GLOBAL ANALYSES OF OSCILLATION NEUTRINO EXPERIMENTS

Concha Gonzalez-Garcia

(ICREA U. Barcelona & YITP Stony Brook)

TAUP 2013, September 12th, 2013

GLOBAL ANALYSES OF OSCILLATION NEUTRINO EXPERIMENTS

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OUTLINE

Determination of 3ν Lepton Flavour Parameters

Light Sterile Neutrinos

Matter Potential/Non-standard Neutrino Interactions

- By 2013 we have observed with high (or good) precision:
  - ∗ Solar ν_e convert to ν_μ/ν_τ (Cl, Ga, **SK, SNO, Borexino**)
  - ∗ Reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km (**KamLAND**)
  - ∗ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS)
  - ∗ Accelerator ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 250[700]$ Km (K2K,T2K, [**MINOS**])
  - ∗ Some accel ν_μ appear as ν_e at $L \sim 250[700]$ Km (**T2K** **(NEW 2013)**, [MINOS])
  - ∗ Reactor $\overline{\nu_e}$ disappear at $L \sim 1$ Km (D-Chooz, **Daya-Bay, Reno**) **(NEW 2012)**

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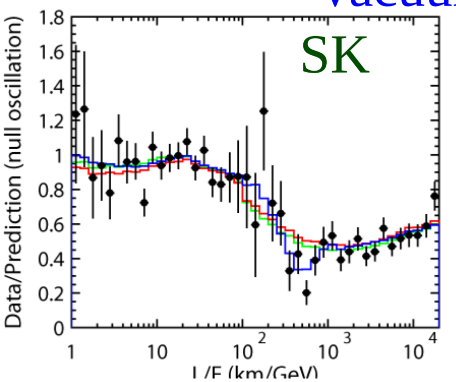
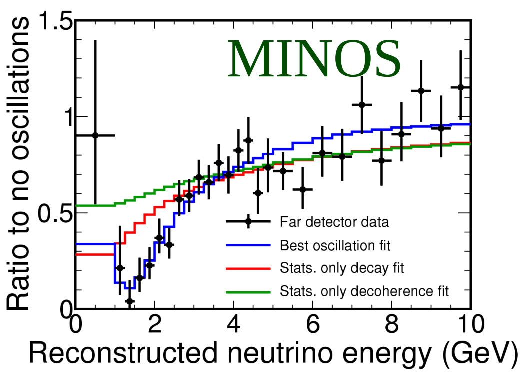
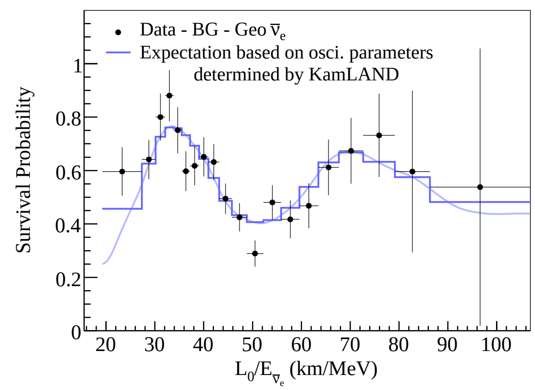
- We have confirmed:

Vacuum oscillation L/E pattern

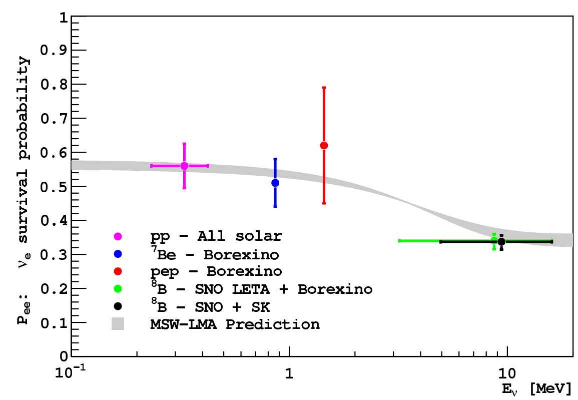






KamLAND

MSW conversion in Sun



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All this implies that neutrinos are massive

and There is Physics Beyond SM

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- The *important* question:

What is the BSM theory?

- The *difficult* path:

Detailed determination of the new low energy parametrization

The New Minimal Standard Model

- Minimal Extensions to 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 $\nu = \nu^c$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \overline{\nu_L} \nu_L^C + h.c.$$

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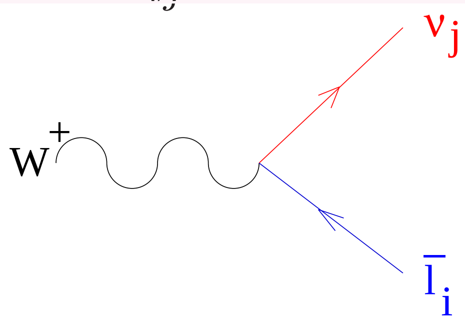
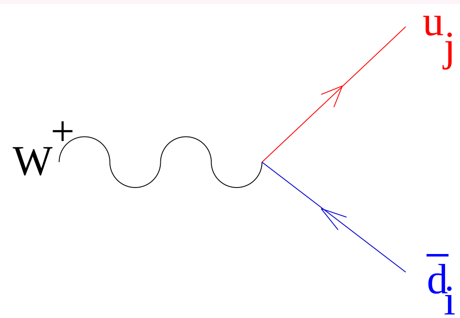
- The charged current interactions of leptons are not diagonal (same as quarks)

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





3ν Flavour Parameters

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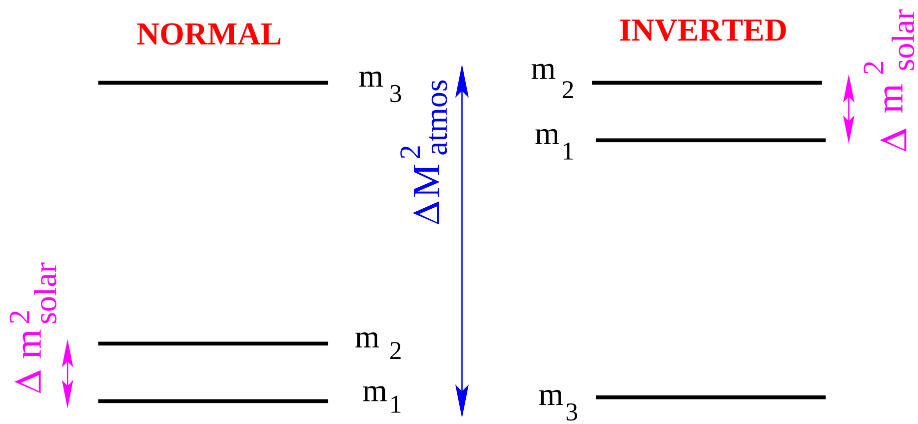
- For for 3 ν's : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

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

- Two Possible Orderings



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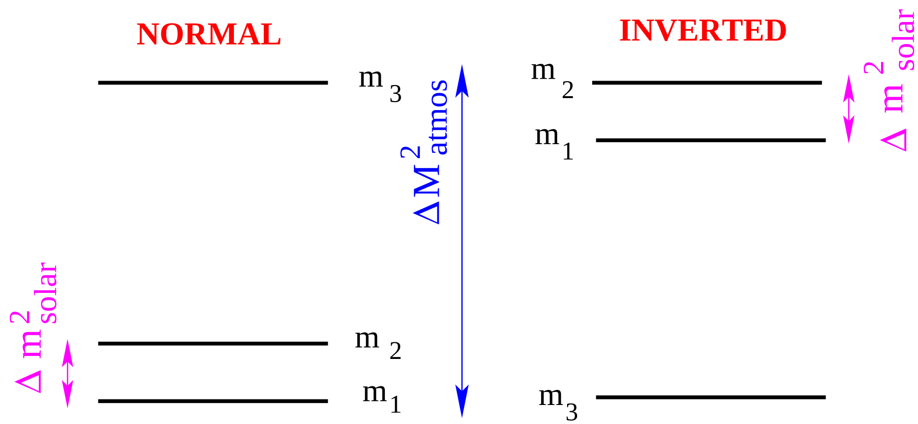
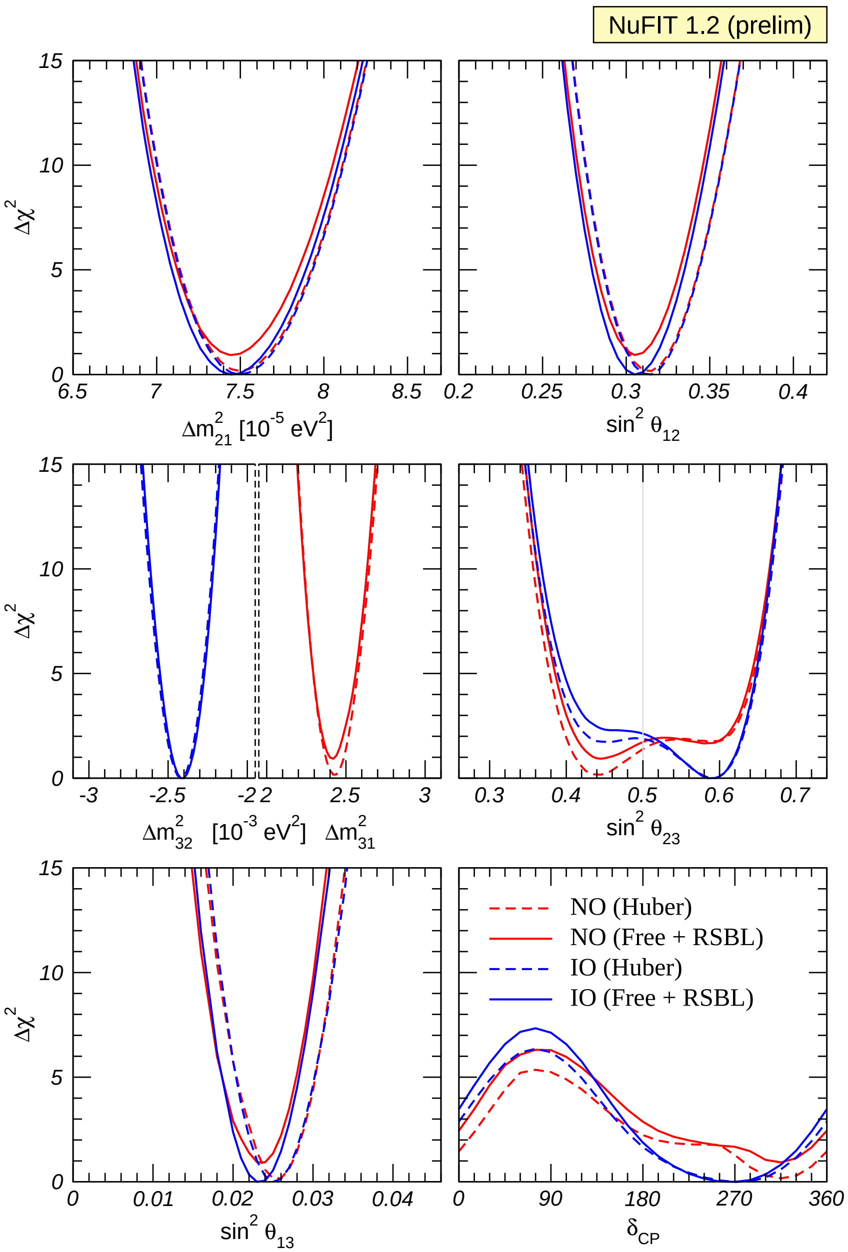


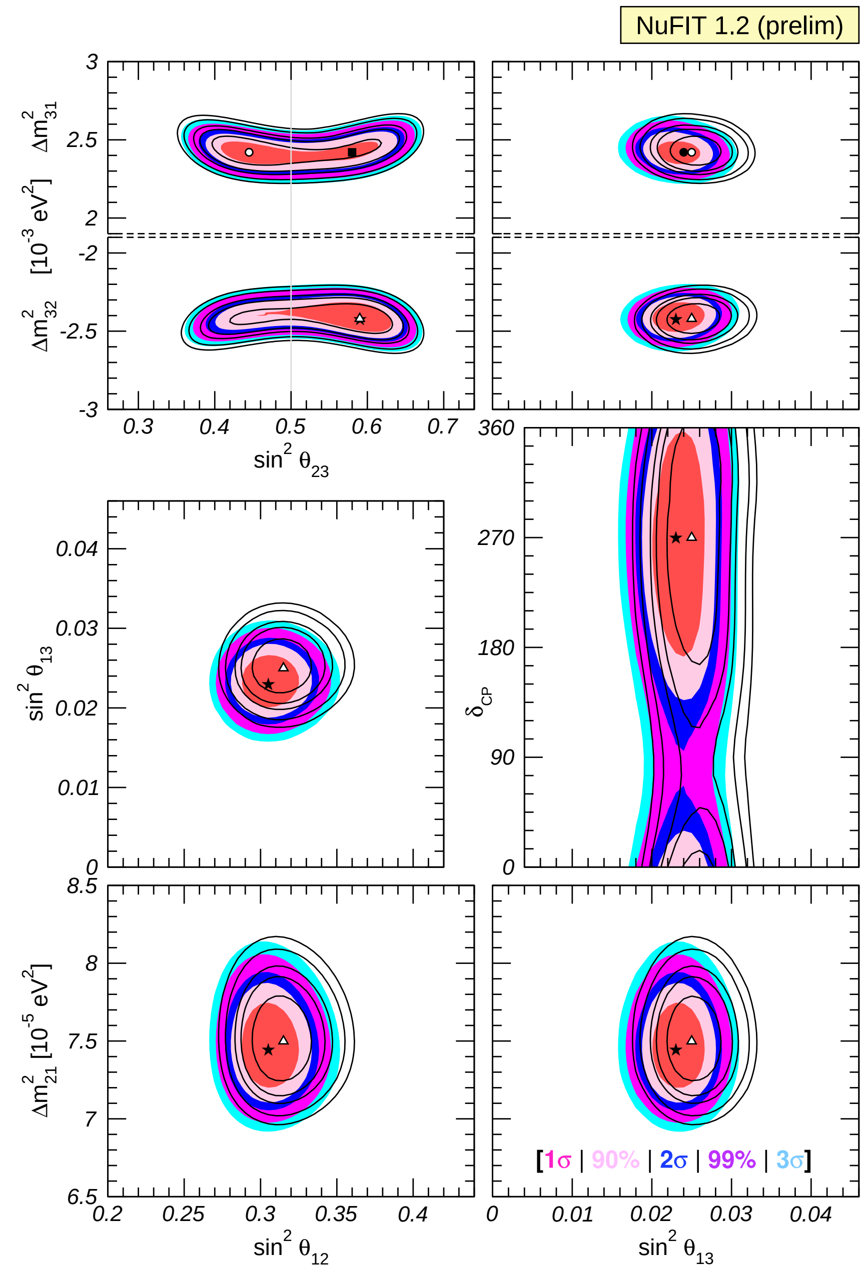
Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\rightarrow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

3 ν Flavour Parameters: Present Status

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

Maltoni, Schwetz, Salvado, MCGG





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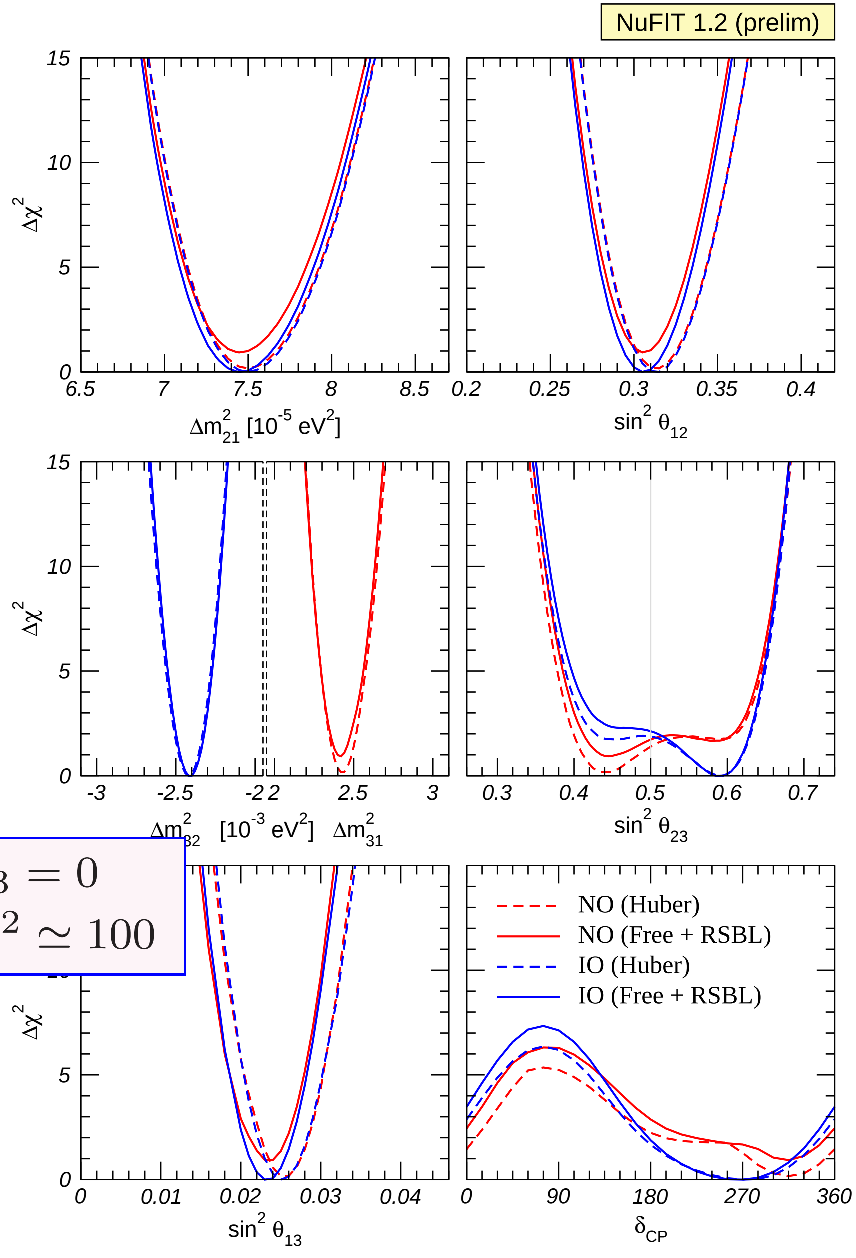
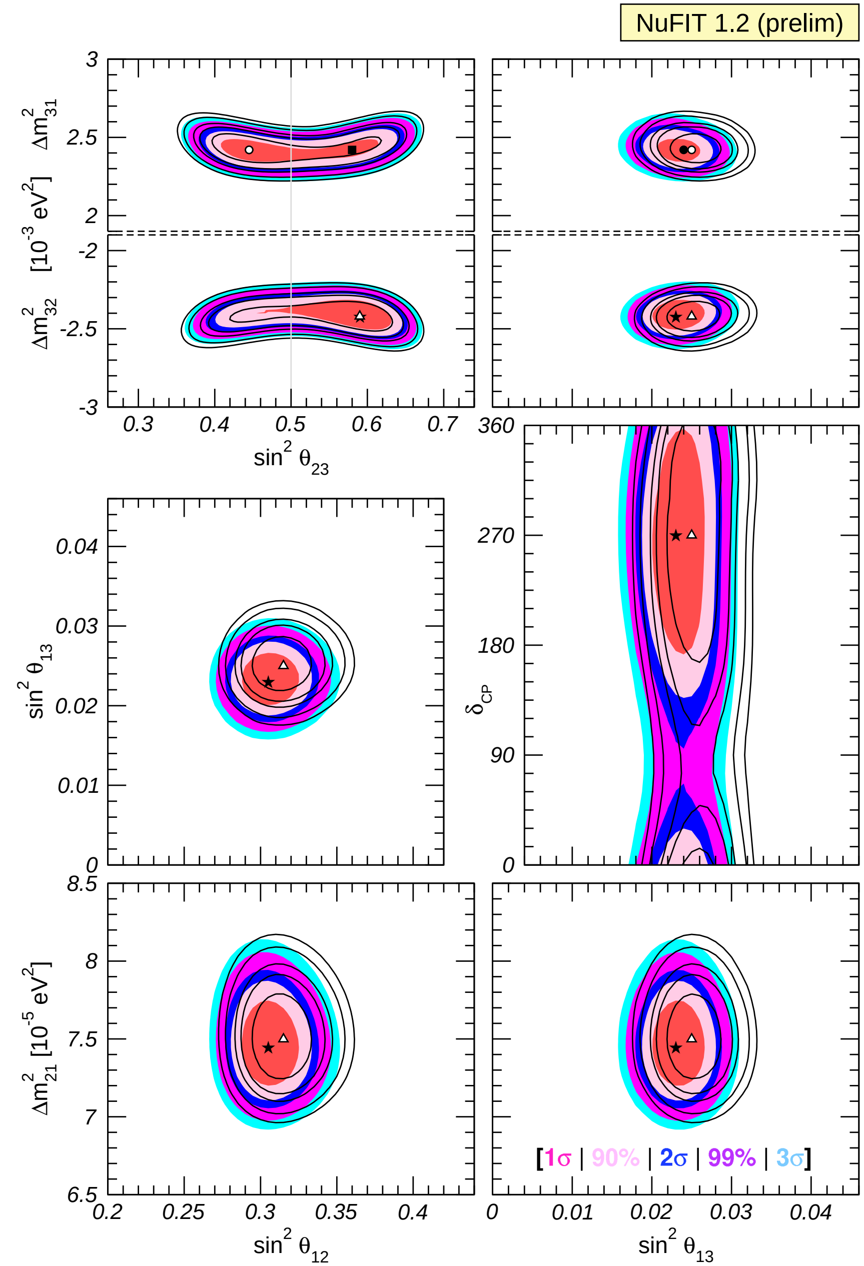


$\theta_{13} = 0$
$\Delta\chi^2 \simeq 100$



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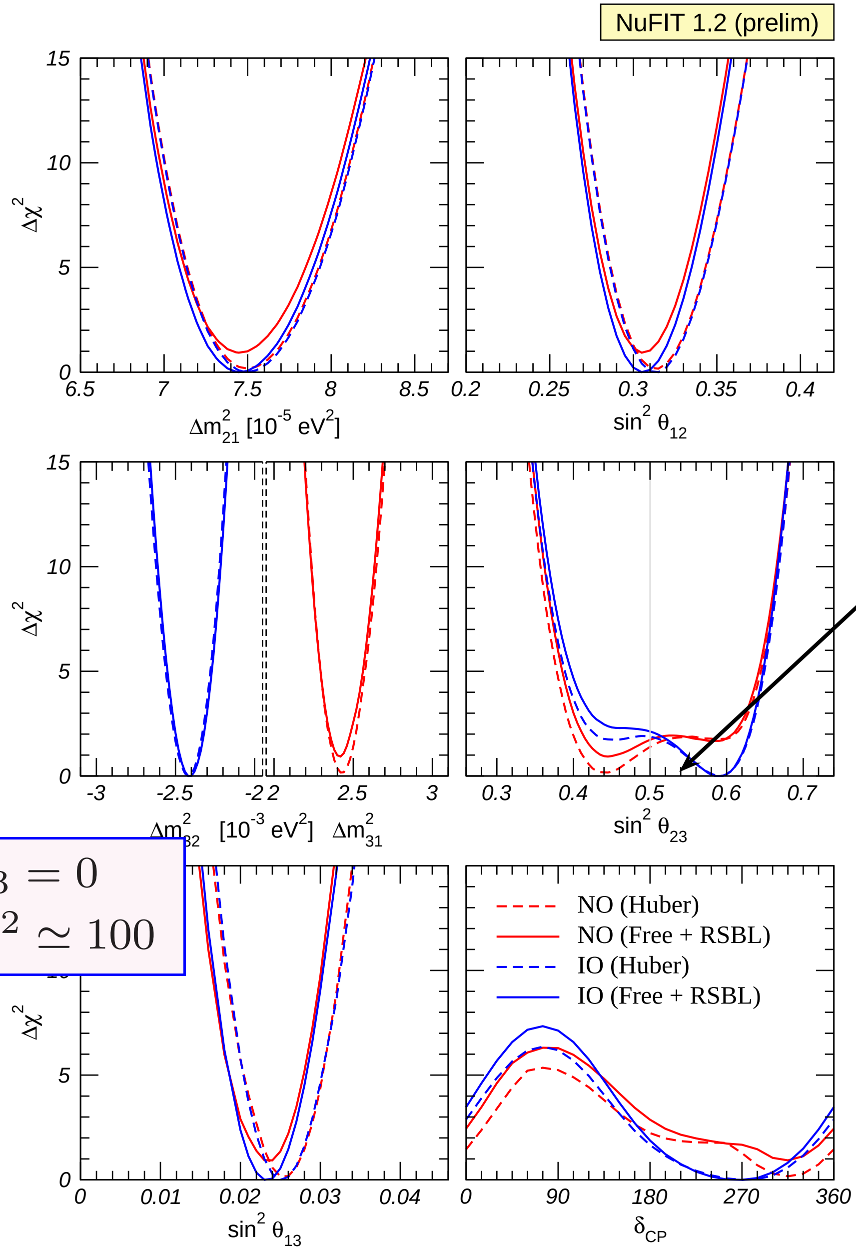
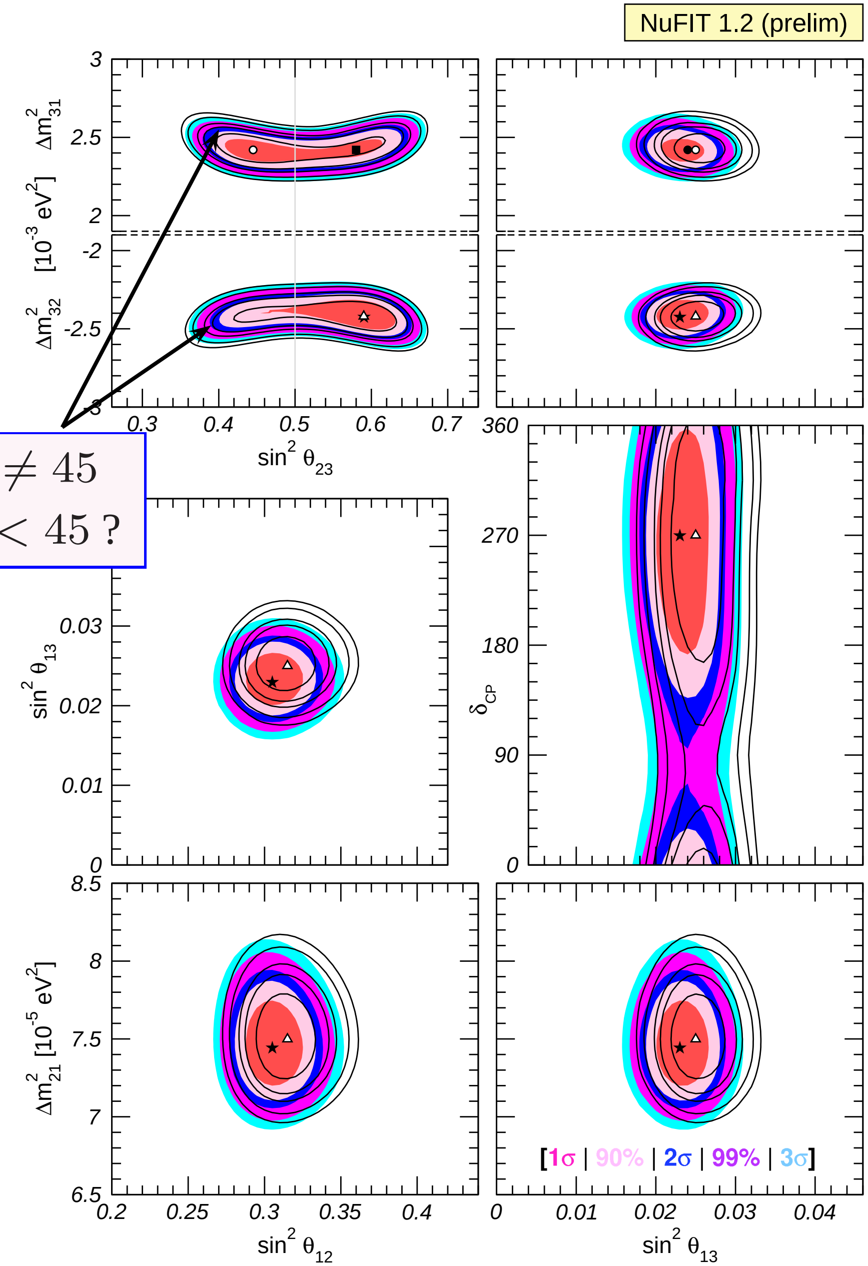


$\theta_{23} \neq 45$

$\theta_{23} < 45$?

$\theta_{13} = 0$

$\Delta\chi^2 \simeq 100$



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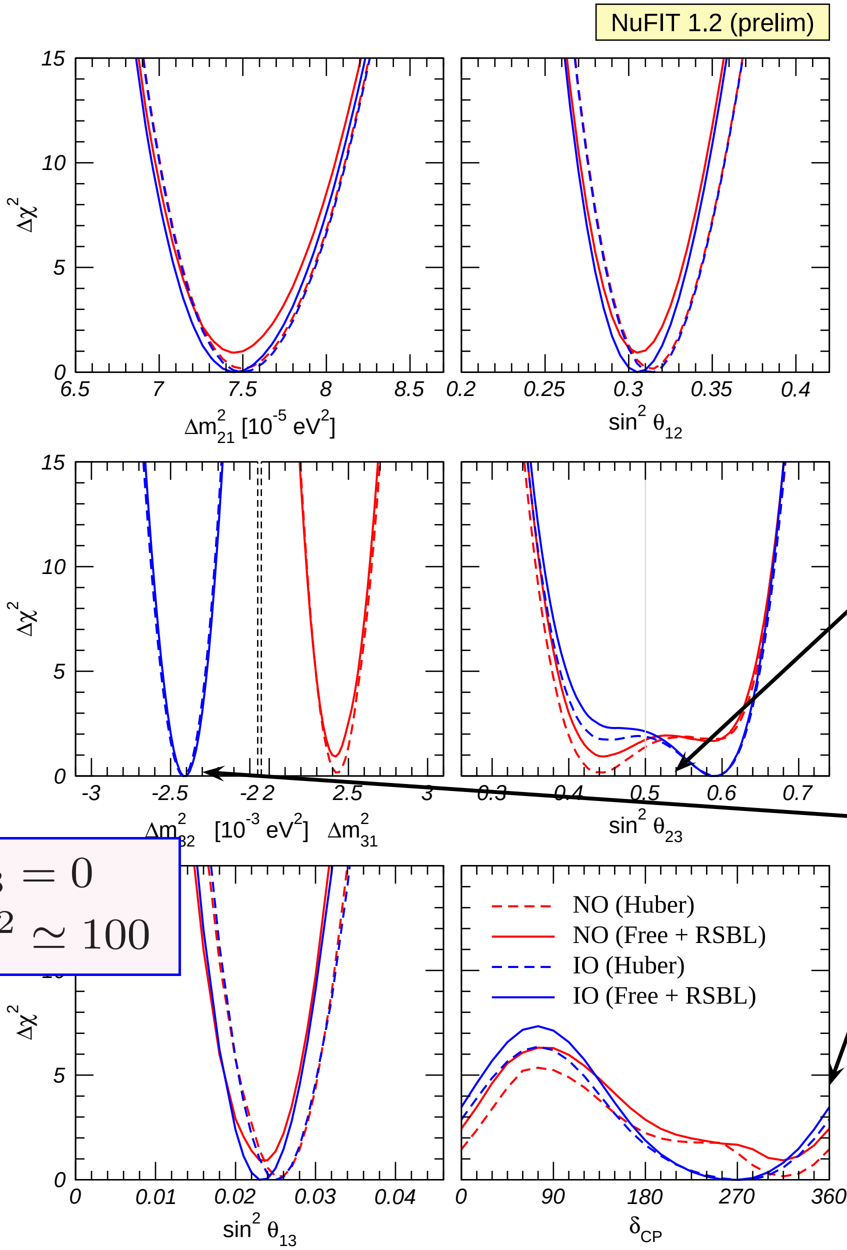

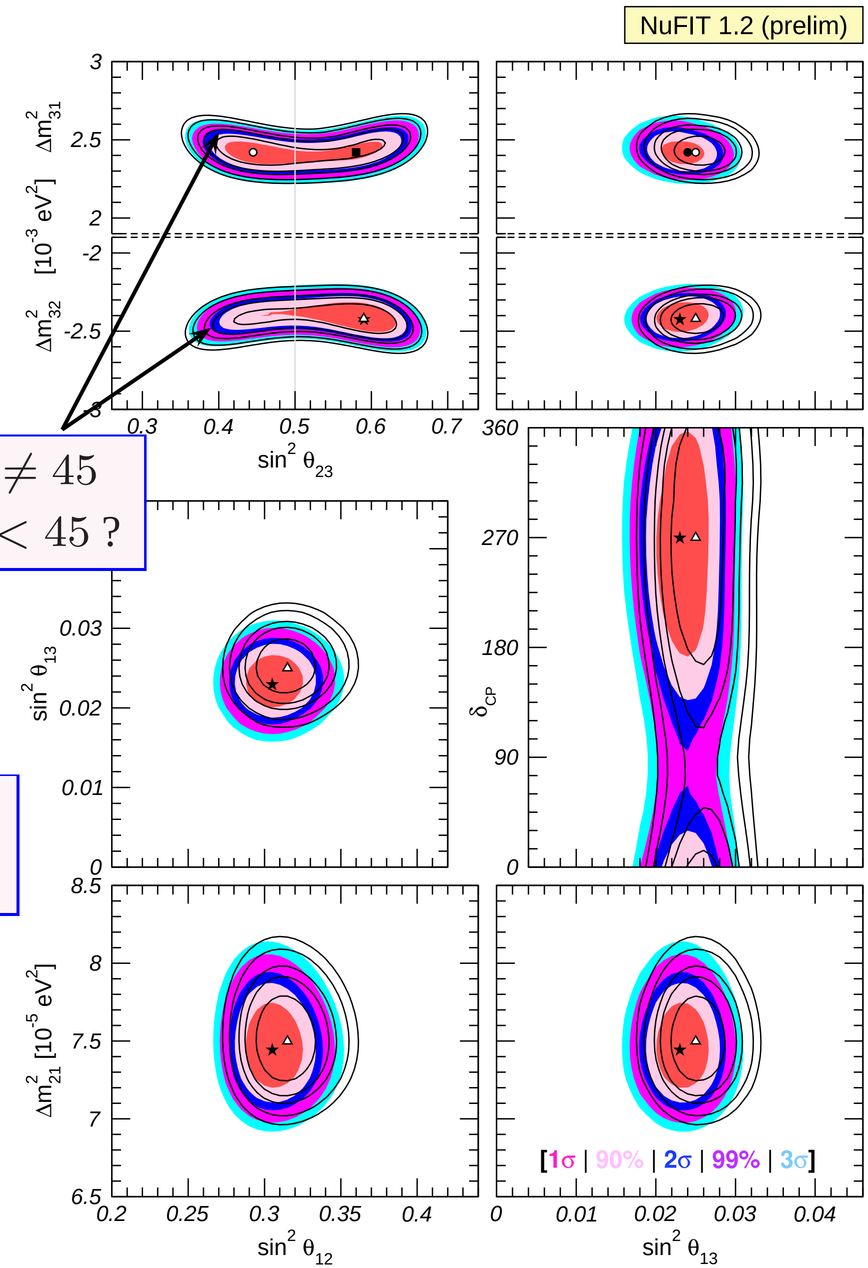

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N/I

$\delta_{\rm cp}$

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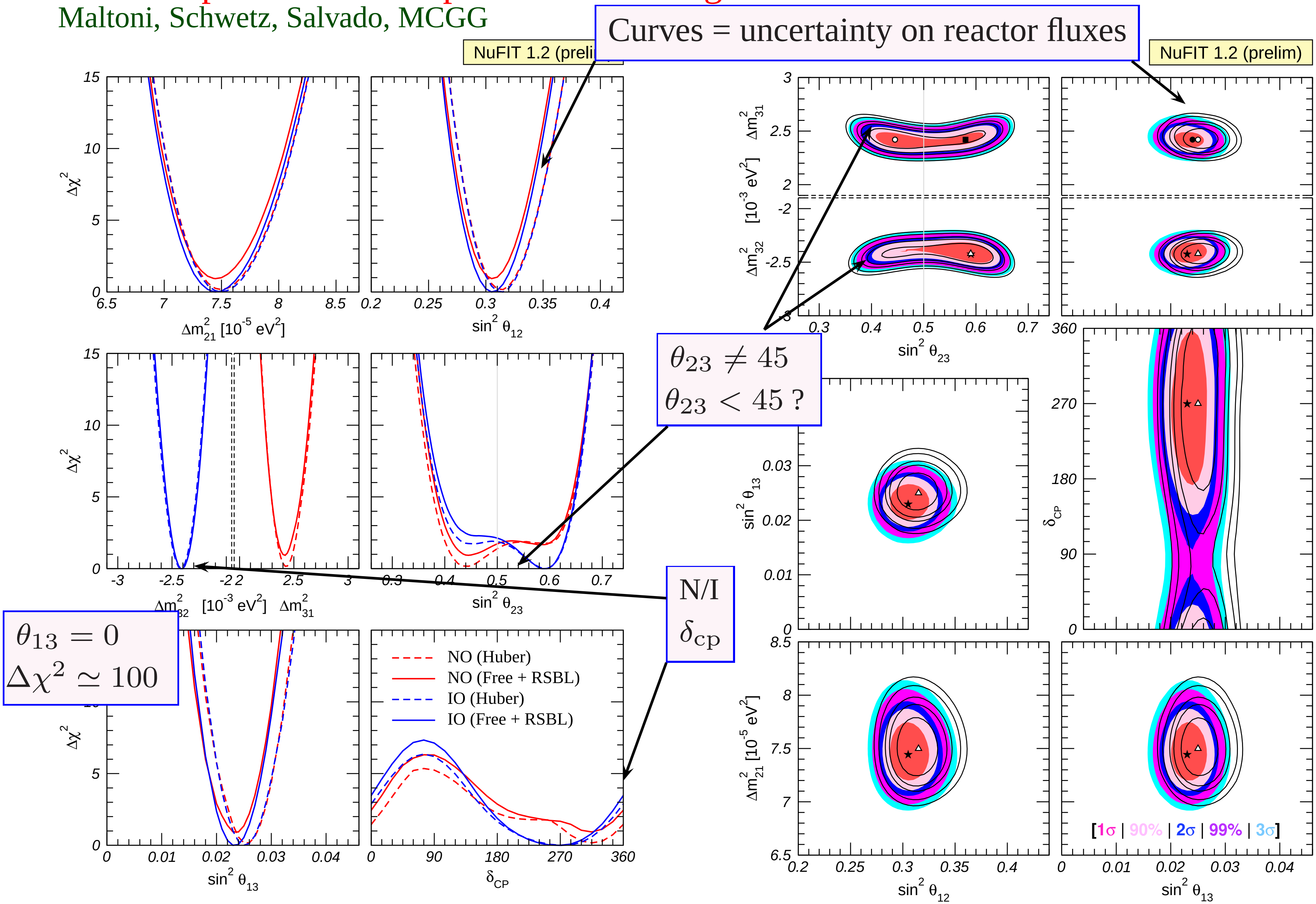

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3 ν Analysis: "12" Sector

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

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

$$P_{ee} \simeq \begin{cases} \text{Solar High E}: c^4_{13}\sin^2 2\theta_{12} \\ \text{Solar Low E}: c^4_{13}\left(1-\sin^2 2\theta_{12}/2\right) \\ \text{Kam}: c^4_{13}\left(1-\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}\right)\end{cases}$$

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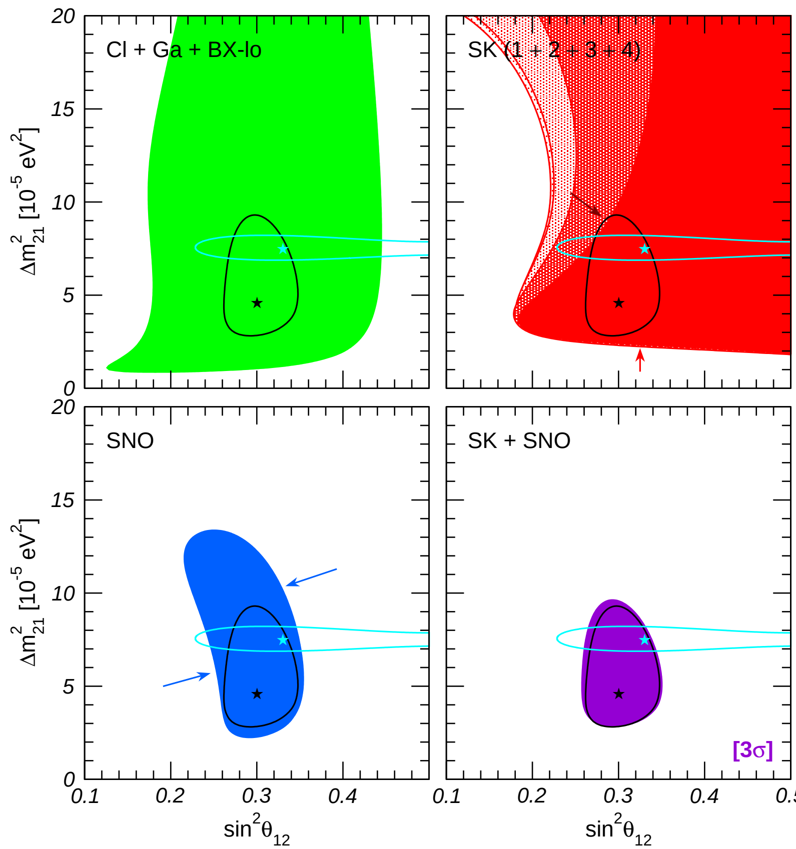
$*$ Solar region determined by High E data

$*$ Param's $\begin{cases} \theta_{12} \text{ SNO most sensitivity} \\ \Delta m^2_{21} \text{ by KamLAND} \end{cases}$

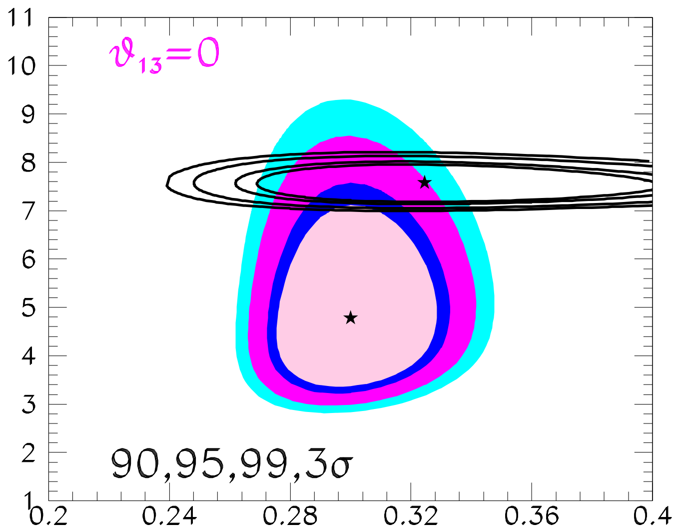
$*$ Tension in best fit between Solar and KamLAND $\Rightarrow \theta_{13}$ and ...?

With $\theta_{13} = 0$



3 ν Analysis: "12" Sector and θ_{13}

- For $\theta_{13} = 0$



$$\sin^2\theta_{12} = \begin{cases} 0.3 \text{ From Solar} \\ 0.325 \text{ From KLAND} \end{cases}$$

3 ν Analysis: “12” Sector and θ_{13}

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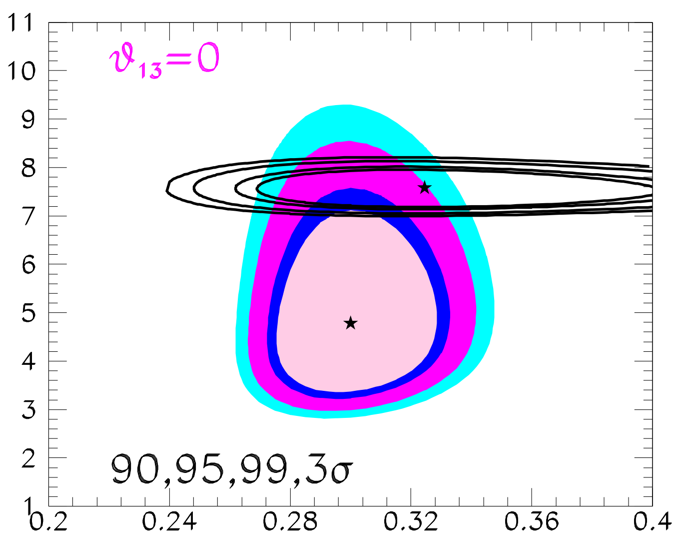

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- When θ_{13} increases

$$P_{ee} \simeq \begin{cases} \text{Solar High E} : c_{13}^4 \sin^2 2\theta_{12} \\ \text{Solar Low E} : c_{13}^4 \left(1 - \sin^2 2\theta_{12}/2\right) \\ \text{Kam} : c_{13}^4 \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E}\right) \end{cases}$$

$\Rightarrow$ KamLAND region shifts left

$\Rightarrow$ Solar slight shifts right (due to High E)

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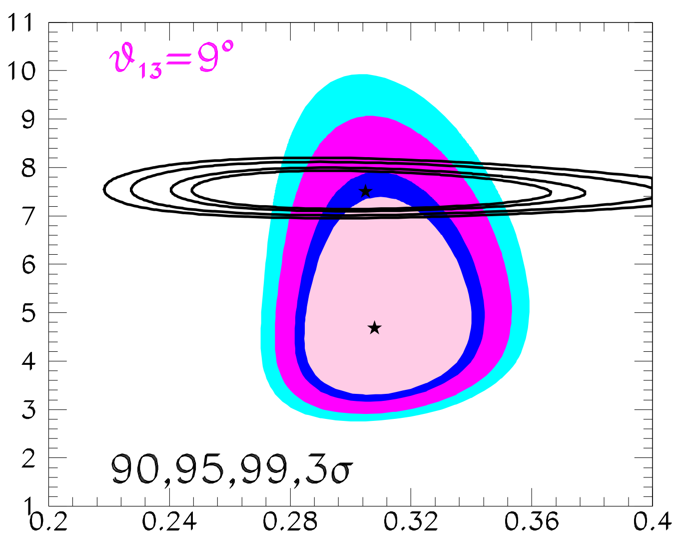
3 ν Analysis: "12" Sector and θ_{13}

- For $\theta_{13} \simeq 9^\circ$



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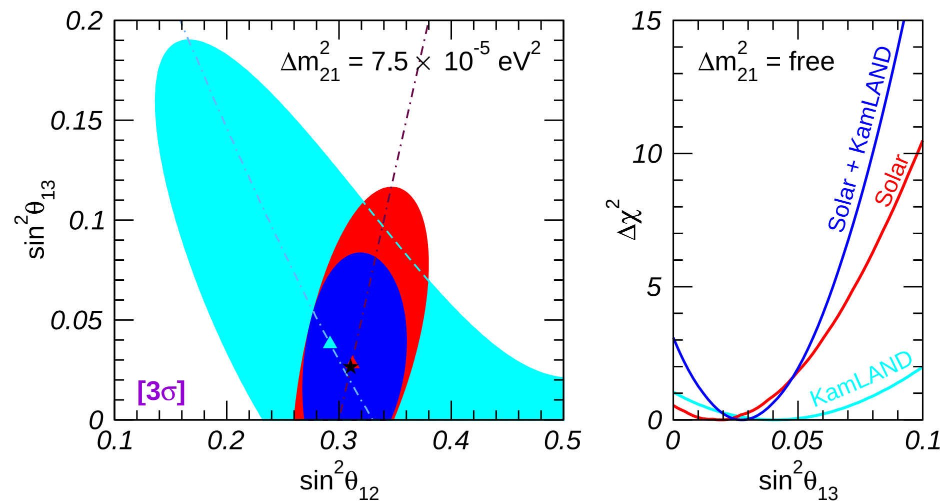
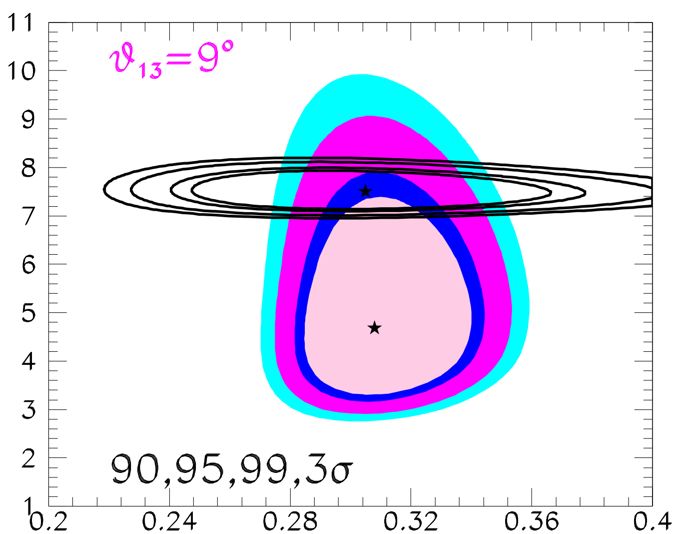


3 ν Analysis: "12" Sector and θ_{13}

- For $\theta_{13} \simeq 9°$



$\Rightarrow$ Good match of best fit θ_{12}

$\Rightarrow$ Residual tension on Δm^2_{21}

- When θ_{13} increases

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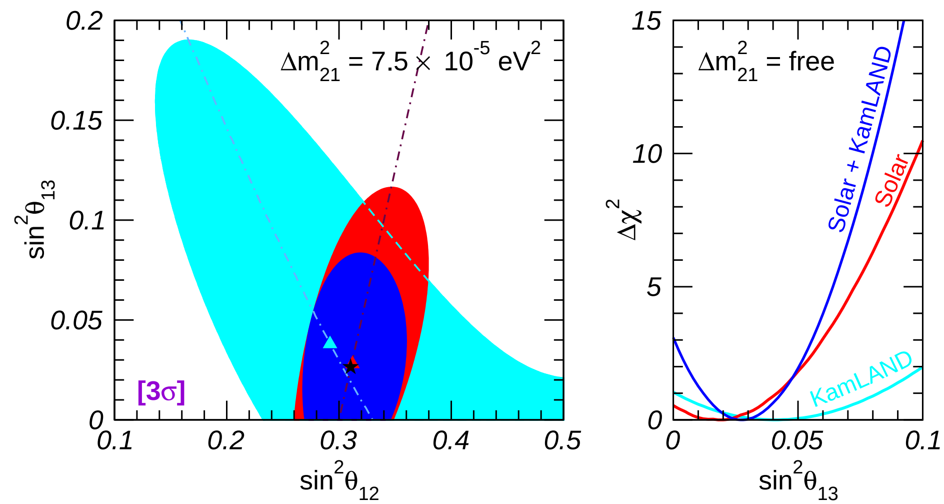

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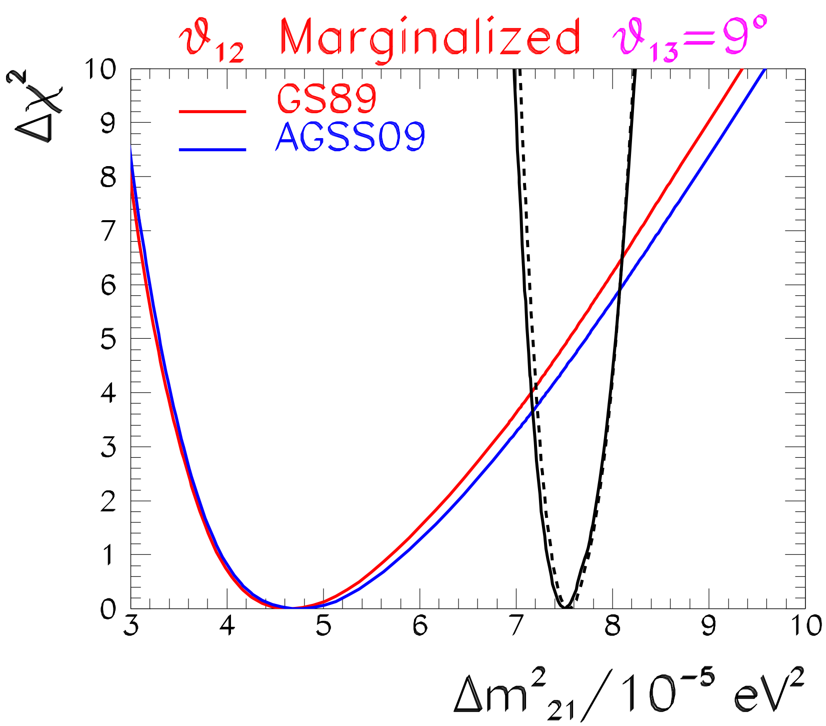
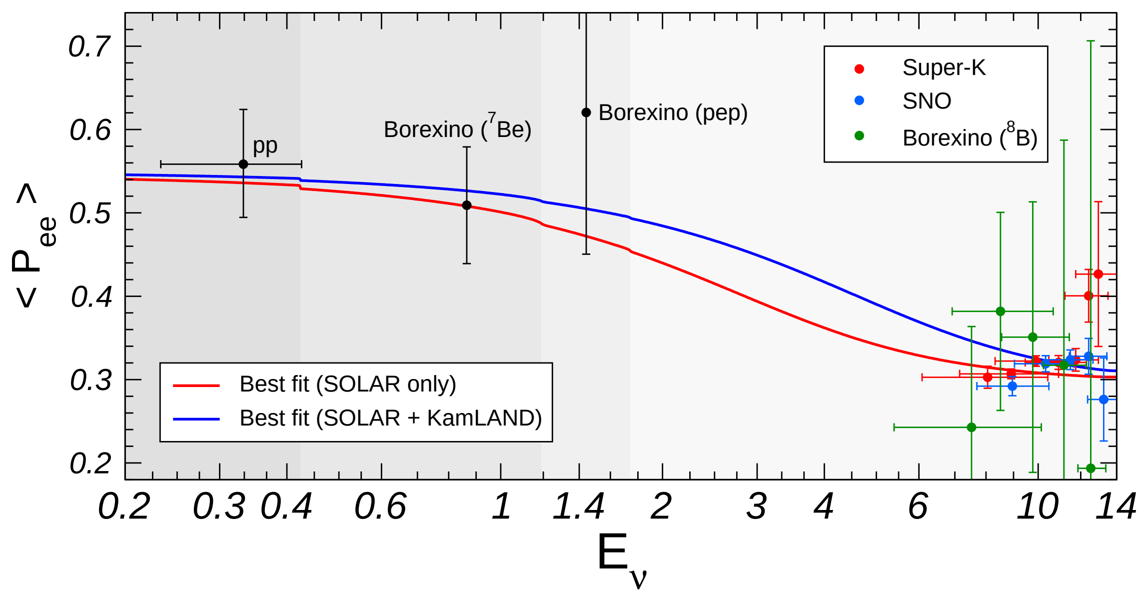
3 ν Analysis: "12" Sector Δm^2_{21}

- Residual tension on Δm^2_{21} between Solar and KamLAND



- Tension related to smaller-than-expected low-E turn up from MSW at best global fit



Talk by A. Renshaw

3 ν Analysis: "12" Sector and 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

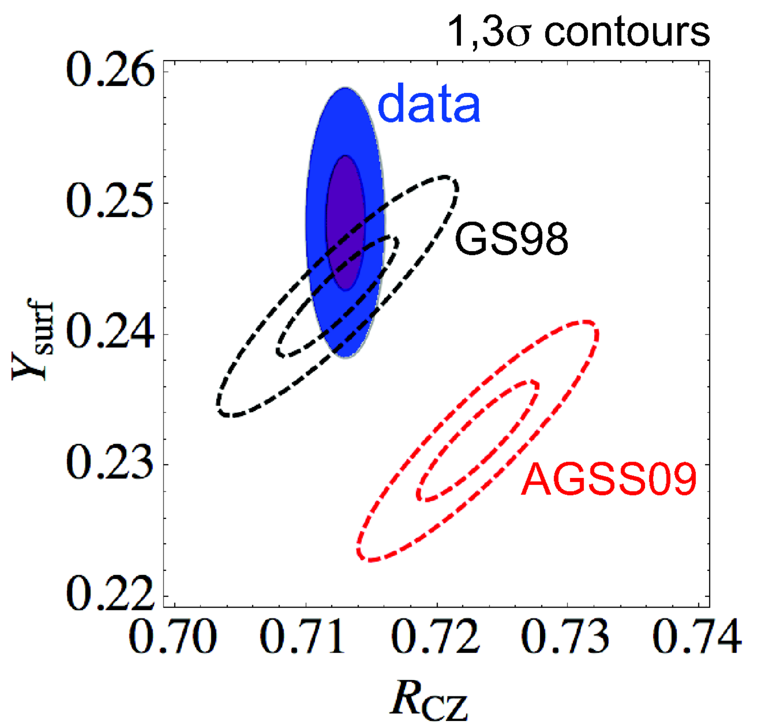


Fig. courtesy of Aldo Ianni

Flux cm^{-2} s^{-1}	GS98	AGSS09
$pp/10^{10}$	$5.97\ (1 \pm 0.006)$	$6.03\ (1 \pm 0.005)$
$pep/10^{8}$	$1.41\ (1 \pm 0.011)$	$1.44\ (1 \pm 0.010)$
$hep/10^{3}$	$7.91 (1 \pm 0.15)$	$8.18\ (1 \pm 0.15)$
$^{7}Be/10^{9}$	$5.08\ (1 \pm 0.06)$	$4.64\ (1 \pm 0.06)$
$^{8}B/10^{6}$	$5.88\ (1 \pm 0.11)$	$4.85\ (1 \pm 0.12)$
$^{13}N/10^{8}$	$2.82\ (1 \pm 0.14)$	$2.07 (1^{+0.14}_{-0.13})$
$^{15}O/10^{8}$	$2.09\ (1^{+0.16}_{-0.15})$	$1.47\ (1^{+0.16}_{-0.15})$
$^{17}F/10^{16}$	$5.65\ (1^{+0.17}_{-0.16})$	$3.48\ (1^{+0.17}_{-0.16})$

Talk by F. Villante

3 ν Analysis: "12" Sector and the Solar Fluxes

– Two sets of SSM:

GS98 uses older metalicities

AGSXX uses newer metalicities

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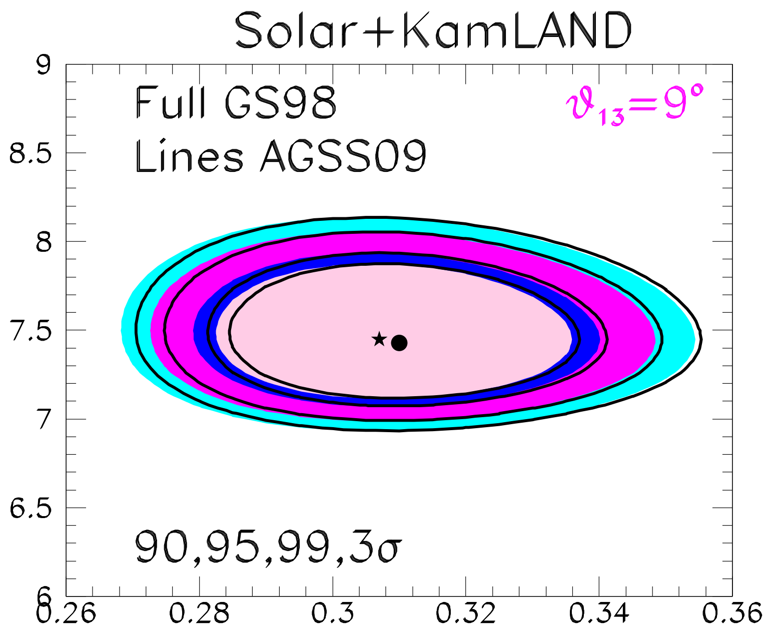
∗ What is the effect on the determination of oscillation parameters?

Very small

Impact in Parameter Determination



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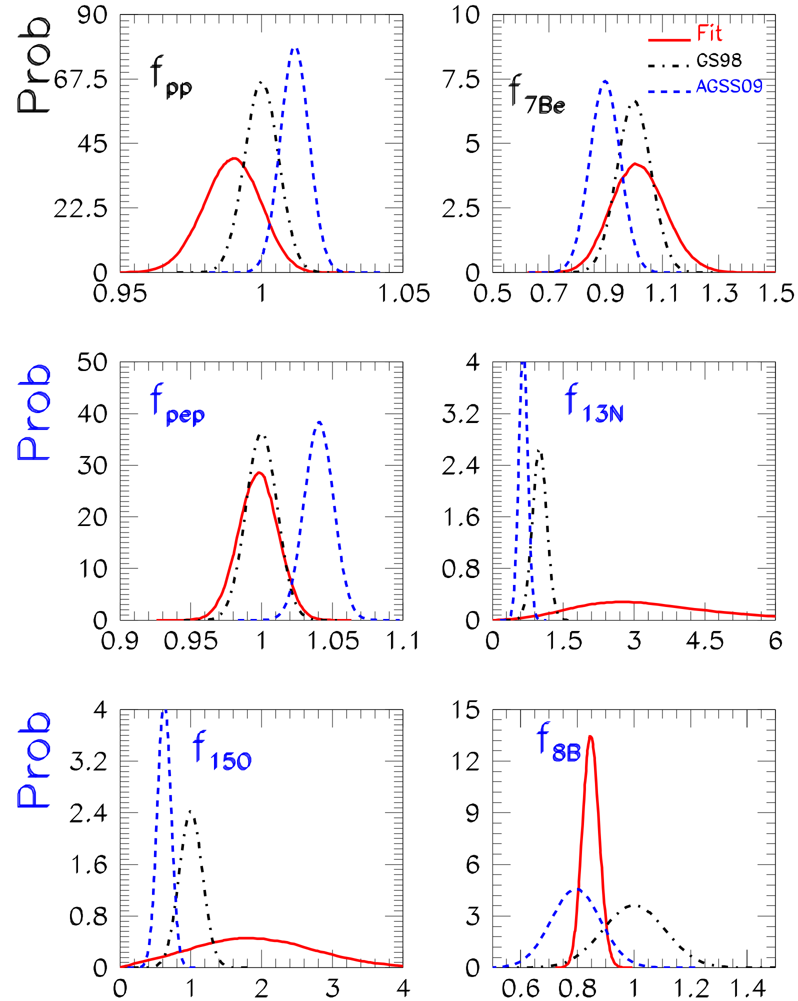
∗ Which SSM does the solar data favour?

Both model statistically equally prob

3ν oscillation fit with solar fluxes free:

(within luminosity constraint)

Comparison with Models



MCG-G,Maltoni,Salvado JHEP 2010

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Some improvement if CNO determined:

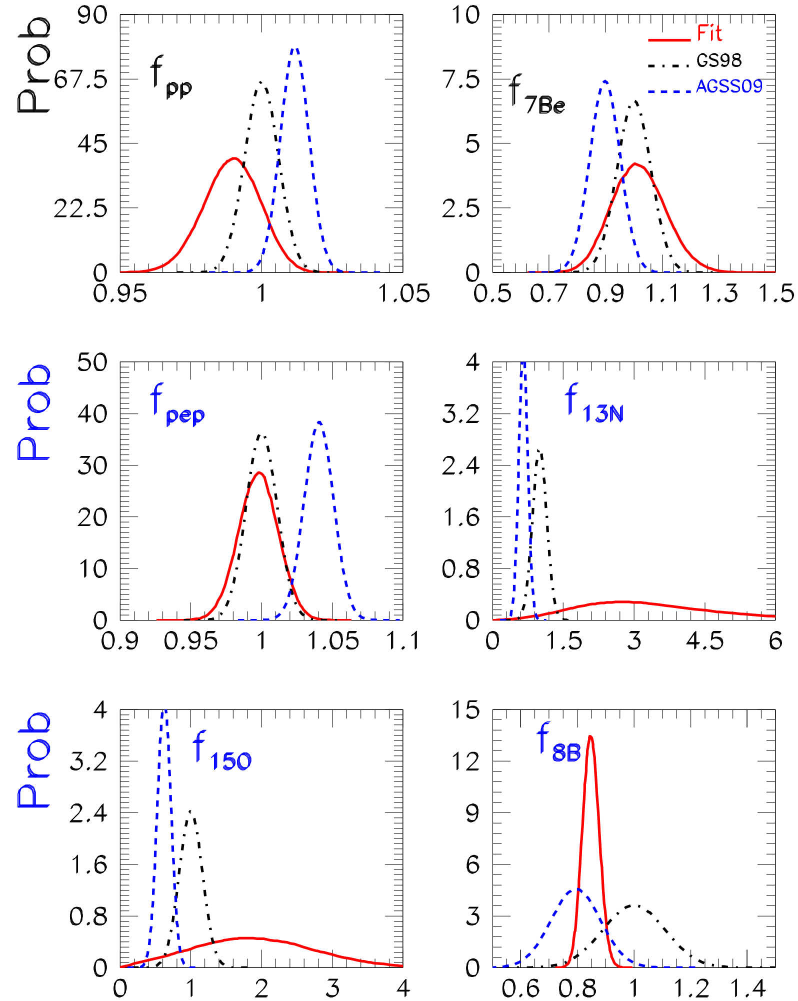
Cleaner Borexino Talk by F. Calaprice

SNO+ Talk by J. Kaspar

3ν oscillation fit with solar fluxes free:

(within luminosity constraint)

Comparison with Models



MCG-G,Maltoni,Salvado JHEP 2010

3 ν Analysis: "23" Sector ATM and LBL ν_μ Disapp

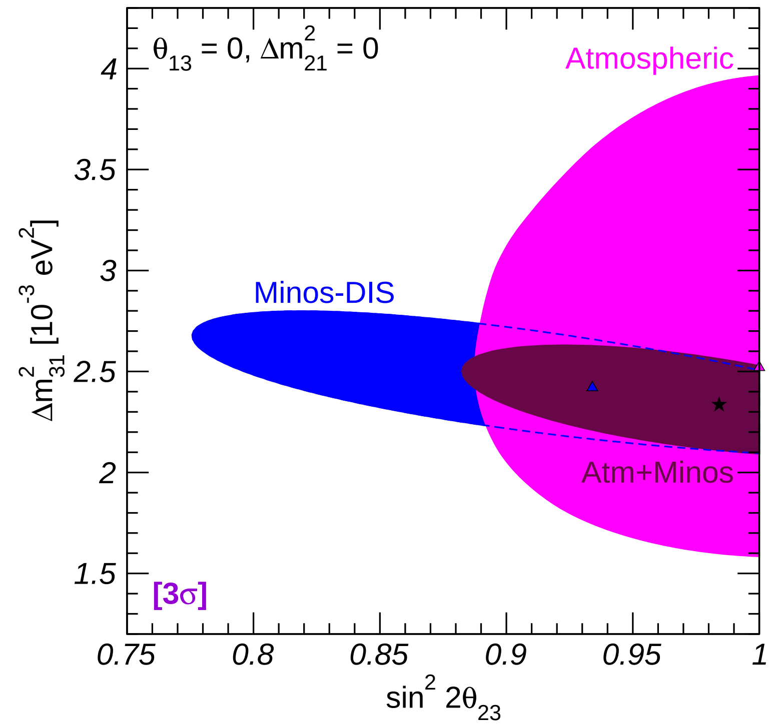
- Dominant Oscillations $\nu_\mu \to \nu_\tau$:

  $*\Delta m^2_{31}$ is best determined by Minos-DIS $\nu_\mu \to \nu_\mu$ data

  $*$ θ_{23} best determined by SK

  $*$ Minos-DIS favours non-maximal θ_{23}

  Talk by P. Vahle



Concha Gonzalez-Garcia

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  - $*$ Minos-DIS slight favour non-maximal θ_{23}
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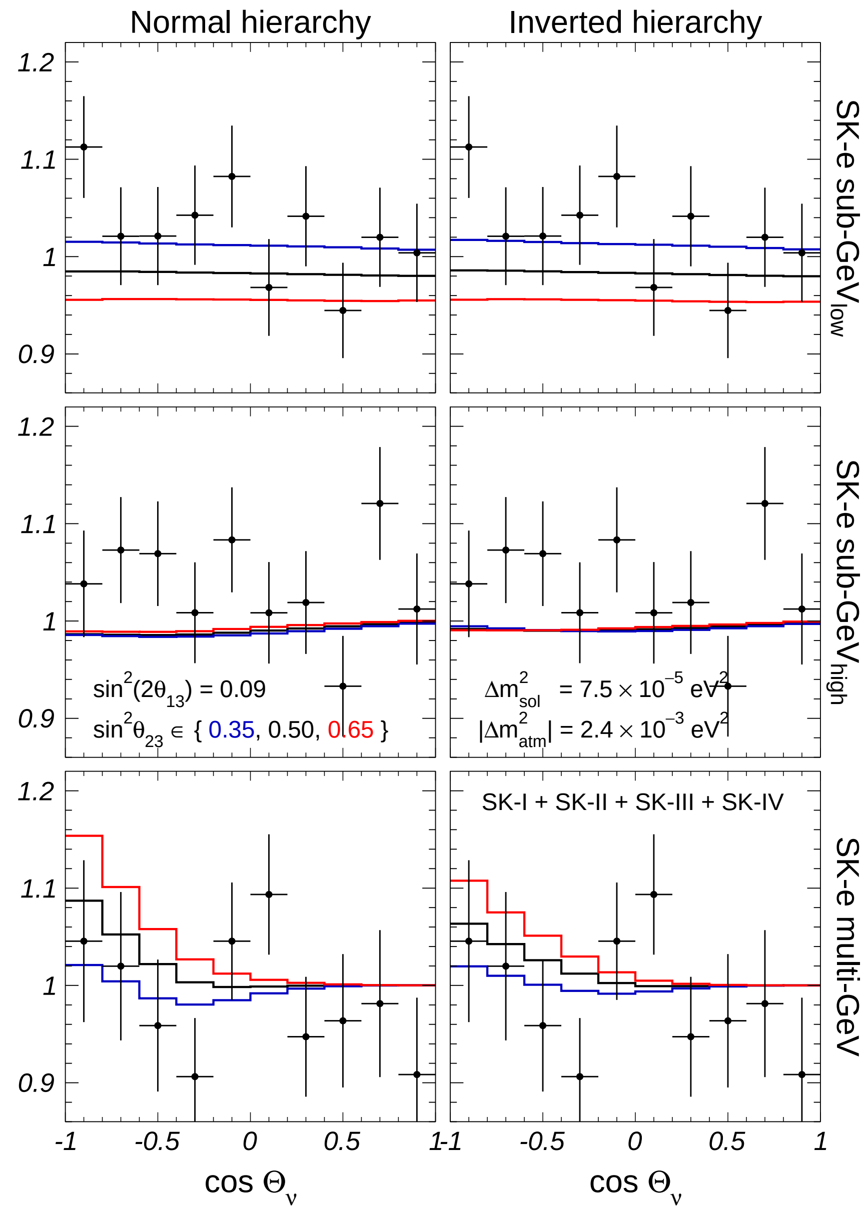
- For $\theta_{31} \neq 0$
  - $*$ATM sensitivity to octant θ_{23} & sign Δm^2_{31}

$$\frac{N_e}{N_e^0} - 1 \simeq (\bar{r}\, c^2_{23} - 1) P_{2\nu}(\Delta m^2_{21}, \theta_{12}) \quad [\Delta m^2_{21} \text{ term}]$$

$$+(\bar{r}\, s^2_{23} - 1) P_{2\nu}(\Delta m^2_{31}, \theta_{13}) \quad [\theta_{13} \text{ term}]$$

$$-2\bar{r}\, s_{13} s_{23} c_{23} Re(A^*_{ee} A_{\mu e}) \quad [\delta_{CP} \text{ term}]$$

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



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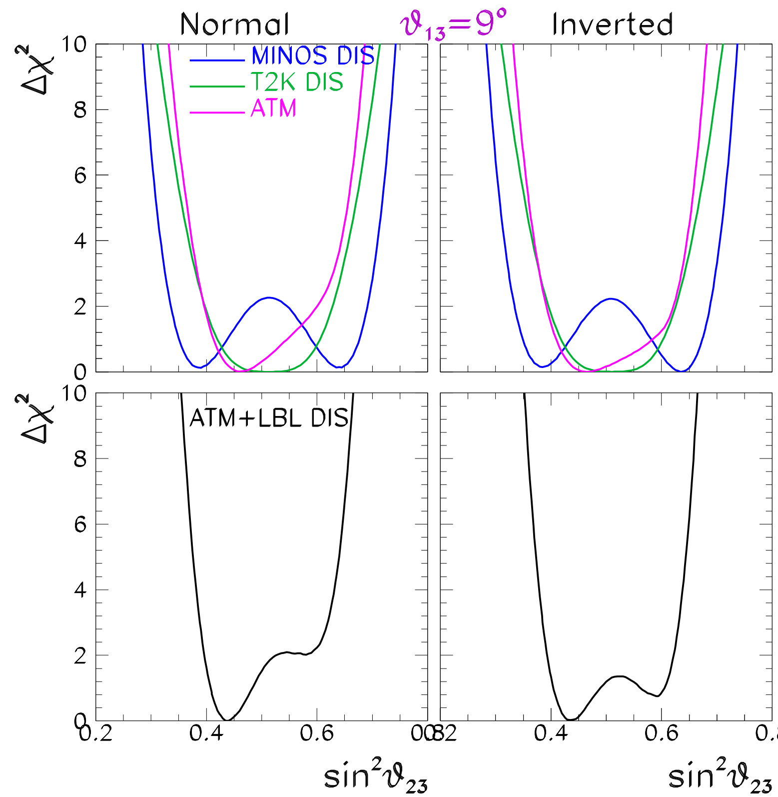

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$*$ In our analysis excess of sub-GeV e's

$\Rightarrow$ slight preference for $\theta_{13} < 45°$ in ATM

Also analysis by Fogli etal 1205.5254

Not so clear in SK analysis

Talks by J. Kameda and K. Okumura

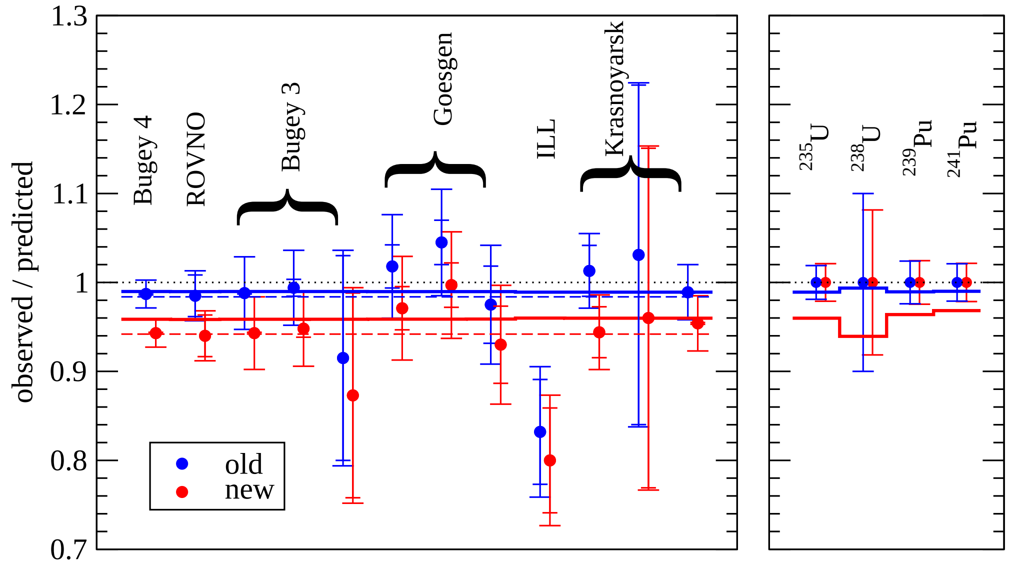
3 ν Analysis: θ_{13} from Reactors and Flux anomaly

- Recently the reactor $\bar{\nu}_e$ fluxes have been recalculated

  T.A. Mueller et al.,[arXiv:1101.2663].;P. Huber, [arXiv:1106.0687].

- Both reevaluations find higher fluxes by about 3.5 %

- So *negative* reactor experiments at short baselines (RSBL) indeed observed a deficit



- If due to oscillations $\Delta m^2 \sim \text{eV}^2 \Rightarrow$ sterile ν's (more soon)

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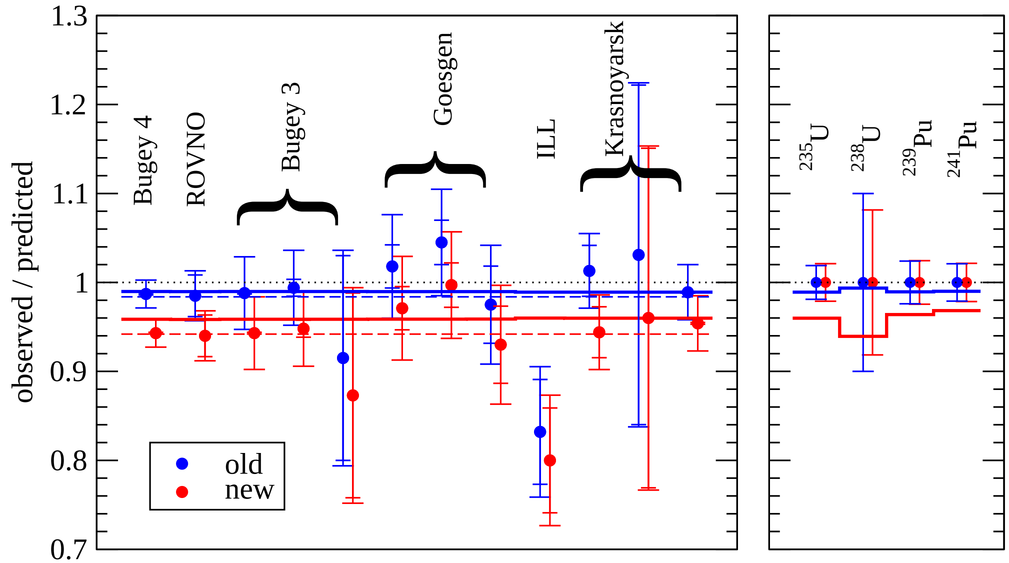
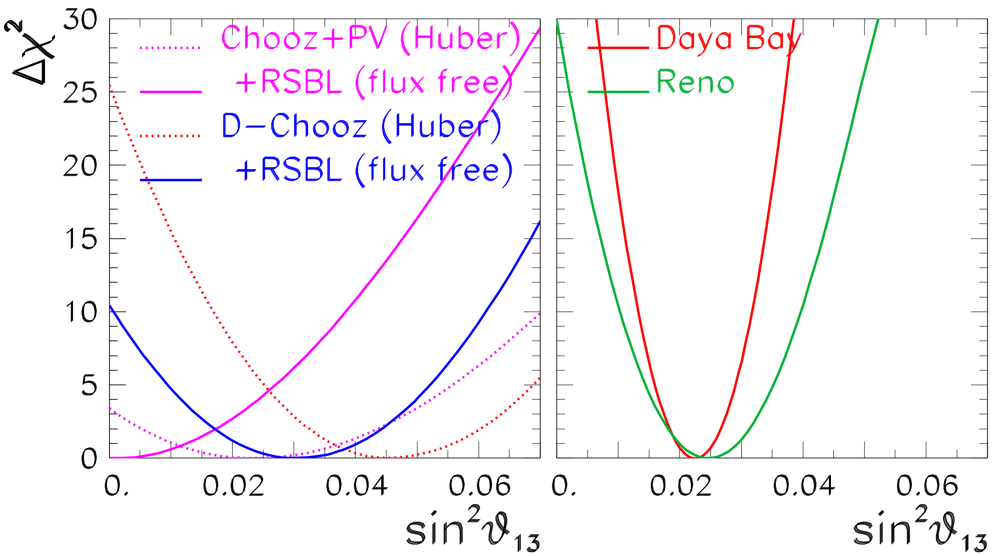
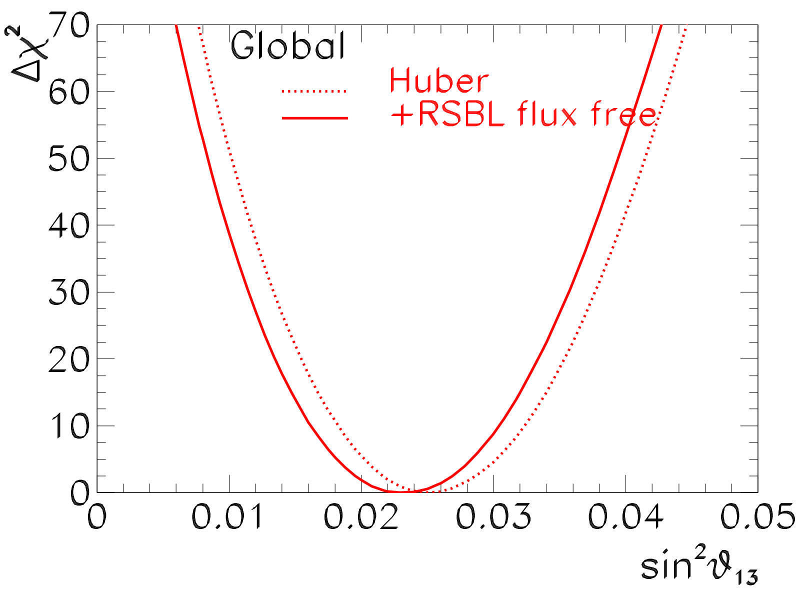


- For 3ν analysis a consistent approach (T. Schwetz et. al. [arXiv:1103.0734]):
  - Fit oscillation parameters and reactor fluxes simultaneously
  - Use theoretical calculation and/or RSBL data as priors

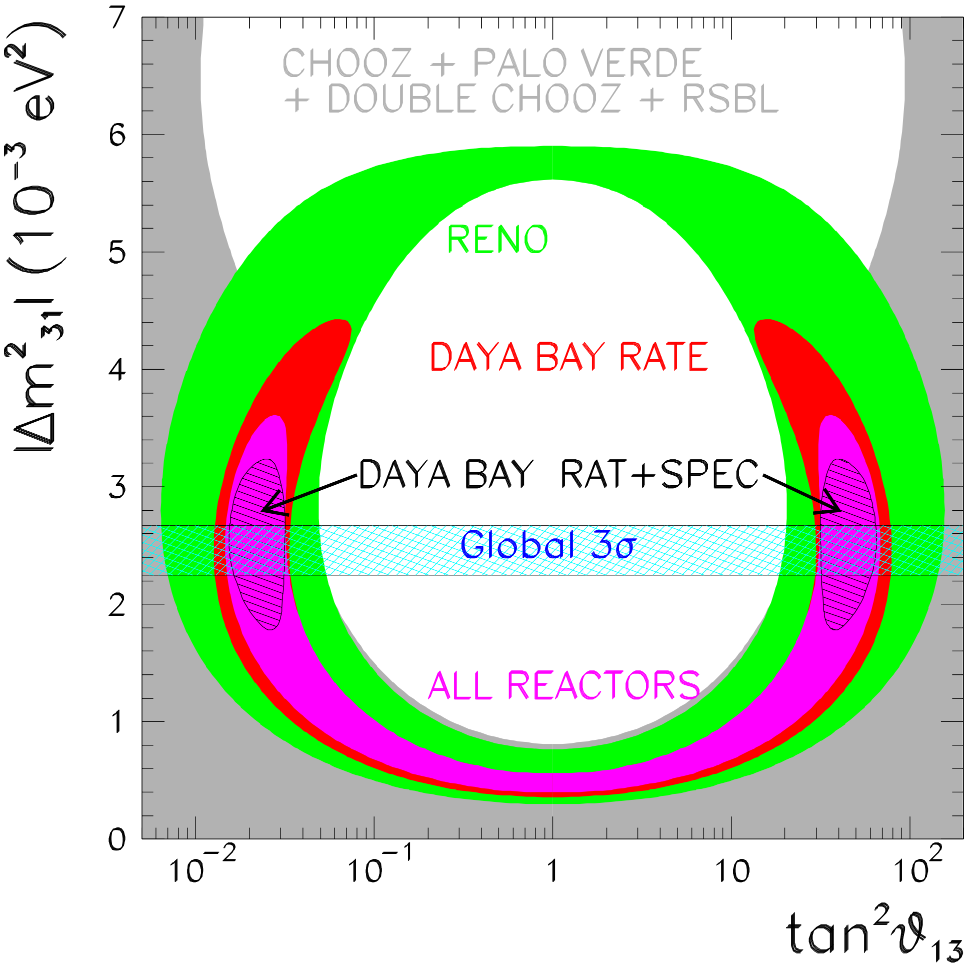
3 ν Analysis: θ_{13} from Reactors and Flux anomaly





- Experiments without near detector (CHOOZ, Palo-Verde,D-CHOOZ) sensitive to the flux assumptions
- DAYA-BAY and RENO Near-Far comparison
  $\Rightarrow$ results flux independent
- Two extreme priors :
  a) Use fluxes from Huber 1106.0687 without RSBL data
  $$\sin^2\theta_{13} = 0.023^{+0.0026}_{-0.0024}$$
  b) Leave flux free and include RSBL
  $$\sin^2\theta_{13} = 0.022^{+0.0026}_{-0.0023}$$
  Uncertainty at $\sim$ 0.5–1σ level

3 ν Analysis: Reactor Data and Δm^2_{31}



3σ regions 2dof

- Due to different baselines the combination of reactors provides independent determination of the largest mass splitting
- Improved with Daya-Bay spectrum

Talks at LEN IV Parallel Session

3 ν Analysis: LBL vs REACT and θ_{23} and Ordering

- In LBL APP $\nu_\mu \to \nu_e$

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

$B_\pm = \Delta_{31} \pm V_E \quad \tilde{J} = c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$

So $\sin^2 2\theta_{\rm APP} = 2\sin^2\theta_{23} \sin^2 2\theta_{13}$

- In LBL DIS $P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{\rm DIS} \sin^2\left(\frac{\Delta_{31} L}{2}\right)$

So $\sin^2\theta_{\rm DIS} = \cos^2\theta_{13} \sin^2\theta_{23} \neq \frac{\pi}{4}$

$\Rightarrow$ two possible octacts for θ_{23}

- In Reactor $P_{ee} \simeq \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{31} L}{2}\right)$

So $\sin^2 2\theta_{\rm REAC} = \sin^2 2\theta_{13}$

$$\text{If} \begin{cases} \sin^2 2\theta_{\rm REAC} \leq \sin^2 2\theta_{\rm APP} & \Rightarrow \theta_{23} \geq \frac{\pi}{4} \text{ favoured} \\ \sin^2 2\theta_{\rm REAC} \geq \sin^2 2\theta_{\rm APP} & \Rightarrow \theta_{23} \leq \frac{\pi}{4} \text{ favoured} \end{cases}$$

3 ν Analysis: LBL vs REACT and θ_{23} and Ordering

- In LBL APP $\nu_\mu \to \nu_e$

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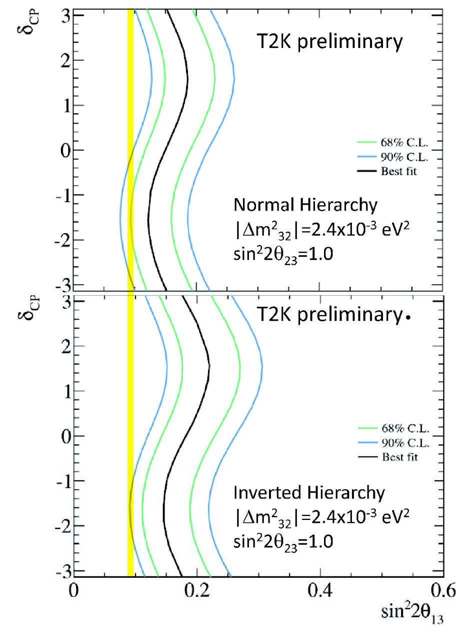

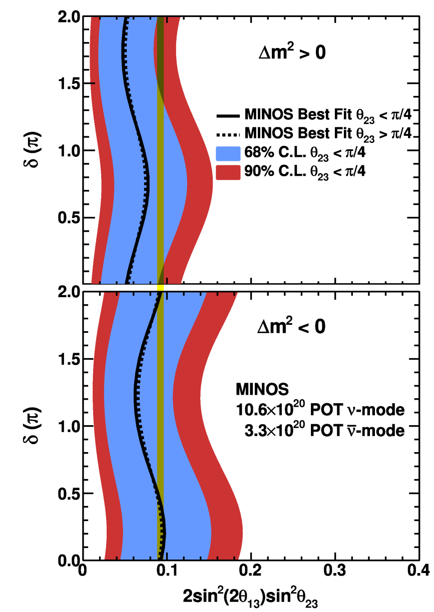

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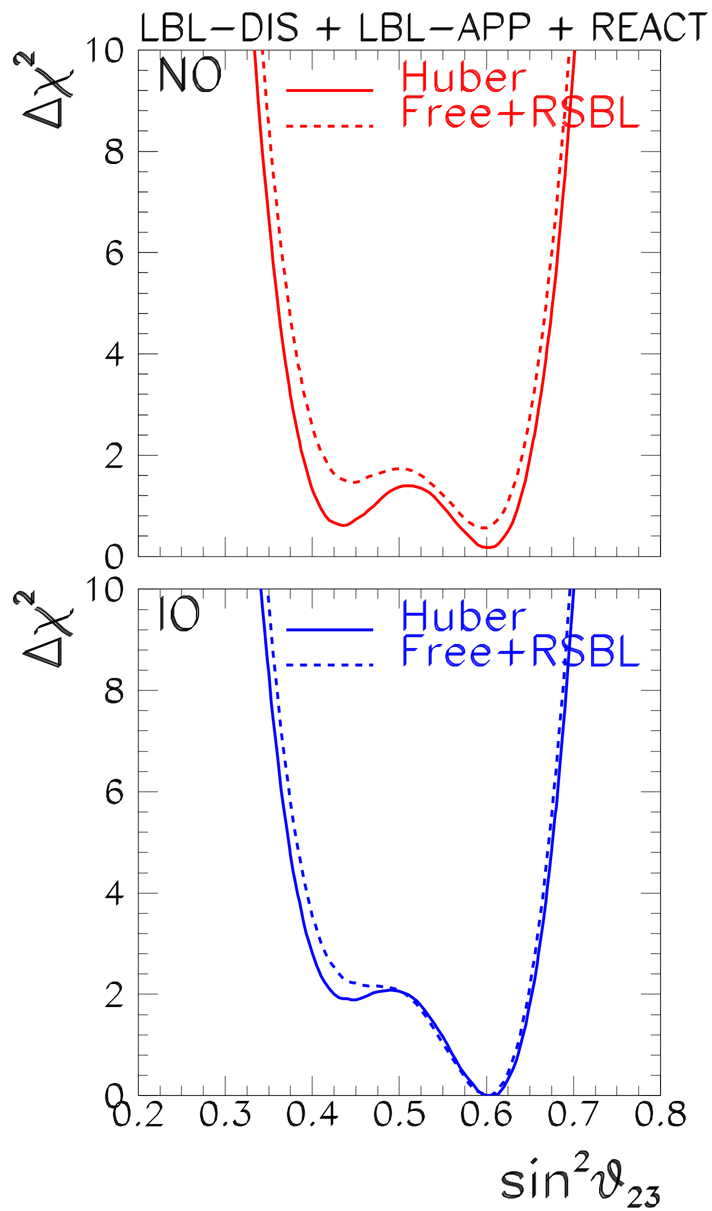
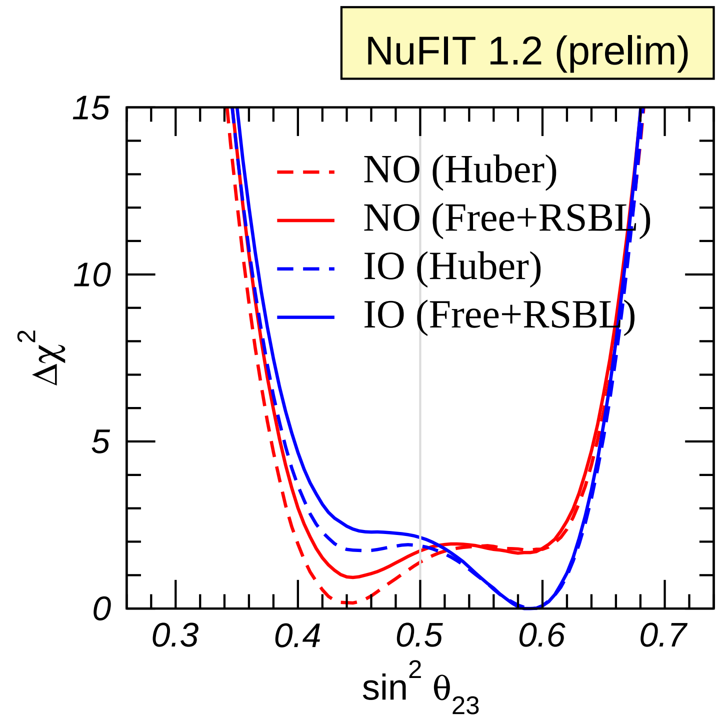
At present with new T2K data

$$\left.\begin{array}{l}\sin^2 2\theta_{\rm REAC} \simeq 0.09 \\ \sin^2 2\theta_{\rm APP-T2K} \simeq 0.1\end{array}\right\} \Rightarrow \theta_{23} \geq \frac{\pi}{4} \quad \text{favoured}$$



3 ν: Global Status of θ_{23} and Ordering

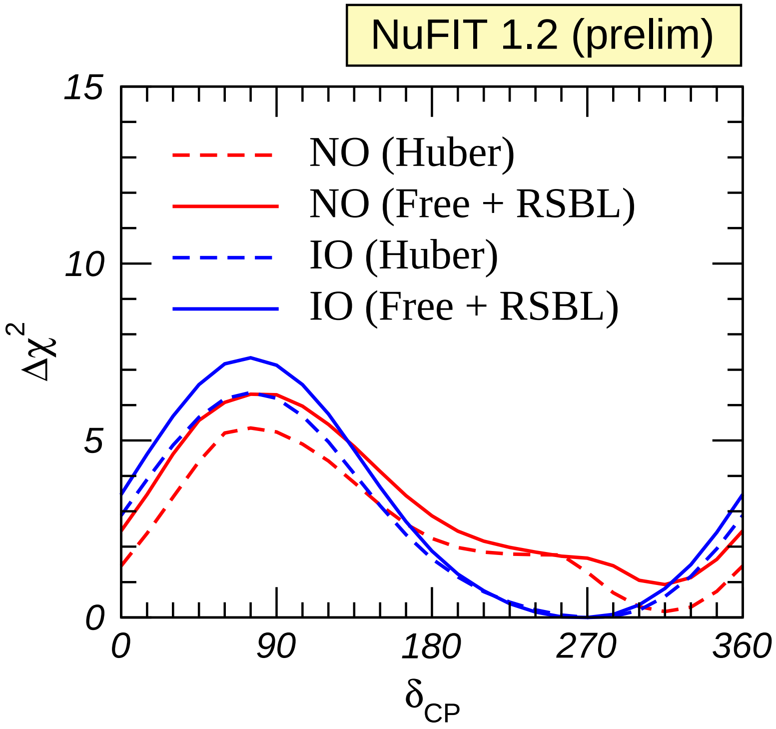
- θ_{23} determination in global analysis:
  - Maximal $\theta_{23} = 45$ Disfavoured at 1.4 σ level
    Now mostly driven by MINOS ν_μ DIS
  - NO: $\theta_{23} < 45$ Favoured at 1.6–2 σ level
    Driven by SK I–IV ATM Sub-GeV ν_e excess
    Also in MINOS-APP+REACT
  - IO: $\theta_{23} > 45$ Favoured at 1.4–1.6 σ level
    Driven by T2K-APP+REACT



- sign($\Delta m^2_{\rm atm}$) determination in global analysis:
  - No significant difference Normal versus Inverted
    IO favoured at 0-1 σ level

3ν Analysis: Leptonic CP violation

- Driven by the LBL-APP vs REACT θ_{13} with slight influence of ATM

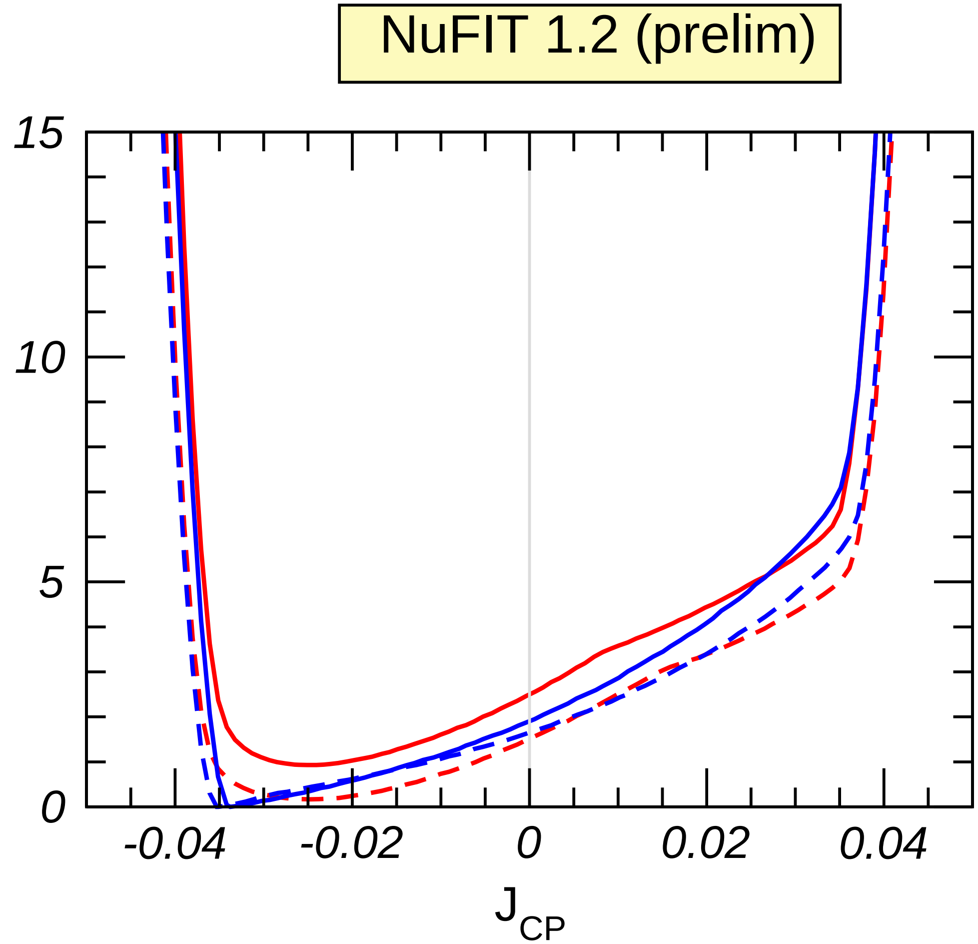


- For IO Best $\delta \simeq 270°$
- For NO Best $\delta \simeq 300°$

($\delta_{CP} = 270 \Rightarrow \sin^2\theta_{T2K}$ is smallest)

- Projection over leptonic Jarkskog param

$$J \equiv \sin_{12}\cos_{12}\sin_{23}\cos_{23}\sin_{13}\cos^2_{13}\sin\delta_{CP}$$



Flavour Parameters: Present Status 1σ (3σ):

z-Garcia

$$\Delta m^2_{21} = 7.45 \pm 0.18 \left({}^{+0.60}_{-0.46}\right) \times 10^{-5}\ \text{eV}^2 \qquad \theta_{12} = 33.5^{\circ}{}^{+0.8}_{-0.7} \left({}^{+2.5}_{-2.1}\right)$$

$$\Delta m^2_{31}(\text{N}) = 2.42^{+0.06}_{-0.06} \left({}^{+0.21}_{-0.18}\right) \times 10^{-3}\ \text{eV}^2 \qquad \theta_{23} = \begin{cases} (\text{N})\ 41.8^{\circ}{}^{+9.2^{\circ}}_{-1.85^{\circ}} \left({}^{+12.8^{\circ}}_{-4.8^{\circ}}\right) \\ (\text{I})\ 50.2^{\circ}{}^{+1.7^{\circ}}_{-2.5^{\circ}} \left({}^{+4.3^{\circ}}_{-12.6^{\circ}}\right) \end{cases}$$

$$|\Delta m^2_{32}|(\text{I}) = 2.42^{+0.07}_{-0.05} \left({}^{+0.19}_{-0.18}\right) \times 10^{-3}\ \text{eV}^2 \qquad \theta_{13} = 8.7^{\circ}{}^{+0.47}_{-0.36} \left({}^{+1.3^{\circ}}_{-1.3^{\circ}}\right)$$

$$\delta_{\text{CP}} = \begin{cases} (\text{N})\ 315^{\circ}{}^{+36^{\circ}}_{-84^{\circ}} \left({}^{+45^{\circ}}_{-315^{\circ}}\right) \\ (\text{I})\ 270^{\circ}{}^{+50^{\circ}}_{-68^{\circ}} \left({}^{+90^{\circ}}_{-270^{\circ}}\right) \end{cases}$$

$$|U|_{\text{LEP}(3\sigma)} = \begin{pmatrix} 0.799 \rightarrow 0.844 & 0.515 \rightarrow 0.581 & 0.129 \rightarrow 0.173 \\ 0.212 \rightarrow 0.527 & 0.426 \rightarrow 0.707 & 0.598 \rightarrow 0.805 \\ 0.233 \rightarrow 0.538 & 0.450 \rightarrow 0.722 & 0.573 \rightarrow 0.787 \end{pmatrix}$$

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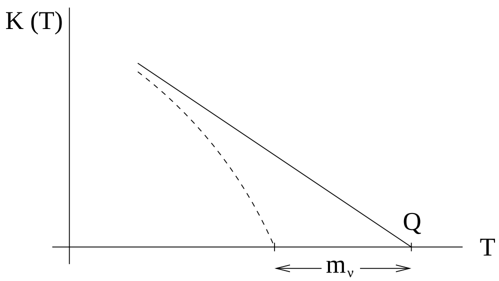
- Good progress but still precision very far from:

$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

Concha Gonzalez-Garcia

Neutrino Mass Scale

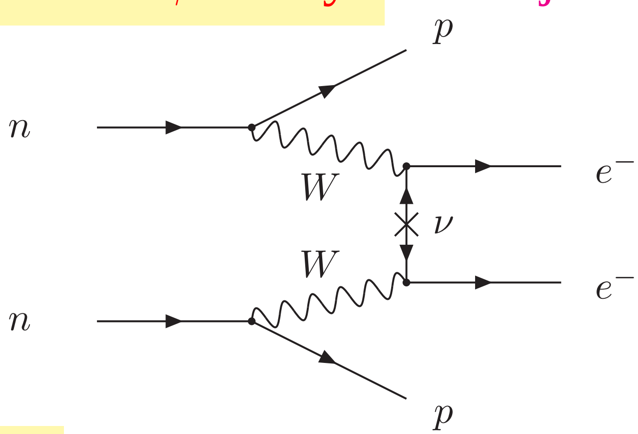
Single β decay: Dirac or Majorana ν mass modify spectrum endpoint



$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2$$

ν-less Double-β decay: $\Leftrightarrow$ Majorana $\nu' s$ sensitive to Majorana phases

If m_ν only source of ΔL $\quad (T^{0\nu}_{1/2})^{-1} \propto (m_{ee})^2$



$$m_{ee} = |\sum U^2_{ej} m_j|$$

$$= \left| c_{13}^2 c_{12}^2 m_1 \, e^{i\eta_1} + c_{13}^2 s_{12}^2 m_2 \, e^{i\eta_2} + s_{13}^2 m_3 \, e^{-i\delta_{CP}} \right|$$

COSMO Neutrino mass (Dirac or Majorana) modify the growth of structures

$$\sum m_i$$

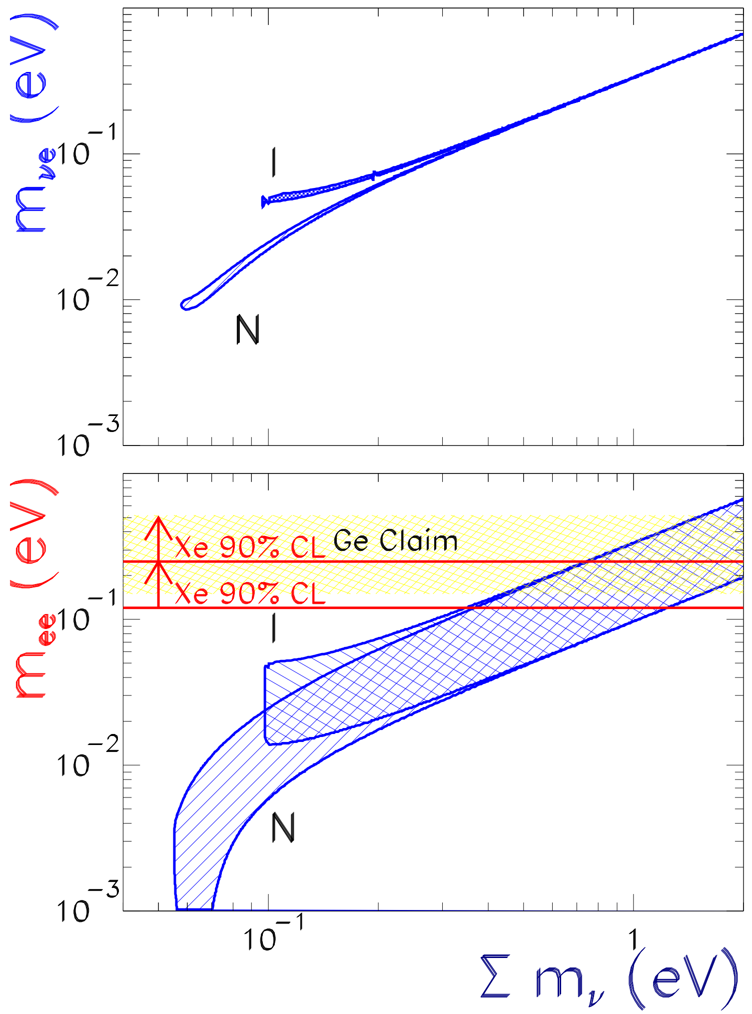
Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

$\Rightarrow$ Correlated ranges for m_{ν_e}, m_{ee} and $\sum m_\nu$

(Fogli *et al* (04))

Maltoni, Schwetz,Salvado, MCGG (95%)



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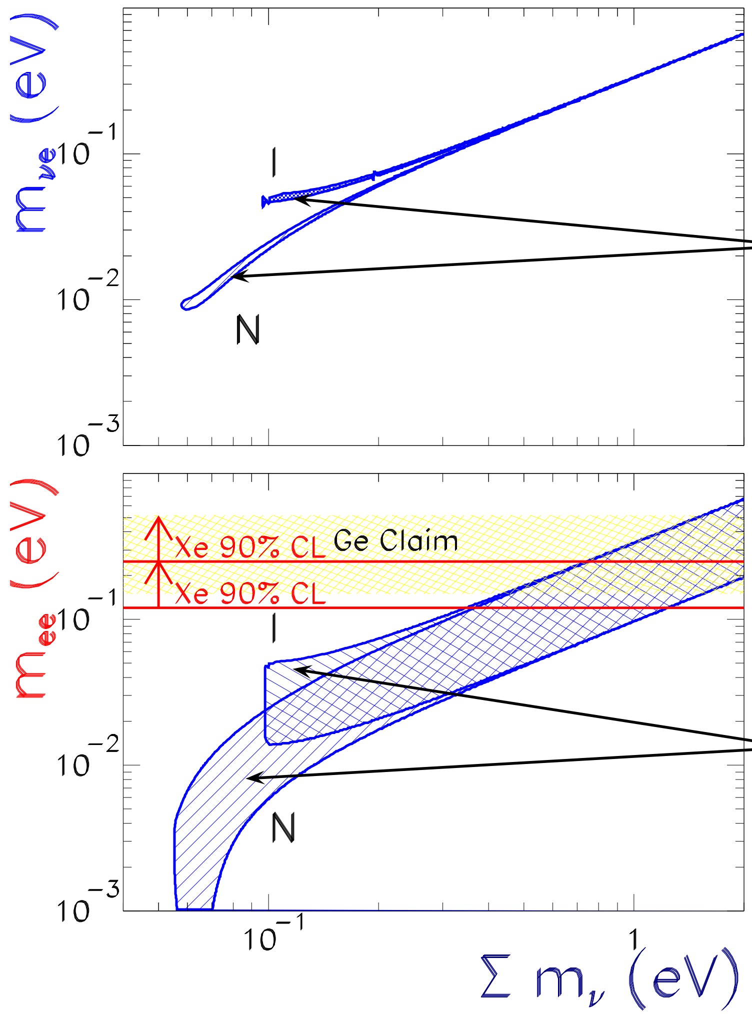

Width due to range in oscillation parameters very narrow

High precision determination of m_{ν_e} and $\sum m_i$ can give information on ordering

Wide band due to unknown Majorana phases

Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

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(Fogli *et al* hep-ph/0408045)

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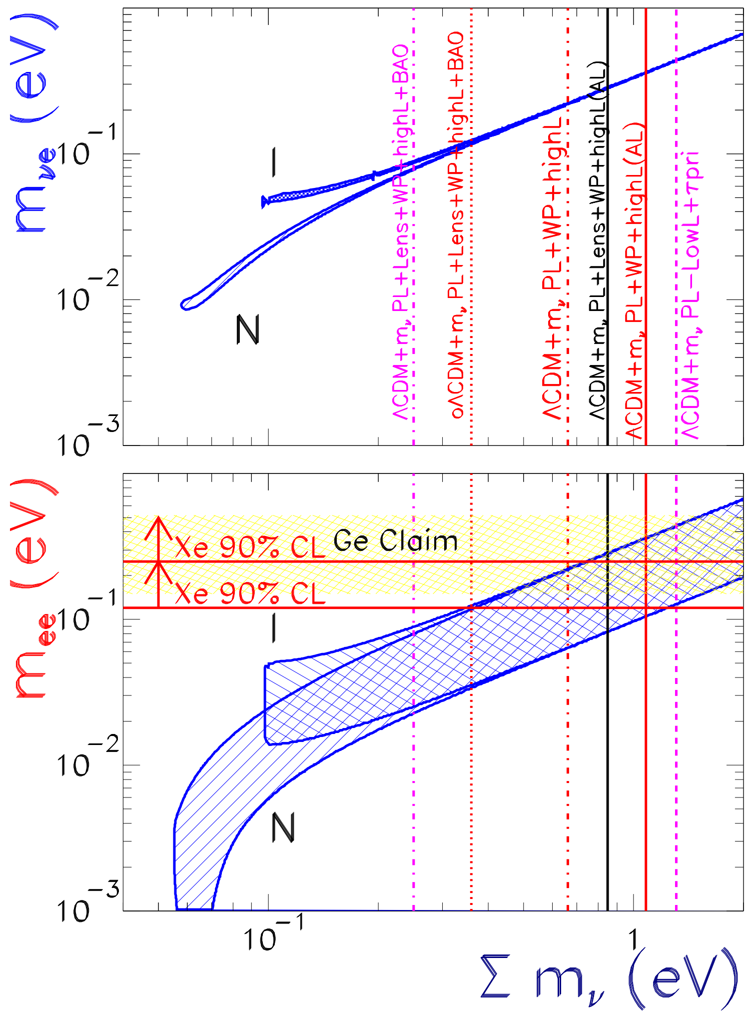


Analysis of Cosmological data

Bound on $\sum m_\nu$ changes with:
cosmo parameters fix in analysis
cosmo observables considered

Model	Observables	Σm_ν (eV) 95%
$\Lambda\text{CDM} + m_\nu$	Planck-lowL+τprior	≤ 1.31
$\Lambda\text{CDM} + m_\nu$	Planck+WP+highL(A_L)	≤ 1.08
$\Lambda\text{CDM} + m_\nu$	Planck+Lens+WP+highL(A_L)	≤ 0.85
$\Lambda\text{CDM} + m_\nu$	Planck+WP+highL	≤ 0.66
$o\Lambda\text{CDM} + m_\nu$	Planck+WP+highL	≤ 0.98
$\Lambda\text{CDM} + m_\nu$	Planck+Lens+WP+highL+BAO	≤ 0.25
$o\Lambda\text{CDM} + m_\nu$	Planck+Lens+WP+highL+BAO	≤ 0.36

Talk by M. Lattanzi

Light Sterile Neutrinos

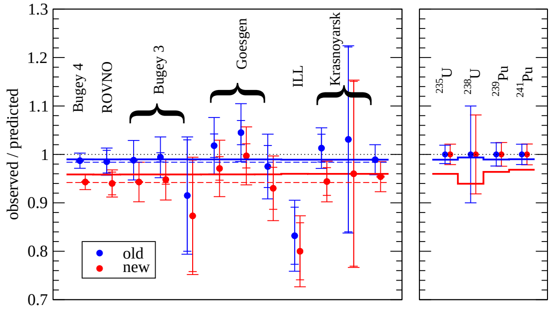
Concha Gonzalez-Garcia

- Several Observations which can be Interpreted as Oscillations with $\Delta m^2 \sim \text{eV}^2$

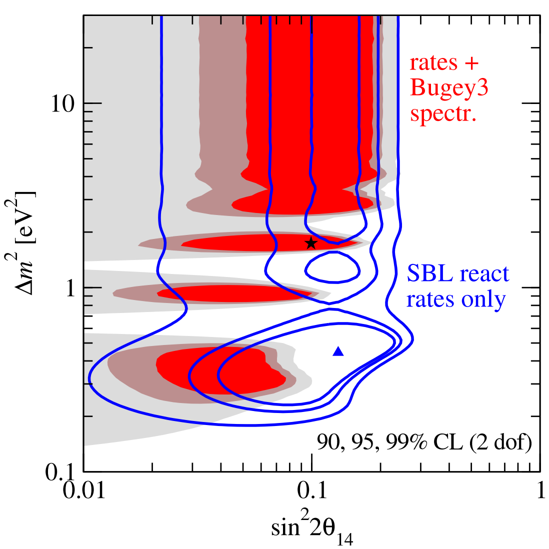
Reactor Anomaly

New reactor flux calculation

$\Rightarrow$ Deficit in data at $L \lesssim 100$ m



Explained as ν_e disappearance



Kopp etal, ArXiv 1303.3011

Gallium Anomaly

Acero, Giunti, Laveder, 0711.4222
Giunti, Laveder,1006.3244

Radioactive Sources (^{51}Cr, ^{37}Ar)

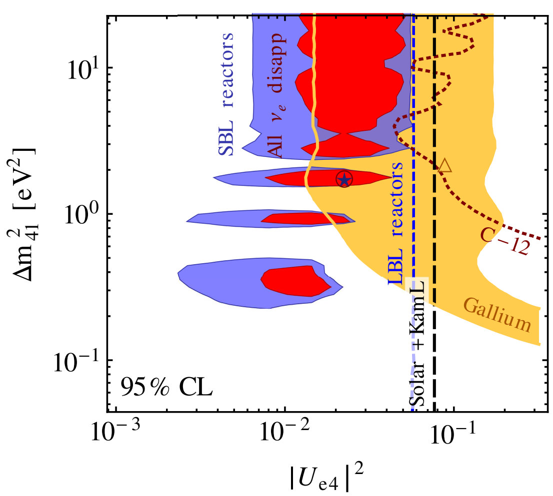
in callibration of Ga Solar Exp;

$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$

Give a rate lower than expected

$$R = \frac{N_{\text{obs}}}{N^{\text{th}}_{\text{Bahc}}} = 0.86 \pm 0.05 \ (2.8\sigma)$$

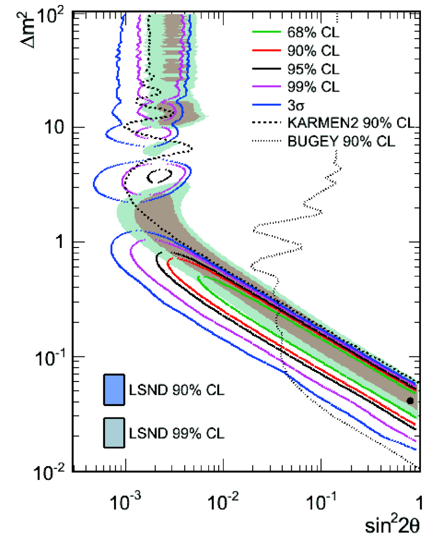
Explained as ν_e disappearance



Kopp etal, ArXiv 1303.3011

LSND, MiniBoone

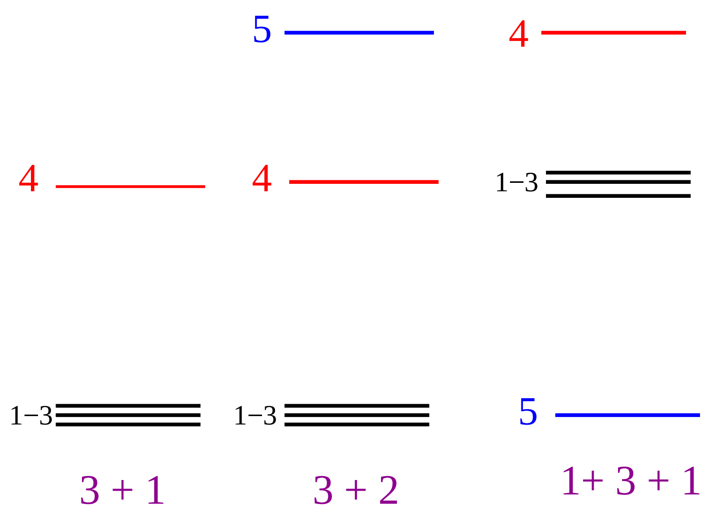
$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



Light Sterile Neutrinos

Concha Gonzalez-Garcia

- These explanations require 3+N_s mass eigenstates $\rightarrow$ N_s sterile neutrinos



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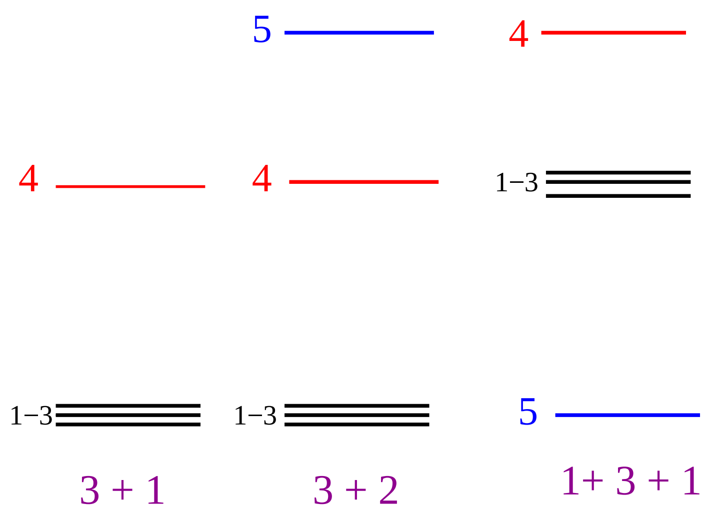


- Problem: fit together
  - $\nu_e \rightarrow \nu_e$ disapp (REACT,Gallium,Solar, LSND/KARMEN)
  - $\nu_\mu \rightarrow \nu_e$ app (LSND,KARMEN,NOMAD,MiniBooNE,E776,ICARUS)
  - $\nu_\mu \rightarrow \nu_\mu$ disapp (CDHS,ATM,MINOS,MiniBooNE)

- Generically: $P(\nu_e \rightarrow \nu_\mu) \sim |U^*_{ei} U_{\mu i}|$ [i =heavier state(s)]

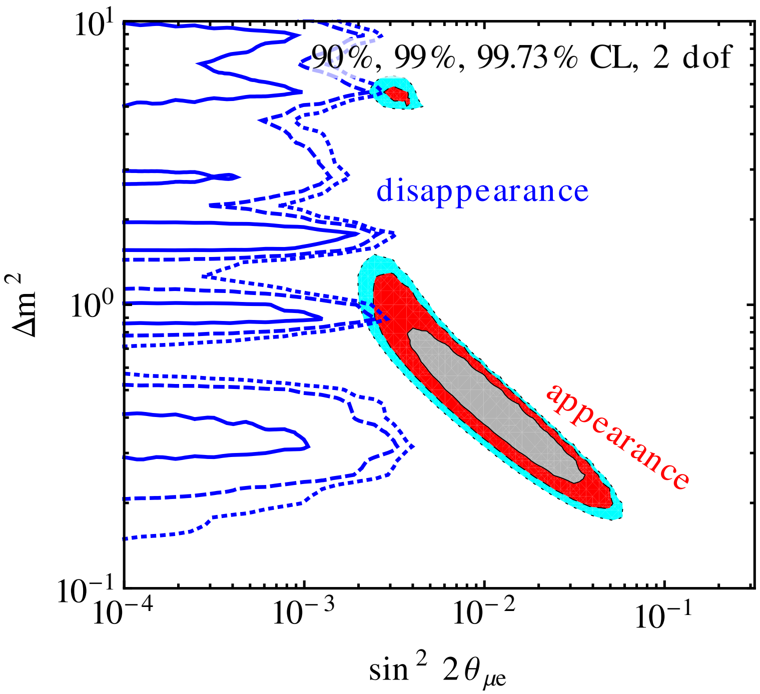
  But $|U_{ei}|$ constrained by $P(\nu_e \rightarrow \nu_e)$ disappearance data
  And $|U_{\mu i}|$ constrained by $P(\nu_\mu \rightarrow \nu_\mu)$ disappearance data
  $\Big\} \Rightarrow$ Severe tension

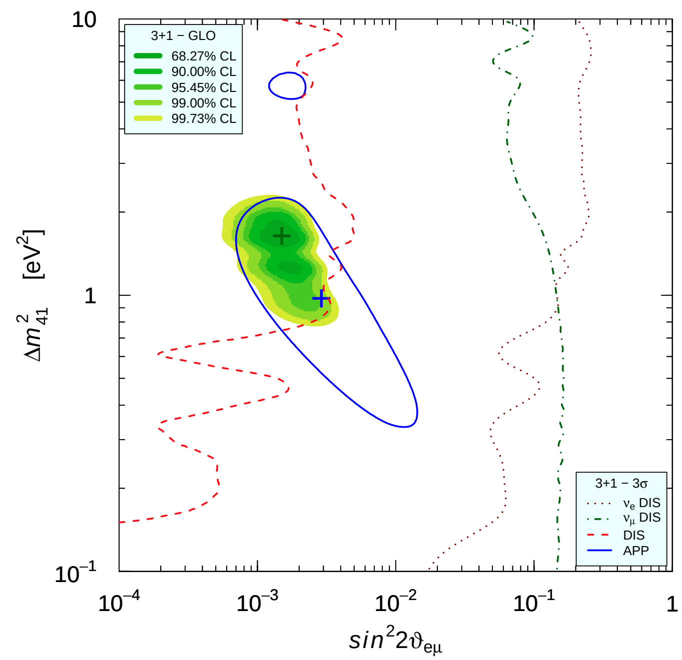
  Talk by J.Kopp

Light Sterile Neutrinos:3+1

- Comparing the parameters required to explain signals with bounds from dissap

Kopp etal, ArXiv 1303.3011 | Giunti etal, ArXiv 1308.5288





– Difference in the analysis of both appearance and dissapearance

– Somewhat different conclusions:

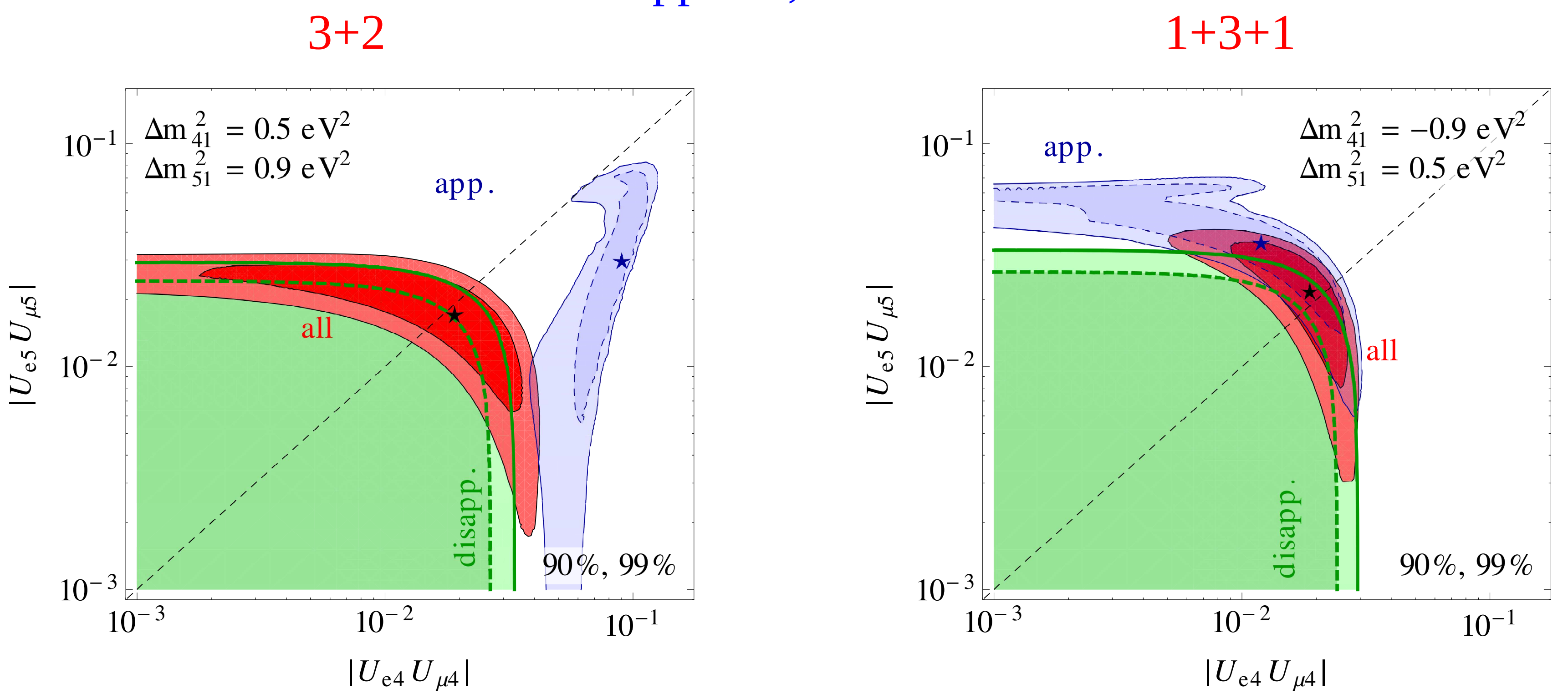
	$\chi^2_{\rm min}$/dof	$\chi^2_{\rm PG}$/dof	PG
K etal	712/(689 − 6)	18.0/2	1.2×10^{-4}
G etal LOW	291.7/(259 − 3)	12.7/2	2×10^{-3}

Light Sterile Neutrinos: Two Steriles

Gonzalez-Garcia

- Comparing the parameters required to explain signals with bounds from dissap

Kopp etal, ArXiv 1303.3011



	$\chi^2_{\rm min}$/dof	$\chi^2_{\rm PG}$/dof	PG
3+2	701/(689 − 14)	25.8/4	3.4×10^{-5}
1+3+1	694/(689 − 14)	16.8/4	2.1×10^{-3}

Also tension with cosmo bounds on dark radiation Talk by N Saviano

Determination of Matter Potential: Non Standard ν Int

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

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

- The most general matter potential can be parametrized

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

Deviations from $H^{\rm SM}_{\rm mat} = \sqrt{2}G_F N_e(r){\rm diag}(1,0,0)$ can be due to NSI

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

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

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

Matter Potential/NSI in ATM and LBL

- Weakest contraints when

2 equal eigenvalues of $H_{\rm mat}$
Friedland, Lunardini,Maltoni 04

- General parametrization for this case

$$H_{\rm mat} = Q_{\rm rel} U_{\rm mat} D_{\rm mat} U^\dagger_{\rm mat} Q^\dagger_{\rm rel}$$

$$\left\{ \begin{array}{ll} Q_{\rm rel} & = \mathrm{diag}\left(e^{i\alpha_1}, e^{i\alpha_2}, e^{-i\alpha_1 - i\alpha_2}\right), \\ U_{\rm mat} & = R_{12}(\varphi_{12})\, R_{13}(\varphi_{13}), \\ D_{\rm mat} & = \sqrt{2} G_F N_e(r) \mathrm{diag}(\varepsilon, 0, 0) \end{array} \right.$$

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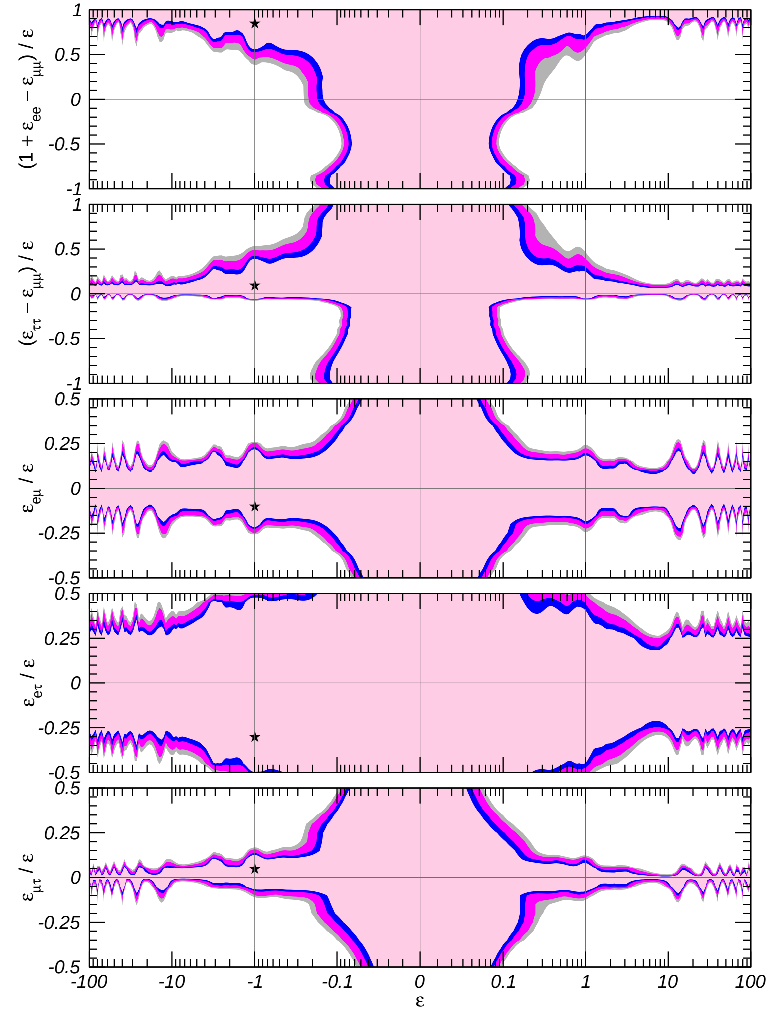
So

$$\begin{aligned} \varepsilon_{ee} - \varepsilon_{\mu\mu} &= \quad \varepsilon\, (\cos^2\varphi_{12} - \sin^2\varphi_{12}) \cos^2\varphi_{13} - 1 \\ \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} &= \quad \varepsilon\, (\sin^2\varphi_{13} - \sin^2\varphi_{12}\, \cos^2\varphi_{13}) \\ \varepsilon_{e\mu} &= -\varepsilon \cos\varphi_{12}\, \sin\varphi_{12}\, \cos^2\varphi_{13}\, e^{i(\alpha_1 - \alpha_2)} \\ \varepsilon_{e\tau} &= -\varepsilon \cos\varphi_{12}\, \cos\varphi_{13}\, \sin\varphi_{13}\, e^{i(2\alpha_1 + \alpha_2)} \\ \varepsilon_{\mu\tau} &= \quad \varepsilon \sin\varphi_{12}\, \cos\varphi_{13}\, \sin\varphi_{13}\, e^{i(\alpha_1 + 2\alpha_2)} \end{aligned}$$

No bound on ε from ATM+LBL



Maltoni, MCG-G, Salvado ArXiv:1103.4265

Matter Potential/NSI in Solar and KamLAND

- In $|\Delta m^2_{31}| \to \infty$: $P_{ee} = c^4_{13} P_{\rm eff} + s^4_{13}$

$$H^{\rm eff}_{\rm mat} = \sqrt{2} G_F N_e(r) \begin{pmatrix} c^2_{13} & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2} G_F \sum_f N_f(r) \begin{pmatrix} -\varepsilon^f_D & \varepsilon^f_N \\ \varepsilon^{f*}_N & \varepsilon^f_D \end{pmatrix}$$

$$\begin{aligned} \varepsilon^f_D &= c_{13} s_{13} \mathrm{Re}\left[e^{i\delta_{\rm CP}} \left(s_{23}\, \varepsilon^f_{e\mu} + c_{23}\, \varepsilon^f_{e\tau} \right) \right] \\ &- \left(1 + s^2_{13}\right) c_{23} s_{23} \mathrm{Re}\left(\varepsilon^f_{\mu\tau} \right) \\ &- \frac{c^2_{13}}{2} \left(\varepsilon^f_{ee} - \varepsilon^f_{\mu\mu} \right) \\ &+ \frac{s^2_{23} - s^2_{13} c^2_{23}}{2} \left(\varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu} \right) \end{aligned}$$

$$\begin{aligned} \varepsilon^f_N &= c_{13} \left(c_{23}\, \varepsilon^f_{e\mu} - s_{23}\, \varepsilon^f_{e\tau} \right) \\ &+ s_{13} e^{-i\delta_{\rm CP}} \left[s^2_{23}\, \varepsilon^f_{\mu\tau} - c^2_{23}\, \varepsilon^{f*}_{\mu\tau} \right. \\ &\left. + c_{23} s_{23} \left(\varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu} \right) \right] \end{aligned}$$

Matter Potential/NSI in Solar and KamLAND

z-Garcia

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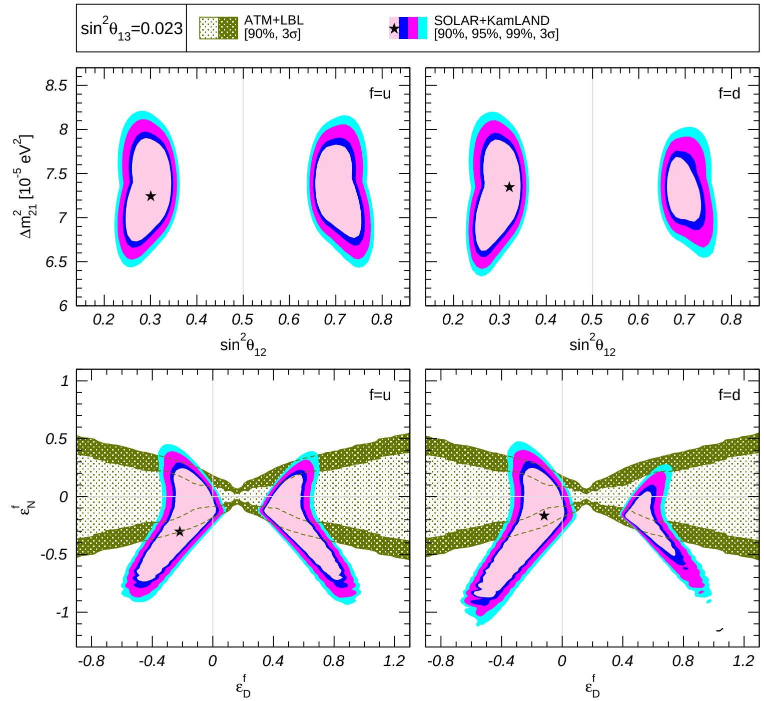
- LMA and LMA-D ($\theta_{12} > \frac{\pi}{4}$) allowed



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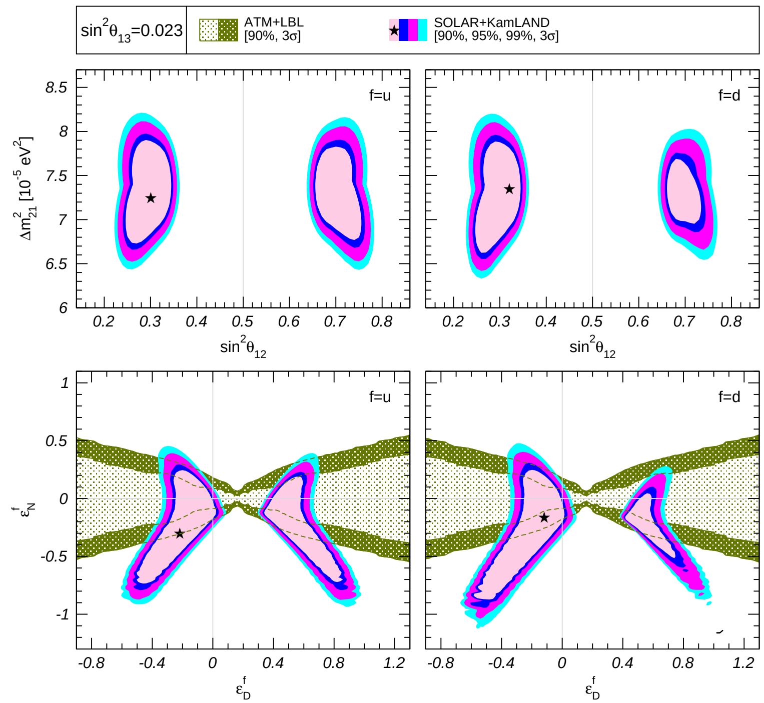
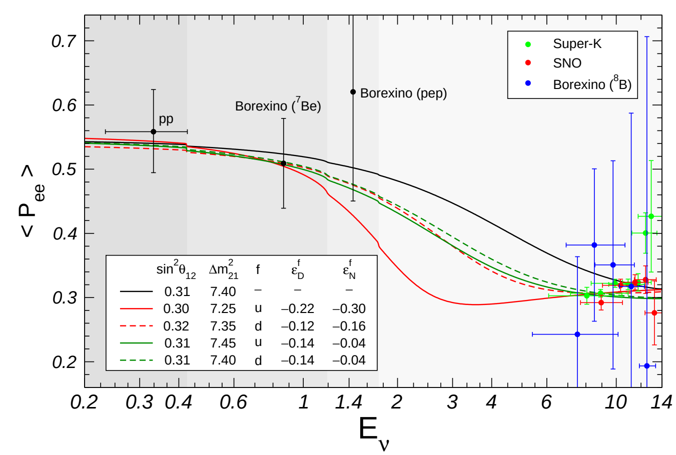


- Better fit with NSI ($\Delta\chi^2_{\rm OSC} \simeq 5$–$7$)

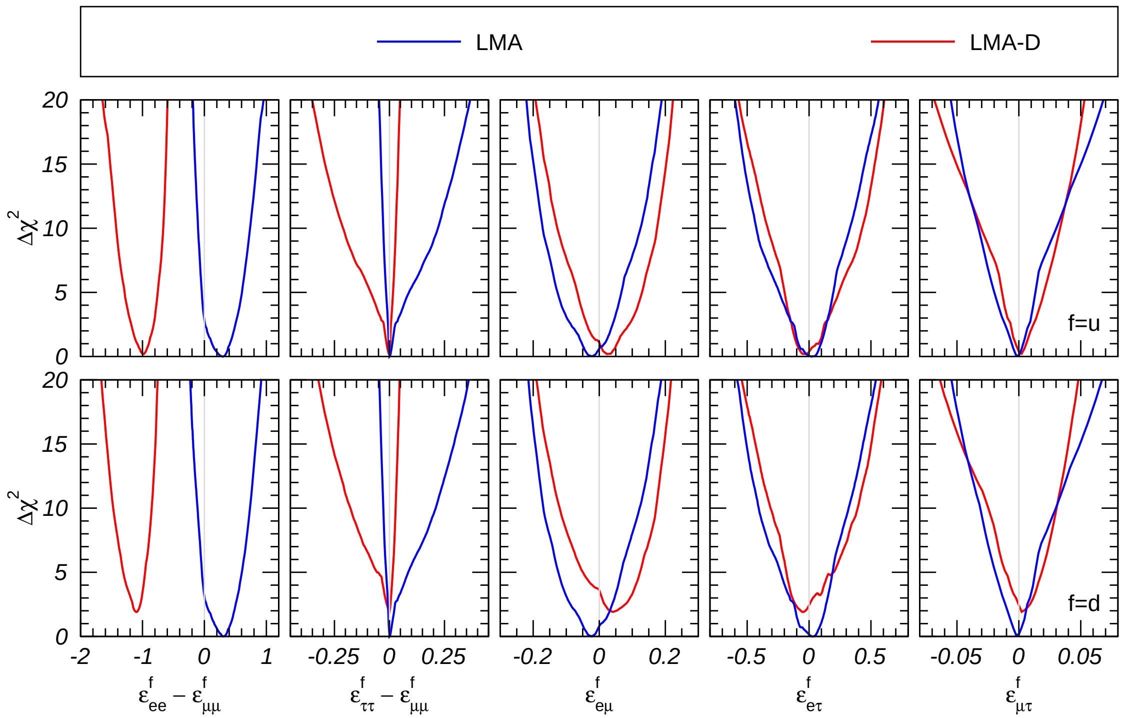


Due to no observation of MSW up-turn

Maltoni, MCG-G, Salvado ArXiv:1103.4265

Matter Potential/NSI: Global Analysis

- All parameter space of matter potential is bounded



Param.	90% CL OSC	90% CL SCATT
$\lvert\varepsilon^u_{ee}\rvert$	0.51–1.19	0.7–1
$\lvert\varepsilon^u_{\tau\tau}\rvert$	0.03	1.4–3
$\lvert\varepsilon^u_{e\mu}\rvert$	0.09	0.05
$\lvert\varepsilon^u_{e\tau}\rvert$	0.15	0.5
$\lvert\varepsilon^u_{\mu\tau}\rvert$	0.01	0.05

Param.	90% CL OSC	90% CL SCATT
$\lvert\varepsilon^d_{ee}\rvert$	0.51–1.17	0.3–0.7
$\lvert\varepsilon^d_{\tau\tau}\rvert$	0.03	1.1–6
$\lvert\varepsilon^d_{e\mu}\rvert$	0.09	0.05
$\lvert\varepsilon^d_{e\tau}\rvert$	0.14	0.5
$\lvert\varepsilon^d_{\mu\tau}\rvert$	0.01	0.05

Bounds from global osc fit stronger than scattering ones for $\varepsilon^{u,d}_{\tau\beta}$

Summary

- First TAUP with the three leptonic mixing angles determined (at $\pm 3\sigma/6$)

$$\Delta m^2_{21} = 7.44 \times 10^{-5}\ \text{eV}^2\ (2.3\%) \qquad \begin{matrix} \Delta m^2_{31} = 2.45 \times 10^{-3}\ \text{eV}^2 & \text{NO} \\ |\Delta m^2_{32}| = 2.43 \times 10^{-3}\ \text{eV}^2 & \text{IO} \end{matrix}\ (2.6\%)$$

$$\sin^2\theta_{12} = 0.3\ (4\%) \qquad \sin^2\theta_{23} = \begin{matrix} 0.59 & \text{IO} \\ 0.44 & \text{NO} \end{matrix}\ (8.2\%) \qquad \sin^2\theta_{13} = 0.023\ (9.6\%)$$

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Majorana or Dirac? θ_{23} Octant

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- Sterile ν's: Not satisfactory description of all LBL anomalies
- Purely empirical determination of matter potential

$\Rightarrow$ strongest constraints on vector NSI of ν_τ