Neutrino Physics Overview:

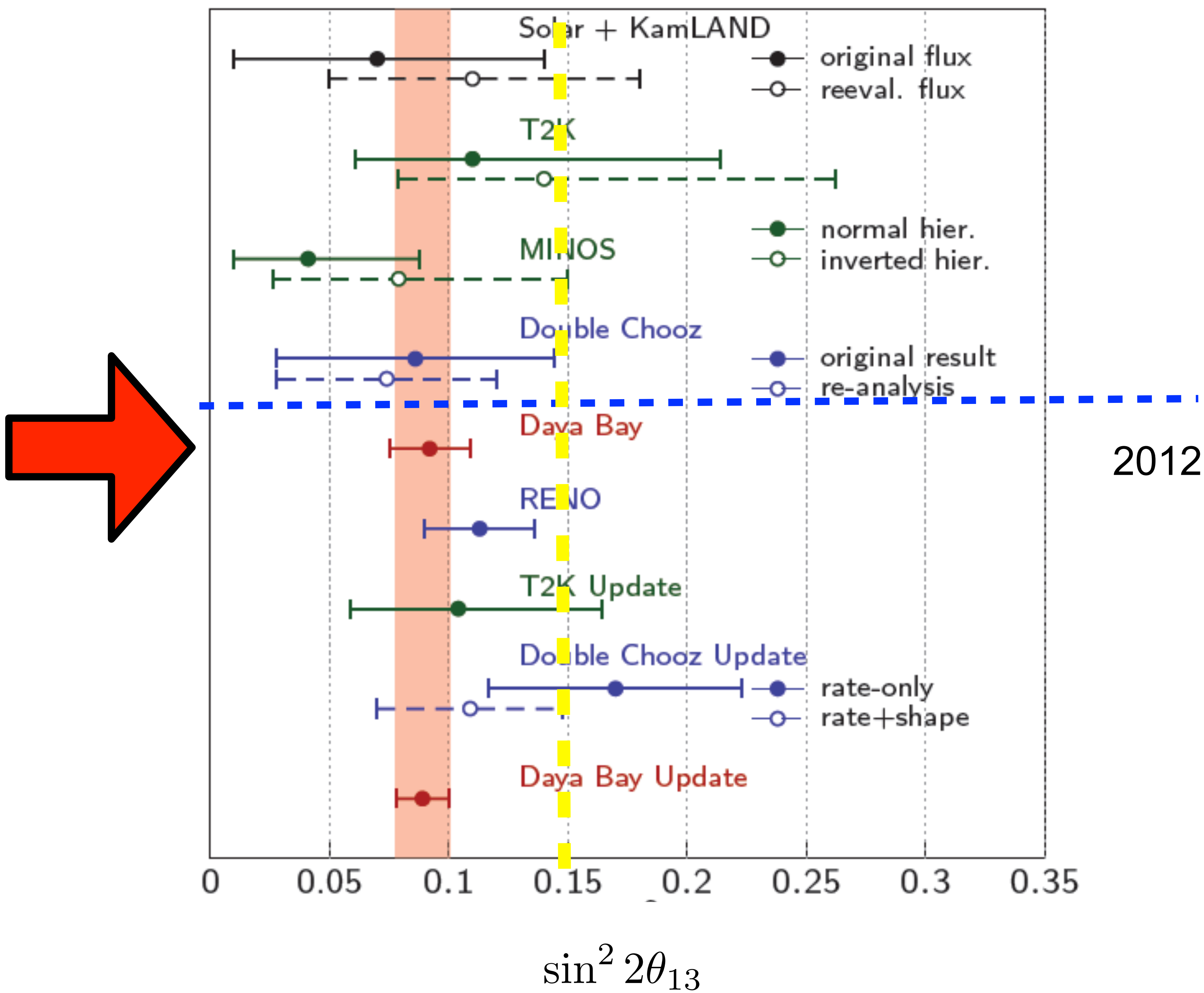
Stephen Parke
Fermilab

- Nu Standard Model
- Beyond Nu Standard Model
- Summary & Conclusions

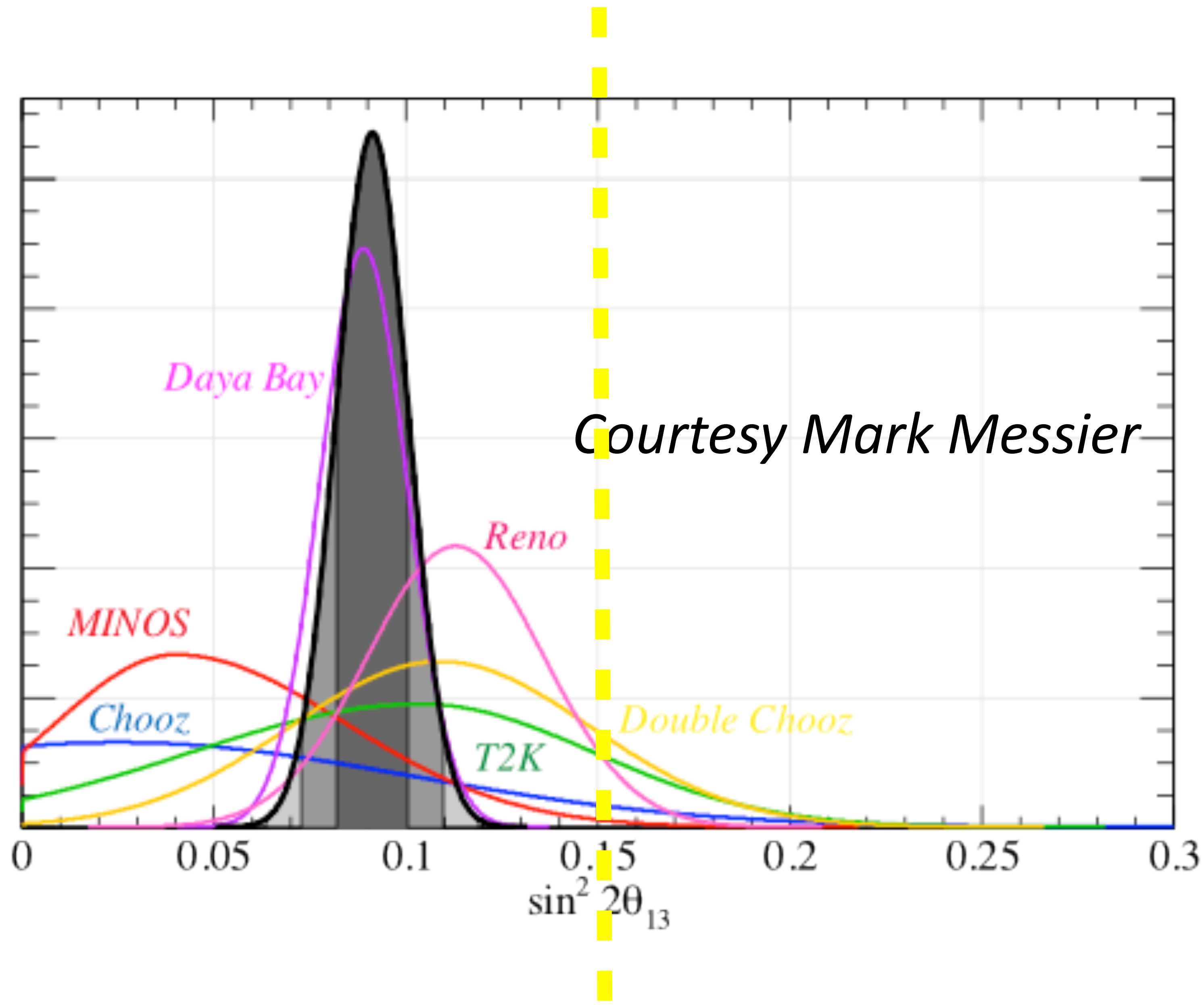
Theta_13 Discovery:

$\sin^2\theta_{13} \approx 0.23$ is the ν_e fraction of ν_3 (the electron poor mass state)

$> 5\sigma$ discovery



World Average: Theta_13



Unanswered Questions !

ν Standard Model

- Nature of Neutrino: Majorana (2 comp) or Dirac (4 comp) fermion?
- CPV in Neutrino Sector: determination Dirac phase δ ?
- Ordering of mass eigenstates: Atmos. mass hierarchy, sign of δm^2_{31} ?
- Is ν_3 more ν_μ or more ν_τ: Octant of θ_{23} $(> \mathrm{or} < \frac{\pi}{4})$
- Majorana Phases: 2 additional phases
- Absolute Neutrino Mass: m_{lite}

credibility of Leptogenesis!

Beyond ν Standard Model

- What is the mass of the Sterile Neutrinos: light? or Superheavy?
- What is the size of Non-Standard Interactions?
- Where are the True Surprises?

Nu Standard Model

- ν Flavor Oscillations/Conversion are a Fact:

Neutrino Oscillation Experiments have revealed that neutrinos change flavor after propagating a finite distance. The rate of change depends on the neutrino energy, E_ν, and the baseline, L. The evidence is overwhelming!

Two different L/E scales have been observed:

- Atmospheric $L/E = 500\ km/GeV$ and Solar $L/E = 15,000\ km/GeV$
  - $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric and accelerator experiments;
  - $\nu_e \to \nu_{\mu,\tau}$ — solar experiments;
  - $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ — reactor experiments;
  - $\nu_\mu \to \nu_{\rm other}$ and $\bar{\nu}_\mu \to \bar{\nu}_{\rm other}$— atmospheric and accelerator expts;
  - $\nu_\mu \to \nu_e$ — accelerator experiments.

The simplest and **only satisfactory** explanation of all this data is that neutrinos have distinct masses, and mix.

Except: LSND, miniBooNE, reactor anomaly, gallium anomaly.

Neutrino Masses and Mixings (NuSM)

Label the Neutrino mass eigenstates such that:

ν_e component of ν_1 > ν_e component of ν_2 > ν_e component of ν_3

i.e. $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

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

smaller ν_e content

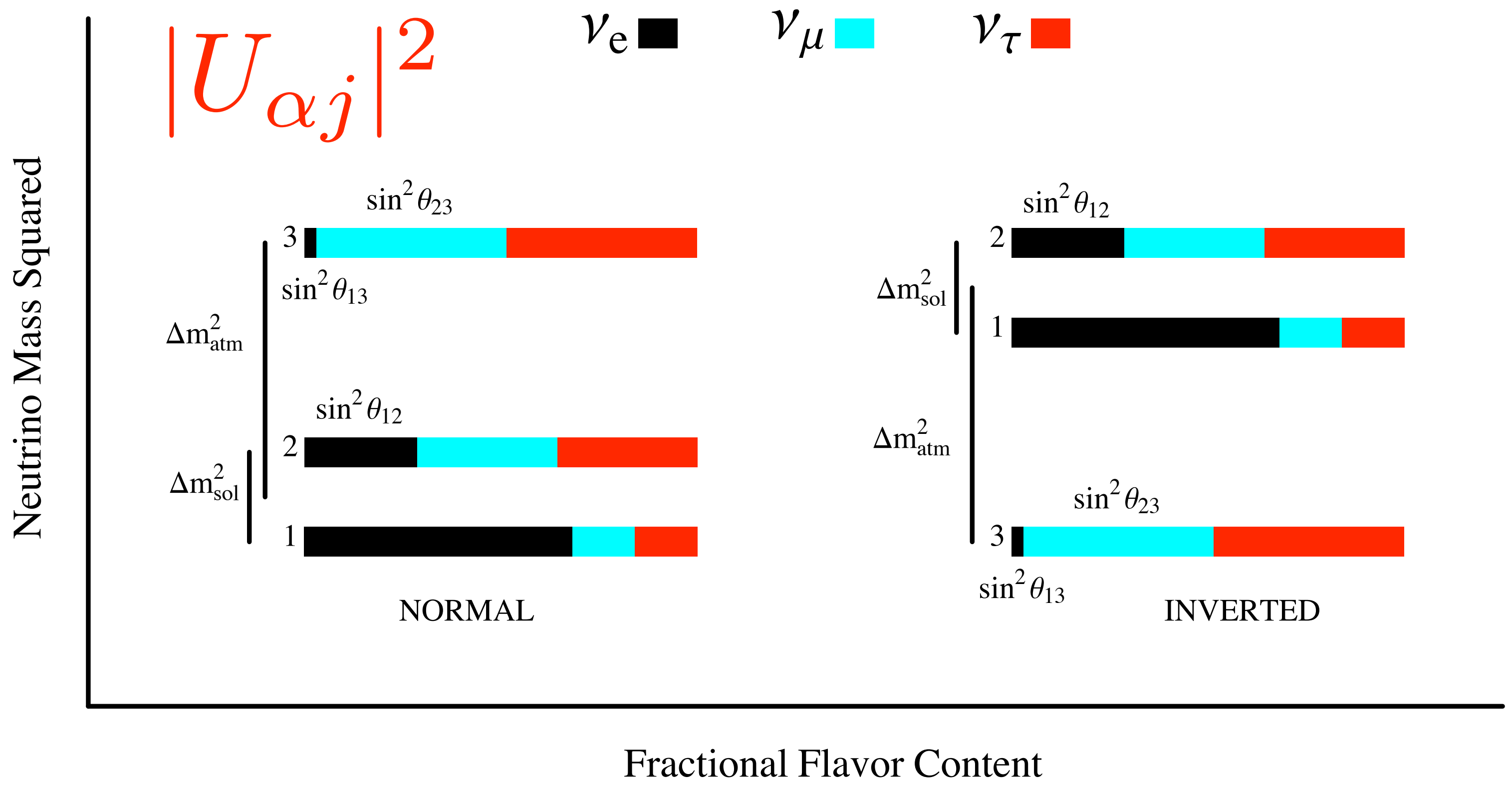
Solar Mass Hierarchy: $m_2^2 > \text{or} < m_1^2$
i.e. sign of δm_{21}^2 determined by SNO $\delta m_{21}^2 > 0$

Atmospheric Mass Hierarchy: $m_3^2 > \text{or} < m_1^2,\ m_2^2$
i.e. sign of δm_{31}^2, δm_{32}^2 UNKNOWN

$$\sin^2\theta_{13} \equiv |U_{e3}|^2 \ll 1,\ \sin^2\theta_{12} \equiv \frac{|U_{e2}|^2}{1-|U_{e3}|^2} \approx |U_{e2}|^2,\ \sin^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{1-|U_{e3}|^2} \approx |U_{\mu 3}|^2$$

Nu Standard Model:

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

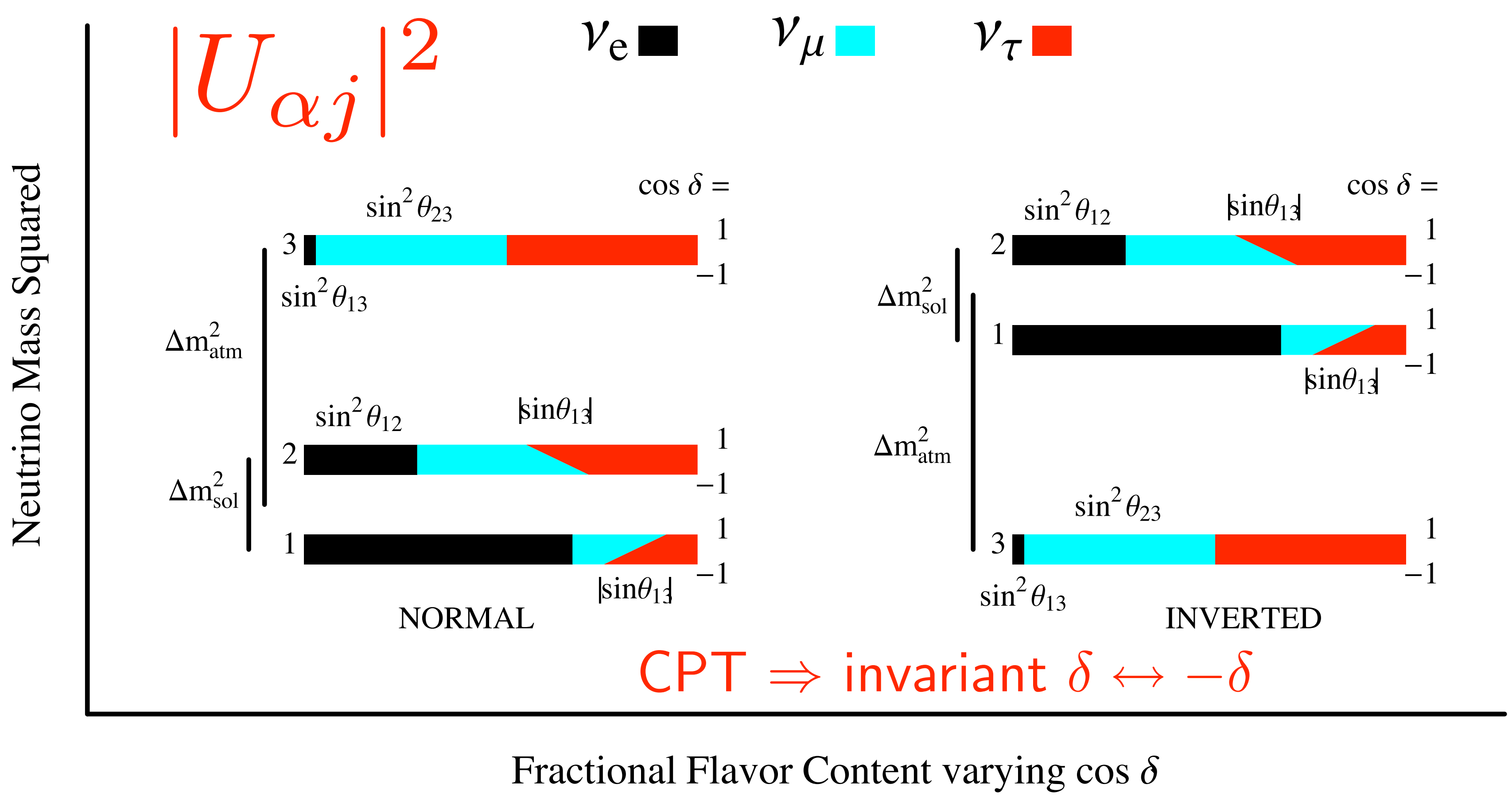
$$\sin^2\theta_{12} \sim \frac{1}{3}$$

$$\sin^2\theta_{23} \sim \frac{1}{2}$$

$$\sin^2\theta_{13} \sim 0.02$$

$$0 \leq \delta < 2\pi$$

Nu Standard Model:



- What is the neutrino mass hierarchy? ($\delta m^2_{31} \equiv m^2_3 - m^2_1 > 0$)
- Is ν_3 mostly ν_μ or ν_τ ? $(\theta_{23} < \pi/4 \ \text{ or } > \pi/4)$
- Is CP Violated in Neutrino Oscillations? ($\delta \neq 0, \pi$)

Global Fits: (Sausages)

Fogli et al arXiv: 1205.5254v3

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 $\oplus$ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

???

3-flavor effects in atmospheric neutrinos

Peres, Smirnov, 99;
Gonzalez-Garcia, Maltoni, Smirnov, 04

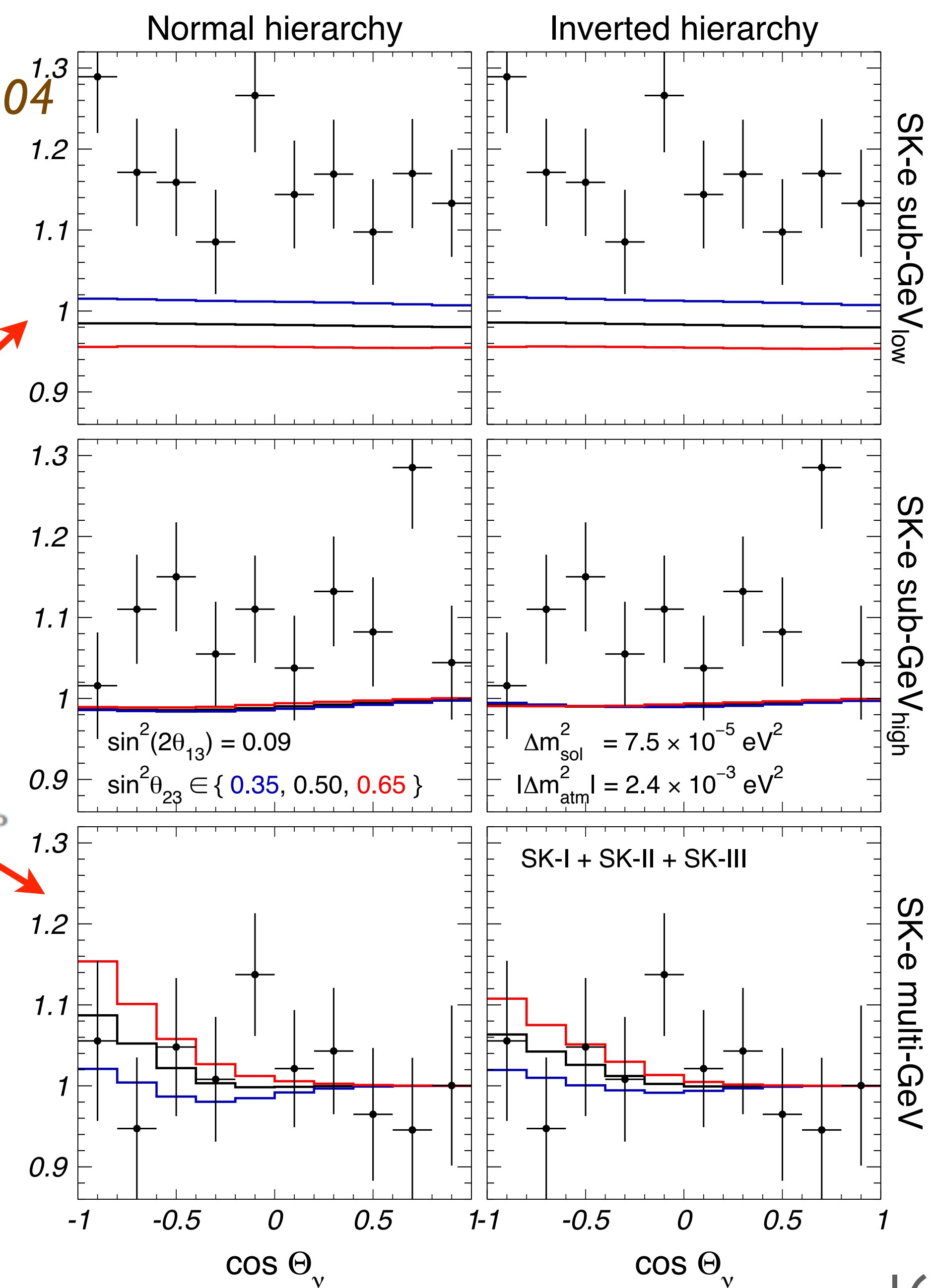
excess in electron-like events:

$$\frac{N_e}{N_e^0} - 1 \simeq (r\, s_{23}^2 - 1)\, P_{2\nu}(\Delta m_{31}^2, \theta_{13}) \quad \theta_{13}\text{-effects}$$

$$+ (r\, c_{23}^2 - 1)\, P_{2\nu}(\Delta m_{21}^2, \theta_{12}) \quad \Delta m_{21}^2\text{-effects}$$

$$- 2 s_{13} s_{23} c_{23}\, r\, \mathrm{Re}(A_{ee}^* A_{\mu e}) \quad \text{interference: } \delta_{CP}$$

$$r = r(E_\nu) \equiv \frac{F_\mu^0(E_\nu)}{F_e^0(E_\nu)} \qquad r \approx 2 \ \text{(sub-GeV)} \qquad r \approx 2.6 - 4.5 \ \text{(multi-GeV)}$$



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adding atmospheric data ?

3-flavor effects in atmospheric neutrinos

Peres, Smirnov, 99;
Gonzalez-Garcia, Maltoni, Smirnov, 04

???? pushes you into first quadrant

excess in electron-like events:

$$\frac{N_e}{N_e^0} - 1 \simeq (r\, s_{23}^2 - 1)\, P_{2\nu}(\Delta m^2_{31}, \theta_{13}) \quad \theta_{13}\text{-effects}$$

$$+ \; (r\, c_{23}^2 - 1)\, P_{2\nu}(\Delta m^2_{21}, \theta_{12}) \quad \Delta m^2_{21}\text{-effects}$$

$$- \; 2 s_{13} s_{23} c_{23}\, r\, \mathrm{Re}(A^*_{ee} A_{\mu e}) \quad \text{interference: } \delta_{CP}$$

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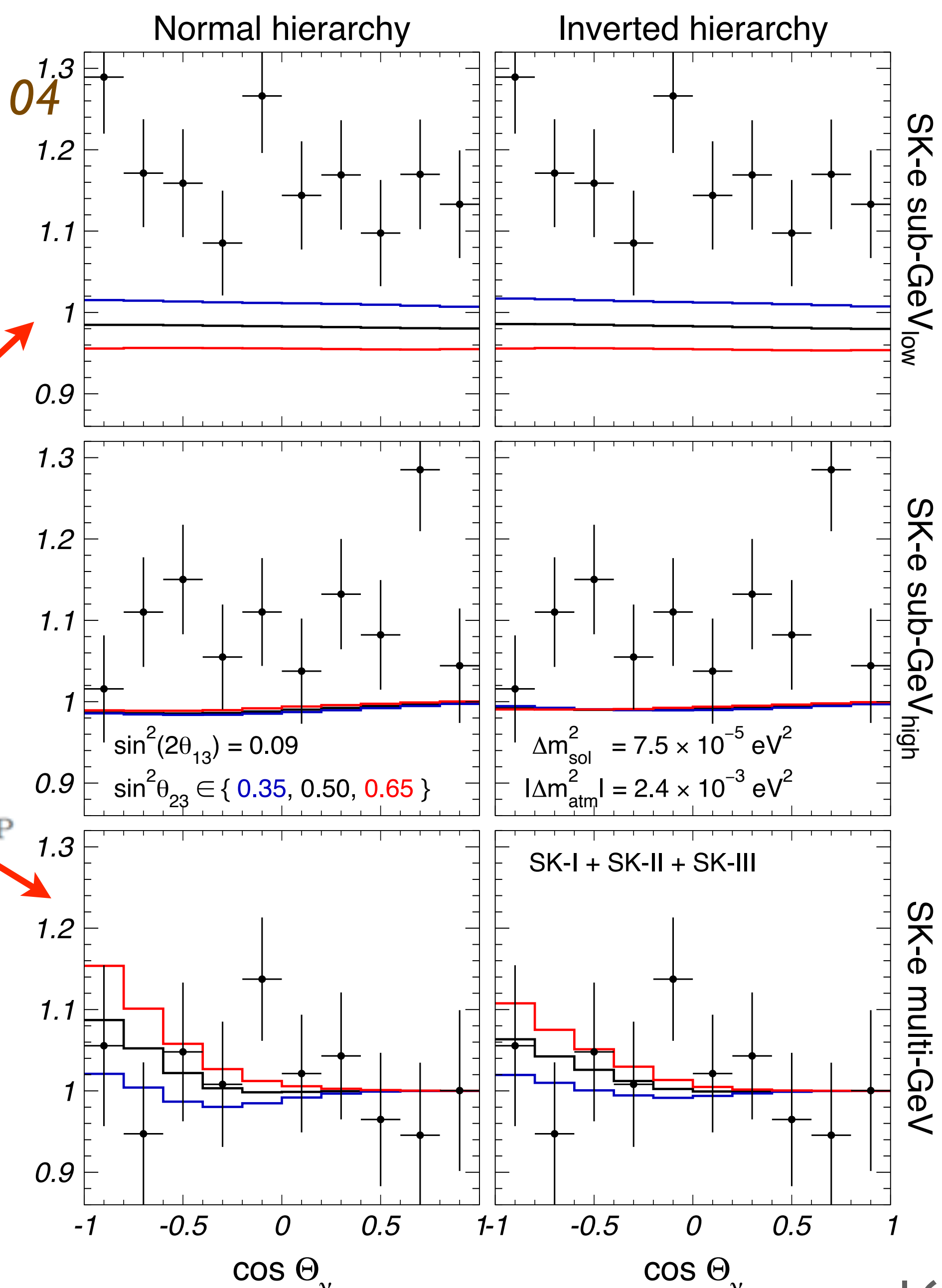

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What we have measured?

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

What we have **really measured** (roughly speaking):

- Solar (21) mass-squared splitting with sign- KamLAND
- Atmospheric [comb of (32) and (31)] mass-squared splitting - absolute value, no sign, MINOS

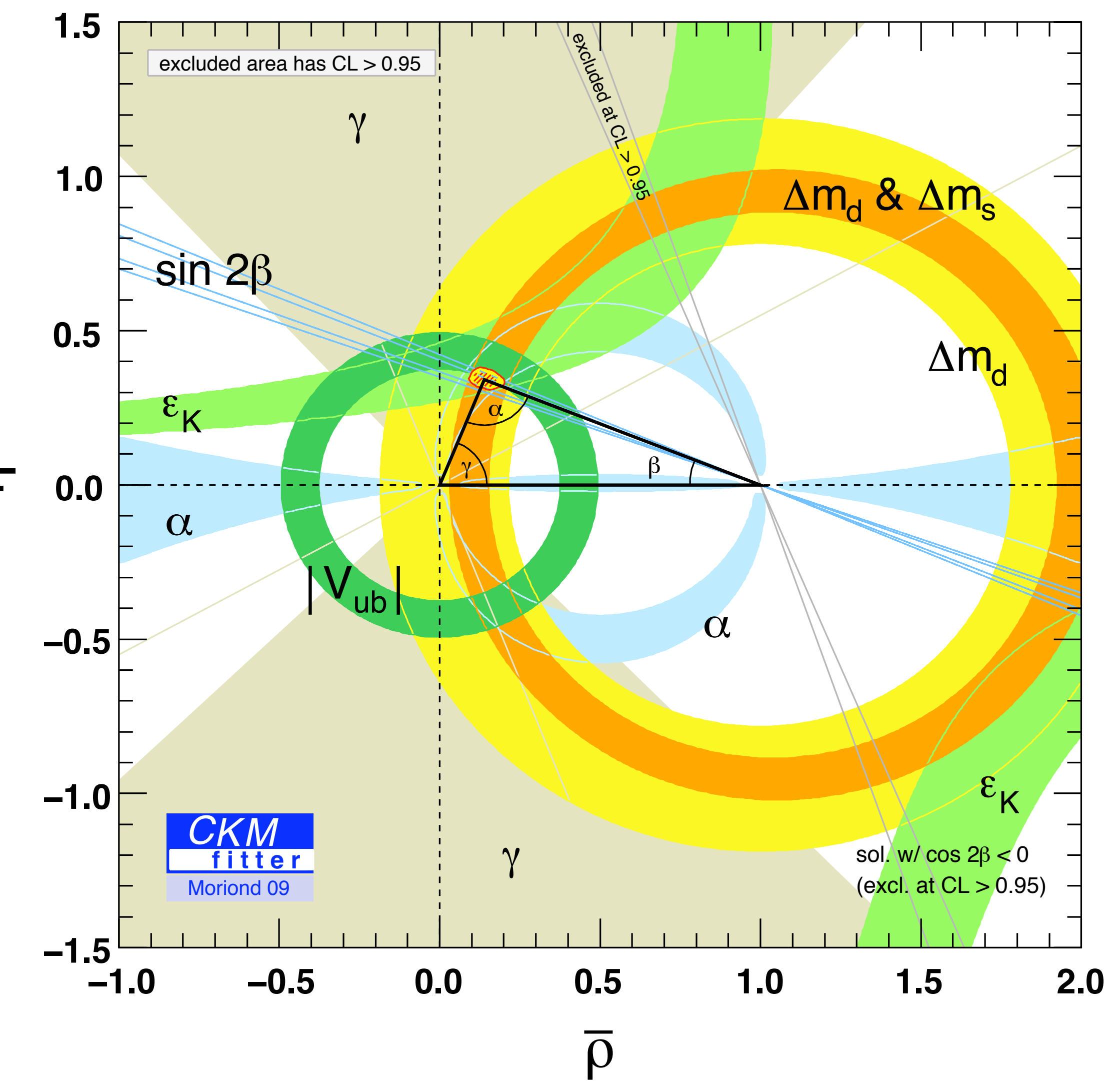
- $|U_{e2}|^2$ - solar data (CC-SNO)
- $|U_{e2}|^2 + |U_{\mu 2}|^2 + |U_{\tau 2}|^2$ - solar data (NC-SNO)
- $|U_{e1}|^2 |U_{e2}|^2$ - KamLAND wiggles

- $|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)$ - Atm data, K2K, MINOS

- $|U_{e3}|^2(1 - |U_{e3}|^2)$ - Double Chooz, Daya Bay, RENO
- $|U_{e3}|^2 |U_{\mu 3}|^2$ - MINOS, T2K

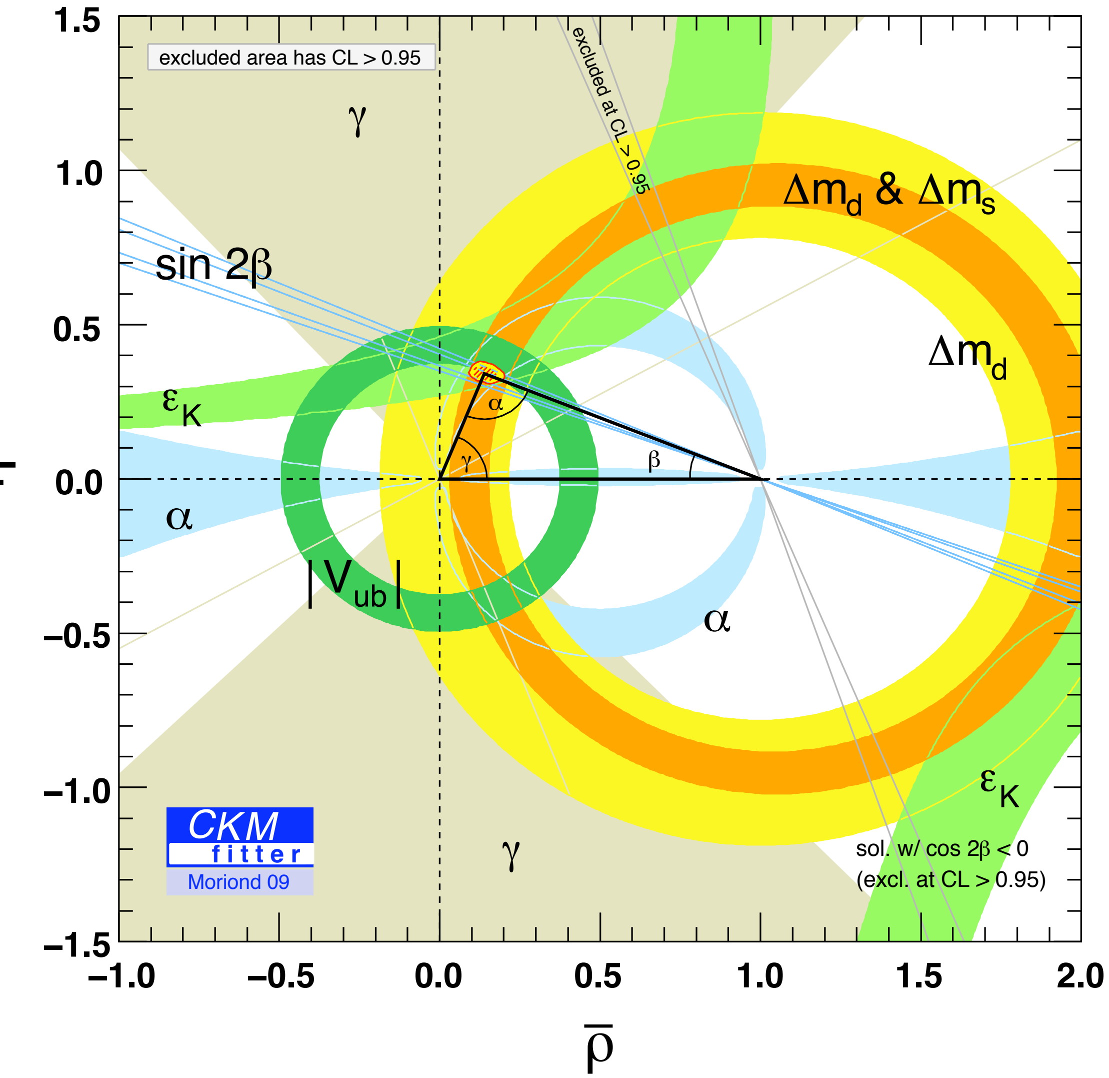
We have a way to go !!!

Unitarity Triangle:



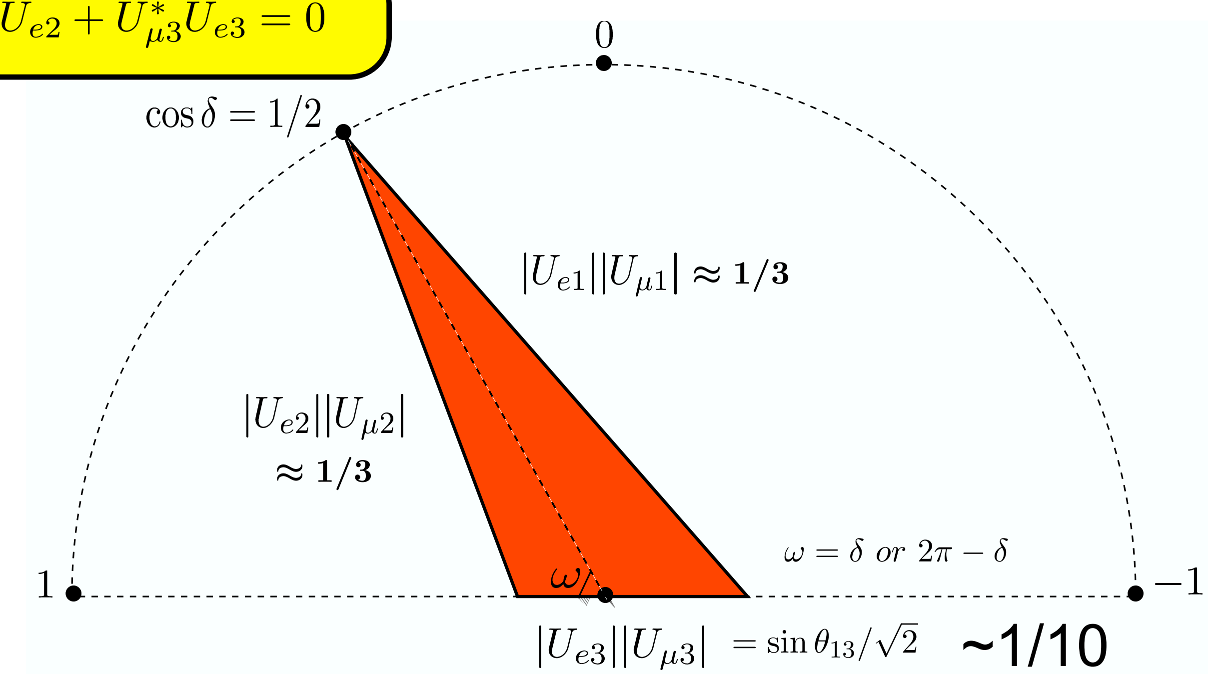
We need to do something similar for the Lepton Sector!

Unitarity Triangle:



Unitarity Triangle:

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



$$|J| = 2 \times Area$$

$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2 \sin\delta$$

We need to do something similar for the Lepton Sector!

Leptons v Quarks:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Very Different !!!

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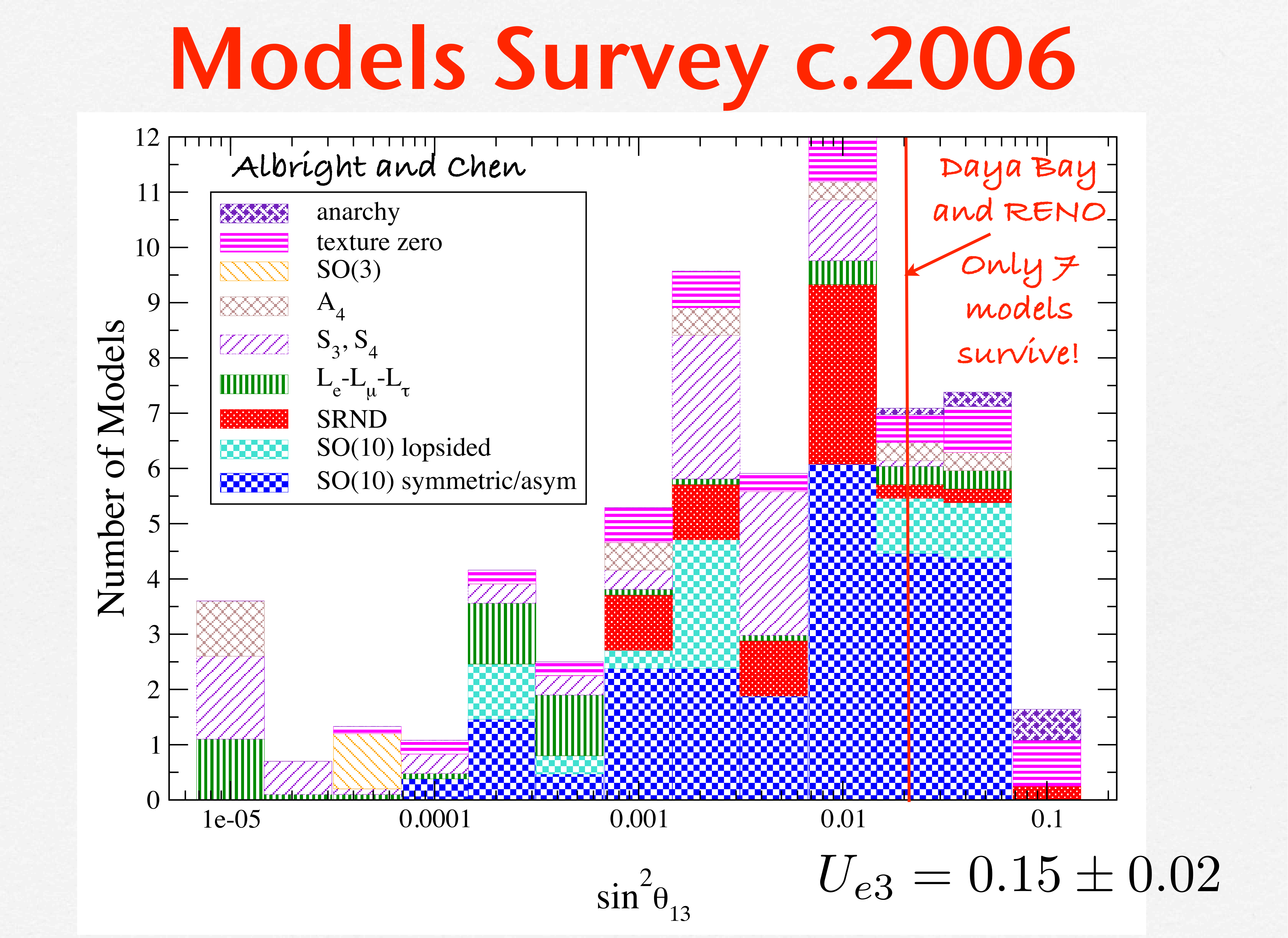
Very Different !!!

Was $\boldsymbol{\theta_{13} \approx \frac{\theta_C}{\sqrt{2}}}$ Predicted?

Models:



$$U_{e3} = 0.15 \pm 0.02$$

Models:

- BM, TBM, GR might only apply to neutrino mixing and $U_{PMNS} = U_e U_\nu^\dagger$ implies $\theta_{13} \approx \frac{\theta_{12}^e}{\sqrt{2}}$
- Solar Sum Rules

  Sum Rule: King ('05); Masina ('05); Antusch, King ('05)

  Charged Lepton Corrections: King ('02), Frampton, Petcov, Rodejohann ('04), Altarelli, Feruglio, Masina ('04), Antusch, King ('04), Ferrandis, Pakvasa ('04), Feruglio ('05), Datta, Everett, Ramond ('05), Mohapatra, Rodejohann ('05) Antusch, Maurer ('11) Mazocca, Petcov, Romanino, Spinrath ('11)
- Bimaximal $\theta_{12} = 45^o + \theta_{13} \cos\delta \rightarrow \delta \approx \pi$
- Tri-bimaximal $\theta_{12} = 35^o + \theta_{13} \cos\delta \rightarrow \delta \approx \pm\frac{\pi}{2}$
- Golden ratio $\theta_{12} = 32^o + \theta_{13} \cos\delta$

Experiment $\theta_{12} = 34^o \pm 1^o$ $\theta_{13} = 9^o \pm 1^o$

Masses & Mixings (conti.)

- Quark-Lepton Complementarity $\theta_{12} + \theta_C = 45^o$
- Solar sum rules
  - Bimaximal $\theta_{12} = 45^o + \theta_{13} \cos\delta$
  - Tri-bimaximal $\theta_{12} = 35^o + \theta_{13} \cos\delta$
  - Golden Ratio $\theta_{12} = 32^o + \theta_{13} \cos\delta$

Plus HO corrections...

- Atm. sum rules
  - Tri-bimaximal-Cabibbo $\theta_{12} = 35^o \quad \theta_{23} = 45^o$, $\theta_{13} = \theta_C/\sqrt{2} = 9.2^o$
  - Trimaximal1 $\theta_{23} = 45^o + \sqrt{2}\theta_{13} \cos\delta$
  - Trimaximal2 $\theta_{23} = 45^o - \dfrac{\theta_{13}}{\sqrt{2}} \cos\delta$

Plus Charged Lepton Corrections...

Now that θ_{13} is measured these predict $\cos\delta$

More on Models:

Indirect Models

King, Ross, de Medeiros Varzielas, Antusch, Malinsky,...

Starting point is type I see-saw

$$m_{LR} = \begin{pmatrix} A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \\ A_3 & B_3 & C_3 \end{pmatrix} \quad M_{RR} = \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix} \rightarrow m^{\nu} = \frac{AA^T}{M_1} + \frac{BB^T}{M_2} + \frac{CC^T}{M_3}$$

$$A^T = (A_1, A_2, A_3) \quad B^T = (B_1, B_2, B_3)$$

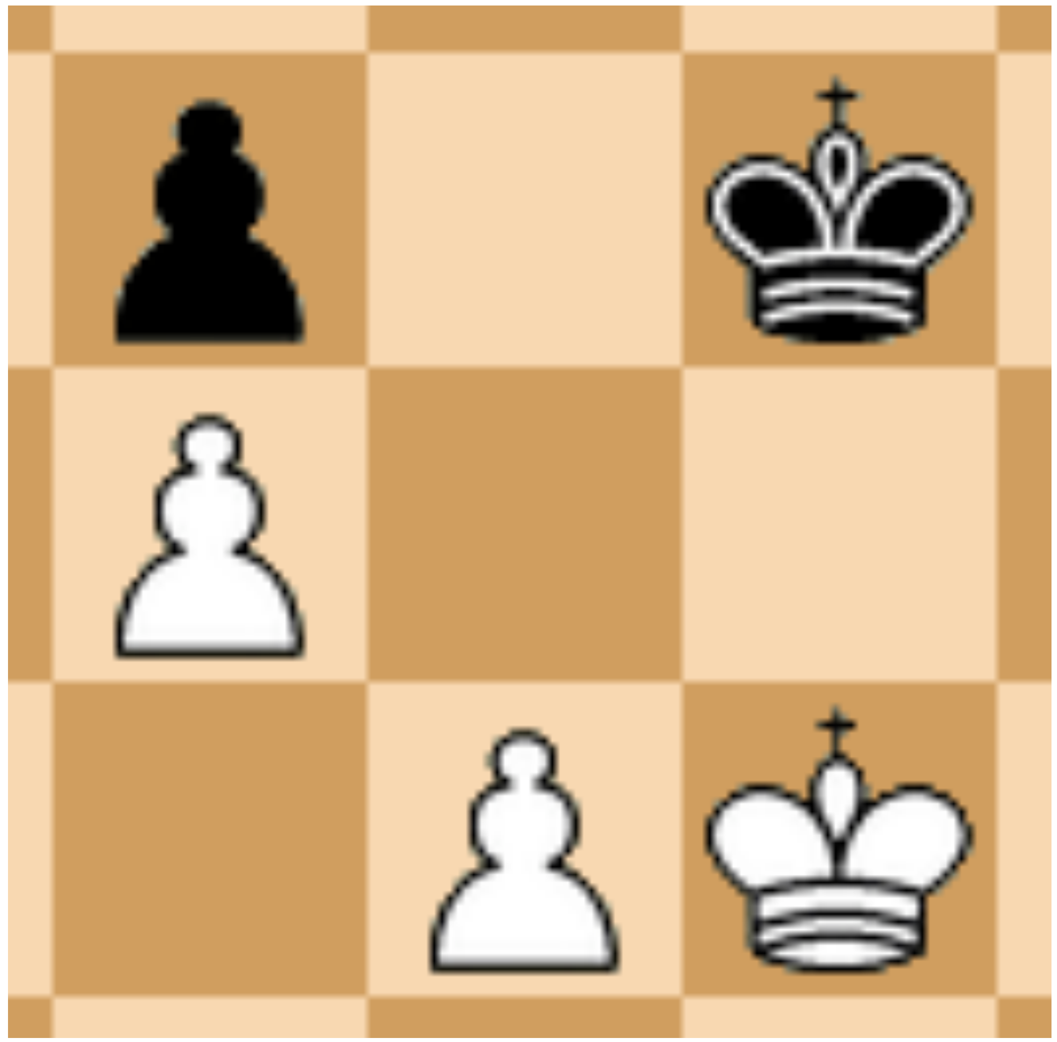
Promote the columns (A,B,C) to dynamical fields

G_F yields special vacuum alignments, for example:

- (A,B,C) proportional to columns of PMNS called Form Dominance (FD) Chen, King('09)
- $AA^T/M_1 \rightarrow 0$ gives hierarchy ($m_1 \rightarrow 0$) called Sequential Dominance (SD) King('98,'02)
- SD with B~(1,1,-1) and C~(0,1,1) called Constrained SD gives TB Mixing King('05)
- SD with B~(1,1,-1) and C~(r,1,1) called Partially CSD gives TBR mixing King('09), King,Luhn('11)
- SD with B~(1,2,0) and C~(0,1,1) called CSD2 gives TM1 mixing Antusch, King, Luhn, Spinrath ('11)

Stephen King @ What's Nu? GGI Florence:
https://indico.cern.ch/sessionDisplay.py?sessionId=98&confId=195985#20120625

Given this end game and part of the chess board:



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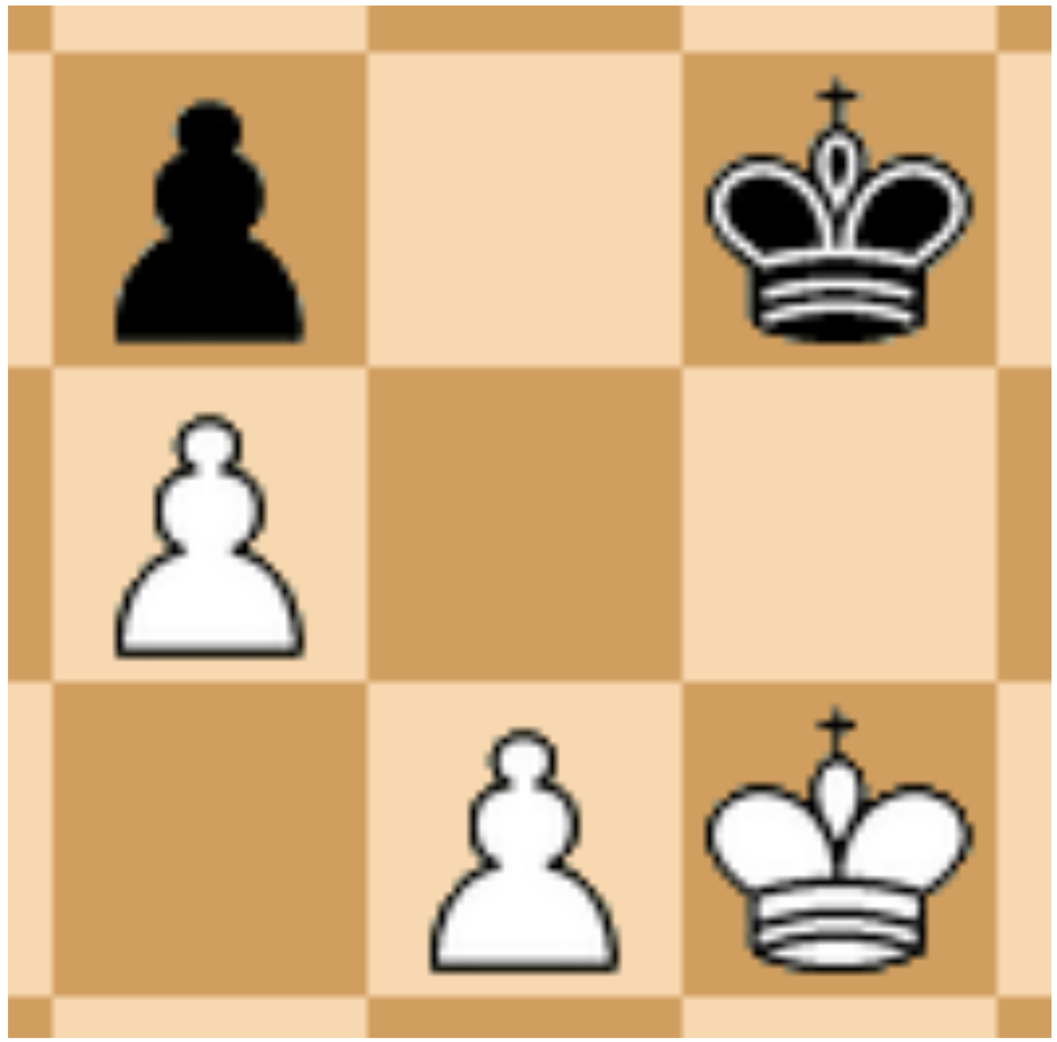

Deduce the rules of chess!!!

CP

$$\nu_\mu \to \nu_e \qquad \Longleftrightarrow \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

T $\Updownarrow$ CPT across diagonals $\Updownarrow$ T

$$\nu_e \to \nu_\mu \qquad \Longleftrightarrow \qquad \bar{\nu}_e \to \bar{\nu}_\mu$$

CP

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

Vacuum LBL: $\nu_\mu \longrightarrow \nu_e$

$$P_{\mu \rightarrow e} \approx | \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} |^2$$

$\Delta_{ij} = \delta m^2_{ij} L / 4E$

$\updownarrow$ CP violation !!!

where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \ \sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \ \sin\Delta_{21}$

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and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \;\sin\Delta_{21}$

$$P_{\mu\rightarrow e} \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}}\cos(\Delta_{32} \pm \delta) + P_{sol}$$

$\updownarrow$

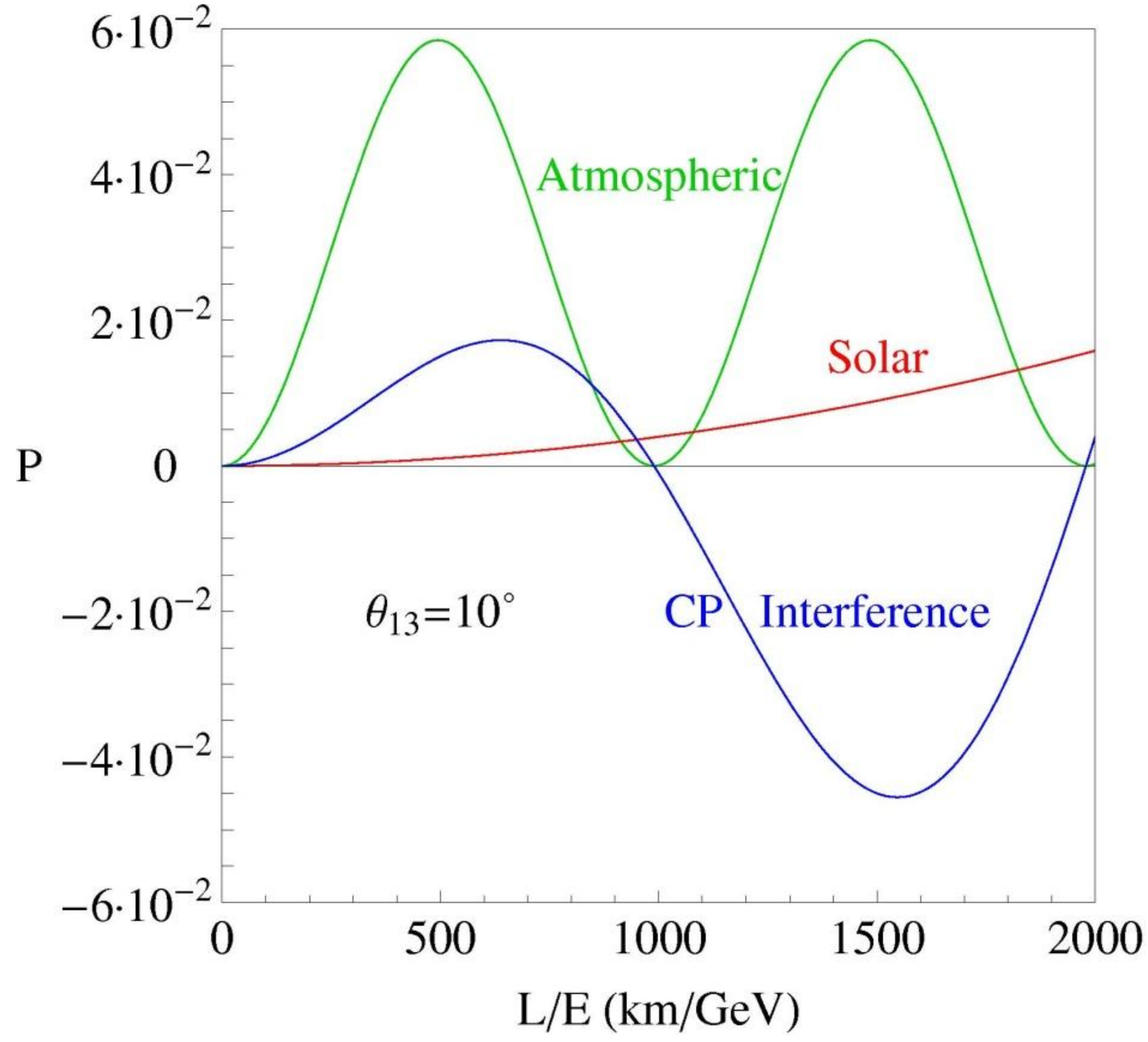
only CPV

$$\cos(\Delta_{32} \pm \delta) = \cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta$$

$$\Delta P_{cp} = 2 \sin\delta \sin 2\theta_{13} \;\sin 2\theta_{23} \sin 2\theta_{12} \cos\theta_{13} \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32}$$

Large Theta_13

vacuum:



from EFM

$\nu_\mu \rightarrow \nu_e$

In Matter:

$$P_{\mu\rightarrow e} \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\,|^2$$

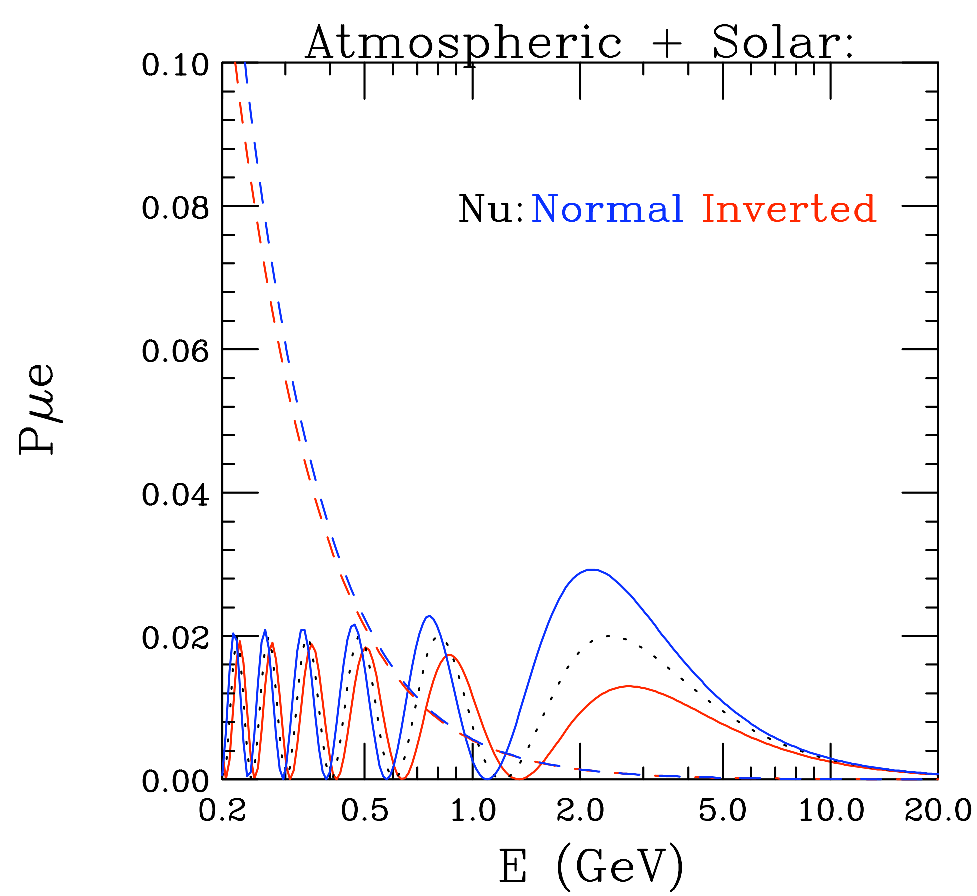
where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\,\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\,\Delta_{31}$

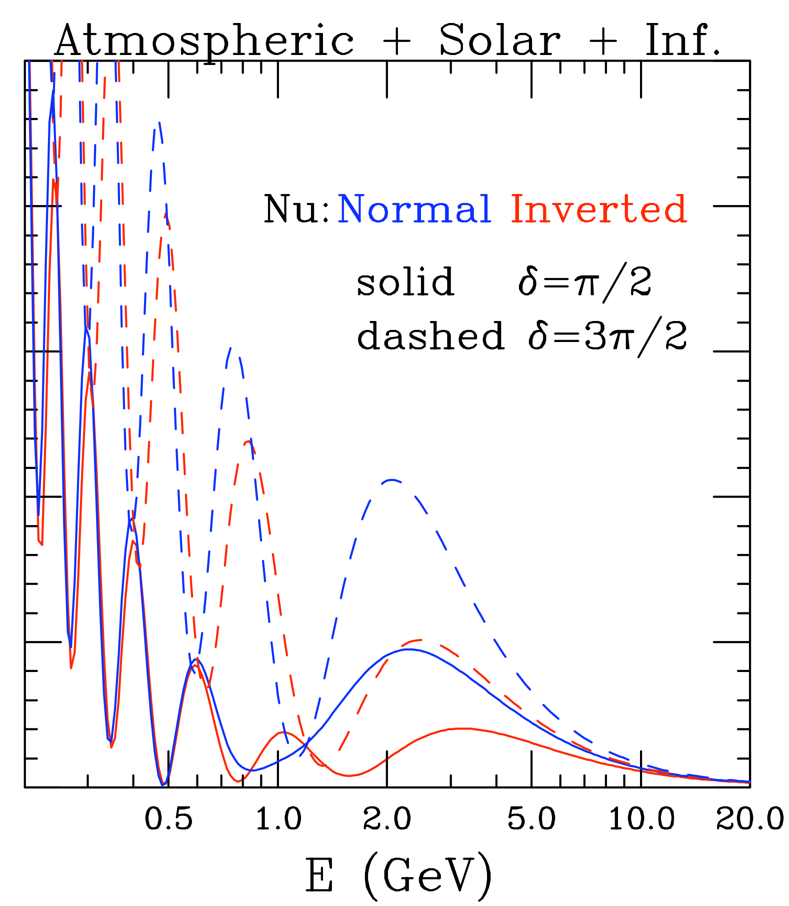
and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\,\frac{\sin(aL)}{(aL)}\,\Delta_{21}$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$

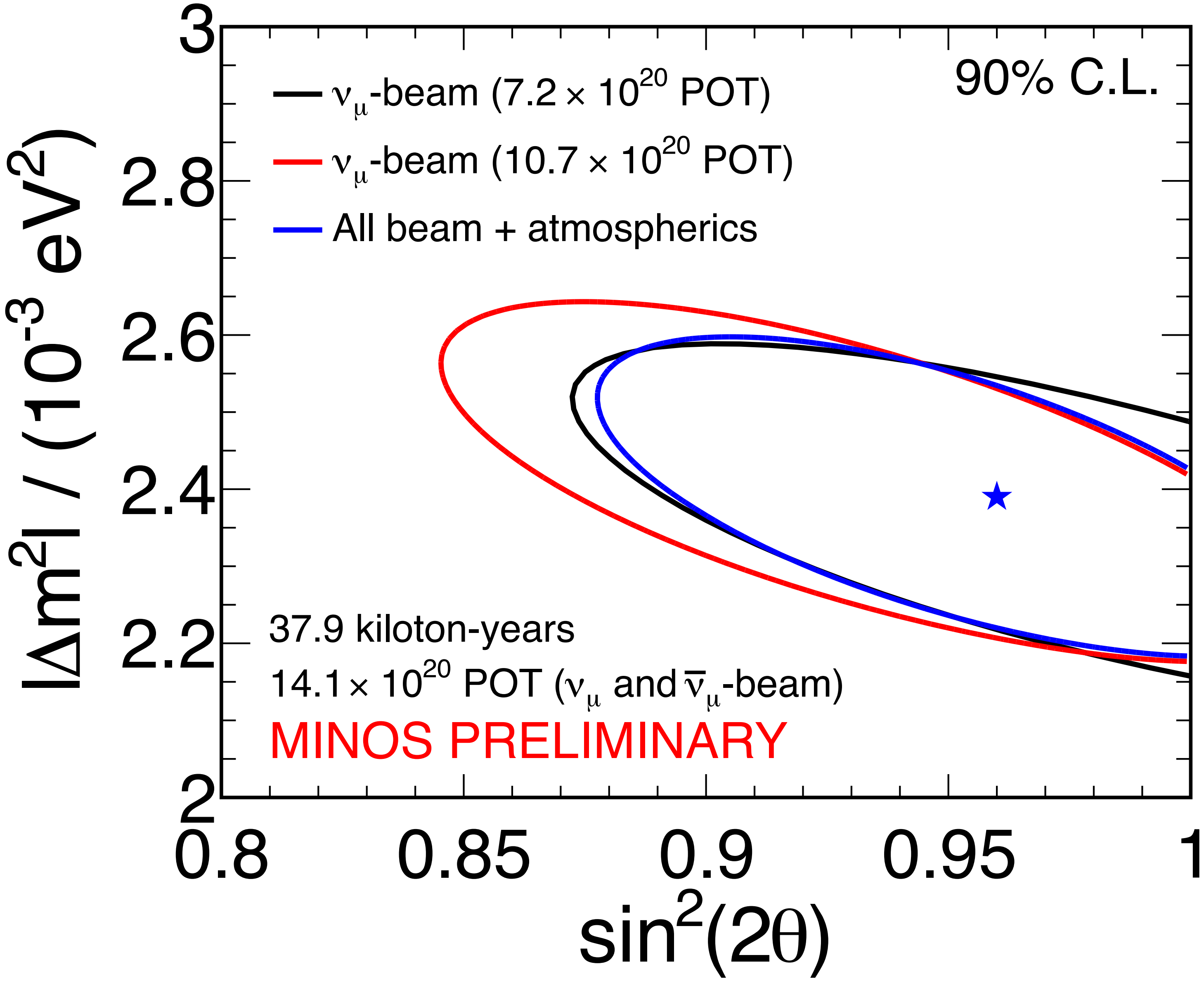




Non-Maximal Theta_23

Contours

Adding in the extra data and the atmospherics



New MINOS neutrino oscillation parameters

$$\Delta m^2 = 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

$$\sin^2(2\theta) = 0.96^{+0.04}_{-0.04}$$

$$\sin^2(2\theta) > 0.90 \text{ at } 90\% \text{ C.L.}$$

New

4*0.4*0.6=0.96

23 MINOS @ Neutrino 2012 by Ryan Nichol

$\boldsymbol{\nu_\mu \longrightarrow \nu_e}$ and $\boldsymbol{\bar\nu_\mu \longrightarrow \bar\nu_e}$

At Vac. Osc. Max. ($\Delta_{31} = \frac{\pi}{2}$)

$$P(\nu_\mu \to \nu_e) + P(\bar\nu_\mu \to \bar\nu_e) \approx 2\sin^2\theta_{23}\sin^2 2\theta_{13} \quad + \quad \mathcal{O}[(aL)\sin\delta]$$

directly comparable to reactor

$$1 - P(\bar\nu_e \to \bar\nu_e) = \sin^2 2\theta_{13}$$

$\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

At Vac. Osc. Max. $(\Delta_{31} = \frac{\pi}{2})$

$$P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 2\sin^2\theta_{23}\sin^2 2\theta_{13} \quad + \quad \mathcal{O}[(aL)\sin\delta]$$

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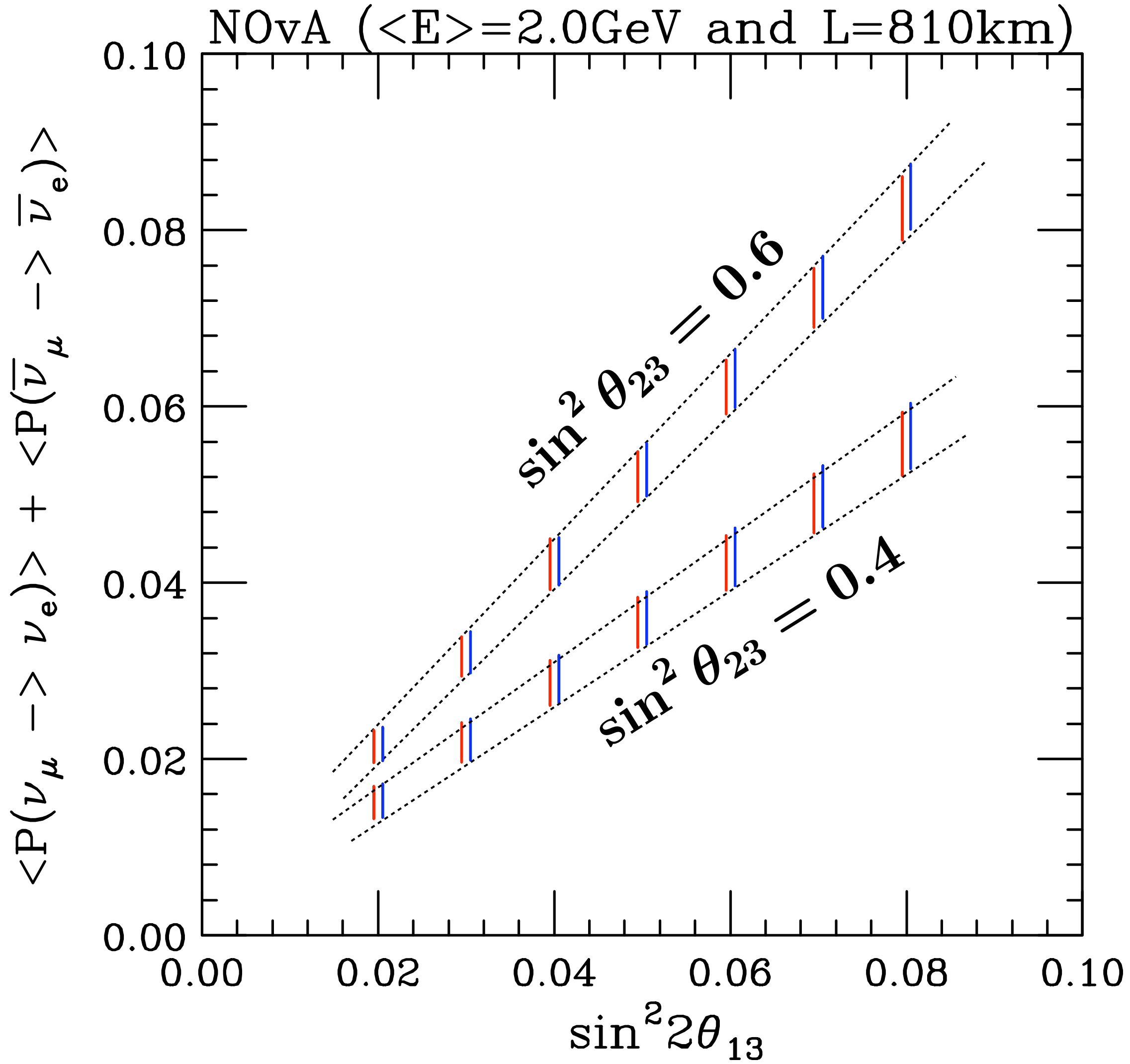
NOvA



For $\sin^2 2\theta_{23} = 0.96$
thus $\sin^2\theta_{23} = 0.4$ or 0.6

(4*0.4*0.6=0.96)

$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

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$$P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 2\sin^2\theta_{23}\sin^2 2\theta_{13} \quad + \quad \mathcal{O}[(aL)\sin\delta]$$

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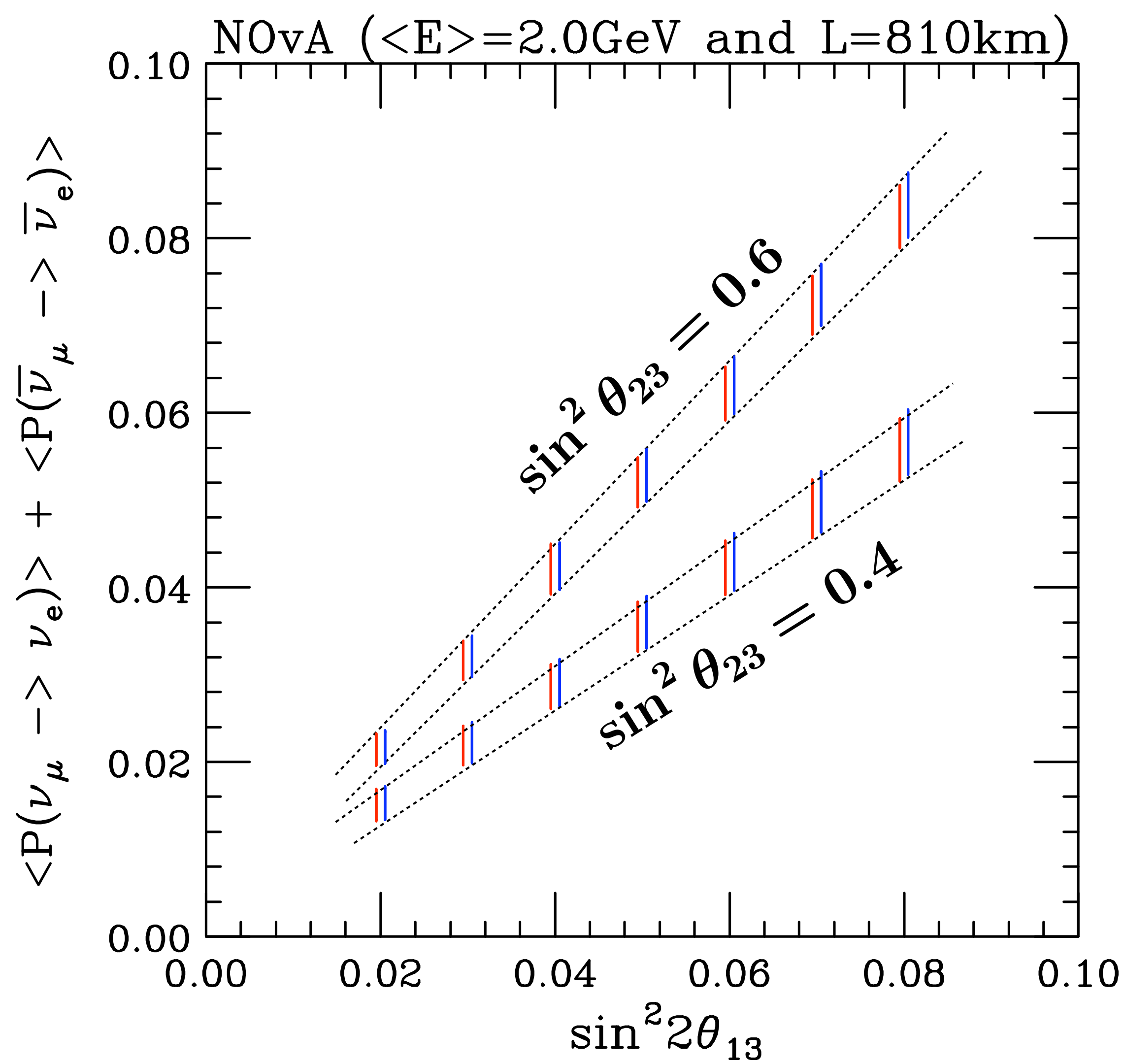
NOvA



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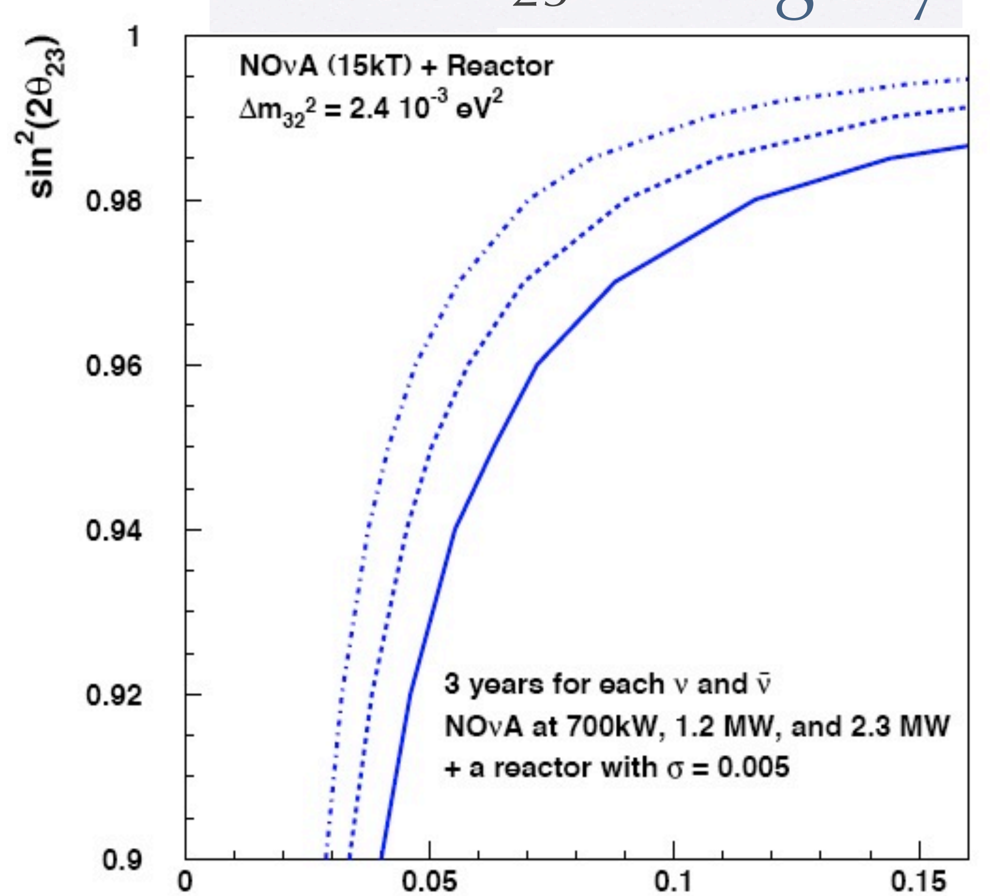
(4*0.4*0.6=0.96)

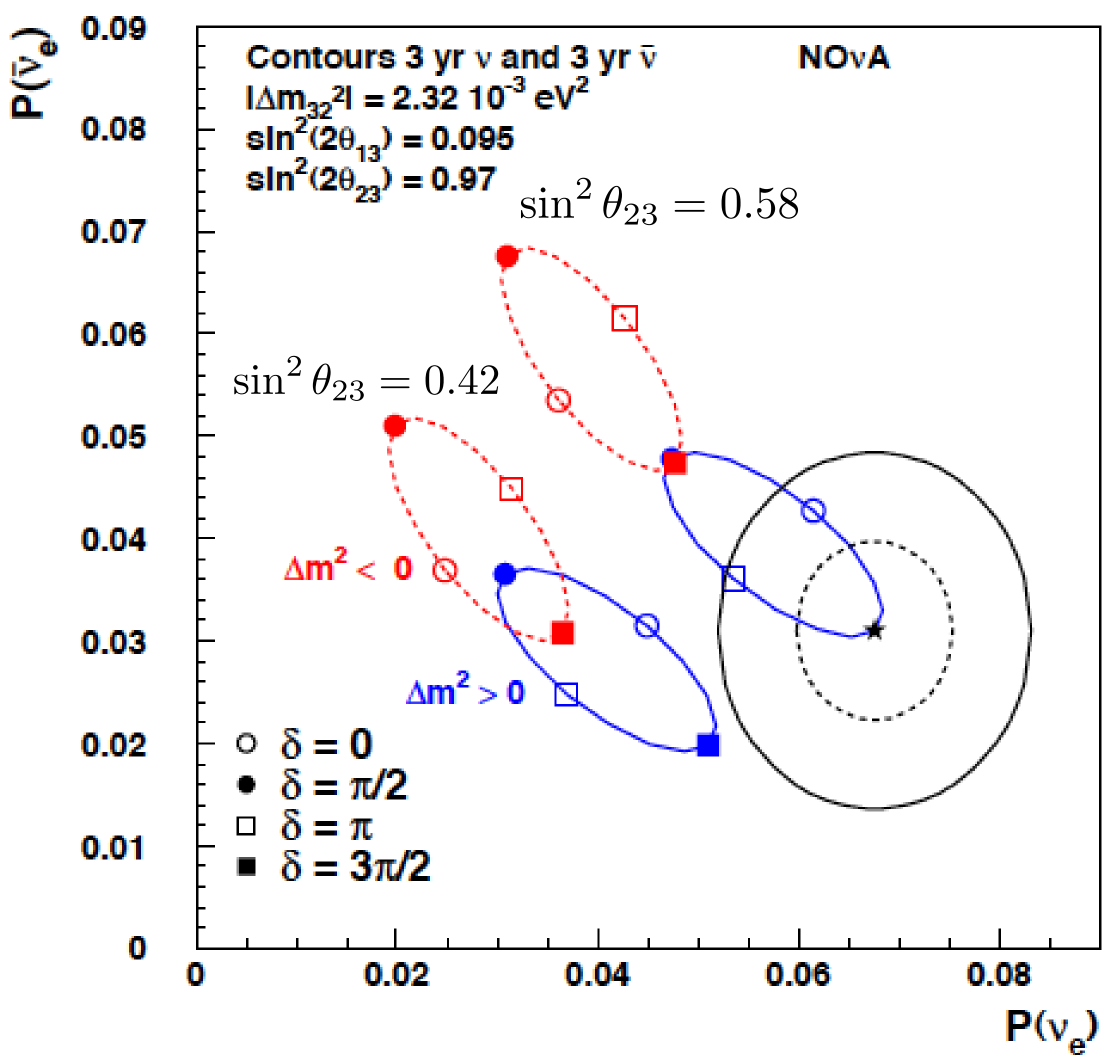
95% CL Resolution of the θ_{23} ambiguity



T2K could also do this, if they ran $\bar{\nu}_\mu$

3 Years Each ν and $\bar{\nu}$

1 and 2 σ Contours for Starred Point

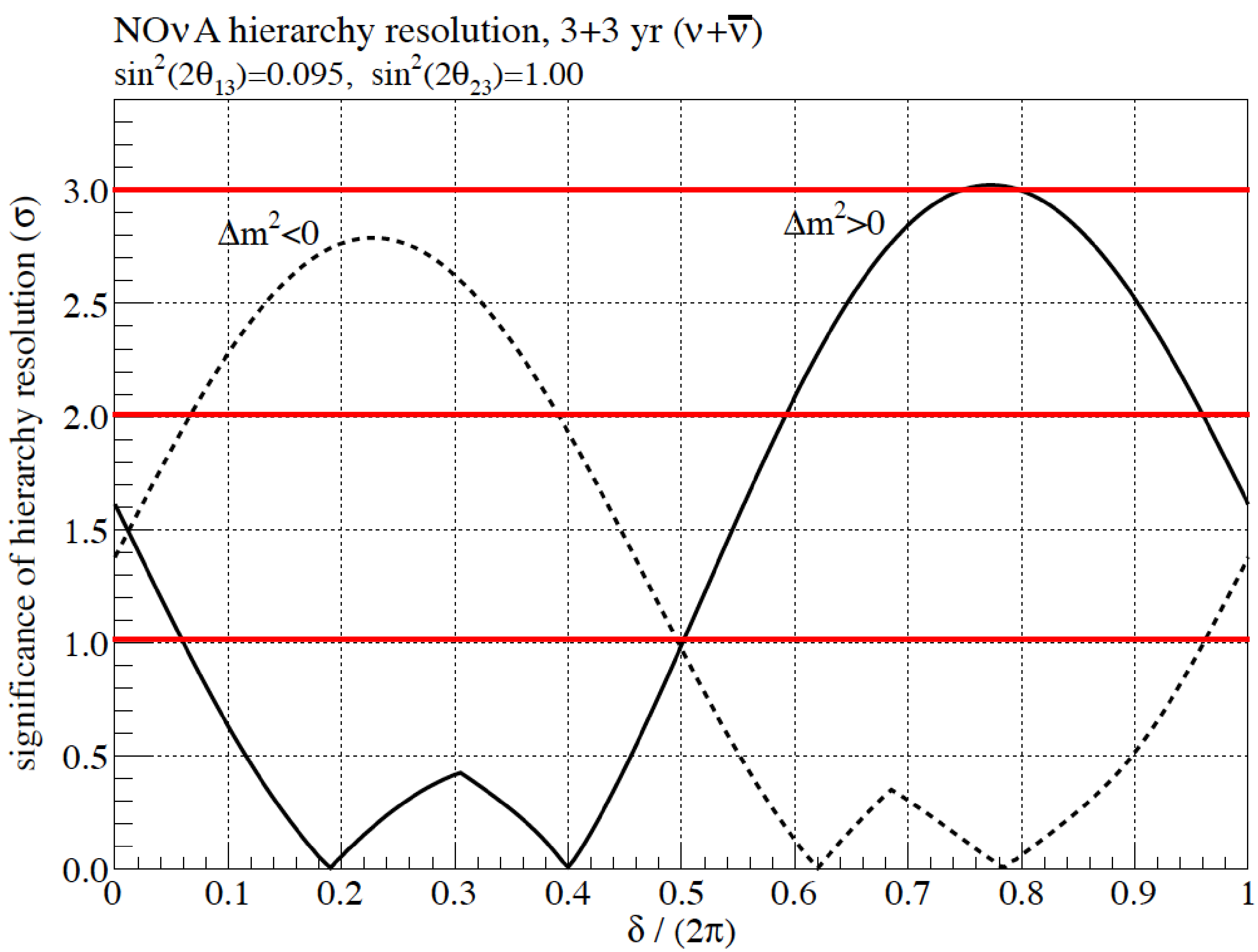


NOvA does about as well with 3 years of each. In addition, this plan rules out no CP violation at a greater significance and it provides a constraint on the model and on the measurements.

$$4 * 0.42 * 0.58 = 0.97$$

Gary Feldman LBNE Reconfiguration Workshop 25 April 2012 9

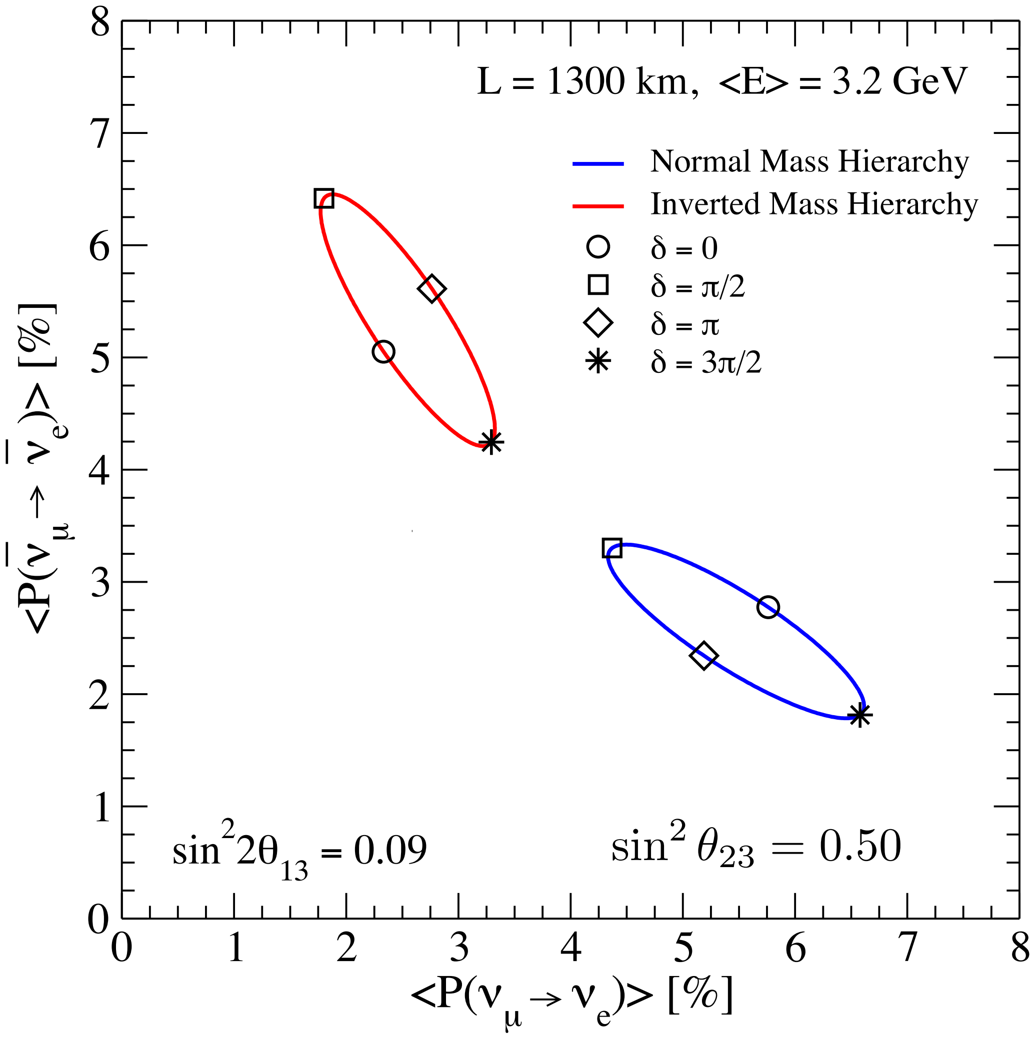
Significance of the Mass Ordering Resolution for NOνA (Plan A)



Rate only
10% systematic
on the background.

Mass Hierarchy : Full LBNE

same L/E as NOvA



Mass Hierarchy : Full LBNE

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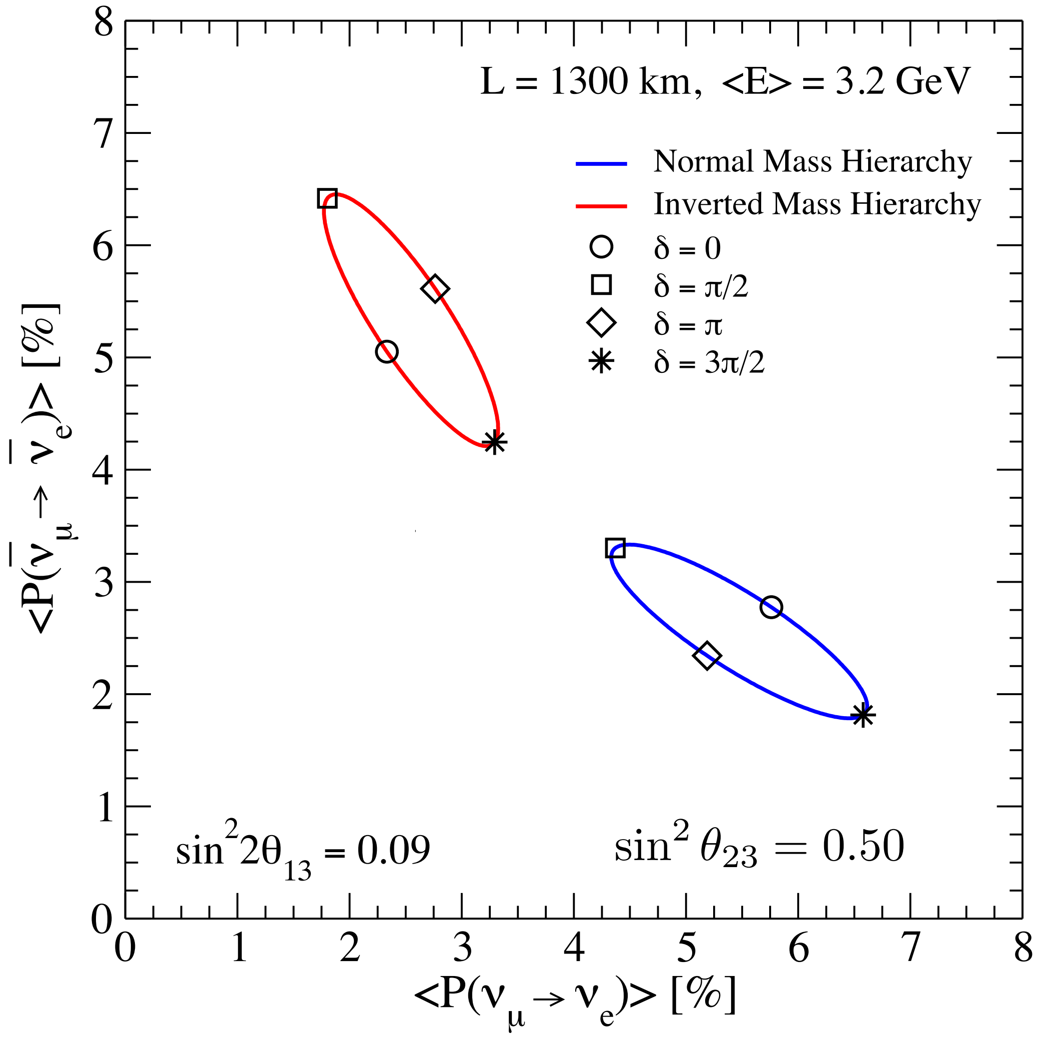
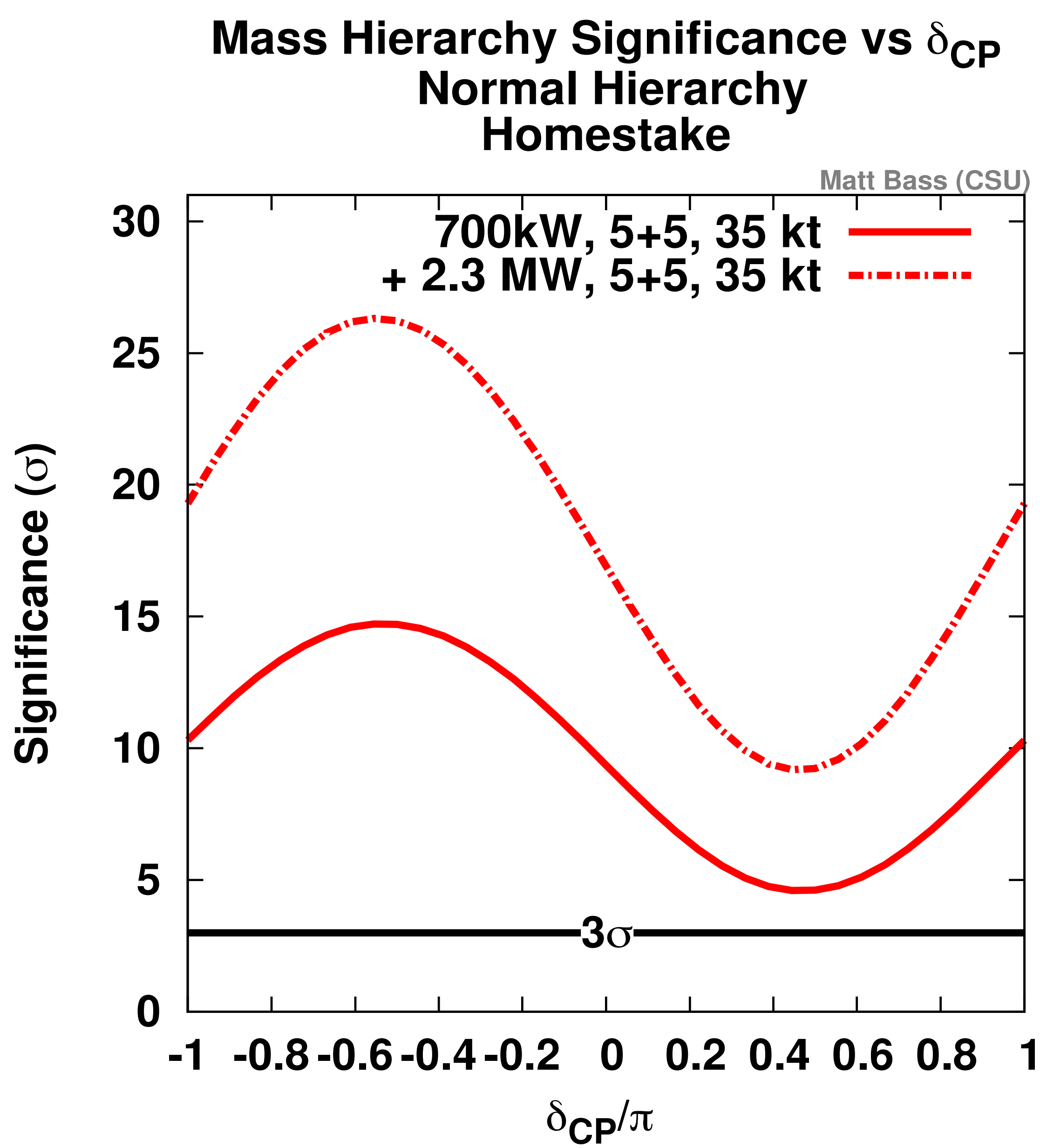
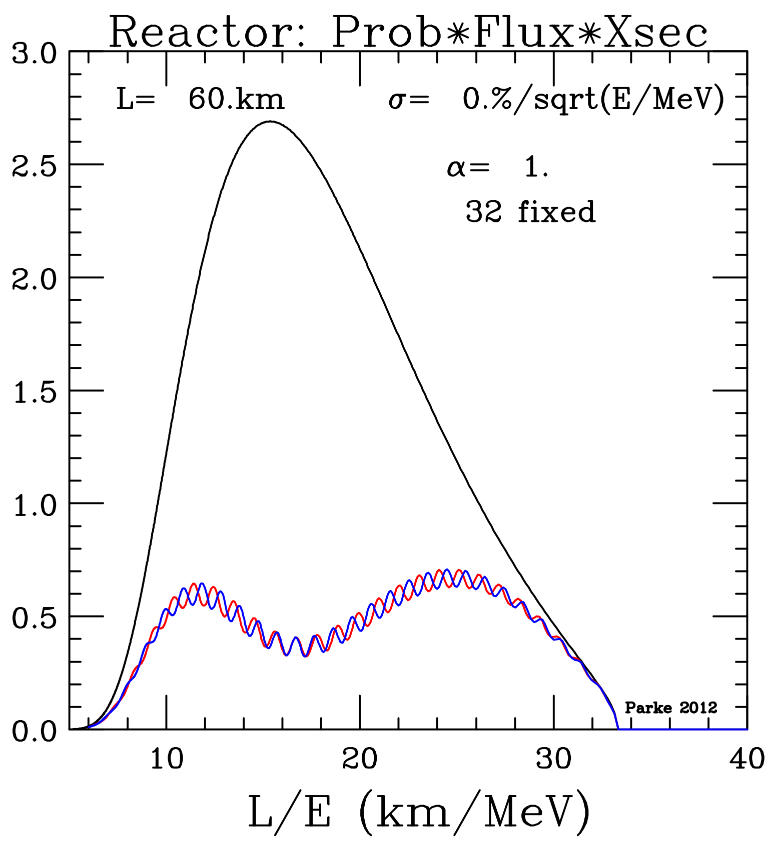


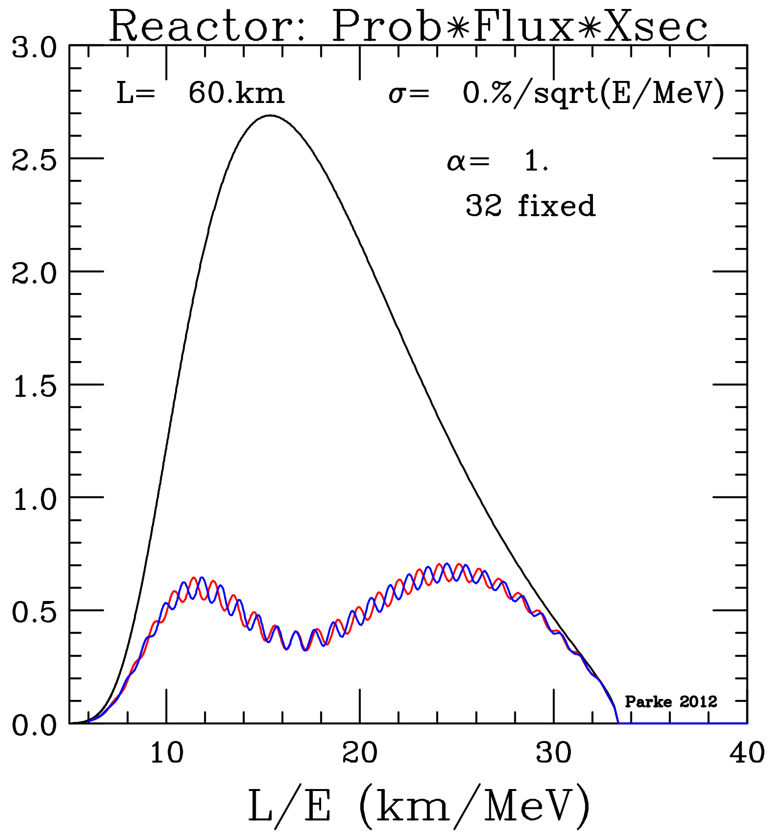


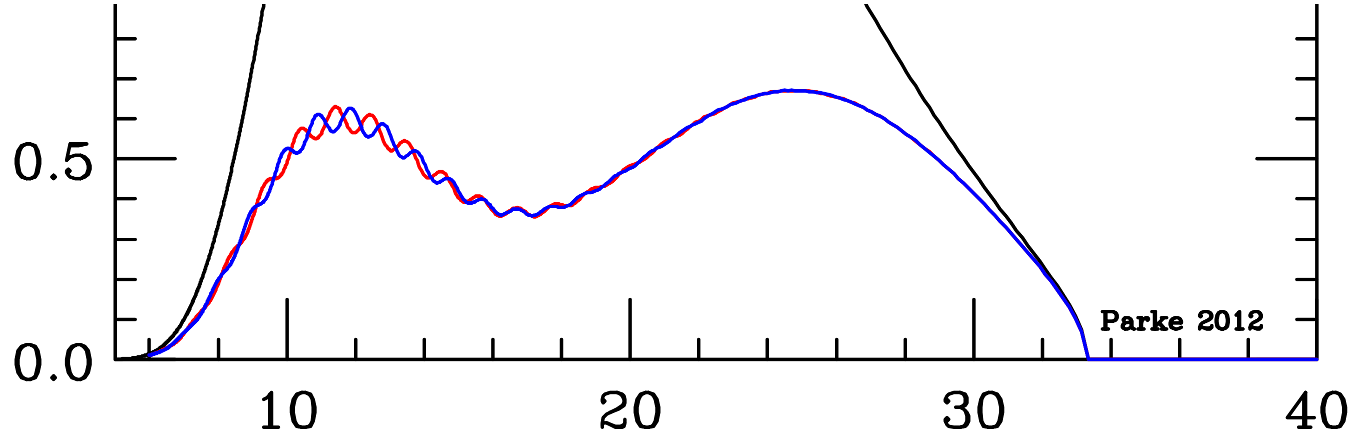
YKK will discuss phasing of LBNE

Reactors & the Mass Hierarchy



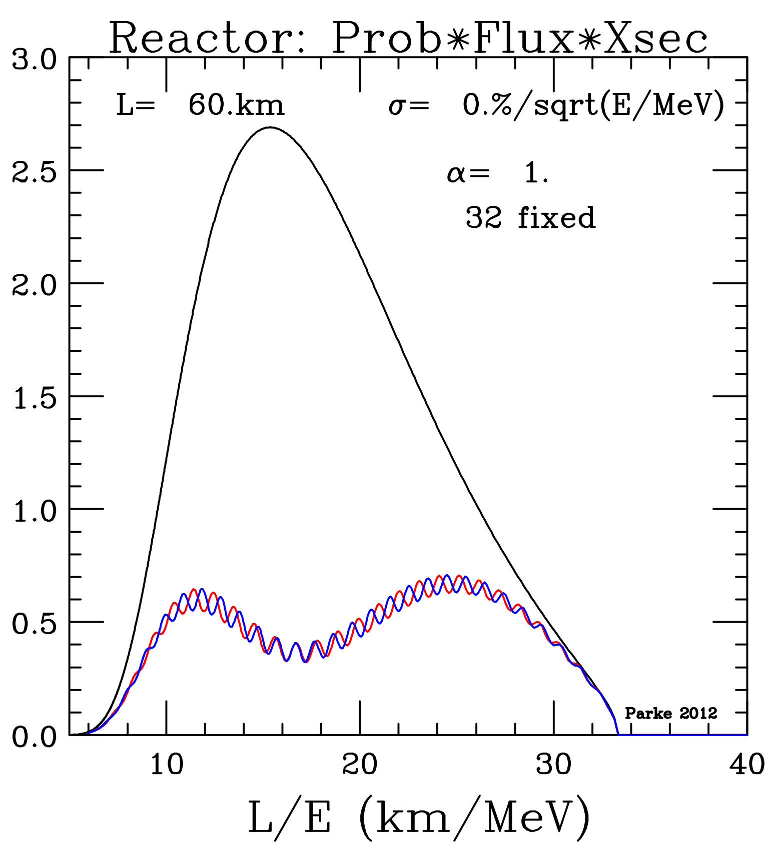
Reactors & the Mass Hierarchy

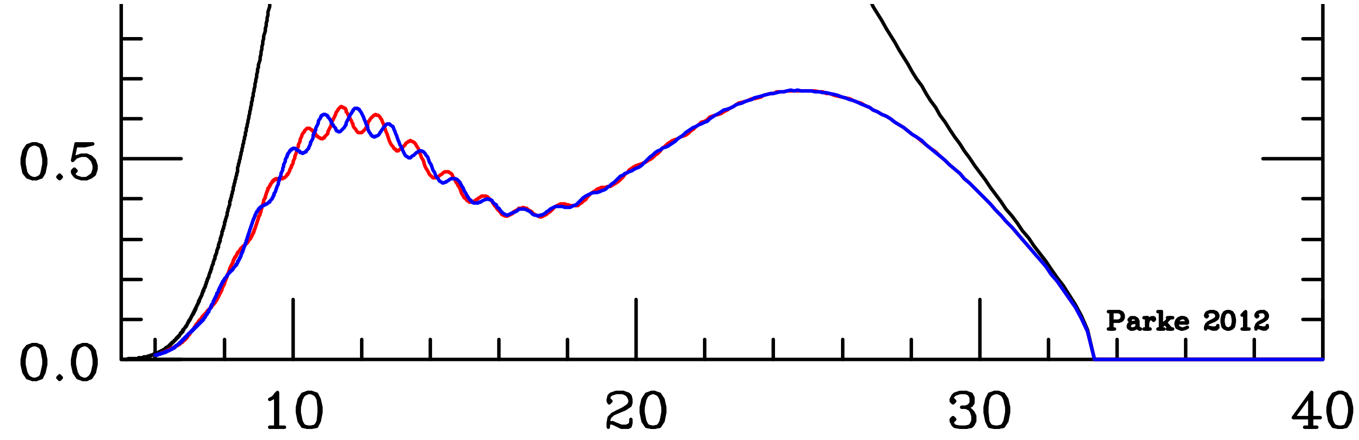




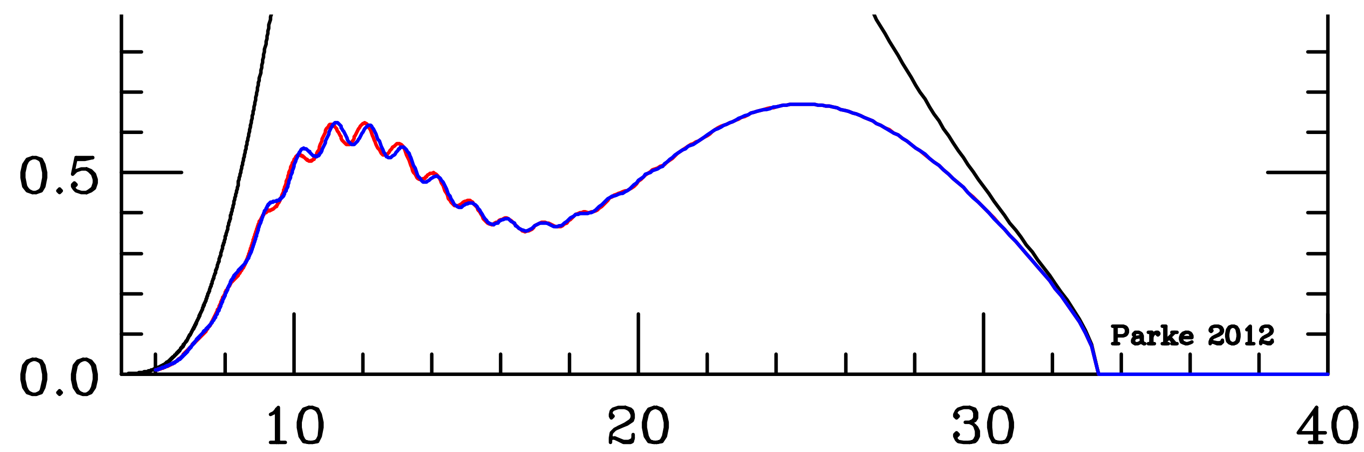
32 fixed

Reactors & the Mass Hierarchy



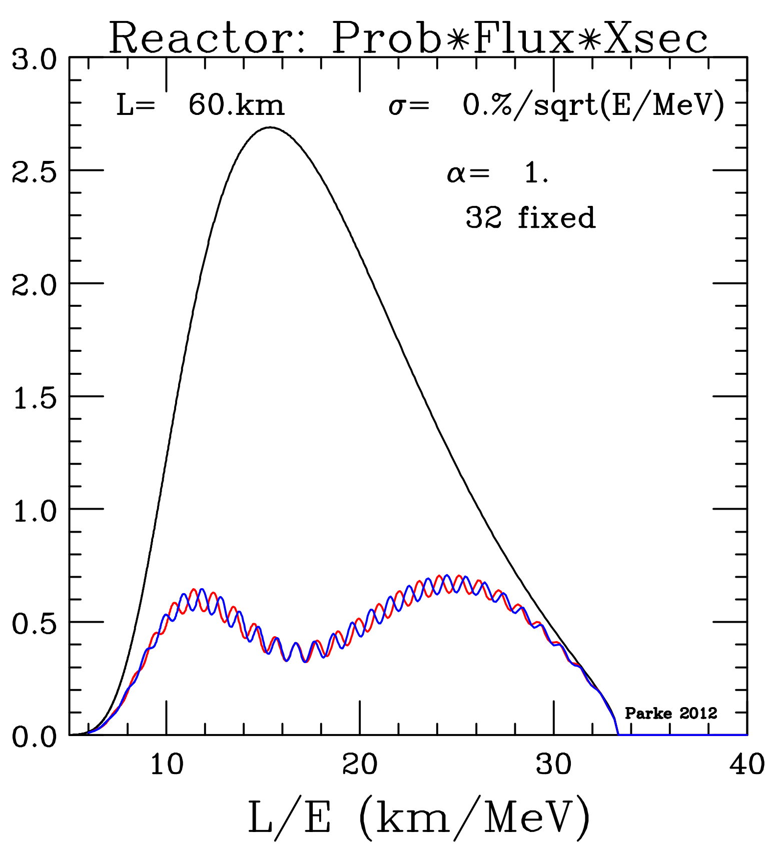


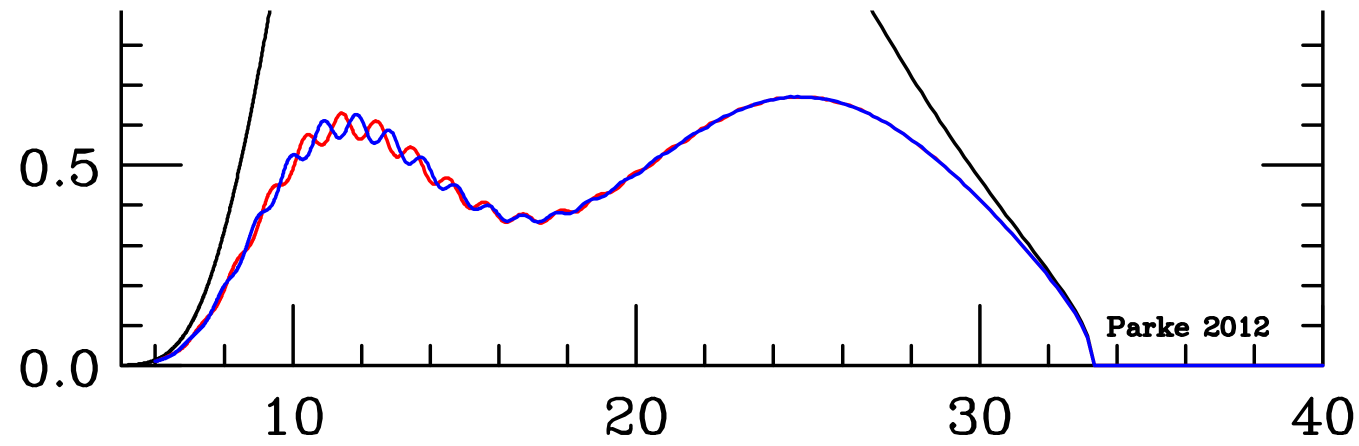
32 fixed



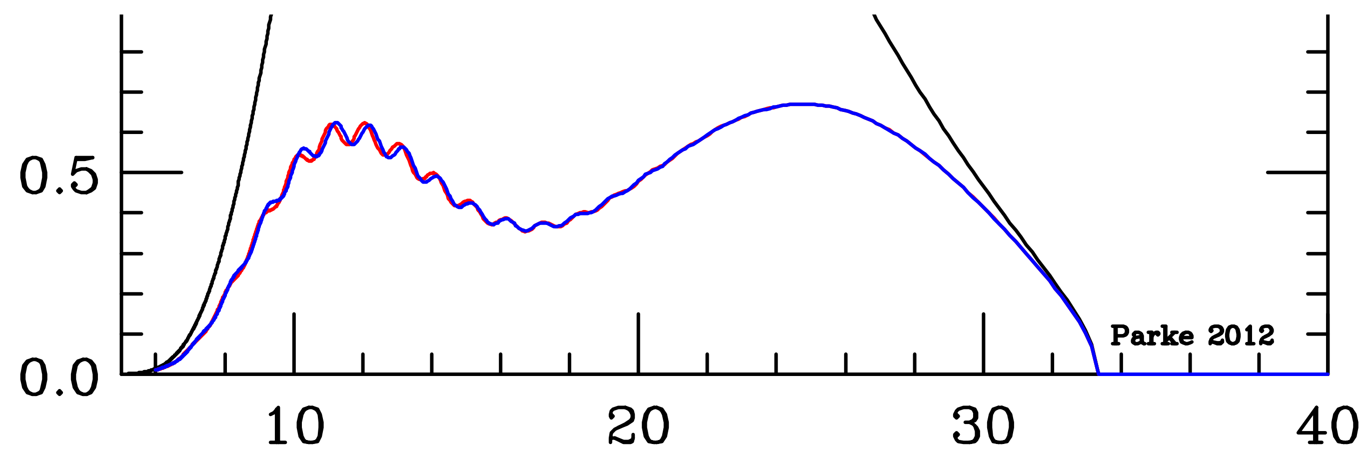
31 fixed

Reactors & the Mass Hierarchy

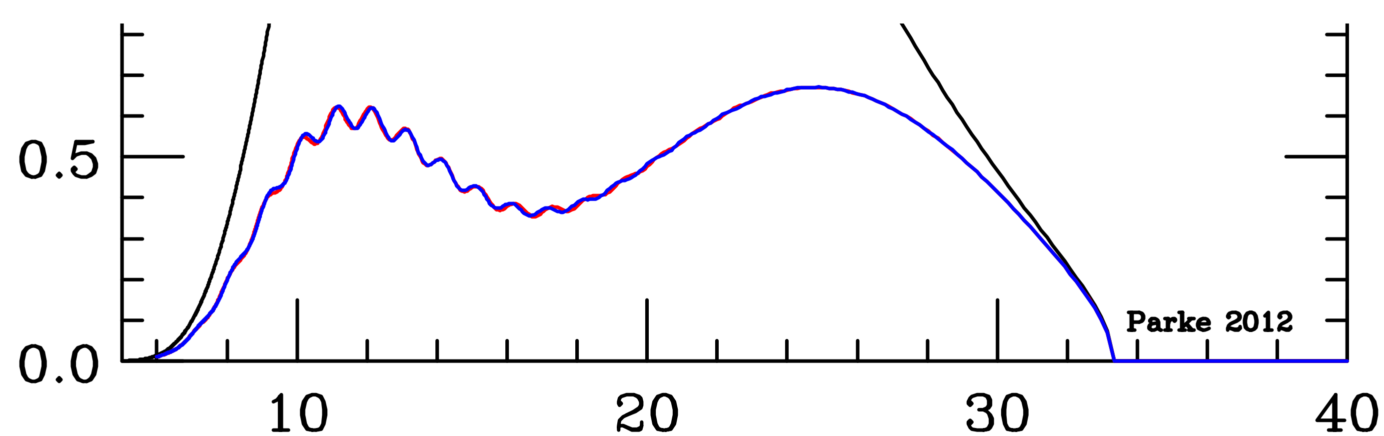




32 fixed

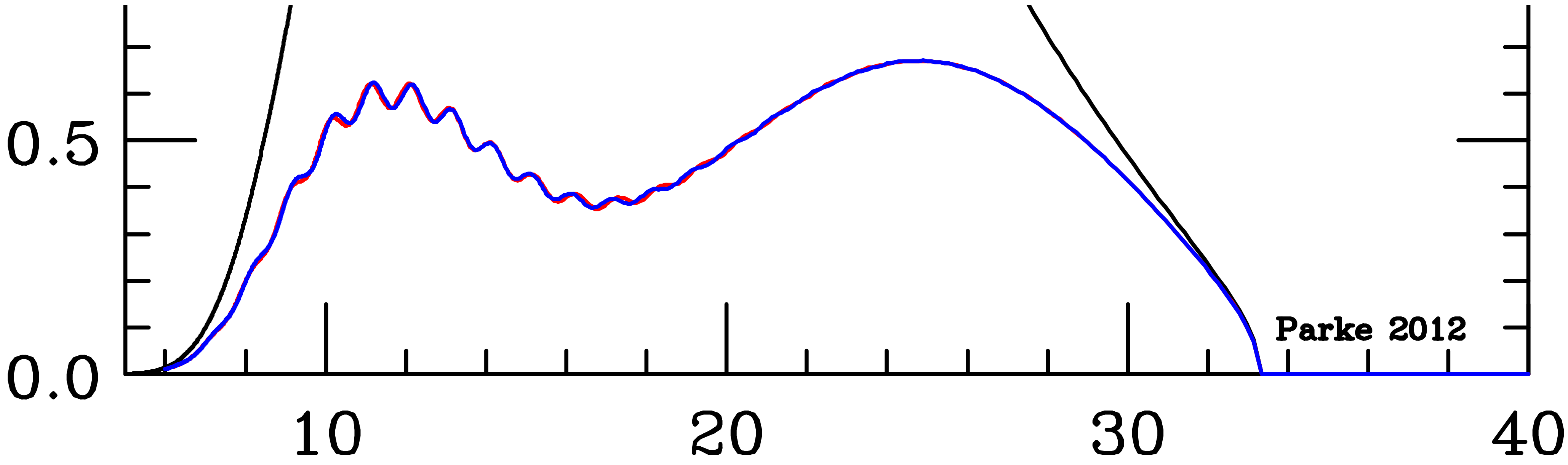


31 fixed

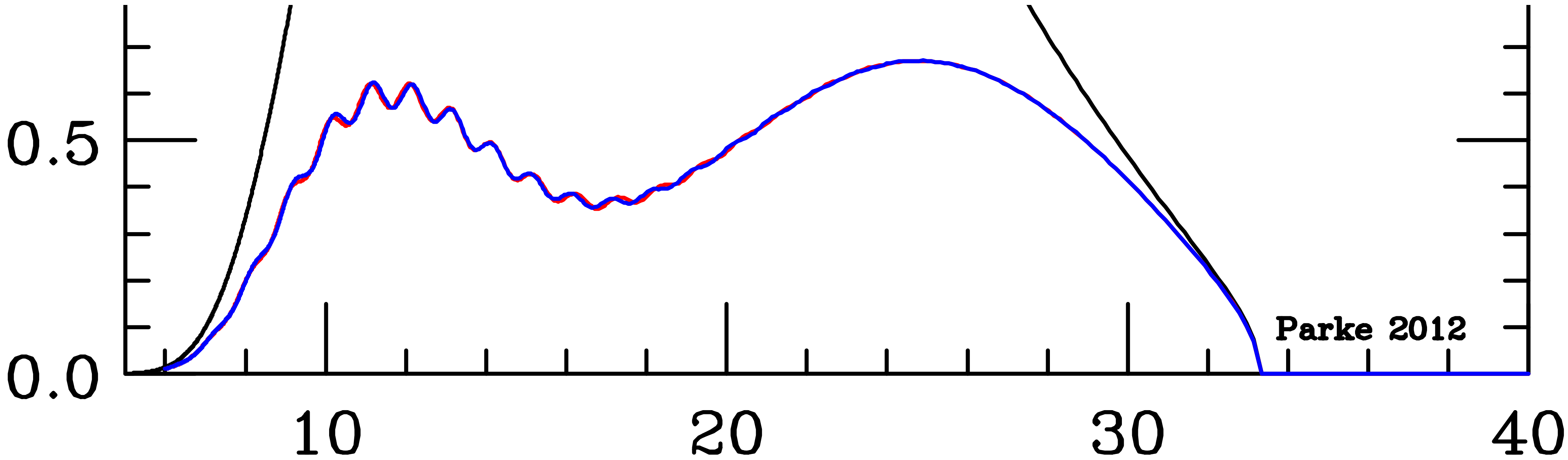


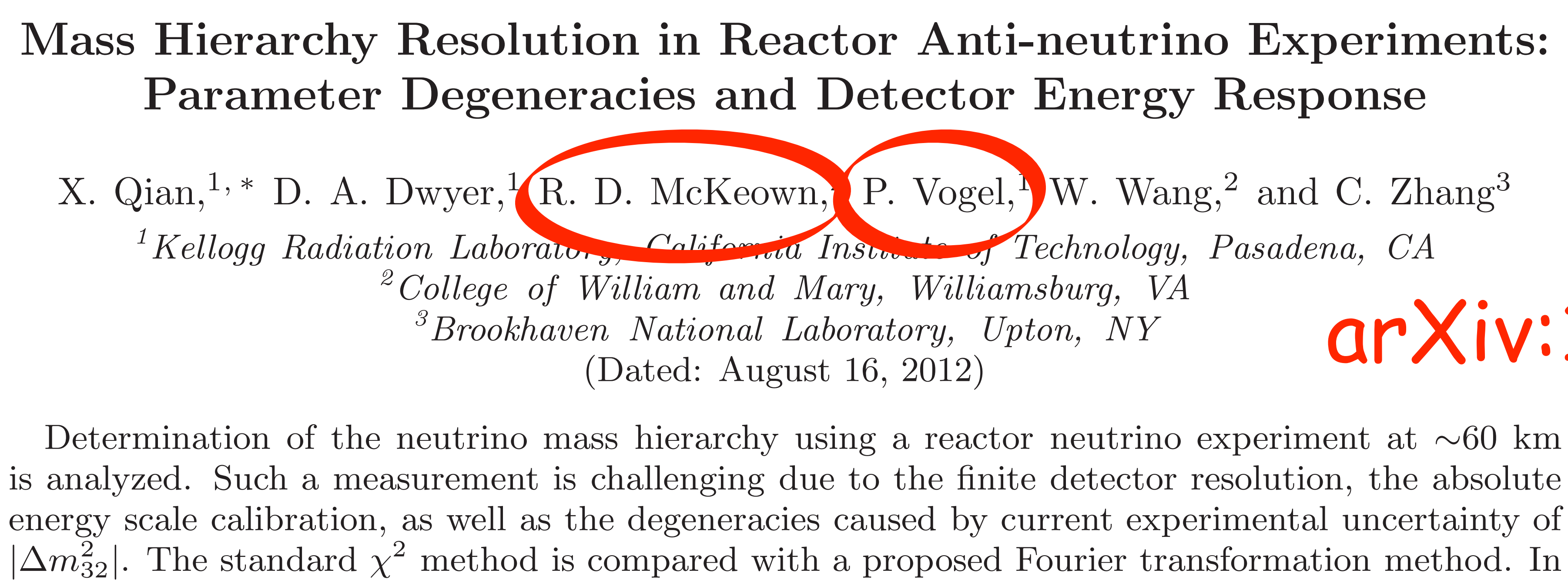
float within uncertainities

Reactors & the Mass Hierarchy (conti)



Reactors & the Mass Hierarchy (conti)




Mass Hierarchy Resolution in Reactor Anti-neutrino Experiments: Parameter Degeneracies and Detector Energy Response

X. Qian,[1,*] D. A. Dwyer,[1] R. D. McKeown,[1] P. Vogel,[1] W. Wang,[2] and C. Zhang[3]

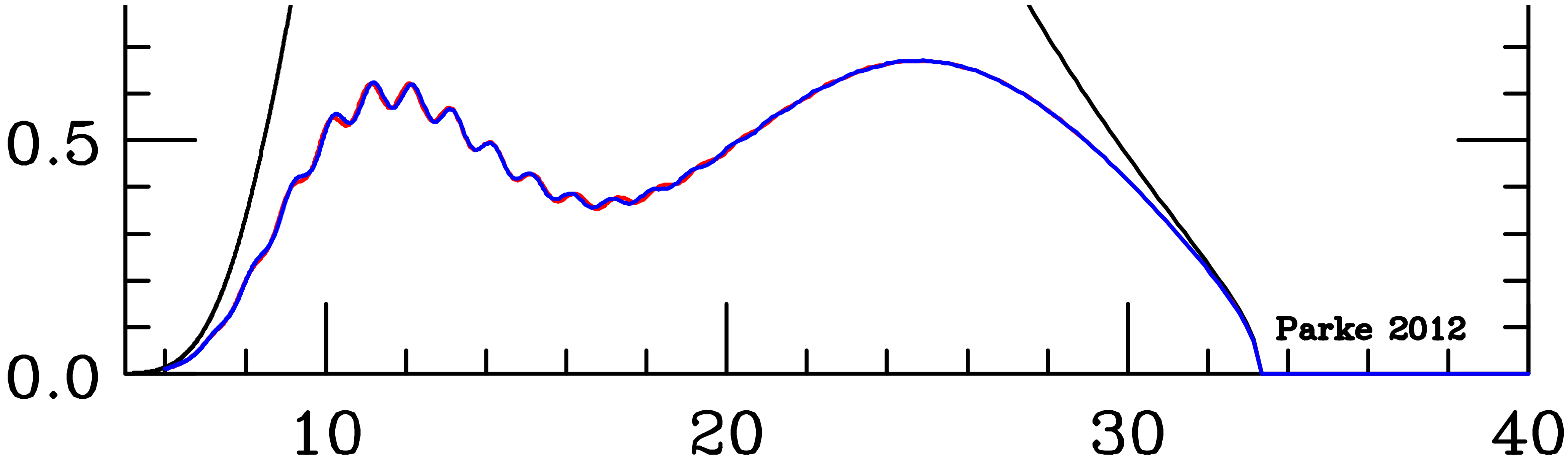
[1] *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA*
[2] *College of William and Mary, Williamsburg, VA*
[3] *Brookhaven National Laboratory, Upton, NY*

(Dated: August 16, 2012)

Determination of the neutrino mass hierarchy using a reactor neutrino experiment at ∼60 km is analyzed. Such a measurement is challenging due to the finite detector resolution, the absolute energy scale calibration, as well as the degeneracies caused by current experimental uncertainty of $|\Delta m^2_{32}|$. The standard χ^2 method is compared with a proposed Fourier transformation method. In

arXiv:1208.1551

Reactors & the Mass Hierarchy (conti)



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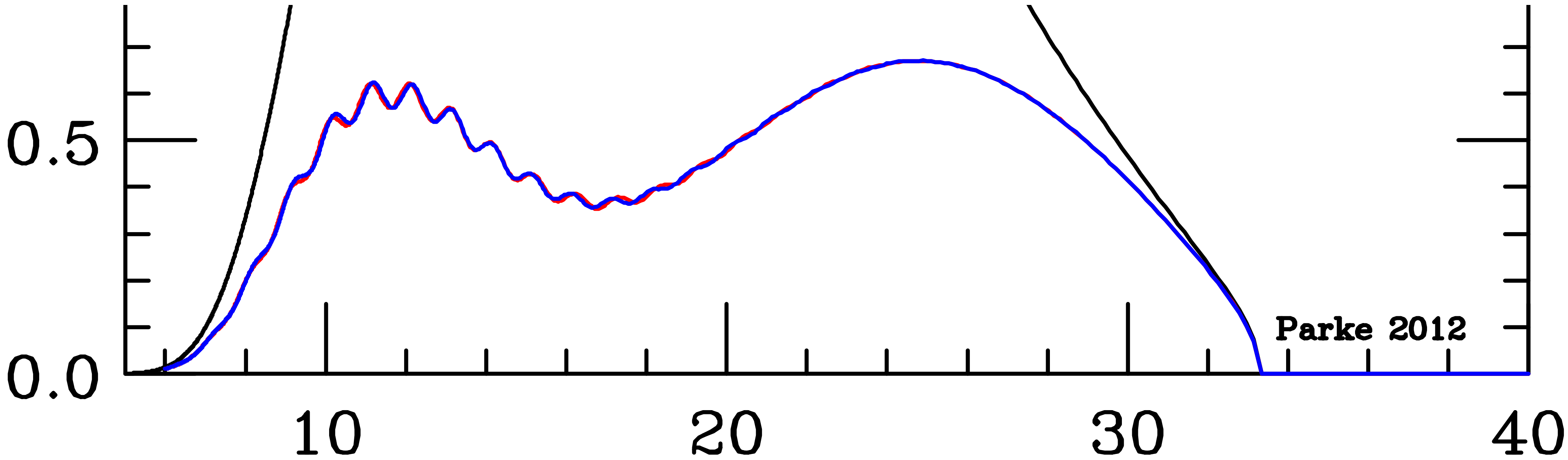
Reactors & the Mass Hierarchy (conti)



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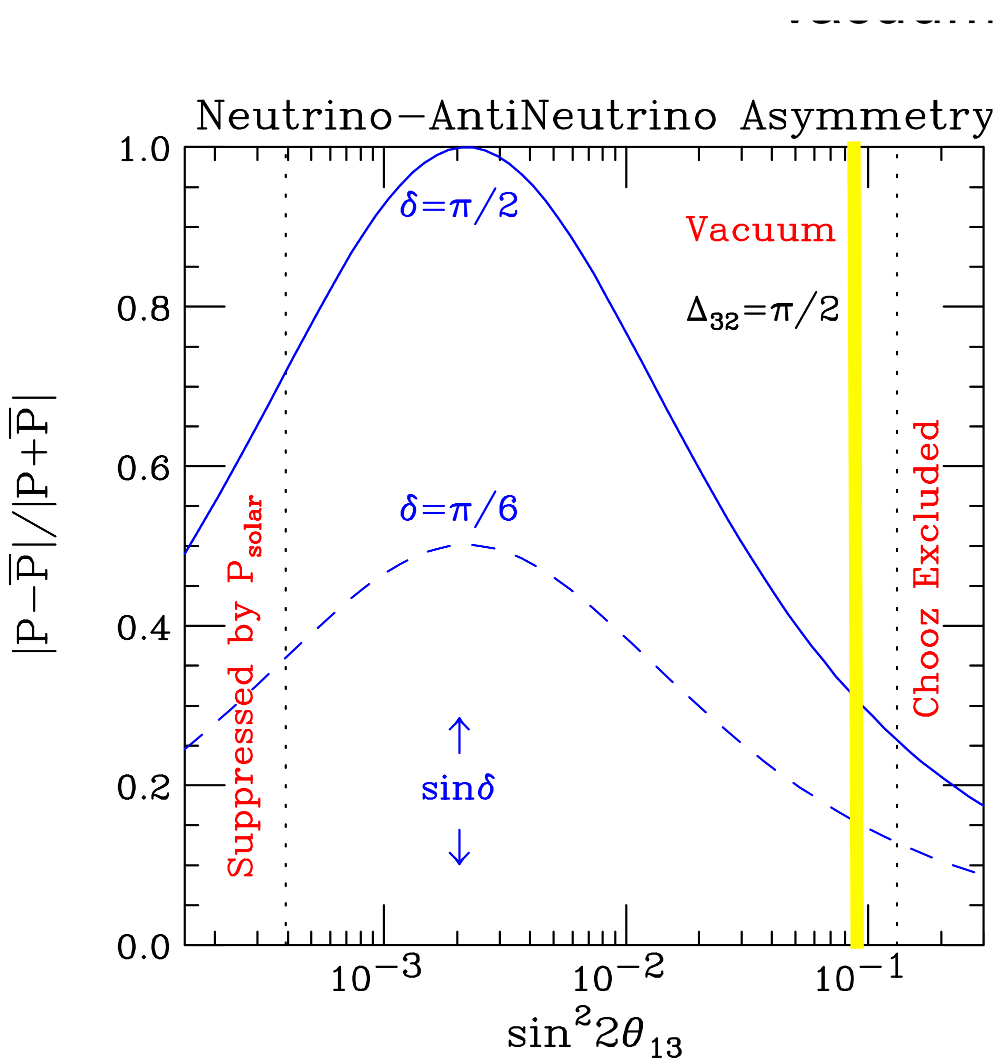
KamLAND achieved 1.9%

CPV & Neutrino Anti-Neutrino Asymmetry:

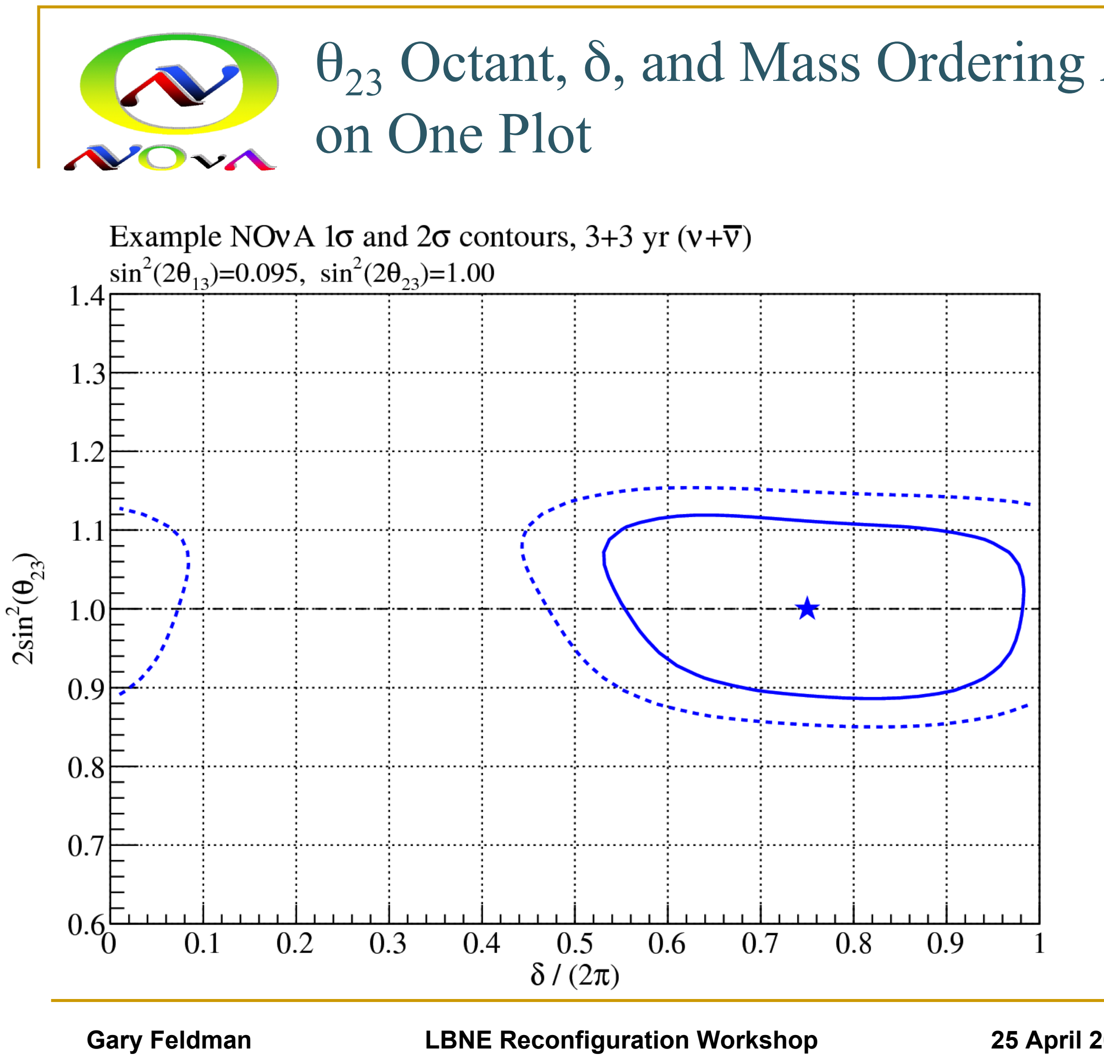
In Vacuum, at 1st Oscillation Maximum:

$$A_{vac} \equiv \frac{|P-\bar{P}|}{|P+\bar{P}|} \approx \frac{1}{11}\frac{\sin 2\theta_{13} \sin\delta}{(\sin^2 2\theta_{13}+0.002)} = 0.3 \ \sin\delta$$

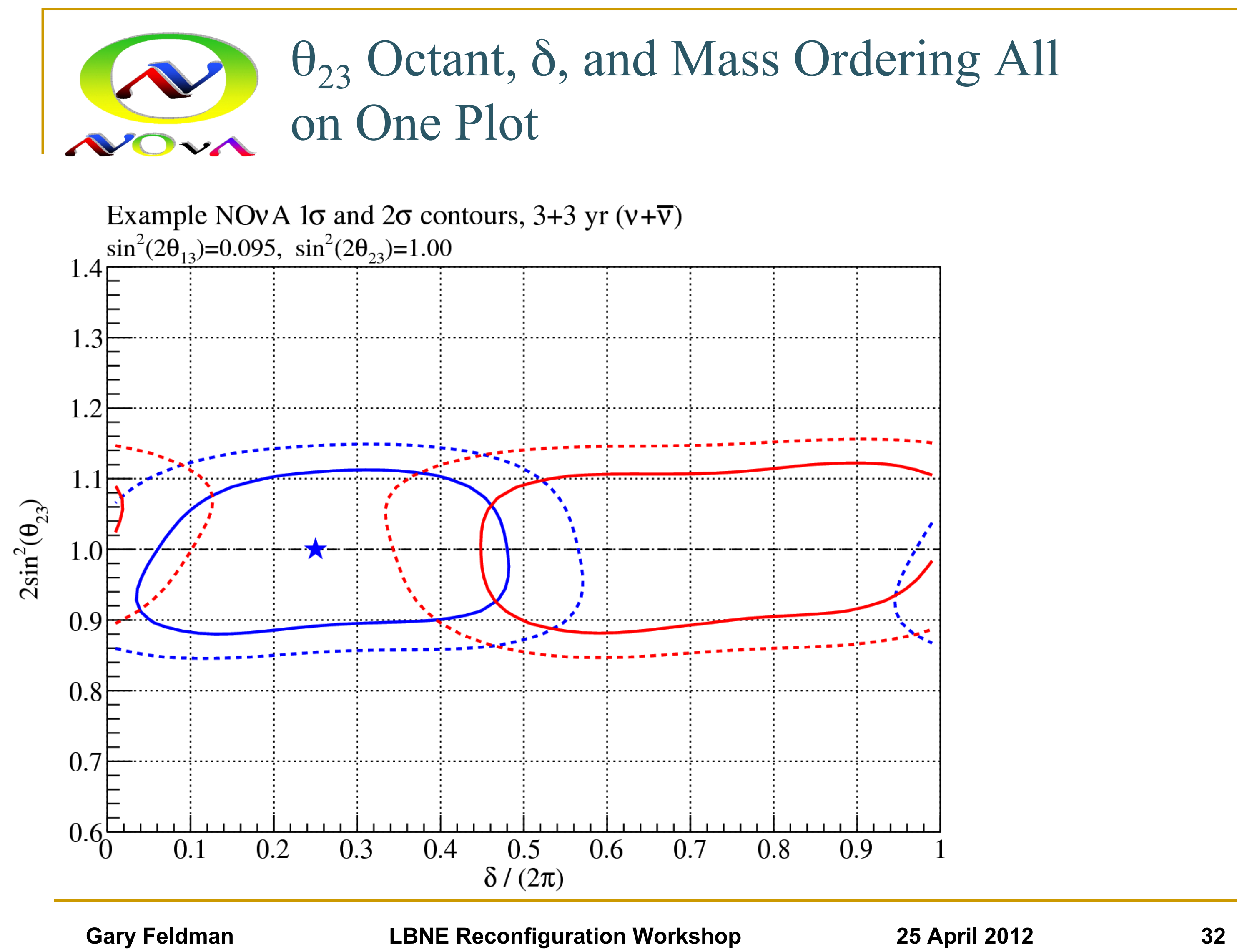
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ ranges is between $\frac{1}{2}$ and 2 times $P(\nu_\mu \to \nu_e)$!!!



CPV in NOvA:



θ23 Octant, δ, and Mass Ordering All on One Plot
Example NOνA 1σ and 2σ contours, 3+3 yr (ν+ν̄)
sin²(2θ13)=0.095, sin²(2θ23)=1.00
2sin²(θ23)
δ / (2π)
Gary Feldman
LBNE Reconfiguration Workshop
25 April 20



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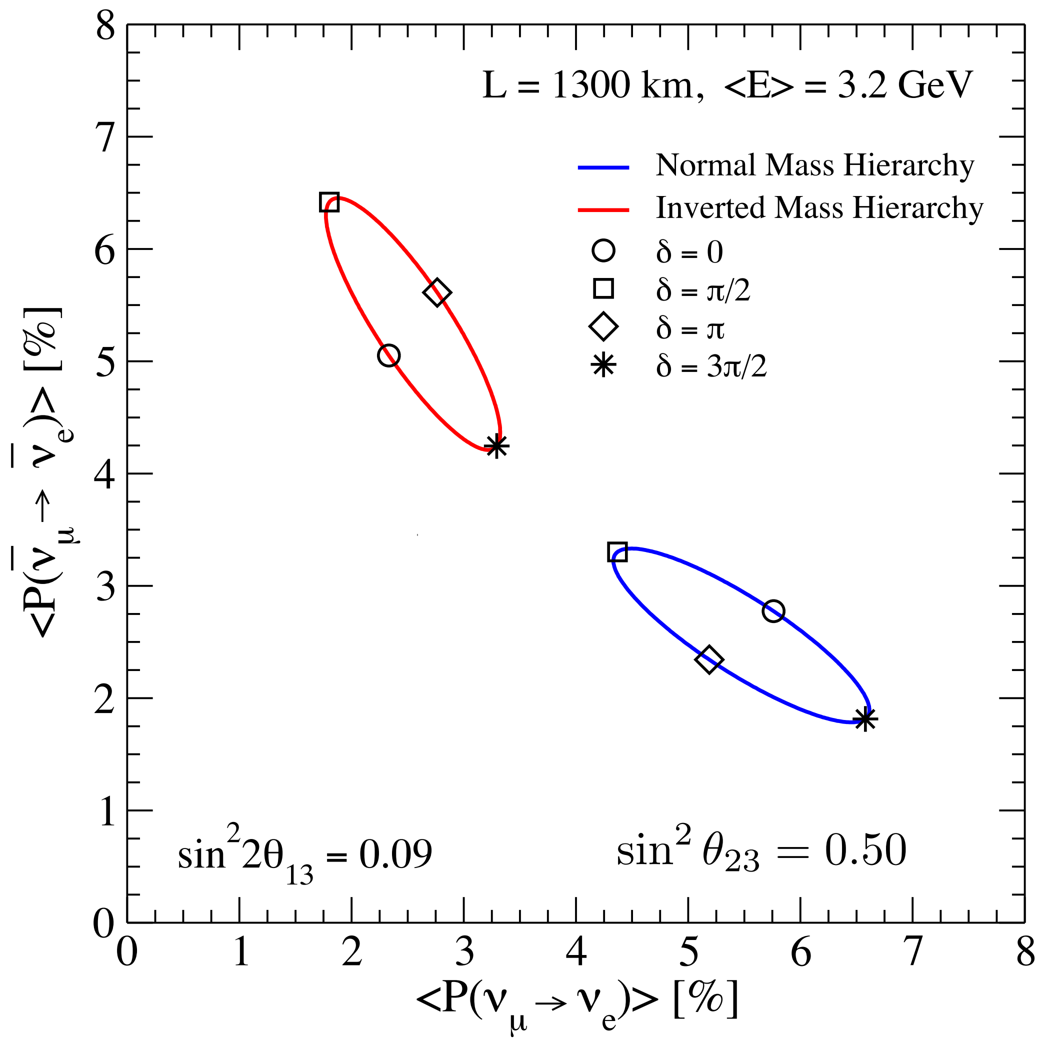
δ / (2π)
Gary Feldman
LBNE Reconfiguration Workshop
25 April 2012
32

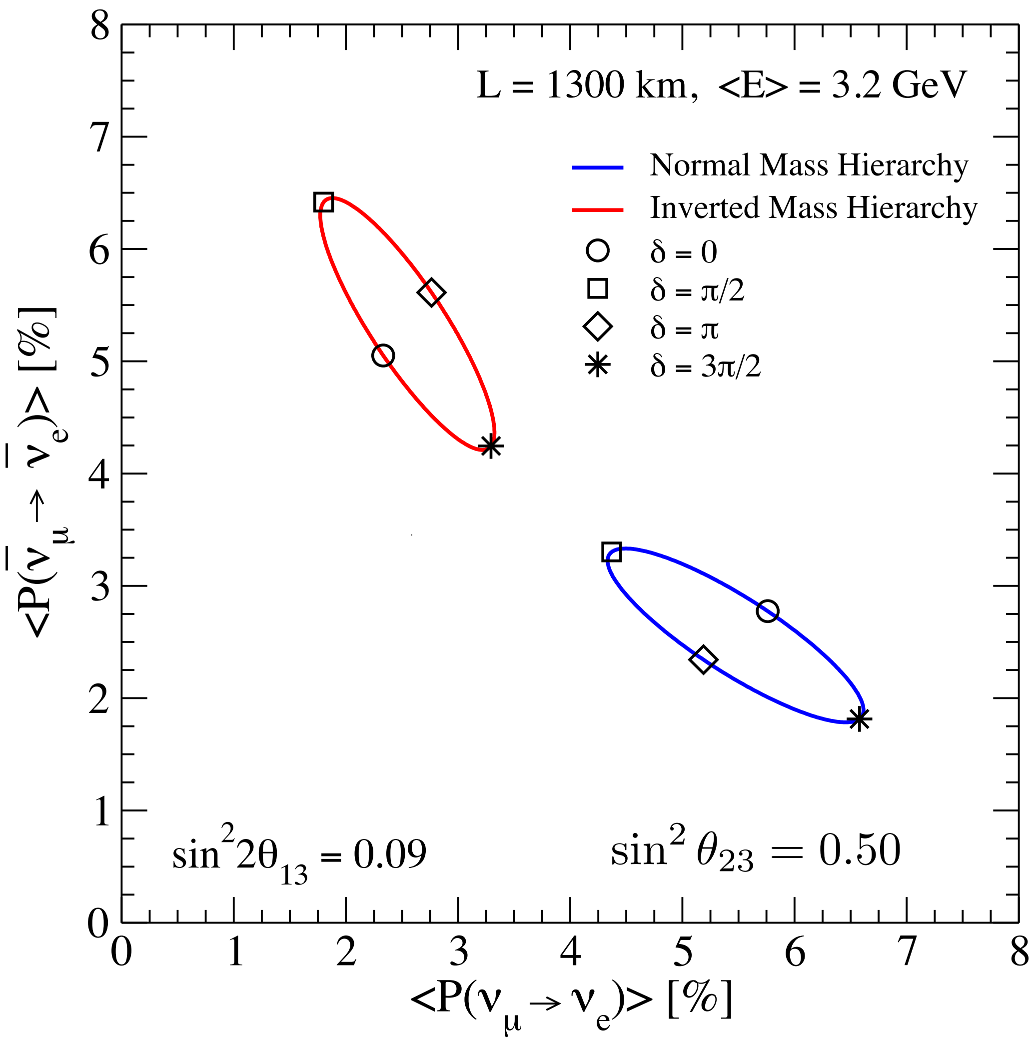
CPV: Full LBNE

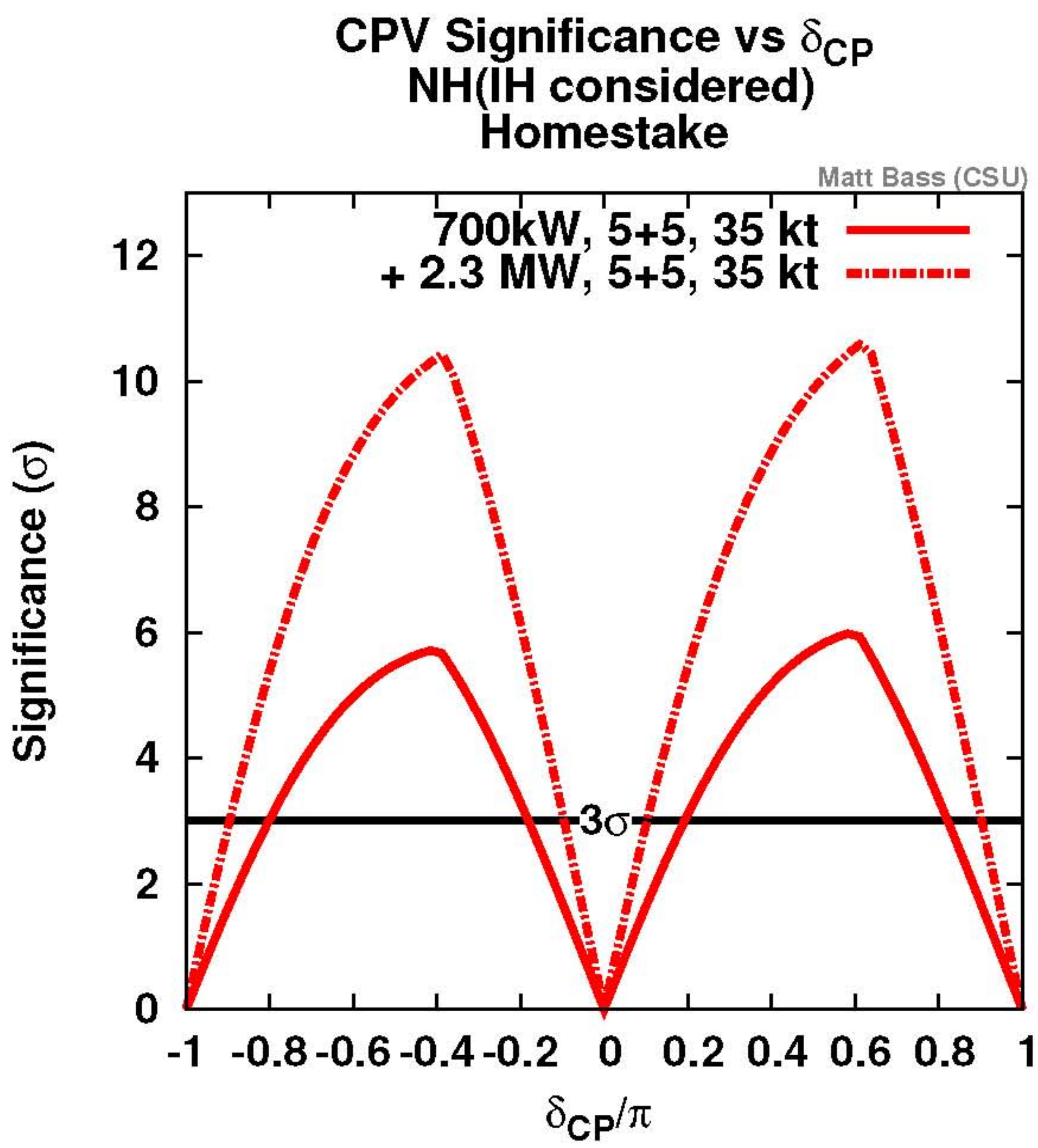
same L/E as NOvA



CPV: Full LBNE

same L/E as NOvA





see YKK for phasing:

Connection to Leptogenesis:

In the type-I see-saw

Kayser arXiv:1012.4469

$$\mathcal{L}_{new} = -\frac{1}{2}\overline{N_R{}^c} M_N N_R - (\overline{\nu_L}\overline{\phi^0} - \overline{\ell_L}\phi^-) y N_R + \text{h.c.} \quad .$$

M's Real

if U is Complex

$$M_\nu = -v^2 U^T (y^* M_N^{-1} y^\dagger) U$$

then generically y is Complex
which gives CPV in decays of the N's

Observation of CPV in Nu Oscillations Enhances the Credibility of Leptogenesis !

Beyond Nu SM

- Sterile
- Non-Standard Interactions (NSI)
- Premature Decoherence
- Neutrino Decay
- Effects of Extra Dimensions
- Surprises !

Tensions in the Nu SM:

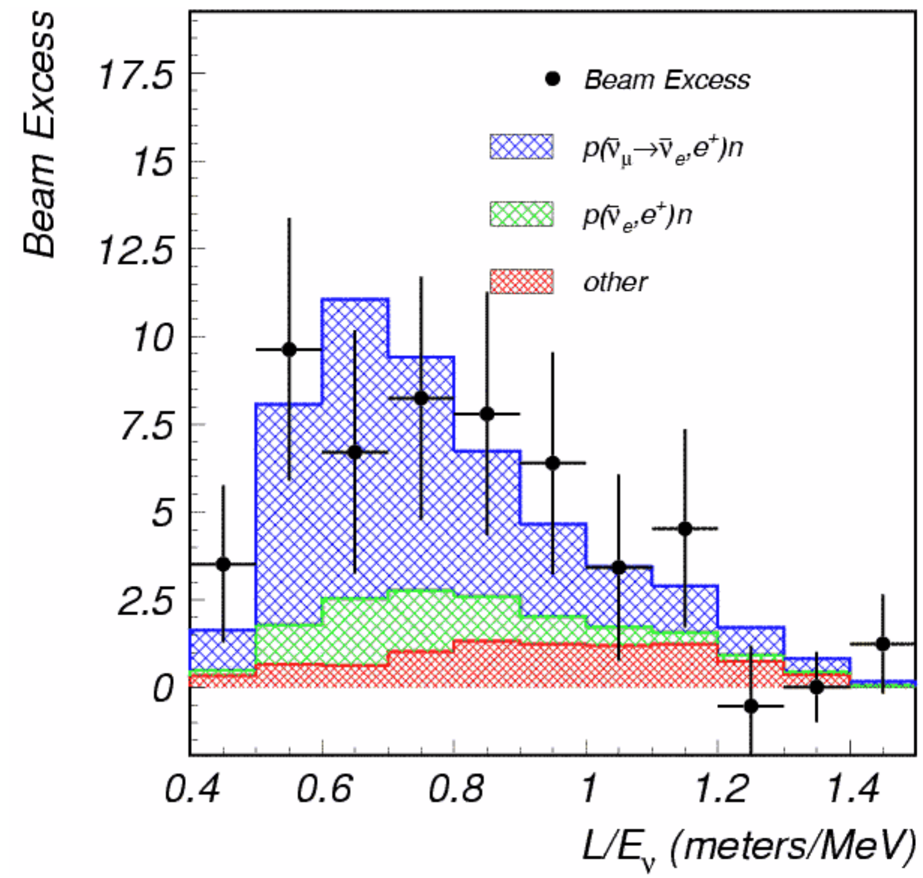
- Gallium: 2.7σ evidence for ν_e disappearance
- LSND: 3.8σ evidence for anti-ν_e appearance
- MiniBooNE: 3.8σ evidence for ν_e and anti-ν_e appearance
- Reactor: 3.0σ evidence for anti-ν_e disappearance

- Can be interpreted as a 4th neutrino state at eV scale mass

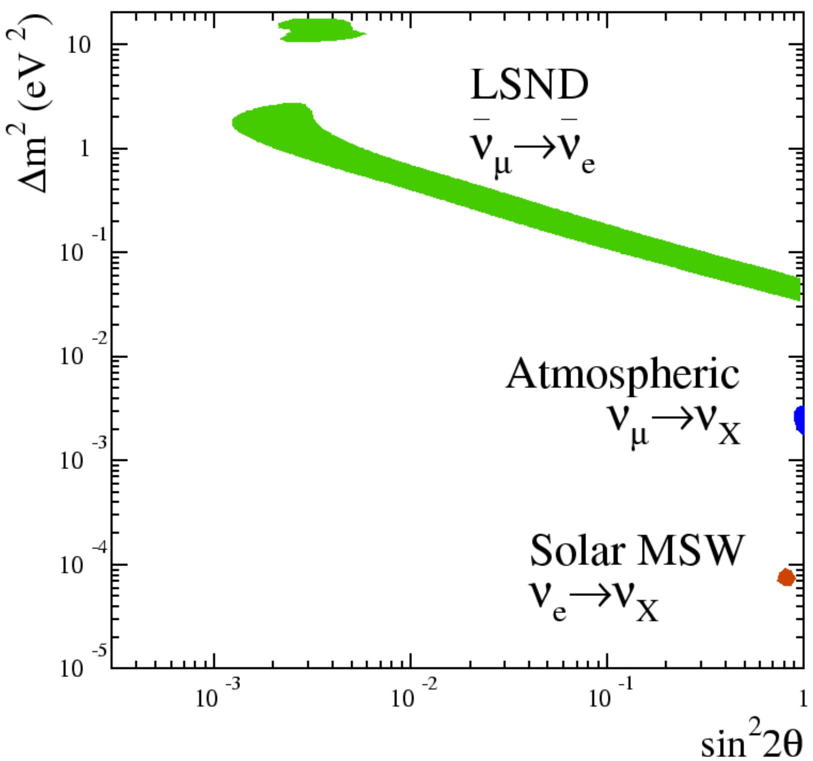
- Only 3 light, Weakly interacting neutrinos (LEP Z width)
- Oscillations with Δm^2_{solar} and Δm^2_{atm} are well established
- Therefore a 4th light state must be sterile

LSND:

- Used 800 MeV protons from LAMPF at Los Alamos in the 1990's



- Searched for anti-ν_e appearance in neutrino beam from pion decay at rest.

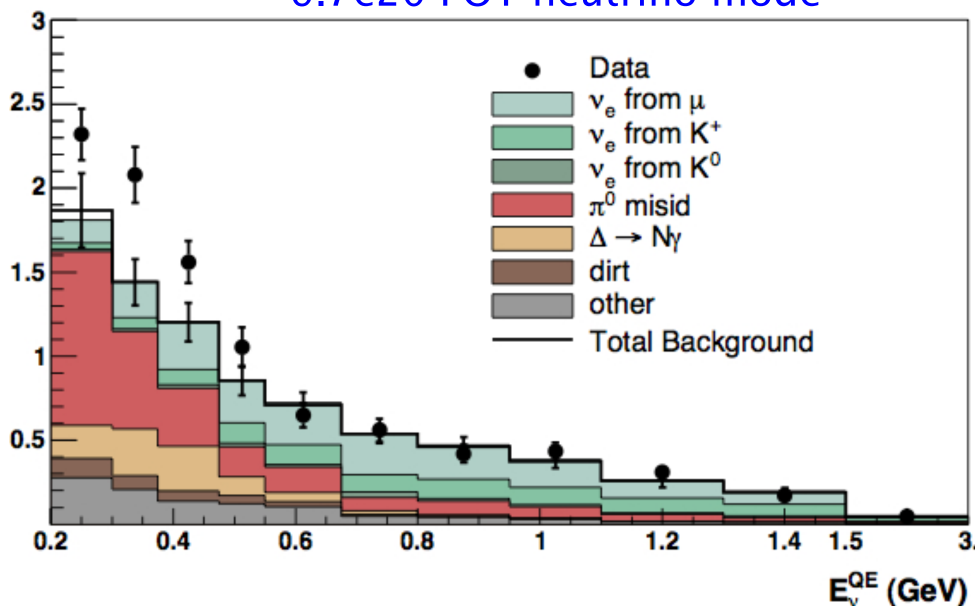


- Found an excess of anti-ν_e over background prediction
  - 87.9 ± 22.4 ± 6.0 (3.8σ)

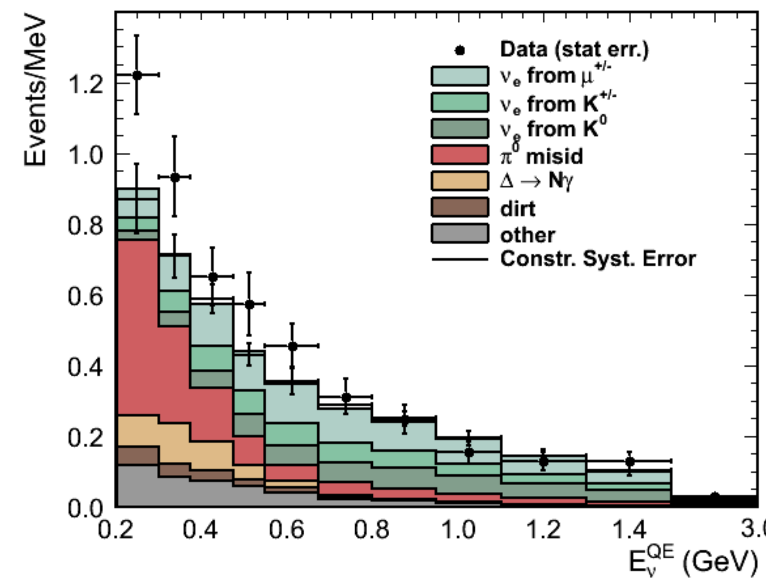
MiniBooNE

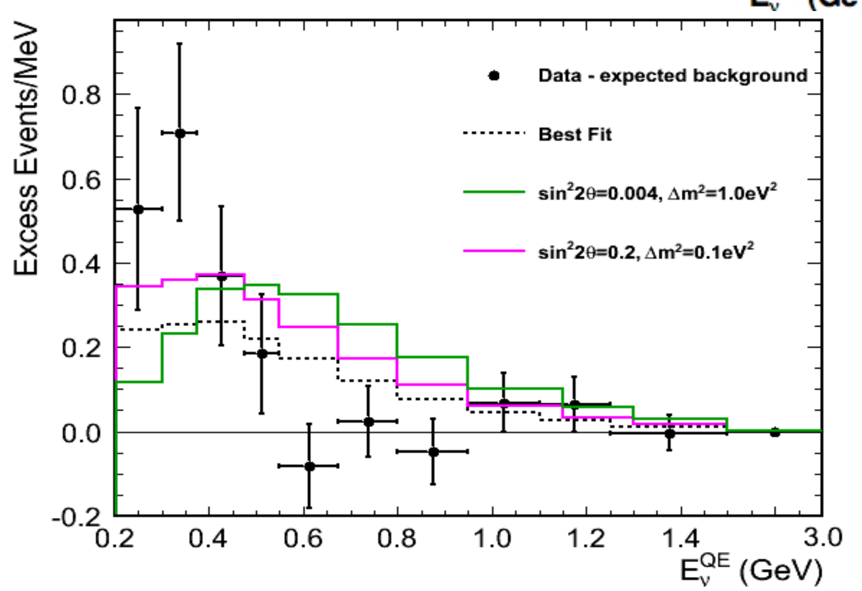
Comparing neutrino to anti-neutrino mode

6.7e20 POT neutrino mode

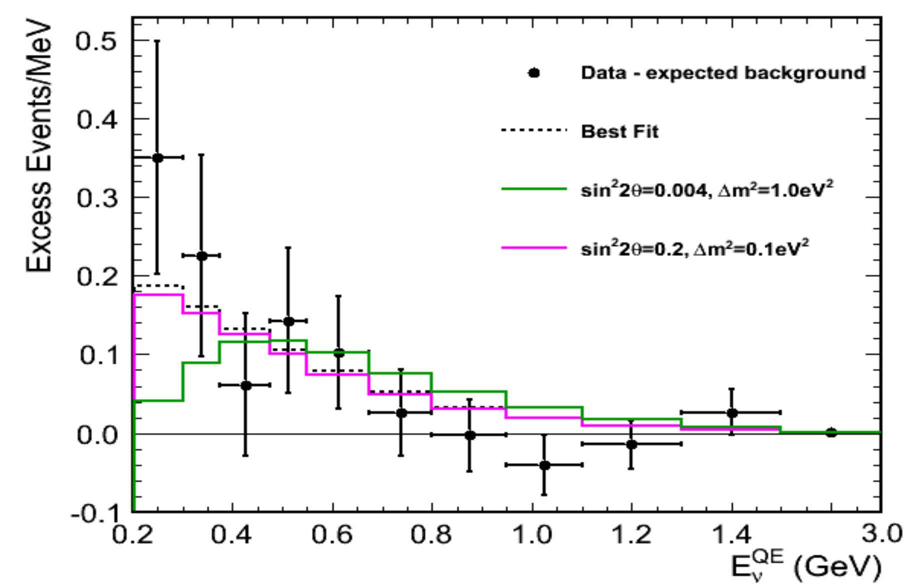


11.3e20 POT anti-neutrino mode

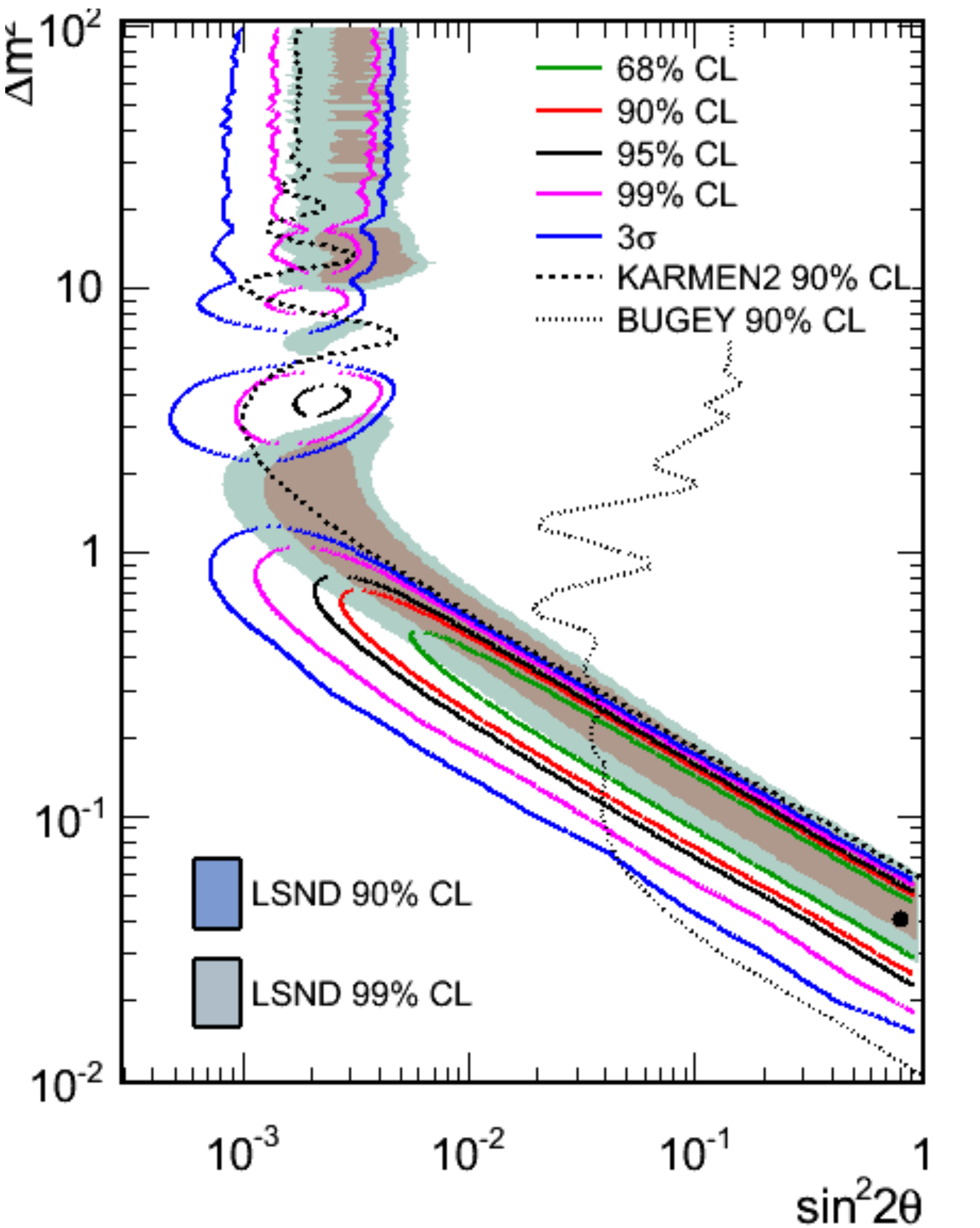




Excess: 146.3 ± 28.4 ± 40.2



Excess: 77.8 +/- 20.0 +/- 23.4

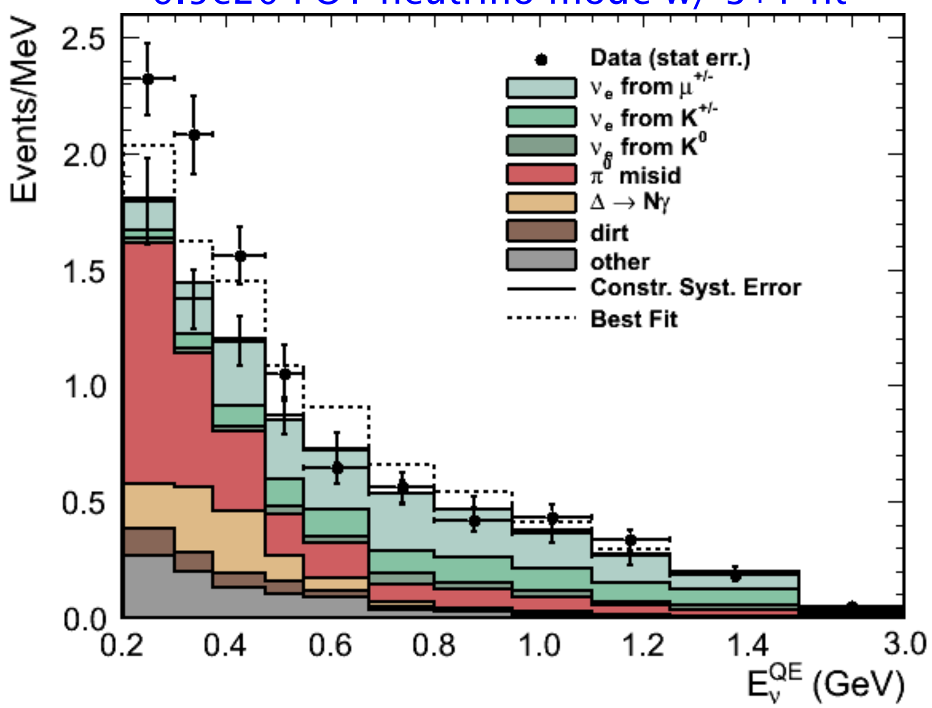


combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%

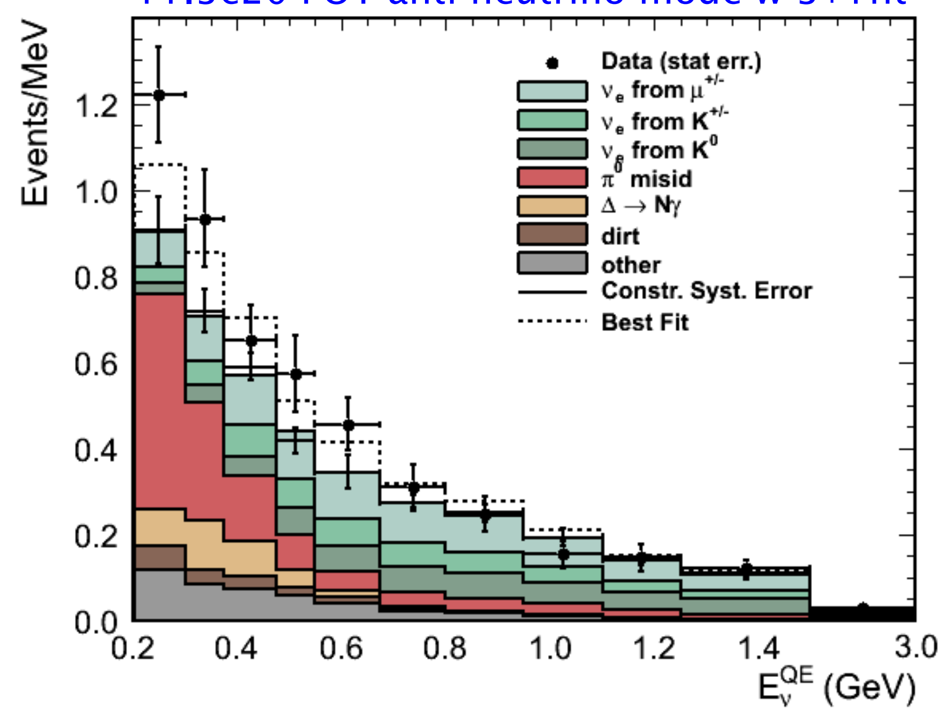
MiniBooNE Conclusions

- MiniBooNE observes an excess of ν_e candidates in the 200-1250 MeV energy range in neutrino mode (3.0σ) and in anti-neutrino mode (2.5σ). The combined excess is 240.3 ± 34.5 ± 52.6 events (3.8σ)
- The event excess is concentrated in the 200-475 MeV region where NC π^0 and other processes leading to a single γ dominate
- Higher statistics anti-υ data is now similar to the neutrino mode data
- It is not yet known whether the MiniBooNE excesses are due to oscillations, some unrecognized NC γ background, or something else

6.5e20 POT neutrino mode w/ 3+1 fit



11.3e20 POT anti-neutrino mode w 3+1fit



MicroBooNE:

- The MicroBooNE detector will be a liquid argon time projection chamber (LAr TPC) containing 170 tons of liquid argon, and located on the Booster Neutrino Beamline.
- The experiment's goal is to begin operation in 2013; availability of funding may constrain the schedule

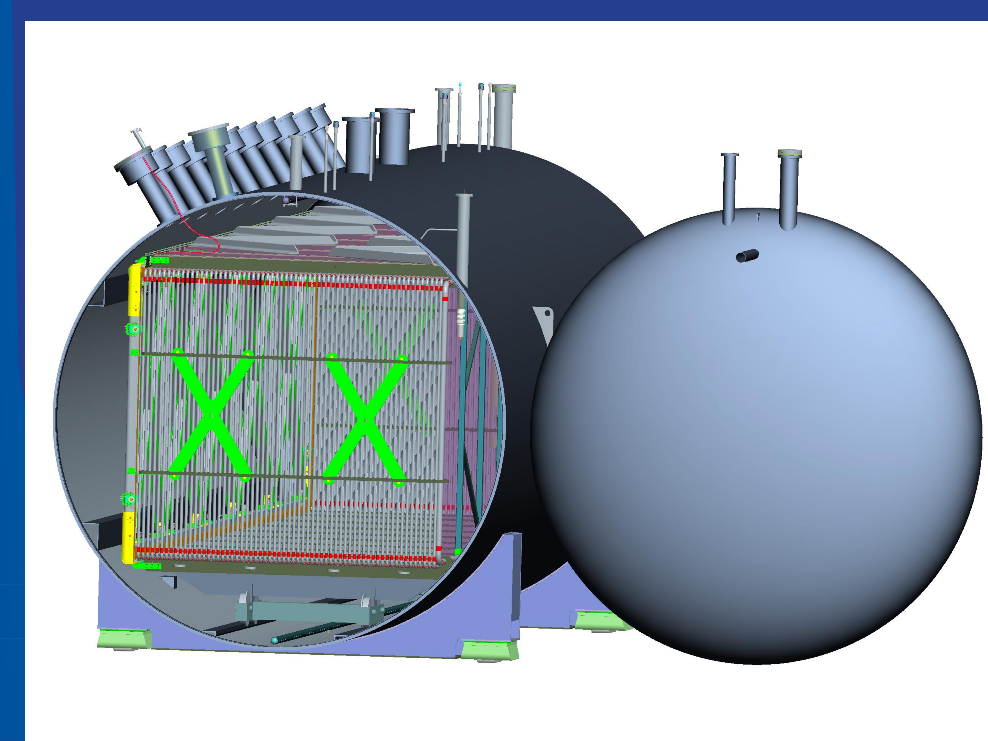
MicroBooNE will :

- Fully test the LAr TPC technology at a scope and scale that will help inform the design and operation of very large LAr TPC detectors for next-generation neutrino oscillation experiments.
  - Purity without evacuation; cold electronics; 2.5 m drift

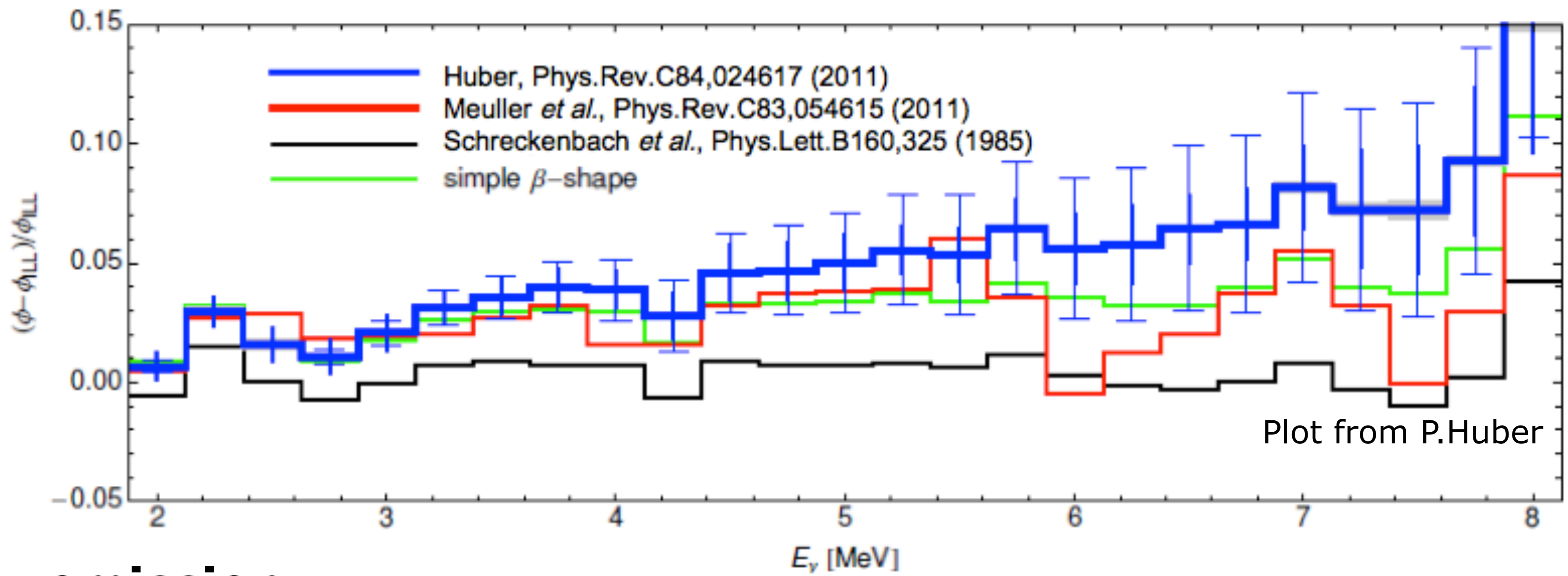
Physics

- Investigate the source of the excess of low energy electron-type neutrinos observed by the MiniBooNE experiment using the unique electron-photon discrimination power offered by a LAr TPC.
- Produce the first high-statistics measurements of neutrino interactions in argon. Currently, such measurements do not exist; they will provide the first constraints for future LAr-based neutrino oscillation experiments.

8 Fermilab Institutional Review, June 6-9, 2011 Fermilab



Reactor Anomaly:



ν emission:

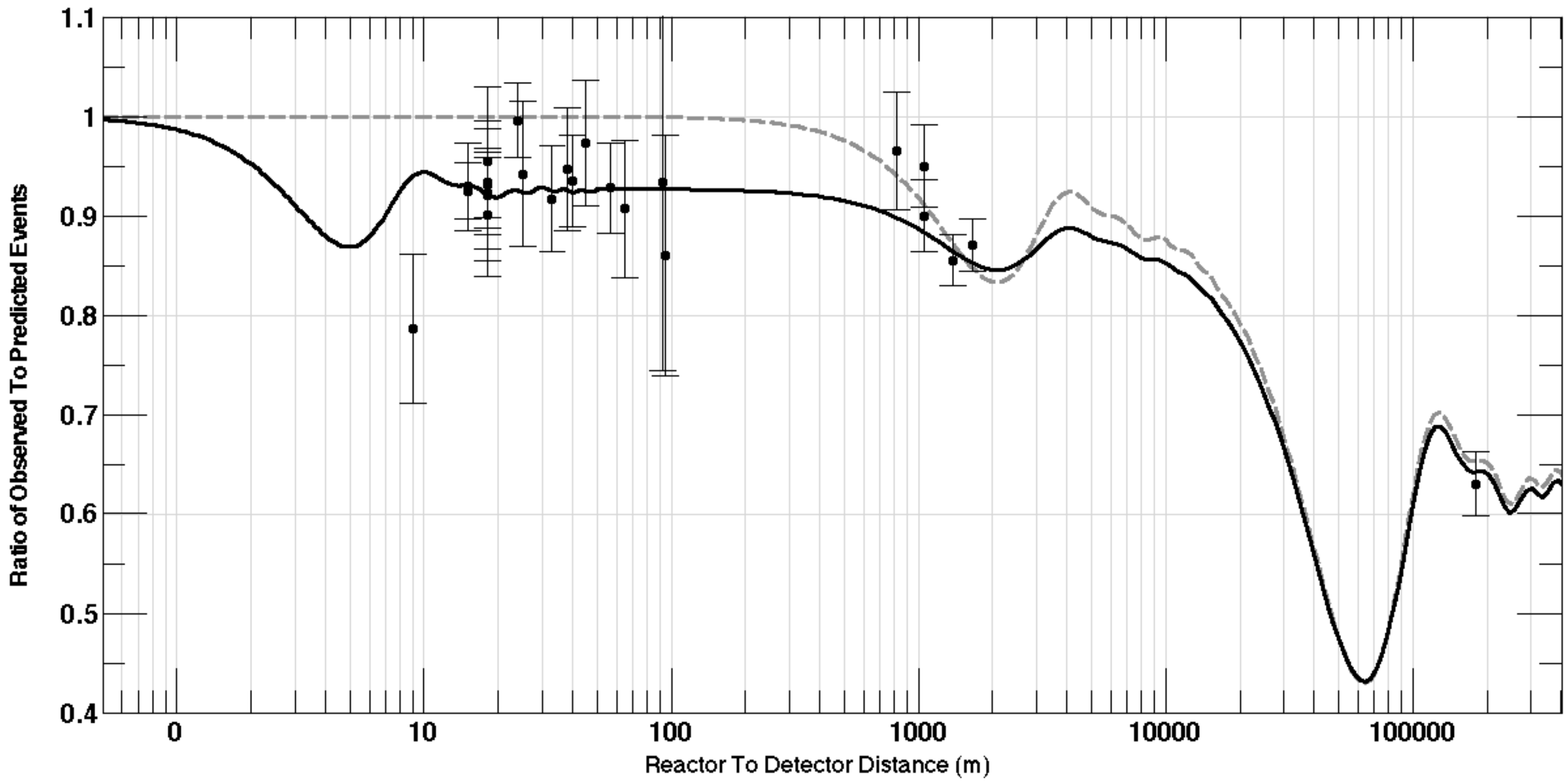
- Improved reactor neutrino spectra produces +3.5%
- Accounting for long-lived isotopes accumulating in reactors produces +1%
- PRC83, 054615 (2011)
- PRC84, 024617 (2011)

ν detection:

- Reevaluation of σ_{IBD} Improved neutron life time measurements produces +1%

Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)

Interpreted as Oscillation with 4th State



Spectral Distortion Exp. at 10m from core are being planned.

Counter Evidence for 4th State:

There are a number of results that are sensitive, but see no evidence for a 4^{th} neutrino state with ~eV mass:-

– CDHS and MiniBooNE searches for ν_μ disappearance

– MiniBooNE search for $\bar{\nu}_\mu$ disappearance

– MINOS search for $\nu_\mu \rightarrow \nu_s$

– Karmen search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

It is hard (impossible?) to fit all data with a single oscillation hypothesis

Future Tests:

- Need a definitive test(s) of the 4th neutrino hypothesis hinted at by the current anomalies

- Many tests proposed. They fall into three types:-
  1) Detector <15 m from compact nuclear reactor
  2) Accelerator based short baseline → **LAr1 NuStorm**
  3) Intense sources close to or in detector

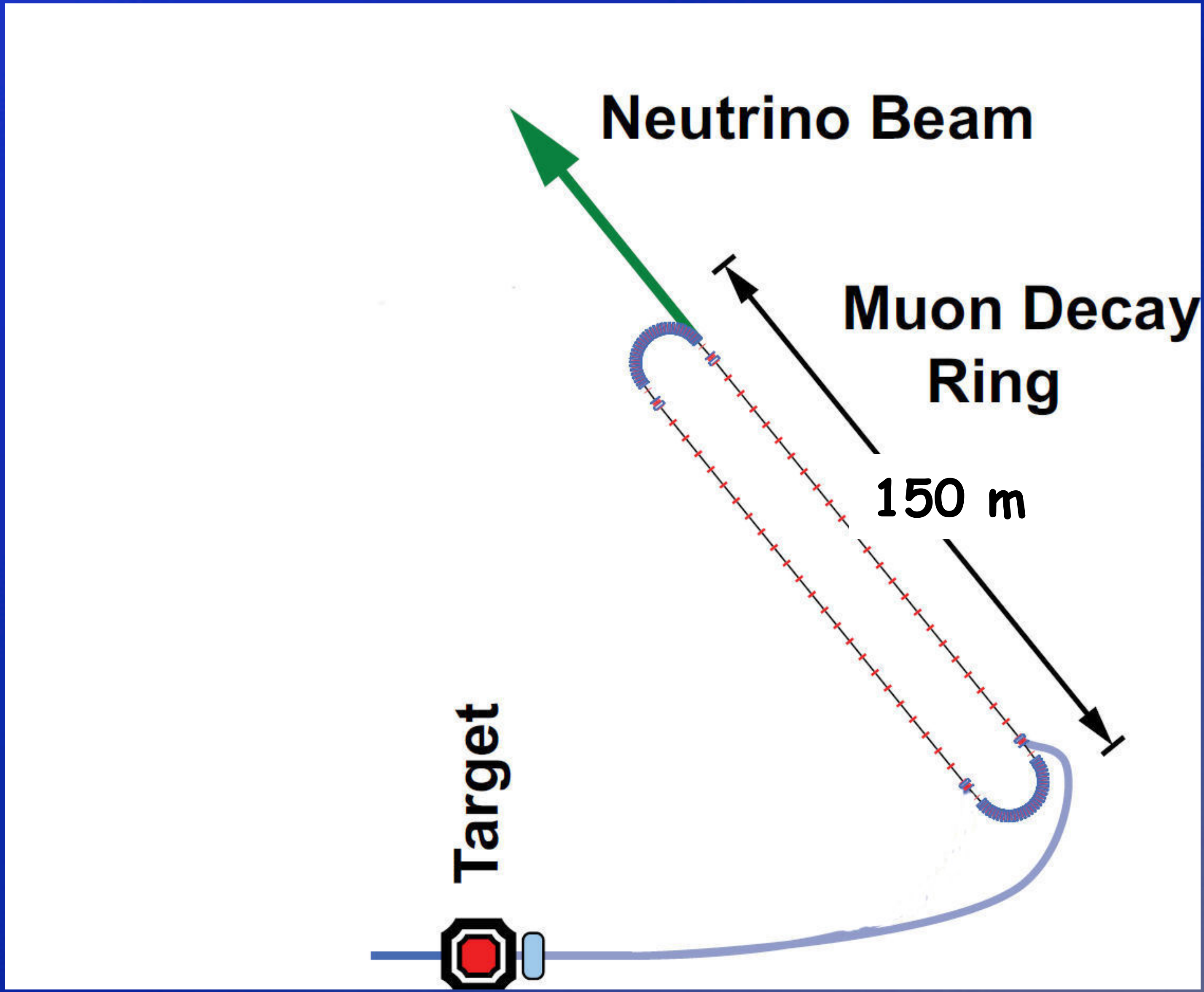
- For definitive test would like oscillation evidence in E and L and redundant cross-checks

- See Sterile Neutrino White Paper
  - arXiv:1204.5379

- Upcoming report from Fermilab Short Baseline Working Group

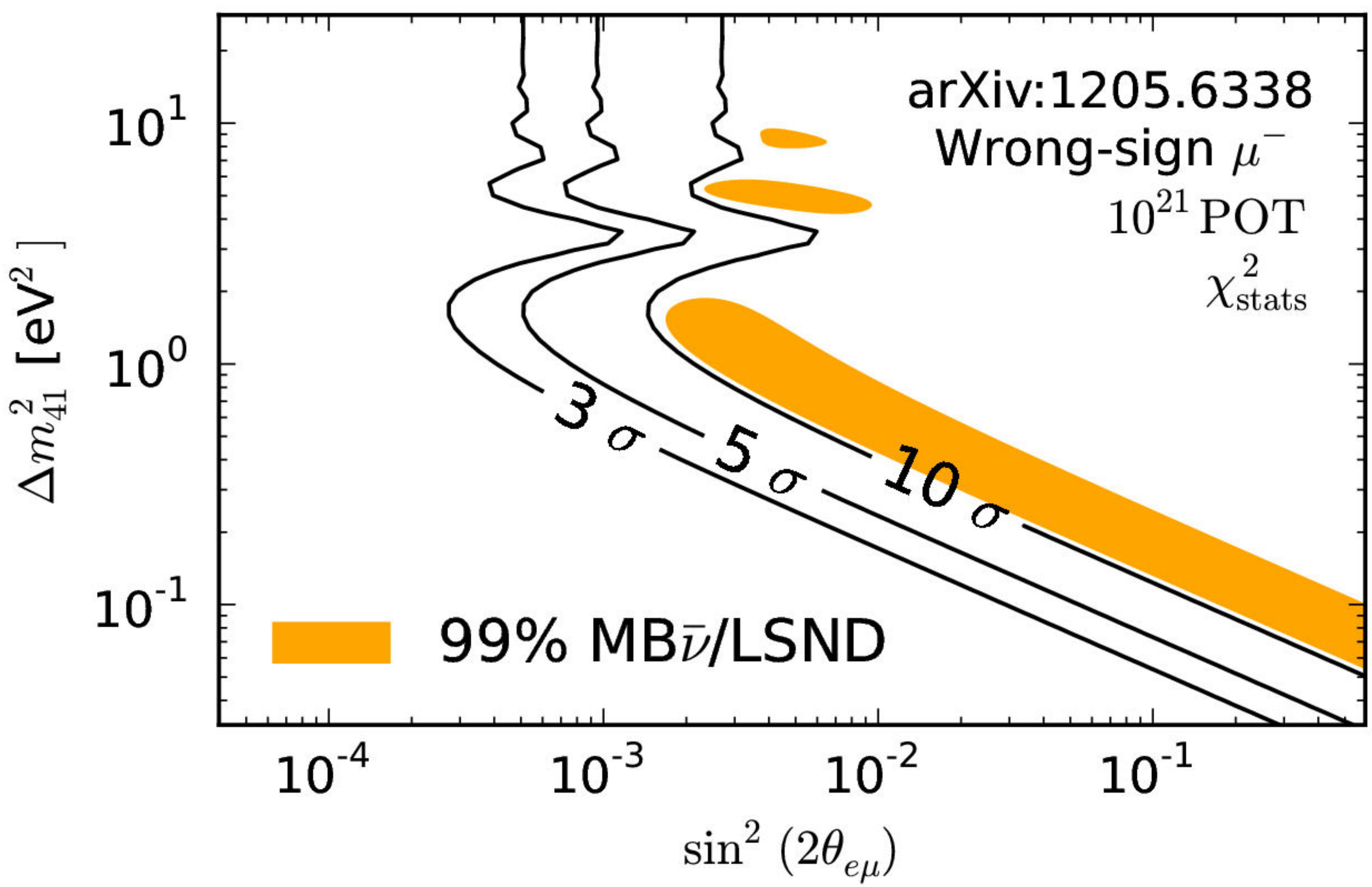
nuSTORM:

- 100 kW Target Station
  - Assume 60 GeV proton
    - Fermilab PIP era
  - Ta target
    - Optimization on-going
  - Horn collection after target
    - Li lens has also been explored
- Collection/transport channel
  - Two options
    - Stochastic injection of π
    - Kicker with $\pi \rightarrow \mu$ decay channel
    - At present NOT considering simultaneous collection of both signs
- Decay ring
  - Large aperture FODO
  - Racetrack FFAG
  - Instrumentation
    - BCTs, mag-Spec in arc, polarimeter



$\nu_e \rightarrow \nu_\mu$ appearance
CPT invariant channel to MiniBooNE

νSTORM



3+1 Assumption

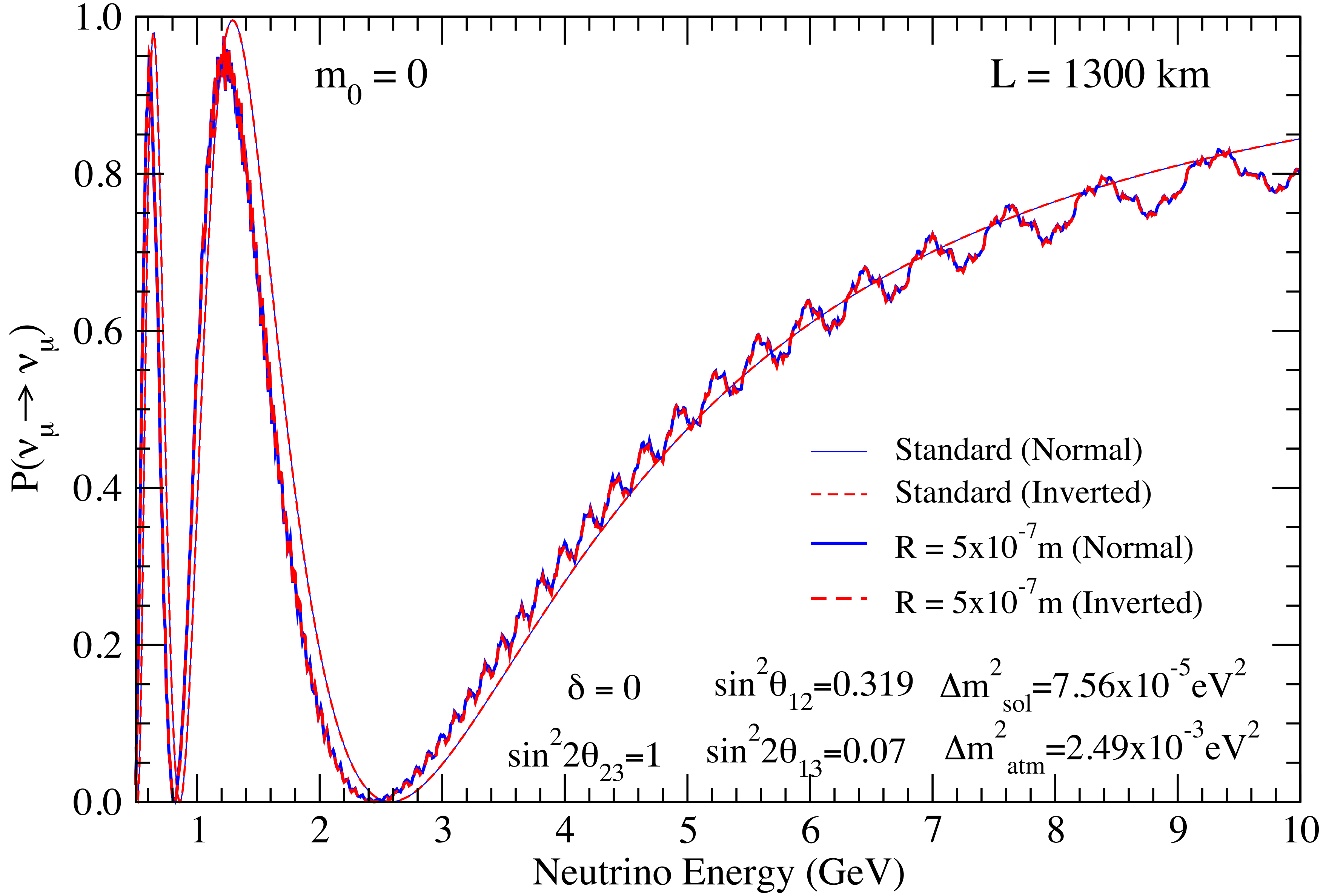
Fermilab

Alan Bross Fermilab Physics Advisory Committee June 21, 2012

29

LBNE & Extra Dimensions:

Machado, Nunokawa and Zukanovich Funchal, arXiv:1101.0003



Summary & Conclusions:

- Nu Standard Model:
  - Sizeable Nu_e fraction of Nu_3 (Large Theta_13) is wonderful opportunity to answer:
    - Is CPV in the Neutrino Sector ?
    - What is the Mass Ordering of Neutrinos ?
    - Which Flavor dominates Nu_3 ? (Nu_mu or Nu_tau)
  - Will Test Predictions of Neutrino Mass Models
  - Enhances Credibility of Leptogenesis
- Beyond Nu Standard Model:
  - Steriles, NSI, Extra D, ...

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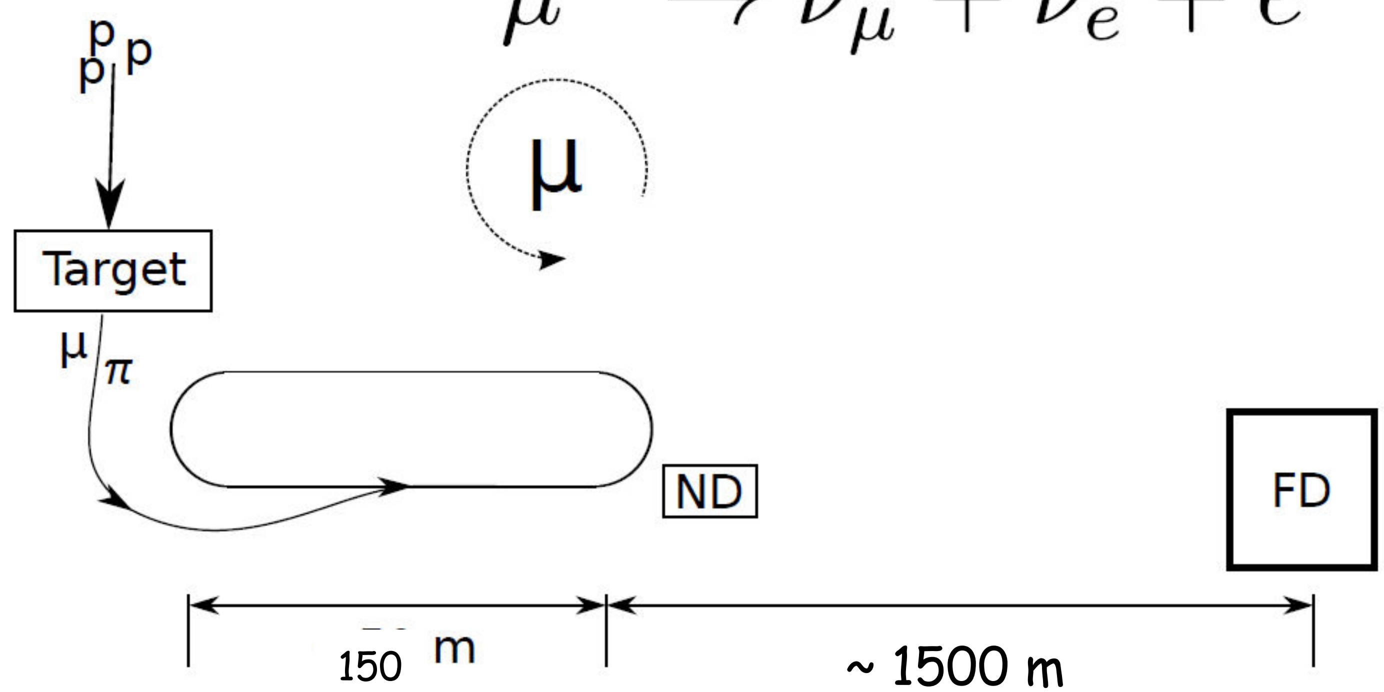
Neutrinos WILL continue to SURPRISES Us !!!

Backup:

νSTORM

Experimental Layout

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



Appearance-only (though disappearance good too!)

$$Pr[e \rightarrow \mu] = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(\frac{\Delta m^2_{41} L}{4E})$$

Appearance Channel:

$\nu_e \rightarrow \nu_\mu$

Golden Channel

Must reject the "wrong" sign μ with great efficiency

Why $\nu_\mu \rightarrow \nu_e$ Appearance Ch. not possible

Fermilab