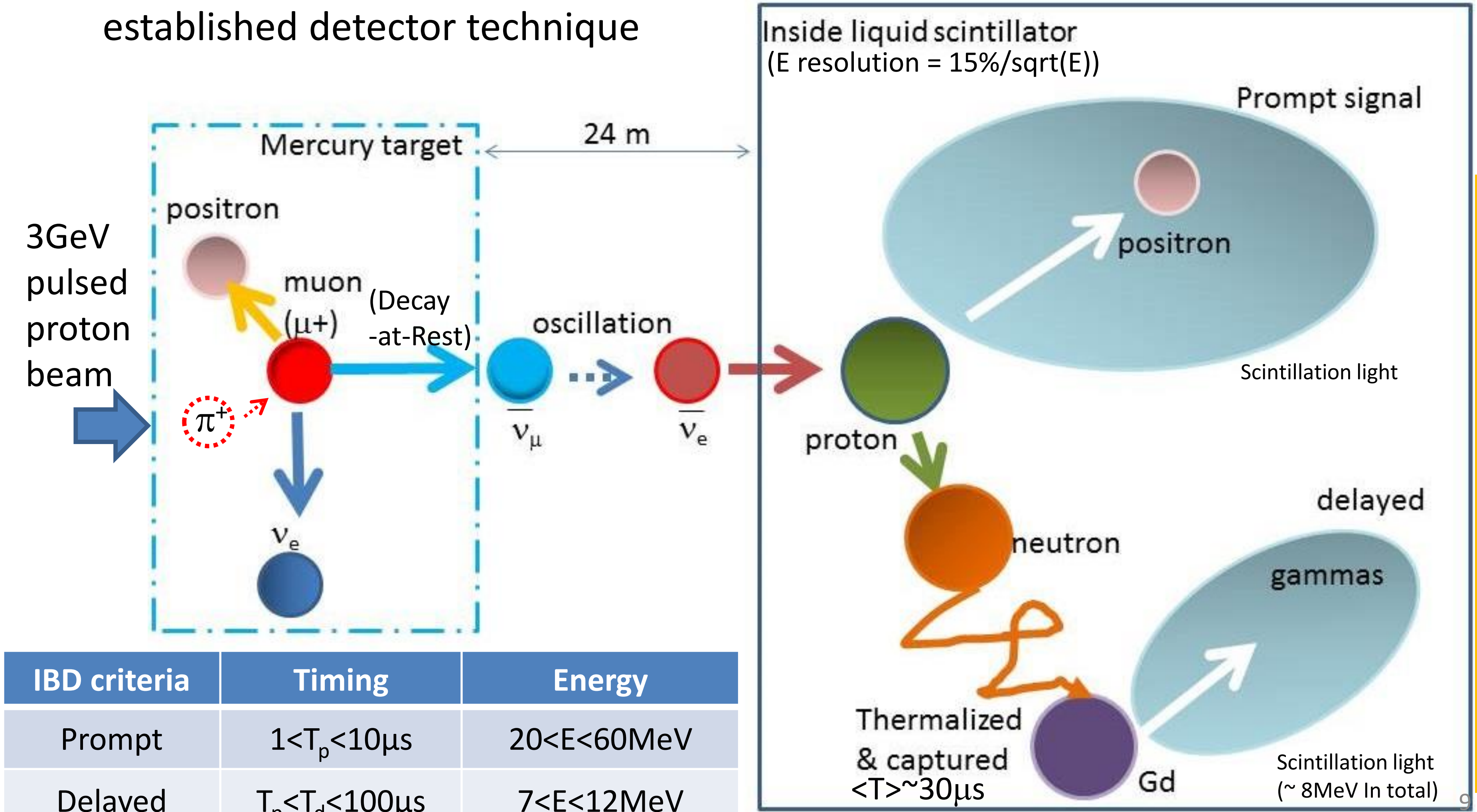
17t Gd-loaded liquid scintillator
(4.6mϕ x 3.5m h)
193 8" (inner)+ 48 5" PMTs (veto)

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

Most of them are same as The LSND.
→ Direct ultimate tests for LSND.

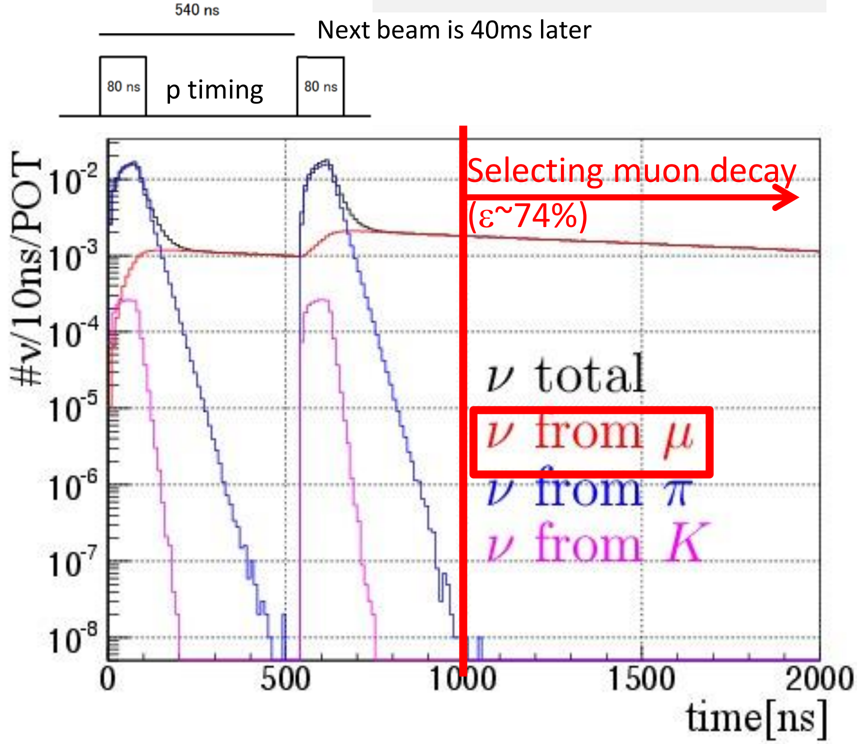
But use much better beam and Gd loaded LS.
→ Much better S/N
→ Much better systematics

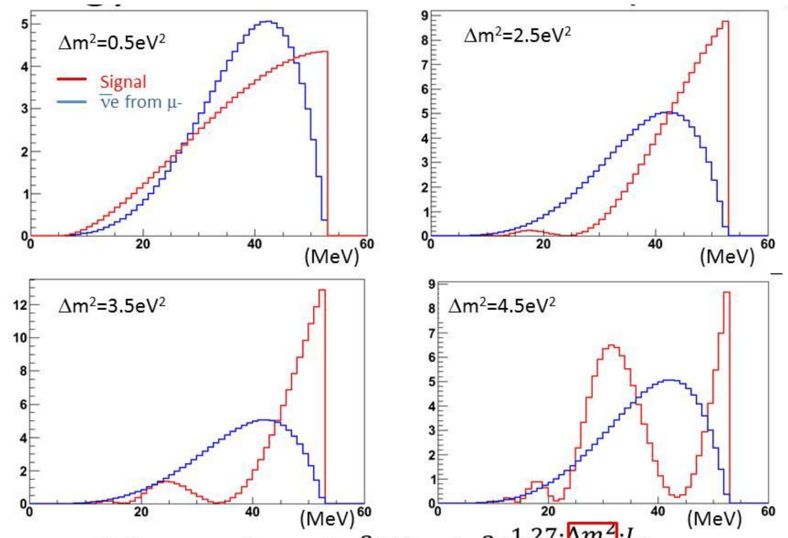
Timing and Energy

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.

M. Harada *et al*, arXiv:1310.1437





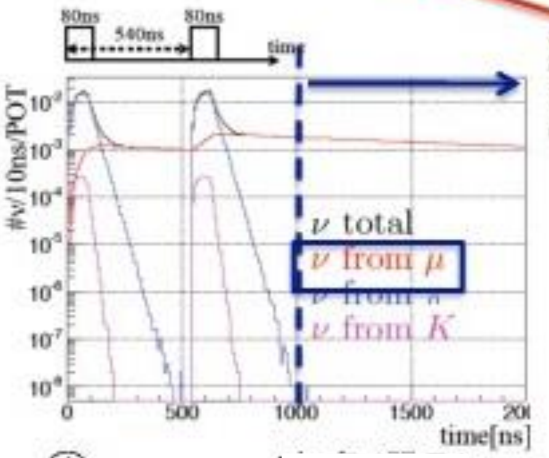
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu}\right)$$

IBD event selection

$\Delta m^2 = 3 eV^2$, $\sin^2 2\theta = 3e^{-3}$ case

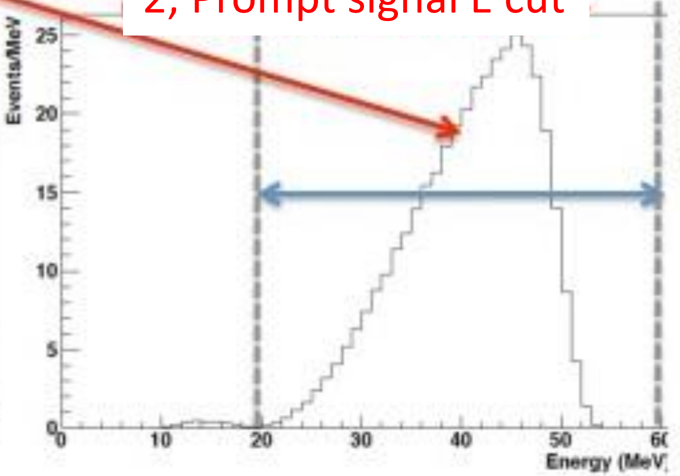
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \rightarrow \bar{\nu}_e \ \ appearance$$

$\bar{\nu}_e + p \rightarrow e^+ + n$ -> n capture ->2(H) or 8MeV(Gd)

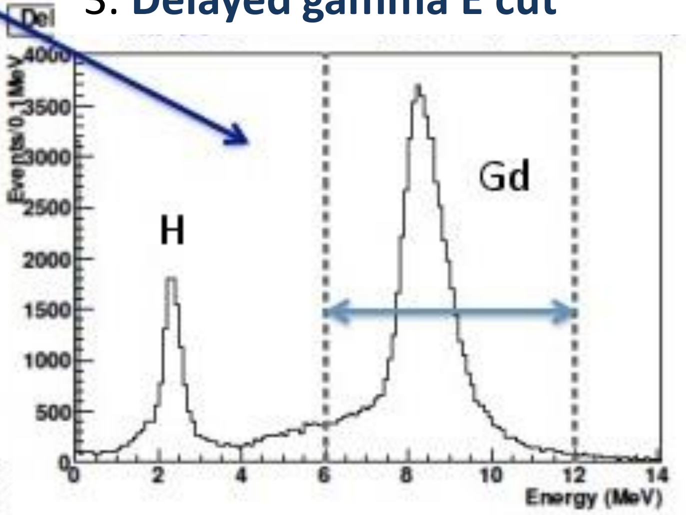


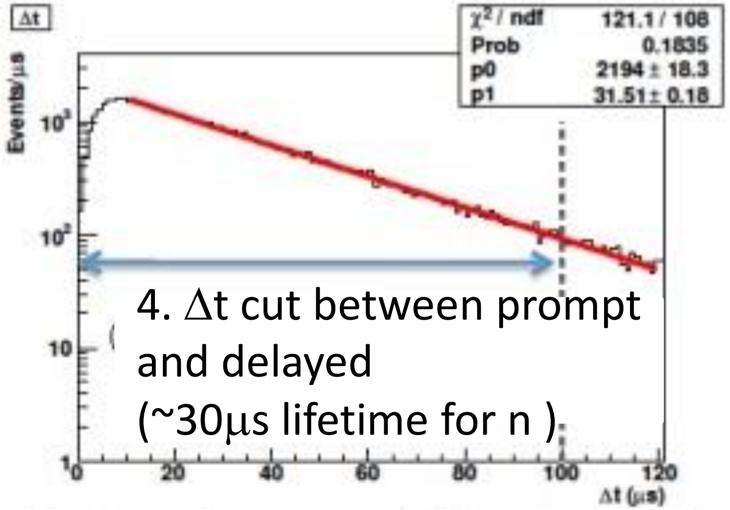
①off bunch

2; Prompt signal E cut

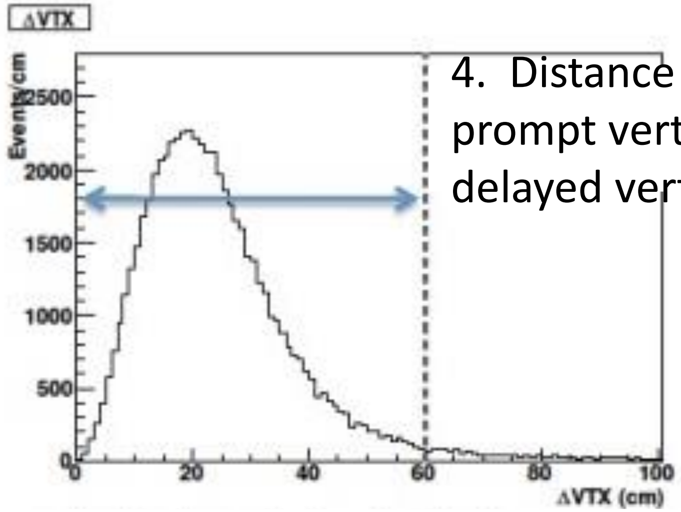


3. **Delayed gamma E cut**





4. Δt cut between prompt and delayed (~30μs lifetime for n)

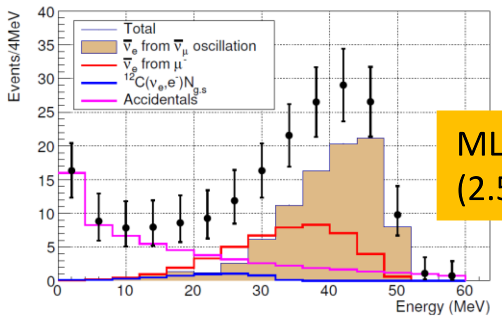


4. Distance cut between prompt vertex and delayed vertex

Selection ε ~ 38%

#events (1MW x 3 years x 1 detector (17tons))

Source	contents	#ev.(17tons x 3years)	Reference : SR2014 (50tons x 5 years)	comments
background	$\overline{\nu}_e$ from μ-	43	237	Dominant BKG
	$^{12}C(\nu_e,e-)^{12}N_{g.s.}$	3	16	
	Beam fast neutrons	Consistent with 0 < 2 (90%CL UL)	<13	Based on real data
	Fast neutrons (cosmic)	~0	37	
	Accidental	20	32	Based on real data
signal		87	480	$\Delta m^2=2.5$, $\sin^2 2\theta=0.003$
		62	342	$\Delta m^2=1.2$, $\sin^2 2\theta=0.003$



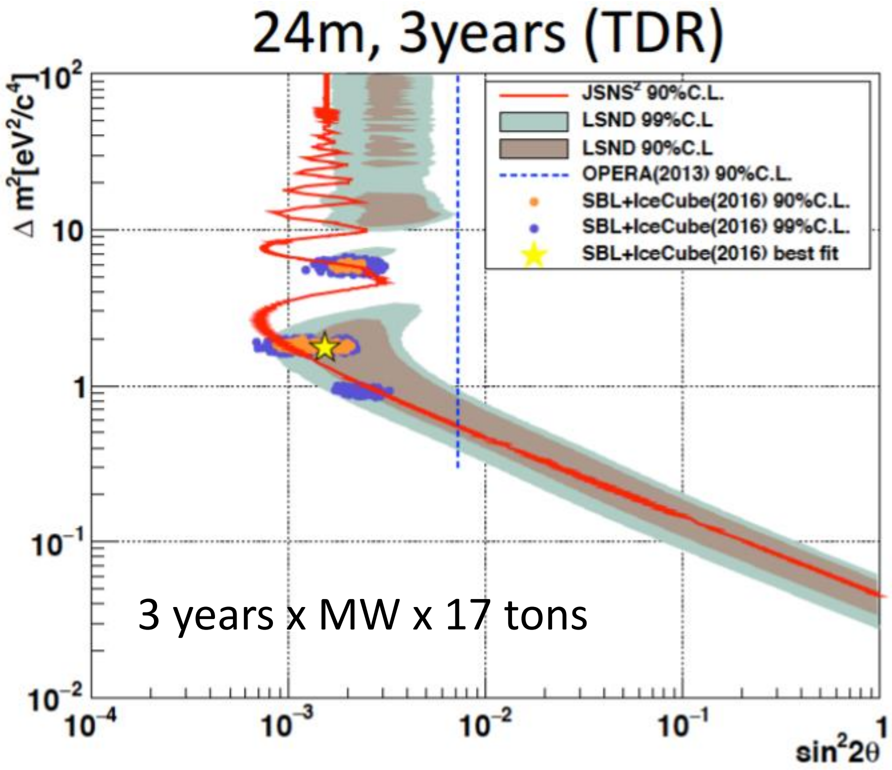
MLF best Δm^2 (2.5eV^2)

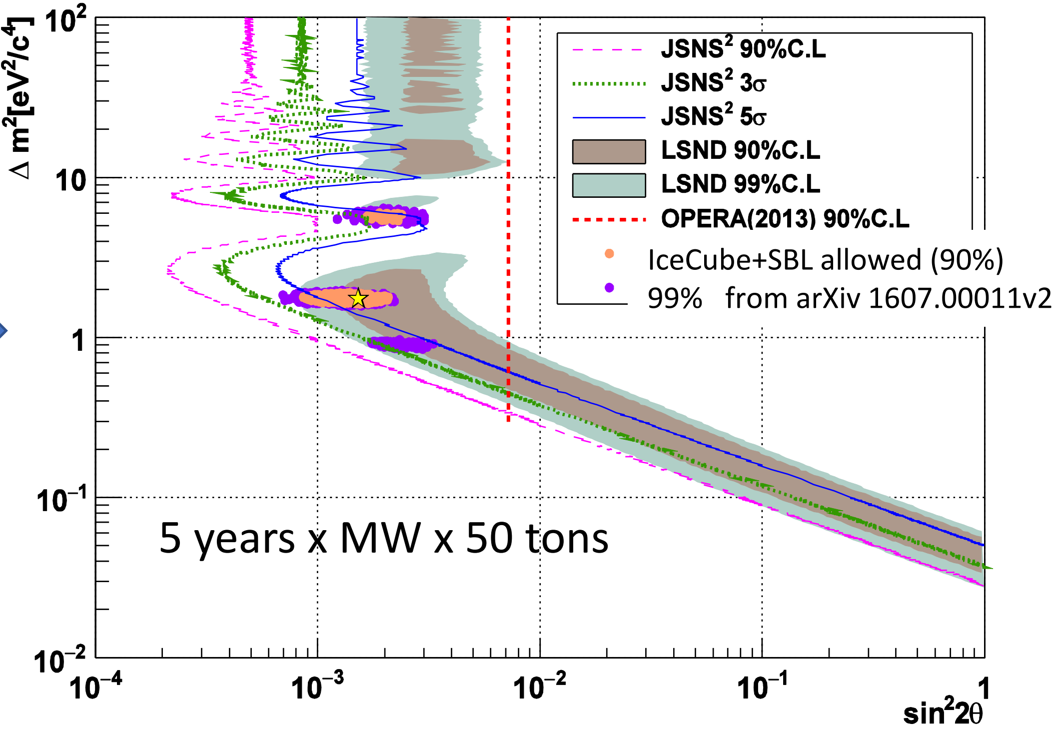
Accidental BKG is calculated by;R acc = ΣR_{prompt} x ΣR_{delay} x Δ_{VTX} x N $_{spill}$

- 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

Sensitivity / Upgrade

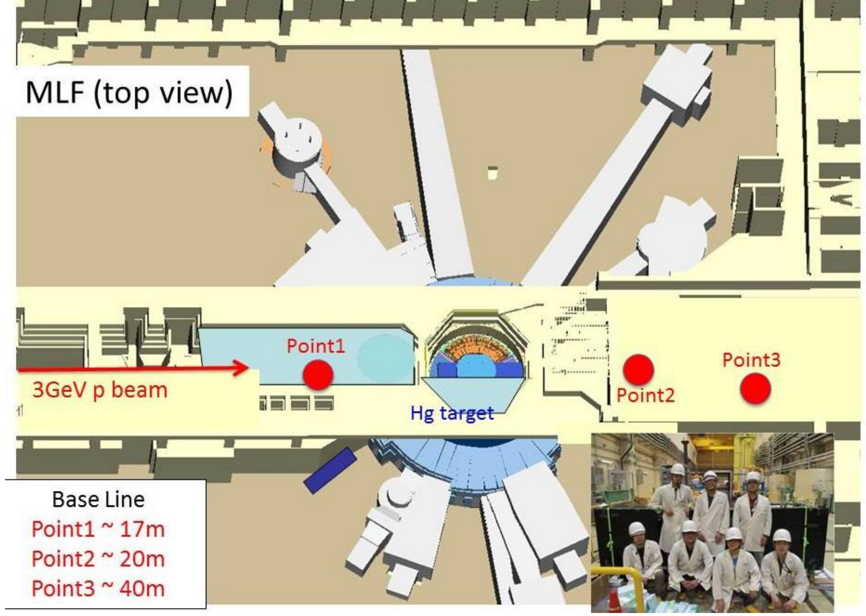
- To have a good international competition capability, we start the experiment with one detector (17tons fiducial volume).
- Even with one detector, we have a good 90% C.L constraints for the best fit point of global fit (of sterile neutrino searches) for 3 years. Left plot
- Meanwhile, we are making effort to obtain the budget to build the 2nd detector. (and enlarged acrylic tanks). This upgrade can make 5σ significance test for the best fit point of the global fit.

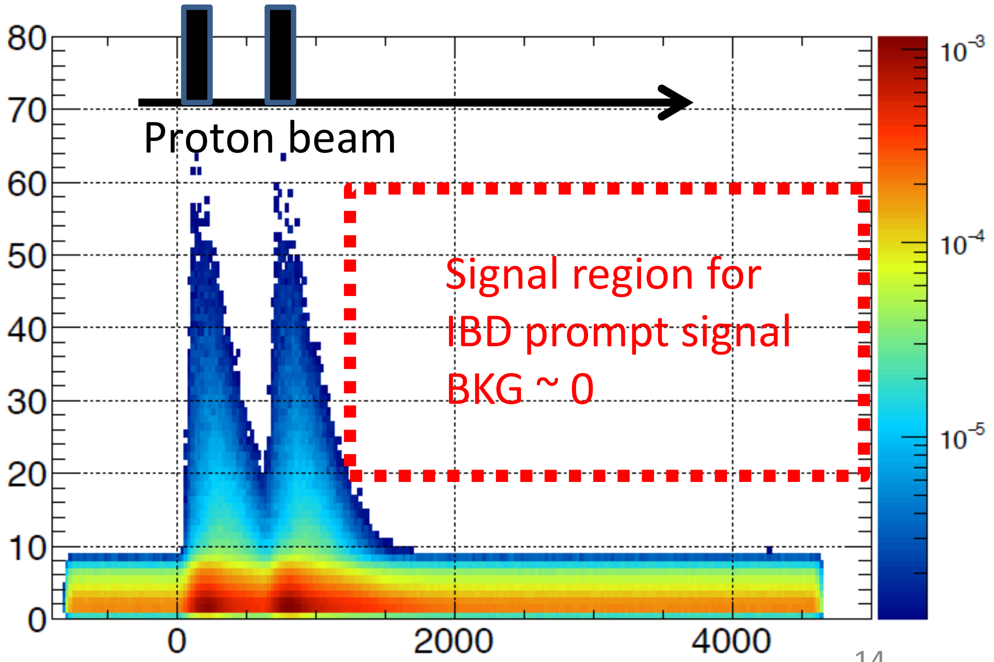




Achievements so far

- 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 was approved for one detector construction**
- **2017-May: Technical Design Report was submitted to J-PARC PAC and arXiv (arXiv:1705.08629 [physics.ins-det])**
- **We aim to start JSNS^2 in JFY2018**

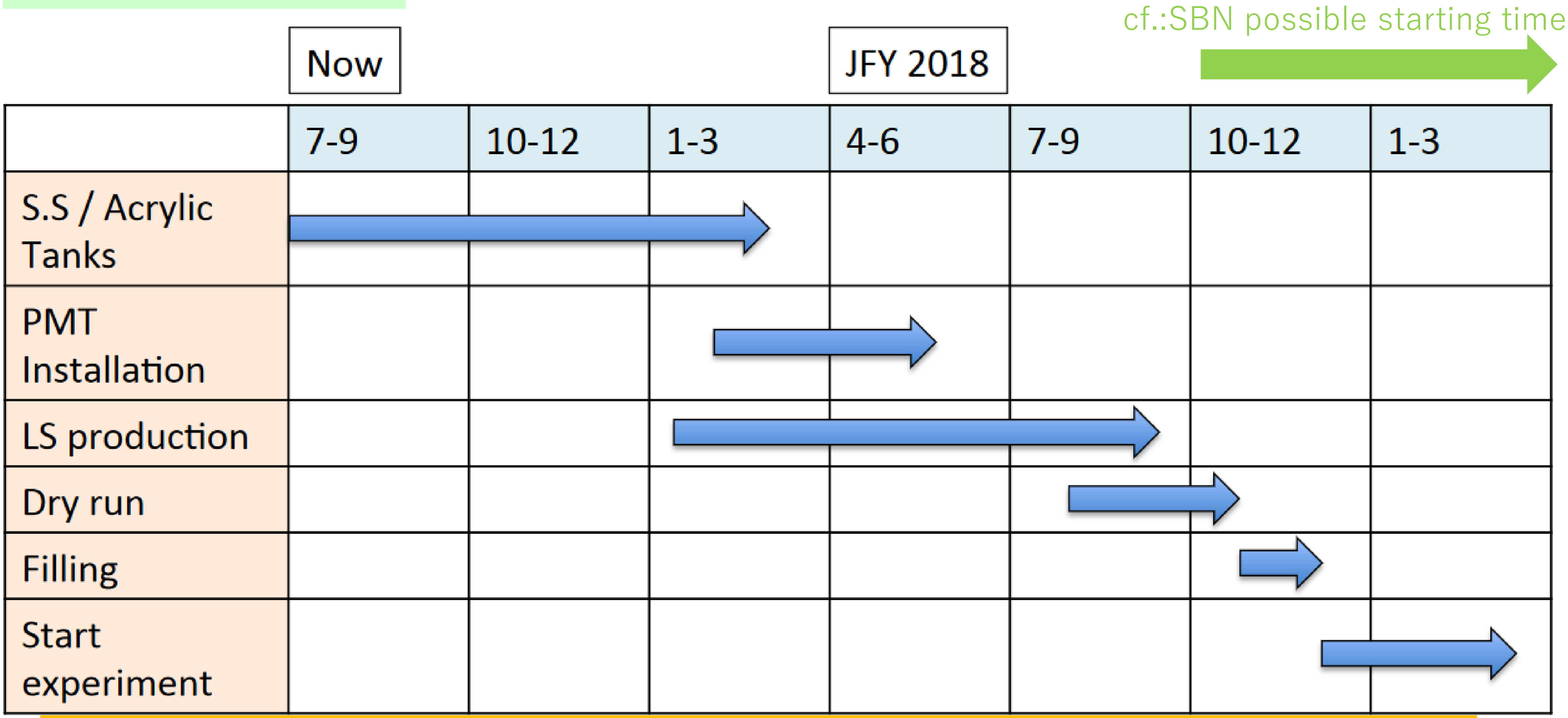




Energy (MeV, vertical) vs timing (ns, horizontal)

Schedule & Status

Overall schedule



(1) A stainless tank will be produced in JFY2017. (2) PMTs can be made within a half of year.
(3) The bid for the acrylic tank will be started soon. (4) LS will be produced at Korea.

KPIPE

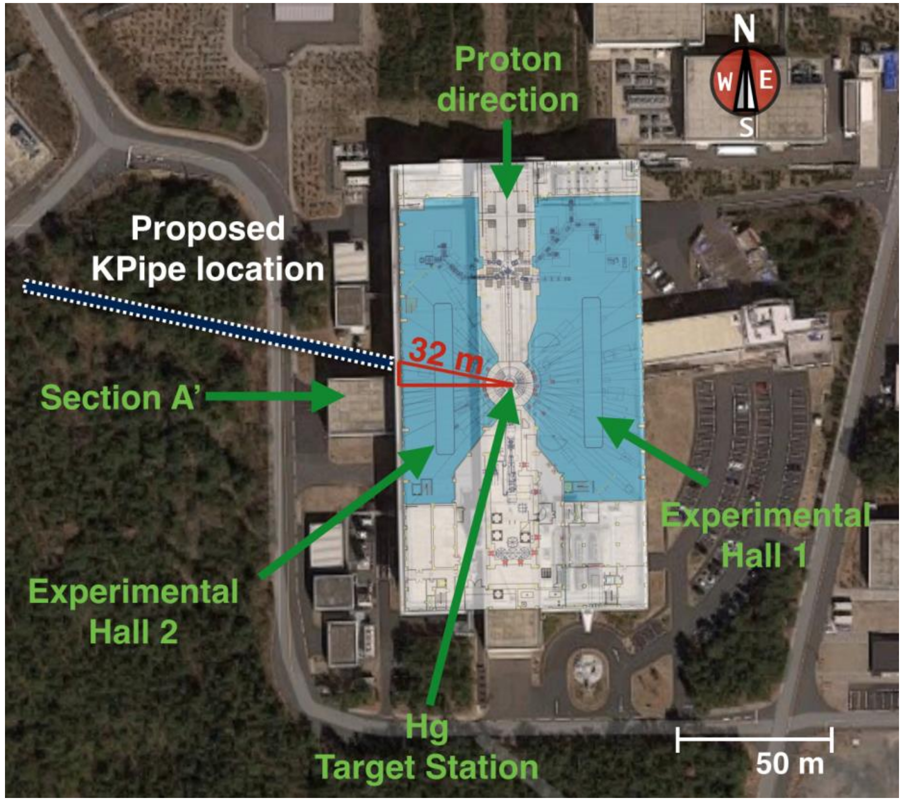
$\nu_\mu \rightarrow \nu_\mu$ is also important.

KPIPE

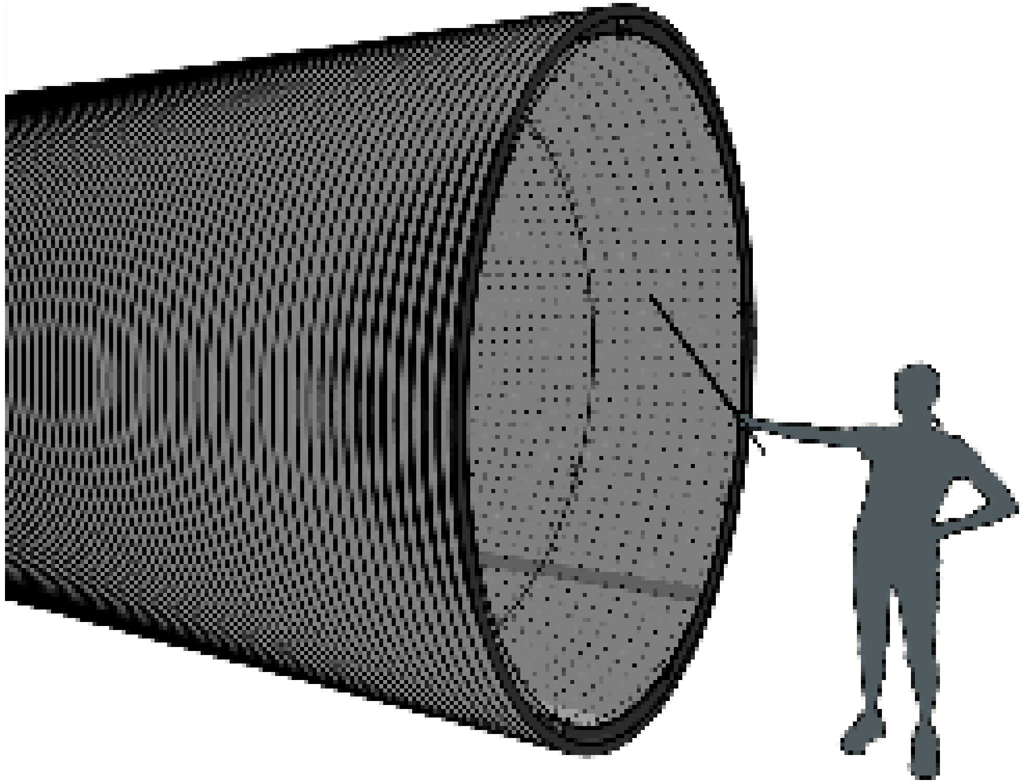
Axani, Collin, Conrad, Shaevitz, Spitz, Wongjirad, Phys Rev. D 92 092010 (2015)

The idea:

Use a very long liquid scintillator detector to look for ν_μ disappearance (in *L*) using 236 MeV KDAR ν_μ CC events



@ J-PARC MLF



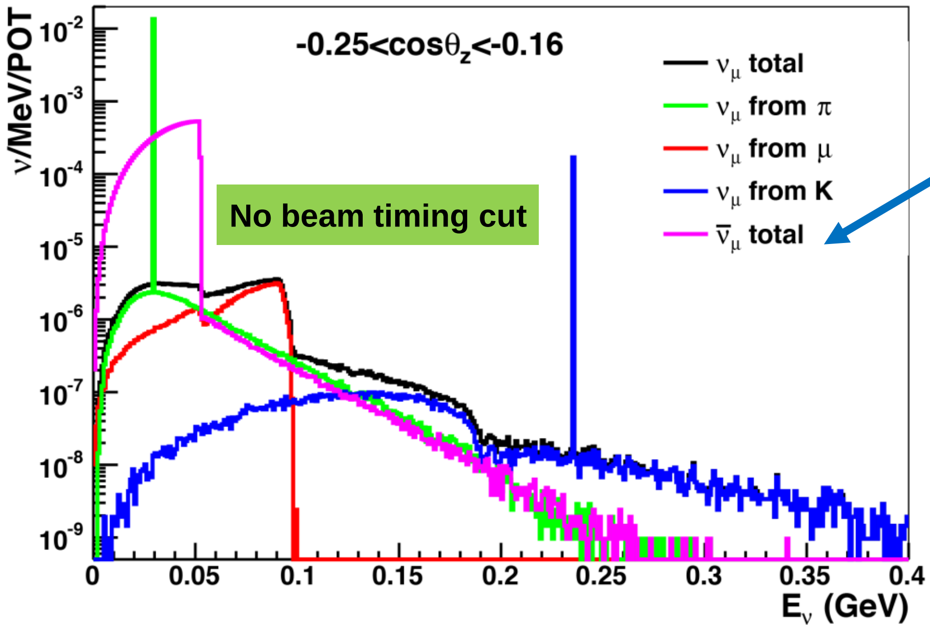
Long LS detector surrounded by SiPMs

KPIPE

Axani, Collin, Conrad, Shaevitz, Spitz, Wongjirad, Phys Rev. D 92 092010 (2015)

A very pure flux of KDAR neutrinos!

Overall Design

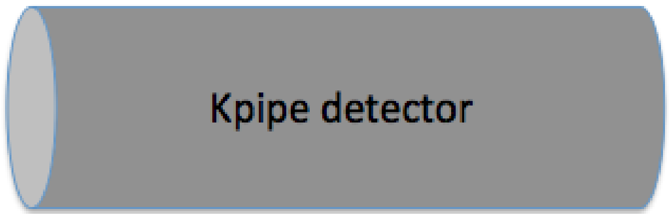


MLF Beam dump

3 GeV proton beam in

Monoenergetic 236 MeV n's from $K^+ \rightarrow \nu_\mu \mu$

Detector sits at $cos\ \theta$<0 with respect to the beam

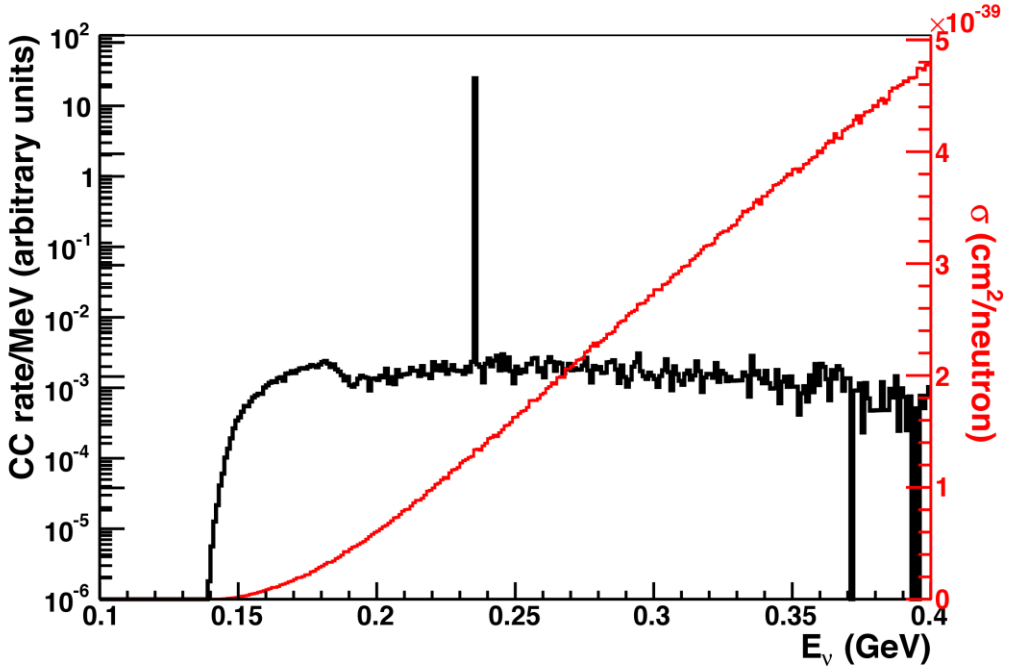


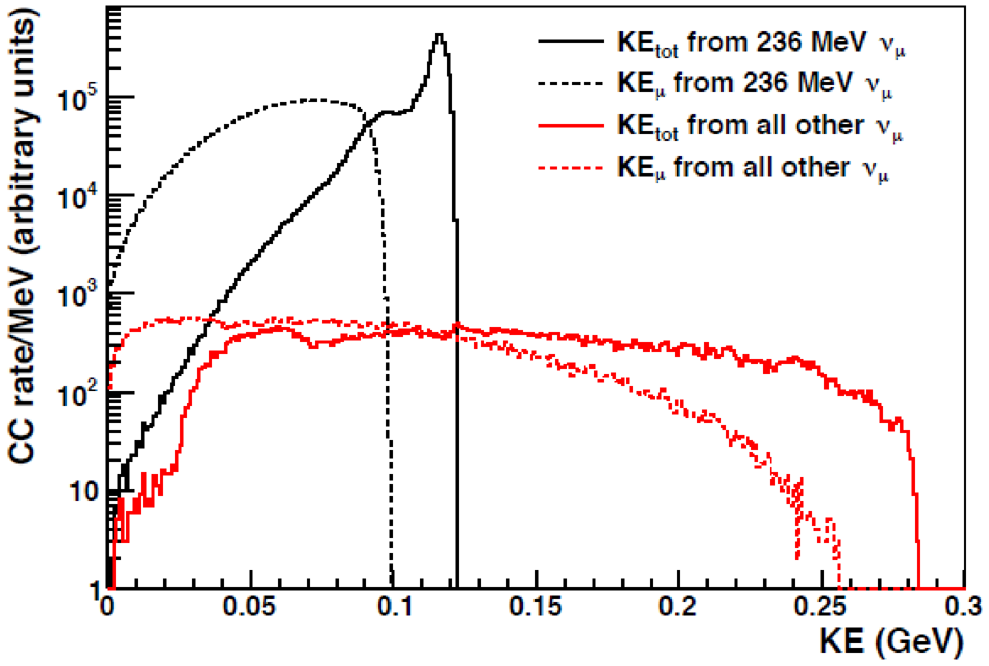
(1) pure, mono-energetic flux of muon neutrinos

(2) long detector to measure the oscillation wave

The beauty of KPIPE

If you detect a numu CC event, you can be 98.5% sure that it was a 236 MeV muon neutrino!



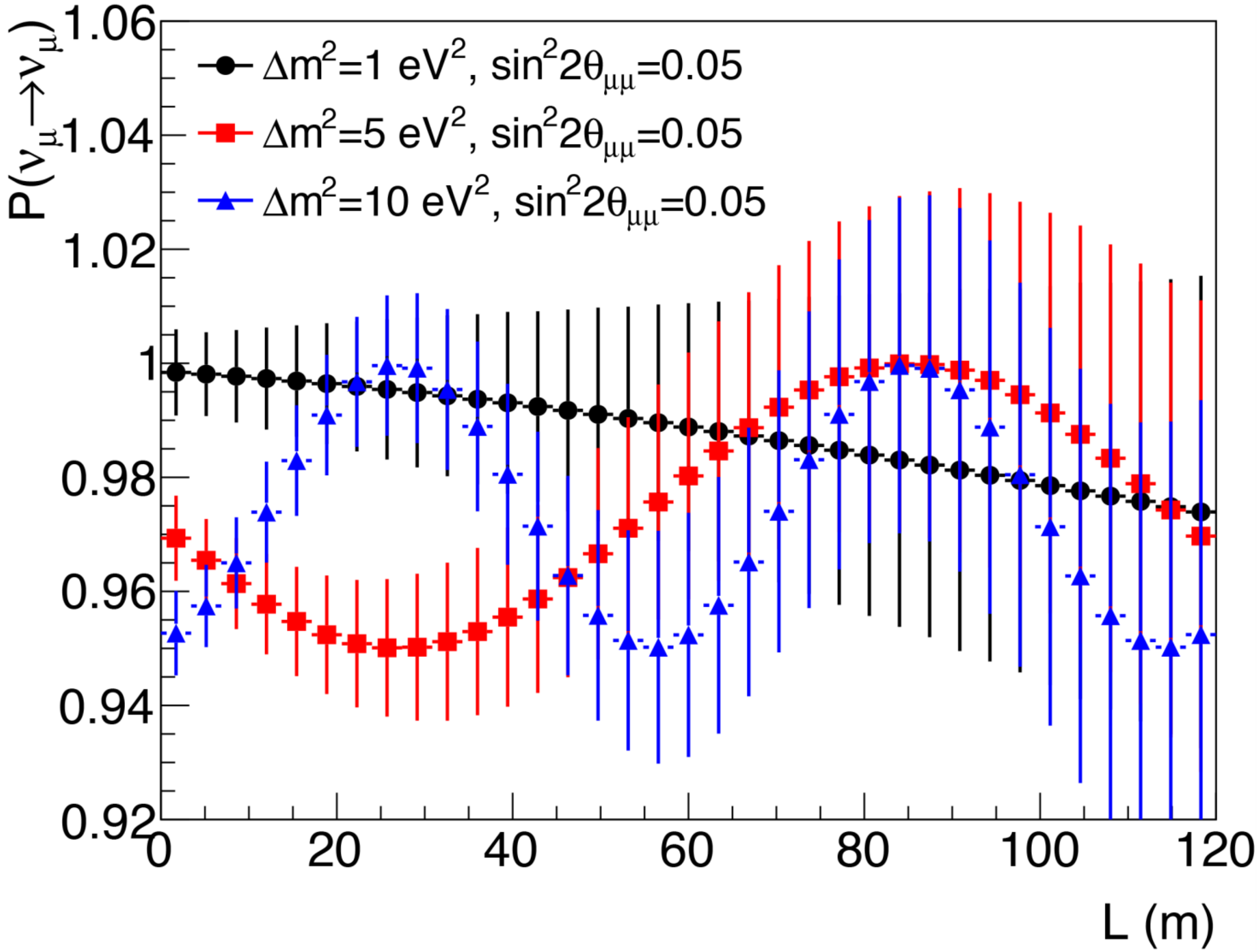


Since you know the energy of the neutrino, you don't need to worry about energy resolution. KPIPE calls for 0.4% photocoverage.

Estimated cost of experiment: $4.5M

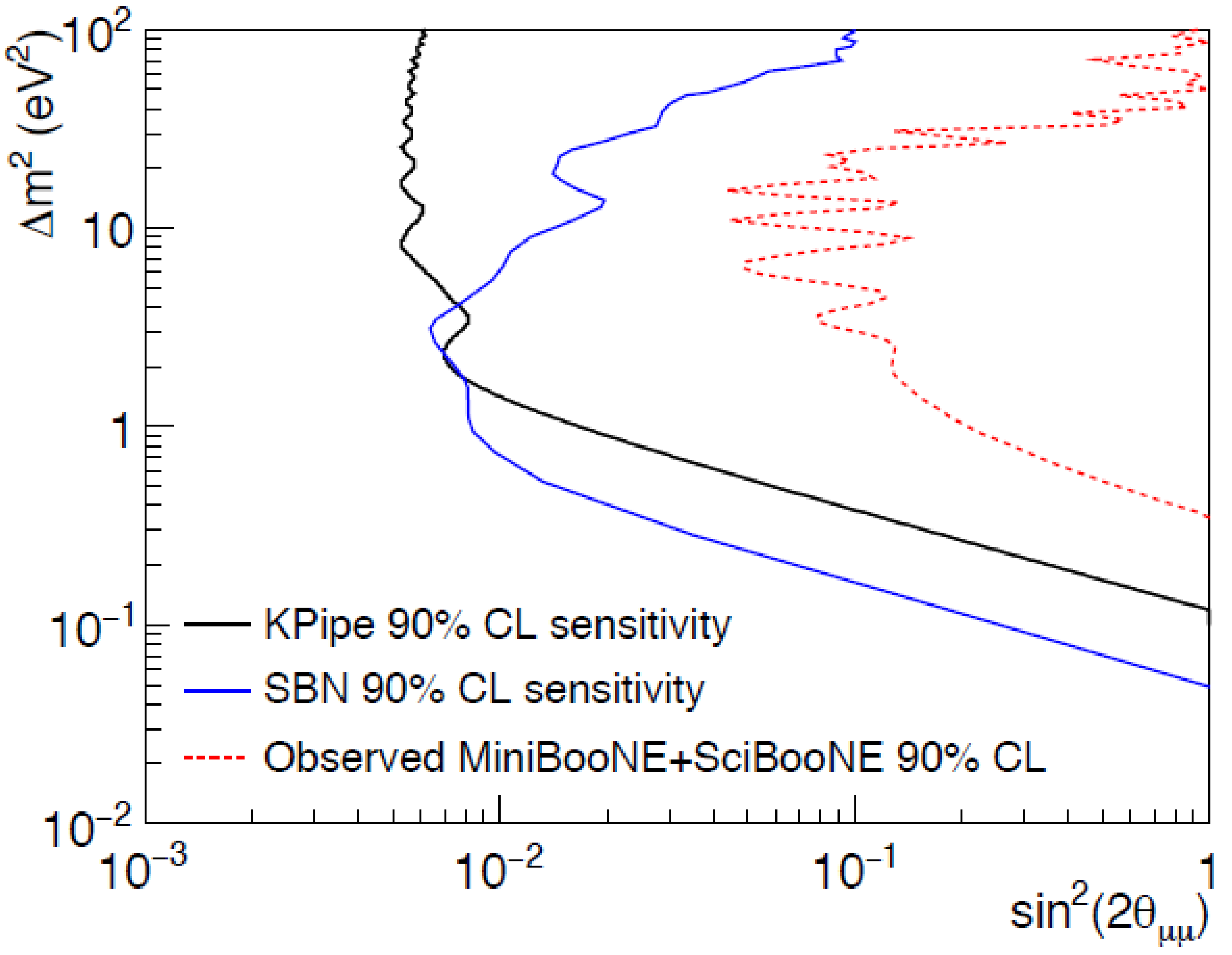
KPIPE cost document: http://hdl.handle.net/1721.1/98388

KPIPE; what would a signal look like?



KPIPE sensitivity

- 6 years of running
- Extends limit at high-Δm^2 by an order of magnitude.
- Highly complementary to SBN program.
  - 6 years of MicroBooNE
  - 3 years of T600 and SBND.

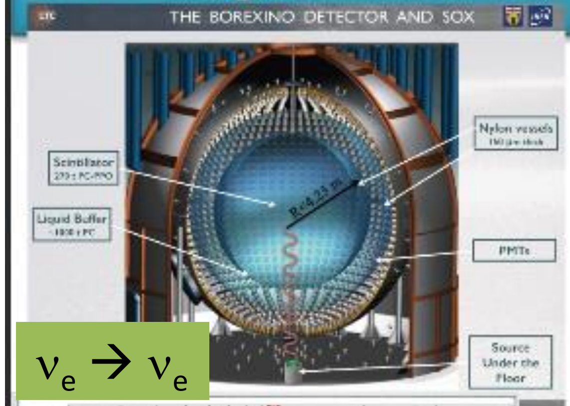


Summary

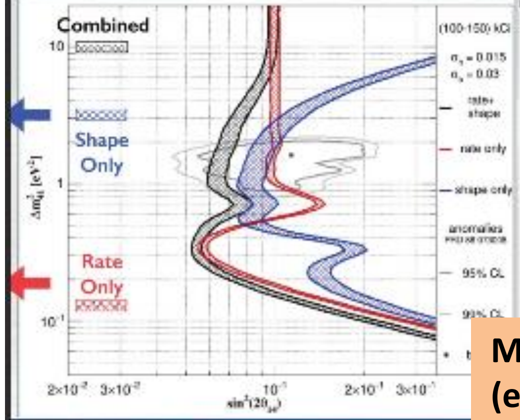
- There are fascinate programs for sterile neutrino searches at J-PARC MLF. ← large number of neutrinos are produced at the mercury target.
  - JSNS^2 : Direct test for the LSND anomaly without any excuses ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
    - Using ultra pure μ Decay-At-Rest neutrinos due to nice beam timing.
    - Gd loaded LS.
    - Improves S/N (by more than 100) and systematic uncertainties.
    - Budget to build one detector was granted in 2016.
    - Technical Design Report (TDR) was submitted to PAC and arXiv:1705.08629.
    - Aim to start the experiment in JFY2018.
  - KPIPE: ν_μ disappearance experiment
    - Using 236 MeV monochromatic neutrinos from Kaon Decay-At-Rest.
    - Oscillation curve can be seen as a function of L. (E is one number.)
    - Comparable sensitivity as SBN program with reasonable cost.
    - Letter of Intent (LoI) was submitted to J-PARC PAC (in 2016).

backup

Next generation sterile experiments are almost ready



$\nu_e \rightarrow \nu_e$



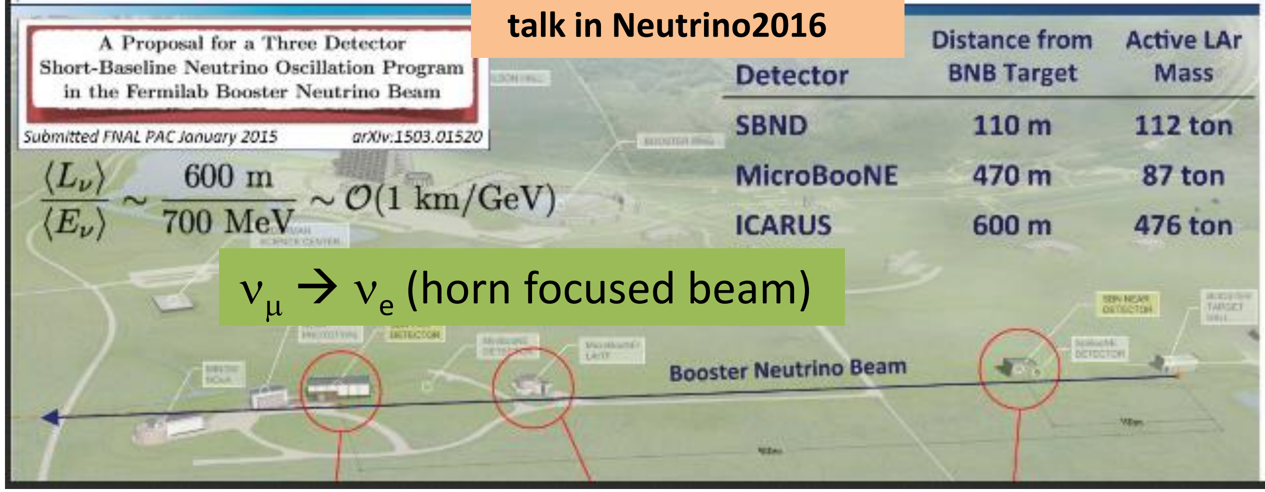
$\overline{\nu}_e \rightarrow \overline{\nu}_e$

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

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

→ **JSNS^2**

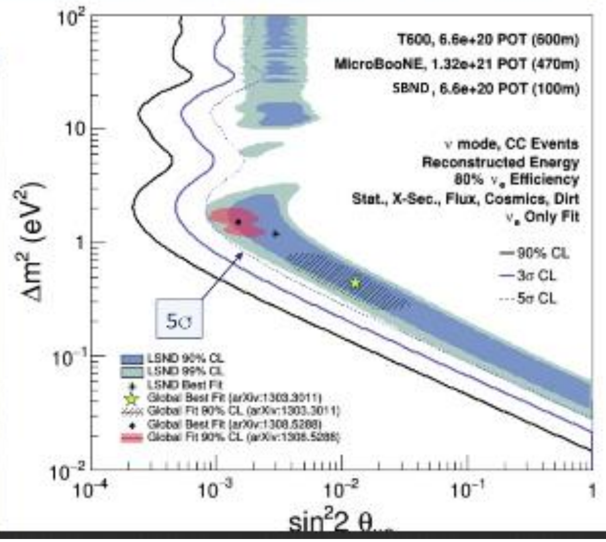
Mauro Mezzetto's (experimental summary) talk in Neutrino2016



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

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)

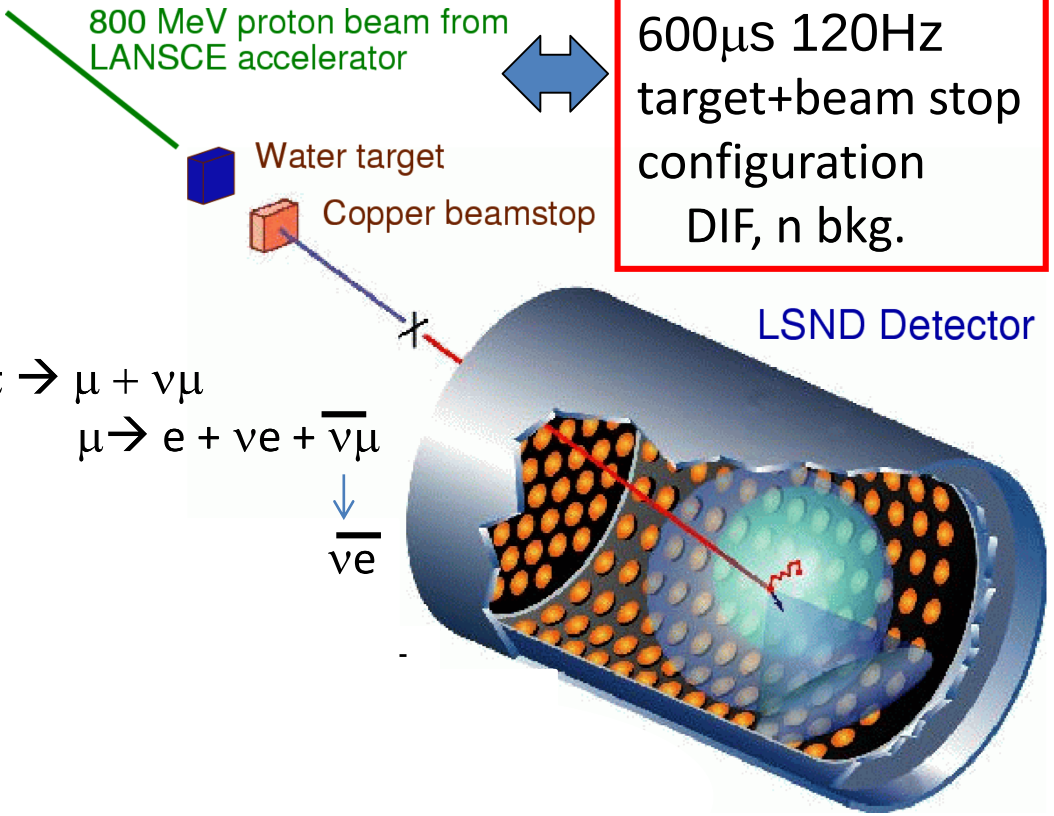


Appearance

LSND $\bar{\nu}_m \rightarrow \bar{\nu}_e$ Signal

1998

600μs 120Hz
target+beam stop
configuration
DIF, n bkg.

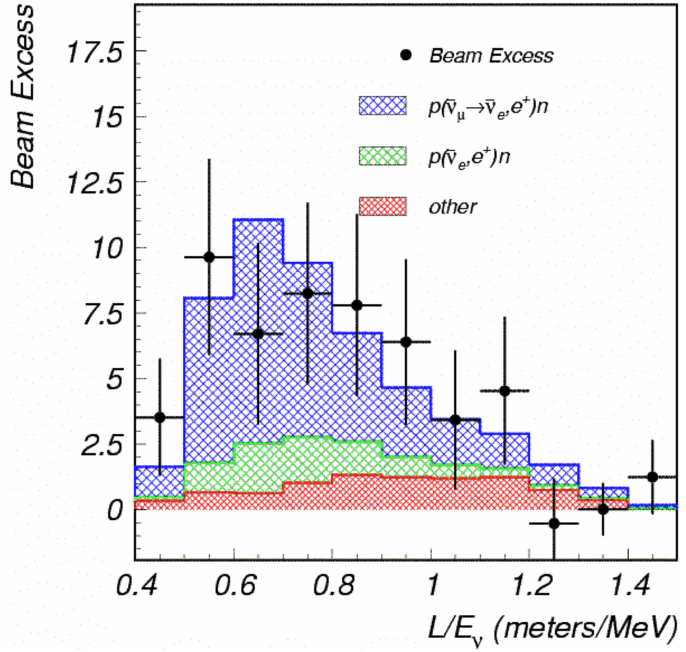


$\pi \rightarrow \mu + \nu\mu$

$\mu \rightarrow e + \nu e + \overline{\nu\mu}$

$\downarrow$

$\overline{\nu e}$



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

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 s evidence for oscillation.

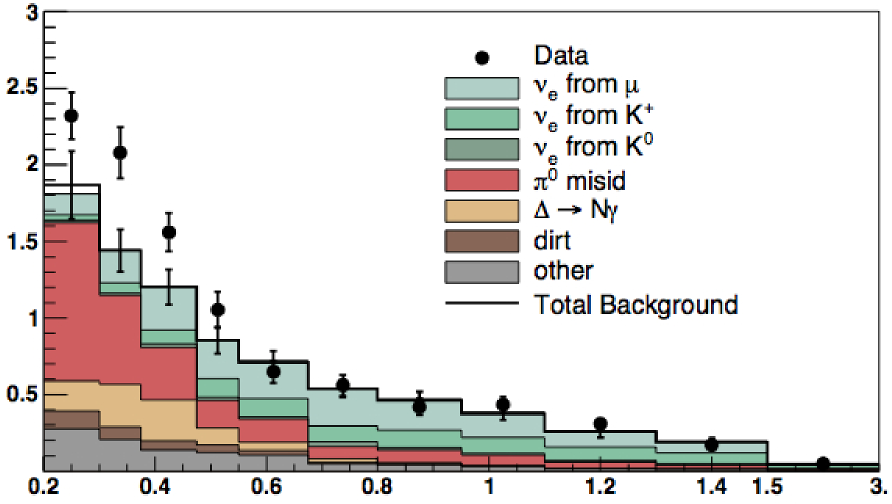
π^-, μ^- absorbed before decay into ν's
there should not be $\overline{\nu e}$ at the level of 7×10^{-4}

Signal : $\overline{\nu e}\ p \rightarrow e^+ n \quad np \rightarrow d\ \gamma(2.2\text{MeV})$

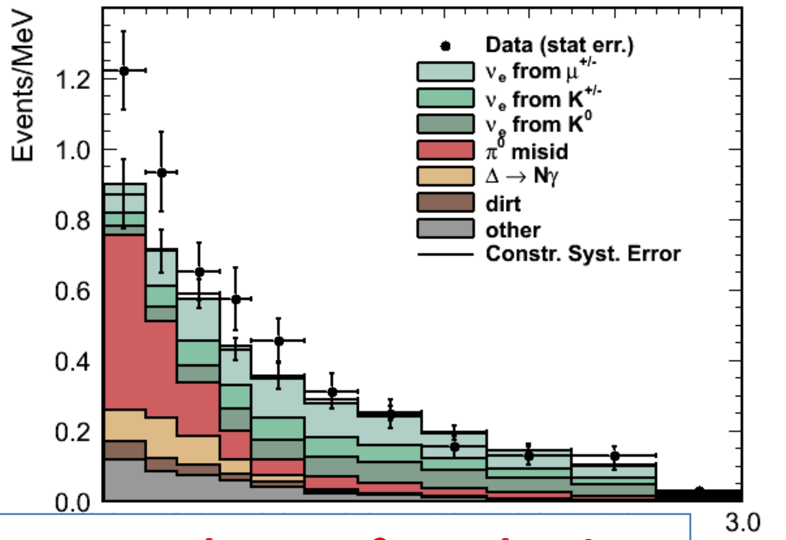
Trial by MiniBooNE @ Fermilab

Chris Polly
NEUTRINO2012

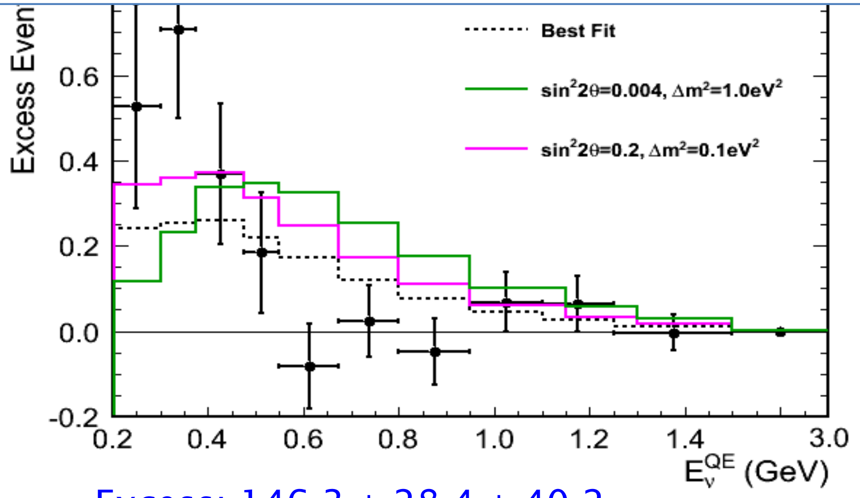
6.7e20 POT neutrino mode



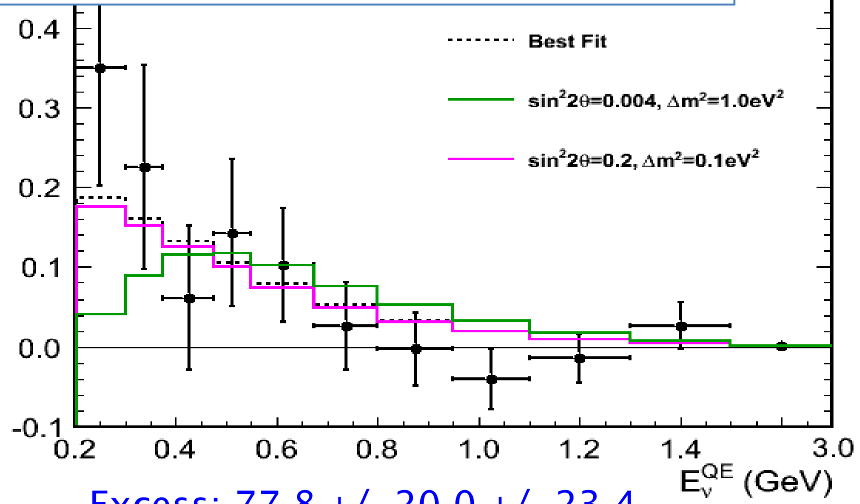
11.3e20 POT anti-neutrino mode



- **Horn focused beam has many backgrounds Ke3, μ decay, π0 production**
- **Eν reconstruction; claimed to have issues by nuclear effects**

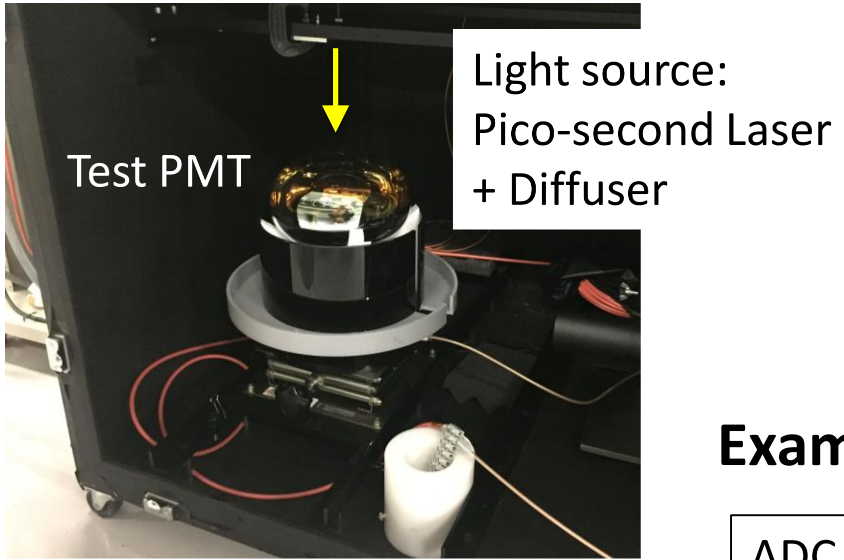


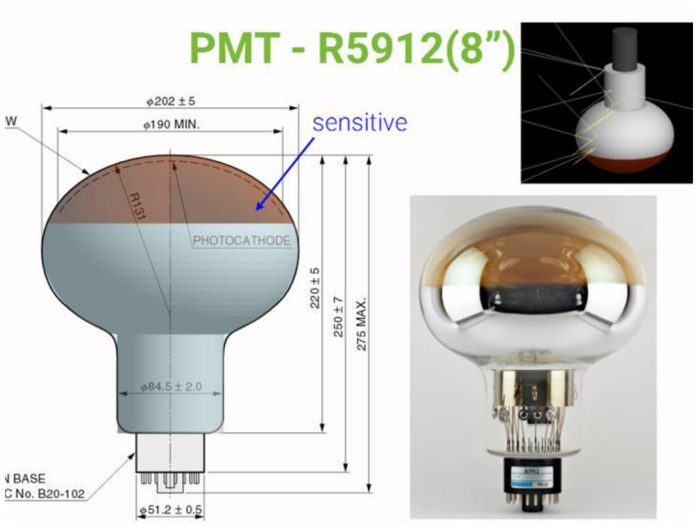
Excess: 146.3 ± 28.4 ± 40.2



Excess: 77.8 +/- 20.0 +/- 23.4

8” PMT pre-calibration





Test item:

Gain, Peak-to-Valley ratio, Transit time spread, QE × CE

Status:

Test conditions are adjusting using an 8”PMT sample.

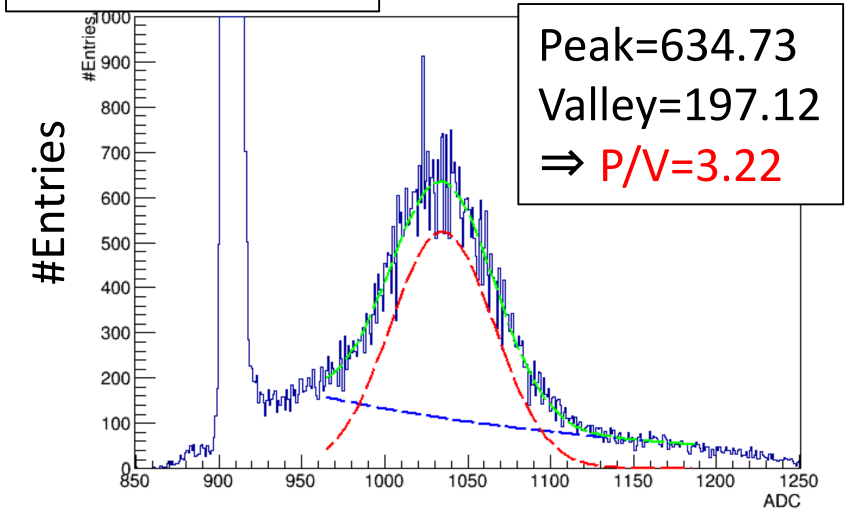
- Light intensity, PMT position, etc…

Examples of measurement

There are almost consistent with Hamamatsu evaluations.

ADC distribution

The HV of 10^7-gain was applied.



Gain curve