# JSNS$^2$: A sterile neutrino search in Japan
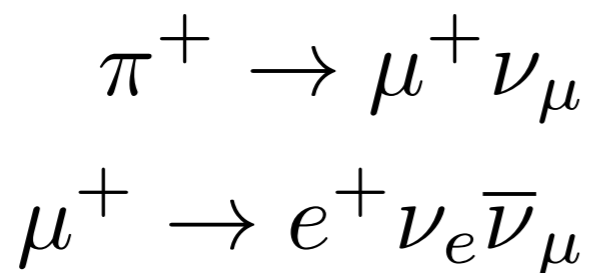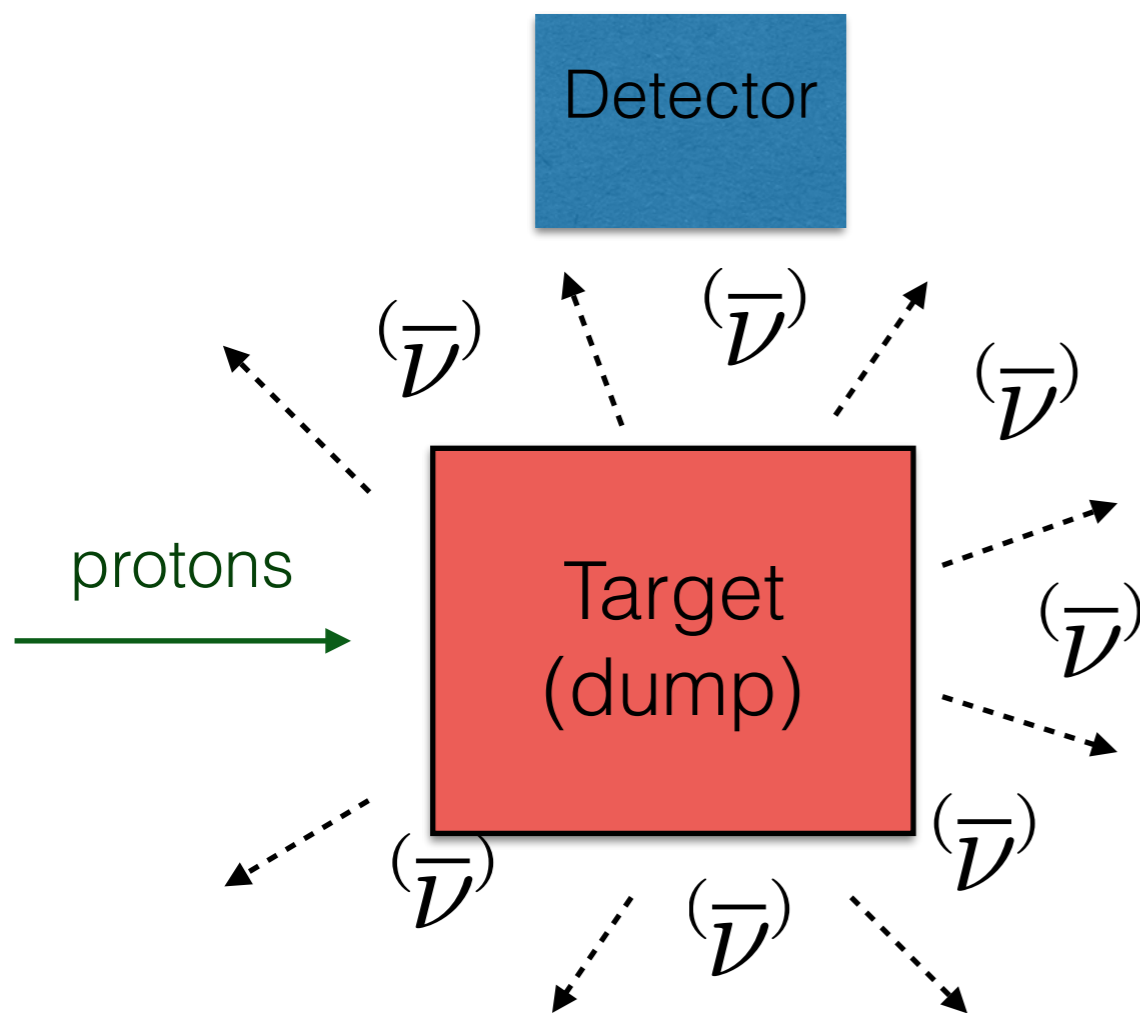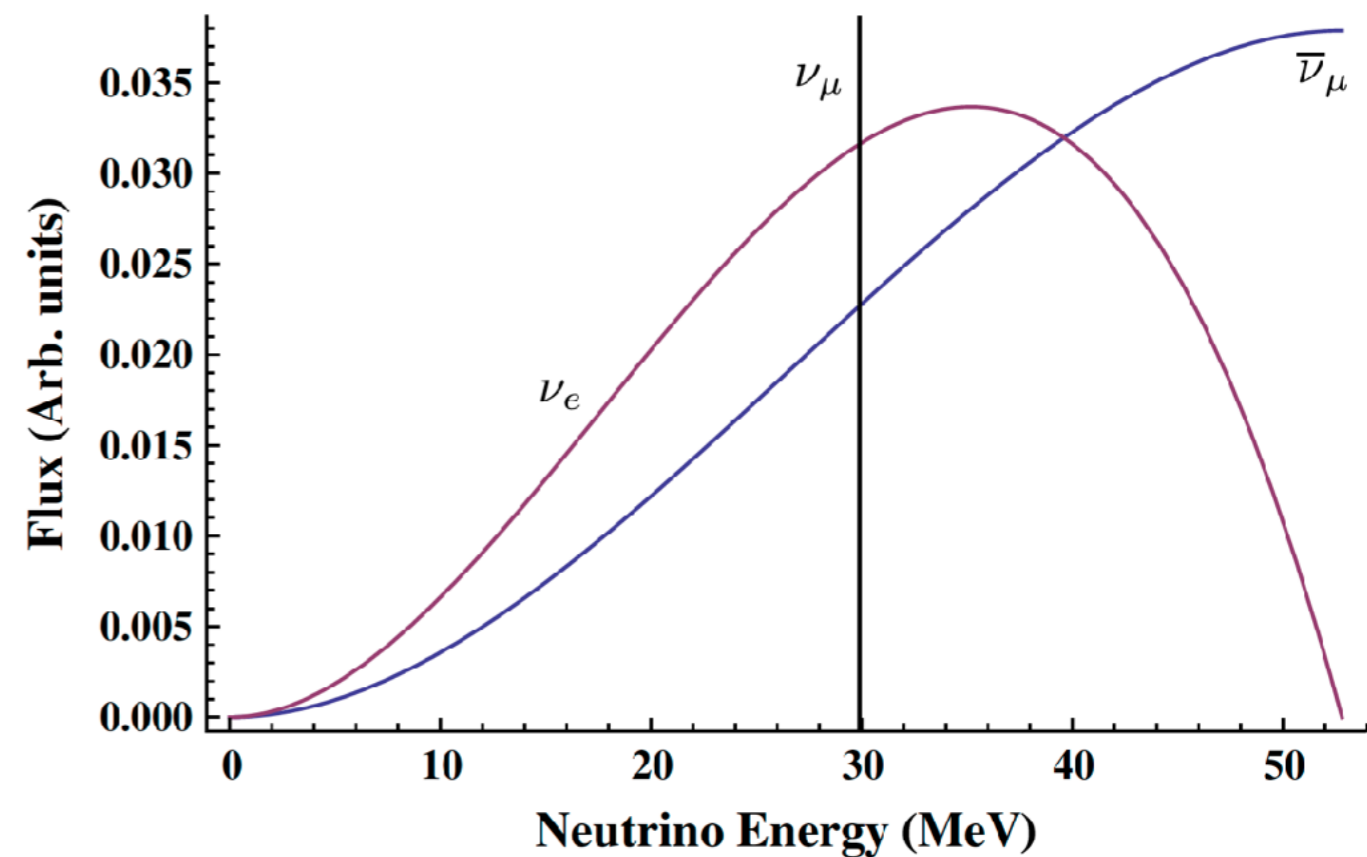
Joshua Spitz, University of Michigan
DPF, 8/3/2017

# Pion and muon decay-at-rest



(negative pions/muons are usually captured in dense target material)

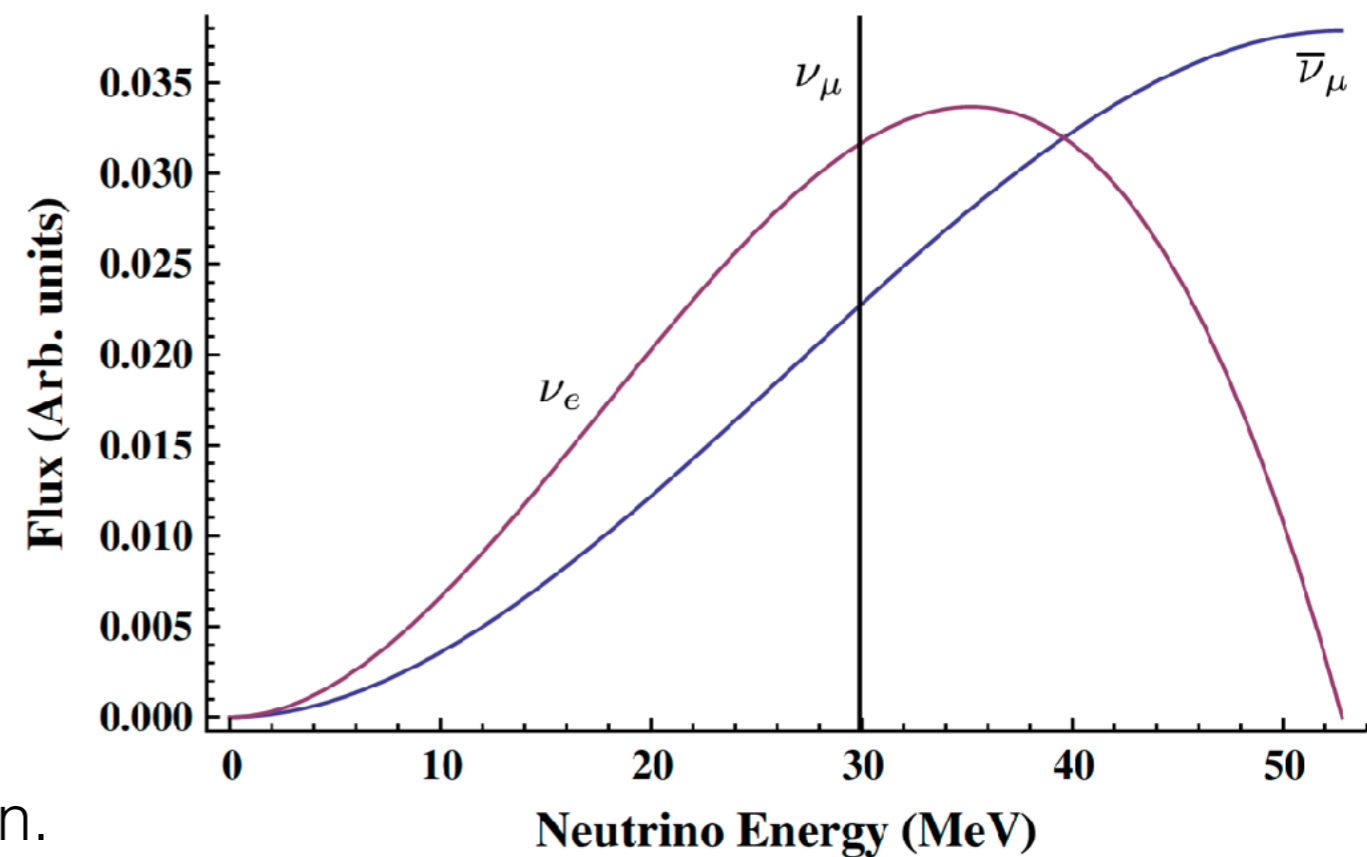# Pion and muon decay-at-rest

$$\pi^+ \to \mu^+ \nu_\mu$$

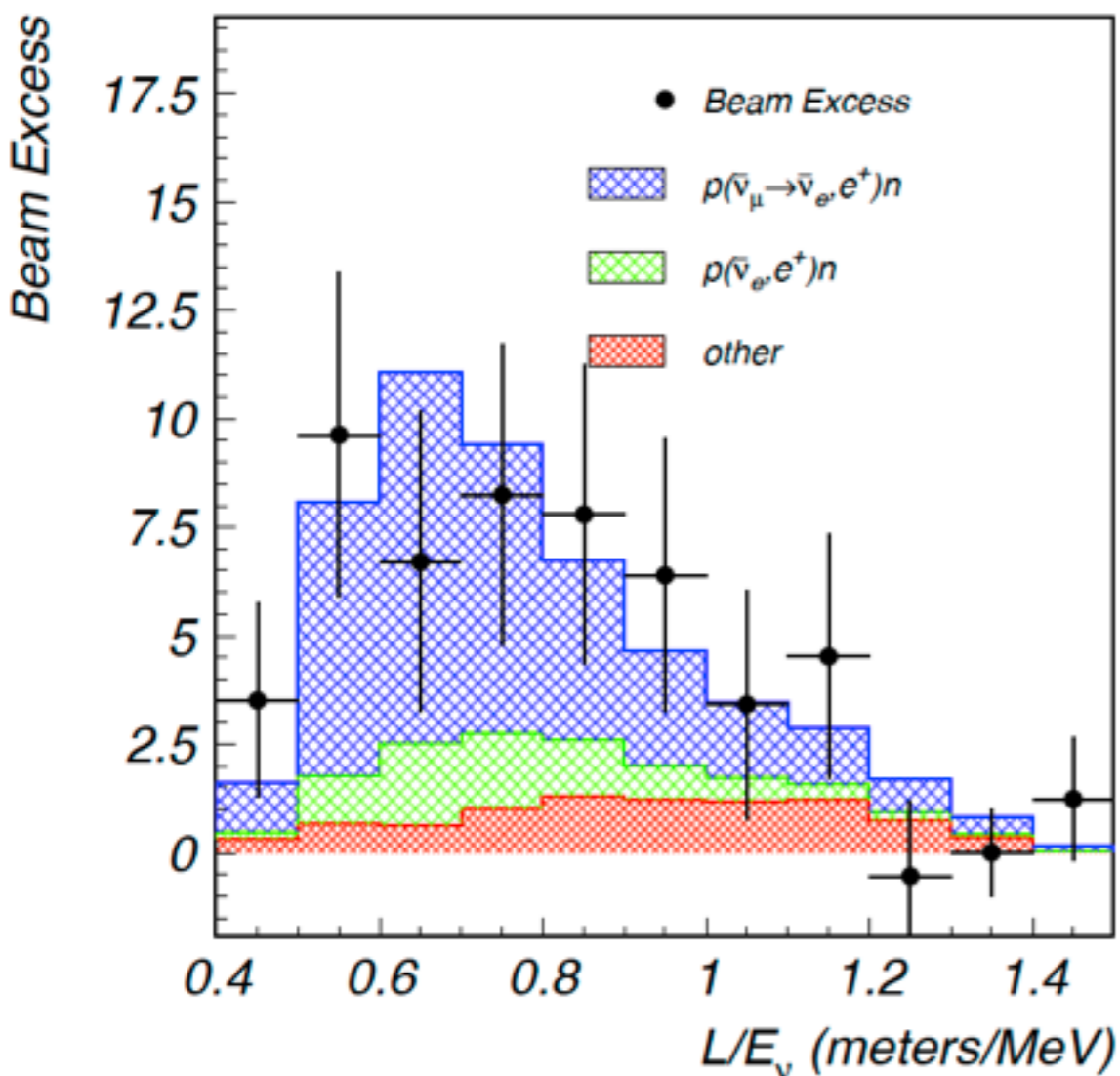$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$

**Why are these neutrinos special?**

- Known energy shape!

- IBD xsec (for nuebar app) is well known.

- IBD events (for nuebar app) are easy to reco/ID.

- Background is low.

# The Liquid Scintillator Neutrino Detector anomaly

## Antineutrinos from an accelerator seem to appear!



- LSND observed $\overline{\nu}_\mu \to \overline{\nu}_e$ at 3.8σ significance with a characteristic oscillation frequency of $\Delta m^2 \sim 1$ eV$^2$.

- That's odd. There are two characteristic oscillation frequencies in the three neutrino picture and they are precisely measured.

$$\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}})$$

# Basically, the anomalies seem to indicate that there may be a new characteristic oscillation frequency mode (indicative of a new neutrino state).

| Experiment name | Type | Oscillation channel | Significance |
|---|---|---|---|
| LSND | Low energy accelerator | muon to electron (antineutrino) | 3.8σ |
| MiniBooNE | High(er) energy accelerator | muon to electron (antineutrino) | 2.8σ |
| MiniBooNE | High(er) energy accelerator | muon to electron (neutrino) | 3.4σ |
| Reactors | Beta decay | electron disappearance (antineutrino) | 1.4-3.0σ (varies) |
| GALLEX/SAGE | Source (electron capture) | electron disappearance (neutrino) | 2.8σ |

(Important: there are also various null results in this "high-frequency oscillation" parameter space!)

# The JSNS$^2$ strategy

- **Primary goal: Test LSND in a cost effective and timely way, w/ an existing beam/building.**

  - LSND is THE experiment that drives the high-$\Delta m^2$ anomalies. J-PARC's MLF and ORNL's SNS are the best (only) places to *directly* study the LSND anomaly.

- **Other physics:**

  - **Collect a large sample (~50k) of monoenergetic 236 MeV muon neutrinos from KDAR; nuclear probe and xsec measurements.**

    - Highly relevant for current/future long baseline programs and all experiments that rely on a model of the neutrino-nucleus interaction. J-PARC MLF is the best place in the world to do this measurement.

  - **Measure supernova neutrino xsec's.**

- **Perform R&D for future liquid scintillator detectors.**

# The JSNS² strategy

- **Primary goal: Test LSND in a cost effective and timely way, w/ an existing beam/building.**

  - LSND is THE experiment that drives the high-$\Delta m^2$ anomalies. J-PARC's MLF and ORNL's

**JSNS²**

Obtained Stage 1 (of 2) approval from PAC in 2015;

Secured funding for first 17 ton detector module in 2016;

Submitted TDR to J-PARC PAC (seeking Stage 2 approval) in 2017;

Construction has begun! We expect first data in late-2018.

- **Measure supernova neutrino xsec's.**

- **Perform R&D for future liquid scintillator detectors.**

# JSNS² collaboration

Technical Design Report (TDR):
Searching for a Sterile Neutrino at J-PARC MLF
(E56, JSNS²)

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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[15] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, JAPAN*
[16] *Department of Physics, Kyoto University, Kyoto, JAPAN*
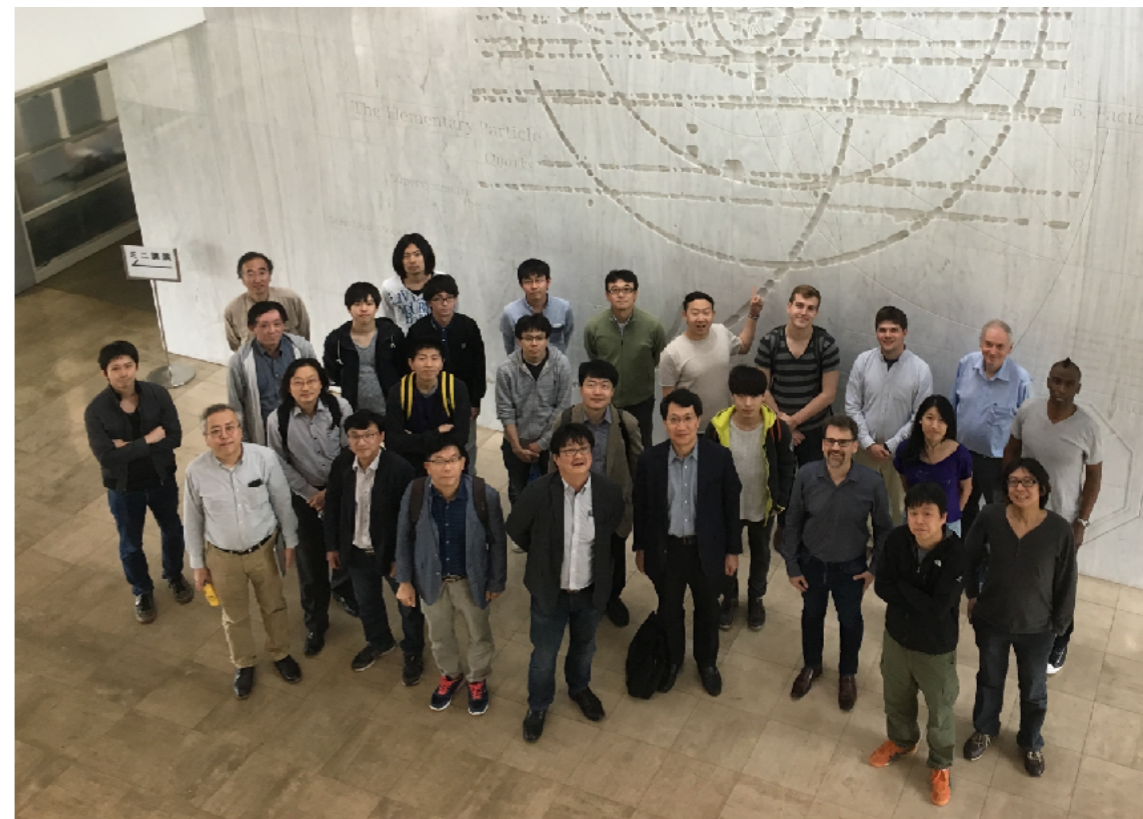[17] *University of Florida, Gainesville, FL, 32611, USA*
[18] *Department of Physics, Sungkyunkwan University, Gyeong Gi-do, KOREA*
[19] *University of Alabama, Tuscaloosa, AL, 35487, USA*
[20] *Colorado State University, Tuscaloosa, AL, 35487, USA*
[21] *Brookhaven National Laboratory, Upton, NY, 11973-5000, USA*

JSNS2 collab. photo,
5/2017 @ KEK



21 institutions, 53 collaborators, Japan/US/Korea

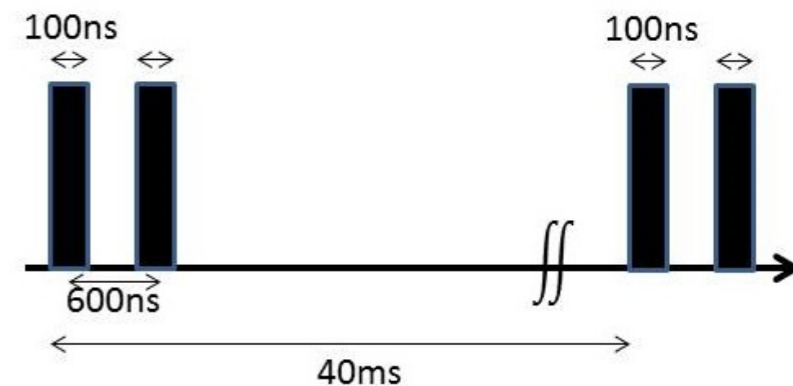JSNS²: J-PARC E56
Sterile ν search
@MLF
http://research.kek.jp/group/mlfnu/

400MeV

3 GeV RCS

J-PARC Facility
(KEK/JAEA )
South to North

Neutrino Beams
(to Kamioka)

25Hz 500kW now &
will be 1MW

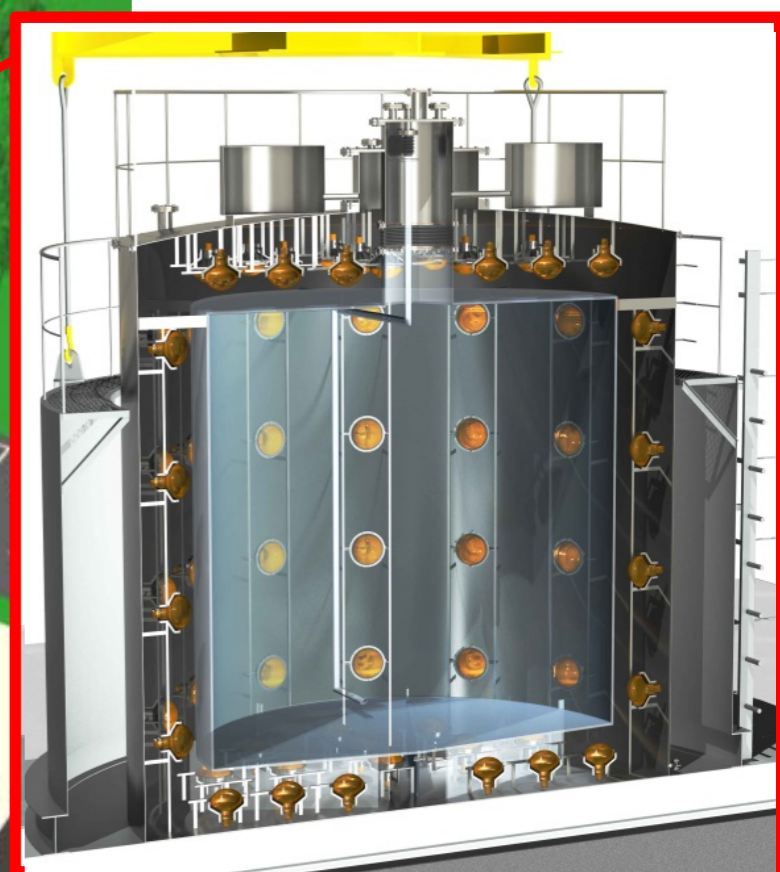Materials and Life
Experimental Facility

30GeV MR

Hadron hall

CY2007 Beams
JFY2008 Beams
JFY2009 Beams

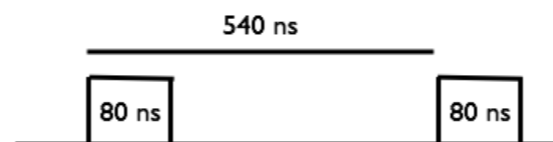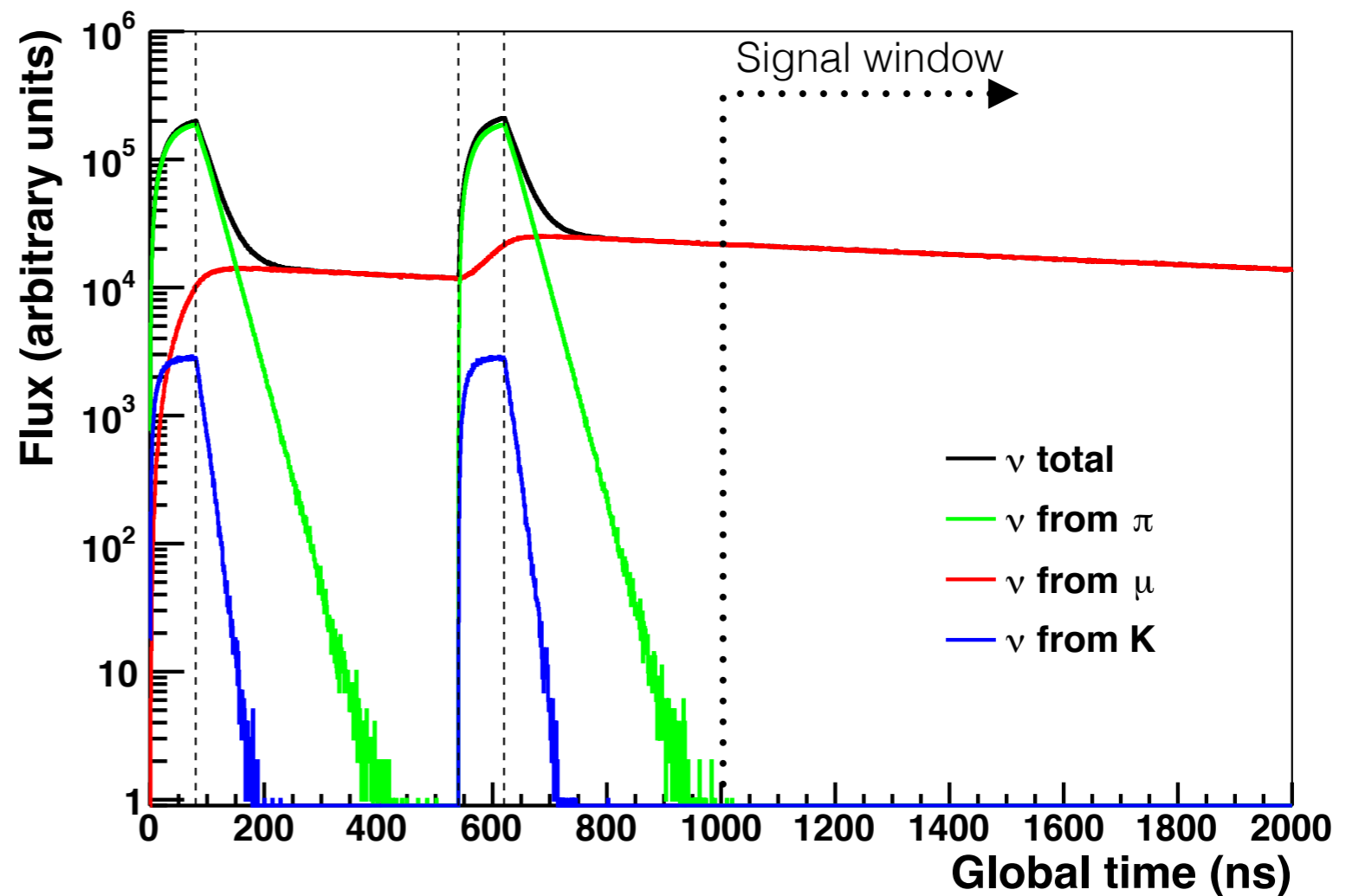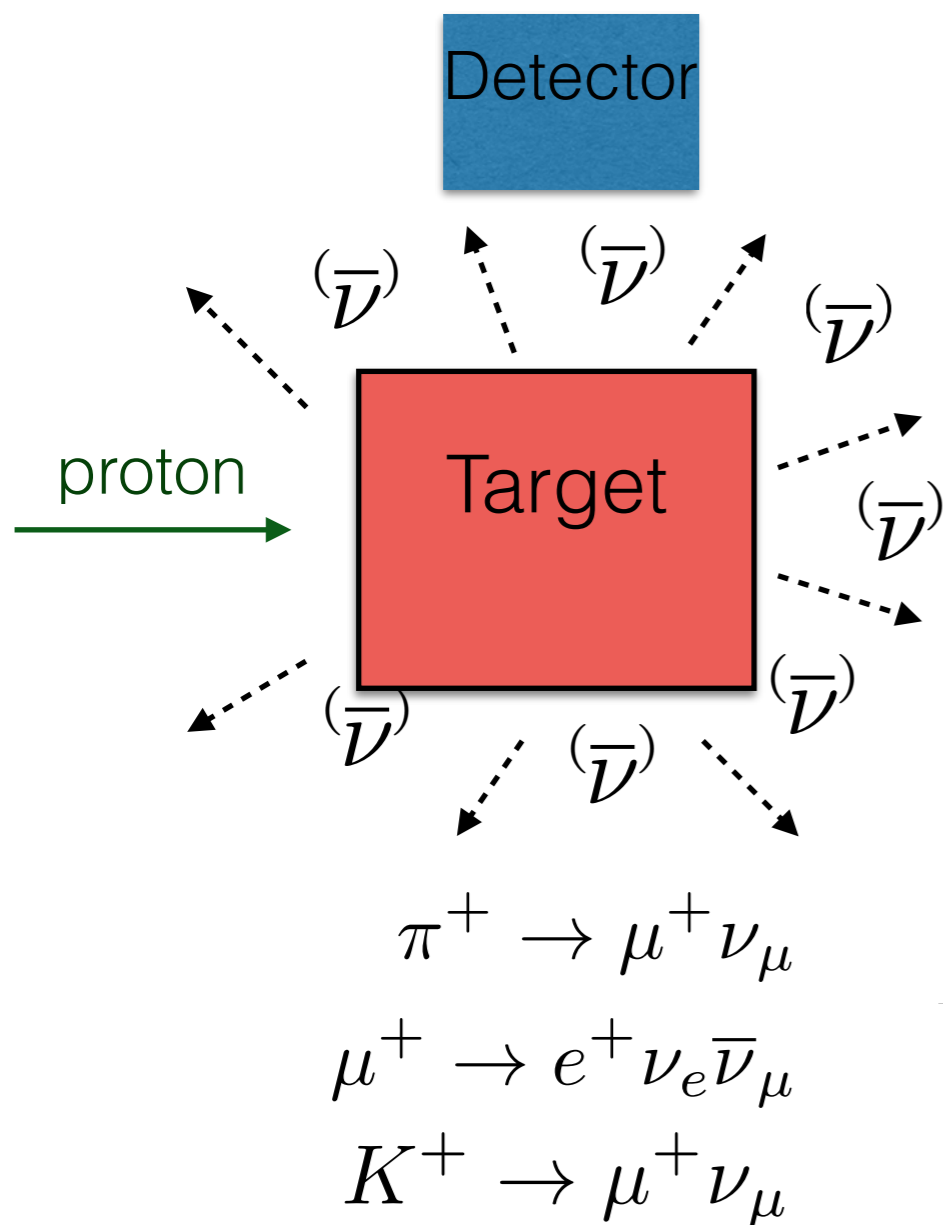Bird's eye photo in January of 2008

MLF building (bird's view)

**Detector @ 3rd floor (24m from target)**

**Hg target = Neutron and Neutrino source**

**3GeV pulsed proton beam**

image

# JSNS² beam timing



Detector

proton

Target

$\overset{(-)}{\nu}$

$\pi^+ \to \mu^+ \nu_\mu$

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$

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

Signal window

Flux (arbitrary units)

Global time (ns)

— ν total
— ν from π
— ν from μ
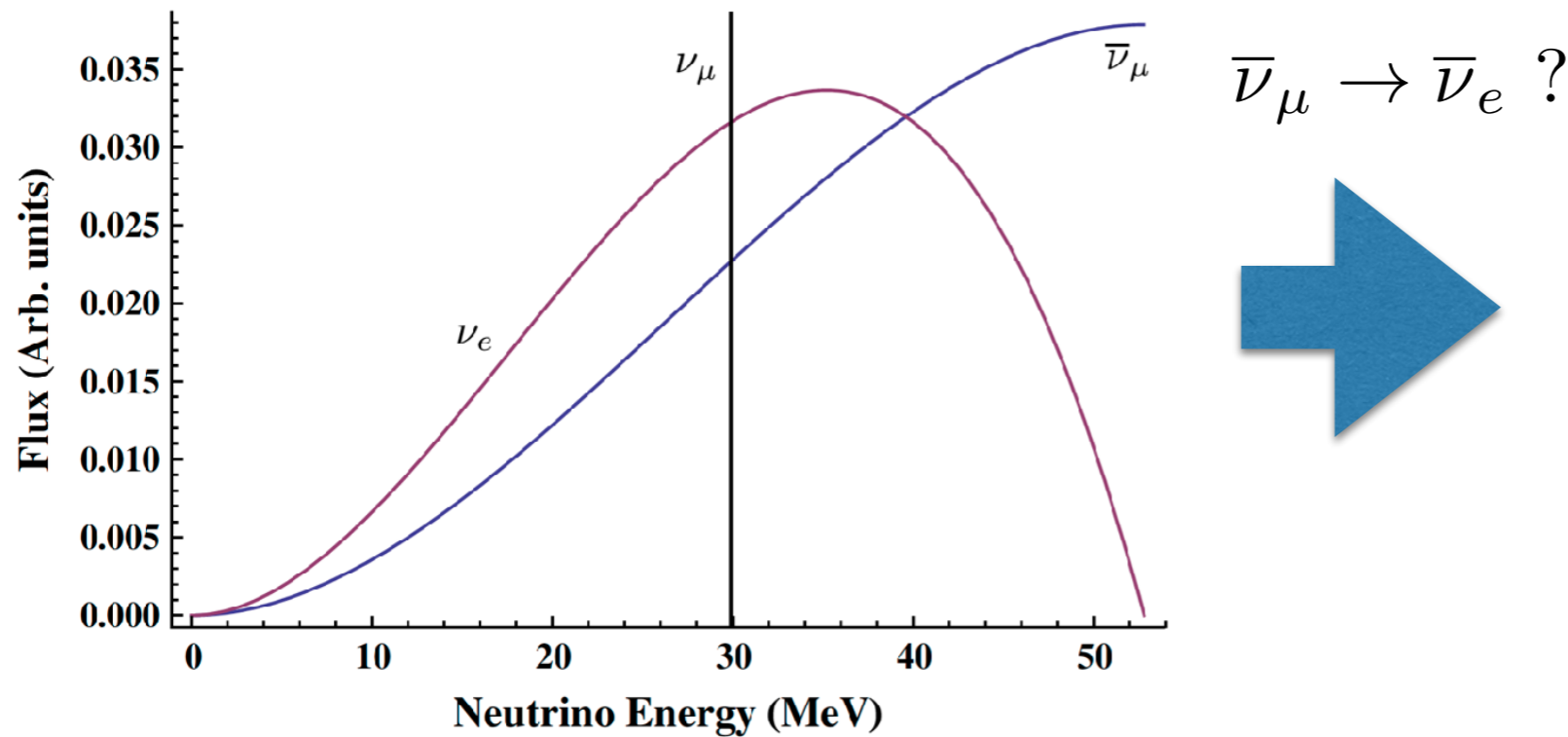— ν from K

540 ns

80 ns    80 ns    Beam structure    25 Hz

# JSNS$^2$ detection principle



- Target volume is Gd-loaded liquid scintillator

  - Phase 0: 17 tons w/ 193 8'' PMTs

  - Future phase: multi-detector (34 tons)

- Energy resolution ~15%/sqrt(E in MeV)

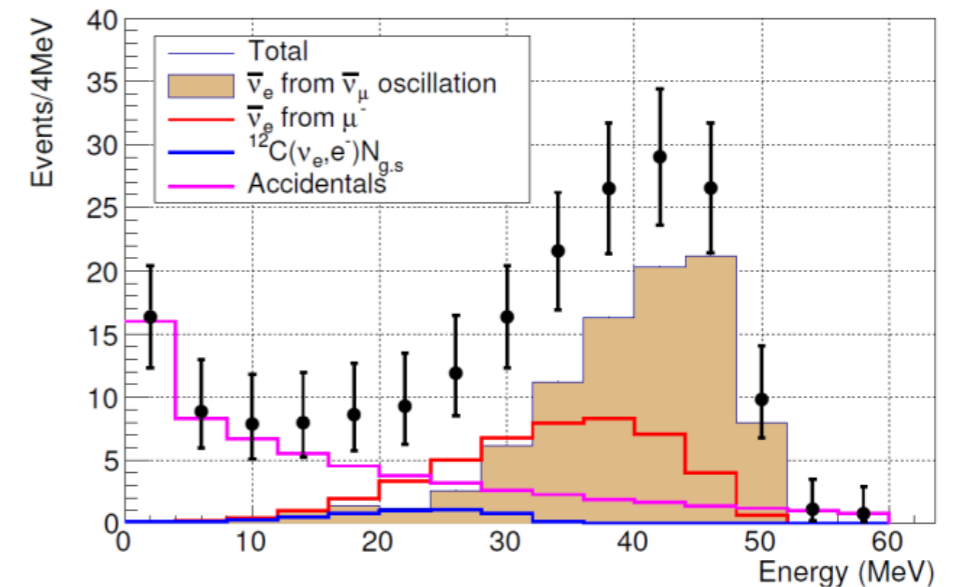$$\overline{\nu}_\mu \to \overline{\nu}_e, \quad \overline{\nu}_e + p \to e^+ + n$$

prompt signal

delayed signal (n-capture)
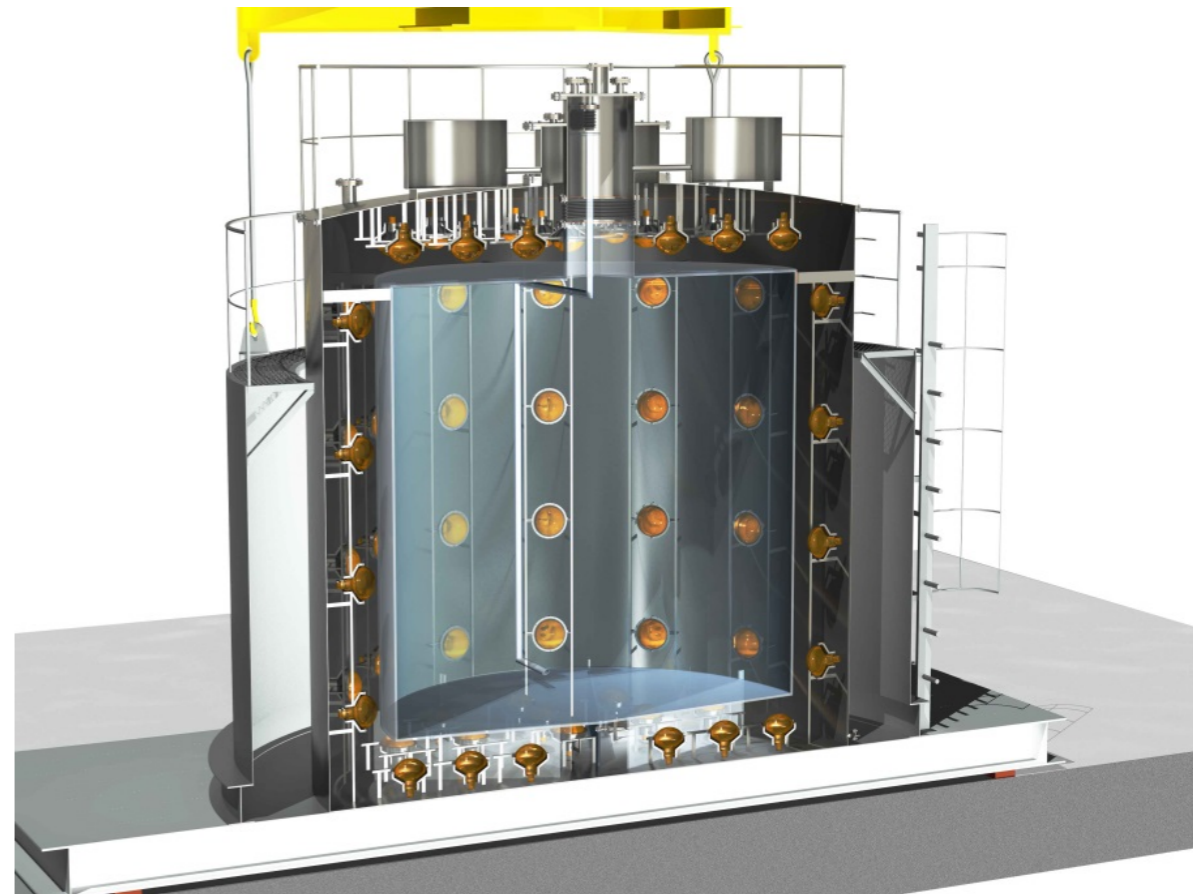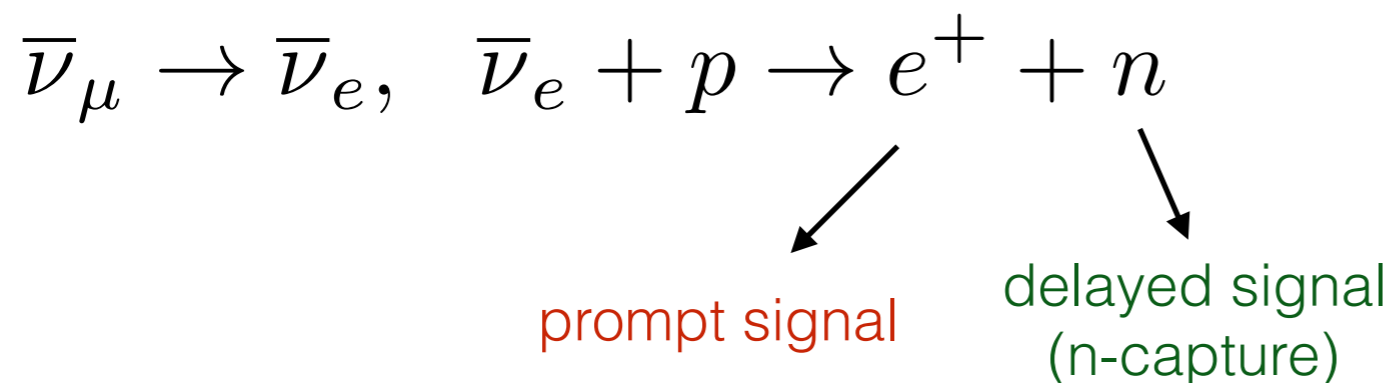
| | Time from beam | Energy |
|---|---|---|
| Prompt signal | $1<T_p<10\mu s$ | $20<E<60MeV$ |
| Delayed signal | $T_p<T_d<100\mu s$ | $7<E<12MeV$ |

# JSNS$^2$ is highly sensitive to *the* smoking gun signature of oscillations: a wiggle in L/E



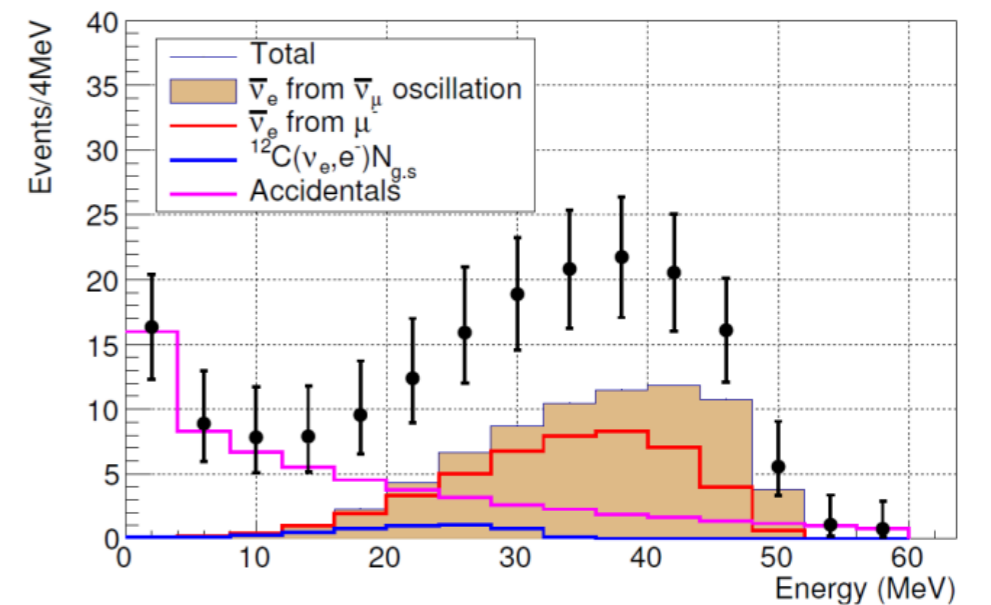$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ ?

Case $\Delta m^2 = 2.5 \text{eV}^2, \sin^2 2\theta = 0.003$



Case $\Delta m^2 = 1.2 \text{eV}^2, \sin^2 2\theta = 0.003$
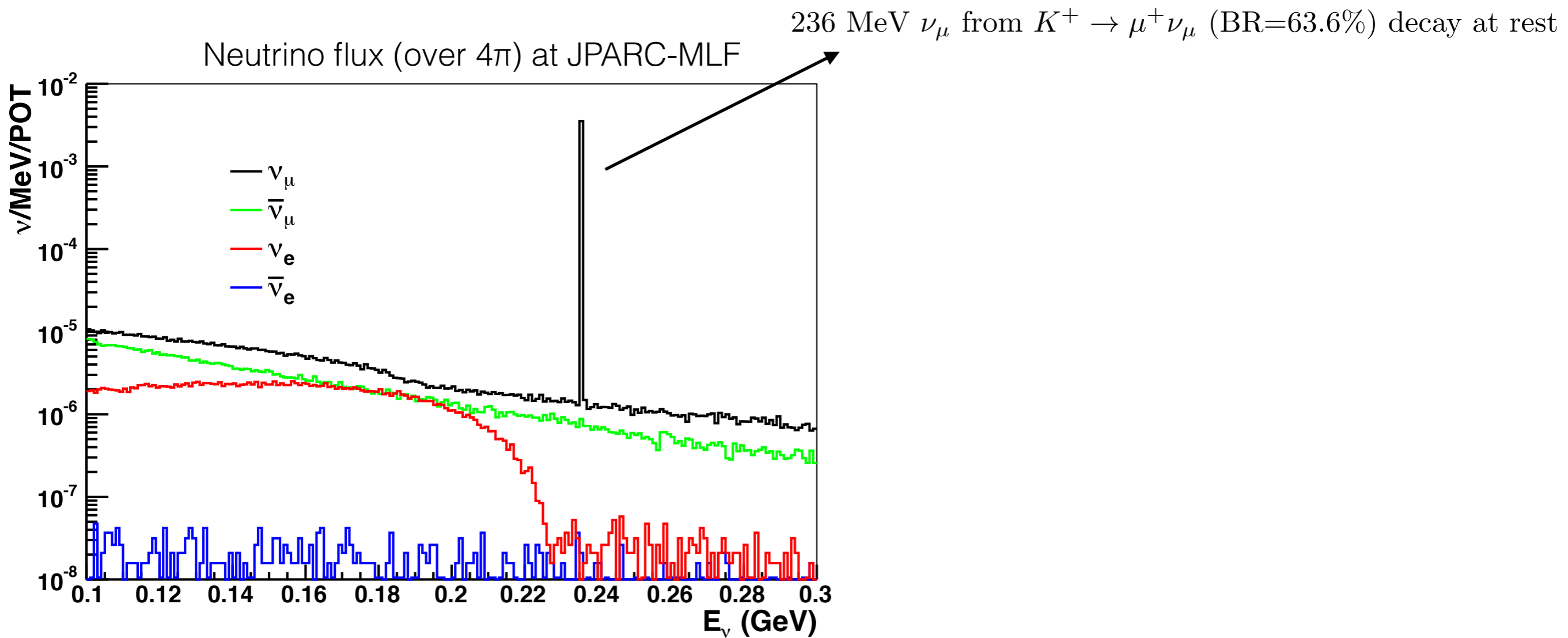
(dominant background: intrinsic nuebar)

(3 years of running)

# JSNS² Phase-0 (*now under construction*) expected sensitivity



17t, 5MWyr, JSNS² 90%C.L.
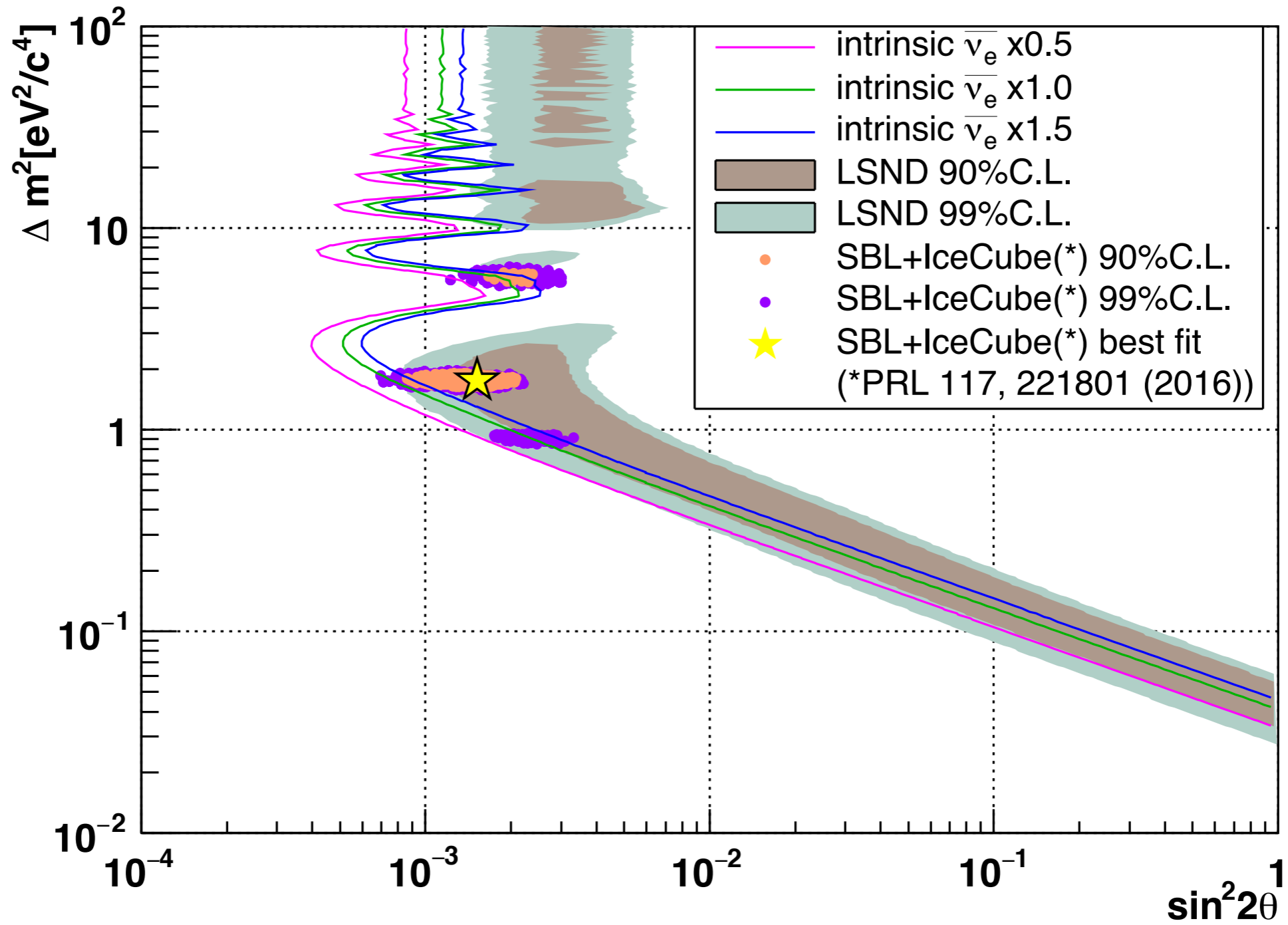
(5 years of running)

# JSNS2 physics: KDAR



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

Neutrino flux (over 4π) at JPARC-MLF

# JSNS² physics: KDAR

Neutrino flux (over 4π) at JPARC-MLF

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



- 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 $\nu_\mu$ CC events |
|---|---|---|---|---|
| JSNS² (JPARC-MLF) | Gd-LS (17 ton) | $1.125 \times 10^{23}$ POT (3 years) | 24 m | 30-60k |

# Conclusion

- J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source (JSNS$^2$;17 tons of Gd-doped liquid scintillator in Phase-0)

  - Excellent sensitivity to a sterile neutrino above 2 eV$^2$.

  - Expect ~50k monoenergetic numu (KDAR) events at 236 MeV.

- First data in late-2018.



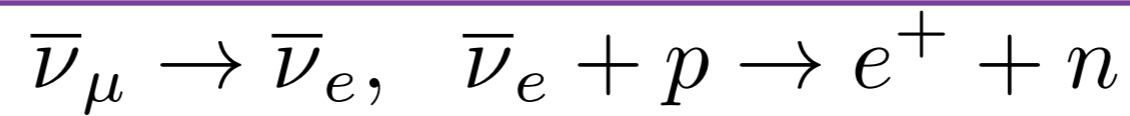MLF 3rd floor @JPARC
(JSNS$^2$ will sit here)

# Backup

# Complementarity to SBN (and others)

- JSNS$^2$ has completely different systematics, energy, background, reconstruction issues, etc. compared to SBN, reactor, and source experiments.

  - The current situation at high-$\Delta m^2$ clearly calls for multiple probes (neutrinos, antineutrinos, appearance, disappearance).

- JSNS$^2$ represents a *direct* test of LSND.

- JSNS$^2$ will use anti-neutrinos. A 3+1 sterile neutrino model is CP-invariant—but nature might not be.

- Similar timeline—healthy competition!

# Signal and background

**Signal**

$$\overline{\nu}_\mu \rightarrow \overline{\nu}_e, \quad \overline{\nu}_e + p \rightarrow e^+ + n$$

prompt signal

delayed signal
(n-capture)

**Background**



Cosmic ray muons

Concrete, Iron, etc

Direct fast neutron

Gd loaded LS

Fast neutron

n

p

thermalized

n Gd

Capture gammas

Recoil proton; 20-60MeV
(mimics IBD prompt)
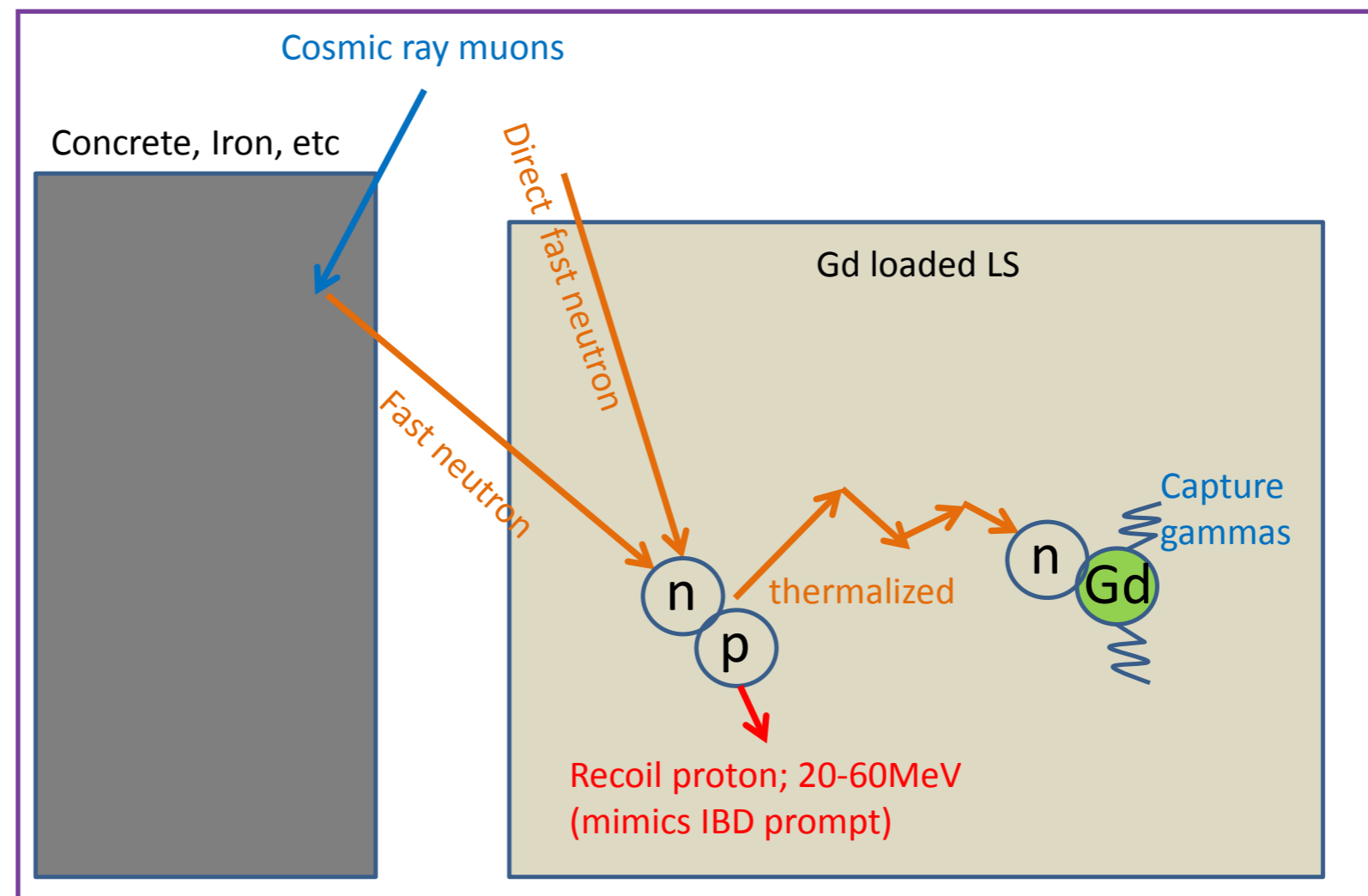
# How to mitigate background?

(separating prompt IBD signal e+ and background n-induced proton)

## Cerenkov light



observed = Cherenkov + Scintillation



| hTime0 | |
|---|---|
| Entries | 564882 |
| Mean | 31.29 ± 0.06494 |
| RMS | 48.59 |
| Integral | 5.598e+05 |

fast(10ns)

slow(150ns)

Total
Cherenkov
Scintillation

time[ns]

## PSD

TailQ/TotalQ



• neutron pulse
• gamma pulse

Tail : 100nsec

Total : 140nsec
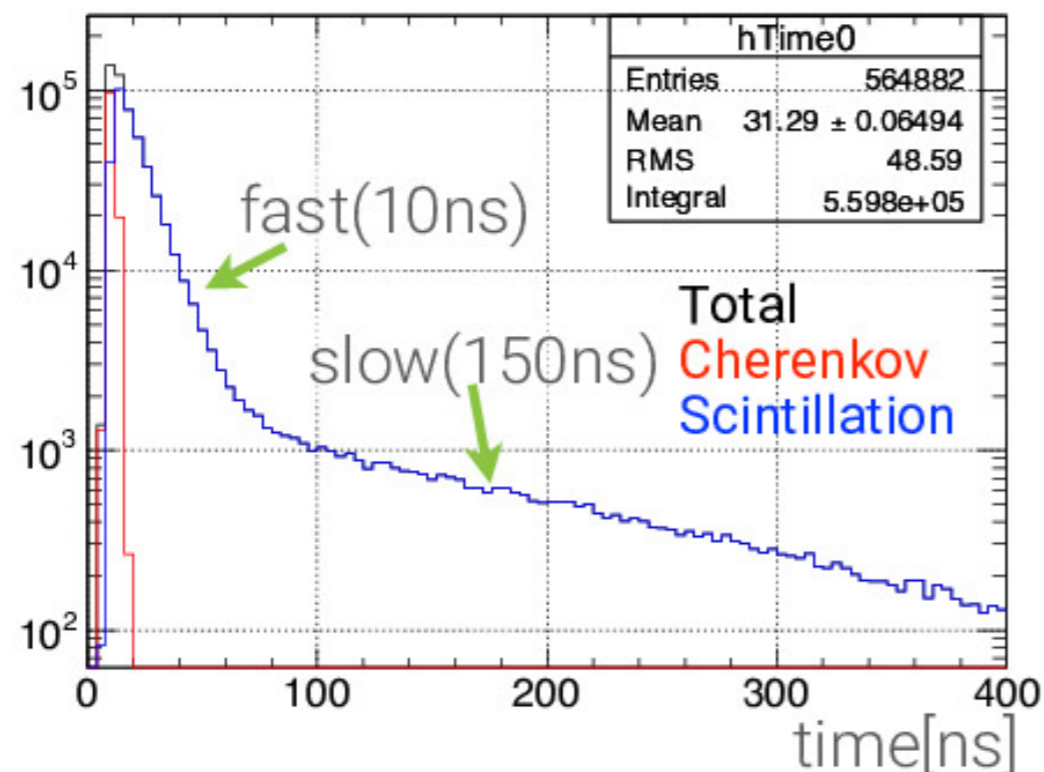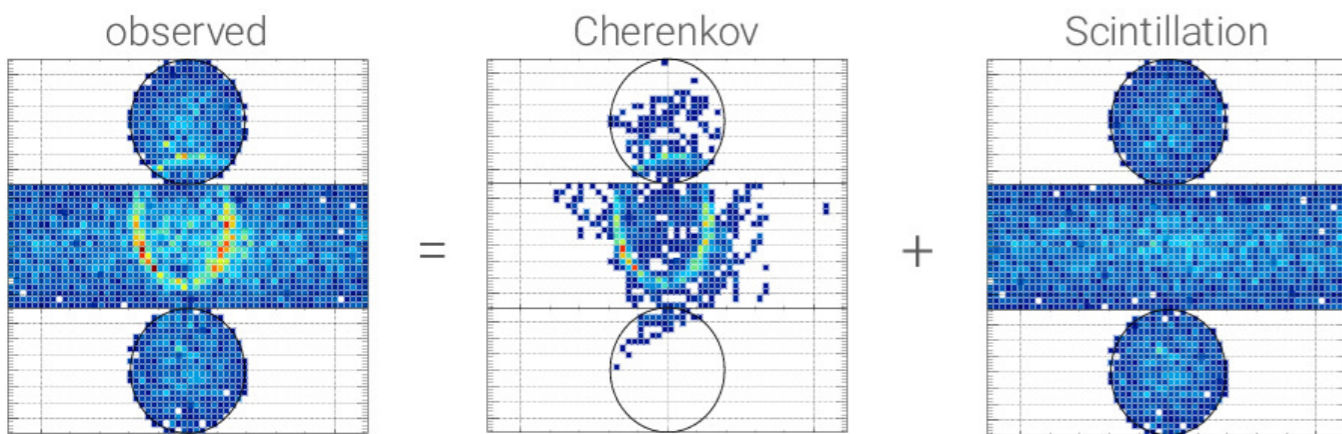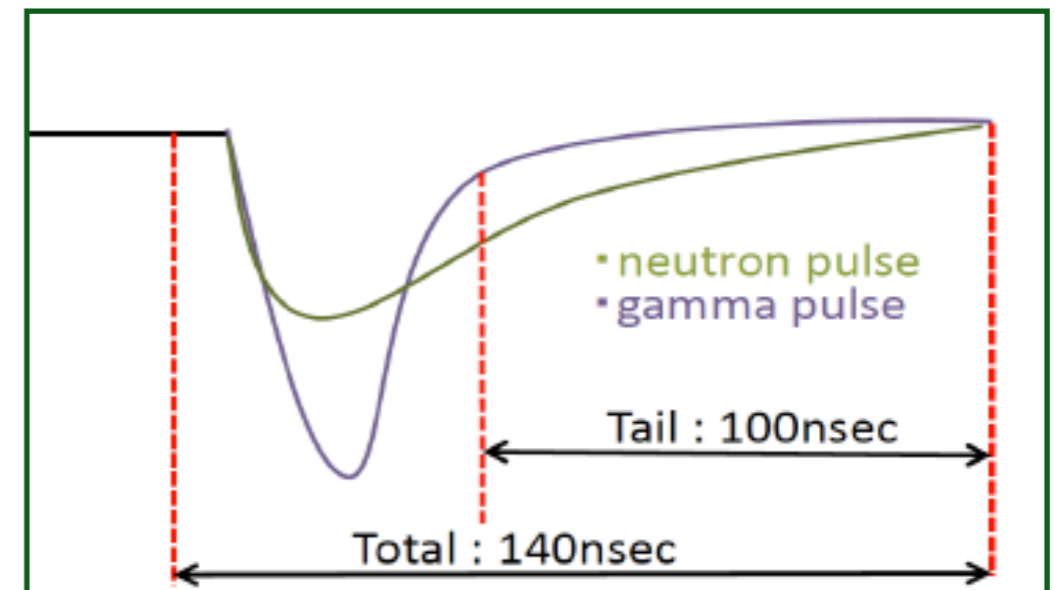
(50 MeV positron sim; dilution factor of 10->1600 photons/MeV)

# JSNS$^2$ will use PSD to mitigate fast neutrons

LAB+3g/l ppo+bis-msb
(tabletop, Cf252 measurement)

LAB+3g/l ppo+bis-msb
(full-size detector expectation)
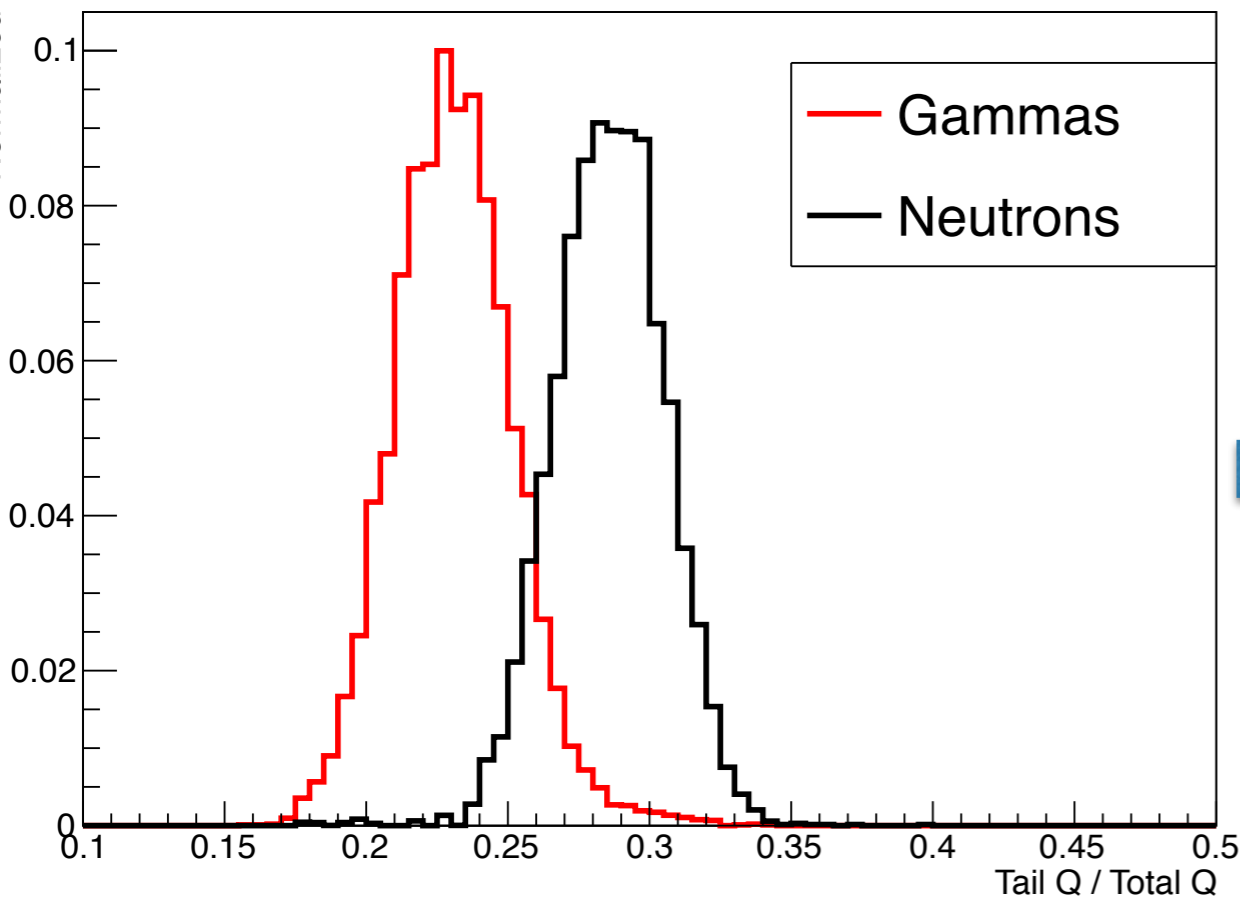


For factor of 100 neutron rejection, 73% efficient.
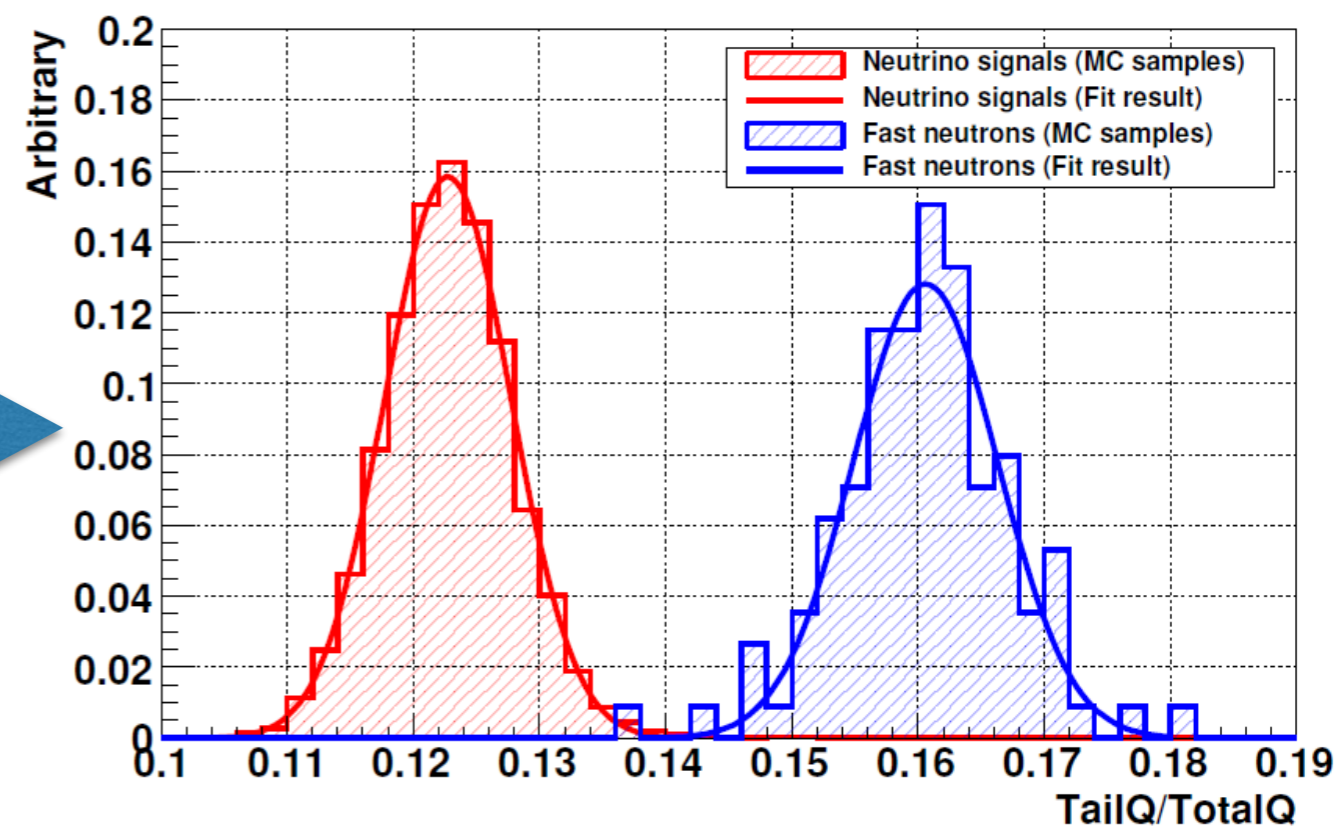
For factor of 100 neutron rejection, 99% efficient.

# LSND and JSNS$^2$ comparison

| | LSND | JSNS$^2$ | Advantage of JSNS$^2$? |
|---|---|---|---|
| Detector mass | 167 ton (liquid scintillator) | 17 ton in Phase-0 (liquid scintillator) | - |
| Baseline | 30 m | 24 m | - |
| Beam kinetic energy | 0.8 GeV | 3 GeV | Higher energy enables KDAR measurements |
| Beam power | 0.056 MW | 1.0 MW (eventually) | Higher |
| Beam pulse | 600 µs,120Hz | 80 ns (x2), 25 Hz | A factor of 300 less steady state background for IBD |
| Capture nucleus | H (2.2 MeV) | Gd (~8 MeV) | Higher S:N and a factor of 6 shorter neutron capture time |

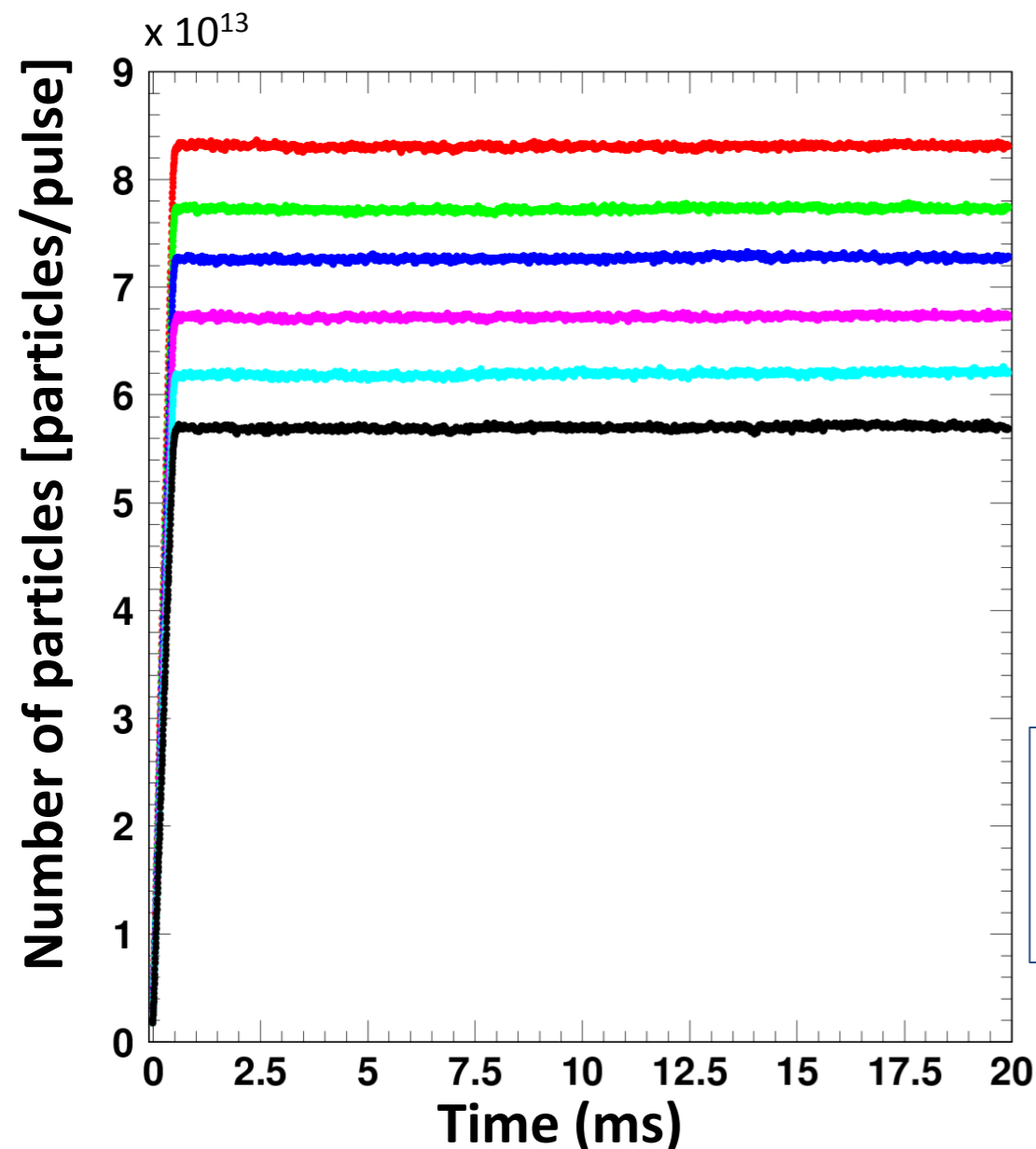# $\overline{\nu}_e$ intrinsic background shape
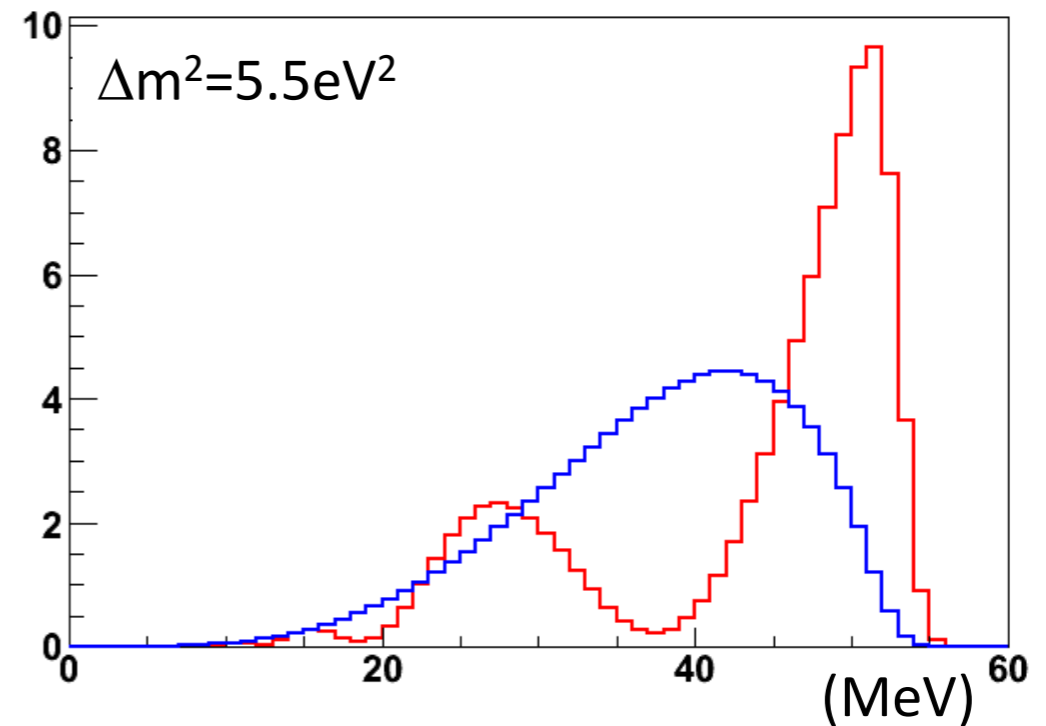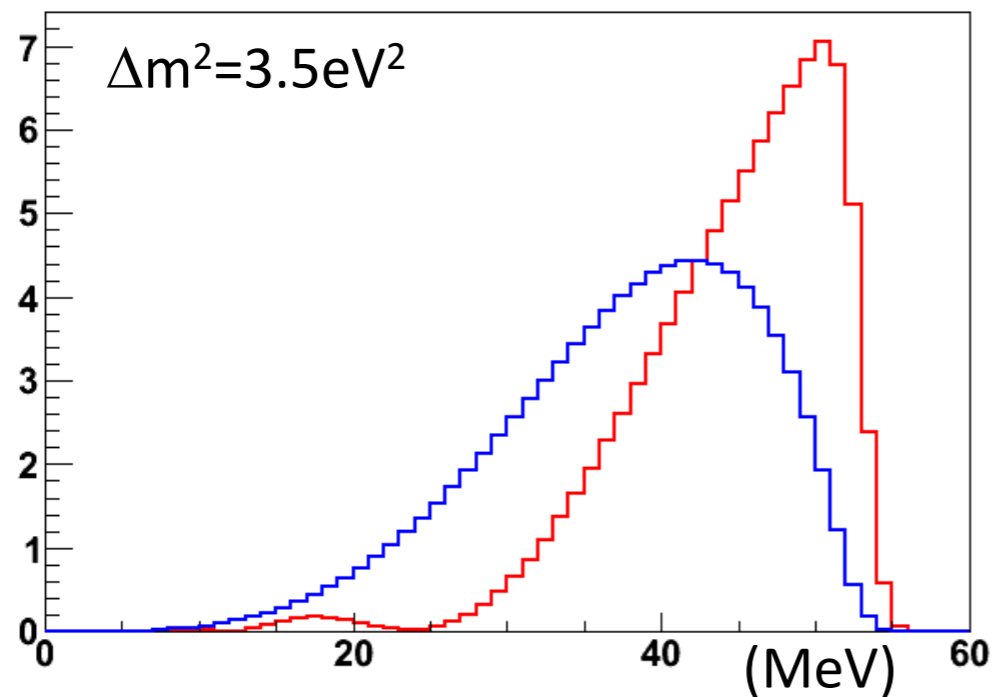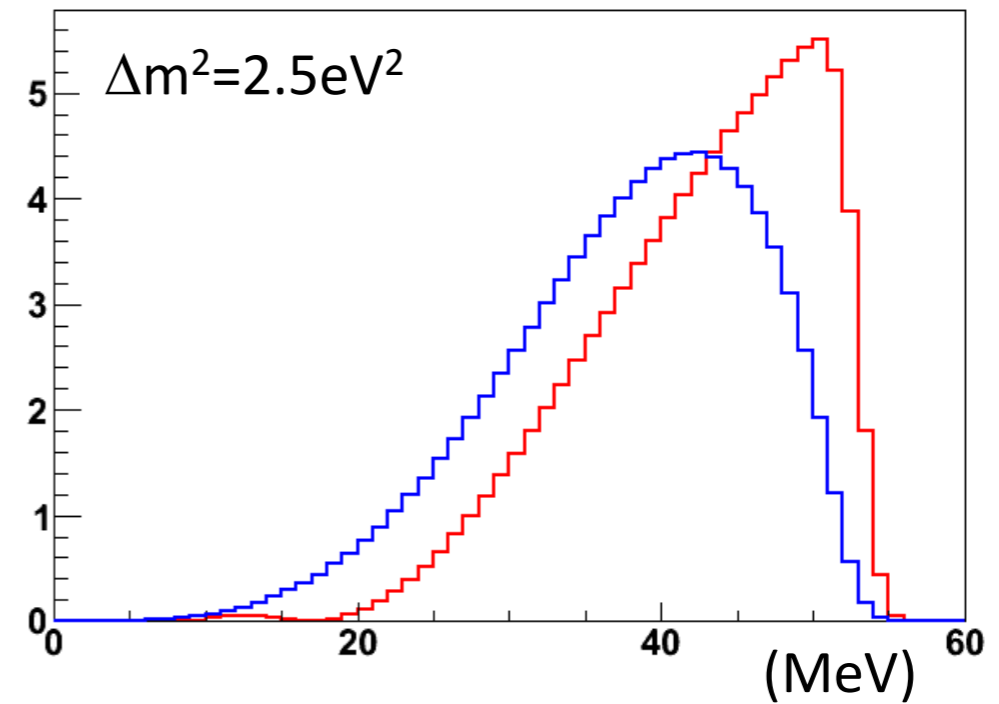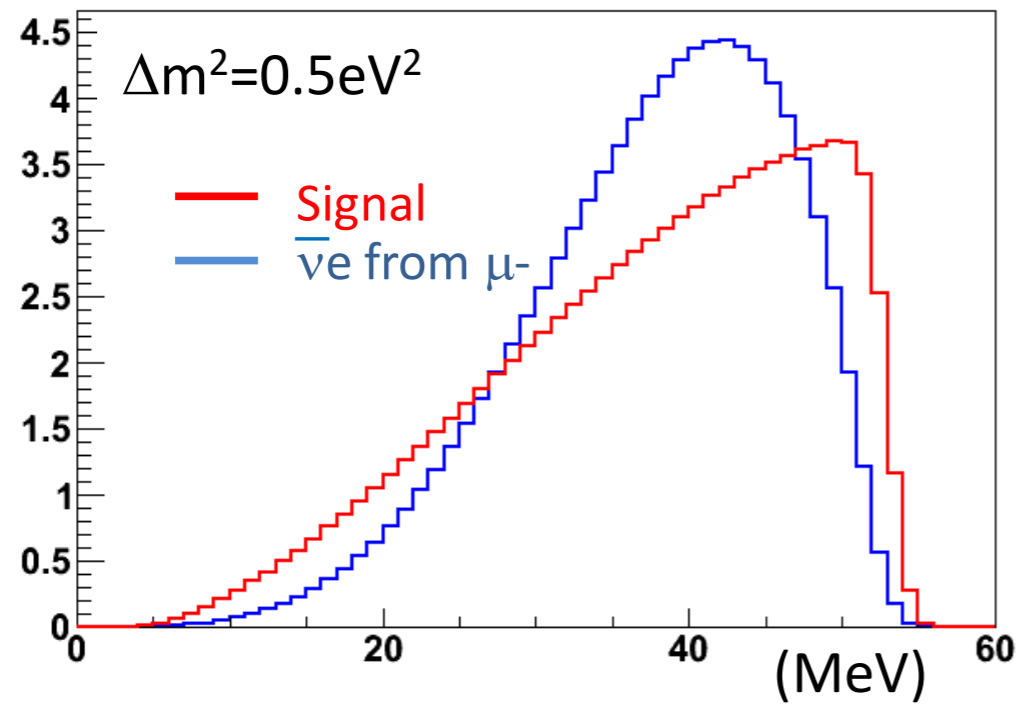


(plots are normalized by area)

M. Harada *et al*, arXiv:1310.1437 [physics.ins-det]

# 1 MW (design goal) demonstrated at JPARC-MLF!

**Result of the RCS 1-MW trial**

2014/12/27



$8.32 \times 10^{13}$ : 999 kW-eq
$7.71 \times 10^{13}$ : 926 kW-eq
$7.24 \times 10^{13}$ : 869 kW-eq
$6.70 \times 10^{13}$ : 804 kW-eq
$6.17 \times 10^{13}$ : 741 kW-eq
$5.66 \times 10^{13}$ : 679 kW-eq

Please note:
this was a short test!

RCS/MLF is now slowly increasing the beam power from 300 kW (current) to maybe ~500 kW in this JFY.

2014年12月27日午前7時31分
1バンチ当たりの粒子数：$8.32 \times 10^{13}$
（～1MW）
ビーム加速成功！

# Is background at MLF ok?

- Direct measurements have been made w/ 500 kg of plastic scintillator and smaller ~10 kg detectors with various levels of shielding and at various positions relative to the source.

  - Beam fast neutrons  (n+p (or C) -> X+$\pi$; $\pi$-> $\mu$ -> e)

  - Accidentals

    - Prompt; gammas or neutrons from cosmics.

    - Delayed; gammas or neutrons from beam.
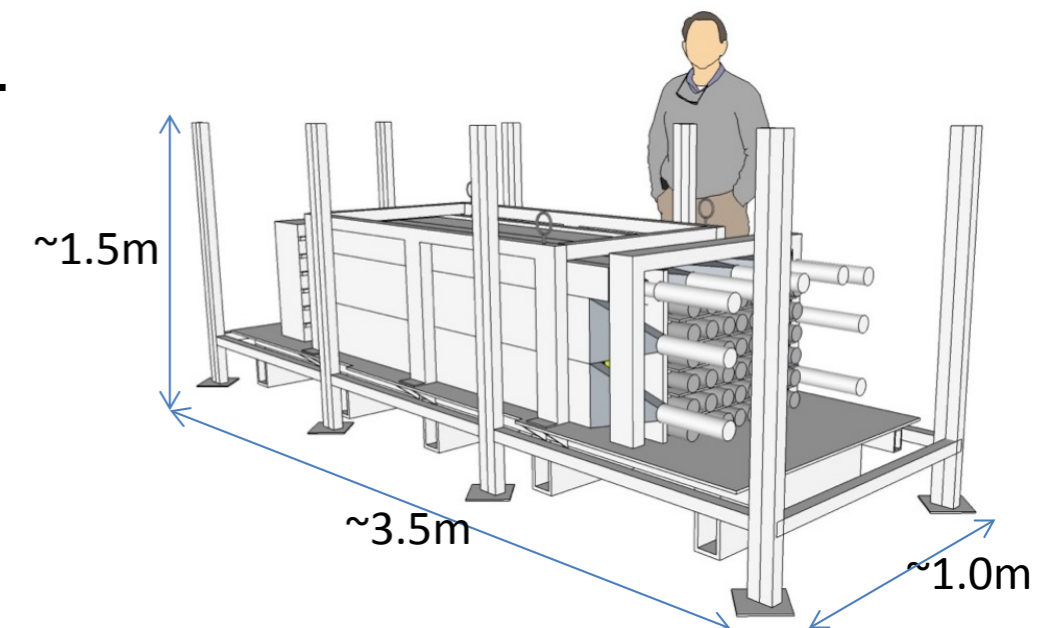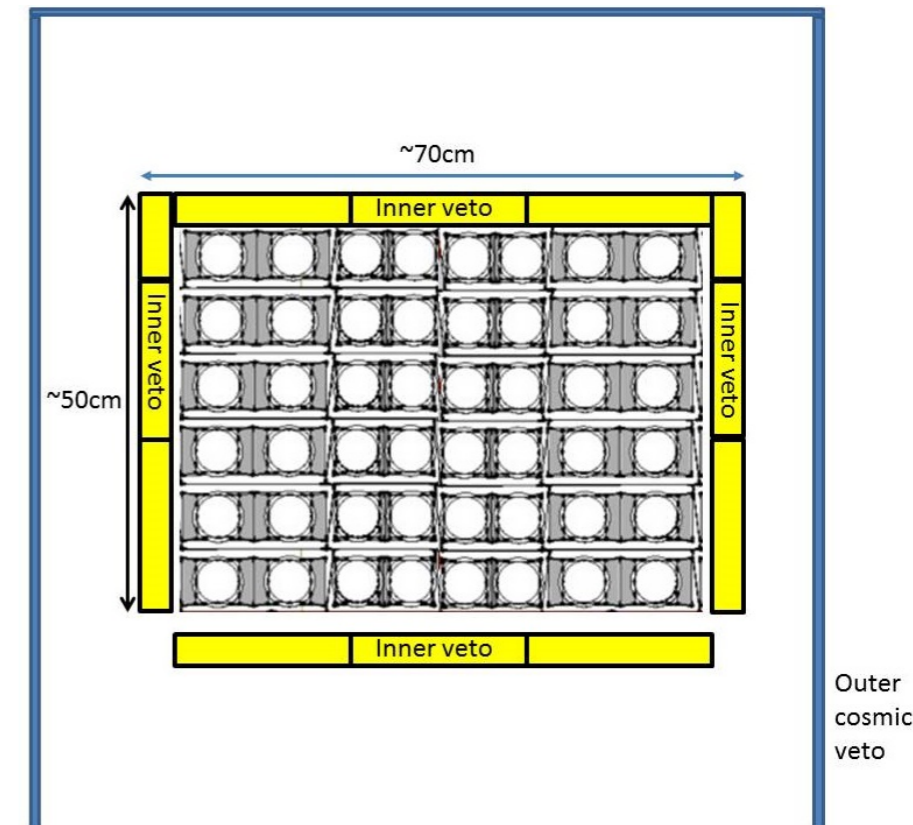
**Selection criteria for IBD**
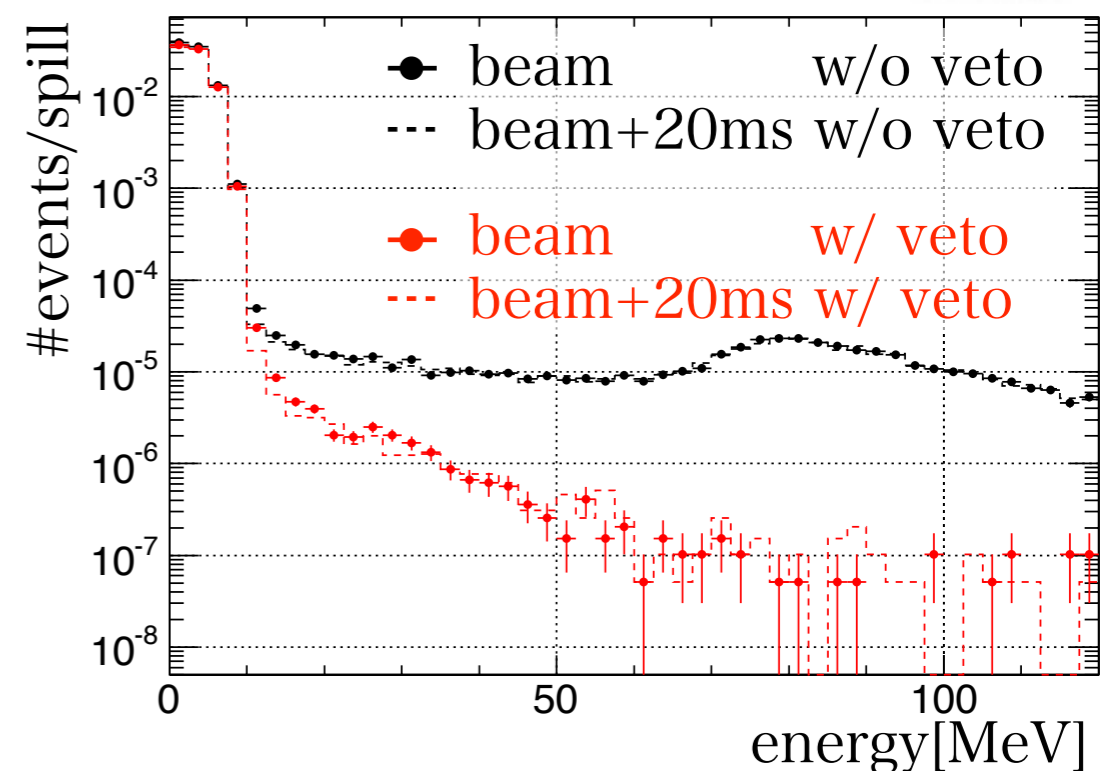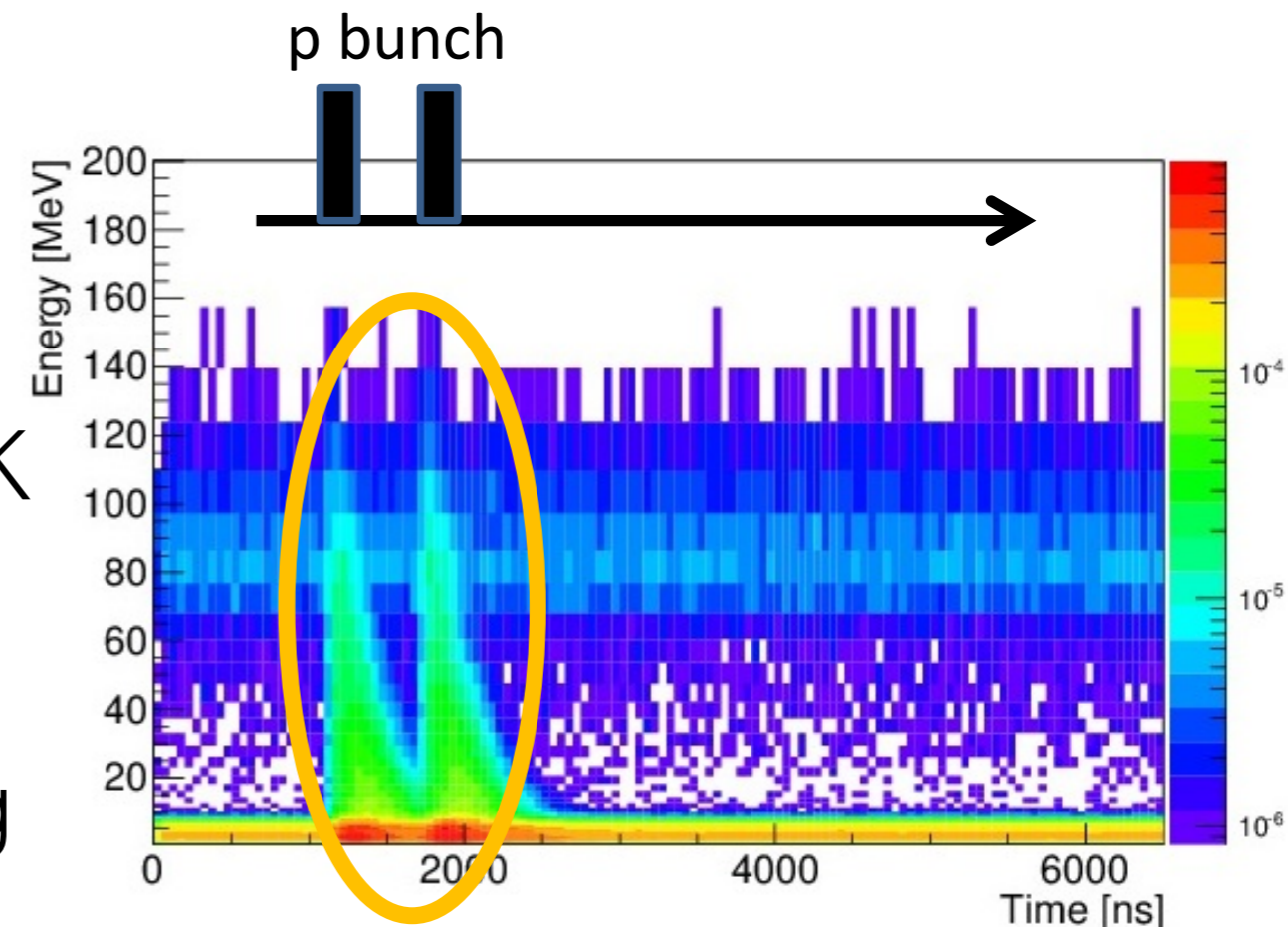
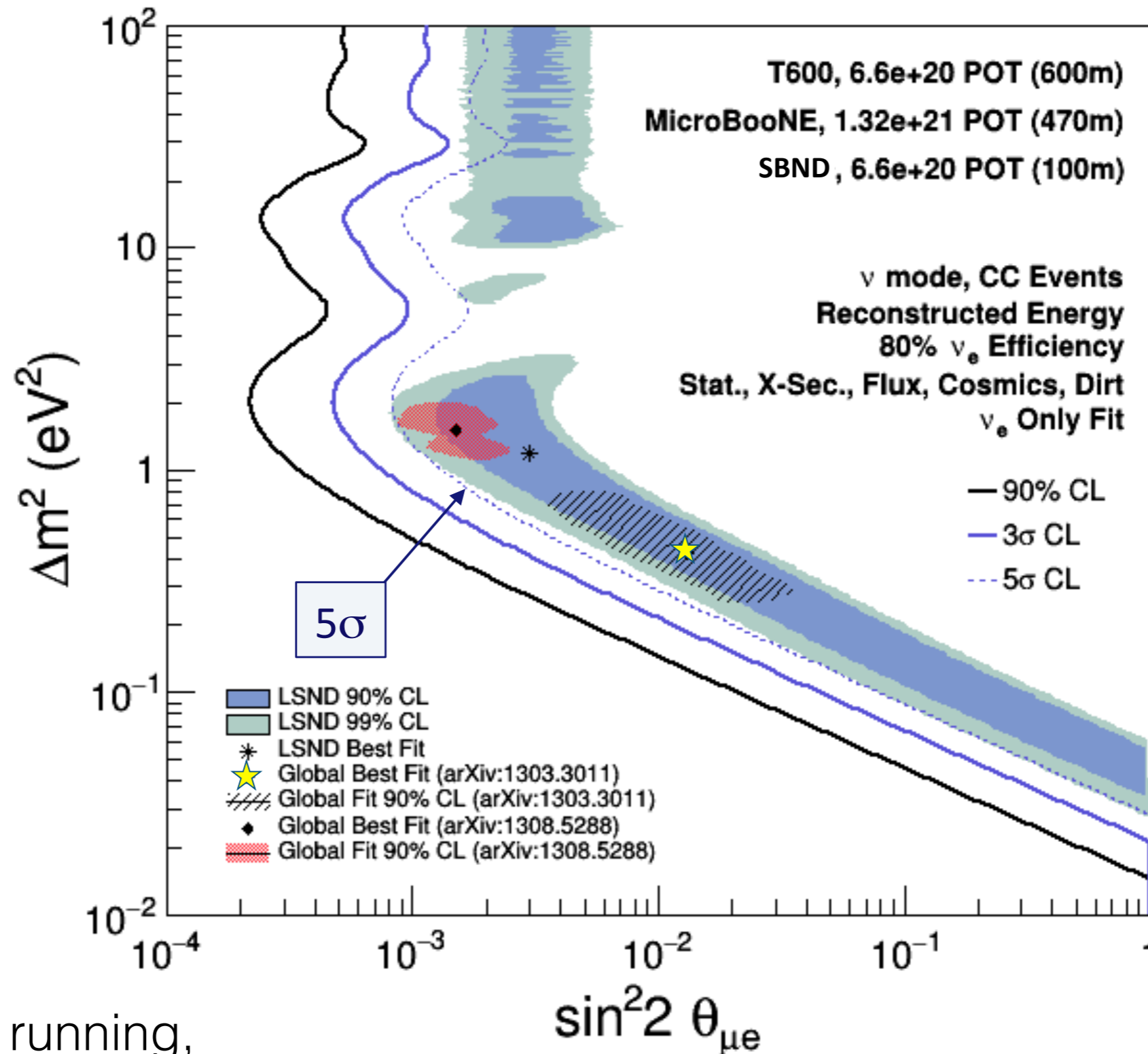|  | Time from beam | Energy |
|---|---|---|
| Prompt signal | 1<T<10μs | 20<E<60MeV |
| Delayed signal | T<100μs | 6<E<12MeV |

# Is background at MLF ok?

p bunch

- Fast neutron background is OK for IBD at 24 m baseline.

- Some additional lead shielding is required for accidental gammas.

**Selection criteria for IBD**

| | Time from beam | Energy |
|---|---|---|
| Prompt signal | 1<T<10μs | 20<E<60MeV |
| Delayed signal | T<100μs | 6<E<12MeV |

Black Sheet
μ-Veto layer

(LS Total: 54t)

3.4m

4.4m

JSNS* Collaboration, arXiv:1502.02255

- ● beam        w/o veto
- ⋯ beam+20ms w/o veto

- ● beam        w/ veto
- ⋯ beam+20ms w/ veto

energy[MeV]

# SBN sensitivity (for comparison)



3 years of running,
including shutdowns, etc.

D. Schmitz, Neutrino 2016 talk