Neutrinos: Not Just Missing ET

Stephen Parke
Fermilab

Neutrinos Physics at Dawn !

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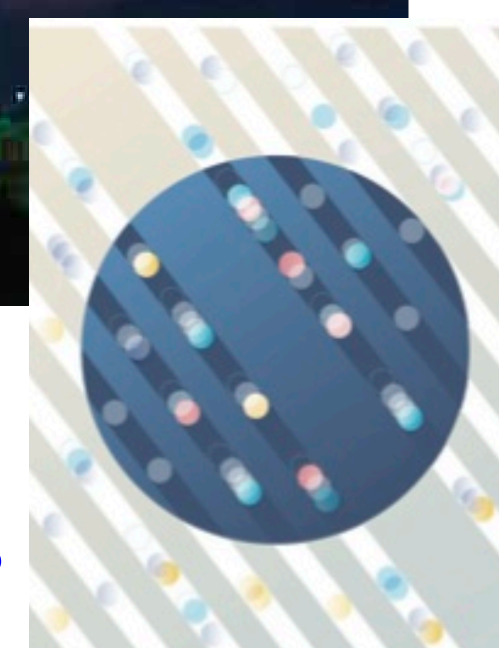


Science Drivers

the physics associated with neutrino mass

"All the News That's Fit to Print"

The New York

VOL. CXLVII . . . . No. 51,179 Copyright © 1998 The New York Times FRIDAY, JUNE 5, 1998

16 years ago

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

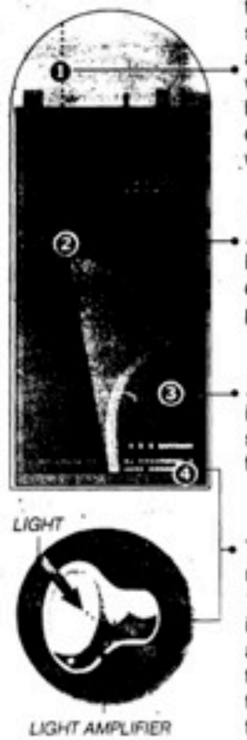
Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos



And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

ν98, @Takayam
June 1998

Atmospheric neutrino results from Super-Kamiokande & Kamiokande

— Evidence for ν_μ oscillations —

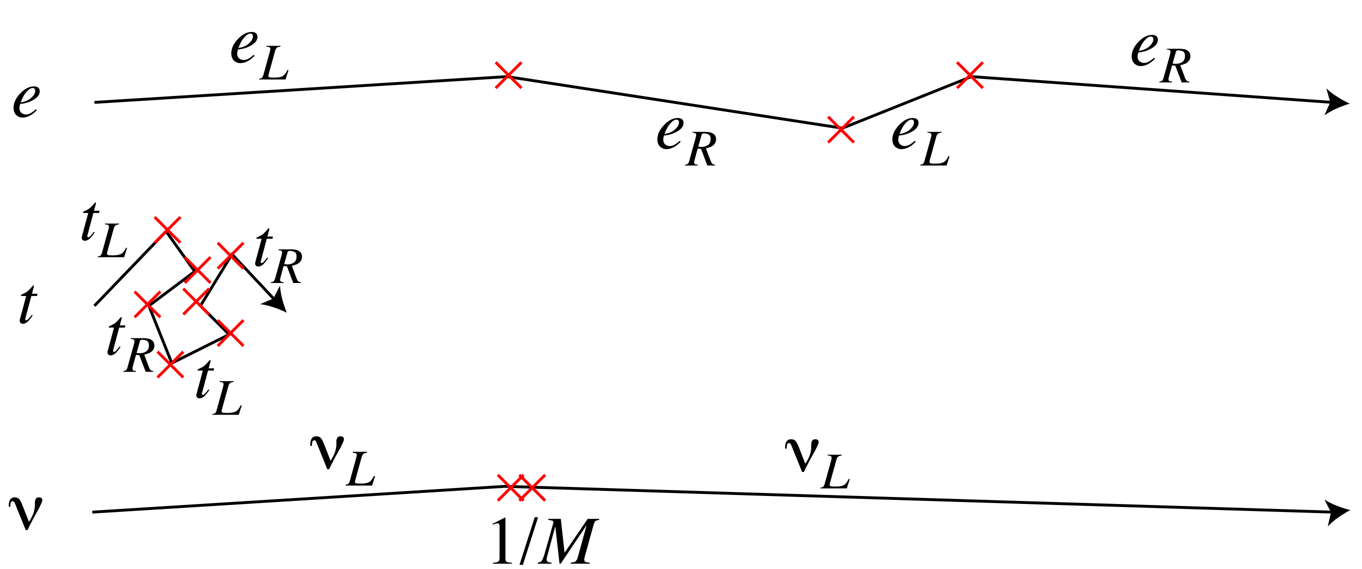
T. Kajita
Kamioka observatory, Univ. of Tokyo
for the {Kamiokande, Super-Kamiokande} Collaborations

http://www-sk.icrr.u-tokyo.ac.jp/nu98/scan/

Question I: What Kind of Mass?

- To Be Majorana or Not To Be Majorana?

Type:	Mass Term	Coupling to Higgs	# comp.	Lepton Number
Dirac:	$\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R$	$\bar{L} H \nu_R$	4	Conserved
Majorana:	$\overline{\nu_L} \nu_L^c$	$\frac{1}{M}(\bar{L}H)^2$	2	Violated



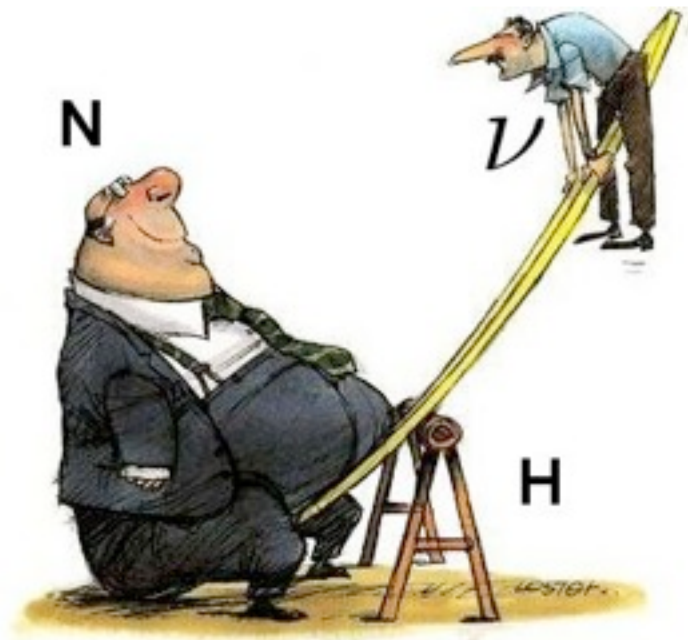
Dirac Nu same

Majorana Nu

$$\Gamma_{\text{tree}}(H \to \nu_i \bar{\nu}_i) \approx \left(\frac{m_{\nu_i}}{m_\tau}\right)^2 \Gamma(H \to \tau\bar{\tau}) \approx 10^{-20}\ \Gamma(H \to \tau\bar{\tau})$$

swamped by $H \longrightarrow ZZ \longrightarrow 4\nu!$

See-saw Mechanism:



- Introduce a right handed neutrino **N**
- Couple it to the Higgs

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow \quad m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

See-saw type I models can be embedded in GUT theories and explain the baryon asymmetry via leptogenesis.

Questions II: What is the Mass of the Sterile Neutrinos?

- How many light Neutrinos?

Except for LSND, MiniBooNE, Reactor and Gallium Anomalies,

3 can fit ALL the data and there is a lot of data ! ! !

- LSND, MiniBooNE, Reactor and Gallium Anomalies

can be fit with additional Light Sterile Neutrino(s) - 1, 2, 3 ...

Growing tension between Appearance data (LSND, MiniBooNE)

and ν_μ and ν_e Disappearance data ! !

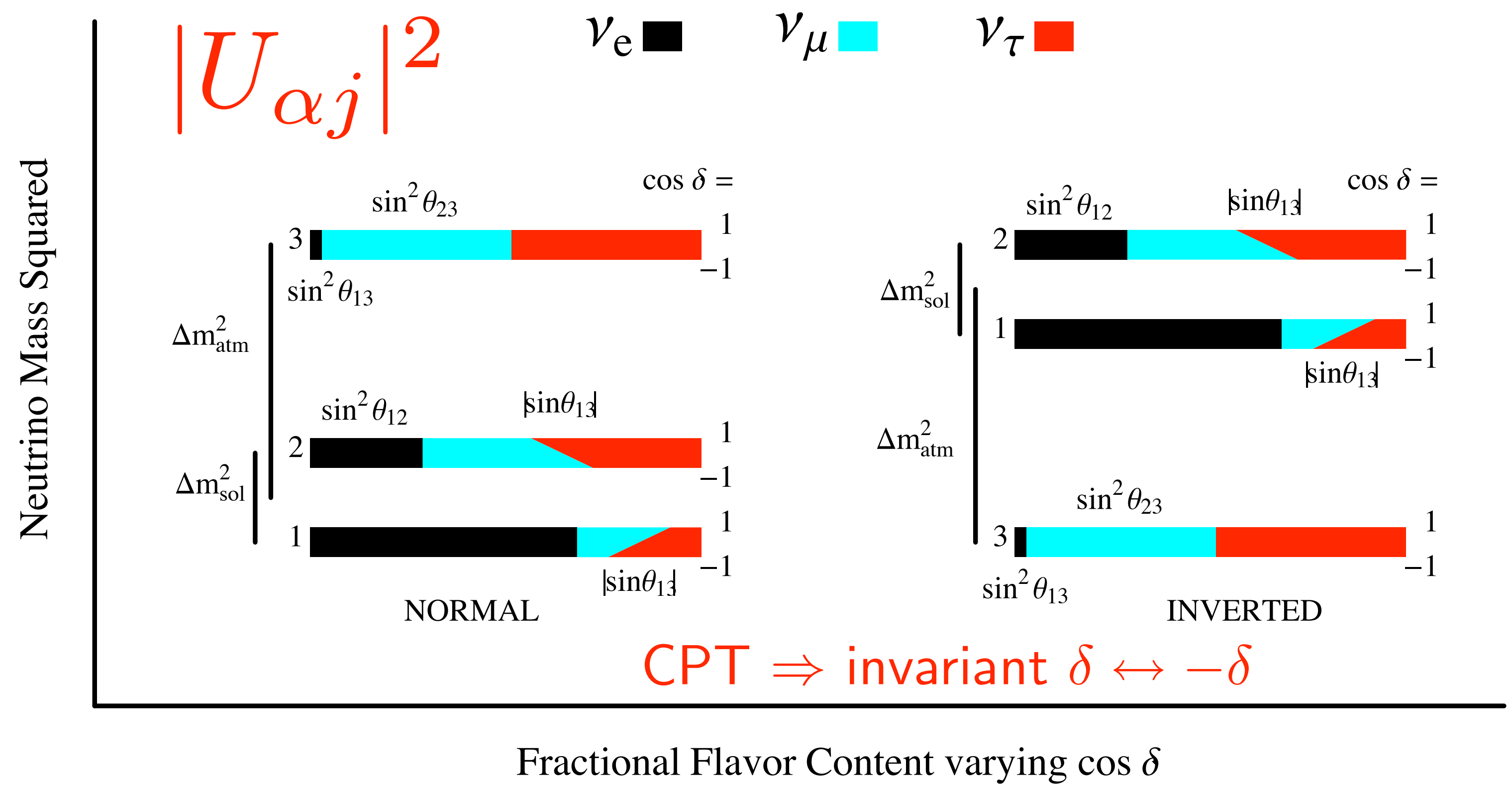
Needs to be definitively resolved:

MicroBooNE, LAr-ND, ICARUS@Fermilab

Question III: Masses and Mixings

- Labeling massive neutrinos:

$$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$$



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

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

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

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

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

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

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

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

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

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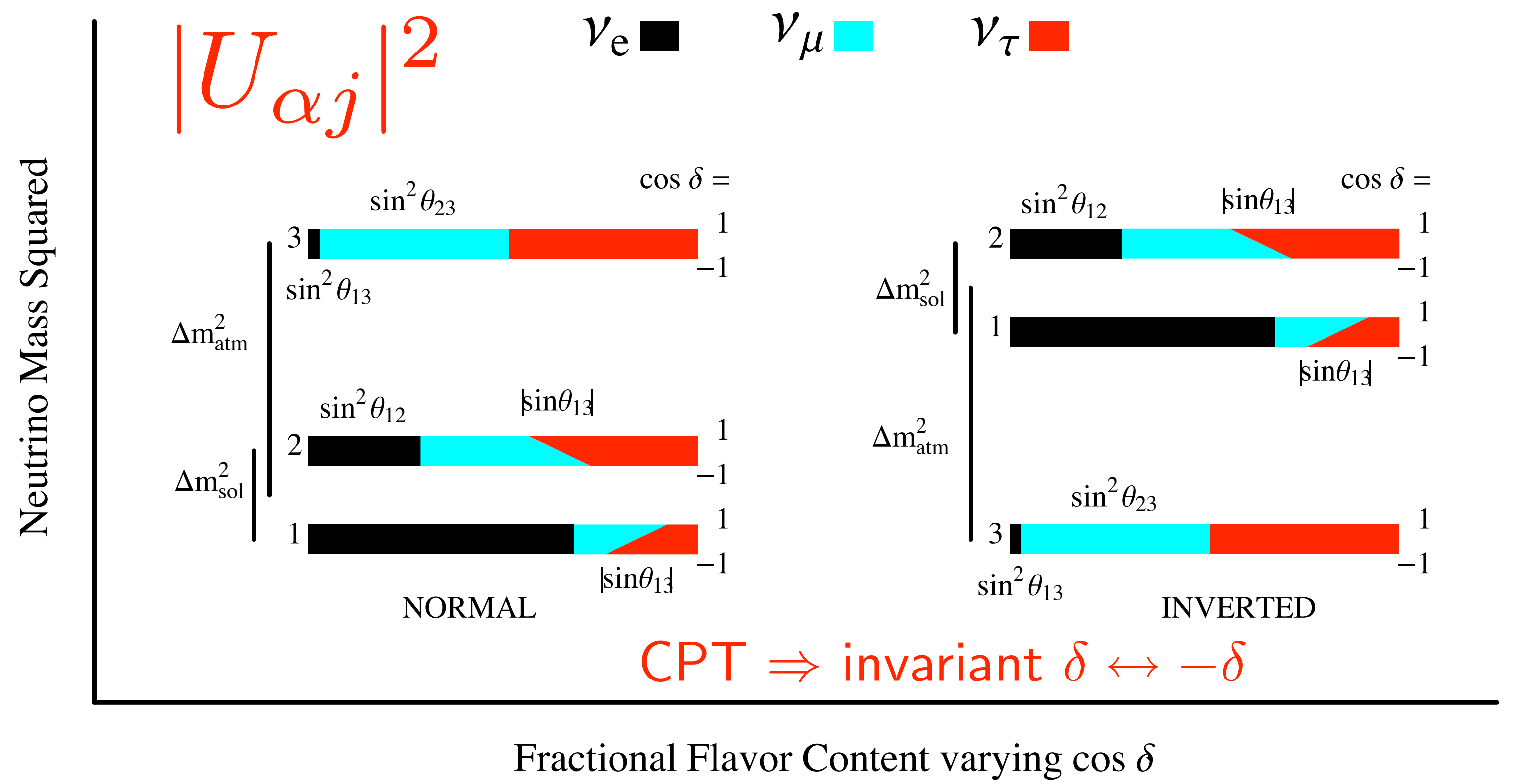

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Question IV: Non-Standard Interactions and other exotica

- Do we need new physics beyond just Neutrino Mass?

Extra Interactions of the Neutrinos?

Do the Massive Neutrinos Decay?

Premature Decoherence?

Lorentz Violations?

....

Neutrino Mixing Matrix: PMNS

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

$\downarrow$ smaller ν_e content

$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

Neutrino Mixing Matrix: PMNS

SNO CC
KamLAND
$|U_{e2}|^2$

Reactor/LBL
$|U_{e3}|^2(1-|U_{e3}|^2)$

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

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$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

Atm Nus/LBL
$|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$

Neutrino Mixing Matrix: PMNS

KamLAND wiggles
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smaller ν_e
content

$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

SK & OPERA Tau's
$|U_{\tau 3}|^2$

Atm Nus/LBL
$|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$

Neutrino Mixing Matrix: PMNS

KamLAND wiggles
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smaller ν_e content

$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

SNO NC
$|U_{e2}|^2 + |U_{\mu 2}|^2 + |U_{\tau 2}|^2$

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$|U_{\tau 3}|^2$

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$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

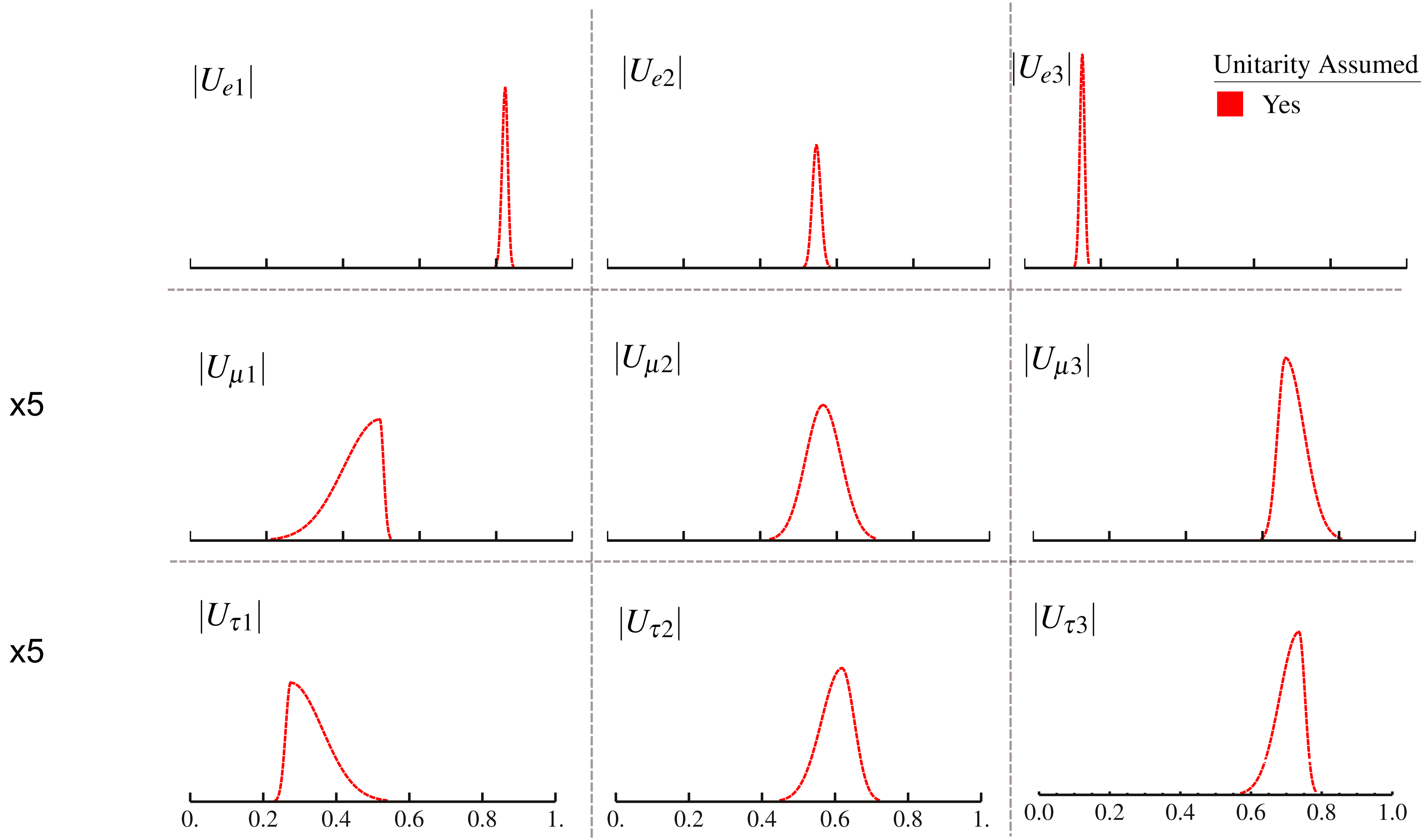
little Information!

SNO NC
$|U_{e2}|^2 + |U_{\mu 2}|^2 + |U_{\tau 2}|^2$

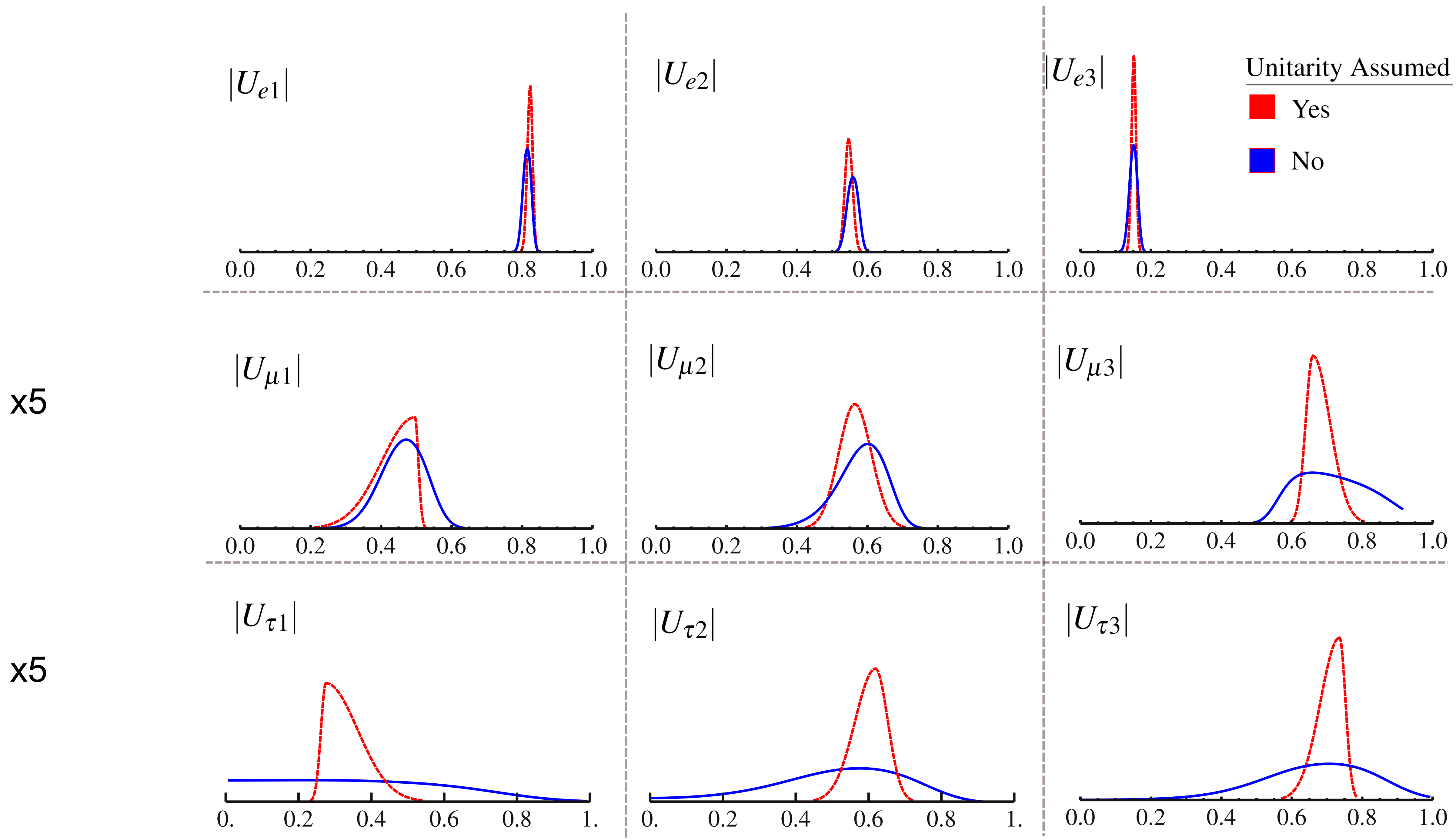
SK & OPERA Tau's
$|U_{\tau 3}|^2$

Atm Nus/LBL
$|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$

Assuming Unitarity:



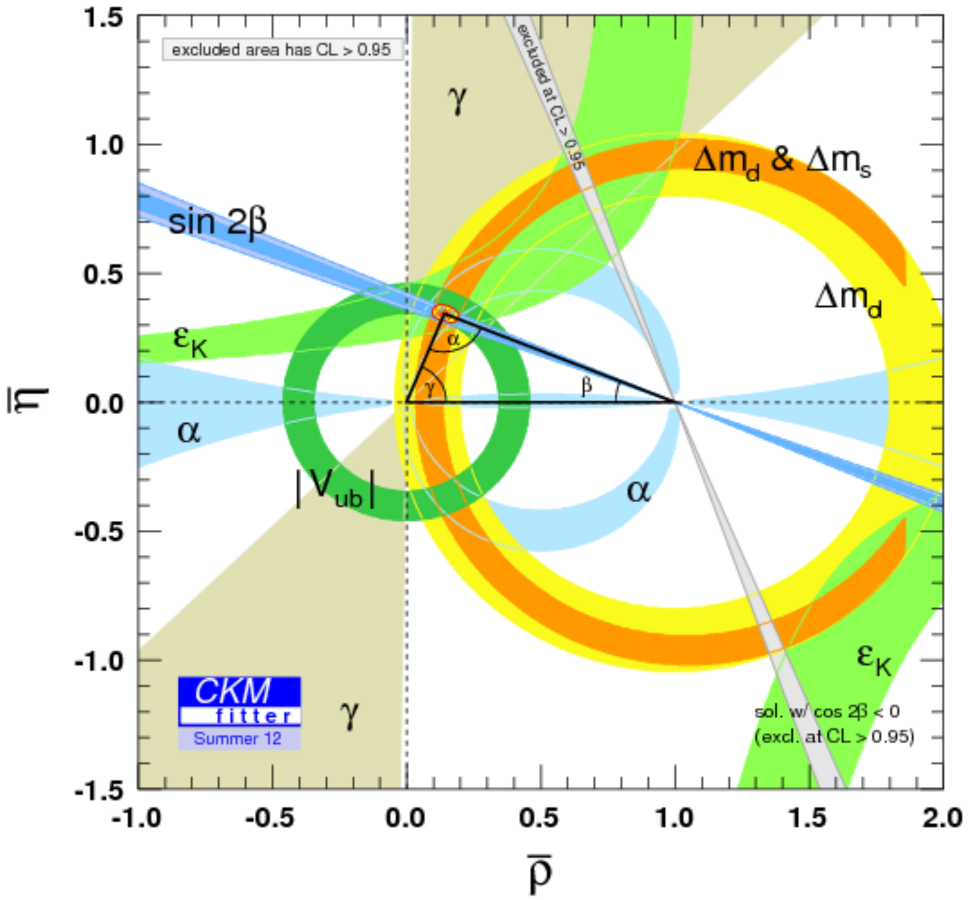
WITHOUT UNITARITY:



Mark Ross-Lonergan, Invisibles Network
Fermilab, Durham

Quark & lepton Unitarity Triangles:

Quark Triangle:



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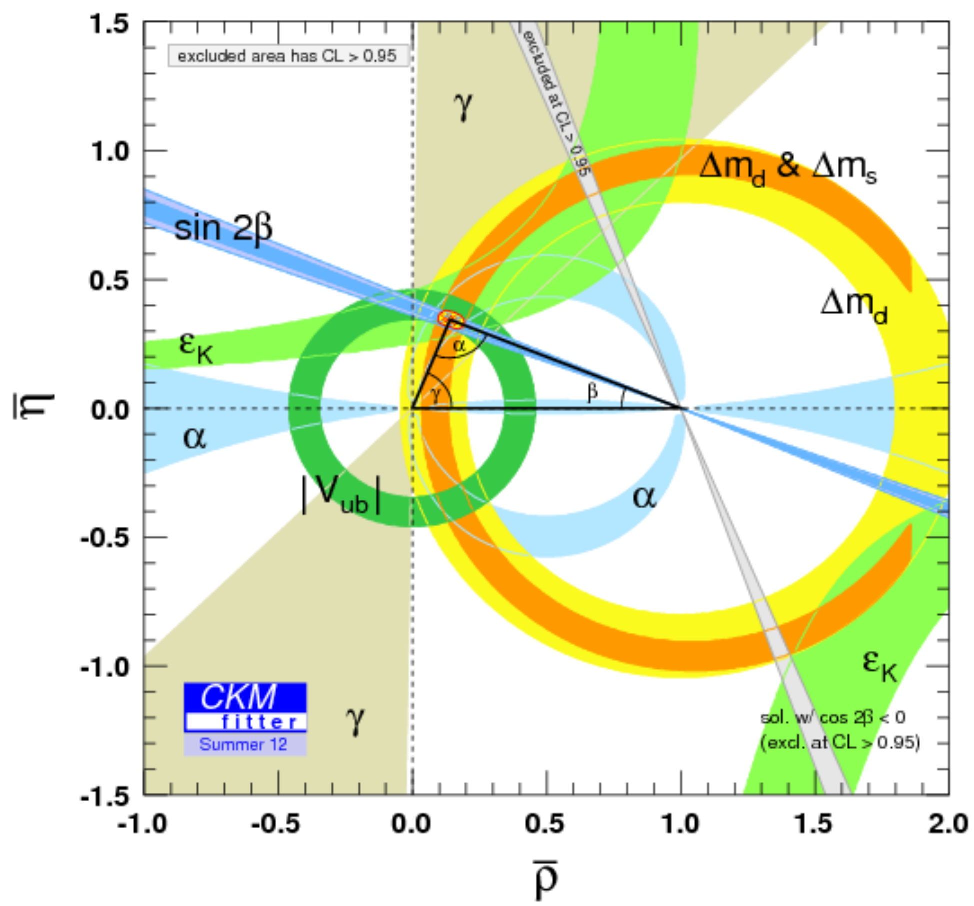
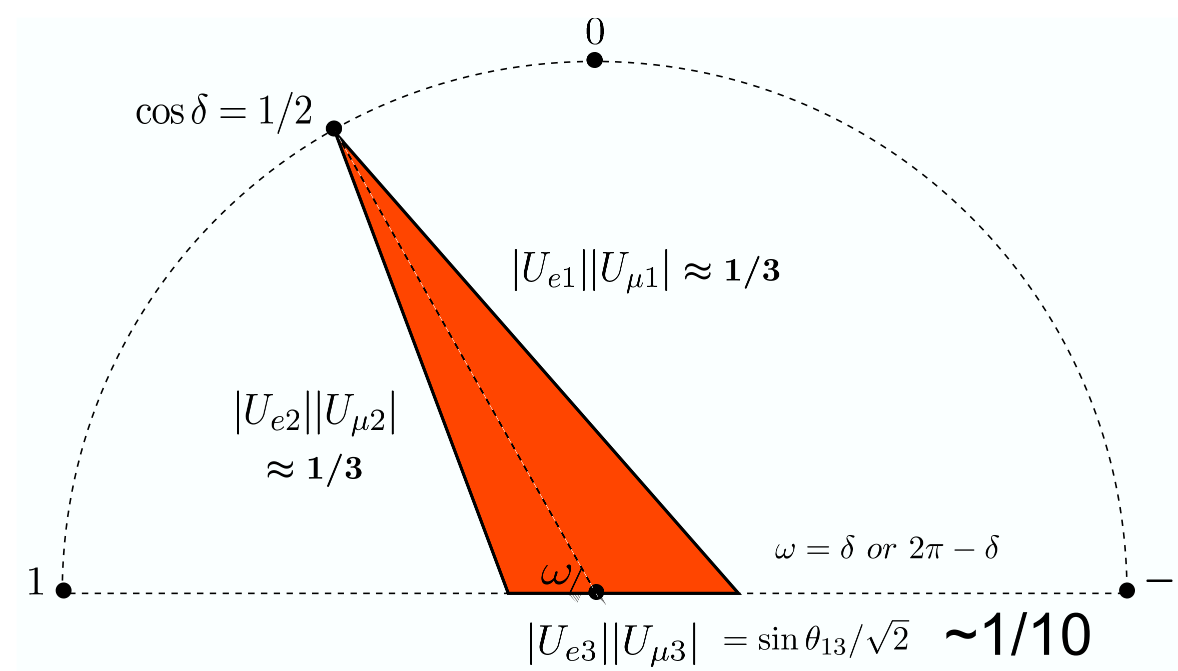


Neutrino Triangle:

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

only Unitarity triangle that doesn't involve ν_τ !

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



$$|U_{e1}||U_{\mu 1}| = 0.0 - 0.5; \;\; |U_{e2}||U_{\mu 2}| = 0.2 - 0.4; \;\; |U_{e3}||U_{\mu 3}| = 0.1(1 \pm 0.2)$$

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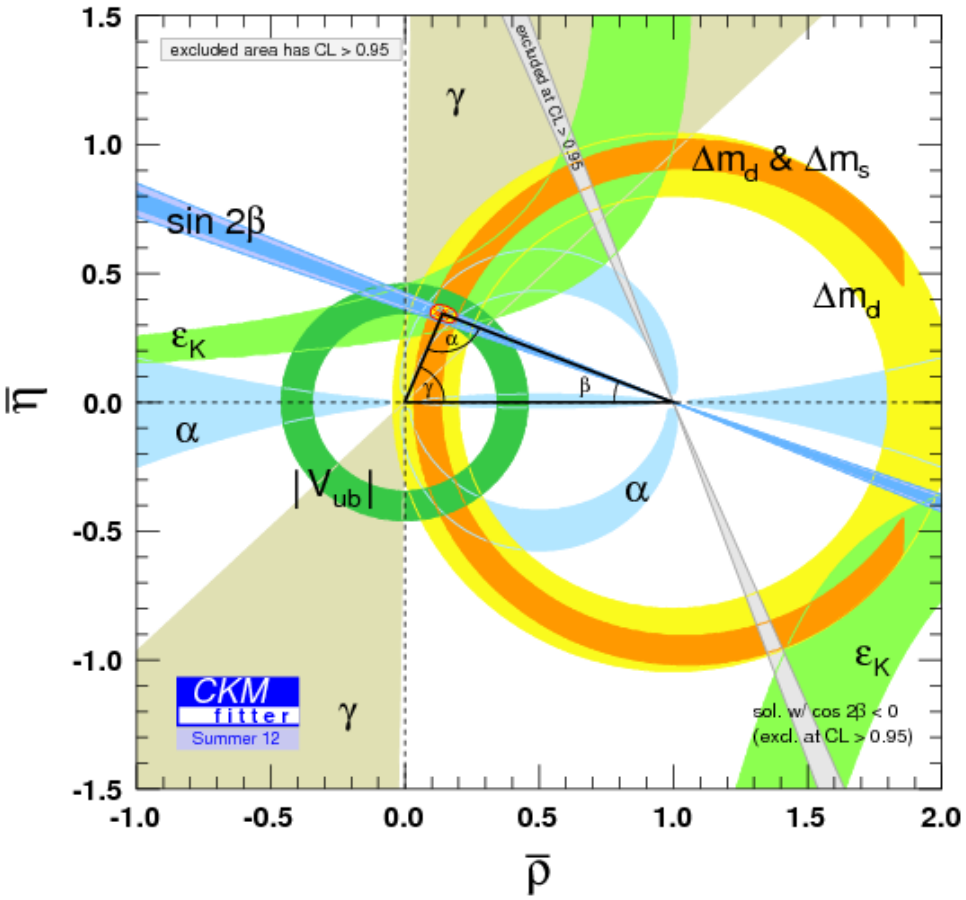

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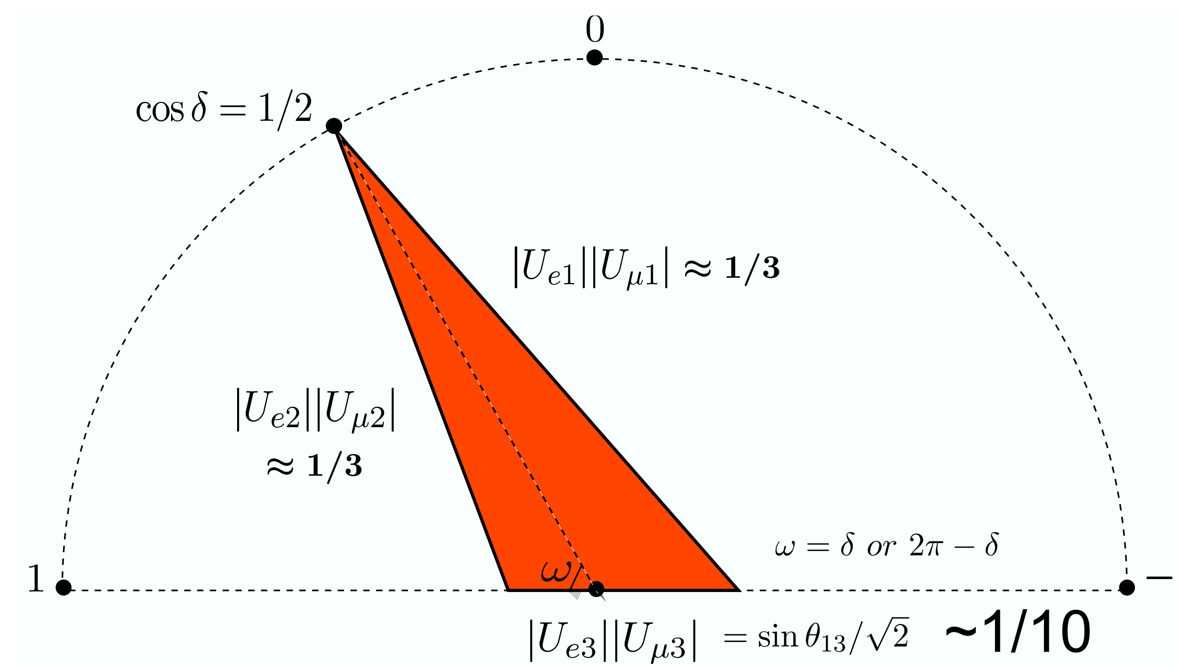

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How to measure $|U_{\mu 1}|^2$ and $|U_{\mu 2}|^2$ separately ? ? ?

Quark & lepton Unitarity Triangles:

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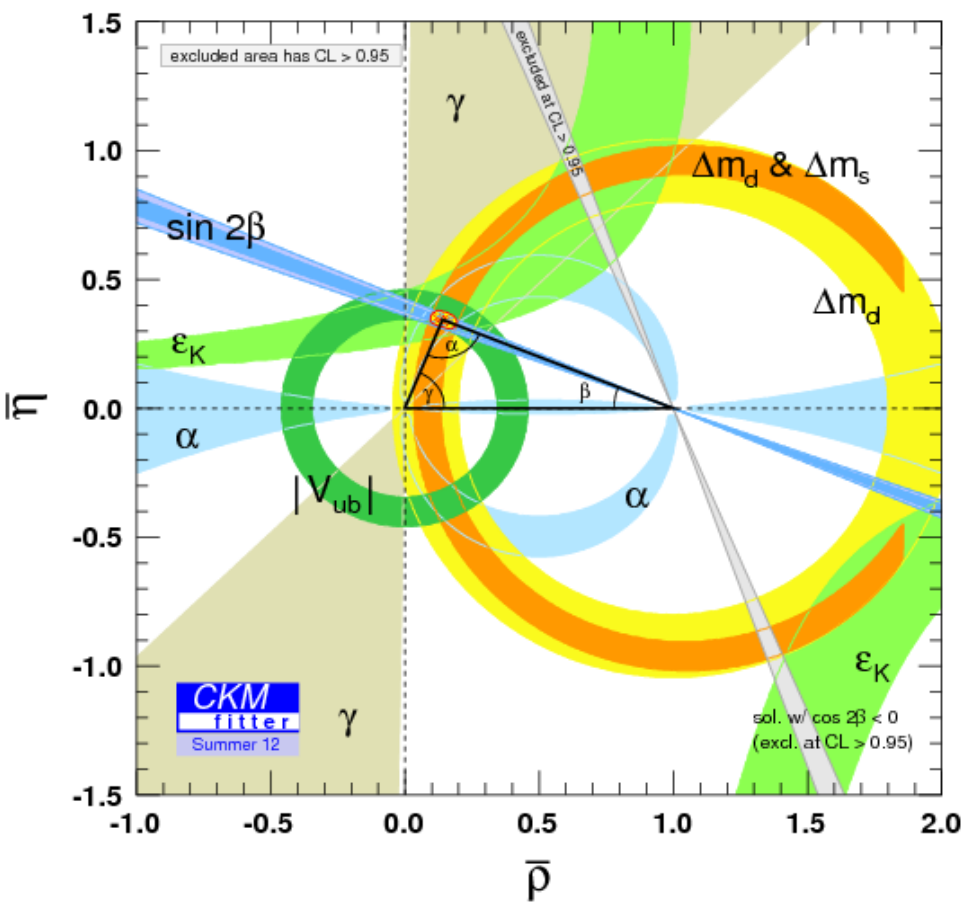

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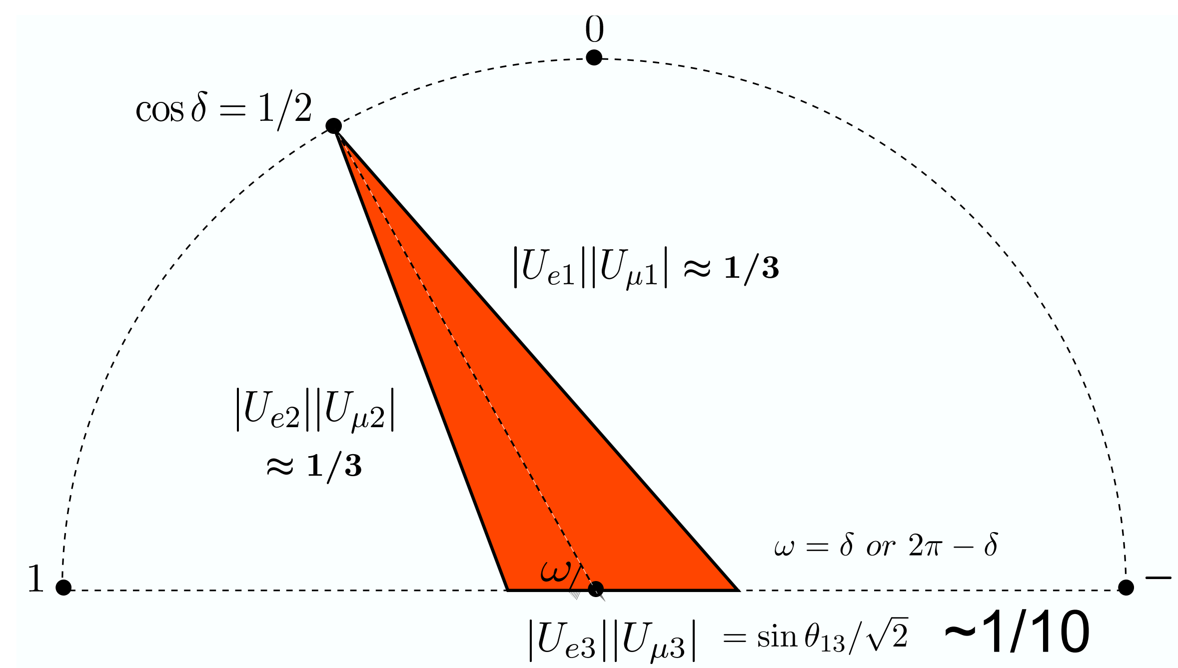

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How to measure $|U_{\mu 1}|^2$ and $|U_{\mu 2}|^2$ separately ? ? ?

Neutrino Factory to detector in geo-synchronous orbit ! ! !

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: $|U_{\mu 3}|^2 > \text{or} < |U_{\tau 3}|^2$ or $\theta_{23} > \text{or} < \pi/4$
- Majorana Phases: 2 additional phases
- Absolute Neutrino Mass: m_{lite}

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} ***Credibility of Leptogenesis !!***

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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?

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Credibility of Leptogenesis !!

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- Where are the True Surprises?

Leptons v Quarks:

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

Very Different !!!

Flavors & quark-lepton unification

Quarks CKM matrix = **1** + (Cabibbo) effects

Leptons' MNSP matrix = **X** + (Cabibbo?) effects

contains two large angles

Cabibbo effects as deviation from **X**

example: $\theta_{13} \simeq \theta_c/\sqrt{2}$ deviation from zero?

speculate: $\theta_{atm} \simeq \pi/4 + O(\theta_c)$ deviation from $\pi/4$?

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 $\theta_{12} = 32^o + \theta_{13} \cos\delta$

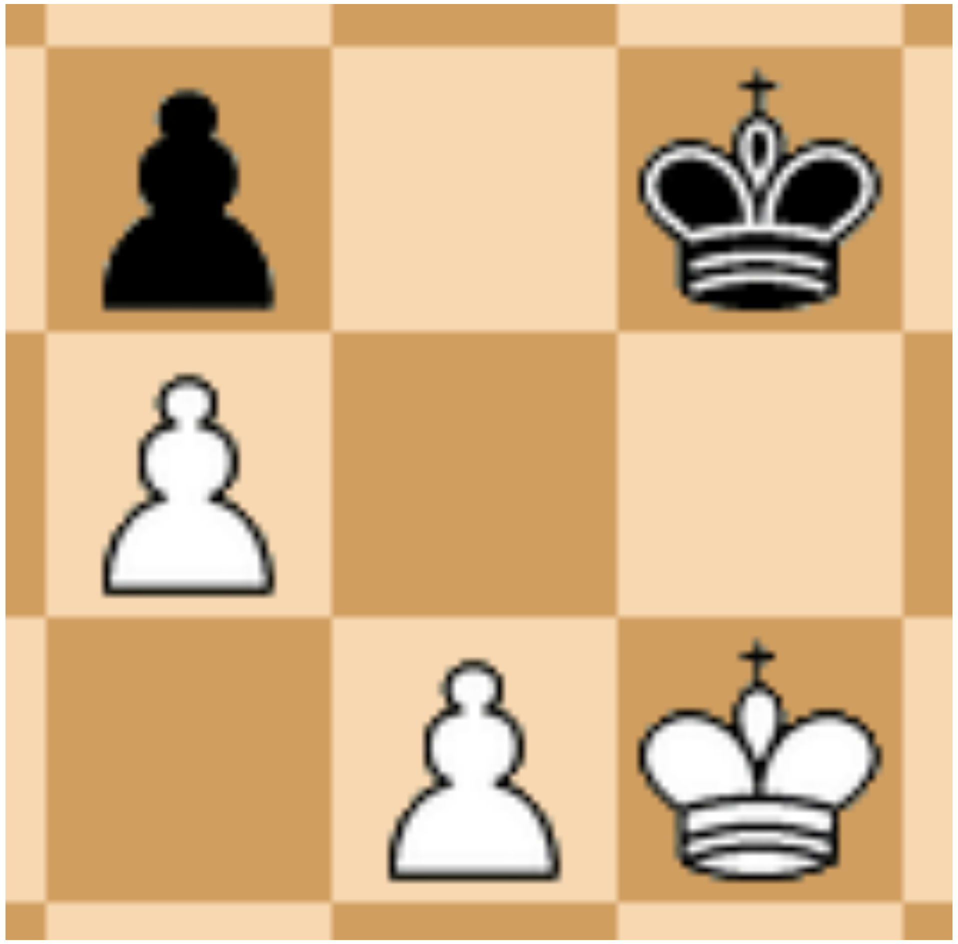
Plus HO corrections...

- 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 $\boxed{\theta_{23} = 45^o + \sqrt{2}\theta_{13} \cos\delta}$
  - Trimaximal2 $\theta_{23} = 45^o - \dfrac{\theta_{13}}{\sqrt{2}} \cos\delta$

Plus Charged Lepton Corrections...

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

Given this end game:



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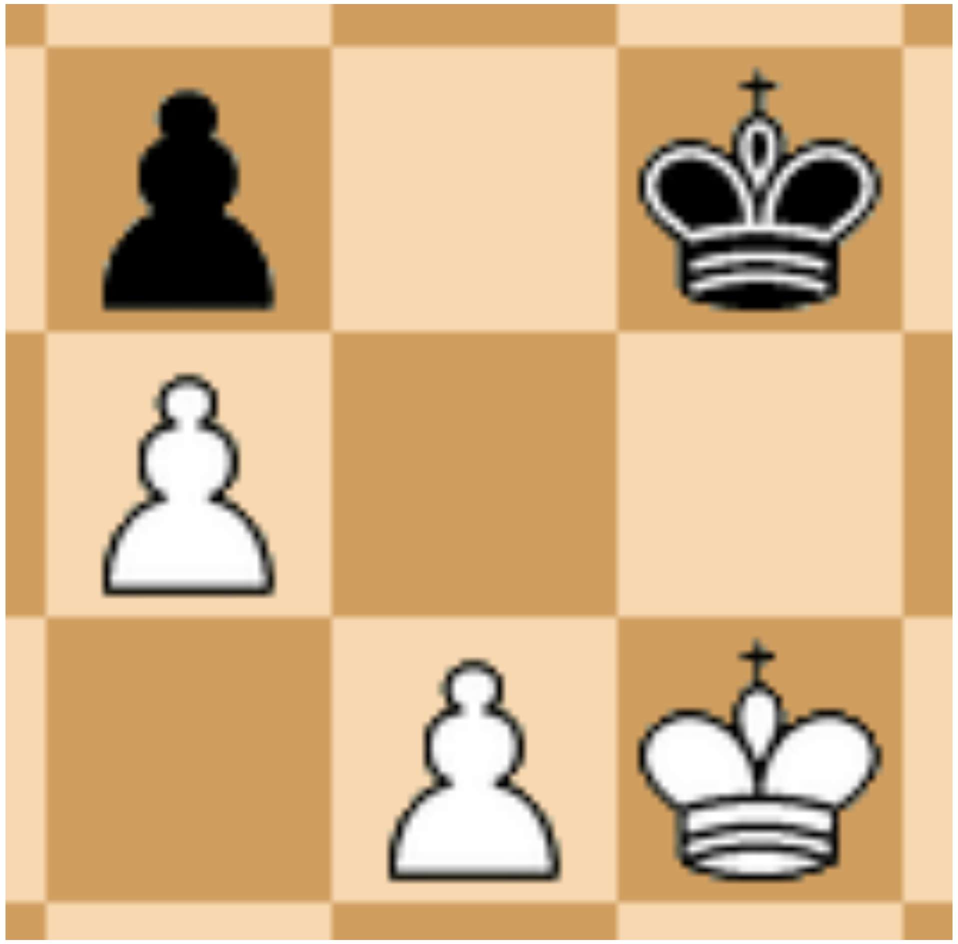

Deduce the rules of chess!!!

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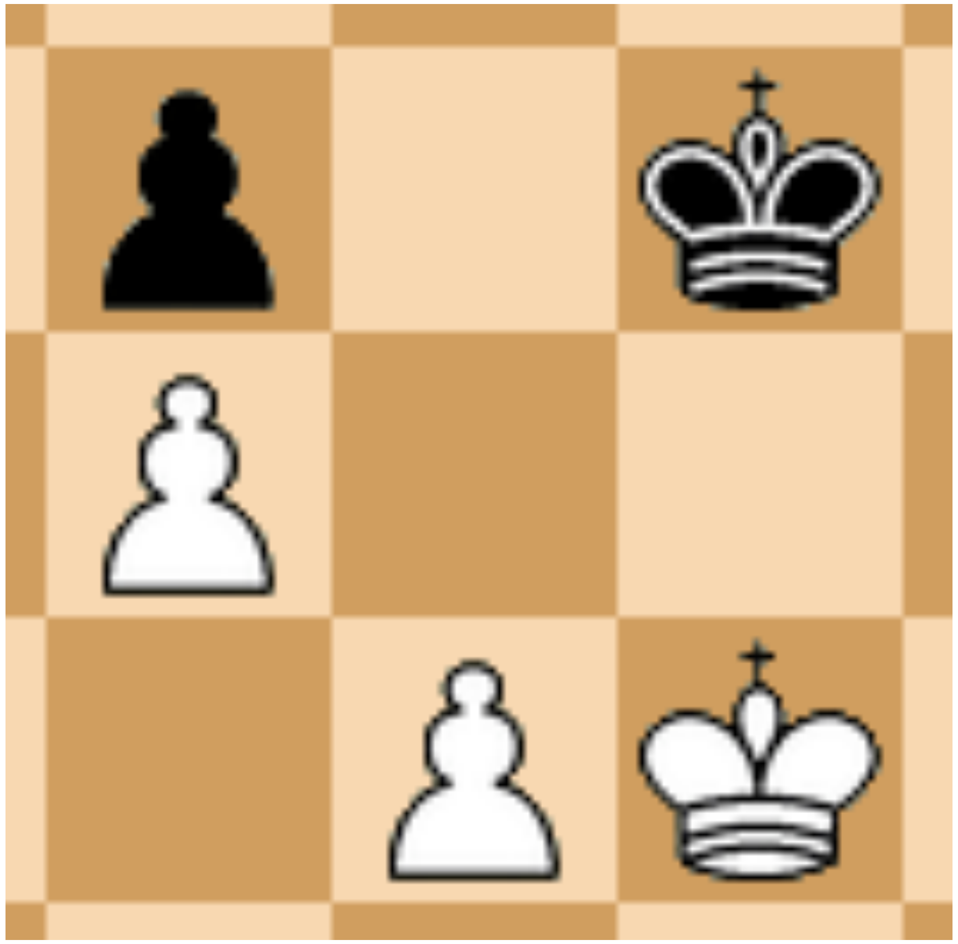


Deduce the rules of chess!!!

theorists need more hints !

Precision Measurements:

Nu_e Disappearance Experiments:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{ee} L}{4E} \right) + O(\Delta^2_{21}) \,,$$

Δm^2_{ee} is the electron neutrino weighted average of Δm^2_{31} and Δm^2_{32}

Reactor Experiments Nu 2014:

Double Chooz: $\sin^2(2\theta_{13}) = (0.09^{+0.03}_{-0.04})$

RENO $\sin^2(2\theta_{13}) = 0.101 \pm 0.008\ (\text{stat.}) \pm 0.010\ (\text{sys.})$

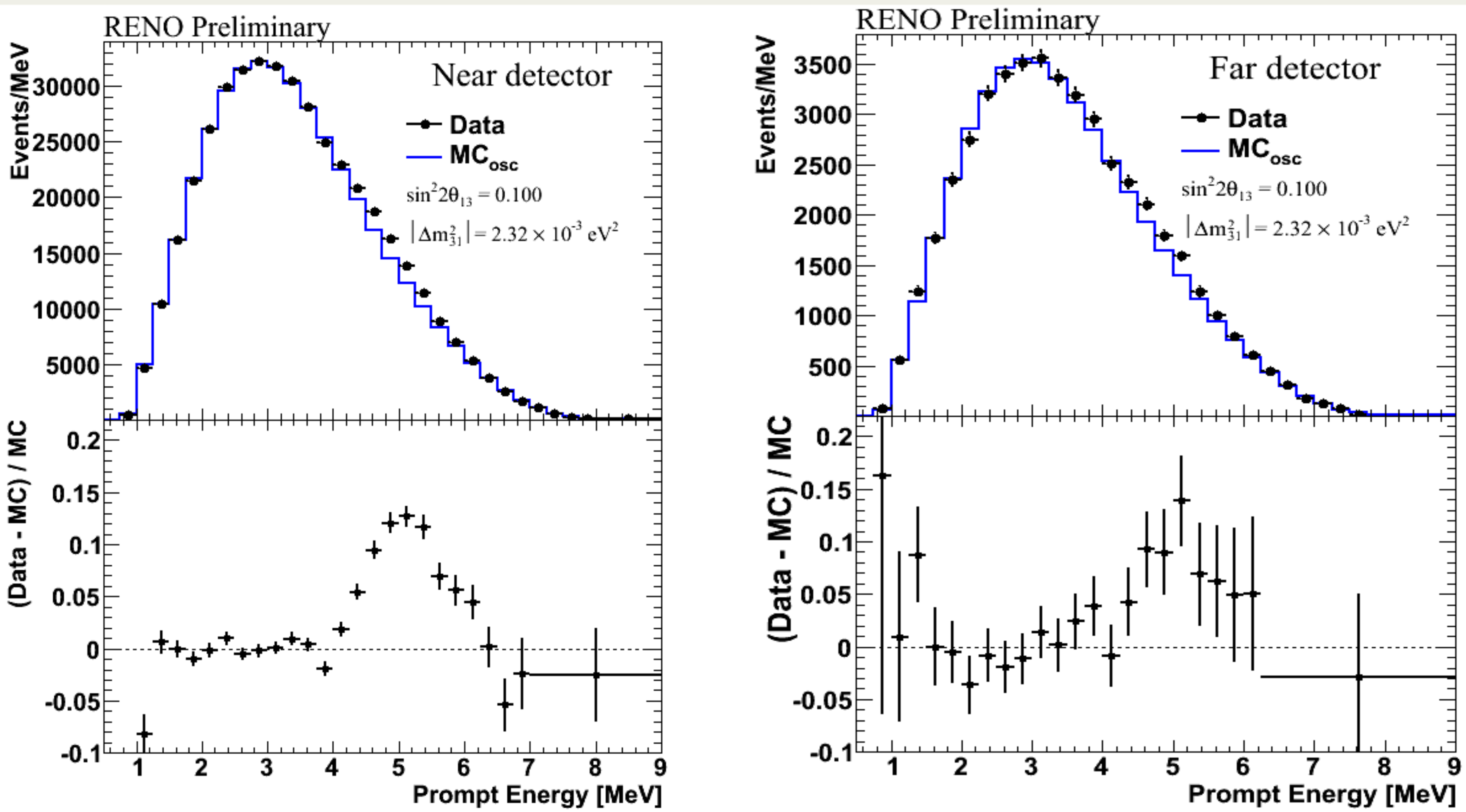
Daya Bay:

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3} \mathrm{eV}^2$$

from RENO:

Observation of new reactor ν component at 5 MeV



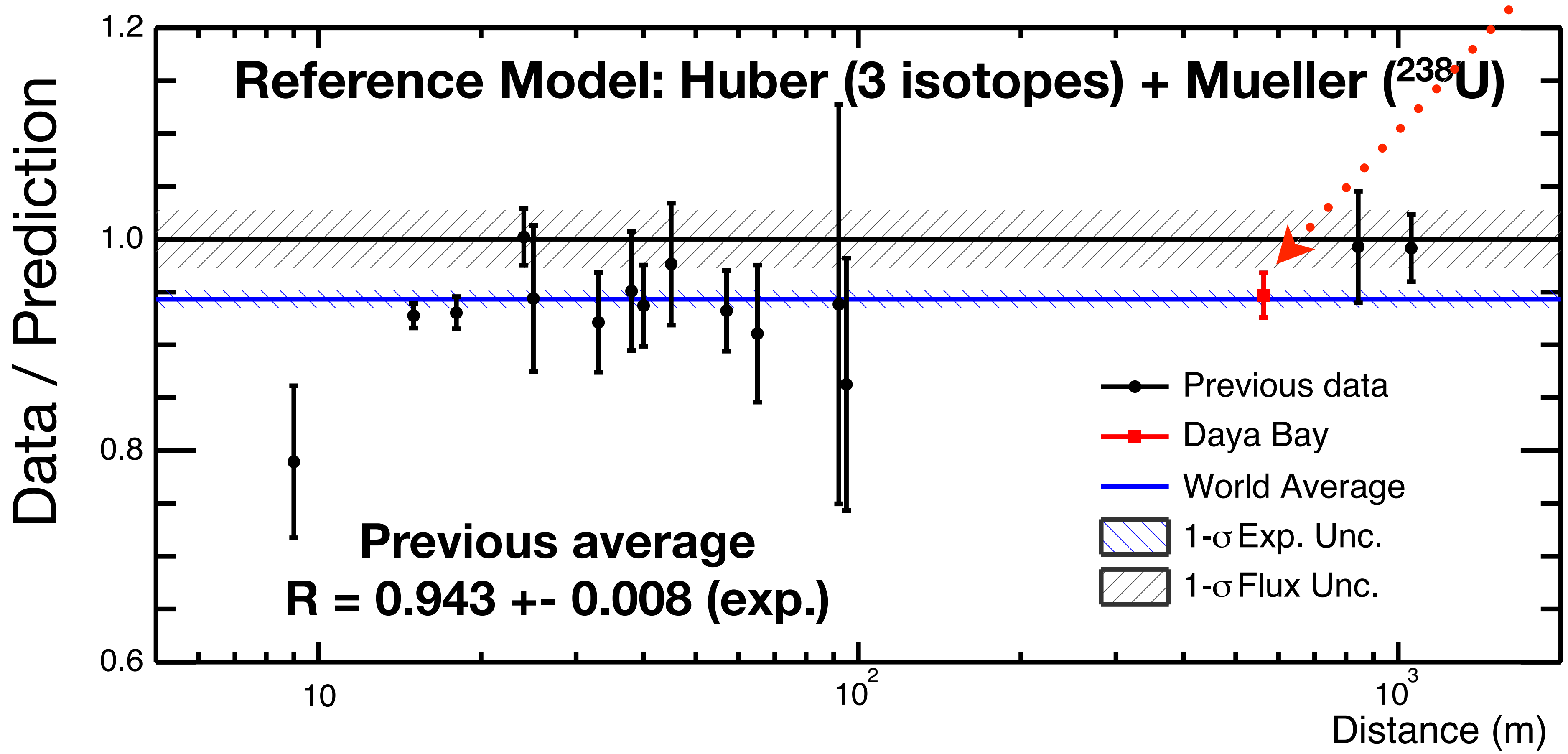
Fraction of 5 MeV excess (%) to expected flux

- Near : 2.303 +/- 0.401 (experimental) +/- 0.492 (expected shape error)
- Far : 1.775 +/- 0.708 (experimental) +/- 0.486 (expected shape error)

Seo Nu 2014

near detectors absolute flux

from Daya Bay:



Zhang Nu 2014

near detectors absolute flux

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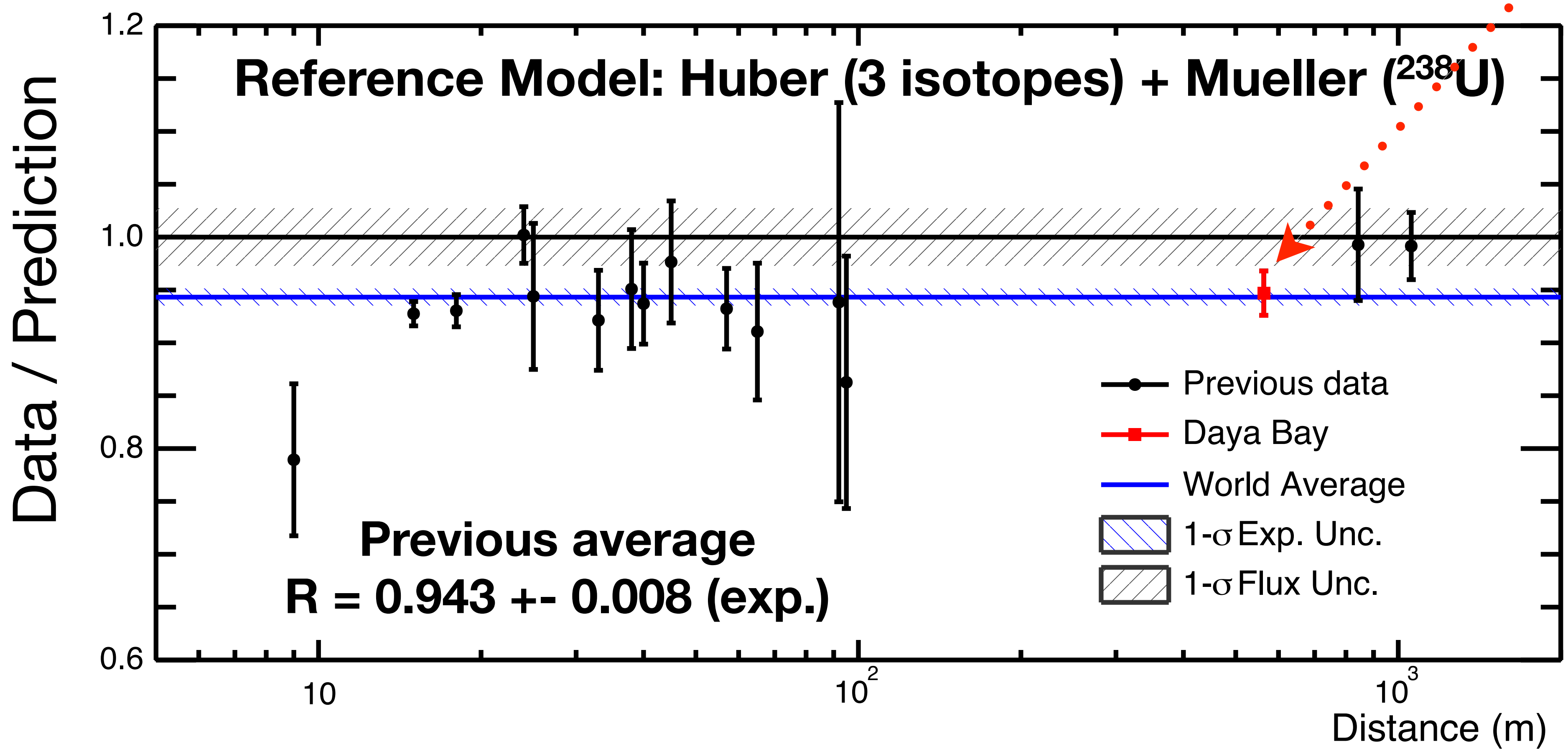


Zhang Nu 2014

In general:

- θ_{13} determined by reactor experiments: eventually 5% or better
- JUNO and RENO-50 best determination of δm^2_{21} and θ_{12}
- Atmospheric Mass Ordering (Hierarchy)? maybe !

Energy resolution and linearity requirements extremely serve!

Nu_mu Disappearance Experiments:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \left(\frac{\Delta m^2_{\mu\mu} L}{4E} \right) + O(\Delta^2_{21}) \, ,$$

$$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) = 4 \cos^2 \theta_{13} \sin^2 \theta_{23}(1 - \cos^2 \theta_{13} \sin^2 \theta_{23})$$

- Non-zero θ_{13} modifies the octant degeneracy ! ! !

$\Delta m^2_{\mu\mu}$ is the muon neutrino weighted average of Δm^2_{31} and Δm^2_{32}

Nu_mu Disappearance Experiments:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m^2_{\mu\mu} L}{4E}\right) + O(\Delta^2_{21}) \,,$$

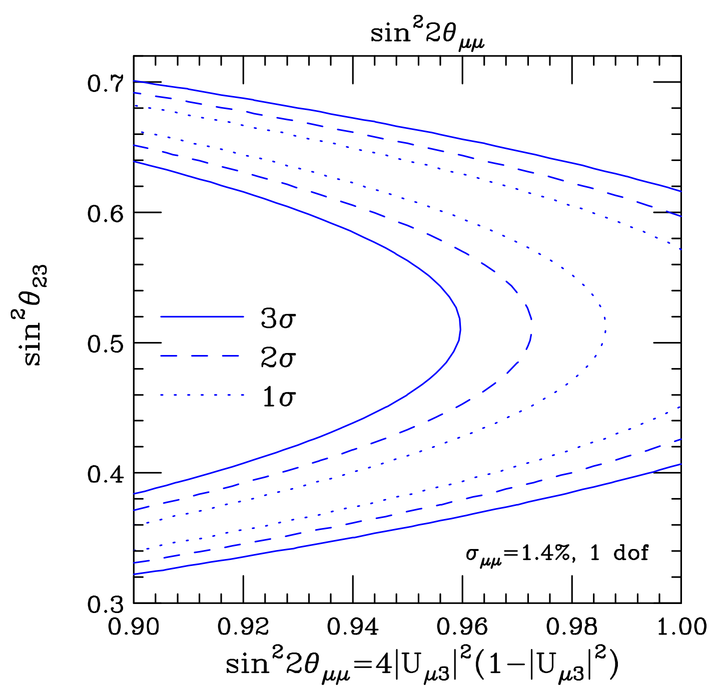
$$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2) = 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23})$$

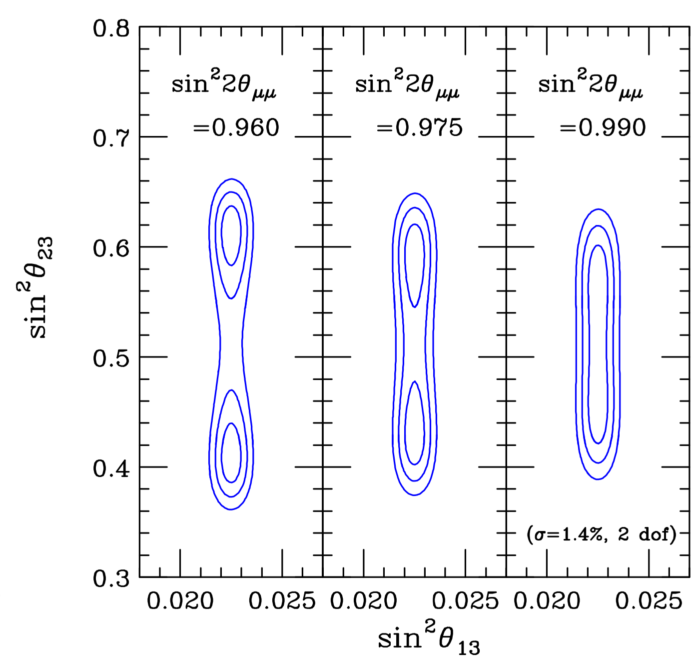
- Non-zero θ_{13} modifies the octant degeneracy ! ! !

$\Delta m^2_{\mu\mu}$ is the muon neutrino weighted average of Δm^2_{31} and Δm^2_{32}

$$\sin^2\theta^{(1)}_{23} = \sin^2\theta_{\mu\mu}/\cos^2\theta_{13} \;\approx\; \sin^2\theta_{\mu\mu}(1+\sin^2\theta_{13}) \,,$$
$$\sin^2\theta^{(2)}_{23} = \cos^2\theta_{\mu\mu}/\cos^2\theta_{13} \;\approx\; \cos^2\theta_{\mu\mu}(1+\sin^2\theta_{13}) \,,$$

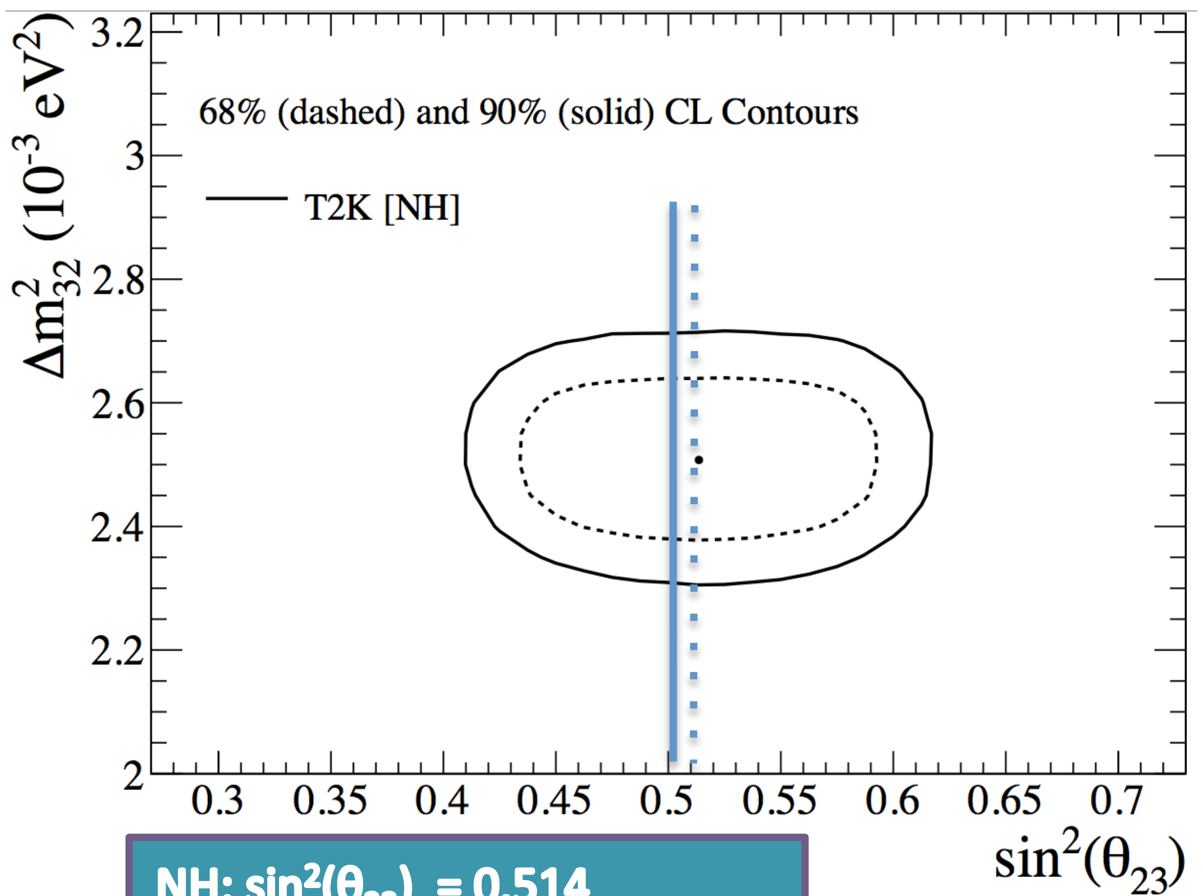
$$\sin^2\theta_{\mu\mu} \leq \frac{1}{2}$$





T2K Disappearance:

Maximal mixing is not the same as maximum disappearance if θ_{13} is not zero!



NH: $\sin^2(\theta_{23})$ = 0.514
NH: Δm^2_{32} = 2.51×10^{-3} eV^2

For θ_{13} given by reactor experiments:

At reactor value: $$\frac{1}{2\cos^2\theta_{13}} \approx 0.513$$

- Near $\pi/4$ the precision on θ_{23} from appearance measurements can exceeds that of disappearance measurements

Appearance Experiments:

$$\begin{array}{ccccc} & & \text{CP} & & \\ & \nu_\mu \to \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \to \bar{\nu}_e & \\ \text{T} & \Updownarrow & \text{CPT across diagonals} & \Updownarrow & \text{T} \\ & \nu_e \to \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \to \bar{\nu}_\mu & \\ & & \text{CP} & & \end{array}$$

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

ν_τ at Neutrino Factory

Appearance Experiments:

$$\begin{array}{ccccc} & & \text{CP} & & \\ & \nu_\mu \longrightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \longrightarrow \bar{\nu}_e & \\ \text{T} & \Updownarrow & \text{CPT across diagonals} & \Updownarrow & \text{T} \\ & \nu_e \longrightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \longrightarrow \bar{\nu}_\mu & \\ & & \text{CP} & & \end{array}$$

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

$\boldsymbol{\nu_\tau}$ at Neutrino Factory

- goal: θ_{23}, δ and atmospheric mass ordering (δm^2_{31})

$$\nu_\mu \longrightarrow \nu_e$$

Vacuum LBL:

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

$$\updownarrow$$

CP violation !!!

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

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

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

$$\nu_\mu \longrightarrow \nu_e$$

Vacuum LBL:

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

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

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

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

only CPV

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

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

$$\nu_\mu \longrightarrow \nu_e$$

In Matter:

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

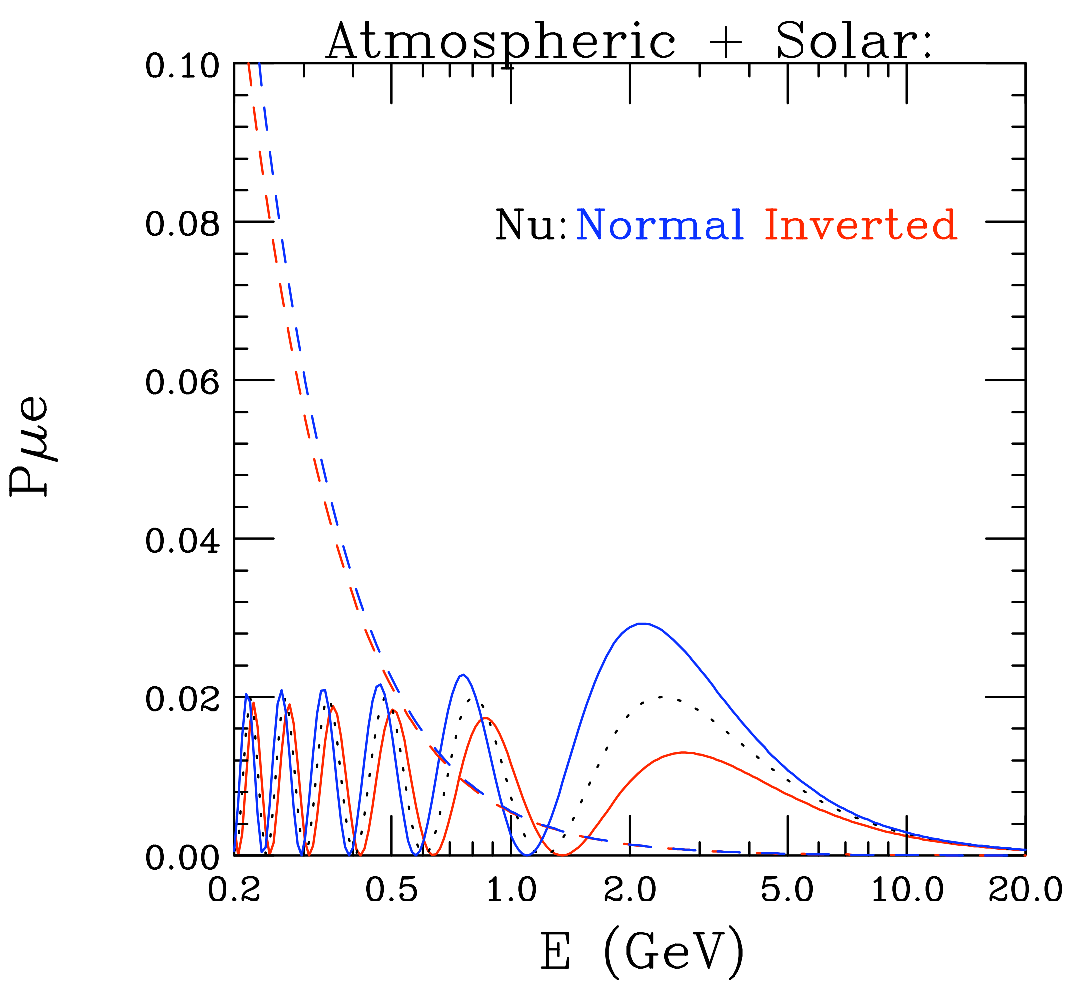
where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\,\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\,\Delta_{31}$

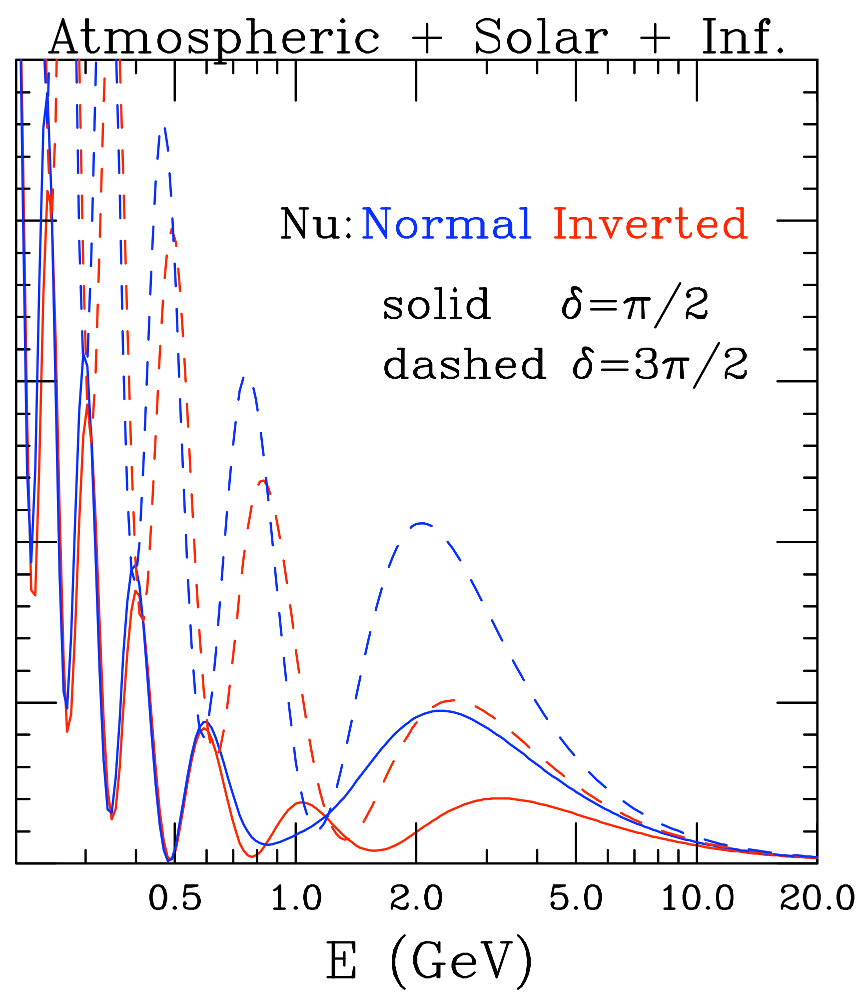
and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\,\frac{\sin(aL)}{(aL)}\,\Delta_{21}$

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

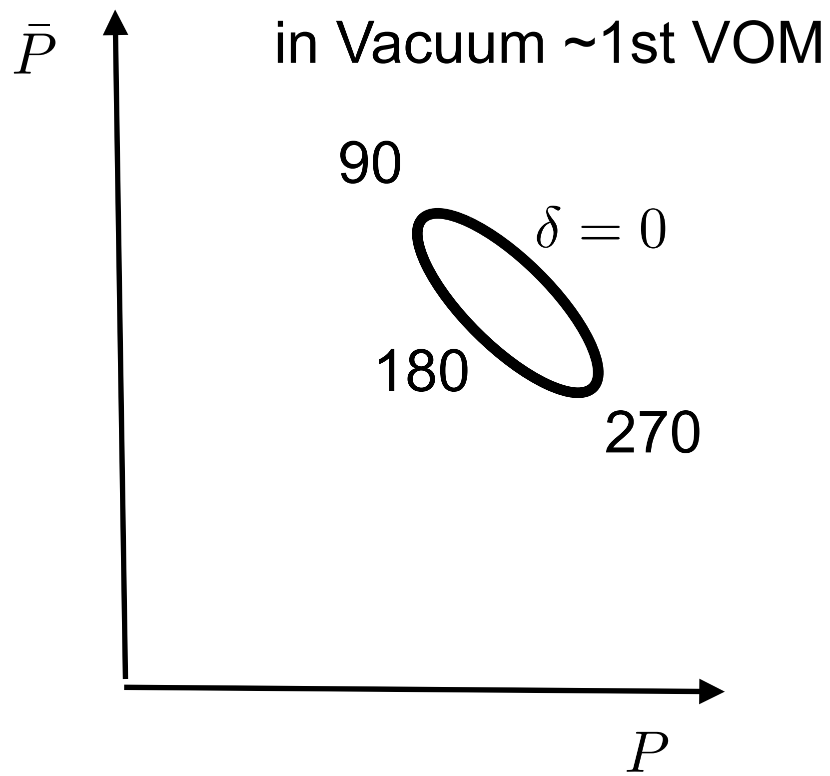
$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

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





BiProbability Diagrams:



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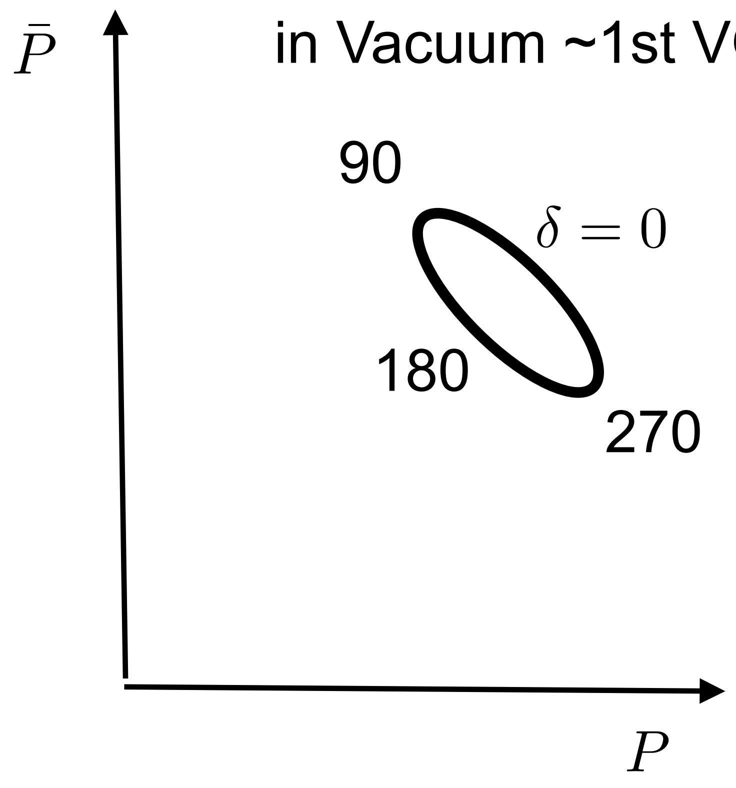
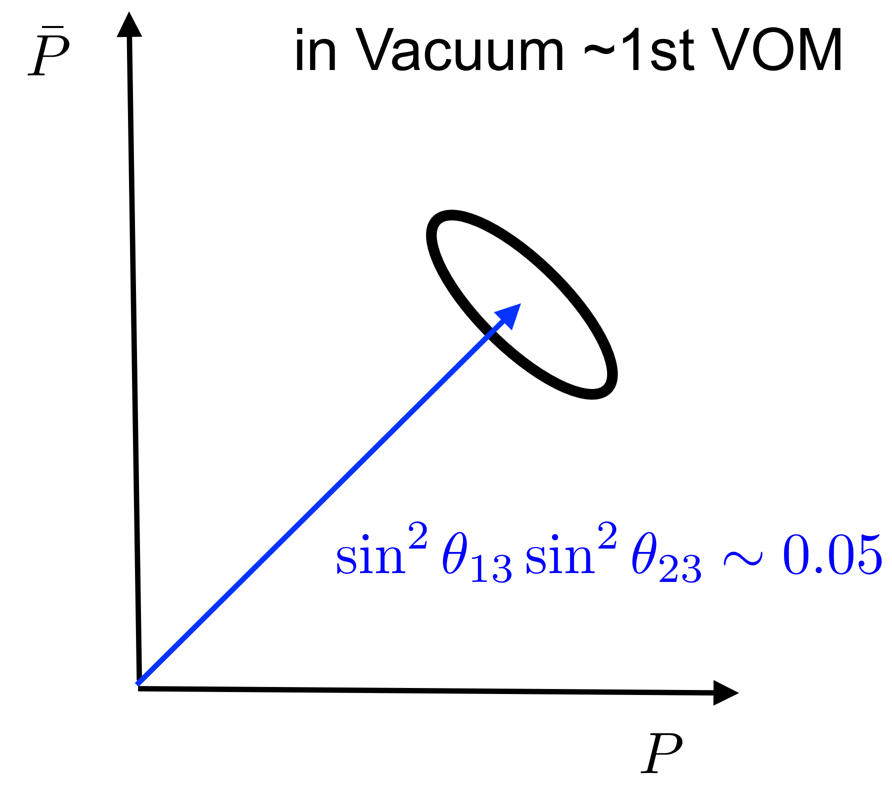
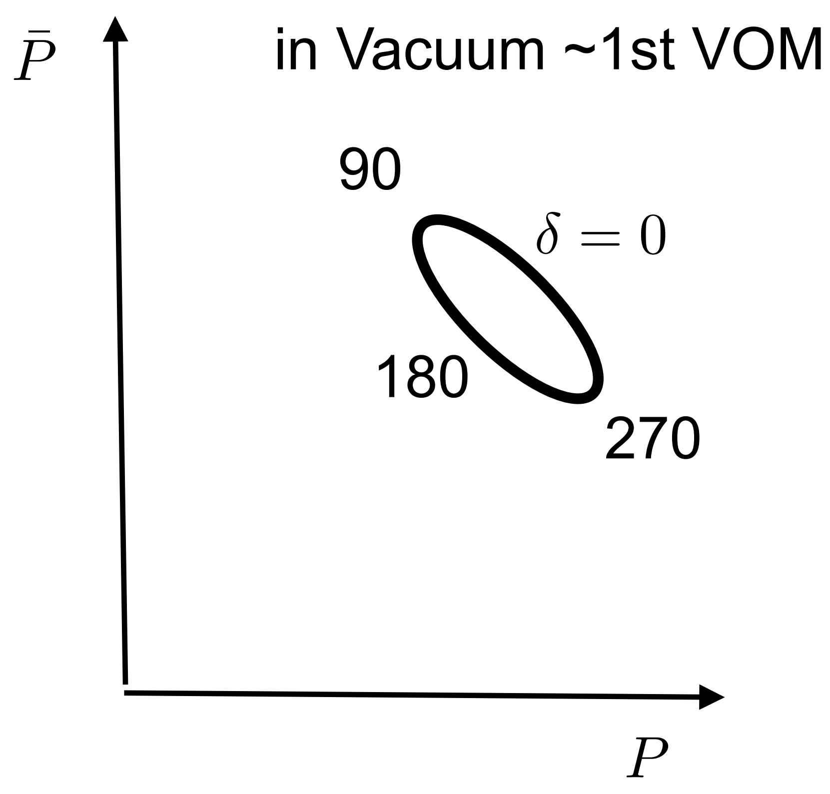
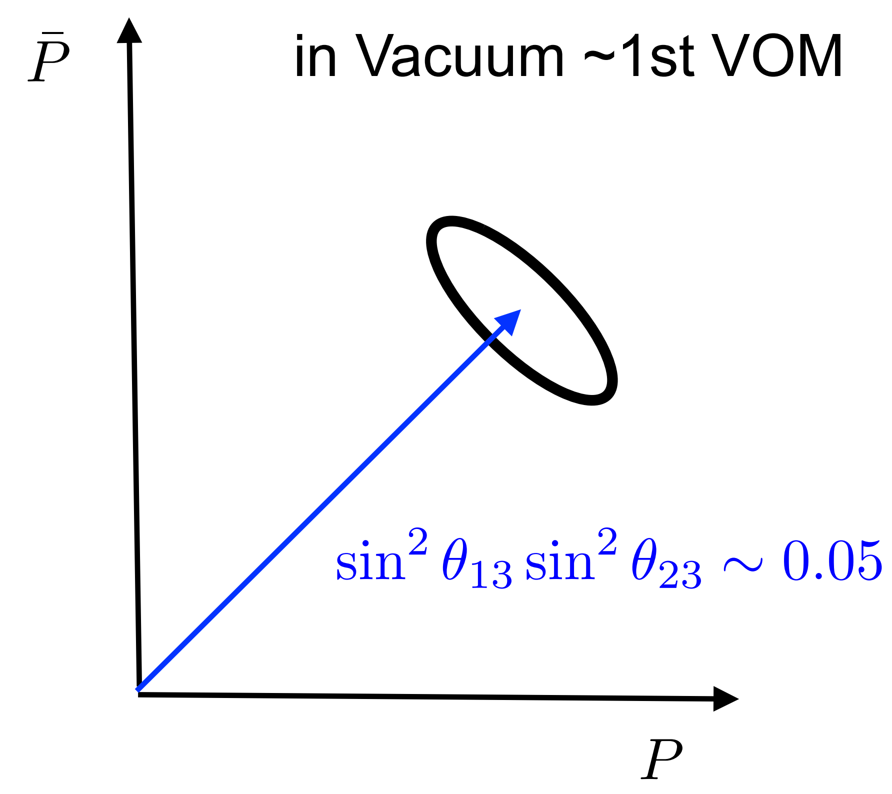
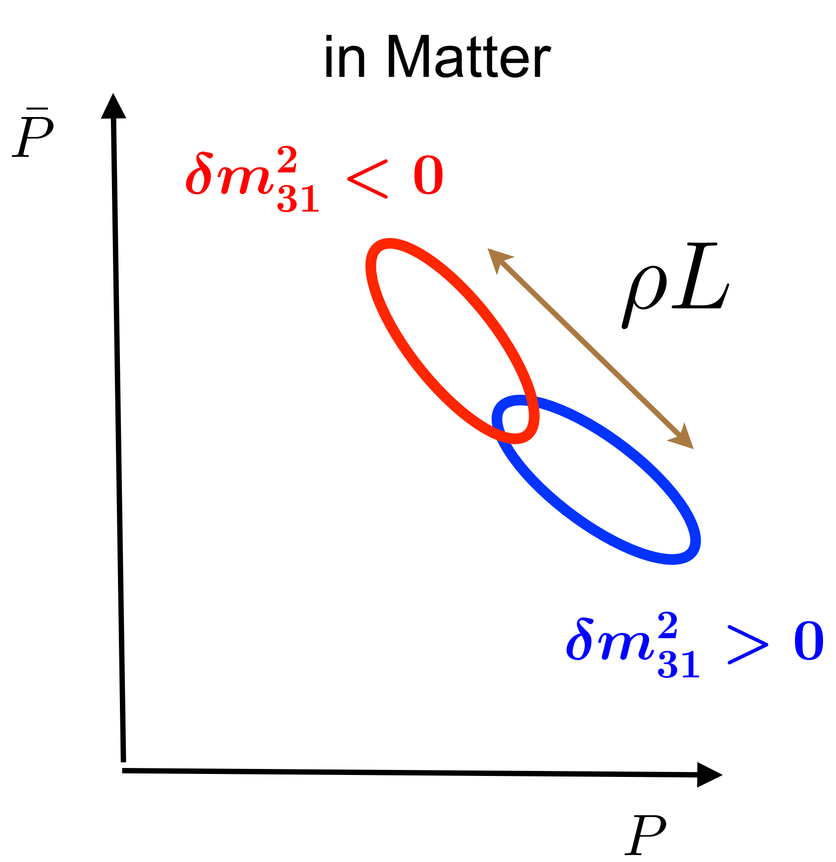




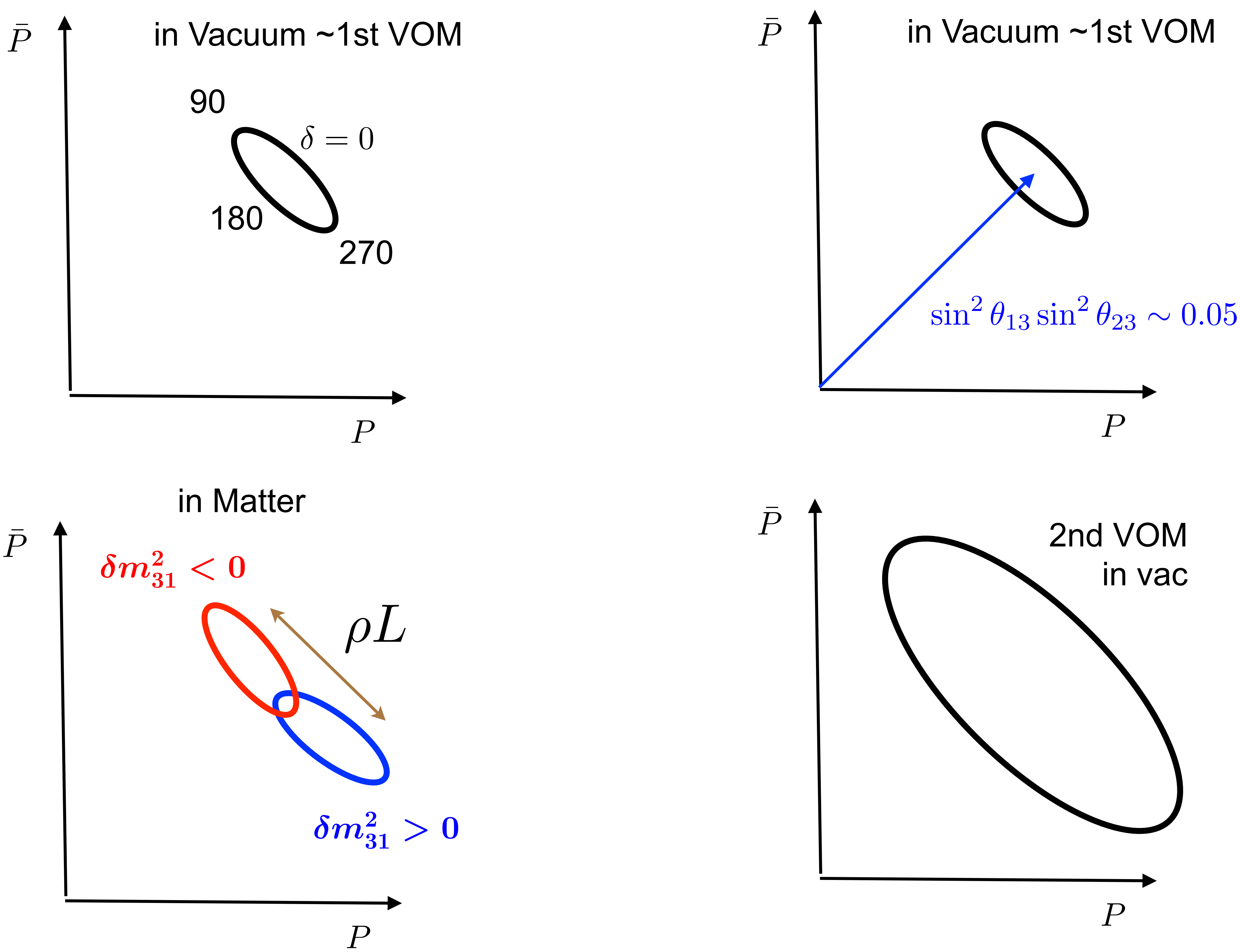
BiProbability Diagrams:





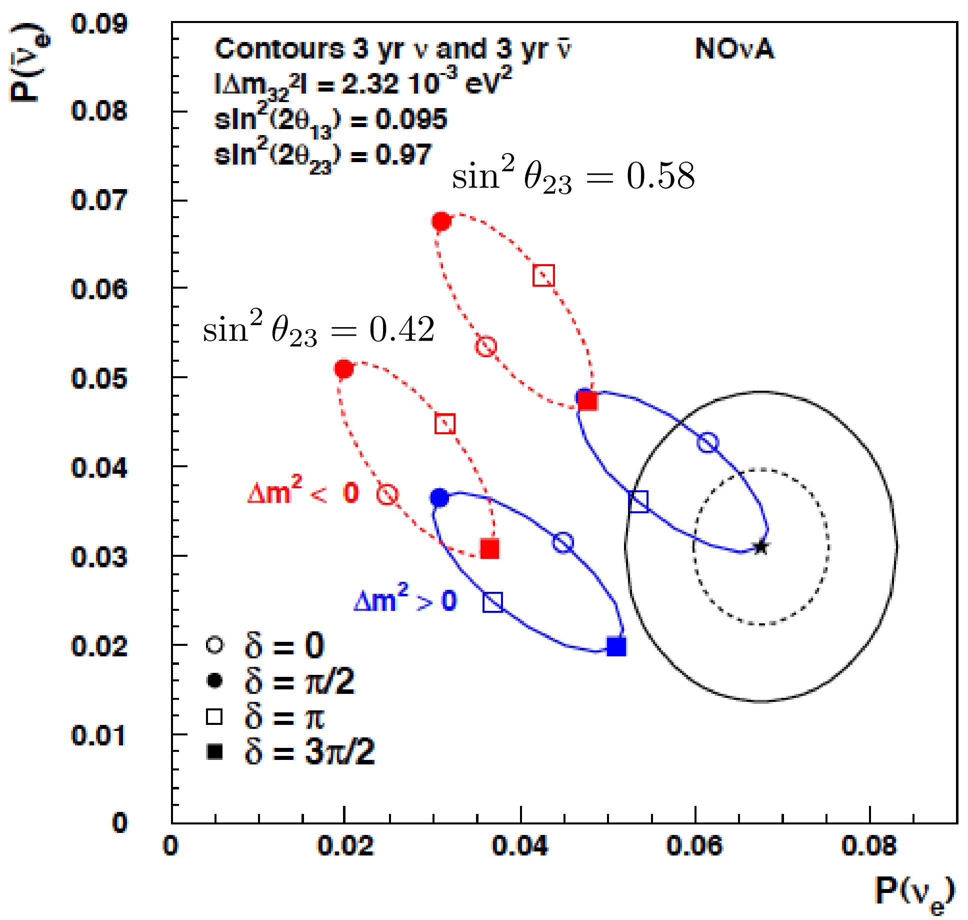


BiProbability Diagrams:

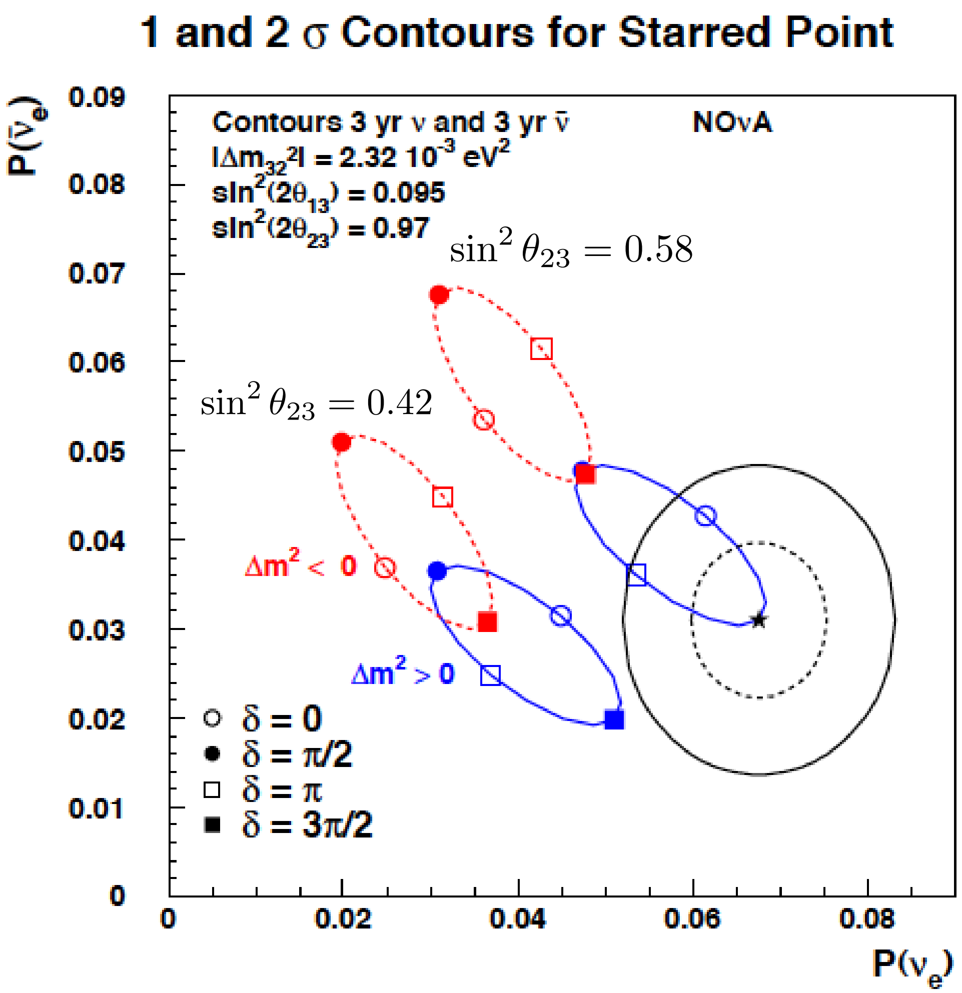


NOvA & LBNF

1 and 2 σ Contours for Starred Point



NOvA & LBNF



- $\sin^2\theta_{23} = 0.42 \quad \Rightarrow \quad \sin^2 2\theta_{\mu\mu} = 0.968$
- $\sin^2\theta_{23} = 0.58 \quad \Rightarrow \quad \sin^2 2\theta_{\mu\mu} = 0.982$

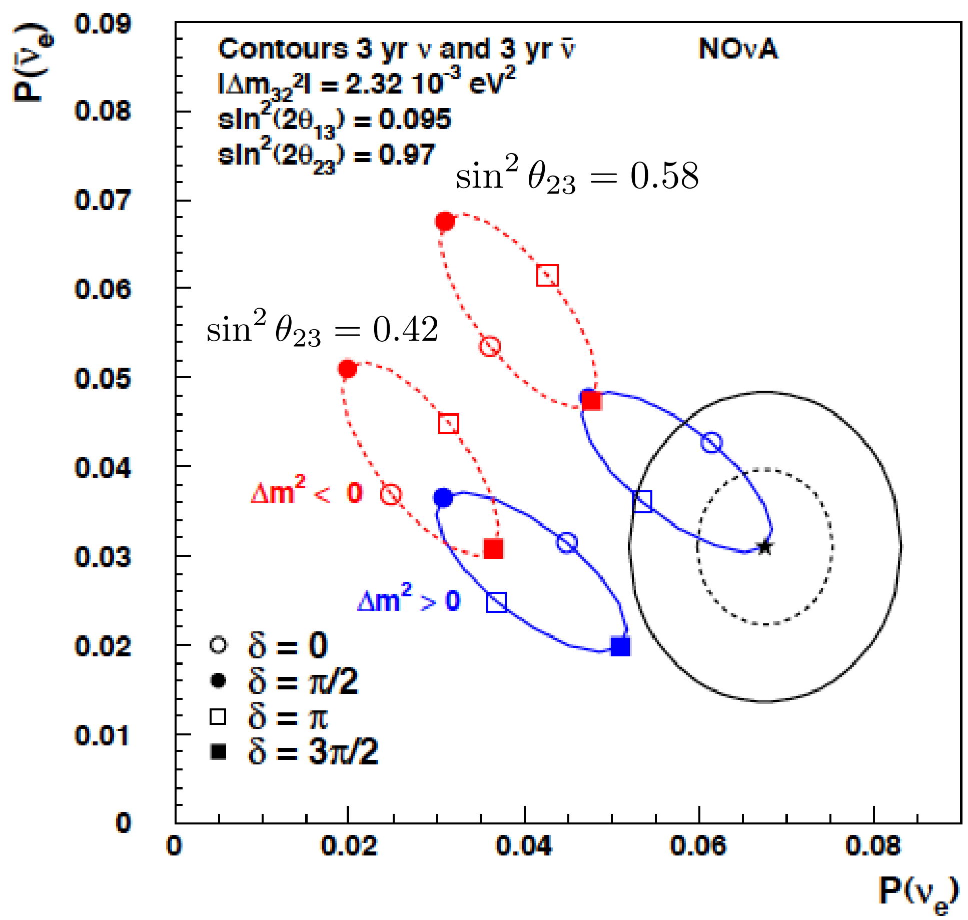
- Can be distinguished in disappearance channel with sufficient precision!

- Why don't use values that cannot be distinguished?

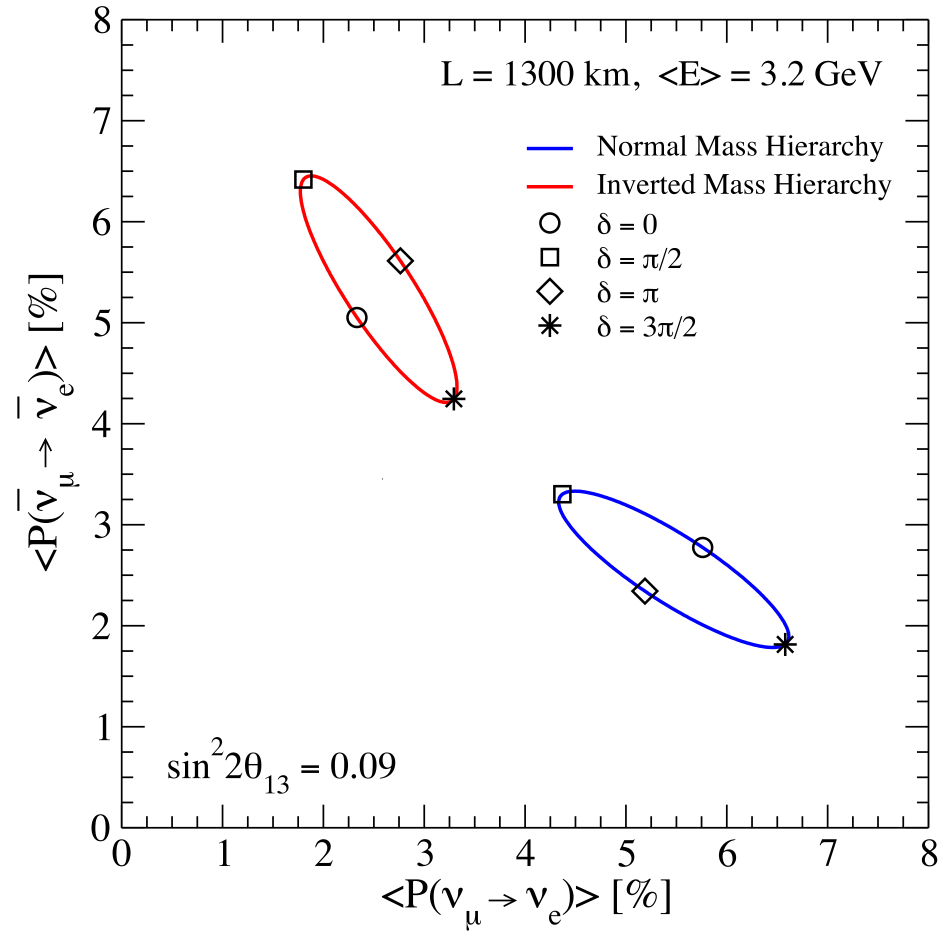
e.g. $\sin^2\theta_{23} = (0.430, 0.594)$

NOvA & LBNF

1 and 2 σ Contours for Starred Point



LBNE:
@ same L/E as NOvA



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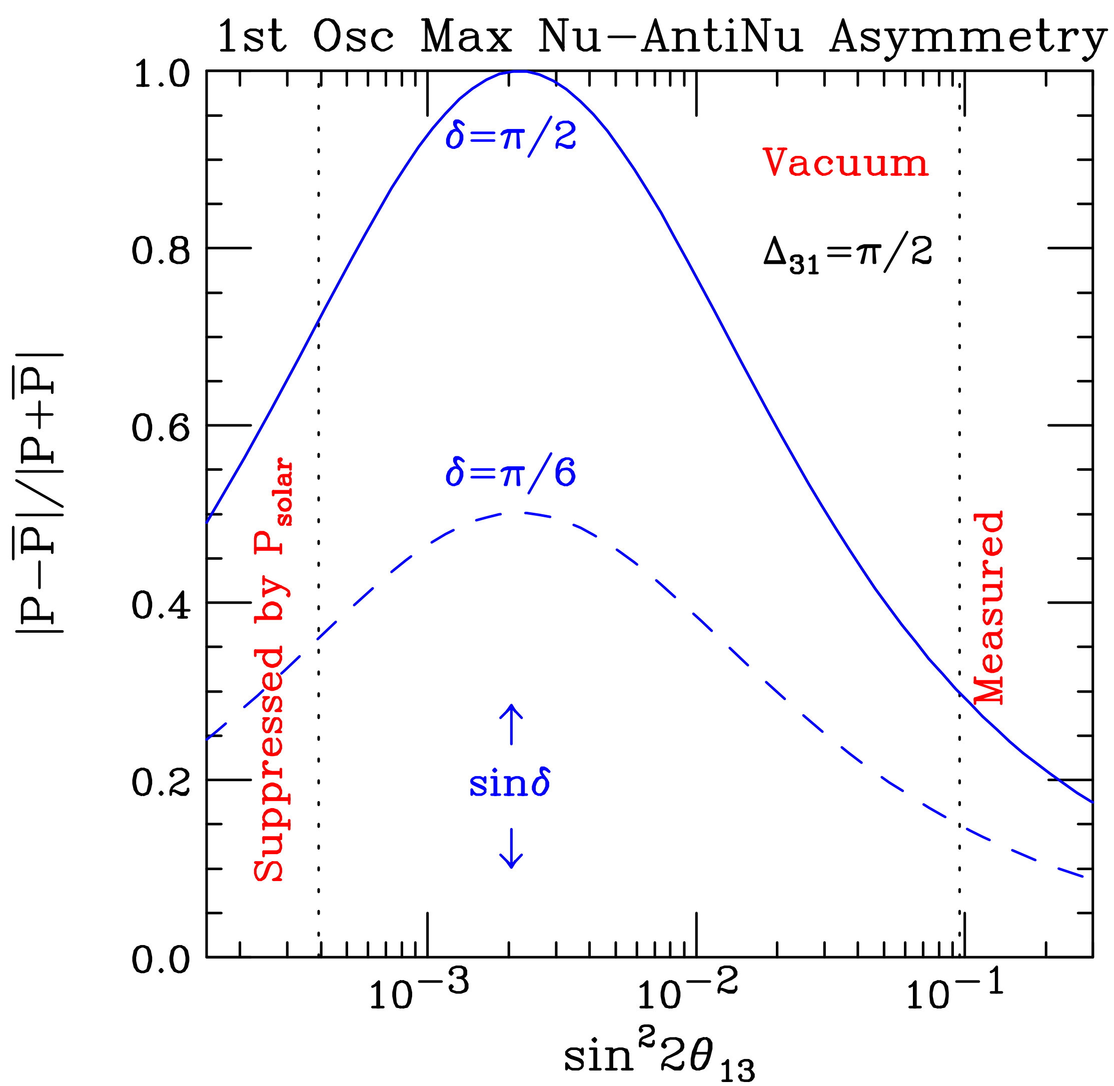
e.g. $\sin^2\bar{\theta}_{23} = (0.430, 0.594)$

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 $P(\nu_\mu \to \nu_e)$!!!



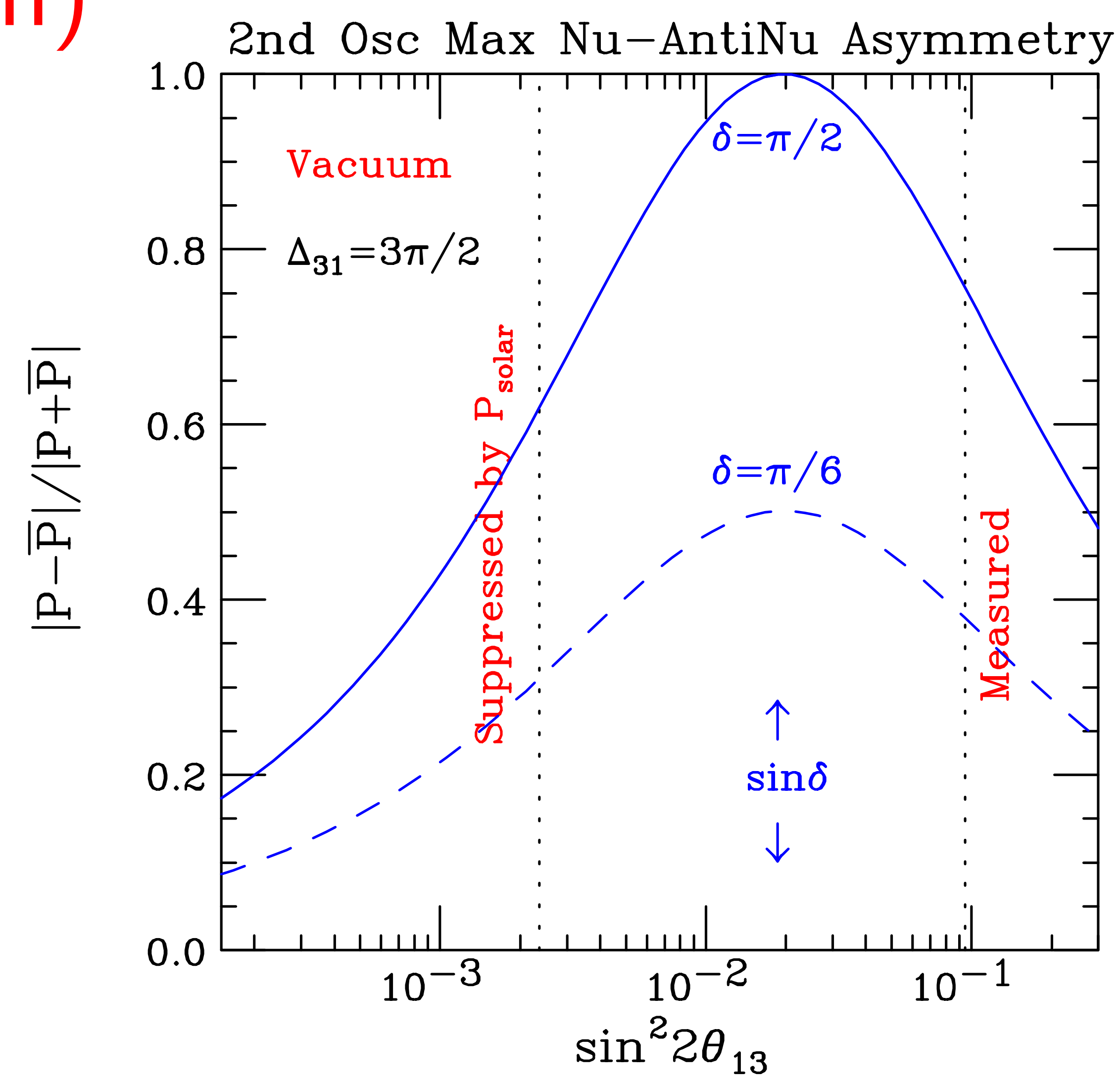
2nd Oscillation Max:

ESS to Garpenburg (540km)

$$A_{vac} \approx 0.75 \sin\delta$$

$A_{vac}(2^{nd}\ \mathrm{OM}) \approx 2.5\ \ A_{vac}(1^{st}\ \mathrm{OM})$

(9/11 of 3)



$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ ranges is between $\frac{1}{7}$ and 7 $P(\nu_\mu \to \nu_e)$

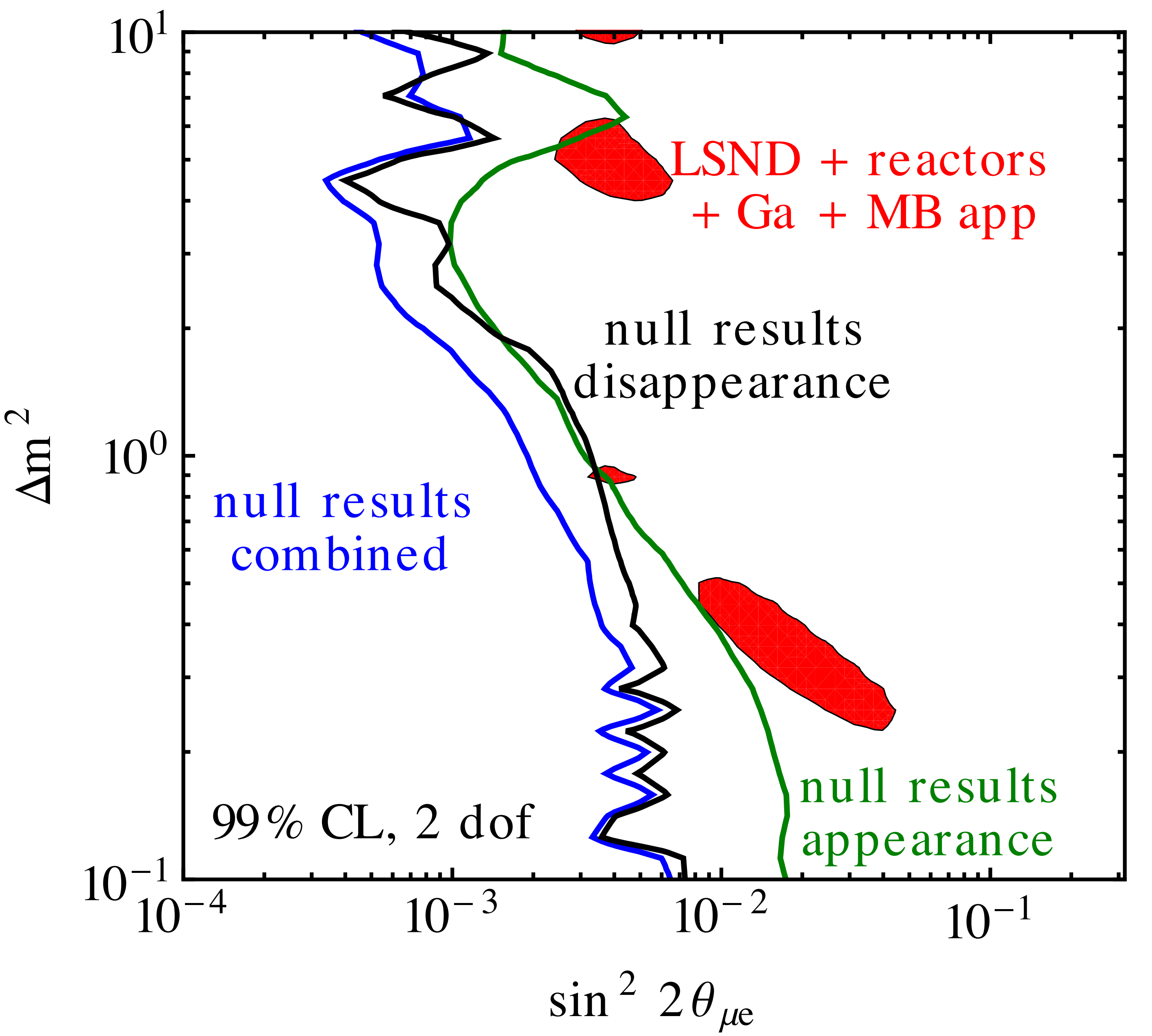
Appearance Probabilities more dynamic near 2nd Osc. Max. than 1st. OM

Leptogenesis:

- CP Violation, as well as L Violation, are key ingredients of Leptogenesis

The observation of L violation and of CPV in the lepton sector would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry.

Tensions in Current Data:



Relation between appearance and disappearance

We find: $\overset{(-)}{\nu}_e$ disappearance experiments consistent among themselves,
$\overset{(-)}{\nu}_e$ appearance experiments consistent among themselves.

But:

$3+1$ neutrinos

At $L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$

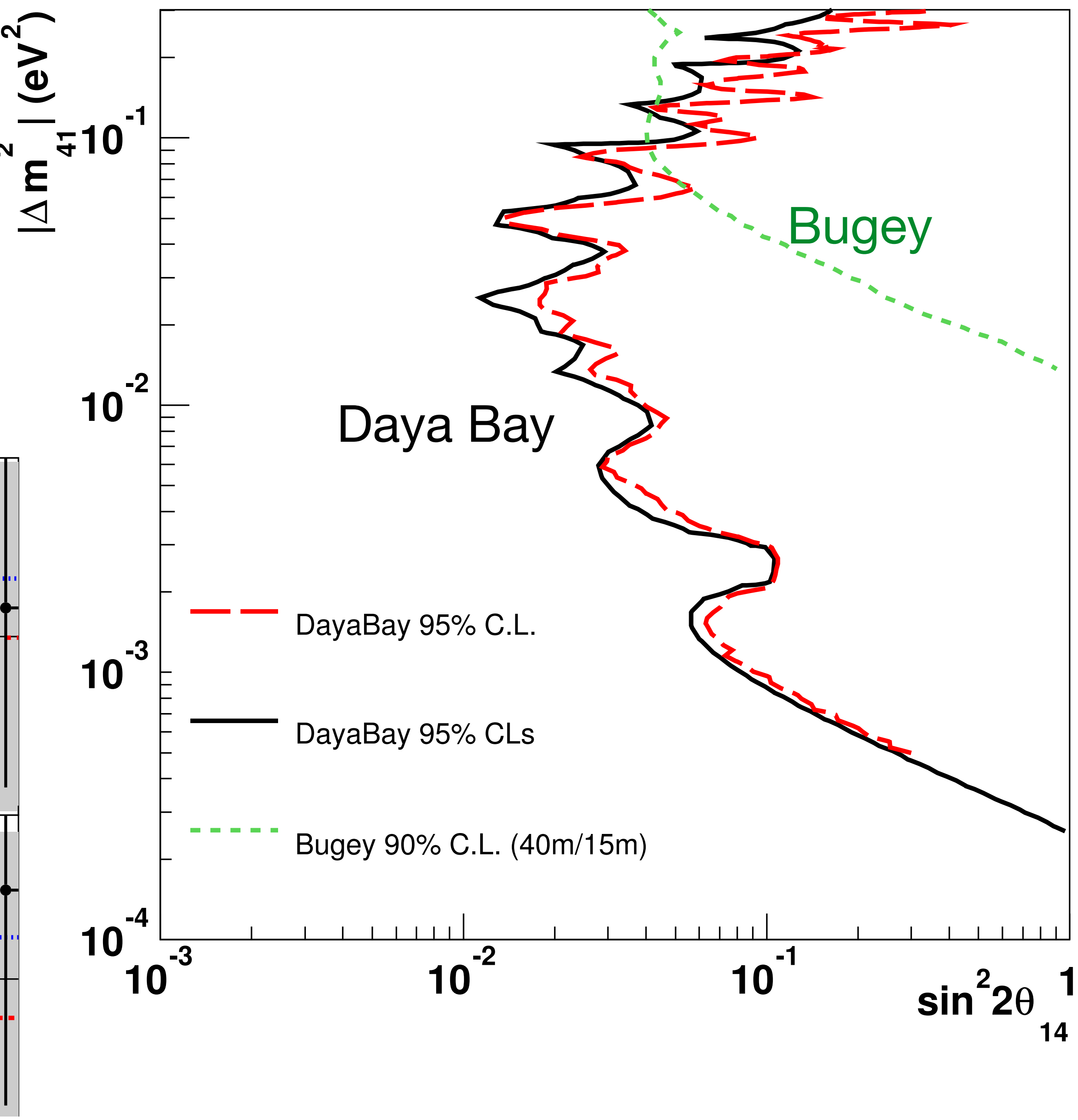
$$P_{ee} = 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$
$$P_{\mu\mu} = 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$
$$P_{e\mu} = 2|U_{e4}|^2|U_{\mu 4}|^2$$

It follows

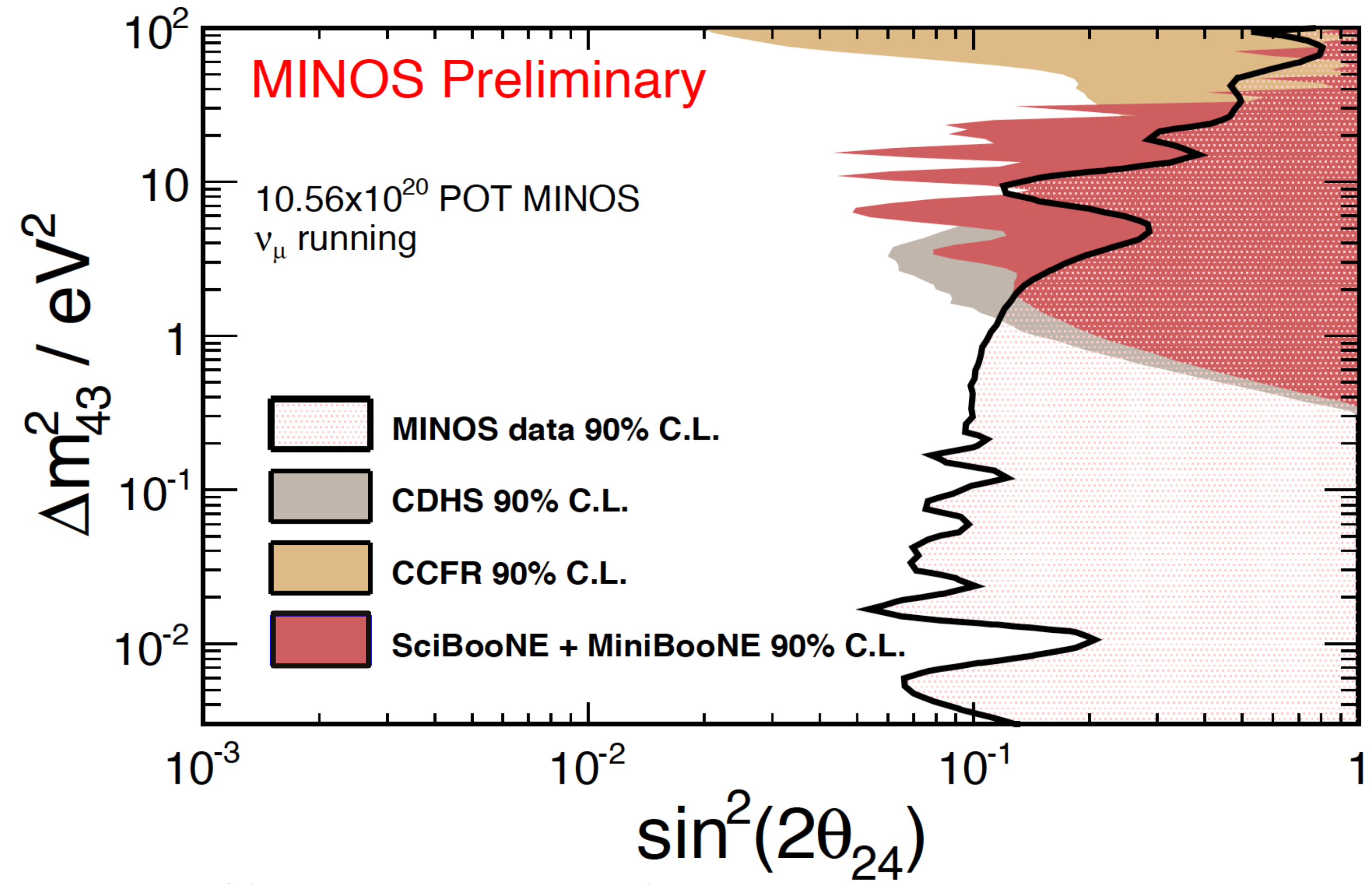
$$2P_{e\mu} \simeq (1 - P_{ee})(1 - P_{\mu\mu})$$

In the $3+1$ case, at large enough baseline, there is a one-to-one relation between the appearance and disappearance probabilities.

New Data:

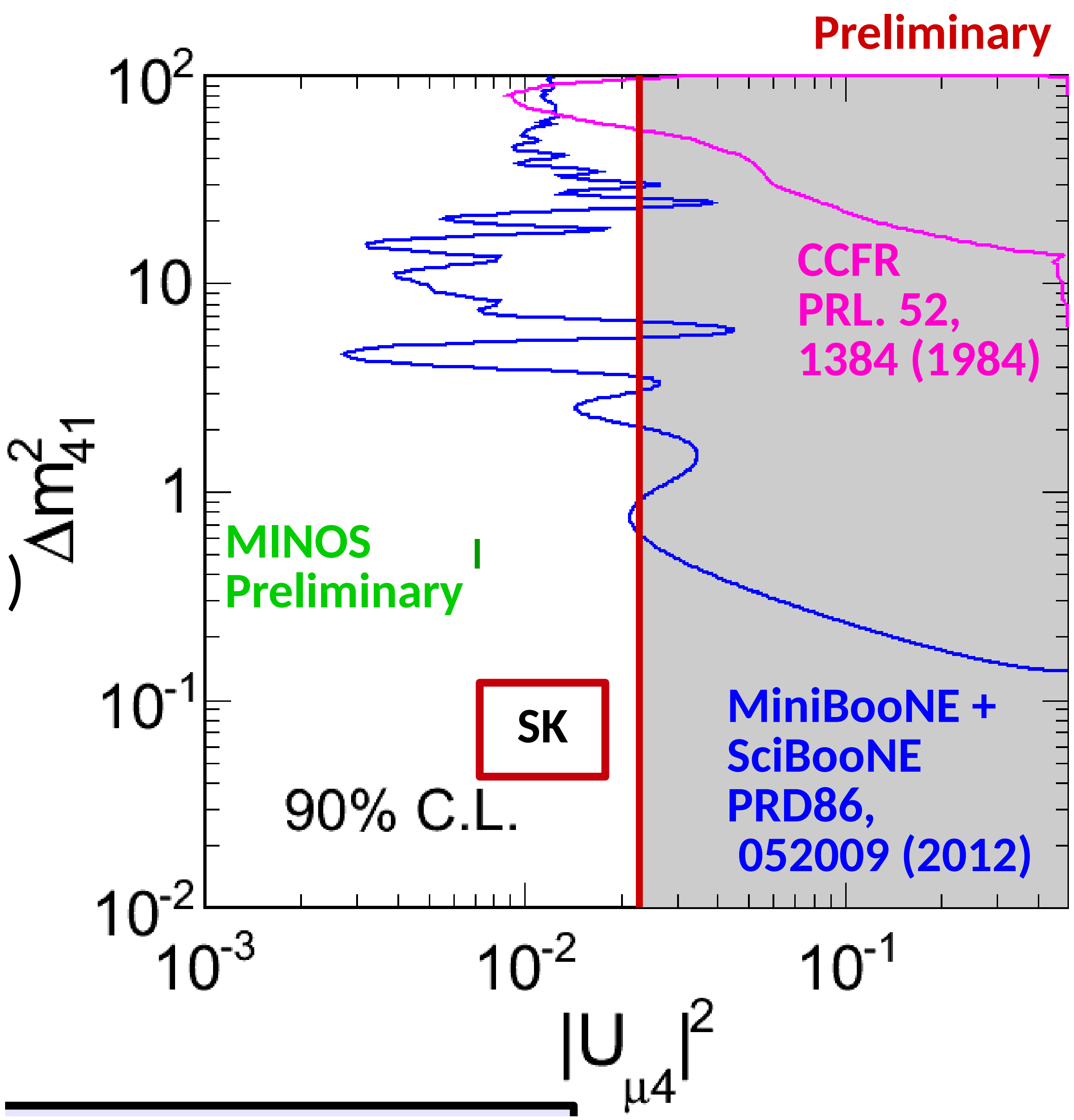


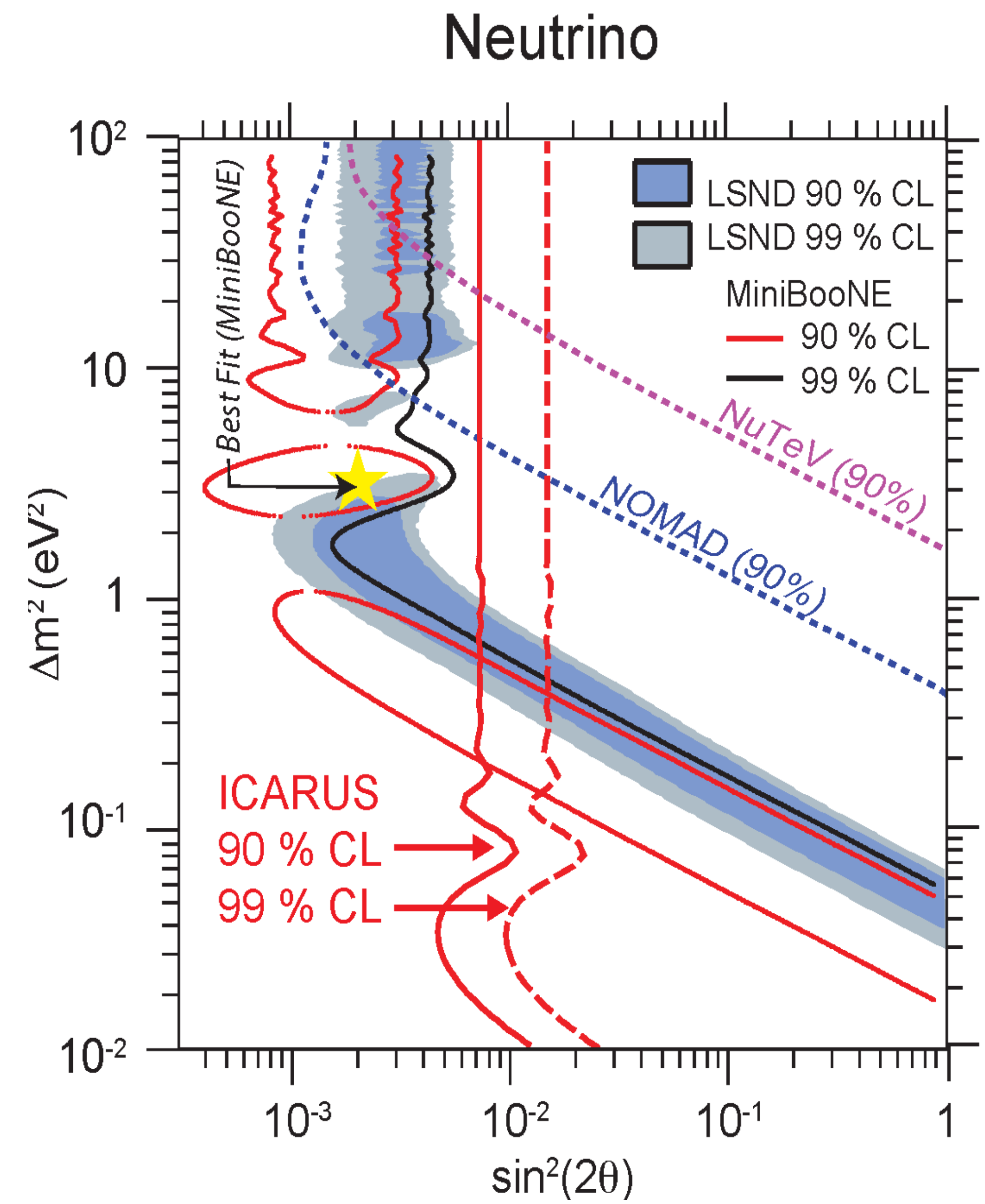
MINOS Disappearance Limit



- Limit is Feldman-Cousins corrected

MINOS 90% C.L. exclusion limit ranges over 4 orders of magnitude in Δm^2_{43}!
Strongest constraint on ν_μ disappearance into ν_s for $\Delta m^2_{43} < 1$ eV^2


Preliminary
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
Δm^2_{41}
$|U_{\mu 4}|^2$
CCFR
PRL. 52,
1384 (1984)
MINOS
Preliminary
SK
90% C.L.
MiniBooNE +
SciBooNE
PRD86,
052009 (2012)


Neutrino
LSND 90 % CL
LSND 99 % CL
MiniBooNE
90 % CL
99 % CL
NuTeV (90%)
NOMAD (90%)
Best Fit (MiniBooNE)
ICARUS
90 % CL
99 % CL
Δm^2 (eV^2)
$\sin^2(2\theta)$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1

Conclusions:

- To Be Majorana or Not To Be Majorana?

- We know ($|U_{e2}|^2$, $|U_{e3}|^2$, $|U_{\mu 3}|^2$) with precision of (5,10,15)% but have little information on the other 6 elements of the PMNS matrix without assuming Unitarity. Stringent tests of the νSM Paradigm needed.

- Determining the Mass Hierarchy & measuring CPV are the next steps. Tau's?

- m_{lite}, if $\ll \delta m^2_{21}$, a new scale to explain !

Conclusions:

- To Be Majorana or Not To Be Majorana?

- We know ($|U_{e2}|^2$, $|U_{e3}|^2$, $|U_{\mu3}|^2$) with precision of (5,10,15)% but have little information on the other 6 elements of the PMNS matrix without assuming Unitarity. Stringent tests of the νSM Paradigm needed.

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- m_{lite}, if $\ll \delta m^2_{21}$, a new scale to explain !

- Are there lite Sterile neutrinos?

Can we exclude $|U_{e4}|^2$ and $|U_{\mu 4}|^2 > 0.01$, say, for $\delta m^2 \sim 1eV^2$

- Solving the Neutrino Masses and Mixing pattern is difficult challenge for Theory! Need hints.

- Where are there further "SURPRISES" in the Neutrino Sector?

Ernest Rutherford:

We haven't got the money,

Ernest Rutherford:

We haven’t got the money,

Ernest Rutherford:

We haven't got the money,

so we'll have to think!