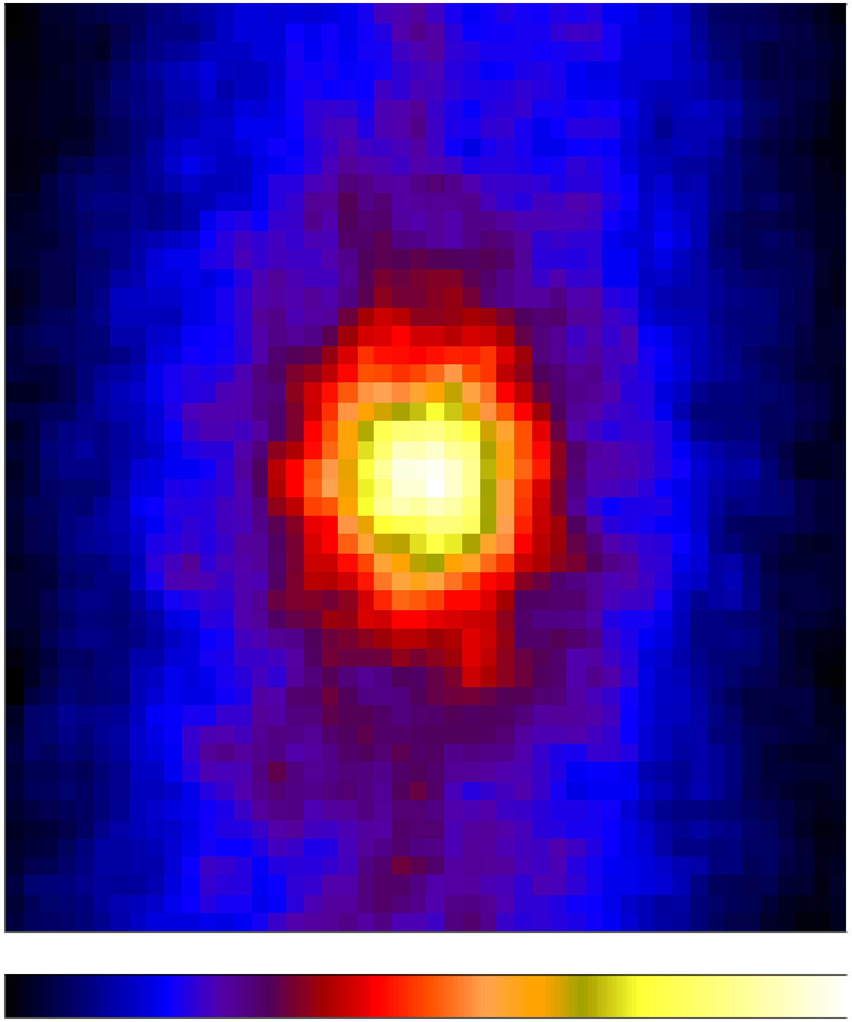
Lecture 3

The neutrino oscillation industry

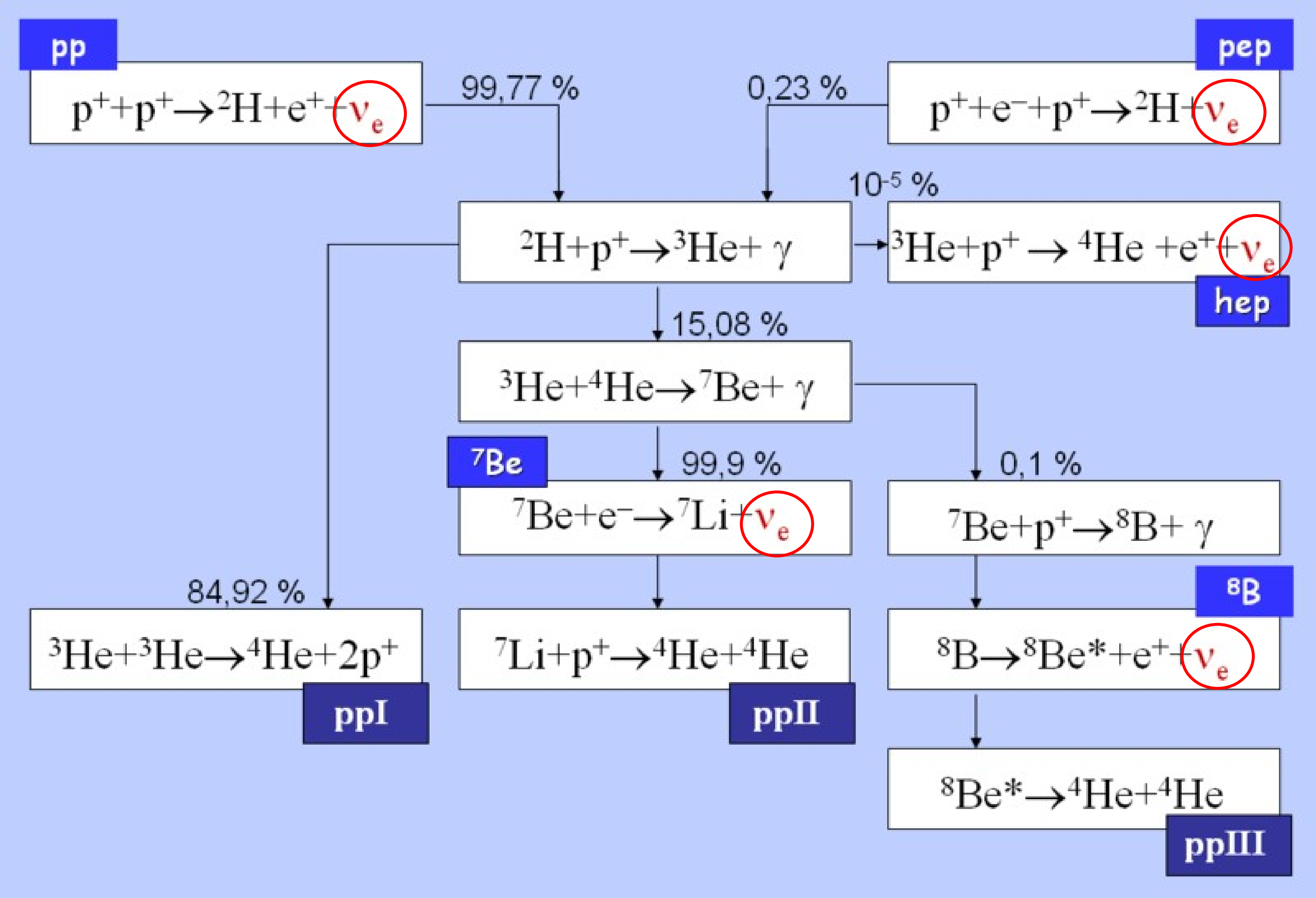
Solar Neutrinos

SuperK : Solar neutrino-gram



- Light from the solar core takes a million years to reach the surface
- Fusion processes generate electron neutrinos which take 2s to leave
- Solar neutrinos are a direct probe of the solar core
- Roughly 4.0×10^{10} solar ν_e per cm^2 per second on earth

Solar neutrino – pp Cycle



pp

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

0,23 %

pep

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

$^2H + p^+ \rightarrow {}^3He + \gamma$

10^{-5} %

$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15,08 %

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

7Be

99,9 %

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

0,1 %

$^7Be + p^+ \rightarrow {}^8B + \gamma$

84,92 %

$^3He + {}^3He \rightarrow {}^4He + 2p^+$

ppI

$^7Li + p^+ \rightarrow {}^4He + {}^4He$

ppII

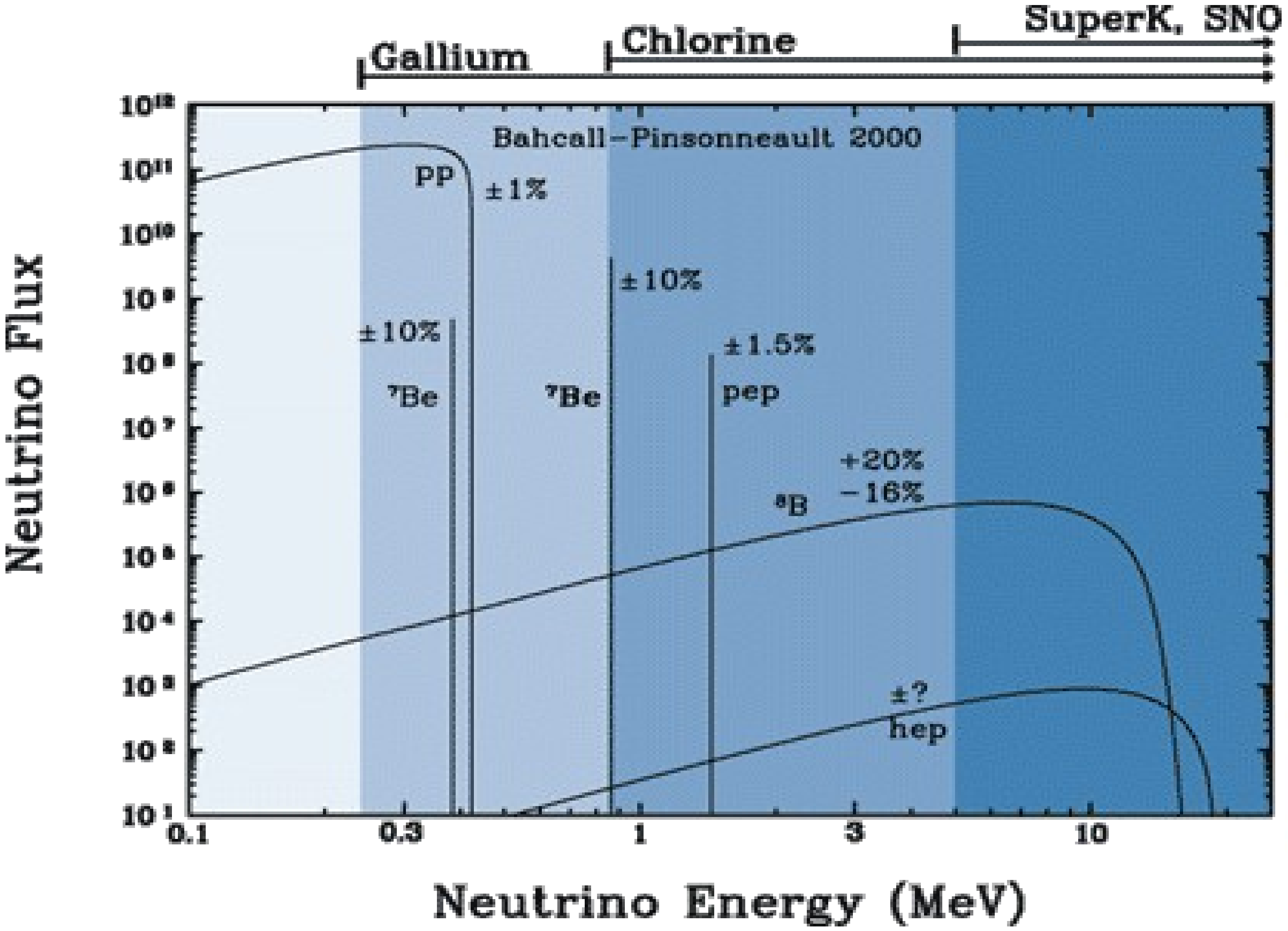
8B

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$^8Be^* \rightarrow {}^4He + {}^4He$

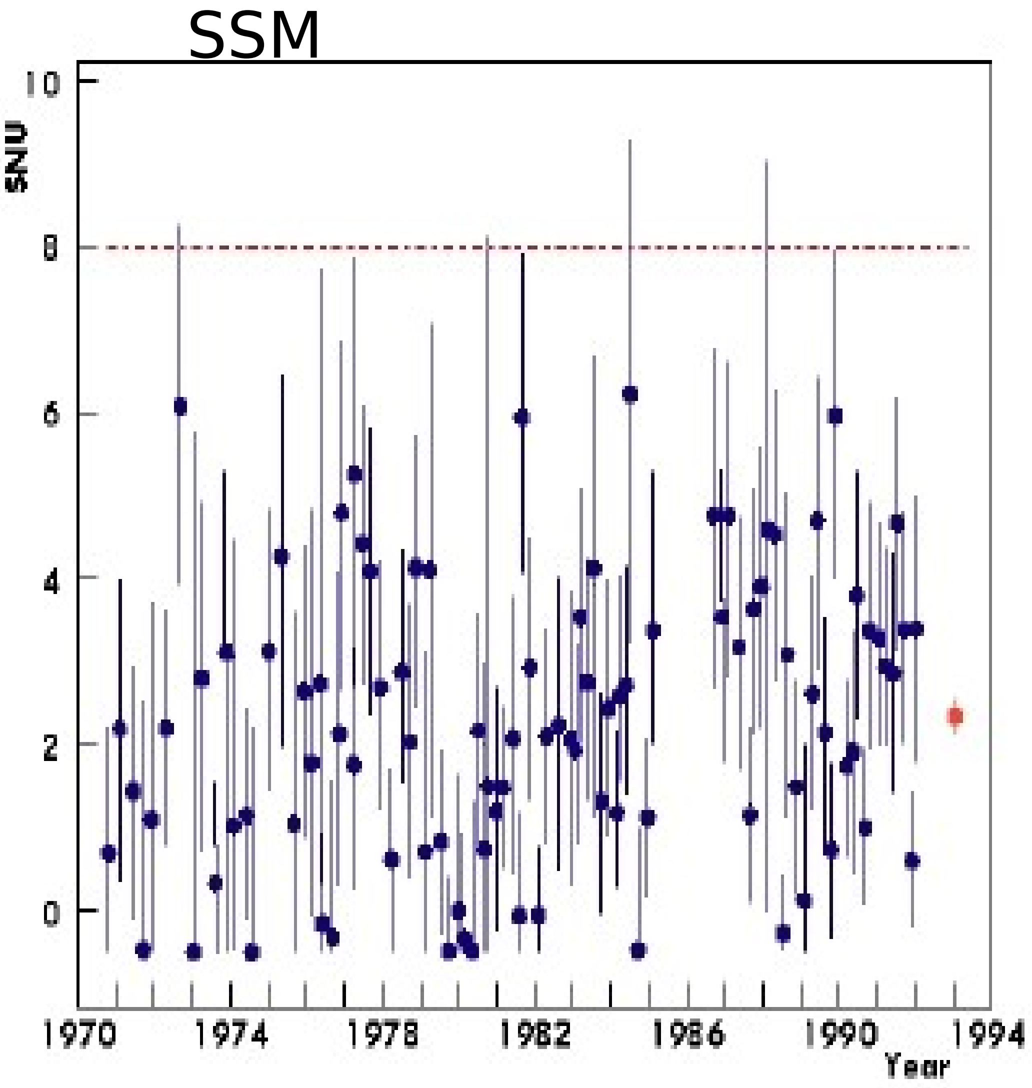
ppIII

Solar Neutrino Flux



As predicted by Bahcall's Solar model

The Solar Neutrino Problem - Homestake



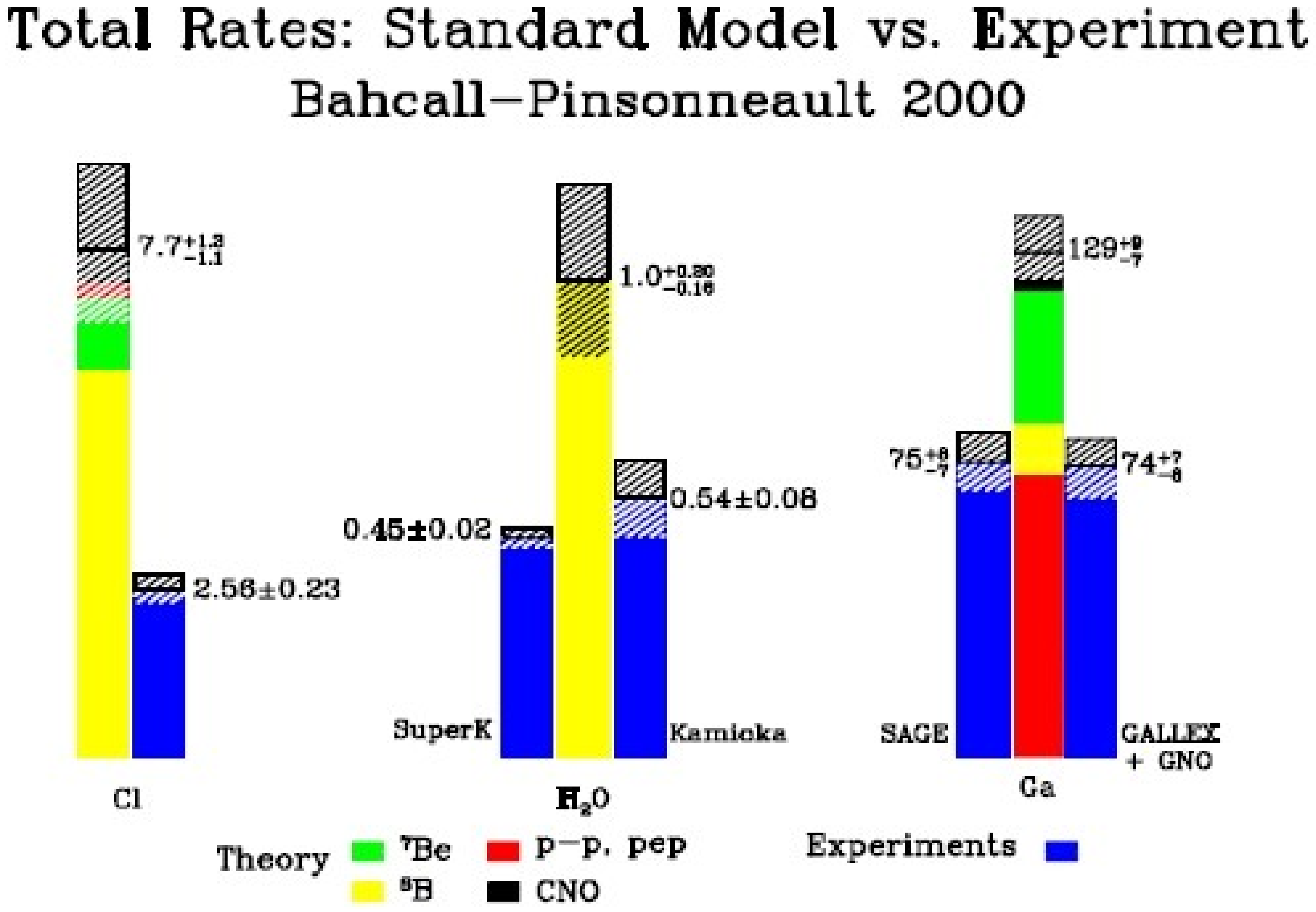
Homestake sensitive to ^{8}B and ^{7}Be *electron neutrinos*

$E_\nu > 800$ keV

Observe 1/3 of the expected number of solar neutrinos

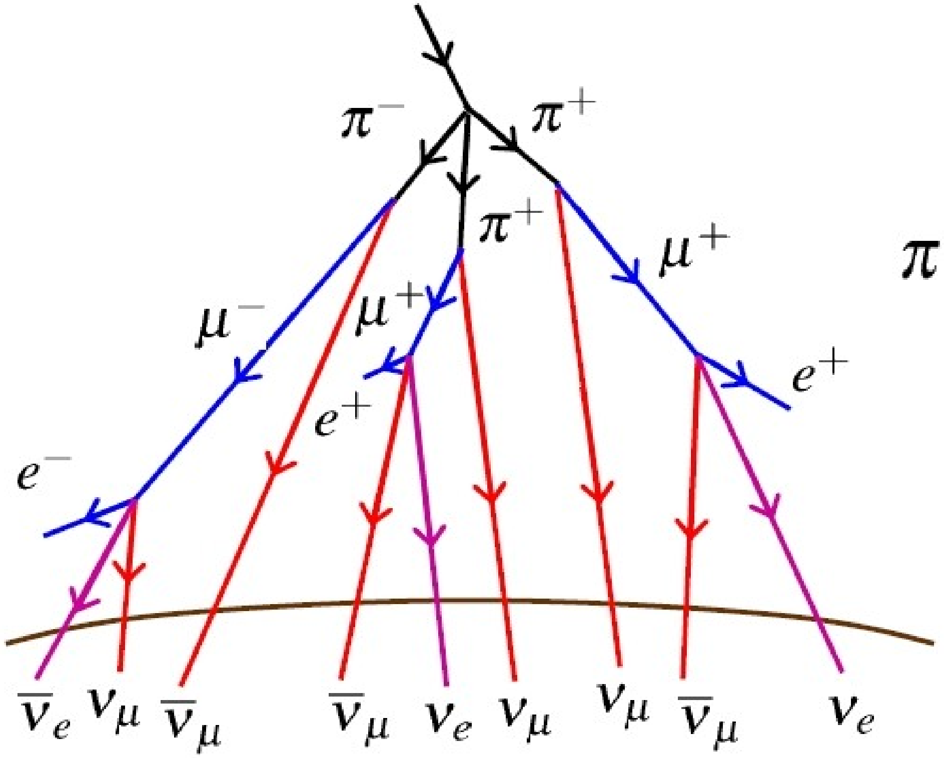
1 SNU = 1 interaction per 10^{36} atoms per second

Experimental summary



Atmospheric neutrinos

High energy cosmic rays interact in the upper atmosphere producing showers of mesons (mostly pions)



Neutrinos produced by

$$\pi^+ \to \mu^+ \nu_\mu \qquad \pi^- \to \mu^- \bar{\nu}_\mu$$

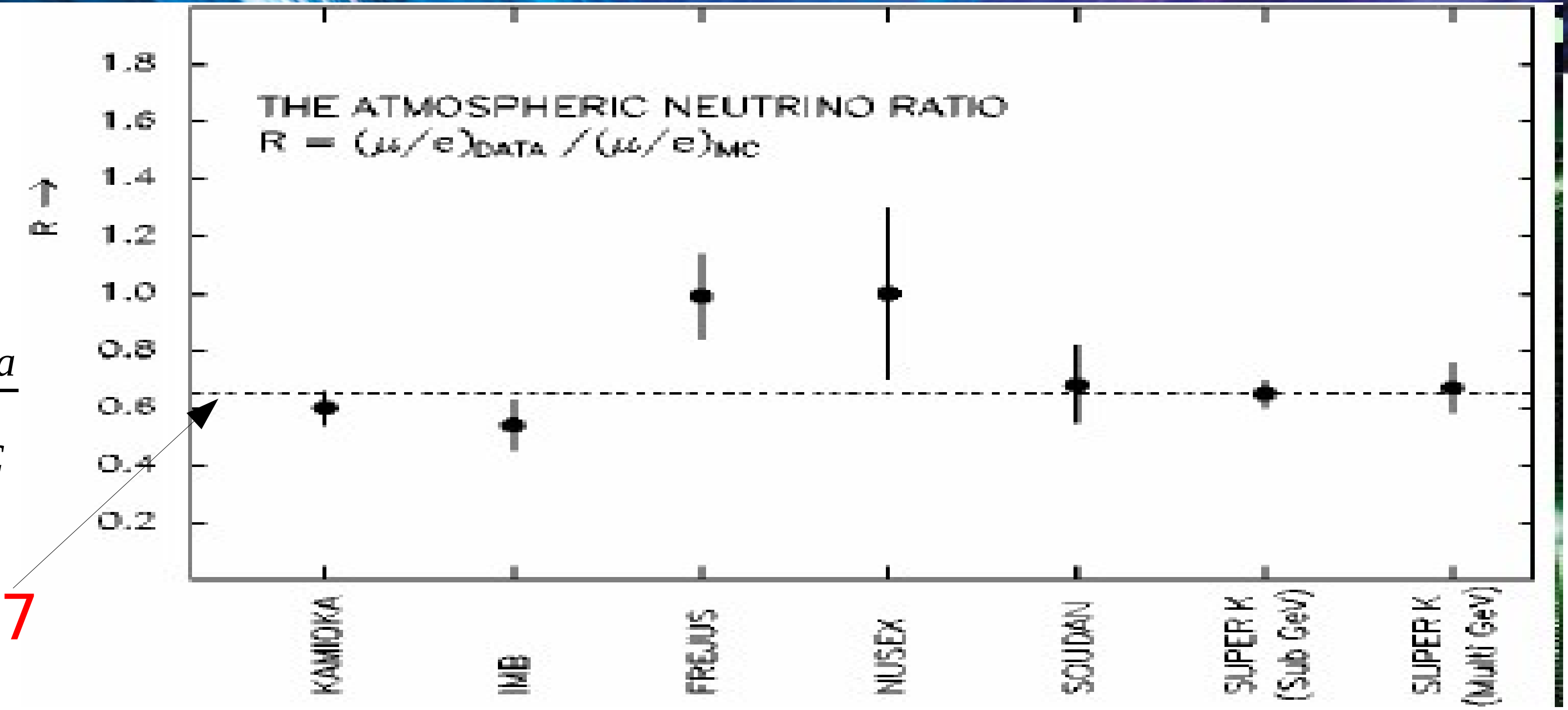
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu \qquad \hookrightarrow e^- \bar{\nu}_e \nu_\mu$$

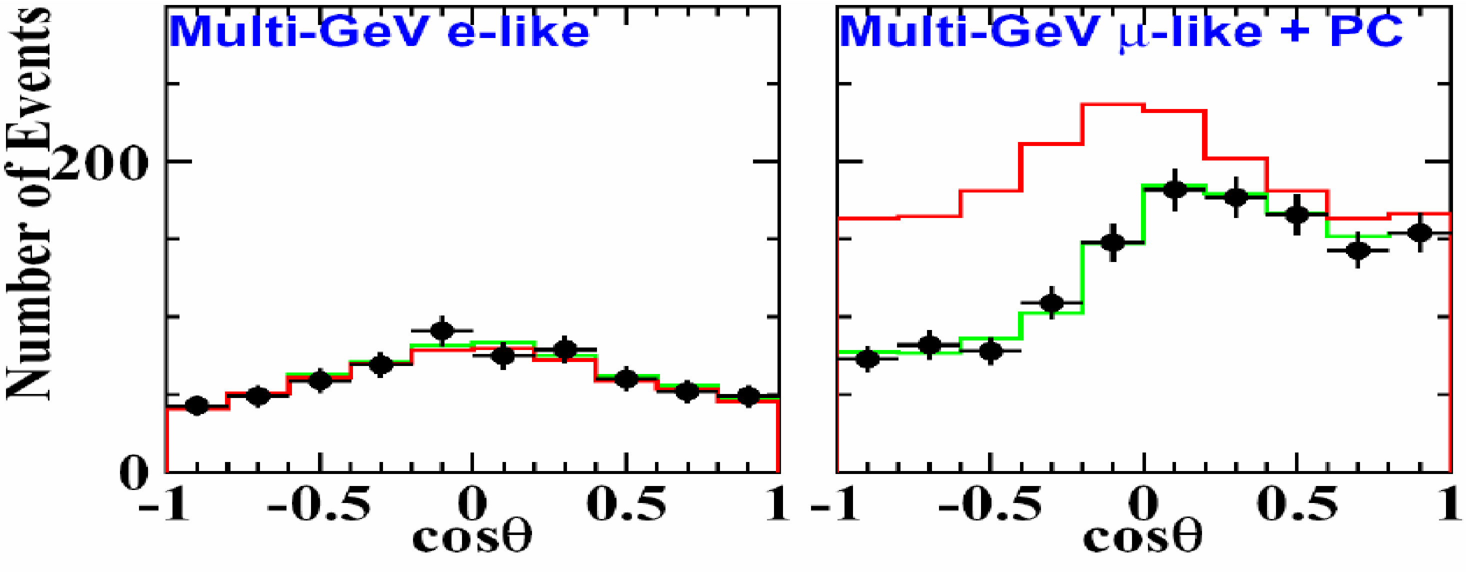
Expect $$\frac{N\left(\nu_\mu + \bar{\nu}_\mu\right)}{N\left(\nu_e + \bar{\nu}_e\right)} \approx 2$$

At higher energies, the muons can reach the ground before decaying so ratio increases

$$R = \frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}$$

R ~ 0.6 - 0.7





The Atmospheric Neutrino Anomaly

Neutrino Flavour Oscillations

Mixing

CKM Mechanism

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

$$d' = d\cos\theta_c + s\sin\theta_c$$

$$s' = -d\sin\theta_c + s\cos\theta_c$$

In the quark sector, the flavour eigenstates (those states which couple to the W/Z) are not identical to the mass eigenstates (those states which are eigenstates of the Hamiltonian)

Weak states →

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.97 & 0.23 & 0.003 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 0.99 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

← Mass states

Mixing

CKM Mechanism

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L , \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

$$d' = d\cos\theta_c + s\sin\theta_c$$

$$s' = -d\sin\theta_c + s\cos\theta_c$$

In the quark sector, the flavour eigenstates (those states which couple to the W/Z) are not identical to the mass eigenstates (those states which are eigenstates of the Hamiltonian)

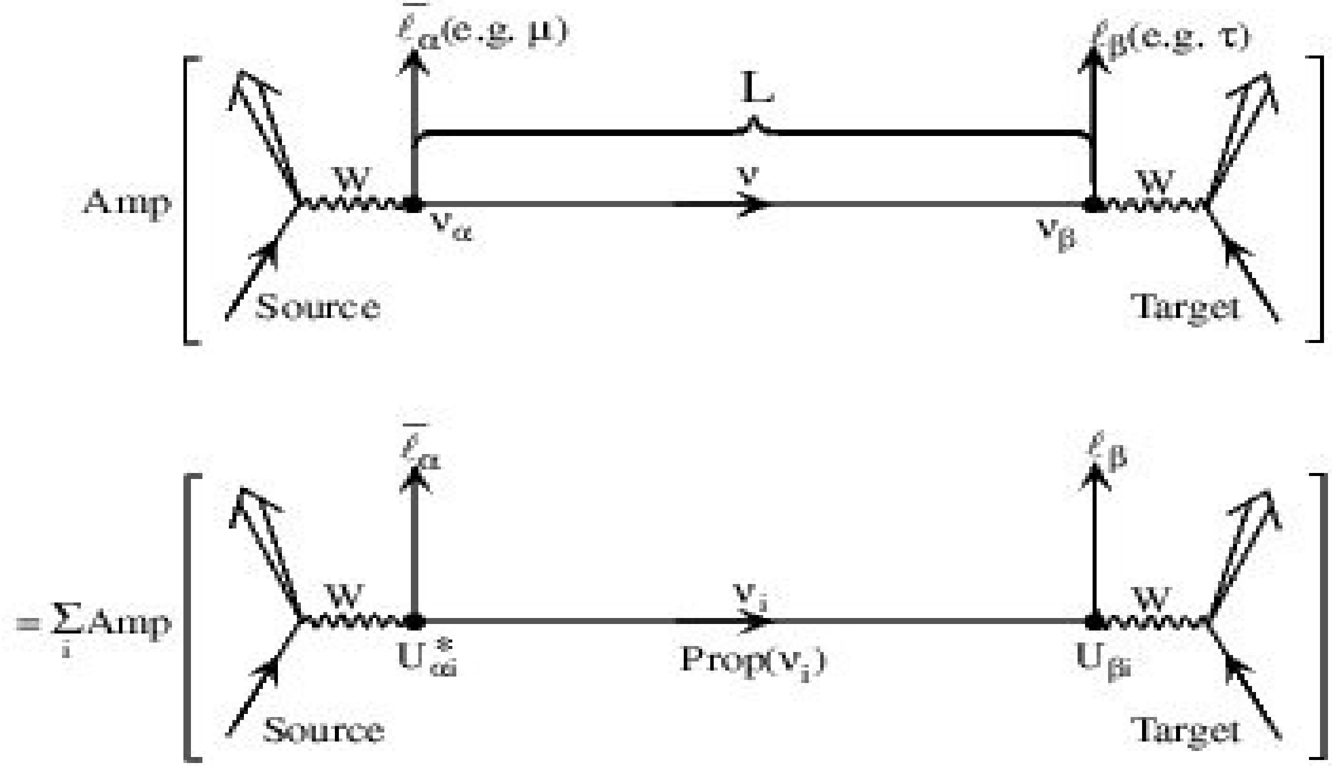
Weak states →

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

← Mass states

Unitary mixing matrix

Neutrino Oscillations



$$Prob(\nu_\alpha \rightarrow \nu_\beta) \propto \left|\sum_i U^*_{\alpha i} \mathrm{Prop}(\nu_i) U_{\beta i}\right|^2$$

If we don’t know which mass state was created then the the amplitude involves a <u>coherent</u> superposition of ν_i states

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

- If $\Delta m_{ij}^2 = 0$ then neutrinos don't oscillate
- Oscillation depends on $|\Delta m^2|$ - absolute masses cannot be determined
- If there is no mixing (If $U_{ai} = 0$) neutrinos don't oscillate
- One can detect flavour change in 2 ways : start with v_α and look for v_β (appearance) or start with v_α and see if any disappears (disappearance)
- Flavour change oscillates with L/E. L and E are chosen by the experimenter to maximise sensitivity to a given Δm^2
- Flavour change doesn't alter total neutrino flux – it just redistributes it amongst different flavours (unitarity)

Two flavour oscillations

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \Rightarrow U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

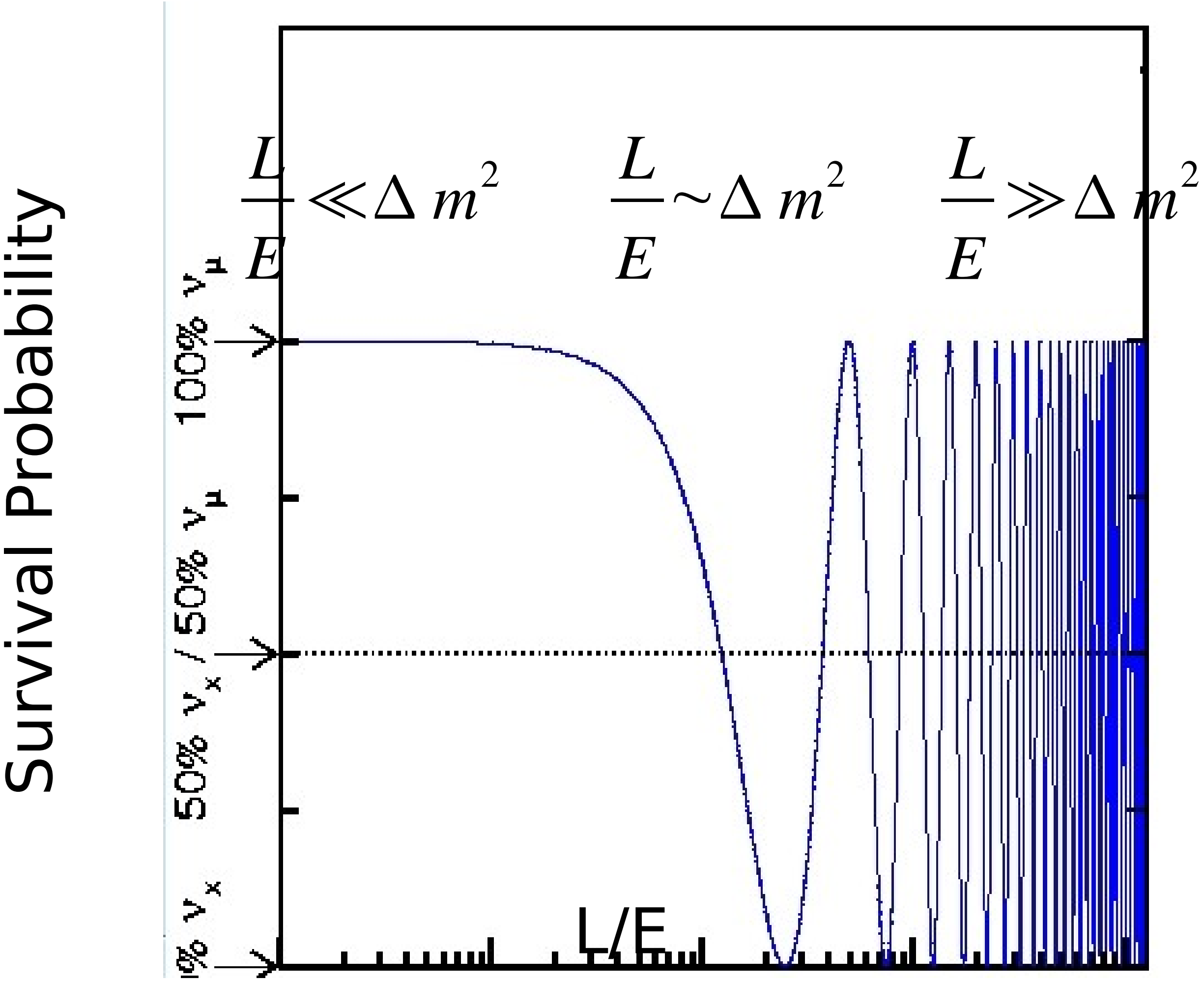
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2(\Delta m_{ij}^2 \frac{L}{4E})$$

$P(\nu_\alpha \to \nu_\beta)$: Appearance Probability
$P(\nu_\alpha \to \nu_\alpha)$: Survival Probability

$$P(\nu_\alpha \to \nu_\beta) = -4(U_{\alpha 1} U_{\beta 1} U_{\alpha 2} U_{\beta 2}) \sin^2(\Delta m_{ij}^2 \frac{L}{4E})$$

$$. = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 (eV^2) \frac{L(km)}{E(GeV)})$$

(changing to useful units)



$\frac{L}{E} \ll \Delta m^2$ $\frac{L}{E} \sim \Delta m^2$ $\frac{L}{E} \gg \Delta m^2$

$$P(\nu_\alpha(0)\rightarrow\nu_\alpha(x))=1-\sin^2(2\theta)\sin^2(1.27\Delta m^2\frac{(L/km)}{(E/GeV)})$$

Question : What would you observe if you were able to know what mass state propagated from source to detector?

Three Flavour Oscillation

The three flavour case is more complicated, but no different

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Leftrightarrow U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

U is the Pontecorvo-Maskawa-Nakayama-Sakata (PMNS) matrix

$$\boxed{\begin{aligned} Prob(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E}) \\ + 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E}) \end{aligned}}$$

Oscillation parameters

$$U=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}=\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha} & 0\\ 0 & 0 & e^{i\beta}\end{pmatrix}$$

2 independent Δm^2

$$Prob(\nu_\alpha \rightarrow \nu_\beta)=\delta_{\alpha\beta}-4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$+2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}\frac{L}{2E})$$

Oscillation parameters

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Three angles

$$Prob(\nu_\alpha \rightarrow \nu_\beta)=\delta_{\alpha\beta}-4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$+2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}\frac{L}{2E})$$

Oscillation parameters

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

CP violating phase

$$Prob(\nu_\alpha \rightarrow \nu_\beta)=\delta_{\alpha\beta}-4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$+2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}\frac{L}{2E})$$

Oscillation parameters

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \boxed{e^{i\alpha}} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Extra Majorana phases

The extra Majorana matrix does not affect flavour oscillation processes.....so is usually dropped. However it will affect the interpretation of neutrinoless double beta decay results

Explaining the solar data

Testing the oscillation hypothesis

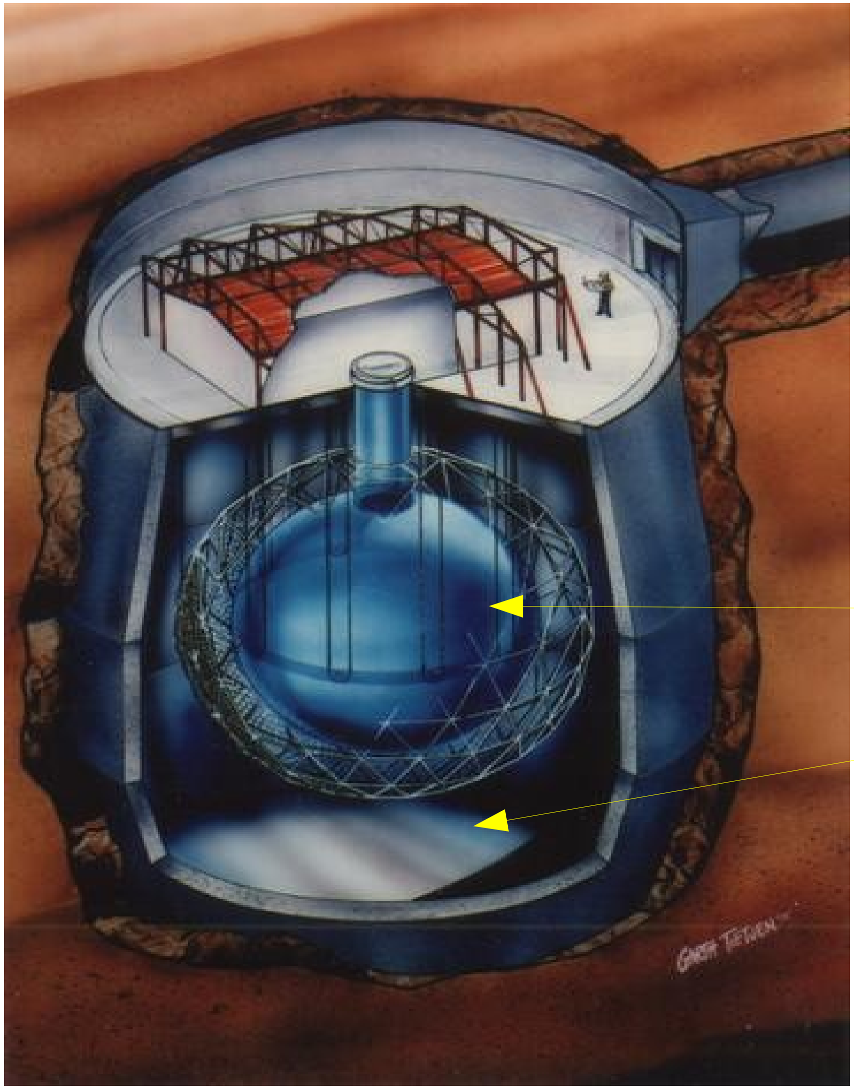
Solar neutrino problem

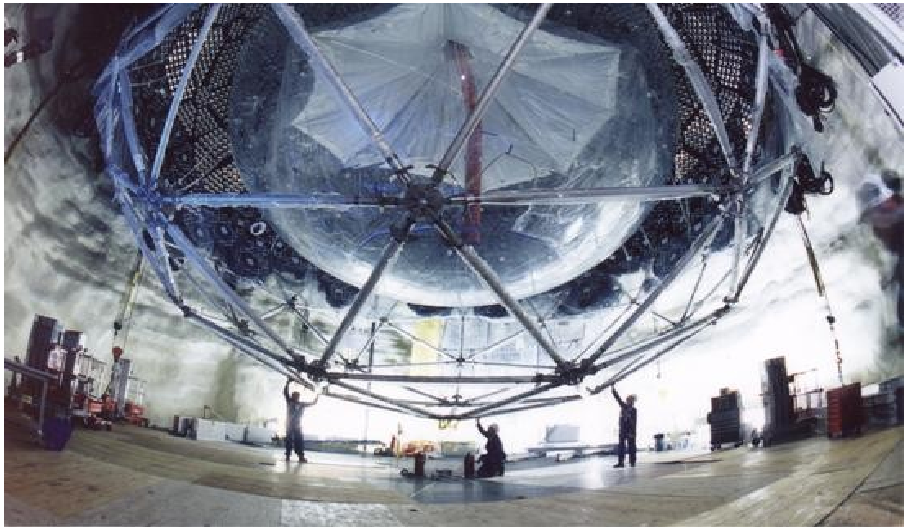
ν_e from sun would change to ν_μ or ν_τ . However these have too little energy to interact via the charged current, and all the detectors are only sensitive to charge current interactions.

Non-ν_e component would effectively disappear, reducing the apparent ν_e flux.

Proof : Neutral current event rate shouldn't change.

Sudbury Neutrino Observatory





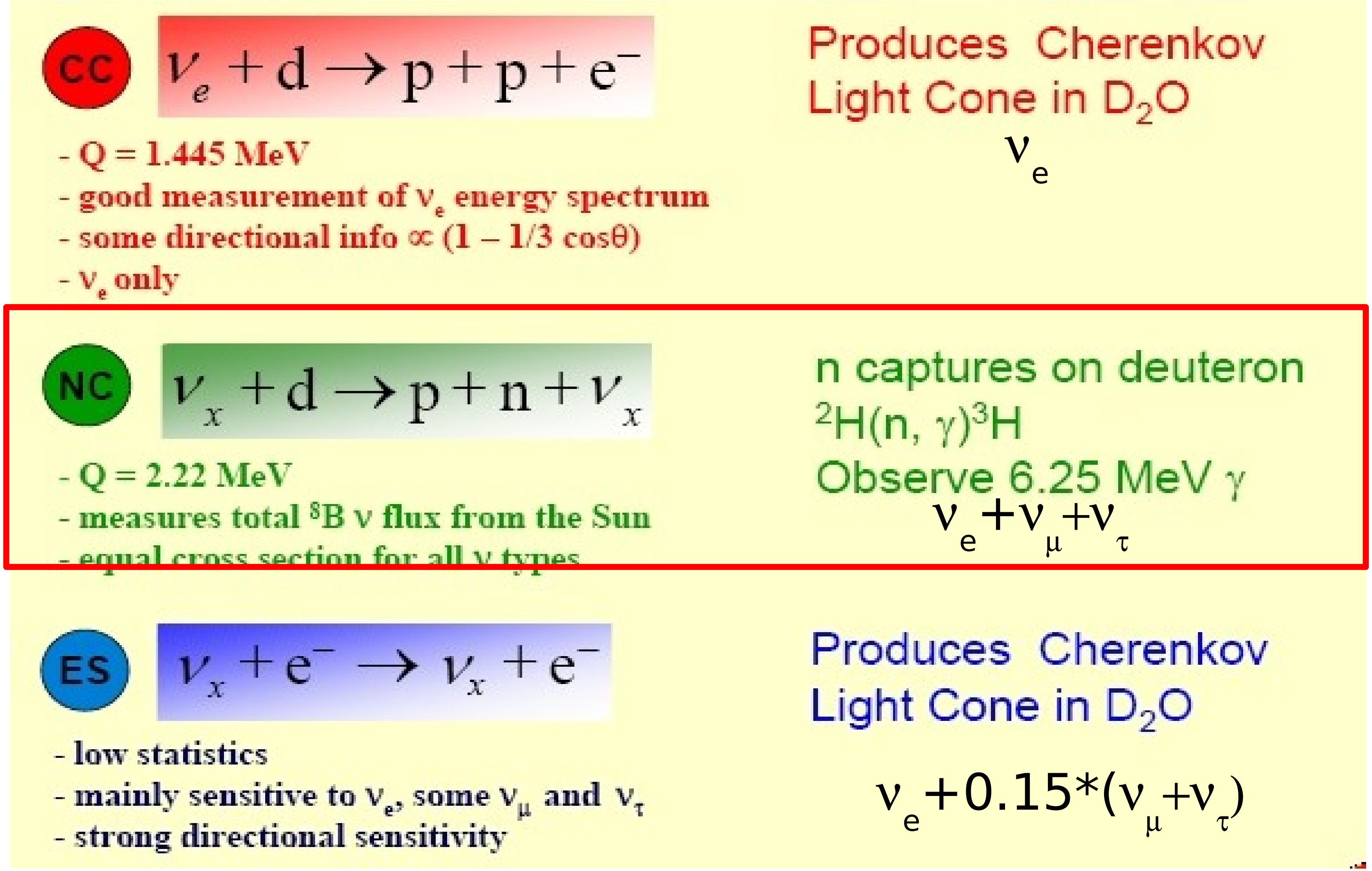
1000 tonnes of D_20

6500 tons of H_20

Viewed by 10,000 PMTS

In a salt mine 2km underground in Sudbury, Canada

SNO



CC $\nu_e + d \rightarrow p + p + e^-$

- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info ∝ (1 – 1/3 cosθ)
- ν_e only

Produces Cherenkov Light Cone in D_2O

ν_e

NC $\nu_x + d \rightarrow p + n + \nu_x$

- Q = 2.22 MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

n captures on deuteron

$^2H(n, \gamma)^3H$

Observe 6.25 MeV γ

$\nu_e + \nu_\mu + \nu_\tau$

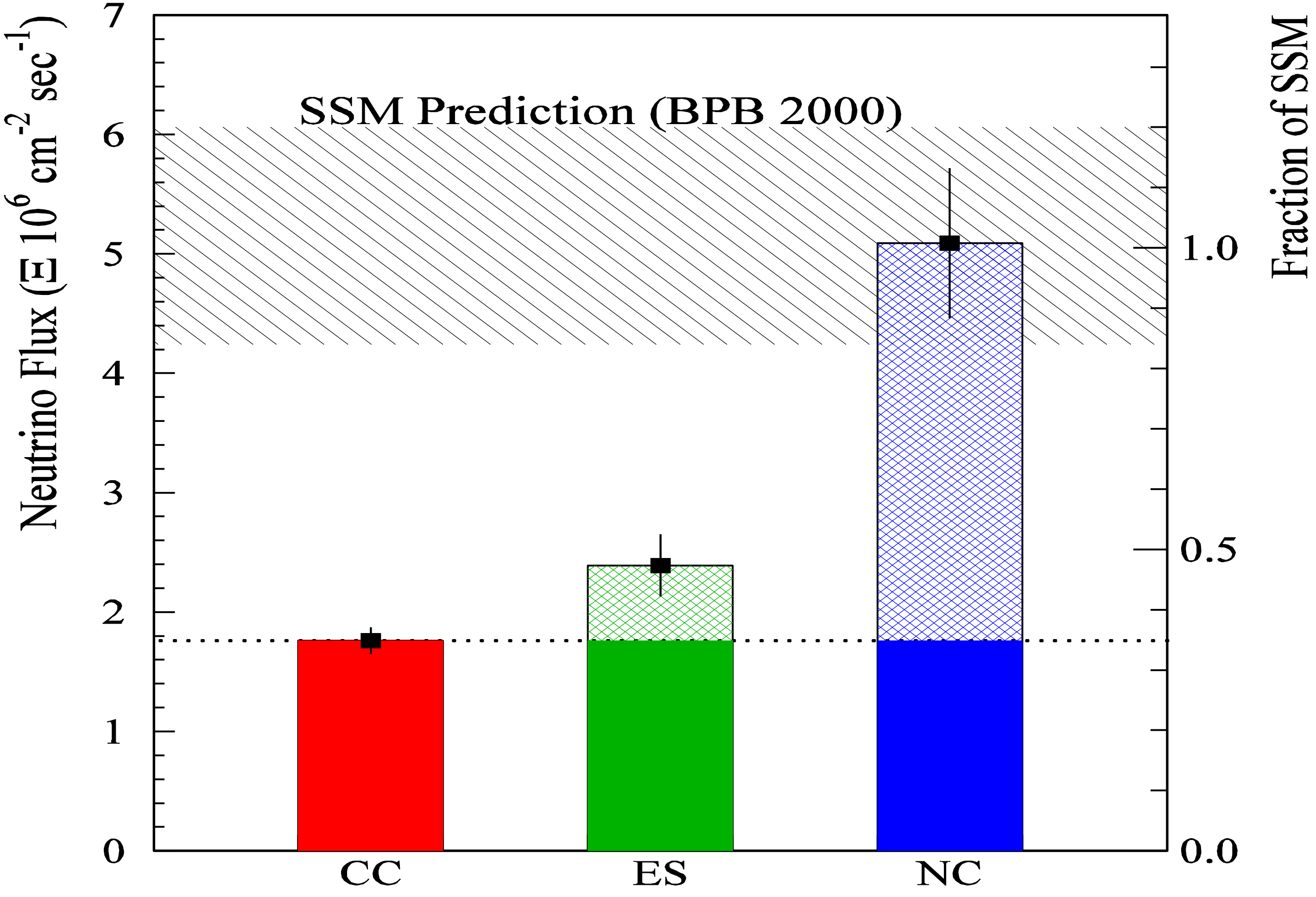
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity

Produces Cherenkov Light Cone in D_2O

$\nu_e + 0.15 * (\nu_\mu + \nu_\tau)$

SNO Results



5.3 σ appearance of $\nu_{\mu\tau}$ in a ν_e beam

Roughly 70% of ν_e oscillates away

Naively…

First instinct is to assume that neutrinos leave the sun as ν_e and oscillate on their way to the earth. Assuming this

$$L \sim 10^8\,km,\ E_\nu < 10\,MeV \rightarrow \Delta m^2 \sim 3\times10^{-10}\,eV^2$$

Naively…

First instinct is to assume that neutrinos leave the sun as ν_e and oscillate on their way to the earth. Assuming this

$$L \sim 10^8\, km\,,\, E_\nu < 10\, MeV \rightarrow \Delta m^2 \sim \boxed{7 \times 10^{-5}\, eV^2}$$

Naively...

First instinct is to assume that neutrinos leave the sun as ν_e and oscillate on their way to the earth. Assuming this

$$L \sim 10^8\, km, E_\nu < 10\, MeV \rightarrow \Delta m^2 \sim \boxed{7 \times 10^{-5}\ eV^2}$$

Oscillations come from phase difference between mass states. In a vacuum the phase diff comes from free particle Hamiltonian. In a material there are interaction potentials as well

$$-i\hbar \frac{\partial \psi}{\partial t} = \boxed{E\psi} = \frac{-\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} \rightarrow -i\hbar\frac{\partial\psi}{\partial t} = \boxed{(E+V)}\psi = \frac{-\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2}$$

$$E^2 - p^2 = m_{vac}^2 \rightarrow (E+V)^2 - p^2 = m_{mat}^2 \rightarrow \boxed{m_{mat} \approx \sqrt{m_{vac}^2 + 2EV}}$$

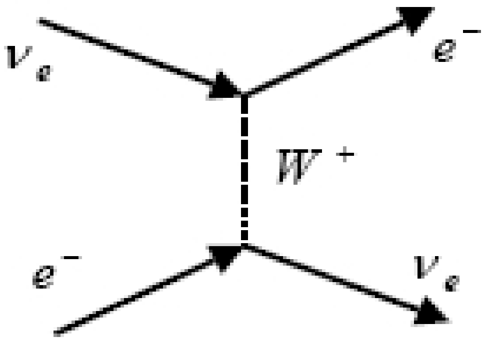
c.f. effective mass of an electron in a semiconductor or light in glass

Oscillations in Matter

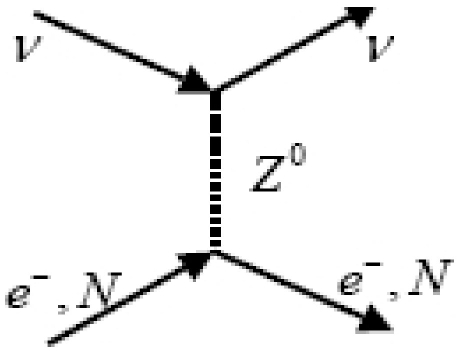
Electrons exist in standard matter – μ/τ do not. Electron neutrinos travelling in matter can experience an extra charged current interaction that other flavours cannot.

$$V_W = \sqrt{2}\, G_F N_e$$

Interaction Potential



ν_e



ν_e, ν_μ, ν_τ

$$V_Z = -\frac{\sqrt{2}}{2} G_F N_n$$

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_M)\sin^2\left(\frac{\Delta m_M^2 L}{4E}\right)$$

Oscillation probability modified by matter effects

$$\boxed{\begin{aligned} \Delta m_M^2 &= \Delta m_V^2 \sqrt{\sin^2(2\theta) + (\cos 2\theta - \zeta)^2} \\ \sin^2 2\theta_M &= \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \zeta)^2} \end{aligned}}$$

$$\zeta = \frac{2\sqrt{2}\, G_F N_e E}{\Delta m_V^2}$$

Implications

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \zeta)^2} \qquad \zeta = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{Vac}}$$

- If $\Delta m^2_{\mathrm{Vac}}$ = 0 or matter is very dense, ζ = ∞ and θ_{m} = 0
- Similarly, if θ_{vac}=0, then θ_{M} = 0 ⇒ need mixing in vacuum
- If there is no matter, then ζ = 0 and we have vacuum mixing
- At a particular electron density, dependent on Δm^2,

$$\zeta = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2} = \cos 2\theta \;\Rightarrow\; \sin^2 2\theta_M = 1$$

Even if the vacuum mixing angle is tiny, there is a density for which the matter mixing angle is maximal

Mass heirarchy

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \zeta)^2} \qquad \zeta = \frac{2\sqrt{2} G_F N_e E}{\Delta m_V^2}$$

If mass of v_1 **<** mass of v_2, $\Delta m_V^2 = m_1^2 - m_2^2 < 0$

$$\zeta = -\frac{2\sqrt{2} G_F N_e E}{|\Delta m^2|} \rightarrow \sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta + |\zeta|)^2}$$

Positive definite – no resonance

If mass of v_1 > mass of v_2, $\Delta m^2 = m_1^2 - m_2^2 > 0$

$$\zeta = \frac{2\sqrt{2} G_F N_e E}{|\Delta m^2|} \rightarrow \sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - |\zeta|)^2}$$

Mass heirarchy

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \zeta)^2} \qquad \zeta = \pm \frac{2\sqrt{2} G_F N_e E}{|\Delta m_V^2|}$$

The effect of matter on neutrino oscillations can be used to measure the mass hierarchy.

This is about the only way we know how to do this.

Mixing matrix

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\boxed{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar sector

$$\theta_{e\mu}=32.5^{\circ}\pm 2.4^{\circ}$$

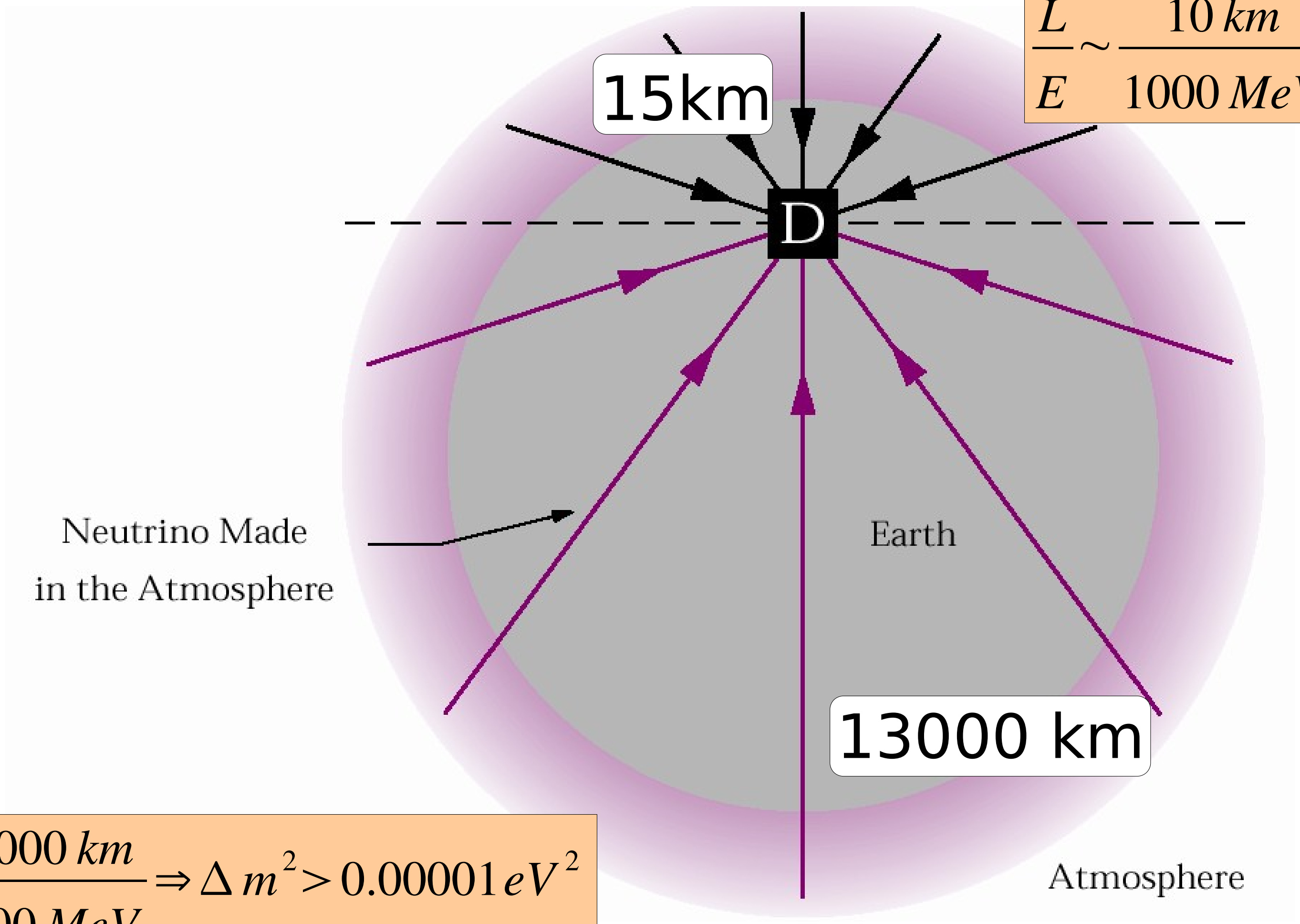
$$\Delta m_{12}^{2}=+7.9\times 10^{-5}\,eV^{2}$$

Explaining the atmospheric data

Cosmic Labs

$\cos\theta_{zenith} = 1.0$

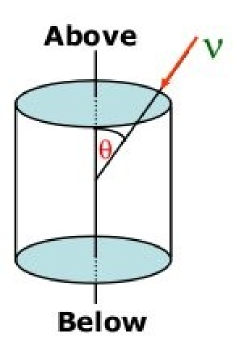
$$\frac{L}{E} \sim \frac{10\,km}{1000\,MeV} \Rightarrow \Delta m^2 > 0.01\,eV^2$$

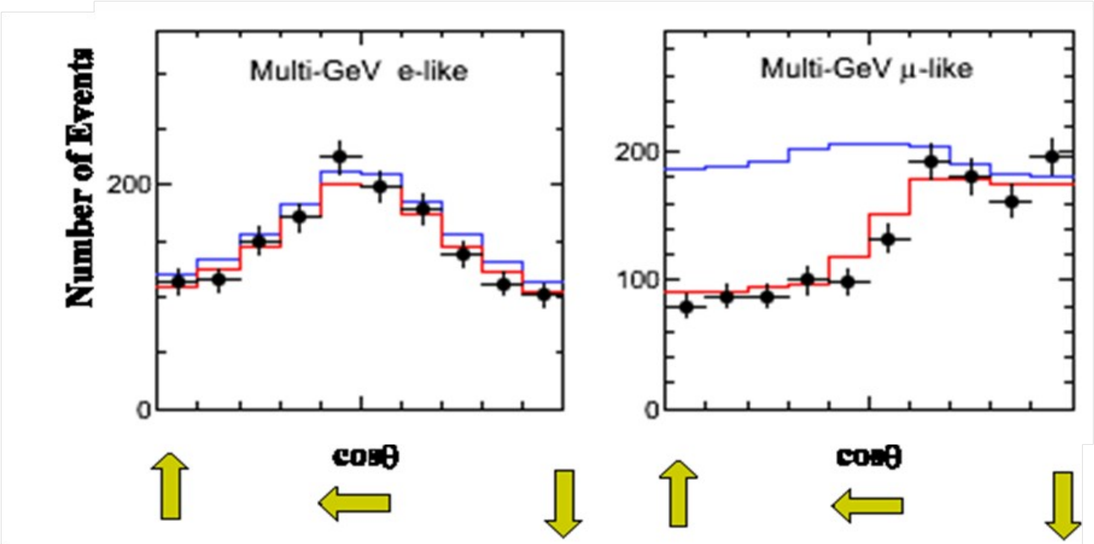


$$\frac{L}{E} \sim \frac{10000\,km}{1000\,MeV} \Rightarrow \Delta m^2 > 0.00001\,eV^2$$

$\cos\theta_{zenith} = -1.0$

Atmospheric results

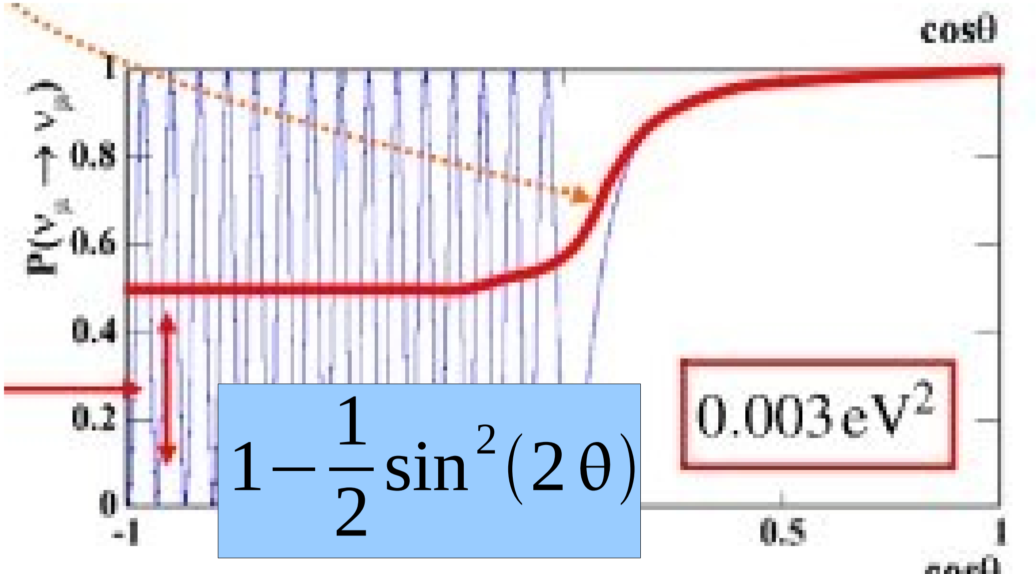




- Prediction for ν_e rate agrees with data.
- ν_μ disappear at large baseline consistent with $\nu_\mu \rightarrow \nu_\tau$
- Don't detect ν_τ as

-below τ mass threshold

-SuperK is awful at τ detection



$$1-\frac{1}{2}\sin^2(2\theta)$$

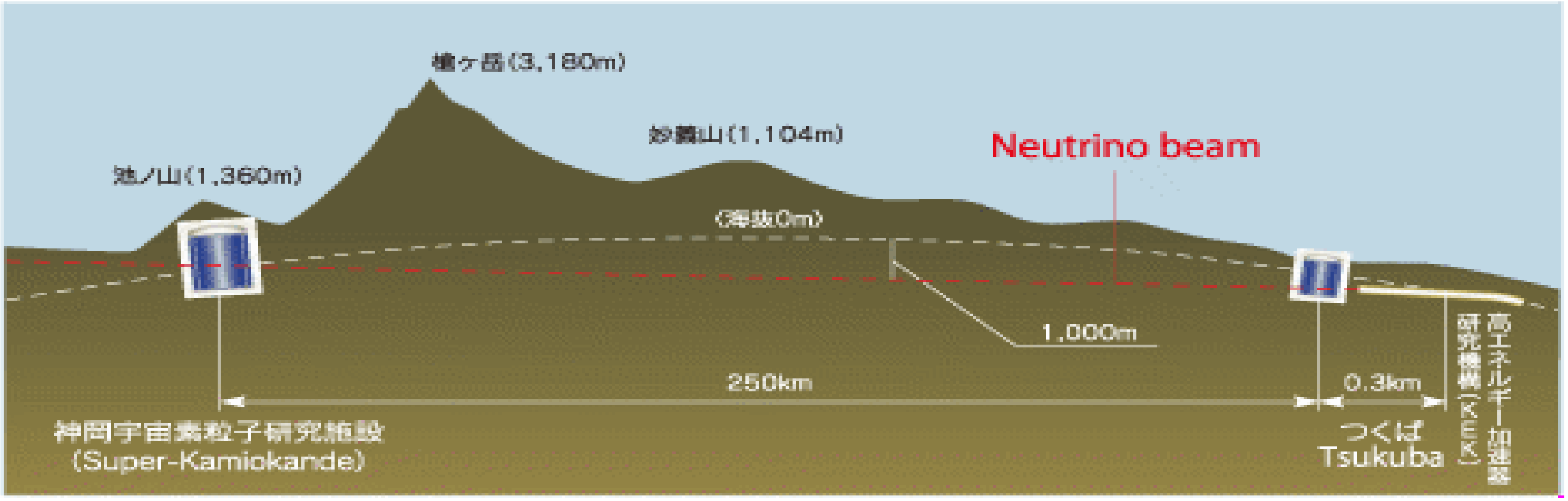
$$\left|\Delta m^2_{atmos}\right| \approx 0.0025\, eV^2$$

$$\sin^2(2\theta_{atmos}) \approx 1.0$$

Accelerator Cross-check

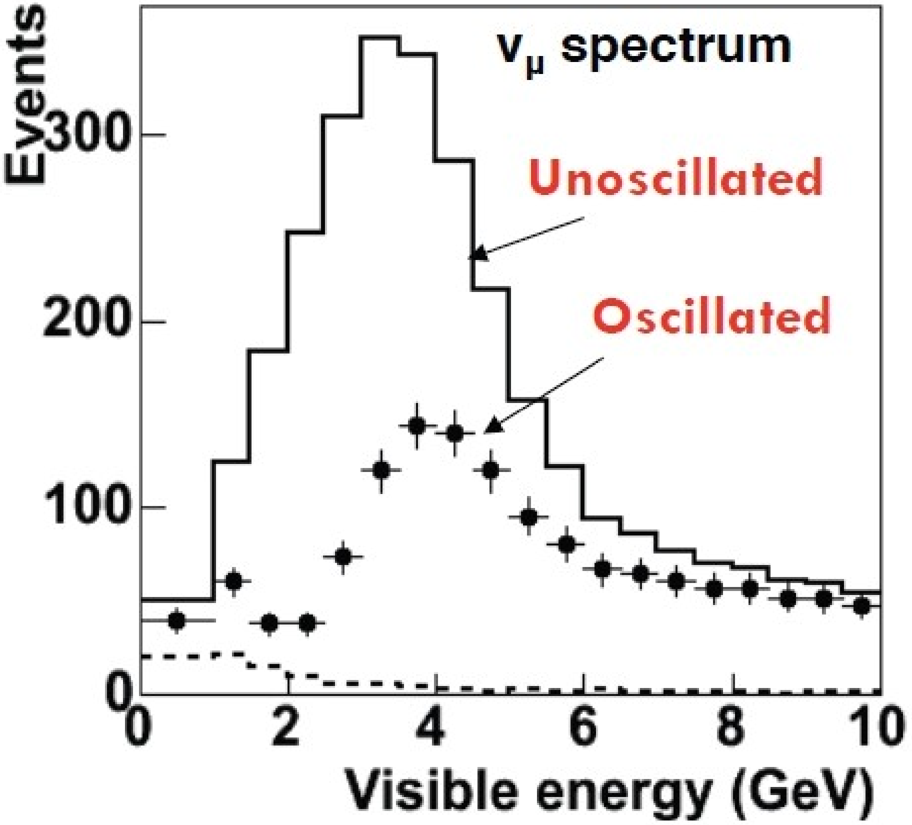
$$\Delta m^2_{atmos} \approx 3 \times 10^{-3}\, eV^2 \rightarrow L/E \approx 400\, km\, GeV^{-1}$$

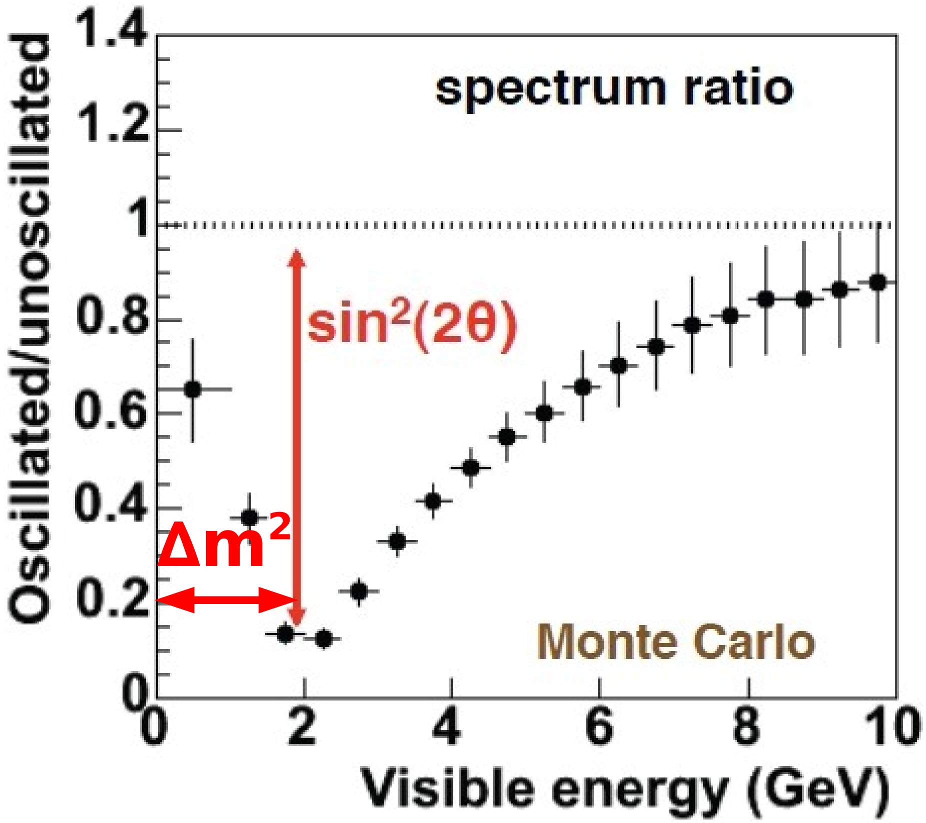
$$L = 250\, km \rightarrow E_\nu \approx 0.6\, GeV$$



Beam events tagged using GPS at both near and far detector sites

Disappearance Experiments





$$P(\nu_\alpha \rightarrow \nu_\alpha) \rightarrow \frac{\Phi_\nu(@FD)}{\Phi_\nu(@ND)}$$

Φ_ν : Neutrino Flux

Use Near Detector to measure Φ_ν(@ND)

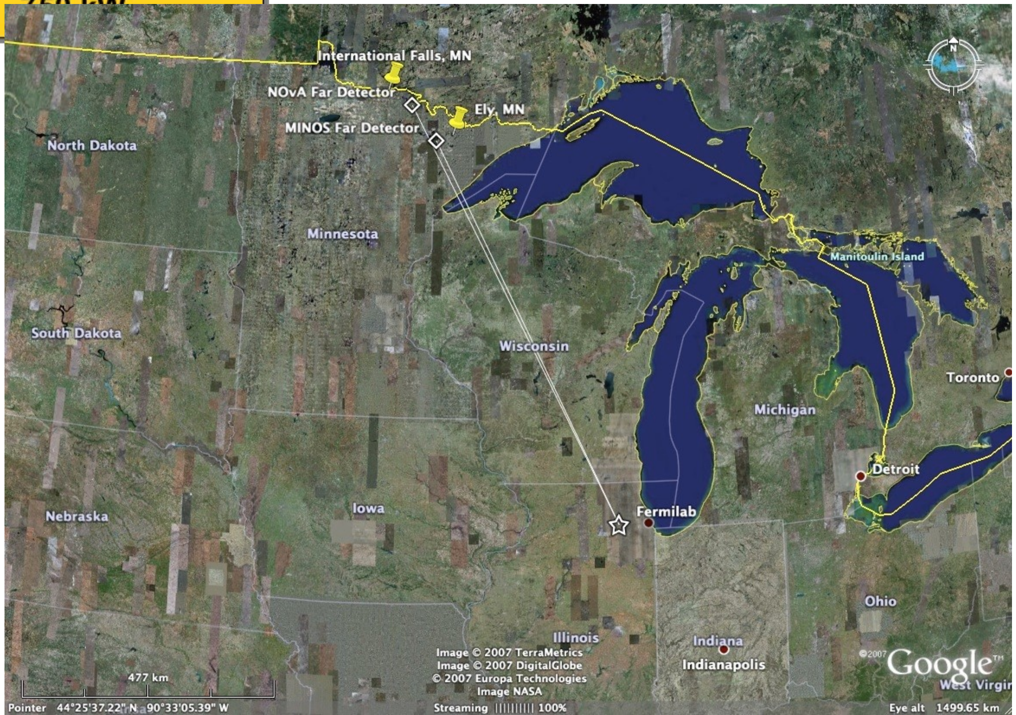
T2K and NOVA

Super-Kamiokande 22.5 kton (fiducial) water cherenkov detector at 295 km

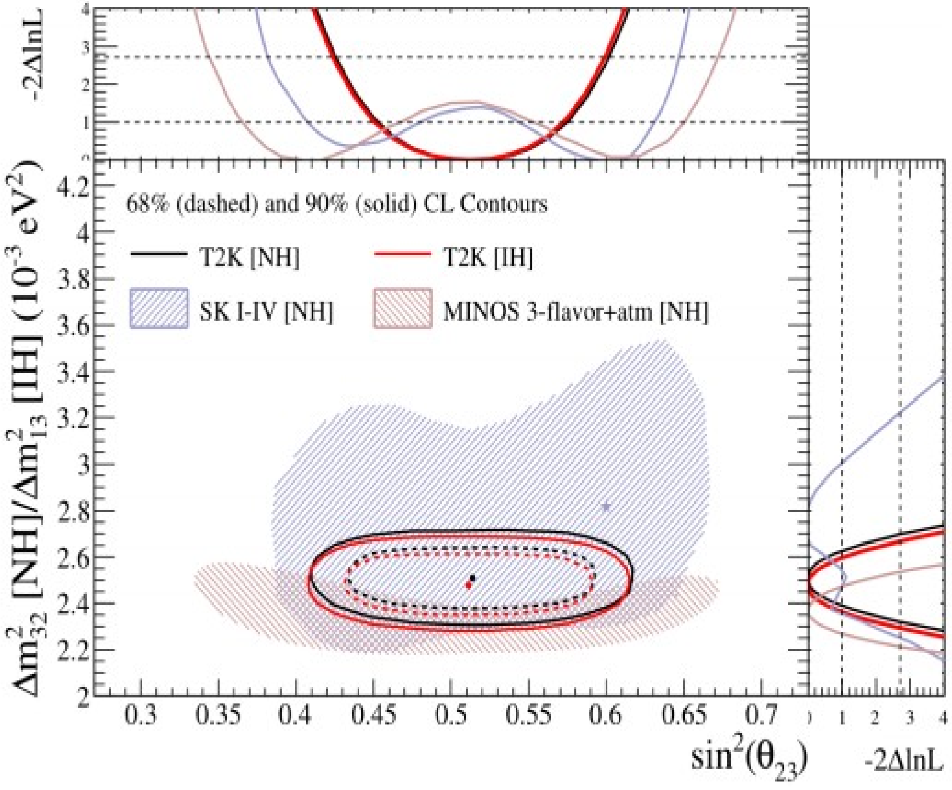
J-PARC: 30 GeV proton beam, design power of

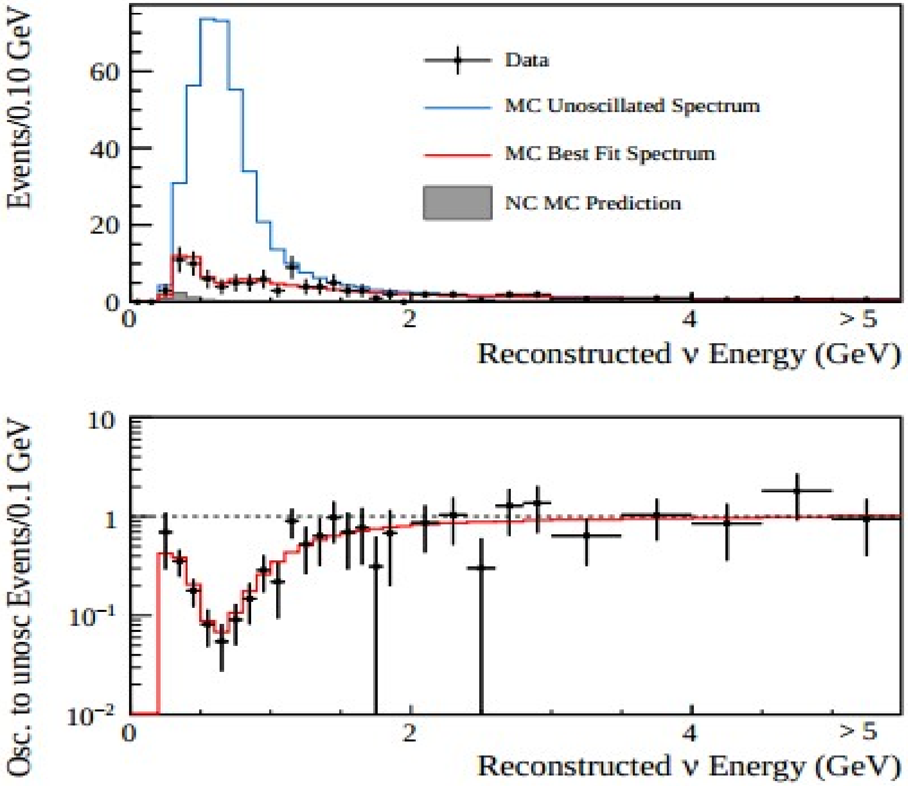
- JPARC to Kamioka
- L = 295 km
- E_ν ~ 0.6 GeV
- Far Det : 22.6 kton water Cerenkov detector

- Fermilab to Ash River, MN
- L = 810 km
- E_ν ~ 2.0 GeV
- Far Det : 14 kton of liquid scintillator (in bars)



T2K Disappearance





$$\frac{\#\,events\,observed}{\#\,events\,expected}=P(\nu_\mu \rightarrow \nu_\mu)=1-\sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\left|\Delta m^2_{23}\right|=(2.51\pm 0.1)\times 10^{-3}\,eV^2$$

$$\sin^2(\theta_{23})=0.514^{+0.055}_{-0.056}\rightarrow \theta_{23}=45.8\pm 3.2$$

(best fit)

Mixing matrix

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \boxed{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}$$

Solar sector : $\nu_\mu \rightarrow \nu_e$

$$\theta_{e\mu} = 33.7^\circ \pm 1.1^\circ$$

$$\Delta m_{12}^2 = +(7.54 \pm 0.24) \times 10^{-5}\, eV^2$$

Atmospheric sector

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

$$\theta_{\mu\tau} = 42^\circ \pm 3.0^\circ$$

$$\Delta m_{23}^2 = \left|(2.43 \pm 0.06) \times 10^{-3}\right| eV^2$$

How do we measure θ_{13}?

$\nu_\mu \rightarrow \nu_e$ oscillations with atmospheric L/E

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(1.27\Delta m^2_{23}\frac{L}{E})$$

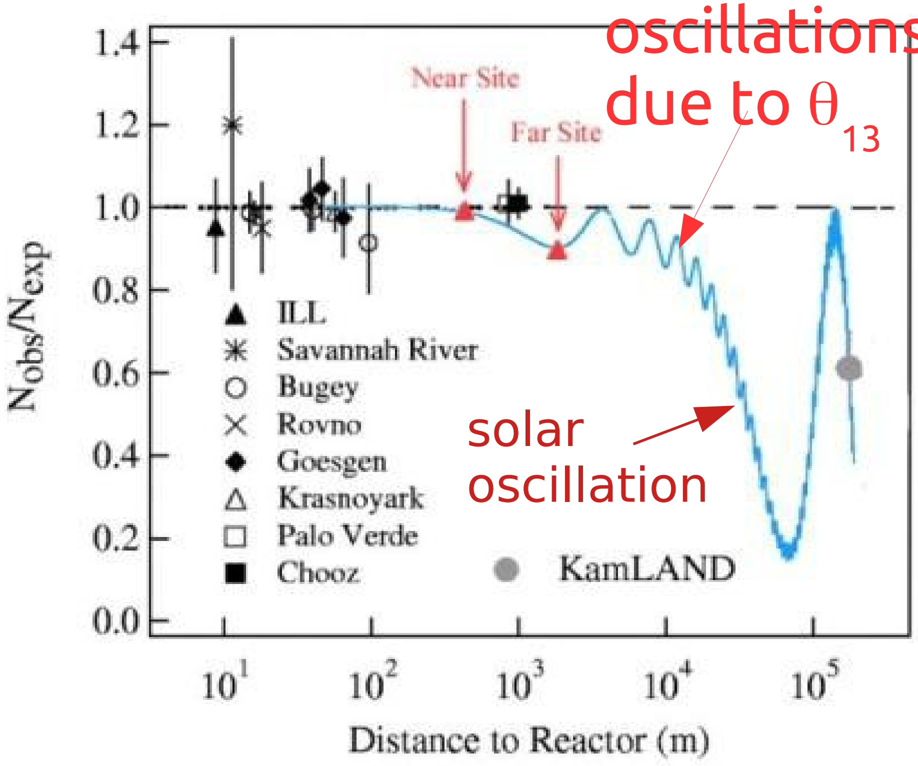
ν_e appearance in a ν_μ beam – ideal for *accelerator experiments*

$\overline{\nu}_e \rightarrow \overline{\nu}_x$ disappearance oscillations with atmospheric L/E

$$p(\overline{\nu}_e \rightarrow \overline{\nu}_x) 1 - \sin^2(2\theta_{13}) \sin^2(1.27\Delta m^2_{23}\frac{L}{E})$$

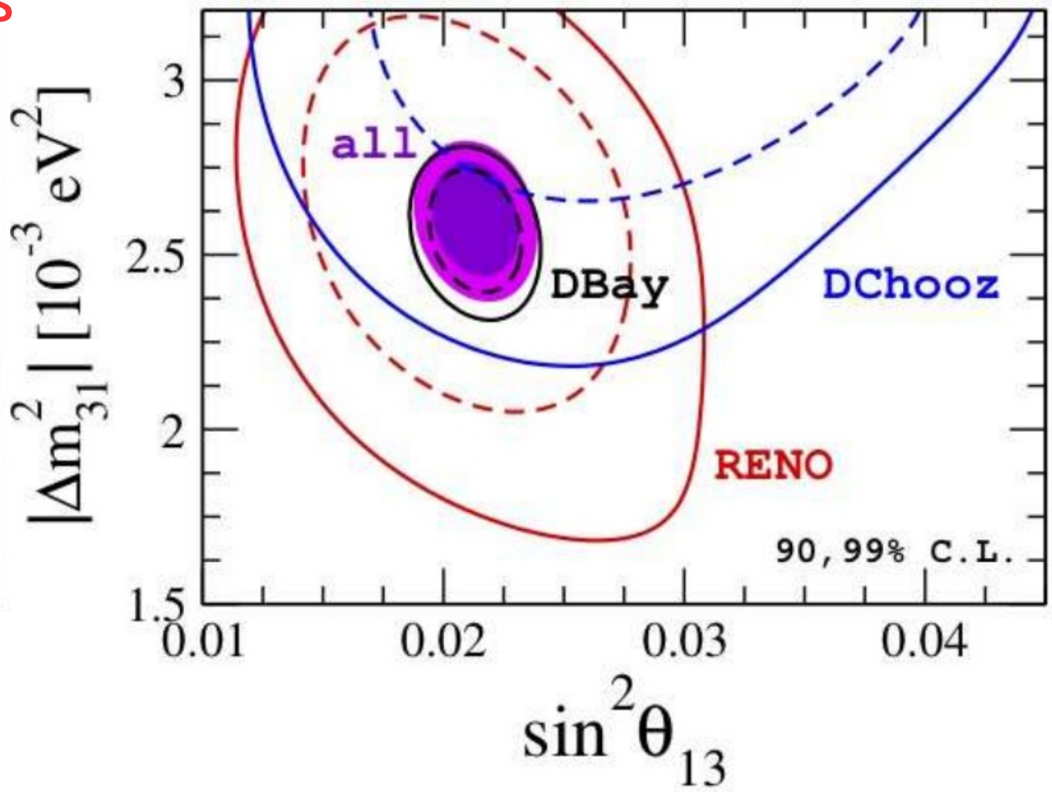
$\overline{\nu}_e$ disappearance – ideal for *reactor experiments*

θ_{13} from reactors



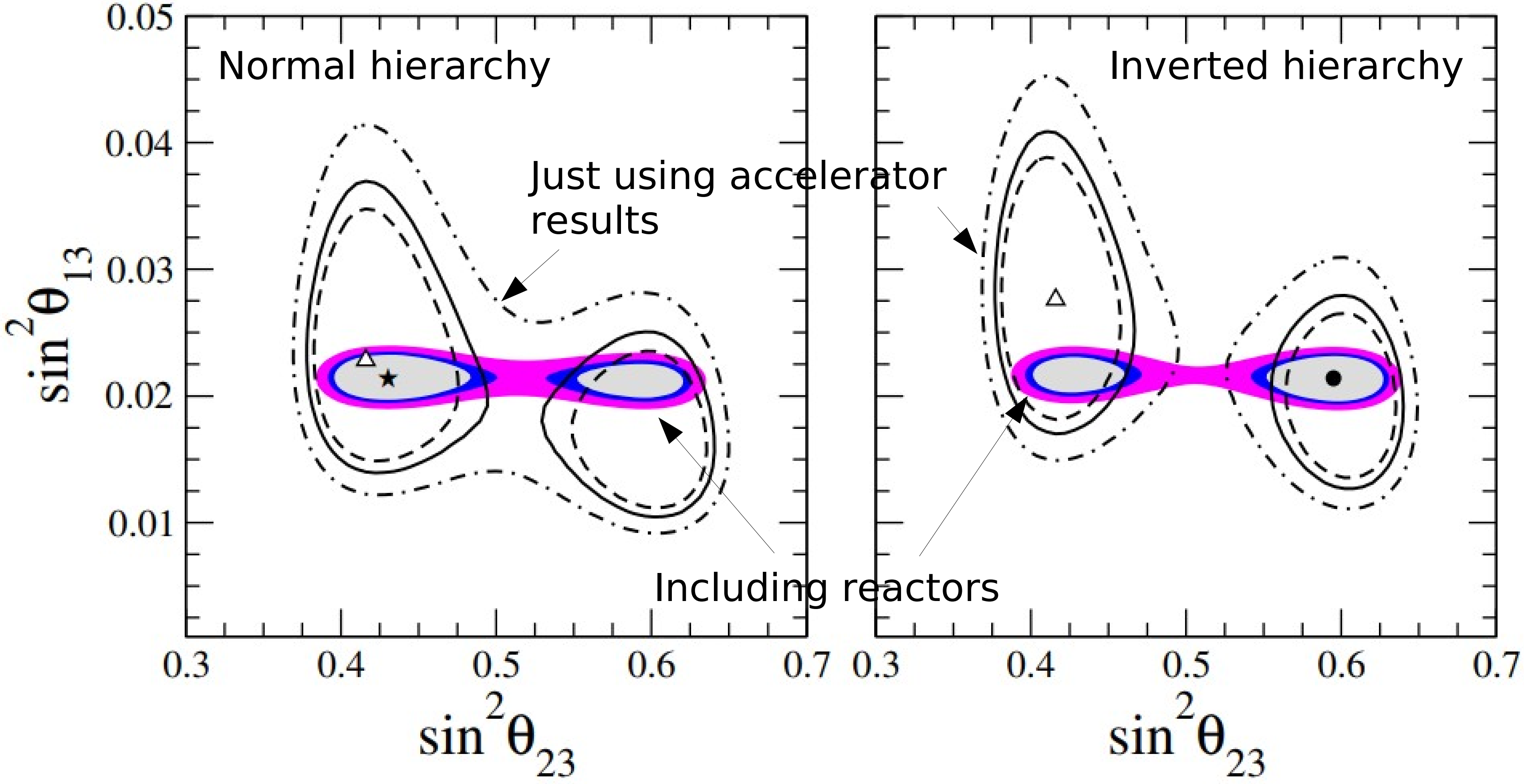
subleading oscillations due to θ_{13}

solar oscillation



$$\boxed{\theta_{13} = (8.44(41) \pm 0.16)^\circ \,(\mathrm{NO(IO)})}$$

Global results



Normal hierarchy

Inverted hierarchy

Just using accelerator results

Including reactors

3-Neutrino Mixing

$$U=\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar sector

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

$$\theta_{12}=34.5^{\circ}\pm 1.1^{\circ}$$

$$\Delta m_{12}^2=+7.56\times 10^{-5}\,eV^2$$

13 Sector

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

$$\theta_{13}=8.44^{\circ}\pm 0.16^{\circ}$$

$$\Delta m_{23}^2=\left|2.52\times 10^{-3}\right|eV^2$$

Atmospheric sector

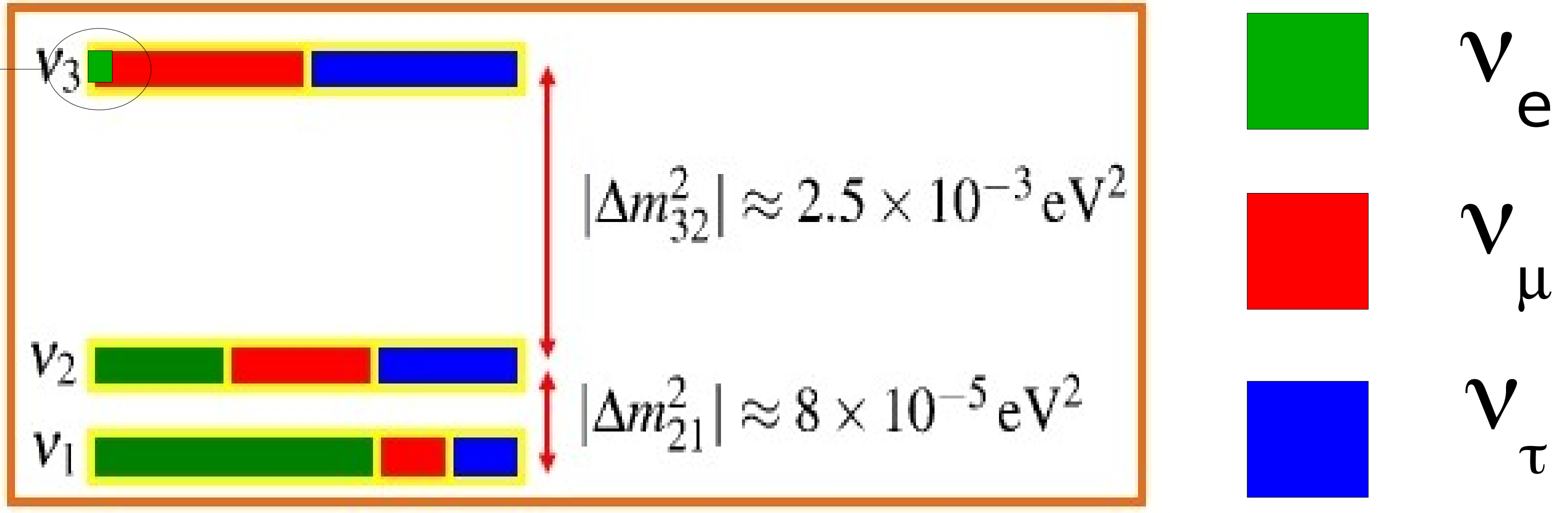
$$\nu_\mu \rightarrow \nu_\tau$$

$$\theta_{23}=41.0(50.5)^{\circ}\pm 1.1^{\circ}$$

$$\Delta m_{23}^2=\left|2.52\times 10^{-3}\right|eV^2$$

Summary of Current Knowledge

θ_{13} : how much ν_e is in ν_3



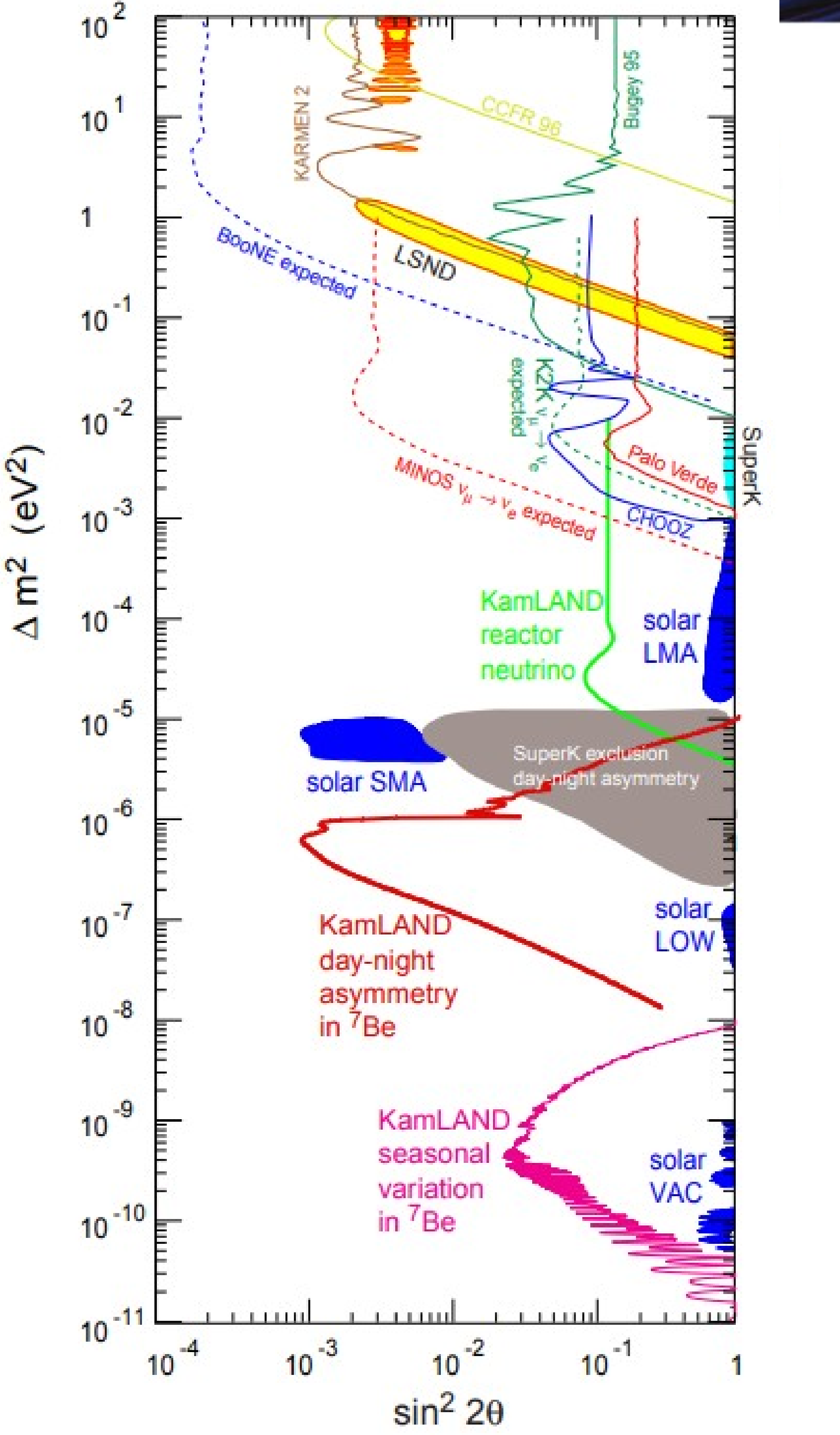
$$U_{MNSP} \approx \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.5 & 0.6 \\ 0.4 & 0.5 & 0.7 \end{pmatrix}$$

Some elements only known to 10-30%

Very very different from the quark CKM matrix

Comparison

State of play : Yr 2000



Lecture 4

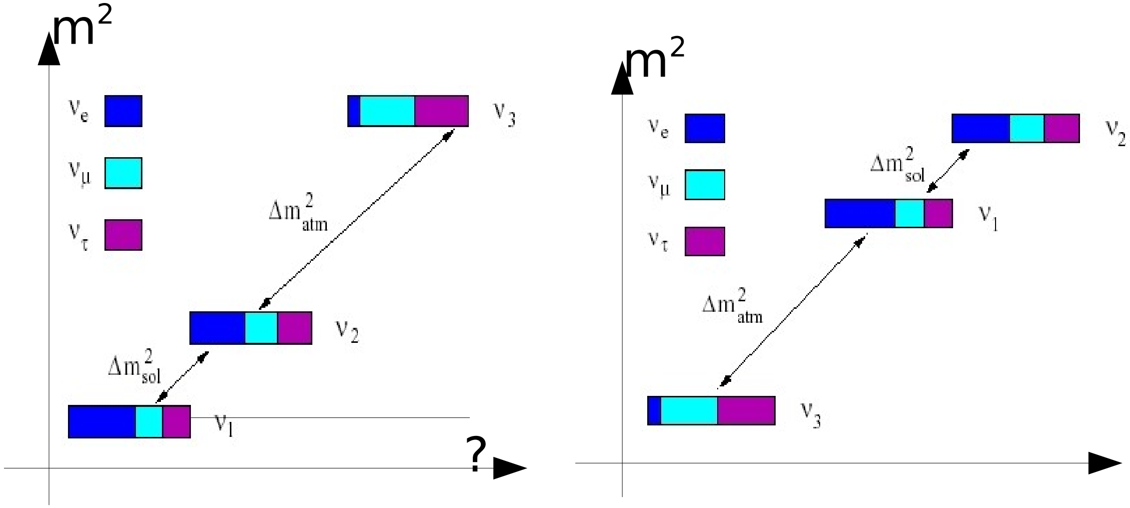
To The Future and Beyond!

The Quest

$$\begin{pmatrix} c_{13} & 0 & \boxed{s_{13} e^{i\delta}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

Value of δ?

Normal or Inverted mass heirarchy?



- Better estimates of the oscillation parameters using accelerators
- Is θ_{23} maximal?
- Is the neutrino Majorana?
- What is the absolute mass?

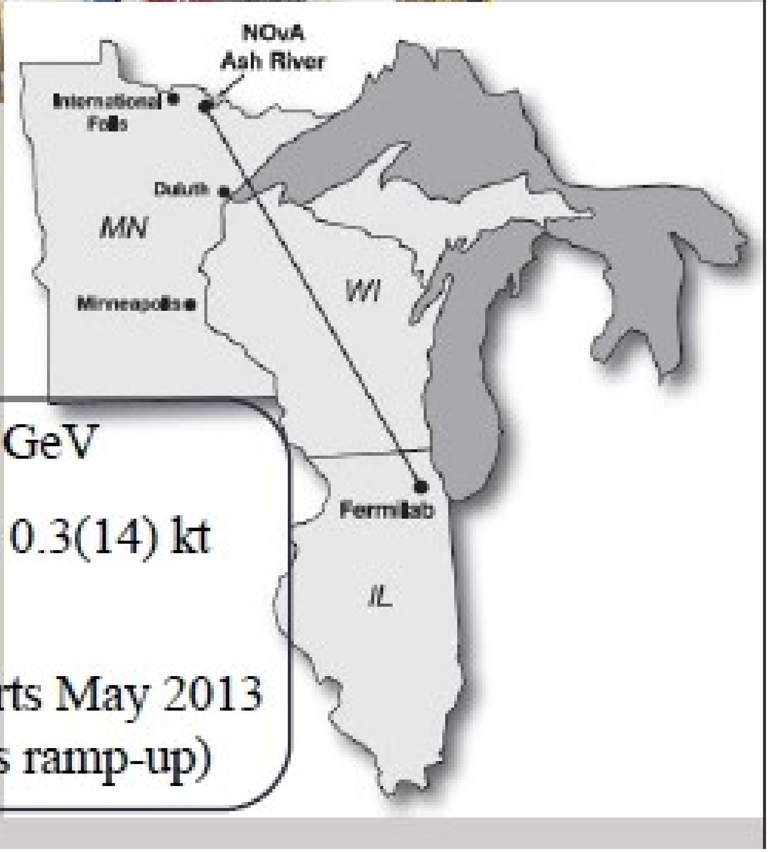
$$U_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.7 & 0.6 \\ 0.4 & 0.5 & 0.7 \end{pmatrix}$$

?

$$U_{CKM} = \begin{pmatrix} 0.975 & 0.222 & 0.004 \\ 0.221 & 0.97 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

Current Experiments

- L=295km, <E>=0.7GeV
- ND280 Near Detector, SuperK (22.5 kt) as Far Detector
- JPARC beam: currently 200kW ramping up to 700kW (<2019)



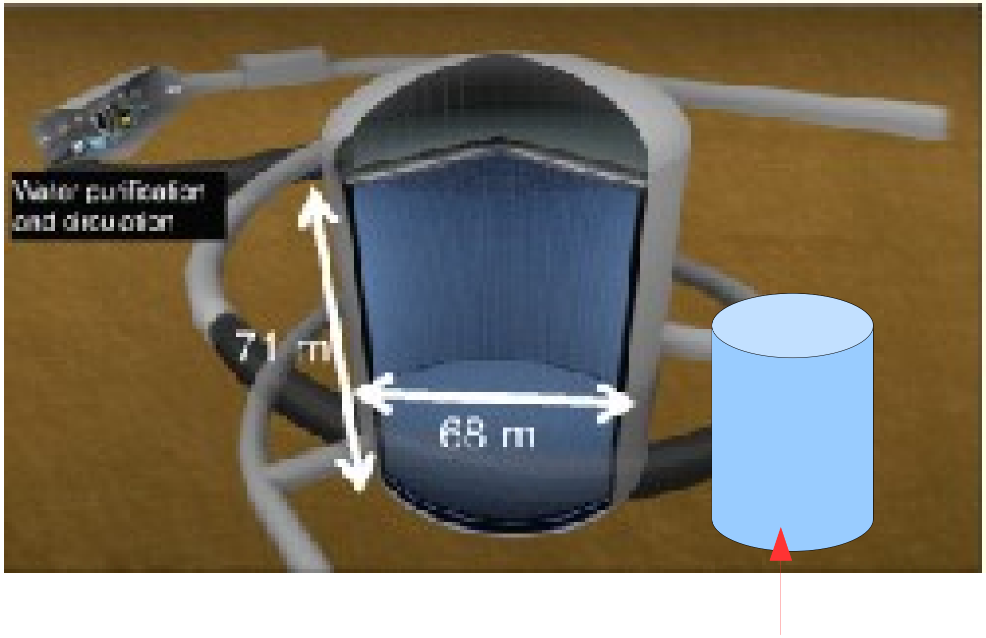
- L=810 km, <E>=2 GeV
- Near(Far) Detector 0.3(14) kt liquid scintillator
- NUMI beam re-starts May 2013 @ 700 kW (6 months ramp-up)

Next generation

DUSEL Underground Neutrino Experiment (DUNE)

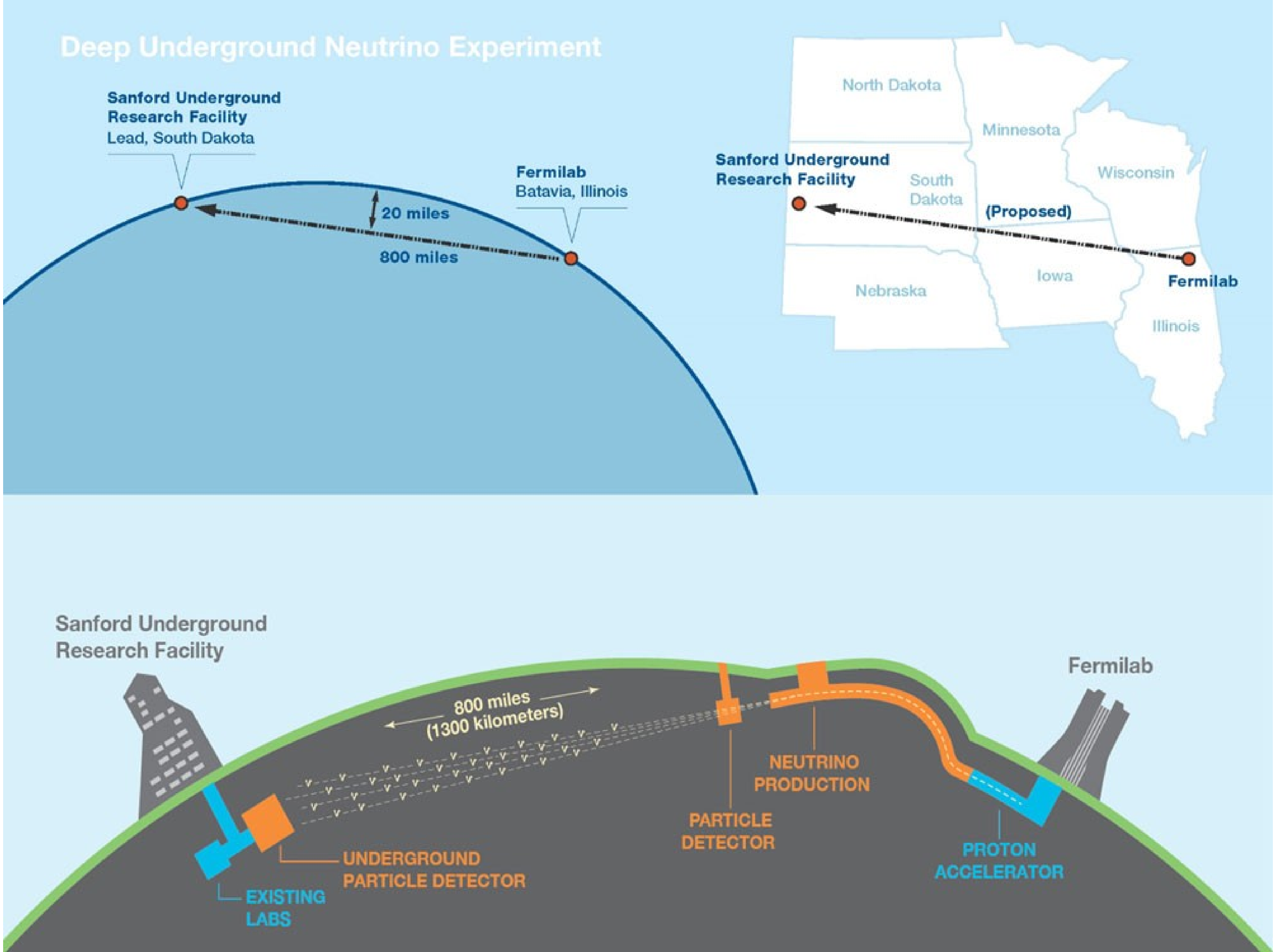
- MW beams
- multi-kton far detectors

Hyper-Kamiokande

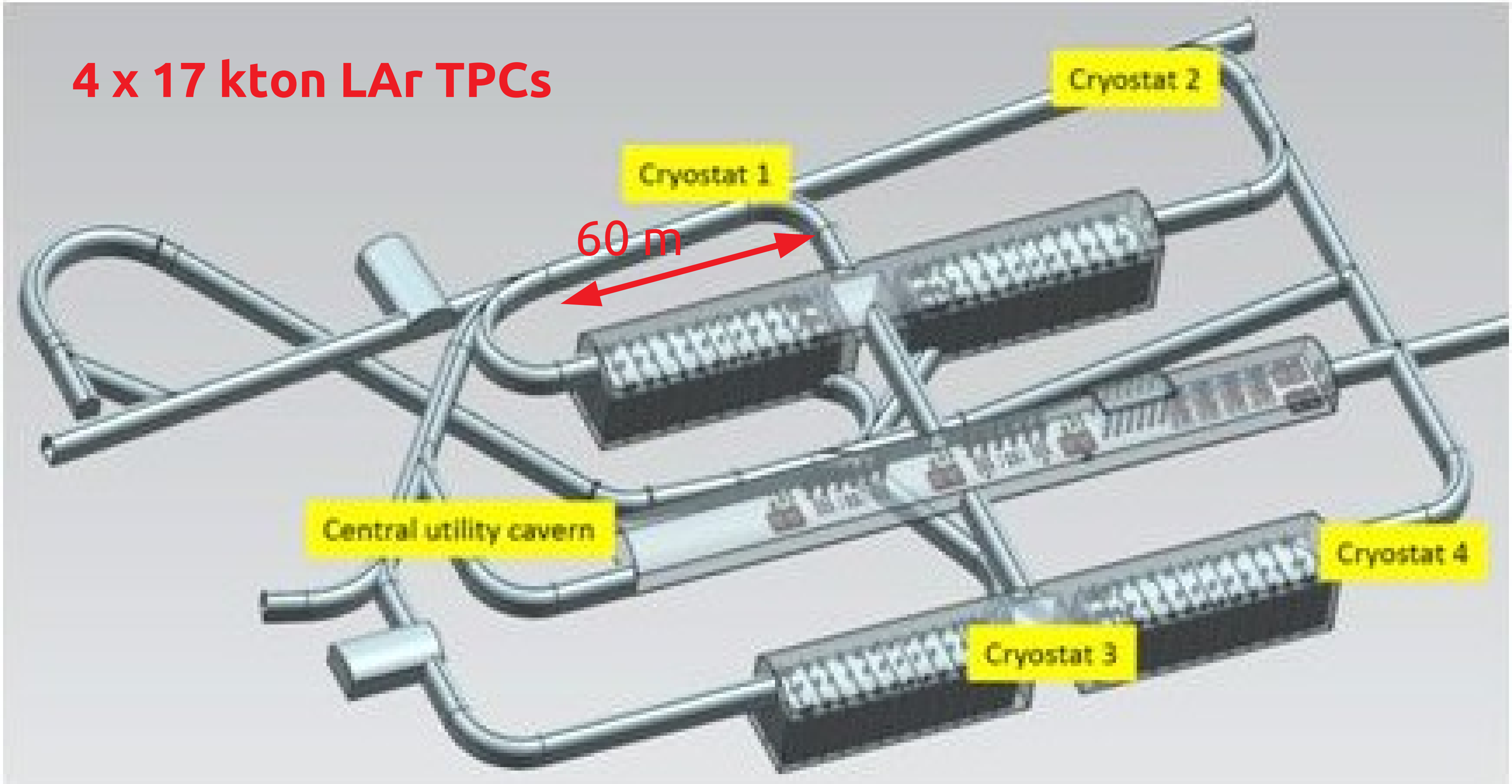


SK (to scale'ish)

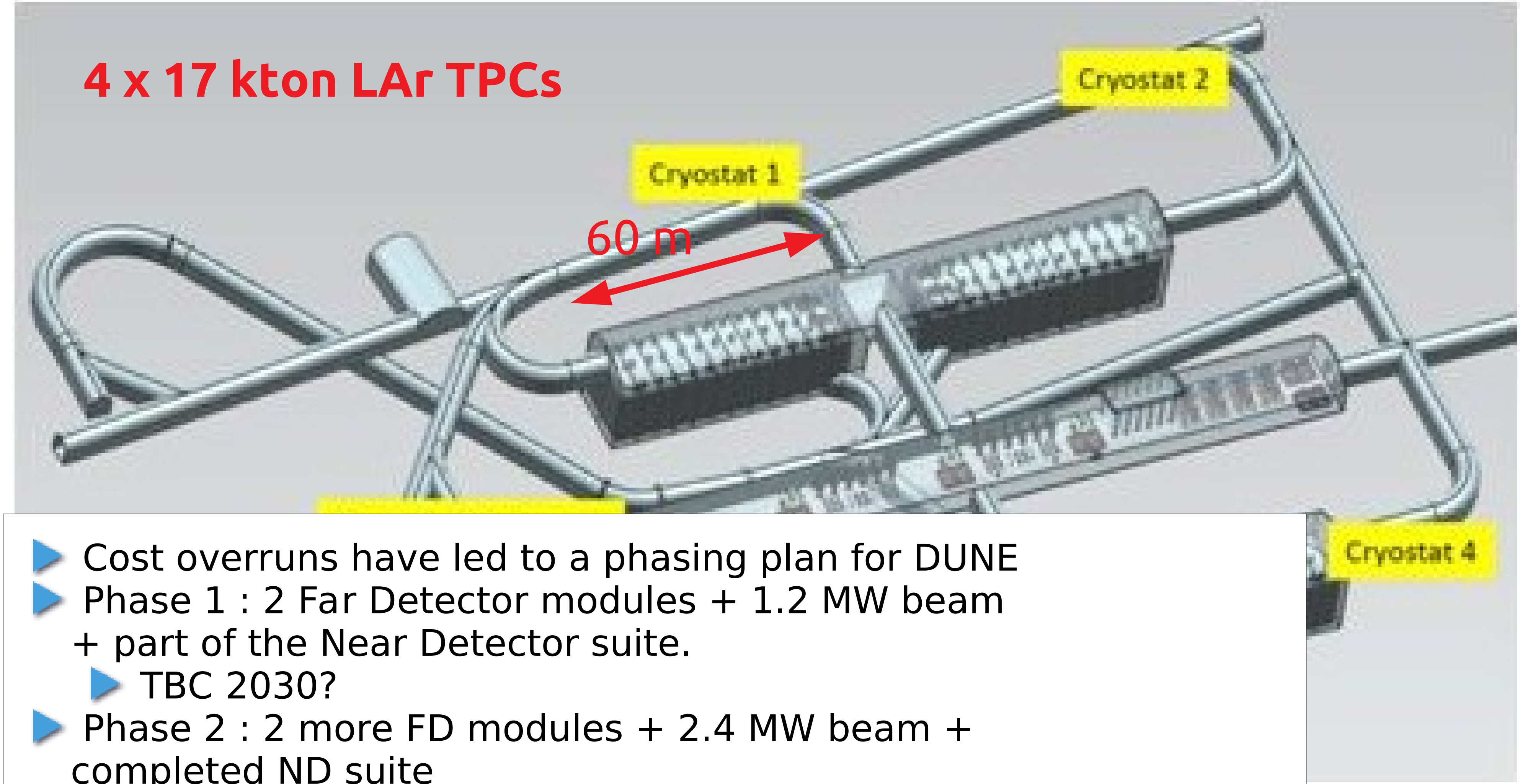
DUNE in the USA



DUNE Far Detector

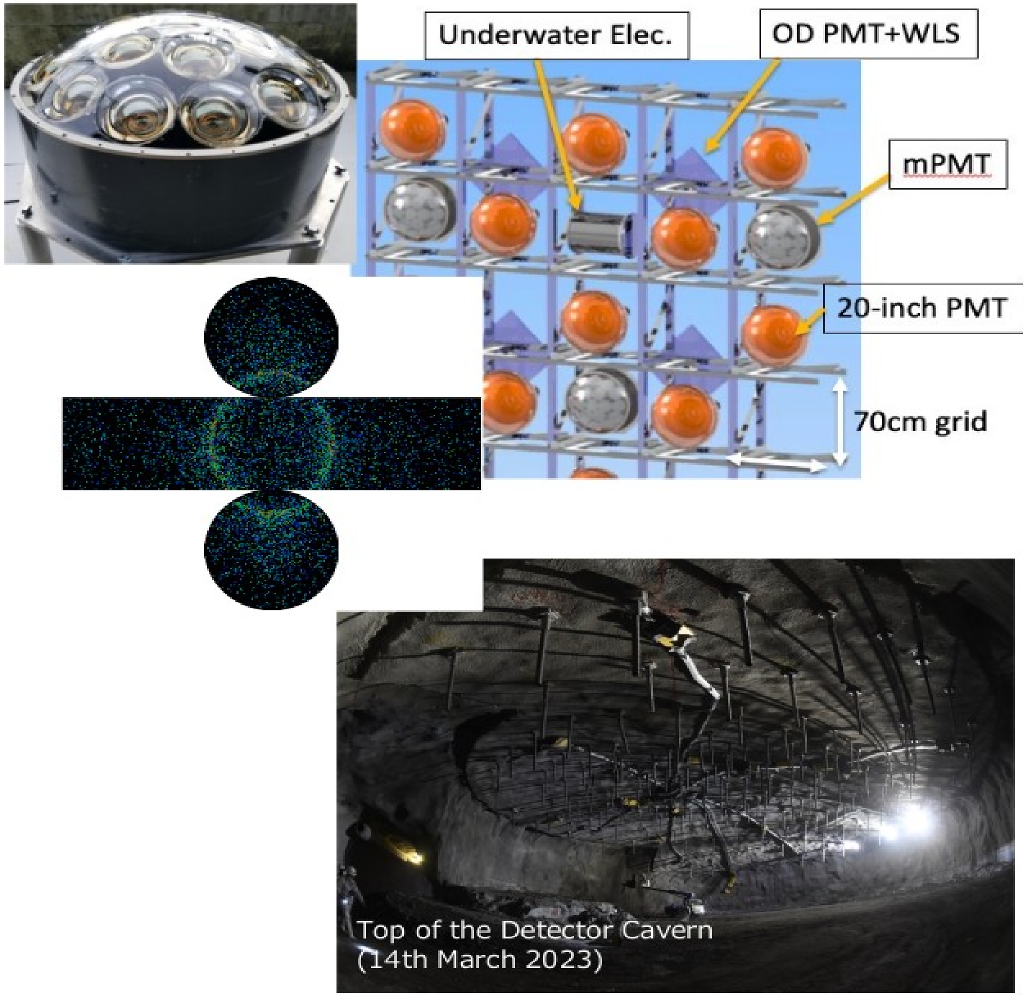


DUNE Far Detector



- Cost overruns have led to a phasing plan for DUNE
- Phase 1 : 2 Far Detector modules + 1.2 MW beam + part of the Near Detector suite.
  - TBC 2030?
- Phase 2 : 2 more FD modules + 2.4 MW beam + completed ND suite
  - TBC 2032???

Hyper-Kamiokande



Top of the Detector Cavern
(14th March 2023)

- Three detectors:
- HK Far Detector
- Upgraded Near detector
- New “Intermediate” detector

- FarDet complete : 2027
- Beam upgrades complete : 2028
- First data : 2028

Construction through to 2027’ish

Super-K : 25 kton water
Hyper-K : 190 kton

Dune / HK Comparison

	DUNE	Hyper-K	T2K
Beam Energy	3 GeV	0.7 GeV	0.7 GeV
Baseline (L)	800 km	295 km	295 km
Beam Power	1.2 MW	1.2 MW	0.5 MW
Type of Beam	Wideband	Off-axis	Off-axis
Mass of far detector	40 kton (P1) up to 80 kton (P2)	190 kton	22.5 kton
Technology	Liquid Ar TPC	Water Cerenkov	Water Cerenkov
Running from	2030'ish	2028'ish	Now

CP violation and the Mass Hierarchy

CP violation and Mass Hierarchy

Measuring δ_{CP} is the ultimate goal of neutrino oscillation experiments. How?

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

$= 0$ if $\alpha = \beta$

CP violation can only take place in *appearance* experiments

Look for $P(\nu_\mu \rightarrow \nu_e) \neq P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$

In all it's naked glory

$$\boxed{P(\nu_\mu(\overline{\nu}_\mu)\rightarrow\nu_e(\overline{\nu}_e)) = P_1+P_2+P_3+P_4}$$

$$P_1 = \sin^2\theta_{23}\underline{\sin^2 2\theta_{13}}\left(\frac{\Delta_{13}}{B_{-+}}\right)^2 \sin^2\left(\frac{B_{+-}}{2}L\right)$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A}{2}L\right)$$

$$P_3 = \underline{\underline{J}}\,\underline{\cos\delta}\,\underline{\cos\left(\frac{\Delta_{23}}{2}L\right)\left(\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_{-+}}\right)}\sin\left(\frac{A}{2}L\right)\sin\left(\frac{B_{-+}}{2}L\right)$$

$$P_4 = \underline{\underline{\pm J}}\,\underline{\sin\delta}\,\underline{\sin\left(\frac{\Delta_{23}}{2}L\right)\left(\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_{-+}}\right)}\sin\left(\frac{A}{2}L\right)\sin\left(\frac{B_{-+}}{2}L\right)$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E}$$

$$A = \sqrt{2}G_F N_e$$

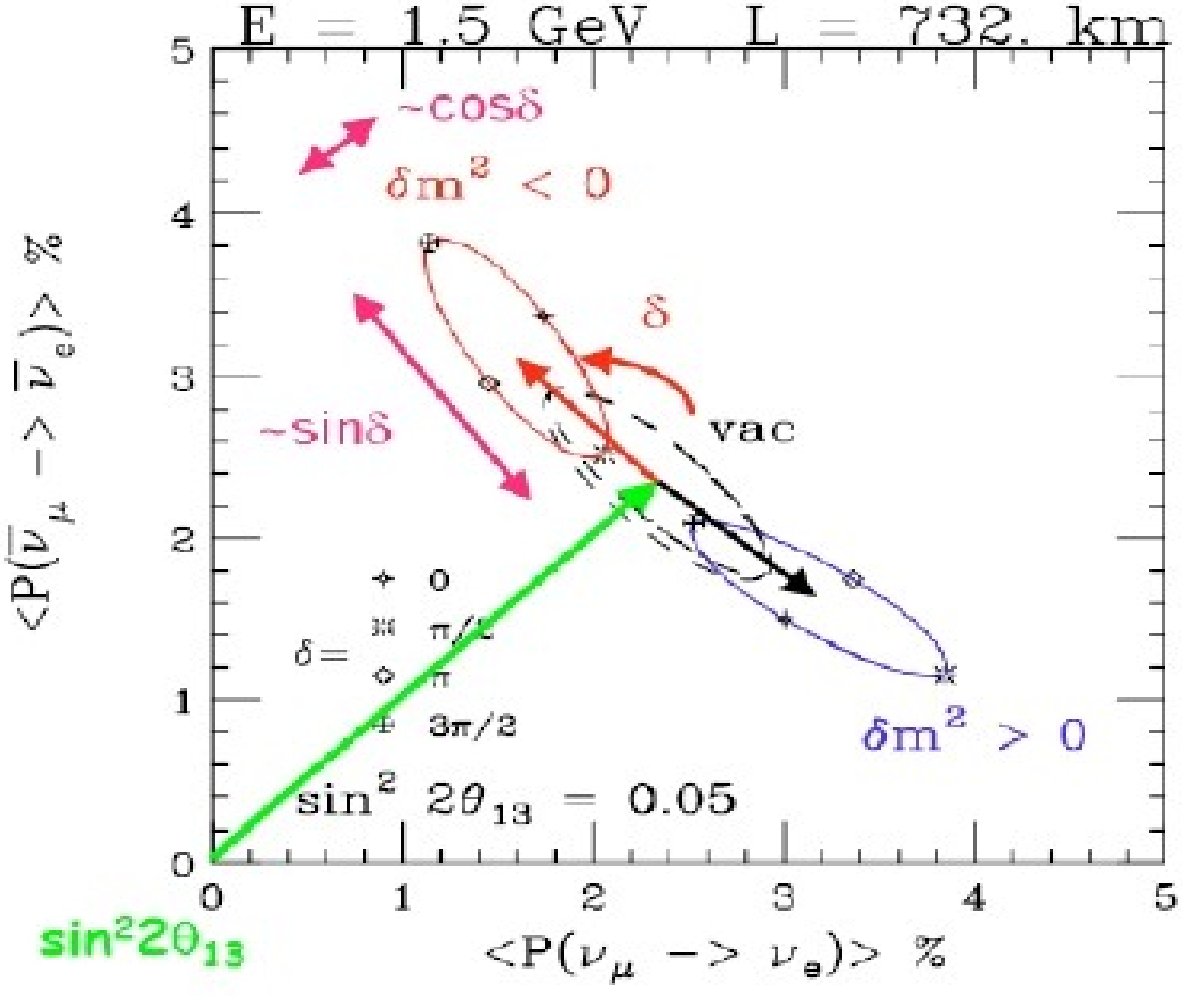
$$B_{-+} = |\Delta_{13} \mp A|$$

$$J = \cos\theta_{13}\, sin2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$

- θ_{13}
- $\theta_{23} > 45$ or $\theta_{23} < 45$
- $\mathrm{Sign}(\Delta m_{23}^2)$
- $\delta_{\chi\Pi}$

Degeneracies

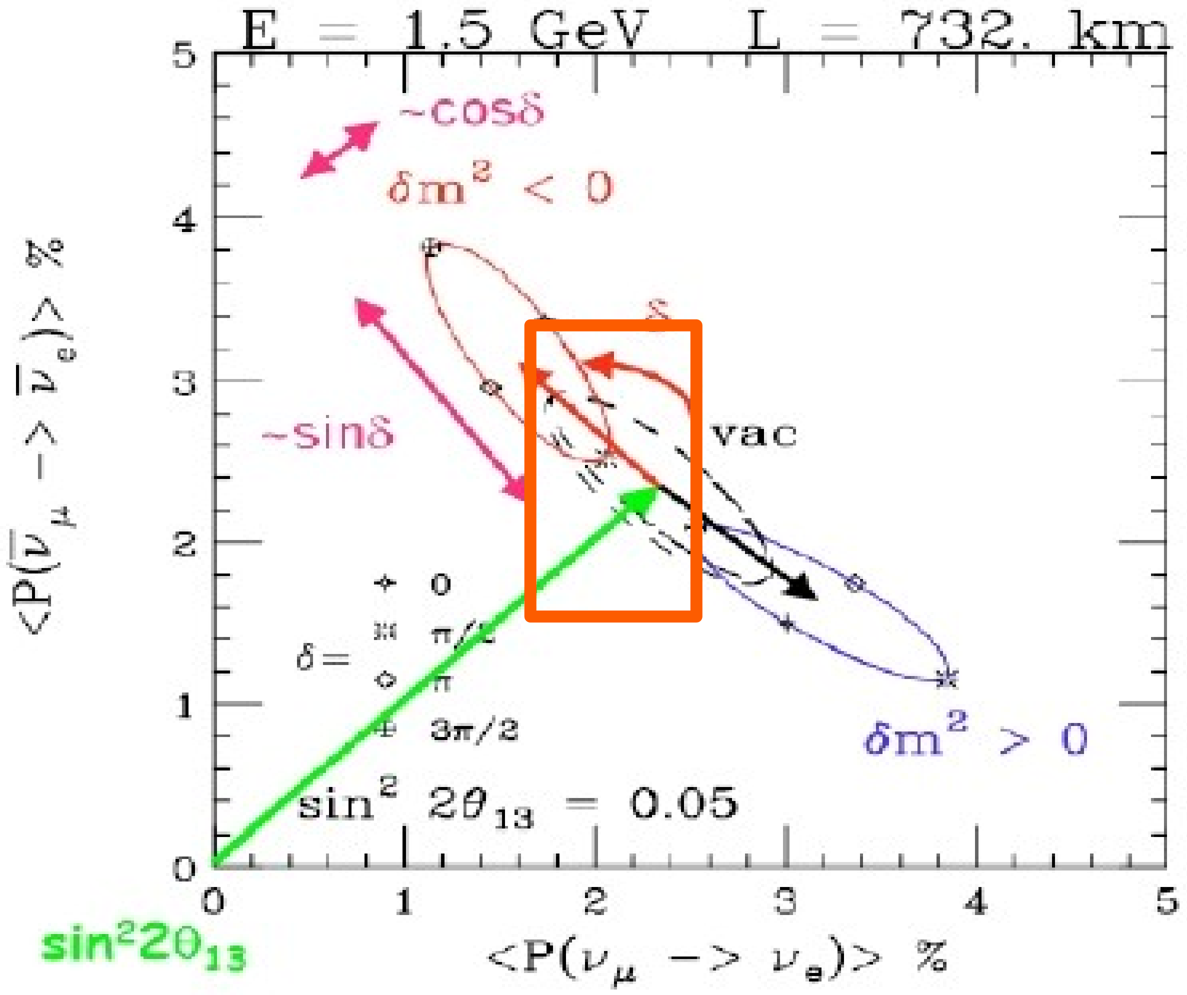
Experiments only measure at most two numbers; but probability has three unknowns and parameters with errors.



Need more than one measurement at different L/E to disentangle the parameter space

Degeneracies

Experiments only measure at most two numbers; but probability has three unknowns and parameters with errors.



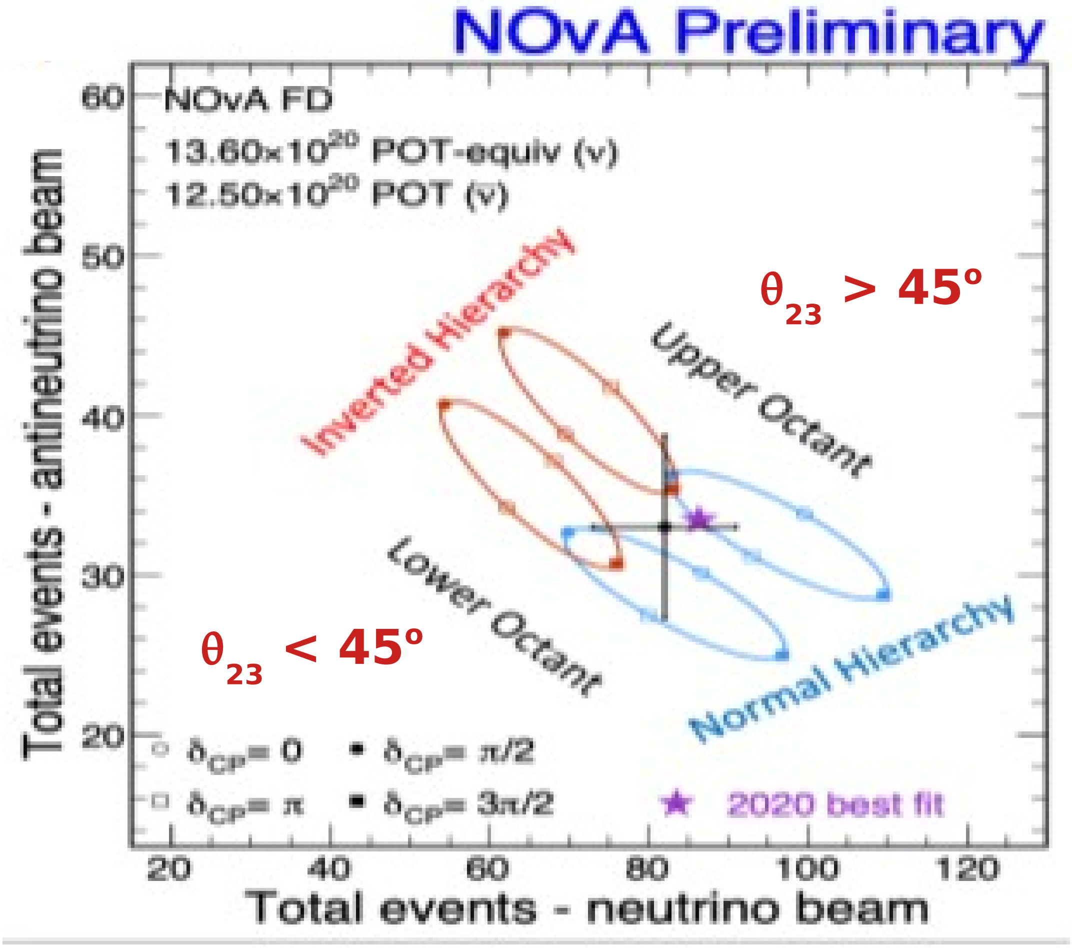
Need more than one measurement at different L/E to disentangle the parameter space

Mass Hierarchy measurements

As baseline grows, matter effects increase

At distances of around 1000 km we can unambiguously identify the mass hierarchy

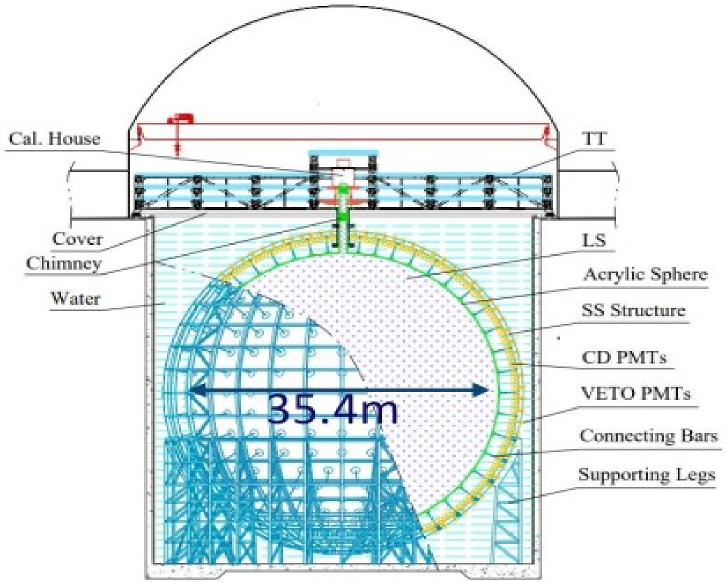
Once we've done that we need to determine CP phase

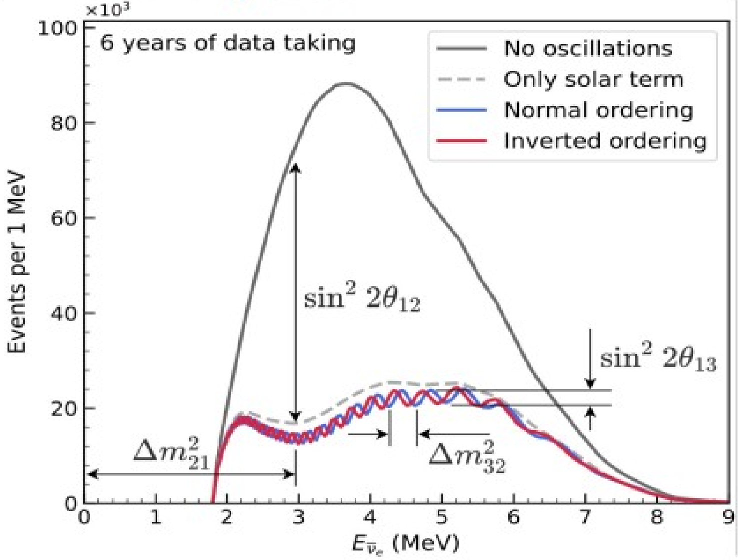


JUNO

Neutrino source: 26.6 GW_{th} from nuclear reactors
Experiment location: Jiangmen, China
Baseline: 53km
Main detector technology: Liquid Scintillator
Current Status: Under construction

- JUNO will measure $\bar{\nu}_e$ from Yangjiang and Taishan power plants
- Main goal: Neutrino Mass ordering
  - Simultaneous measurement of Δm^2_{31} and Δm^2_{32}
  - Independent of δCP and octant of θ_{23}
    - 6 years operation to determine mass hierarchy at 3σ

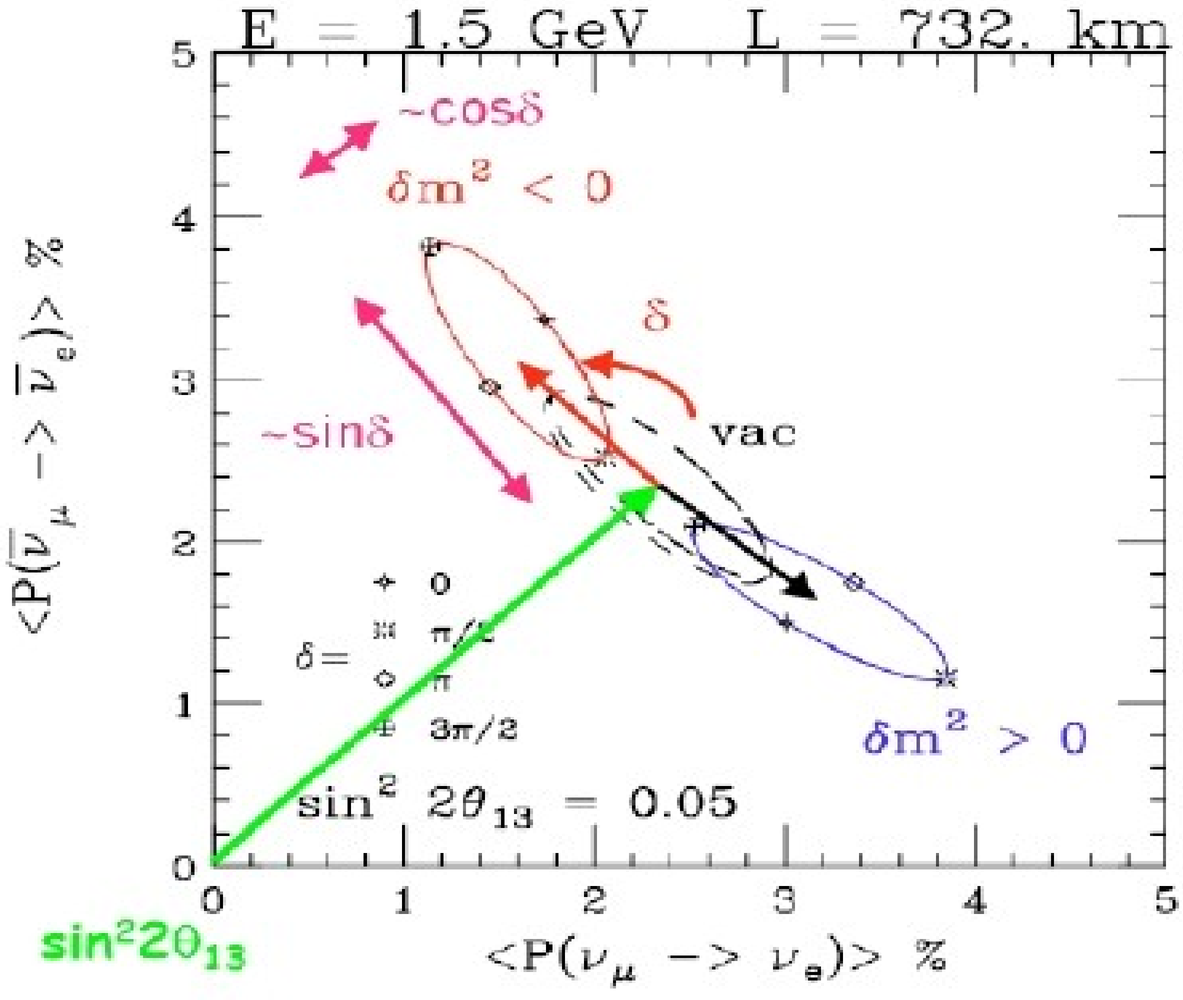




Largest liquid scintillator detector ever build

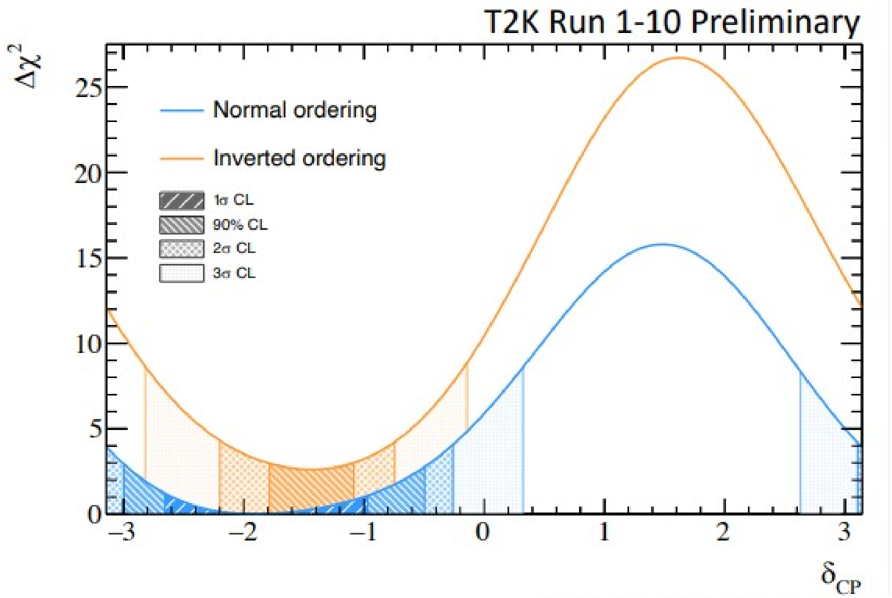
Data taking to begin 23-24

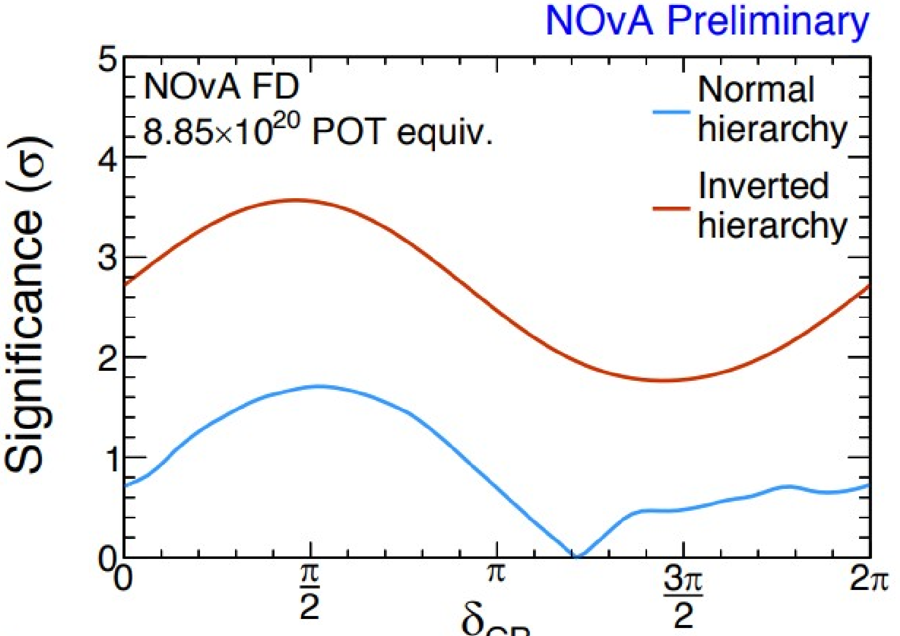
CP violation



- If mass heirarchy is known then “all” we need to do is precisely measure the v_e appearance probability for neutrino and anti-neutrino beams and that will give us δ_{CP}
- Do this at at least two independent L/E

Hints : T2K & NOvA

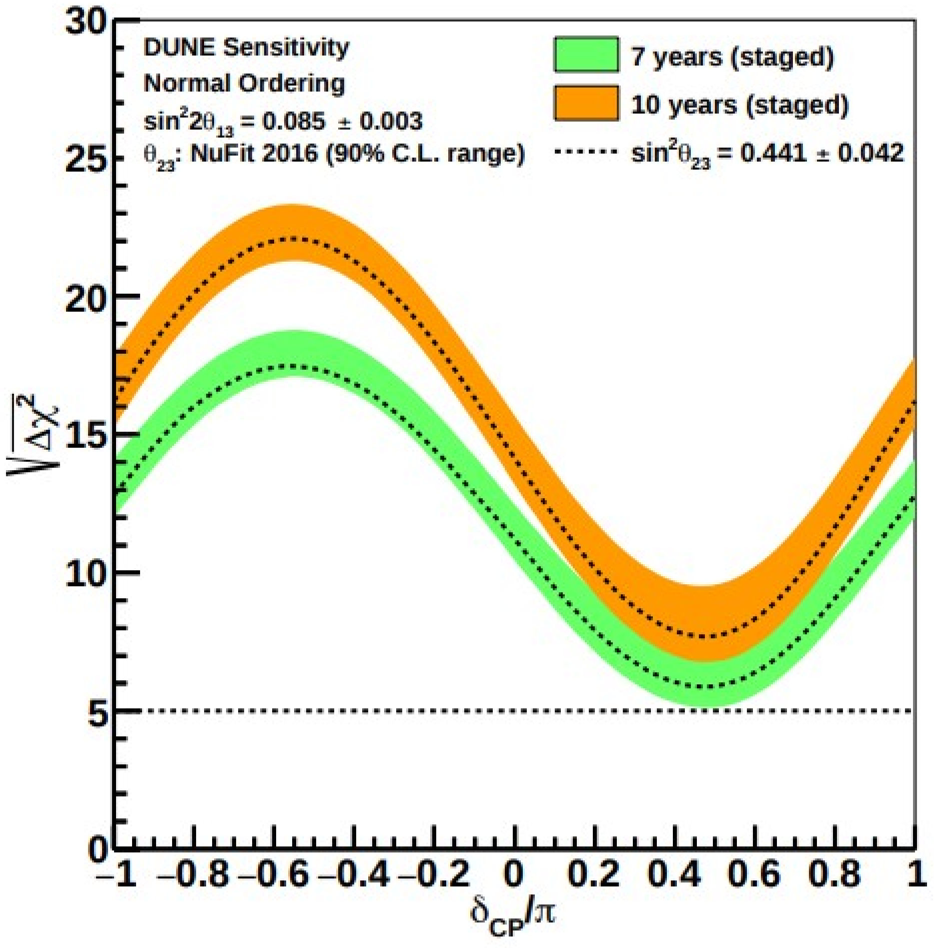


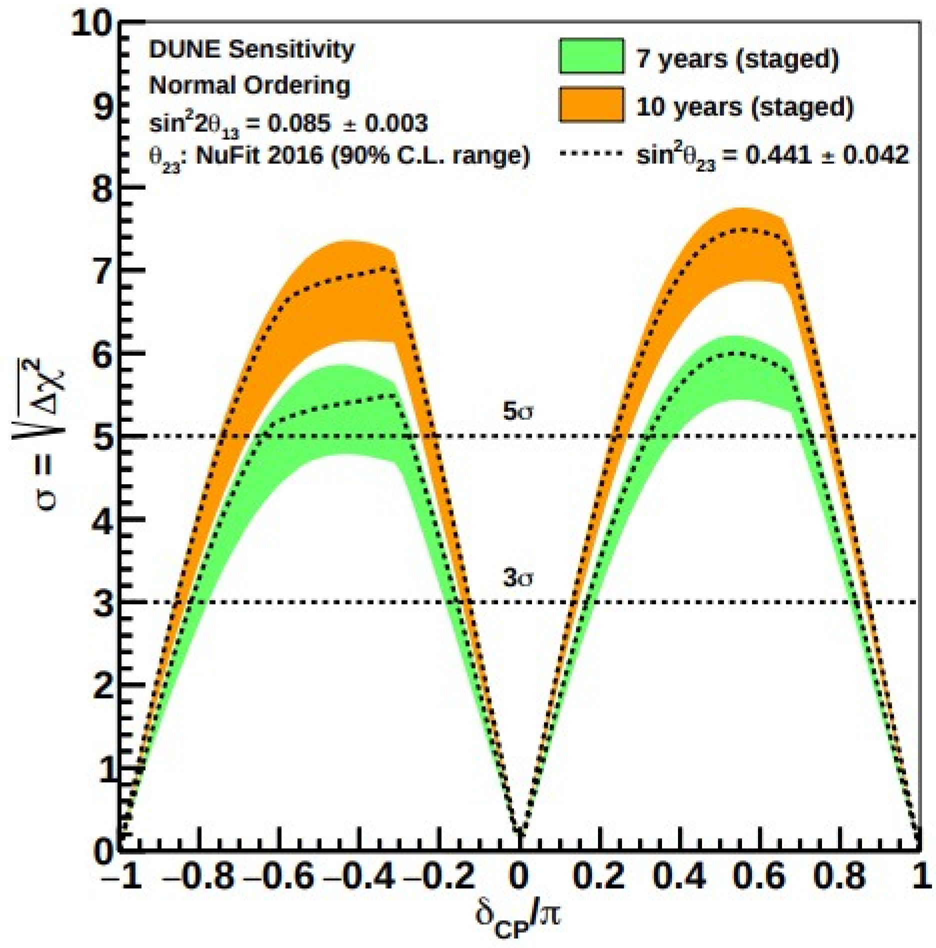


- Normal ordering weakly favoured
- 90% CL δ_{CP} : [-2.8,-0.8]
- δ_{CP} = 0 disfavoured at 3σ

- Best fit: Normal hierarchy favoured at 1.8 σ
- δ_{CP} = 1.21 π
- Excludes δ_{CP} = π / 2 in the inverted hierarchy at > 3 σ

δ_{CP} : DUNE Sensitivity

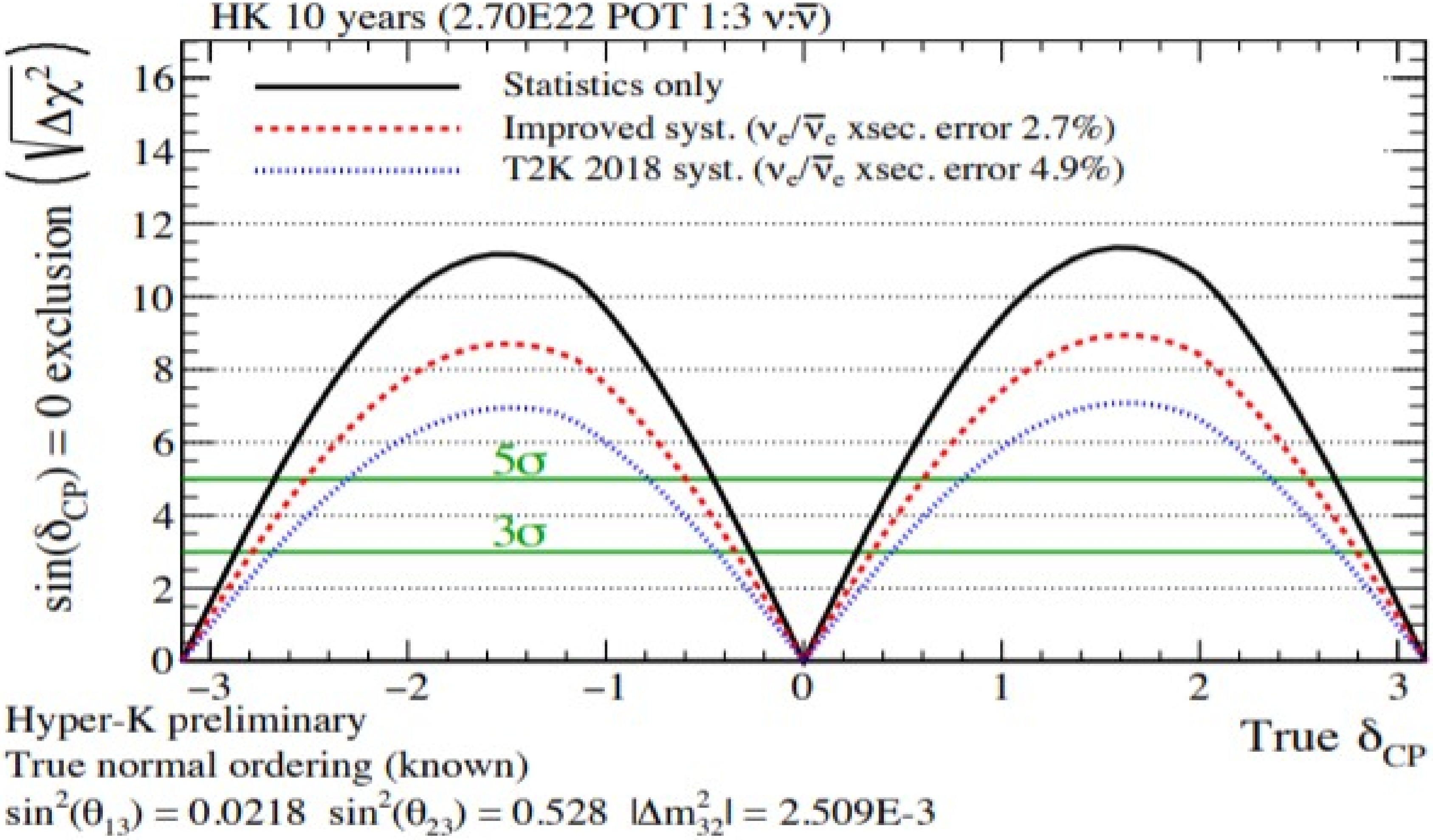




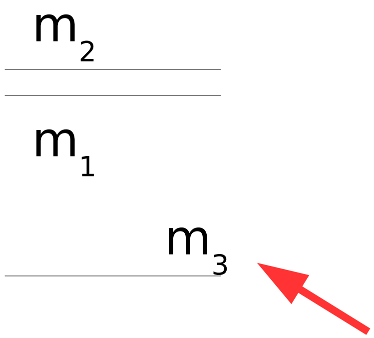
> 5 σ reach after 7 years of running over entire δ_{CP} range

> 5 σ reach after 10 years if δ_{CP} exists in ±[0.2-0.8]п

HK δ_{CP} Sensitivity



Mass hierarchy from 0νββ decay



$$\Gamma_{0\nu\beta\beta} \propto m_{\nu_e}^2 = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 + m_3 |U_{e3}|^2 \right|^2$$

In the inverted hierarchy : $m_3 << m_1 \approx m_2$, $\Delta m_{13}^2 \approx \Delta m_{23}^2$ and m_3 is the lightest mass state, so we can write

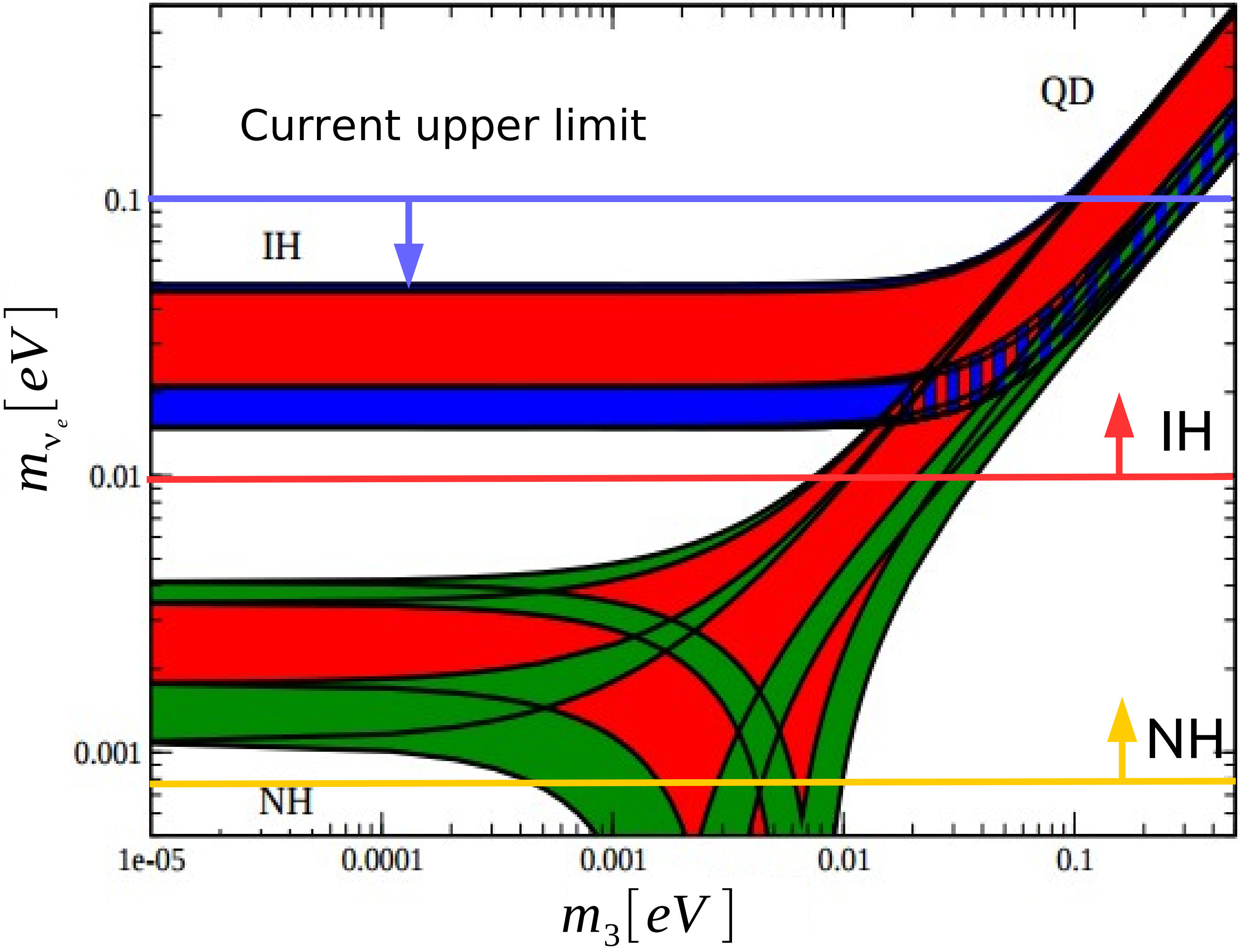
$$m_{\nu_e} = |U_{e1}|^2 \sqrt{m_3^2 + \Delta m_{23}^2} + |U_{e2}|^2 \sqrt{m_3^2 + \Delta m_{23}^2} + |U_{e3}|^2 m_3^2$$

Setting m_3 to zero (not a bad approximation) one can show that

$$m_{\nu_e} > \sqrt{\Delta m_{23}^2} \cos^2 \theta_{13}$$

i.e for the inverted hierarchy, the decay rate, $\Gamma_{0\nu}$, would have a *lower limit at small* m_3

Mass hierarchy & 0νββ decay



- Experimental limit needs to decrease by a factor of 10
- Limit scales with mass and run time
- Experiments need to be 10 times bigger and run 10 times longer
- These are being built now.

Mass Hierarchy Determination

A number of different experiments, both accelerator and 0nbb decay focused, are now trying to determine the mass hierarchy.

Timescale : ~ 6 years from now for 4 σ good indication from NOVA + T2K + JUNO

Measurement of δ_{CP}

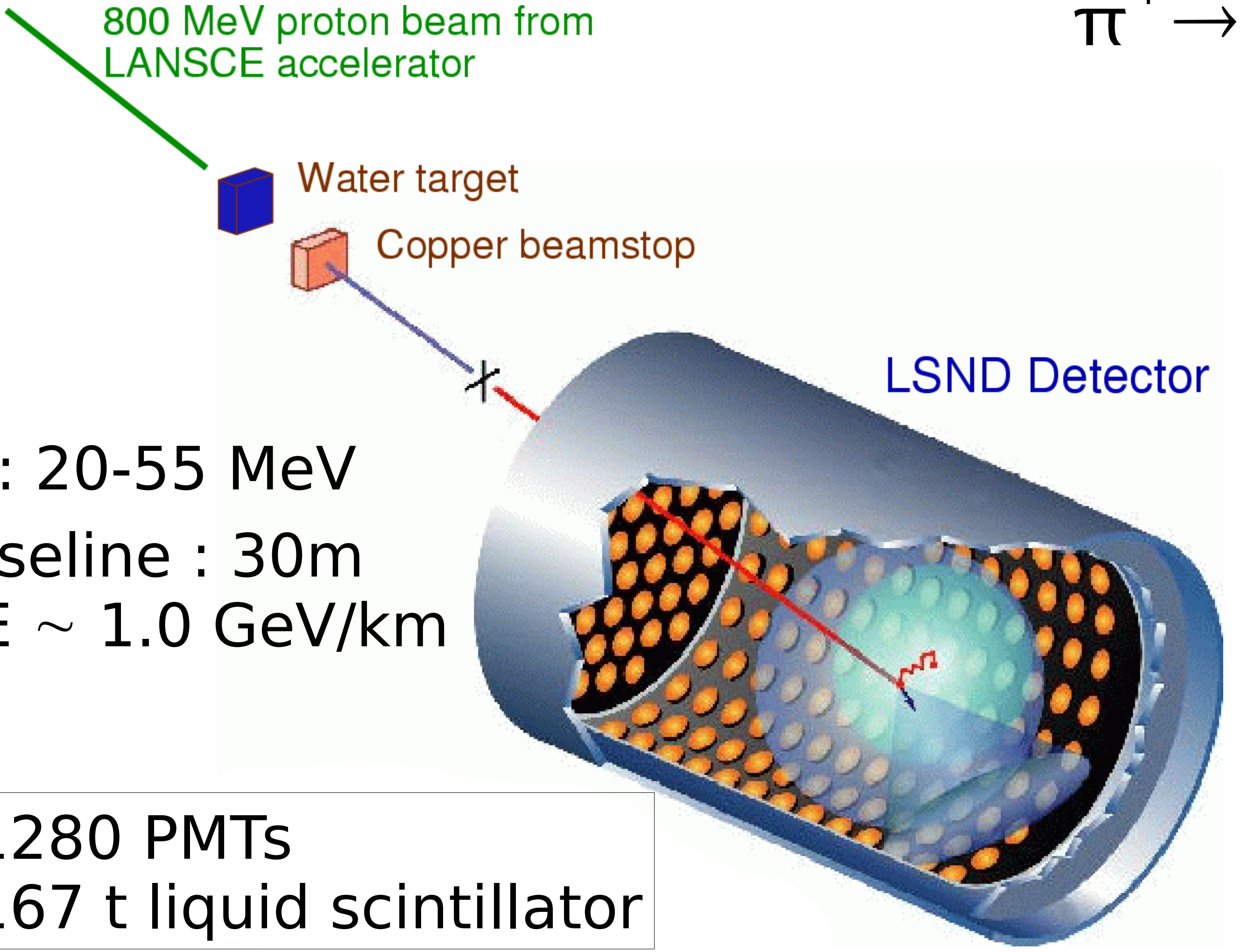
Next generation of experiments are being planned to measure this

Timescale : 7-9 years from now (including 6 for construction) for 3σ sensitivity to distinguish from no CP-violation scenario (if true δ_{CP} is π/2).

15-20 years for a measurement of δ_{CP} to a precision of 20^o (if true δ_{CP} is π/2).

LSND

The LSND experiment was the first accelerator experiment to report a positive appearance signal



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

$$\Updownarrow$$

$$\bar{\nu}_e$$

E_ν : 20-55 MeV
baseline : 30m
L/E ~ 1.0 GeV/km

1280 PMTs
167 t liquid scintillator

$$\bar{\nu}_e p \rightarrow e^+ n$$

20-60 MeV

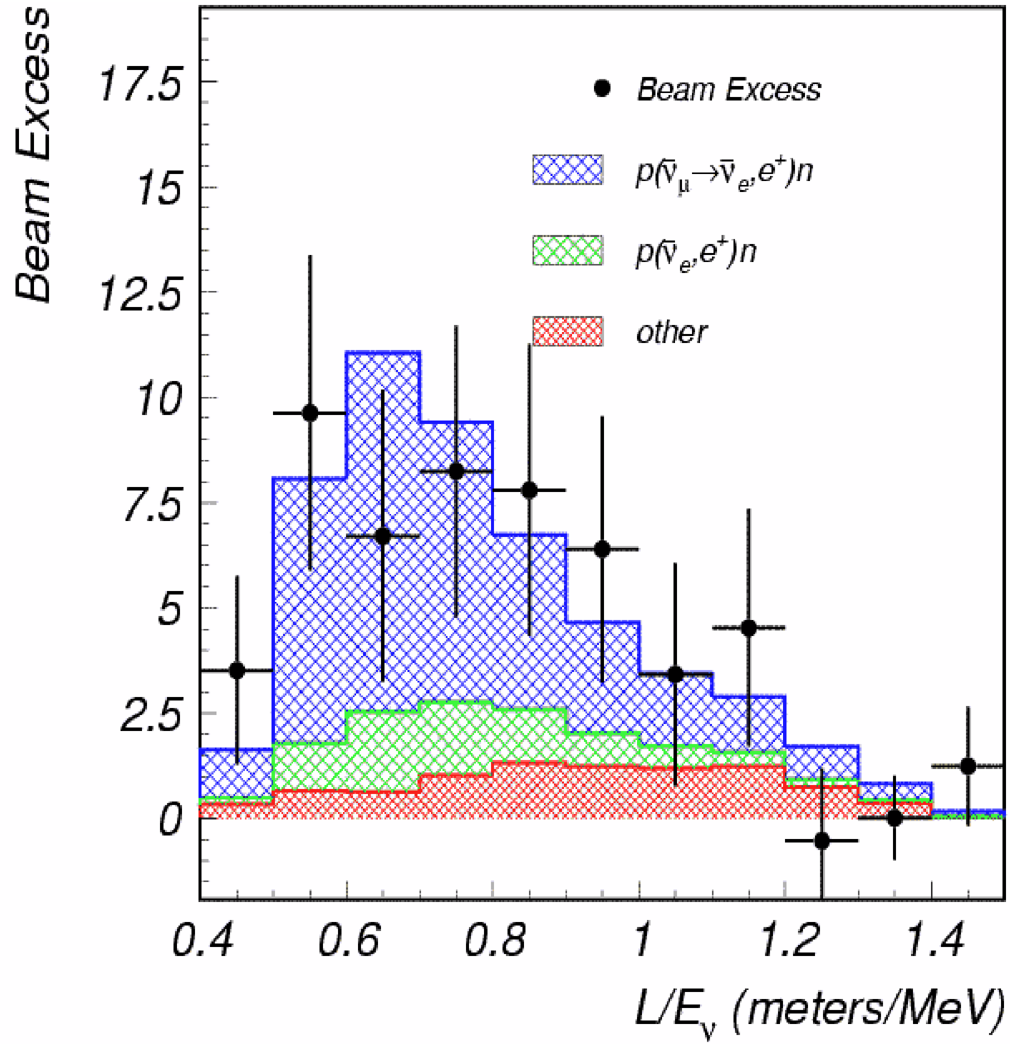
$$n\, p \rightarrow \gamma\, d$$

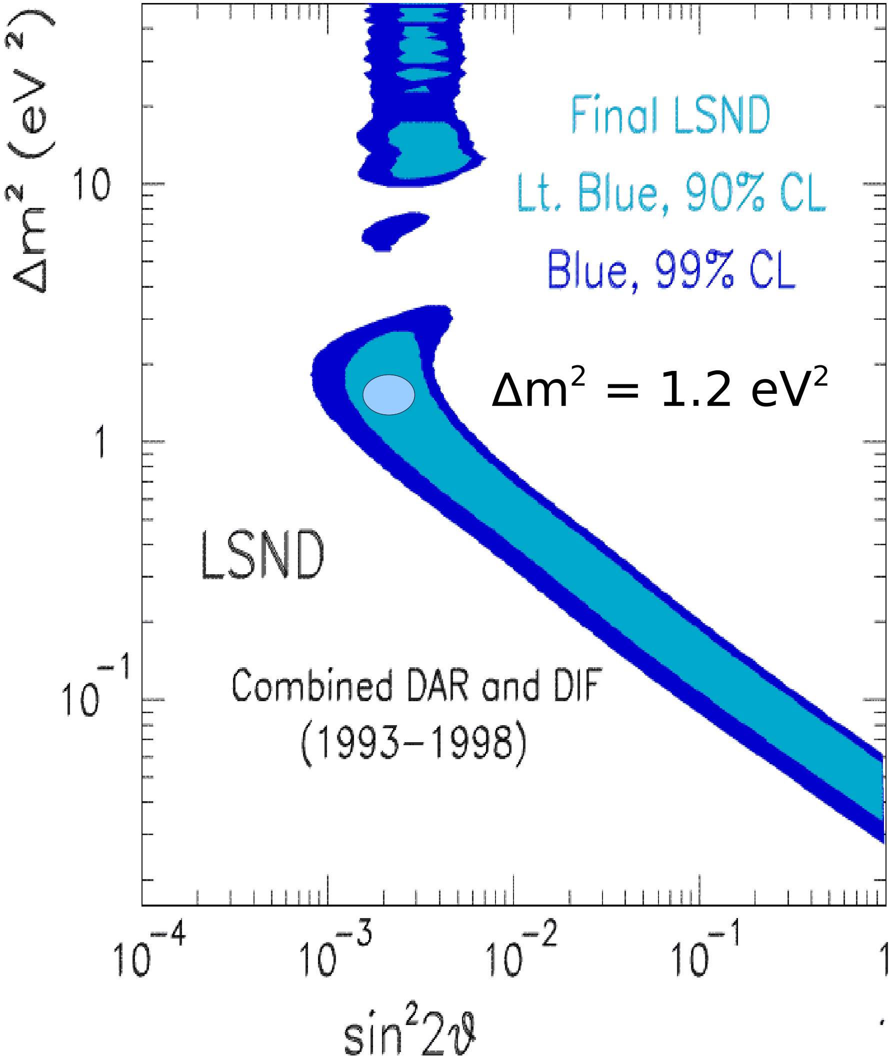
2.2 MeV

LSND Result (1997)

87.9 ± 22.4 ± 6 excess events from $\bar{\nu}_\mu \to \bar{\nu}_e$

3.3 σ evidence for oscillations



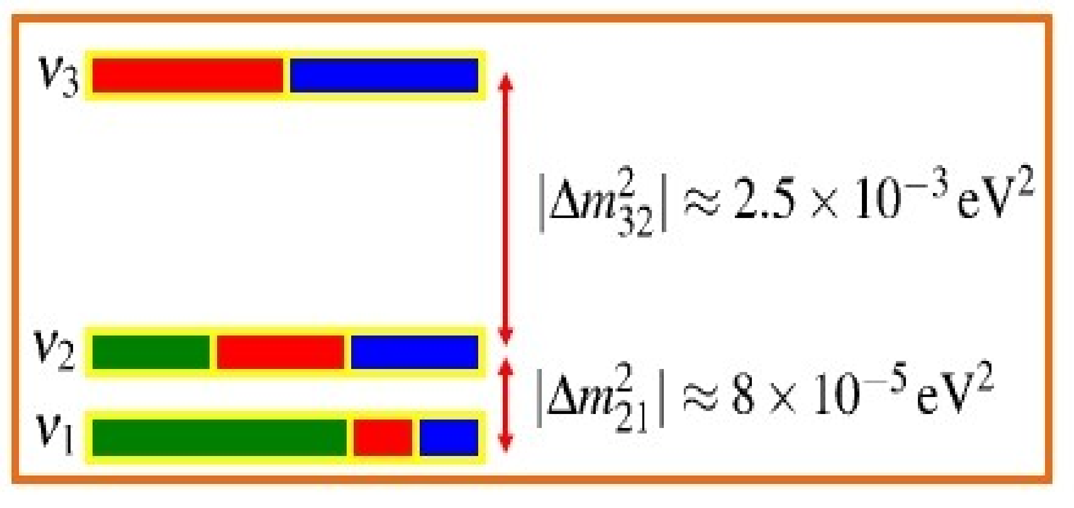


$\Delta m^2 = 1.2$ eV^2

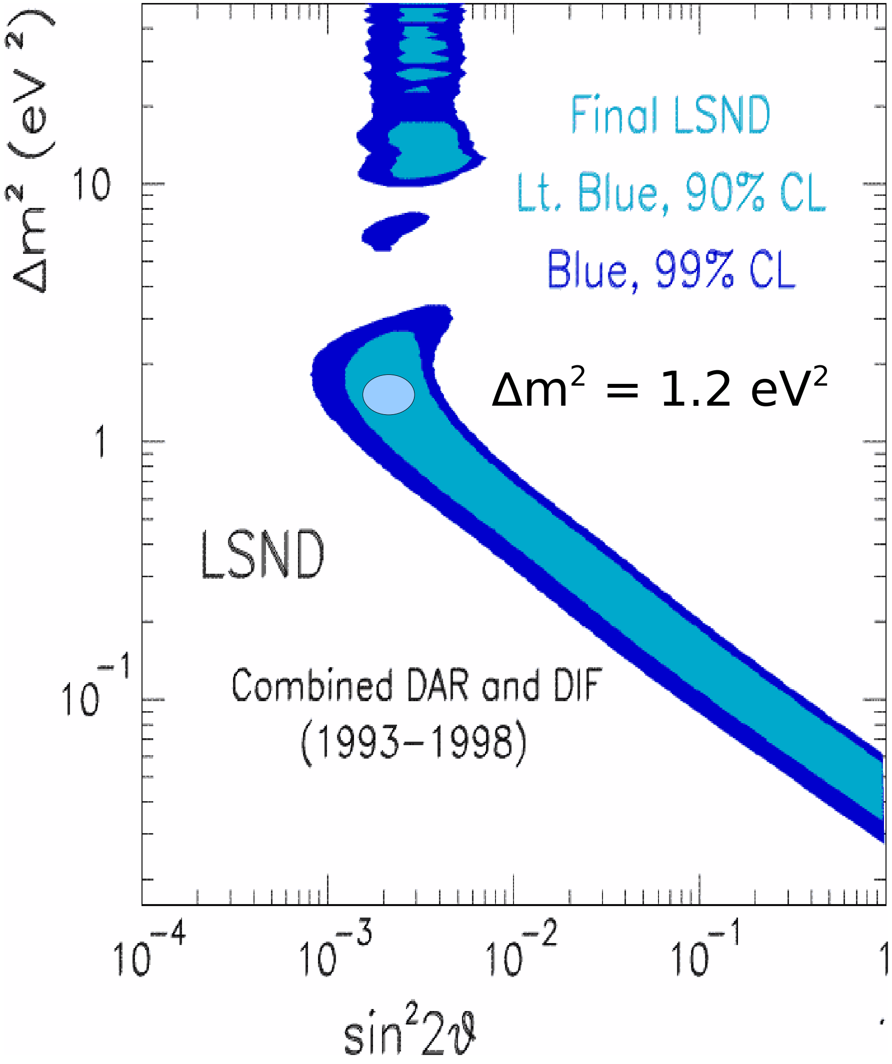
LSND Result (1997)

87.9 ± 22.4 ± 6 excess events from $\bar{\nu}_\mu \to \bar{\nu}_e$

3.3 σ evidence for oscillations

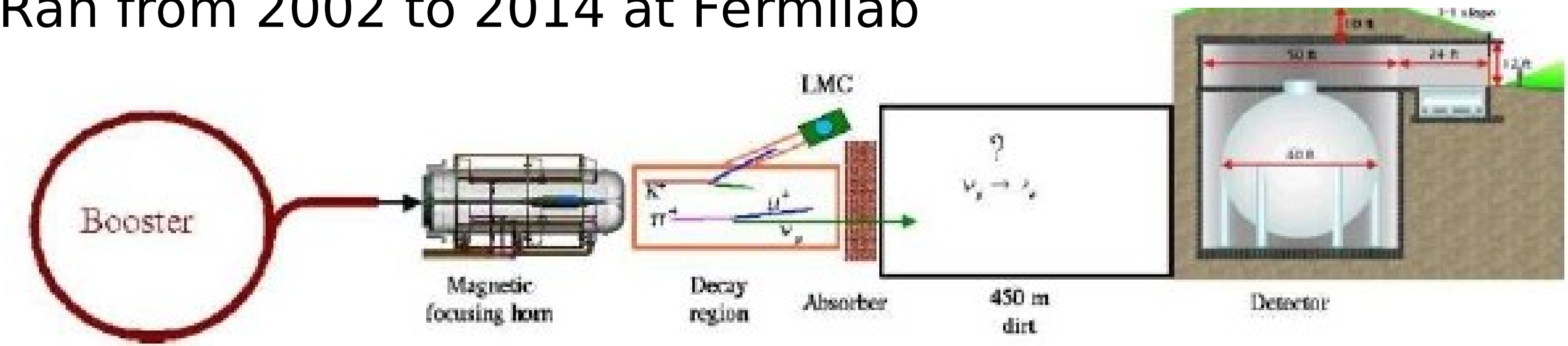


- Already know 2 mass splittings
- LSND implies : $\Delta m^2 \approx 1\ \mathrm{eV}^2$
- 3 independent Δm^2 implies
- **4 neutrino mass states!?!?**



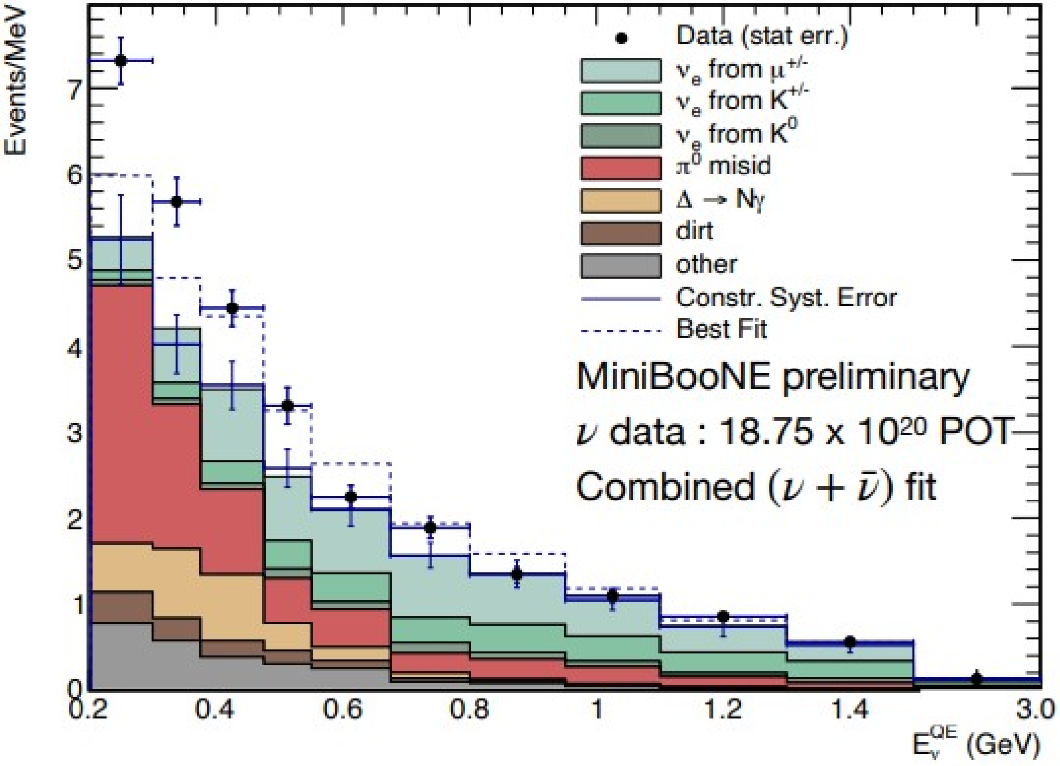
MiniBooNE

Ran from 2002 to 2014 at Fermilab

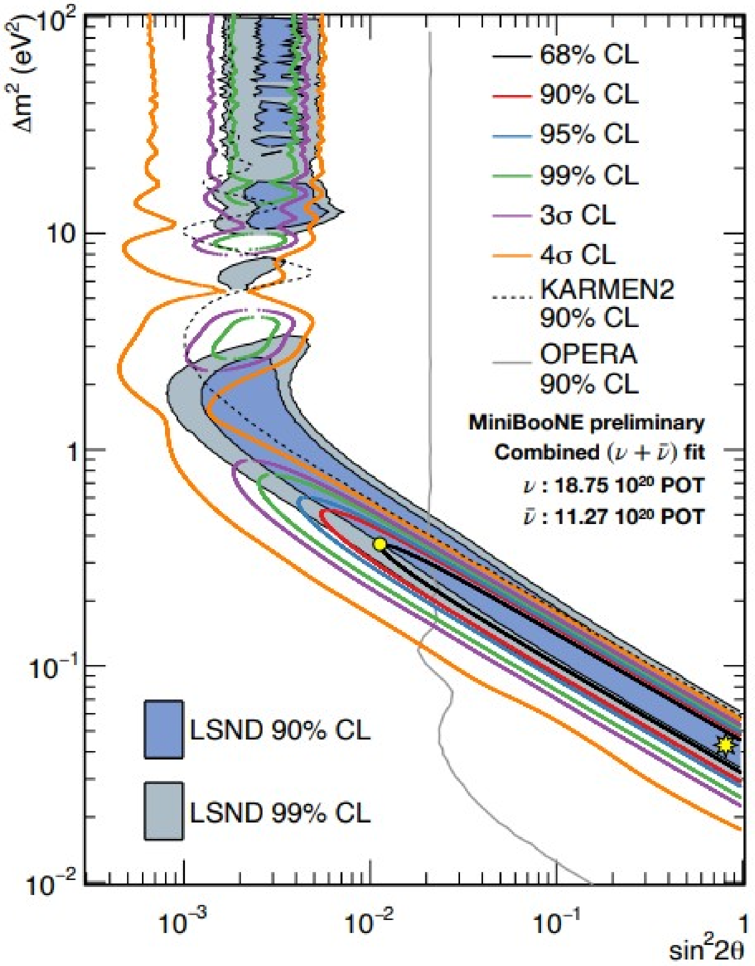


- Average neutrino energy ≈ 1 GeV
- L/E the same as LSND
- Same technology as LSND
- Different energy = different event types = different systematics

miniBooNE Results



Excess at the level of 4.8 σ

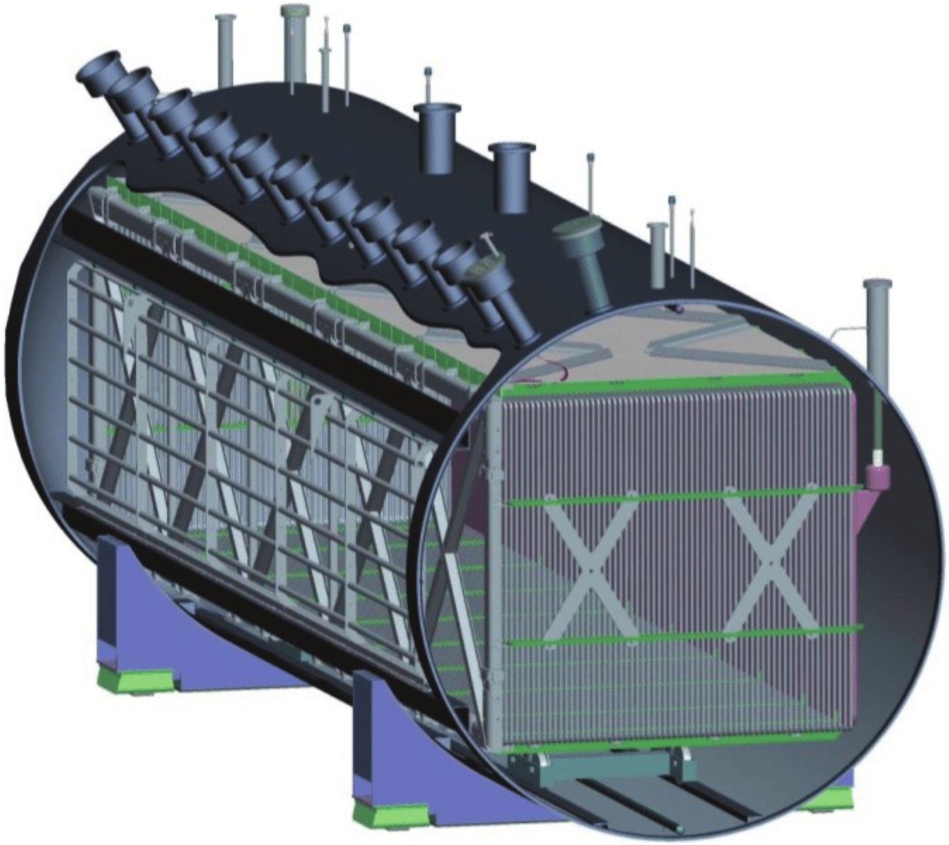


Neutrino + Anti-Neutrino Mode

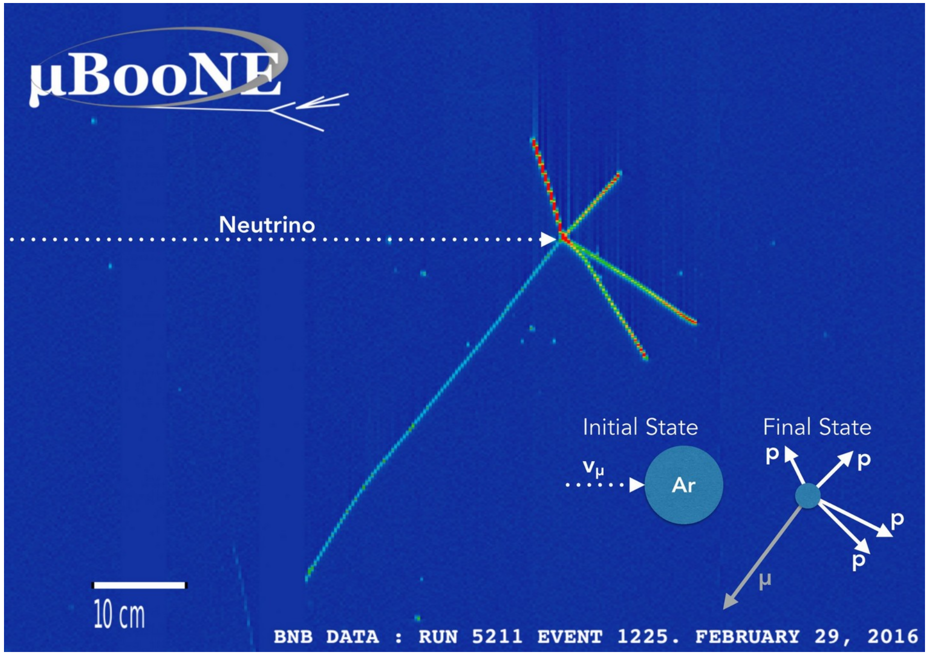
$$(\Delta m^2, \sin^2 2\theta) = (0.043\ \text{eV}^2,\ 0.807)$$

$$\chi^2/ndf = 21.7/15.5\ (\text{prob} = 12.3\%)$$

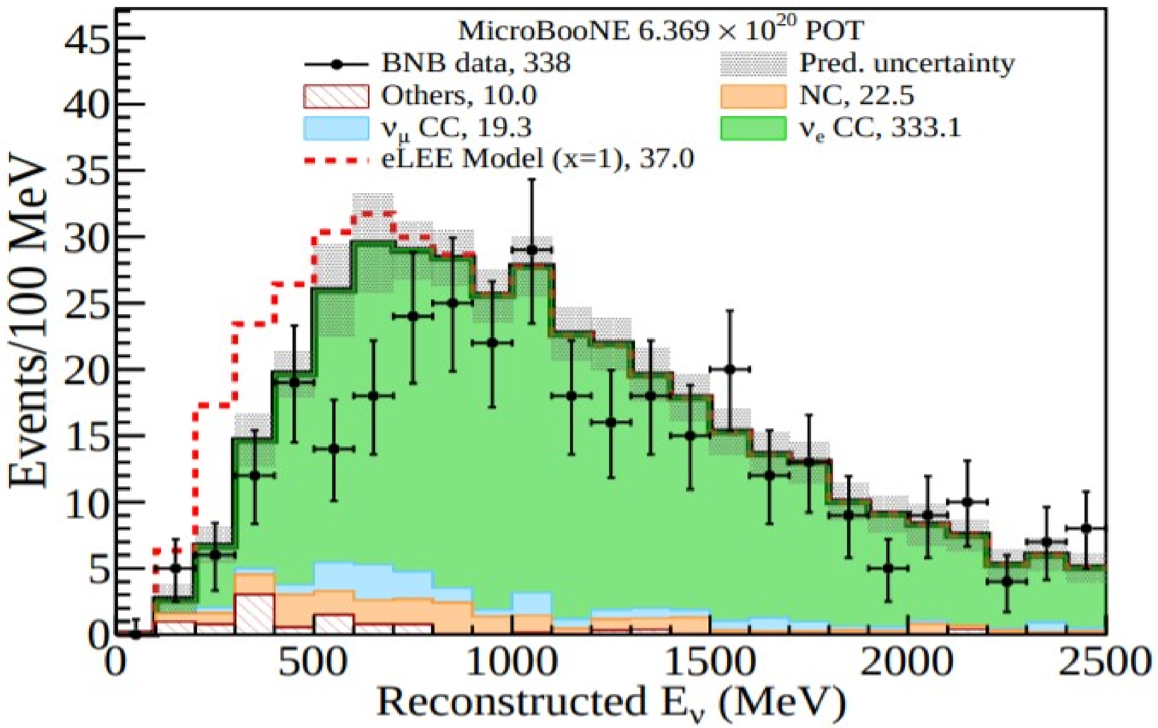
MicroBooNE



- 170 ton LAr TPC
- Operating in the same beam as LSND and miniBooNE
- Capable of reconstructing electrons and photons



Low Energy Excess



Reconstructed energy spectrum for inclusive ν_e event sample

- No sign of excess of low energy electrons or photons.
- ?????
- LSND/MiniBoone are seeing something though. What?
- Doesn’t rule out steriles though.

The Gallium Anomaly

We've discussed the Homestake experiment which studied the reaction

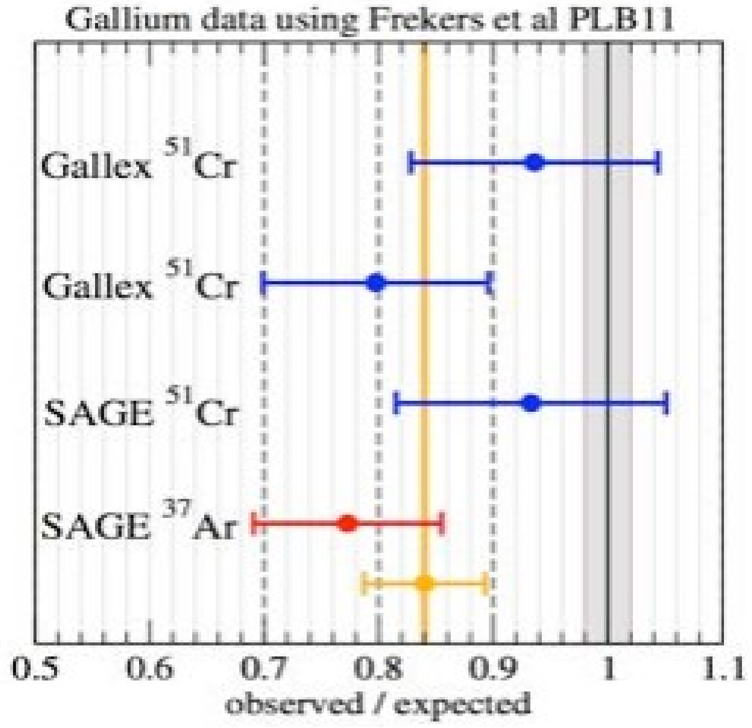
$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e^-$$

A couple of experiments (SAGE and GALLEX) also studied

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}\mathrm{Ge} + e^-$$

In early 2000's the response of GALLEX was being tested using MCi radioactive sources.

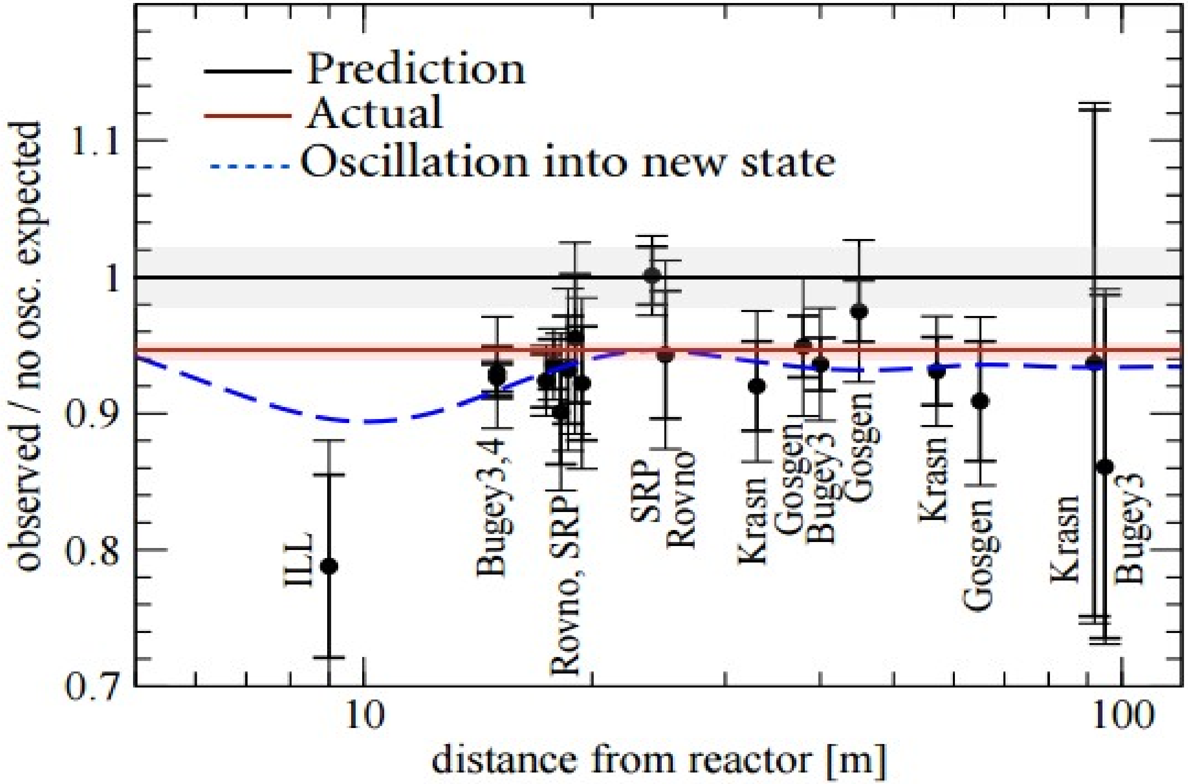
Sources emitted ν_e which were then observed using the standard Ge signature



$$L/E \approx 0.1\,m/0.1\,MeV \rightarrow \Delta m^2 \approx 1\,eV^2$$

(or is it our understanding of the low energy ν-Ga cross section, or is it just bad luck?)

Reactor Anomaly



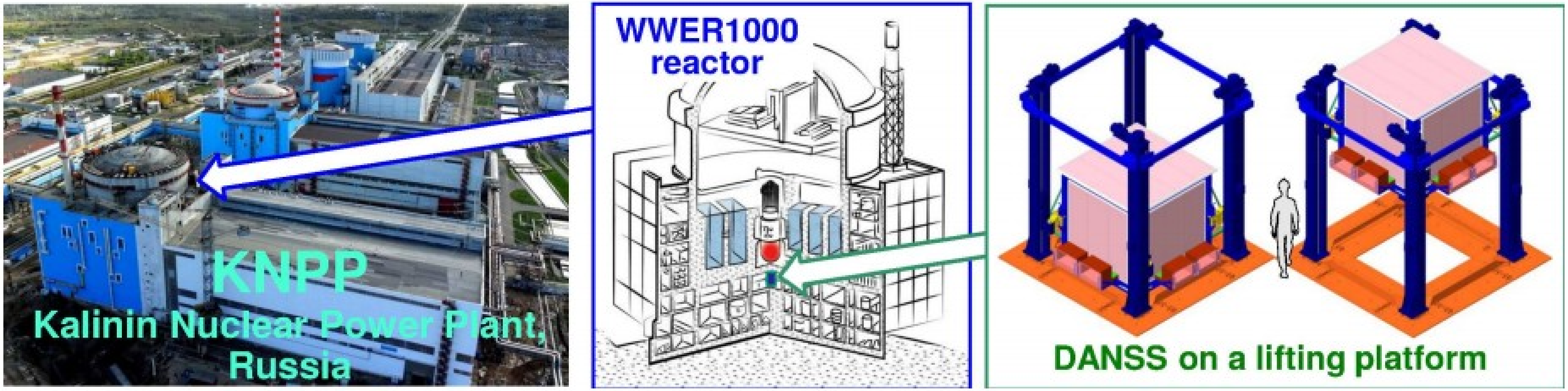
↓ 2.7σ deficit

Deficit consistent with a sterile state with $\Delta m^2 \sim 1.5\ \mathrm{eV}^2$

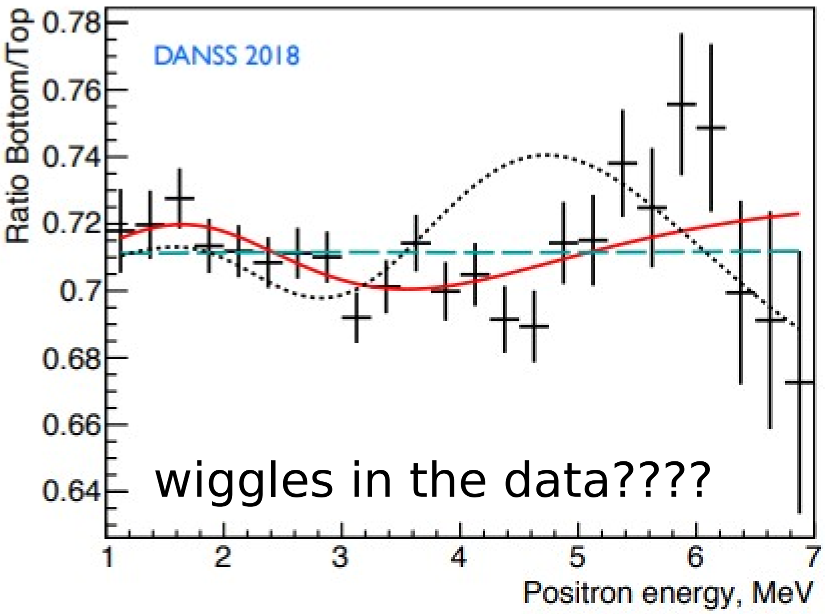
Reactor antineutrino flux calculations are VERY hard to do

It’s almost certain that this is an issue with the calculation of the antineutrino flux NOT steriles.

Reactor Experiments

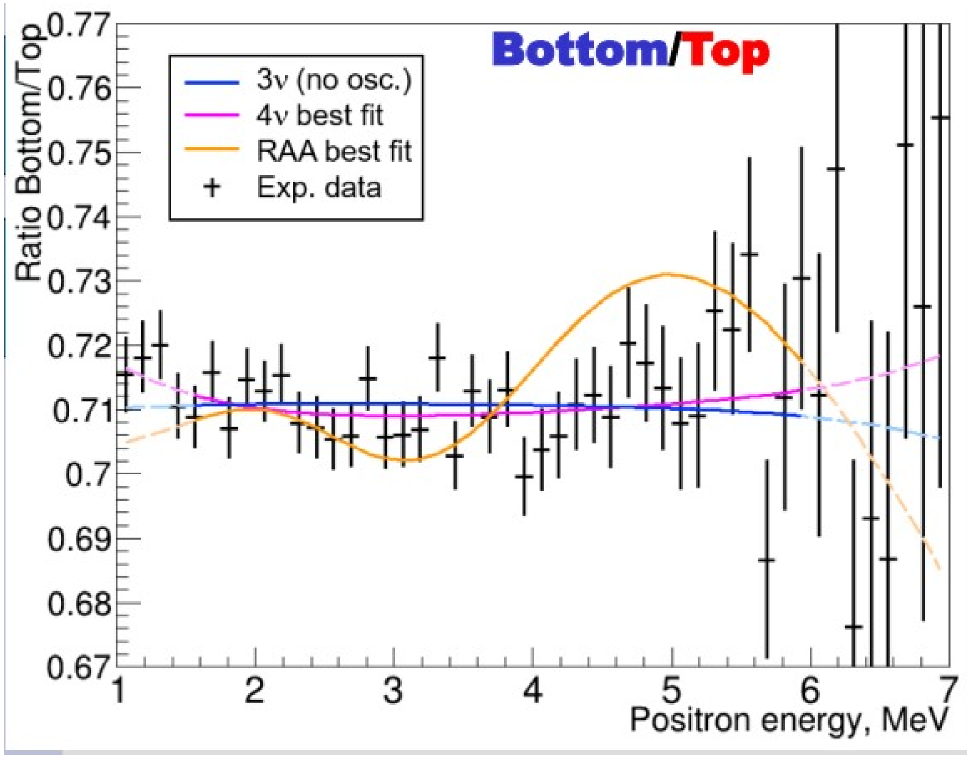


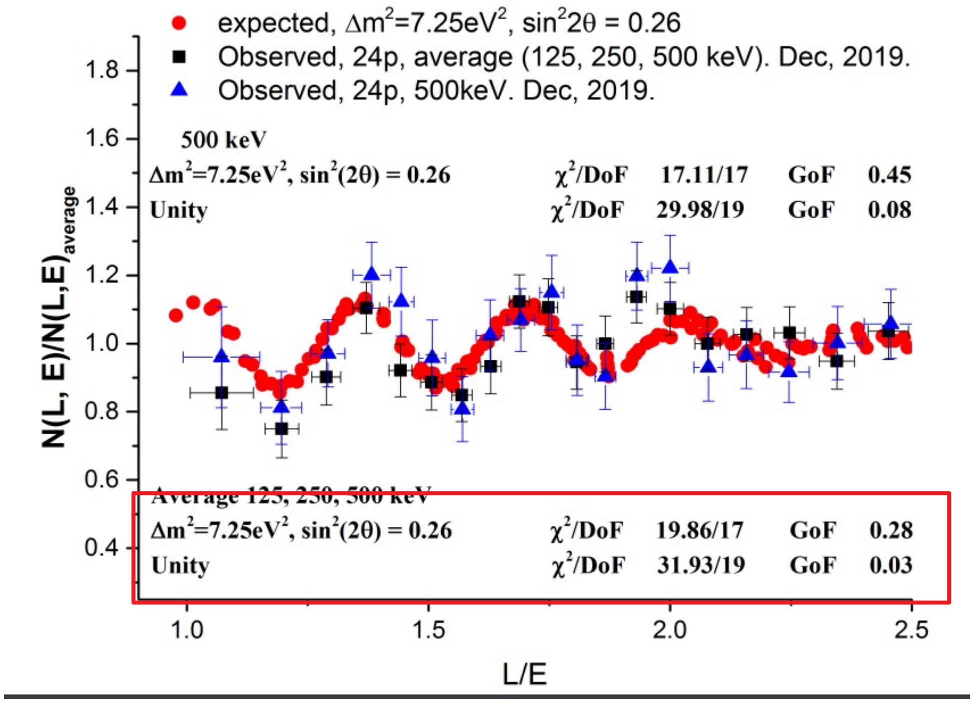
- Installed on a moveable platform under a 3 GW reactor
- Large neutrino flux
- Variable source-distance distance using the same detector
- Down : 12.7 m from reactor
- Up : 10.7 m from reactor



wiggles in the data????

Reactor Experiments





DANSS (2020)
No visible effect

Neutrino4 (2020)
Claimed signal

Situation unclear : other experiments (Stereo, SoLiD, Prospect) don’t see oscillations like this.

Decaying sterile neutrinos?

CPT Violation?

3+1 sterile?
3+2 ?
3+n ?

Lorentz violation?

Extra dimensions?

Experimental problems?

No bleedin' idea

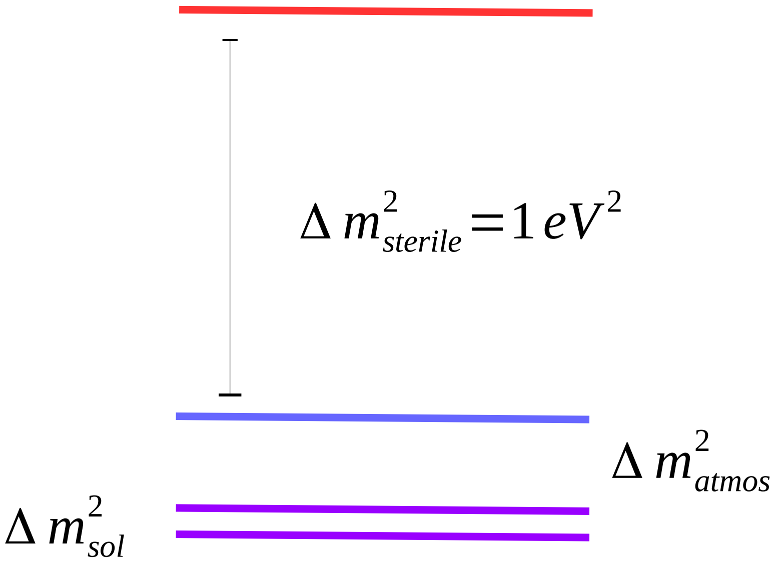
Wait for more data

Summary of sterile hints

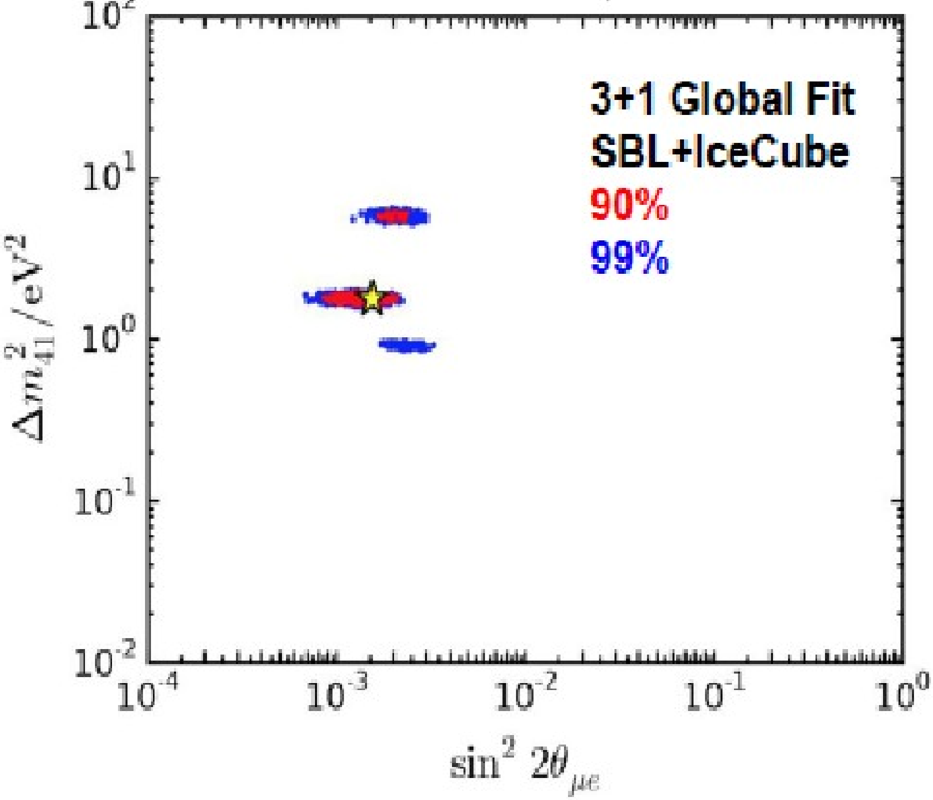
There are odd hints, each at the level of 2-3 σ, that they may be at least one other light sterile state floating around with $\Delta m^2 \sim 1$ eV^2. This is not very easy to fit into the standard model.

It is very hard to find an oscillation model, including steriles, which is consistent with *all* of the data

Current “best model” is a 3+1 model but it doesn't fit very well



Collin et al, arXiv:1607.00011v2



Summary of sterile hints

There are still a couple of odd hints, each at the level of 2-3 σ, that are consistent with the existence of at least one other light sterile state floating around with $\Delta m^2 \sim 1$ eV^2.

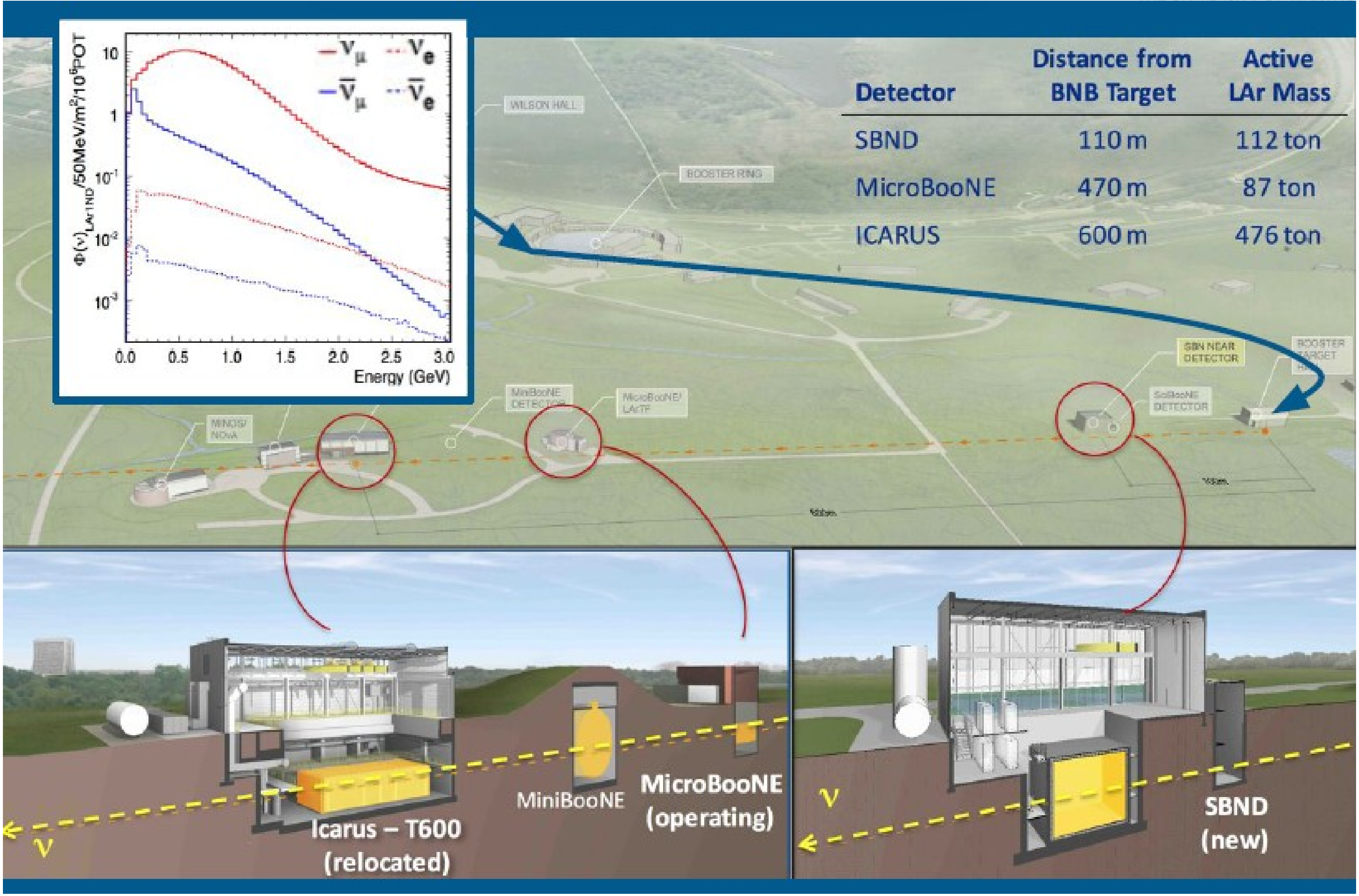
This is not very easy to fit into the standard model.

It is very hard to find an oscillation model, including steriles, which is consistent with *all* of the data

Current “best model” is a 3+1 model but it doesn't fit very well

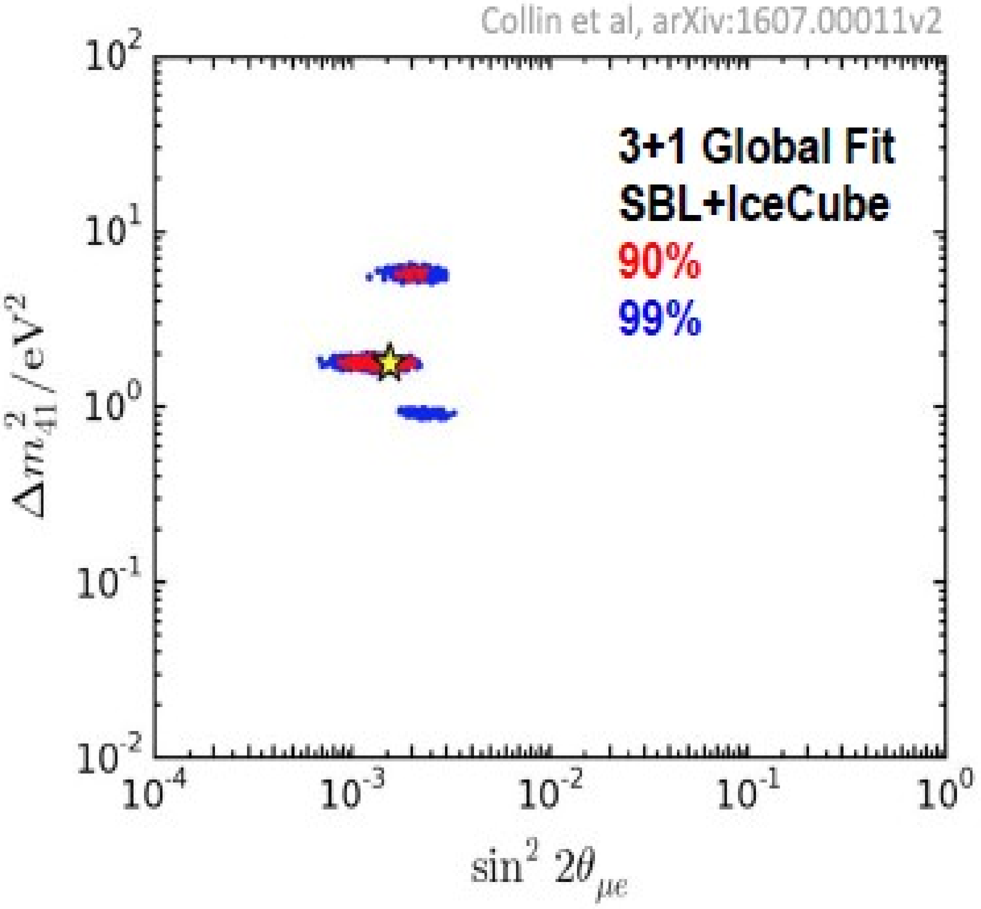
Issue has come off the boil over the last year or so...

SBND

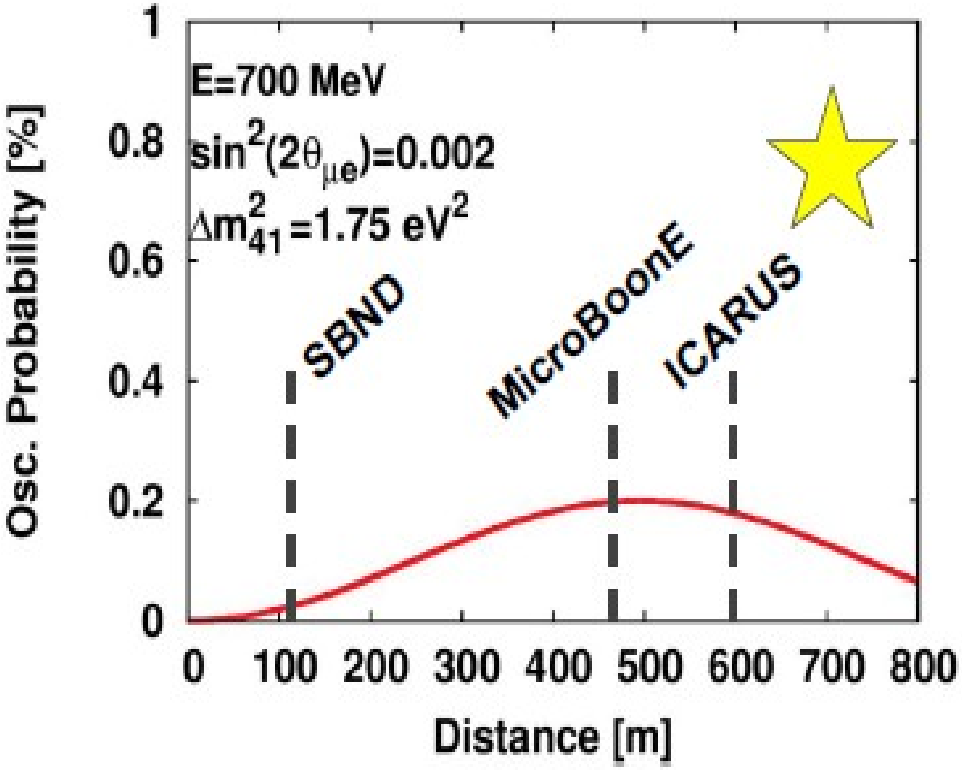


Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

SBND



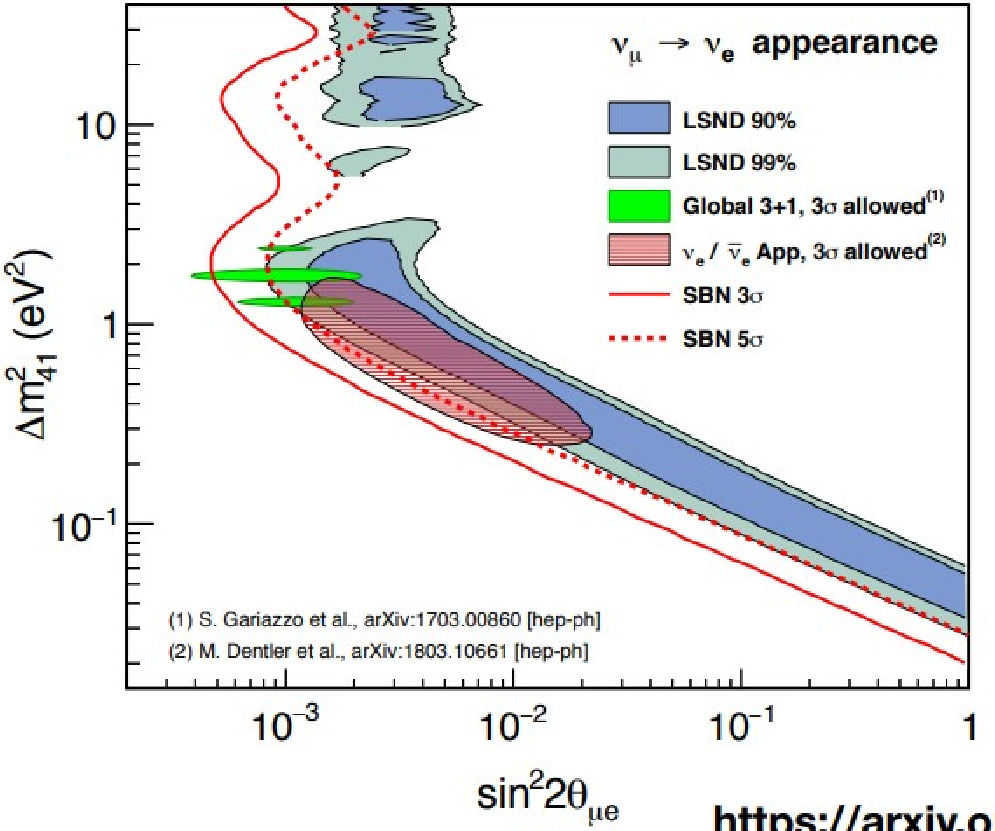
Collin et al, arXiv:1607.00011v2
3+1 Global Fit
SBL+IceCube
90%
99%
$\Delta m^2_{41}/\mathrm{eV}^2$
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
$\sin^2 2\theta_{\mu e}$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}



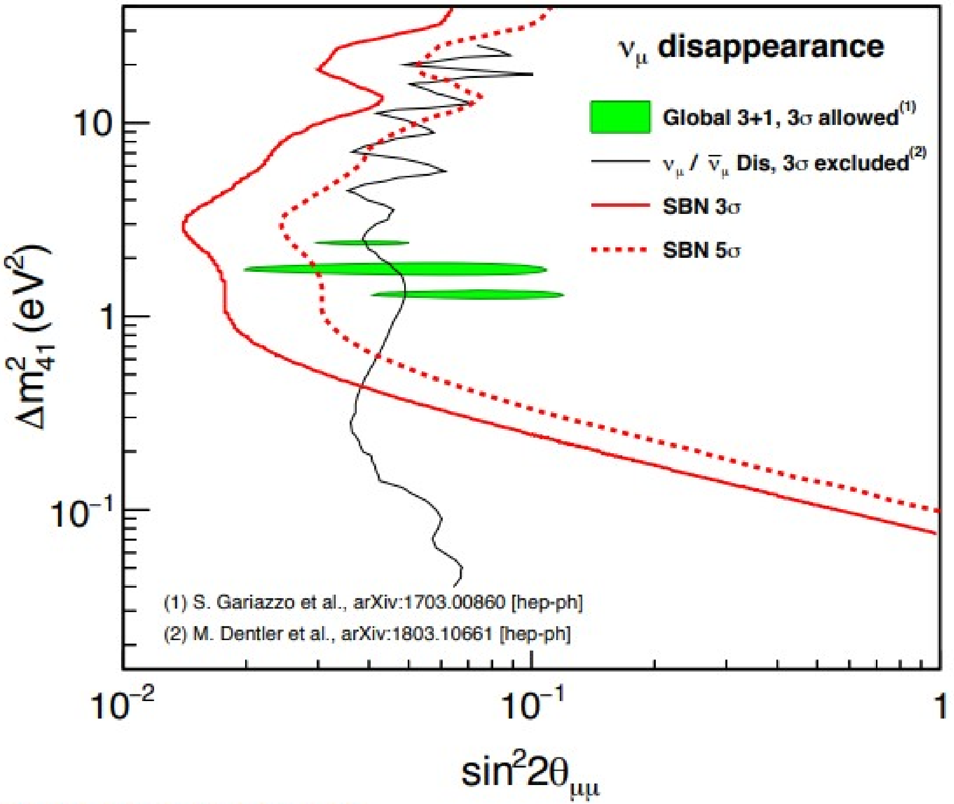
E=700 MeV
$\sin^2(2\theta_{\mu e})=0.002$
$\Delta m^2_{41}=1.75$ eV^2
SBND
MicroBoonE
ICARUS
Osc. Probability [%]
1
0.8
0.6
0.4
0.2
0
Distance [m]
0
100
200
300
400
500
600
700
800

SBND

ν_e appearance



ν_μ disappearance



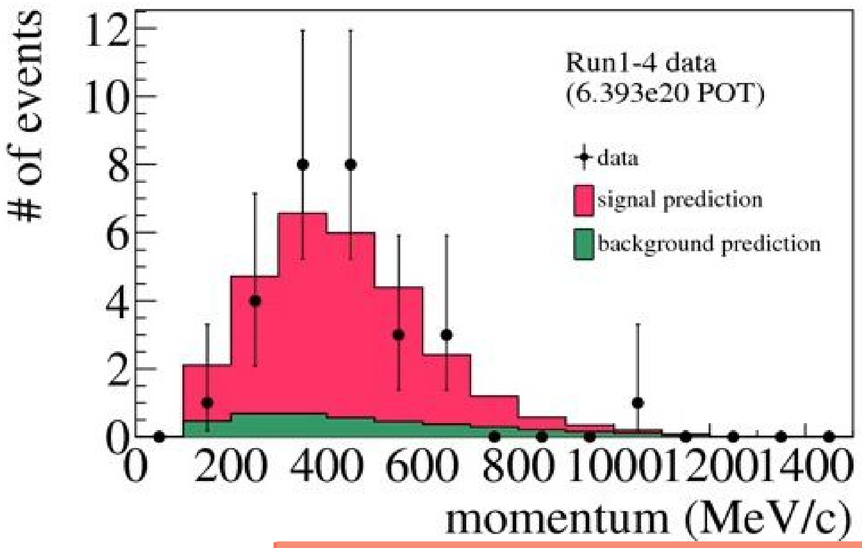
https://arxiv.org/pdf/1903.04608.pdf

- SBN cover much of the parameters allowed by past anomalies at >5σ significance

- Starts taking data soon

Neutrino Cross-sections

Systematic Uncertainties



To do these sort of measurements

Measure number of events at Far Detector

Compare with expected number of events

$$\mathit{Expected\ Number\ of\ events} = \sigma \Phi T \epsilon$$

Cross Section

10-100%

Neutrino Flux

5-10%

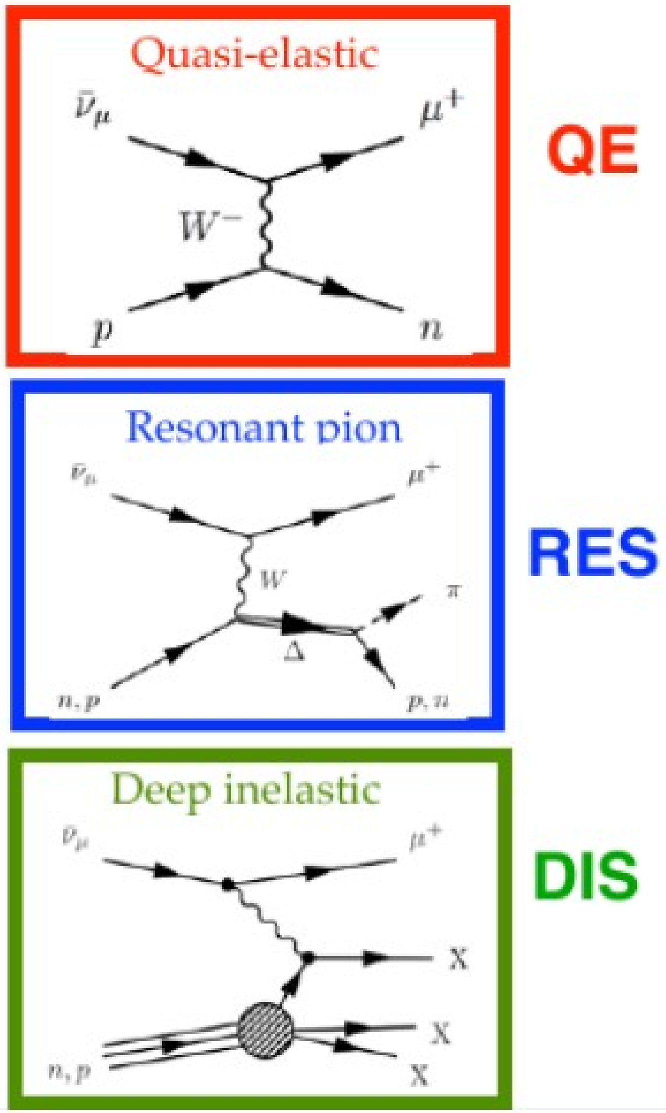
Number of Targets

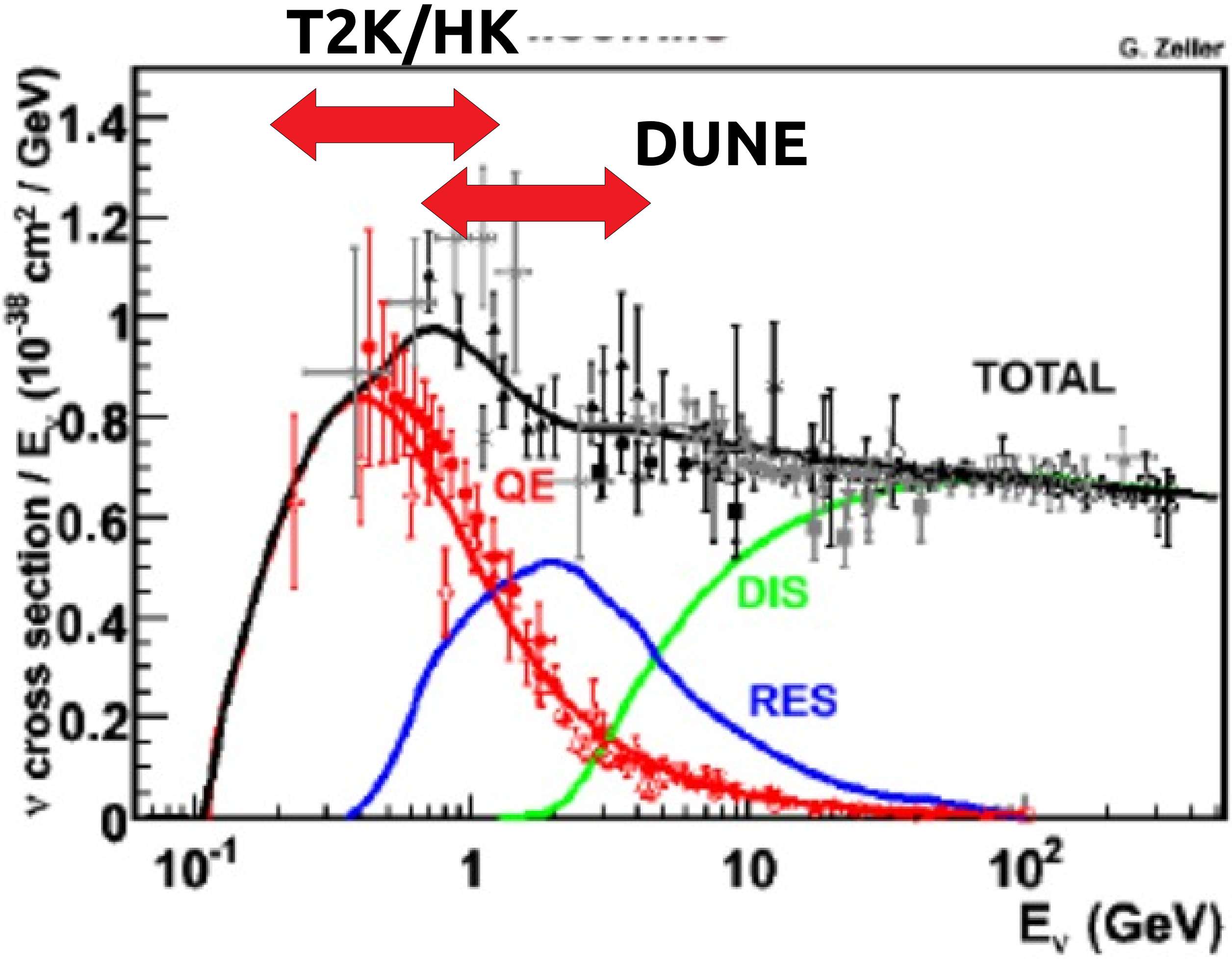
1-2%

Selection Efficiency

10%

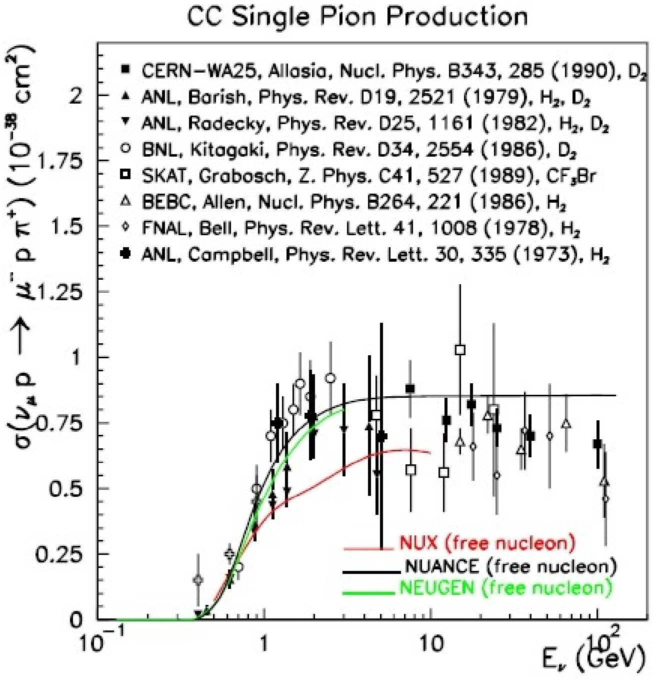
Neutrino Interactions



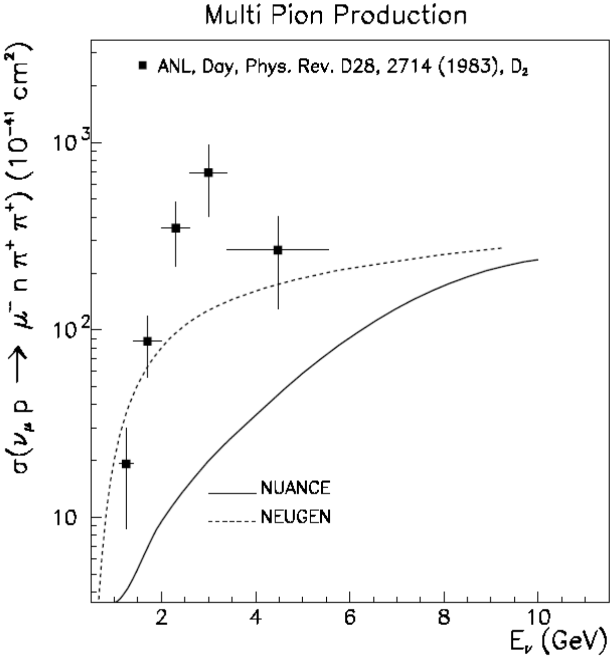


Xsec data pre 2007

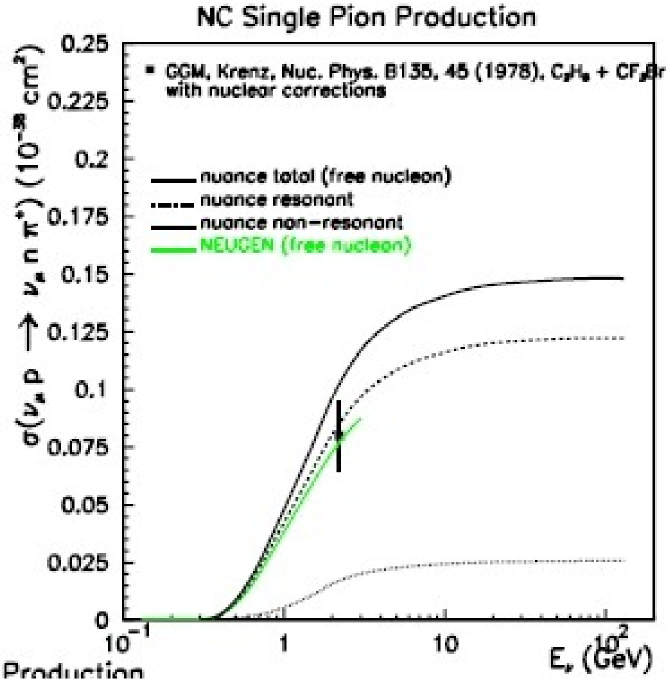
The data was impressively imprecise



$$\nu_{\mu} p \rightarrow \mu^{-} p \pi^{+}$$

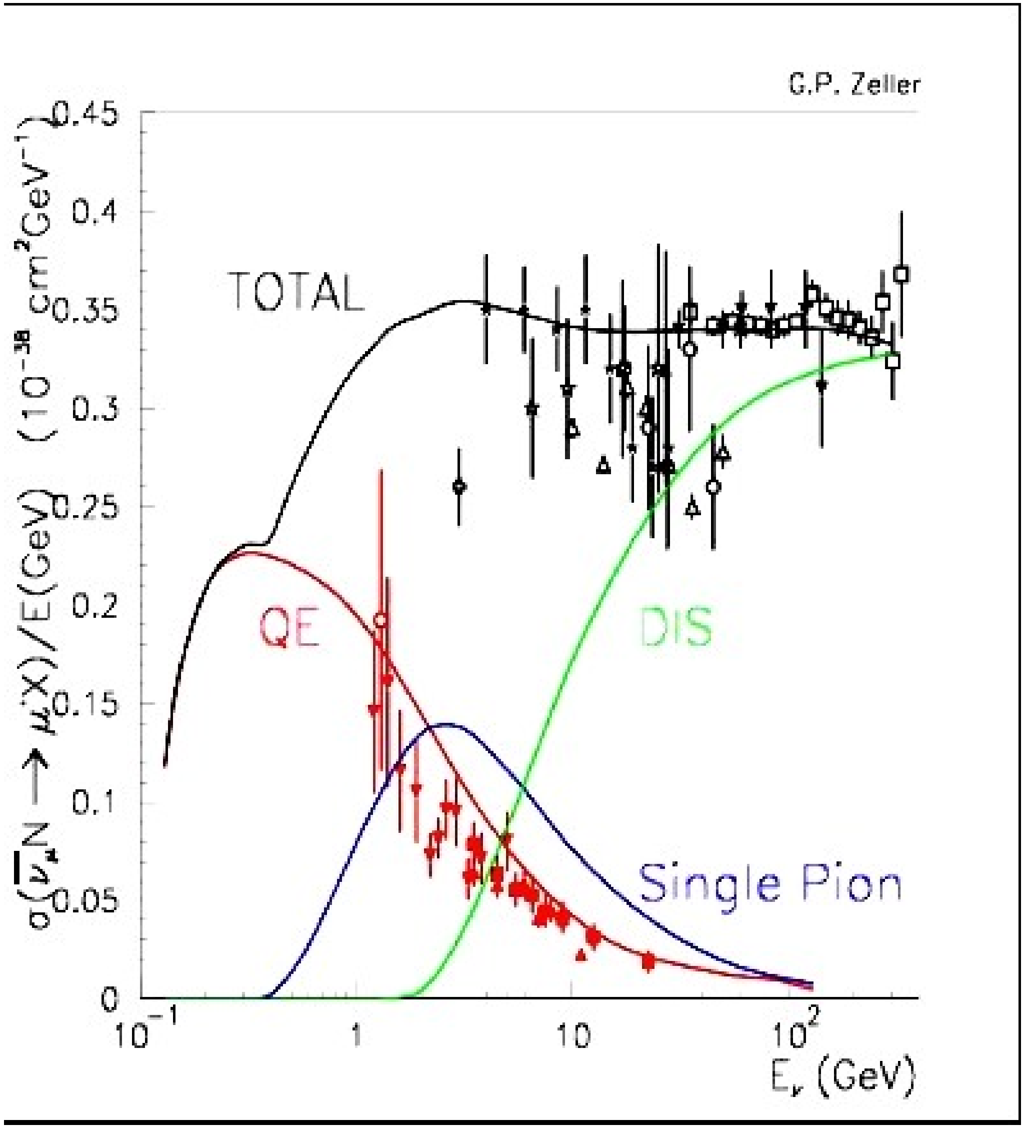


$$\nu_{\mu} p \rightarrow \mu^{-} n \pi^{+} \pi^{+}$$

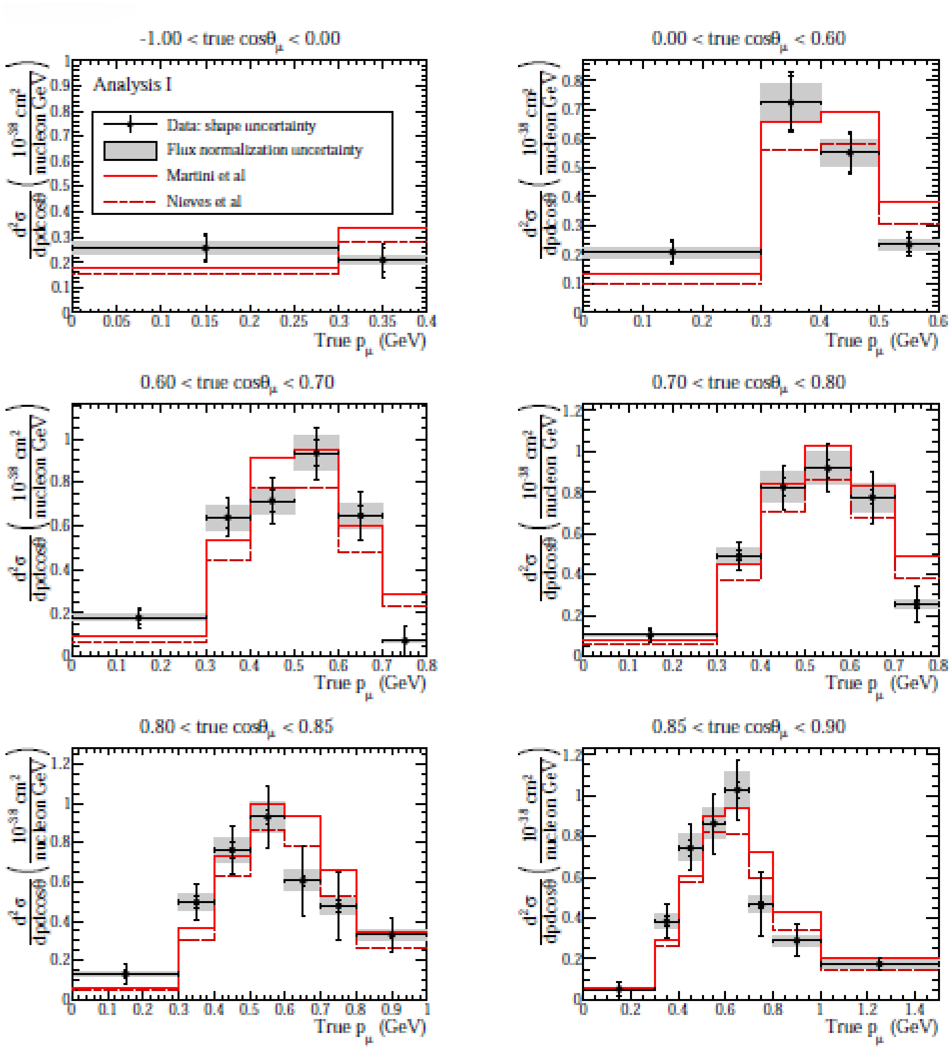


$$\nu_{\mu} p \rightarrow \nu_{\mu} n \pi^{+}$$

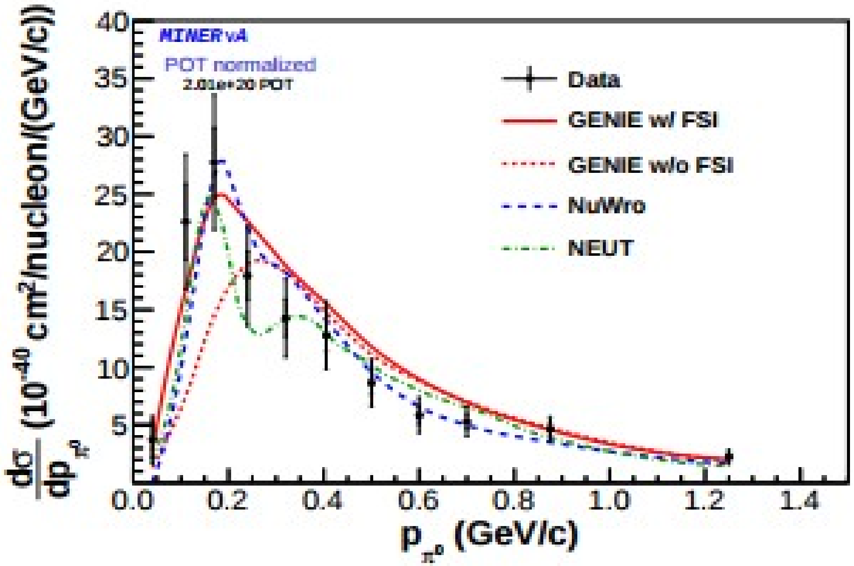
World Data for Antineutrinos



It’s slowly getting better



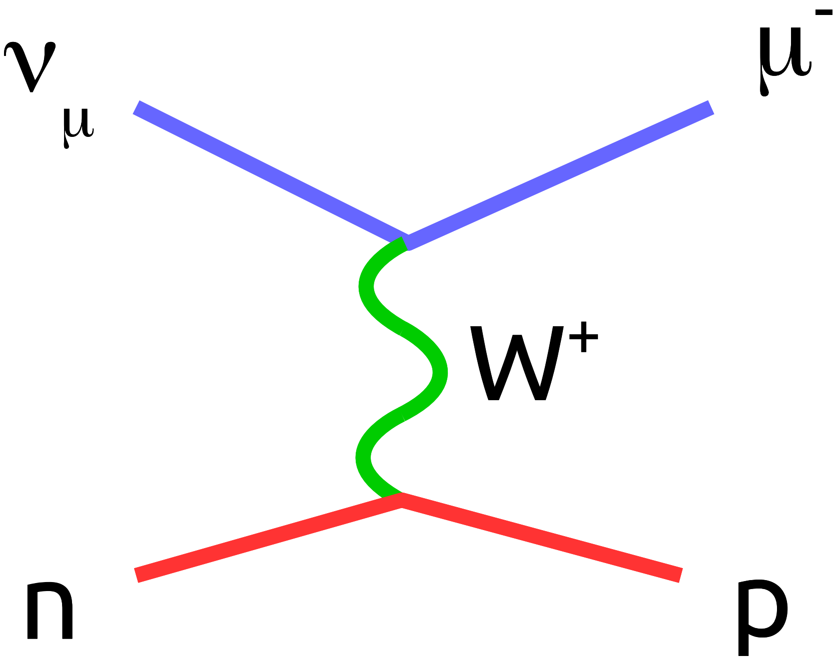
CC 0π differential Xsec from T2K
arXiv:1602.03652



CC π^0 differential xsec from MINERvA
Phys.Lett. B749 (2015) 130-136

Lot's of effort going into trying to understand neutrino interaction cross sections

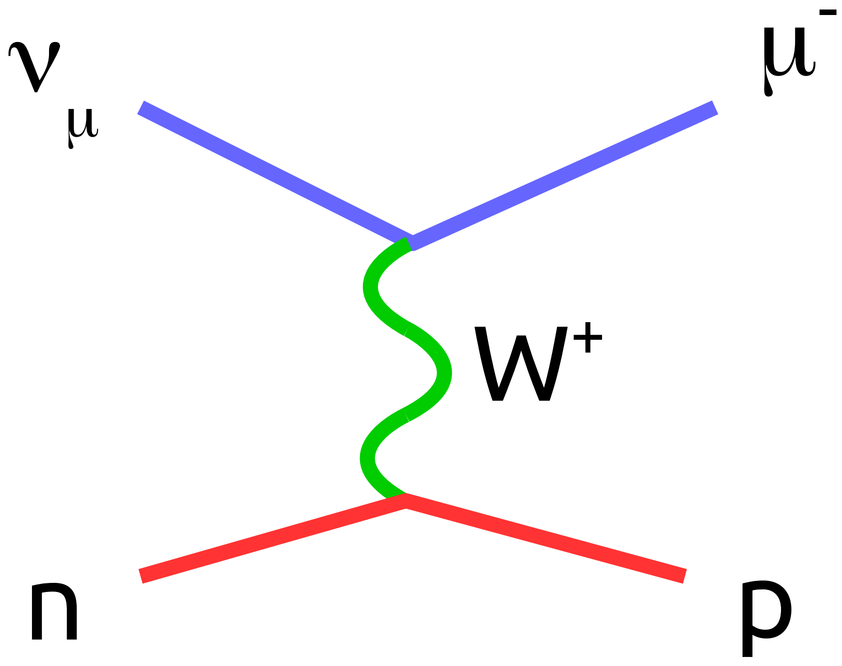
eg : Quasi-Elastic Scattering



- Usually thought of as a single nucleon knock-out process
- In the past has been used as a “standard candle” to normalise other cross sections
- Heavily studied in the 1970's and 1980's and considered to be “understood”

I. Very important for current oscillation experiments as it dominates the total cross section at a few GeV

Quasi-Elastic Scattering

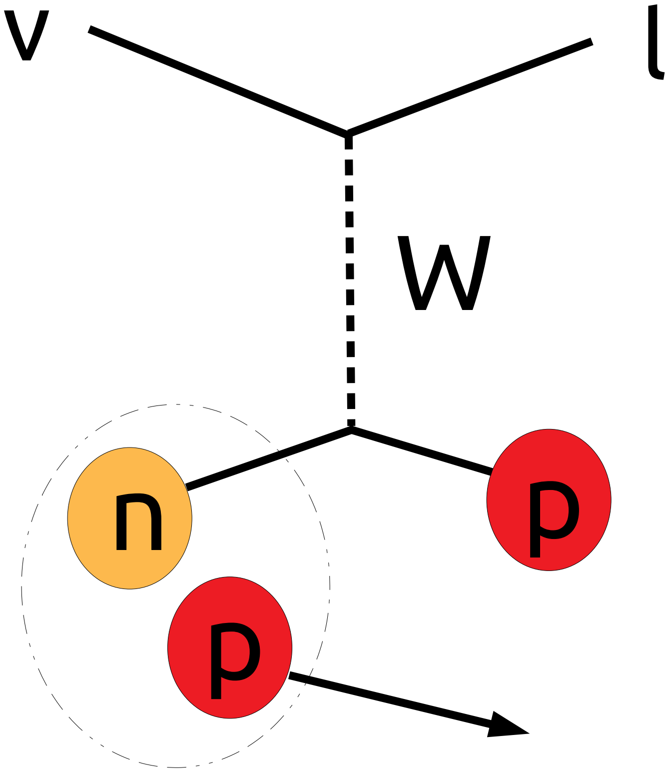


- Usually though of as a single nucleon knock-on process
- In the past has been used as a “standard candle” to normalise other cross sections
- Heavily studied in the 1970's and 1980's and considered to be “understood”

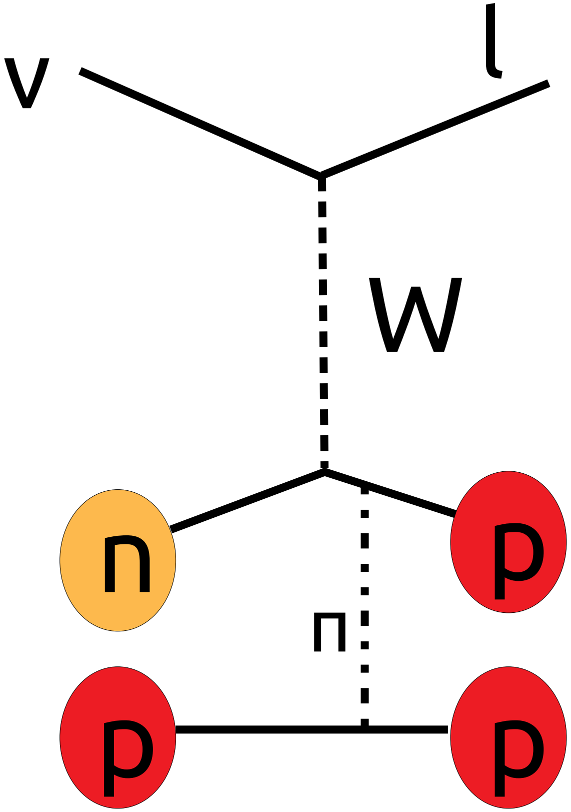
II. Energy reconstruction is unbiased assuming 2 body kinematics

$$E_{\nu;rec} = \frac{2(m_N - E_B)E_\mu - (E_B^2 - 2m_N E_B + m_\mu^2)}{2(m_N - E_B - E_\mu + |p_\mu| \cos\theta_\mu)}$$

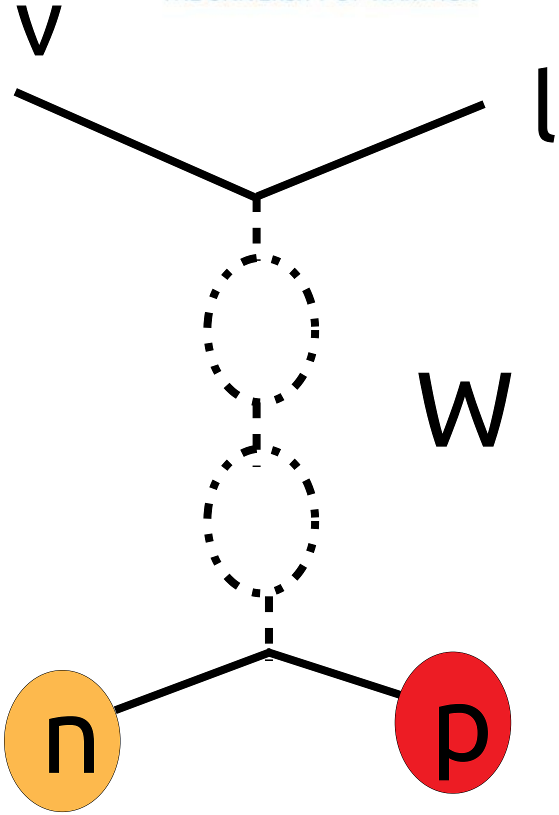
Nuclear Effects



Short-range correlations (SRC)



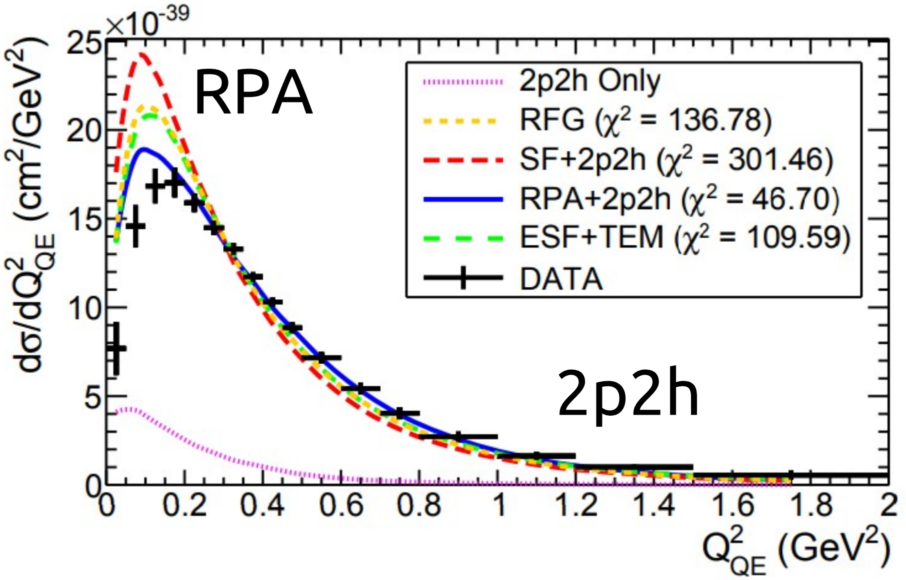
Meson Exchange Currents (MEC)

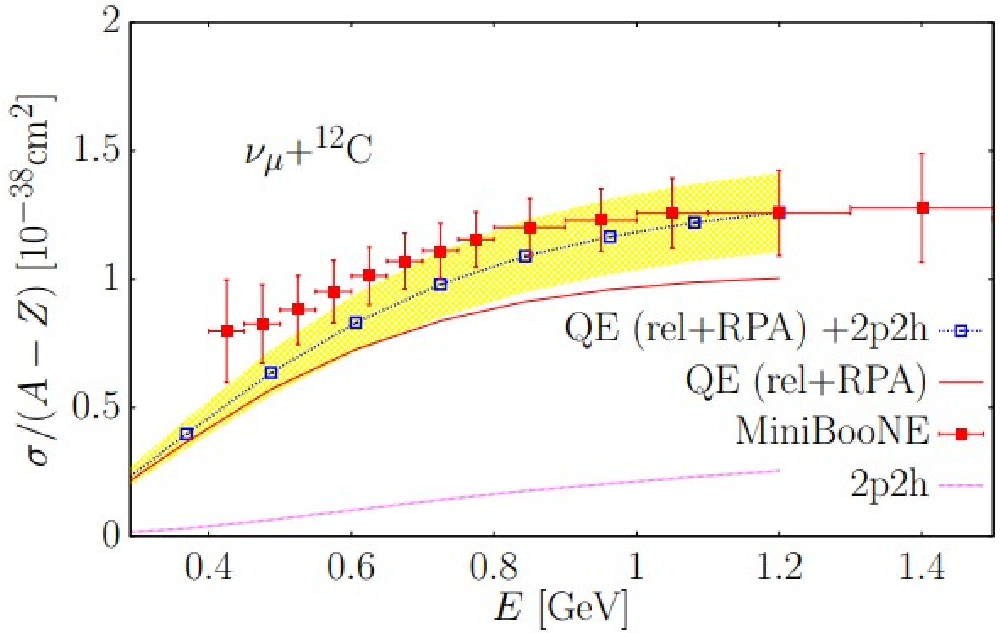


RPA effects
W polarisation changes strength of weak interaction

2p2h processes - medium to high Q^2

Effect of nuclear corrections

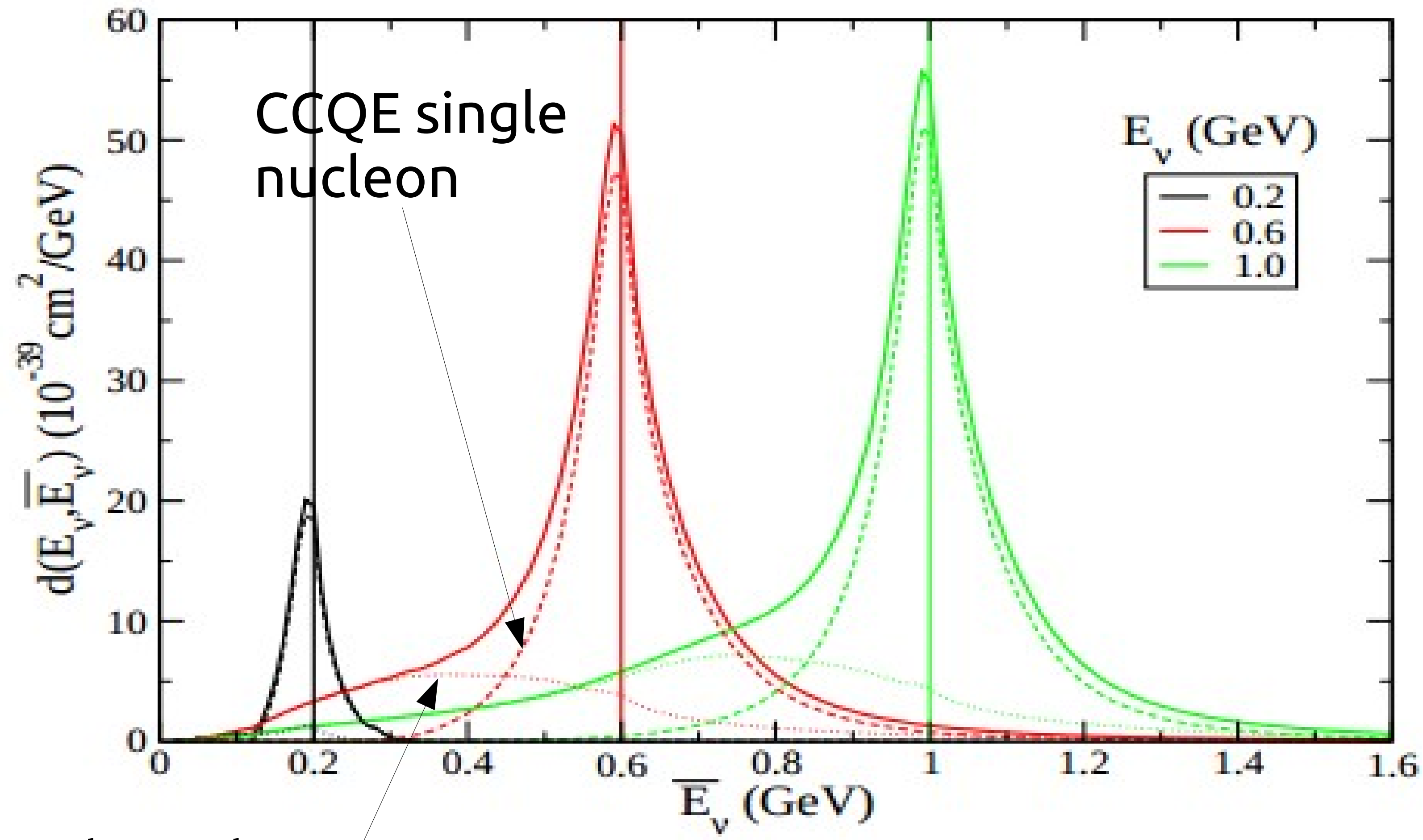




- Models change Q^2 shape in different regions

- Models add a new channel which increases the total cross section

Effect on energy reconstruction

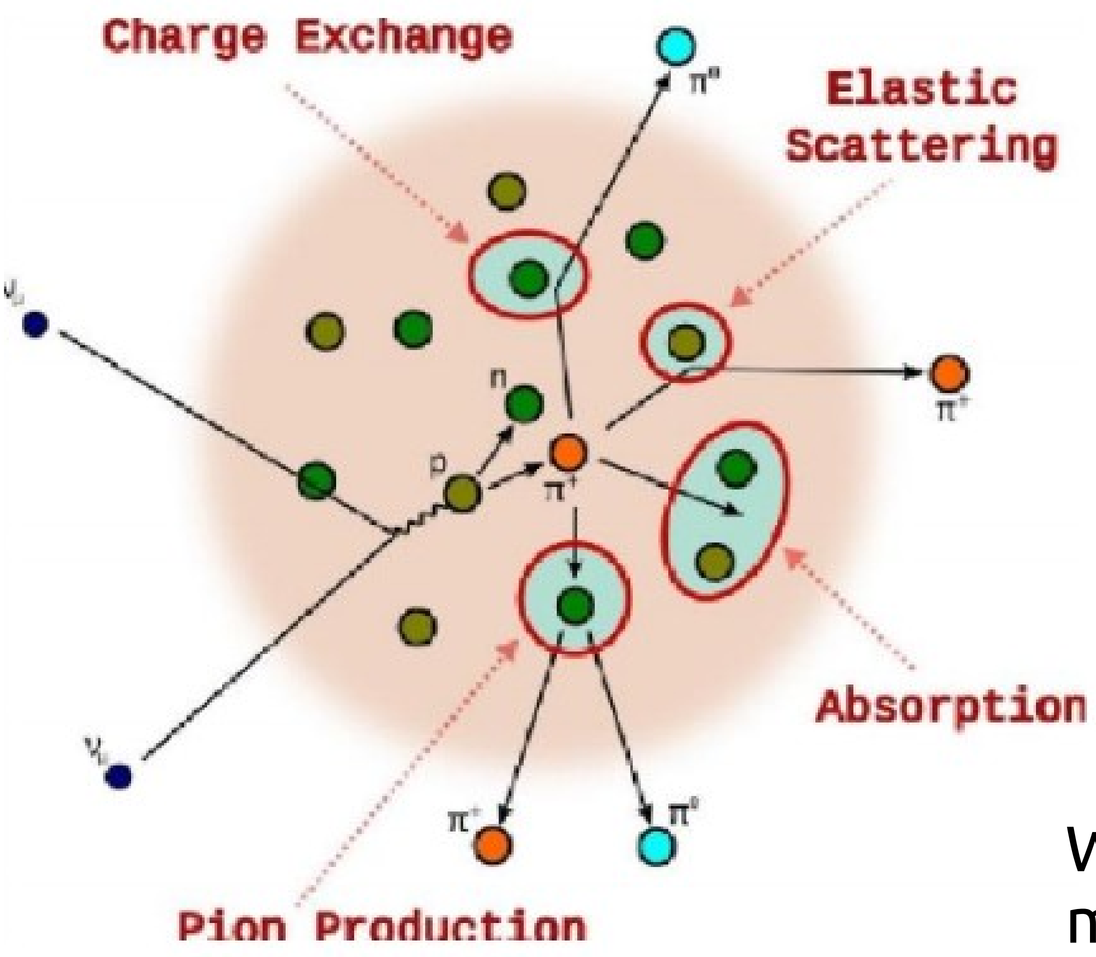


CCQE single nucleon

Multinucleon

Martini et al, arxiv : 1211.1523

Final State Interactions



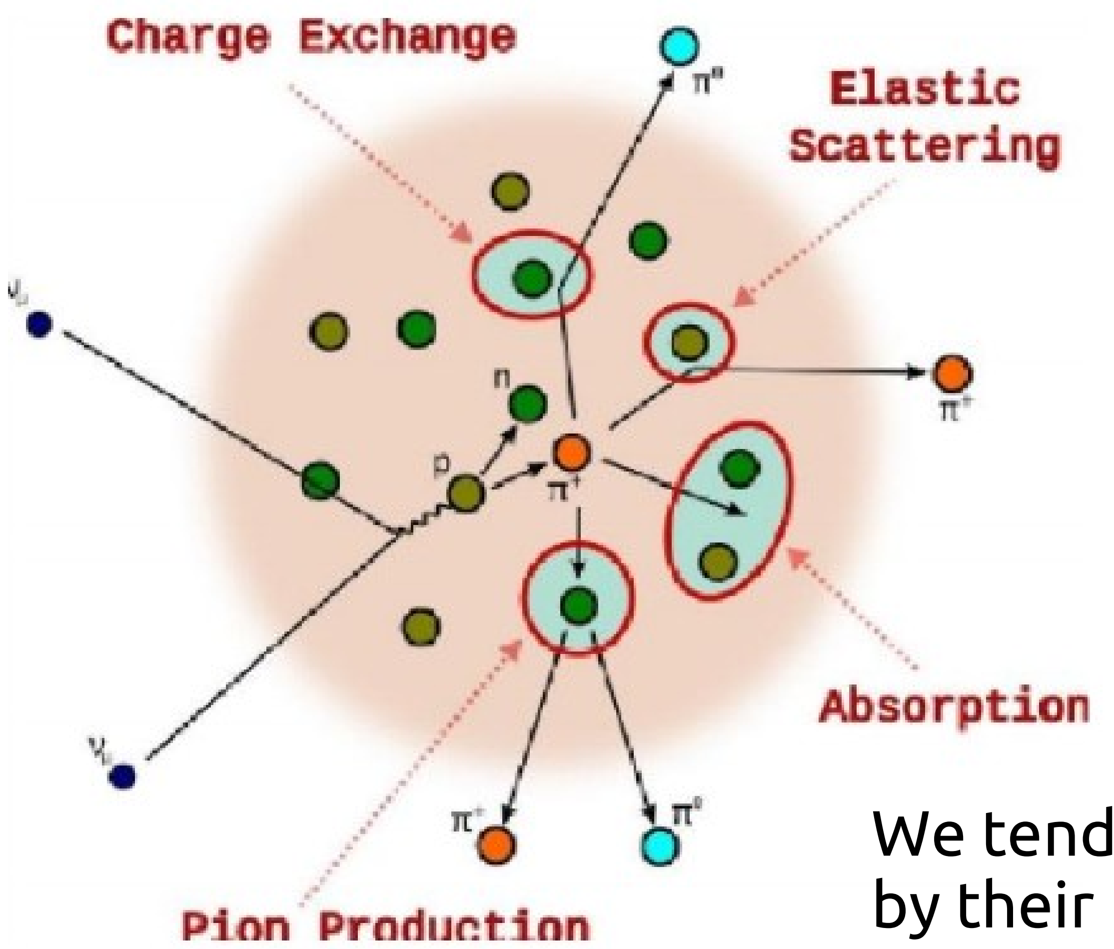
In the nuclear medium

- Outgoing protons can
  - Scatter
  - Lose energy

- Outgoing pions can
  - scatter
  - be absorbed
  - create more pions
  - charge exchange

What you see in the detector may not be what happened at the interaction point

Final State Interactions



In the nuclear medium

- Outgoing protons can
    - Scatter
    - Lose energy
- Outgoing pions can
    - scatter
    - be absorbed
    - create more pions
    - charge exchange

We tend to categorise events
by their final state content now
rather than their theoretical “label”

Lesson learned….

- It’s taken T2K more than 10 years to understand the simplest neutrino interaction – and we still don’t really understand the hadronic side of any interaction.
- We have managed to halve the systematic uncertainty from the model.
- Any experiment at different energies or using different types of nuclei as targets will have similar problems.
- I’m looking at you, DUNE
- DUNE operates at 3 GeV – the region of resonance production which hasn’t had anywhere near as much theoretical attention as QE at T2K energies has – and uses Argon.
- DUNE does have the advantage that its Far Detector and Near Detector have the same target material (Ar) so the relative effects sort-of cancel.

Concluding Remarks

The neutrino is : light, neutral, left-handed (chiral) and almost left-handed (helicity). It is generated purely in weak interactions (which is why it is chiral). Their cross sections are tiny and we need big detectors to look at them. They mix and can undergo flavour oscillations.

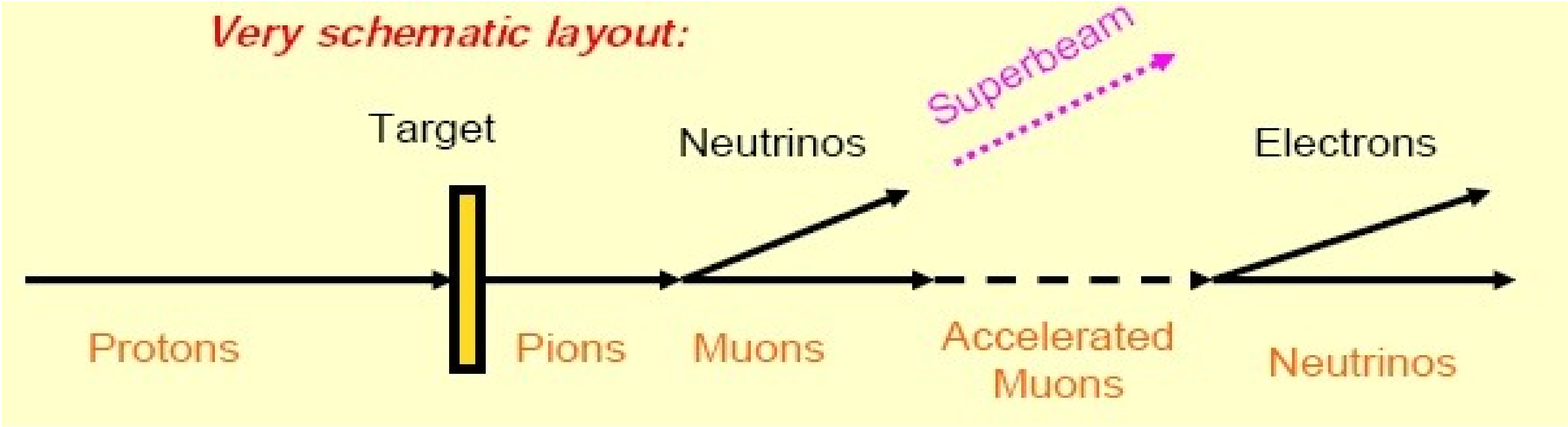
They may be the reason that we are here at all.

But...what is their mass? Why is it so small? Why are the mixing parameters so odd? Is there a 1 eV sterile state? Is it Majorana? If not – then how do you explain mass without the Higgs? What is the CP violating phase?

Still lots of questions remain – watch this space.....

Neutrino Factories

In a conventional beam the neutrinos from pion decay
In a neutrino factory the neutrinos come from muon decay

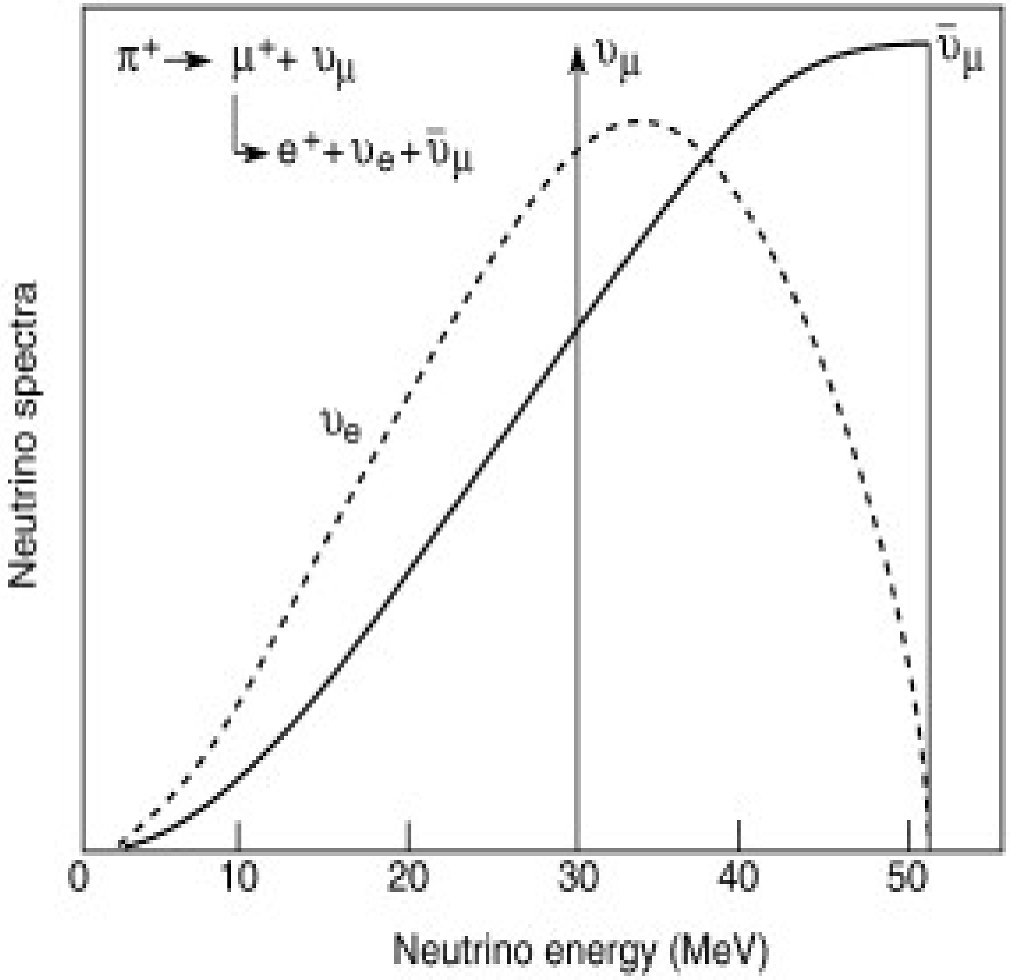


$$\mu^- \rightarrow \nu_\mu \overline{\nu_e} e^-$$

$$\mu^+ \rightarrow \overline{\nu_\mu} \nu_e e^+$$

Beam is very clean
50% ν_μ, $\overline{\nu}_e$
Extremely high flux
Precise and predictable energy spectrum

Neutrino Spectra & Event rates



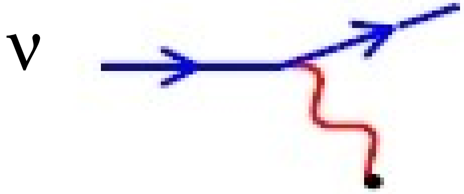
Event rate : 20 million events per 100 g per cm^2 of material per year

T2K Equivalent : 120 per 100g per cm^2 per year

Fantastic for neutrino interaction studies

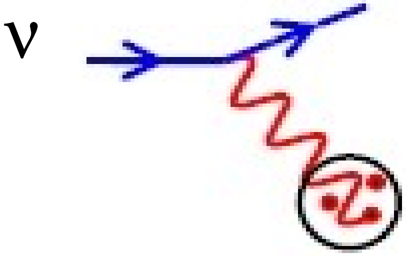
A neutrino can see....

- Very low Q^2, $\lambda > r_p$, and scattering is off a “point-like” particle

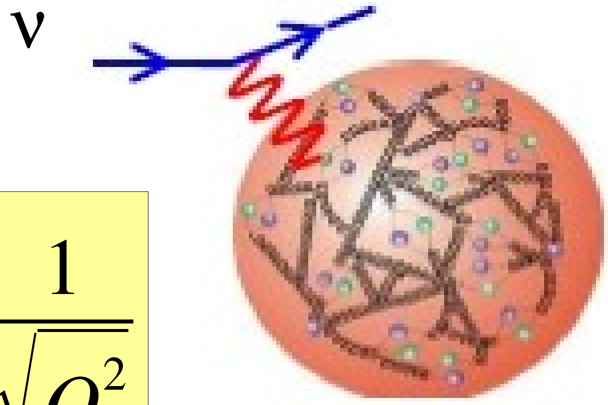


- Low Q^2, $\lambda \sim r_p$, scattering is off an extended object

- High Q^2, $\lambda < r_p$, can resolve quark in the nucleon



- Very High Q^2, $\lambda << r_p$, can resolve sea of quarks and gluons in nucleon

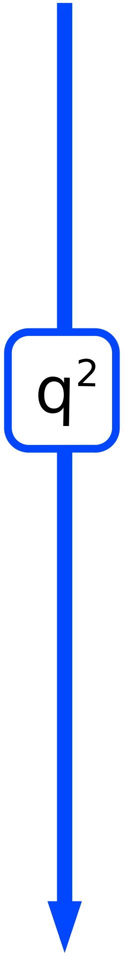


$$\lambda = \frac{1}{p} \sim \frac{1}{\sqrt{Q^2}}$$

Neutrino-Nucleon Interactions

CC – W$^{\pm}$ exchange

- Quasi-elastic Scattering
  Target changes but no breakup
  $\nu_\mu + n \rightarrow \mu^- + p$
- Coherent/Diffractive production
  Target unchanged
  $\nu_\mu + n \rightarrow \mu^- + n + \pi^+$
- Nuclear resonance production
  Target goes to excited state and decays
  $\nu_\mu + n \rightarrow \mu^- + p + \pi^0$ (N* or Δ)
  $n + \pi^+$
- Deep Inelastic Scattering
  Target breaks up
  ν_μ + quark → μ^- + quark'

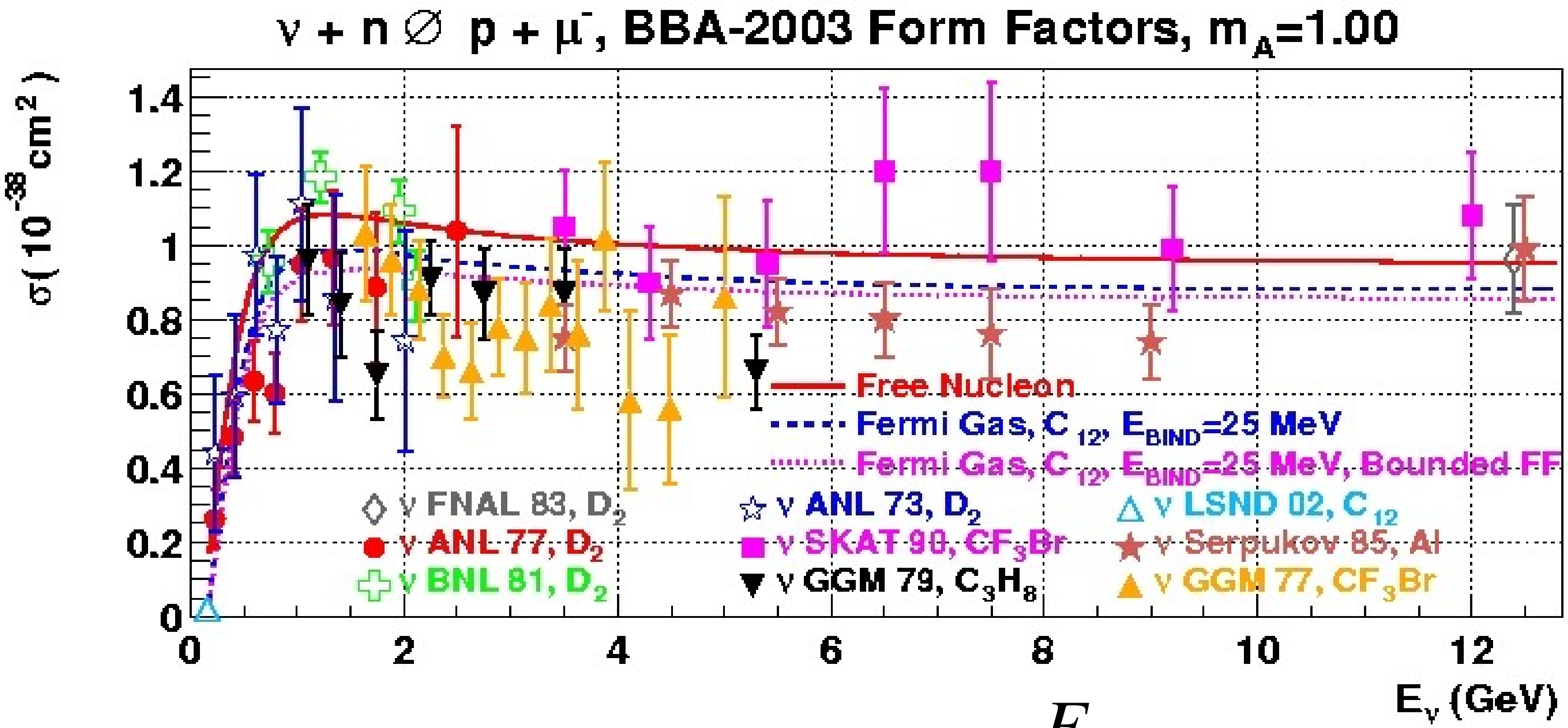


NC – Z^0 exchange

- Elastic Scattering
  Target unchanged
  $\nu_\mu + n \rightarrow \nu_\mu + n$
- Coherent/Diffractive production
  Target unchanged
  $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$
- Nuclear resonance production
  Target goes to excited state and decays
  $\nu_\mu + N \rightarrow \nu_\mu + N + \pi$ (N* or Δ)
- Deep Inelastic Scattering
  Target breaks up
  ν_μ + quark → ν_μ + quark

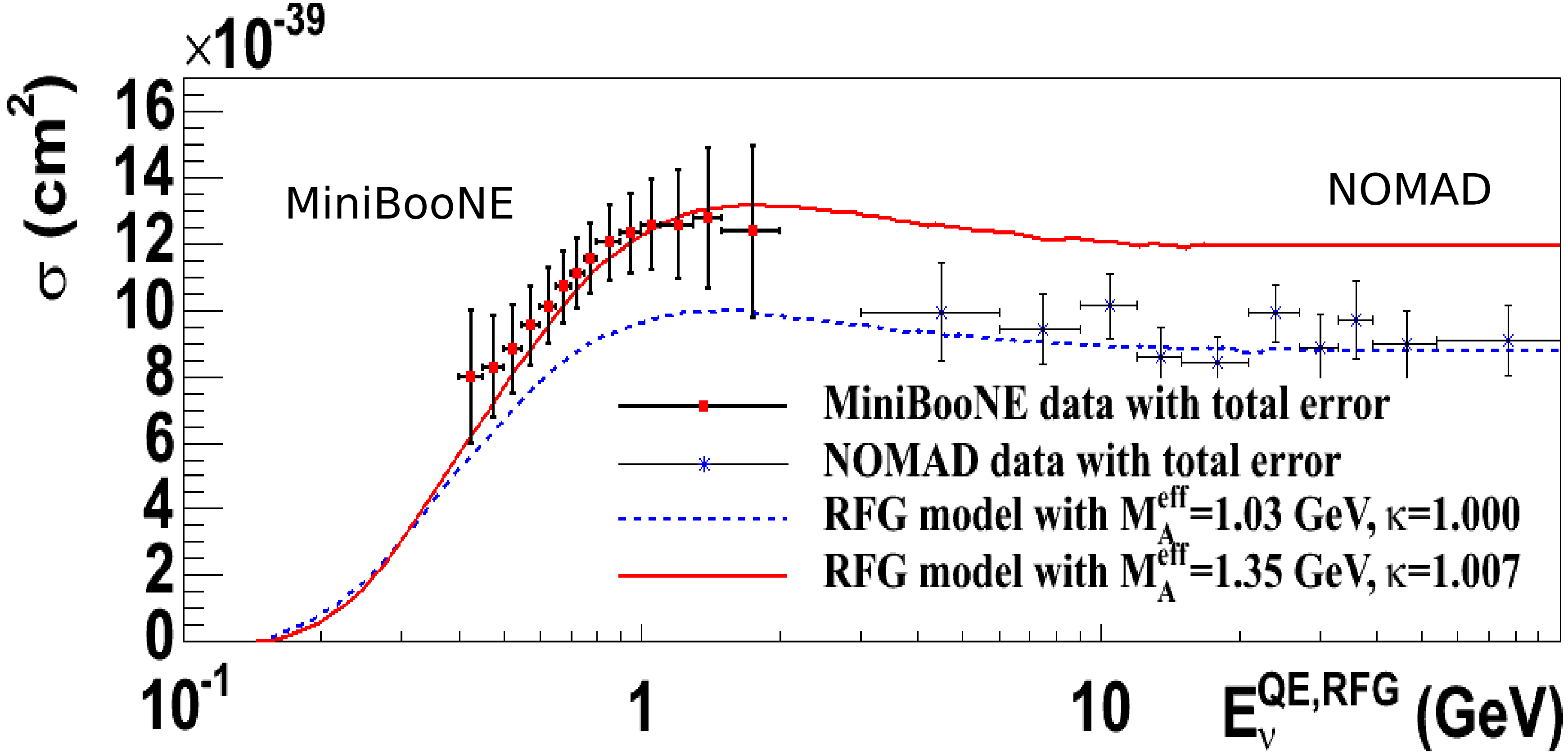
Problems with QE

The CC QE process is the best known neutrino process occurring at a few GeV



$$\sigma_{QE} \sim 0.975 \times 10^{-38} \left(\frac{E_\nu}{1\,GeV} \right) cm^2$$

It's getting better

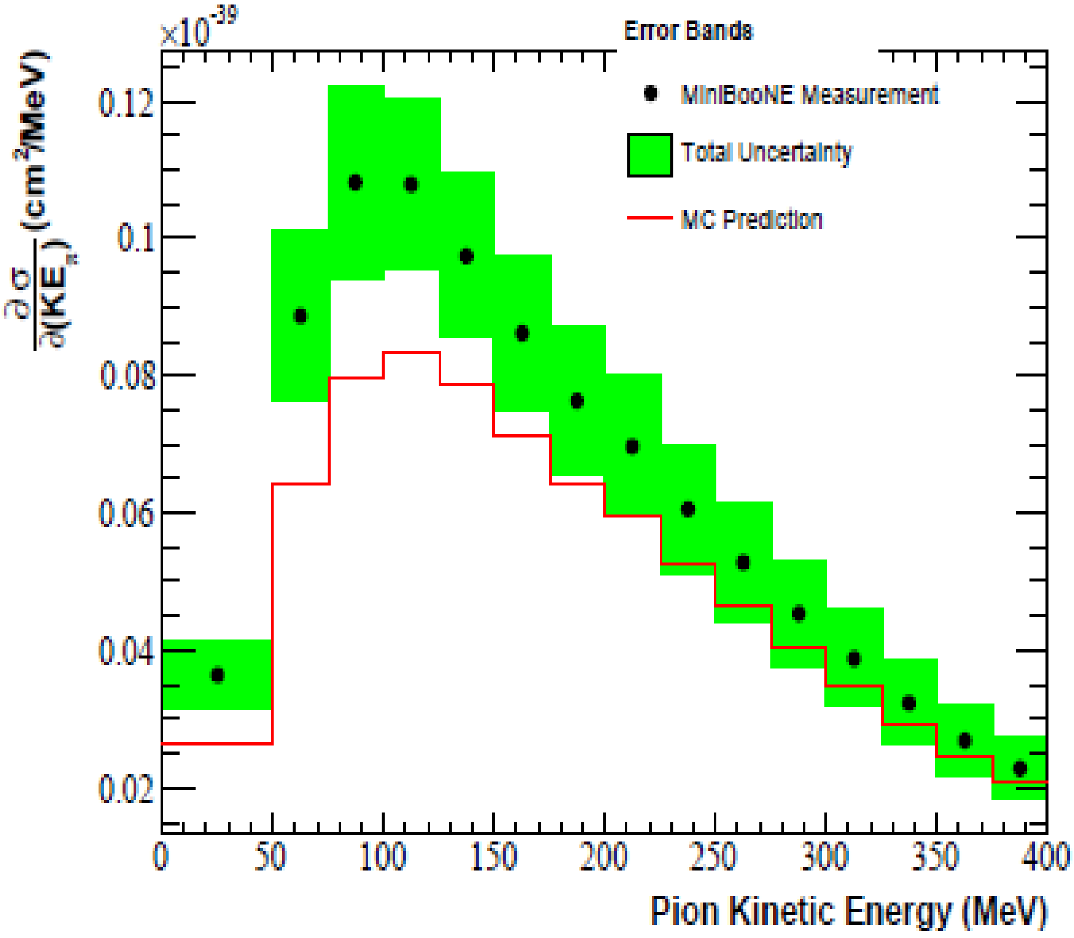


Note tension between low and high energy measurements

Both on carbon target

Y. Nakajima *NuInt11*

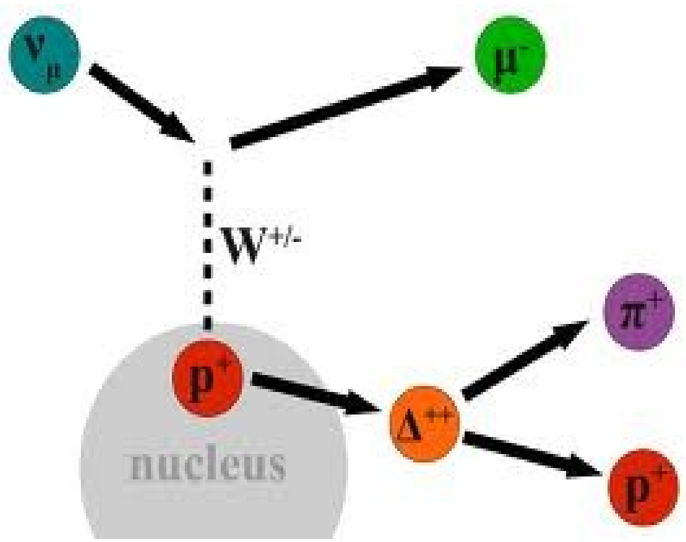
Sort-of getting better



- Cross section for CC ν interactions producing a single π exiting the nucleus
- Data from NOMAD, SciBooNE, T2K & K2K also available or becoming available

MiniBooNE

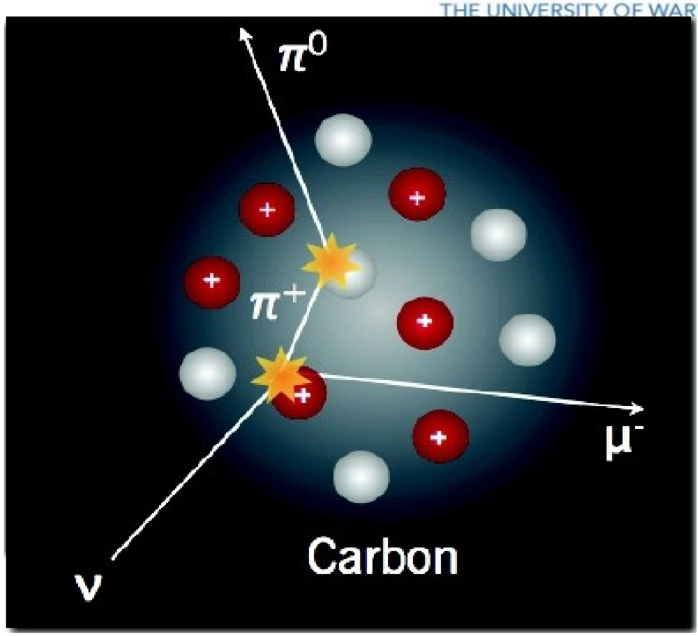
Resonance and Nuclear Effects



Nuclear rescattering

→

Charge exchange

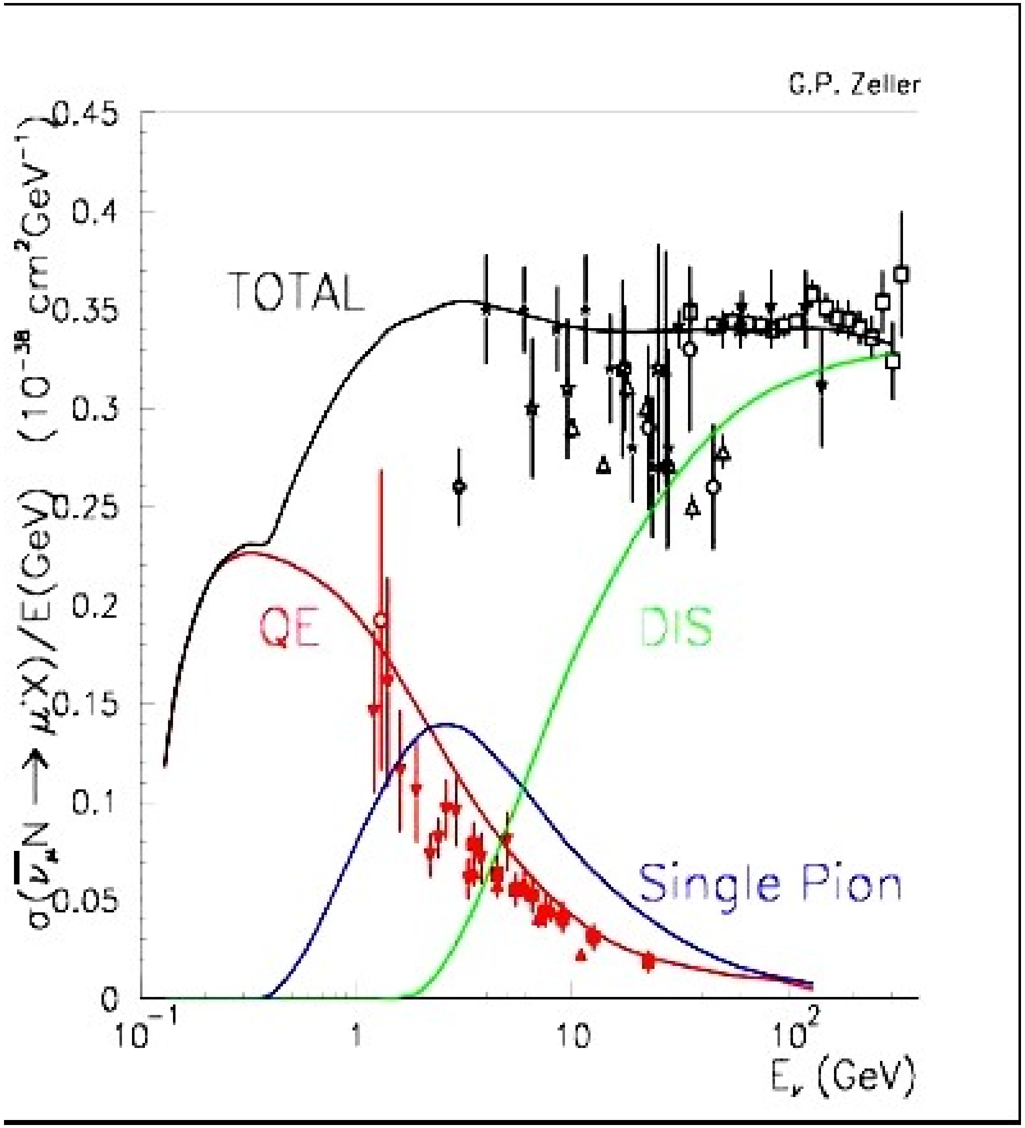


$$\nu_\mu + p \rightarrow \Delta^{++} \rightarrow \pi^+ + p$$

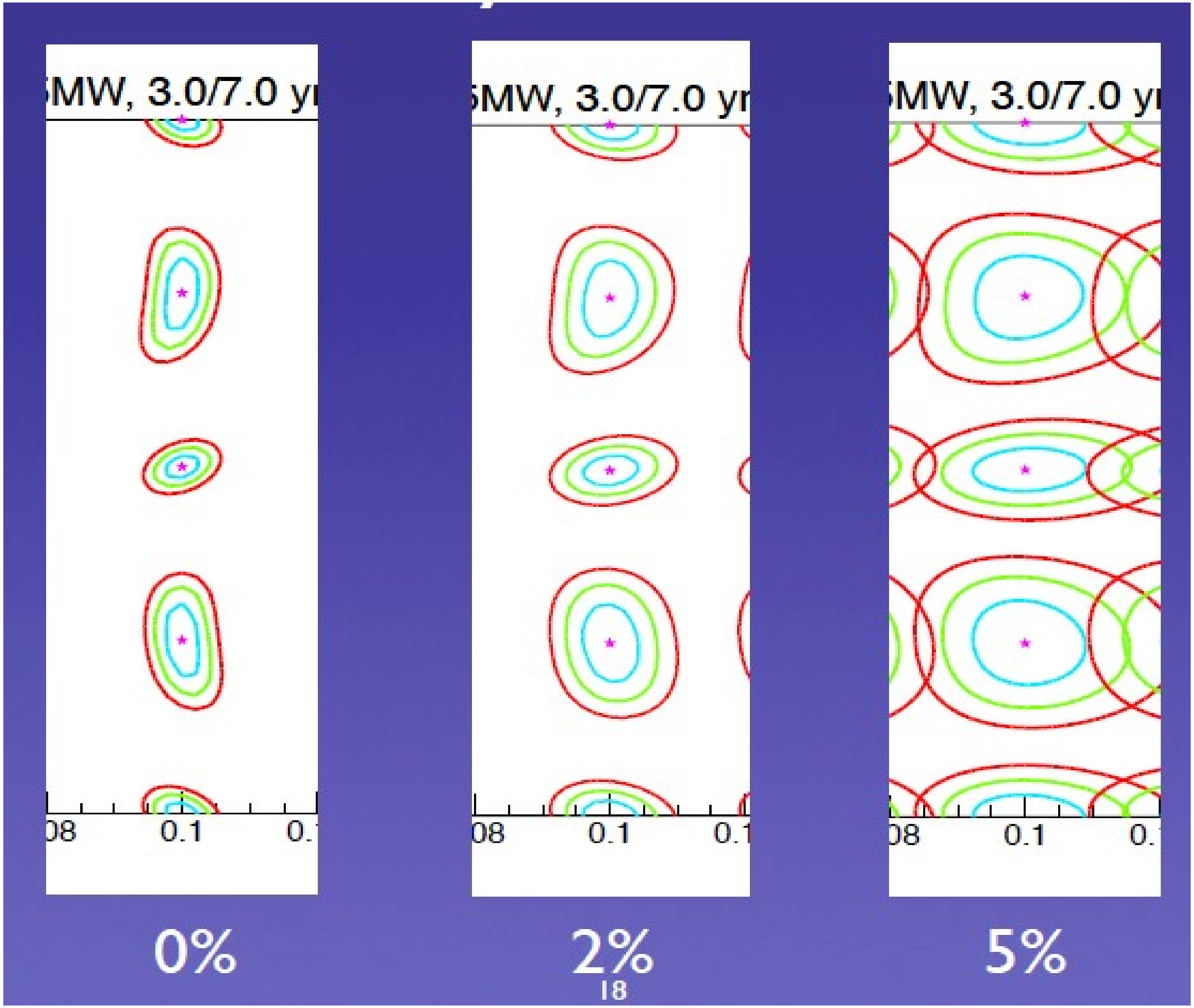
$$\nu_\mu + p \rightarrow \Delta^{++} \rightarrow \pi^+ + p \rightarrow \pi^0 + p$$

In the past few years neutrino physics has gone from basic tree-level physics to an understanding that (i) nuclear effects are important (ii) we don't know enough about them and (iii) theorists and the electron scattering community can really help here.

World Data for Antineutrinos



Effect of Systematics



0% 2% 5%

?

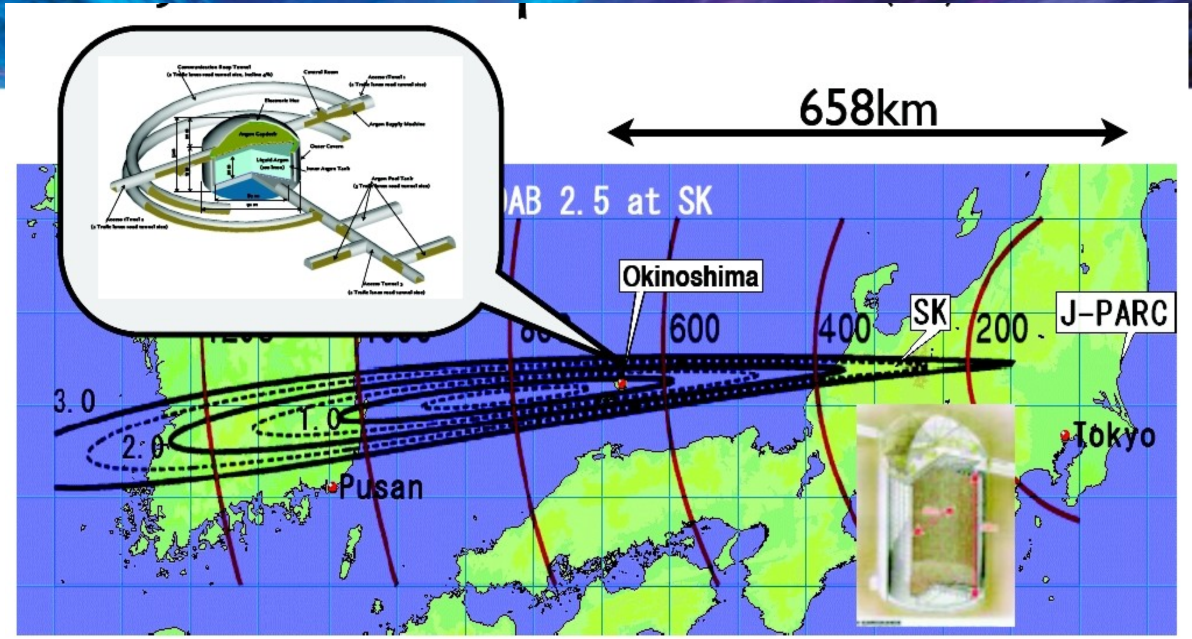
Summary

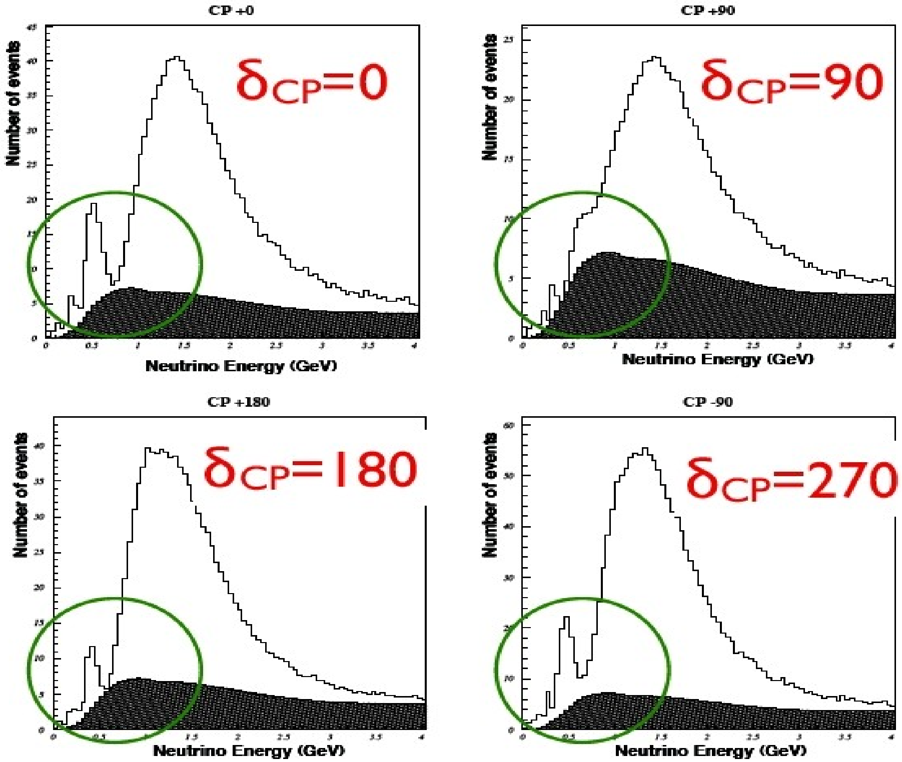
- We measure events = flux*cross section
- We don't generally have a handle on the flux to better than 10% - there is a lot of work trying to deal with this.
- The other side of the coin, cross-sections, are even more poorly known.
- We need new, high-statistics, measurements of these cross sections on multiple target materials and at multiple energies.

OA Beam

L = 660 km

500 MeV @ 2^{nd} Max

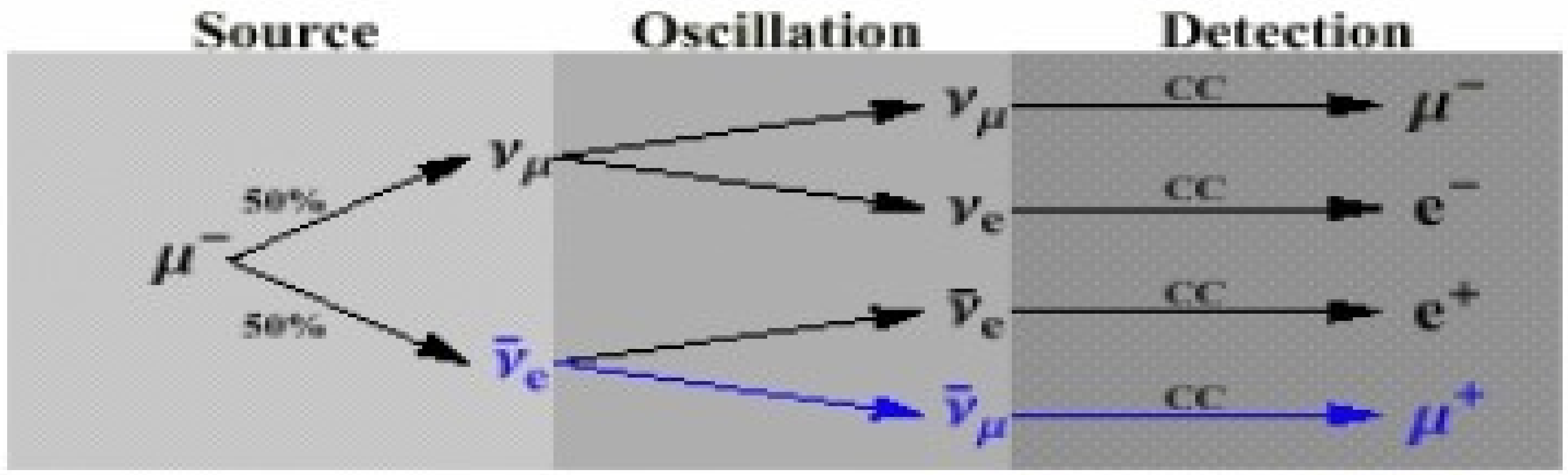




$\sin^2 2\theta_{13}=0.03$ & varying CP phase

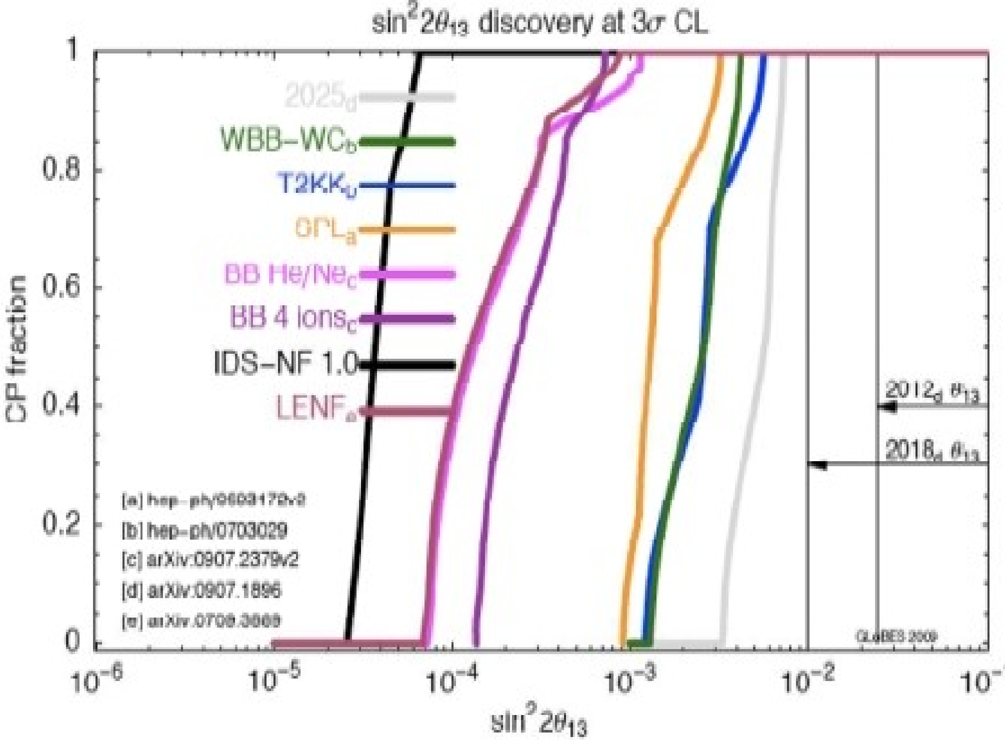
- ν only run
- Can detect CP Violation at 3 sigma significance if $\sin^2(2\theta_{13})>0.02$

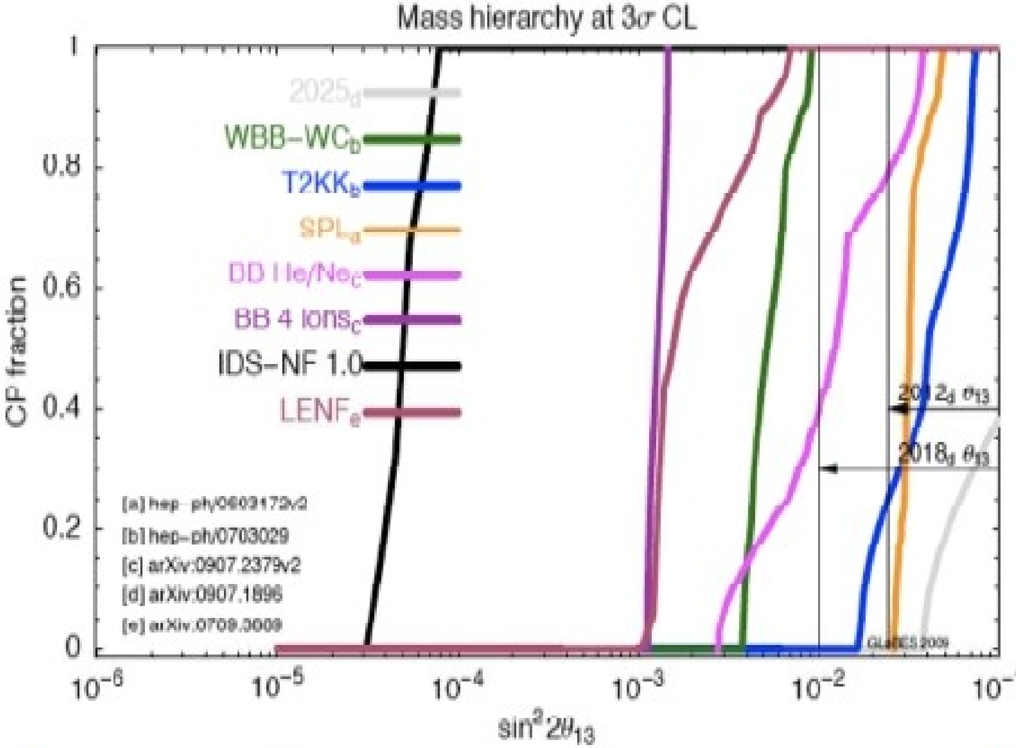
Neutrino Factory

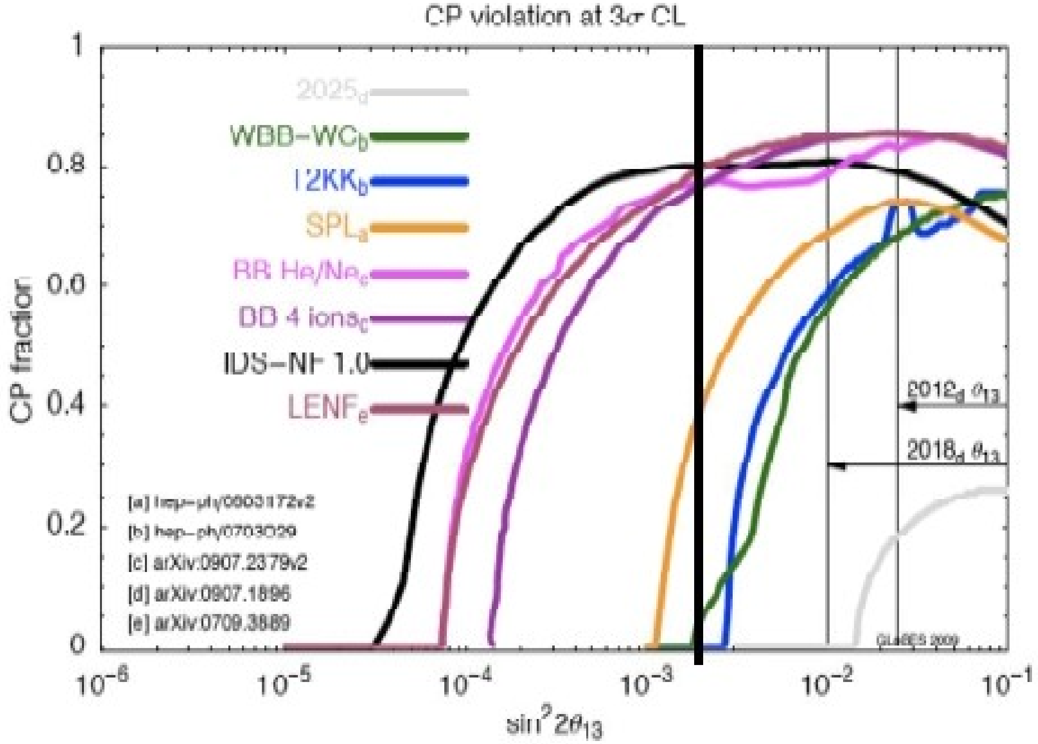


Golden channel

- No background from other neutrino flavours
- But this requires the charge of the final state lepton to be known
- Need to magnetise the far detector

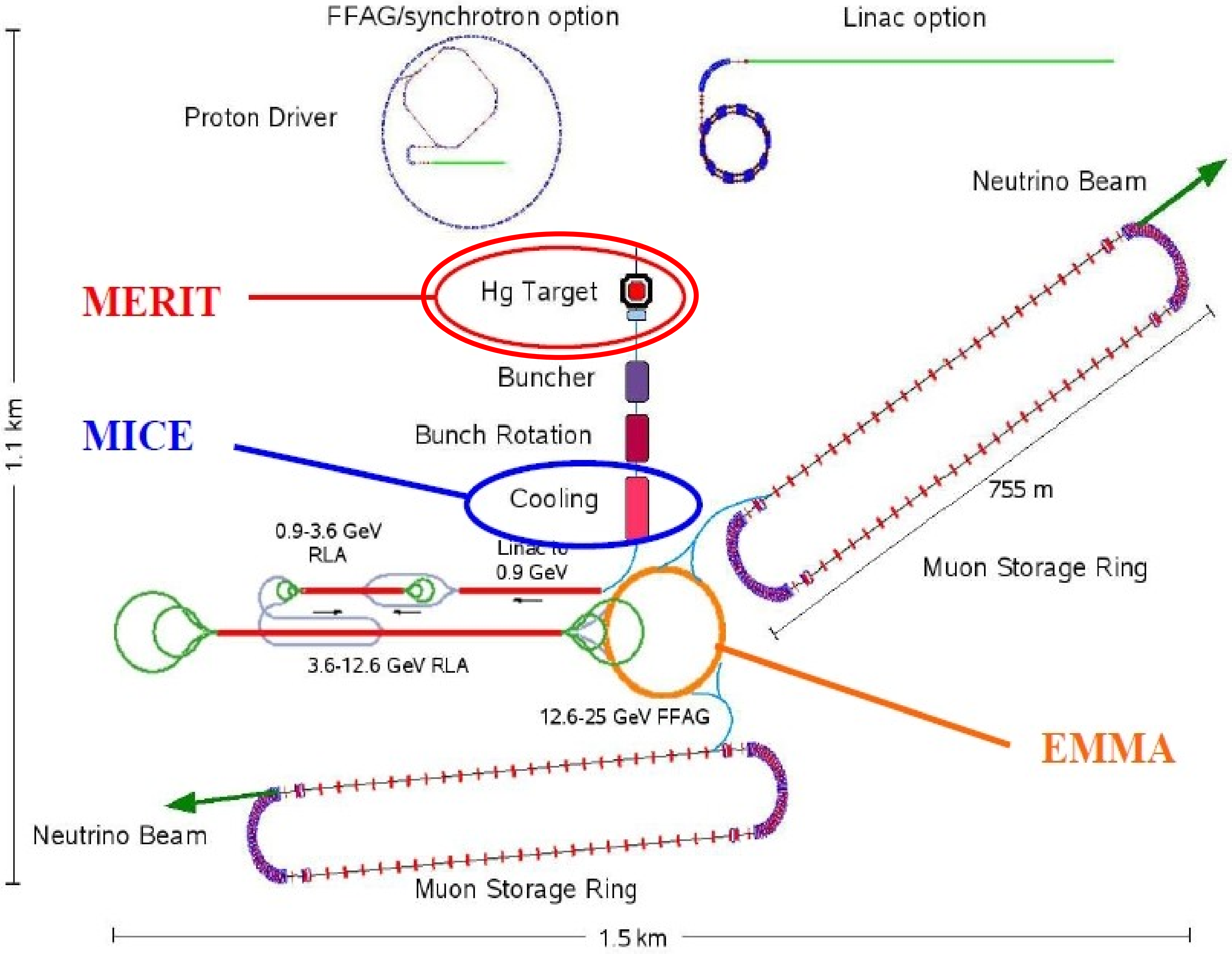

sin²2θ₁₃ discovery at 3σ CL


Mass hierarchy at 3σ CL

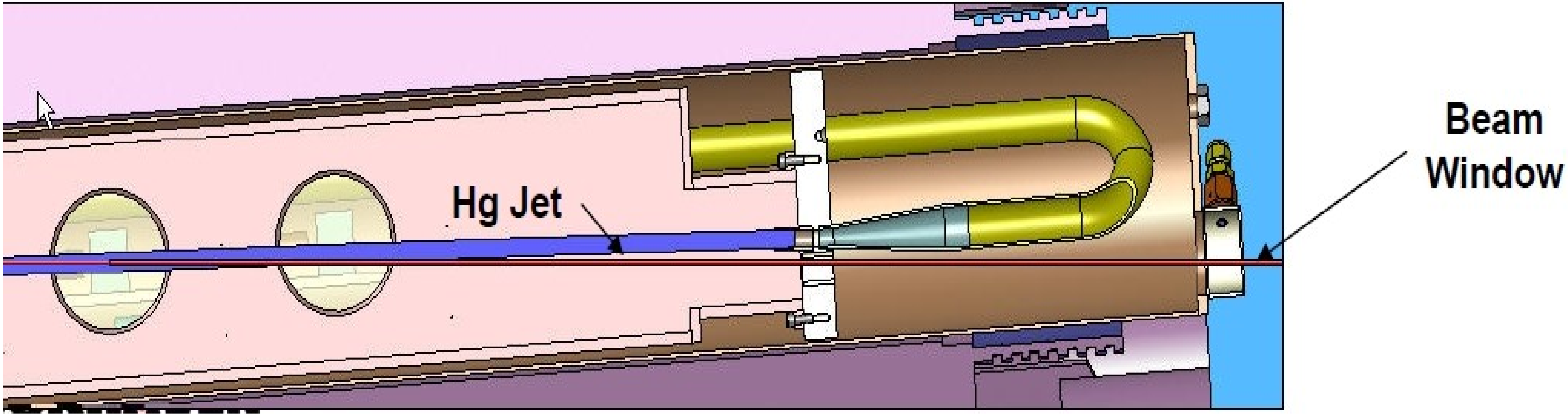

CP violation at 3σ CL

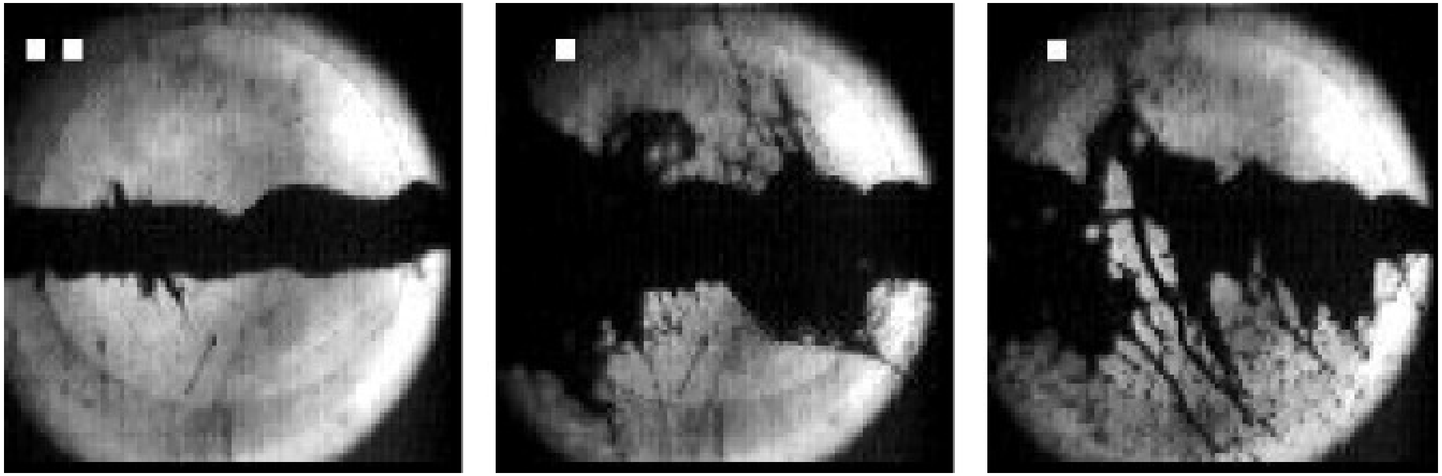
- Neutrino Factory outperforms other options:
  - Larger discovery reach
- Competitors (large θ_{13}):
  - Beta beam:
    - But requires large Ne flux, high-γ, and/or 4-ions
  - Low energy Neutrino Factory:
    - See later, but, reduced redundancy/flexibility

EUROnu: 1005.3146v1

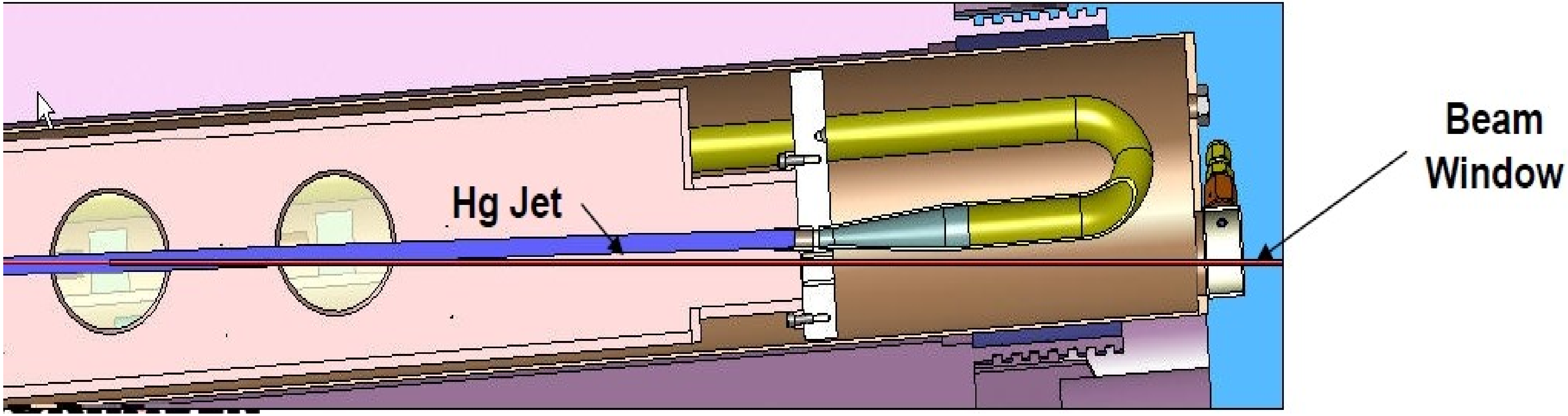

FFAG/synchrotron option
Linac option
Proton Driver
Neutrino Beam
MERIT
Hg Target
Buncher
MICE
Bunch Rotation
Cooling
755 m
0.9-3.6 GeV
RLA
Linac to
0.9 GeV
Muon Storage Ring
3.6-12.6 GeV RLA
12.6-25 GeV FFAG
EMMA
Neutrino Beam
Muon Storage Ring
1.1 km
1.5 km

Targetry – MERIT Experiment

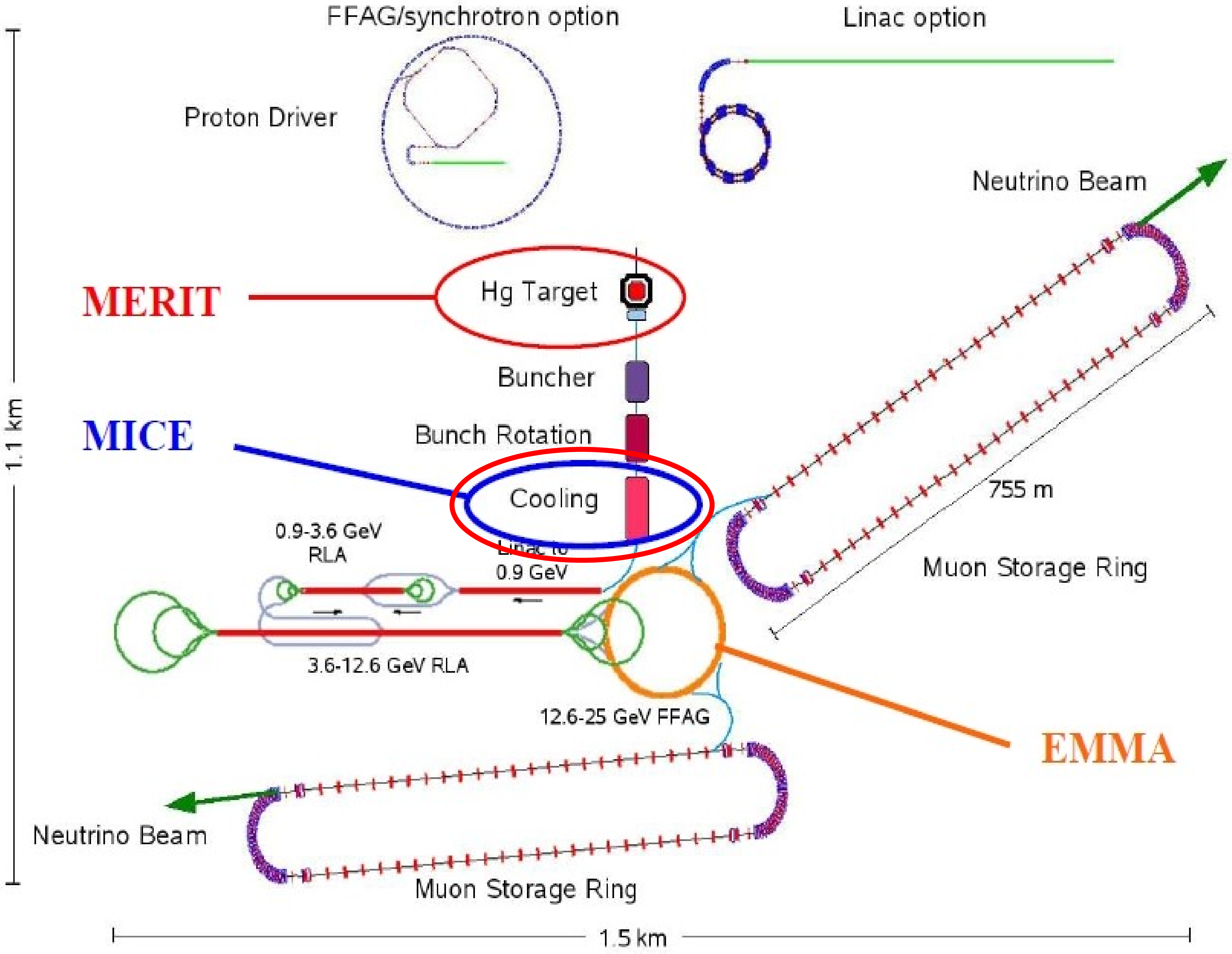




Targetry – MERIT Experiment



Other ideas out there : supercooled tungsten ring
tungsten powder jet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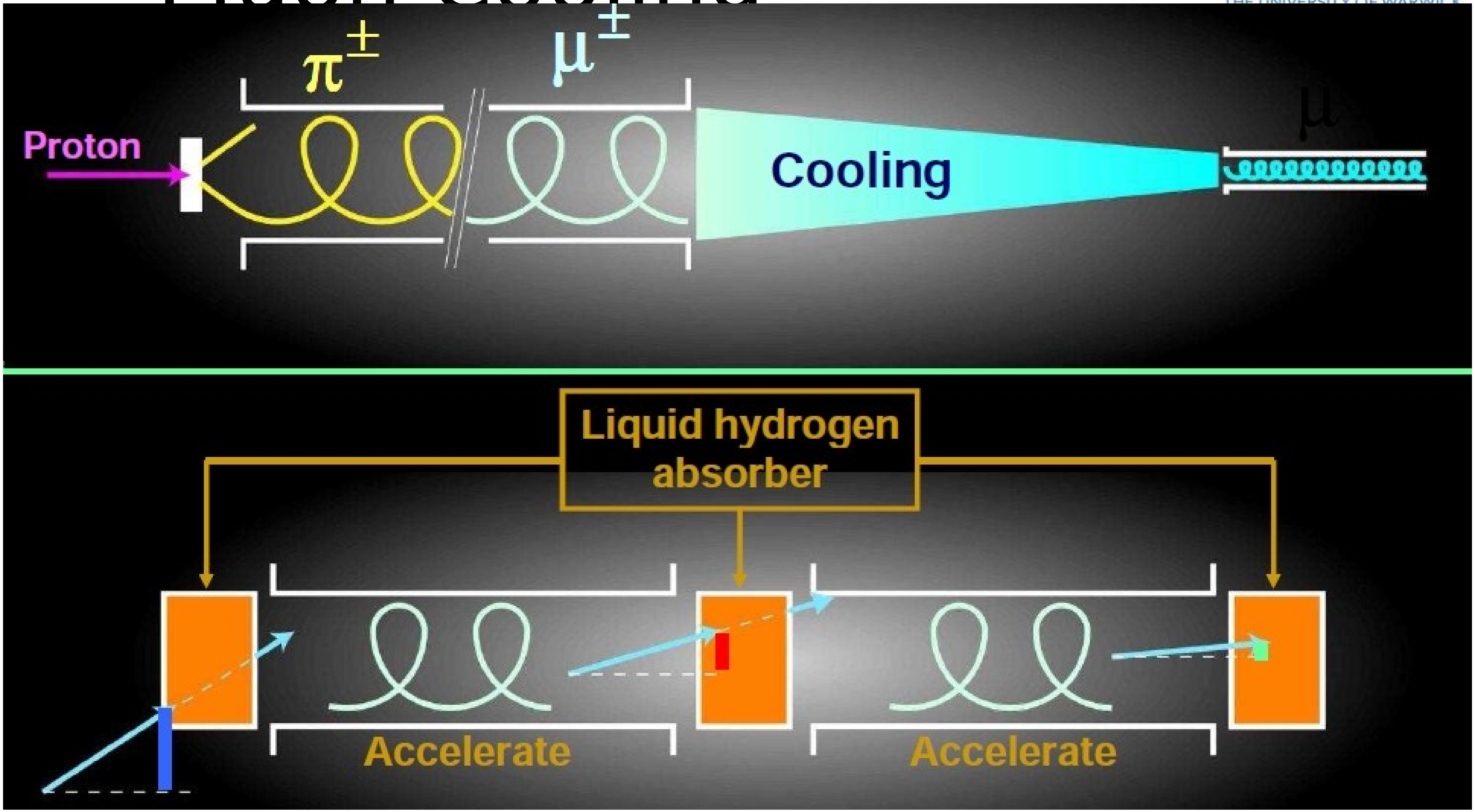
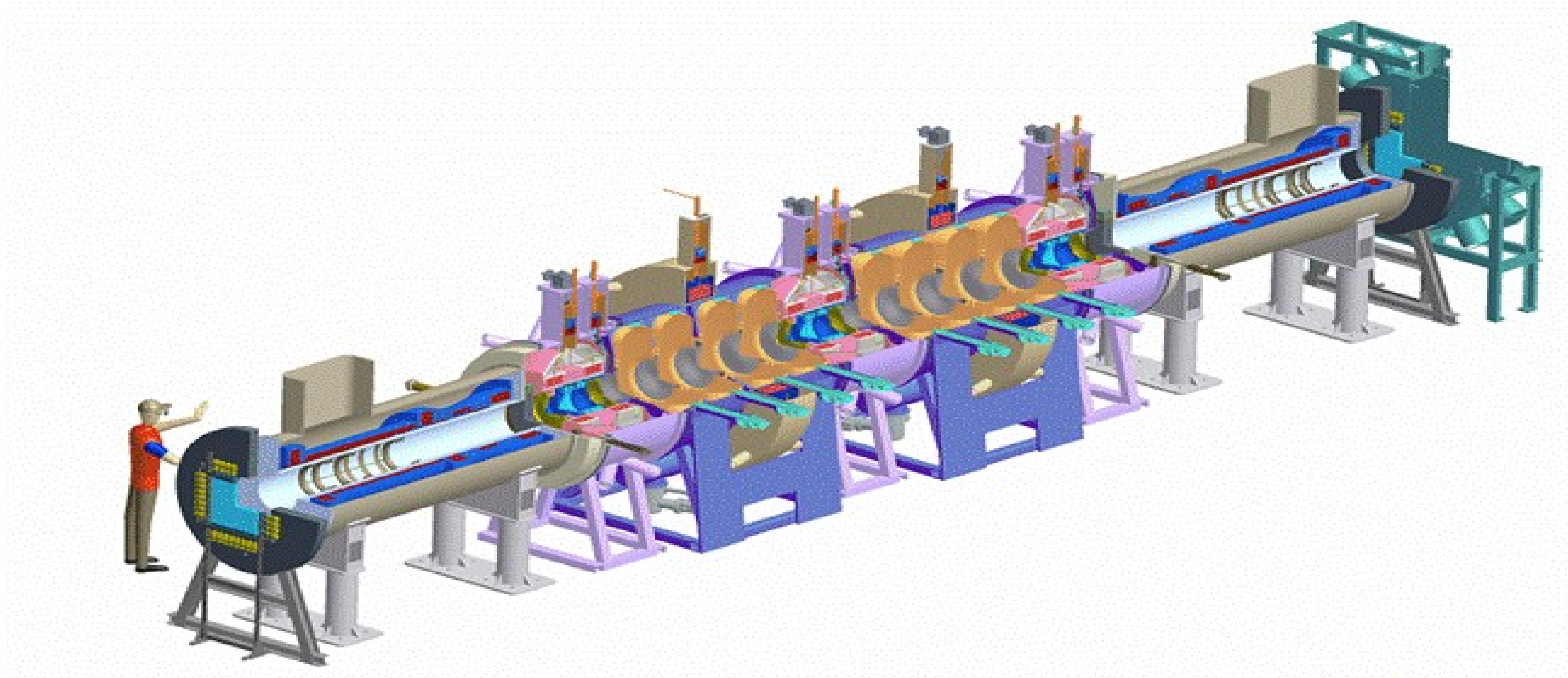
Muon Storage Ring
1.1 km
1.5 km

Muon Cooling



MICE

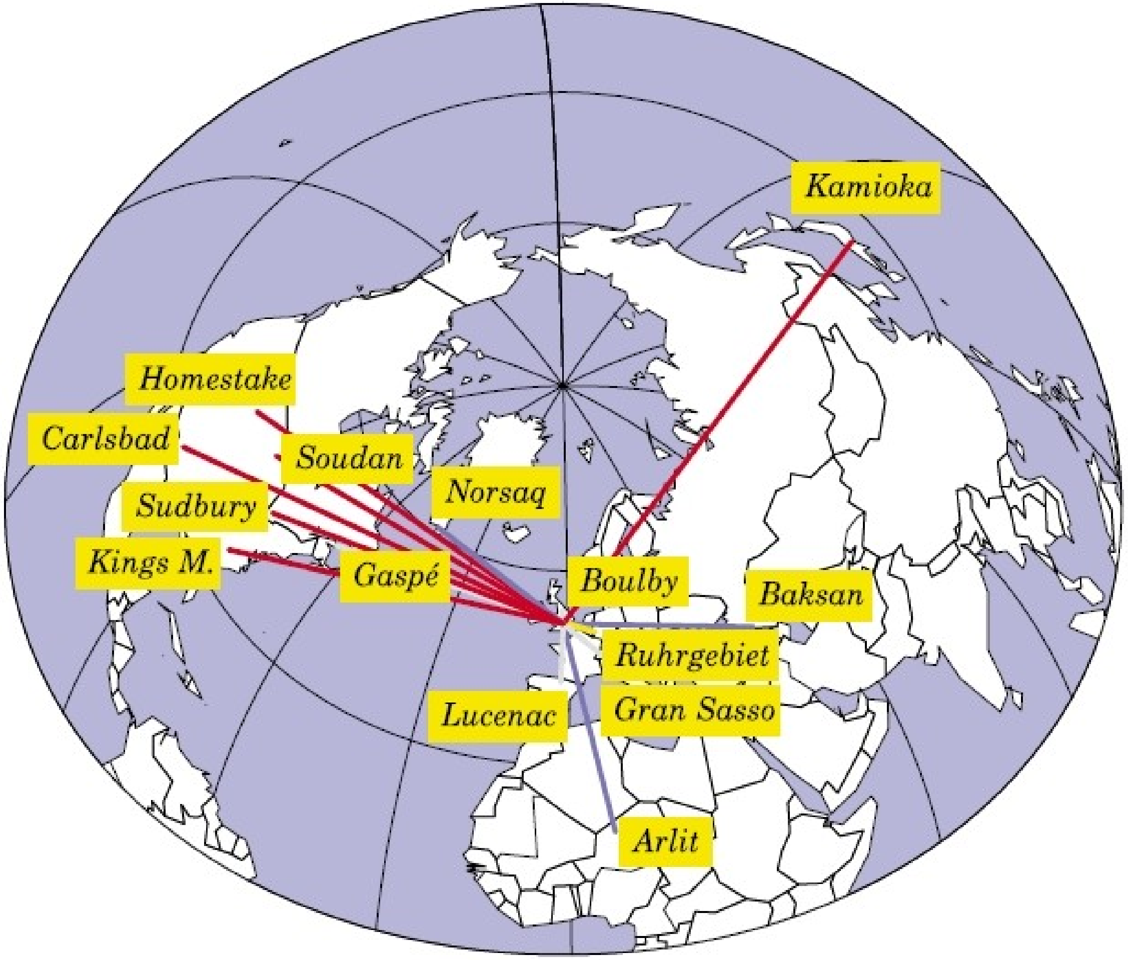


Muon Ionisation Cooling Experiment @ Rutherford Labs in Ox

Detectors

Physics sensitivity prefers two 50 kton (mass of the Titanic) detectors around 4000 km from the beam, and around 7500 km from the beam

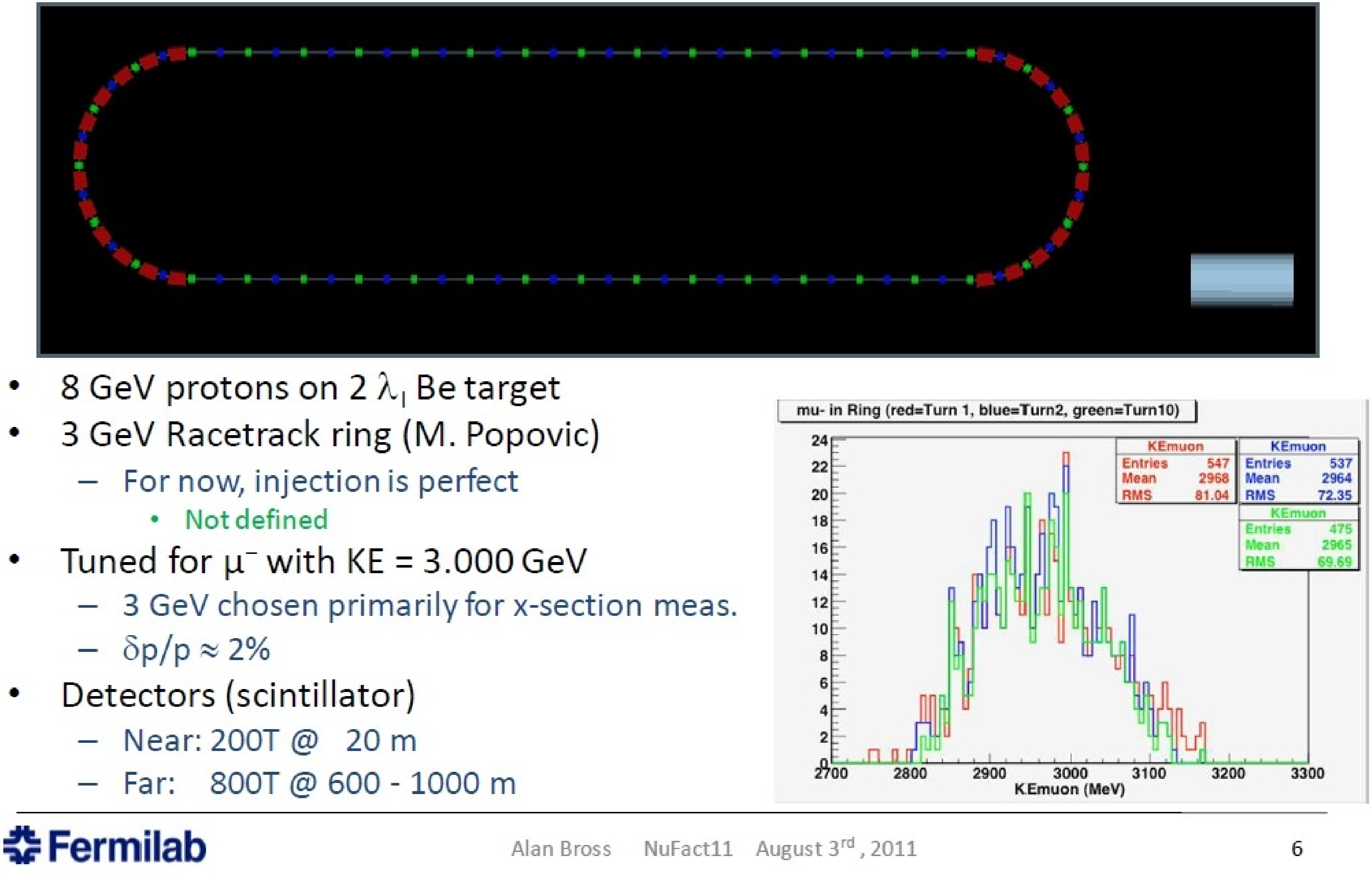
🟦 Arlit:	3636
🟦 Baskan:	3366
⬜ Boulby:	229
🟥 Carlsbad:	7293
🟨 Essen:	565
⬜ Gaspe:	4264
⬜ GranSasso:	1514
🟥 Homestake:	6655
🟥 Kamioka:	8621
🟥 KingsMountain:	6095
⬜ Lucenac:	1002
🟦 Norsaq:	2788
🟥 Soudan:	5925
🟥 Sudbury:	5548



Neutrino Factory Summary

- Best discovery potential and sensitivity from all options
- Couldn't be built now. If we decided to build one it, and it's
- detectors, wouldn't be ready until 2025 or so.
- Design study underway and the problems are being
- addressed by demonstrator experiments
- Only way to generate large fluxes of electron neutrinos.

Very low energy NUFACT?



- 8 GeV protons on 2 λ_I Be target
- 3 GeV Racetrack ring (M. Popovic)
  - For now, injection is perfect
    - Not defined
- Tuned for μ^- with KE = 3.000 GeV
  - 3 GeV chosen primarily for x-section meas.
  - $\delta p/p \approx 2\%$
- Detectors (scintillator)
  - Near: 200T @ 20 m
  - Far: 800T @ 600 - 1000 m

Concluding Remarks

We have gone through a lot but I can easily fill another 15 hours of lectures.

The neutrino is : light, neutral, left-handed (chiral) and almost left-handed (helicity). It is generated purely in weak interactions (which is why it is chiral). It is generated by many sources : the Big Bang, astrophysical events, supernova, the sun, cosmic rays, radioactive decays, and countless other sources. We can generate them in reactors and accelerators. Their cross sections are tiny and we need big detectors to look at them. They mix and oscillate.

They may be the reason that we are here at all.

But...what is their mass? Why is it so small? Why are the mixing parameters so odd? Still lots of questions remain. We have a 20 year plan for trying to deal with them.

In words

Because ν_e can suffer an extra interaction it picks up an effective mass that is slightly different from its vacuum mass. From another point of view, the extra interaction gives the ν_e an apparent inertia with respect to the other neutrinos.

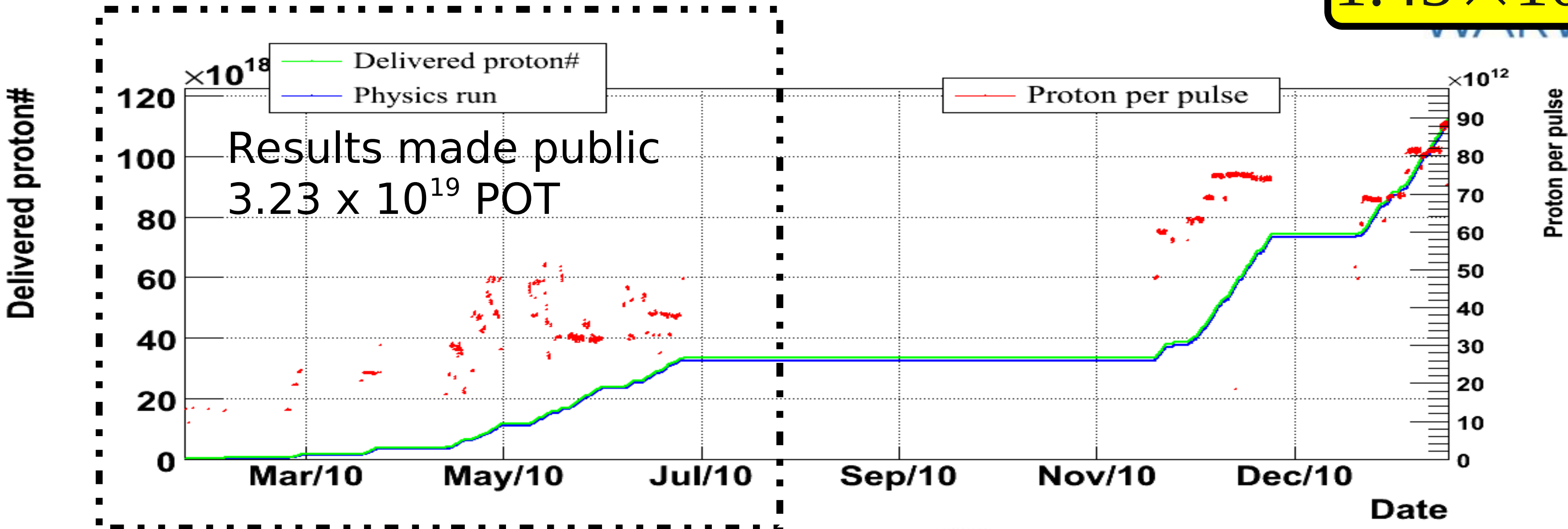
Think of this in much the same way as phonons in crystals which have “effective” masses arising from interactions with the crystal lattice

Matter presents an effective refractive index for ν_e

This inertia is felt by some linear combination of the mass eigenstates, and hence passed to the other flavours. Oscillations still happen, but now with a different effective mass splitting

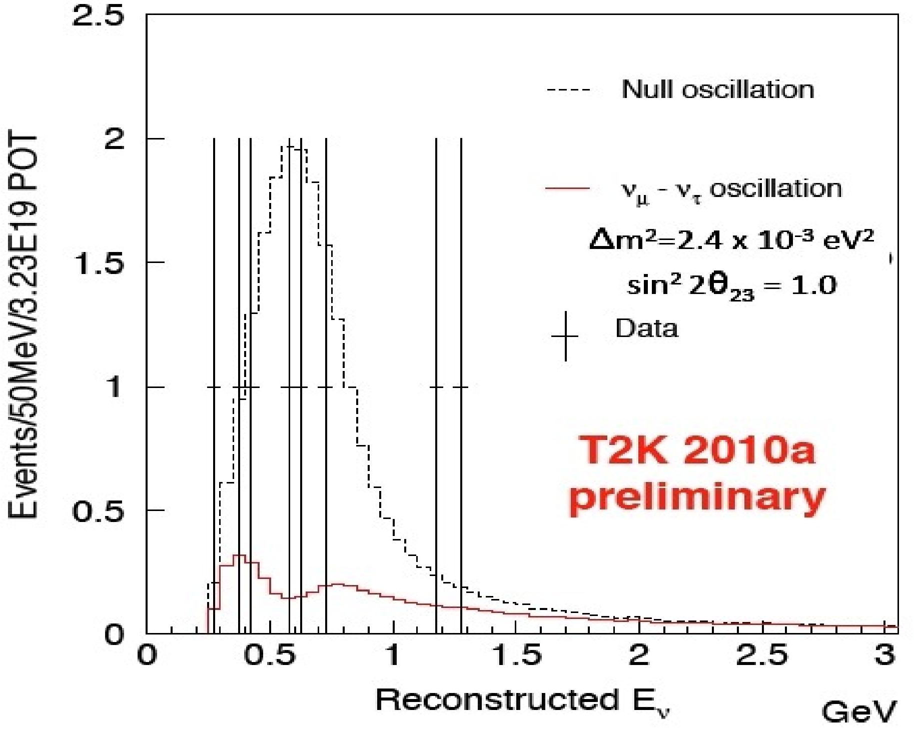
Results to date

$1.45\times10^{20}\ POT$

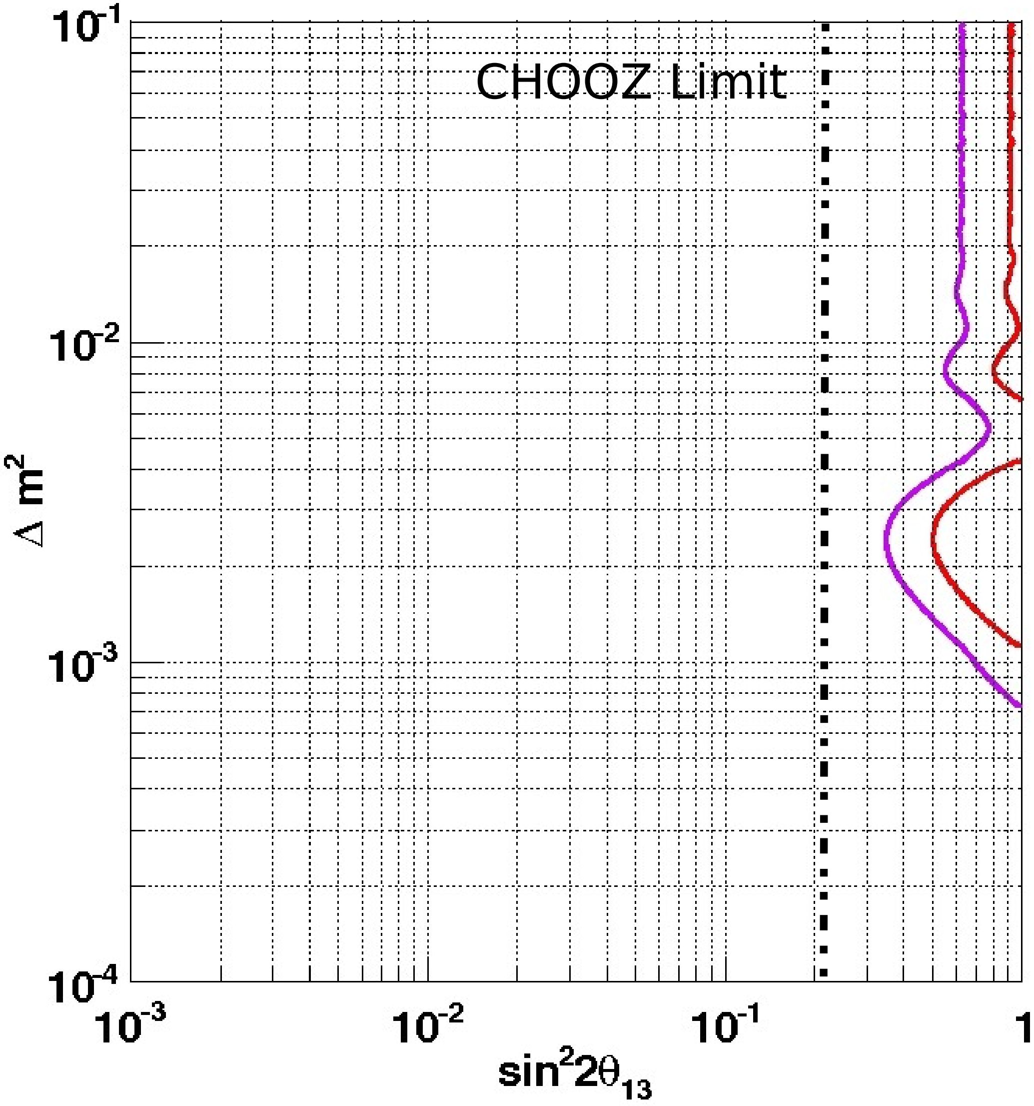


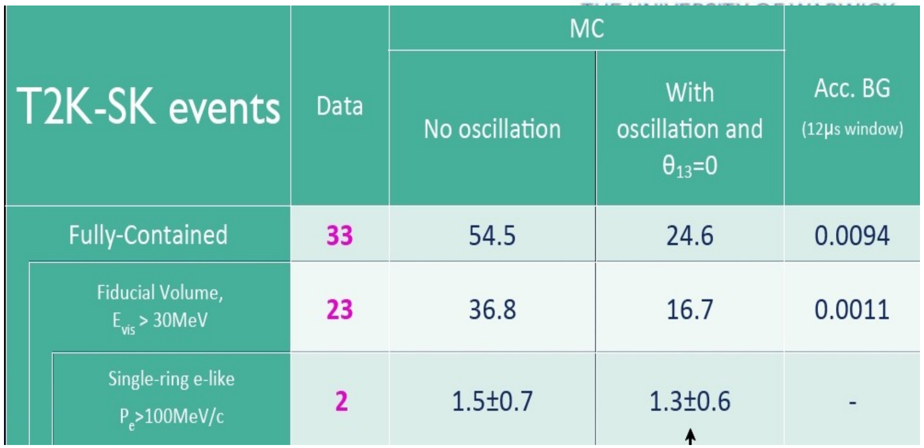
Results made public
3.23×10^{19} POT

- 8 n_{μ} events observed in SK
- 22.8 ± 1.3 events expected in the absence of oscillations
- 6.3 ± 1.0 events expected if
  - $\Delta m^2 = 2.4 \times 10^{-3}\ \mathrm{eV}^2$
  - $\sin^2 2\theta_{23} = 1.0$



n Appearance





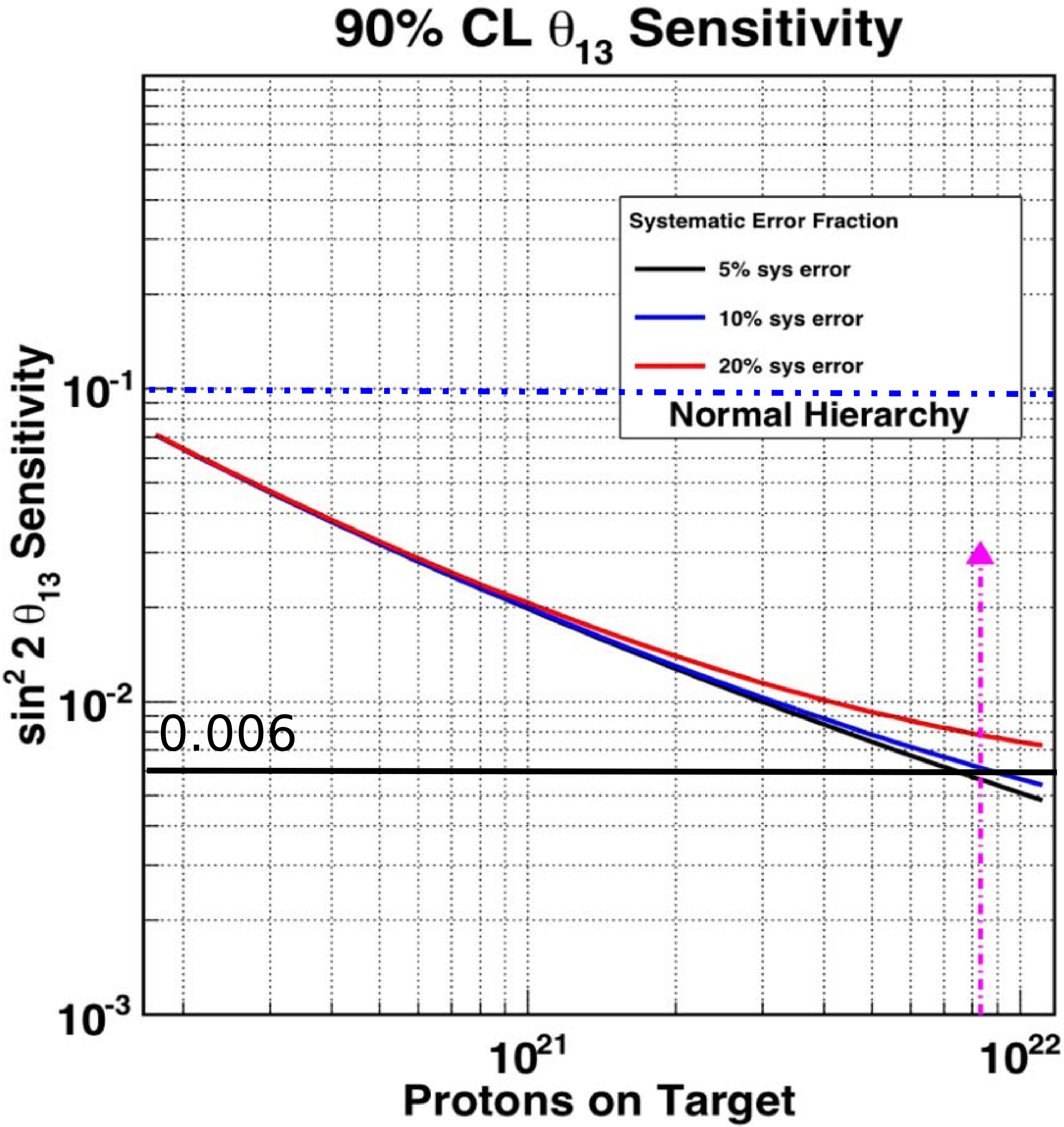
T2K-SK events	Data	MC		Acc. BG (12μs window)
		No oscillation	With oscillation and $\theta_{13}=0$	
Fully-Contained	33	54.5	24.6	0.0094
Fiducial Volume, E_{vis} > 30MeV	23	36.8	16.7	0.0011
Single-ring e-like P_e>100MeV/c	2	1.5±0.7	1.3±0.6	-

$$\sin^2(2\theta_{13}) < 0.5 @ 90\ CL$$

$$\Delta m_{23}^2 = 2.4\times10^{-3}\,eV^2$$

We have 4 times the amount of data released in the can which should push the limit down to about 0.1.

Expect release of this data by summer.



Reno result

5 years nomina
running period

Earthquake

- Subsidence at the LINAC building

- But the near detector seems to be superficially OK

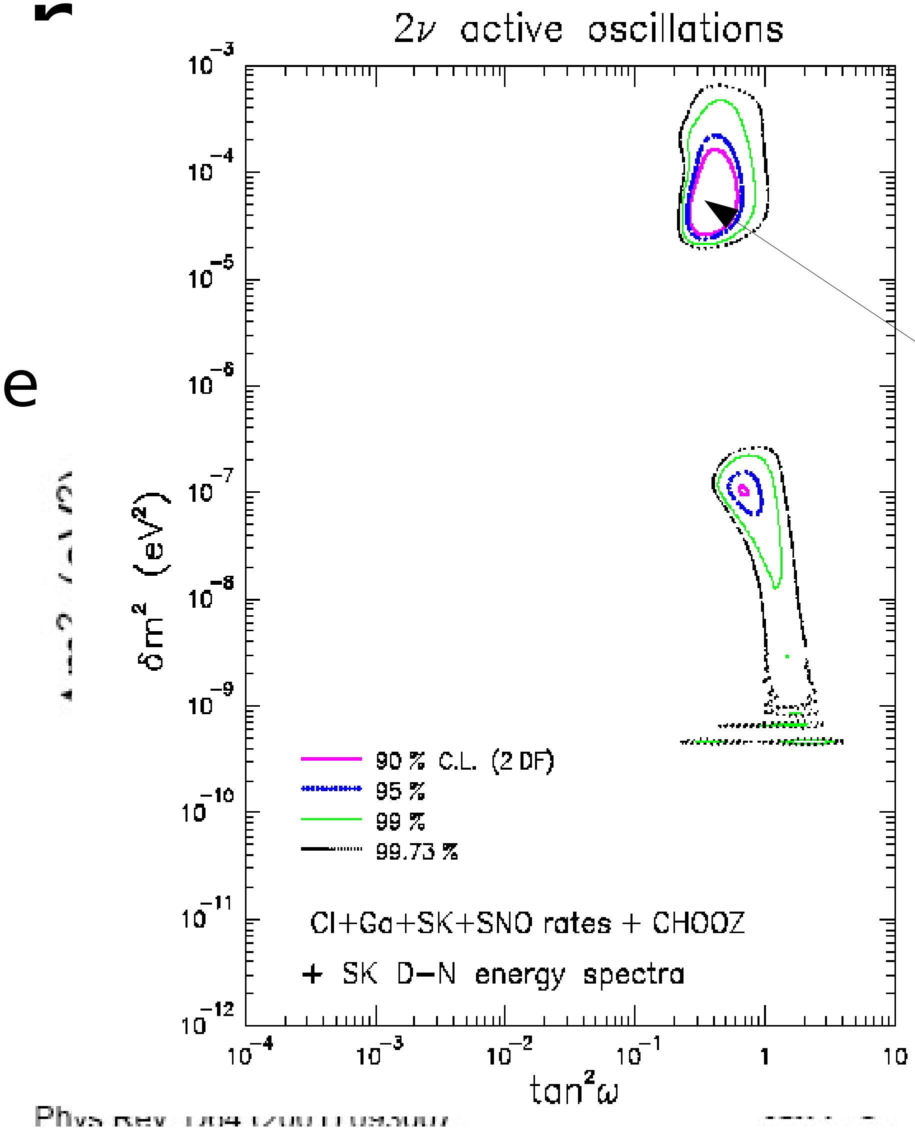
- The accelerator magnets may need realignment but the ring seems to be also OK

- Japanese build for earthquakes

Adding SNO to the

The data shows that the solar oscillations come mostly from the MSW effect.

The neutrinos have oscillated before they get to the solar surface.



$$\theta_{e\mu} = 32.5^{o} \pm 2.4^{o}$$

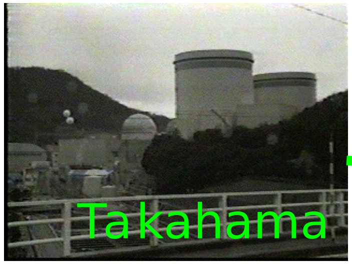
$$\Delta m_{12}^{2} = \textcircled{+} 7.1 \times 10^{-5}\, eV^{2}$$

Transition mostly

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

KamLAND

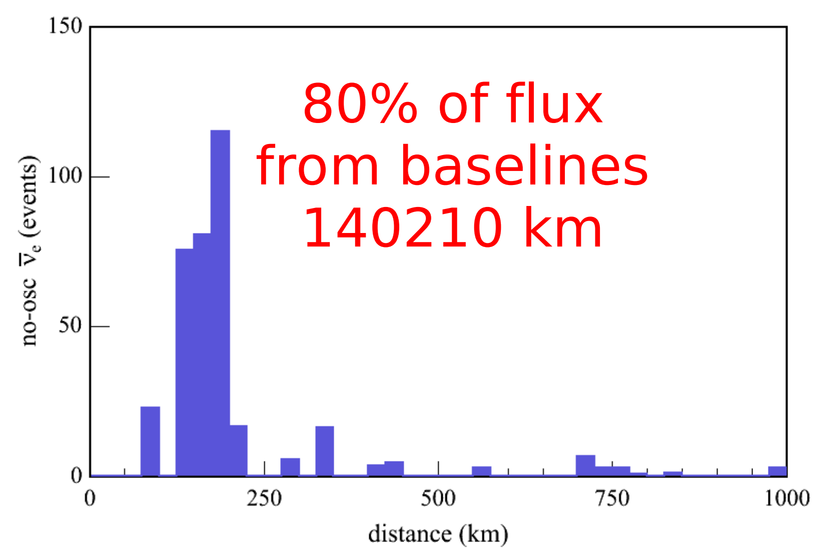
Kashiwazaki


Takahama


Ohi

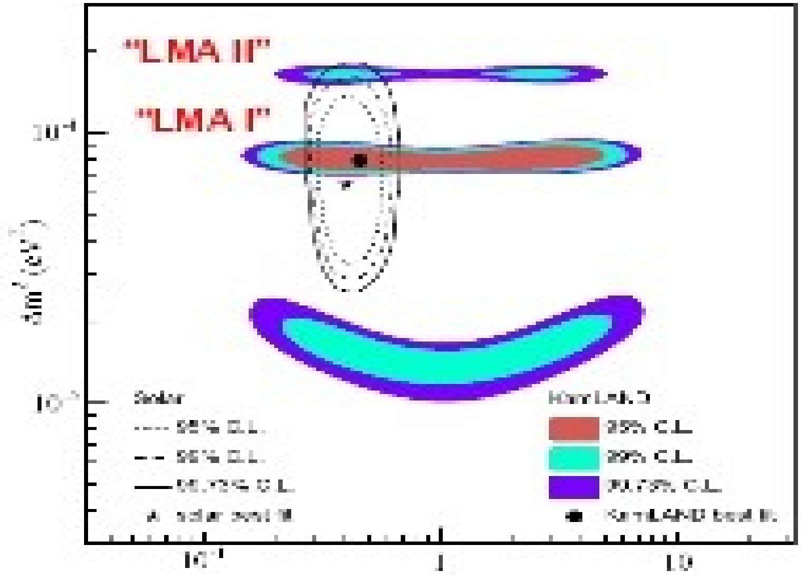
KamLAND uses
the entire Japanese
nuclear power
industry as a
longbaseline source

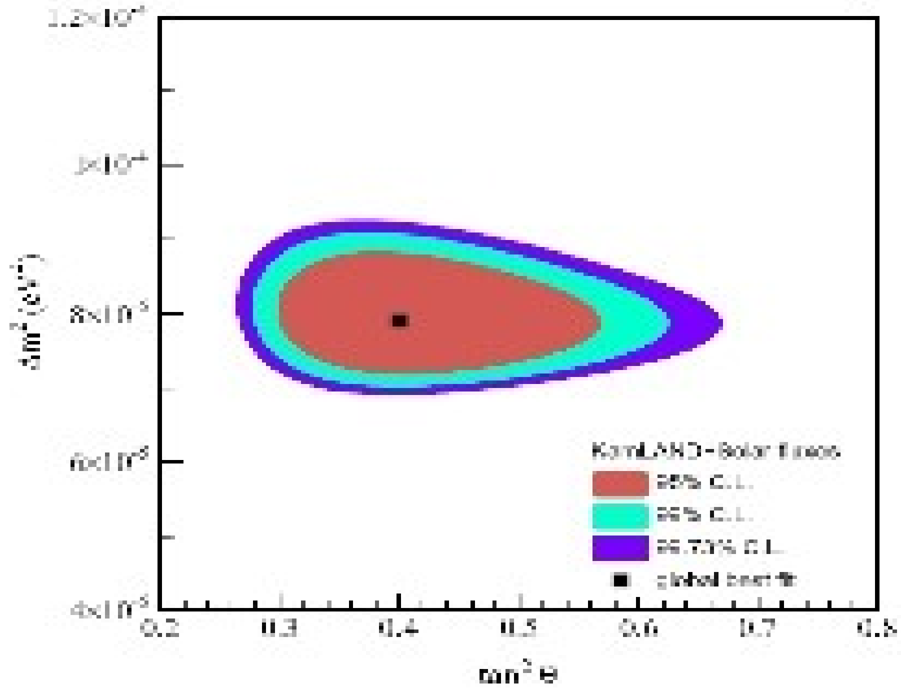
KamLAND @ Kamioka

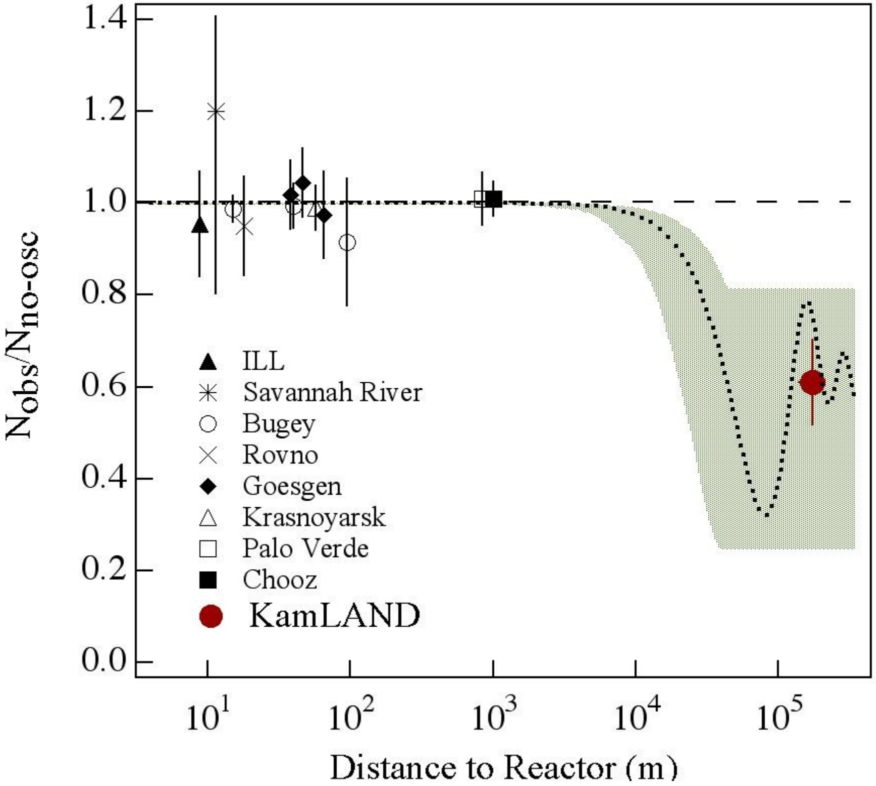


80% of flux
from baselines
140210 km

KamLAND



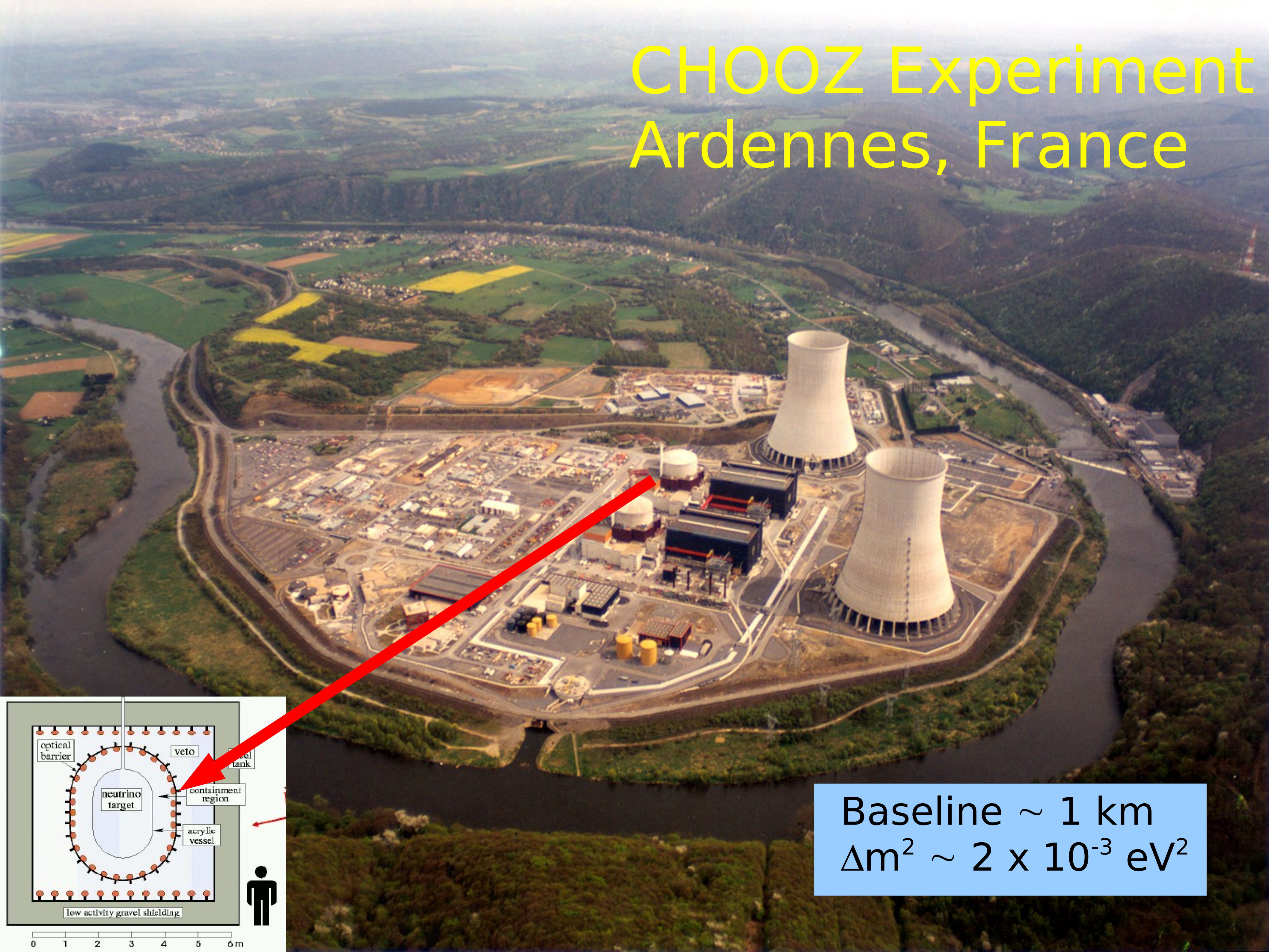




$$\Delta m_{12}^2 = +7.9 \pm 0.5 \times 10^{-5}\, eV^2$$

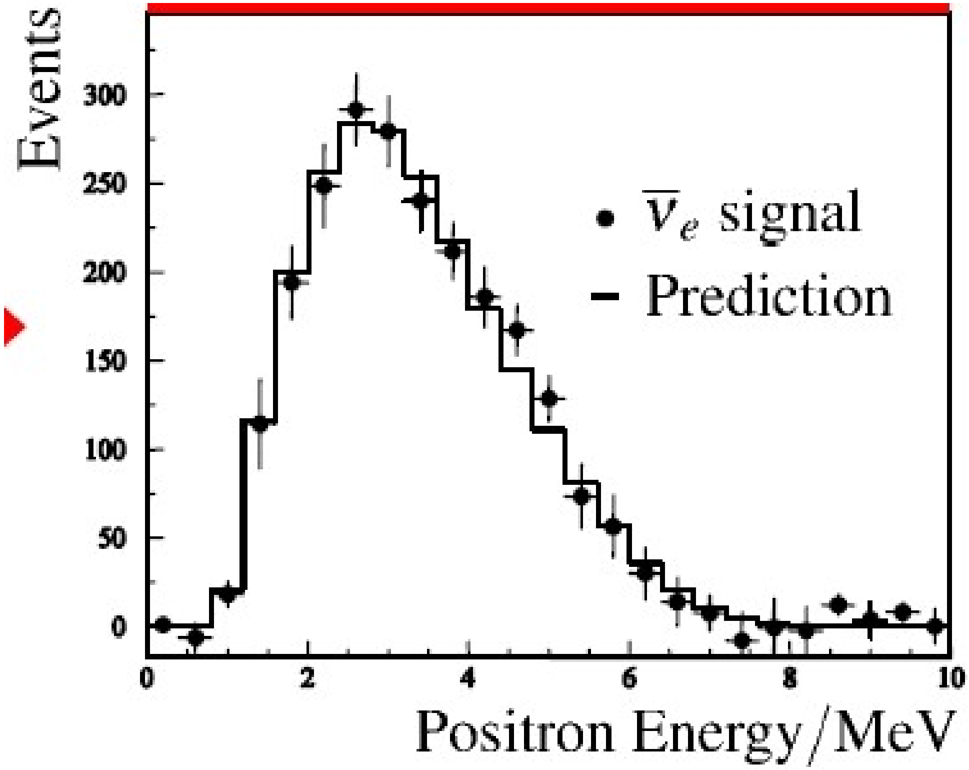
$$\tan^2(\theta) = 0.4 \pm 0.09$$

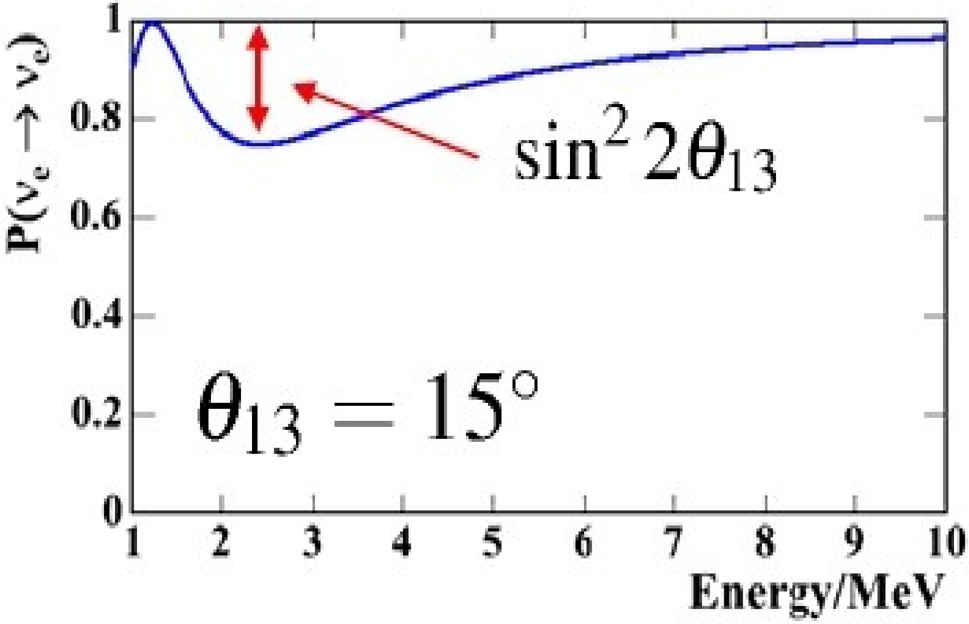
CHOOZ Experiment
Ardennes, France



Baseline ~ 1 km
$\Delta m^2 \sim 2 \times 10^{-3}$ eV^2

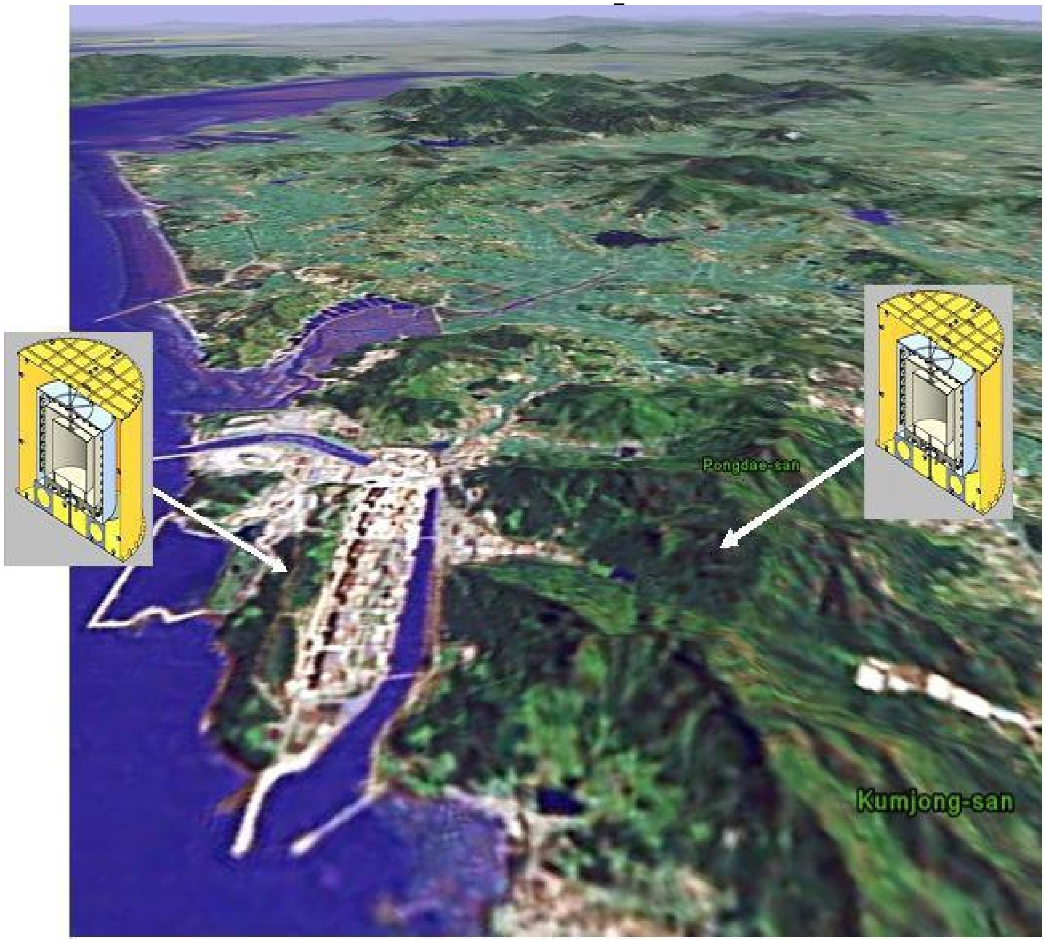
$$R=\frac{N_{observed}}{N_{expected}}=1.01\pm 2.8\,\%(stat)\pm 2.7\,\%(sys)$$





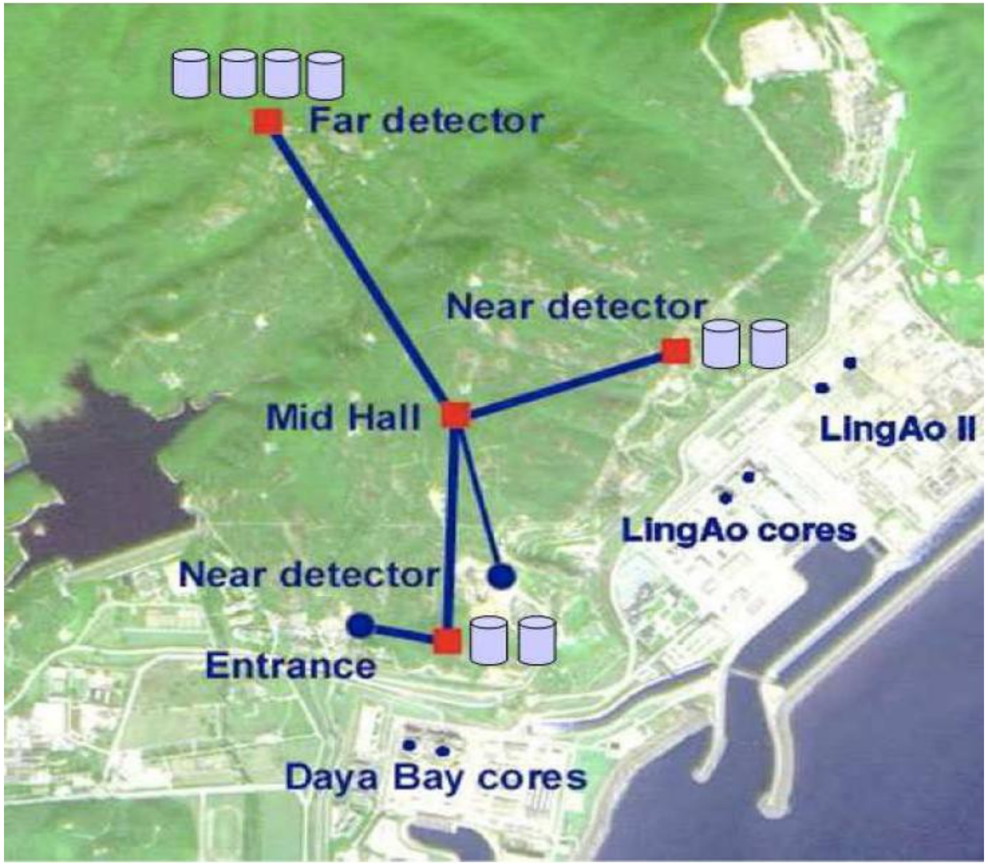
$$\sin^2(2\,\theta_{13})<0.12-0.2 \;\;\Rightarrow\;\; \theta_{13}<10\,deg$$

That was until 2



RENO (Reactor Experiment for Neutrino Oscillation) - almost exclusively a South Korean experiment

Daya Bay - south China - larger international experiment



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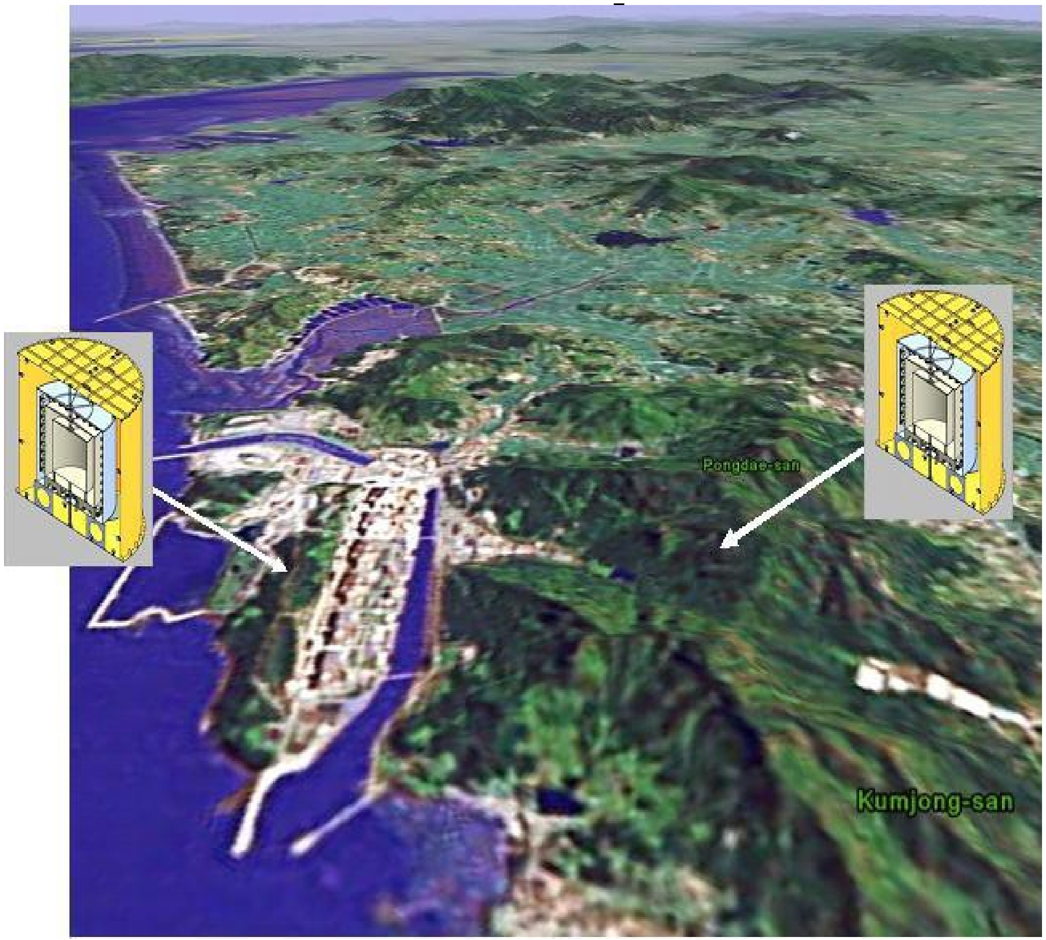

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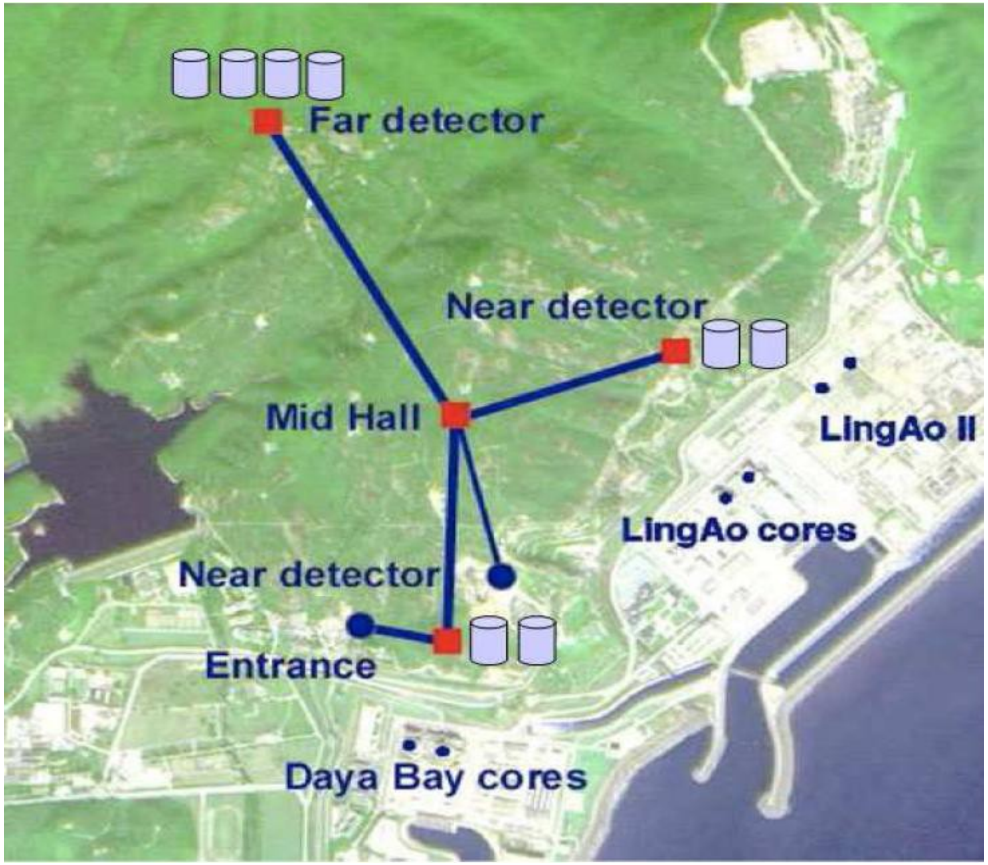
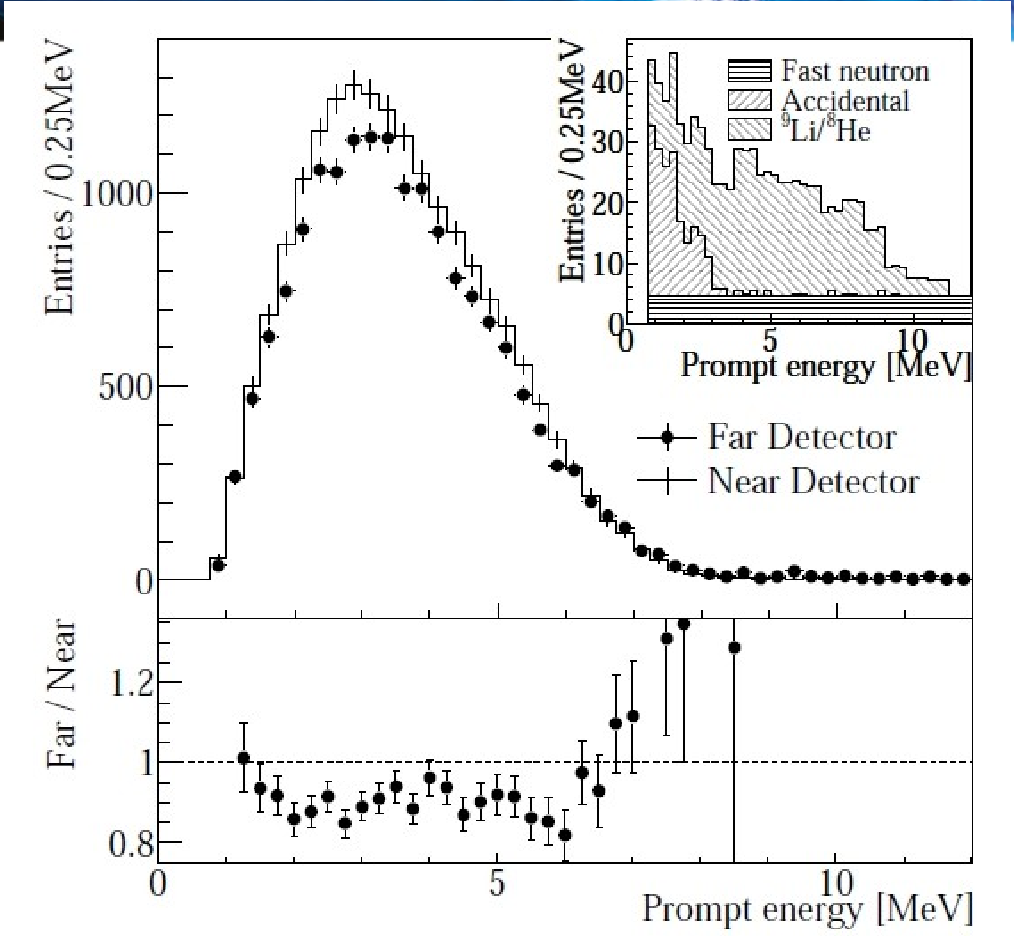
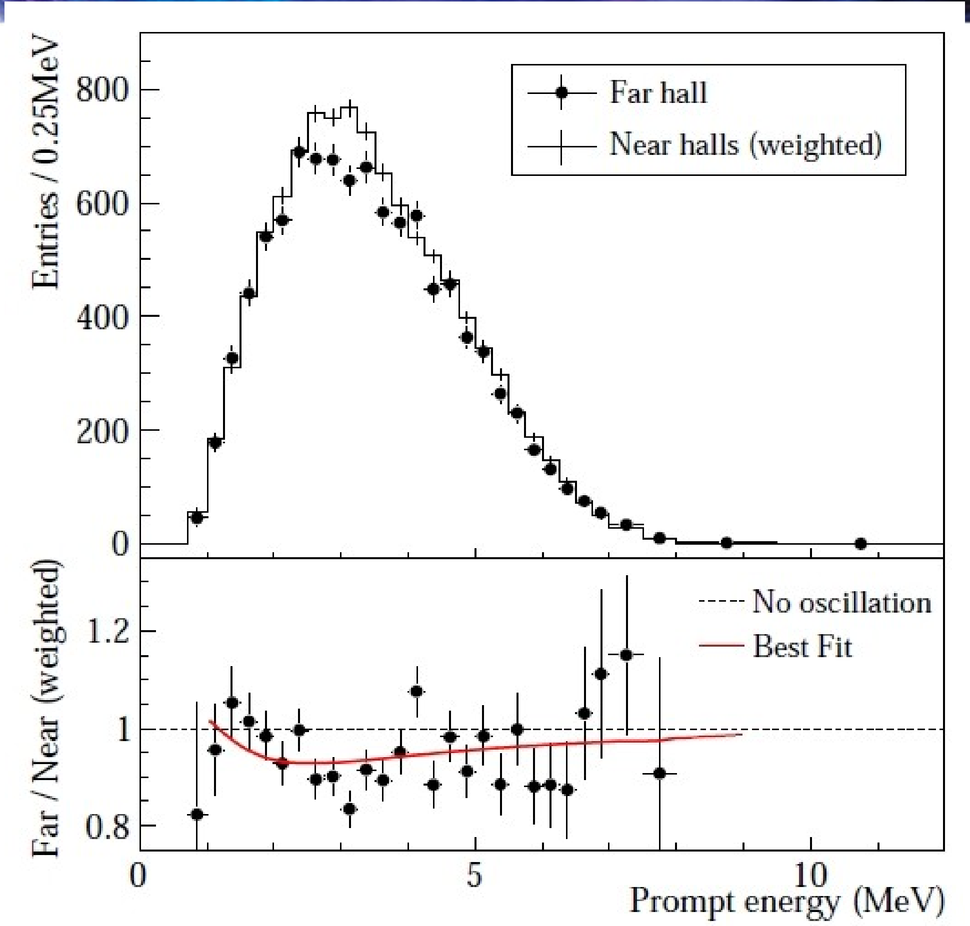




Reno electron energy spectrum



Daya Bay electron energy spectrum

$$\left.\begin{array}{l} \sin^2(2\theta_{13})(Reno)=0.113\pm0.013(stat)\pm0.019(sys) \\ \sin^2(2\theta_{13})(Daya\,Bay)=0.092\pm0.016(stat)\pm0.005(sys) \end{array}\right\} 8/9^\circ$$

What do we know now?

12 (Solar) sector
SNO,KamLAND,SuperK

$$\Delta m^2_{12} = +(7.9 \pm 0.6) \times 10^{-5}\, eV^2$$

$$\sin^2(2\theta_{12}) = (0.85 \pm 0.1)$$

23 (Atmos.) sector
SuperK,K2K,MINOS

$$\left|\Delta m^2_{23}\right| = (2.8 \pm 0.4) \times 10^{-3}\, eV^2$$

$$\sin^2(2\theta_{23}) > 0.92\,(1.0\,?)$$

13 (Atmos.) sector
CHOOZ,KamLAND

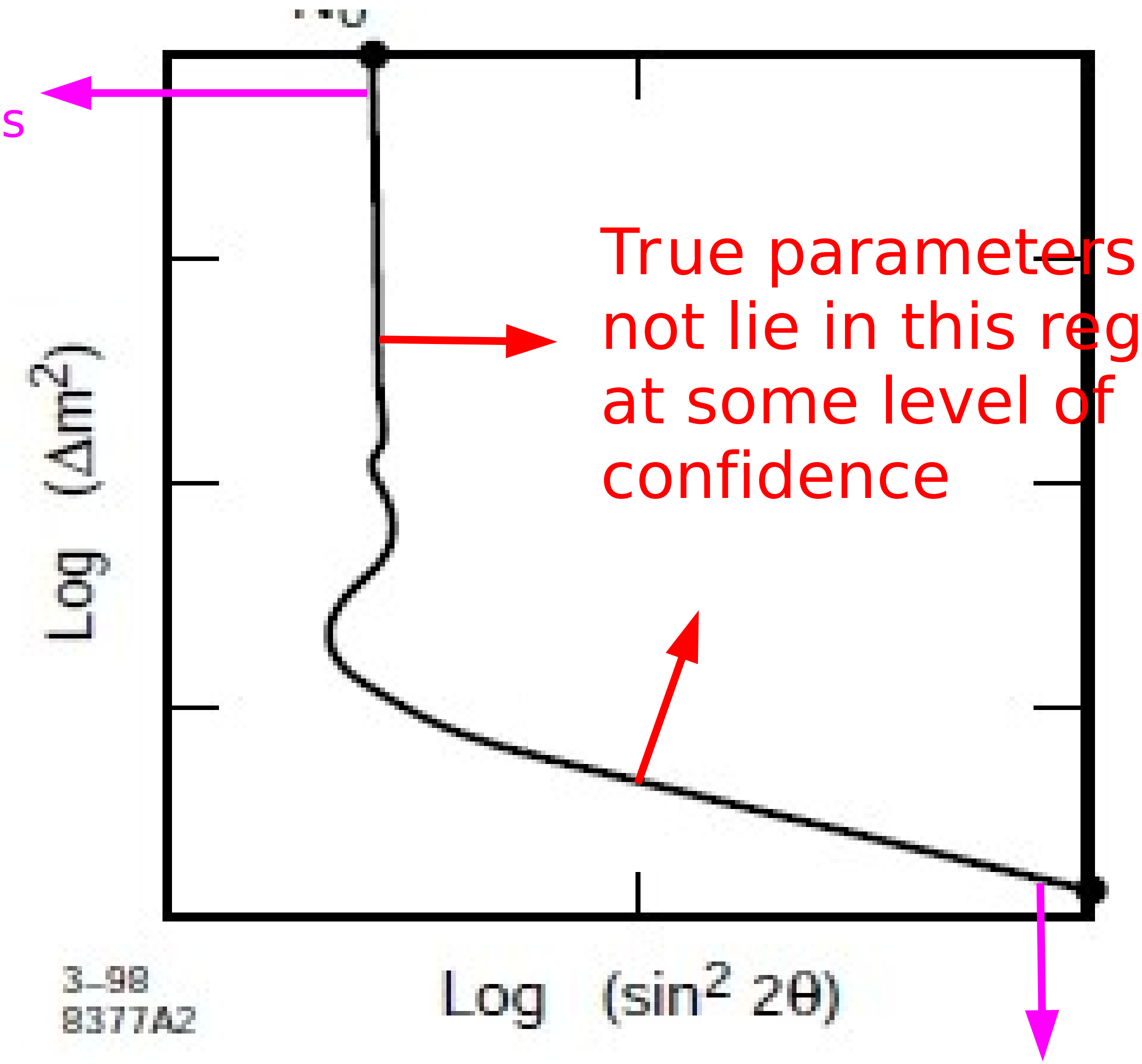
$$\left|\Delta m^2_{13}\right| = (2.8 \pm 0.4) \times 10^{-3}\, eV^2$$

$$\sin^2(2\theta_{13}) = (0.089 \pm 0.01)$$

No knowledge of δ_{CP} or sign of Δm_{23}^{2}

Exclusion Plots

Limit scales with number of events



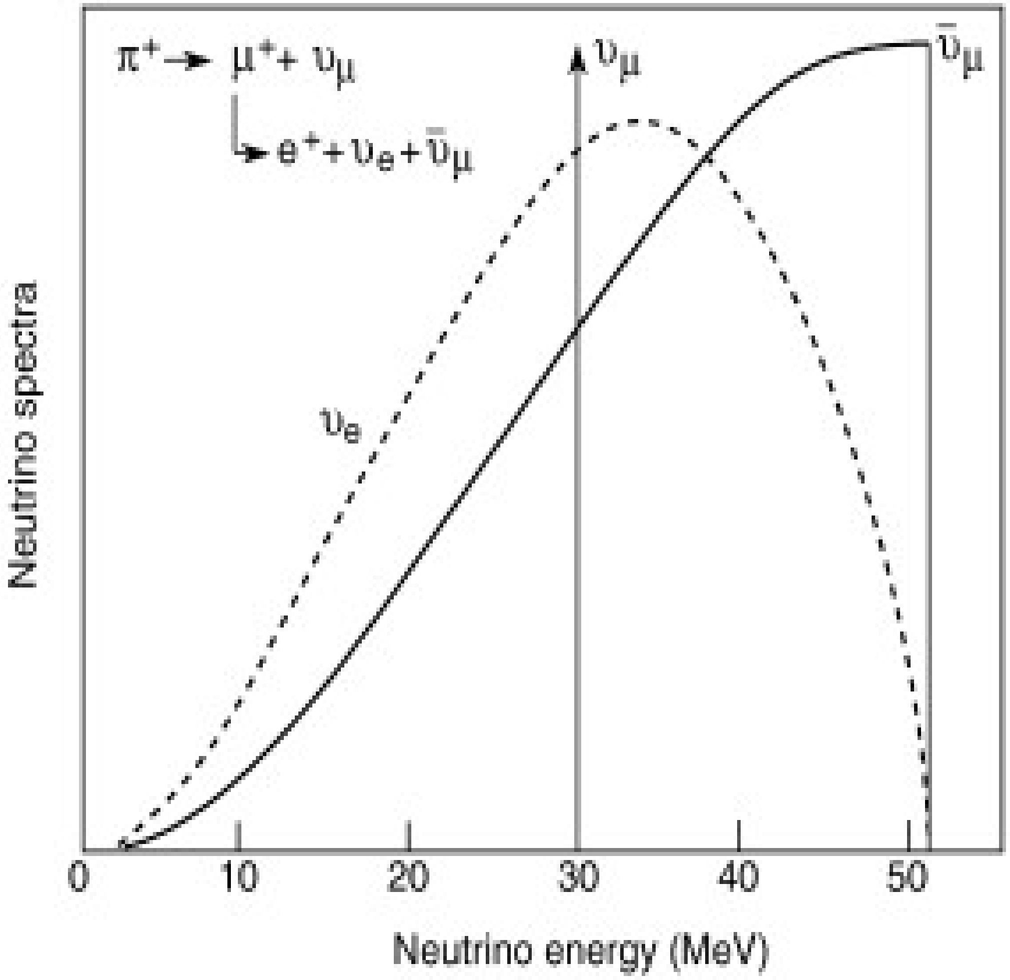
True parameters do not lie in this region at some level of confidence

Limit scales with energy resolution

Probability is a fn of 2 parameters

No signal : P(oscillation) < α

Neutrino Spectra & Event rates

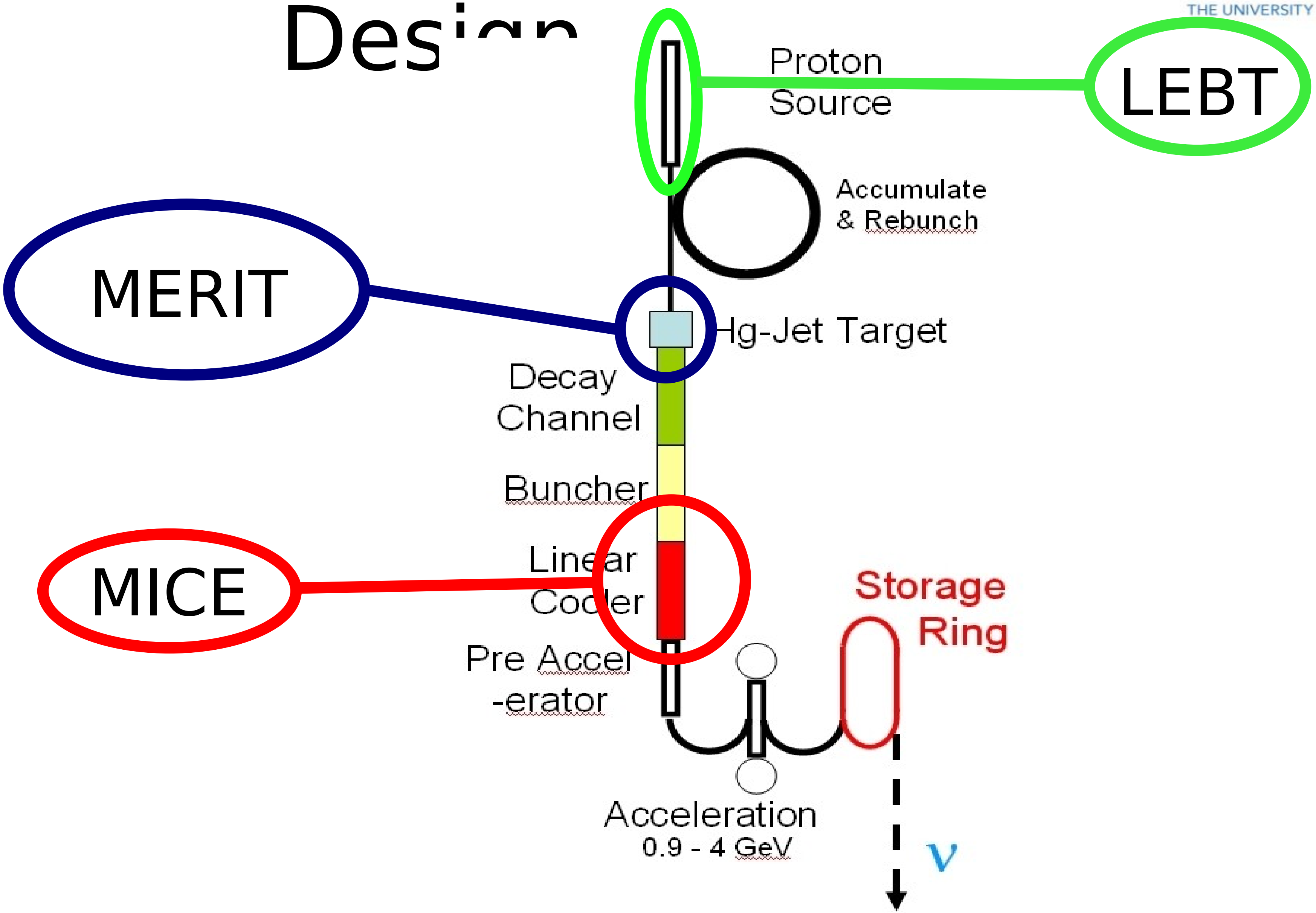


Event rate : 20 million events per 100 g per cm^2 of material per year

T2K Equivalent : 120 per 100g per cm^2 per year

Fantastic for neutrino interaction studies

Neutrino Factory Design



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- Only way to generate large fluxes of electron neutrinos.

CP Violation and Mass Heirarchy

CP violation implies that neutrinos and antineutrinos oscillate with different probabilities

...or if the Majorana issue haunts you, it implies that the probability of the left-chiral oscillation process

$$l^-_\alpha W^+ \rightarrow l^+_\beta W^-$$

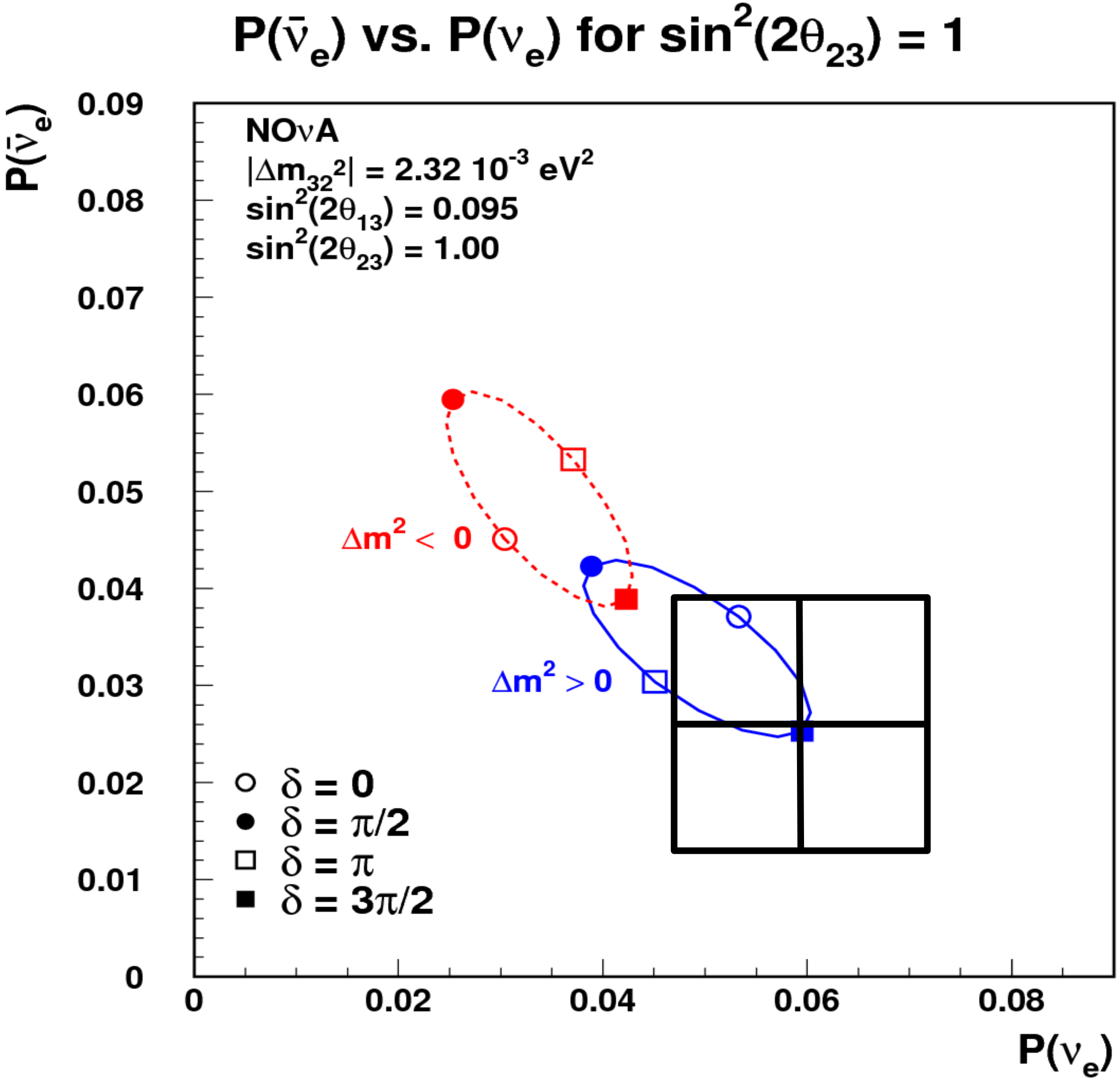
is different from the probability of the right-chiral oscillation process

$$l^+_\alpha W^- \rightarrow l^-_\beta W^+$$

So to search for it we need to look at oscillations in a neutrino beam and oscillations in an antineutrino beam and compare

For $\theta_{13} = 9^{o}$

$E_{\nu} = 2$ GeV



But it's hard...

1. We are assuming that the initial target nucleon is just sitting still before interaction. Actually in the nucleus it has some initial momentum distribution.

The initial state model modifies the scattering angles and momentum spectra of the outgoing final state

2. The outgoing final state can interact with the target nucleus.

This nuclear re-interaction affects the outgoing nucleon momentum direction and charge (through charge exchange interactions)

Theoretical uncertainties are **large**

- At least 15%
- If precise knowledge is needed for a particular target

(e.g. Water, hydrocarbon) then measurements are needed

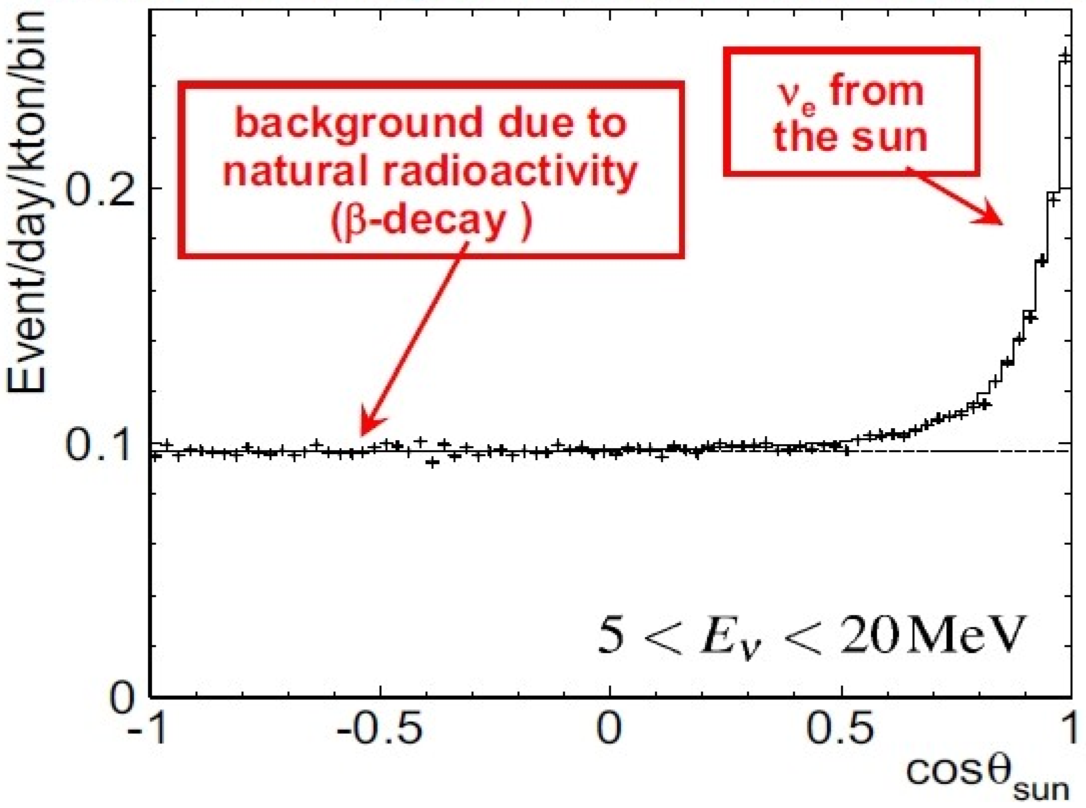
I. Something wrong with the experimental method. Either experiment is faulty or we the neutrinos we are seeing aren't coming from the sun.

II. Something wrong with the solar model

III. Something wrong with the neutrinos

(Super)Kamiokande

1987 – Kamiokande : 1000 phototubes, 5000 tons of water
1997 – SuperKamiokande : 11000 PMT, 50000 tons of water



S.Fukada et al., Phys. Rev. Lett. 86 5651-5655, 2001

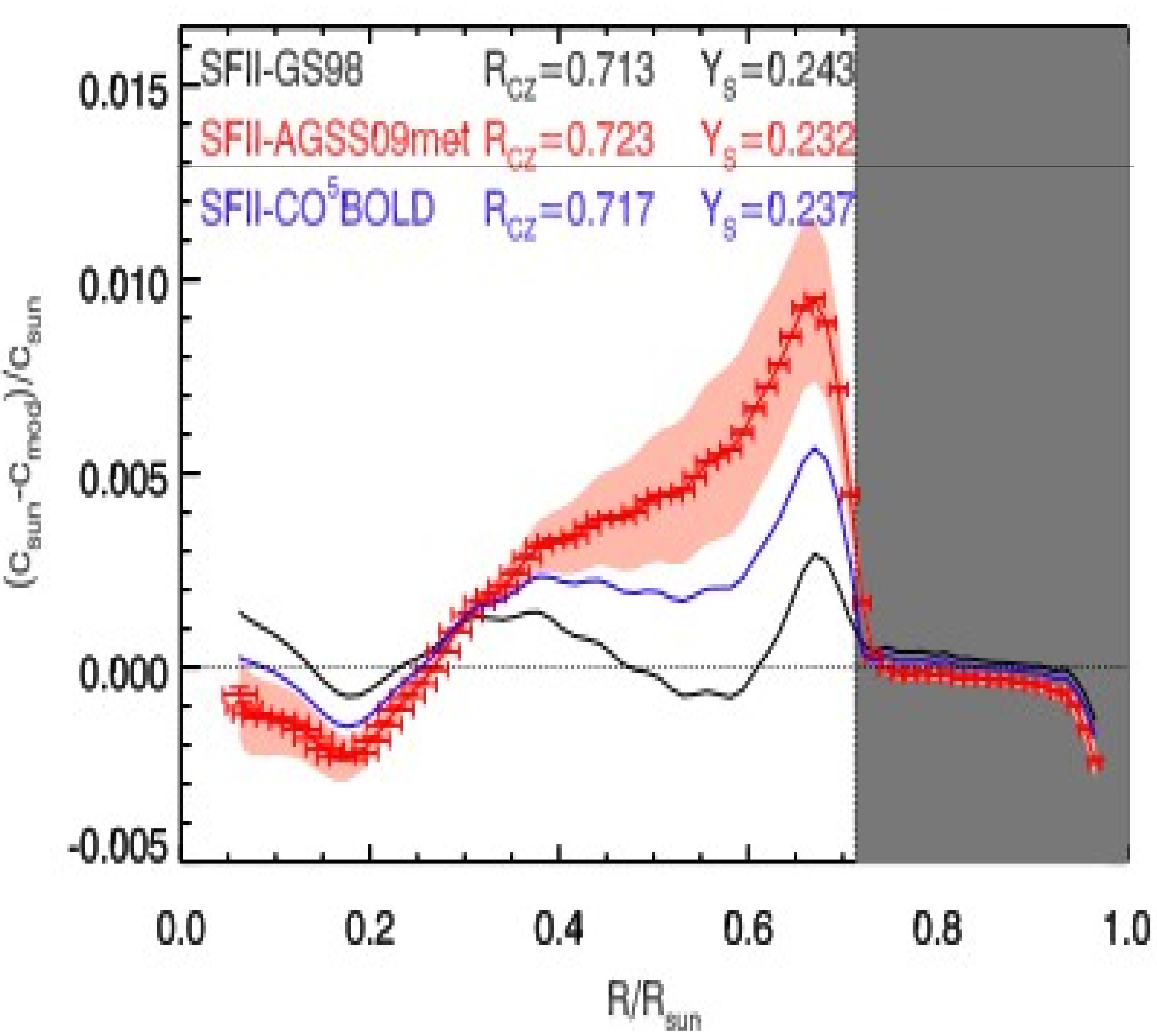
SuperK can only observe the ^{8}B flux (> 5 MeV)

$$\boxed{\frac{Data}{SSM}=0.451\pm0.017}$$

Confirmation that
it wasn't just the radio-
Chemical experiments

SuperK only sensitive to ν_e

Helioseismology



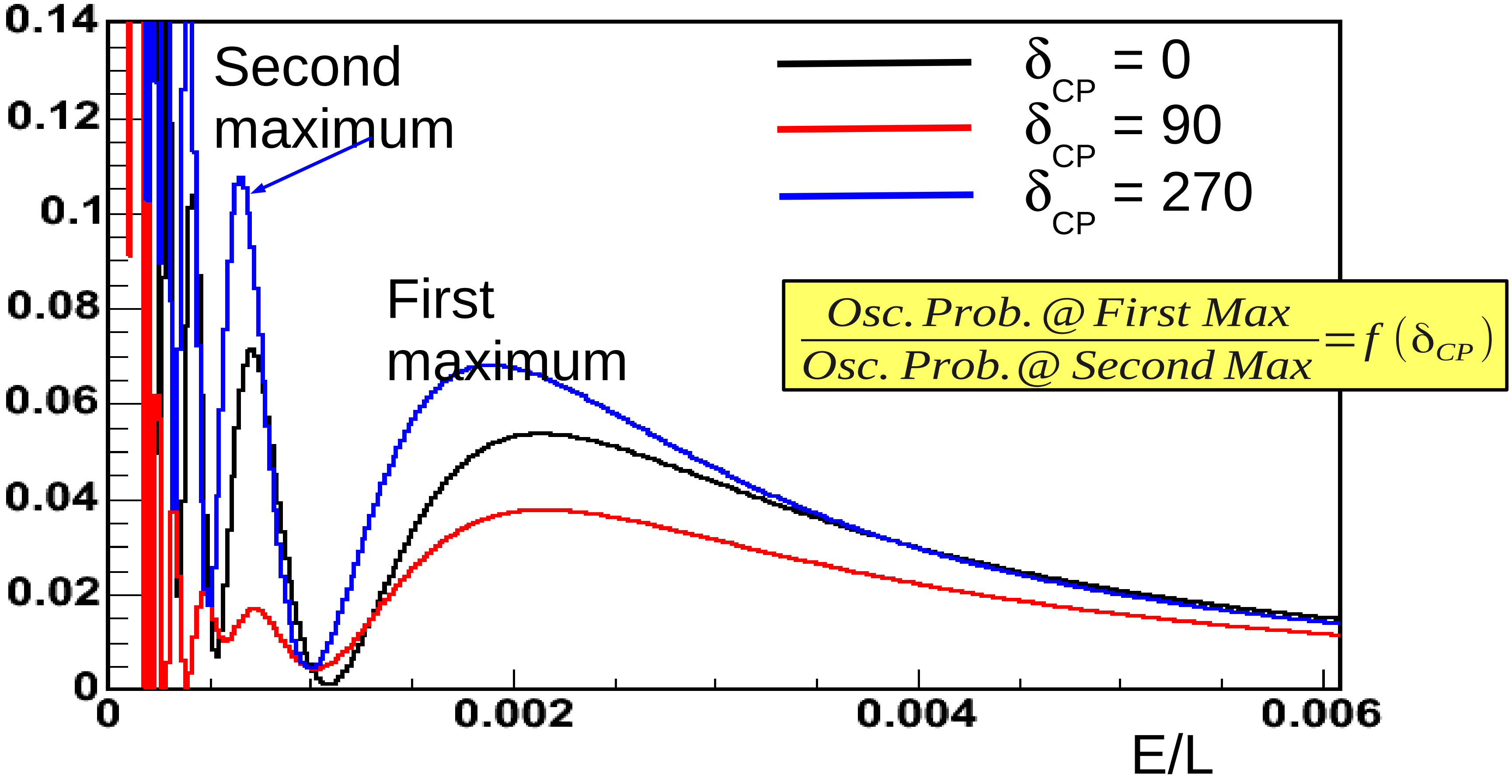
$$\Phi_\nu \propto T - T^{25}$$

Dependence of solar neutrino flux on temperature varies hugely with component

Sound speed depends on plasma density and therefore temperature.

Why is DUNE using a WBB?

$\nu_\mu \rightarrow \nu_e$ oscillation probability

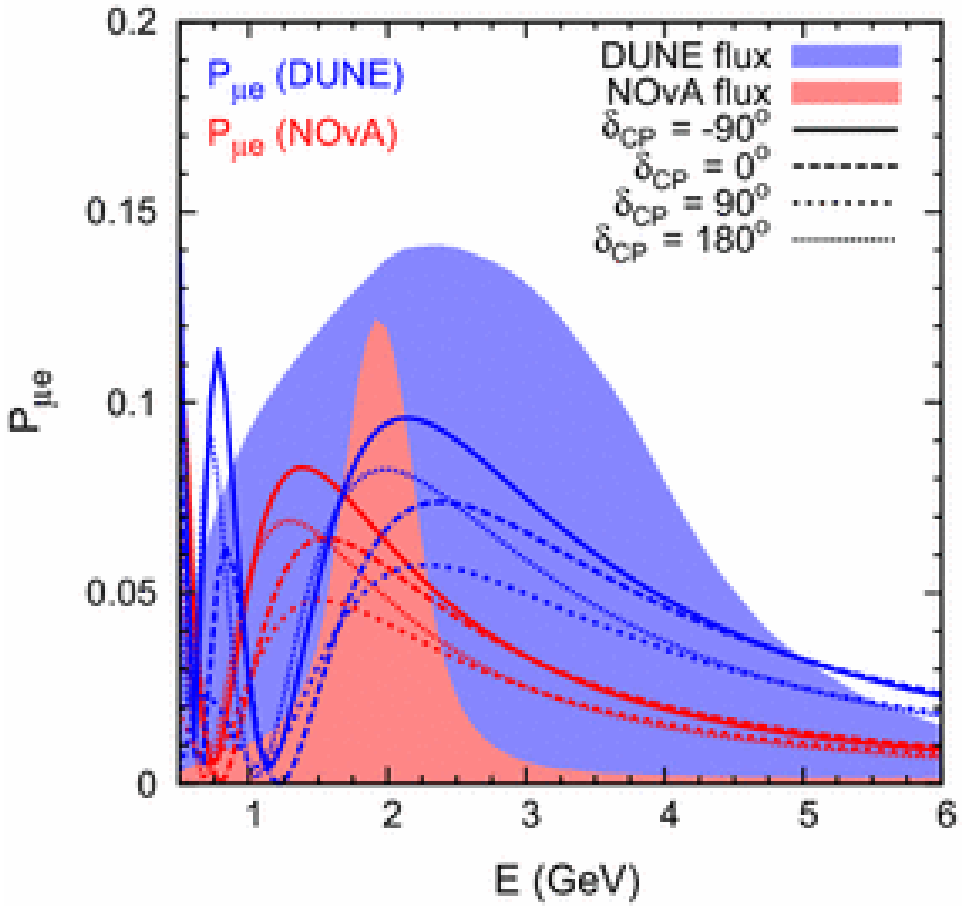


$$\frac{Osc.\,Prob.\,@\,First\,Max}{Osc.\,Prob.\,@\,Second\,Max} = f\left(\delta_{CP}\right)$$

DUNE wants to measure first and second oscillation maxima

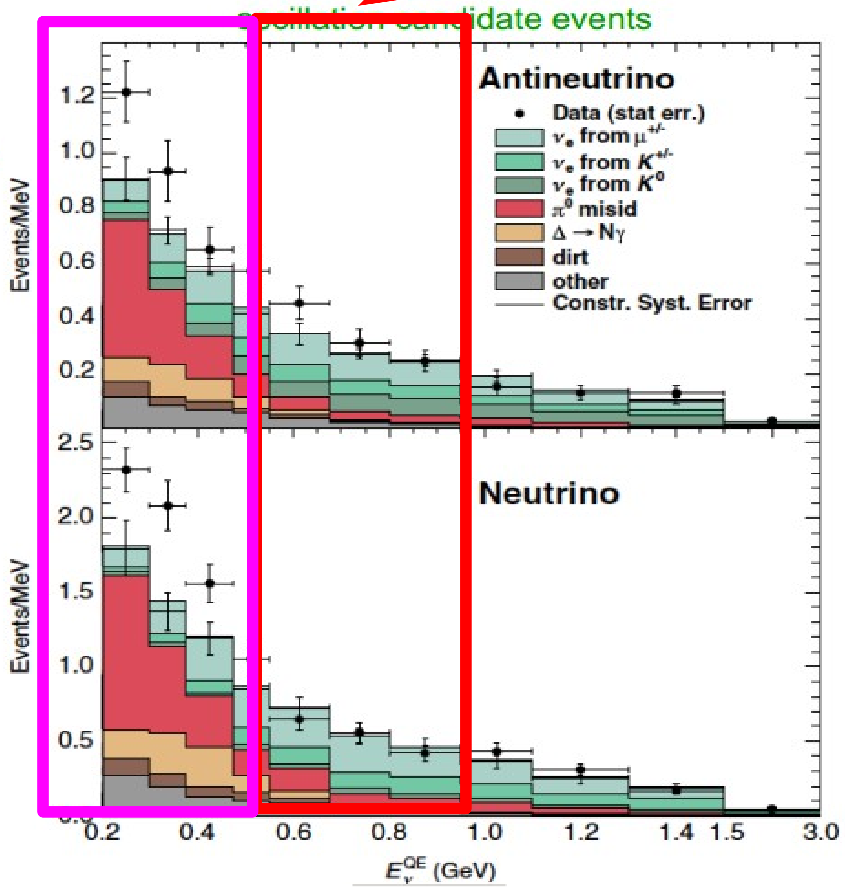
Why is DUNE using a WBB?

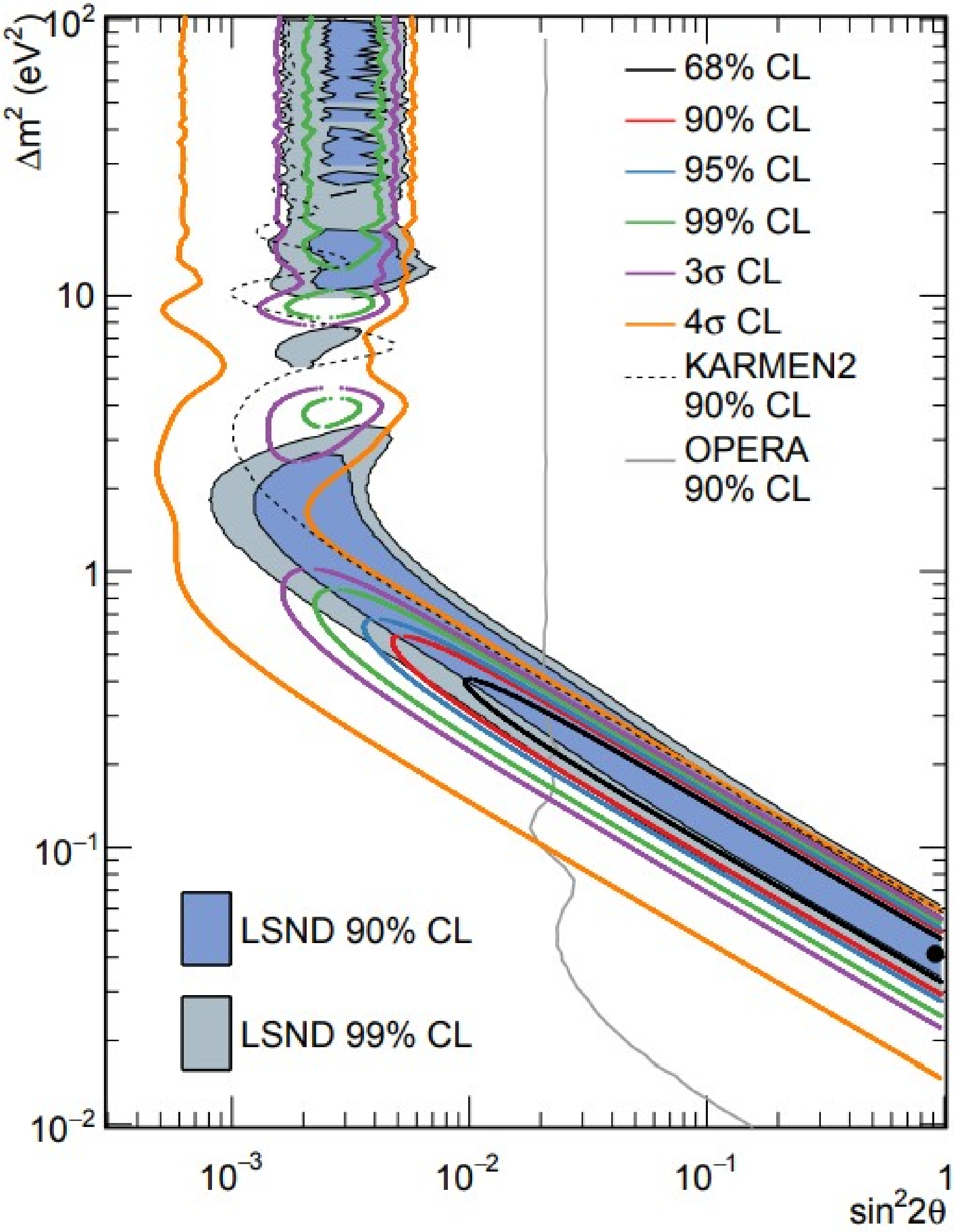
$\nu_\mu \rightarrow \nu_e$ oscillation probability



DUNE wants to measure first and second oscillation maxima
Severe challenge to neutrino energy reconstruction algorithms and
Understanding of energy resolution systematics

LSND L/E Region





- 2013 analysis
- No excess of ν_e events in signal region (E>450 MeV)
- Unknown excess of events at low energy (where NC γ/π^0 would be)