Status of Neutrino Physics after Neutrino 2016:

Stephen Parke - Fermilab
WH3W #366

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Preamble:
Three Neutrino Flavors

PMNS matrix

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

Mass Eigenstates Labeled by Decreasing ν_e content

flavor states

Mass Eigenstates

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  and Inverted Ordering: $m_3^2 < m_1^2 < m_2^2$ NOνA, LBNF, $\cdots$

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- $0.06\ \text{eV} < \sum m_i < 0.5\ \text{eV} \approx m_e/10^6$

PMNS matrix

$\longleftrightarrow$ 500 km/GeV

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500 km/GeV

15,000 km/GeV

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Usual representation:

23 13 12

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})$$

Atmospheric	Reactor/Interference	Solar
$\mu \to \tau$	$\mu \leftrightarrow e$	$\mu \to e$
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Atmospheric: $\mu \rightarrow \tau$, 500 Km/GeV

Reactor/Interference: $\mu \leftrightarrow e$, 500 Km/GeV

Solar: $\mu \rightarrow e$, 15,000 Km/GeV

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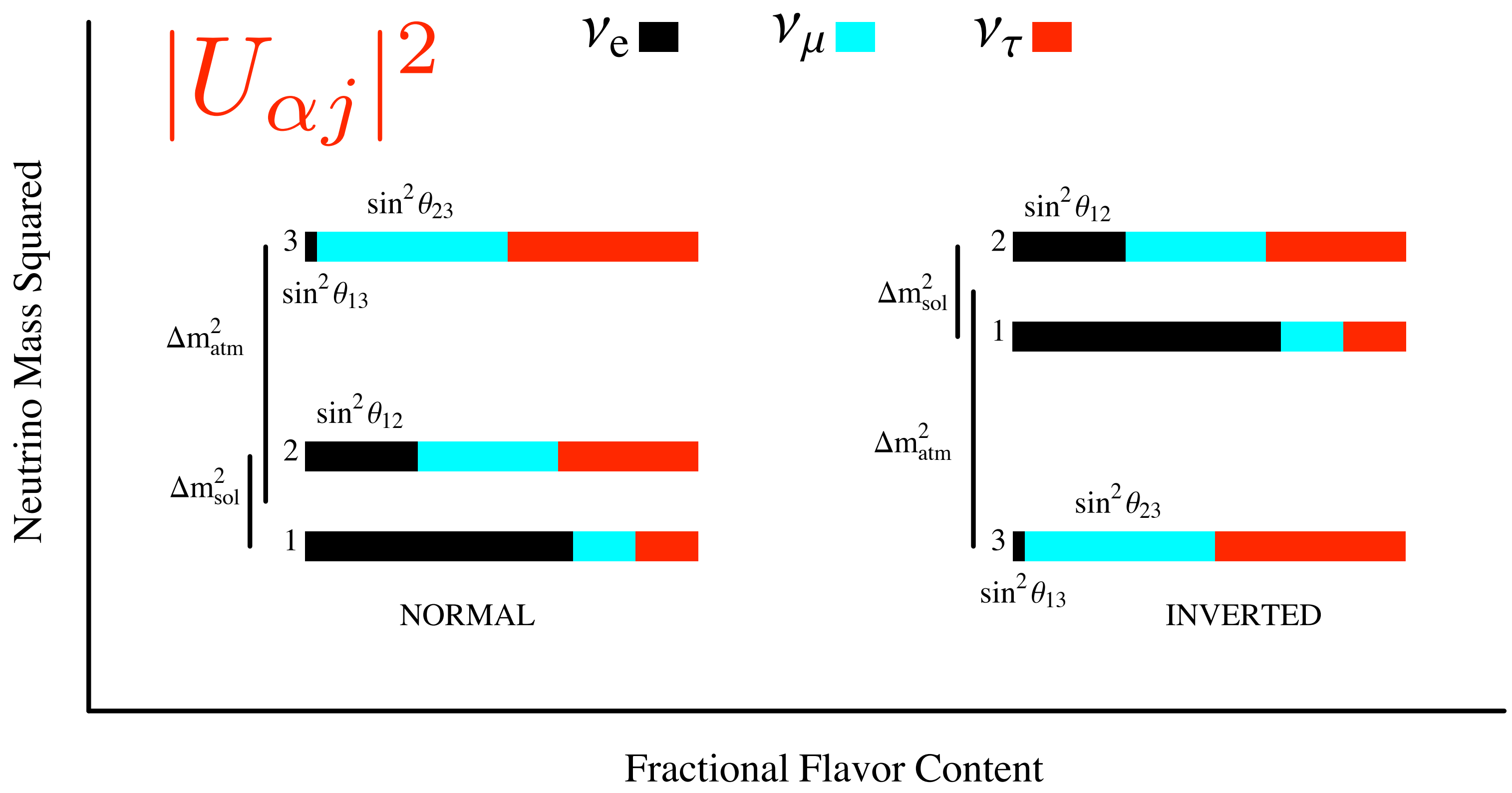
UNITARITY IS BUILT IN: $U^\dagger U = 1$

Flavor Content of Mass Eigenstates:

- Labeling massive neutrinos: $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$



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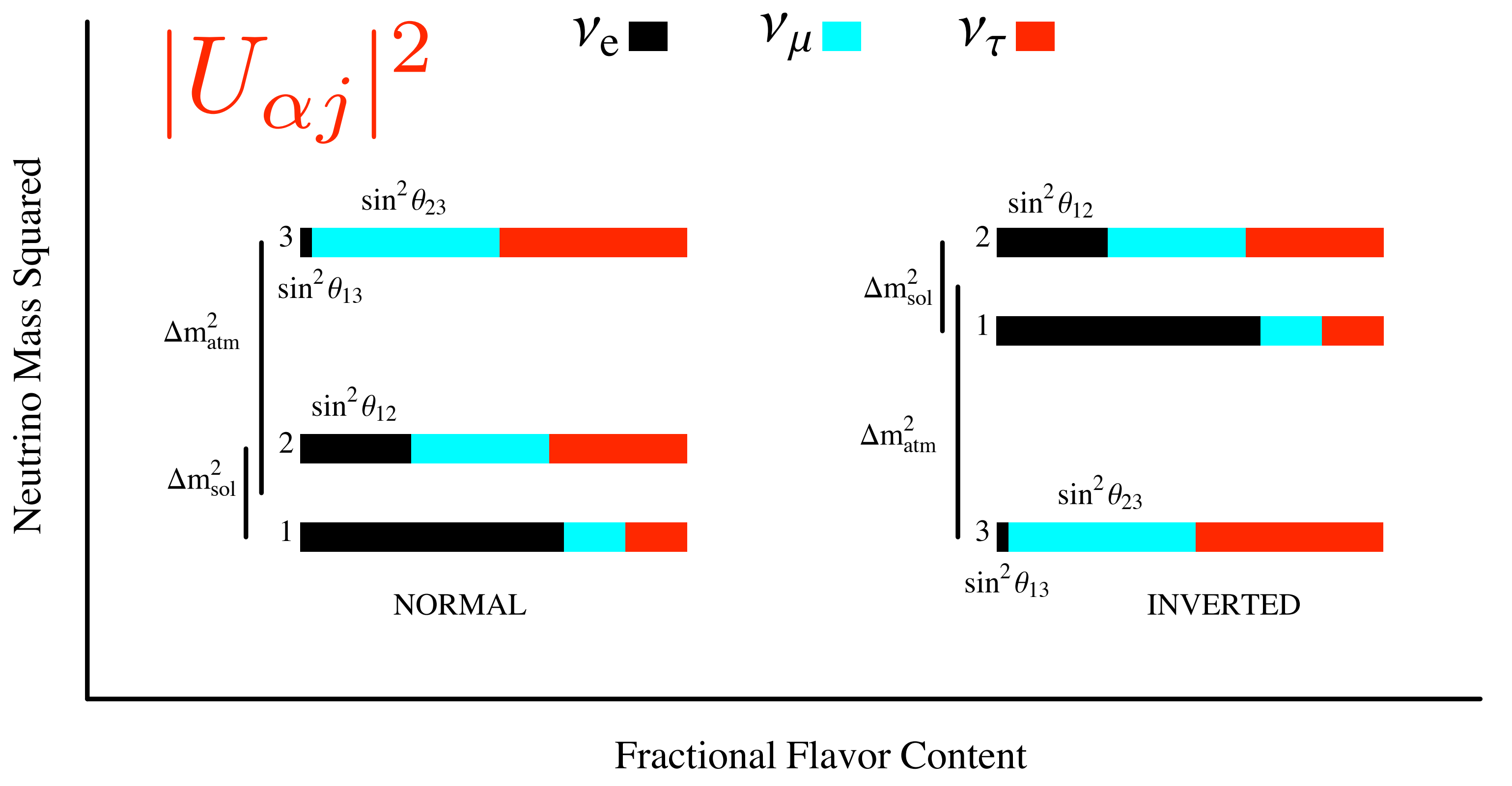

$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ \mathrm{eV}^2$$

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

$$\sqrt{\delta m^2_{atm}} = 0.05\ \mathrm{eV} < \sum m_{\nu_i} < 0.5\ \mathrm{eV}.$$

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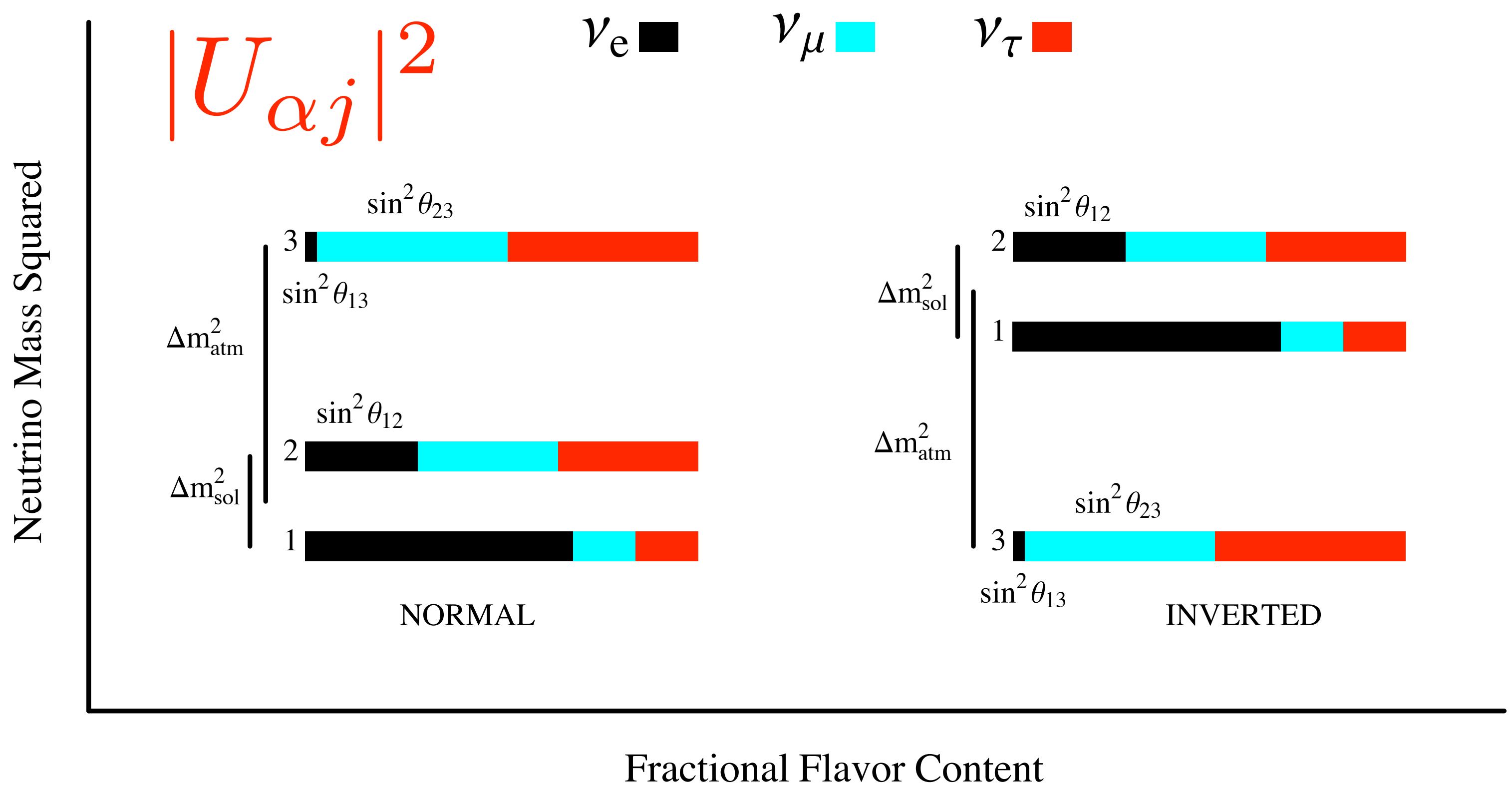

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$$\sin^2\theta_{12} \sim \frac{1}{3}$$

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

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

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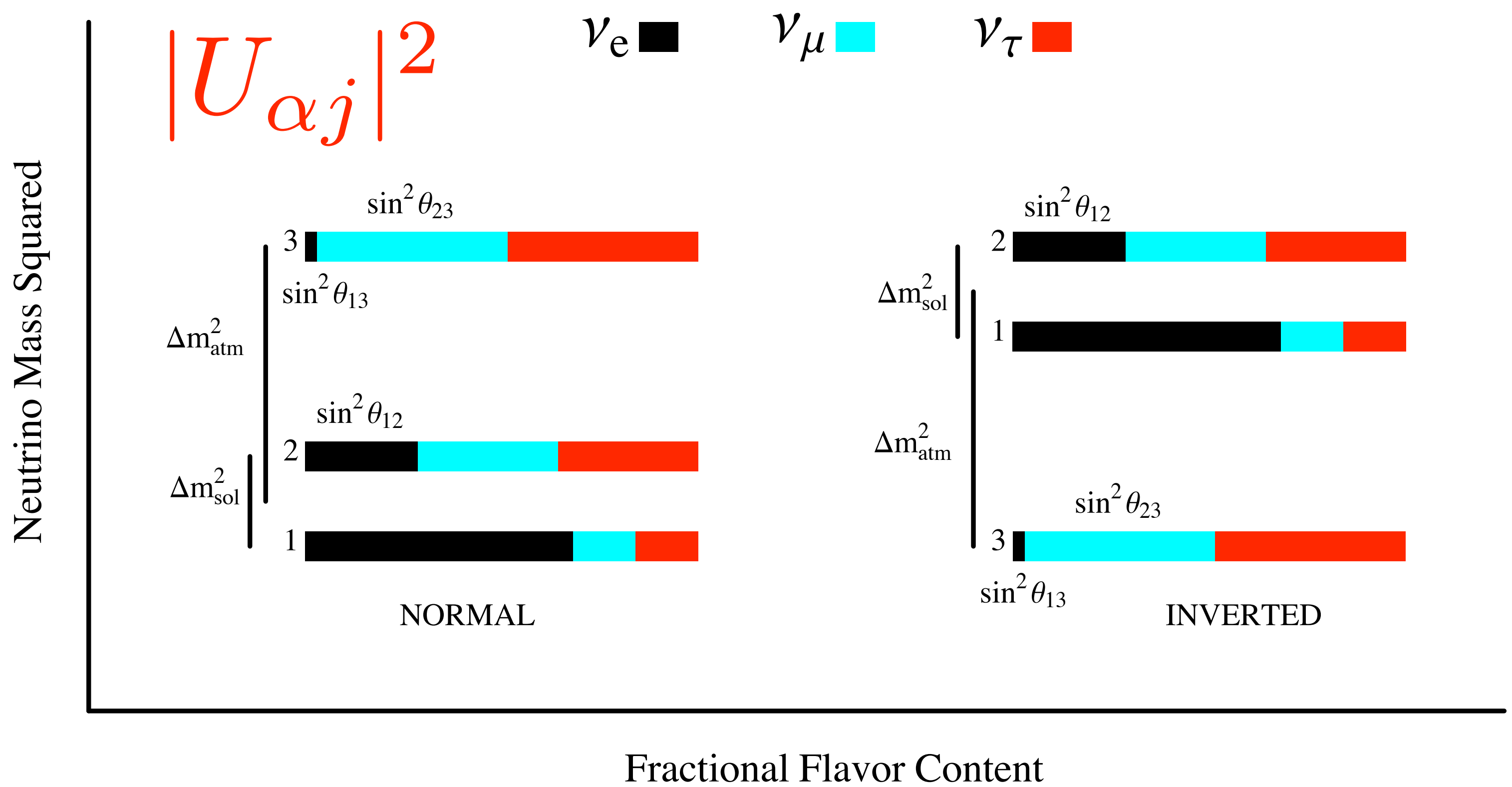

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$$0 \leq \delta < 2\pi$$

3 Flavor Oscillation Probabilities

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\sum_i U^*_{\alpha i}\, e^{-i m_i^2 L/2E}\, U_{\beta i}\,|^2$$

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decompose flavor states into mass eigenstates

$\Rightarrow$ then propagator

$\Rightarrow$ decompose mass eigenstates into flavor states

3 examples:

Using: $\boldsymbol{\Delta_{ij} = \Delta m^2_{ij} L/4E = 1.27... \left(\frac{\Delta m^2_{ij}\ L}{eV^2\ km}\right) \ \left(\frac{GeV}{E}\right)}$

(derive the number 1.27... by putting in $\hbar$ and c's)

Disappearance Probabilities (in vacuum):

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - 4 \sum_{i<j} |U_{\alpha i}|^2 |U_{\alpha j}|^2 \sin^2 \Delta_{ji} \, .$$

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$$\begin{aligned} P(\nu_e \to \nu_e) &\approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee} \\ &\quad - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \\ P(\nu_\mu \to \nu_\mu) &\approx 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} \, (1 - \cos^2 \theta_{13} \sin^2 \theta_{23}\,) \sin^2 \Delta_{\mu\mu} \\ &\quad + \mathcal{O}(\Delta^2_{21}) \end{aligned}$$

$\Delta_{ee} \approx \Delta_{31}$ and $\Delta_{\mu\mu} \approx \Delta_{32}$

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Appearance Probabilities (in vacuum):

$$P(\nu_\mu \to \nu_e) \approx \ ?$$

Reactor θ_{13} Experiments

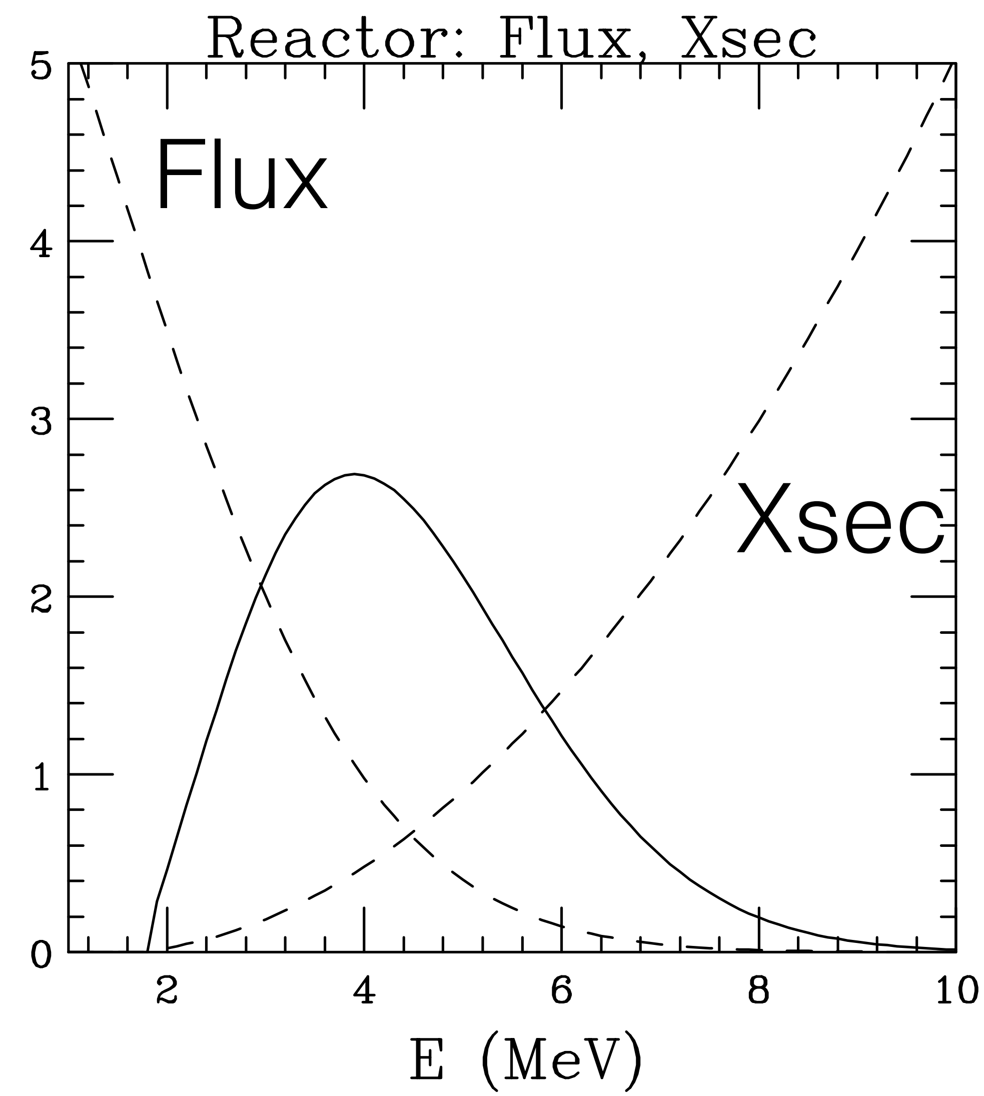
Daya Bay

Double Chooz

RENO

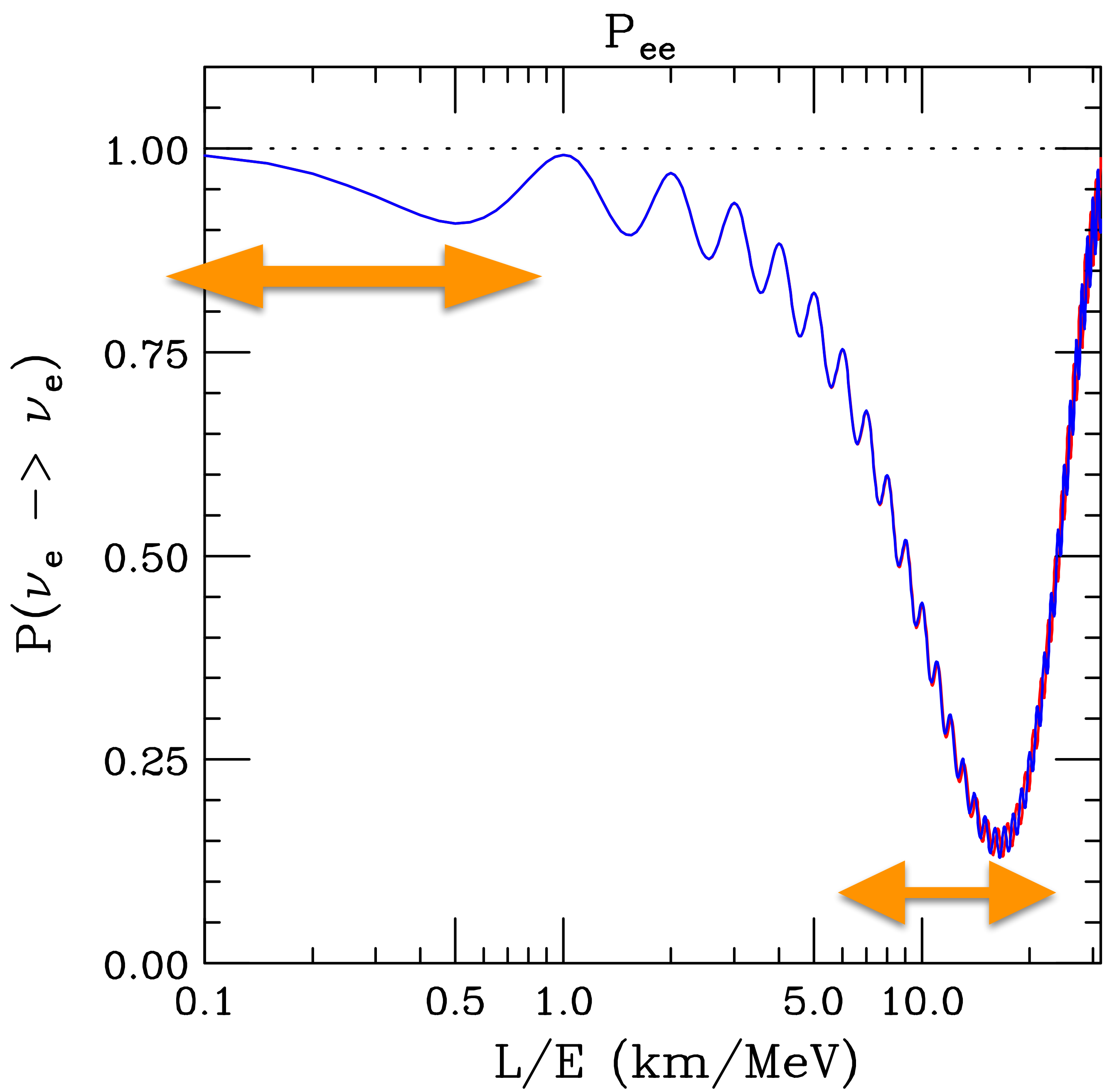
Flux & Cross Section:

Total is
2 x 10^20 /sec/GW-Th



nu_e Disappearance

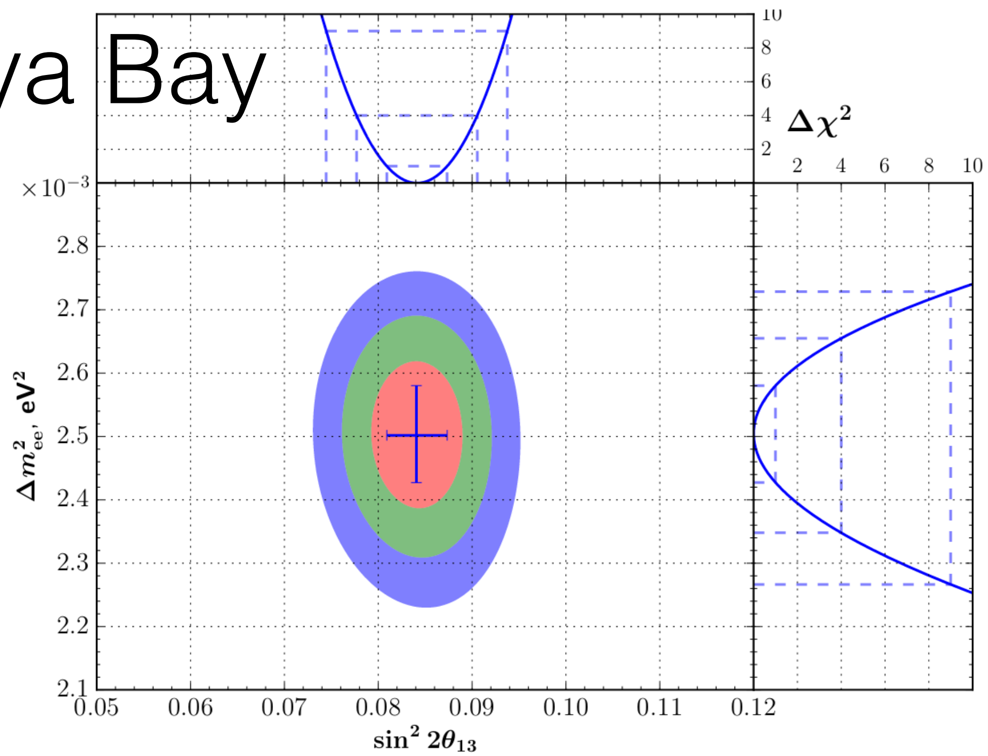
Daya Bay
RENO
D-Chooz



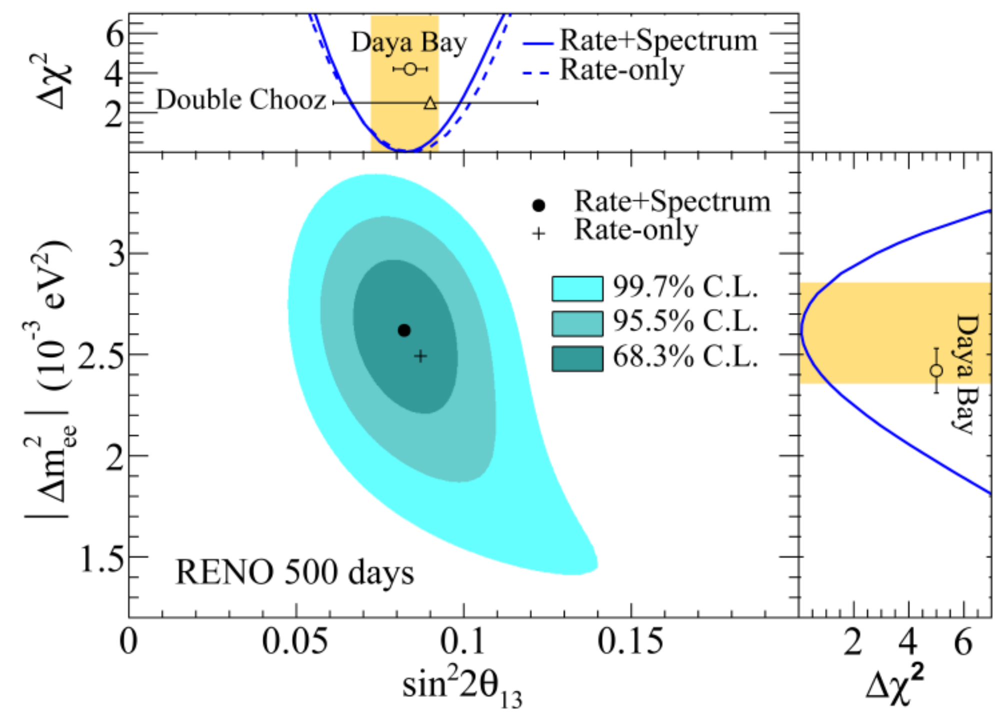
JUNO
RENO 50

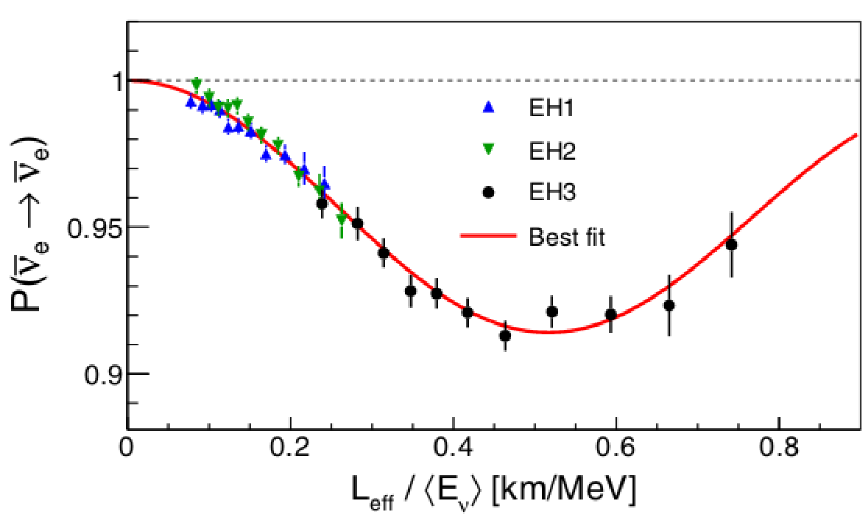
The fraction of ν_3 that is ν_e: (aka $|U_{e3}|^2 = \sin^2\theta_{13}$)

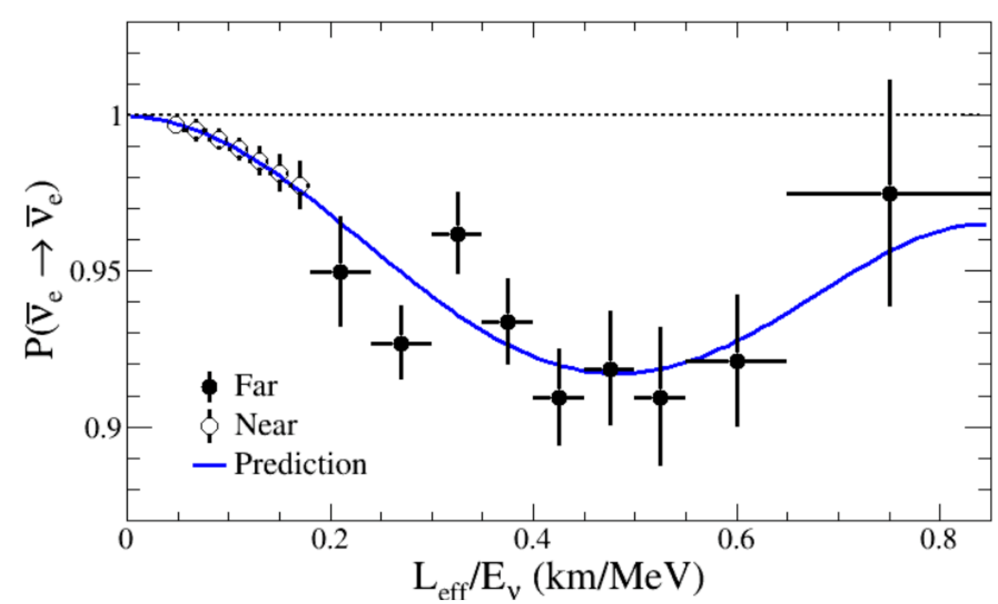
Daya Bay



RENO







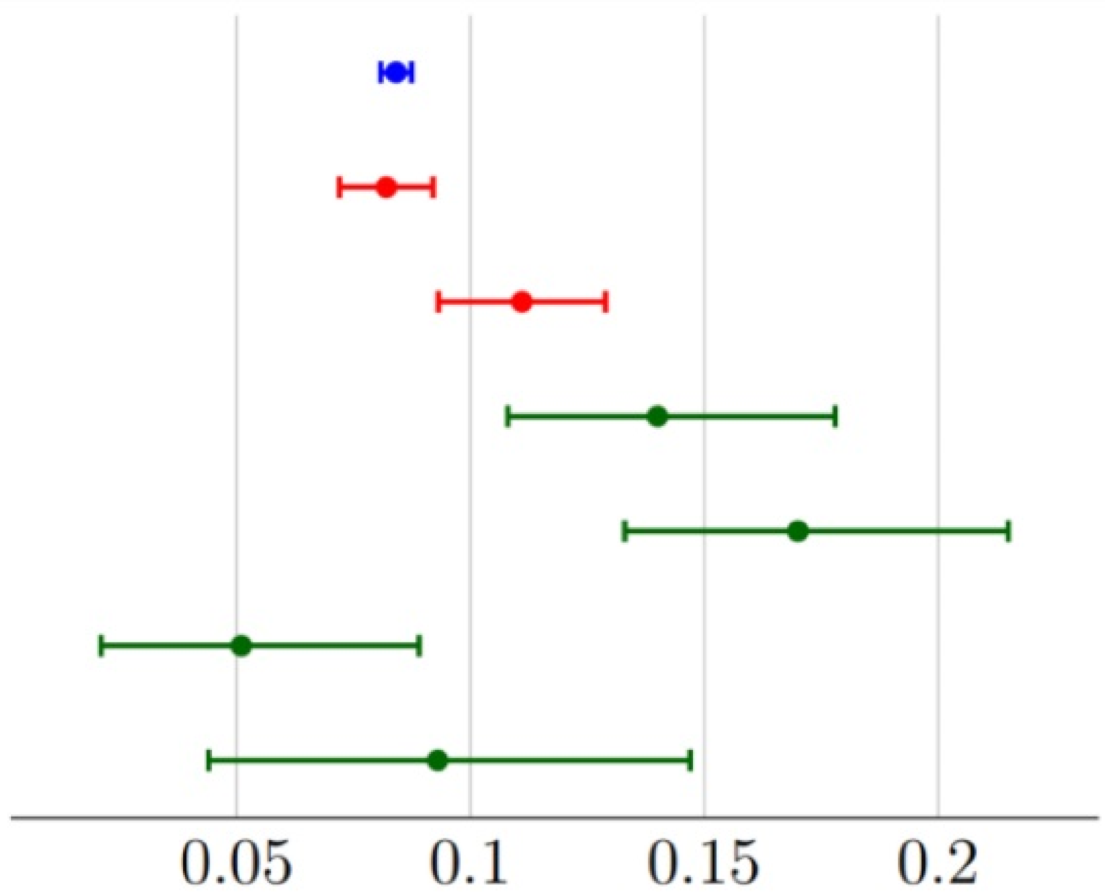
$\sin^2 2\theta_{13}$ = [8.41 ± 0.27(stat.) ± 0.19(syst.)] × 10^{-2}
$|\Delta m^2_{ee}|$ = [2.50 ± 0.06(stat.) ± 0.06(syst.)] × 10^{-3}eV^2
χ^2/NDF = 232.6/263

$$\left|\Delta m^2_{ee}\right| = 2.62\,^{+0.21}_{-0.23}(\text{stat.})\,^{+0.12}_{-0.13}(\text{syst.})\ \ (\times 10^{-3}\,eV^2)$$

$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$$

θ_{13}

Experiment		Value
Daya Bay		0.0841 ± 0.0033
RENO		0.082 ± 0.010
D-CHOOZ		0.111 ± 0.018
T2K	NH	$0.140^{+0.038}_{-0.032}$
	IH	$0.170^{+0.045}_{-0.037}$
MINOS	NH	$0.051^{+0.038}_{-0.030}$
	IH	$0.093^{+0.054}_{-0.049}$

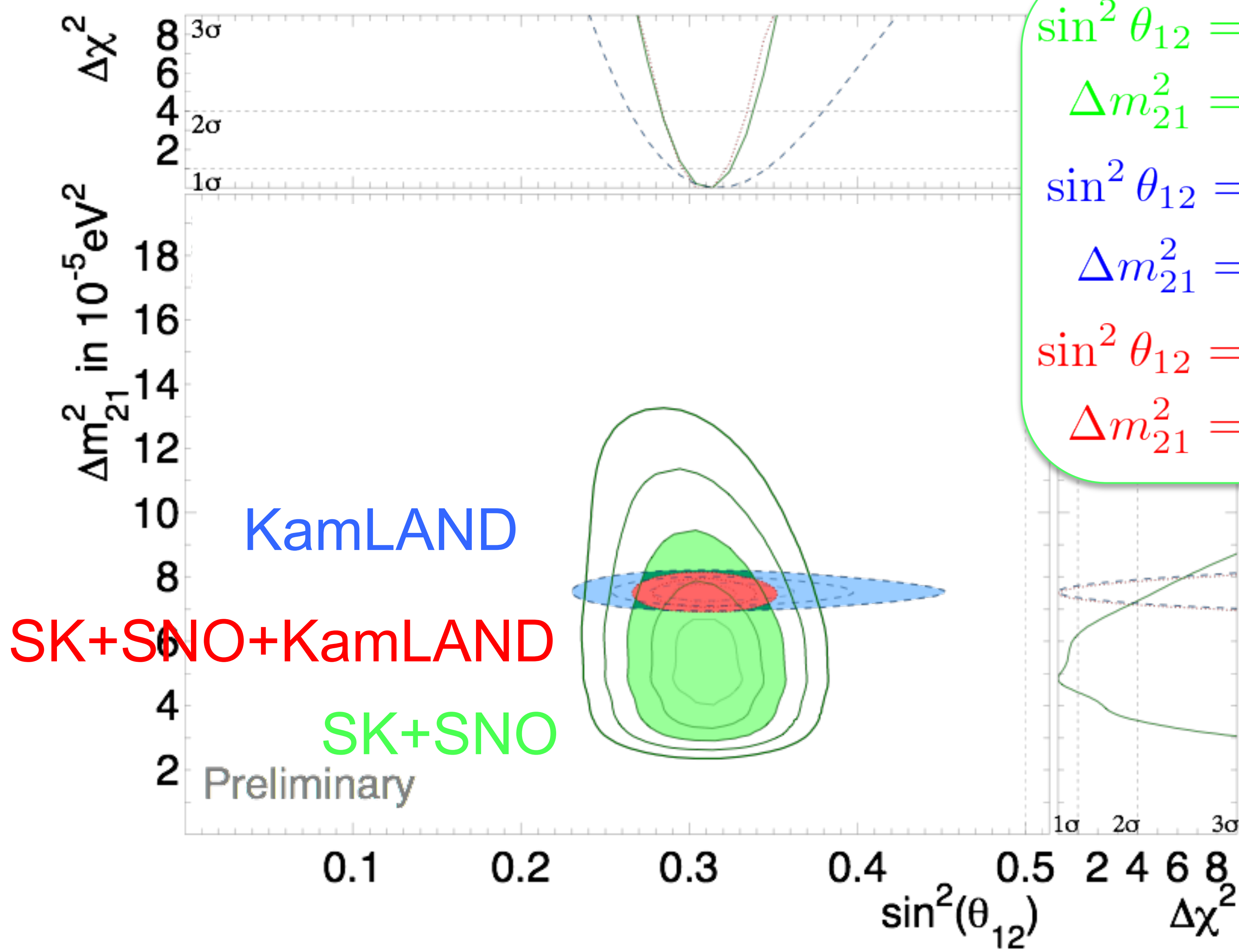


The fraction of ν_2 that is ν_e:

(aka $|U_{e2}|^2 = \cos^2\theta_{13}\sin^2\theta_{12} \approx \sin^2\theta_{12}$)

Super-K+SNO vs. KamLAND

filled regions: 3σ



$\sin^2\theta_{12} = 0.311 \pm 0.014$

$\Delta m^2_{21} = 4.83^{+1.26}_{-0.62}$

$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$

$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$

$\sin^2\theta_{12} = 0.309 \pm 0.013$

$\Delta m^2_{21} = 7.48^{+0.19}_{-0.17}$

The unit of Δm^2_{21} is $10^{-5}eV^2$

$\sin^2\theta_{13} = 0.0219 \pm 0.0014$

25

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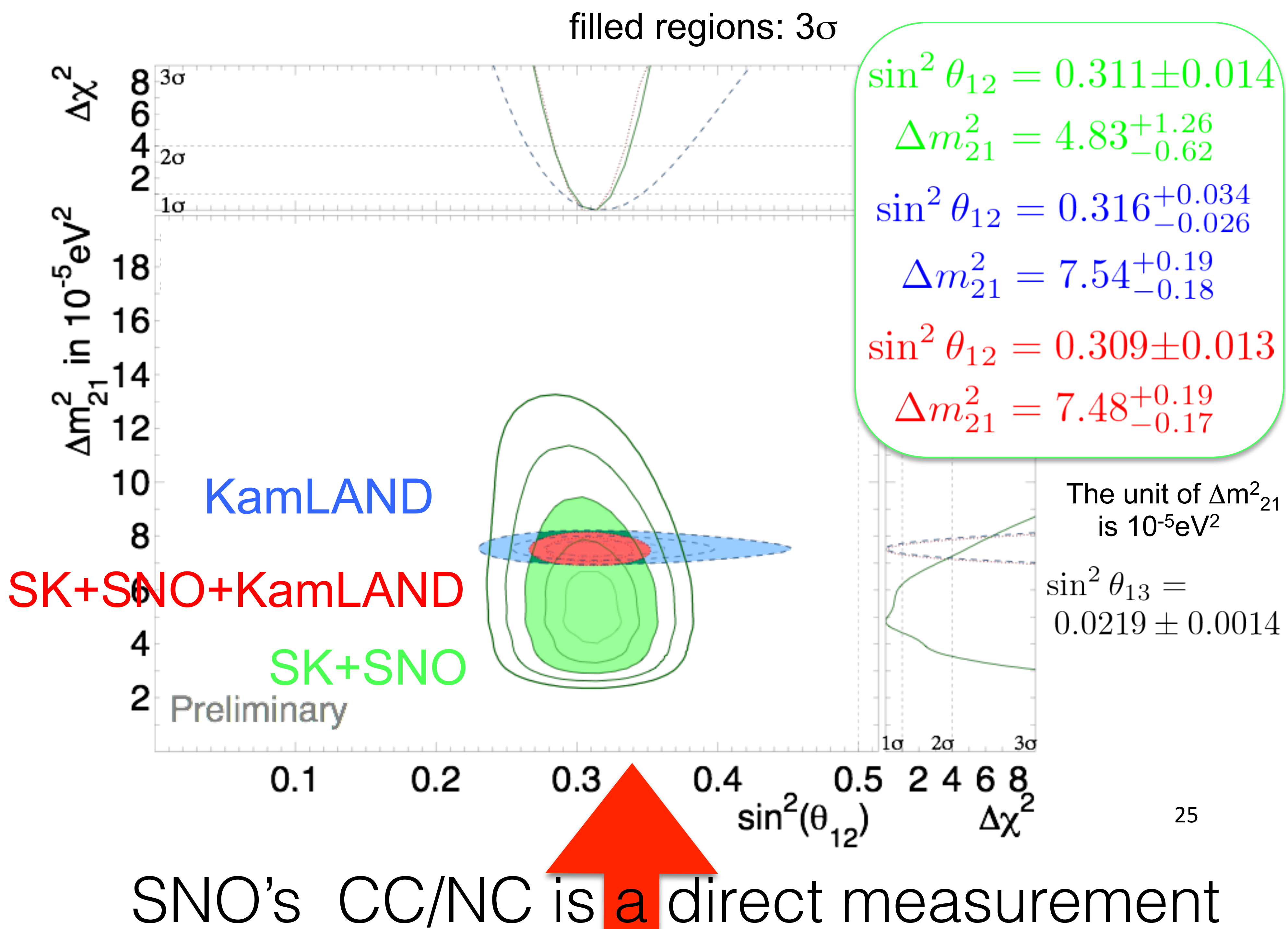
Super-K+SNO vs. KamLAND



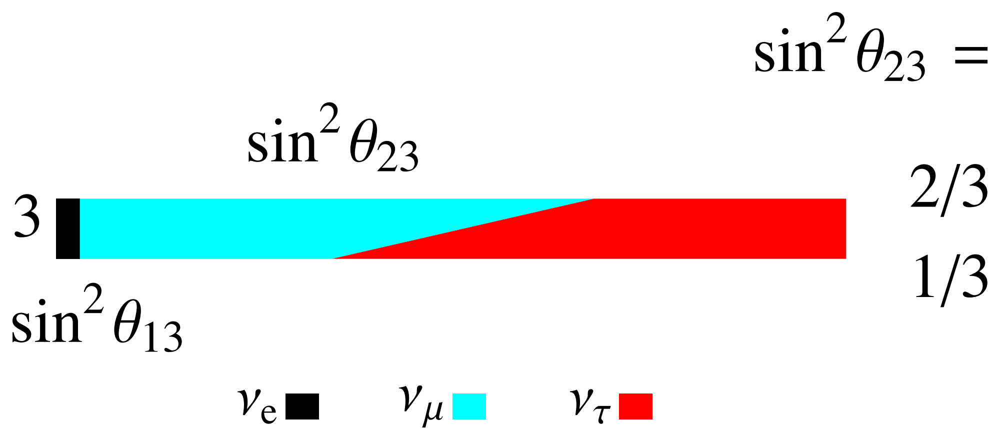
SNO's CC/NC is a direct measurement

Important Questions:

- Dominant Flavor Content of v_3
- Mass Ordering
- Is there CP Violation
- Dirac OR Majorana
- Beyond Nu Standard Model

- Dominant Flavor Content of v_3

Is $\sin^2\theta_{23}$ < or > 0.5 ?



• Dominant Flavor Content of v_3

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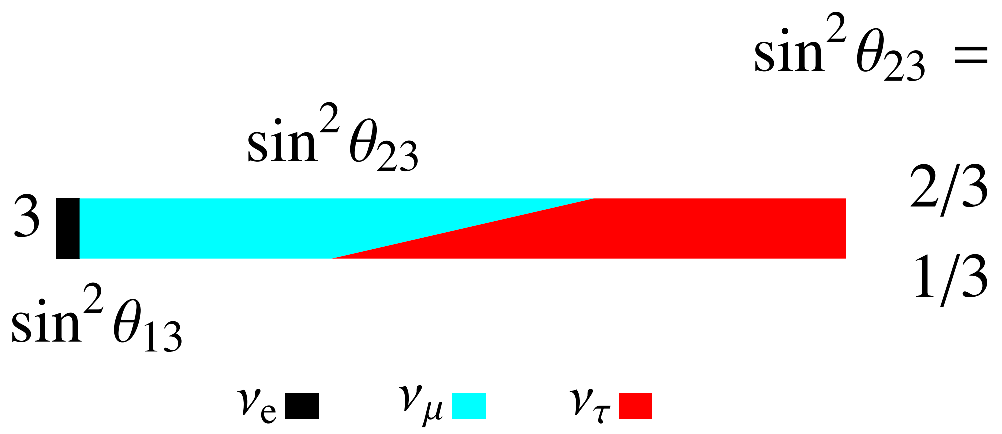
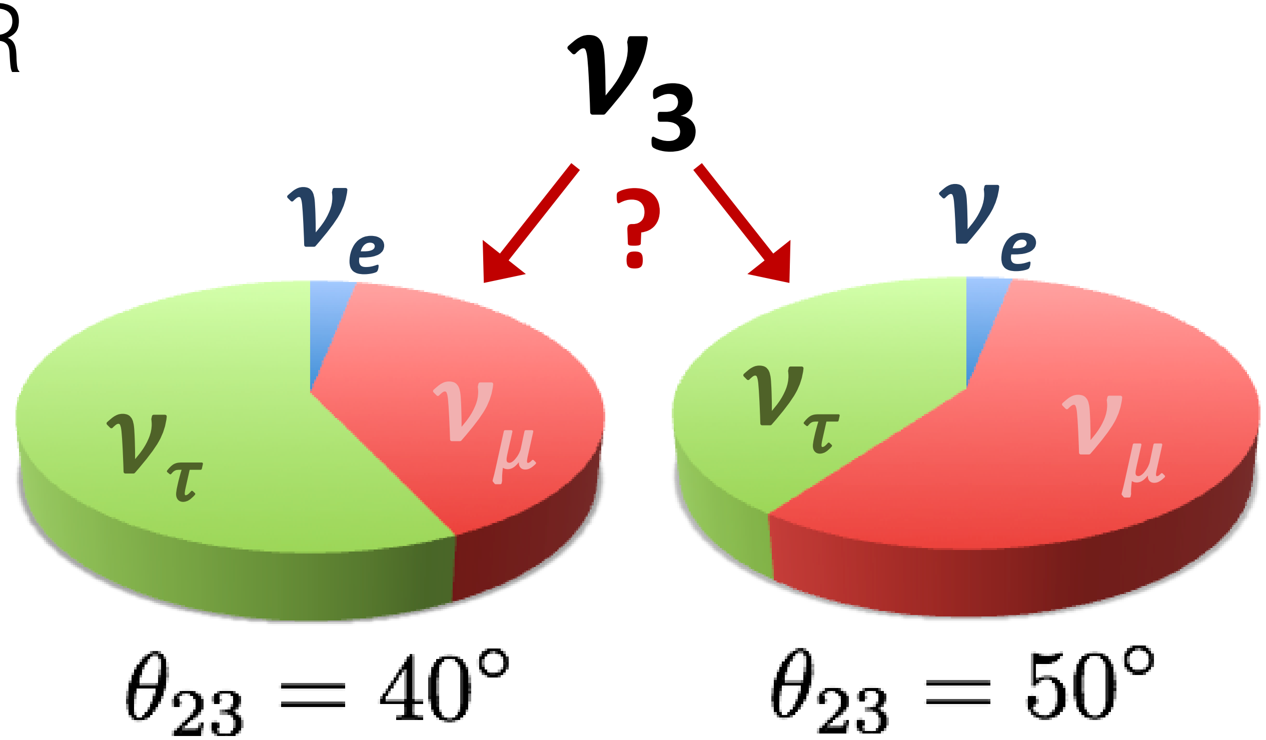
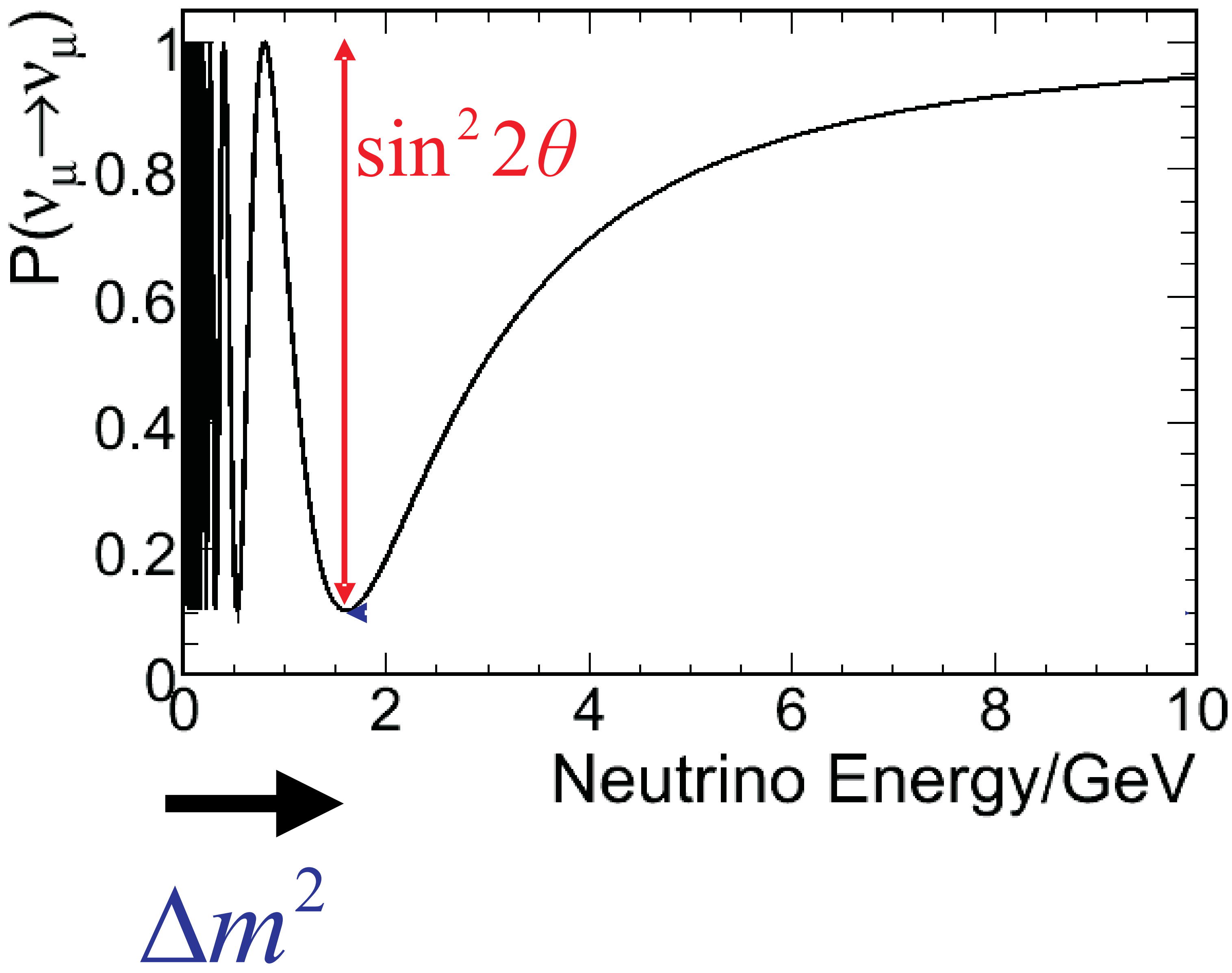


OR



NOvA Nu_mu Disappearance:



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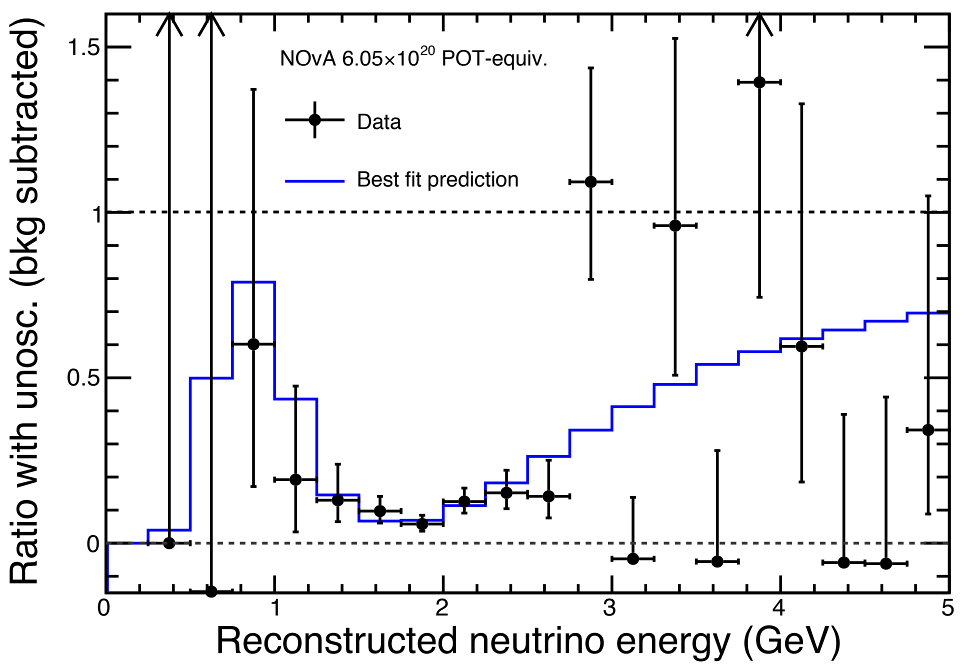
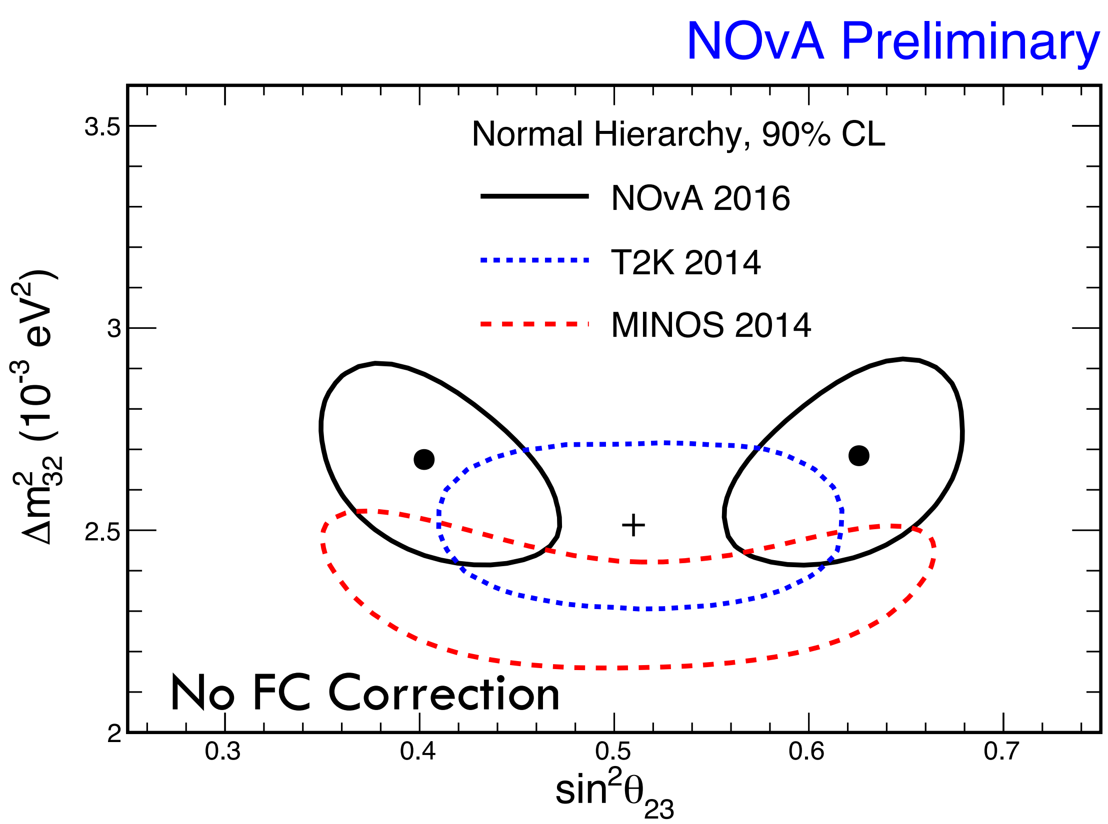




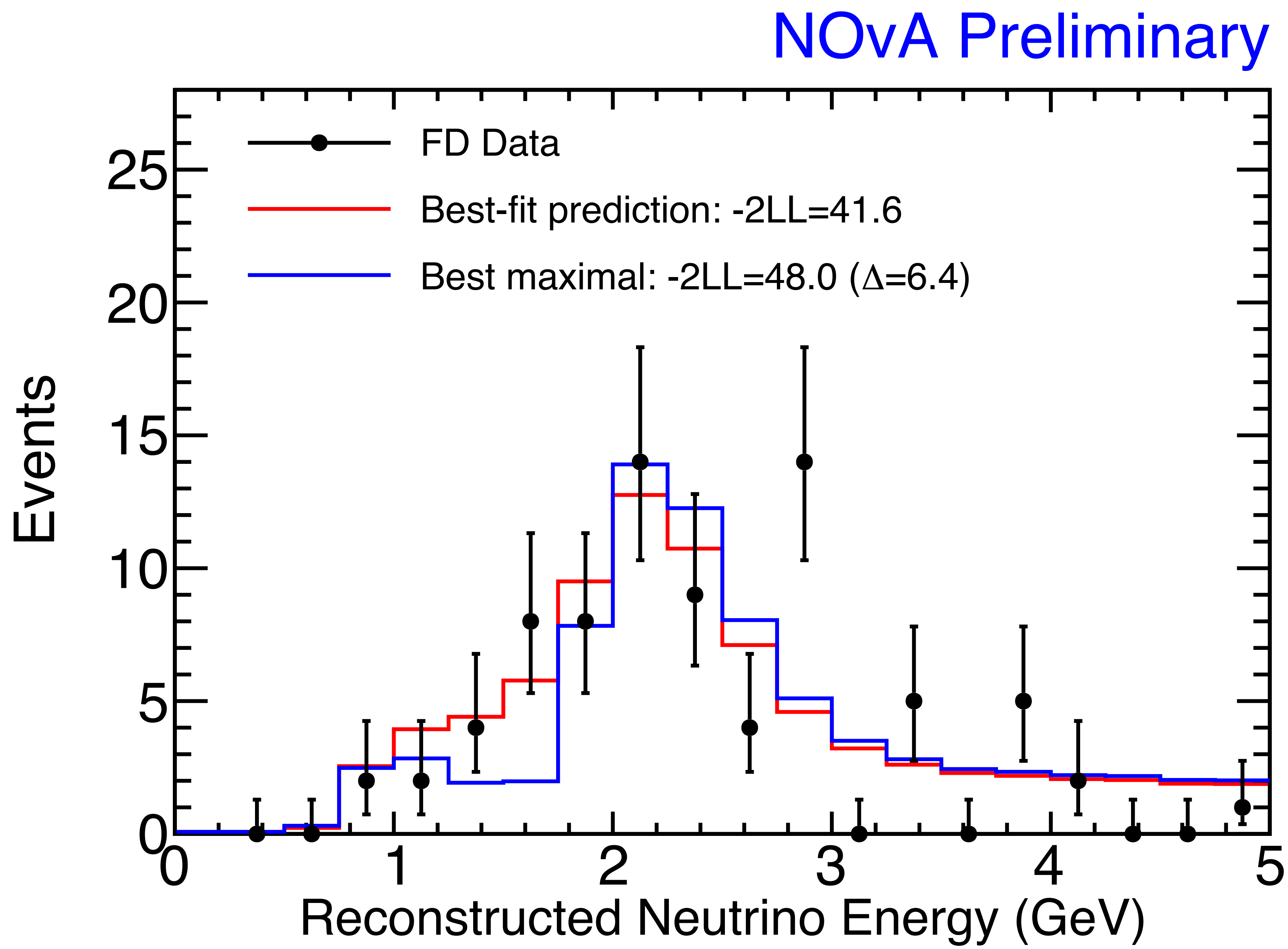
- 78 events observed in FD
  - 473±30 with no oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

Best Fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\text{eV}^2$$

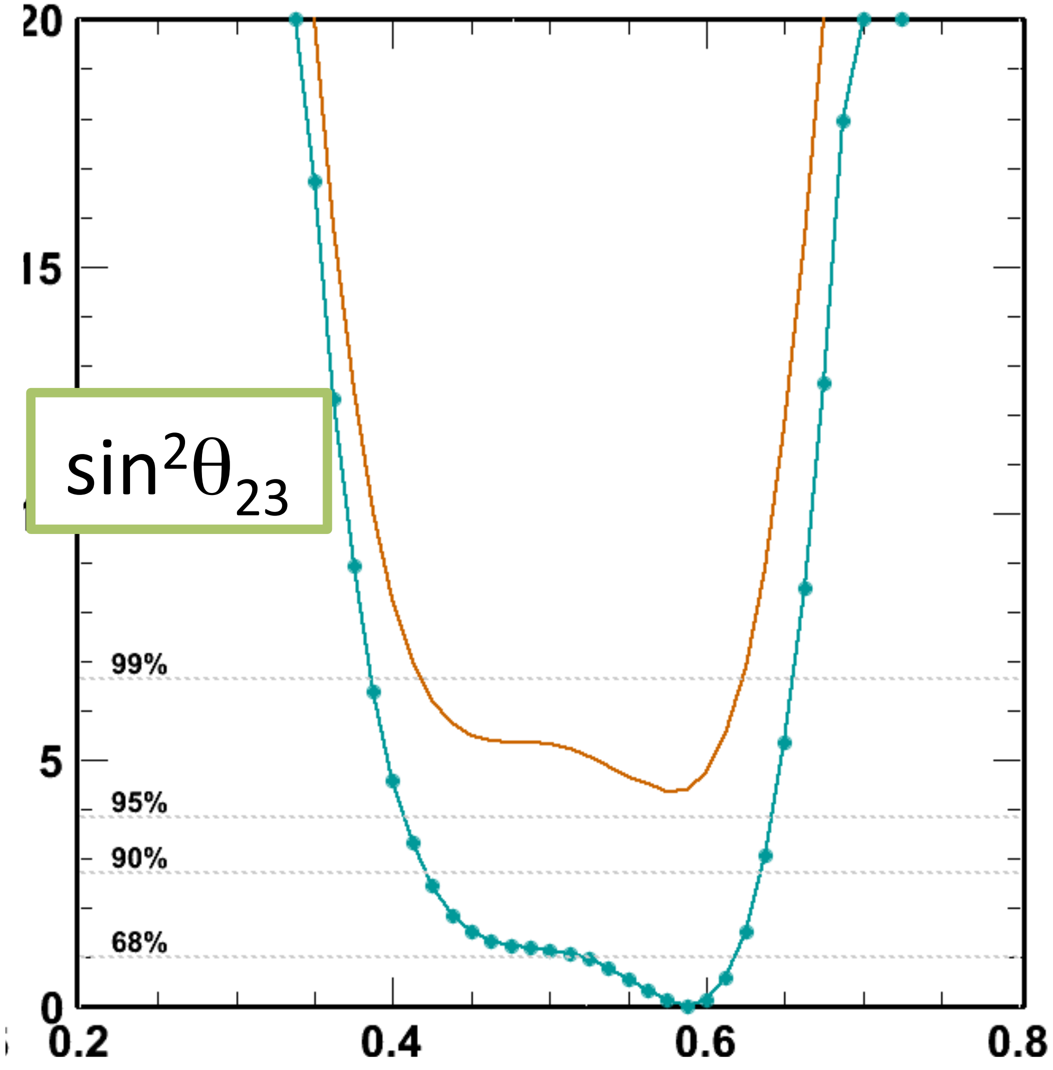
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

NOvA conti



Maximal mixing excluded at 2.5σ

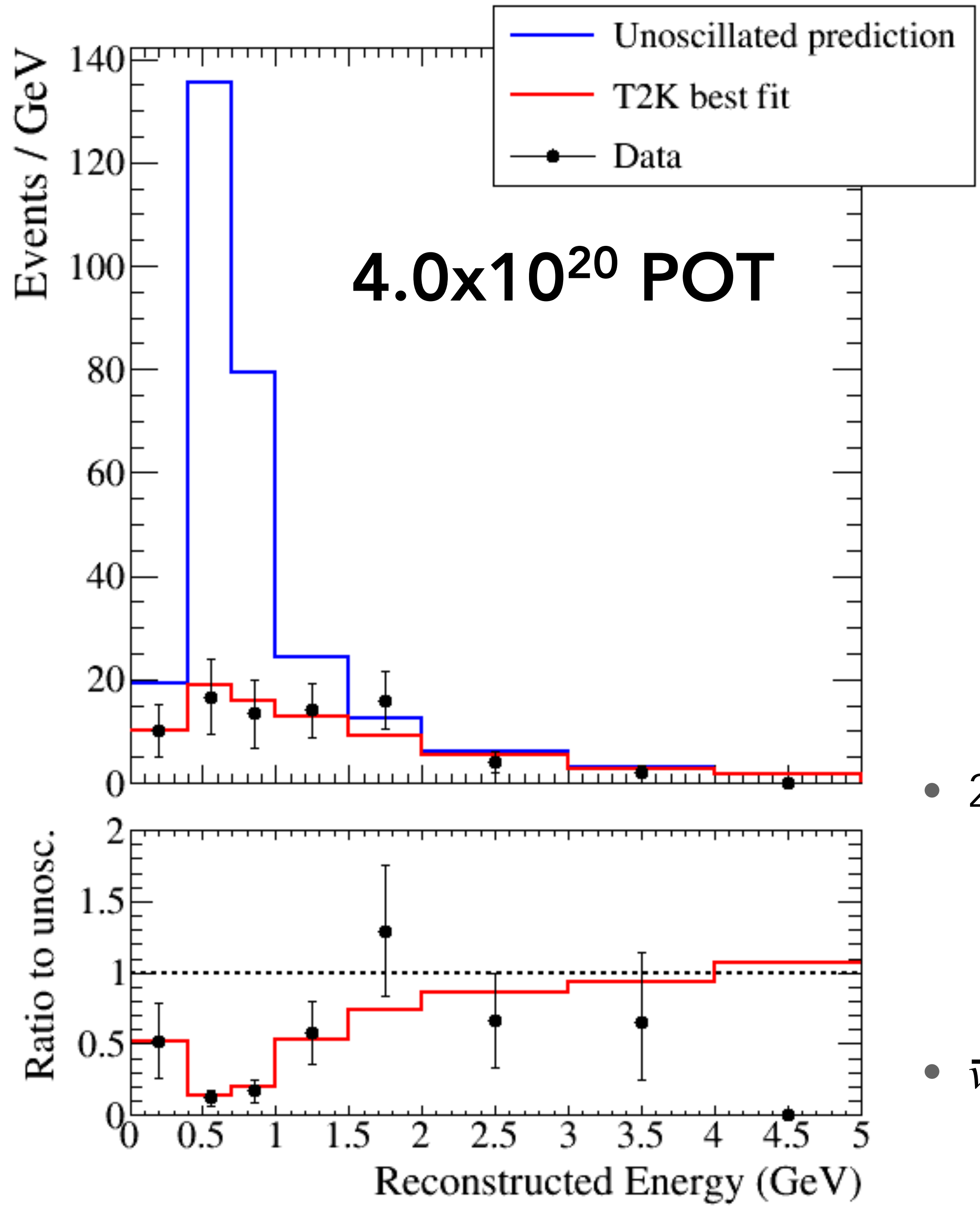
SK -only
Atmospheric Neutrinos

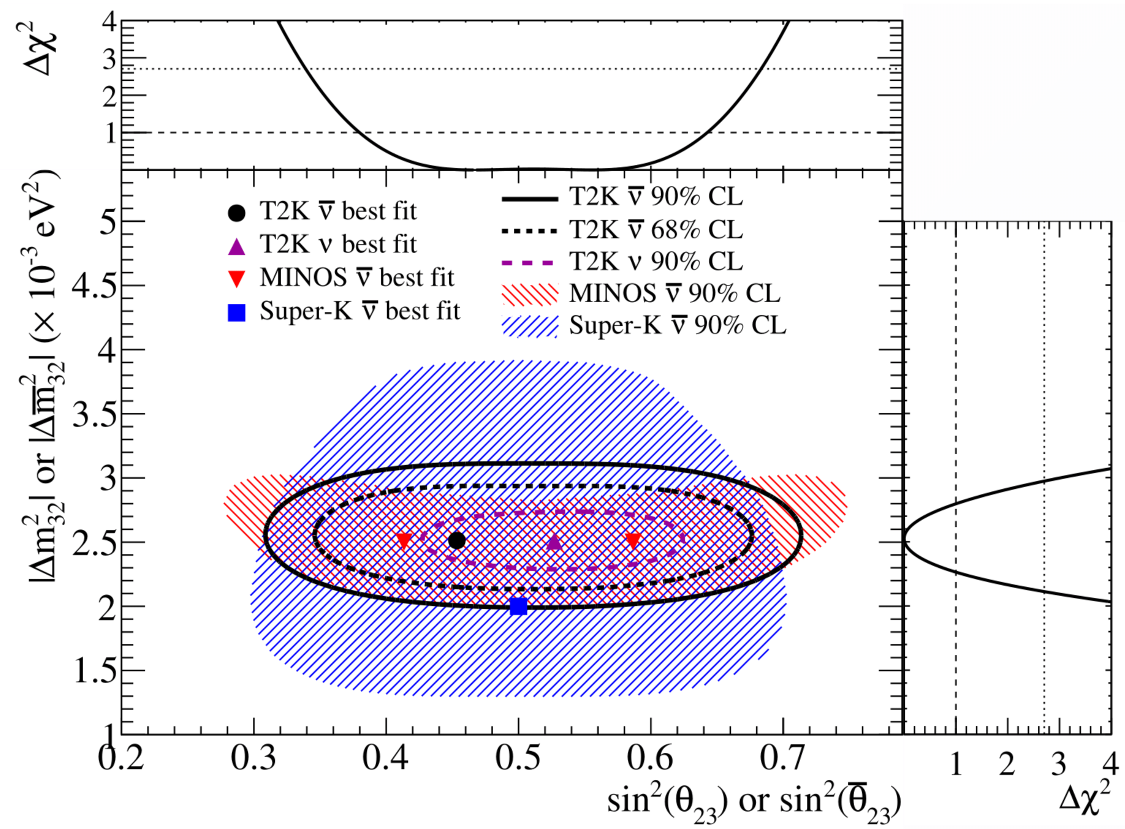


IO
NO

T2K anti-nu_mu Disappearance:

FIRST ANTINEUTRINO RESULTS



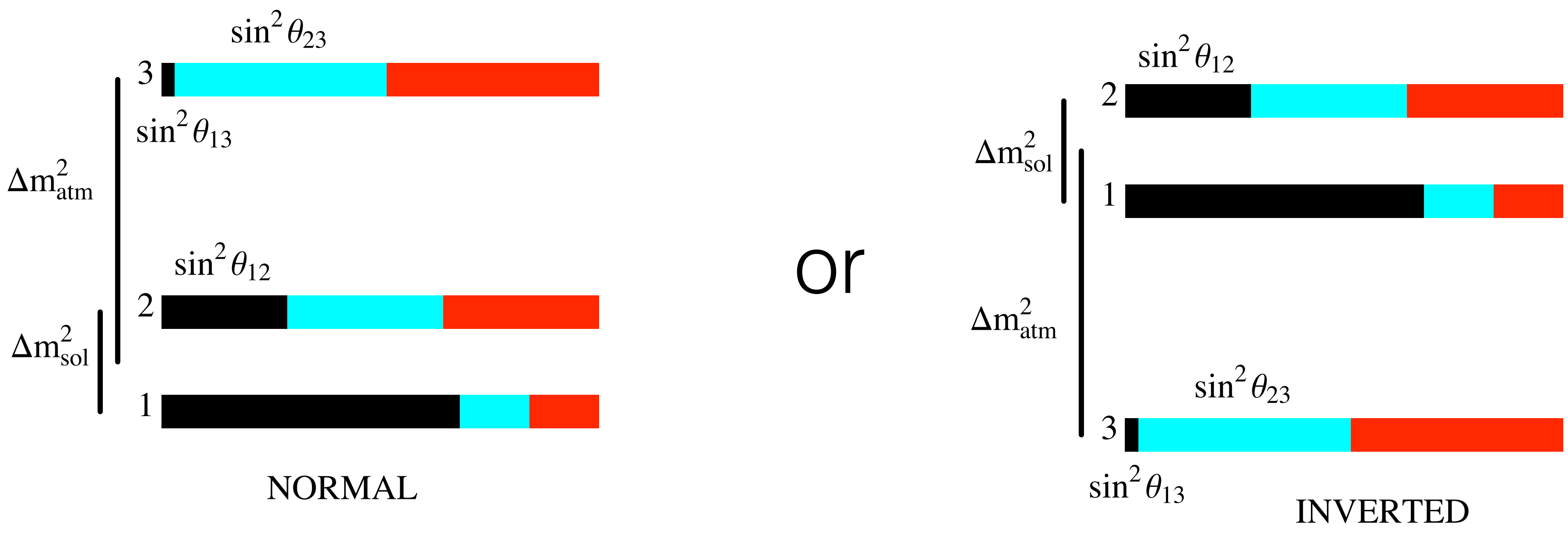


- 2015 $\bar{\nu}_\mu$ disappearance analysis
  - Competitive measurement of antineutrino disappearance parameters with 1 year of data.
  - Phys.Rev.Lett. 116 (2016) no.18, 181801
- $\bar{\nu}_e$ appearance results
  - 3 events observed
  - 3.2 expected with current best-fit values (δ_{CP}~ -π/2)

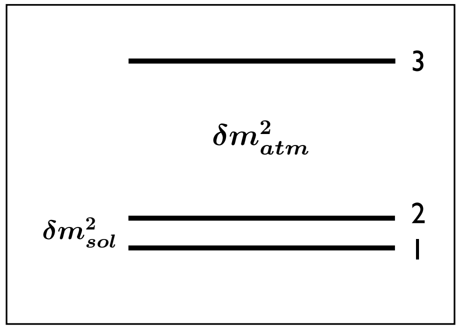
17

- Mass Ordering

• Mass Ordering



- Mass Ordering



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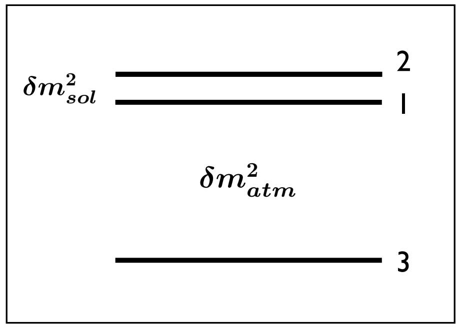

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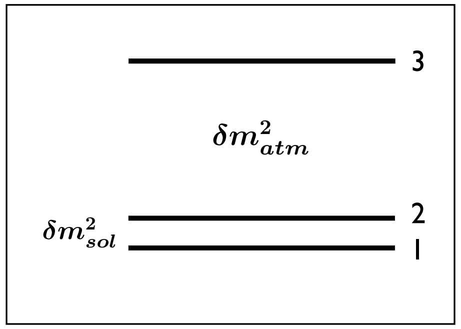

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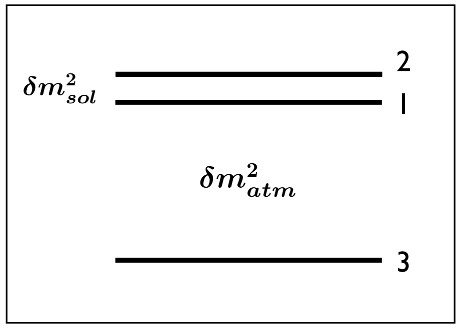
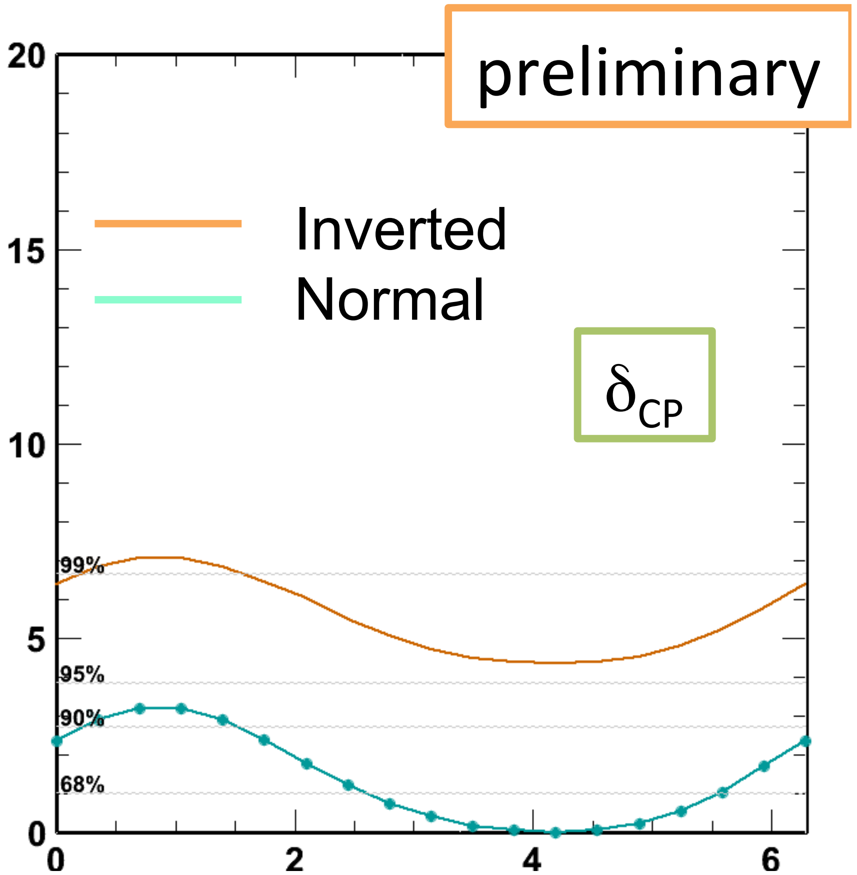
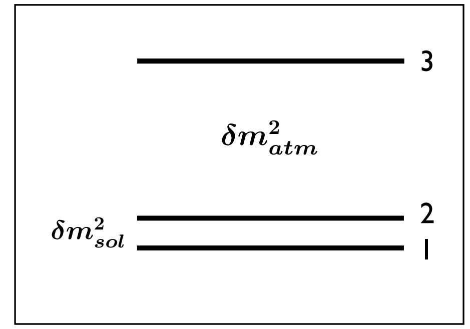


SK-only

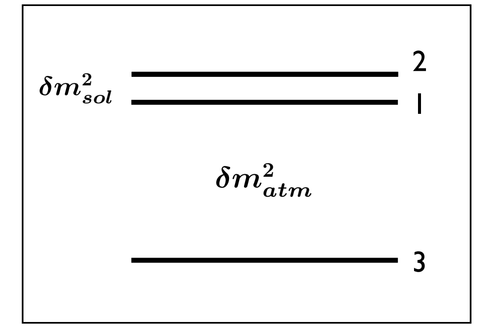


SK : $\Delta\chi^2$(IH-NH)=4.3

- # Mass Ordering

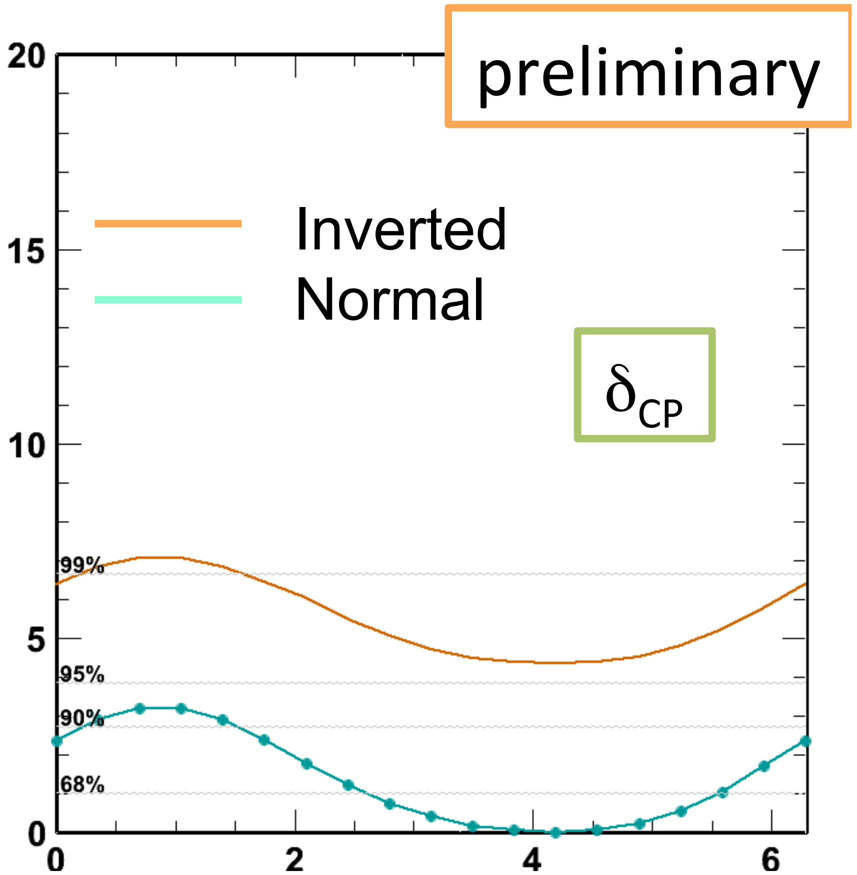


OR



	NH	IH	SUM
$\sin^2\theta_{23} \leq 0.5$	0.218	0.072	0.290
$\sin^2\theta_{23} > 0.5$	0.529	0.181	0.710
SUM	0.747	0.253	1.000

SK-only



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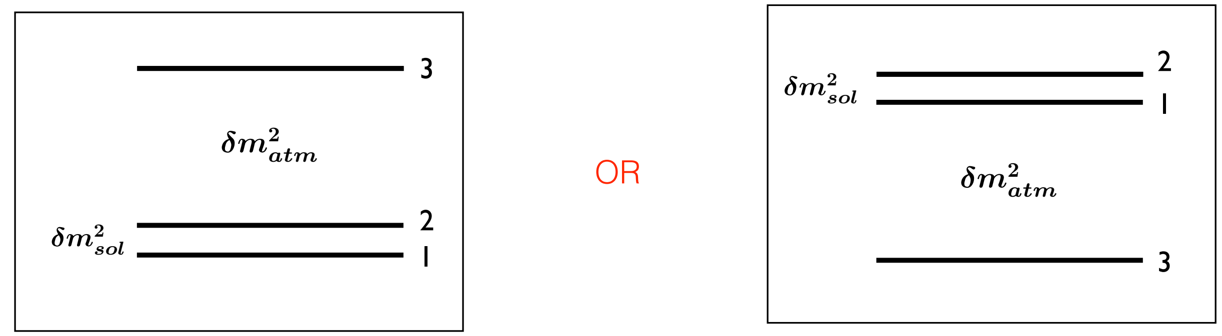

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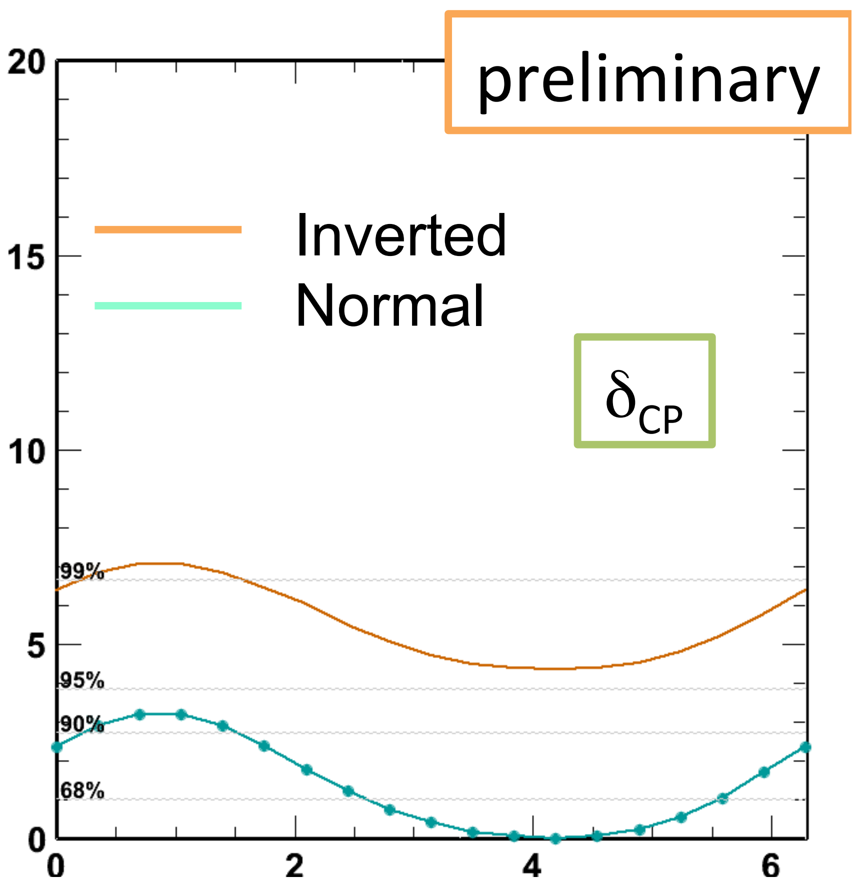

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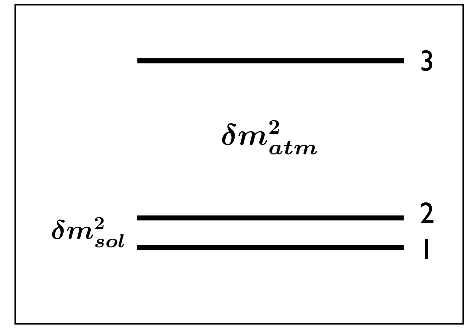
T2K

NOνA : $\Delta\chi^2$(IH-NH)=0.47

• Mass Ordering



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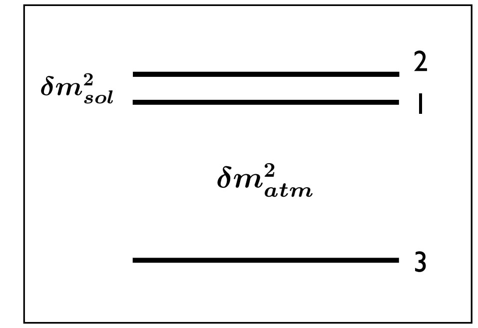

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T2K

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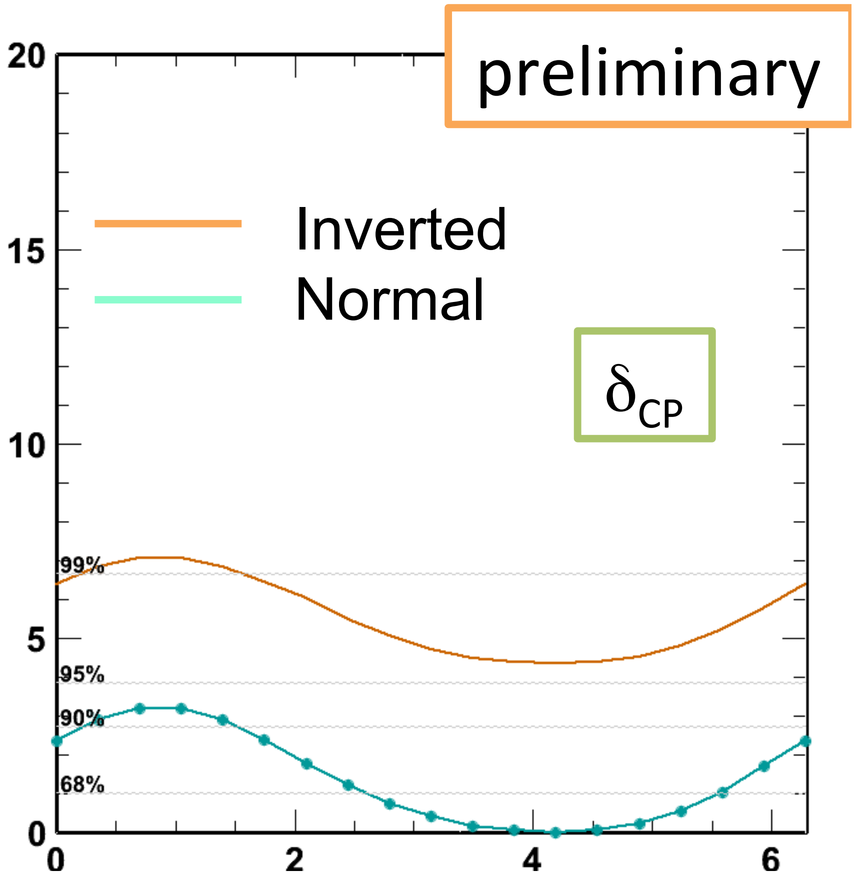

SK : $\Delta\chi^2$(IH-NH)=4.3

NOνA : $\Delta\chi^2$(IH-NH)=0.47

Global fits:

Absolute minimum in NO, $\Delta\chi^2$(IO-NO) = 3.1

- Is there CP Violation

$$P(\nu_\mu \to \nu_e) \quad \neq \quad P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

in vacuum

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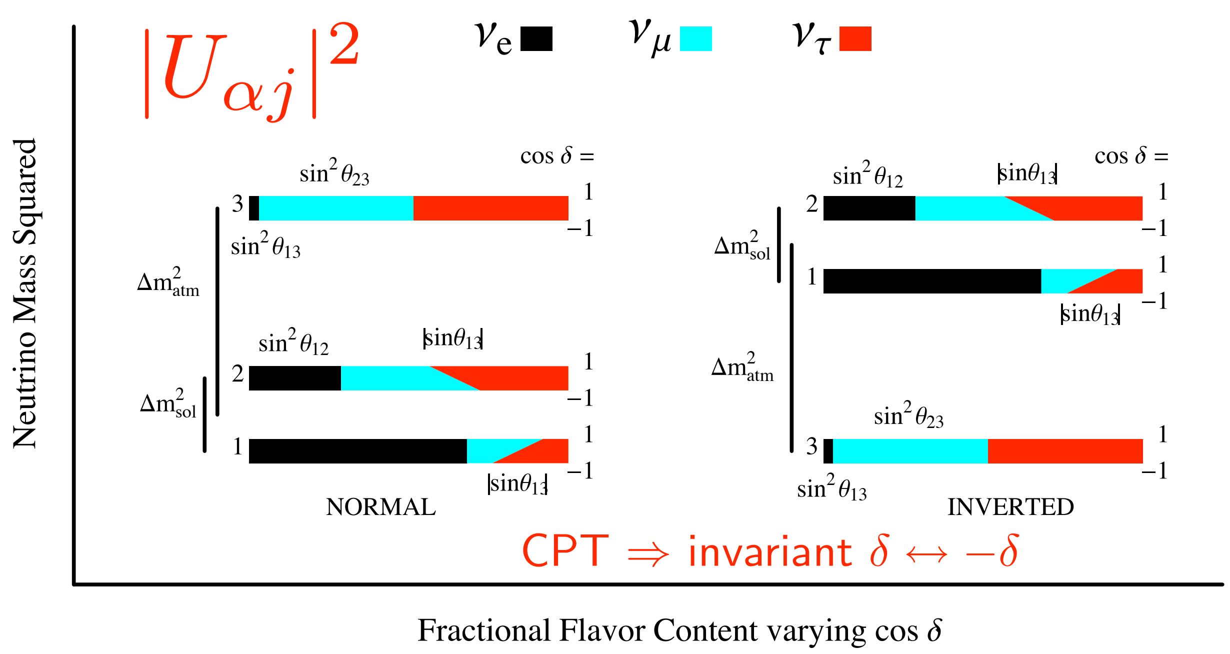

• Is there CP Violation

CP

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

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

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

CP

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

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

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

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

only CPV

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

$\nu_\mu \longrightarrow \nu_e$

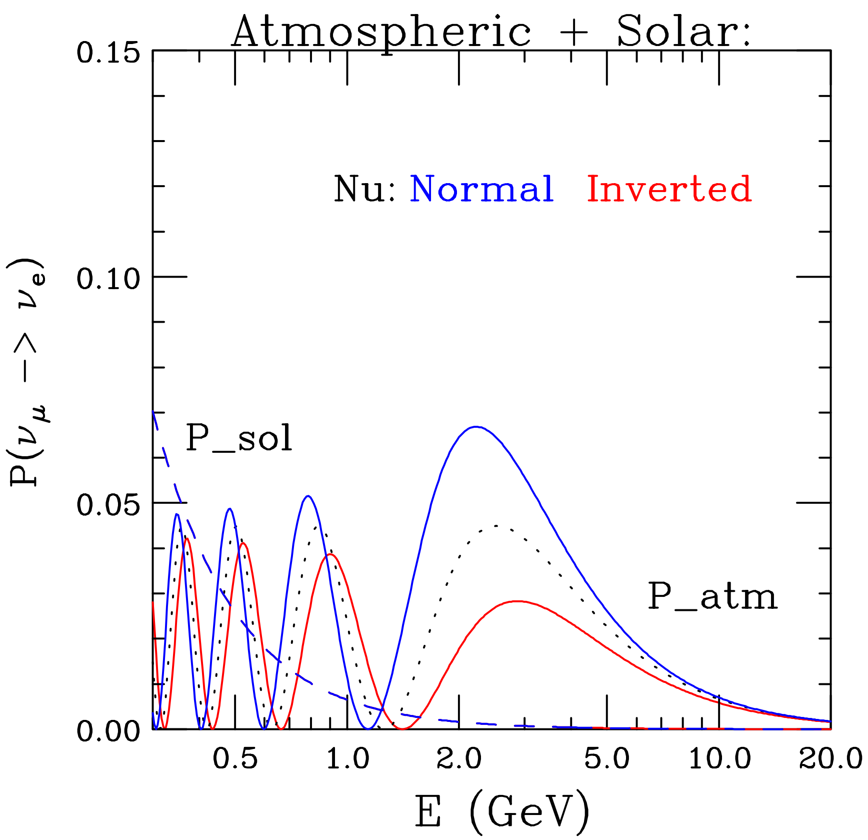
In Matter:

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

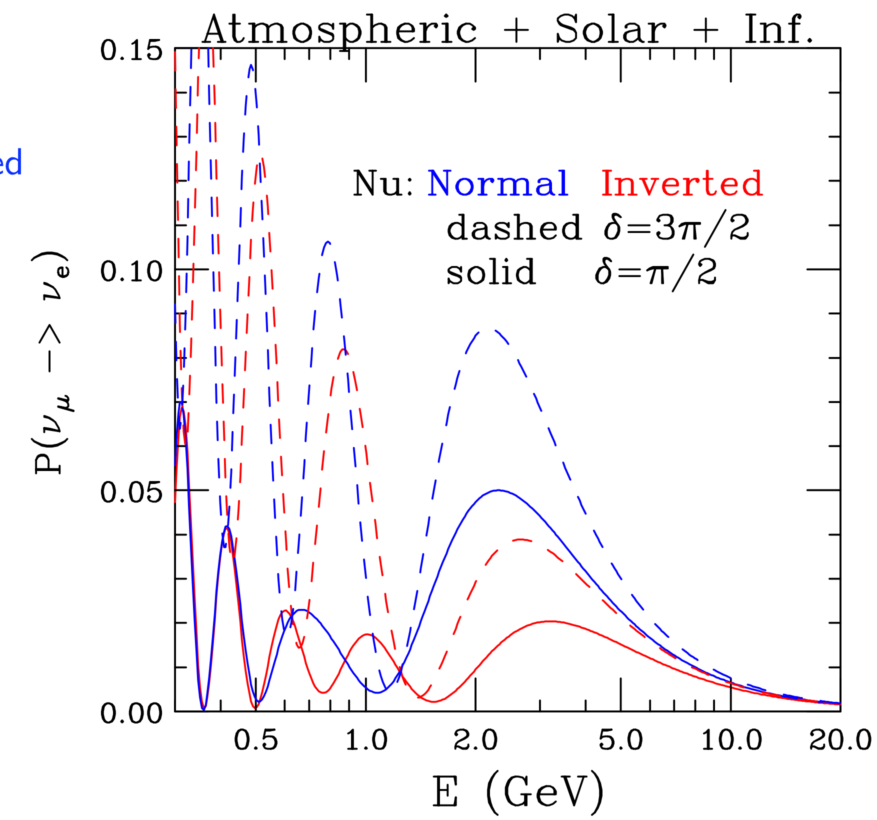
$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

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

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



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



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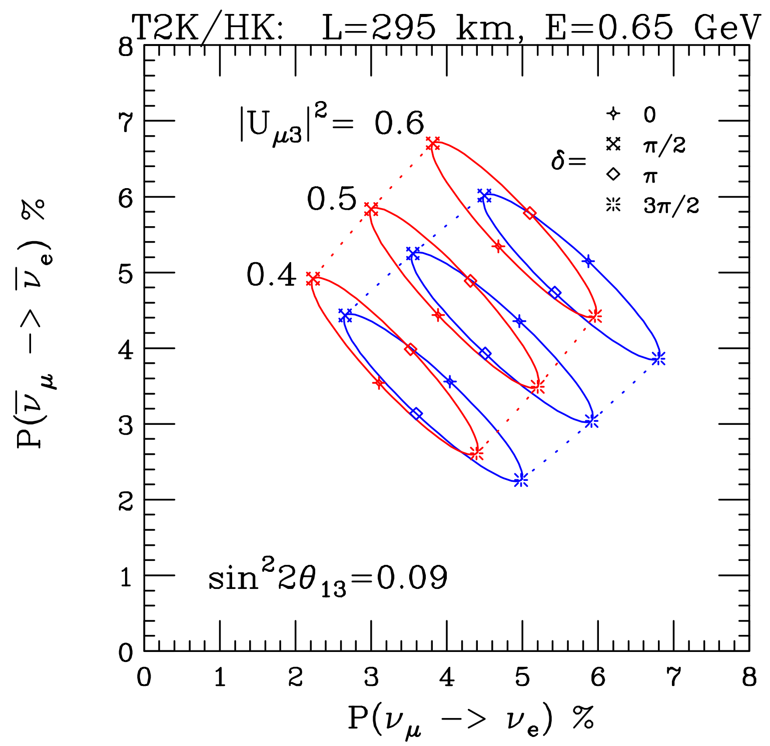
Correlations between Neutrino and Antineutrino nu_e Appearance

Normal Ordering — Inverted Ordering

T2K/HK



$\nu_\mu \to \nu_\mu$ gives:

$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu3}|^2(1-|U_{\mu3}|^2) = 0.96 \ - \ 1.00$ $\quad$ $|U_{\mu3}|^2 \leftrightarrow (1-|U_{\mu3}|^2)$ degeneracy !

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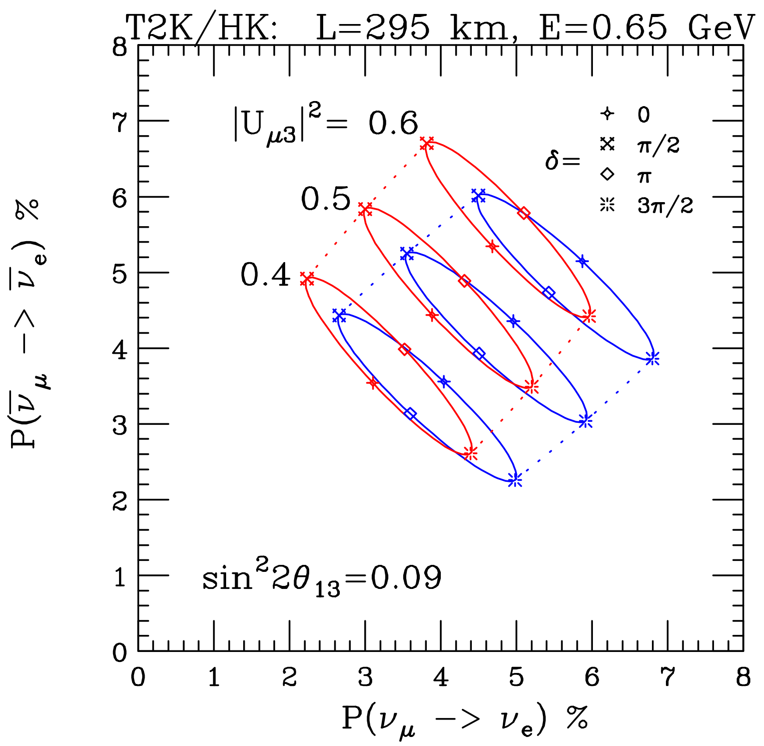
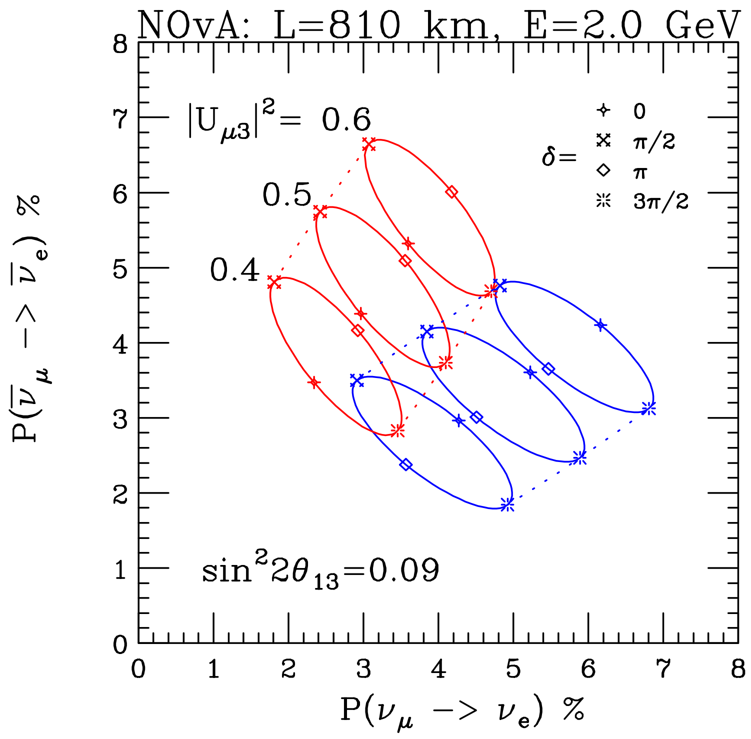


NOvA



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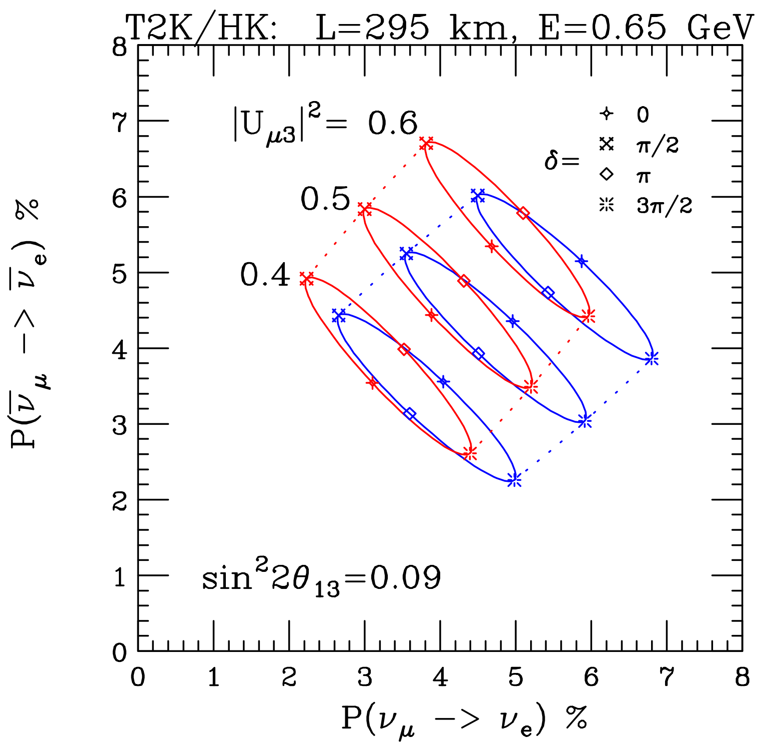
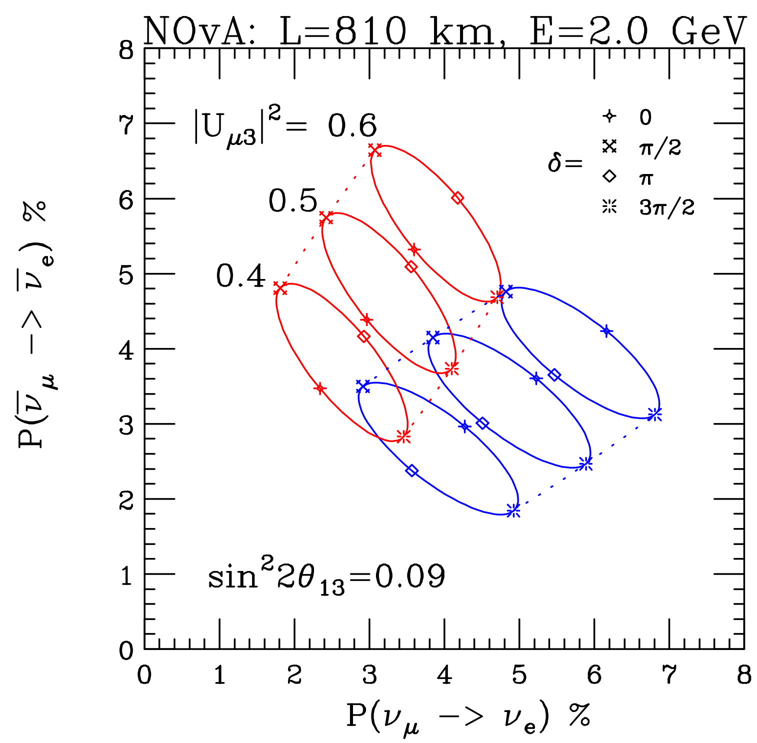
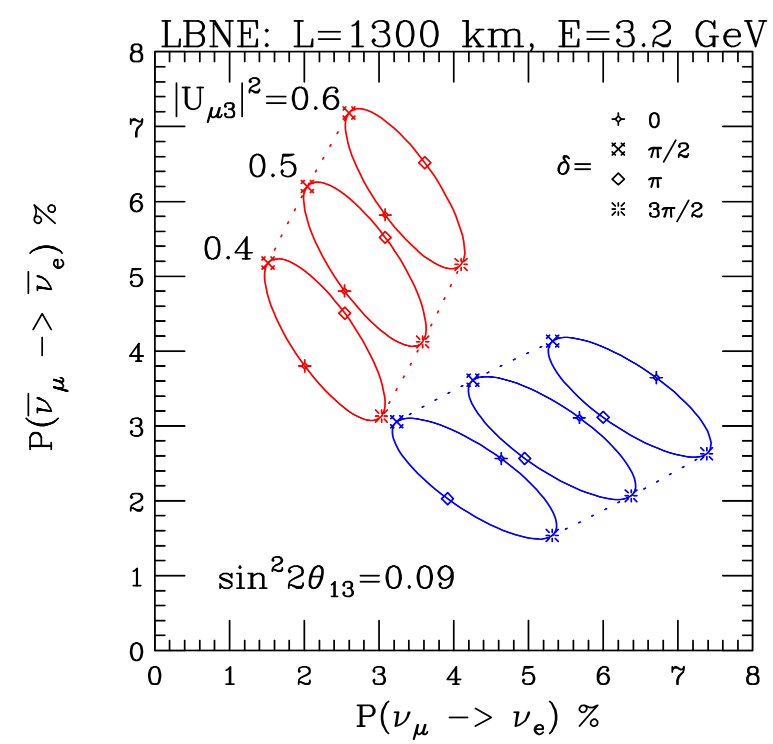


NOvA



DUNE



Same L/E as NOνA

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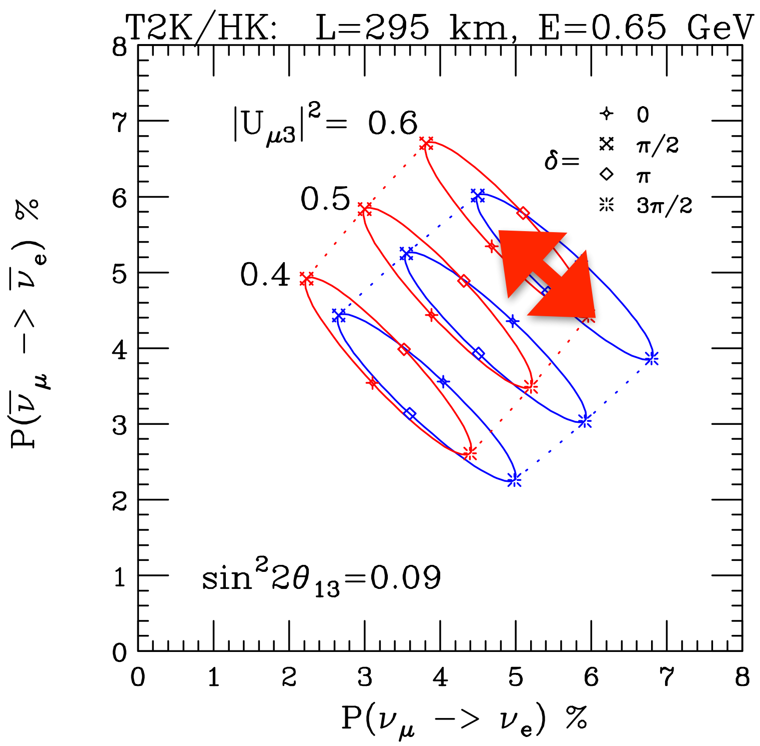
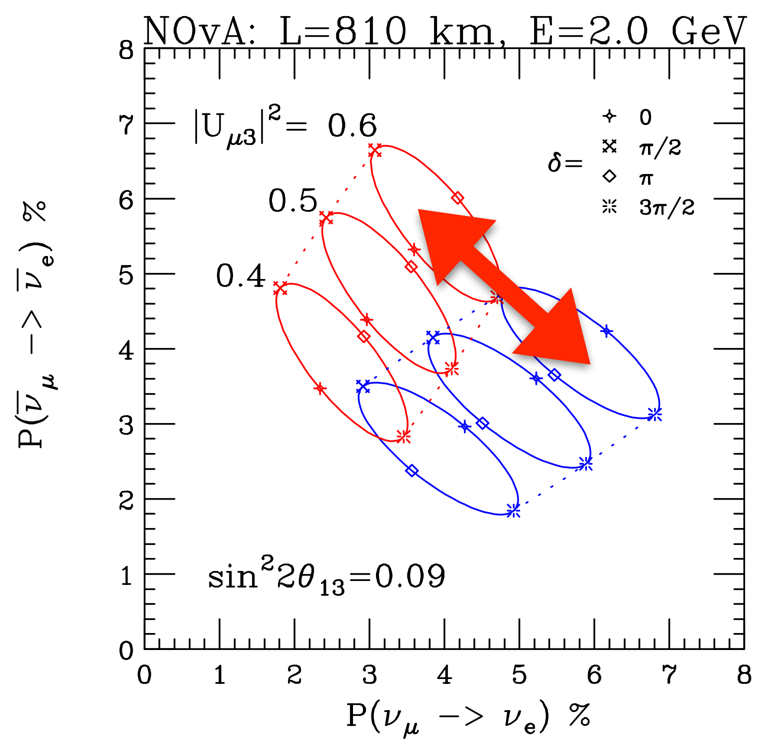
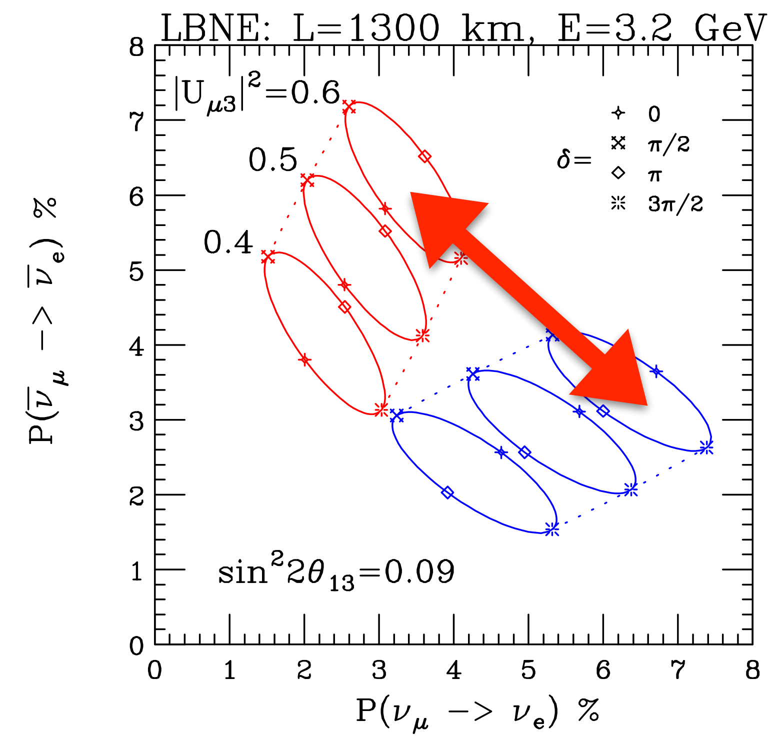
T2K/HK



NOvA



DUNE



$\propto \rho L \ \sin^2\theta_{23}$

Same L/E as NOνA

O. Mena + SP hep-ph/0408070

$\nu_\mu \to \nu_\mu$ gives:

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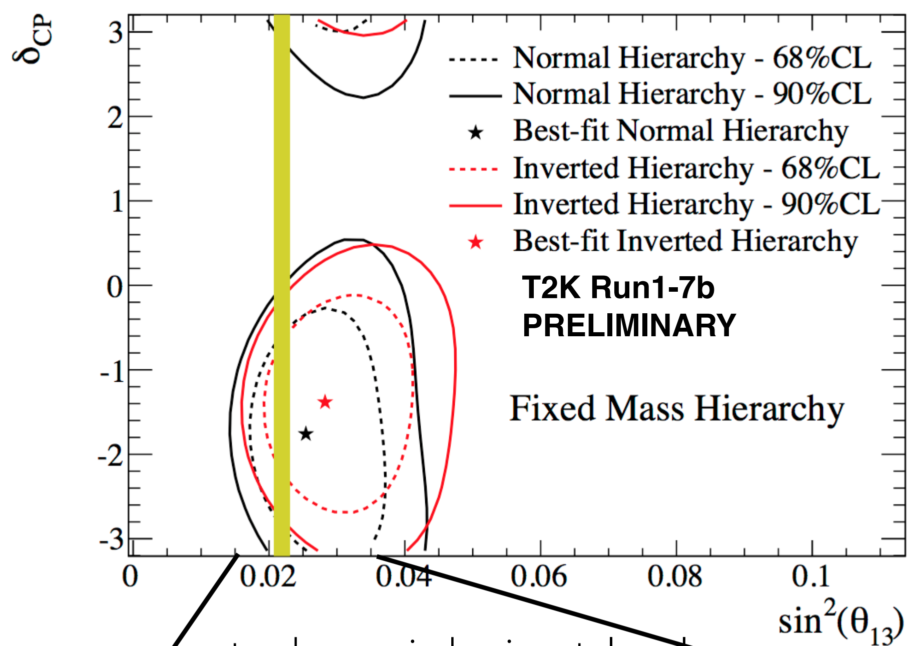
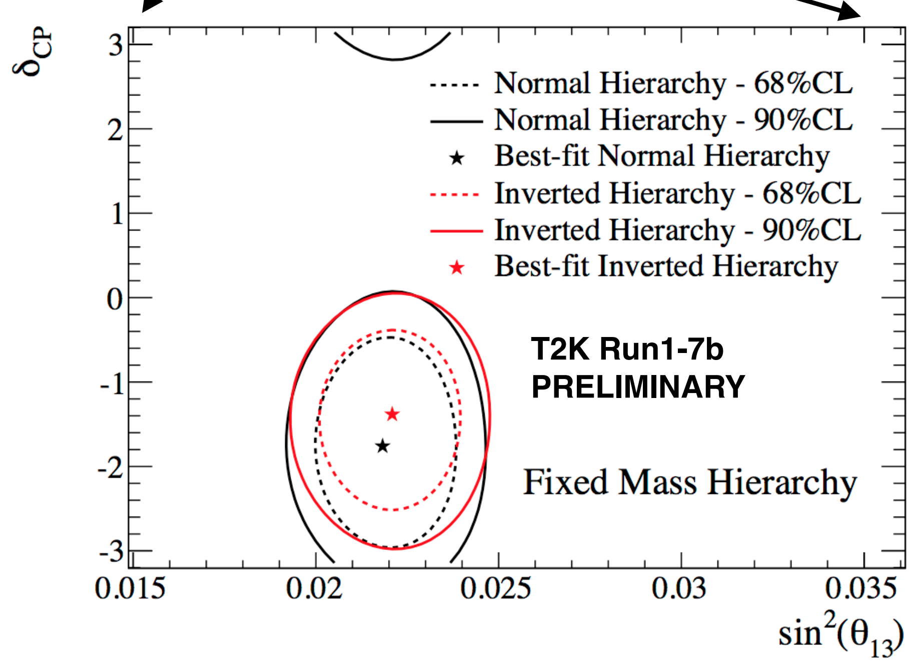
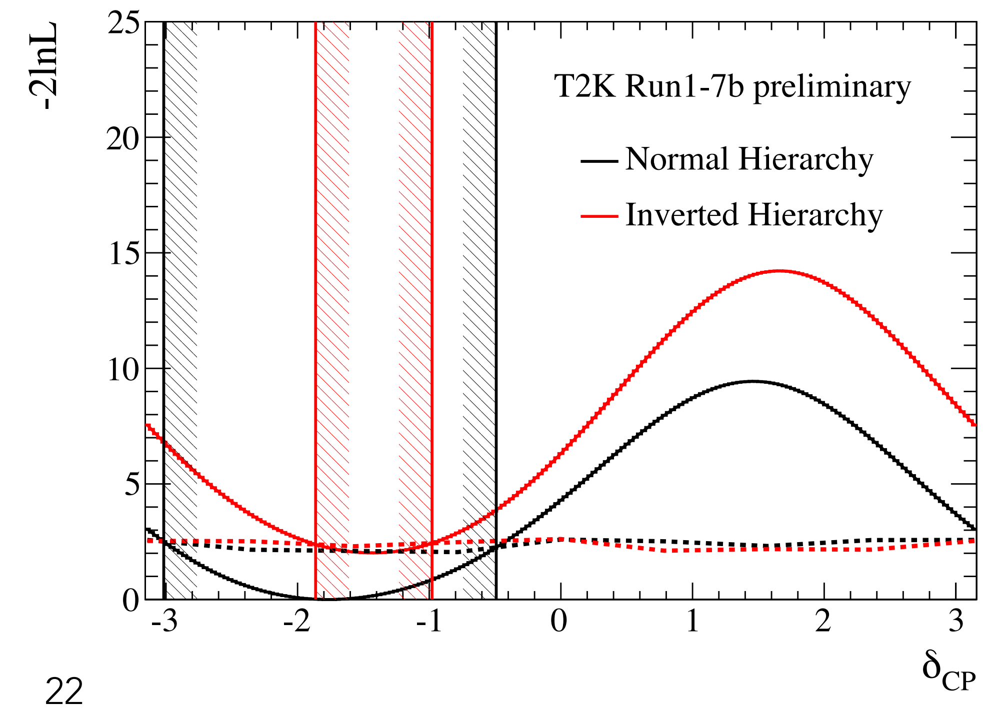
δ_{CP} vs. θ_{13}



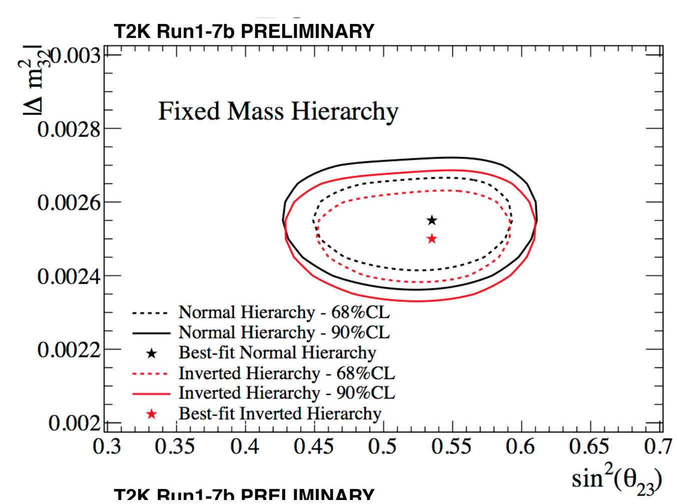
note change in horizontal scale

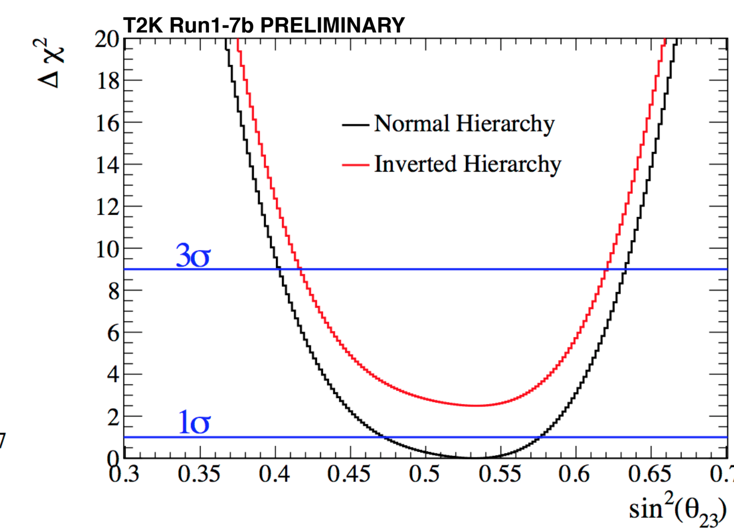




22

$\sin^2\theta_{23}$

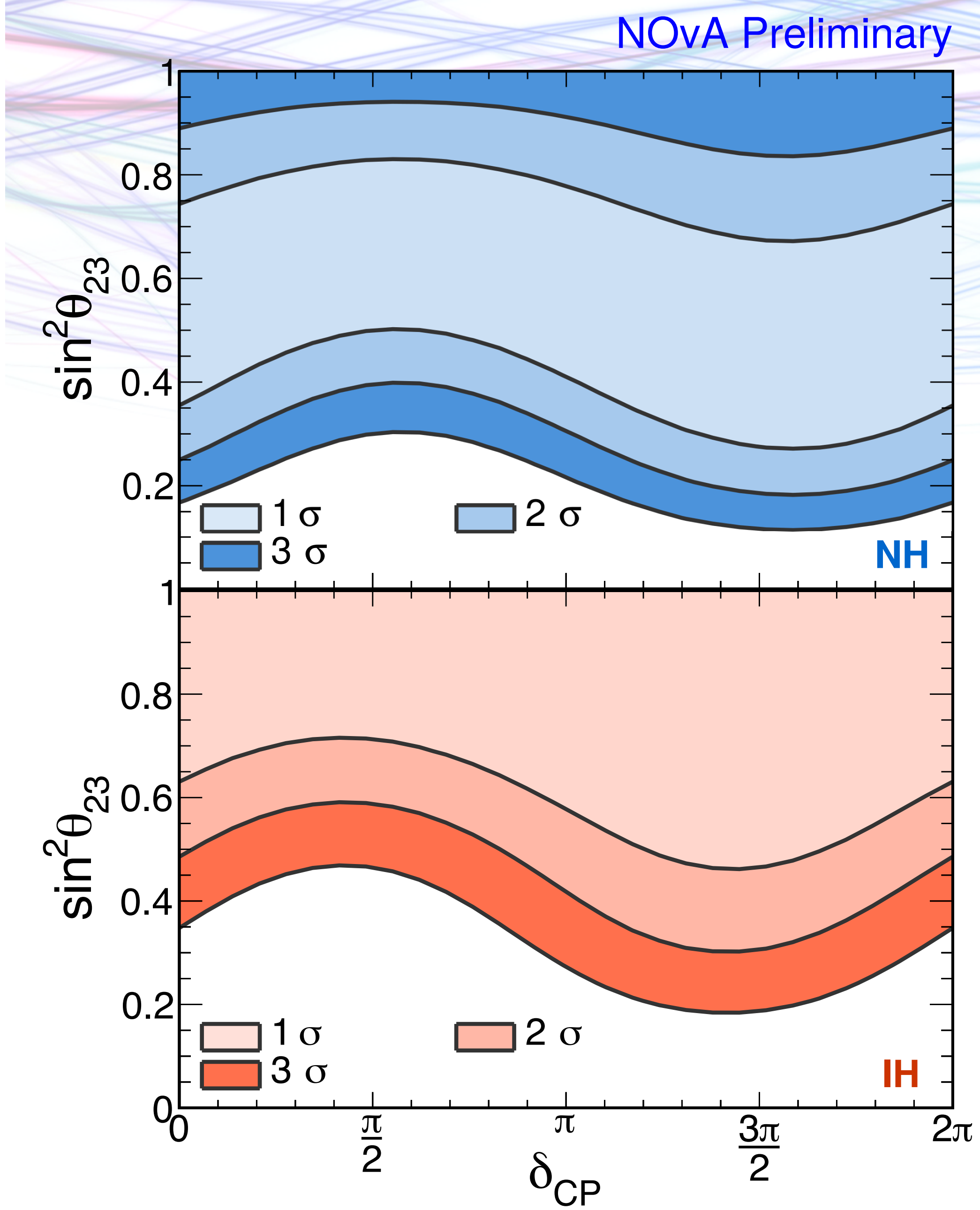




NOvA

ν_e fit results

- Constrain θ_{13} to reactor average $\sin^2 2\theta_{13} = 0.085 \pm 0.005$

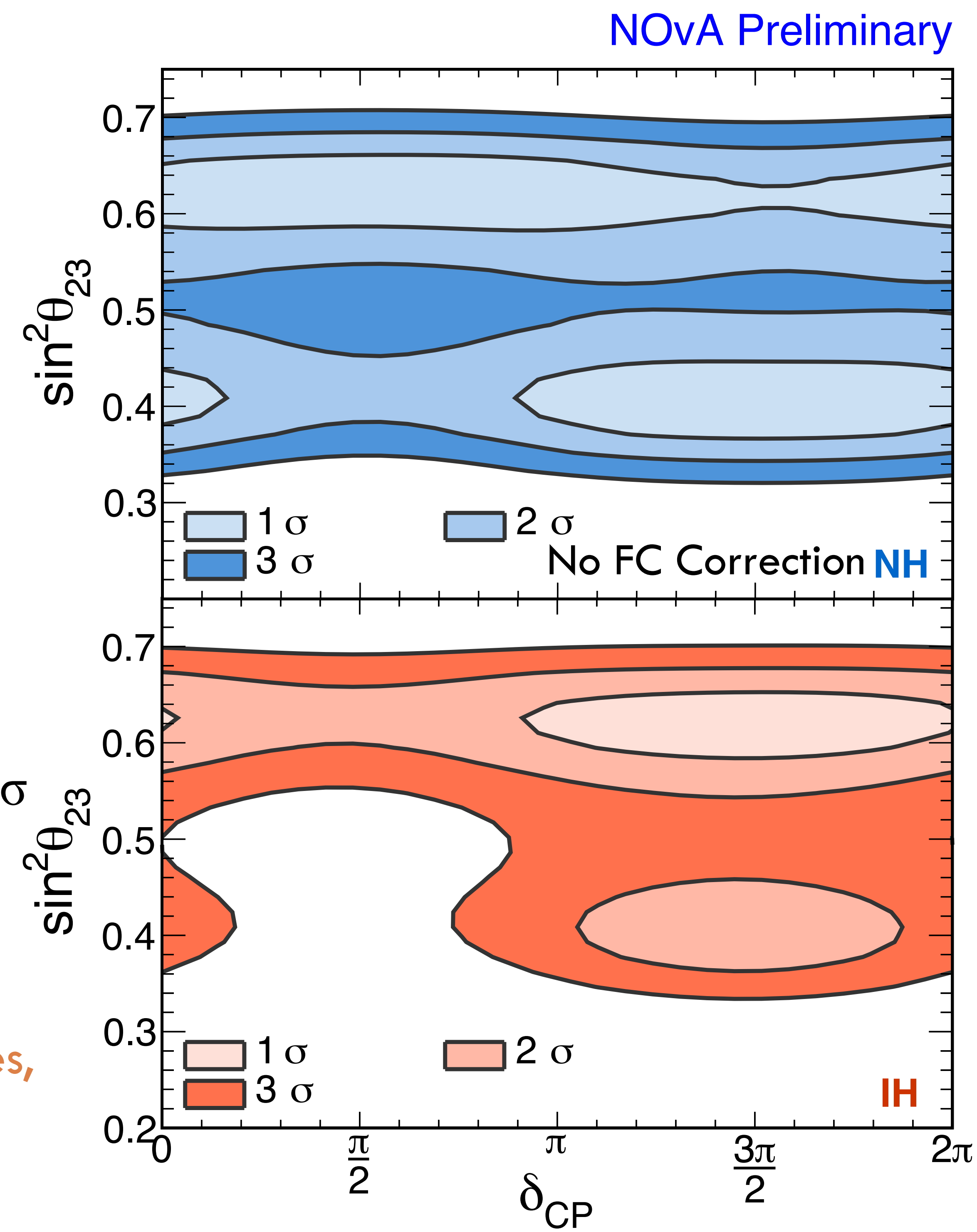


NOvA

- Fit for hierarchy, $\boldsymbol{\delta}_{CP}$, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated
- Global best fit Normal Hierarchy

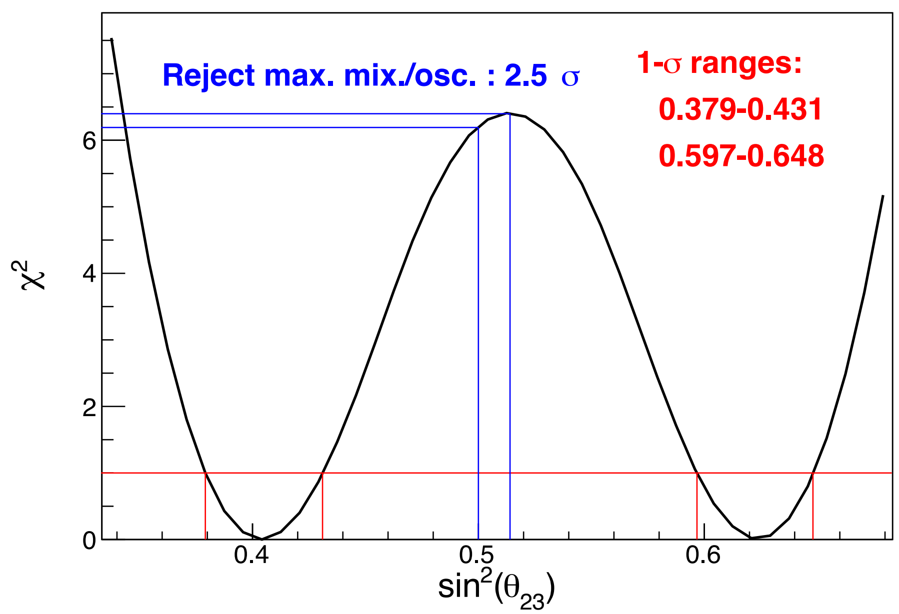
$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around $\boldsymbol{\delta}_{CP}=\pi/2$

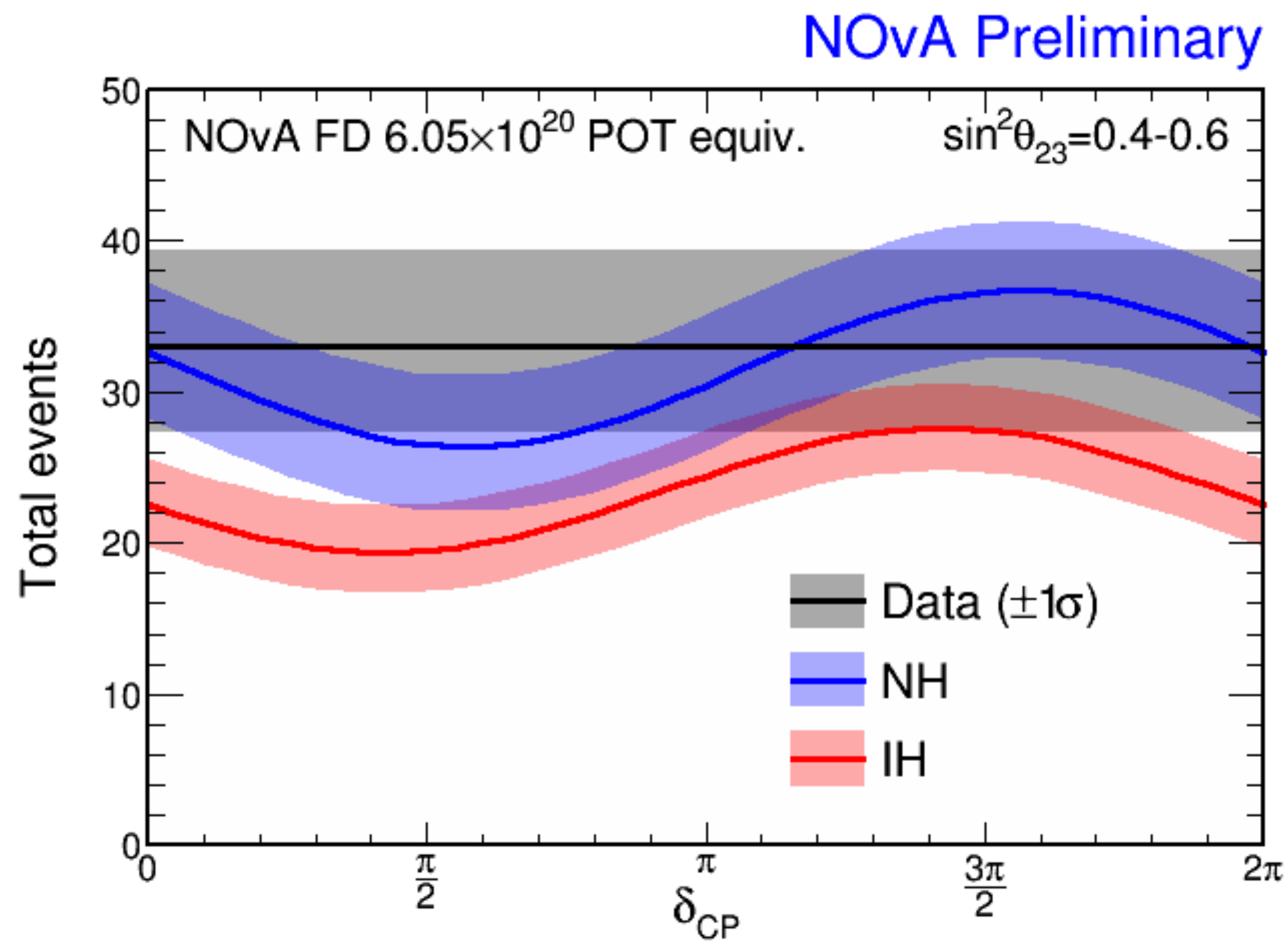


Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing
Planned for Spring 2017

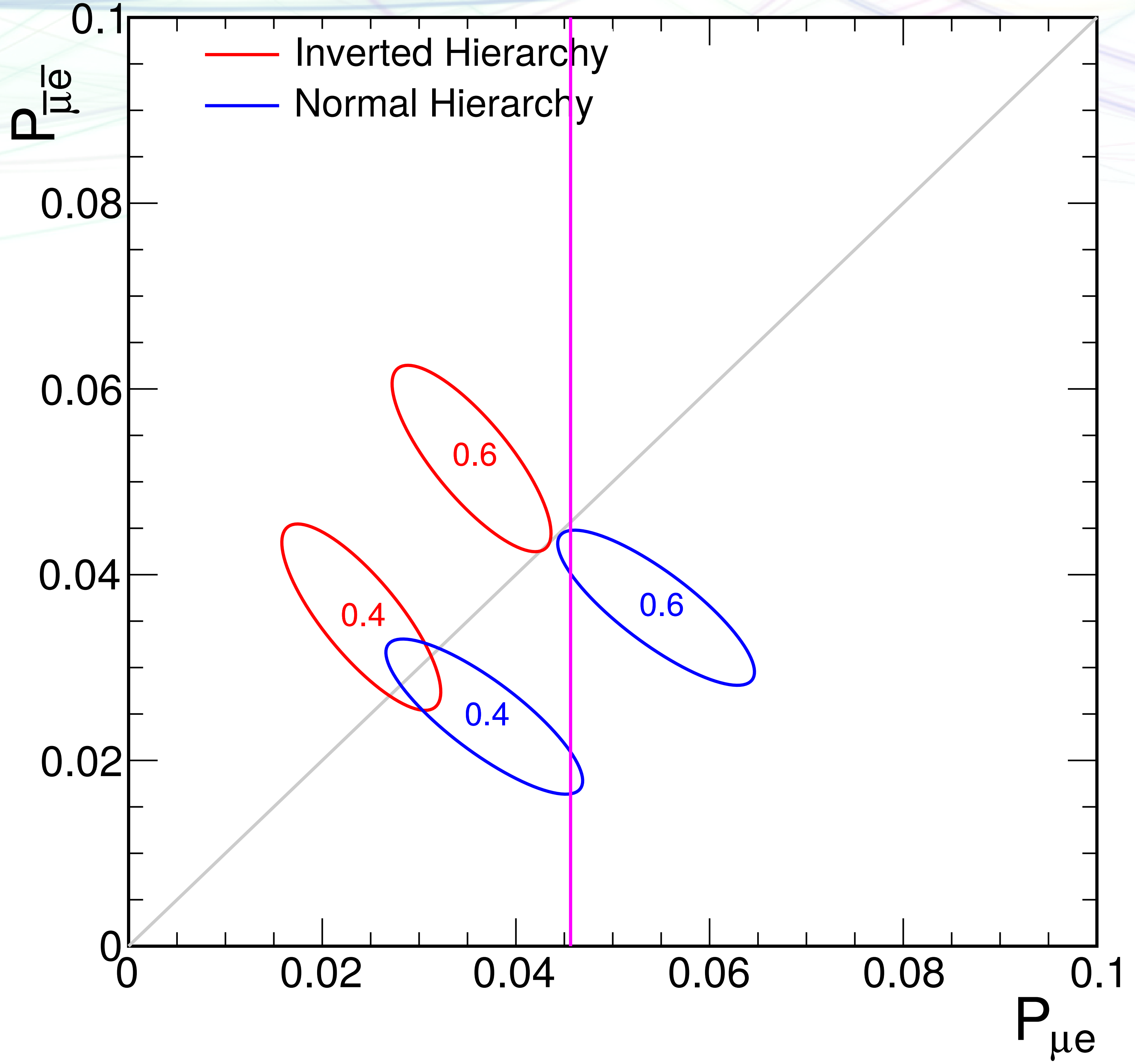
NOvA



Reject max. mix./osc. : 2.5 σ
1-σ ranges:
0.379-0.431
0.597-0.648
χ^2
$\sin^2(\theta_{23})$



NOvA Preliminary
NOvA FD 6.05×10^20 POT equiv.
$\sin^2\theta_{23}$=0.4-0.6
Total events
Data (±1σ)
NH
IH
δ_{CP}


Inverted Hierarchy
Normal Hierarchy
0.6
0.4
0.6
0.4
0.1
0.08
0.06
0.04
0.02
0
0
0.02
0.04
0.06
0.08
0.1
$P_{\mu e}$
$P_{\bar{\mu}\bar{e}}$

The Three Important Questions:

- Is there CP Violation
- Mass Ordering
- Dominant Flavor Content of ν_3

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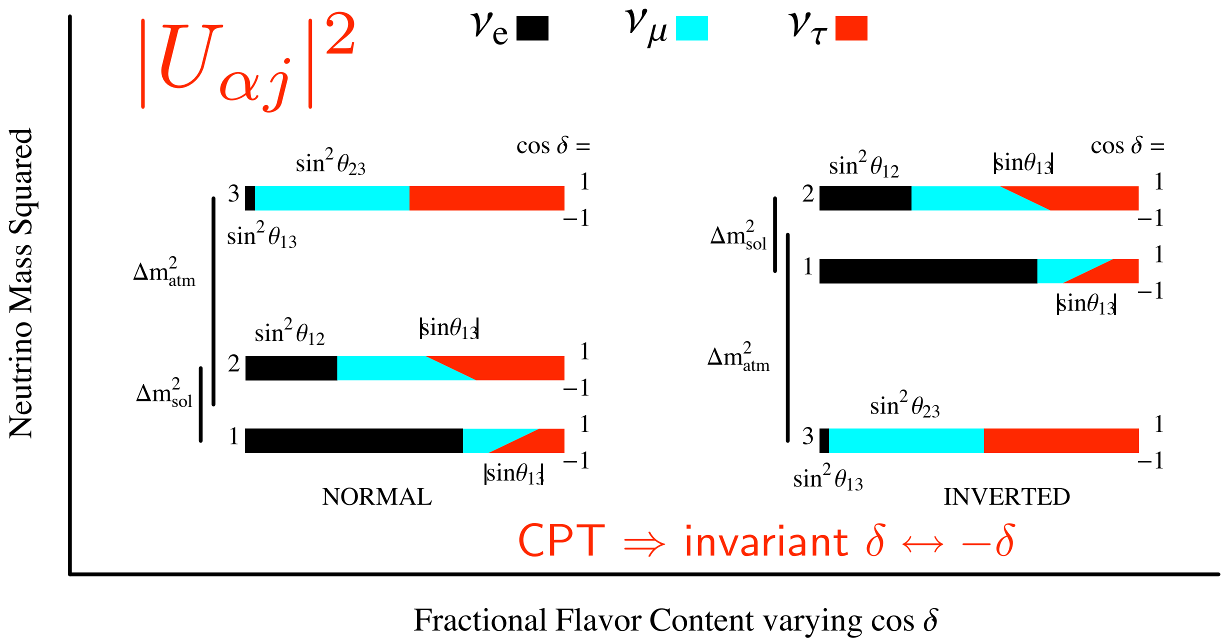

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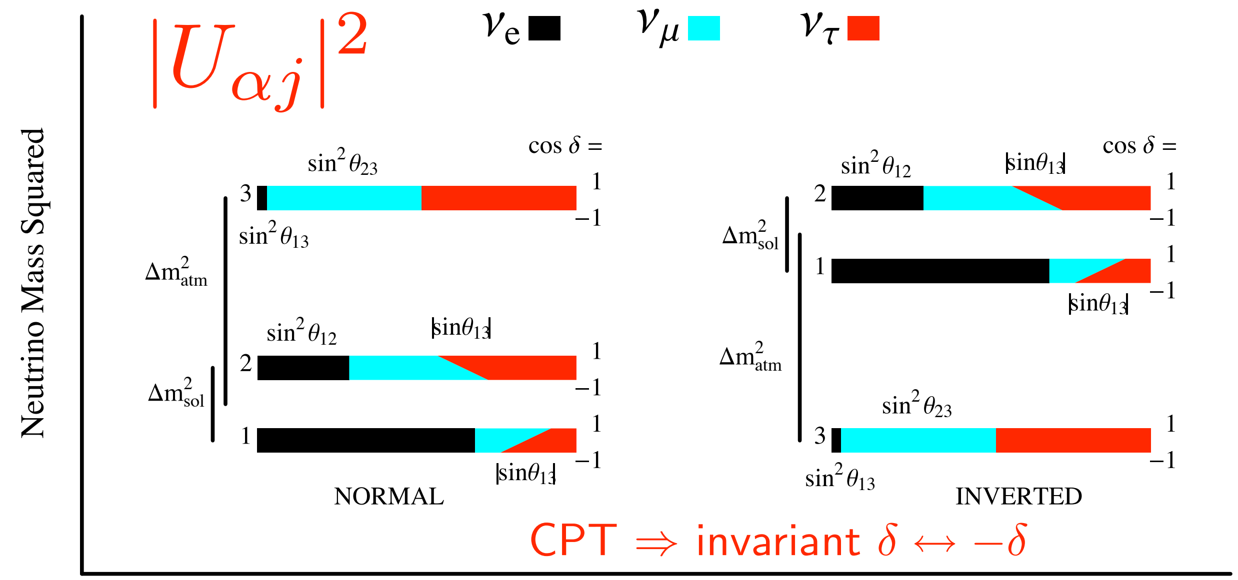
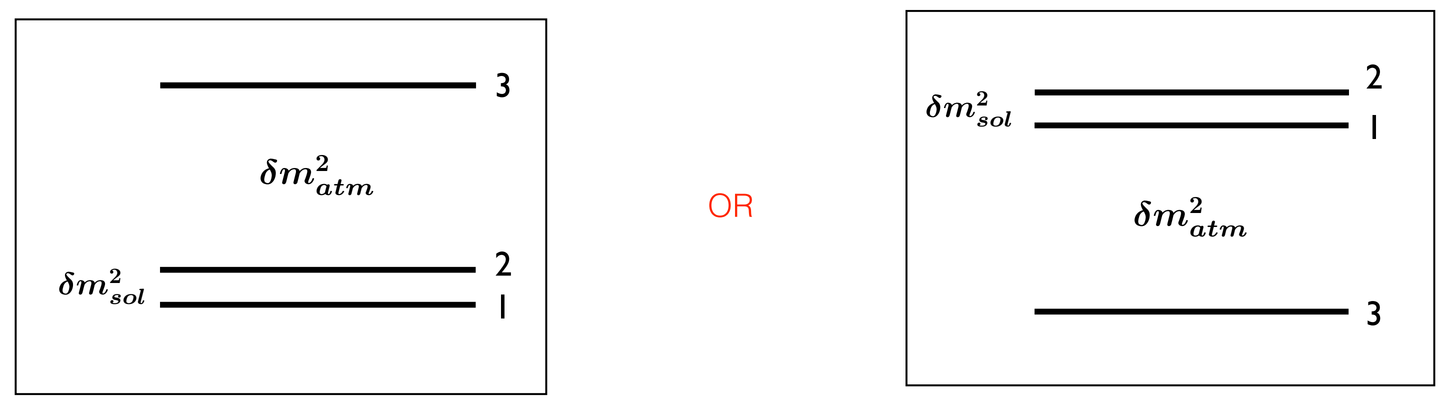


Fractional Flavor Content varying cos δ

- Is there CP Violation

- Mass Ordering



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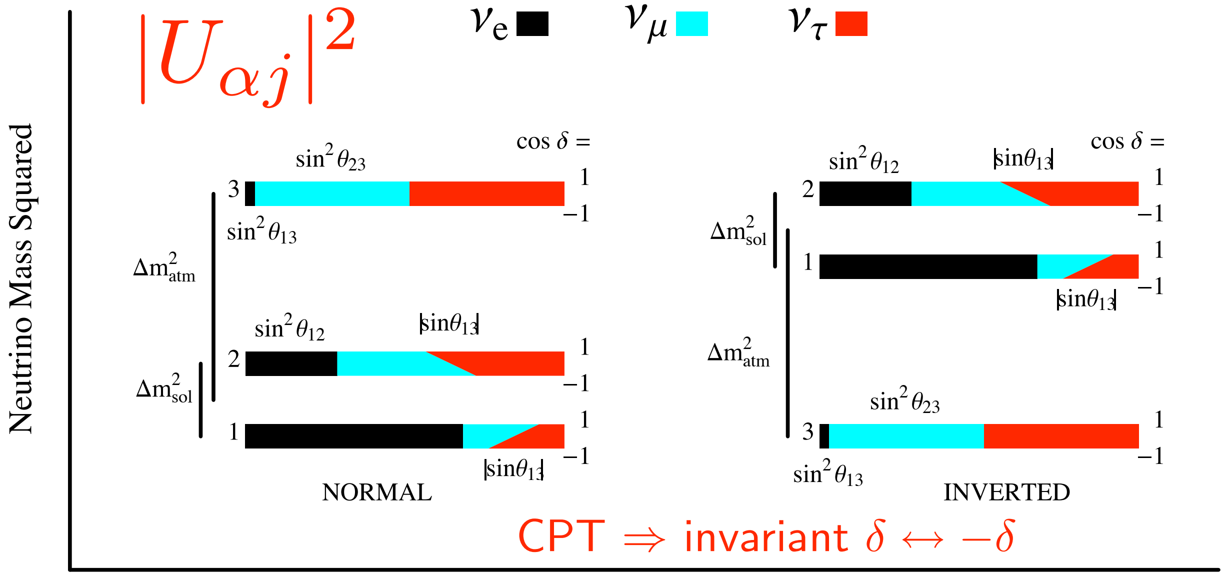
The Three Important Questions:



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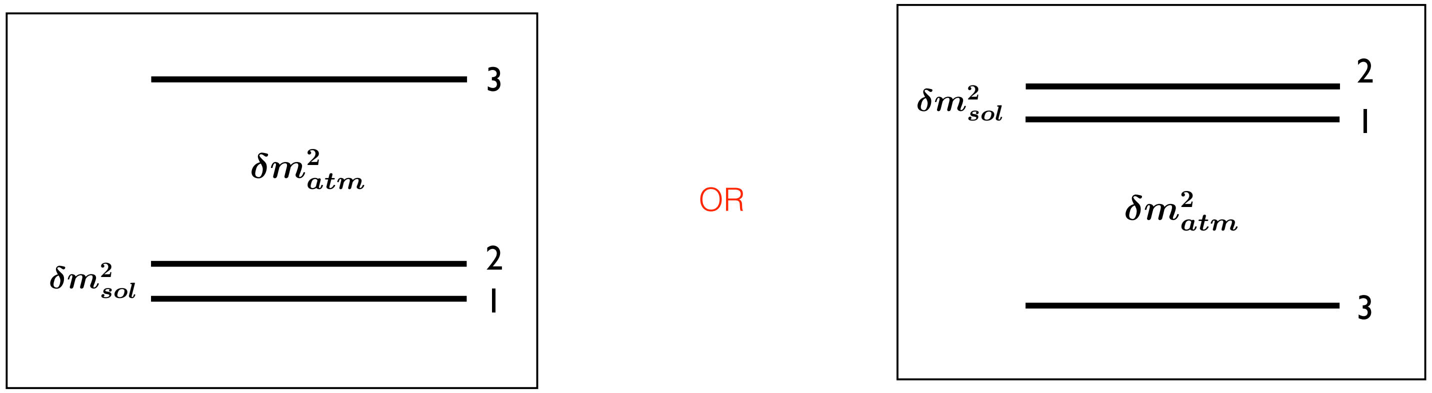
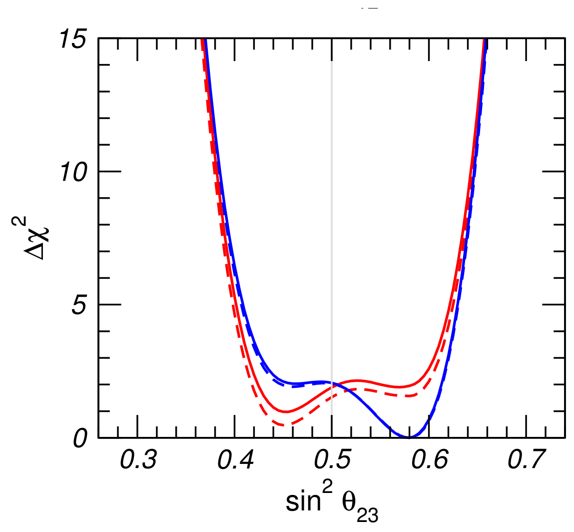
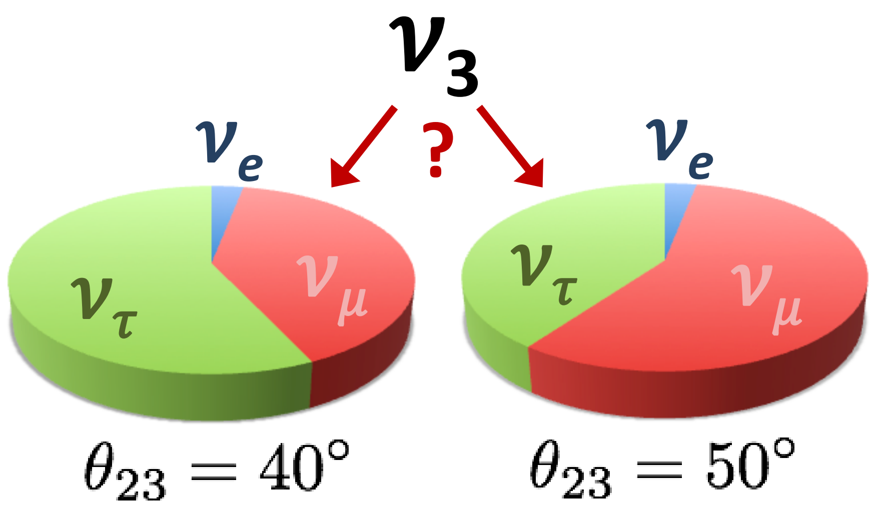


- Mass Ordering

- Dominant Flavor Content of ν_3

θ_{23} octant ?





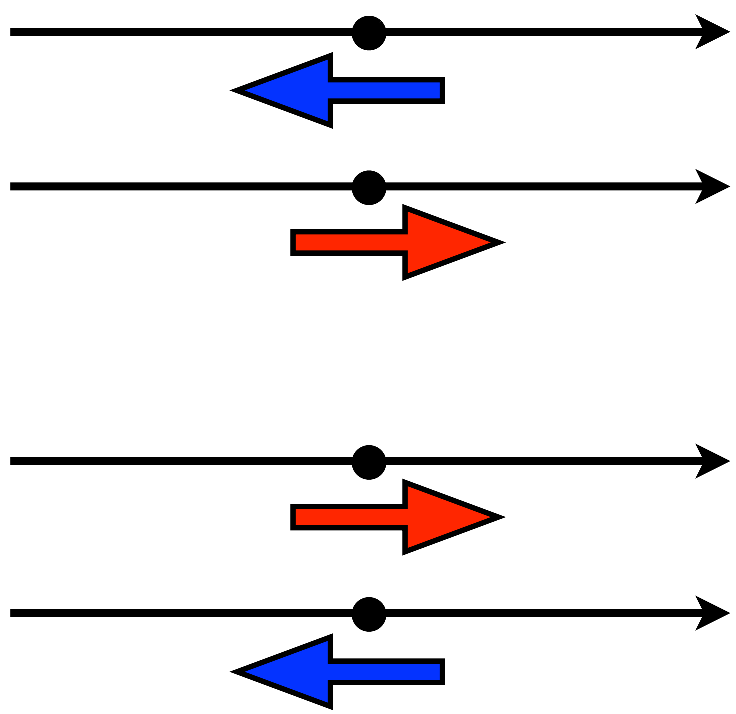
Dirac or Majorana

· Dirac OR Majorana

Dirac 4 comps

ν
$L = 1$

$\bar{\nu}$
$L = -1$



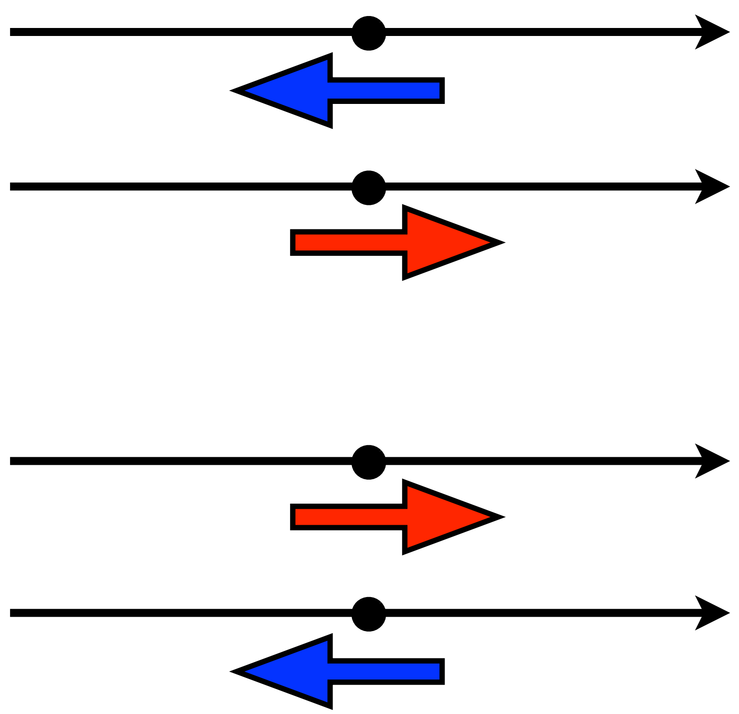
helicity	l^-	l^+
L	1	0
R	$(\frac{m_\nu}{E})^2$	0
R	0	1
L	0	$(\frac{m_\nu}{E})^2$

$$(\frac{m_\nu}{E})^2 = (\frac{1eV}{1GeV})^2 = 10^{-18}$$

• Dirac OR Majorana

Dirac 4 comps

ν
$L = 1$



$\bar{\nu}$
$L = -1$

helicity	l^-	l^+
L	1	0
R	$(\frac{m_\nu}{E})^2$	0
R	0	1
L	0	$(\frac{m_\nu}{E})^2$

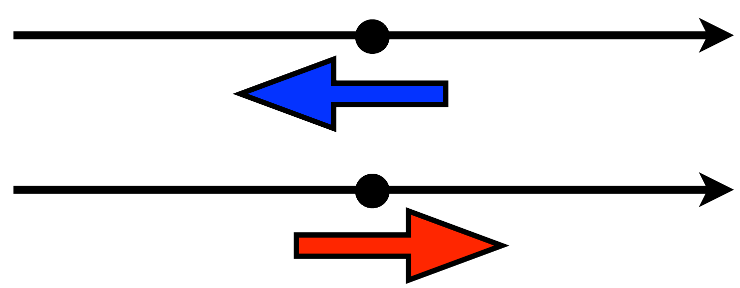
$$(\frac{m_\nu}{E})^2 = (\frac{1eV}{1GeV})^2 = 10^{-18}$$

....

Majorana 2 comps

ν

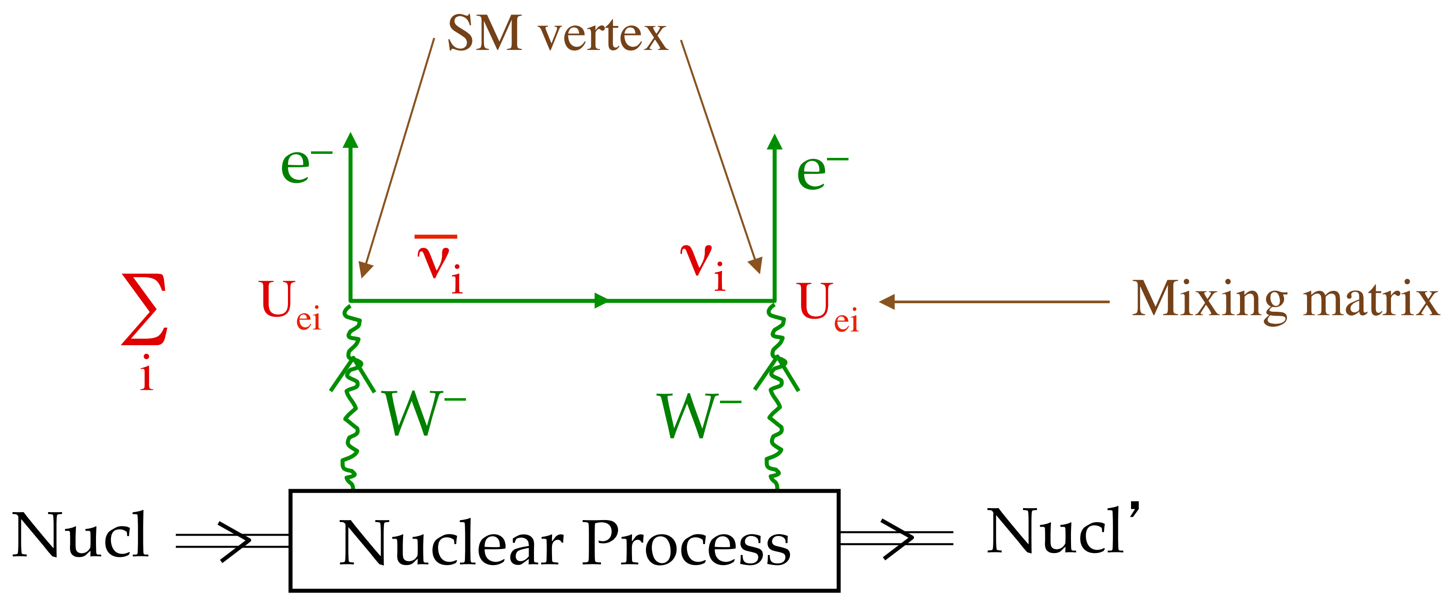
$\bar{\nu}$



helicity	l^-	l^+
L	1	$(\frac{m_\nu}{E})^2$
R	$(\frac{m_\nu}{E})^2$	1

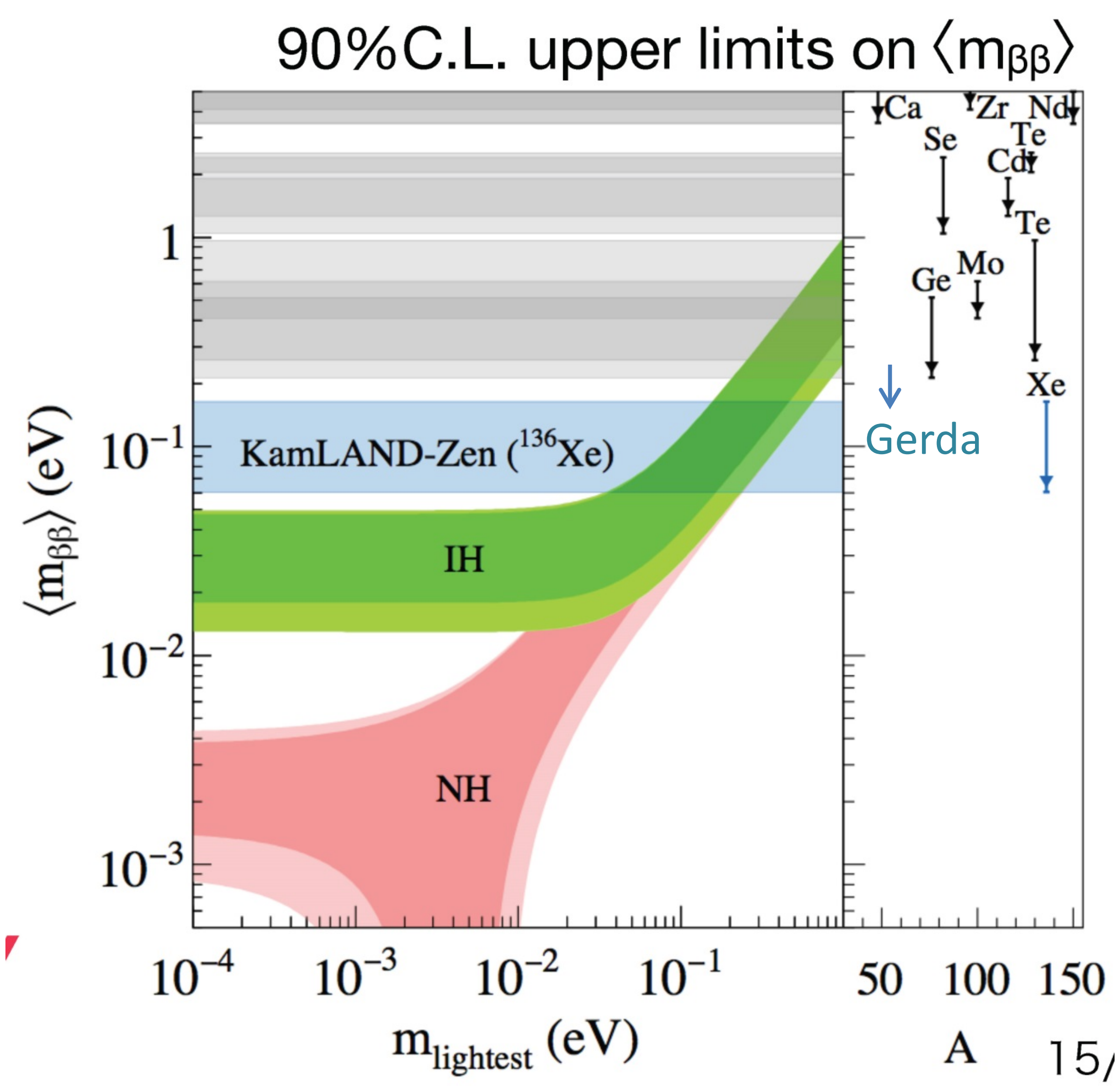
$$\nu = \bar{\nu}$$

Majorana or Dirac:



$$\mathrm{Amp}[0\nu\beta\beta] \propto \left|\sum m_i U_{ei}^2\right| \equiv m_{\beta\beta}$$

The mass is the source of the lepton number violation.



- Beyond Nu Standard Model

More then 3 Neutrinos:

More than 3 neutrinos?

Non-unitary mixing

$$\widetilde{U}$$

$$U^{N\times N} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu N} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s_{N_s} 1} & U_{s_{N_s} 2} & U_{s_{N_s} 3} & \cdots & U_{s_{N_s} N} \end{pmatrix}$$

Results valid for Dirac or Majorana

Giunti

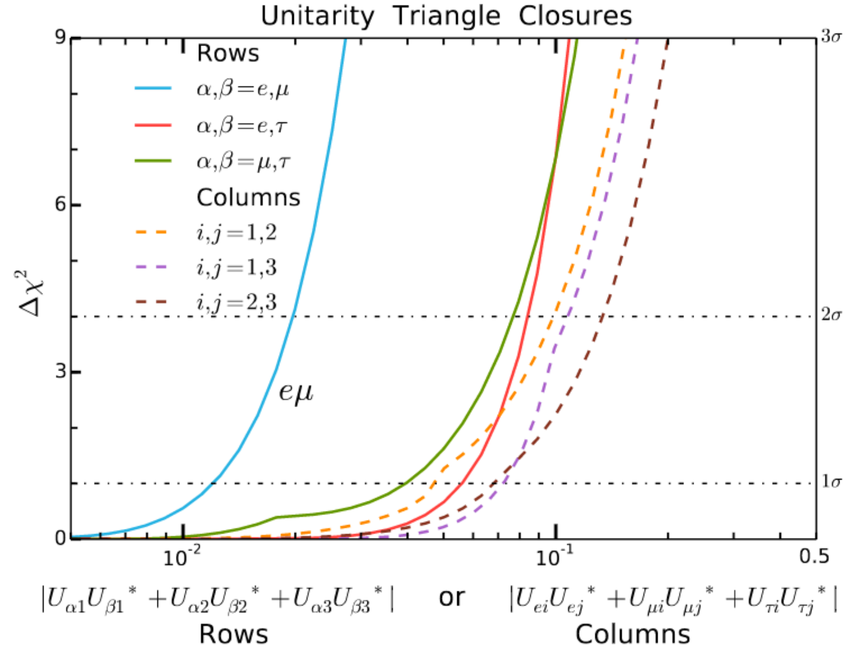
Bounds on non-unitary mixing

For Dirac or Majorana

→ If sterile masses between eV and keV :

$$|U|_{3\sigma}^{\substack{\text{w/o Unitarity}\\ \text{(with Unitarity)}}} = \begin{pmatrix} 0.76 \to 0.85 & 0.50 \to 0.60 & 0.13 \to 0.16 \\ (0.79 \to 0.85) & (0.50 \to 0.59) & (0.14 \to 0.16) \\ 0.21 \to 0.54 & 0.42 \to 0.70 & 0.61 \to 0.79 \\ (0.22 \to 0.52) & (0.43 \to 0.70) & (0.62 \to 0.79) \\ 0.18 \to 0.58 & 0.38 \to 0.72 & 0.40 \to 0.78 \\ (0.24 \to 0.54) & (0.47 \to 0.72) & (0.60 \to 0.77) \end{pmatrix}$$

[Parke, Ross-Lonergan, PRD 93 (2016) 113009]



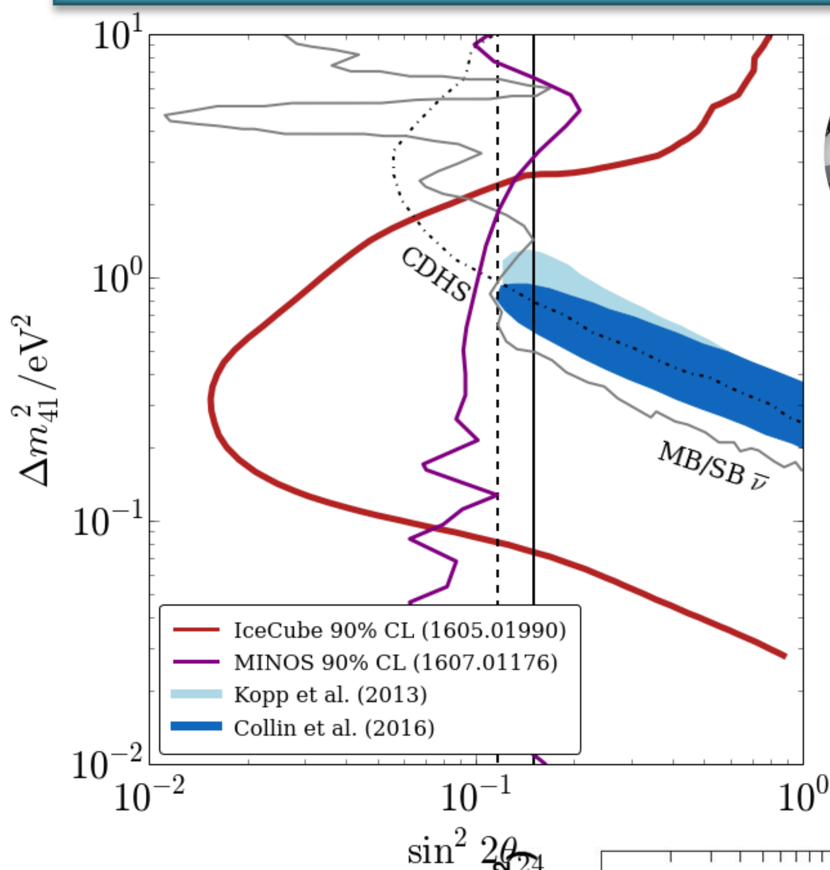
→ If steriles heavier than electroweak scale:

$$\widetilde{U} = (\mathbf{1} - \eta)\, U$$

$$2|\eta| \leq \begin{pmatrix} 2.5 \times 10^{-3} & 2.4 \times 10^{-5} & 2.7 \times 10^{-3} \\ 2.4 \times 10^{-5} & 4.0 \times 10^{-4} & 1.2 \times 10^{-3} \\ 2.7 \times 10^{-3} & 1.2 \times 10^{-3} & 5.6 \times 10^{-3} \end{pmatrix} \quad \text{at } 2\sigma$$

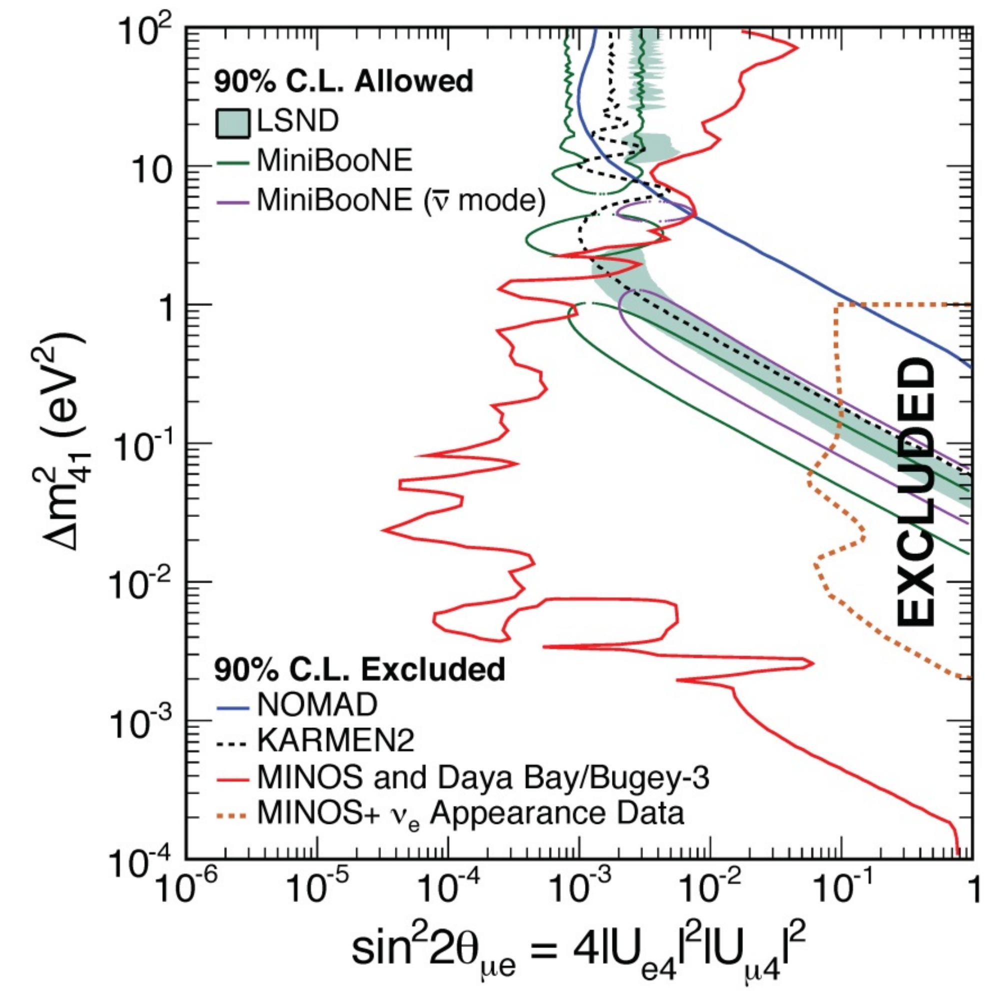
[Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda, PLB 649 (2007) 427]
[Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, arXiv:1605.08774]

No positive results on steriles

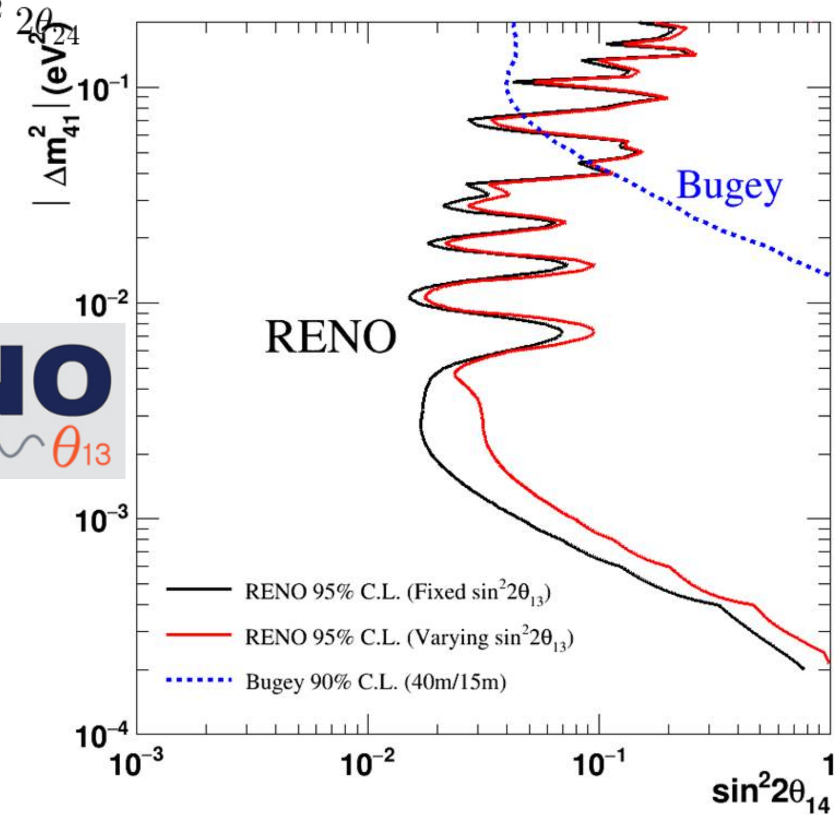


IceCube

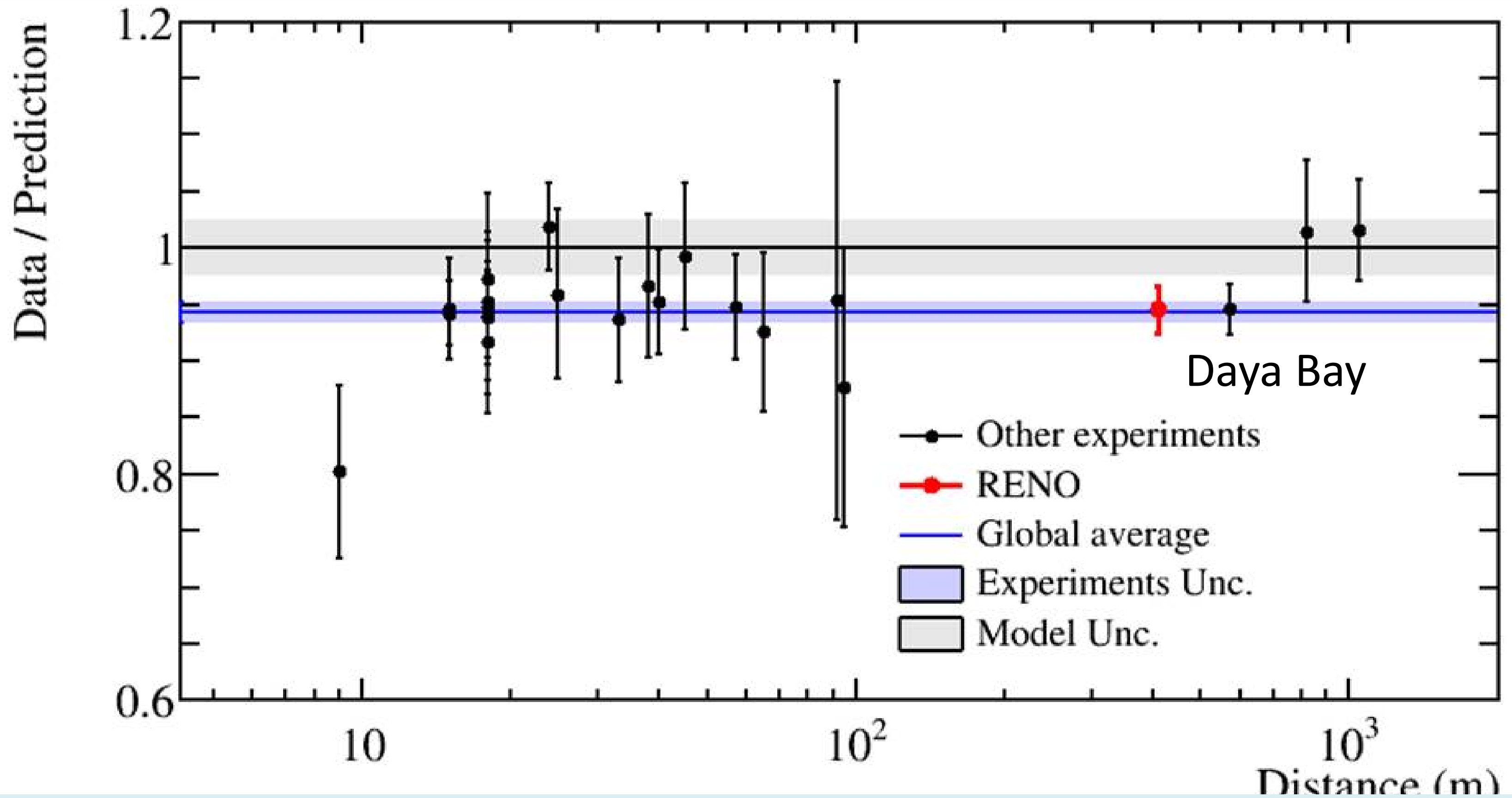
Daya Bay, Minos and Bugey 3 combined



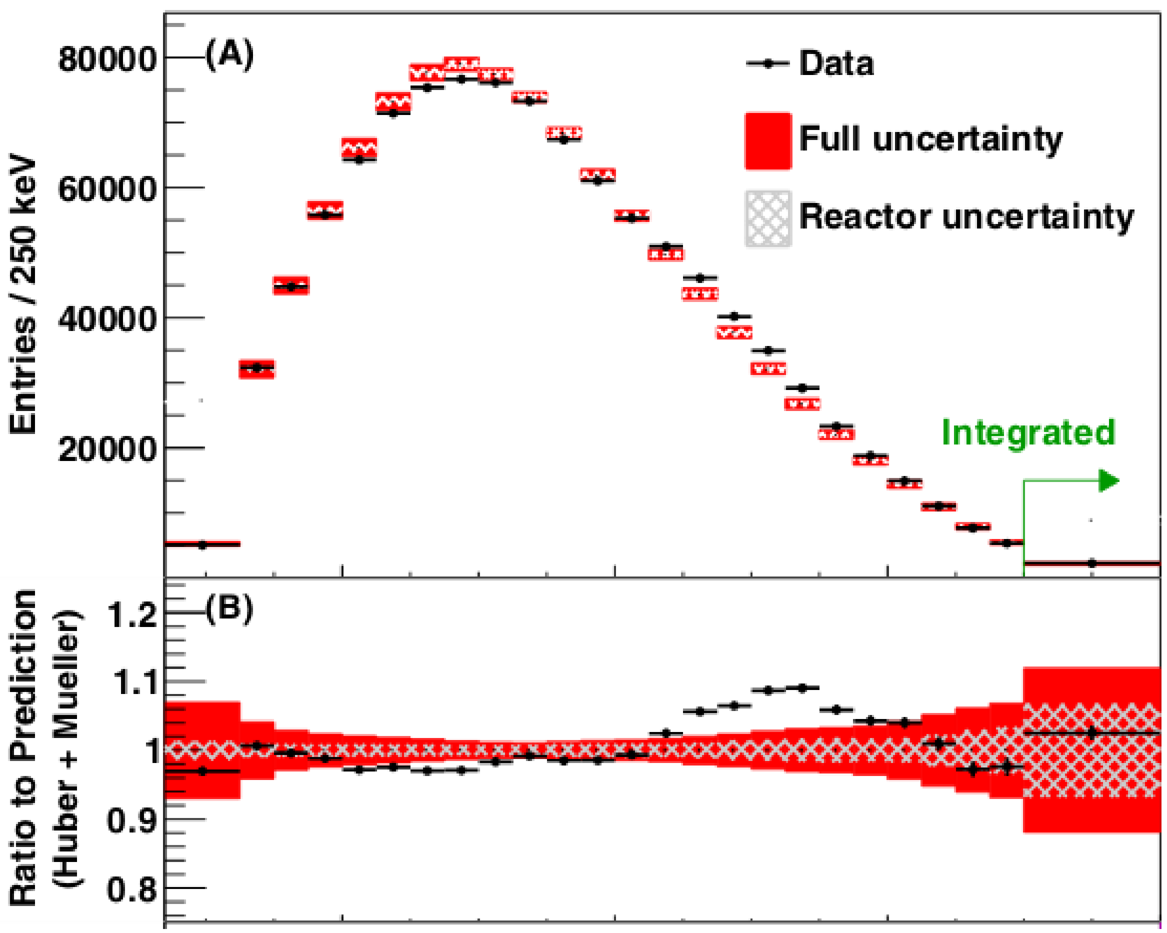
RENO



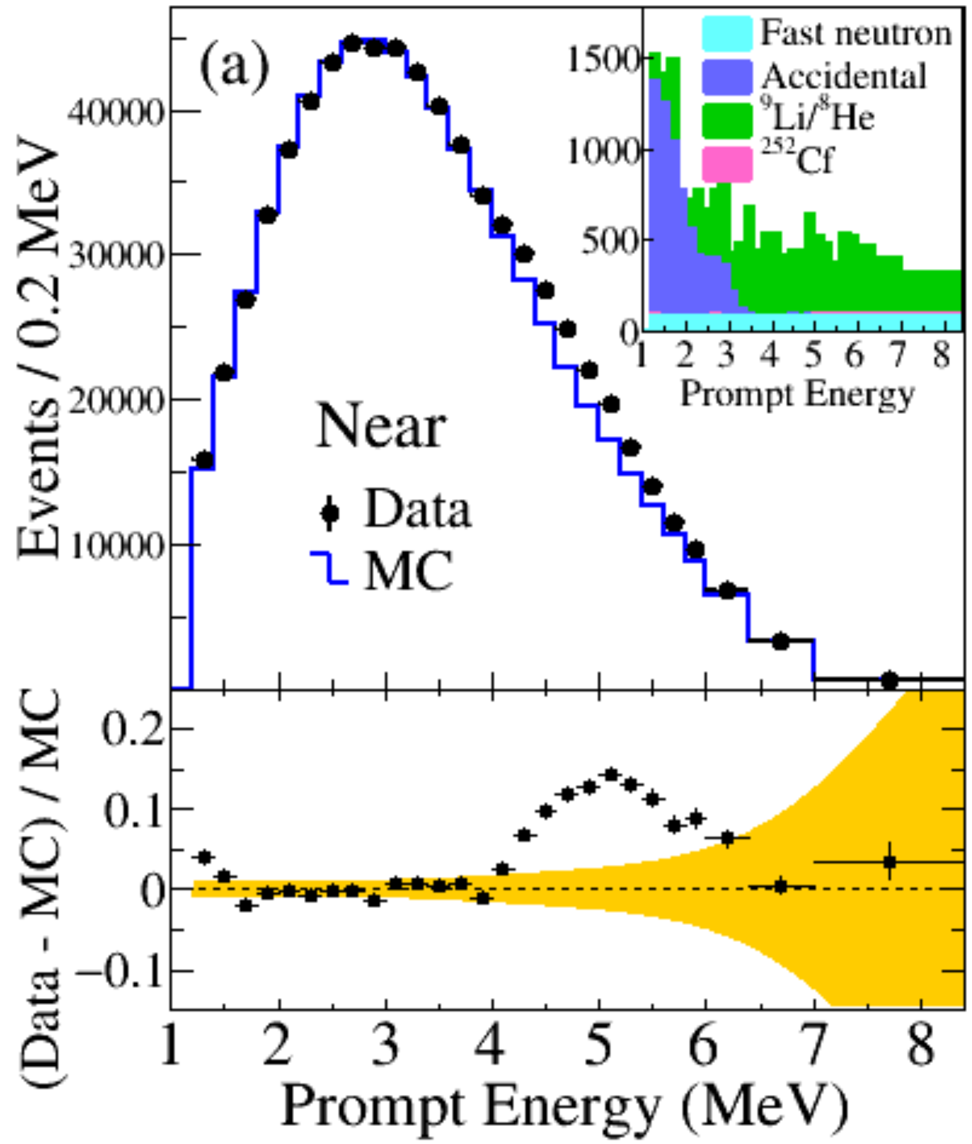
…except the deficit of absolute reactor neutrino fluxes



Daya Bay



RENO



- **4.4σ local significance at 4~6MeV**

Fraction of 5 MeV excess: **2.46 ± 0.27 (%)**

Significance of the 5 MeV excess: ~**9σ**

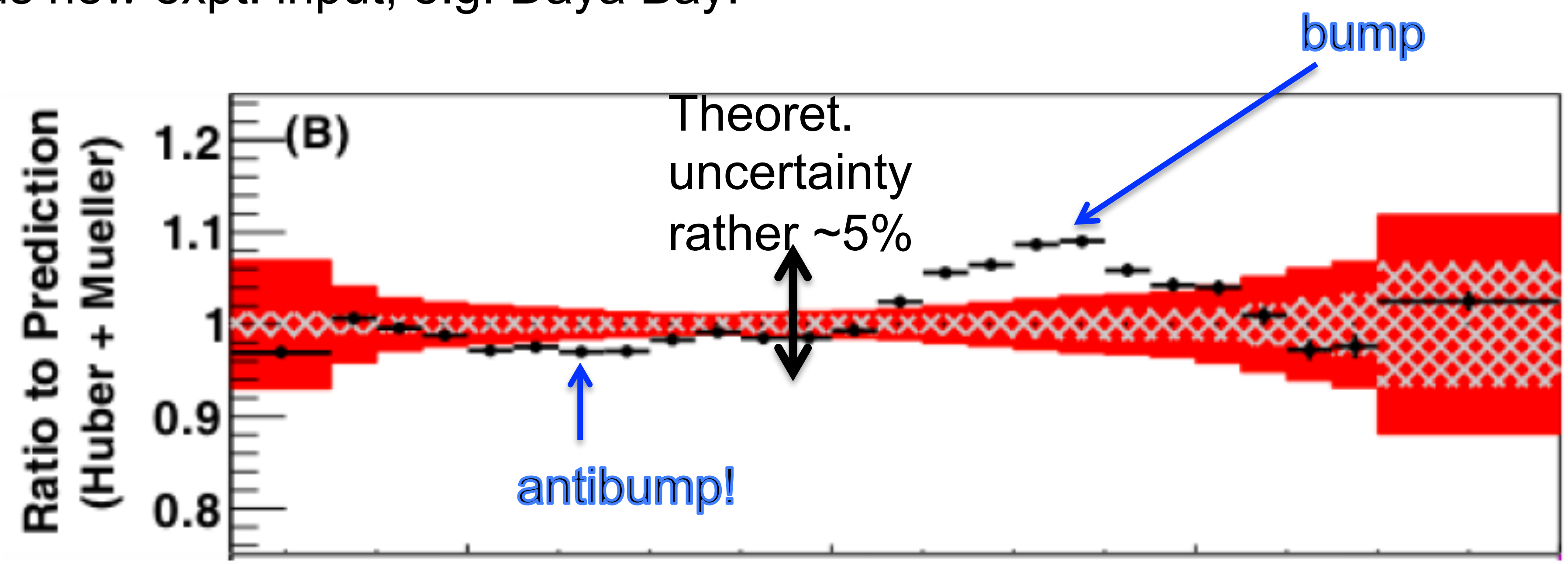
Huber

At E_ν ~ # MeV : **nuclear physics theoretical uncertitude ~ 5%**

while the "deficit" in reactor flux was ~3%

* Intense theoretical analysis of 5MeV bump discovered by RENO: inconclusive
* Plus new expt. input, e.g. Daya Bay:

Yu



Or let us declare the reactor anomaly hibernating...

as possible hint of steriles

(exptal. program important to ensure

< % level in reactor physics)

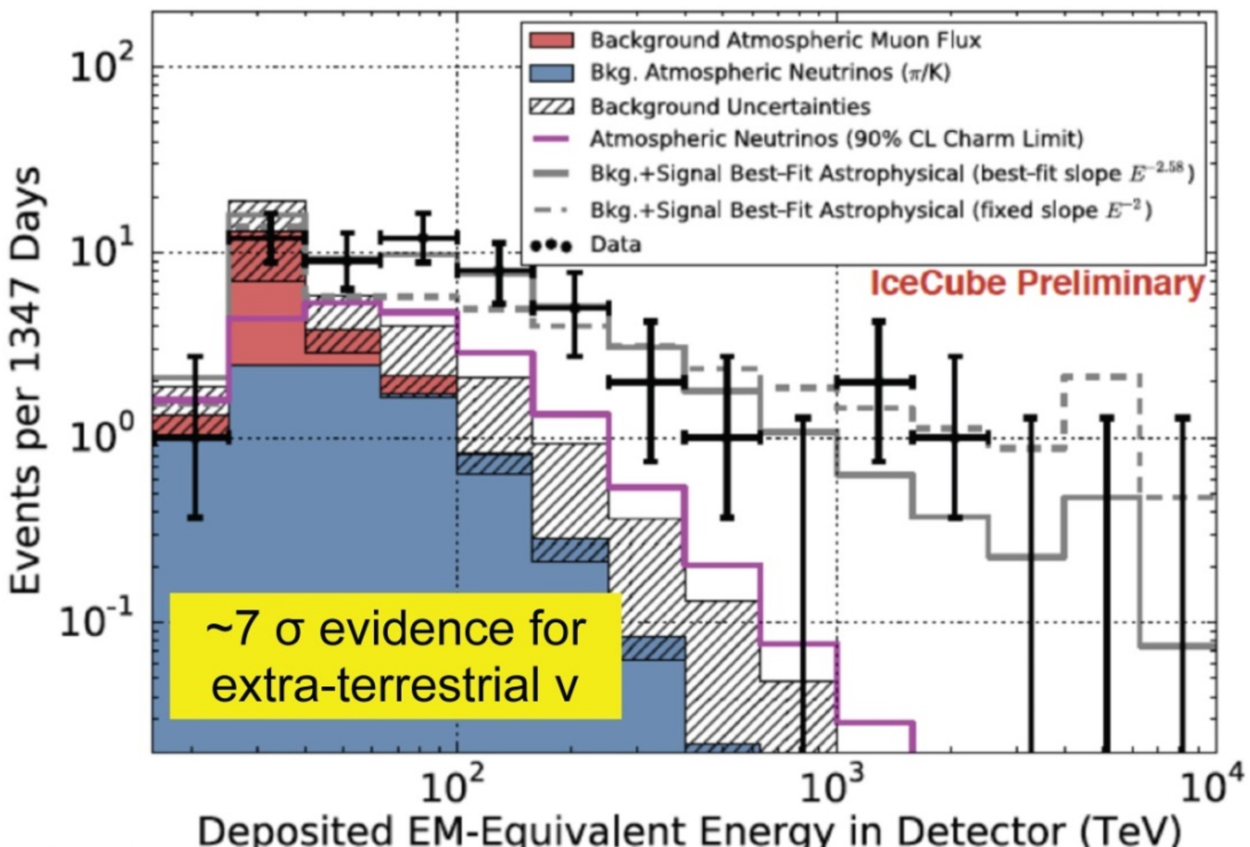
Do the fits with 5% theoret. error

- Neutrino Astronomy

Neutrino Astronomy:

Energy Spectrum

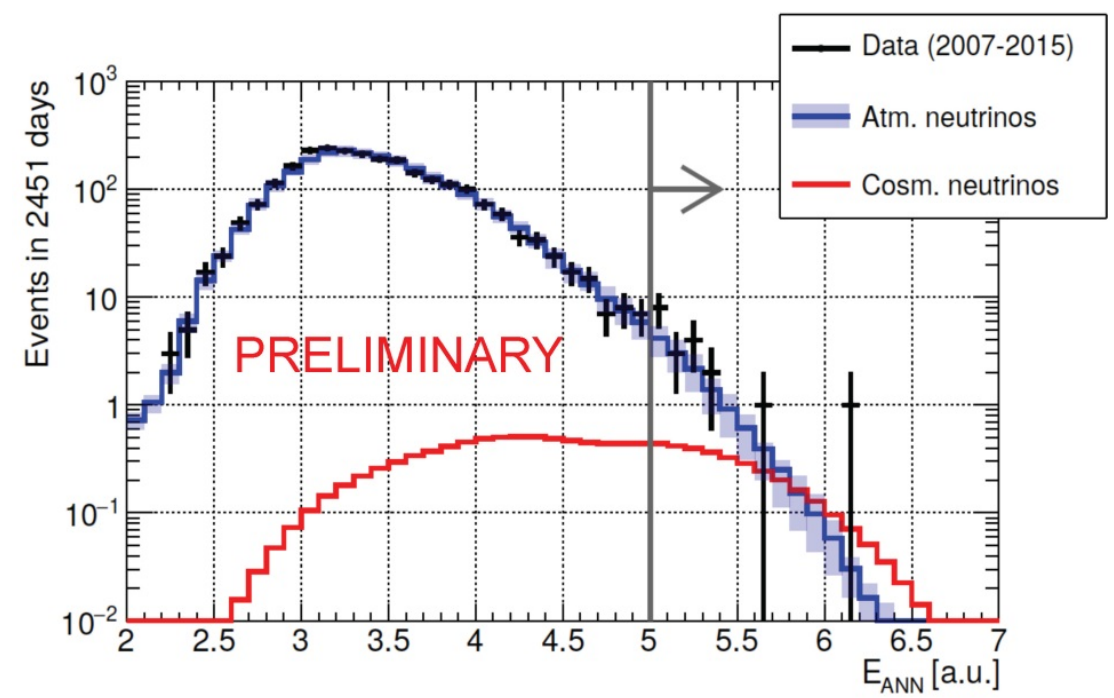
54 events observed with 20±6 expected from atmosphere



4 yr update of
PRL2014, Science 2013

ICECUBE

Antares:
Observed 19
Expected 13.5 +/-2, ~ 3 IC



Important Questions:

- Dominant Flavor Content of ν_3
- Mass Ordering
- Is there CP Violation
- Dirac OR Majorana
- Beyond Nu Standard Model