NEUTRINO MASSES, MIXING AND CPV CIRCA 2016

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http://www.nu-fit.org

ν in the SM

The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

There is no ν_R

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There is no ν_R

$\Downarrow$

Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$

$\Downarrow$

ν *strictly* massless

- By 2016 we have observed with high (or good) precision:

  $*$ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS, ICECUBE)

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All this implies that L_α are violated

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- The *starting* path:

Precise determination of the low energy parametrization

The New Minimal Standard Model

- Minimal extension to introduce L_α violation $\Rightarrow$ give Mass to the Neutrino:

  $*$ Introduce ν_R AND impose L conservation $\Rightarrow$ Dirac $\nu \neq \nu^c$:

$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  $*$ NOT impose L conservation $\Rightarrow$ Majorana $\nu = \nu^c$

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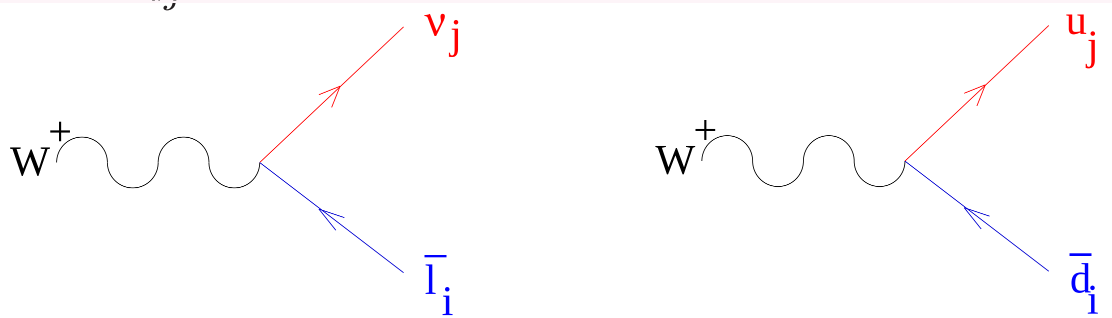
- The charged current interactions of leptons are not diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W^+_\mu \sum_{ij} \left(U^{ij}_{\rm LEP}\, \overline{\ell^i}\, \gamma^\mu\, L\, \nu^j \;+\; U^{ij}_{\rm CKM}\, \overline{U^i}\, \gamma^\mu\, L\, D^j \right) \;+\; h.c.$$



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- In general for $N = 3 + m$ massive neutrinos U_{LEP} is $3 \times N$ matrix

$$U_{LEP} U_{LEP}^\dagger = I_{3\times 3} \qquad \text{but in general} \qquad U_{LEP}^\dagger U_{LEP} \neq I_{N\times N}$$

- U_{LEP}: $3(N-2)$ angles + $2N-5$ Dirac phases + $N-1$ Majorana phases

Effects of ν Mass: Oscillations

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \to \nu_\alpha + N'$

  is a linear combination of the mass eigenstates ($|\nu_i\rangle$) : $|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i} \, |\nu_i\rangle$

- After a distance L it can be detected with flavour β with probability

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j\neq i}^{n} \mathrm{Re}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{j\neq i} \mathrm{Im}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin(\Delta_{ij})$$

$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\mathrm{eV}^2} \frac{L/E}{\mathrm{Km/GeV}}$$

No information on ν mass scale nor Majorana versus Dirac

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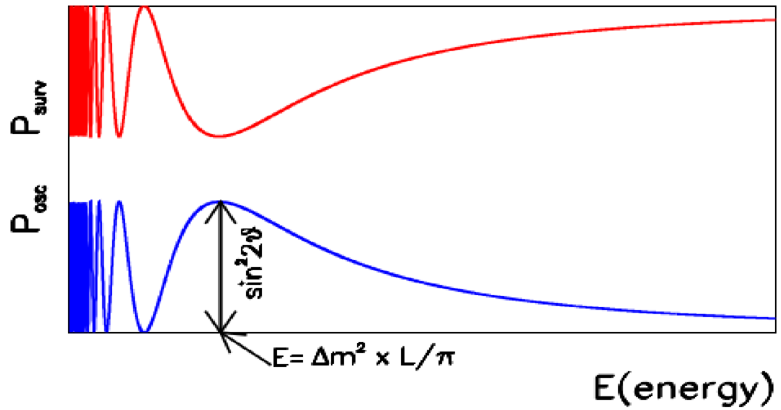
- For dominant 2-state oscillations:

$P_{\rm surv} = 1 - P_{osc}$ Disappear

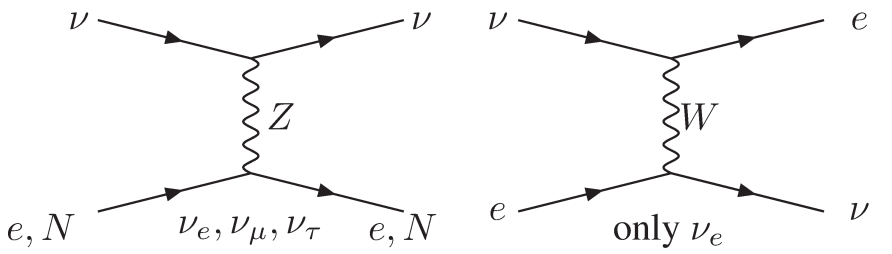
$P_{osc} = \sin^2(2\theta)\, \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$ Appear



Matter Effects

- If ν cross matter regions (Sun, Earth...) it interacts *coherently*

  – But Different flavours have different interactions :



$\Rightarrow$ Effective potential in ν evolution : $V_e \neq V_{\mu,\tau} \Rightarrow \Delta V^{\nu} = -\Delta V^{\bar{\nu}} = \sqrt{2} G_F N_e$

$$-i \frac{\partial}{\partial x} \begin{pmatrix} \nu_e \\ \nu_X \end{pmatrix} = \Big[\big[- \begin{pmatrix} V_e - V_X - \frac{\Delta m^2}{4E} \cos 2\theta & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \Big] \begin{pmatrix} \nu_e \\ \nu_X \end{pmatrix}$$

$\Rightarrow$ *Modification of mixing angle and oscillation wavelength* (MSW)

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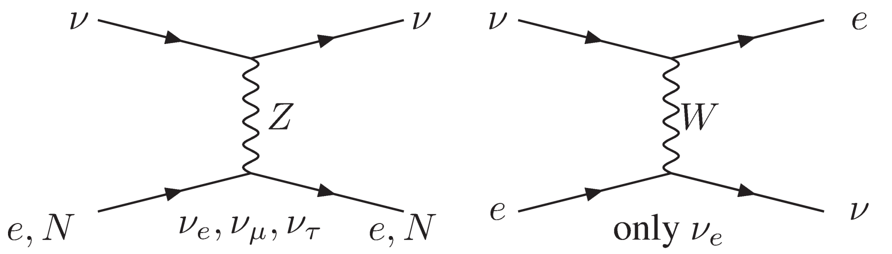

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$\Rightarrow$ *Modification of mixing angle and oscillation wavelength* (MSW)

- Mass difference and mixing in matter:

$$\Delta m^2_m = \sqrt{(\Delta m^2 \cos 2\theta - 2E\Delta V)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\Delta m^2_{mat}}$$

$\Rightarrow$ For solar $\nu's$ in adiabatic regime

$$P_{ee} = \frac{1}{2}\left[1 + \cos(2\theta_m)\cos(2\theta)\right]$$

$\Rightarrow$ Dependence on sign of Δm^2

and θ octant

in LBL terrestrial experiments

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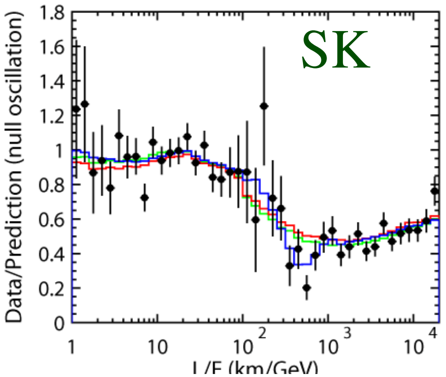
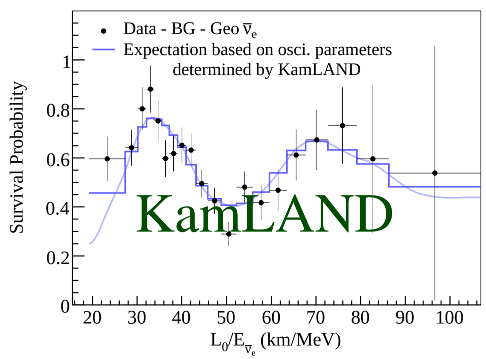
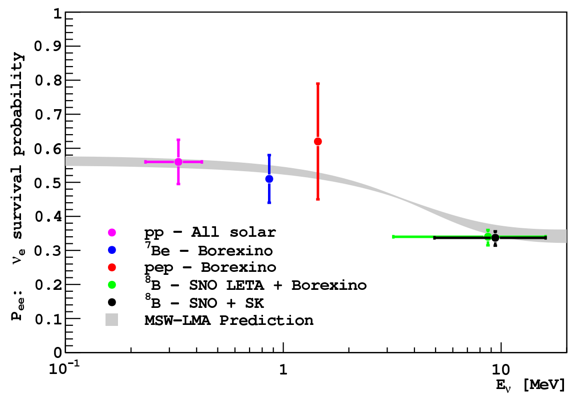
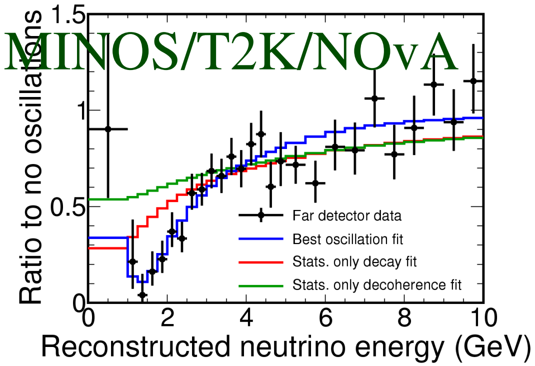
- Confirmed: Vacuum oscillation L/E pattern with 2 frequencies

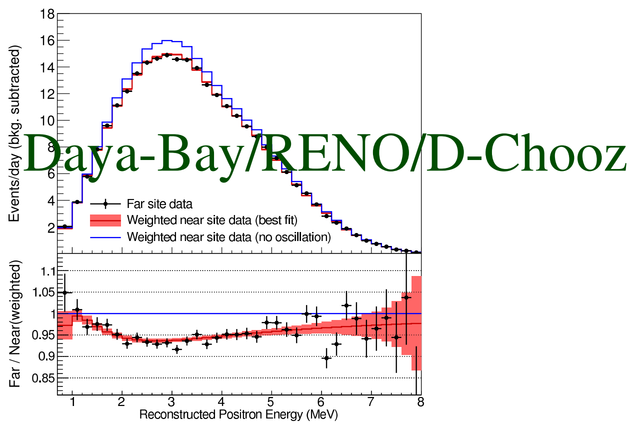




MSW conversion in Sun





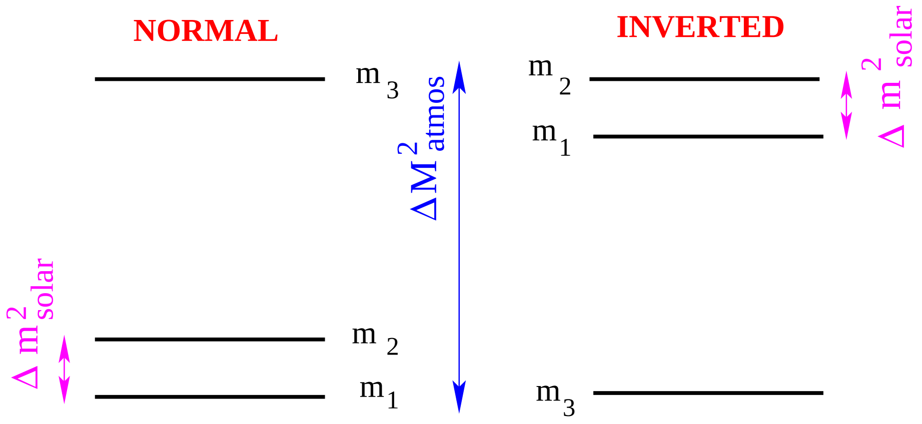


3ν Flavour Parameters

- For for 3 ν's : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta_{\rm cp}} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta_{\rm cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Two Possible Orderings



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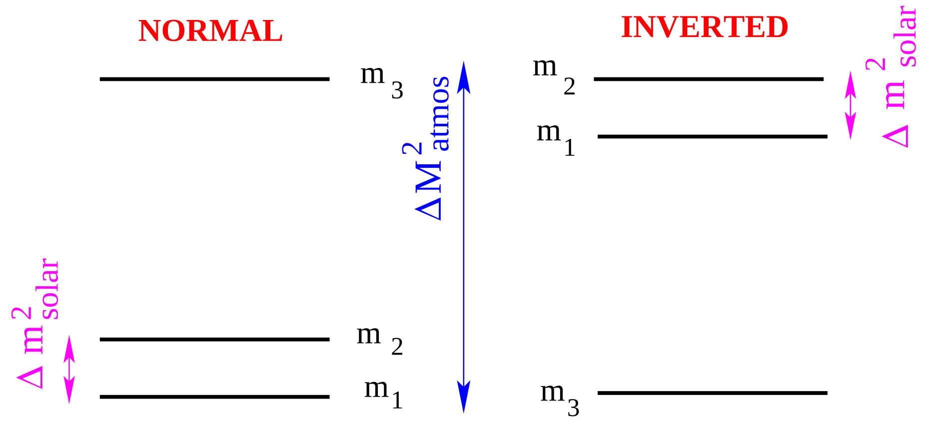
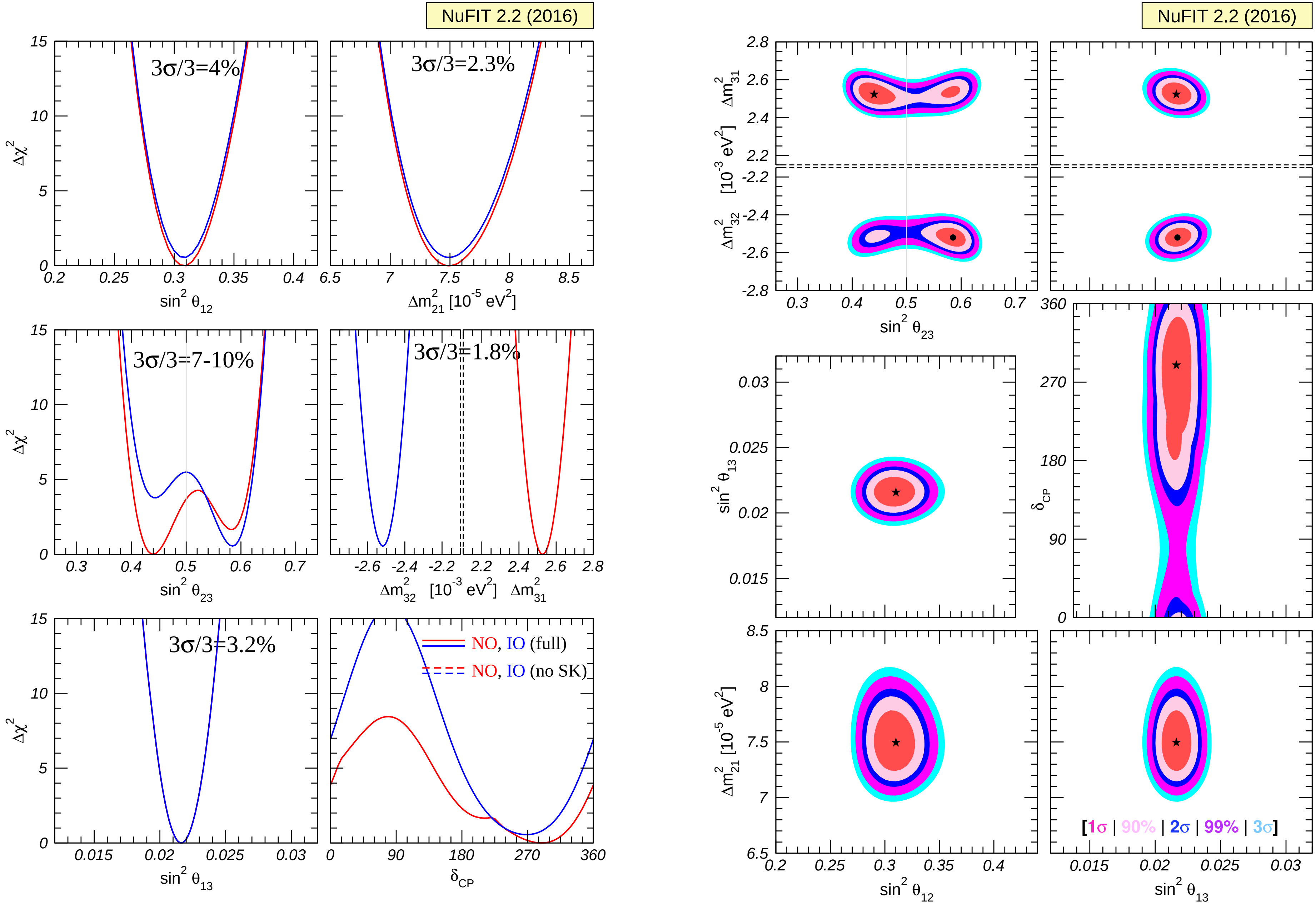


Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\rightarrow \theta_{23}$	$\Delta m^2_{\rm atm}$, θ_{13} ,$\delta_{\rm cp}$
Acc LBL ν_μ Disapp (Minos,T2K,NOvA)	$\rightarrow \Delta m^2_{\rm atm}$	θ_{23}
Acc LBL ν_e App (Minos,T2K,NOvA)	$\rightarrow \theta_{13}$	$\delta_{\rm cp}$, θ_{23}

3 ν Flavour Parameters: Status in 9/2016

Global 6-parameter fit http://www.nu-fit.org

Maltoni, Schwetz, Martinez-Soler, Esteban, MCG-G



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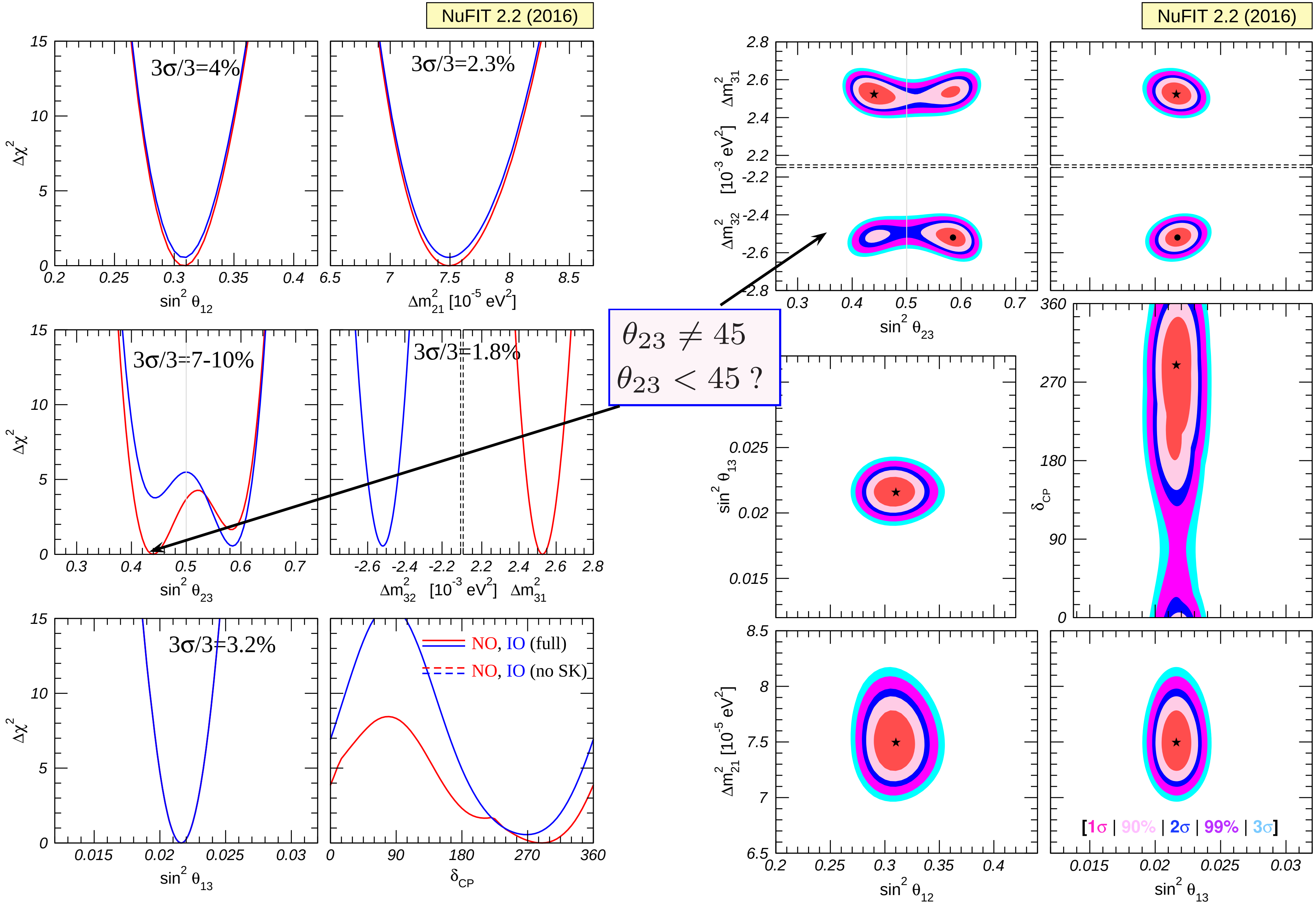

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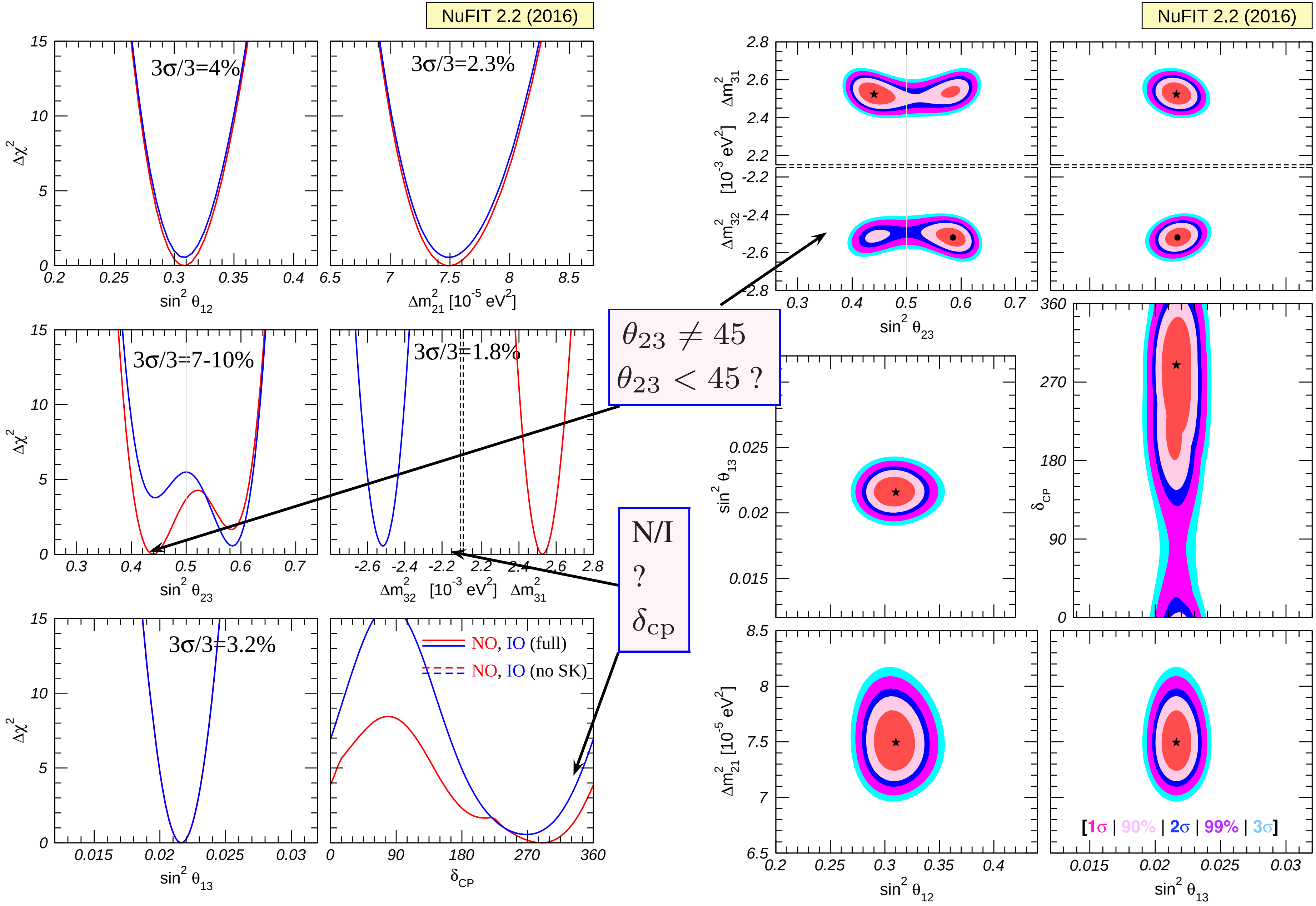


$\theta_{23} \neq 45$

$\theta_{23} < 45$?

N/I

?

δ_{cp}

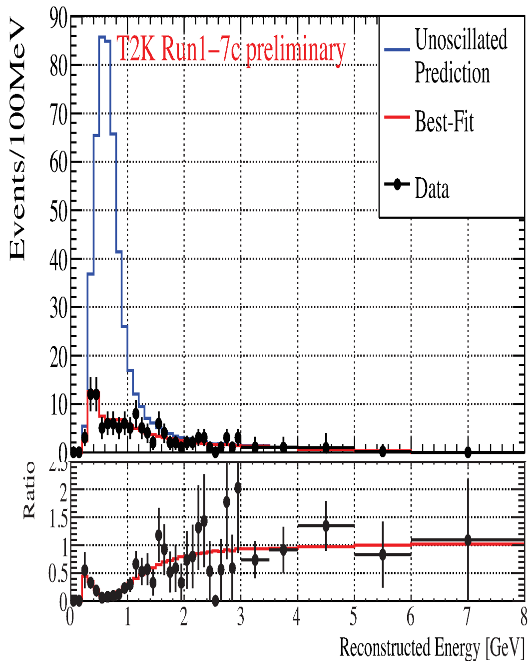
3 ν Analysis: θ_{23}

- Best determined in ν_μ and $\bar{\nu}_\mu$ disapperance in LBL

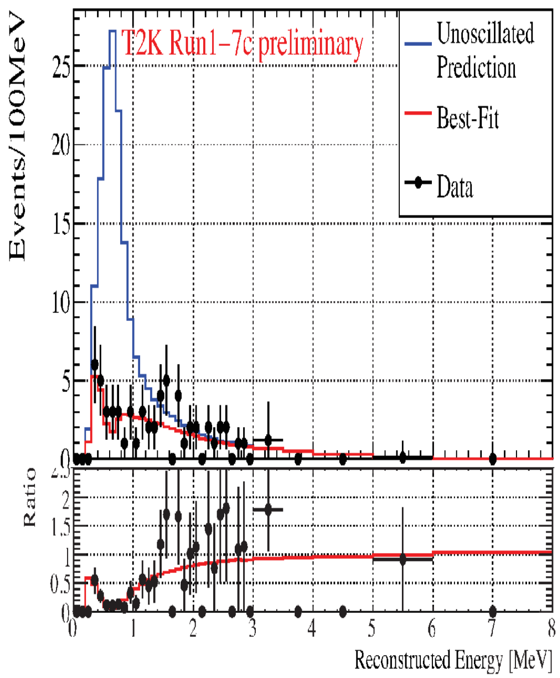
$$P_{\mu\mu} \simeq 1 - (c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \mathcal{O}(\Delta m^2_{21})$$

- At osc maximum $\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) = 1 \Rightarrow P_{\mu\mu} \simeq 0$ for $\theta_{23} \simeq \frac{\pi}{4}$

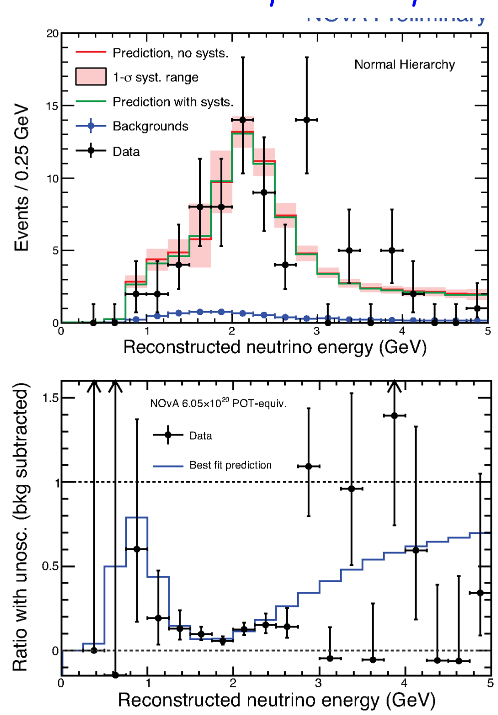
T2K $\nu_\mu \to \nu_\mu$



T2K $\bar{\nu}_\mu \to \bar{\nu}_\mu$



NOvA $\nu_\mu \to \nu_\mu$



3 ν Analysis: θ_{23}

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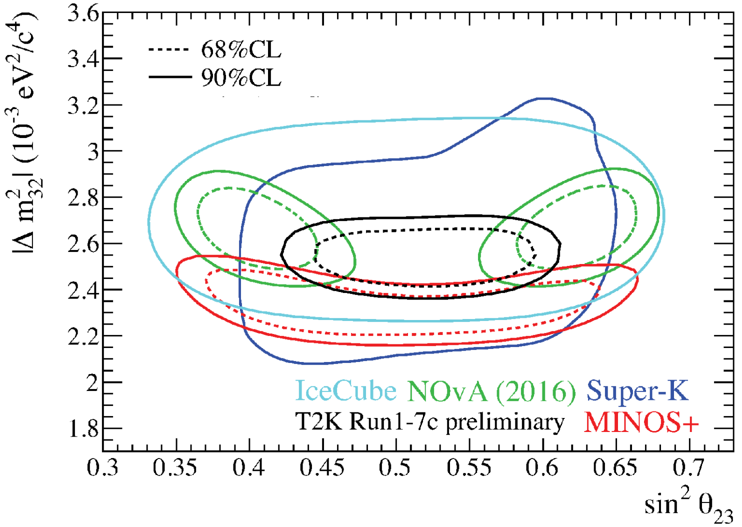
$$P_{\mu\mu} \simeq 1 - (c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \mathcal{O}(\Delta m_{21}^2)$$

- Allowed regions by the different experiments:



In making this figure θ_{13} is constrained by prior from reactor data

Caution: Not the same using θ_{13} reactor prior than combining with reactor results (because of Δm_{32}^2 in reactors)

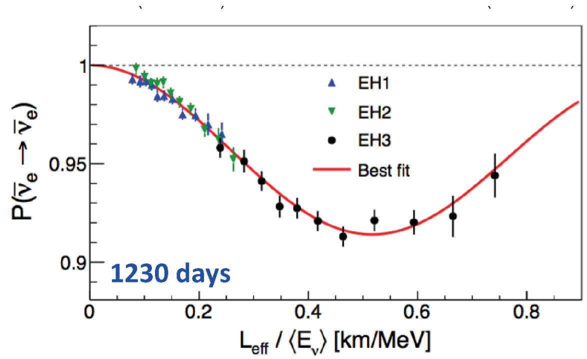
3 ν Analysis: Δm^2_{23} in LBL vs Reactors

- At LBL determined in ν_μ and $\bar\nu_\mu$ disapperance spectrum

$$P_{\mu\mu} \simeq 1 - (c^4_{13}\sin^2 2\theta_{23} + s^2_{23}\sin^2 2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \mathcal{O}(\Delta m^2_{21})$$

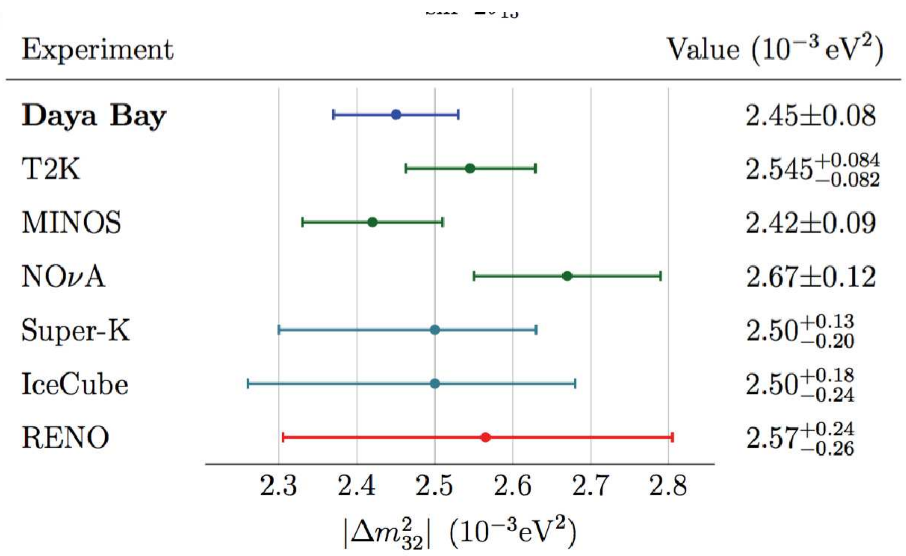
- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar\nu_e$ disapp spectrum

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - c^4_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



$$\Delta m^2_{ee} \simeq |\Delta m^2_{32}| \pm c^2_{12}\Delta m^2_{21} \simeq |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}\ \mathrm{eV}^2$$

Nunokawa,Parke,Zukanovich (2005)



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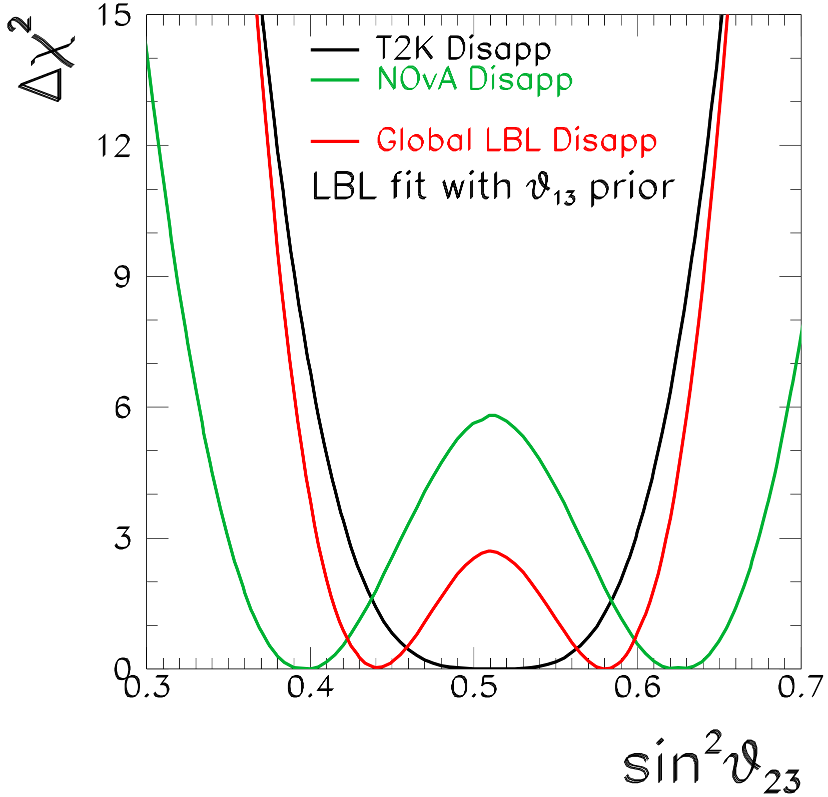
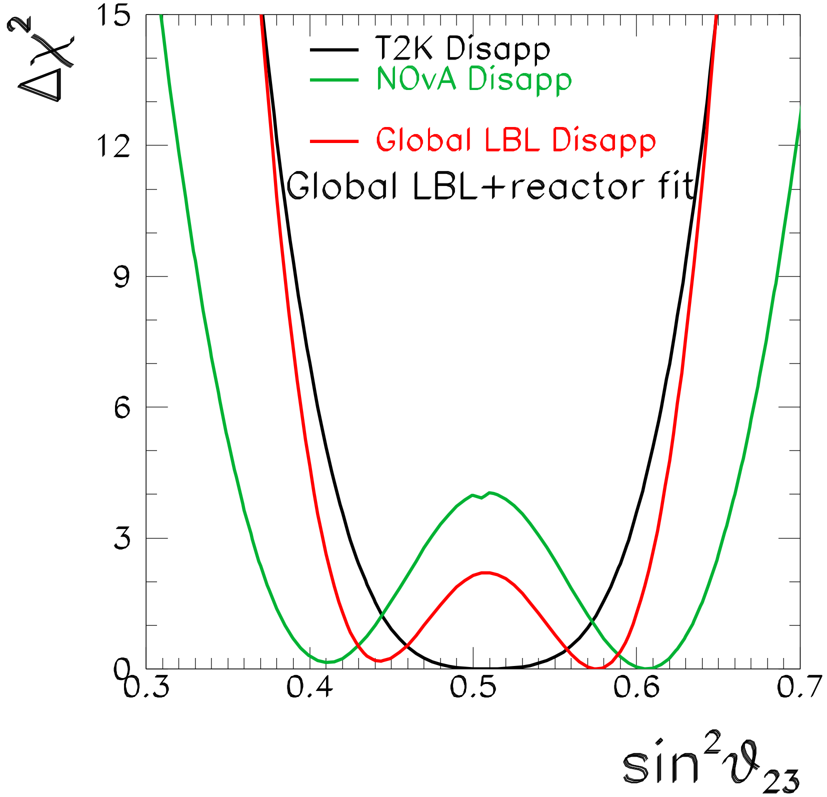




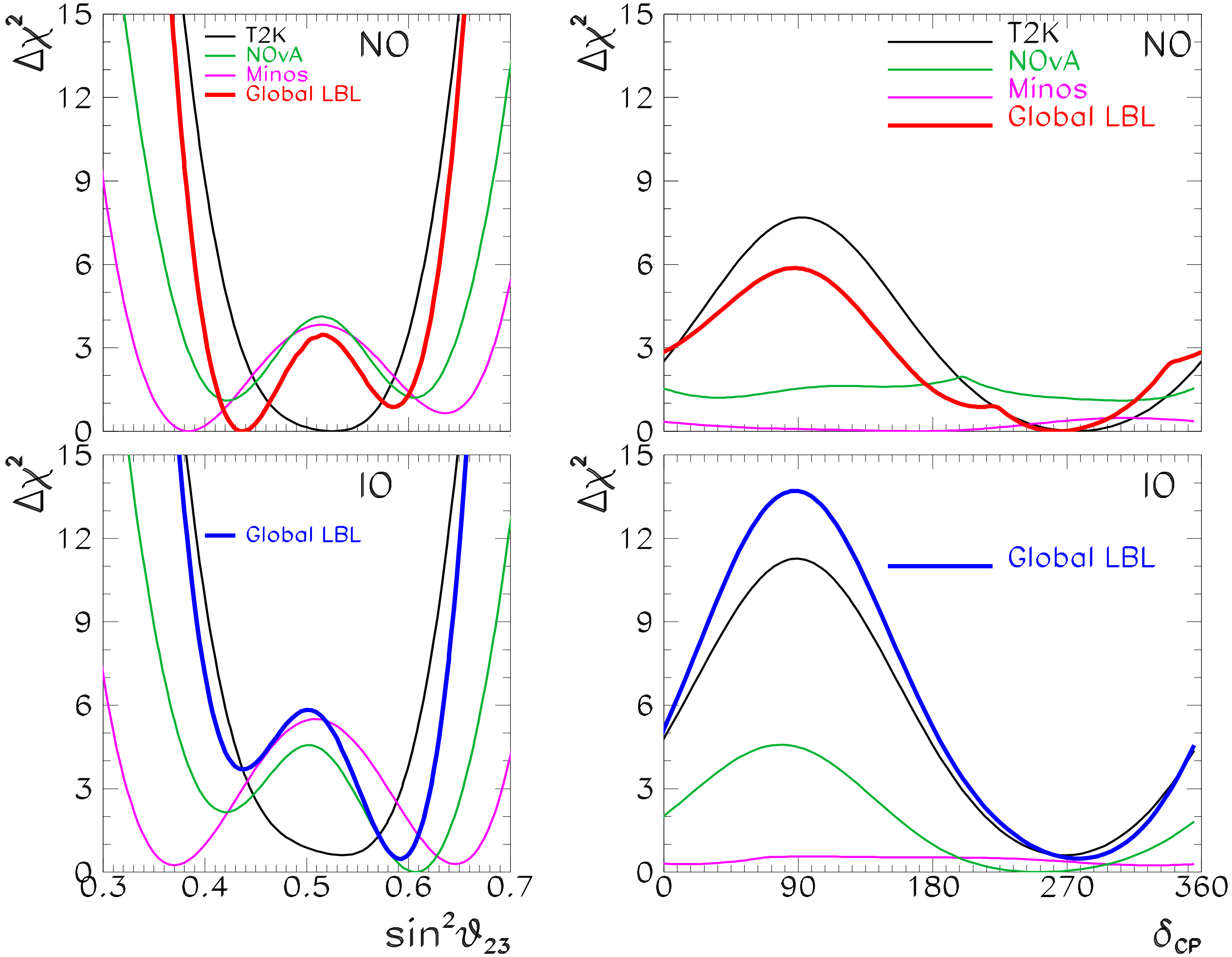
$\Rightarrow$ Impact on CL of non-maximality (also of Ordering and $\delta_{\rm CP}$)

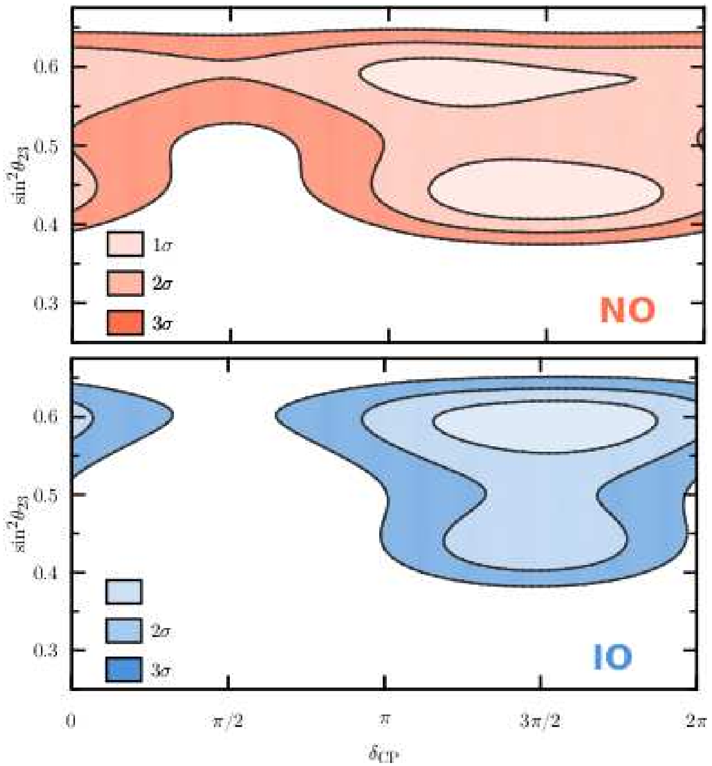
3 ν Analysis: θ_{23} Octant, Ordering, $\delta_{\rm CP}$ in LBL

- Dominant information from ν_e apperance in LBL

$$P_{\mu e} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) + \tilde{J}\,\frac{\Delta_{21}}{V_E}\,\frac{\Delta_{31}}{B_\mp}\,\sin\left(\frac{V_E L}{2}\right)\sin\left(\frac{B_\mp L}{2}\right)\cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{4E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad \tilde{J} = c_{13}\,\sin^2 2\theta_{13}\,\sin^2 2\theta_{23}\,\sin^2 2\theta_{12}$$





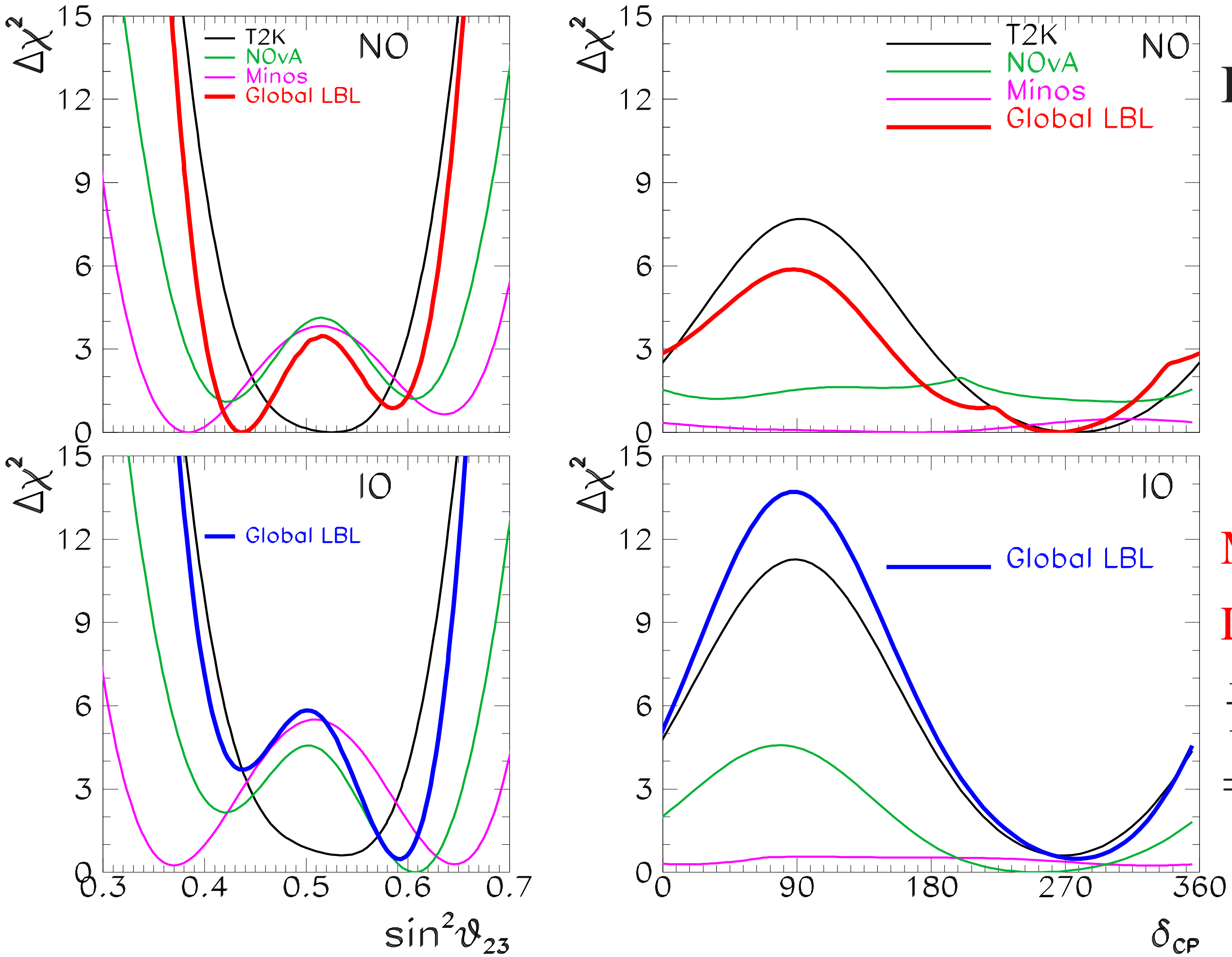
In all cases full LBL+reactor combination

3 ν Analysis: θ_{23} Octant, Ordering, $\delta_{\rm CP}$ in LBL

- Dominant information from ν_e apperance in LBL

$$P_{\mu e} \simeq s^2_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) + \tilde{J}\,\frac{\Delta_{12}}{V_E}\,\frac{\Delta_{31}}{B_\mp}\,\sin\left(\frac{V_E L}{2}\right)\sin\left(\frac{B_\mp L}{2}\right)\cos\left(\frac{\Delta_{31} L}{2}\pm\delta_{CP}\right)$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{4E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad \tilde{J} = c_{13}\,\sin^2 2\theta_{13}\sin^2 2\theta_{23}\sin^2 2\theta_{12}$$



In T2K:

	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

More ν_e than expected for any $\delta_{\rm CP}$

Less $\bar{\nu}_e$ than expected for any $\delta_{\rm CP}$

$\frac{P^{\nu}_{e\mu}}{P^{\bar{\nu}}_{e\mu}}$ Max for NO & $\delta_{\rm CP} = \frac{3\pi}{2}\left(\equiv -\frac{\pi}{2}\right)$

$\Rightarrow$ Significance of $\delta_{\rm CP} = \frac{3\pi}{2}$ and NO larger than expected

In all cases full LBL+reactor combination

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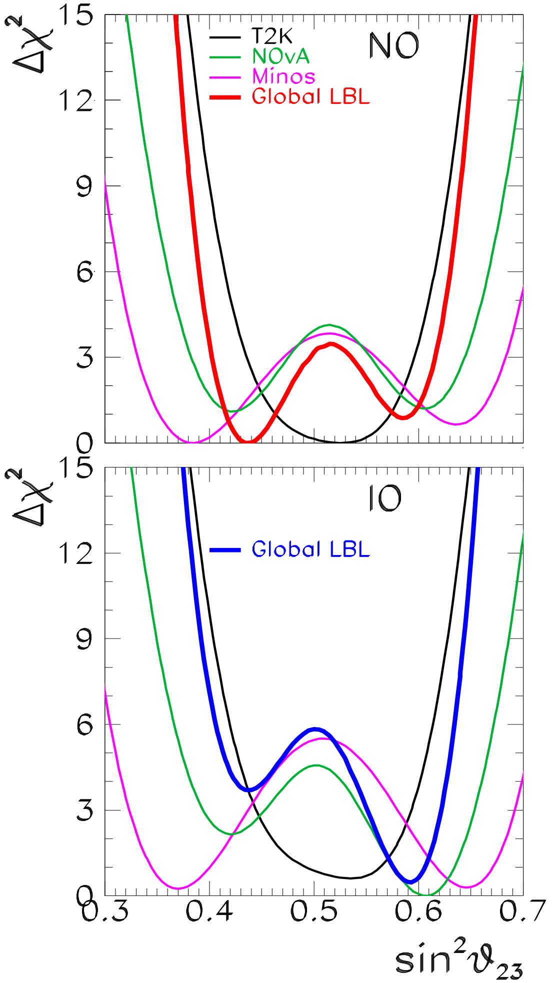
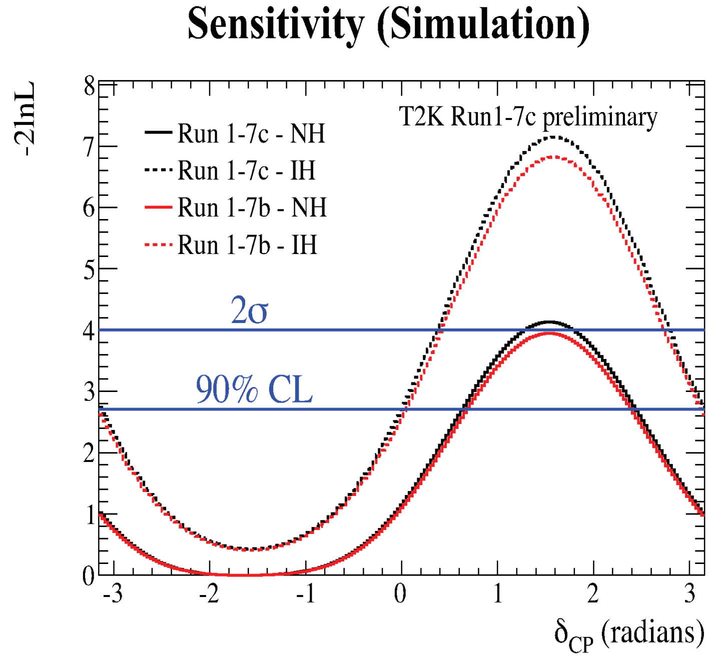
$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad \tilde{J} = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$



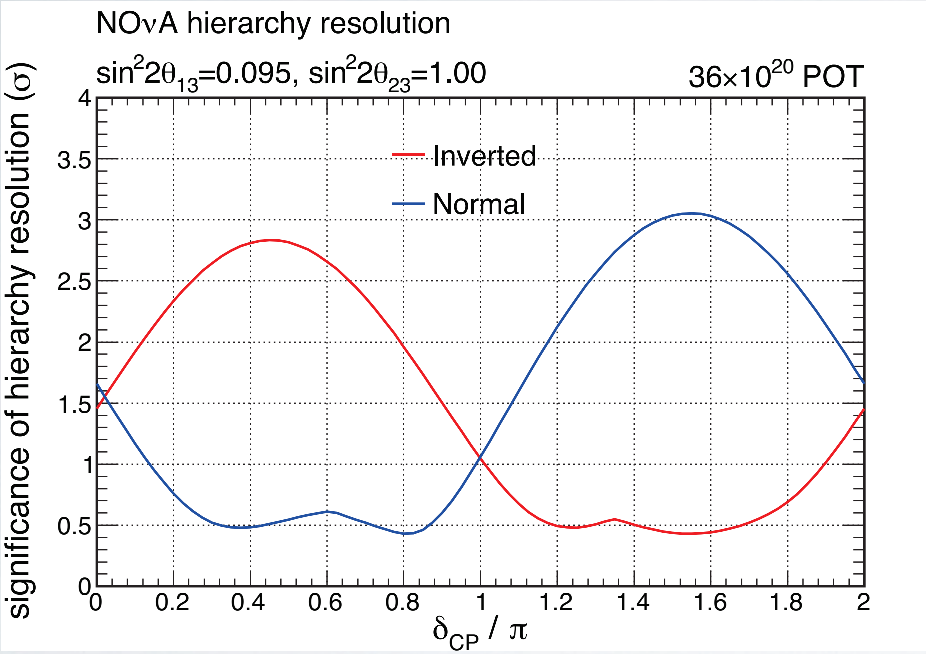
In T2K:

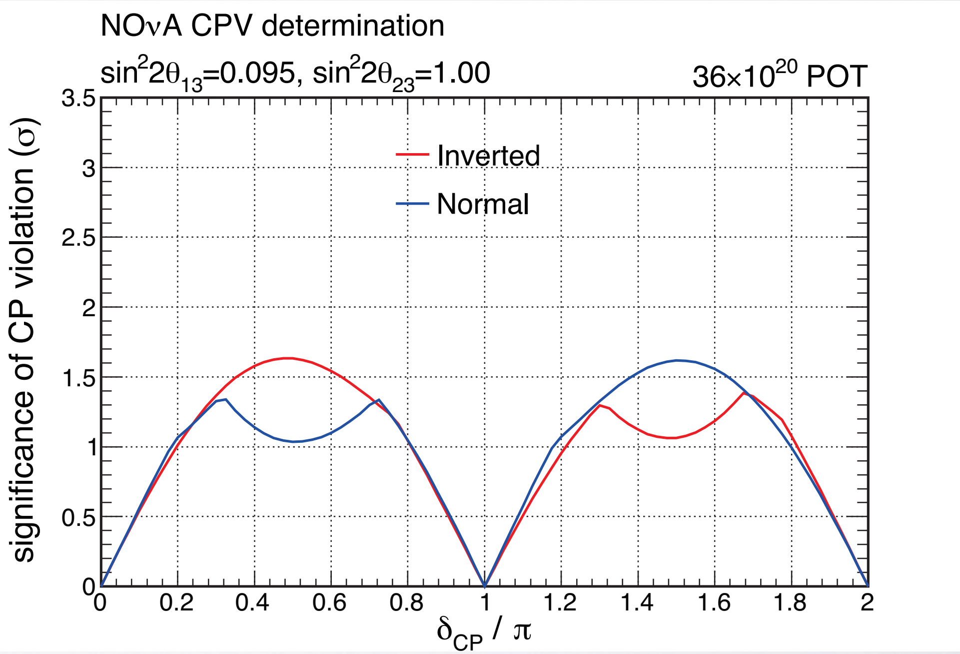


$\Rightarrow$ Significance of $\delta_{CP} = \frac{3\pi}{2}$ and NO larger than expected

In all cases full LBL+reactor combination

MASS HIERARCHY AND CP-VIOLATION



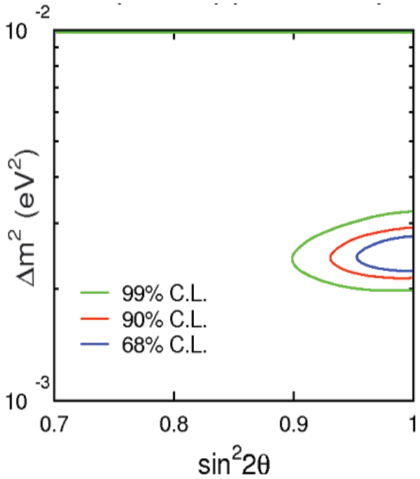


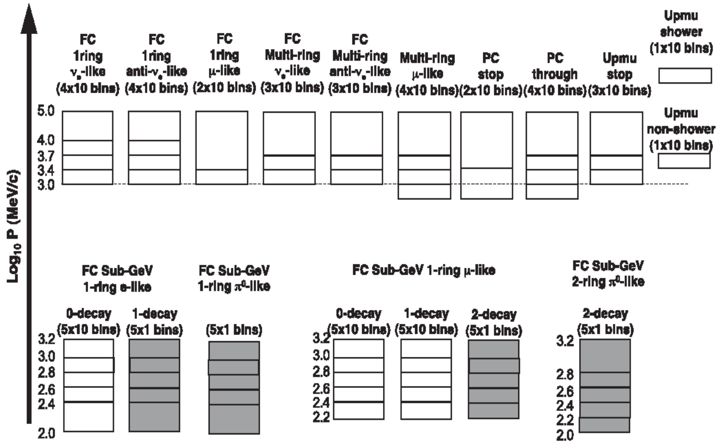
3+3 years (ν_μ +anti-ν_μ): 2 sigma in about 30% of the δ_{CP} range

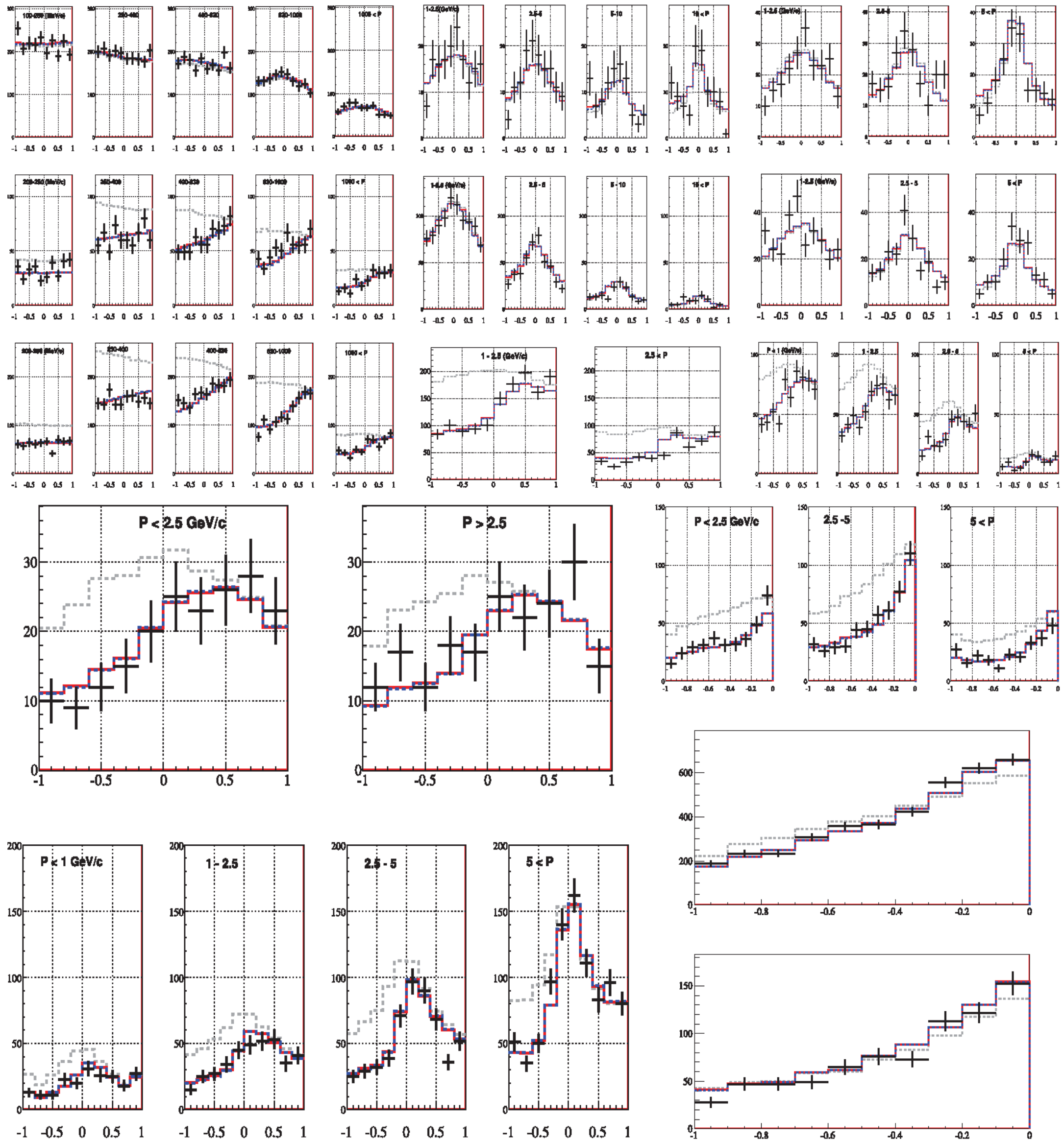
Just 1.5 sigma in 10% of the range

Atmospheric neutrinos: getting the most from SK data

- SK(1–4) data: ~~480~~ 580 bins defined by flavor, charge, topology, momentum, . . . ;
- channel: $\nu_\mu \to \nu_\tau$;
- perfect fit with just 2 params: $(\Delta m^2, \theta)$.





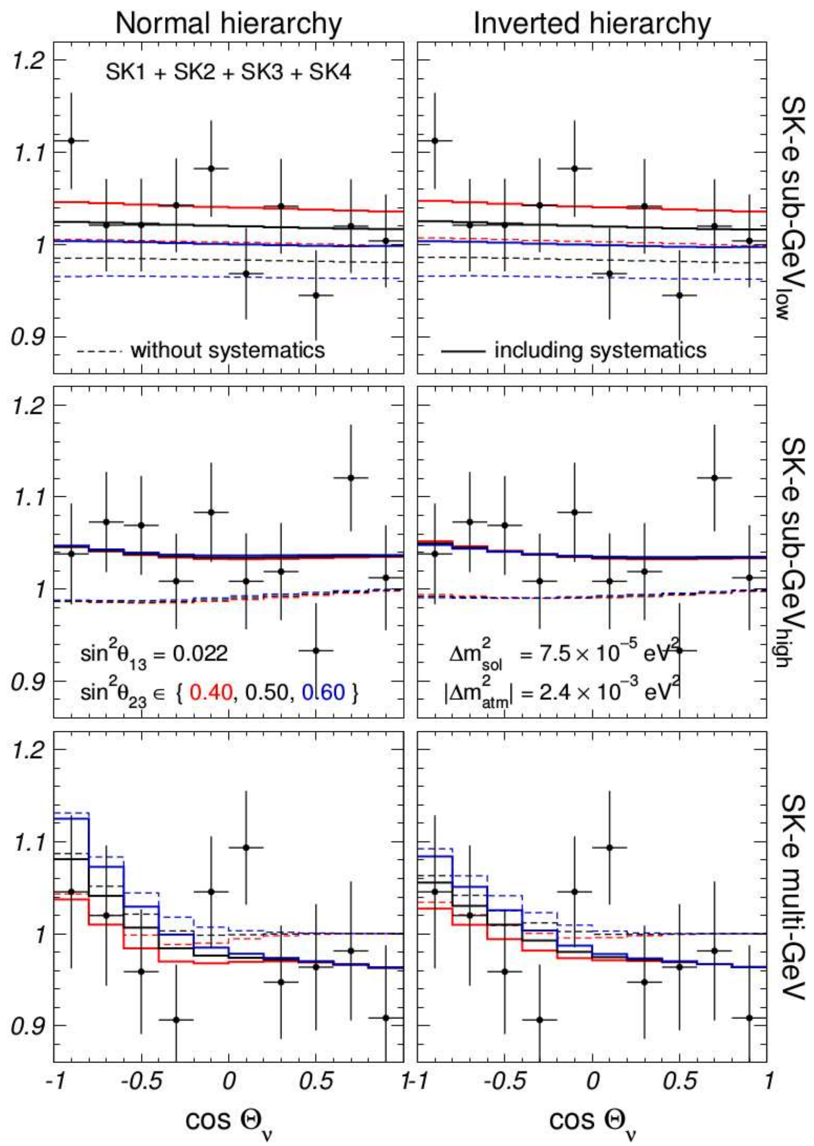


3 ν Analysis: Ordering, $\delta_{\rm CP}$ in ATM

- For $\theta_{31} \neq 0$ ATM sensitivity to octant θ_{23} & ordering & $\delta_{\rm CP}$

$$\frac{N_e}{N_e^0} - 1 \simeq (\bar r\, c_{23}^2 - 1) P_{2\nu}(\Delta m^2_{21}, \theta_{12}) \quad [\Delta m^2_{21} \text{ term}]$$
$$+(\bar r\, s_{23}^2 - 1) P_{2\nu}(\Delta m^2_{31}, \theta_{13}) \quad [\theta_{13} \text{ term}]$$
$$-2\bar r\, s_{13} s_{23} c_{23} Re(A^*_{ee} A_{\mu e}) \quad [\delta_{CP} \text{ term}]$$

$$\bar r \equiv \Phi^0_\mu / \Phi^0_e \simeq 2\text{(subG)}, 2.6\text{–}4.6\text{(multiG)}$$



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$$
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& + (\bar r\, s_{23}^2 - 1) P_{2\nu}(\Delta m^2_{31}, \theta_{13}) \quad [\theta_{13} \text{ term}] \\
& - 2\bar r\, s_{13} s_{23} c_{23} Re(A^*_{ee} A_{\mu e}) \quad [\delta_{CP} \text{ term}]
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$$

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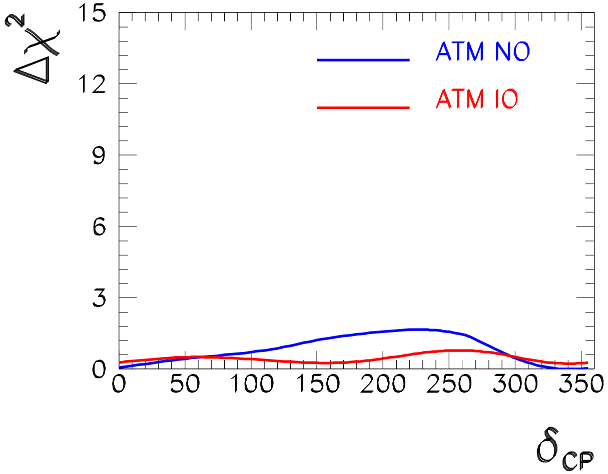
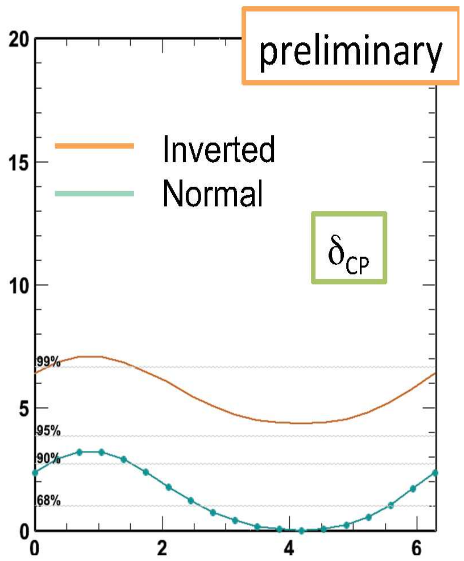
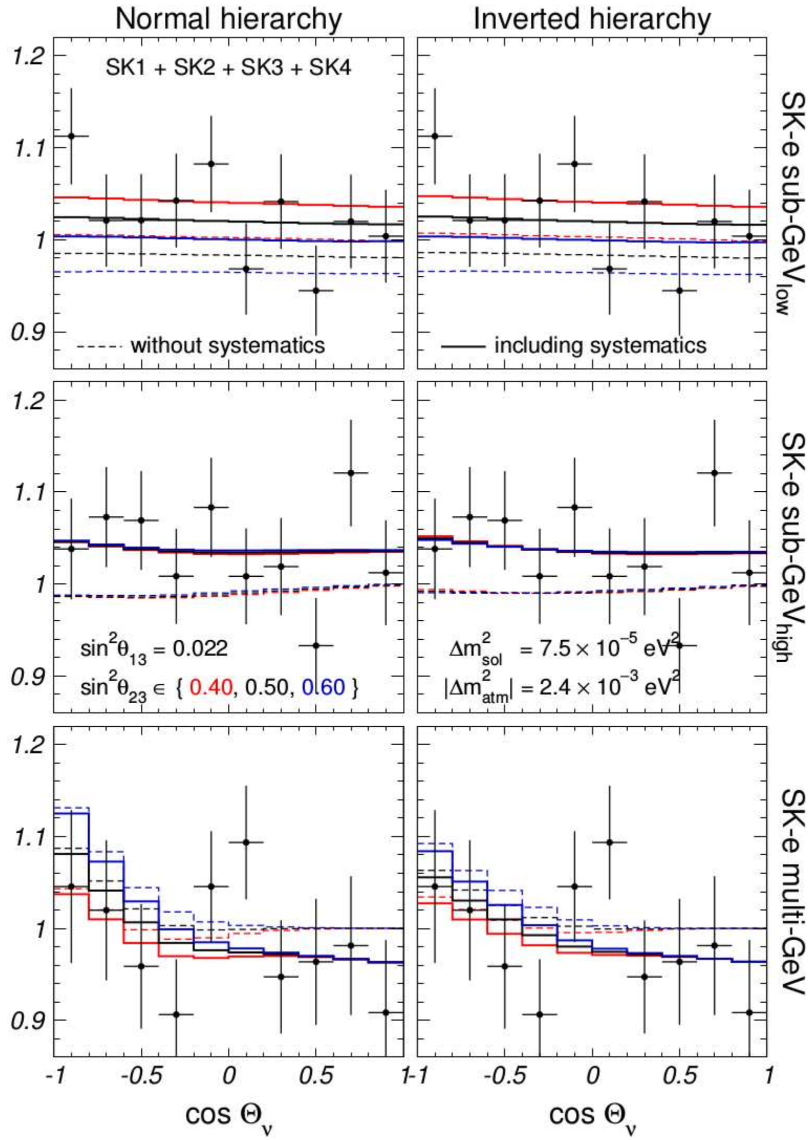


NuFIT 2.2



SK Fit Nu2016 talk

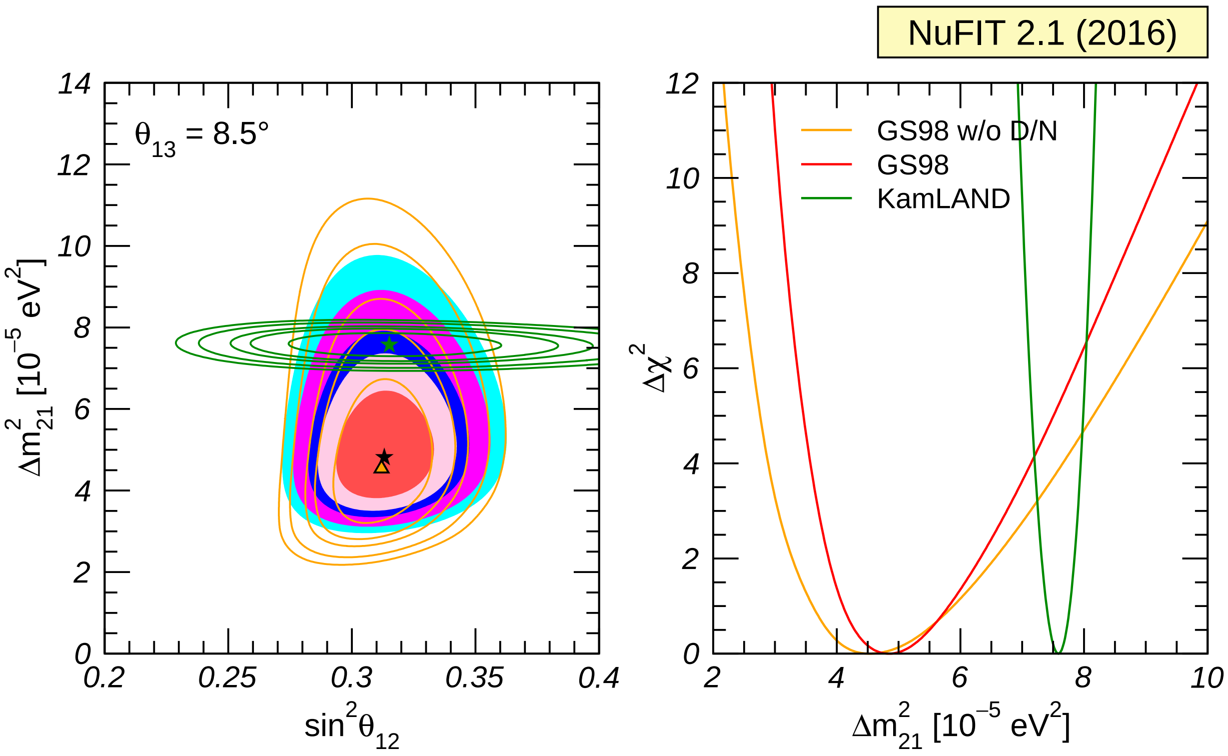


Issues in 3 ν Analysis: Δm^2_{21} KamLAND vs SOLAR

- $\Delta m^2_{13} \gg E/L \Rightarrow$ $\boxed{P^{3\nu}_{ee} = c^4_{13} P_{2\nu} + s^4_{13}}$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_a\end{pmatrix} = \left[\frac{\Delta m^2_{21}}{4E}\begin{pmatrix}-\cos 2\theta_{12} & \sin 2\theta_{12}\\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} \pm \sqrt{2}G_F N_e \begin{pmatrix}c^2_{13} & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_a\end{pmatrix}$$

- With $\theta_{13} \simeq 9^\circ$ θ_{12} OK. But $\sim 2\sigma$ tension on Δm^2_{12}



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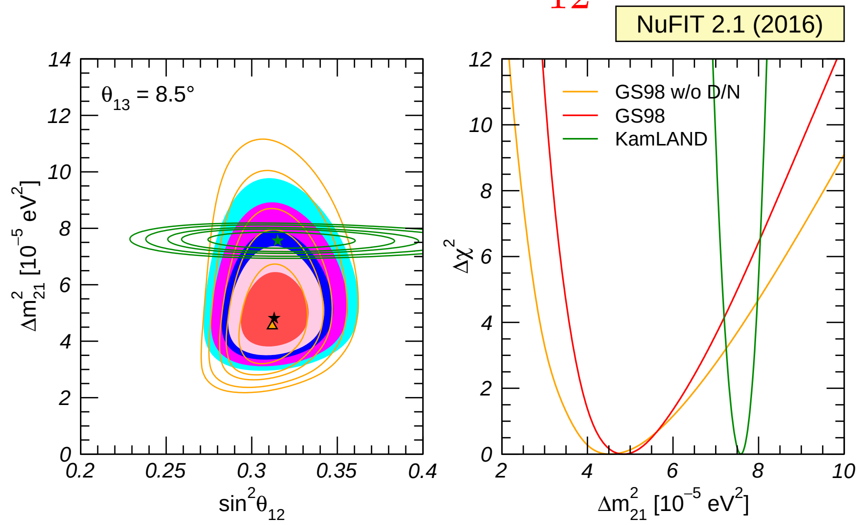
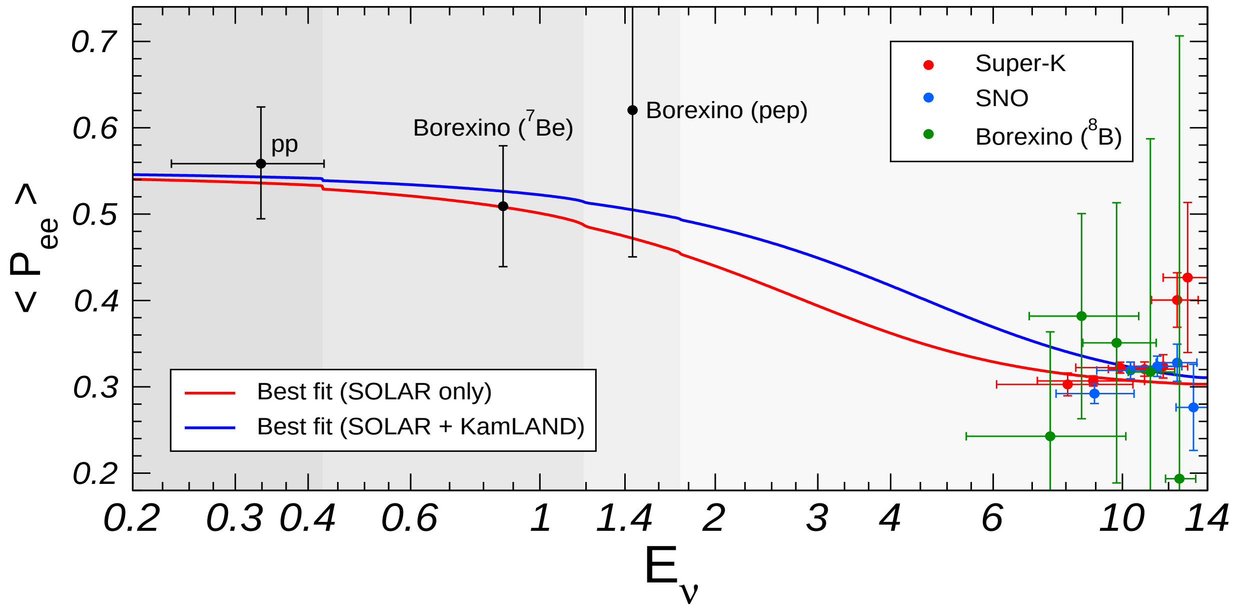


Tension related to: a)"too large" of Day/Night at SK

b) smaller-than-expected low-E turn up from MSW at best global fit



Modified matter potential?

Non Standard ν Int:Determination of Matter Potential

M. Maltoni, MCGG arXiv:1307.3092

- Including non-standard neutrino NC interactions with fermion f

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon^{fP}_{\alpha\beta}(\bar\nu_\alpha\gamma^\mu L\nu_\beta)(\bar f\gamma_\mu P f)\,, \qquad P = L, R$$

- In the three-flavor oscillation picture, the neutrino evolution equation reads:

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H^\nu\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} \quad \text{with} \;\; H^\nu = H_{\rm vac}+H_{\rm mat} \quad \text{and} \quad H^{\bar\nu} = (H_{\rm vac}-H_{\rm mat})^*$$

with most general matter potential

$$H_{\rm mat} = \sqrt{2}G_F N_e(r)\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix} + \sqrt{2}G_F\sum_{f=e,u,d}N_f(r)\begin{pmatrix}\varepsilon^f_{ee}&\varepsilon^f_{e\mu}&\varepsilon^f_{e\tau}\\ \varepsilon^{f*}_{e\mu}&\varepsilon^f_{\mu\mu}&\varepsilon^f_{\mu\tau}\\ \varepsilon^{f*}_{e\tau}&\varepsilon^{f*}_{\mu\tau}&\varepsilon^f_{\tau\tau}\end{pmatrix}$$

with $\varepsilon^f_{\alpha\beta} = \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}$

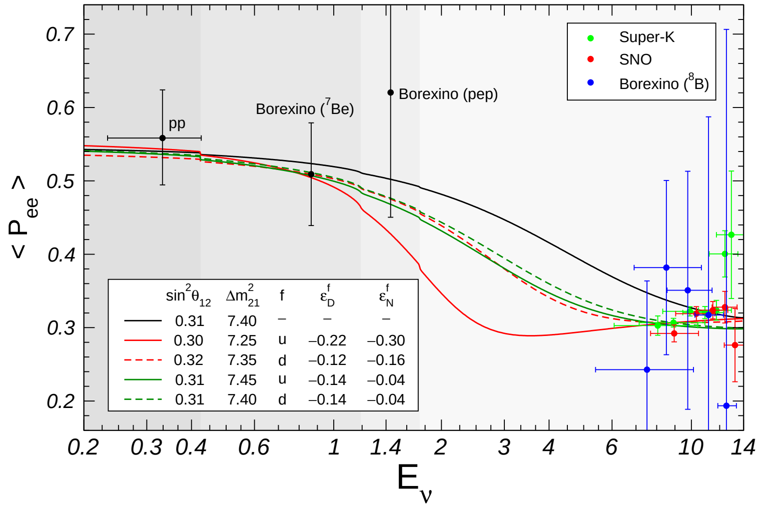
- The 3ν evolution depends on 6 (vac) + 8 per f (mat)= 14 Parameters

$\Rightarrow$ Parameters degeneracies (some well-known but being rediscovered lately ...)

Global Analysis of OSC+NSI

M. Maltoni, MCGG arXiv:1307.3092

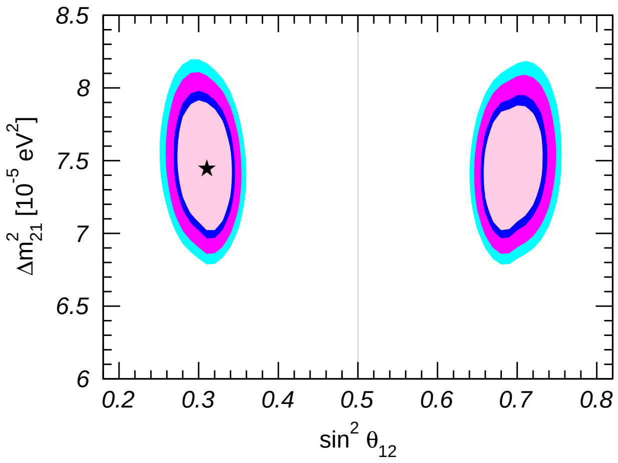
- Better fit with NSI ($\Delta\chi^2_{\rm OSC} \simeq 5$–$7$)



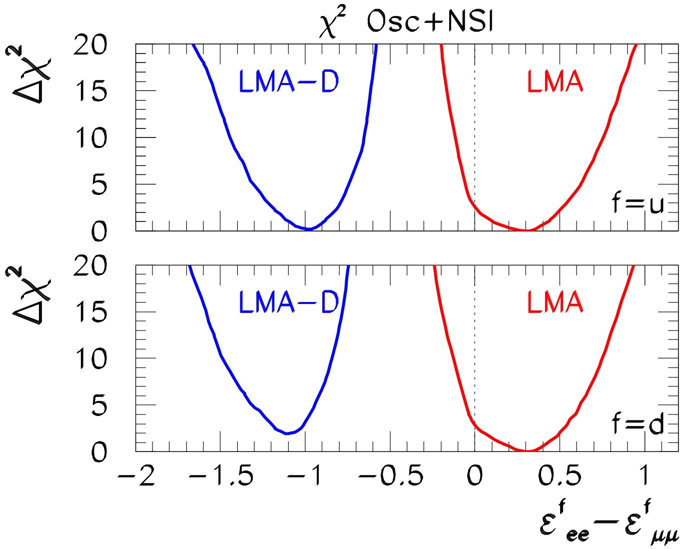
- All NSI parameters bounded 1-10%

		90% CL	
Param.	best-fit	LMA	LMA $\oplus$ LMA − D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	+0.298	[+0.00, +0.51]	$\oplus$ [−1.19, −0.81]
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	+0.001	[−0.01, +0.03]	[−0.03, +0.03]
$\varepsilon^u_{e\mu}$	−0.021	[−0.09, +0.04]	[−0.09, +0.10]
$\varepsilon^u_{e\tau}$	+0.021	[−0.14, +0.14]	[−0.15, +0.14]
$\varepsilon^u_{\mu\tau}$	−0.001	[−0.01, +0.01]	[−0.01, +0.01]
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	+0.310	[+0.02, +0.51]	$\oplus$ [−1.17, −1.03]
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	+0.001	[−0.01, +0.03]	[−0.01, +0.03]
$\varepsilon^d_{e\mu}$	−0.023	[−0.09, +0.04]	[−0.09, +0.08]
$\varepsilon^d_{e\tau}$	+0.023	[−0.13, +0.14]	[−0.13, +0.14]
$\varepsilon^d_{\mu\tau}$	−0.001	[−0.01, +0.01]	[−0.01, +0.01]

- New LMA-D ($\theta_{12} > \frac{\pi}{4}$) Miranda, Tortola, Valle (2004)



Requires $\varepsilon_{ee} - \varepsilon_{\mu\mu} \sim -2$ ($V \to -V$)



- Other experimental limits?

Only NC ν_μN (NuTeV) and ν_e N (CharmII)

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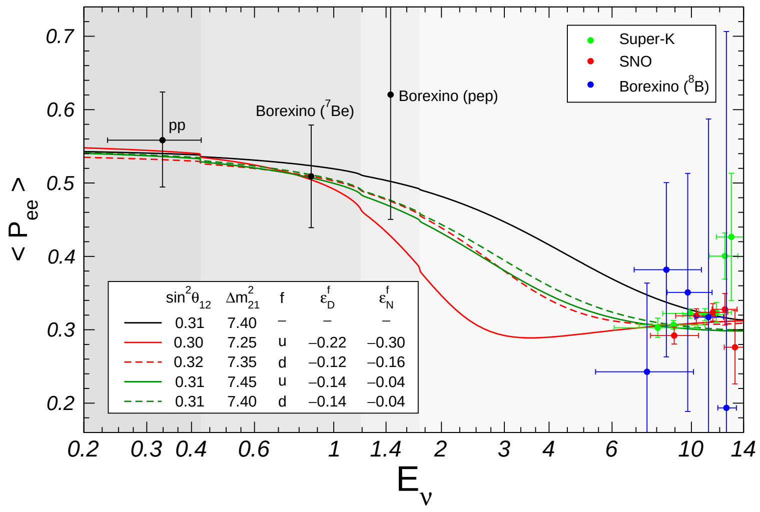

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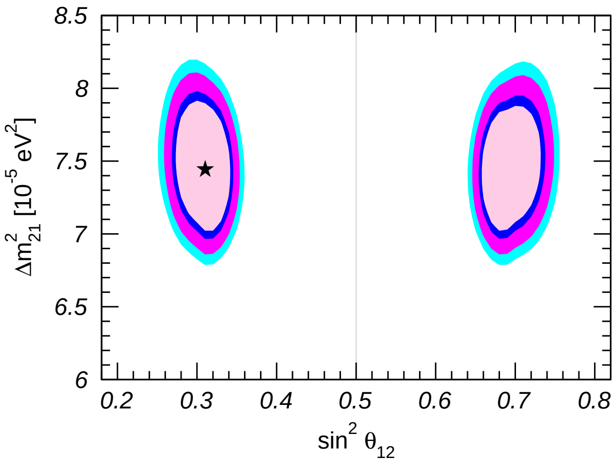

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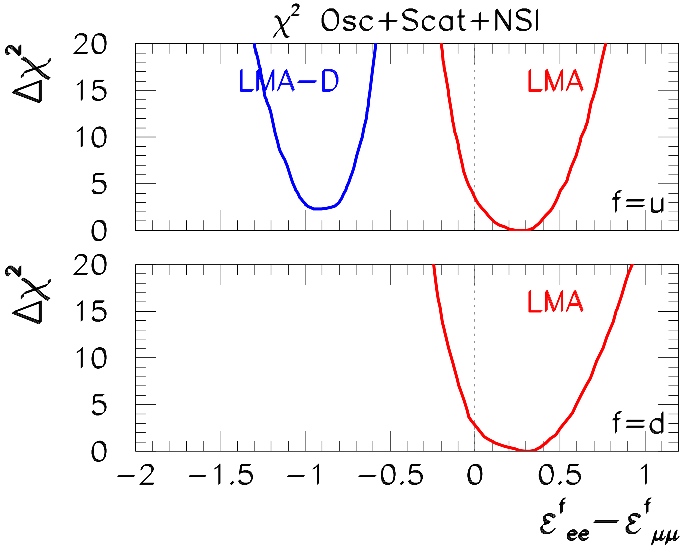

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- Other experimental limits?

Only NC ν_μN (NuTeV) and ν_e N (CharmII)

Summary

• 3ν parameter determination (at $\pm 3\sigma/6$)

$$\Delta m^2_{21} = 7.49 \times 10^{-5}\ \mathrm{eV}^2\ (2.3\%) \qquad \sin^2\theta_{12} = 0.308\ (4\%)$$

$$\begin{array}{l} \Delta m^2_{31} = 2.526 \times 10^{-3}\ \mathrm{eV}^2 \quad \mathrm{NO} \\ \Delta m^2_{32} = -2.518 \times 10^{-3}\ \mathrm{eV}^2 \quad \mathrm{IO} \end{array} (1.8\%) \quad \sin^2\theta_{23} = \begin{array}{l} 0.440 \quad \mathrm{NO} \\ 0.584 \quad \mathrm{IO} \end{array} (7\text{–}10\%) \quad \sin^2\theta_{13} = 0.0216\ (3.2\%$$

$$|U|_{\mathrm{LEP}(3\sigma)} = \begin{pmatrix} 0.789 \to 0.843 & 0.517 \to 0.584 & 0.139 \to 0.155 \\ 0.234 \to 0.518 & 0.449 \to 0.696 & 0.617 \to 0.787 \\ 0.251 \to 0.528 & 0.463 \to 0.706 & 0.600 \to 0.774 \end{pmatrix}$$

• Not significantly determined:

$*$ Ordering: $\chi^2_{\mathrm{IO}} = \chi^2_{\mathrm{NO}} < 1$

$*$ θ_{23} Octant: $\chi^2_{<45^\circ} - \chi^2_{>45^\circ} < 1$, $\chi^2_{45^\circ} - \chi^2_{\neq 45^\circ} = 3.8$

$*$ CPV? $\begin{array}{l} \mathrm{NO}: \Delta\chi^2 > 4 \ \text{ for } \delta_{\mathrm{CP}}\ 2^\circ \to 150^\circ \\ \mathrm{IO}: \Delta\chi^2 > 9 \ \text{ for } \delta_{\mathrm{CP}}\ 15^\circ \to 150^\circ \end{array}$

$\Rightarrow$ Some progress but not final answer expected with current experiments

• Ignored:

$*$ Majorana or Dirac: ν-less $\beta\beta$

$*$ Absolute ν mass: Katrin? Cosmo?

$*$ LBL anomalies: More light ν-like states?

• More physics in present data

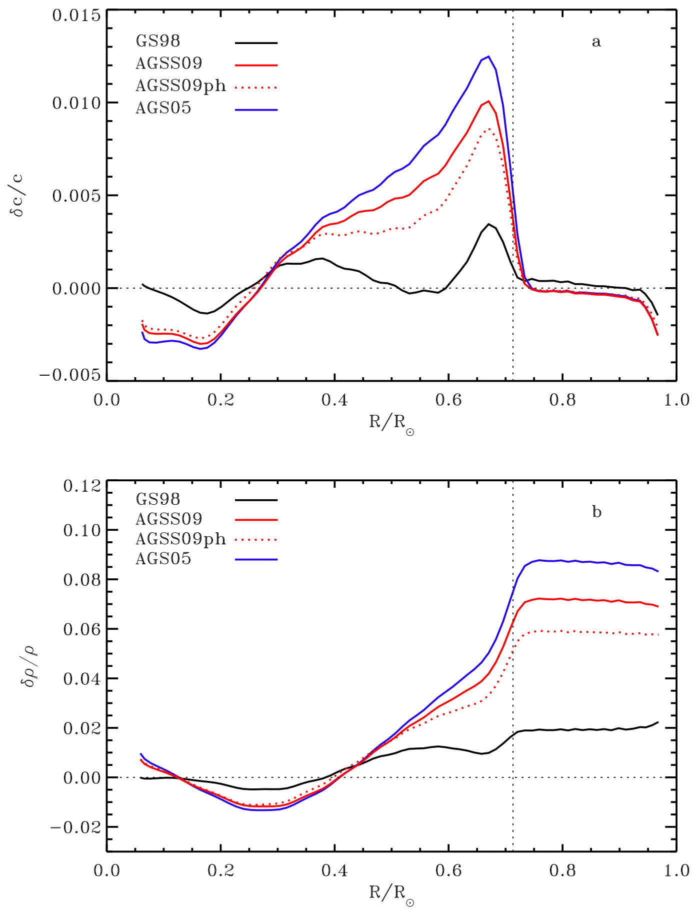
NSI, Lorentz Invarance, Tests of CPT …

Tests of the Sun, of ATM fluxes, of reactors …

Issues with the Solar Fluxes

– Newer determination of abundance of heavy elements in solar surface give lower values

– Solar Models with these lower metalicities fail in reproducing helioseismology data



– Two sets of SSM:

Starting from Bahcall *etal* 05, Serenelli *etal* 0909.2668

GS98 uses older metalicities

AGSXX uses newer metalicities

Flux $cm^{-2}\ s^{-1}$	GS98	AGSS09	Diff (%)
$pp/10^{10}$	5.97	$6.03\ (1 \pm 0.005)$	0.8
$pep/10^{8}$	1.41	$1.44\ (1 \pm 0.010)$	2.1
$hep/10^{3}$	7.91	$8.18\ (1 \pm 0.15)$	3.4
$^{7}Be/10^{9}$	5.08	$4.64\ (1 \pm 0.06)$	8.8
$^{8}B/10^{6}$	5.88	$4.85\ (1 \pm 0.12)$	17.7
$^{13}N/10^{8}$	2.82	$2.07(1^{+0.14}_{-0.13})$	**26.7**
$^{15}O/10^{8}$	2.09	$1.47\ (1^{+0.16}_{-0.15})$	**30.0**
$^{17}F/10^{16}$	5.65	$3.48\ (1^{+0.17}_{-0.16})$	**38.4**

Most difference in CNO fluxes

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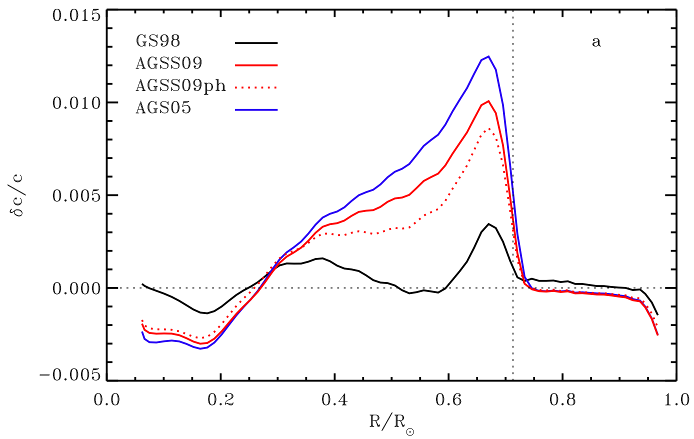

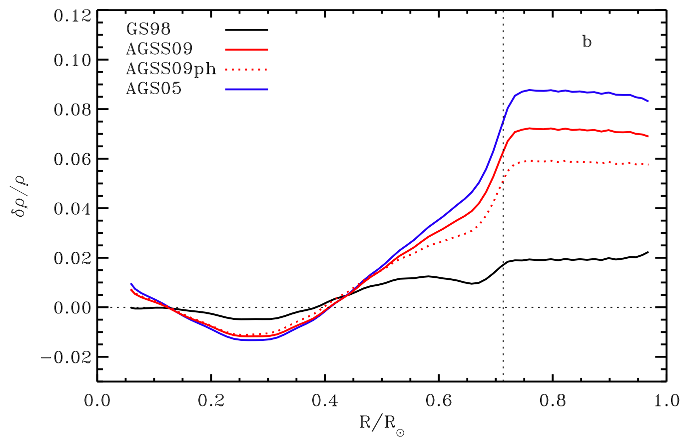

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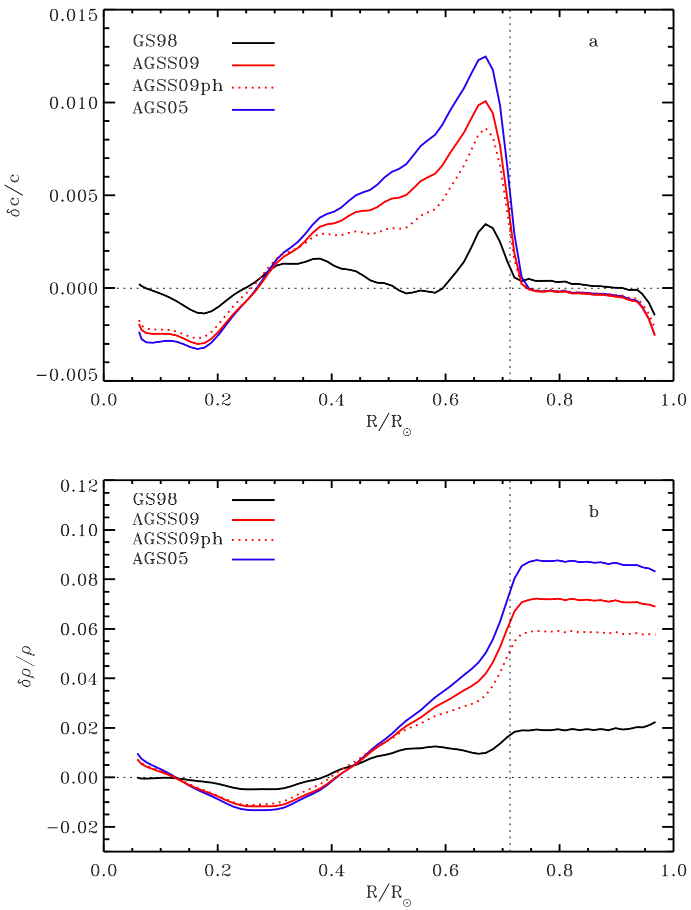

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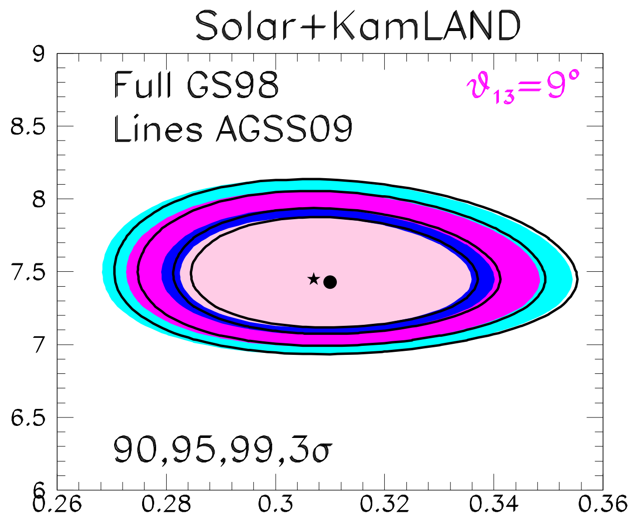
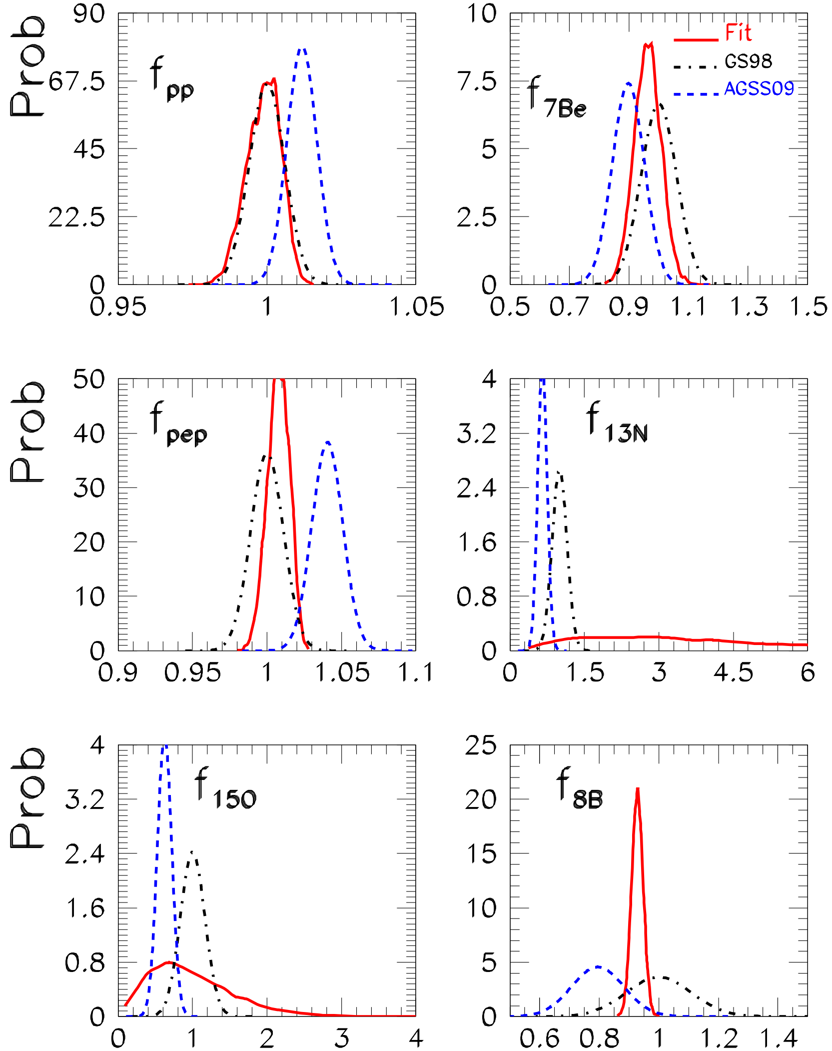
–Impact in Osc Parameter Determination



Neglegeable $\Rightarrow$ Possible to Invert and Extract Fluxes from Data.

Learning how the Sun Shines with $\nu's$

Results of Oscillation analysis with solar flux normalizations free: $f_i = \frac{\Phi_i}{\Phi_i^{GS98}}$



Present limit on CNO:

$$\frac{L_{\rm CNO}}{L_\odot} < 2\,\% \; (3\sigma)$$

Test of Luminosity Constraint:

$$\frac{L_\odot(\nu - \text{inferred})}{L_\odot} = 1.04 \pm 0.07$$

Comparing with the Models:

Both statistically equally probable

New experiments needed
more sensitive to CNO fluxes

New models with new Nuclear Rates
New problems with Helioseismology

Bergstrom,MCG-G,Maltoni,Peña-Garay,Serenelli, Song, ArXiv:1601:00972

Bergstrom,MCG-G,Maltoni,
Peña-Garay,Serenelli,Song, in preparation

Future for CP and Ordering: Strategies

- $\nu/\bar\nu$ comparison with or without Earth matter effects in $\nu_\mu \to \nu_e$ & $\bar\nu_\mu \to \bar\nu_e$ at LBL: DUNE (wide band beam, L=1300 km), HK (narrow band beam, L=300 km)

$$P_{\mu e} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\Delta_{31}\pm V}\right)^2 \sin^2\left(\frac{\Delta_{31}\pm V\, L}{2}\right)$$
$$+8\, J_{\rm CP}^{\max} \frac{\Delta_{12}}{V} \frac{\Delta_{31}}{\Delta_{31}\pm V} \sin\left(\frac{V L}{2}\right) \sin\left(\frac{\Delta_{31}\pm V L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$J_{\rm CP}^{\max} = c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12}$$

  – Challenge: Parameter degeneracies, Normalization uncertainty, E_ν reconstruction

- Earth matter effects in large statistics ATM ν_μ disapp : HK,INO, PINGU,ORCA ...

  – Challenge: ATM flux contains both ν_μ and $\bar\nu_\mu$, ATM flux uncertainties

- Reactor experiment at $L \sim 60$ km (vacuum) able to observe the difference between oscillations with Δm^2_{31} and Δm^2_{32}: JUNO, RENO-50

$$P_{\nu_e,\nu_e} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]$$

  – Challenge: Energy resolution

Lepton Mixing Unitarity

- Previous results assume $U_{\rm LEP}$ to be unitary
- If ν_L mixed with m extra states $U_{\rm LEP} = (K_{l,3\times 3}\, , K_{h,3\times m})$ Schechter, Valle (1980)

  And $U_{\rm LEP} U^\dagger_{\rm LEP} = I_{3\times 3}$ but in general $U^\dagger_{\rm LEP} U_{\rm LEP} \neq I_{(3+m)\times(3+m)}$
- If m states are heavy $(M >> E_\nu)$ oscillations measure $K_{L,3\times 3}$ (not unitary)

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- But this unitarity violation $\Rightarrow$ Flavour Changing Neutral Currents
  Flavour Violation in Charged Lepton Processes
  Universality Violation of Charge Current ...

- Constraints on these processes limit leptonic unitarity violation to

$$|K_l K_l^\dagger| = \begin{pmatrix} 0.9979 - 0.9998 & < 10^{-5} & < 0.0021 \\ < 10^{-5} & 0.9996 - 1.0 & < 0.0008 \\ < 0.0021 & < 0.0008 & 0.9947 - 1.0 \end{pmatrix}$$

Antusch *et al* ArXiv:1407.6607

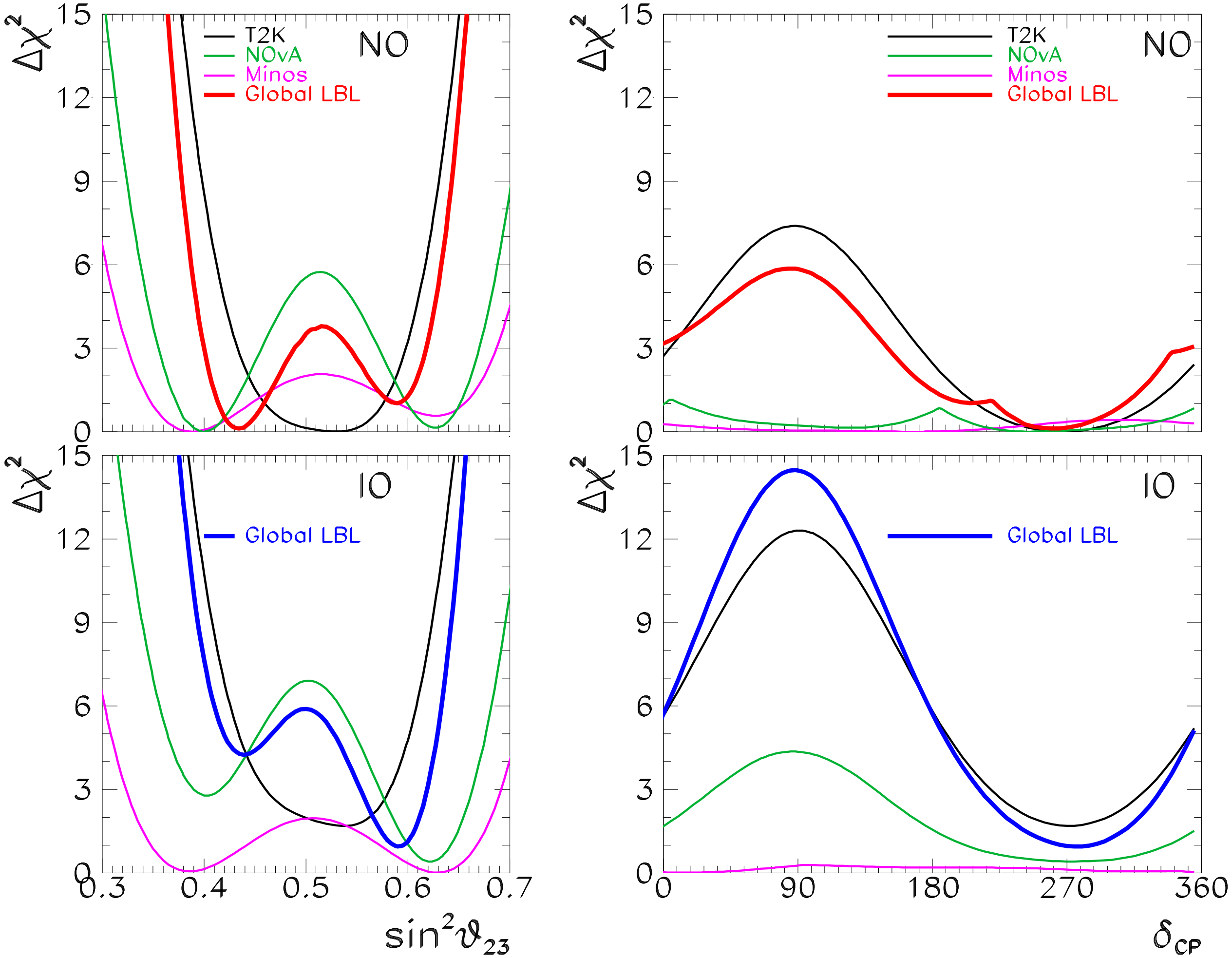
or equivalently $K_l \simeq (I+\epsilon)U(\theta_{ij},\delta,\eta_i)$ with $|\epsilon_{\alpha j}| \leq$ few $\times\, 10^{-3}$ while $K_h \sim \mathcal{O}(\epsilon)$

$3\ \nu$ Analysis: θ_{23} Octant, Ordering, $\delta_{\rm CP}$ in LBL

- Dominant information from ν_e apperance

$$P_{\mu e} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) + \tilde{J}\, \frac{\Delta_{12}}{V_E}\, \frac{\Delta_{31}}{B_\mp} \sin\left(\frac{V_E L}{2}\right) \sin\left(\frac{B_\mp L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad \tilde{J} = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$



In all cases using θ_{13} reactor prior