A search for neutrinos beyond three active neutrinos at the J-PARC MLF

-How many leptons exist in nature?-

Jan. 31, 2013

at KEK

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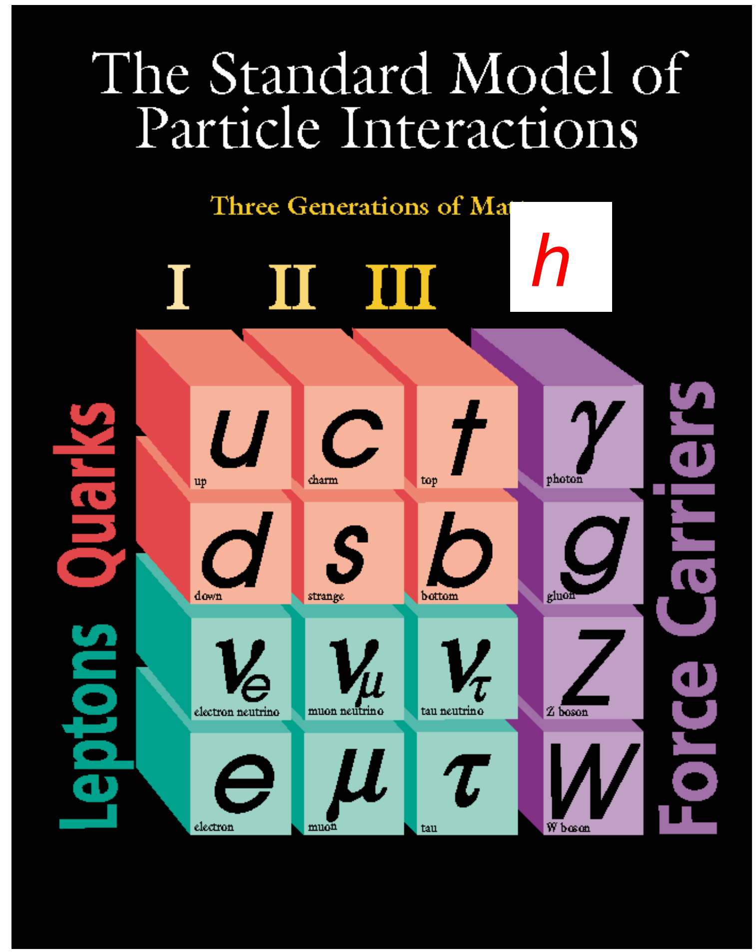
Contents

A basic question in Flavor Physics even after Higgs discovery

1. How many generations exist?
   - $\Gamma_{inv} \rightarrow$ $N\nu = 2.984 \pm 0.008$
   - Even neutrino, 4th one does not exist below $M_Z/2$
2. No more elementary fermion in 3 generation?

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix},\ u_R,\ d_R \quad \cdot\cdot$$

$$\begin{pmatrix} e_L \\ \nu_{eL} \end{pmatrix},\ e_R \quad \nu_{eR} \cdot\cdot$$



Sterile neutrinos

- Sterile neutrinos are naturally present in many theories beyond the Standard Model,
  - Example, see-saw partner ν_R, ν^c_L (no weak int.)
    states m^2/M , M : mixture of active and sterile

- no idea on number of sterile neutrinos
- no definite mass scale
  - One sterile ν can act as 'dark matter'
  - Heavy sterile ν's can be a source of CPV for lepto-genesis
    - νMSM for example
  - Light, mostly sterile states (small mixing with active v's) may affect the expansion rate of early Universe (with many assumptions) $0\nu2\beta$ constraint mass from above

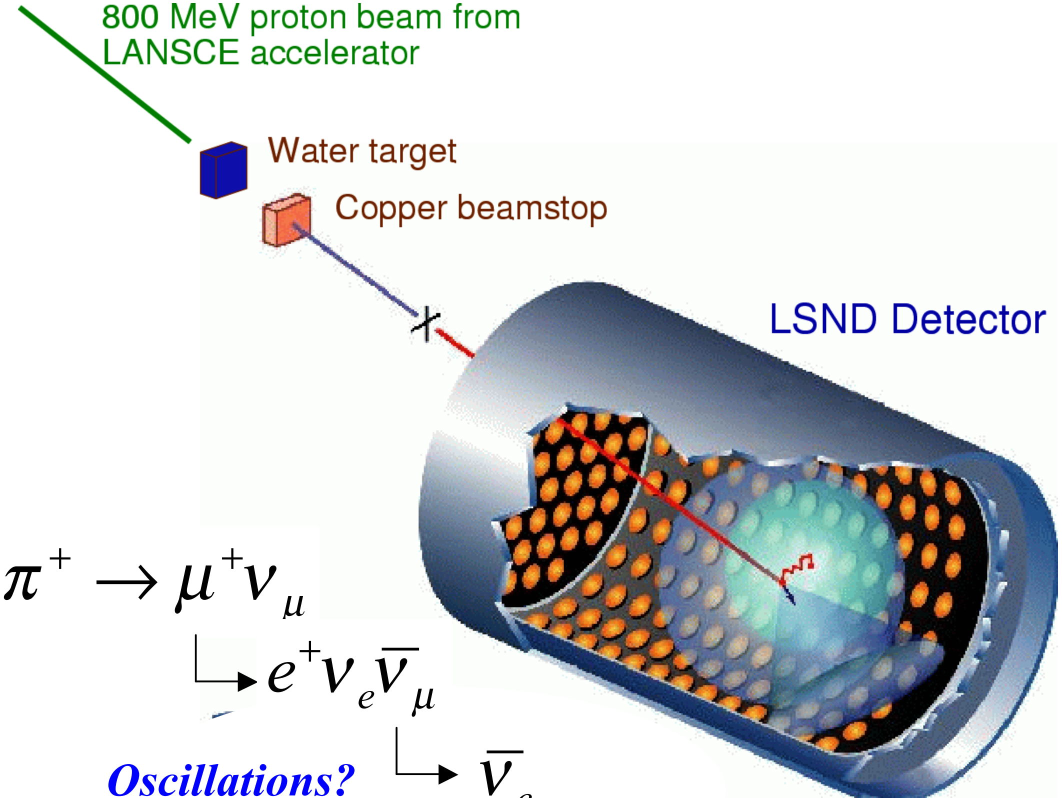
Experimental indications

Appearance (of active neutrino) and
Disappearance (of active neutrinos)

Appearance

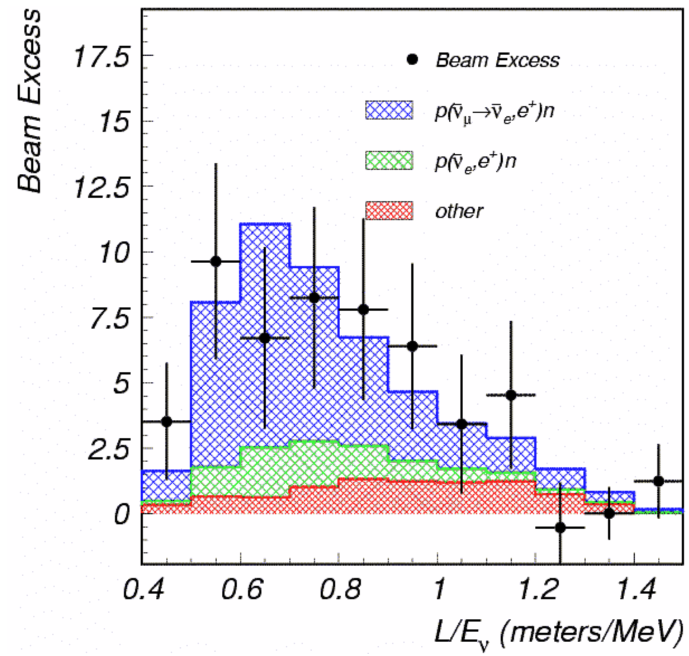
LSND $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Signal

1998



$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \overline{\nu}_\mu$$

Oscillations? $\hookrightarrow \overline{\nu}_e$



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

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

3.8 σ evidence for oscillation.

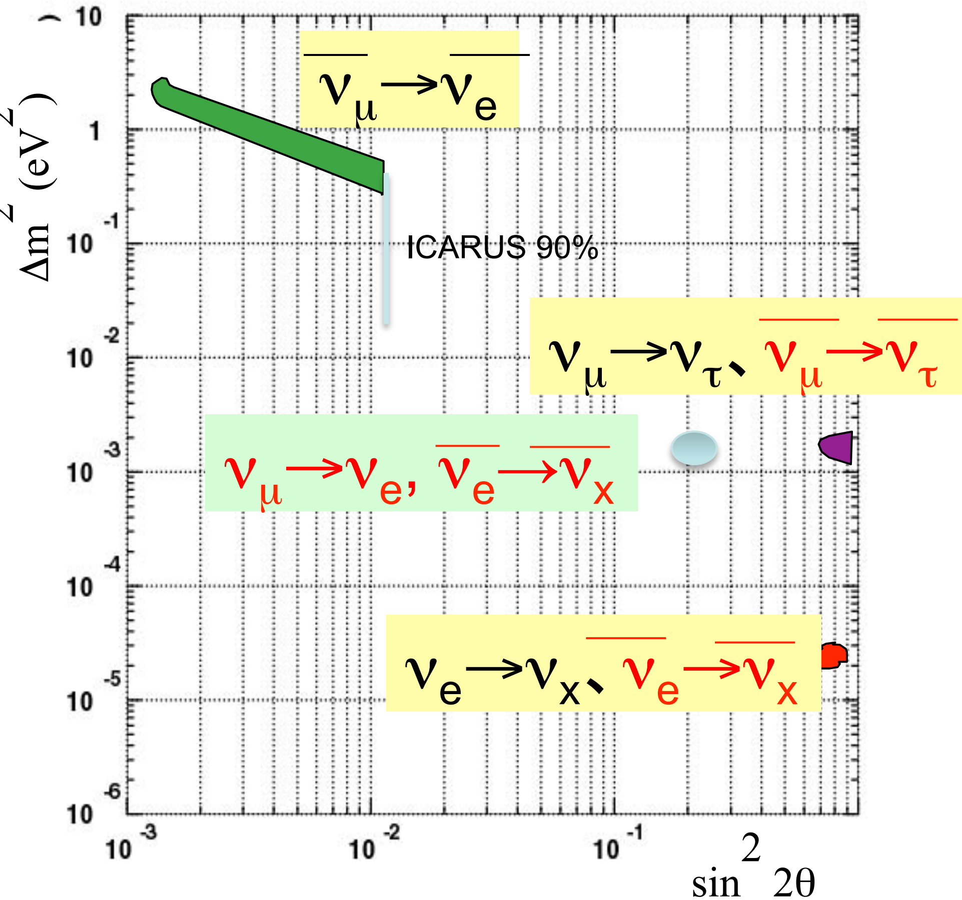
π^-, μ^- absorbed before decay into ν's
there should not be $\overline{\nu}_e$ at the level of $7\text{x}10^{-4}$

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

'Evidence' of more than 3 ν

Either some of the data are not due to oscillations,

or there must be at least one undiscovered "sterile" neutrino



$\Delta m^2_{12} = m_2^2 - m_1^2$ ~8 $10^{-5} eV^2$
$\Delta m^2_{23} = m_2^2 - m_3^2$ ~±2.5 10^{-3} eV^2
$\Delta m^2_{31} = m_3^2 - m_1^2$~ ±2.5 $10^{-3} eV^2$

Cannot make Δm^2 ~ $1 eV^2$
More than 3 eigenstates but Z width limits #ν =3
Sterile

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

$$
= \begin{bmatrix} 0.8 & 0.55 & 0.15 & \varepsilon_1 \bullet \\ -0.4 & 0.6 & 0.7 & \varepsilon_2 \bullet \\ 0.4 & 0.6 & 0.7 & \varepsilon_3 \bullet \\ \varepsilon_4 & \varepsilon_5 & \varepsilon_6 & 1 \\ \bullet & \bullet & \bullet & \end{bmatrix} \quad \text{MNS}
$$

Appearance and Disappearance at short distance

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

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

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

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

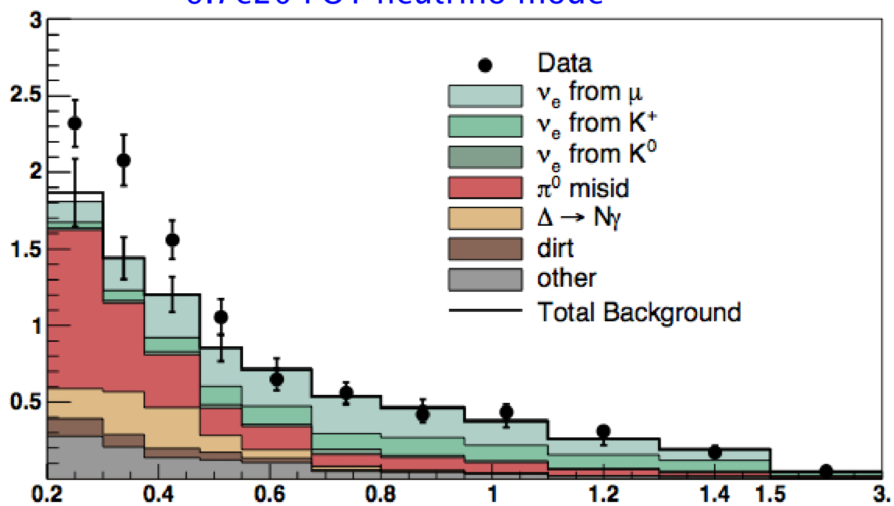
Appearance < Disappearance

Parameter region of interest

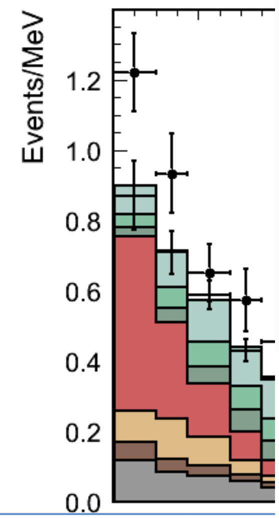
Why LSND MiniBooNE are not believed to be true?

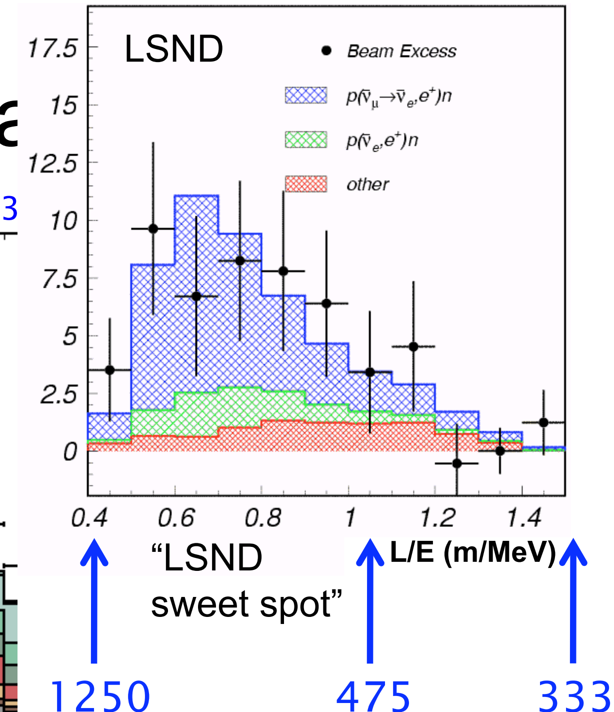
Trial by MiniBooNE @ Fermila

6.7e20 POT neutrino mode

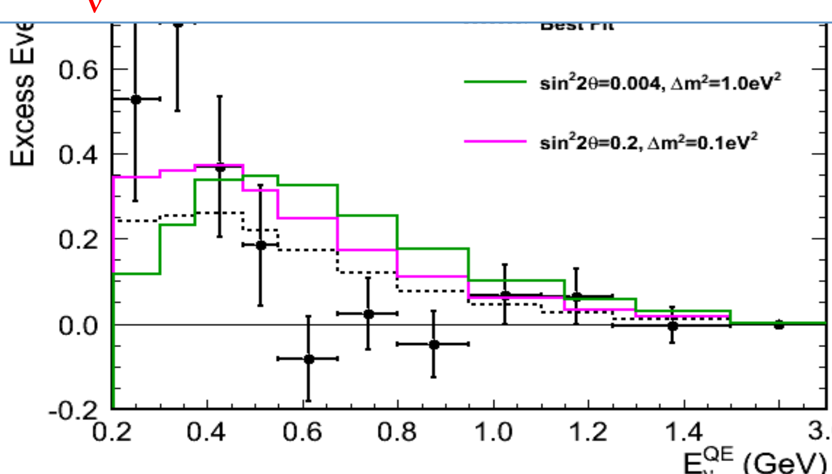


11.3

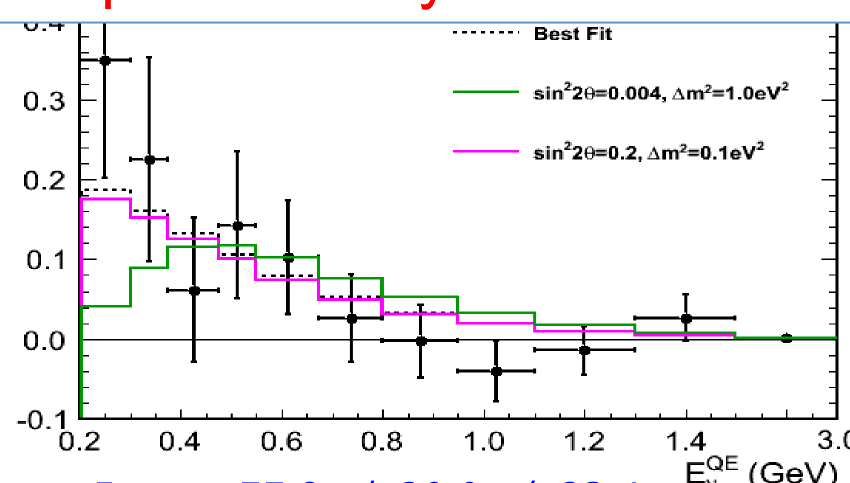




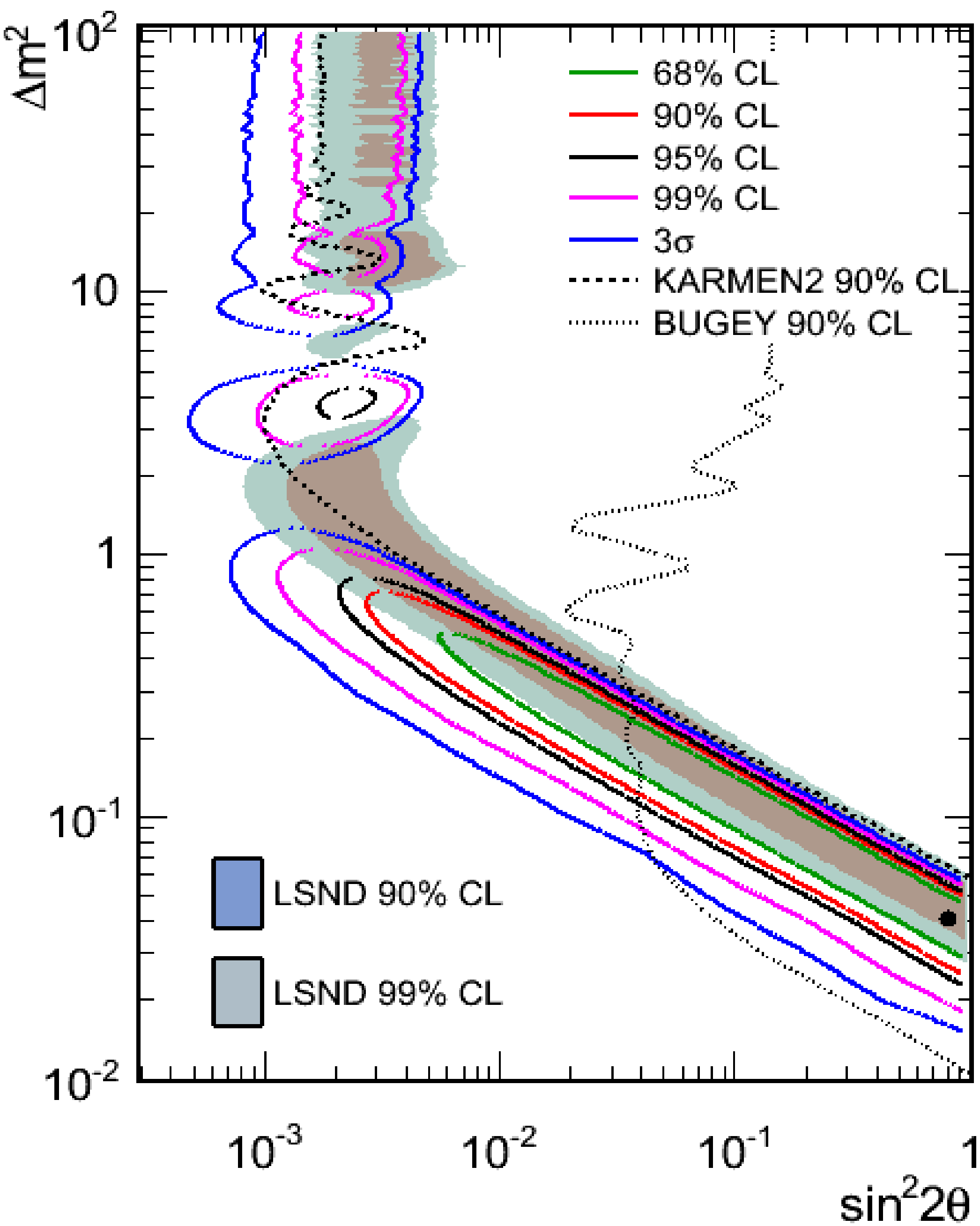
- Many backgrounds Ke3, μ decay, $\pi0$ produ
- E_ν reconstruction claimed to have problems by nuclear effects



Excess: 146.3 ± 28.4 ± 40.2

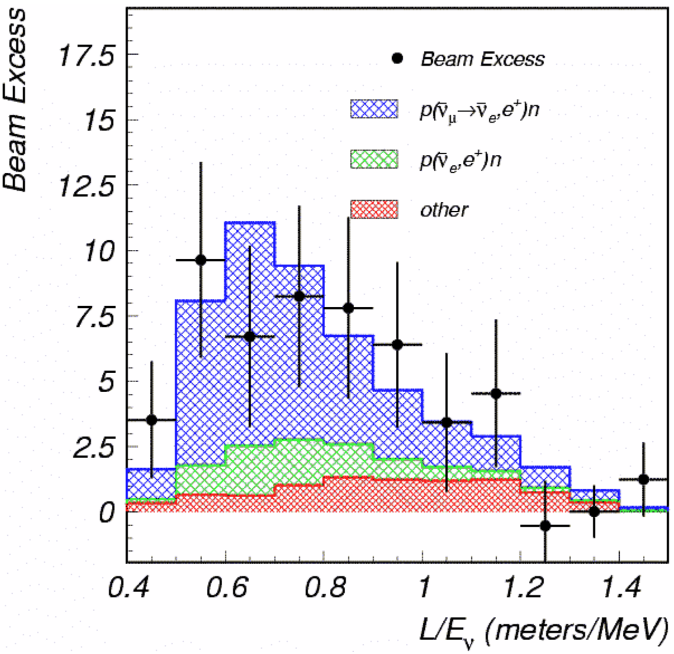


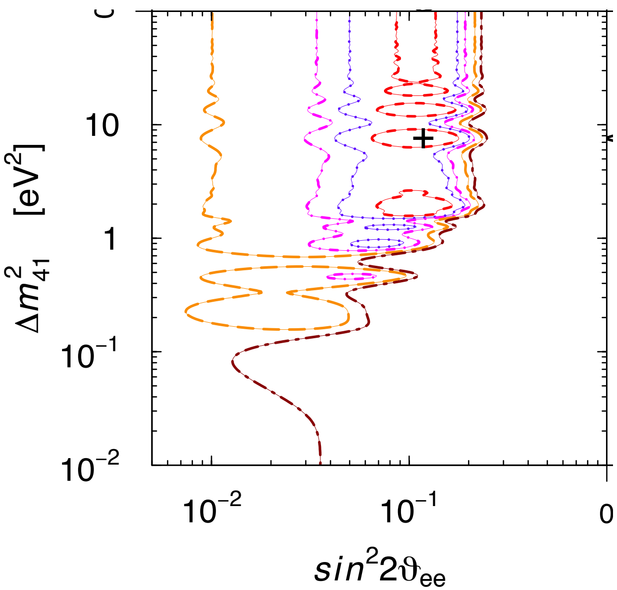
Excess: 77.8 +/- 20.0 +/- 23.4



Chris Polly
NEUTRINO2012

LSND & MiniBooNE combined





GALLEX,REACTOR
νe disappearance

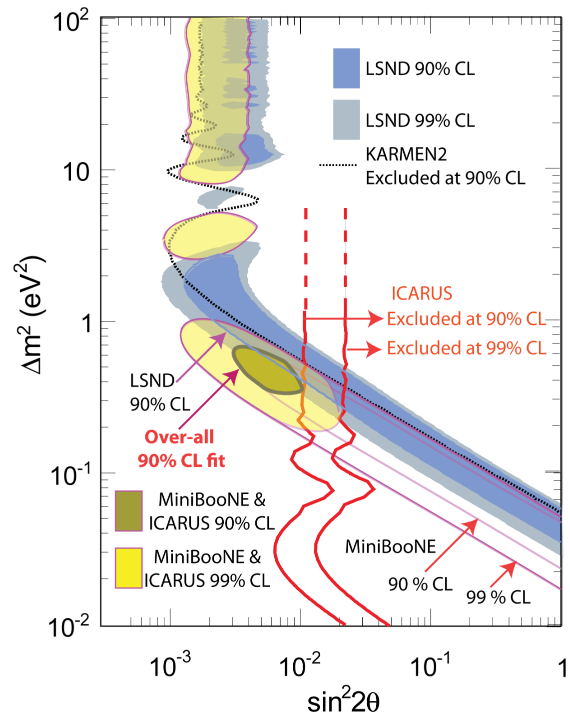
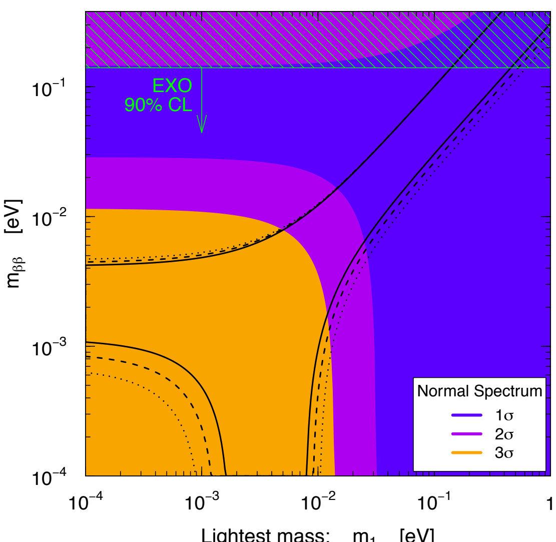
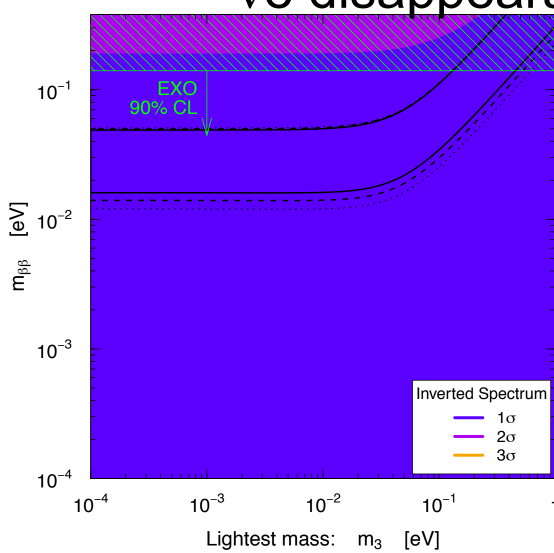


Figure 5. Regions $\Delta m^2, \sin^2(2\theta)$ of the ICARUS experiment compared with the published results of LSND, combined neutrino and anti-neutrino data from MiniBooNE and acceptance regions of KARMEN2. While for $\Delta m^2 >> 1\,eV^2$ there is already disagreement between the allowable regions from the published experiments, for $\Delta m^2 \leq 1\,eV^2$ the ICARUS result now allows to define a much smaller, narrower region centered around $(\Delta m^2, \sin^2(2\theta)) = $ (0.5 eV² and 0.05) in which there is a 90 CL over all agreement.





depends on NH, IH cancellation?

Δm^2 ~0.2-100 eV^2 ?

$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta} + U_{e4}^2 m_4 \bullet\bullet \right|$$

Limitations of LSND, KARMEN, MiniBooNE

- LSND Shortcomings:
  - bad duty factor (6%) of LINAC
    - could not separate of π (prompt ν_μ) μ(delayed ν_μ, ν_e)
    - neutron backgrounds
  - DIF background (detector was in forward direction)
- KARMEN Shortcomings:
  - PID (e, recoil p):neutron backgrounds for prompt signal
  - low beam current (160kW), small detector size
- MiniBooNE (and decay in flight) Shortcomings:
  - high backgrounds (0.6%) from NCpi0
  - intrinsic ν_e from μ and Ke3 decay
  - Eν reconstruction problem due to nuclear effect (binding, multi-nucleons correlation etc.)

A experiment with decay at rest neutrino source at MLF

A definite measurement of νe appearance (LSND effect)

(Possibly νe disappearance)

(NC disappearance)

Advantage at J-PARC MLF

1. Accelerator beam
2. $\overline{\nu}_e$ contamination
3. Signal

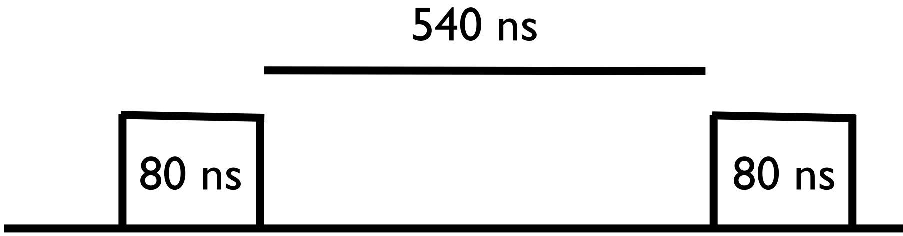
π, μ Decay at rest source at MLF

- 3GeV RCS

25 Hz harmonic number 2

~80 nsec bunch width

bunches separated by 540 ns



- 3 GeV protons + Hg
- π^+, π^- stop by dEdX

$\pi^+ \rightarrow \mu^+ \nu_\mu$ (25 ns)

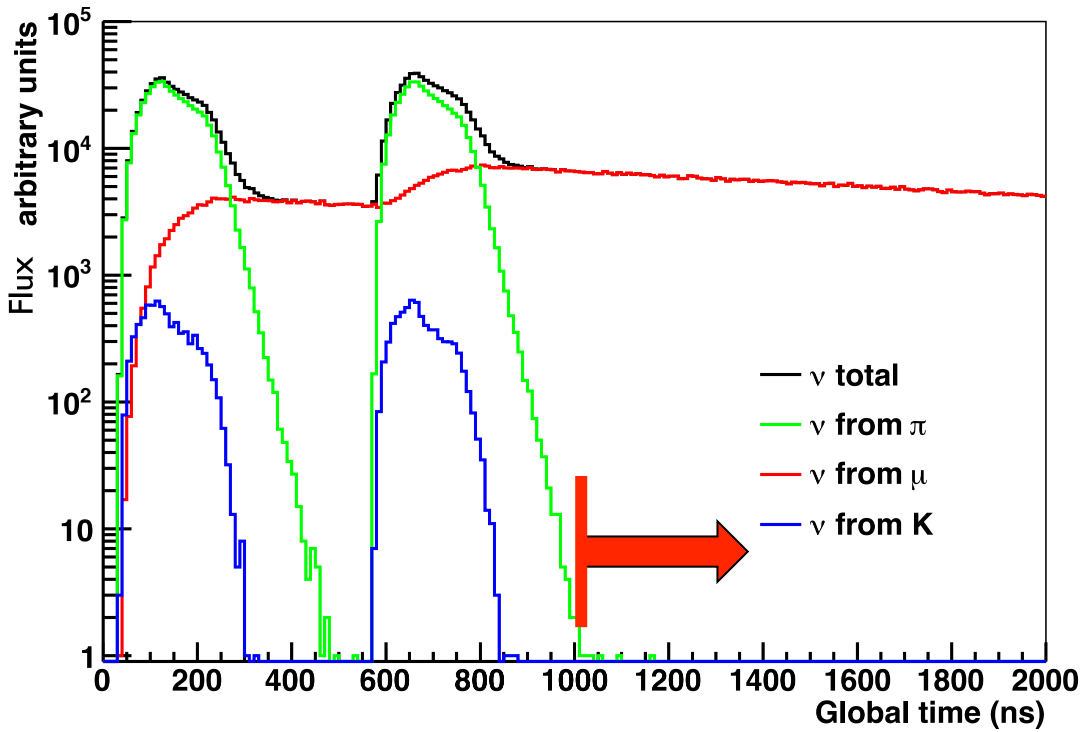
$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$

π^- ~99% absorbed

μ^- ~94% captured

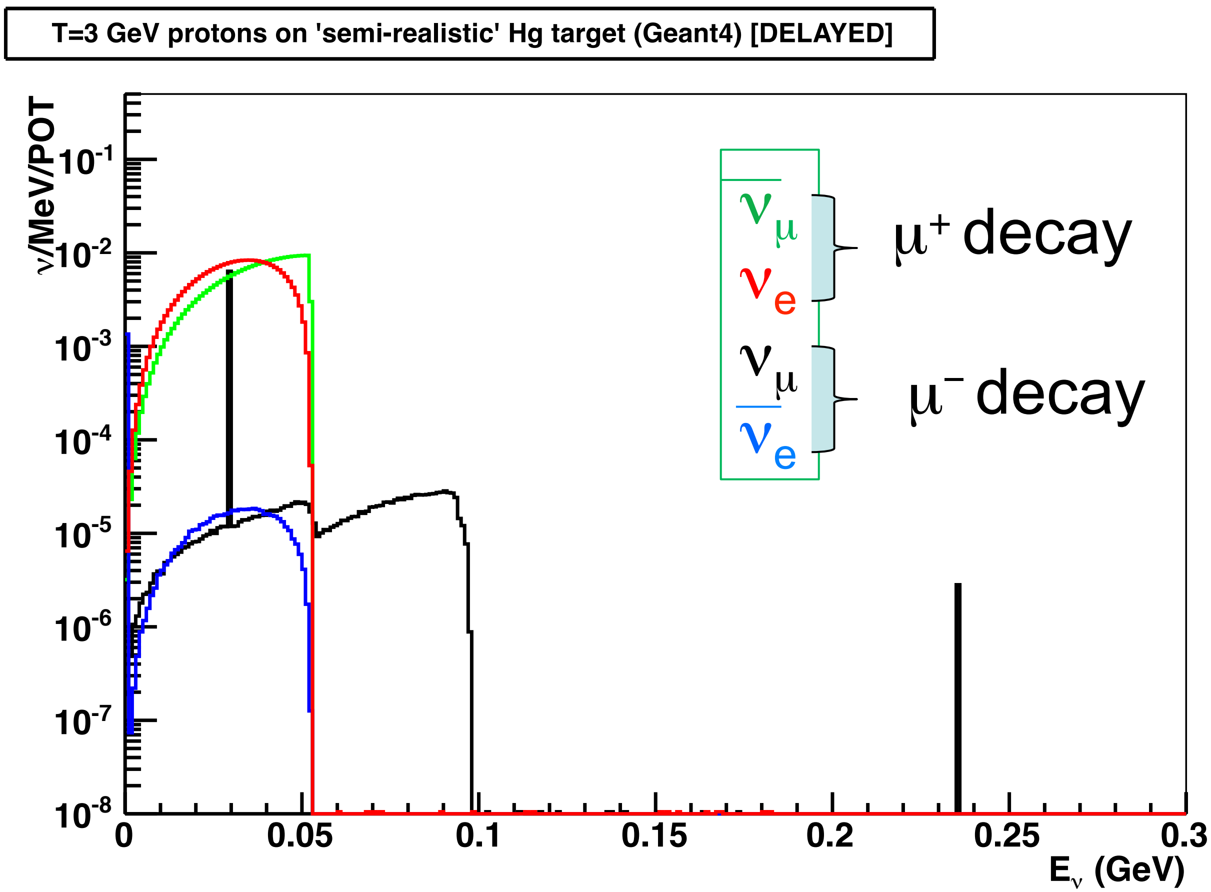
1% x 6% ~10^{-3} of μ^-

$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$



Delayed (from μ^+ DAR)

Outside of: 0-150 ns OR 620-770 ns



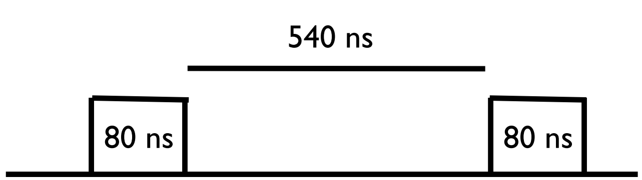
μ^+ decay
μ^- decay

μ^- capture

and
π,K left over

No DIF !

Josh Spitz(MIT)



Beam structure

Neutrinos from stopping μ decays

- ν_e C $\rightarrow e^-$ N_{gs}, N_{gs} β decay

  $\rightarrow e^-$ N*

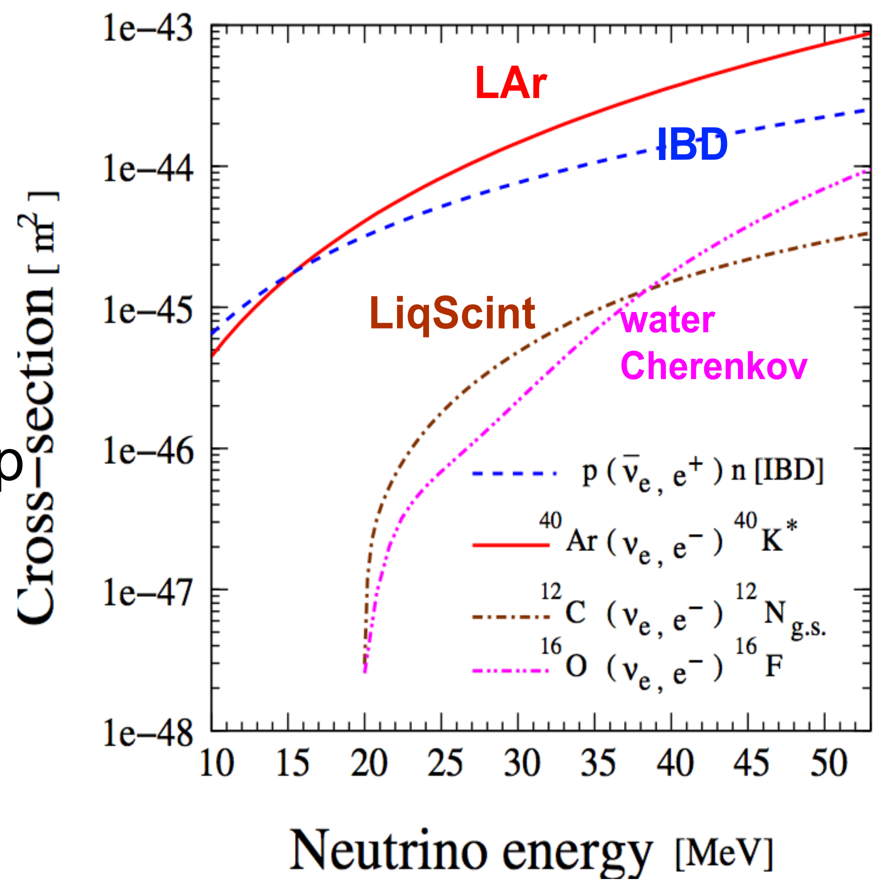
  End point ~17 MeV

- ν_μ, $\overline{\nu}_\mu$ NC

  elastic scattering, nuclear breakup

- $\overline{\nu}_e$ p $\rightarrow e^+$ n, n p $\rightarrow$ d γ (2.2 MeV)

- ν $e^- \rightarrow e^-$ ν



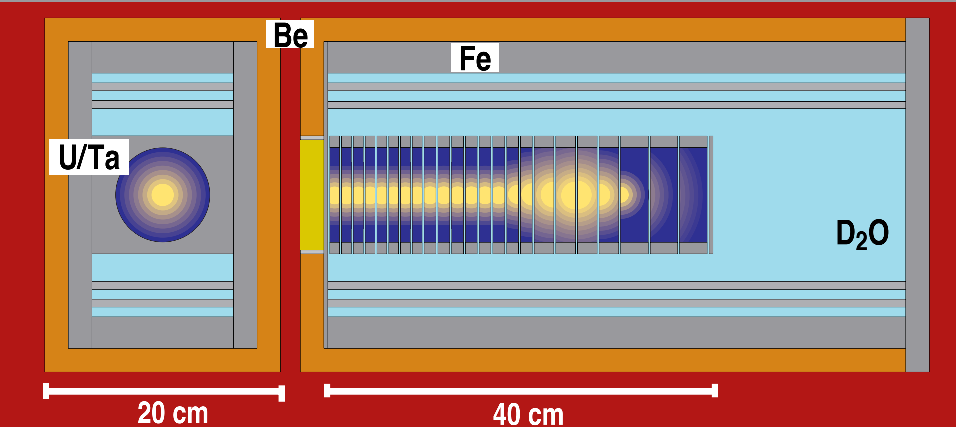
Event rate at RCS 1MW 4000hr /yr operation

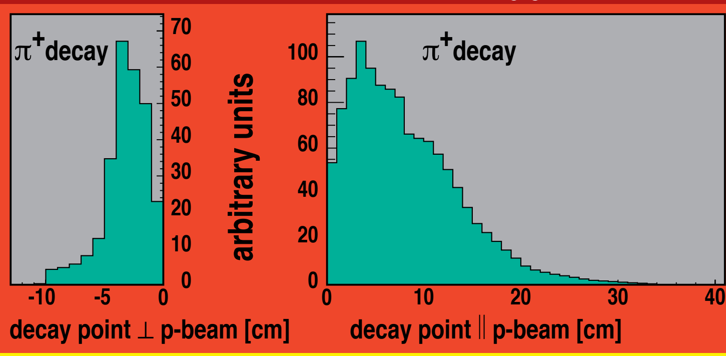
- # protons — $3x10^{22}$ prtotons
- # stopping π^+, μ^+ — $0.77x10^{22}$ (π/p=0.258)
- IBD cross sec. — $\sigma = 9.3x10^{-48} E_\nu^2$(MeV) m^2
- ν Flux — $1.5x10^{18}$ /(d/20m)^2 ν' s/m^2
- # free protons /m of CH_2 — 1/7x $6x10^{29}$ /m^3
- Event rates of E_ν (MeV) with 1-ton detector at d(m) from the MLF target — 1.2 x E_ν^2/(d/20)^2

- (# stopping K^+ (to be measured) — 10^{20} K^+ decays/yr !)

$\overline{\nu_e}$ contamination

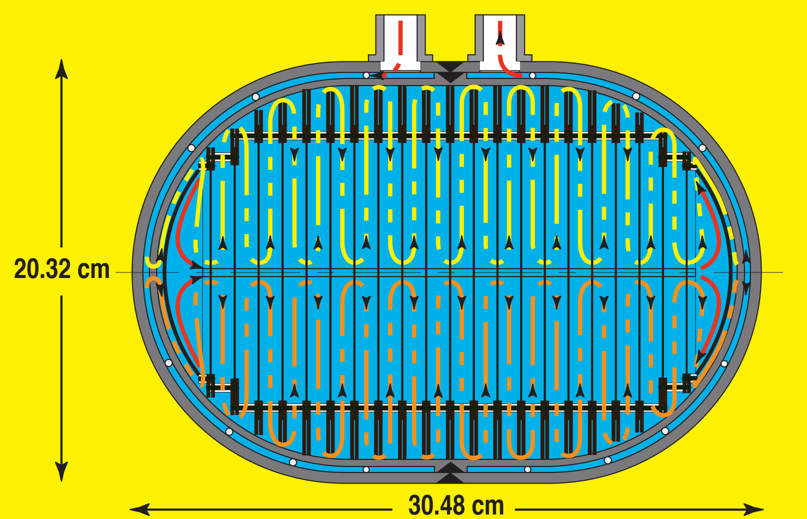
SPALLATION TARGET ISIS / LAMPF





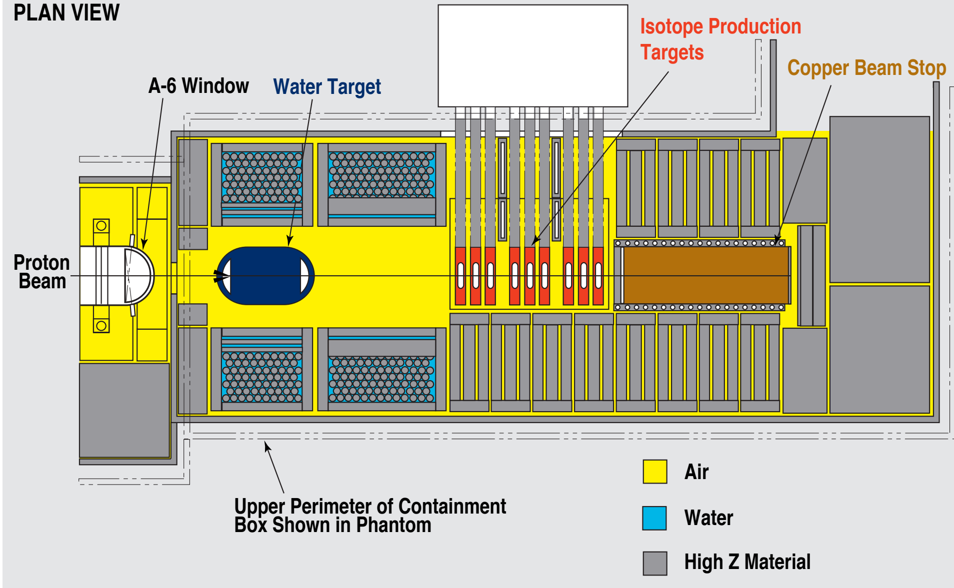
DISC DIAMETER
9 cm

BEAM DIAMETER
0.7 cm

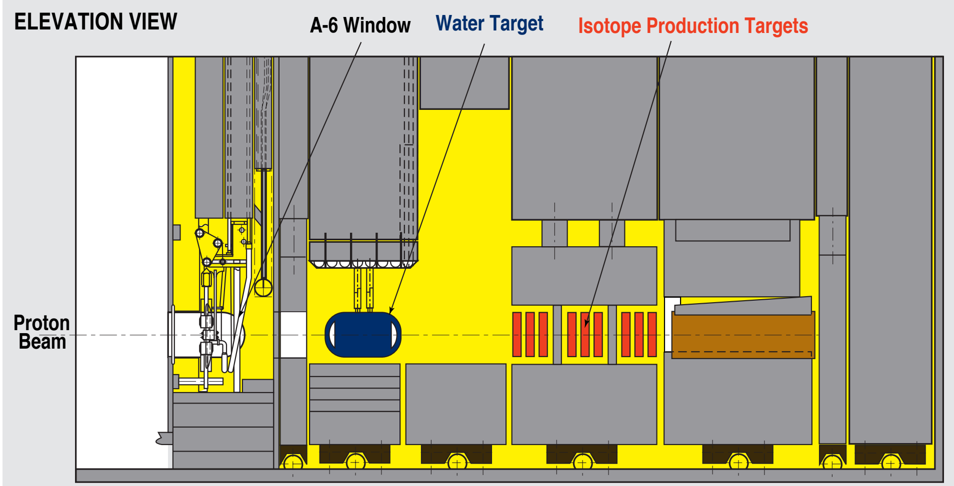


LSND TARGET AREA

PLAN VIEW

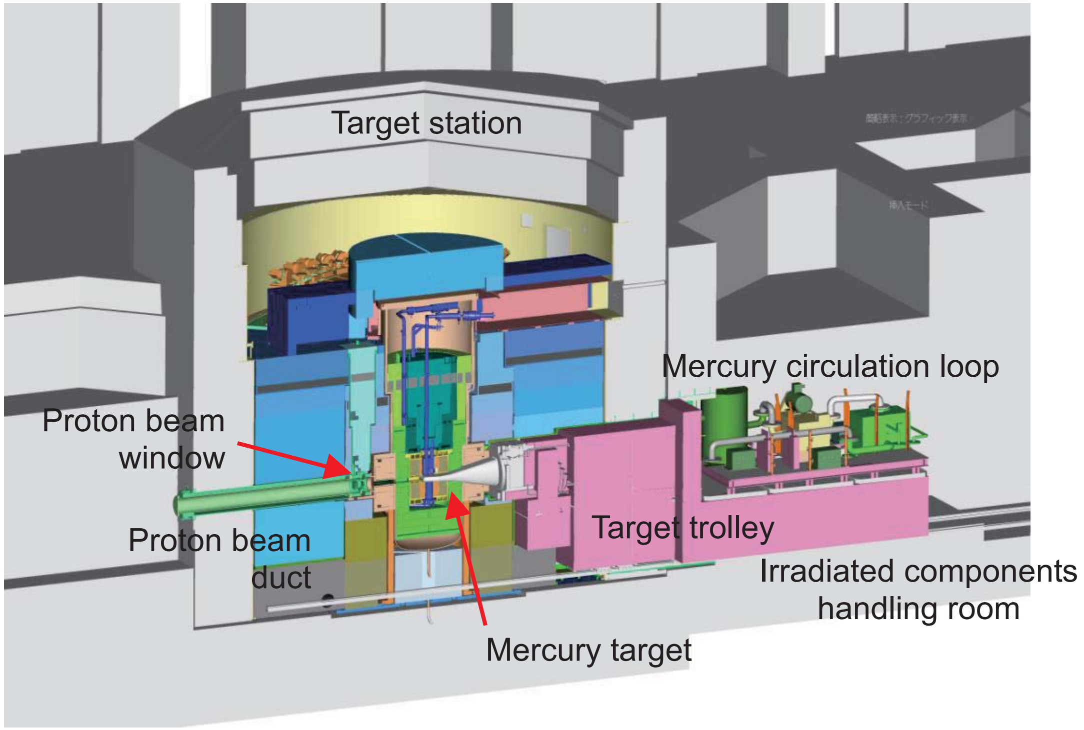


ELEVATION VIEW



WATER - TARGET REMOVED DURING 1995

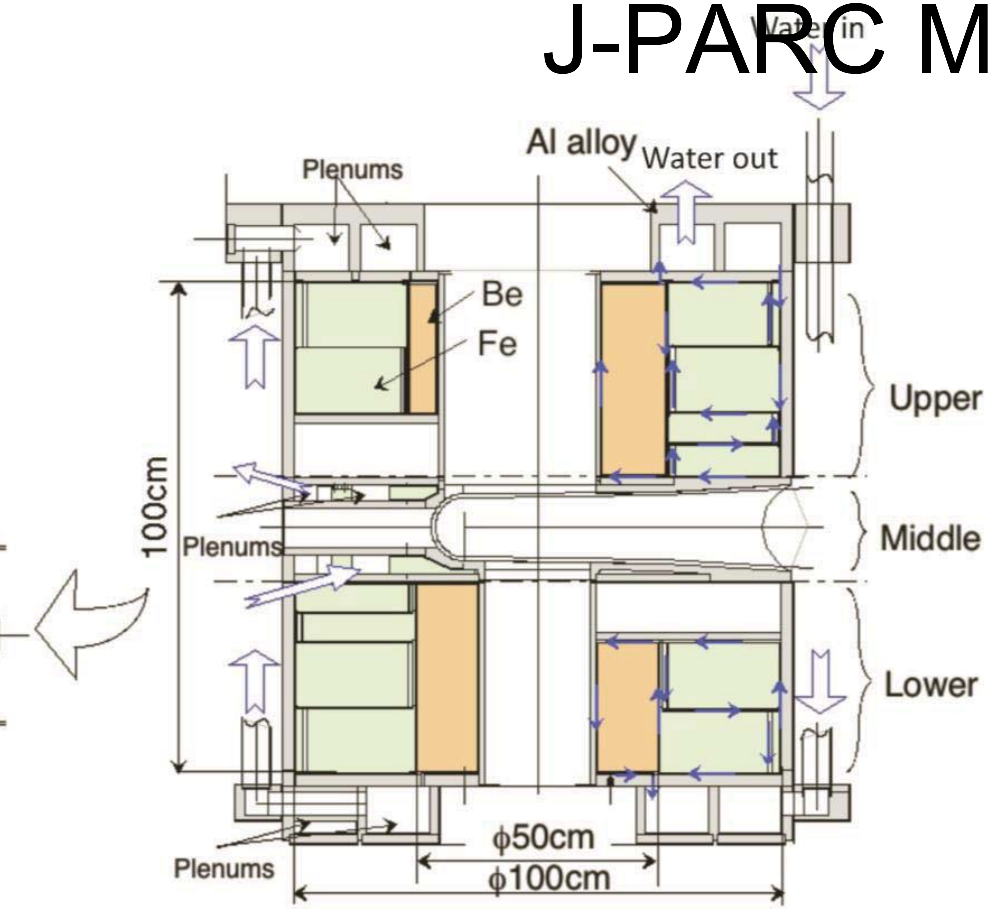
J-PARC Hg target assembly

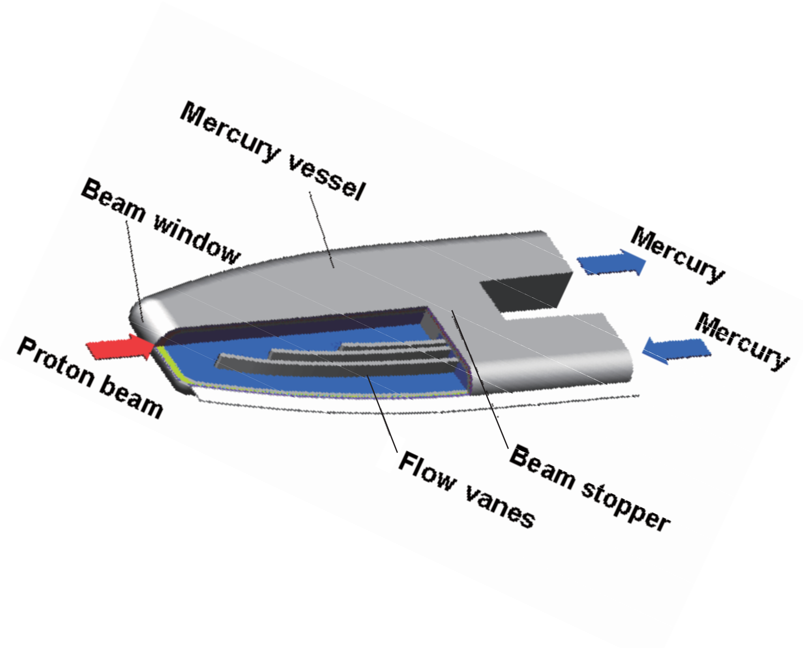


2.1.3: A cutaway view of the target station and the target system in the irradiation components

Cutaway view of whole target assembly

J-PARC MLF target

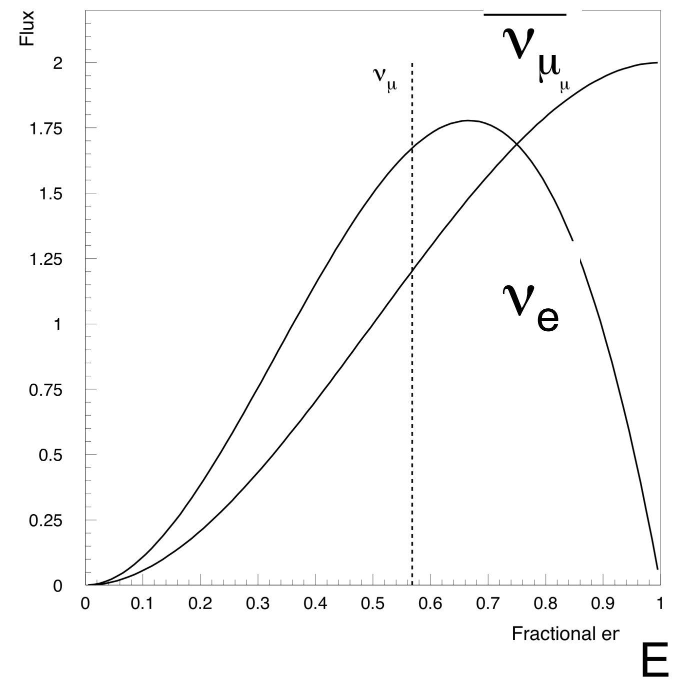




	Target	π^- absorb	μ^- capture	suppression
KARMEN	Ta+D_2O	98.8%	93%	8.4x10^{-4}
LSND	H_2O	96%	88%	5x10^{-3} (?)
J-PARC	Hg+Be	99%	94%	6x10^{-4}

Signal

- Pulsed beam enables to separate μ decays from beam n, π decay
  ➔ main components are $\overline{\nu_\mu}$ and ν_e
- Due to nuclear absorption, $\overline{\nu_e}$ contamination is ~10^{-3}
- Well defined spectrum shape of ν from stopping π, μ, (K)



- Well defined cross section for $\nu_e\ p \rightarrow e^+\ n$ (IBD)

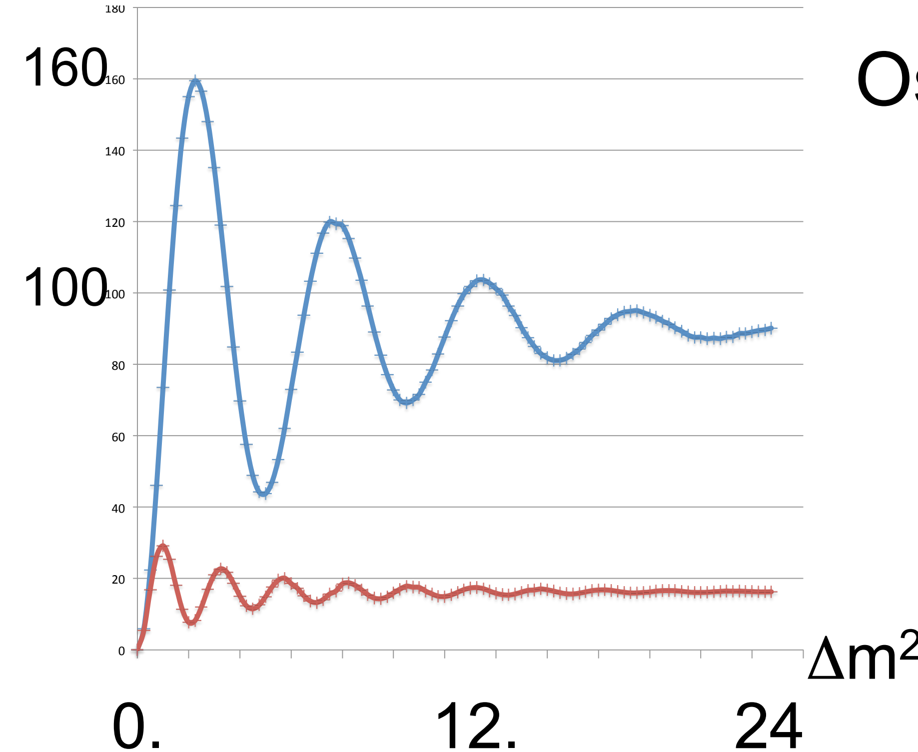
$$\sigma_{IBD} = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(g_V^2 + 3g_A^2)\left(1 - \frac{1.3}{E_\nu(\mathrm{MeV})}\right)\sqrt{1 - 2\frac{Q}{E_\nu} + \frac{Q^2 - m_e^2}{E_\nu^2}}\,\theta(E_\nu - Q)$$

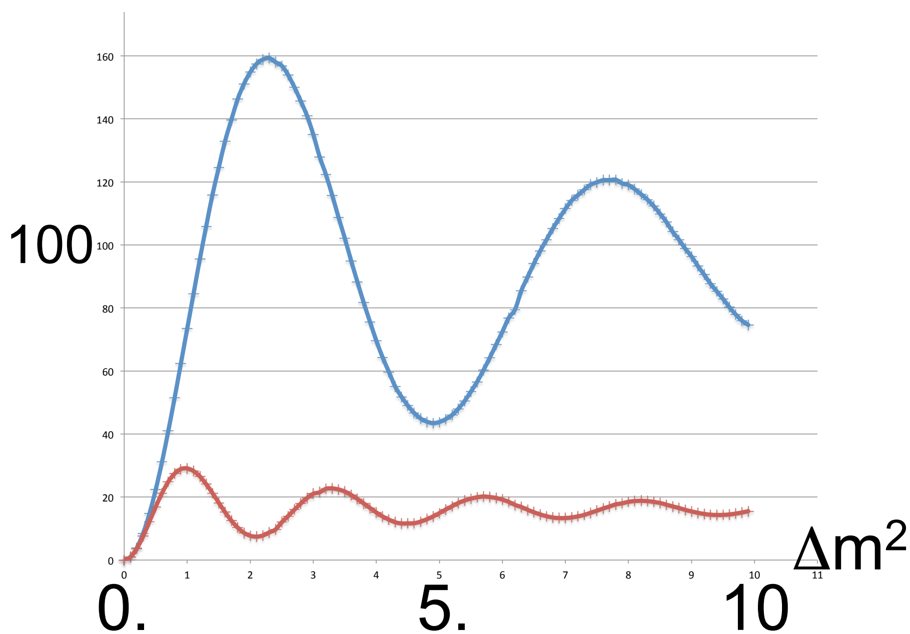
- $E_\nu = E_e$

⇔ LSND-LINAC, Decay in flight source, MiniBooNE etc.

Detector consideration

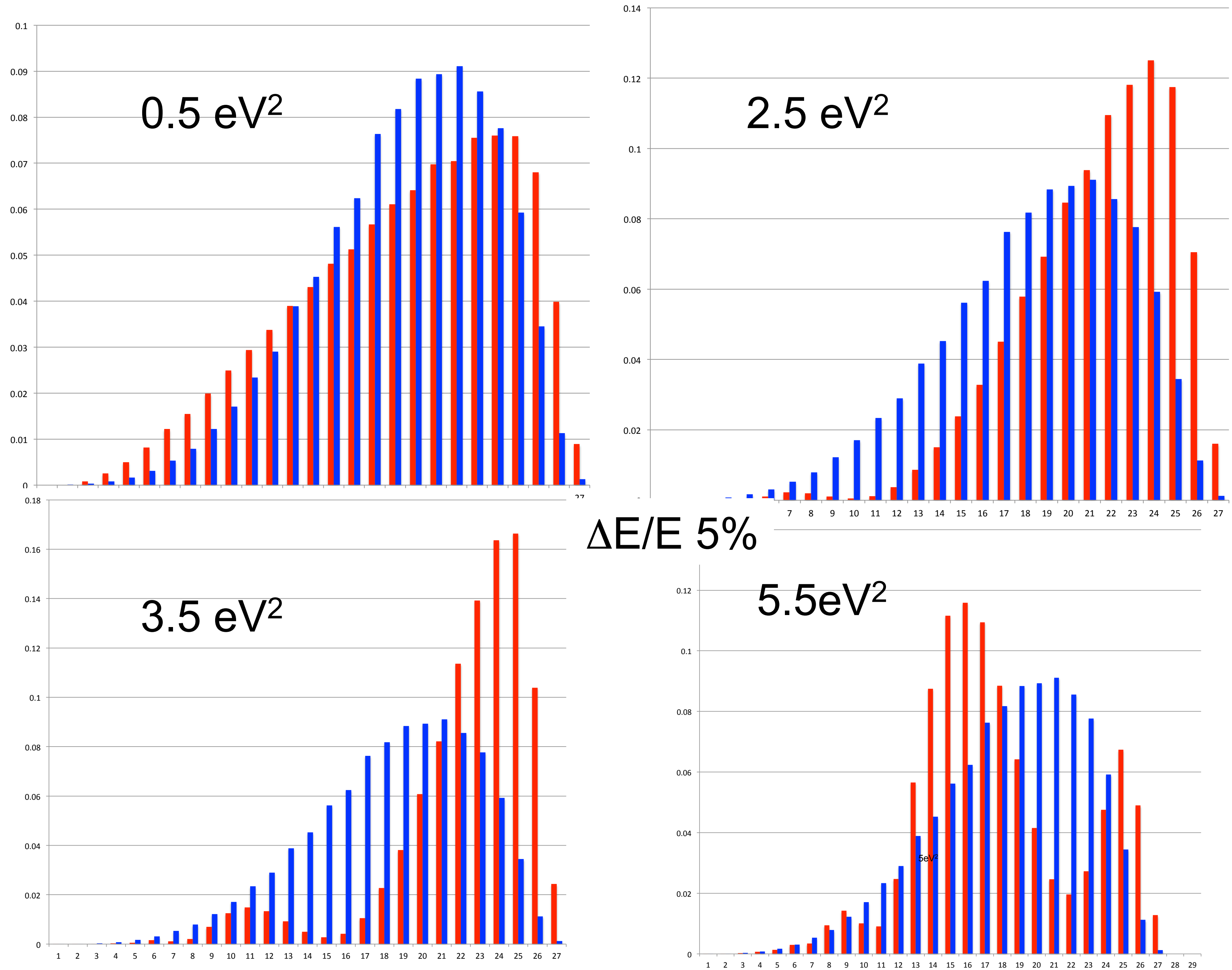
A possible strategy





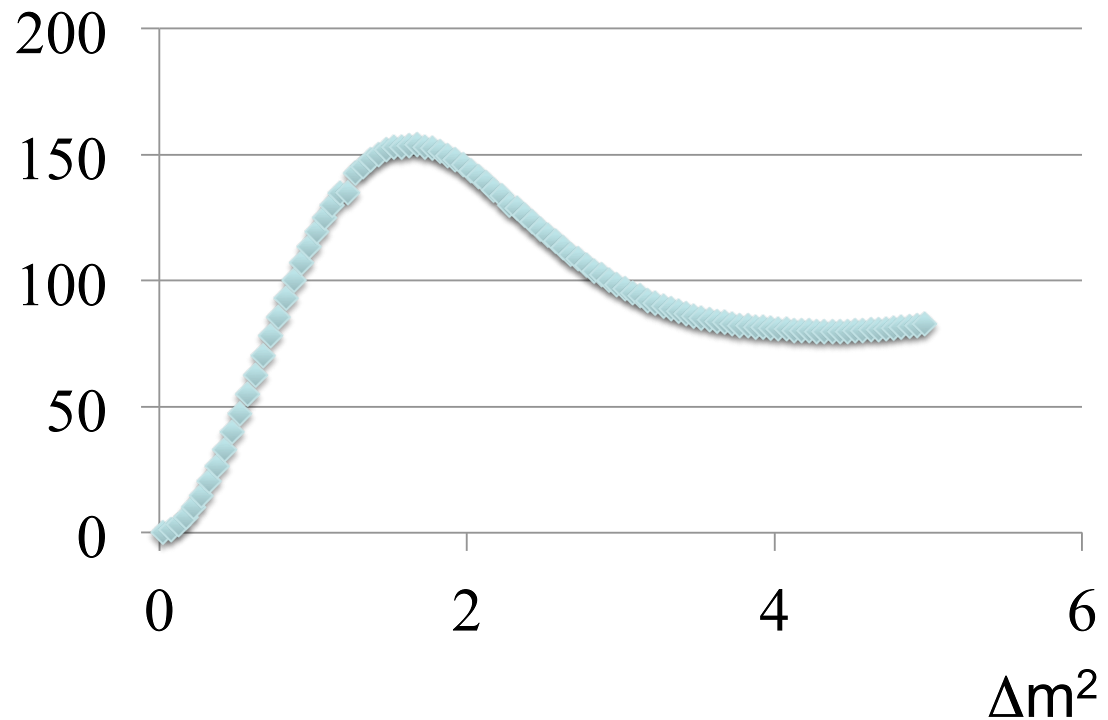
Oscillation signal rates /yr

- Experimental strategy depends
  - badget
  - neutron backgrounds
- Oscillation signals at 20m and 50m with 5m long detector along the beam
- 5mx5mx5m at the distance 20m, assumming $\sin^2 2\theta = 10^{-3}$, 50% detection eff.


0.5 eV²
2.5 eV²
3.5 eV²
5.5eV²
ΔE/E 5%

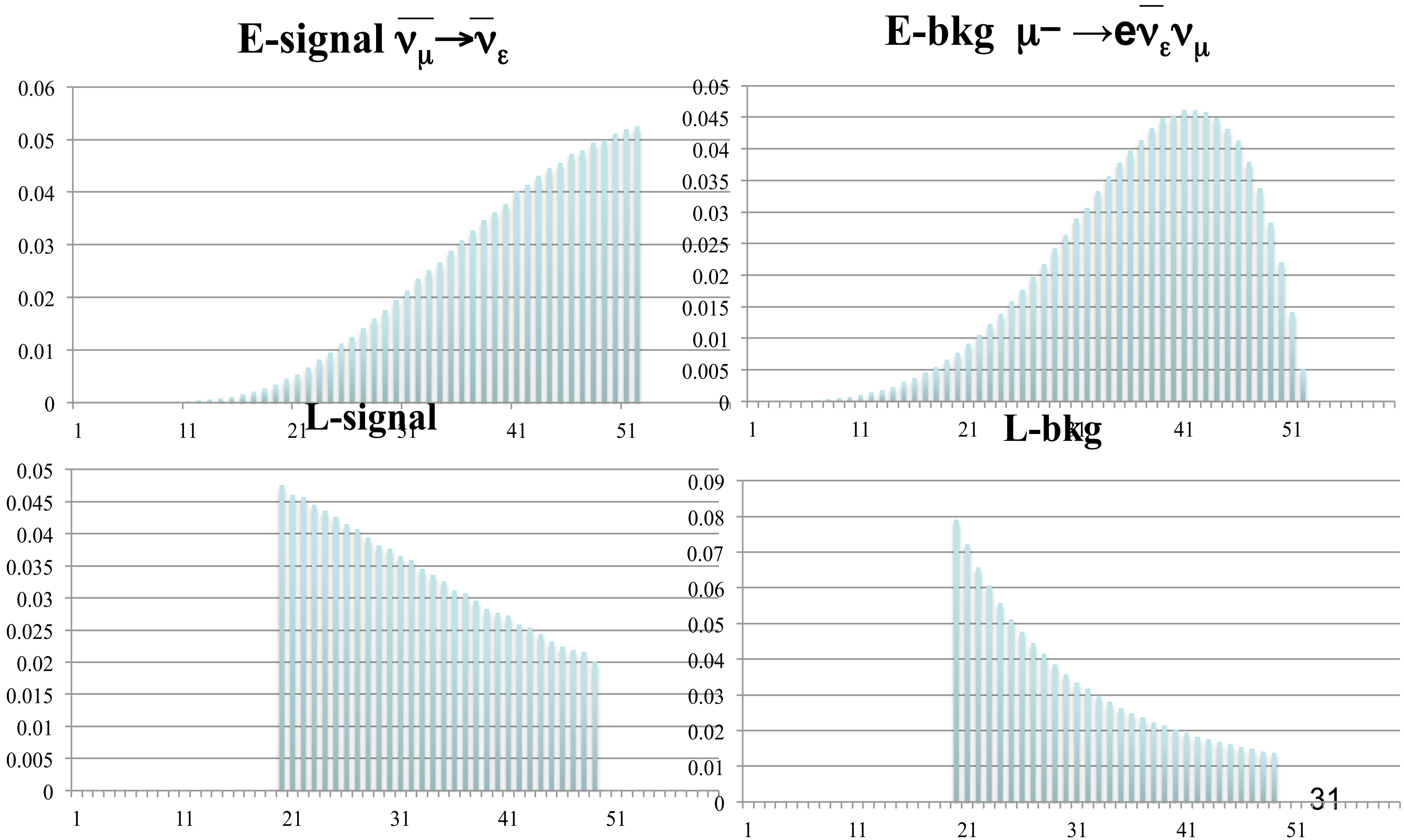
- For $\Delta m2$ <~1 eV^2 and complete coverage, longer baseline with long detector
- Near detector ~100t to find large Δm^2 oscillation or define beam without oscillation

\# of events/2yr
1MW, 4000hr, 3mx3mx30m, with 50% detection eff.

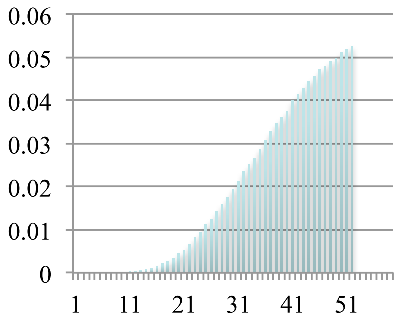


beam contamination from μ^- decay ~ 150 events/2yr

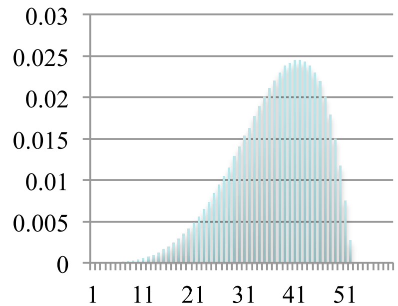
Differentiation of signal and backgrounds (Δm^2=1eV^2 20m-50m)



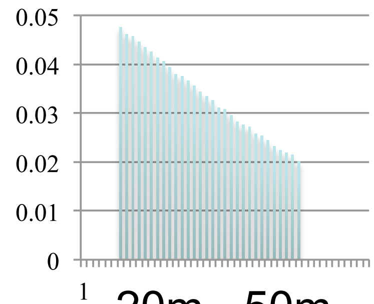
E signal



E backg

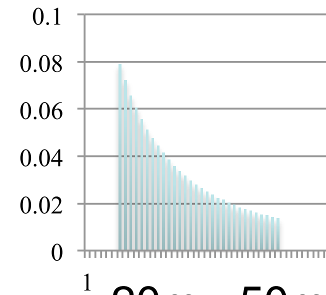


Signal dist.



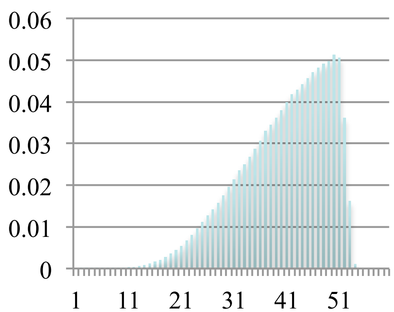
20m - 50m

Bckg L dist

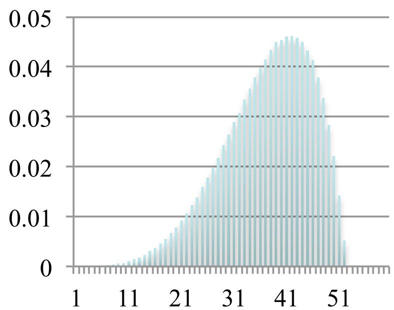


20m - 50m

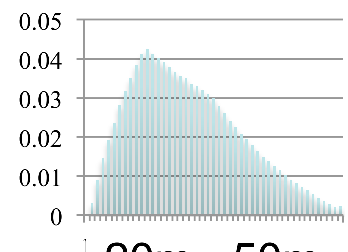
E signal-resol



E bckg-resol

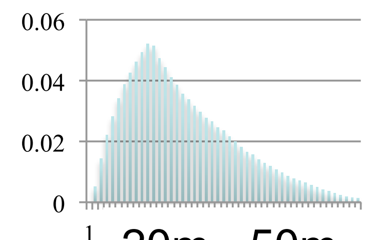


Signal Dist - resol



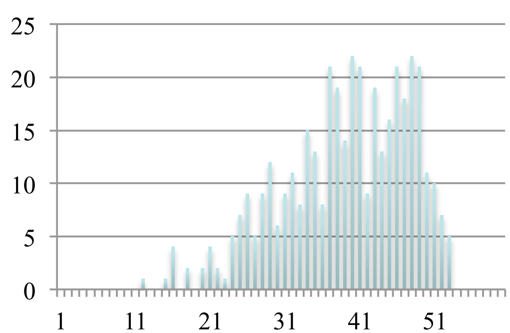
20m - 50m

Bckg L dist resol



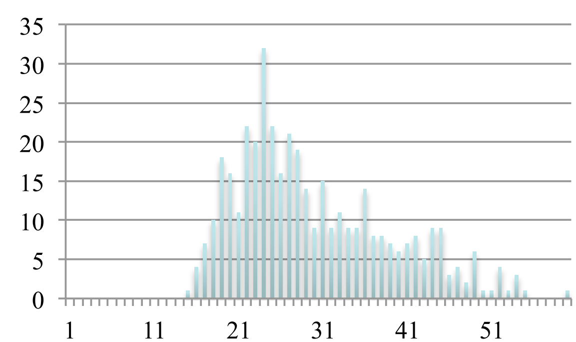
20m - 50m

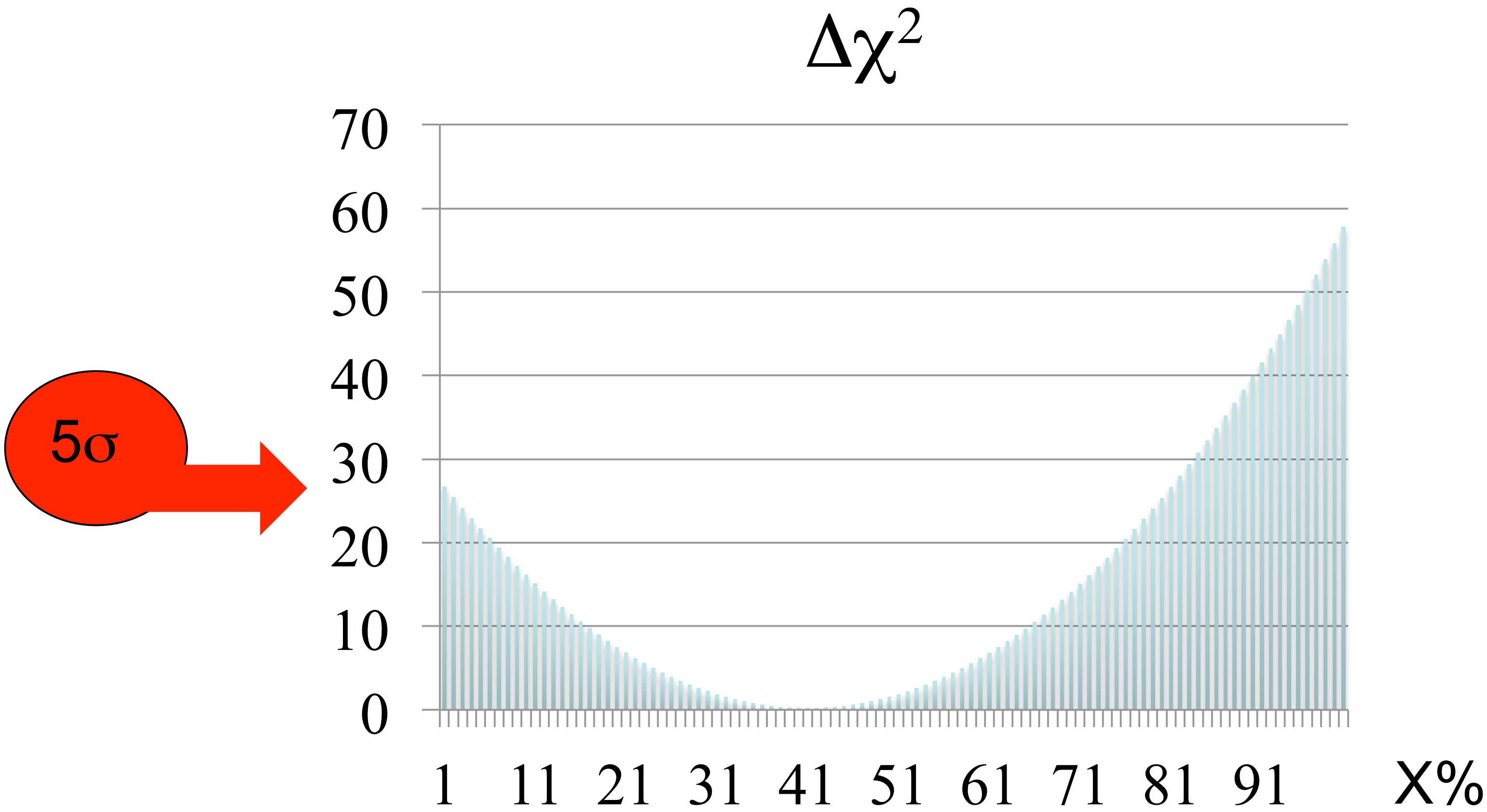
E obs



Take χ^2 of E- and L-distributions with sum of two components

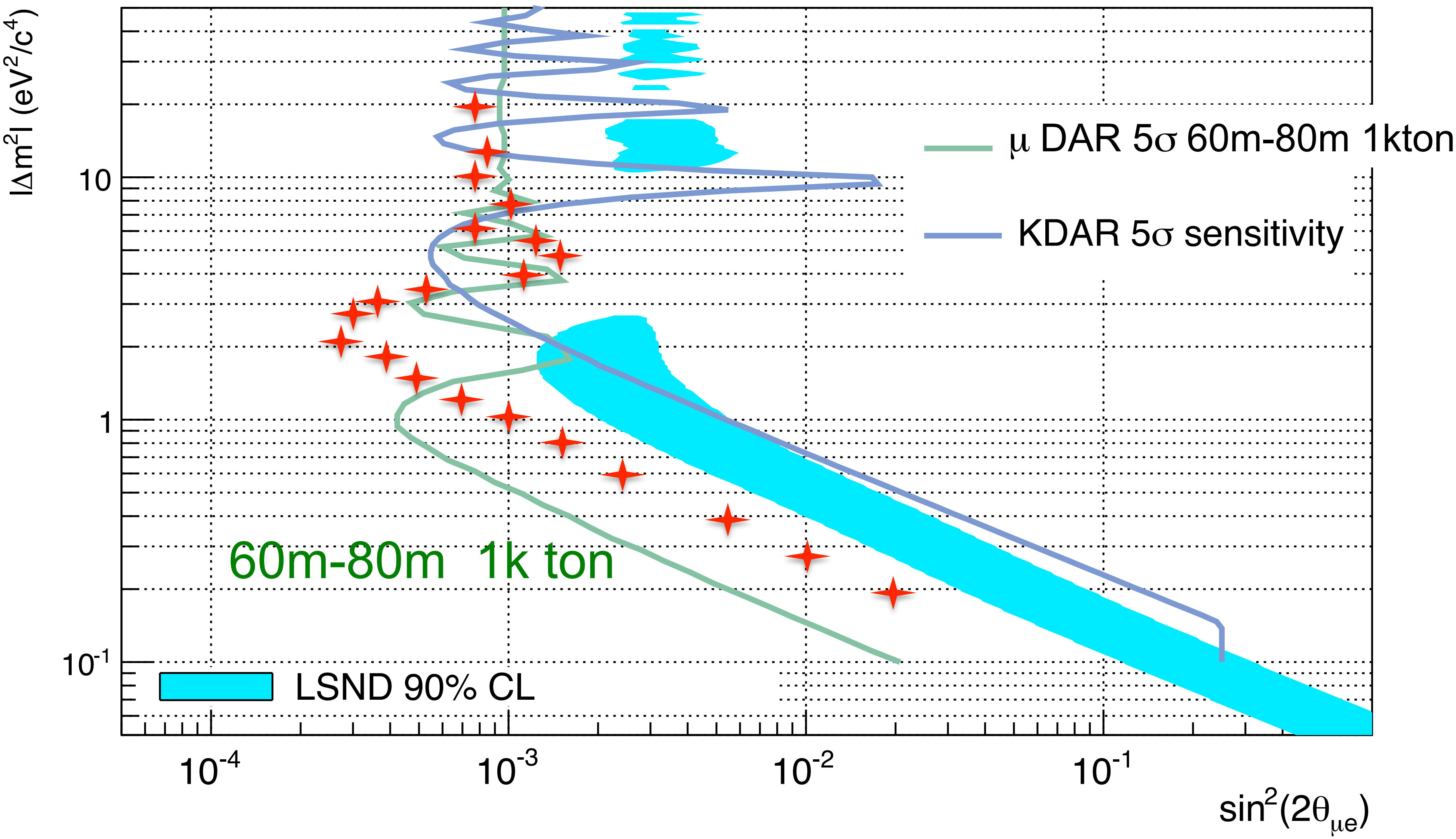
dist obs





$$\Delta\chi^2 = \Delta \sum_{\substack{\text{distance}\\ \text{energy}}} \left[\frac{(\text{obs} - (X \times \text{signal} + (1-X) \times \text{bckg})}{\text{error}} \right]^2$$

μ DAR 5 σ on anti-ν_e appearance 20m-50m (270 ton) in two year



Other possible measurements

ν_e disappearance (off bunch timing beam)

- $\mu^+ \to e^+ \ \nu_\mu \ \nu_e$ ve C→e^- Ngs σ $8.9 \times 10^{-42} E^2$
  - coincidence of e^- and N_{gs} decay, shape of E_e

Proof of sterile (NC disappearance)

$\pi^+ \to \mu^+ \nu_\mu$ ν C → ν C*(15.11) 2.8×10^{-42}

- Monochromatic $\nu\mu$ NC disappearance in fixed interval
- On bunch timing, n backgrounds?
- Continuous spectrum ν's suppressed by μ life time

- $K^+ \to \mu^+ \nu_\mu$ $\nu_\mu C \to \mu^- N^*$ 8.4×10^{-39}

  $\nu_\mu \to \nu_e$, $\nu_e C \to e N^*$ 1.4×10^{-38}

  - small backgrounds because of higher energy
  - nuclear effect and K production rate are unknown

  Could be checked with LAr 250L

Critical item and preparation

- By 1 ton scintillator before 2013 shut down
  - Neutron background rate in-situ as a function of bunch timing by 1 ton scintillator
  - >10 MeV $e^{\pm}$ equivalent for 10 μsec
  - 2.2 MeV γ equivalent for ~200 μsec
- By 250L LAr detector in 2014
  - K production and stopping rate by 3 GeV protons
  - Broadening of charged lepton from 235 MeV ν
  - Identification of background events

- Design of a liquid scintillator detector with E resolution (5% or better), position resolution (<25cm) and e-, p- ID capability

A possible time line

2013   On-going

- Calibration of 250L LAr in charged particle beam K1.1BR
- Neutron background measurement at BL13 with 1 ton Scintillator before shutdown

Proposals

2014 (RCS tuning and start working for 1MW operation)

- Install 250L LAr in MLF
- Kaon stopping rate by K->μ ν_μ , ν_μ n->μ p study nuclear effects
- Install liq. scintillation detectors in MLF

2015- μ DAR, K-DAR oscillation search

- anti-ν_ε appearance search –refute or confirm LSND
- Test for the disappearance to Sterile ν
- Studies with K-DAR 235 MeV monochromatic ν

Summary

- Establishing or refuting the light sterile neutrino is vital to not only particle physics but also to the understanding of Universe and its evolution in general.
- J-PARC MLF has unique capabilities of providing intense neutrinos with well defined spectrum
- anti-ν_e appearance can be tested with high accuracy with a reaction with well defined cross section
- Neutron background rate is critical to whole program

- NC disappearance could be a direct test of sterile neutrino
- Physics with ~10^{20} Kaon decays