Goals of Long Baseline Neutrino Experiments

- "Ultra-sensitivity"
- Neutrino Physics Context
- "Current and Pending" long baseline experiments
- Goals of planned long baseline experiments

Josh Klein
University of Pennsylvania

“Ultra Sensivtivity”

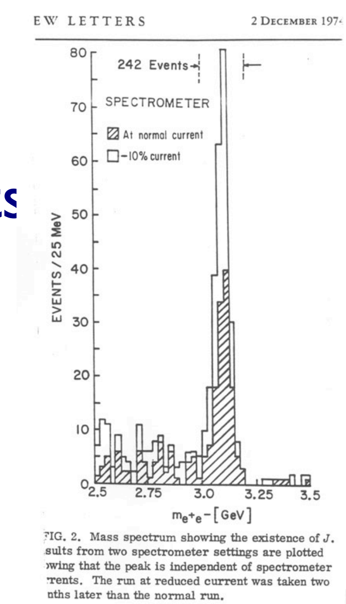
Two Basic Approaches

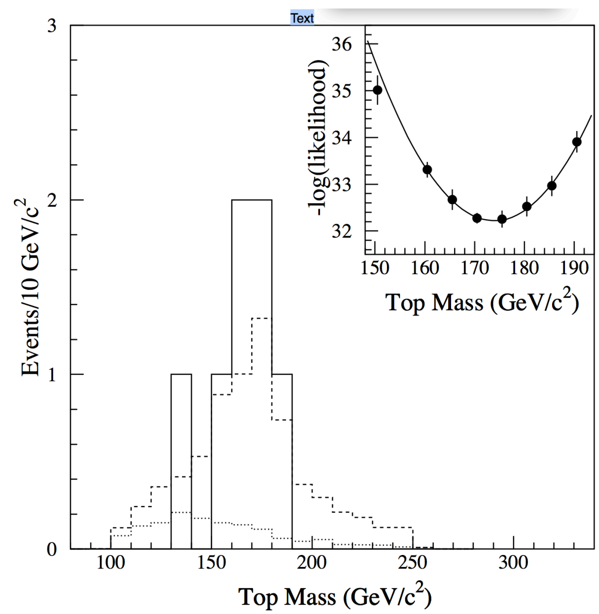
1. Rare process

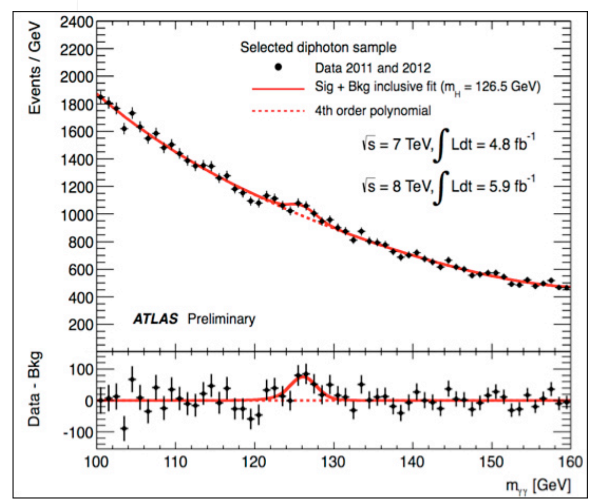
Looking for a few (or zero) events

Examples:

- Discovery of charm
- Discovery of top
- Discovery of Higgs
- SUSY searches
- Neutrinoless double beta decay
- Direct WIMP detection experiments







“Ultra Sensitivity”

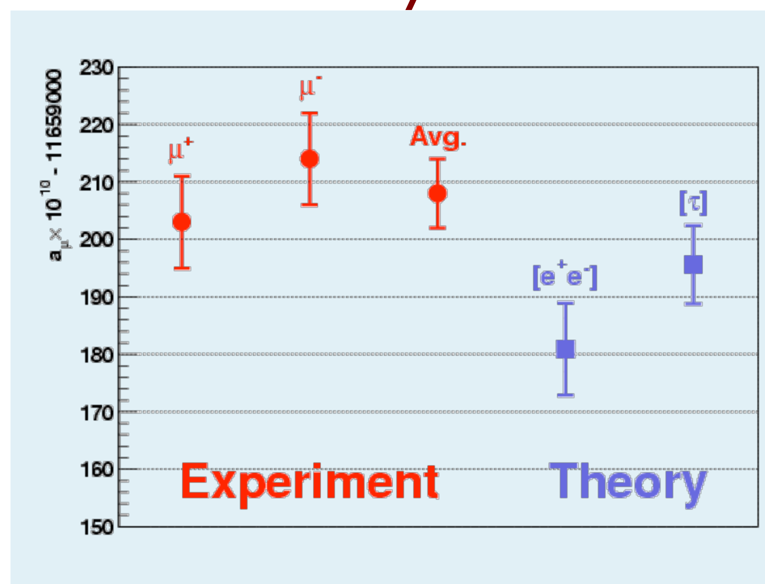
Two Basic Approaches

2. Precision Measurement

Measuring things very precisely?

Examples:

- Precession of the orbit of Mercury: 43 arcsecs/century!
- g-2

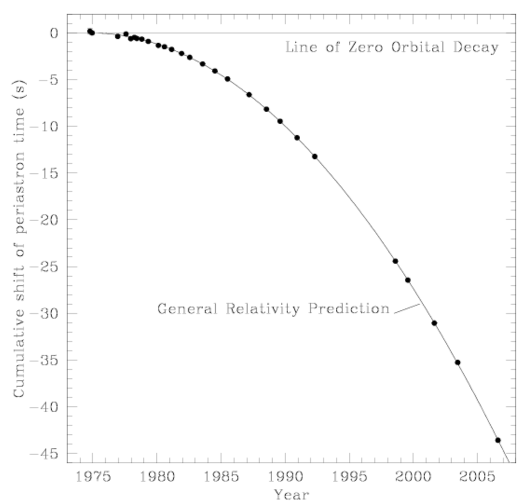


- Pulsar periods

Table 2
Astrometric and Spin Parameters

Parameter	Value[a]
t_0 (MJD)[b]	52984.0
α (J2000)	$19^h15^m27^s.99928(9)$
δ (J2000)	$16^\circ06'27''.3871(13)$
μ_α (mas yr^{-1})	$-1.43(13)$
μ_δ (mas yr^{-1})	$-0.70(13)$
f (s^{-1})	16.94053778563(15)
$\dot{f}$ (s^{-2})	$-2.4761(9) \times 10^{-15}$
Glitch epoch (MJD)	52770(20)
Δf (s^{-1})	$6.2(2) \times 10^{-10}$

Notes.
[a] Figures in parentheses represent estimated uncertainties in the last quoted digit. The estimated uncertainties range from (3–10)× the formal fitted uncertainties, in order to also reflect variations resulting from different assumptions regarding timing noise, etc.
[b] This quantity is the epoch of the next six measurements tabulated here.



"Ultra Sensitivity"

Parameters…

- What about:
  - Mass of the strange quark
  - Weak coupling constant G_F
  - Mass of the τ
  - θ_{13}

    T2K measured this with 17 events: is that rare process?
    RENO/Daya Bay measured this by carefully measuring reactor antineutrino spectra: is that precision measurement?

“Ultra Sensitivity”

Modified Definitions

- Rare Process

  Something completely new, just above detection threshold
  Often predicted by non-standard models
  But can sometimes be complete, unlooked-for surprises

- Precision Measurement

  Comparison of a measurement to *an explicit, often “standard” prediction*.
  Need not be “precise,” only “precise enough” to test the model.
  Measurements of standard parameters are a pre-requisite.
  This is the canonical scientific method approach.

Q: What new (particle) physics has been discovered via precision measurement in the last 40 years?

The Model

Solar and atmospheric neutrino disappearance explained by mixing between ν weak-interaction "flavor" eigenstates and mass eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

This was a model taken over "whole cloth" from the quark sector. Has 7 total parameters, that initially explained two signals.

(Q: What is a "mass eigenstate"?)
(Q: Can you put a neutrino in a "mass eigenstate"?)

The Model

"Freshman" Two-Flavor Context

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$\begin{aligned} |\nu_e> &= \cos\theta|\nu_1> + \sin\theta|\nu_2> \\ |\nu_\mu> &= -\sin\theta|\nu_1> + \cos\theta|\nu_2> \end{aligned}$$

$$|\nu_e(t)> = \sum_a U_{ea} e^{-im_a^2 t/2p} |\nu_a> \qquad <\nu_\mu|\nu_e(t)> = \sum_a U^*_{a\mu} U_{ea} e^{-im_a^2 t/2p}$$

$$\begin{aligned} P(t = L, \nu_\mu \to \nu_e) &= \left| \langle \nu_e | \nu_\mu(t) \rangle \right|^2 \\ &= \left| U_{1e} U_{1\mu} \right|^2 + \left| U_{2e} U_{2\mu} \right|^2 + 2 U_{1e} U_{1\mu} U_{2e} U_{2\mu} \cos\left(\frac{\Delta m^2 L}{4 E_\nu} \right) \end{aligned}$$

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4 E_\nu} \right)$$

The Model

Three Flavors

$$P(\nu_l \to \nu_{l'}) = \sum_j |U_{l'j}|^2 \, |U_{lj}|^2 \; + 2 \sum_{j>k} |U_{l'j} \, U_{lj}^* \, U_{lk} \, U_{l'k}^*| \cos\left(\frac{\Delta m_{jk}^2}{2p} \, L - \phi_{l'l;jk}\right)$$

$$\phi_{l'l;jk} = \arg\left(U_{l'j} \, U_{lj}^* \, U_{lk} \, U_{l'k}^*\right)$$

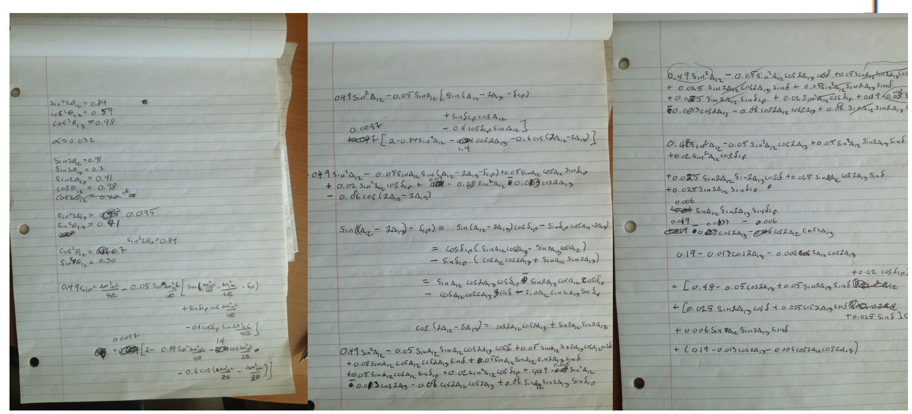
Don't try this at home…

$$\begin{aligned} P_{\text{vac}}(\nu_\mu \to \nu_e) &= \sin^2 2\theta_{12} c_{23}^2 c_{13}^2 \sin^2 \alpha\Delta \\ &- \frac{1}{2} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} c_{13} \sin \alpha\Delta \Big[\sin[(\alpha - 2)\Delta - \delta_{CP}] \\ &\qquad + \sin \delta_{CP} \cos \alpha\Delta - \cos 2\theta_{12} \cos \delta_{CP} \sin \alpha\Delta \Big] \\ &+ \frac{1}{4} \sin^2 2\theta_{13} s_{23}^2 \Big[2 - \sin^2 2\theta_{12} \sin^2 \alpha\Delta - 2c_{12}^2 \cos 2\Delta - 2s_{12}^2 \cos 2(\alpha - 1)\Delta \Big] \end{aligned}$$

$$c_{ij} = \cos\theta_{ij}, \; s_{ij} = \sin\theta_{ij}$$

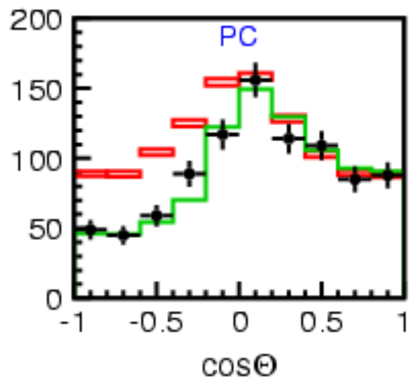
$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$$

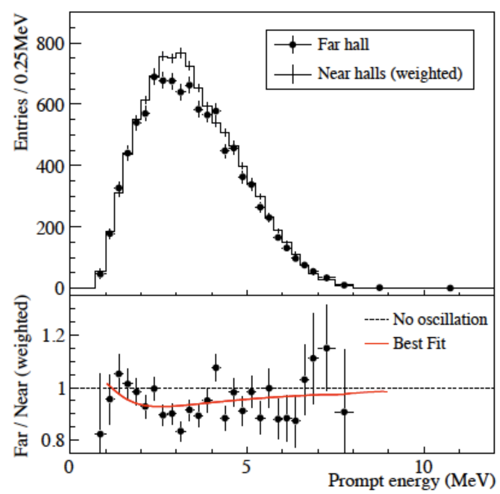
$$\Delta = \frac{\Delta m_{31}^2 L}{4E}$$

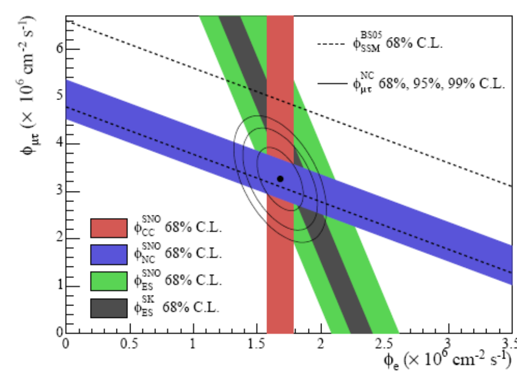


The Model

$$U=\overbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}^{\text{`atmospheric'}}\times\overbrace{\begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}}^{\text{`reactor'}}\times\overbrace{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}^{\text{`solar'}}$$







$$0.407 \le \sin^2\theta_{23} \le 0.583$$

$$\theta_{23} \sim 40^0$$

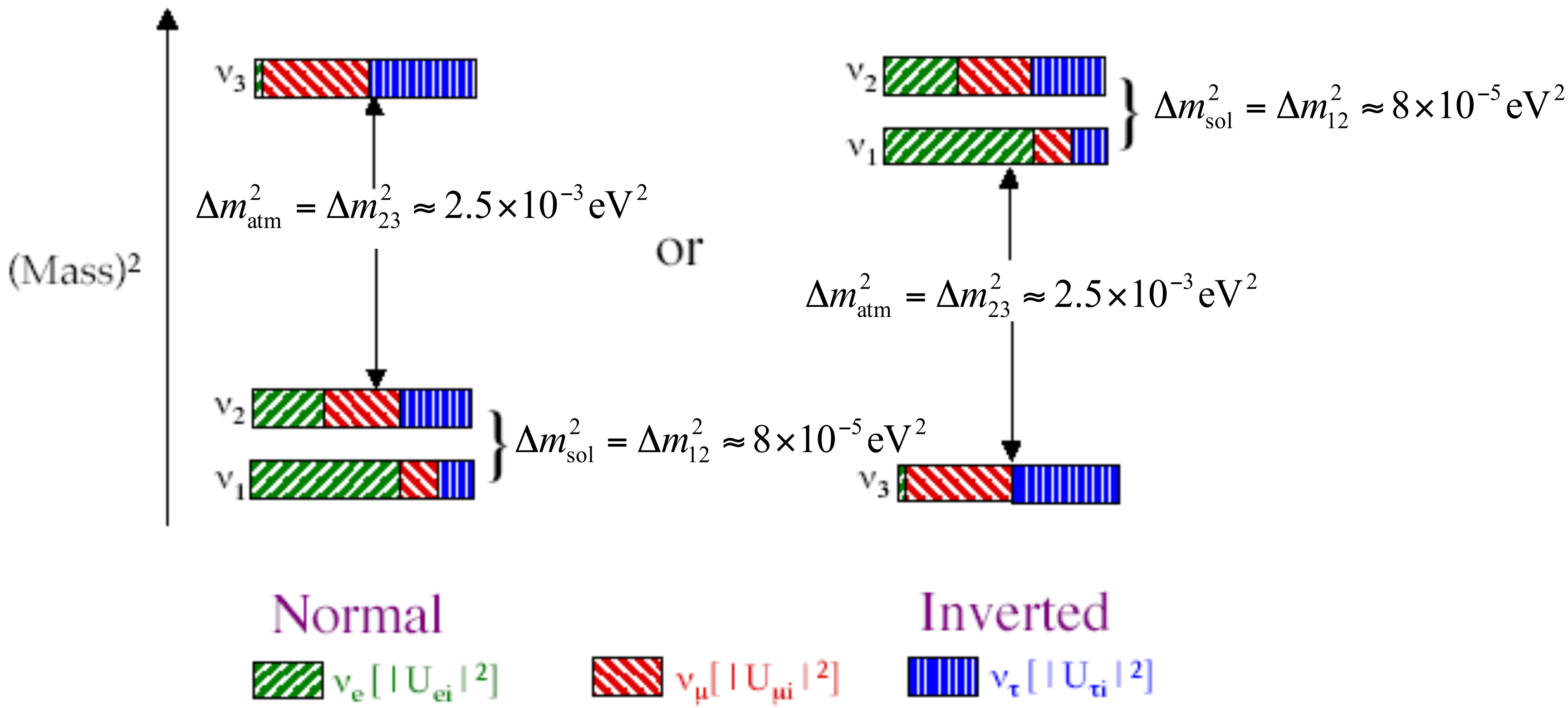
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$

$$\theta_{13} \sim 9^0$$

$$\tan^2\theta_{12} = 0.446^{+0.030}_{-0.029}$$

$$\theta_{12} \sim 33^0$$

The Model



B.Kayser, FCP05

Don't know yet absolute offset for m:

$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2\, m_i^2} < 2.2\,\mathrm{eV}$ (direct searches from tritium β-decay)

$\sum m_i < (0.3-1.3)\,\mathrm{eV}$ (cosmological data+model)

The Model

Incredible luck!---

$$P \sim \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

$1.27\Delta m_{12}^2 = 10^{-4}$ GeV/km $\quad$ $1.27\Delta m_{23}^2 = 3\times 10^{-3}$ GeV/km

$$P \sim \sin^2 2\theta$$

$\sin^2 2\theta_{12} \sim 0.84$ $\quad$ $\sin^2 2\theta_{23} \sim 1.0$ $\quad$ $\sin^2 2\theta_{13} \sim 0.10$

The Model

Neutrinos and Antineutrinos

You often find statements like,
"Neutrinos are unique in that they may be their own antiparticles…"

But let's be clear:
Lepton number conservation is an *observation* about the (old) SM Lagrangian, not a fundamental symmetry that is required or enforced.

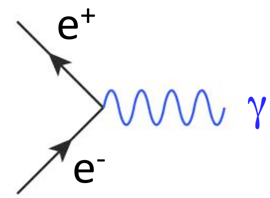
Lepton flavor number was the same thing, before neutrino mixing.

The Model

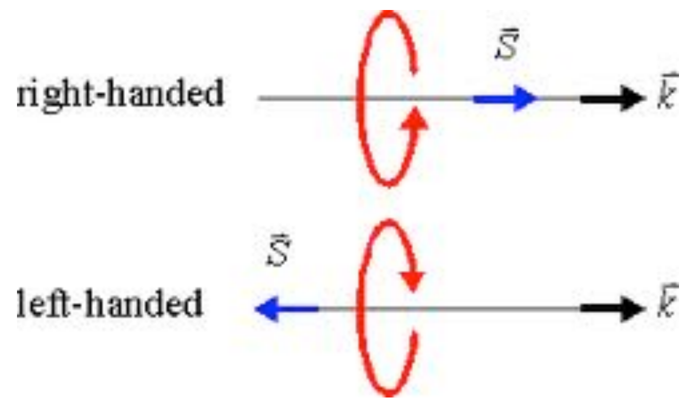
Neutrinos and Antineutrinos

Antimatter is easy to think about for charged particles:

$$e^- \leftrightarrow e^+$$



But weak interaction distinguishes particles by handedness---it couples to left-handed electrons and right-handed positrons.



So there are really 4 kinds of electron in nature:

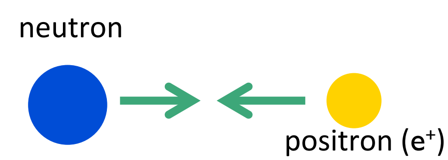
$$e_L^-,\ e_R^-,\ e_L^+,\ e_R^+$$

Weak+EM

EM only

Weak+EM

Nothing fundamentally "anti" about "antimatter"



The Model

Neutrinos and Antineutrinos

If neutrinos were massless then just two states possible:

$$\nu_L, \bar{\nu}_R$$

(Weak interactions only)

And since: $$\nu_L + \underset{\substack{\uparrow \\ \text{particle}}}{n} \rightarrow \underset{\substack{\uparrow \\ \text{particle}}}{p} + \underset{\substack{\uparrow \\ \text{particle}}}{e_L^-} \qquad \bar{\nu}_R + \underset{\substack{\uparrow \\ \text{particle}}}{p} \rightarrow \underset{\substack{\uparrow \\ \text{particle}}}{n} + \underset{\substack{\uparrow \\ \text{antiparticle}}}{e_R^+}$$

we called ν_R the "antineutrino:"

But now we know neutrinos have mass, so 4 states possible:

	"Old"		"New" (Have no weak interactions)
"Dirac neutrinos"	ν_L		ν_R
	$\bar{\nu}_R$	How are these different?	$\bar{\nu}_L$

The Model
Neutrinos and Antineutrinos

"Old" — "New" (Have no weak interactions)

"Dirac neutrinos"
$$\left\{\begin{matrix} \nu_L \\ \bar{\nu}_R \end{matrix}\right. \qquad \begin{matrix} \nu_R \\ \bar{\nu}_L \end{matrix}$$

How are these different?

So maybe we only have two states after all:

$$\nu_L \qquad \nu_R$$

Which basically means

$$\nu = \bar{\nu}$$ "Majorana neutrinos"

So what?

The Model

If neutrinos are Majorana, then:

1. We need a new (non-Higgs) mass-generating mechanism
   - Simplest term is dimension-5 and not renormalizable!
2. We likely have observed low-energy consequences of very high E scale physics
3. We may have an explanation for the matter/antimatter asymmetry
   - "Leptogenesis"
   - Requires Majorana CP phases

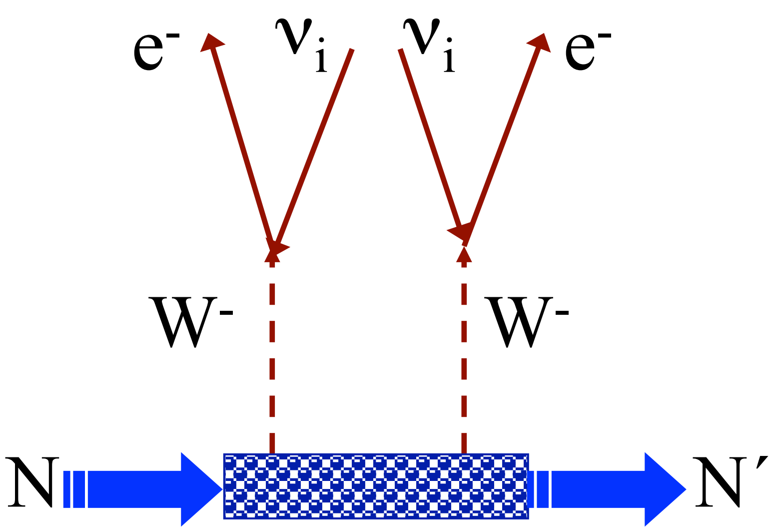
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

If neutrinos are Dirac, then:

1. Matter and antimatter are *fundamentally* different things
2. We have states that don't really do much

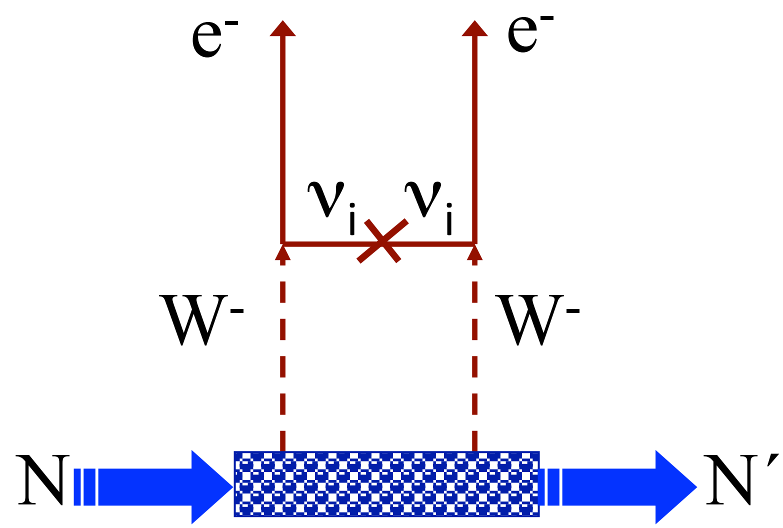
The Model

Two-neutrino double beta decay



Rare process with half-lives of ~10^{21} years

Neutrinoless double beta decay



$$T_{1/2} \propto m_{\beta\beta}^2 \sim 10^{27} \text{ years}$$

Mass is mixed average, including phases

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

$$m_{\beta\beta} = \cos^2\theta_{12}\cos^2\theta_{13}m_1 + e^{2i\lambda_2}\sin^2\theta_{12}\cos^2\theta_{13}m_2 + e^{2i(\lambda_3-\delta_{CP})}\sin^2\theta_{13}m_3$$

Large coeffs. *Small coeff.*

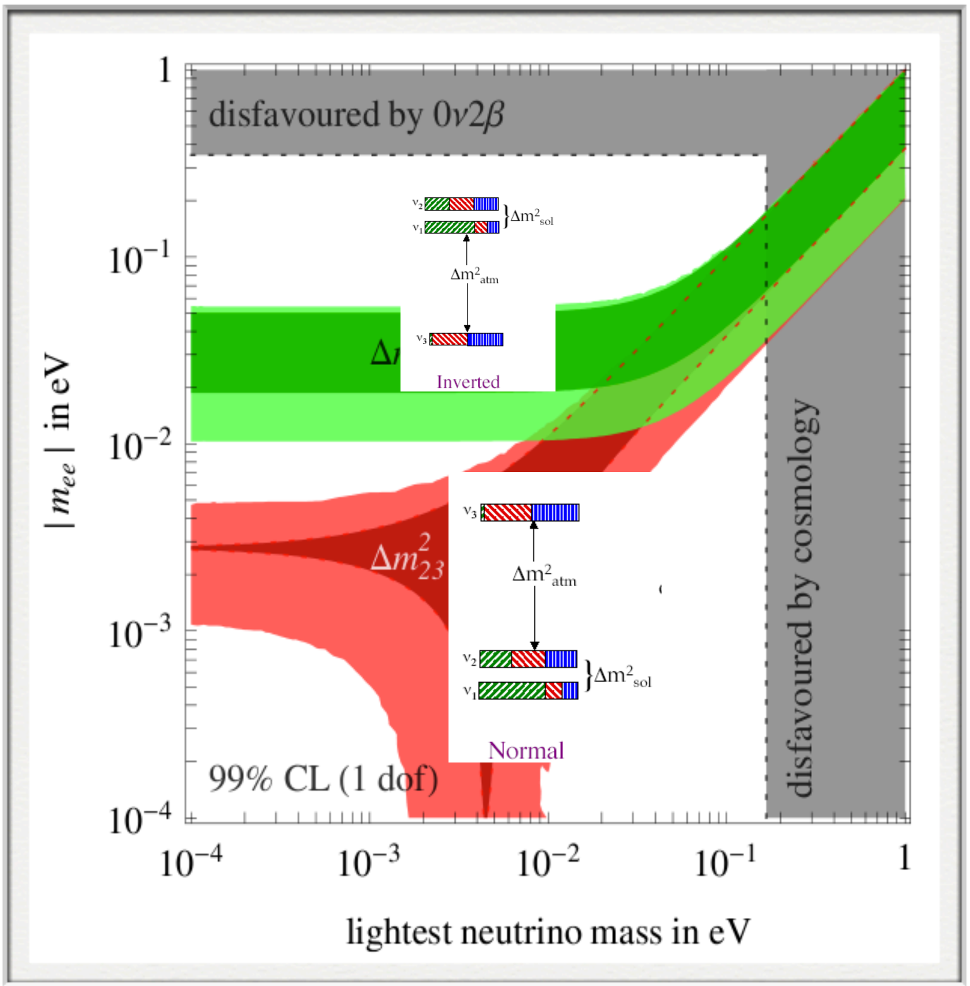
Fortunately, Avogadro's number is very big, so 10^{27} years ~ 1 tonne of isotope

Unfortunately, we don't know $m_{\beta\beta}$, or even which m_i is biggest.

The Model

$$m_{\beta\beta} = \cos^2\theta_{12}\cos^2\theta_{13}m_1 + e^{2i\lambda_2}\sin^2\theta_{12}\cos^2\theta_{13}m_2 + e^{2i(\lambda_3-\delta_{CP})}\sin^2\theta_{13}m_3$$

$$m_{\beta\beta} = 0.69m_1 + 0.72m_2e^{2i\lambda_2} + 0.02m_3e^{2i(\lambda_3-\delta_{CP})}$$



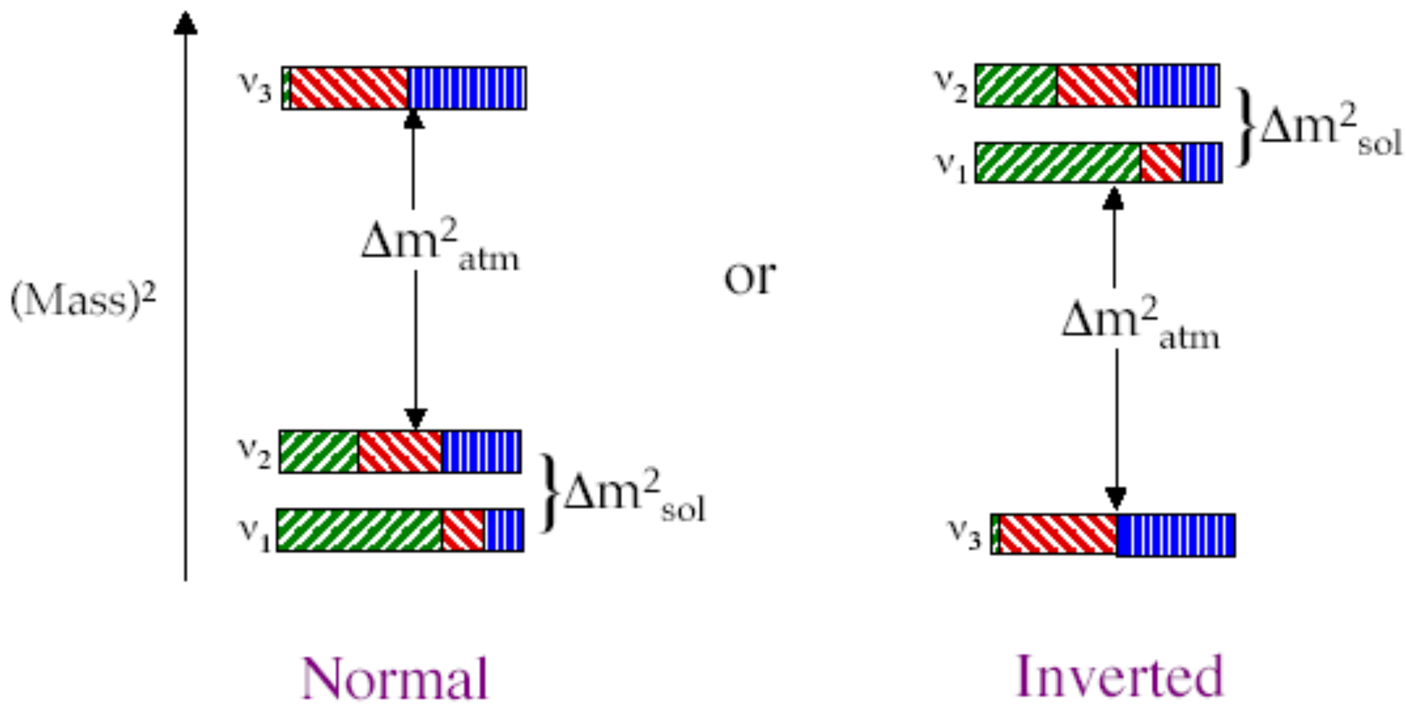
If next-generation $0\nu\beta\beta$ experiments see nothing, then:

If $\Delta m^2_{23}<0$ OR $m_1>20$ meV

- ➢ Neutrinos are Dirac

The construction of the new Standard Model depends critically on the mass “hierarchy”

The Model



Mass hierarchy is also a prediction of many theories beyond the Standard Model (including SUSY)

The Story So Far

- 5 out of 7 parameters of 3-flavor mixing model measured
- Majorana question not yet answered
- Additional 2 phases for Majorana neutrinos not known
- Precision measurement tests require precise predictions….

So what does this model predict?

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Measure parameters

Predict Mixing

$$U = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix}$$

The thing we measure appears to be the thing we're testing.

The Model

- ν `interferometry' probes flavor non-diagonal processes

Matter effect is an example:

To see how this works, re-do survival probability in flavor basis:

$$|\nu_e> \;=\; \cos\theta|\nu_1> + \sin\theta|\nu_2>$$

$$|\nu_\mu> \;=\; -\sin\theta|\nu_1> + \cos\theta|\nu_2>$$

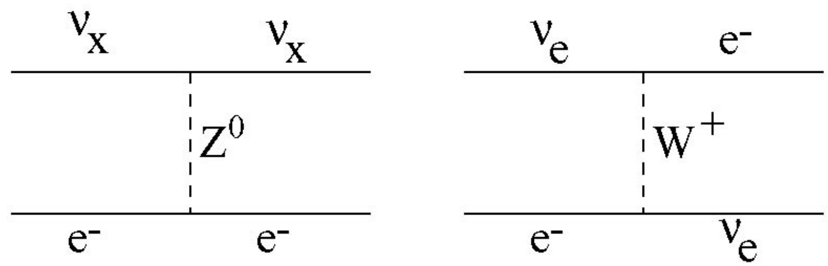
$$<\nu_e|H|\nu_e> \;=\; <\nu_e|H|\nu_1\cos\theta + \nu_2\sin\theta> \approx \; p + \frac{m_1^2\cos^2\theta + m_2^2\sin^2\theta}{2p}$$

$$\imath\frac{\partial}{\partial t}\frac{1}{2}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2\cos 2\theta}{2p} & \frac{\Delta m^2\sin 2\theta}{2p} \\ \frac{\Delta m^2\sin 2\theta}{2p} & \frac{\Delta m^2\cos 2\theta}{2p}\end{pmatrix}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$

The Model

- ν \`interferometry' probes flavor non-diagonal processes

But matter is made only of first-generation material….



All neutrino flavors **Only electron neutrinos**

$$< \nu_e | H_W | \nu_e >= \sqrt{2} G_F N_e \longrightarrow \tilde{H} = \tilde{H_f} + \tilde{H_W}$$

(for ν's, we can treat bulk matter as just a potential term!)

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\sqrt{2}G_f N_e - \frac{\Delta m^2}{2p}\cos^2\theta & \frac{\Delta m^2}{4p}\sin 2\theta \\ \frac{\Delta m^2}{4p}\sin 2\theta & -\frac{\Delta m^2}{2p}\sin^2\theta\end{pmatrix}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$

$$P_{\nu_e \to \nu_e}(E_{\nu_e}, L, \theta, \Delta m^2) = 1 - \sin^2\theta_m \sin^2\frac{\pi L}{\lambda_m}$$

The Model

- ν `interferometry' probes flavor non-diagonal processes

$$P_{\nu_e \to \nu_e}(E_{\nu_e}, L, \theta, \Delta m^2) = 1 - \sin^2\theta_m \sin^2 \frac{\pi L}{\lambda_m} \qquad \lambda_m = \frac{2\pi}{\sqrt{\left(\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e\right)^2 + \left(\frac{\Delta m^2}{2E}\right)\sin^2 2\theta}}$$

Effective mixing angle in matter is Energy and density-dependent:

$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e} \xrightarrow{\textit{Resonance when}} \sqrt{2}G_f N_e - \frac{\Delta m^2}{2E}\cos 2\theta = 0$$

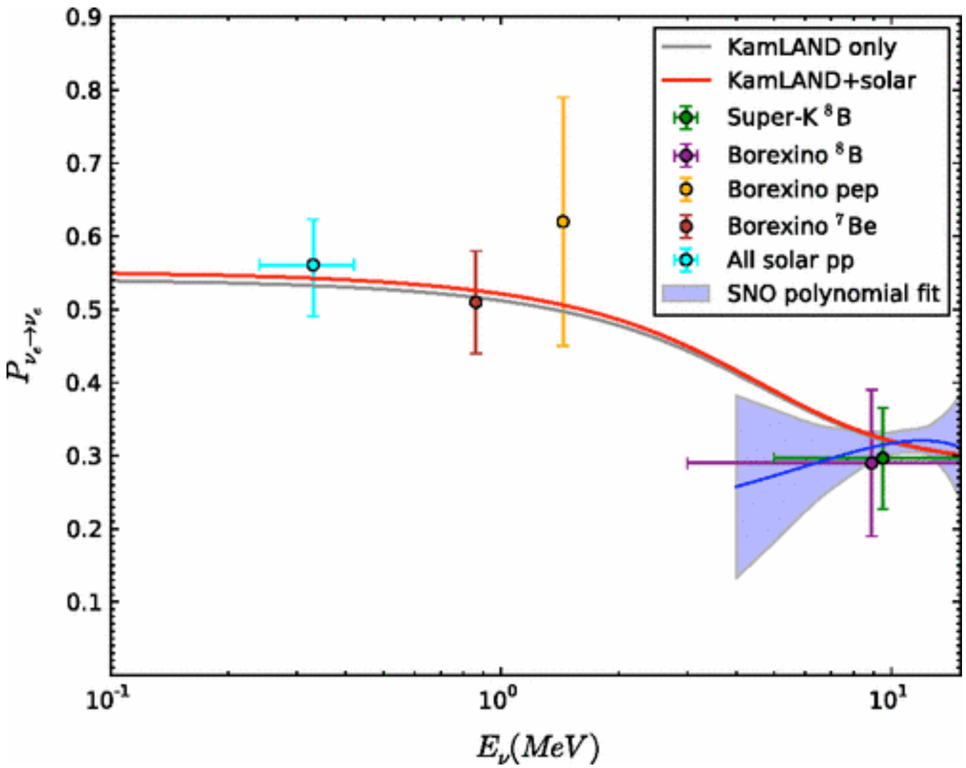
Notes:

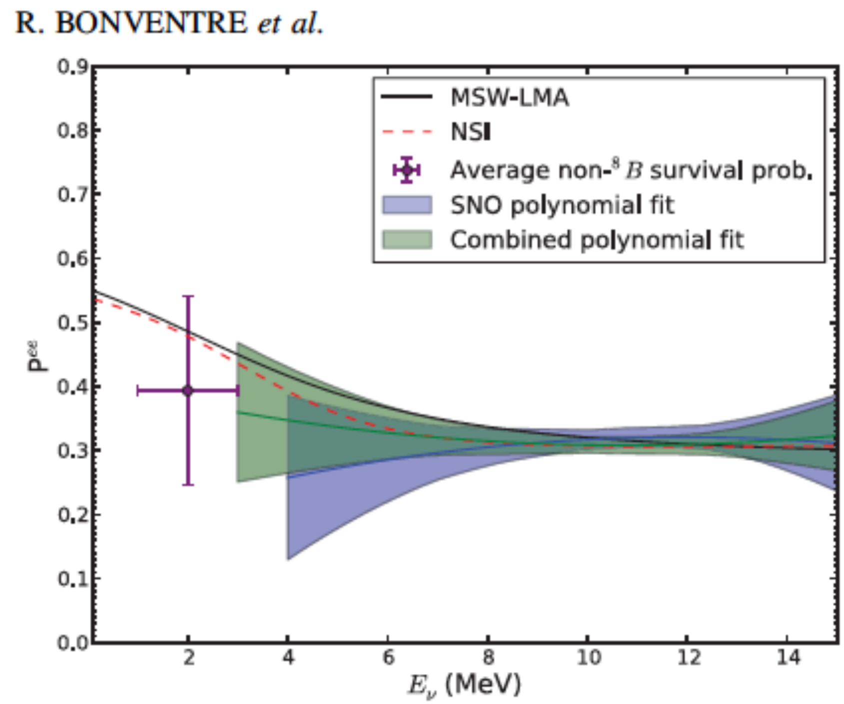
- The *sign* of Δm^2 matters
- The sign of the potential changes for antineutrinos (no antimatter)
- Physically, this is a lot like regeneration of K^0_S from a K^0_L beam.
- Or maybe rotation of polarization via birefrigence
- This is a "standard" model prediction for neutrinos

Bottom line: Anything that distinguishes flavor or mass states changes the pattern.

The Model

Matter effect has been observed in only one case so far:



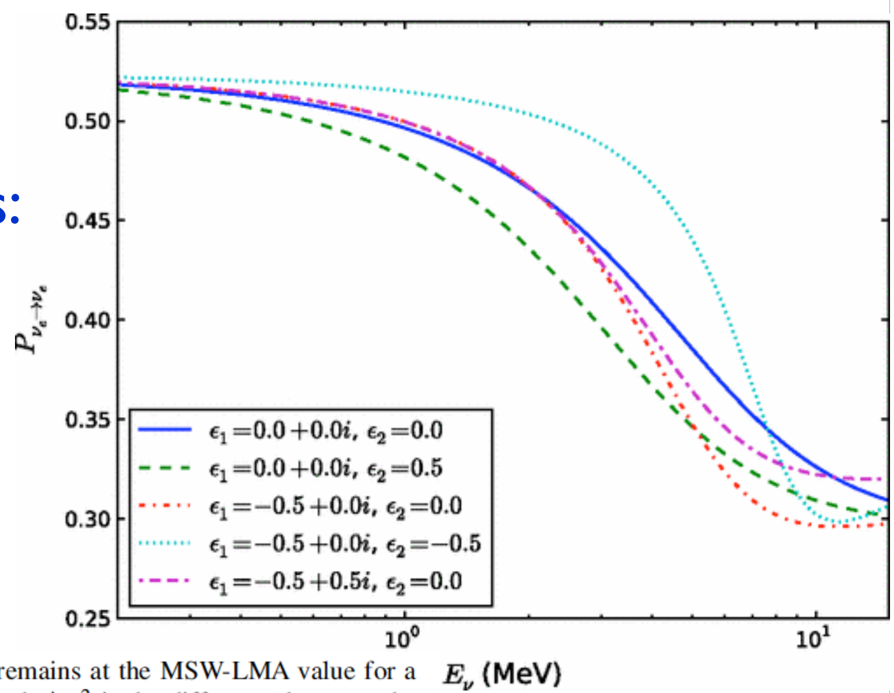


Bonventre, LaTorre, et al, PRD 88 2013

Suppression at high energies because $\nu_{sun}=\nu_2=1/3\nu_e$

Other Models

But can't exclude lots of other models:



Bonventre, LaTorre, et al, PRD 88 2013

TABLE III. Comparison of survival probability fits to standard MSW-LMA. If the best fit remains at the MSW-LMA value for a model, a 90% confidence level upper limit (1 d.o.f.) on the model's parameters is given instead. $\Delta\chi^2$ is the difference between the model's best-fit point and the MSW-LMA best fit. The final column gives the largest confidence level at which MSW-LMA is excluded.

Model	Best fit	$\Delta\chi^2$	Additional d.o.f.	C.L.
MSW-LMA	$\Delta m^2_{21} = 7.462 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.301$, $\sin^2\theta_{13} = 0.0242$	0	⋯	⋯
MSW-LMA (AGSS09SF2)	$\Delta m^2_{21} = 7.469 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{13} = 0.0240$	2.8	⋯	⋯
NSI (ϵ_1 real, $\epsilon_2 = 0$)	$\epsilon_1 = -0.145$	−1.5	1	0.78
NSI ($\epsilon_2 = 0$)	$\epsilon_1 = -0.146 + 0.031i$	−1.5	2	0.53
NSI (ϵ_1 real)	$\epsilon_1 = 0.014$, $\epsilon_2 = 0.683$	−1.9	2	0.60
MaVaN neutrino density dependence	$m_{1,0} < 0.033$ eV	0	1	0.0
MaVaN fermi density dependence	$\alpha_2 = 6.30 \times 10^{-5}$, $\alpha_3 = i2.00 \times 10^{-5}$	−3.3	2	0.81
Long-range scalar leptonic force	$k_S = 6.73 \times 10^{-45}$, $\lambda = 1.56 R_\odot$, $m_{1,0} = 0$ eV	−2.9	3	0.58
Long-range vector leptonic force	$k_V = 3.26 \times 10^{-54}$, $\lambda = 16.97 R_\odot$	−1.8	2	0.59
Long-range tensor leptonic force	$k_T < 1.3 \times 10^{-61}$ eV^{-1}	0	2	0.0
Nonstandard solar model without flux constraint	$\delta_0 = 0.57$	−4.6	1	⋯

The Model

When matter effects are included in full three-flavor P_{surv}…

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}$$ "θ_{13} term"

$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

"CP term" $$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

"solar term" $$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta) \cdot \sin^2\Delta_{21}$$

"matter terms"

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1-2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2S_{13}^2) \cdot \sin^2\Delta_{31},$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu} \qquad a = 2\sqrt{2} G_F n_e E$$

$$= 7.6 \times 10^{-5} \rho\left[g/cm^3\right] \times E_\nu\left[GeV\right]$$

Lots of signs that matter:

- Δ: $\Delta m^2 < 0$?
- δ: ν vs. anti-ν
- a: ν vs. anti-ν

The Model

Lots of signs that matter:

- Δ: $\Delta m^2<0$?
- δ: ν vs. anti-ν
- A: ν vs. anti-ν

On the upside:

- Oscillations can tell us the mass hierarchy!
- Oscillations can tell us δ!

On the downside:

- This can be very confusing, and can even cancel—
- Matter effect enhances $\nu_\mu \rightarrow \nu_e$ for normal hierarchy, suppresses it for IH, and just the opposite for the anti-nus.

Predictions for Long Baseline Experiments

- Neutrinos don't just transform, they *oscillate*
- Coherent interactions with matter alter oscillation pattern
- Mixing parameters are universal
  - Neutrinos and antineutrinos have the same mixing parameters
  - And it doesn't matter how you measure them
- $\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{13}^2 = 0$
- For 3 light flavors, mixing matrix is unitary…

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} U_{e1}^* & U_{\mu1}^* & U_{\tau1}^* \\ U_{e2}^* & U_{\mu2}^* & U_{\tau2}^* \\ U_{e3}^* & U_{\mu3}^* & U_{\tau3}^* \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$U_{e1}U_{e1}^* + U_{\mu1}U_{\mu1}^* + U_{\tau1}U_{\tau1}^* = 1$$

$$U_{e2}U_{e2}^* + U_{\mu2}U_{\mu2}^* + U_{\tau2}U_{\tau2}^* = 1$$

$$U_{e3}U_{e3}^* + U_{\mu3}U_{\mu3}^* + U_{\tau3}U_{\tau3}^* = 1$$

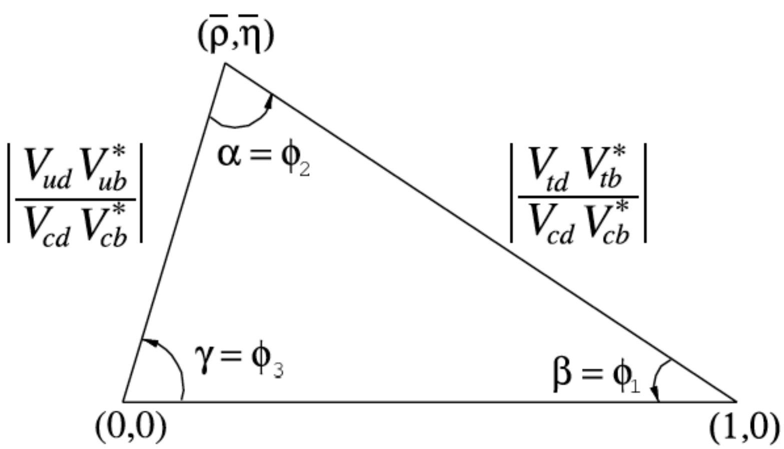
$$U_{e1}U_{\mu1}^* + U_{e2}U_{\mu2}^* + U_{e3}U_{\mu3}^* = 0$$

$$U_{e1}U_{\tau1}^* + U_{e2}U_{\tau2}^* + U_{e3}U_{\tau3}^* = 0$$

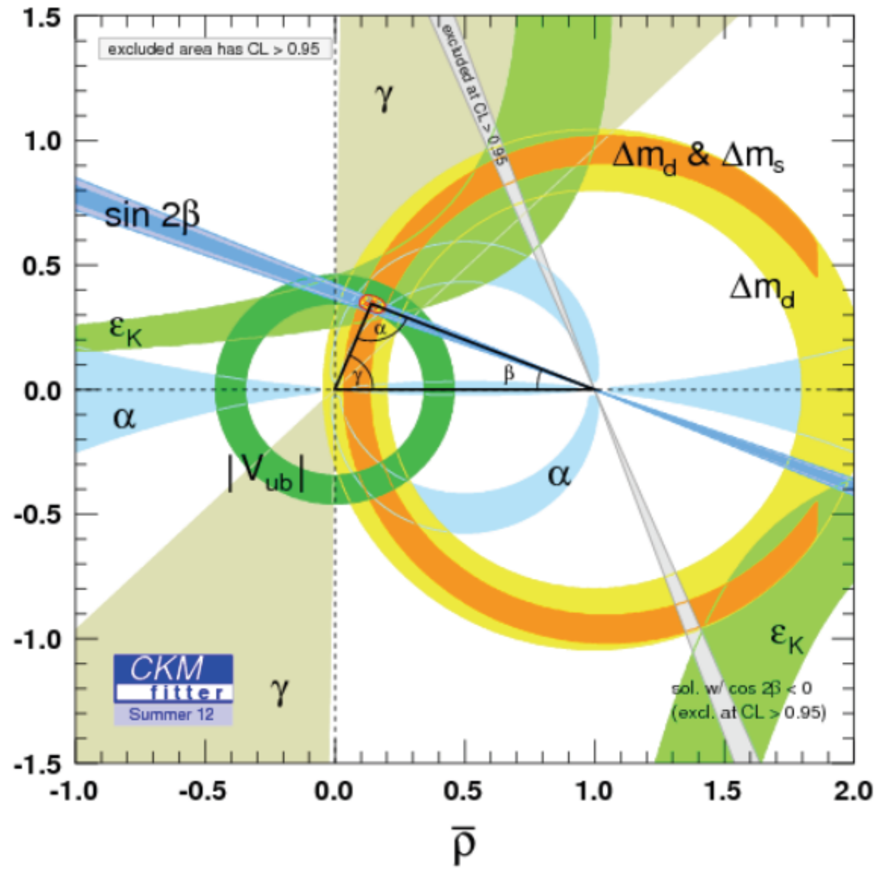
$$U_{\mu1}U_{\tau1}^* + U_{\mu2}U_{\tau2}^* + U_{\mu3}U_{\tau3}^* = 0$$

Unitarity Envy?

$$V_{\mathrm{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



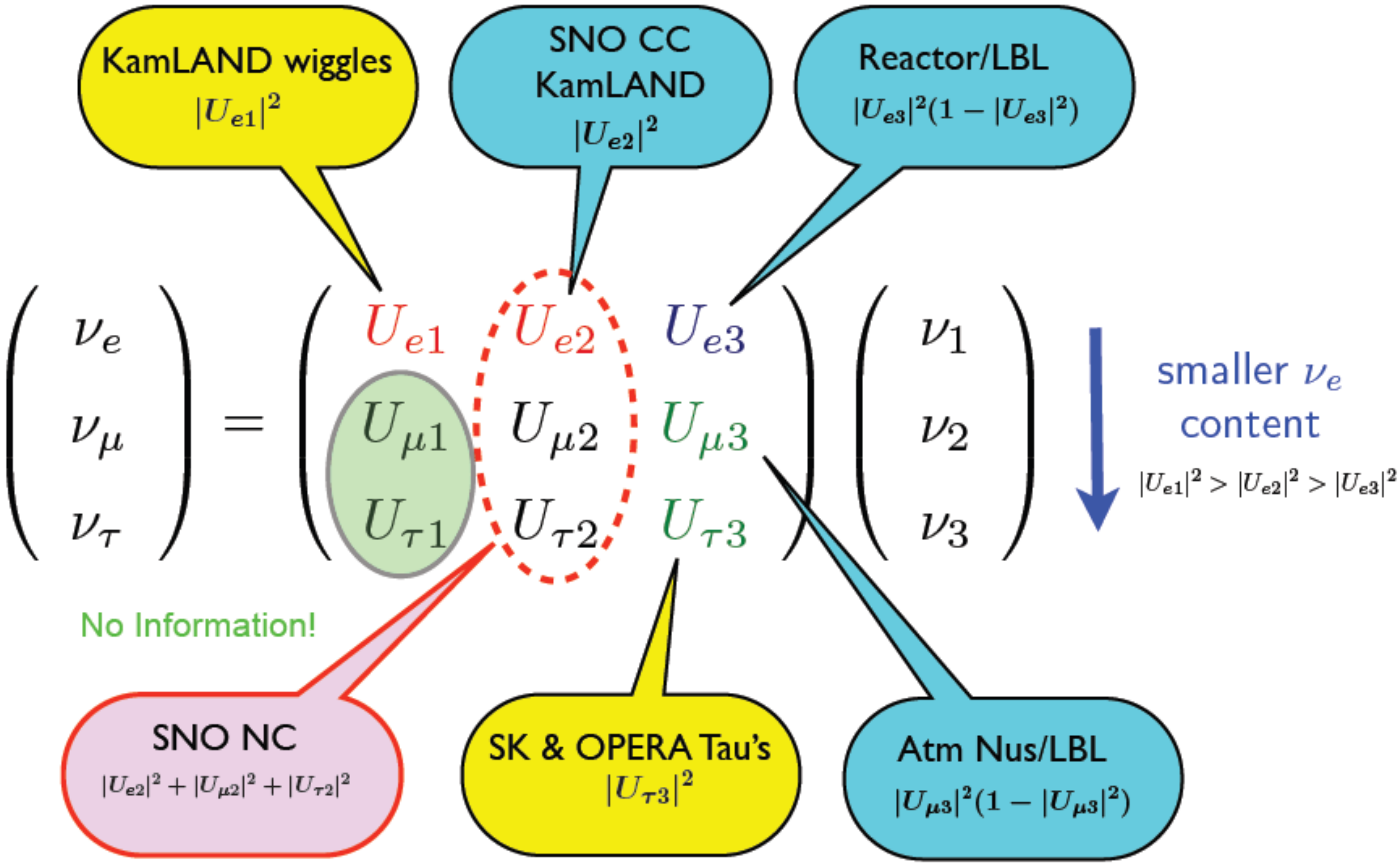
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Many different processes provide independent measurements of CKM matrix elements; Unitarity "tested" by combinations of elements according to unitarity conditions.

Well…so where's our triangles?

Unitarity Envy?



S. Parke 2014

Unitarity Envy?

What would non-unitarity mean <u>*observationally*</u> for neutrinos?

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} U^*_{e1} & U^*_{\mu 1} & U^*_{\tau 1} \\ U^*_{e2} & U^*_{\mu 2} & U^*_{\tau 2} \\ U^*_{e3} & U^*_{\mu 3} & U^*_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$P(\nu_l \to \nu_{l'}) = \sum_j |U_{l'j}|^2 \, |U_{lj}|^2 \; + 2 \sum_{j>k} |U_{l'j} \, U^*_{lj} \, U_{lk} \, U^*_{l'k}| \cos(\frac{\Delta m^2_{jk}}{2p} L - \phi_{l'l;jk})$$

$$\phi_{l'l;jk} = \arg\left(U_{l'j} \, U^*_{lj} \, U_{lk} \, U^*_{l'k}\right)$$

"All the neutrinos, all the time."

"True" non-unitarity of the mixing matrix means would mean this

$$P_{\nu_\mu \to \nu_e} + P_{\nu_\mu \to \nu_\tau} + P_{\nu_\mu \to \nu_\mu} = 1$$

is not true. Where do the neutrinos go?

Unitarity Envy?

What would non-unitarity mean *observationally* for neutrinos?

"True" non-unitarity of the mixing matrix means would mean this

$$P_{\nu_\mu \to \nu_e} + P_{\nu_\mu \to \nu_\tau} + P_{\nu_\mu \to \nu_\mu} = 1$$

is not true. Where do the neutrinos go?

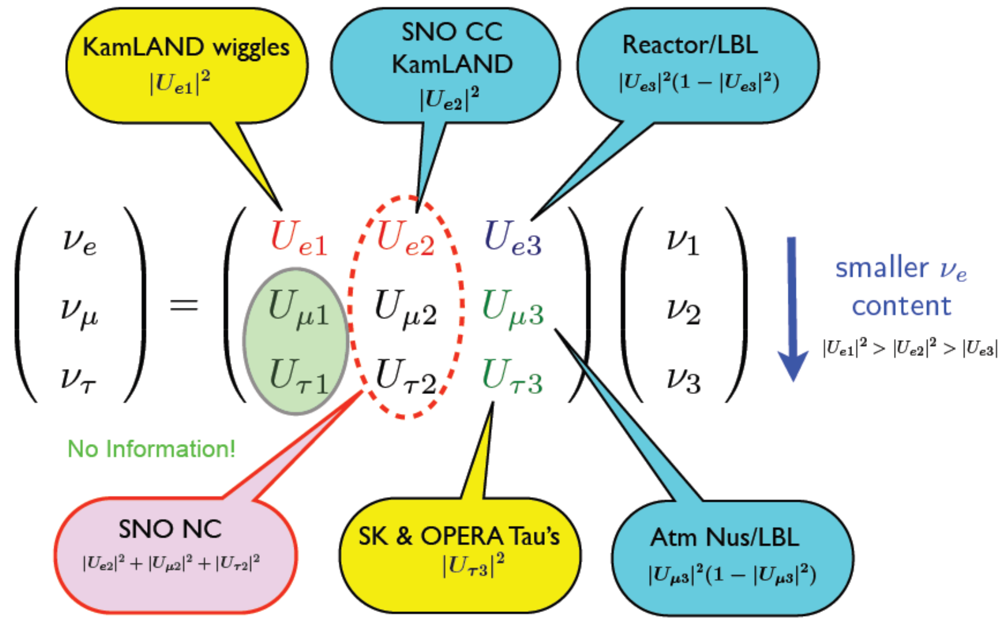
Any mixed sterile state would also show up via kinematics---
oscillation pattern would be consistent with a "new" Δm^2---
or via neutral current disappearance (unless it DOES interact via NC)

Unitarity Envy?

What would non-unitarity mean *observationally* for neutrinos?

But perhaps there can be an "effective" non-unitarity

$$U^*_{\mu 1} U_{e1} + U^*_{\mu 2} U_{e2} + U^*_{\mu 3} U_{e3} = 0$$



You think you are measuring matrix elements but really something else

$$P(t=L, \nu_\mu \to \nu_e) = \left| \langle \nu_e | \nu_\mu(t) \rangle \right|^2$$

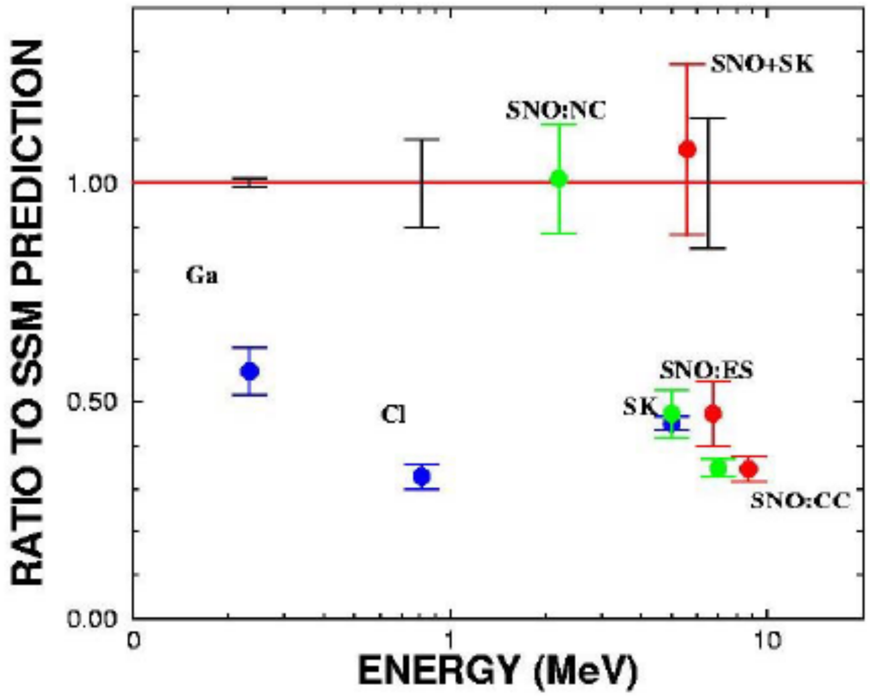
$$= \left| U_{1e} U_{1\mu} \right|^2 + \left| U_{2e} U_{2\mu} \right|^2 + 2 U_{1e} U_{1\mu} U_{2e} U_{2\mu} \cos\left(\frac{\Delta m^2 L}{4 E_\nu} \right)$$

Unitarity Envy?

Example from an Alternate History:

Wolfenstein goes into finance, Mikheyev never meets Smirnov….

…and SNO is the only solar neutrino experiment, and does a "rate-only" measurement



SNO doesn't know it is measuring an almost "pure" U_{e2}, but instead thinks it is measuring…

$$= \left|U_{1e}U_{1\mu}\right|^2 + \left|U_{2e}U_{2\mu}\right|^2 + 2U_{1e}U_{1\mu}U_{2e}U_{2\mu}\cos\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

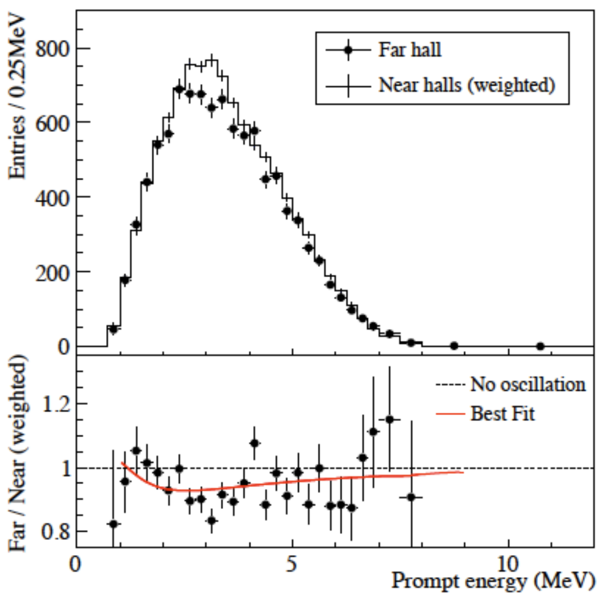
Unitarity Envy?

Example from an Alternate History:

$$= \left|U_{1e}U_{1\mu}\right|^2 + \left|U_{2e}U_{2\mu}\right|^2 + 2U_{1e}U_{1\mu}U_{2e}U_{2\mu}\cos\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

SNO gets Δm^2 wrong (thinks oscillation length is of order1 AU!), so maybe KamLAND gets cancelled.

Daya Bay still runs, because atmospheric data point to a relevant Δm^2.



And because of "wrong" solar data, it thinks it gets a very pure measure of $|U_{e3}|$.

Long baseline and atmospheric experiments then measure $|U_{\mu 3}|$.

Then

$$\boxed{U^*_{\mu 1}U_{e1} + U^*_{\mu 2}U_{e2} + U^*_{\mu 3}U_{e3} = 0}$$

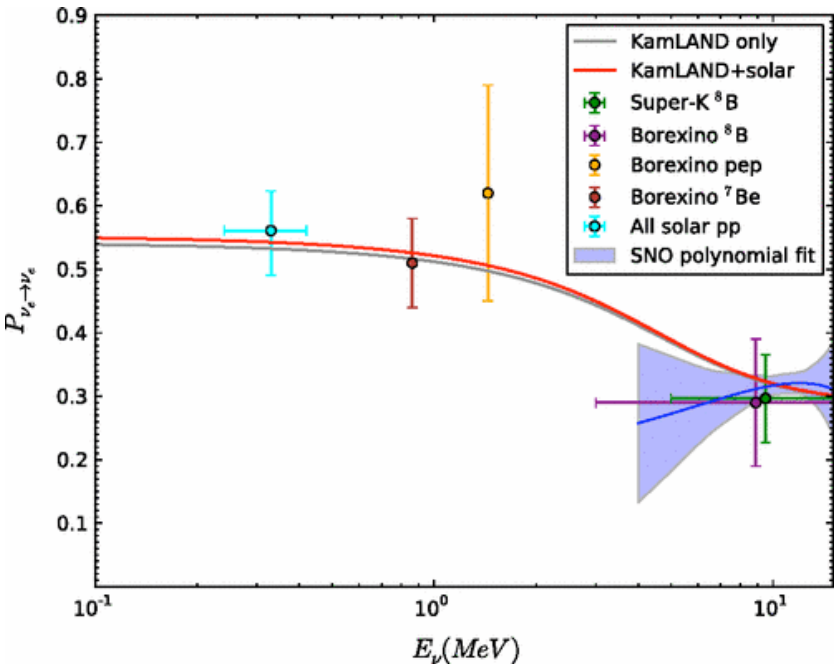
Might have "discovered" the matter effect. Maybe.

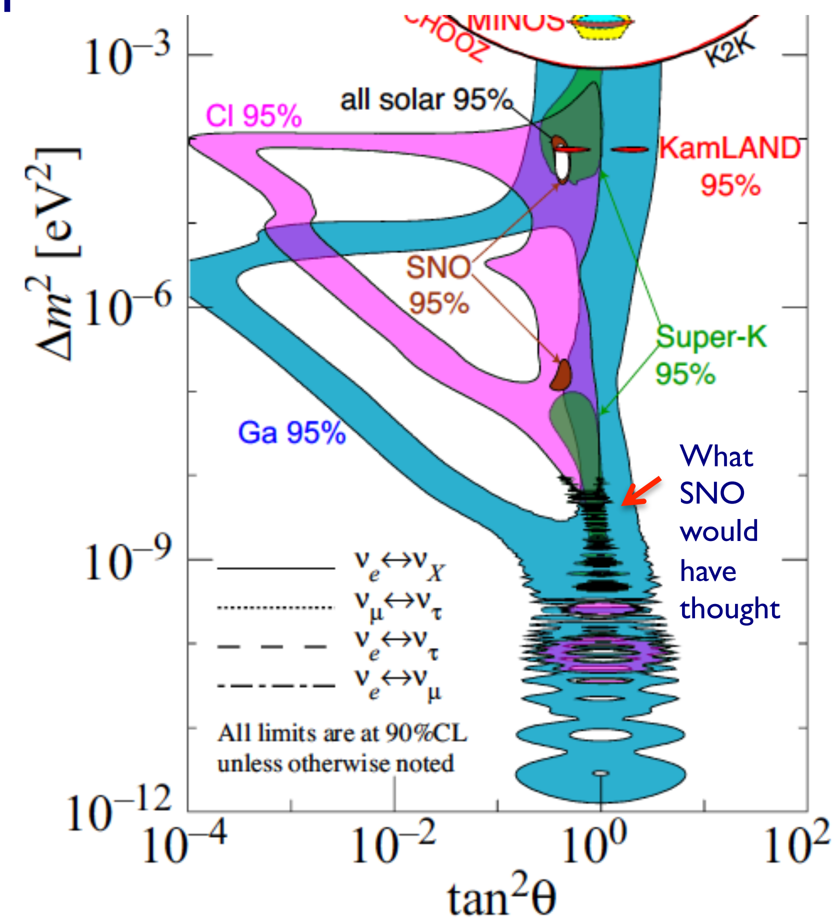
Unitarity Envy?

Example from an Alternate History:

$$U_{\mu 1}^* U_{e1} + U_{\mu 2}^* U_{e2} + U_{\mu 3}^* U_{e3} = 0$$

But this is a much crappier way of finding new physics in the neutrino sector than by just doing experiments:





Unitarity Envy?

The richness of neutrino oscillation phenomenology

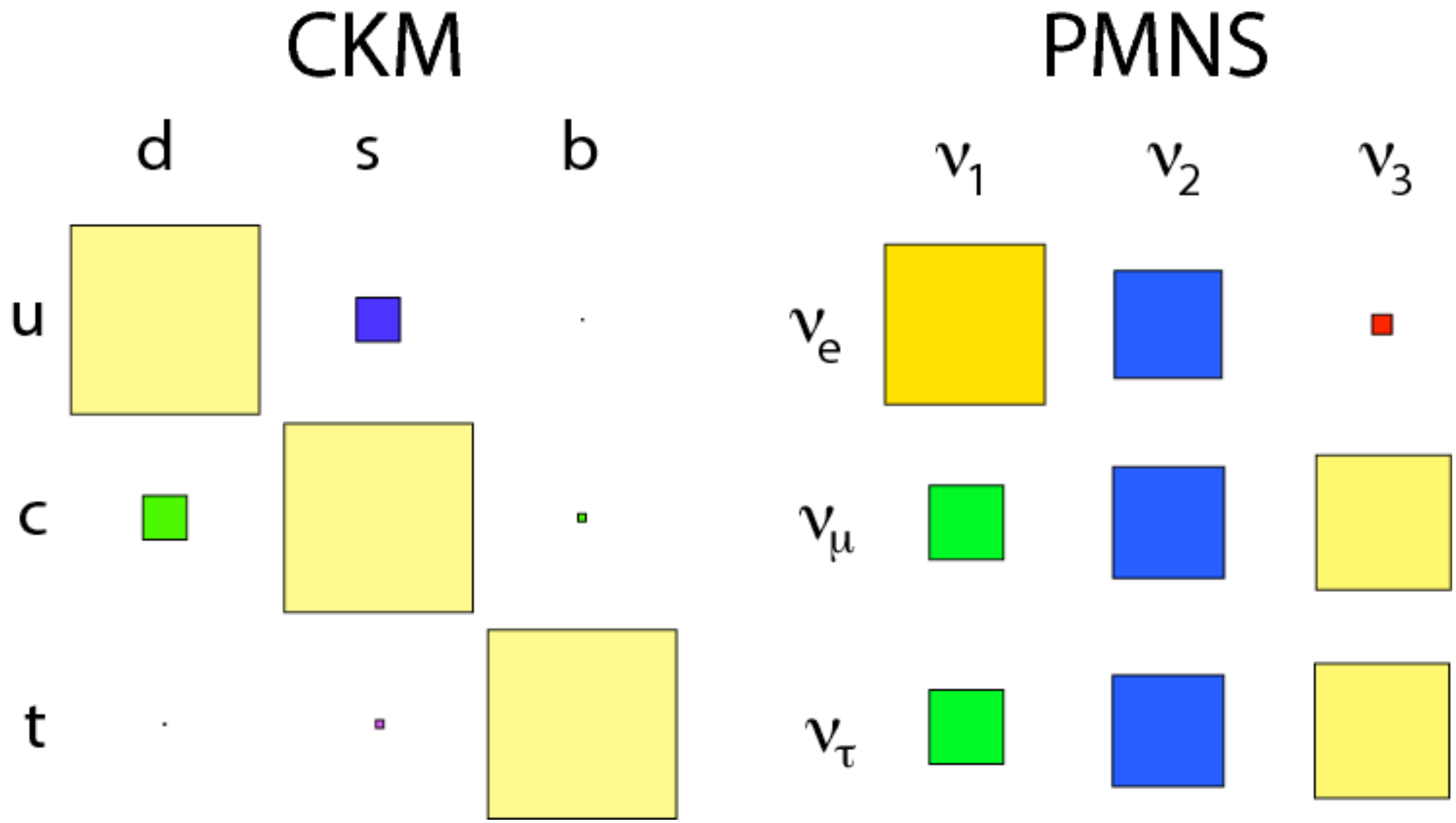
$$
\begin{aligned}
P_{\text{vac}}(\nu_\mu \to \nu_e) = &\sin^2 2\theta_{12} c_{23}^2 c_{13}^2 \sin^2 \alpha\Delta \\
&- \frac{1}{2} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} c_{13} \sin \alpha\Delta \Big[\sin[(\alpha - 2)\Delta - \delta_{CP}] \\
&\qquad + \sin \delta_{CP} \cos \alpha\Delta - \cos 2\theta_{12} \cos \delta_{CP} \sin \alpha\Delta \Big] \\
&+ \frac{1}{4} \sin^2 2\theta_{13} s_{23}^2 \Big[2 - \sin^2 2\theta_{12} \sin^2 \alpha\Delta - 2c_{12}^2 \cos 2\Delta - 2s_{12}^2 \cos 2(\alpha - 1)\Delta \Big]
\end{aligned}
$$

Provides much better handles on new physics than a mathematical test.

This is because:

- Neutrinos are all so light that any practical decay leads always to a coherent sum
- We have no easy way of making pure "mass eigenstates"

Nevertheless…



PoS ICHEP2012 (2013) 033 arXiv:1212.6374 SU-HEP-1-2012

Which is weirder? (And should we even ask that?)

Nevertheless…

A physicist-designed Universe would probably have just 3 possible generational structures:

- 0 generations (nice and simple, but boring)
- 1 generation (simple and you still can build matter in principle)
- ∞ generations (why not?)

Is 3 a strange number? Other "fundamental 3s":

- Triplet splittings
- Quark colors
- Charges (-1/3,+2/3) or (+1,-1,0)
- Others…

Nevertheless…

The best way to ensure we never develop a theory of flavor would be to stop measuring things.

Theories of "quark-lepton complementarity" predict relationships between mixing parameters, e.g.:

$$\Theta_{12}^{CKM} + \theta_{12}^{PMNS} = 45^o \qquad \Theta_{23}^{CKM} + \theta_{23}^{PMNS} = 45^o$$

$$(13.02 \pm 0.04)^o + (33.58^{+0.85}_{-0.75})^o = (46.6^{+0.9}_{-0.8})^o \qquad (2.35^{+0.06}_{-0.04})^o + (40.37^{+2.88}_{-1.23})^o = (42.7^{+2.9}_{-1.3})^o$$

Other Models…

Precision tests are less exciting without alternate models…

- Non-standard interactions
  - (the original motivation for Wolfenstein's "matter effect" paper were flavor-changing neutral currents (FCNC)

Same as mentioned earlier---any non-diagonal process:

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\mathrm{MSW}}$$

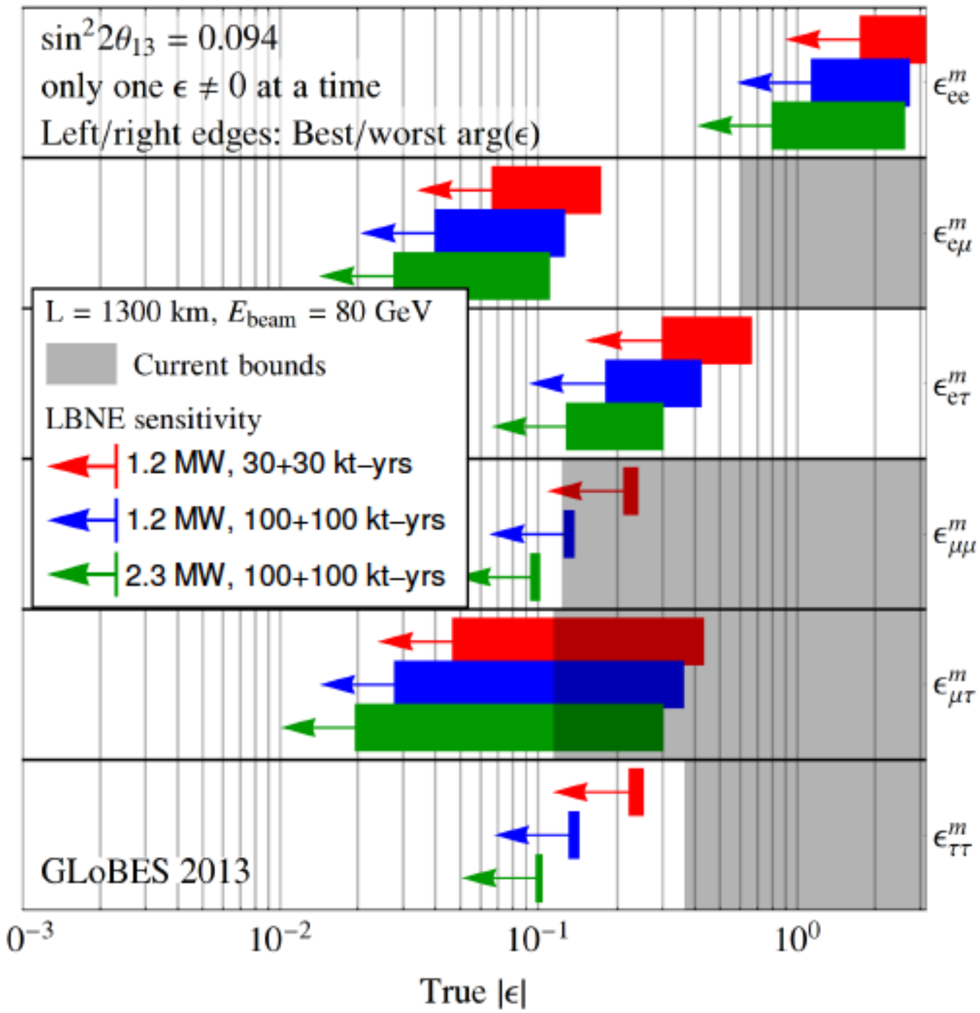
Each of these εs is a deviation from "standard" prediction

$$\tilde{V}_{\mathrm{MSW}} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

Other Models…

Precision tests are less exciting without alternate models…

- Non-standard interactions



Other Models…

Precision tests are less exciting without alternate models…

- Long-range forces
- Sterile neutrinos (see de Gouvea/Schmitz) talks
- Neutrino decay
- Neutrino decoherence
- Lorentz invariance violation (see Kayser talk)
  - Really?? Well, $\gamma_\nu = E_\nu / m_\nu > 10^{10}$ for 1 GeV neutrino!
  - LHC protons have $\gamma_p = E_p / m_p \sim 10^4$
  - Cosmic-ray protons beyond GZK cuttoff also have $\gamma \sim 10^{10}$
- Equivalence Principle violations…?

Not just with oscillations:

Do neutrinos and antineutrinos fall at the same rate?

Over 1000 km, neutrinos fall a bit over 50 μm.

With enough statistics and a precise (structured) beam profile, could you tell?

(Definitely a precision measurement!)

CP Violation

In vacuum:

$$P_{\rm vac}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12} c_{23}^2 c_{13}^2 \sin^2 \alpha\Delta$$
$$- \frac{1}{2} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} c_{13} \sin \alpha\Delta \Big[\sin[(\alpha - 2)\Delta - \delta_{CP}]$$
$$+ \sin \delta_{CP} \cos \alpha\Delta - \cos 2\theta_{12} \cos \delta_{CP} \sin \alpha\Delta \Big]$$

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin\delta \Big]$$

$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \qquad c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

$$\Delta = \frac{\Delta m_{31}^2 L}{4E}$$

$$P_{\nu_e \to \nu_\mu} - P_{\bar{\nu}_e \to \bar{\nu}_\mu} = J_{CP} = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin\delta.$$

CP Violation

In vacuum:

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

- Very lucky that solar parameters were LMA (large mixing angle)!
- Lucky that θ_{13} was small but not too small!

Q:Uh…can this happen if neutrinos are Majorana?

CP Violation

In vacuum:

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

A: Sure, this is CP violation, and all that matters is that we look at differences between CP conjugate states, not "particles" and "antiparticles"

CP Violation

Should we bother measuring δ?

- "Models can be built…" and "arguments can be made" that connect δ to Majorana CP violation and leptogenesis.

$|\sin\theta_{13}\sin\delta| \gtrsim 0.11$ (Pascoli, Petcov, Riotto, Nuc. Phys. B 774, (2007))

- But we should remember that this

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

is a ***prediction*** of the 3-flavor model. δ can (in principle) be measured independently of A_{CP} using just the oscillation patterns. With such a measurement, we predict the oscillation probabilities for anti-ν_μs into anti-ν_es and ask:

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \stackrel{?}{\simeq} \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

CP Violation

In reality, life is not so simple…

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

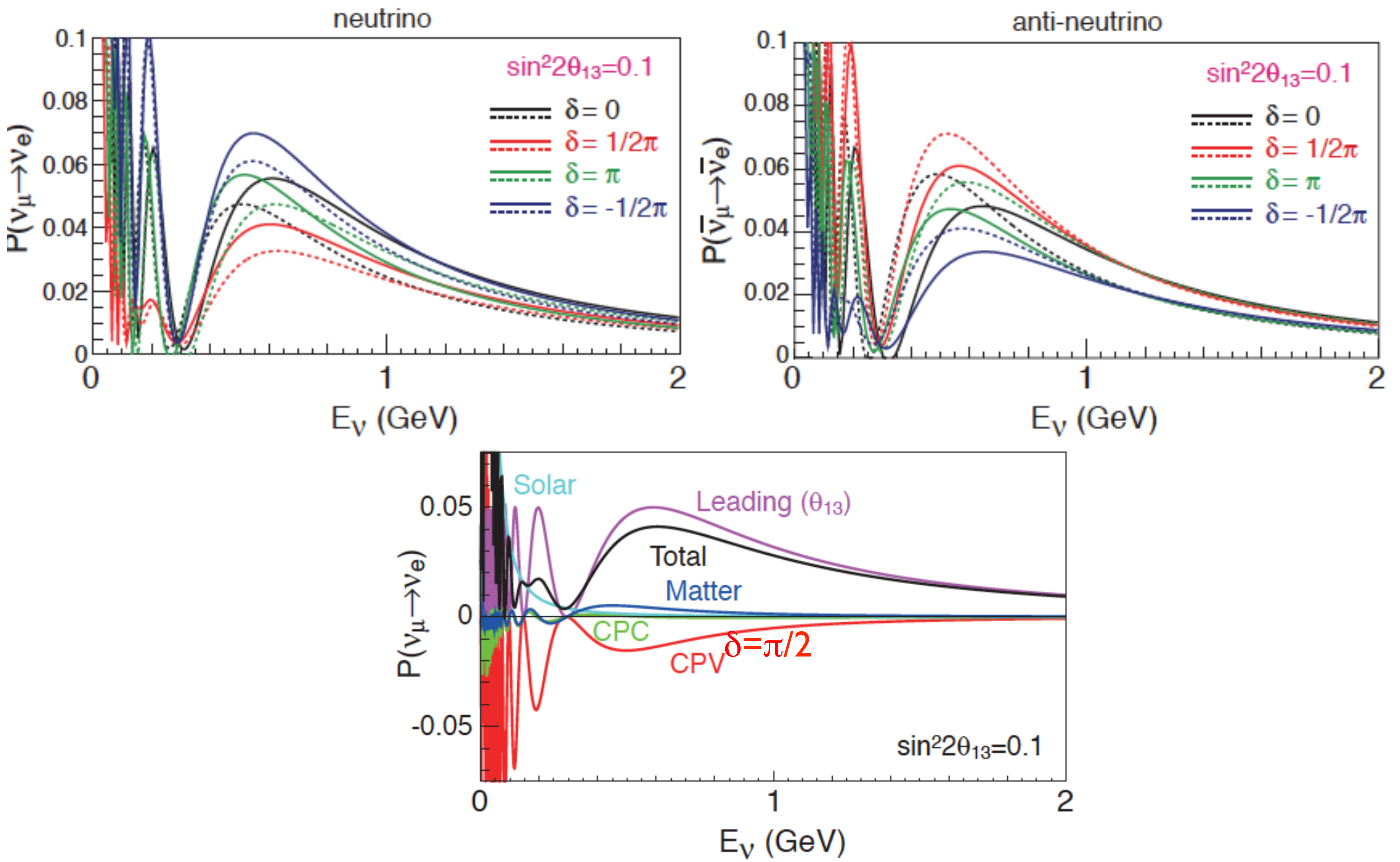
$$a = 2\sqrt{2} G_F n_e E$$

$$\mathcal{A}_{cp}(E_\nu) \approx \frac{\cos\theta_{23} \sin 2\theta_{12} \sin\delta}{\sin\theta_{23} \sin\theta_{13}} \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects.}$$

CP Violation

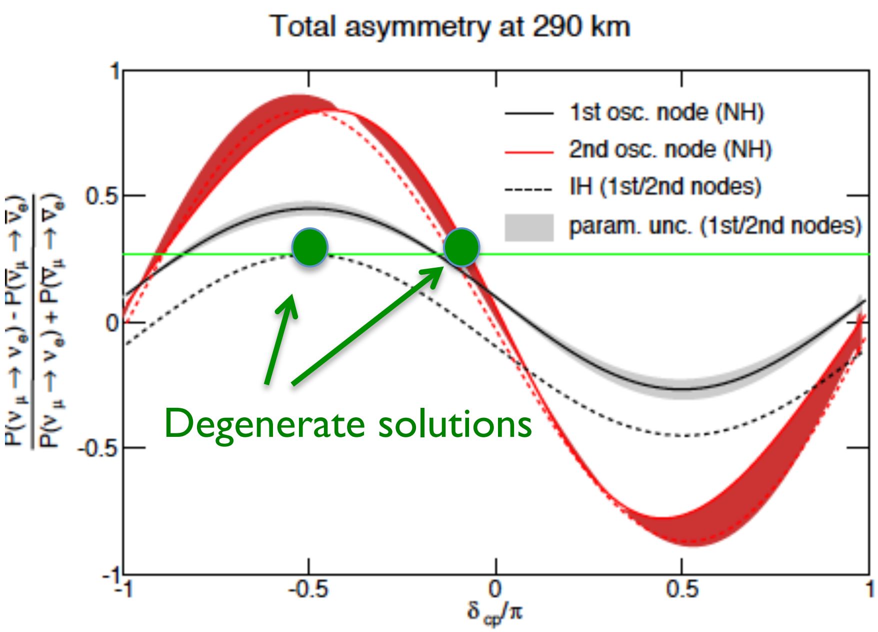
In reality, life is not so simple…

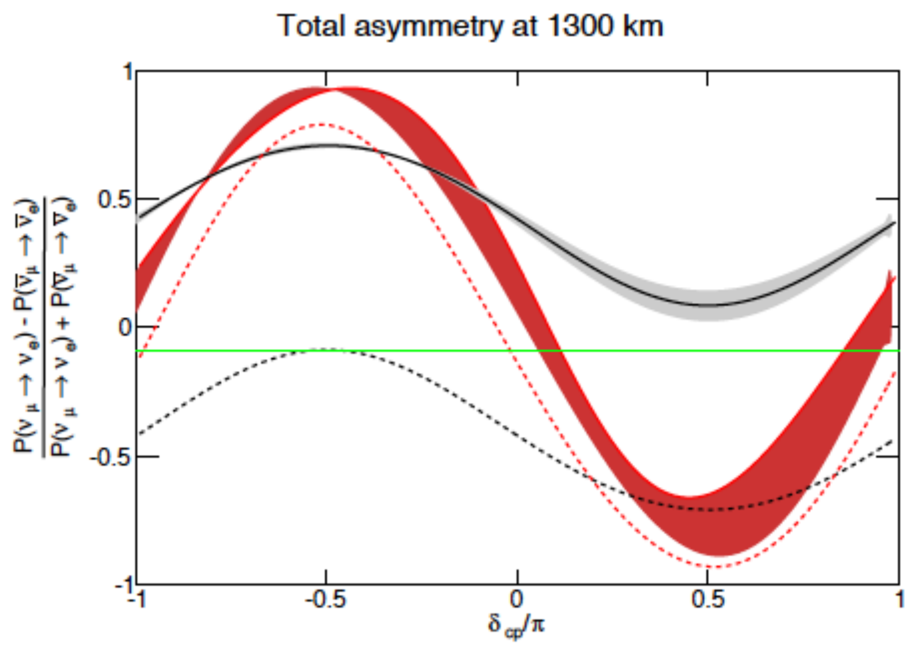
L=239 km



CP Violation

In reality, life is not so simple…





$$A_{cp}(E_\nu) \approx \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right) + \text{matter effects.}$$

“Long Baseline” Experiments

- Supernova neutrinos: $L=10^{18}$ km
- Solar neutrinos: $L=1.5\times10^{8}$ km
- Atmospheric neutrinos: L~50 km-12,000 km
- Long baseline neutrinos: L=240-2000 km

PHYSICAL REVIEW D VOLUME 15, NUMBER 3 1 FEBRUARY 1977

Neutrino oscillations and the number of neutrino types*

A. K. Mann and H. Primakoff
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19174
(Received 7 July 1976; revised manuscript received 27 September 1976)

A brief treatment of neutrino oscillations, generalized to an arbitrary number of neutrino types, is given as the basis for design of a feasible experiment to search for neutrino oscillations using the neutrino beam produced at a high-energy proton accelerator.

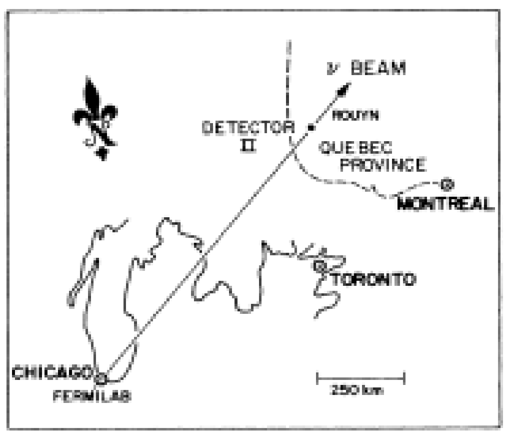


FIG. 4. Approximate geography of the proposed experiment. The present ν beam at Fermilab is directed 38°13′52″ east of north as indicated roughly.

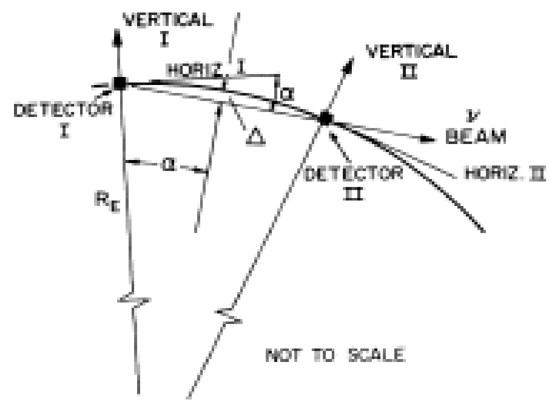
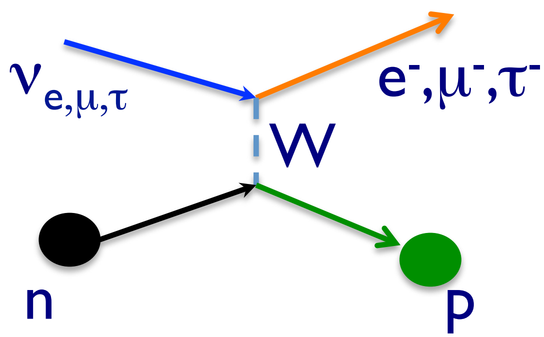


FIG. 1. Geometry of a feasible experiment. If the distance between detectors I and II is 1000 km, then $\alpha = 0.078$ rad and $\Delta = 19$ km. R_E is the radius of the earth $= 6.4\times10^{3}$ km.

Long Baseline Experiments

Advantages:

- High energies (100 MeV-10 GeV) mean fewer backgrounds
- In principle all charged leptons possible in final state via CC



Exclusive appearance measurements possible!

- Total flux measurement via NC also possible
- Can control (select) the baseline depending on physics
- Can control neutrino energies
- Can control flavor content to a certain extent
- Can turn the beam off! (~most of every few seconds…)
- Can measure critical beam and cross section parameters
  - (if you're willing and can afford a near detector)
- Wide range of detector technologies possible

Goals Have Evolved….

P-875: A Long-baseline Neutrino Oscillation Experiment at Fermilab

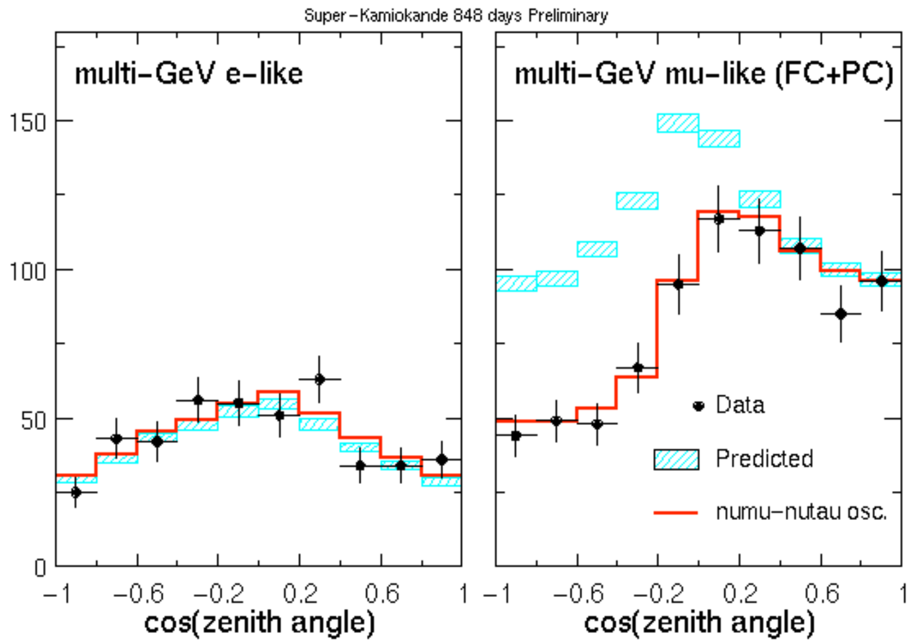
February 1995

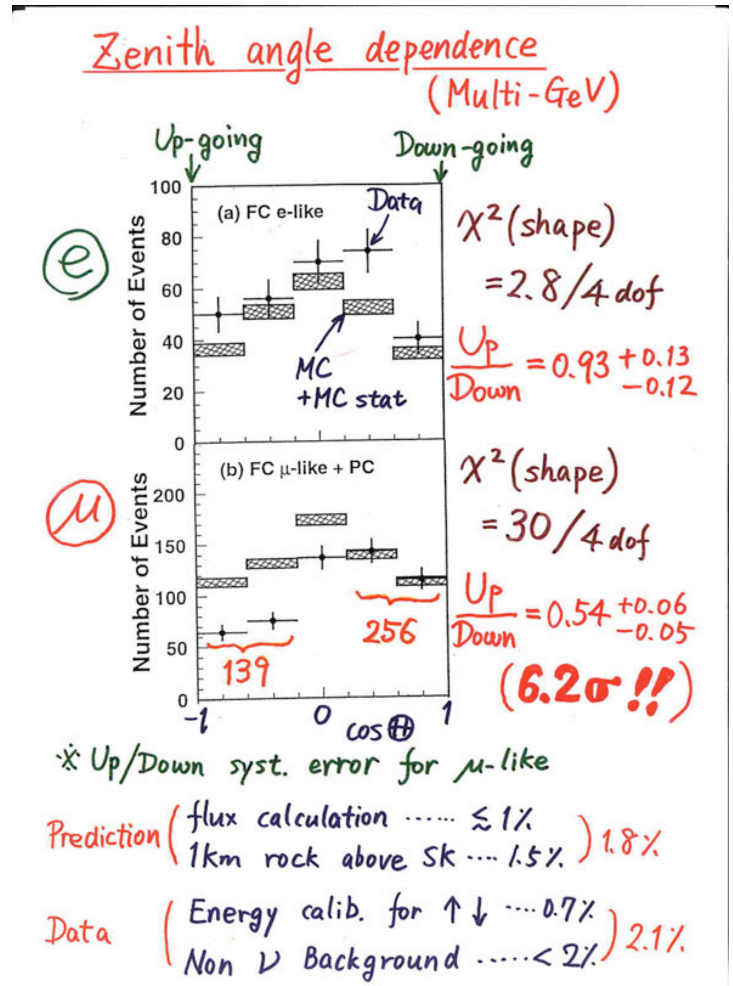
The MINOS* Collaboration

However the experimental picture is not a compelling one, due in part to the upward muon data, the upward stopping muon data, and the Frejus data. This situation provides strong motivation for a study with the well controlled systematics of an accelerator experiment. The long baseline neutrino oscillation experiment described in this proposal will achieve this goal.

The bottom line is that a new accelerator based long baseline oscillation experiment is clearly desirable to clarify the situation. There are several plausible physics scenarios in which our experiment could observe an oscillation signal:

Goals Have Evolved….

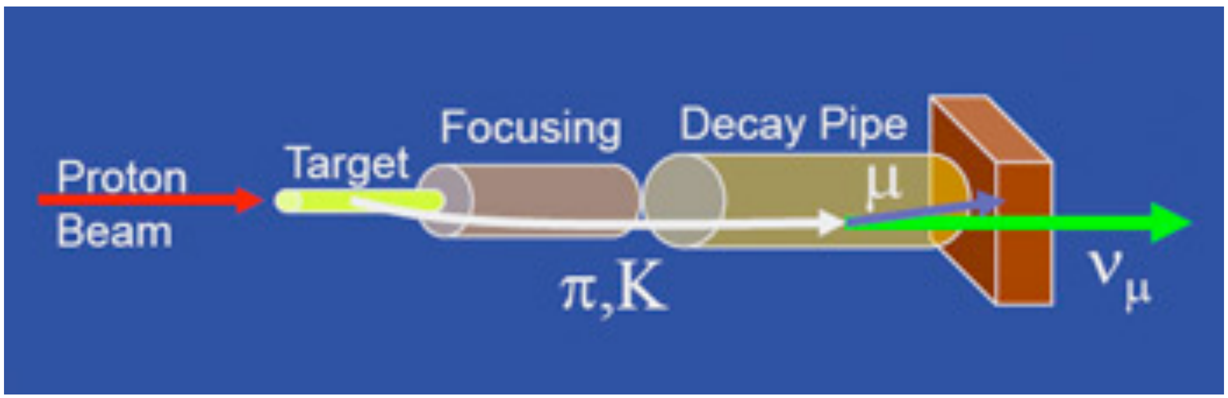


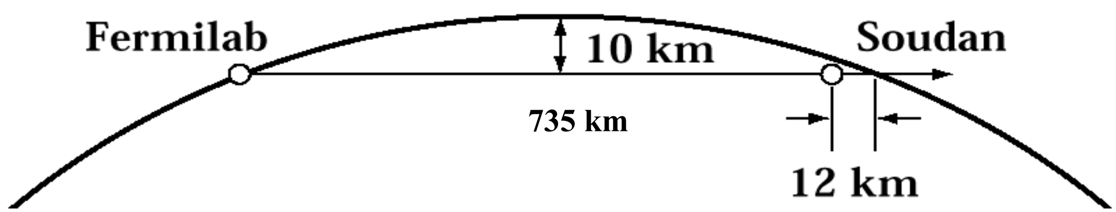


T. Kajita

Long Baseline Experiments

For all currently existing or planned Long Baseline experiments, beam is intended to be ν_μs, created by decaying πs.





Antineutrinos can be enriched by changing sign of focusing current.

Long Baseline Experiments

Beam content is mostly

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

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

For a finite decay pipe, flavor content ~ ratio of lifetimes

$$\frac{N_{\nu_e}}{N_{\nu_\mu}} = \frac{N_{\bar{\nu}_\mu}}{N_{\nu_\mu}} \approx 0.01$$

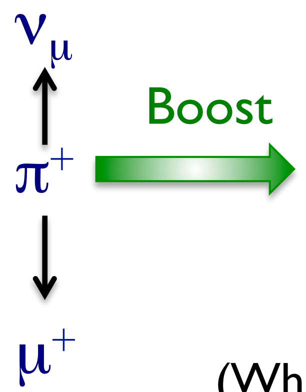
$+ \; K^+ \rightarrow \mu^+ \nu_\mu$ (10% of primaries, x65% BR)

$+ \; \pi^+ \rightarrow e^+ \nu_e$ (10^{-4})

$+ \; K^+ \rightarrow e^+ \pi^0 \nu_e$ (10% of primaries, x5% BR)

Long Baseline Experiments

Beams can be "wide band" (on-axis), or "narrow band" (off-axis)



$$\tan\theta = \frac{E_\nu^\star \sin\theta^\star}{\gamma_\pi E_\nu^\star(\beta_\pi + \cos\theta^\star)}$$

$$\tan\theta_C = \frac{1}{\gamma_\pi\beta_\pi} \rightarrow \theta_C \approx \frac{1}{\gamma_\pi} = \frac{m_\pi}{E_\pi} \ll 1.$$

(When $\theta^*=\pi/2$)

For very fast πs, $\beta_\pi \approx 1$ so we can just write

$$\tan\theta \approx \frac{E_\nu^\star \sin\theta^\star}{\gamma_\pi E_\nu^\star(1 + \cos\theta^\star)} \approx \frac{E_\nu^\star \sin\theta^\star}{E_\nu}$$

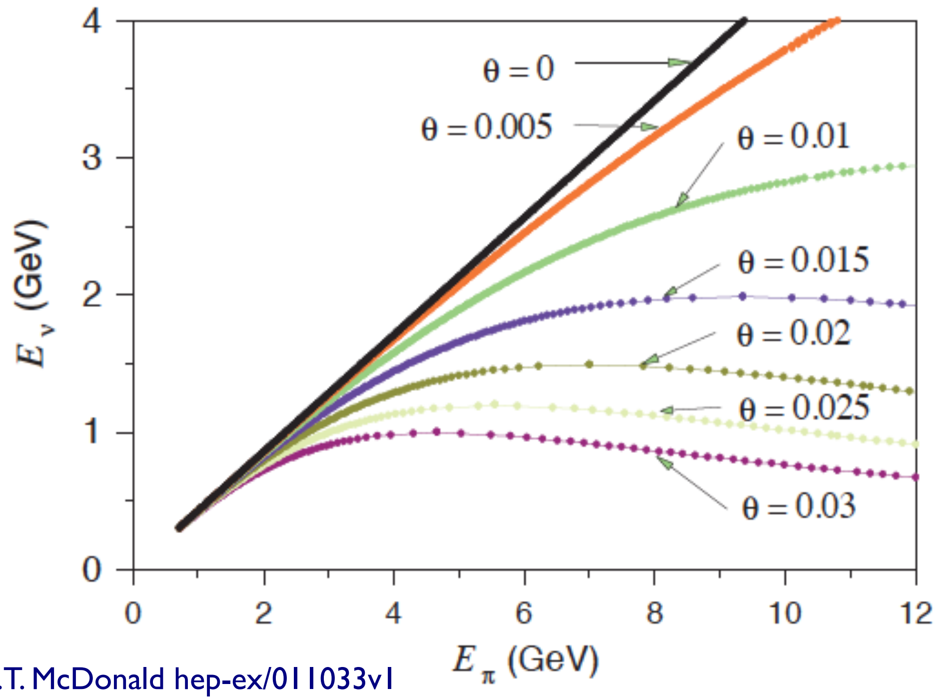
Since $\sin\theta \leq 1$, maximum lab angle a neutrino of energy E_ν can have is

$$\theta_{\max} \approx \frac{E_\nu^\star}{E_\nu} \approx \frac{30 \text{ MeV}}{E_\nu}$$

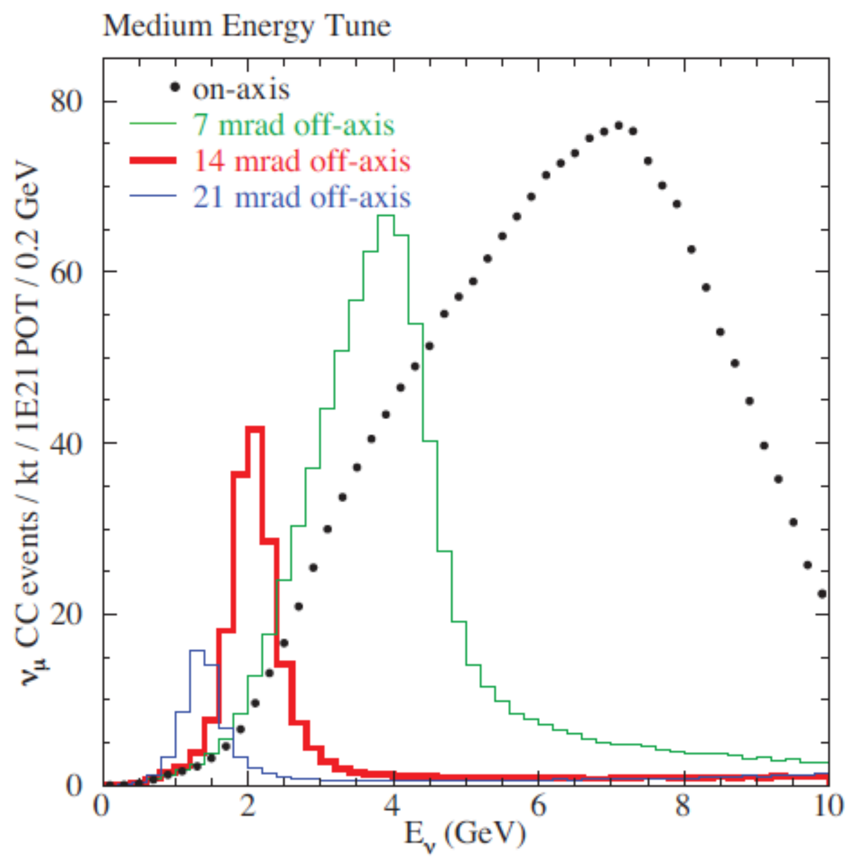
So as you go to higher angles, you see a lower energy beam.

Long Baseline Experiments

Beams can be “wide band” (on-axis), or “narrow band” (off-axis)



K.T. McDonald hep-ex/011033v1



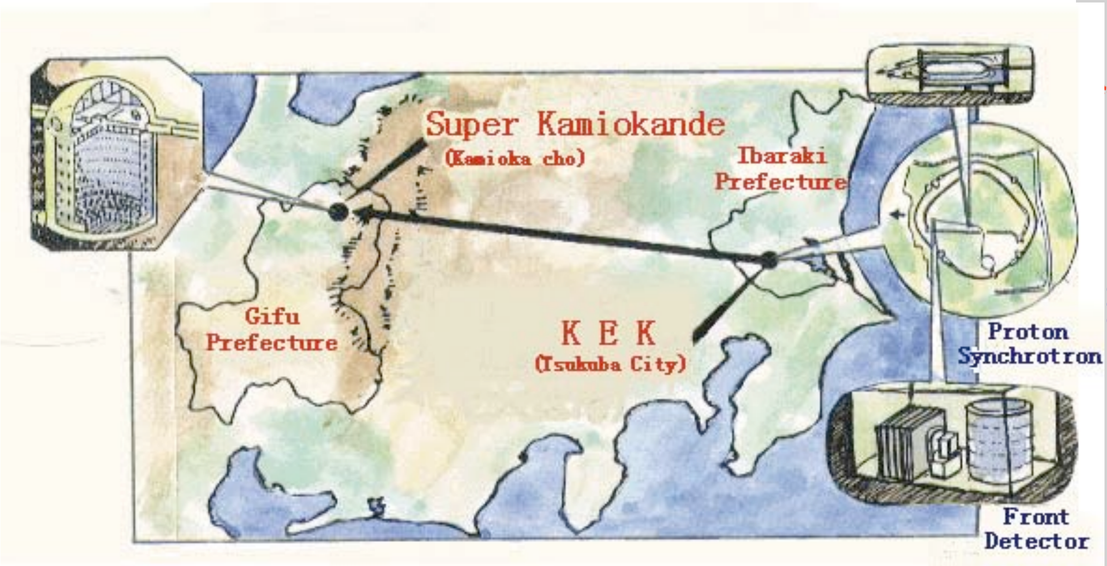
Measurements so Far

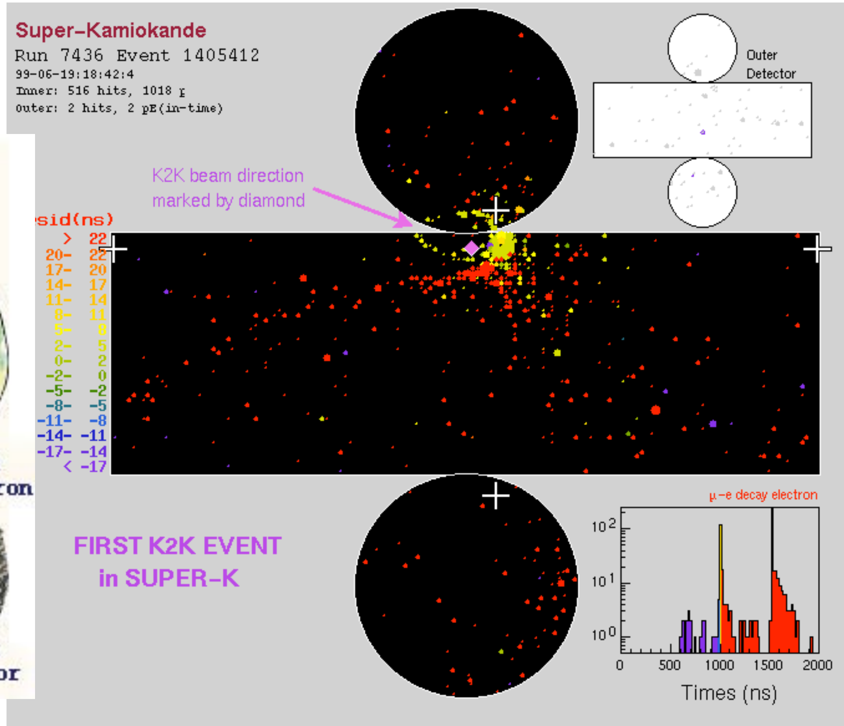
- K2K

Primary goal was confirmation of Super-K atmospheric measurements via (simple) vacuum disappearance:

$$P_{\nu_{\mu\to\nu_\mu}} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{23}(eV)L(km)}{E_\nu(GeV)}\right)$$

On-axis, wideband beam
L=250 km, E~1.3 GeV→L/E~200



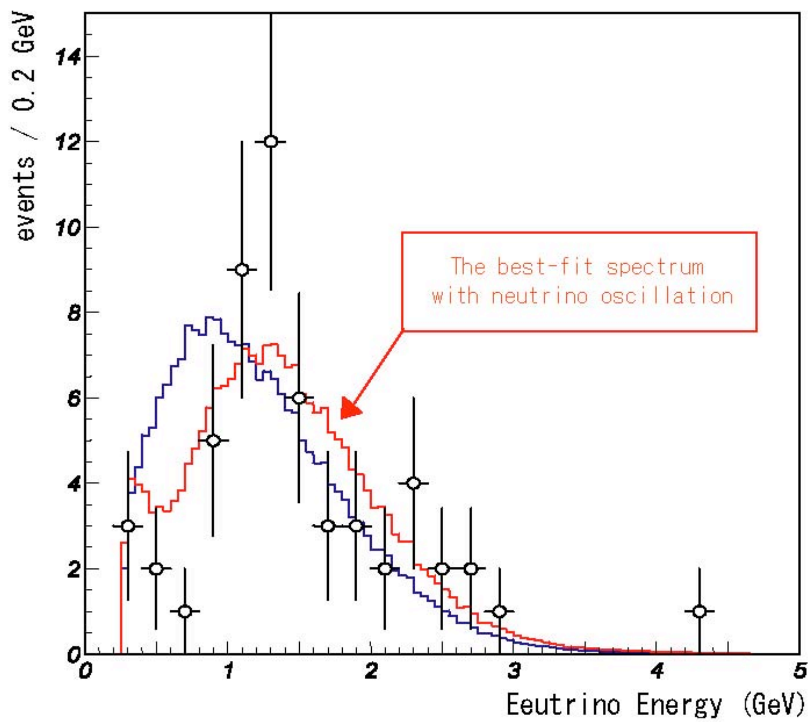


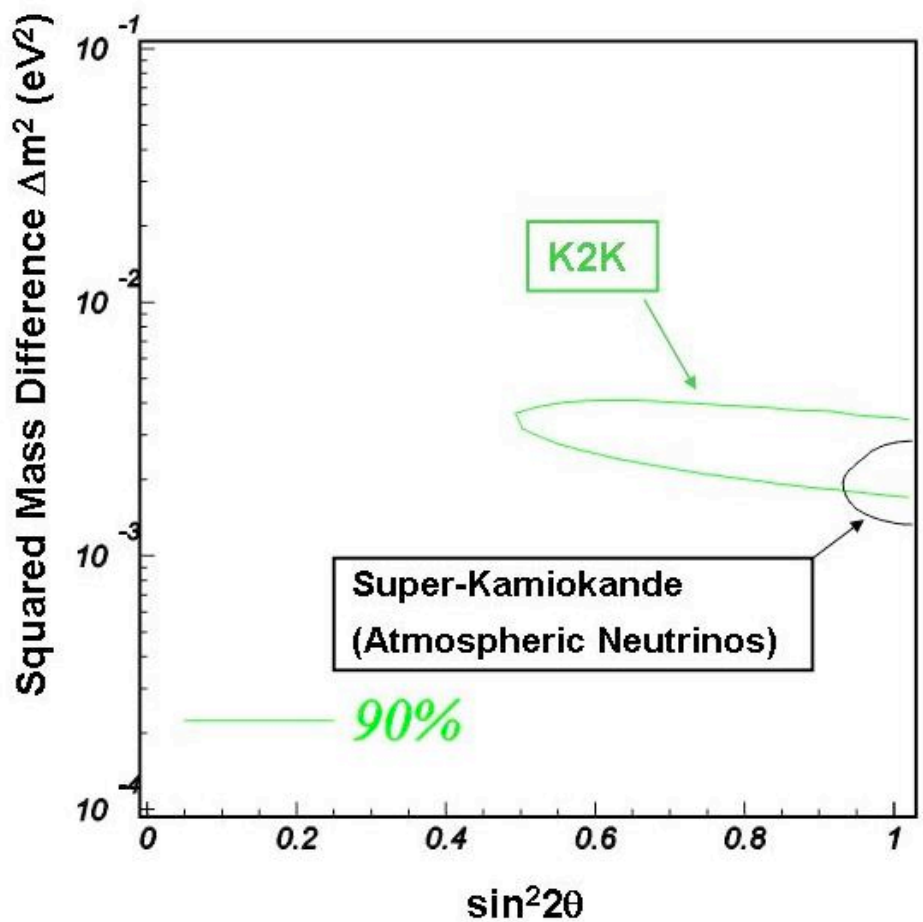
First Measurements

- K2K

Primary goal was confirmation of Super-K atmospheric measurements

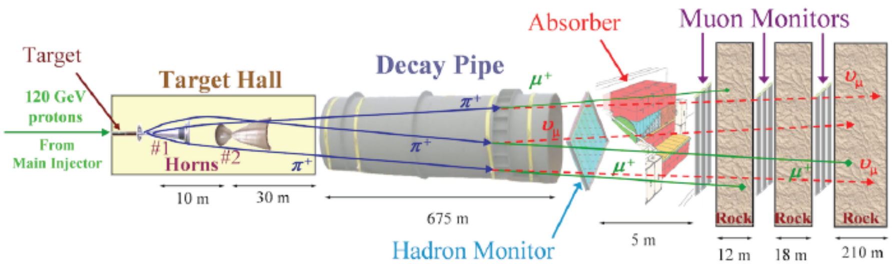
112 events detected vs. $150.9^{+11.6}_{-10.0}$ expected.





First Precision Measurements

- MINOS
- Goals were precision measurement of mixing in "atmospheric sector"
- Searches for new physics



First Precision Measurements

- MINOS
- Goals were precision measurement of mixing in "atmospheric sector"
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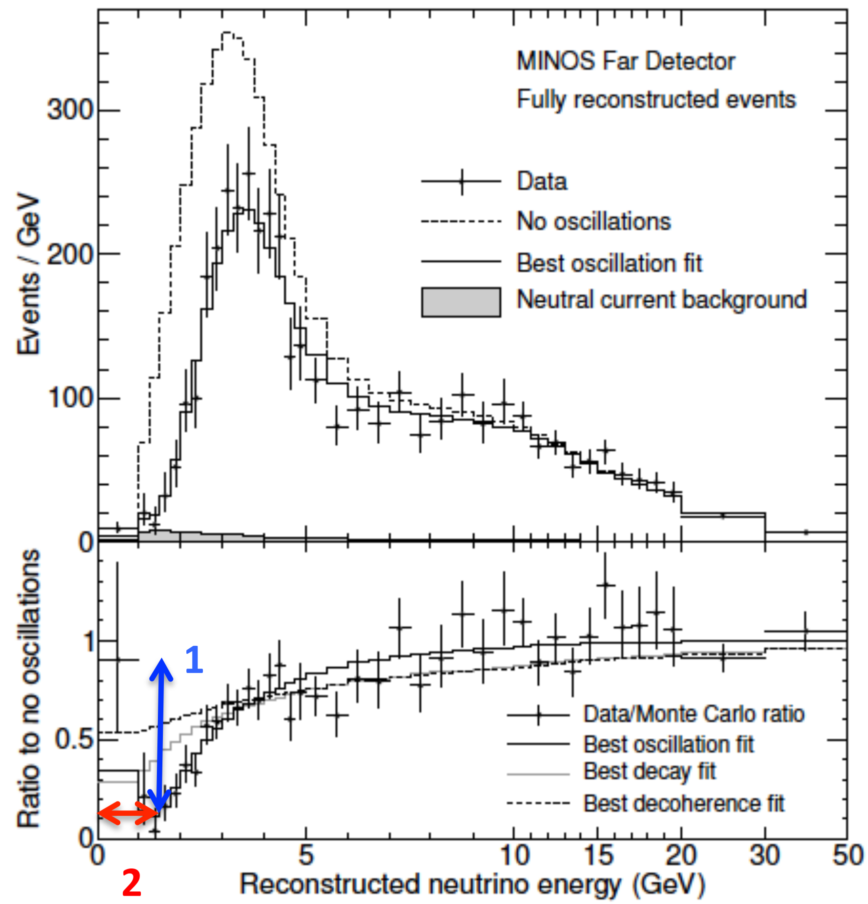
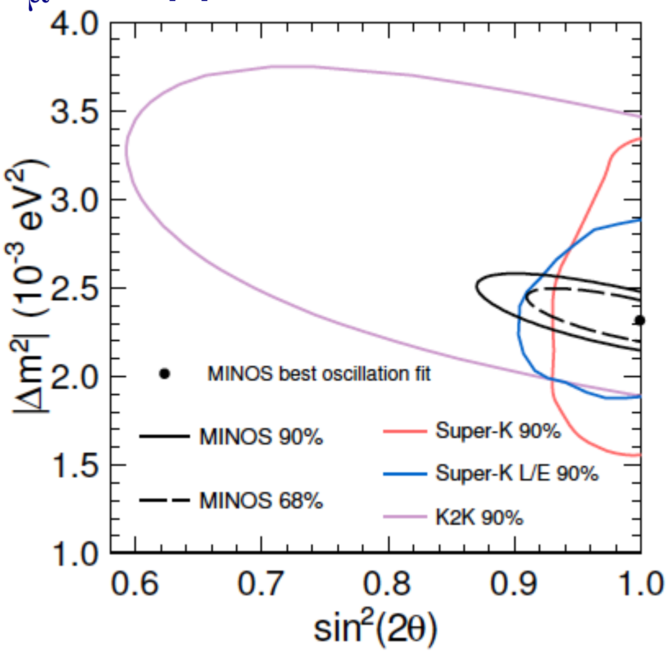
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \overset{1}{\boxed{\sin^2 2\theta_{23}}} \sin^2\left(\frac{1.27\,\overset{2}{\boxed{\Delta m^2_{23}}}(eV^2)L(km)}{E_\nu(GeV)}\right)$$

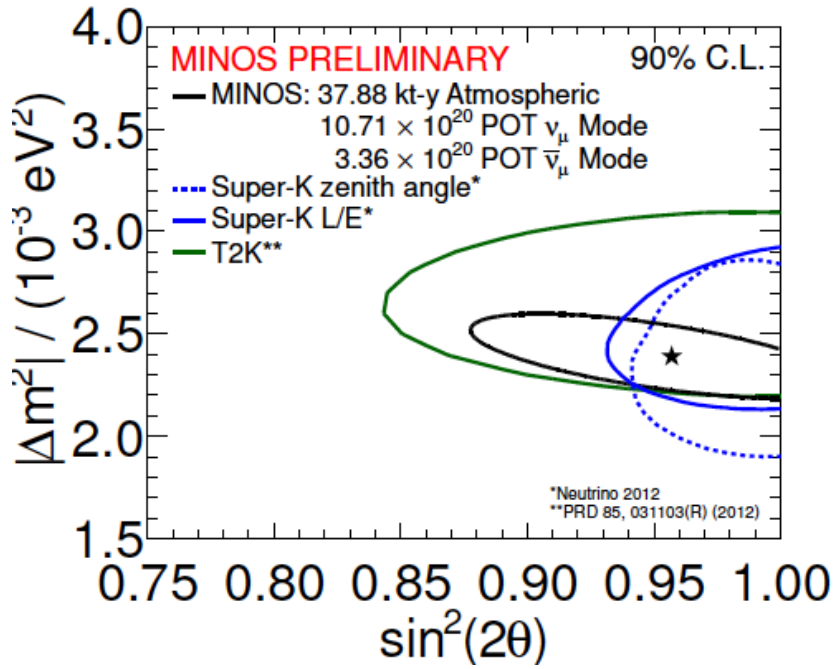


First Precision Measurements

- MINOS
- Primary goal was precision "atmospheric sector" measurements via ν_μ disappearance

θ_{23} starting to "pull away" from 45°





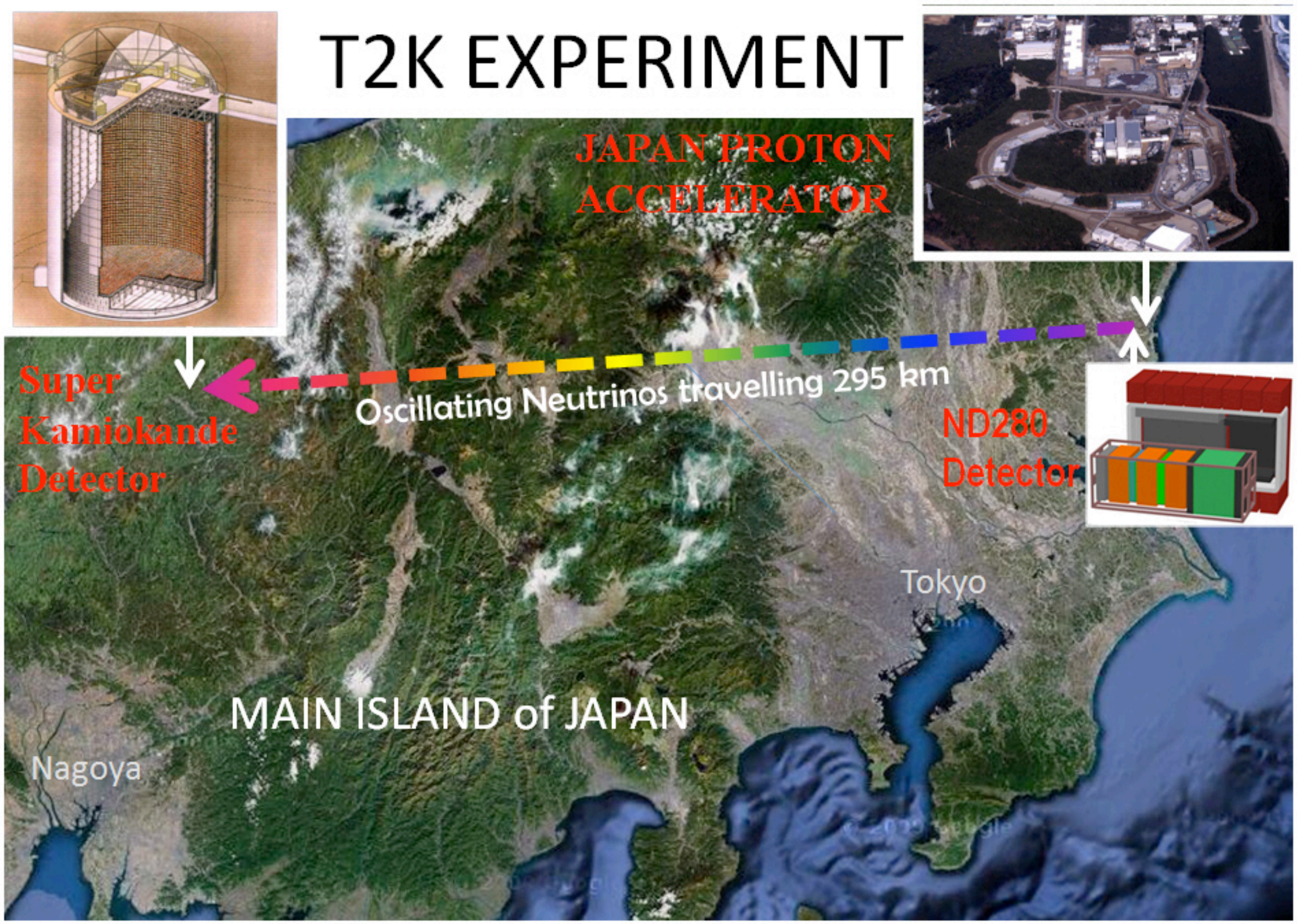
- Also some sensitivity to ν_e appearance
- Searches for new physics

First precision tests of ν vs anti-ν mixing parameters

Measurements so Far

- T2K: First off-axis beam experiment

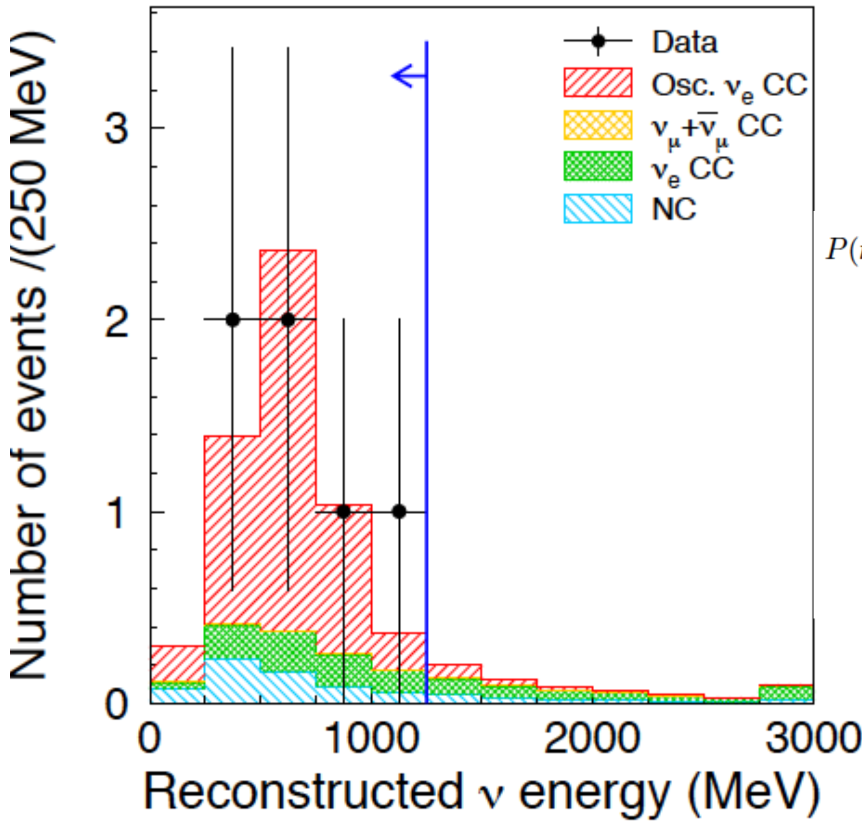
Primary goal was measurement of θ_{13} via *appearance*



Measurements so Far

- T2K: First off-axis beam experiment

Primary goal is measurement of θ_{13} via *appearance*



Precision measurement opportunity!

T2K measures:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},
\end{aligned}
$$

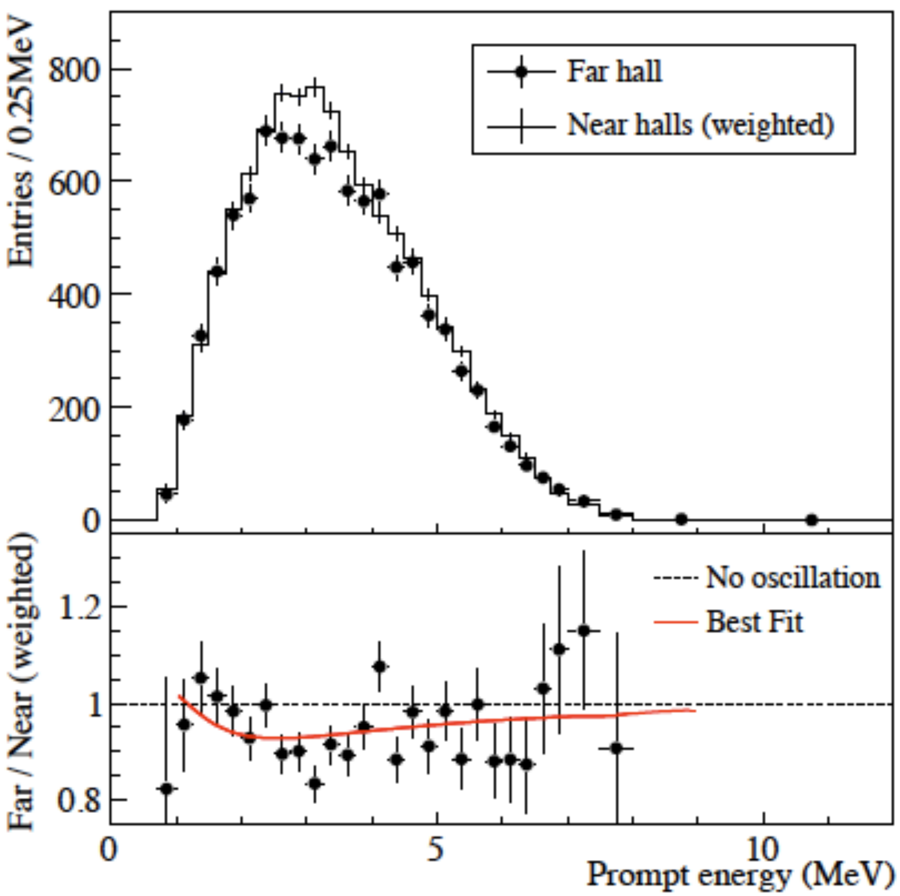
And extracts $\sin^2 2\theta_{13}$ constraining known parameters and allowing unknowns to float.

Measurements so Far

- T2K vs. Reactor

Reactor experiments measure:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$



I.e., antineutrino *disappearance*, extracting θ_{13} independent of matter effects, CP violation.

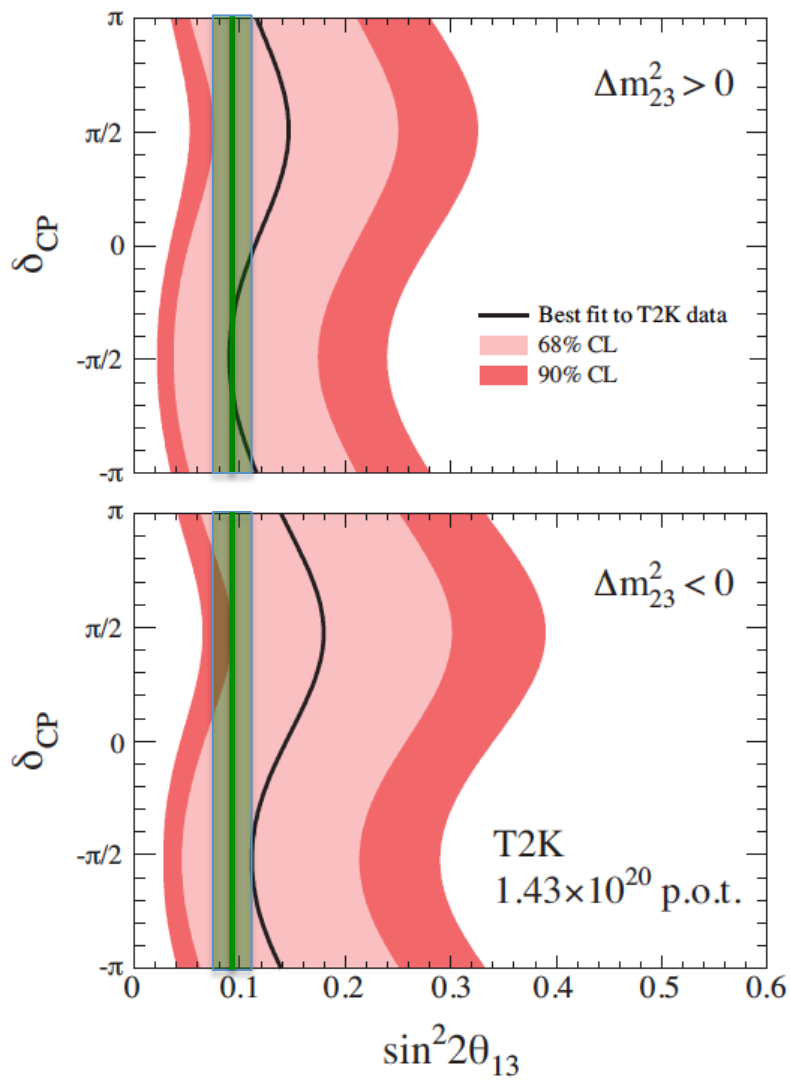
They had better get the same value of $\sin^2 2\theta_{13}$!

Do they?

Measurements so Far

- T2K vs. Reactor

Yeah, but…clearly more precision on the appearance side is needed.

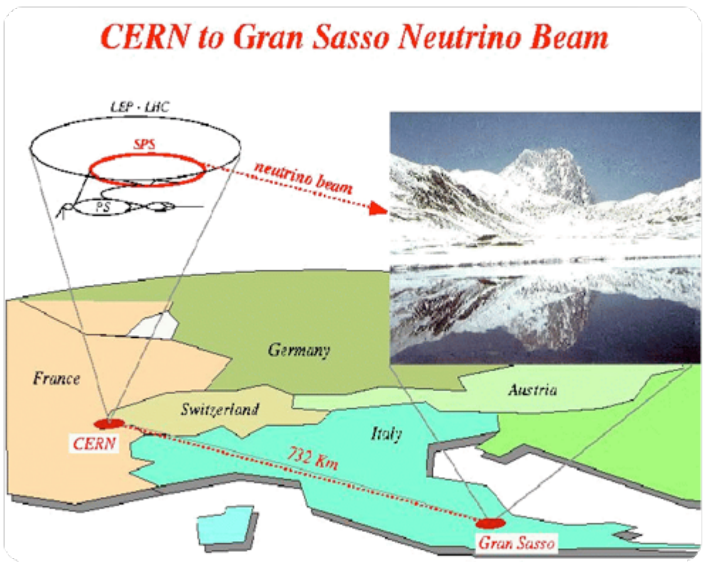


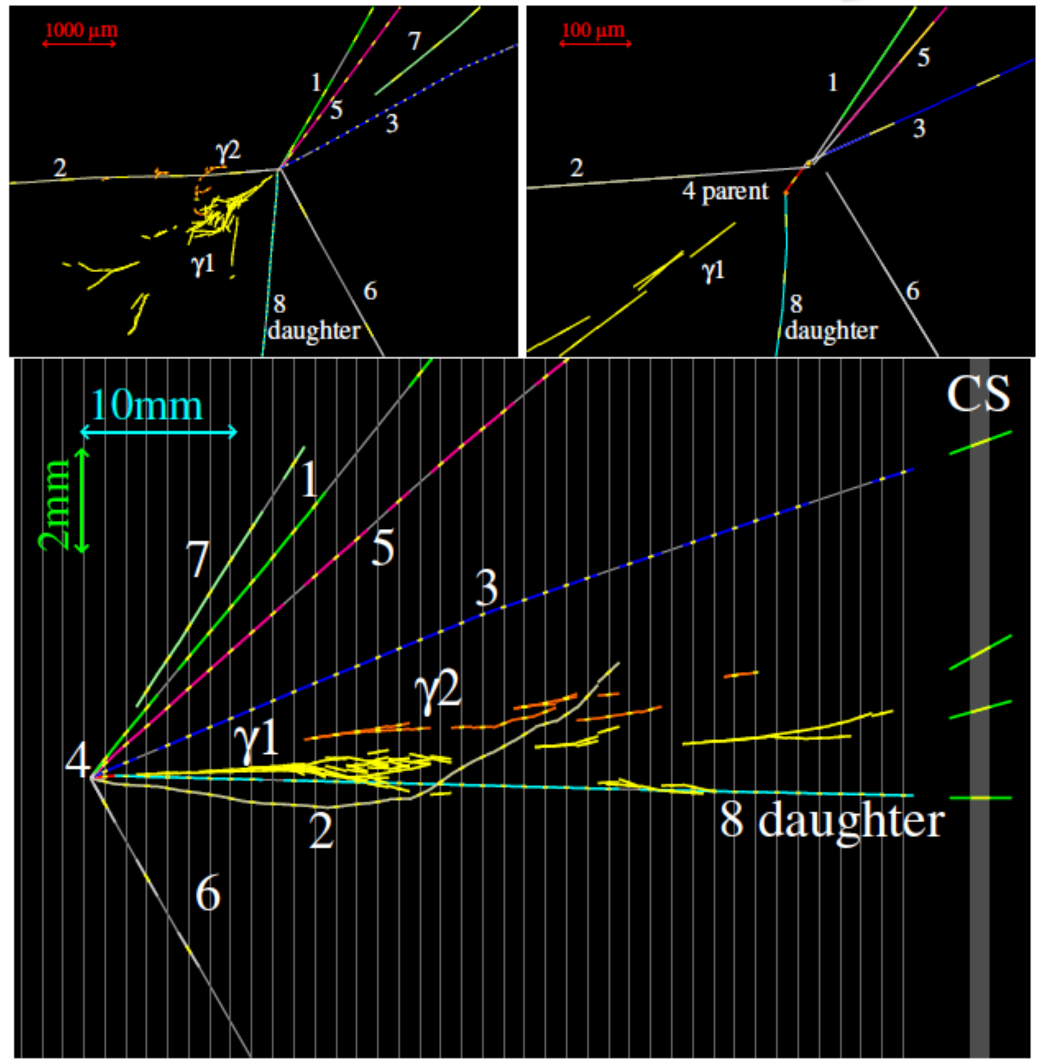
Measurements so Far

- OPERA

Primary goal is measurement of ν_τ appearance

1 of 2 events so far…



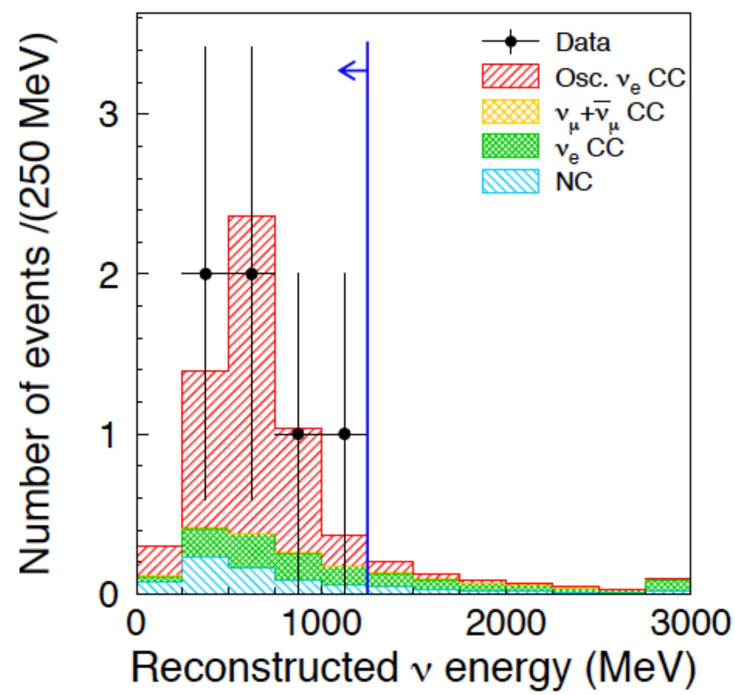


Goals for Next and Future Generations

T2K's observation of ν_e appearance is the real herald of the "3-flavor era"

The goals of future experiments are now very clear:

- Determination of the Mass Hierarchy
- CP Violation
- Searches for new physics
- "Octant" of θ_{23}



Goals for Next and Future Generations

- "Octant" of θ_{23}

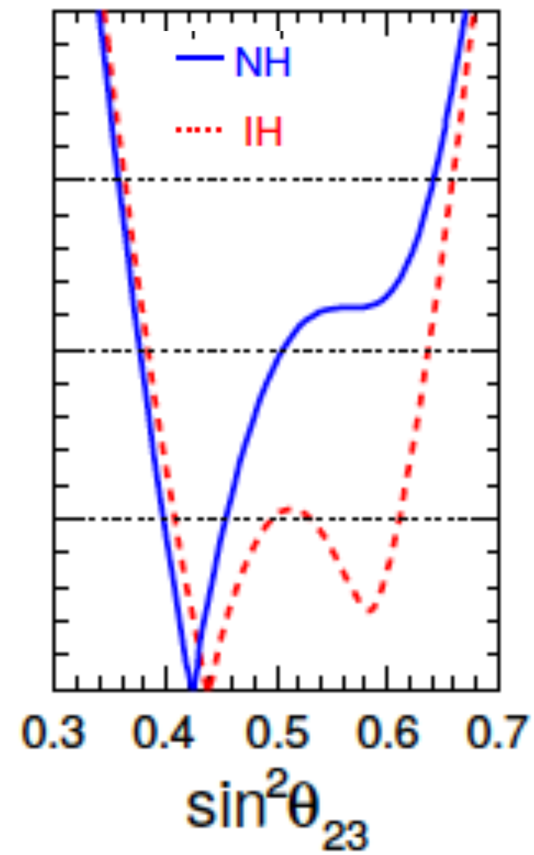
Most of the information on the value of q23 comes from disappearance data, whose leading behavior is

$$P_{\nu_{\mu\to\nu_\mu}} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{23}(eV)L(km)}{E_\nu(GeV)}\right)$$

But…

$\sin^2(2x40°)=0.9698$, while $\sin^2(40°)=0.4131$

$\sin^2(2x50°)=0.9698$, while $\sin^2(50°)=0.5868$

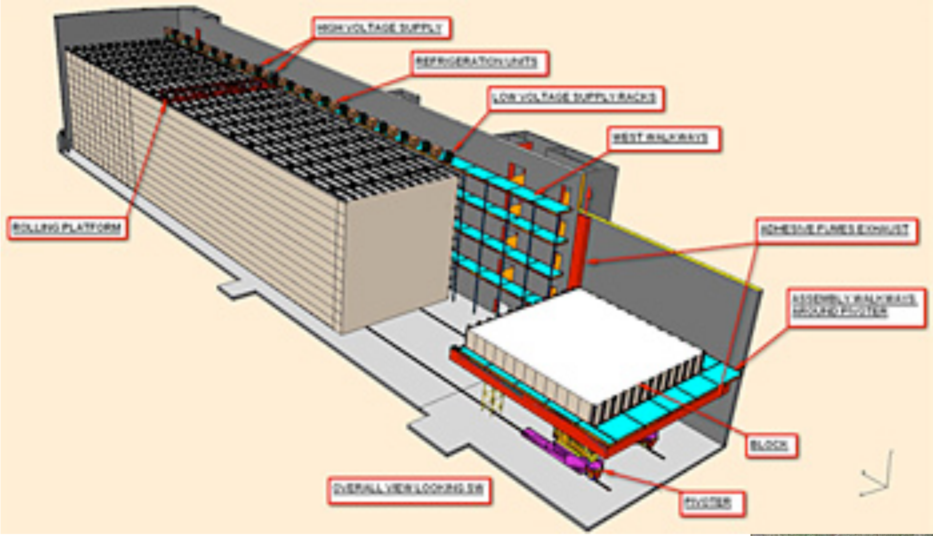


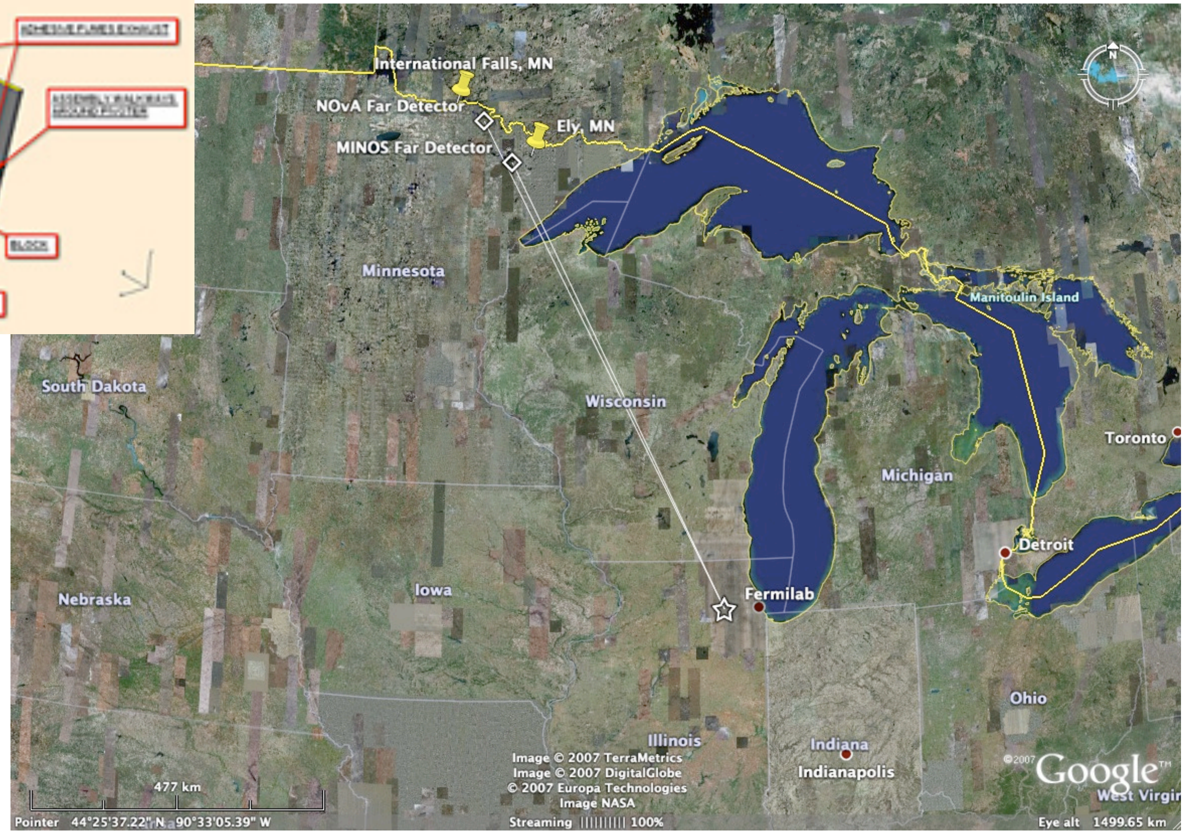
$$\begin{aligned}P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\ & +8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\ & -8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\ & +4S_{12}^2 C_{13}^2(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta) \cdot \sin^2\Delta_{21} \\ & -8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1-2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\ & +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2S_{13}^2) \cdot \sin^2\Delta_{31},\end{aligned}$$

Upcoming Measurements

NOνA: Off-axis beam

Primary goals are mass hierarchy and CP violation

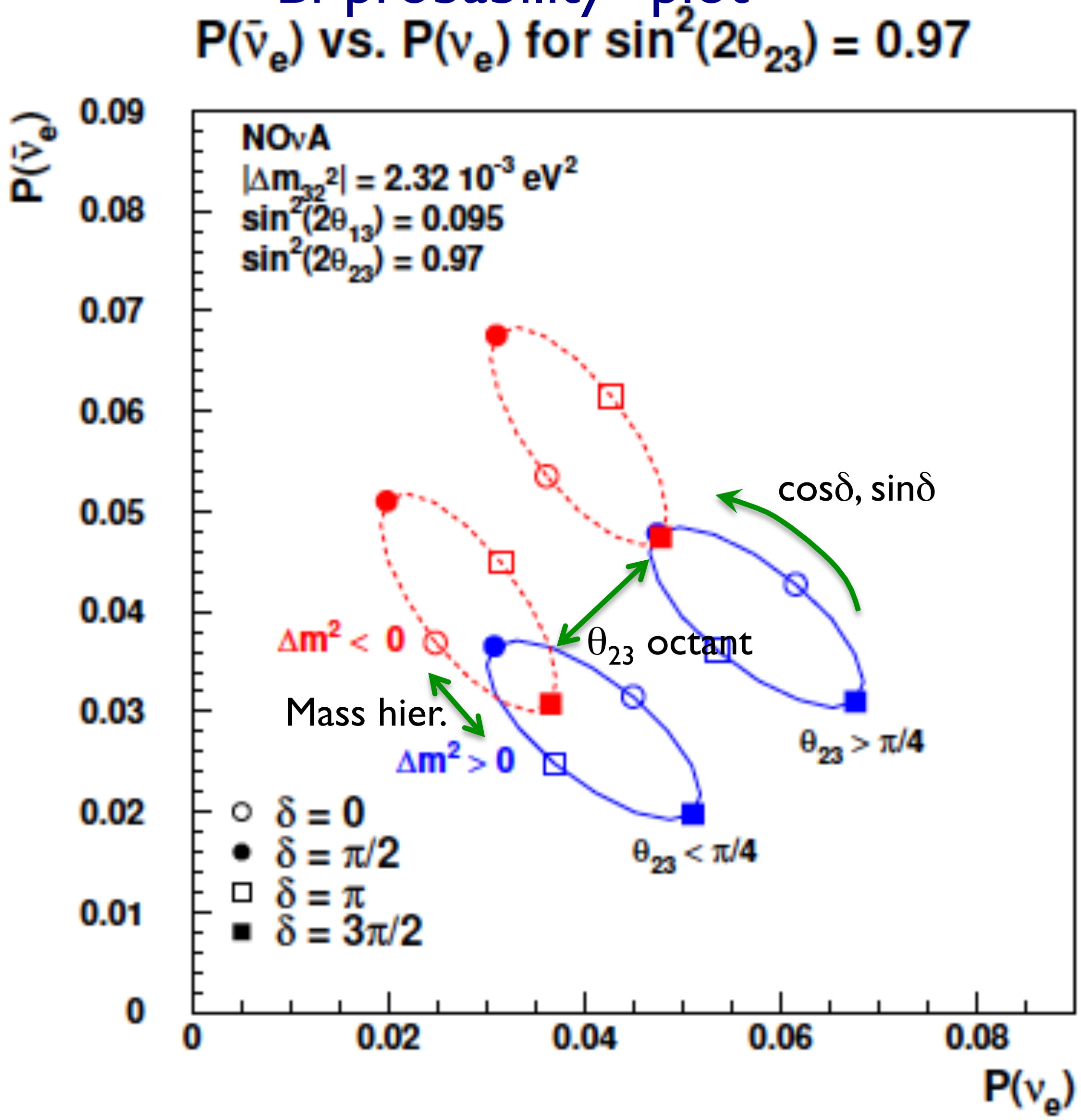




Upcoming Measurements

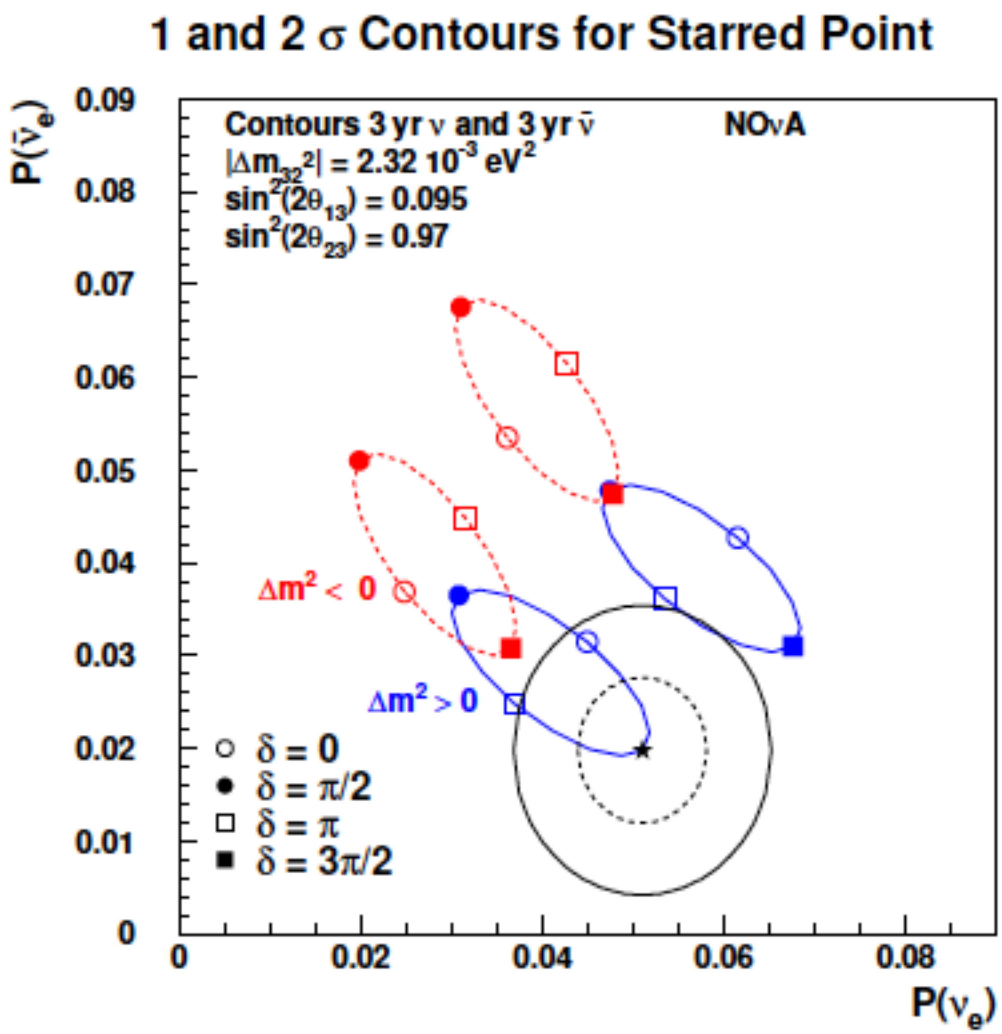
NOνA

"Bi-probability" plot



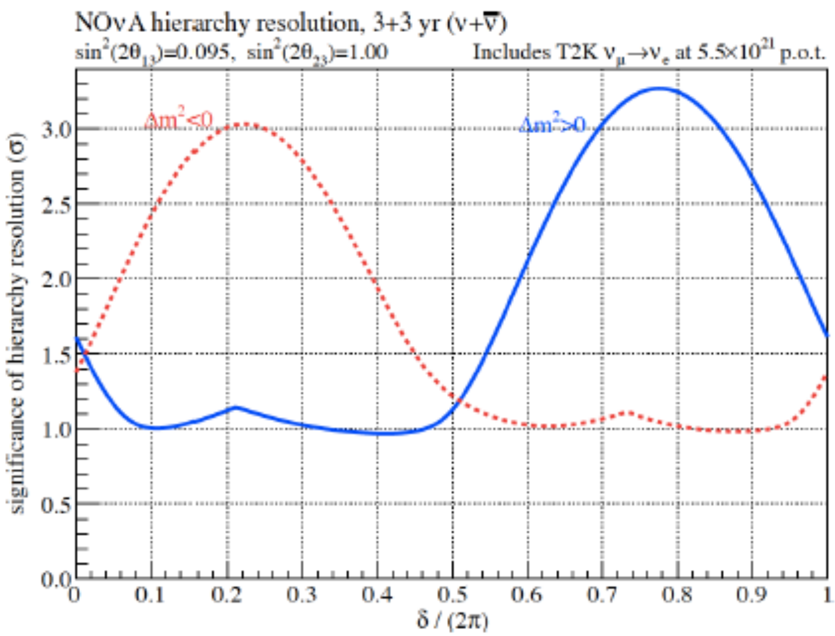
Upcoming Measurements

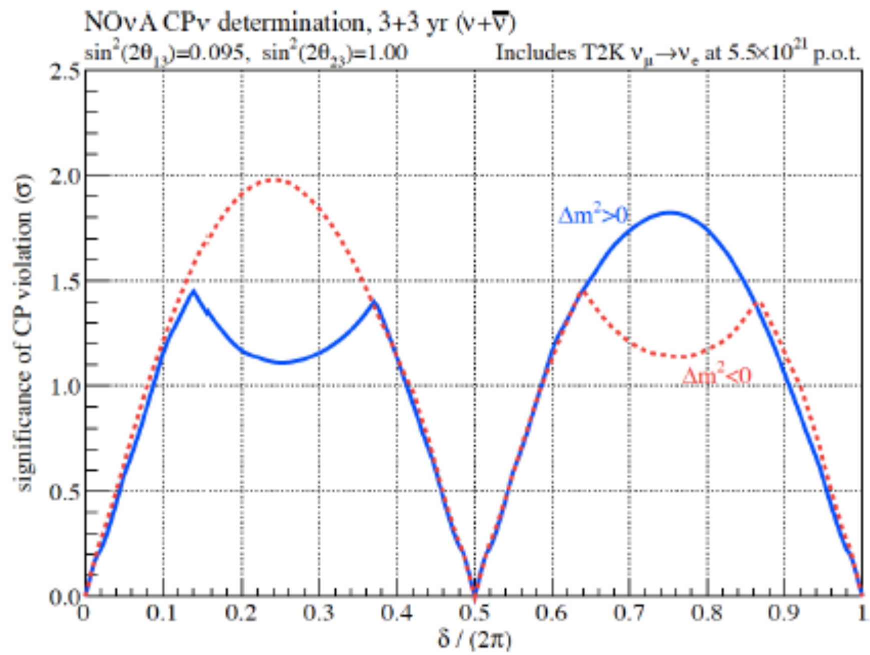
NOνA



Upcoming Measurements

NOνA+T2K

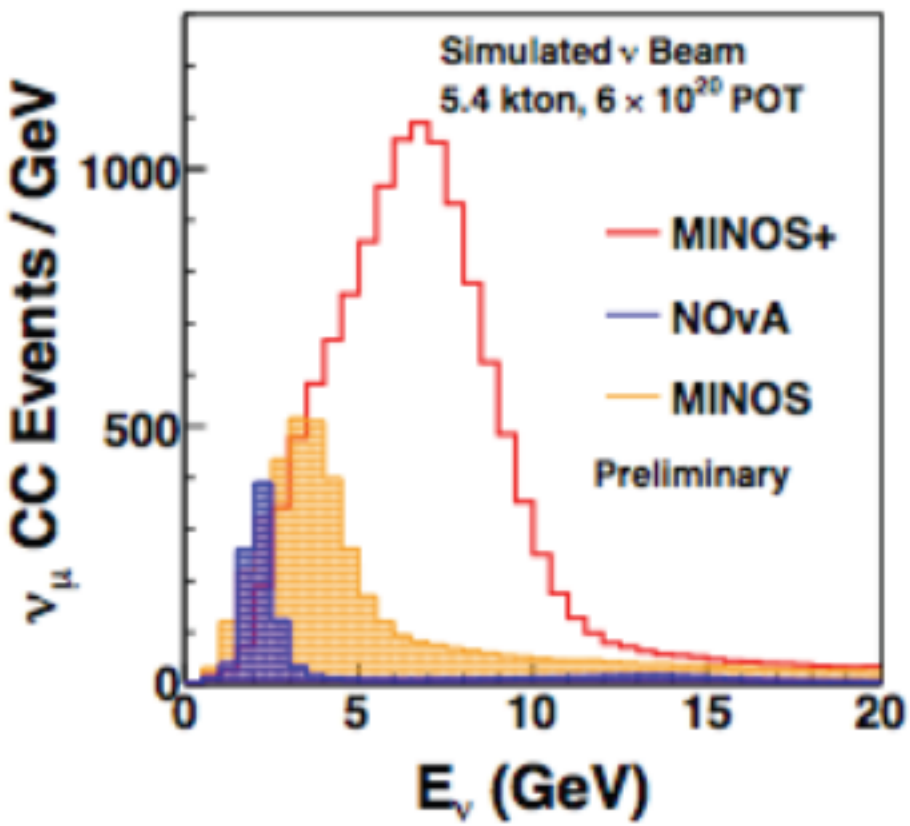


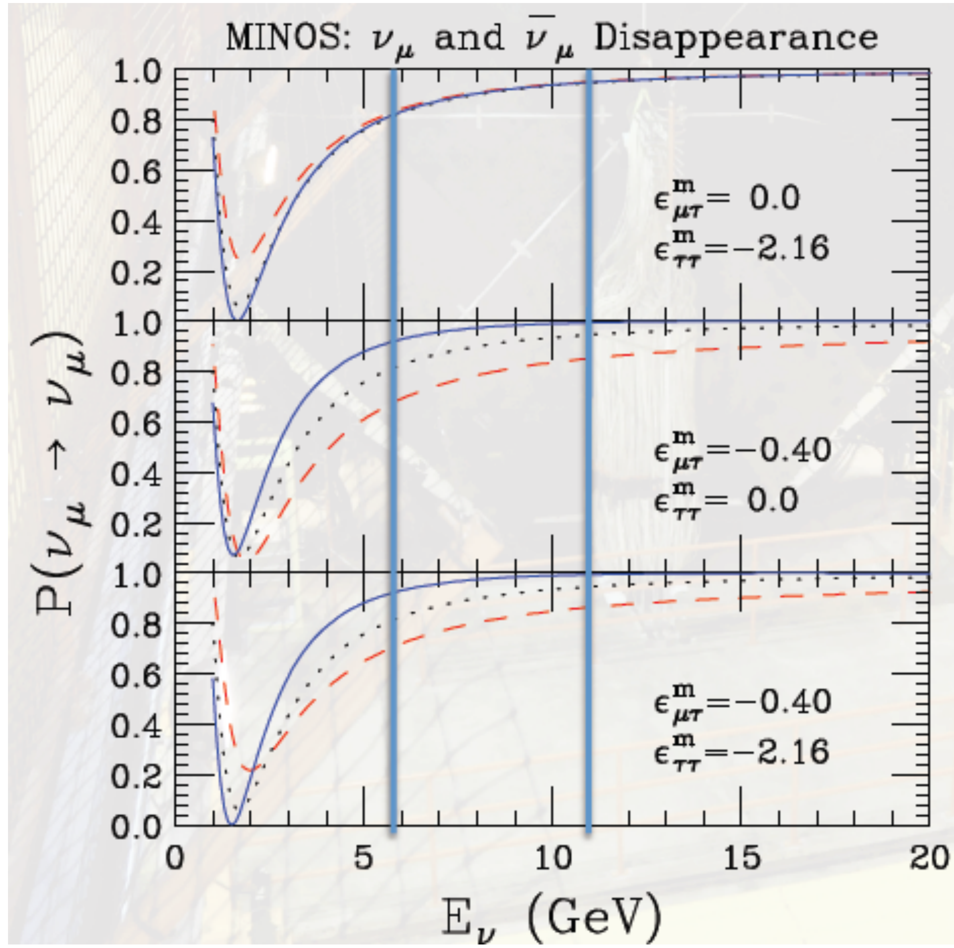


Planned Measurements

MINOS+

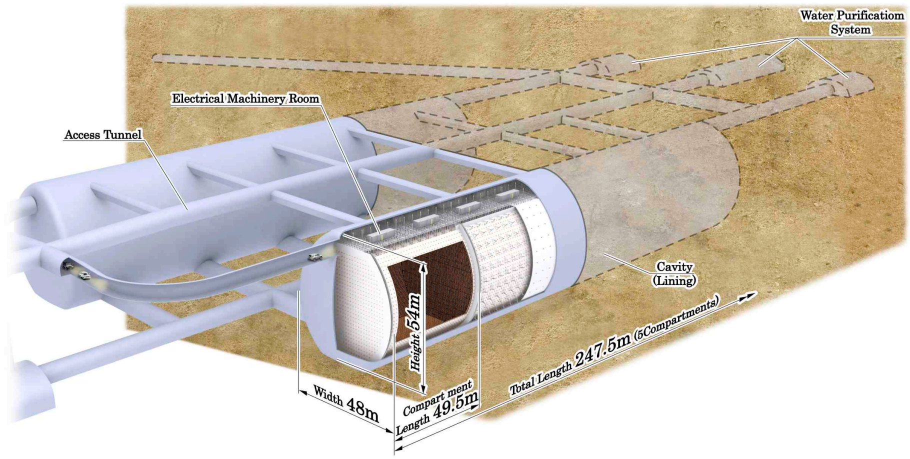
Goals are precision searches for new physics with higher flux



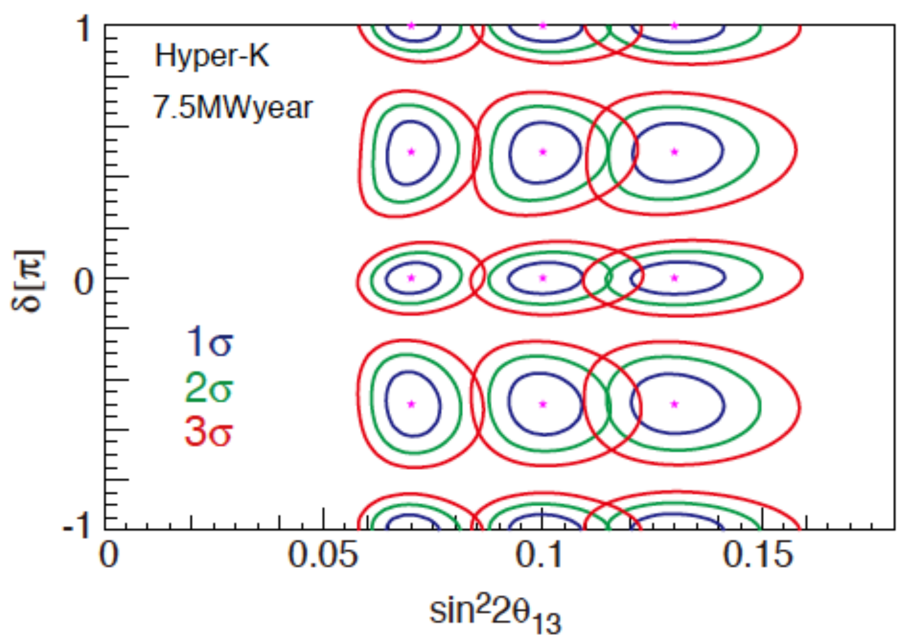


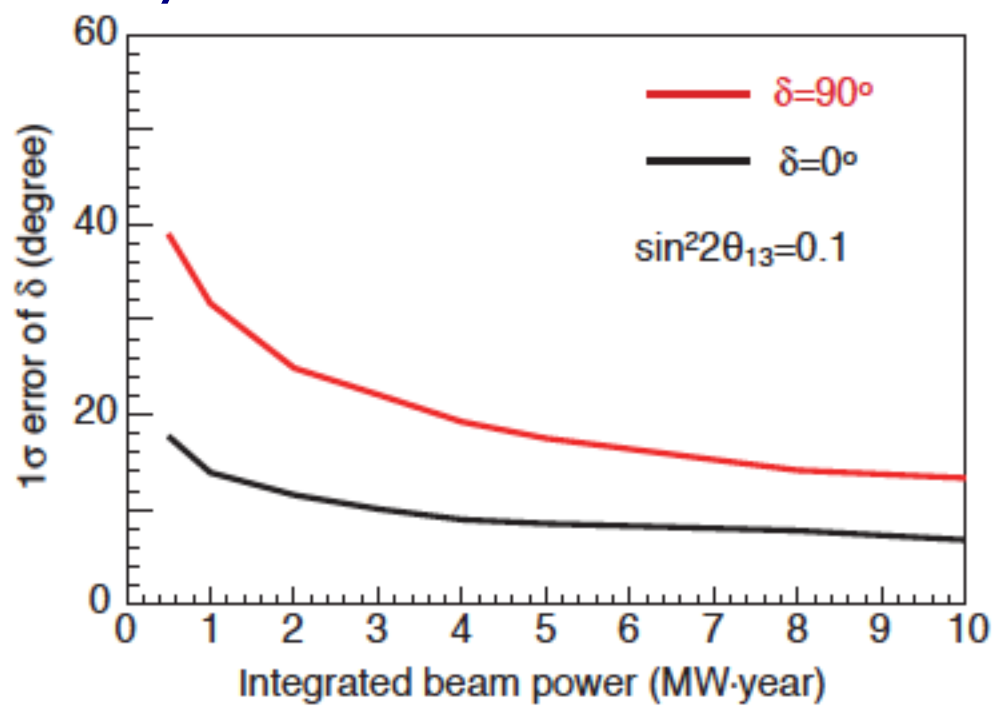
Planned Measurements

T2HK



Primary goal is measurement of δ
Best sensitivity when MH measured by someone else



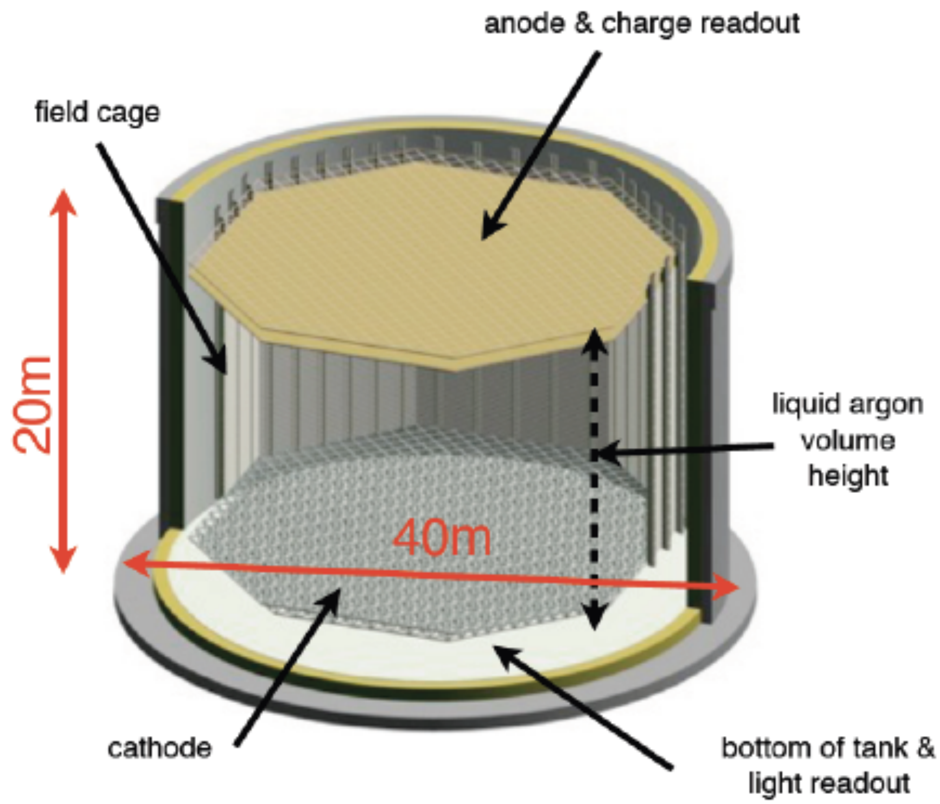


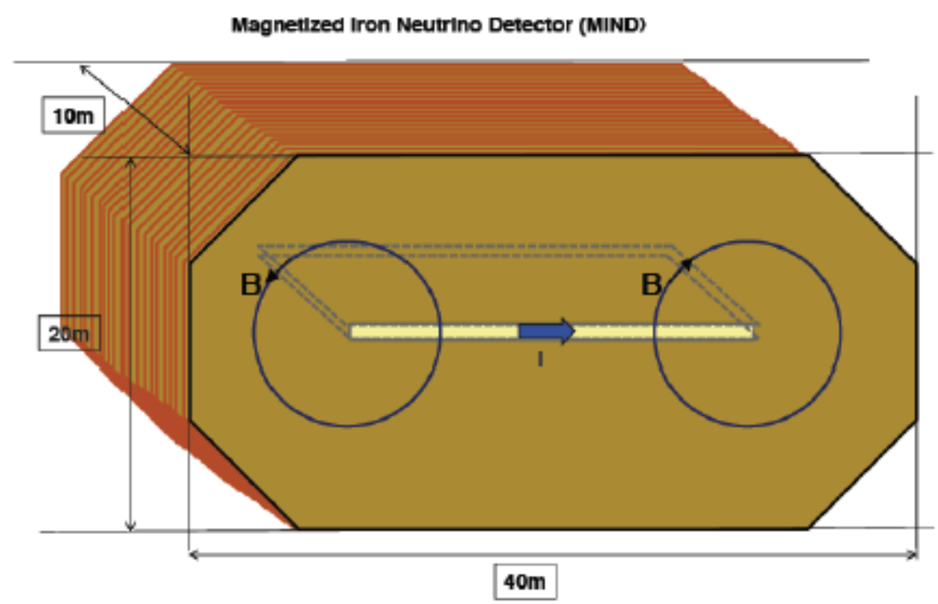
Planned Measurements

LBNO

Primary goal is measurement of δ and MH

Very long baseline (L=2300 km) means higher energy beam, keeping reasonably interaction probability.

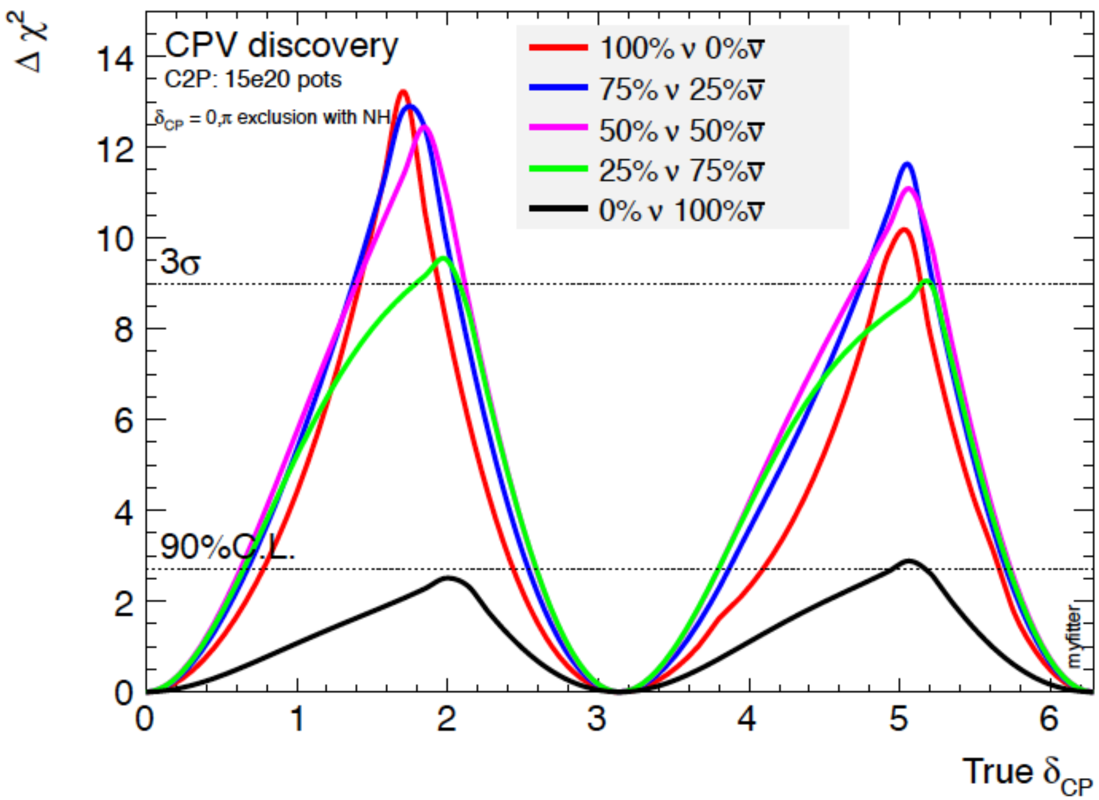


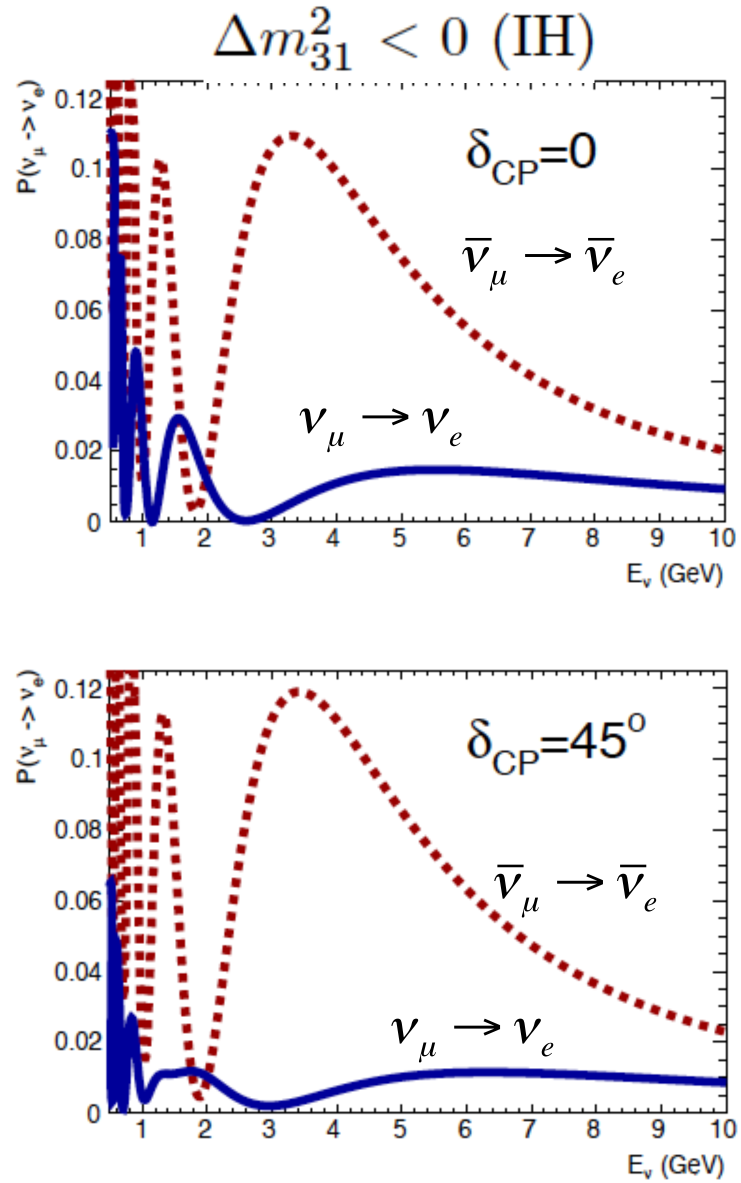


Planned Measurements

LBNO

Ambiguities between matter effect and CP violation removed by looking at details of oscillation spectrum.

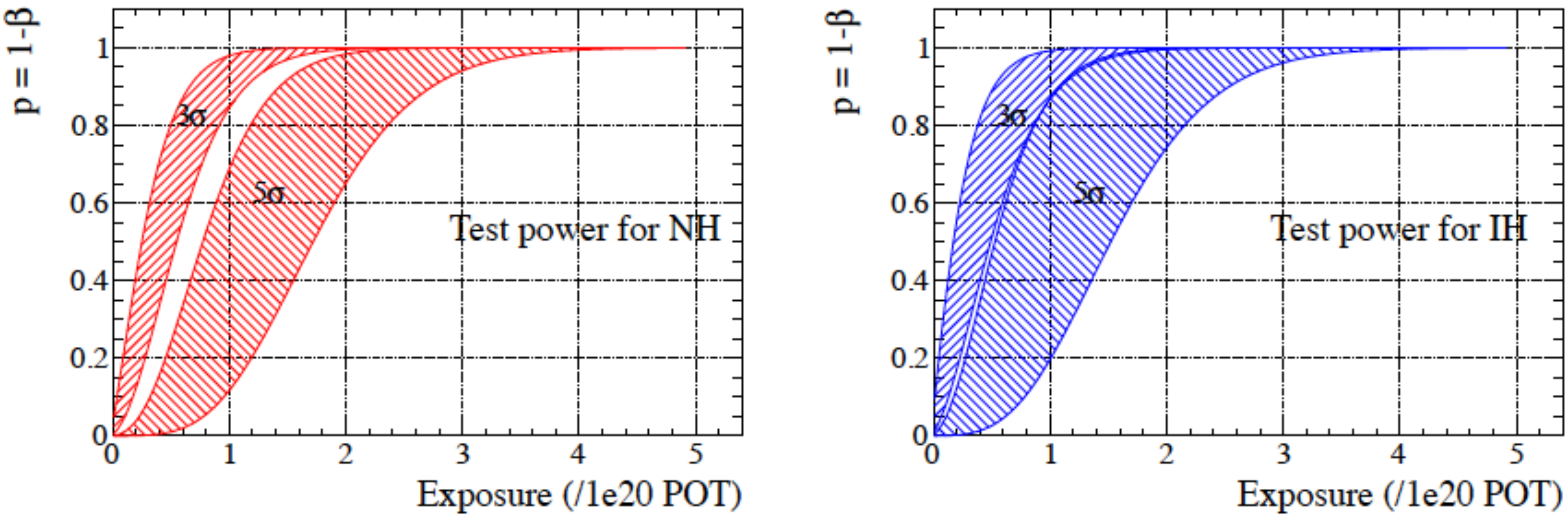




Planned Measurements

LBNO

Ambiguities between matter effect and CP violation removed by looking at details of oscillation spectrum.

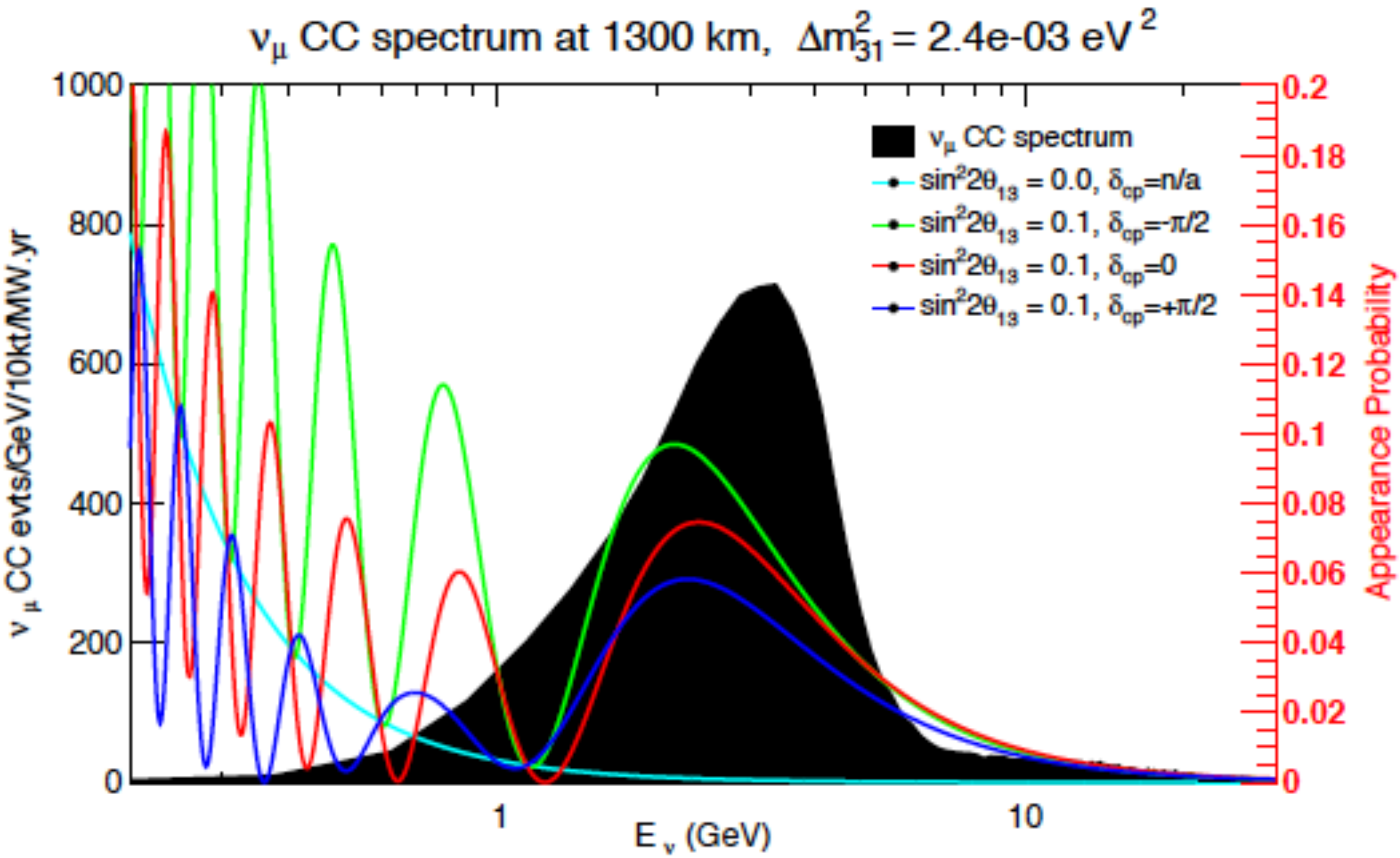


This plots the "power" of the NH or IH test as a function of beam; in other words, the fraction of time for a given significance that the experiment correctly rejects the wrong hypothesis.

Planned Measurements

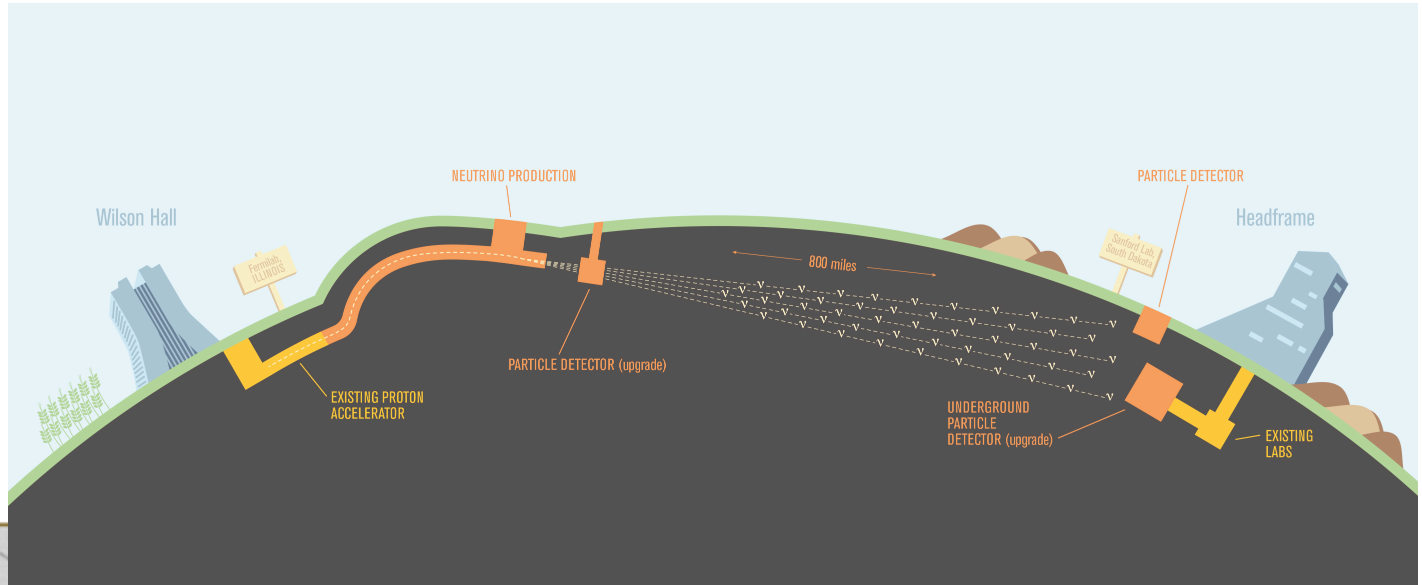
LBNE

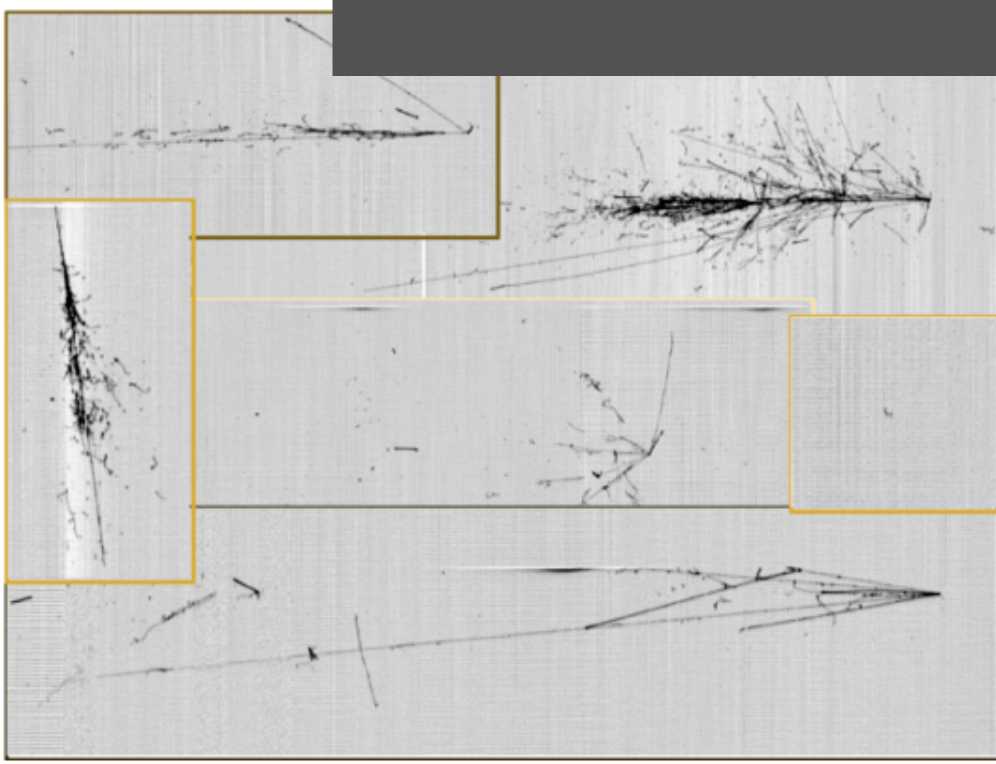
Primary goals are CP violation and MH, also octant of θ_{23}

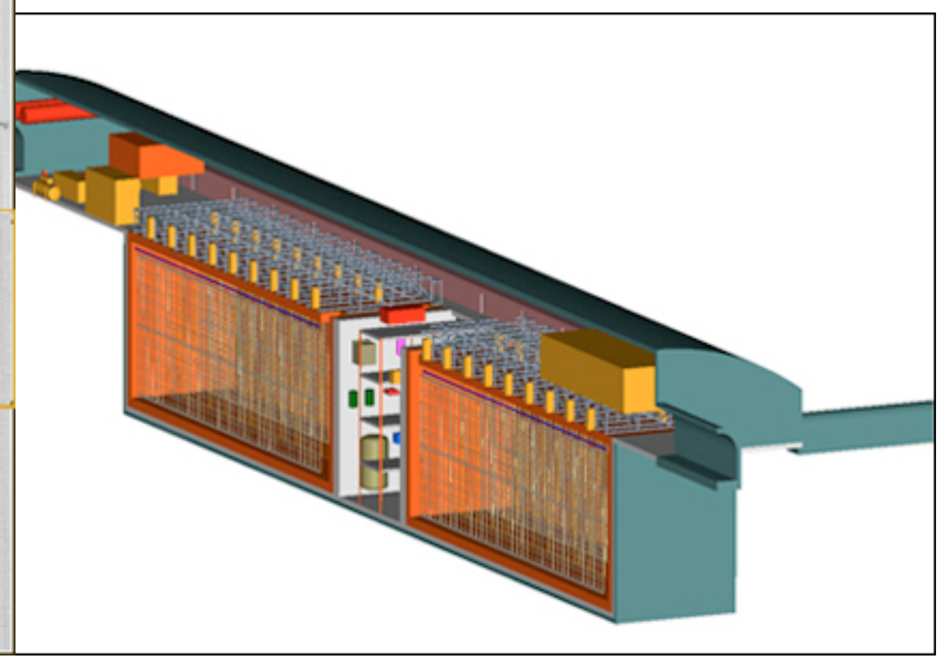


Planned Measurements

LBNE



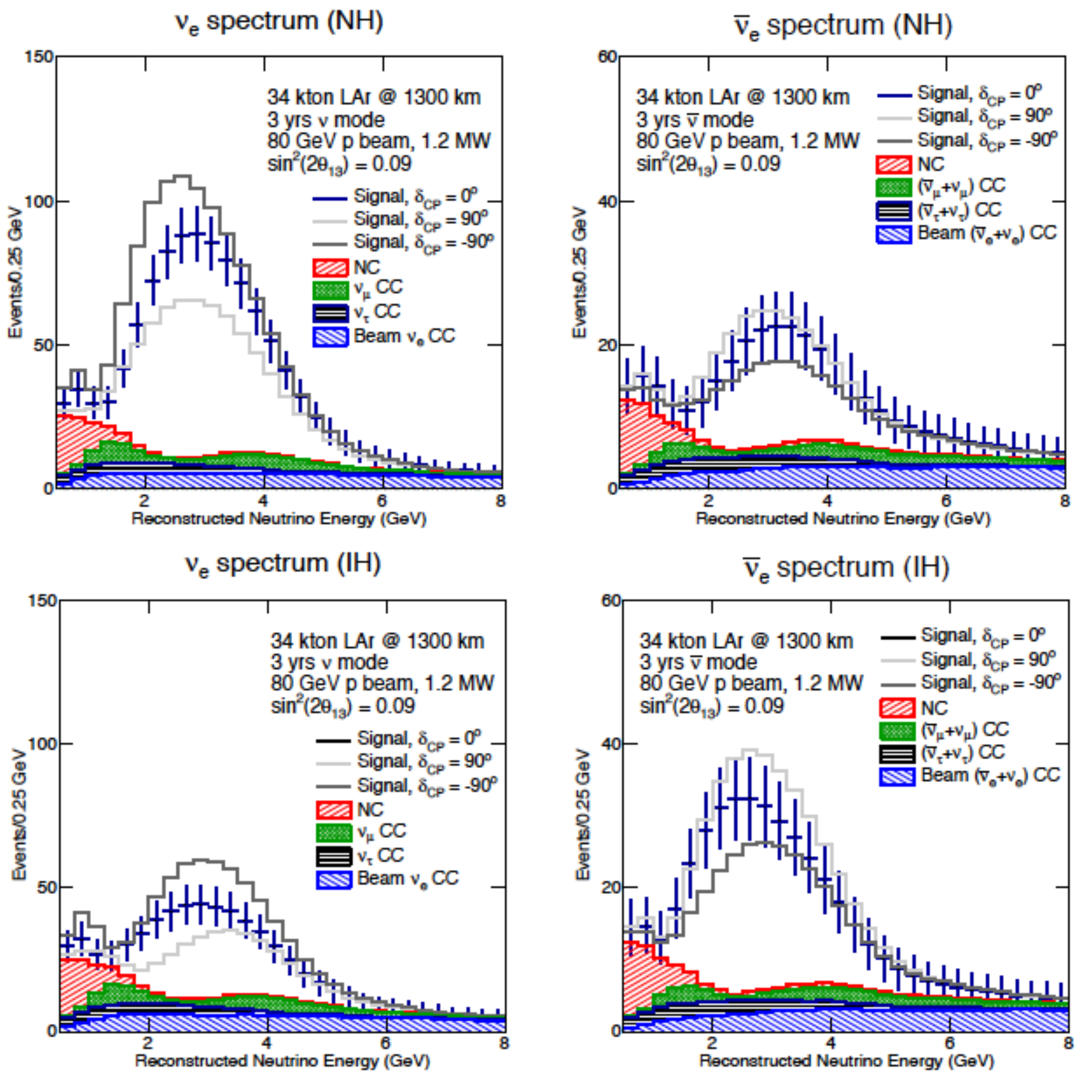




Planned Measurements

LBNE

Primary goals are CP violation and MH, also octant of θ_{23}



Planned Measurements

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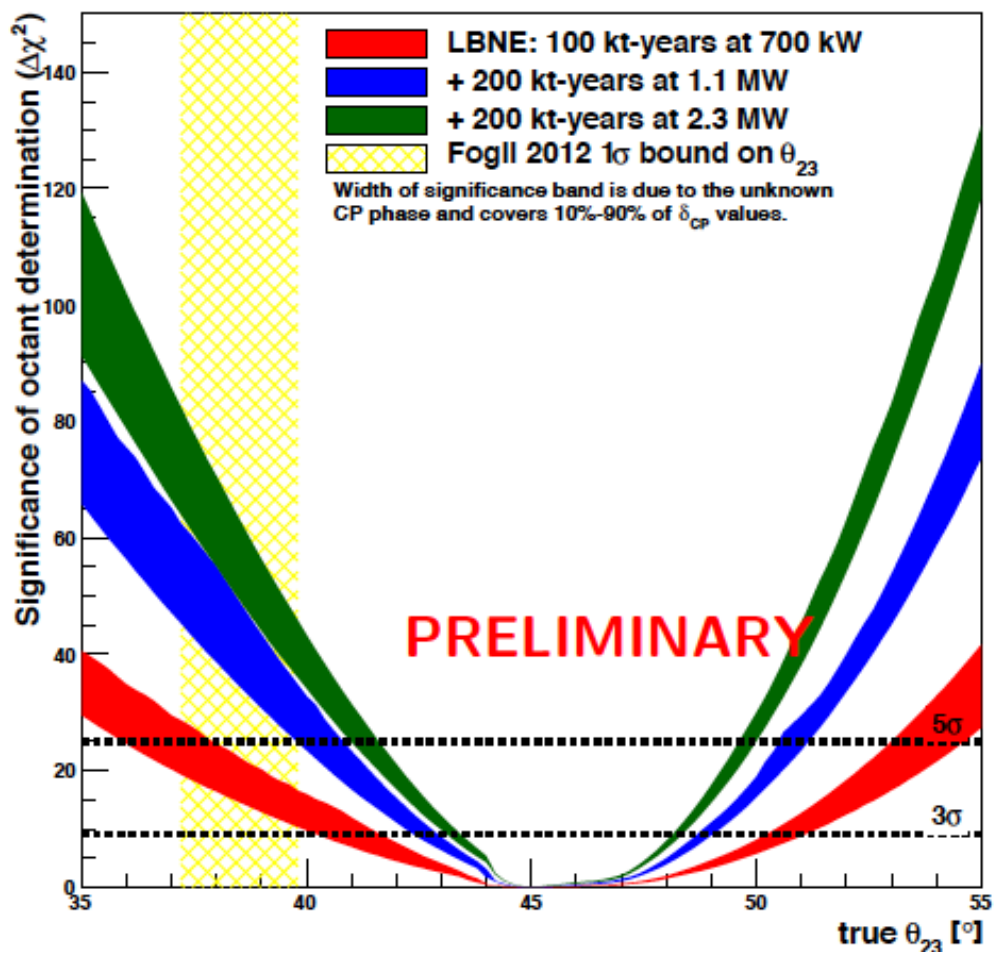
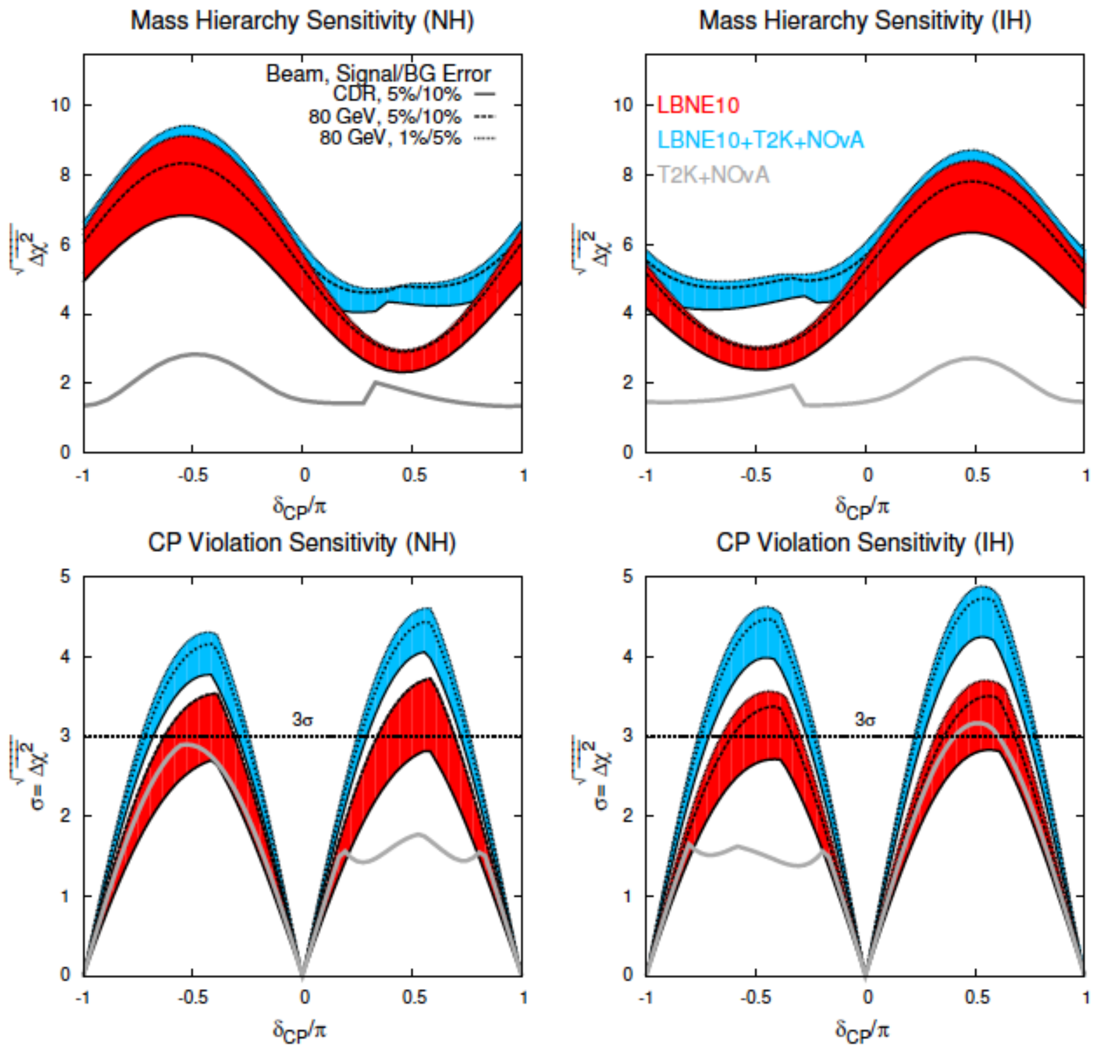


Planned Measurements

LBNE

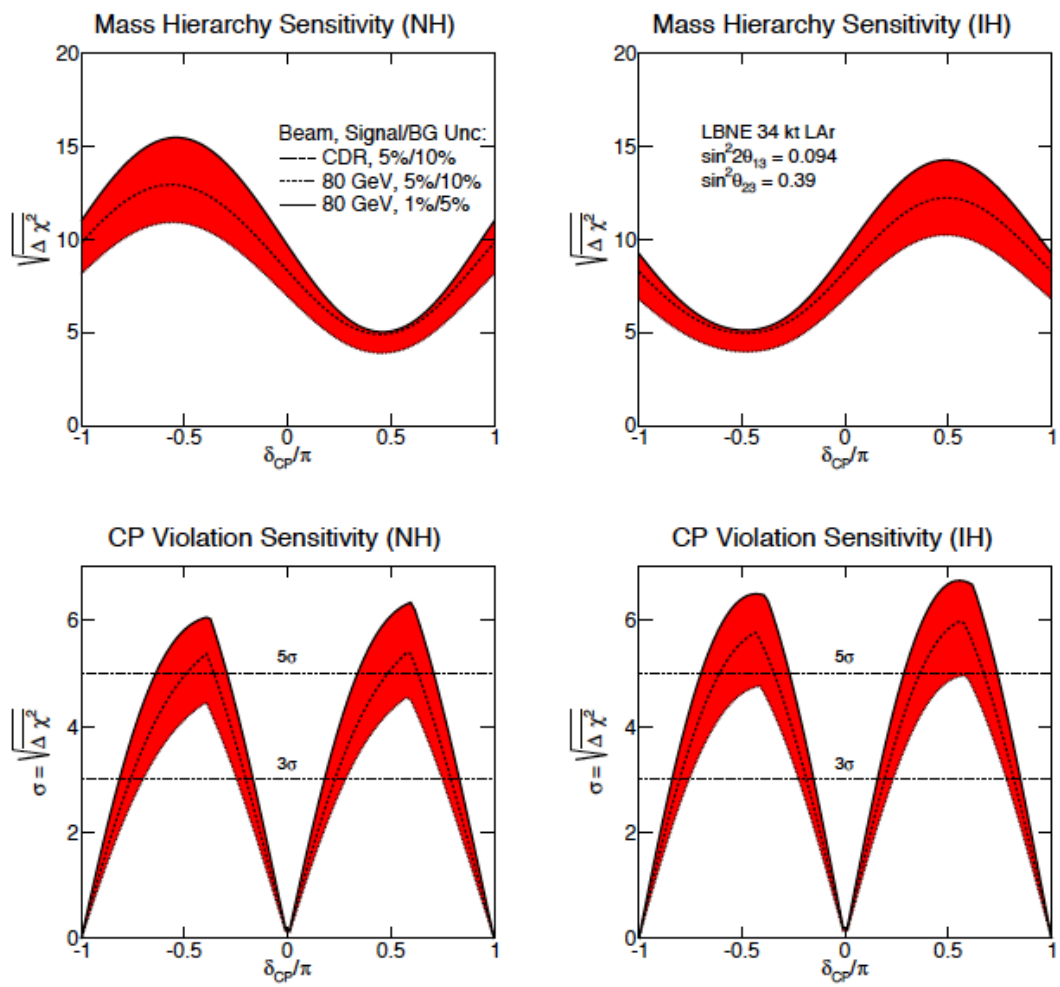
Primary goals are CP violation and MH, also octant of θ_{23}



Planned Measurements

LBNE

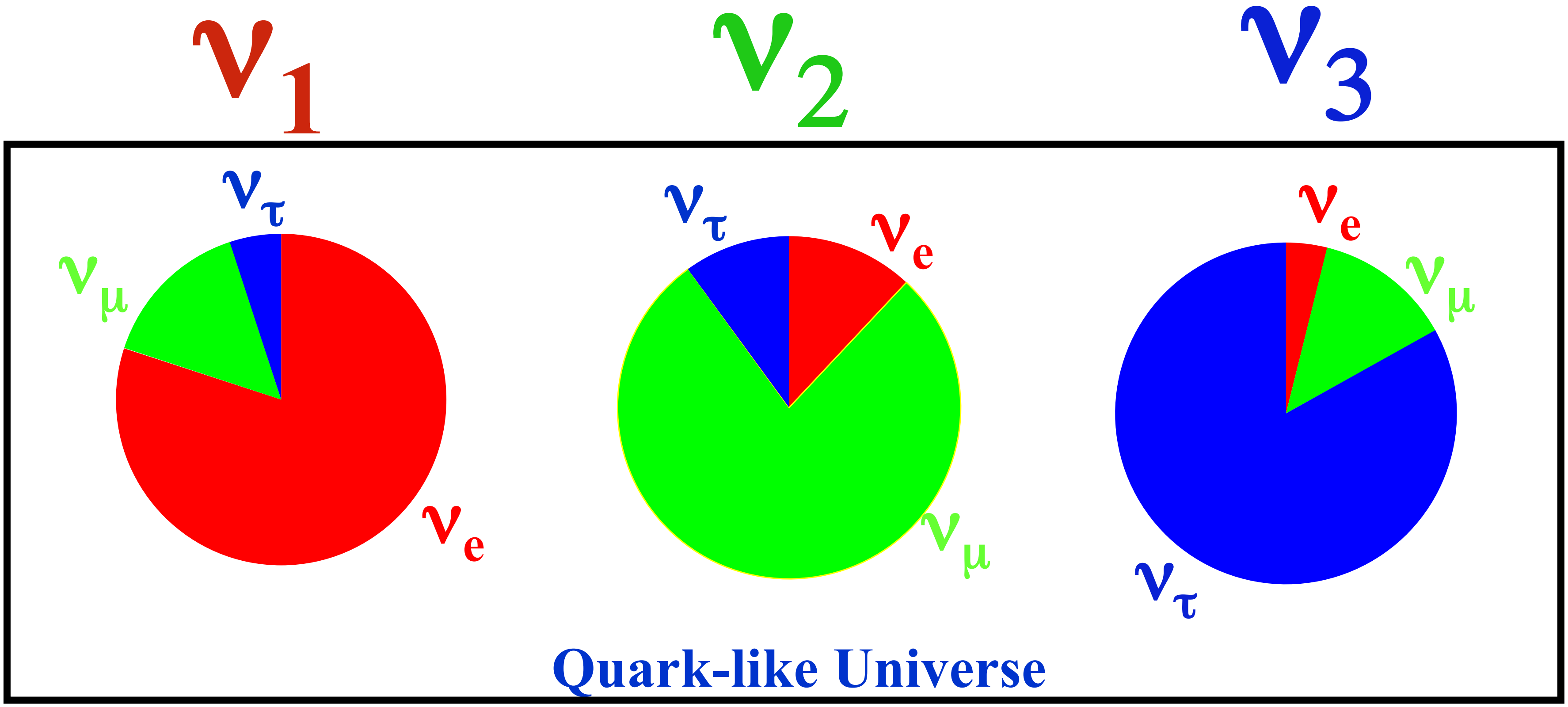
Primary goals are CP violation and MH, also octant of θ_{23}



Summary

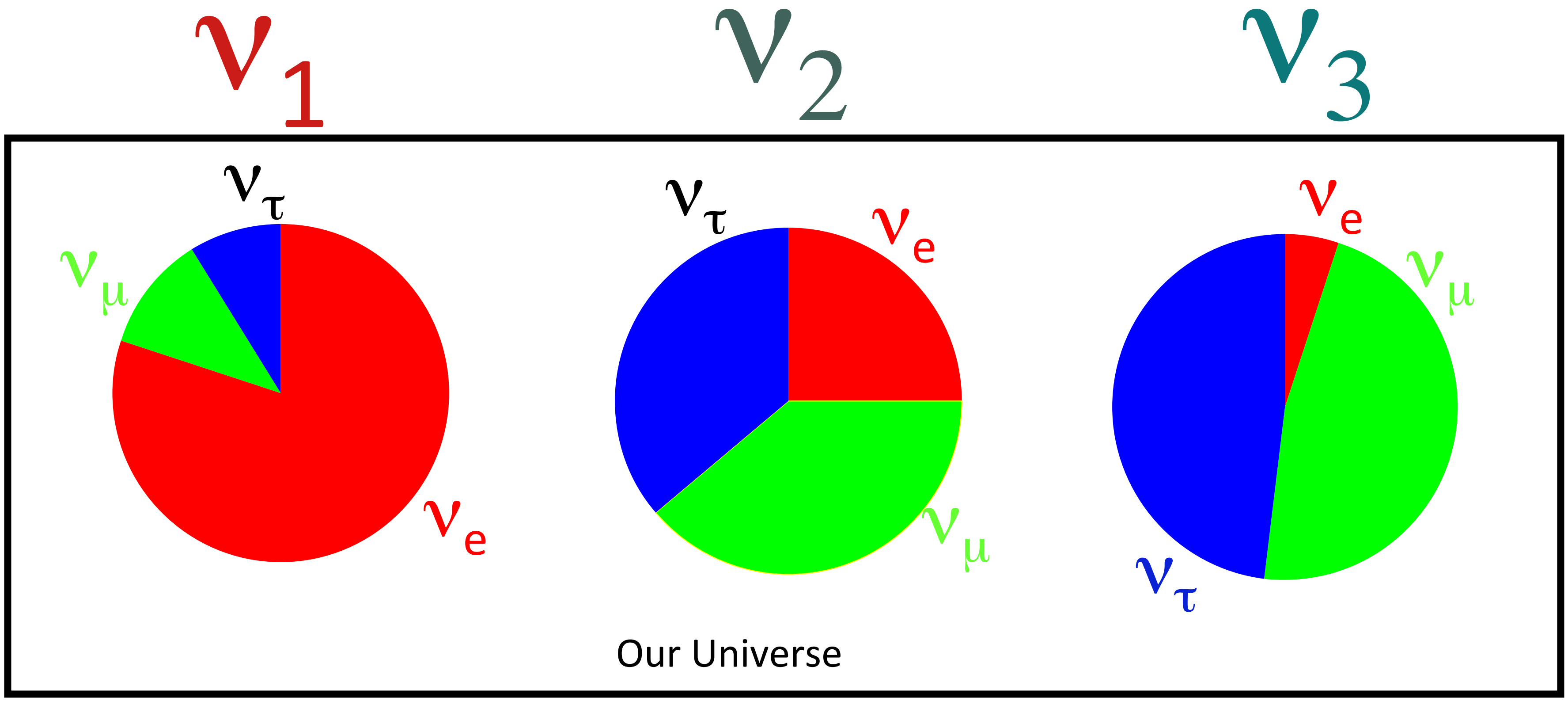
- Precision era of neutrino physics just beginning
  - We do not yet even know the details of the model we're testing
- Mass hierarchy is a critical measurement
  - Provides context for 0nbb searches and hence determines character of new physics
- Measurement of δ and subsequent test of whether it predicts a CP violation effect is particularly interesting
  - May be connected to matter/antimatter asymmetry
- Three-flavor era of neutrino mixing has begun with many experiments aiming to explore the richness of this phenomenlogy

Nevertheless…



Which is weirder? (And should we even ask that?)

Nevertheless…



Which is weirder? (And should we even ask that?)