GLOBAL ANALYSIS OF NEUTRINO OSCILLATION DATA

Concha Gonzalez-Garcia

(YITP Stony Brook & ICREA U. Barcelona)

Recent Developments in Neutrino Physics and Astrophysics

Gran Sasso, Sept 2017

http://www.nu-fit.org

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Determination of 3ν Lepton Flavour Parameters

Matter Potential/Non-standard Neutrino Interactions

Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

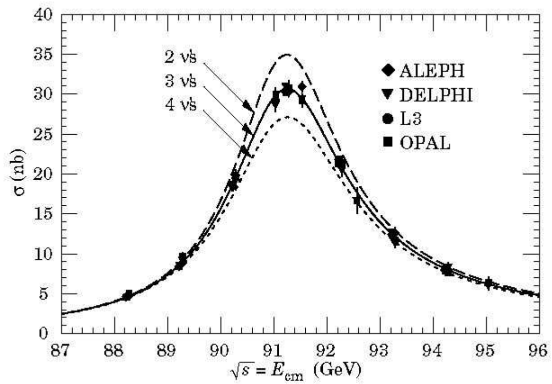
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

With three generation of fermions

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	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

Three and only three



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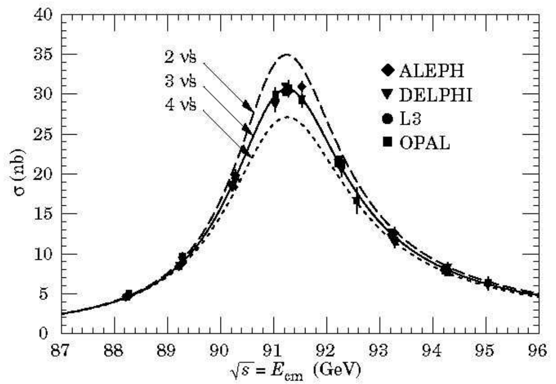

There is no ν_R

$\Downarrow$

Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$ (hence $L = L_e + L_\mu + L_\tau$)

$\Downarrow$

ν *strictly* massless

- By 2017 we have observed with high (or good) precision:

  - $*$ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS, ICECUBE)
  - $*$ Accel. ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NOνA**)
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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 allow for LFV $\Rightarrow$ 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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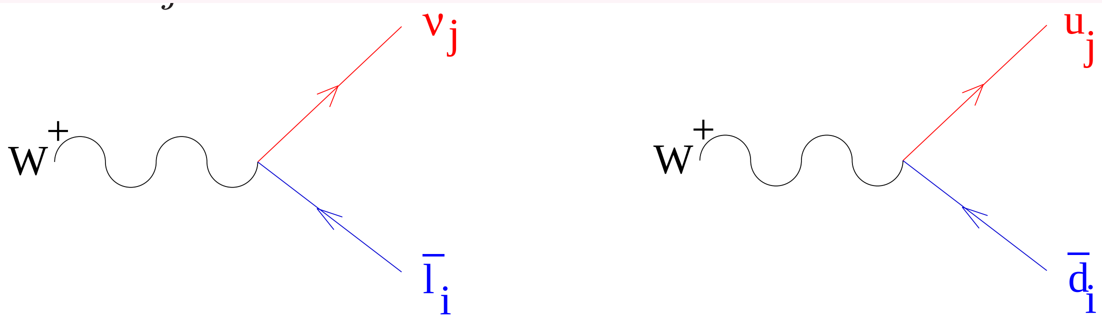
- The charged current interactions of leptons are not diagonal (same as quarks)

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



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

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

- $U_{\rm LEP}$: $3 + 3s$ angles + $2s + 1$ Dirac phases + $s + 2$ Majorana phases

ν Mass Oscillations in Vacuum

- 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

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

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

No information on ν mass scale nor Majorana versus Dirac

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- When osc between 2-ν dominates:

$$P_{\alpha\alpha} = 1 - P_{osc} \qquad \text{Disappear}$$

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

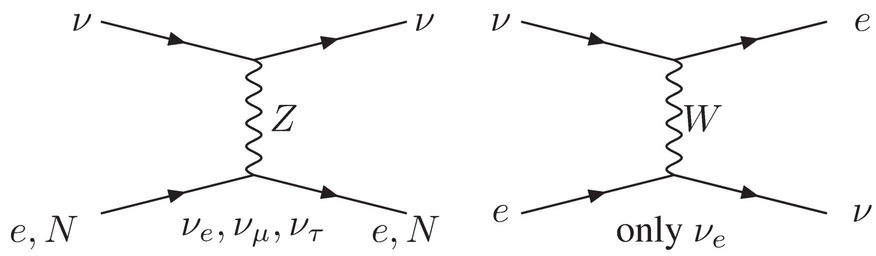
$\Rightarrow$ No info on sign of Δm^2 and θ octant

Matter Effects

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

  – But Different flavours

  have different interactions :



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

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

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

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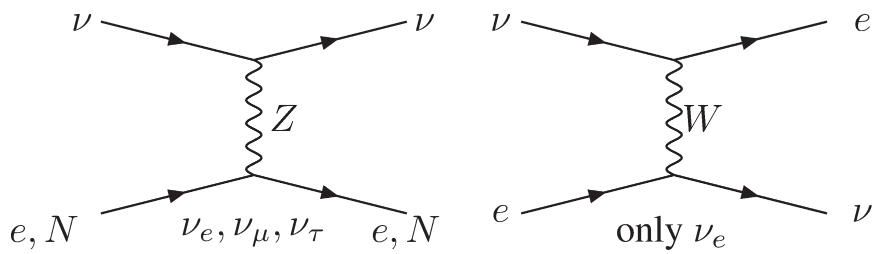

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$\Rightarrow$ *Modification of mixing angle and oscillation wavelength* (MSW)

- 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

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

Dependence on θ octant

$\Rightarrow$ In LBL terrestrial experiments

Dependence on sign of Δm^2

and θ octant

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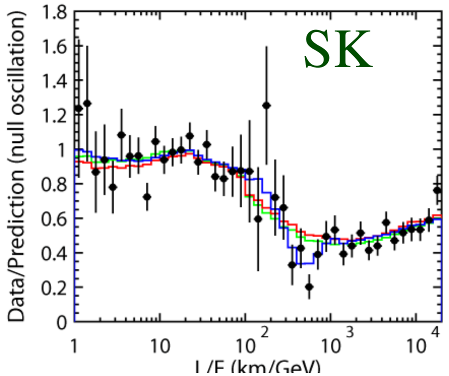
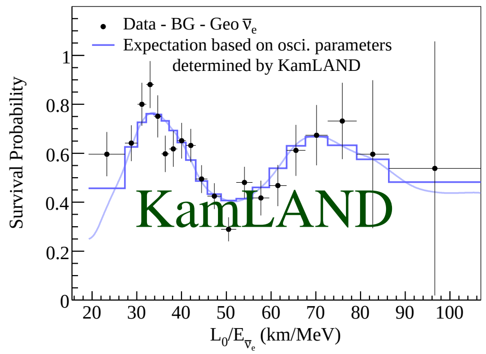
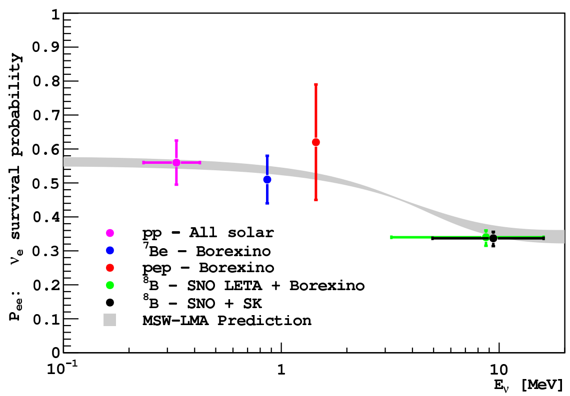
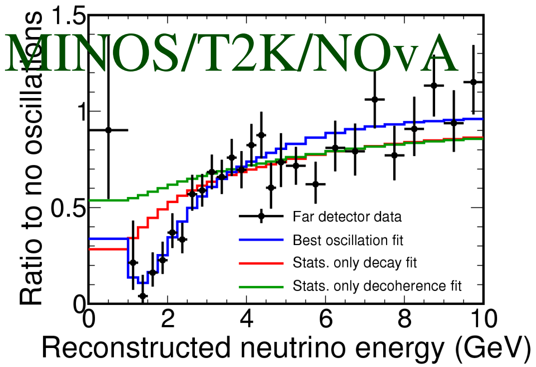
- Confirmed: Vacuum oscillation L/E pattern with 2 frequencies

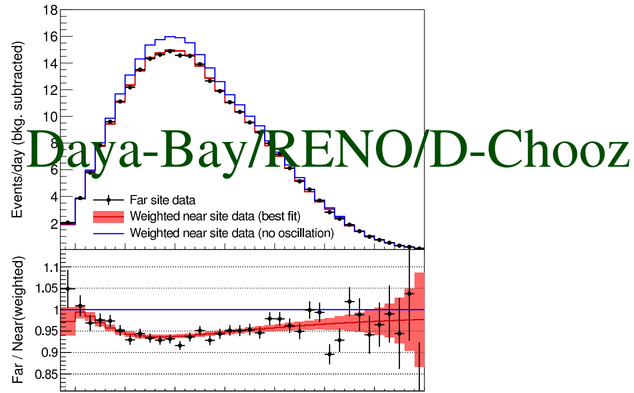
MSW conversion in Sun









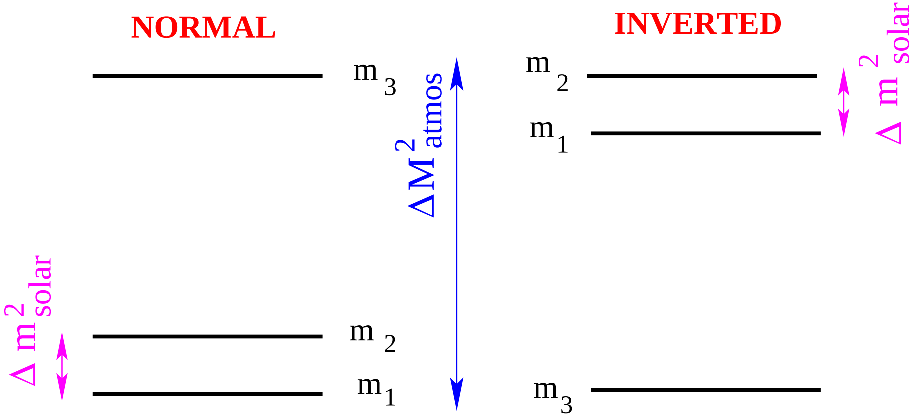


3ν Flavour Parameters

- 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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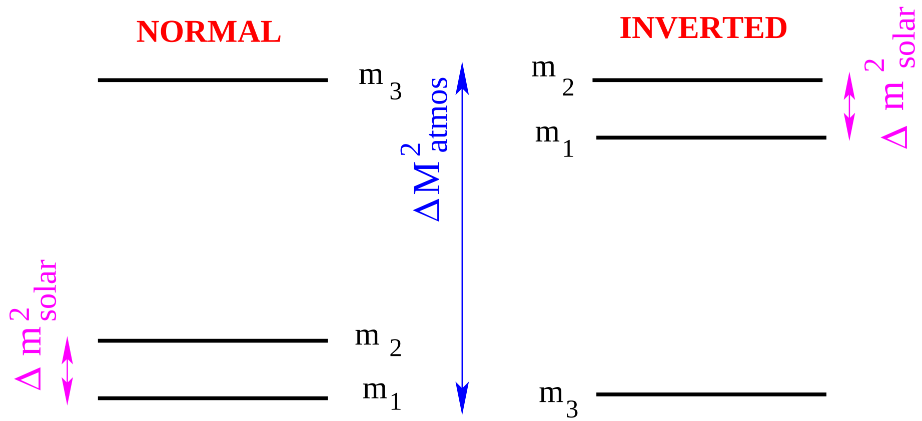
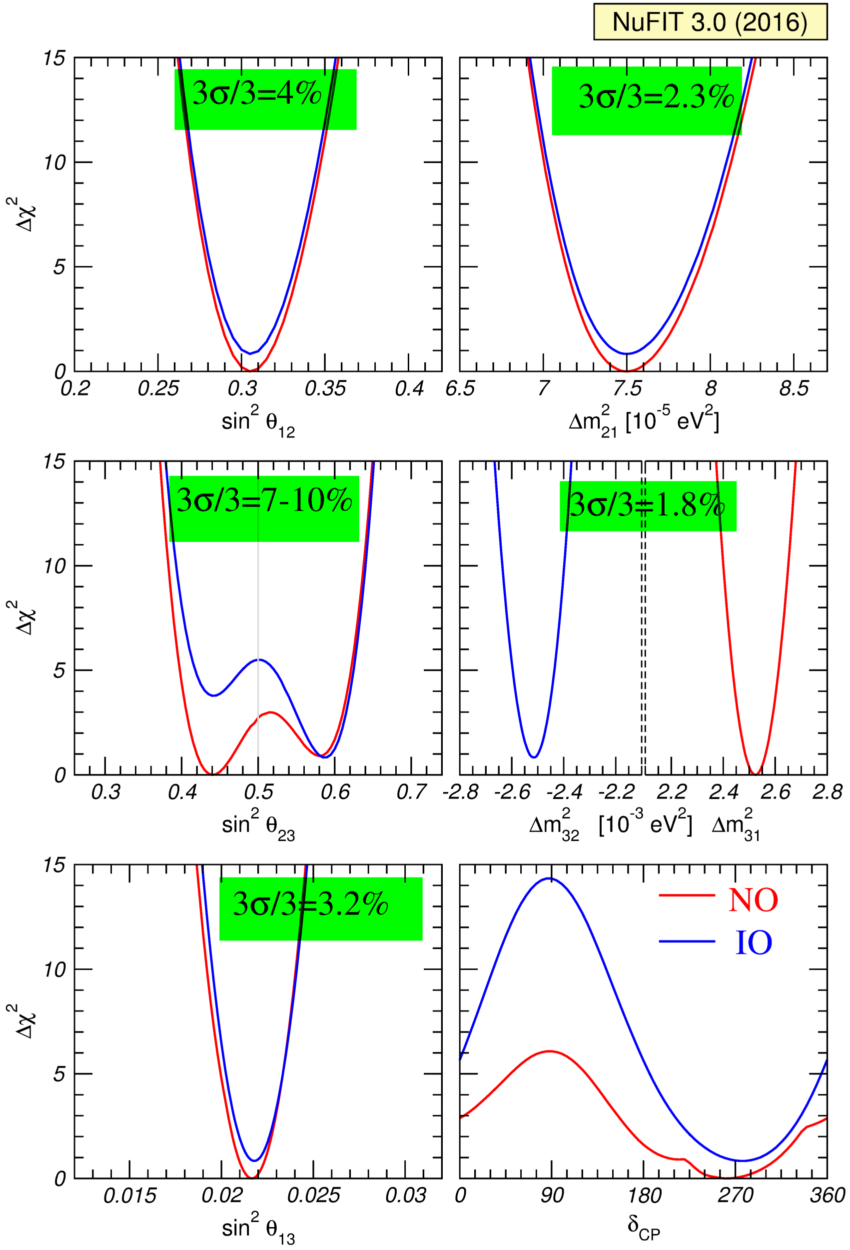


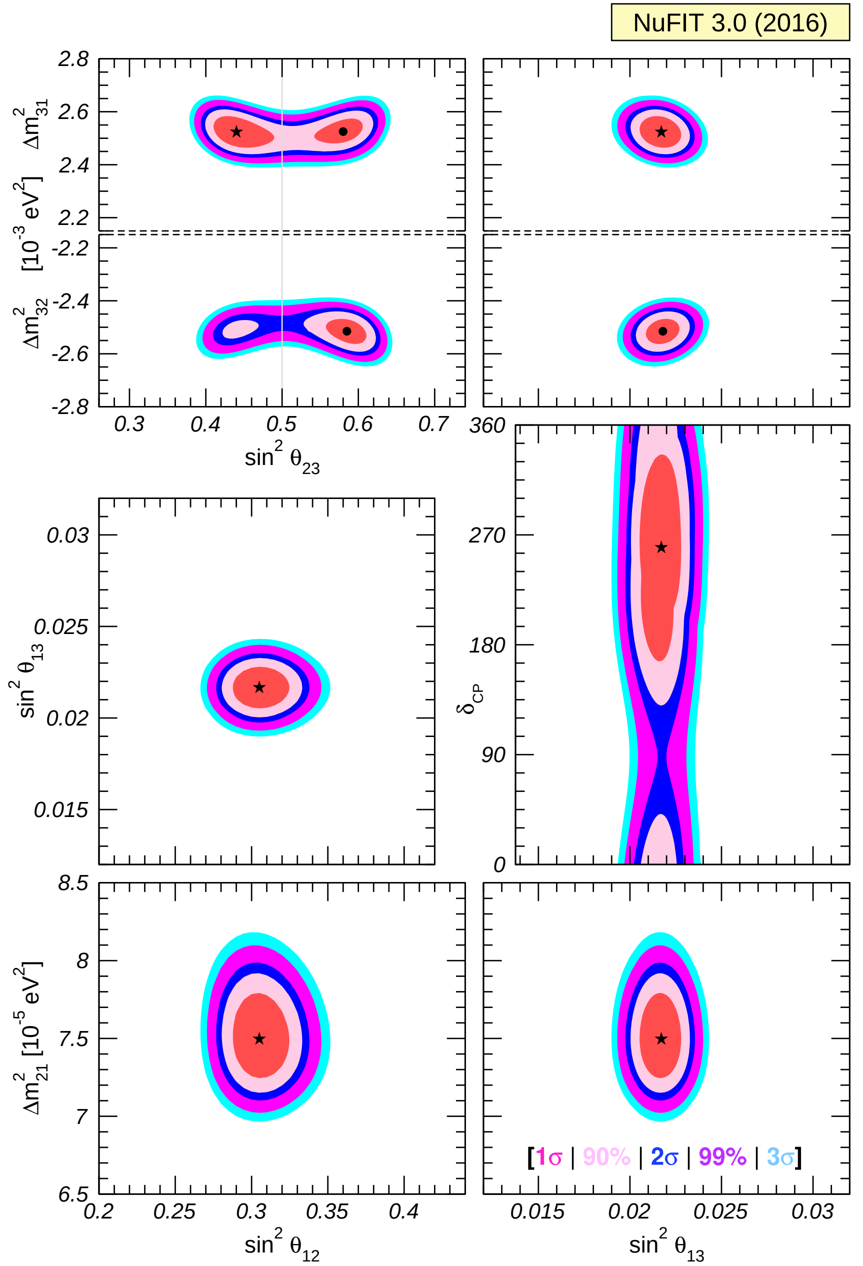
Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\to \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\to \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	$\to \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\to \theta_{23}$	$\Delta m^2_{\rm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

3 ν Flavour Parameters: Status Spring 2017

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

Esteban, Maltoni, Martinez-Soler, Schwetz, MCG-G ArXiv:1611:01514





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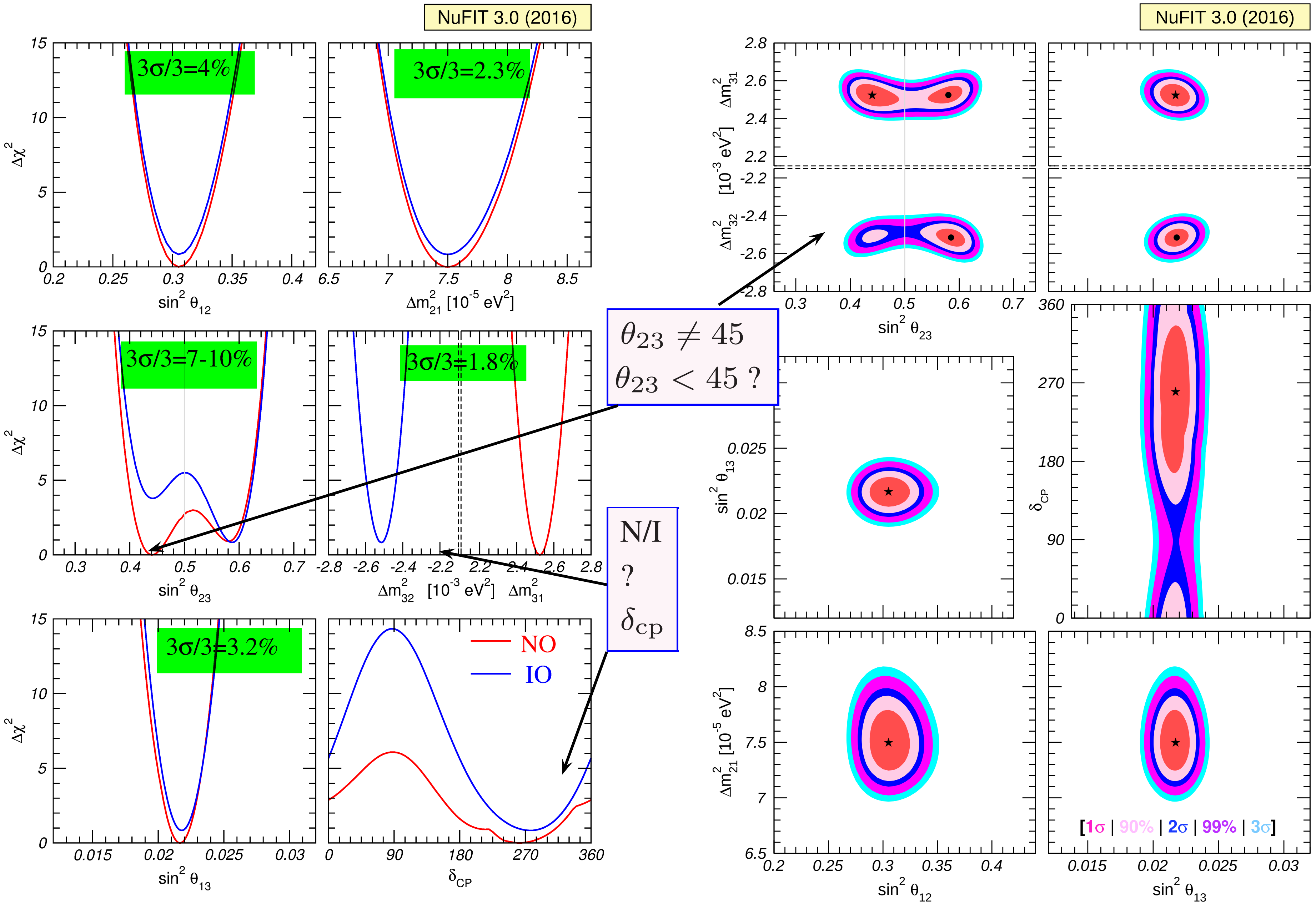

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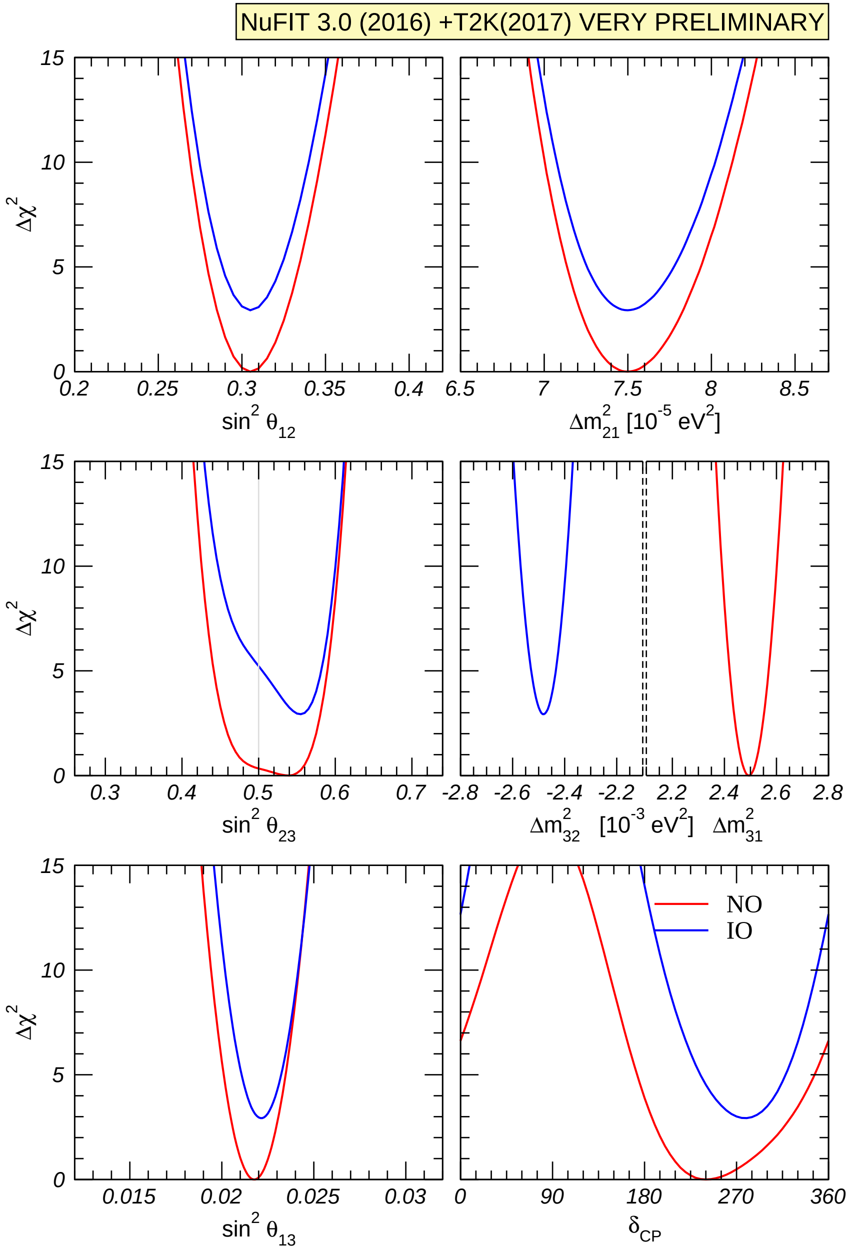
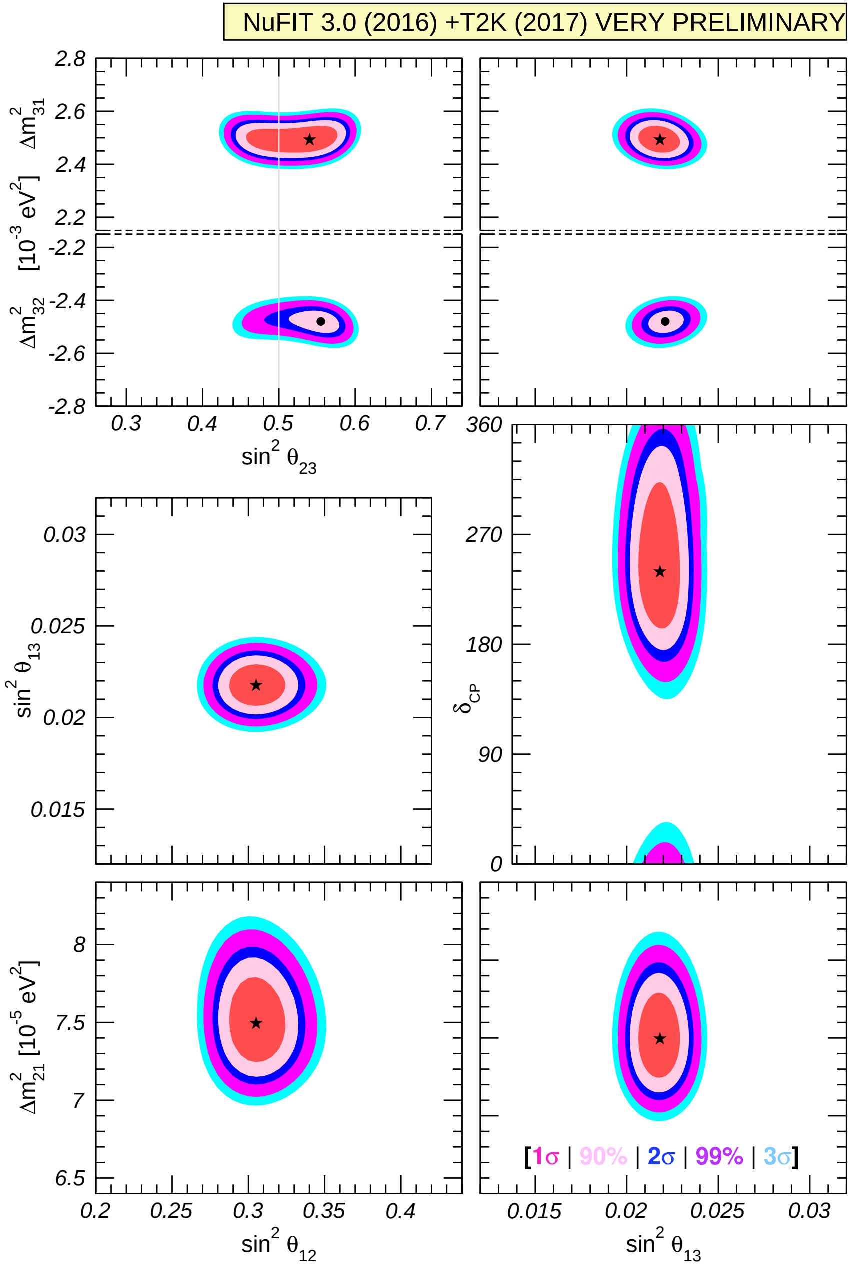
Esteban, Maltoni, Martinez-Soler, Schwetz, MCG-G effect OF T2K (2017) VERY PRELIMINARY





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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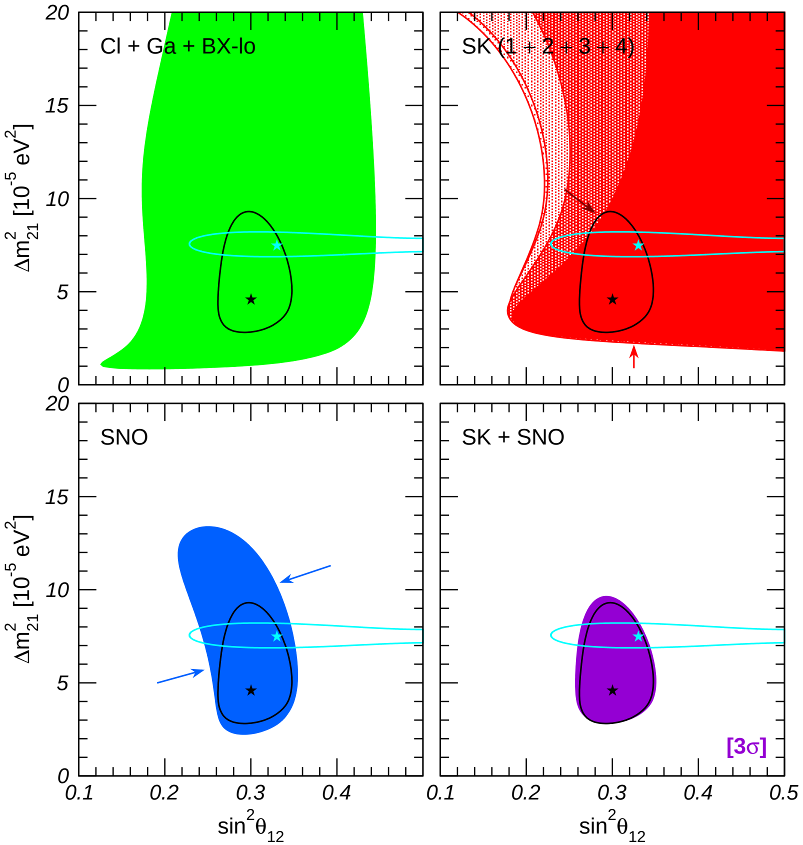
$*$ Solar region determined by High E data

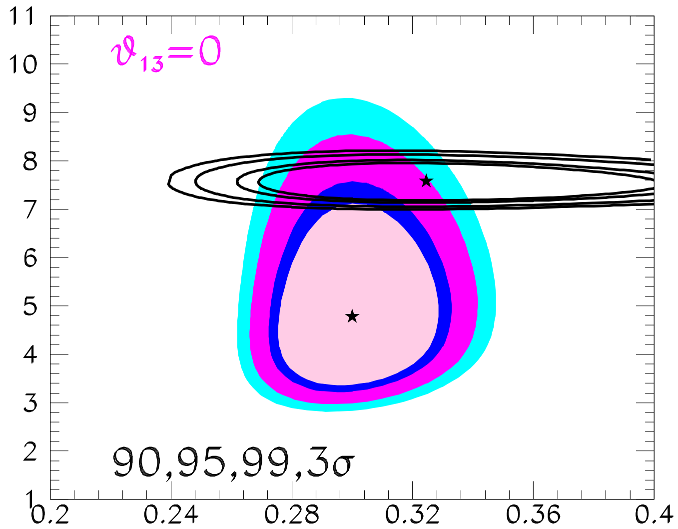
$*$ Param's $\begin{cases} \theta_{12} \text{ SNO most sensitivity} \\ \Delta m^2_{21} \text{ by KamLAND}\end{cases}$

With $\theta_{13} = 0$



3 ν Analysis: "12" Sector and θ_{13}

- For $\theta_{13} = 0$



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

- When θ_{13} increases

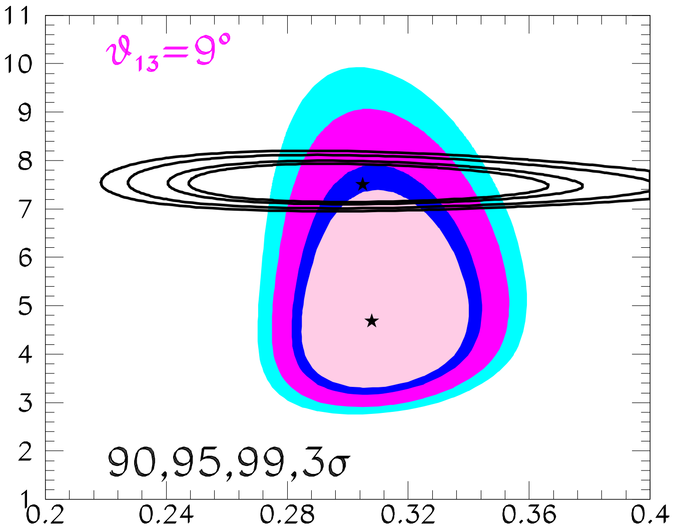
$$P_{ee} \simeq \begin{cases} \text{Solar High E}: c_{13}^4 \sin^2 2\theta_{12} \\ \text{Solar Low E}: c_{13}^4 \left(1 - \sin^2 2\theta_{12}/2\right) \\ \text{Kam}: c_{13}^4 \left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E}\right) \end{cases}$$

$\Rightarrow$ KamLAND region shifts left

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

3 ν Analysis: "12" Sector and θ_{13}

• For $\theta_{13} \simeq 9^\circ$



⇒ Good match of best fit θ_{12}

⇒ Residual tension on Δm^2_{21}

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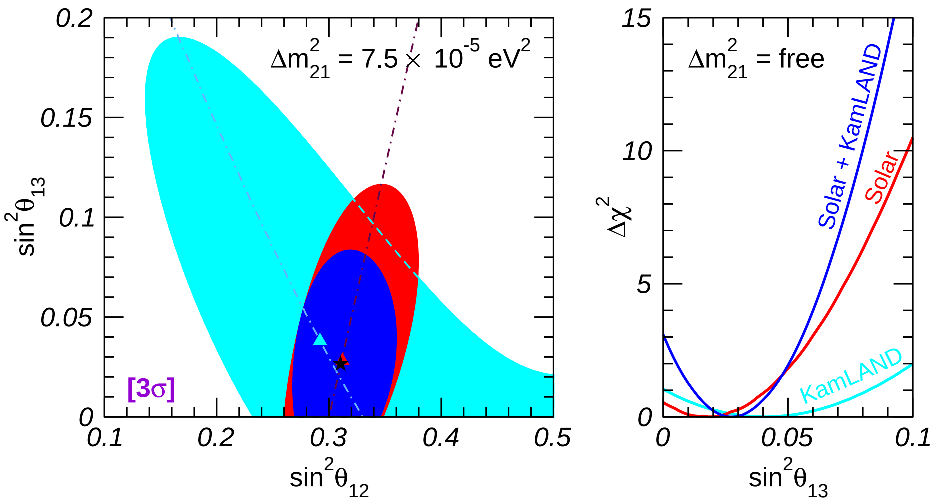
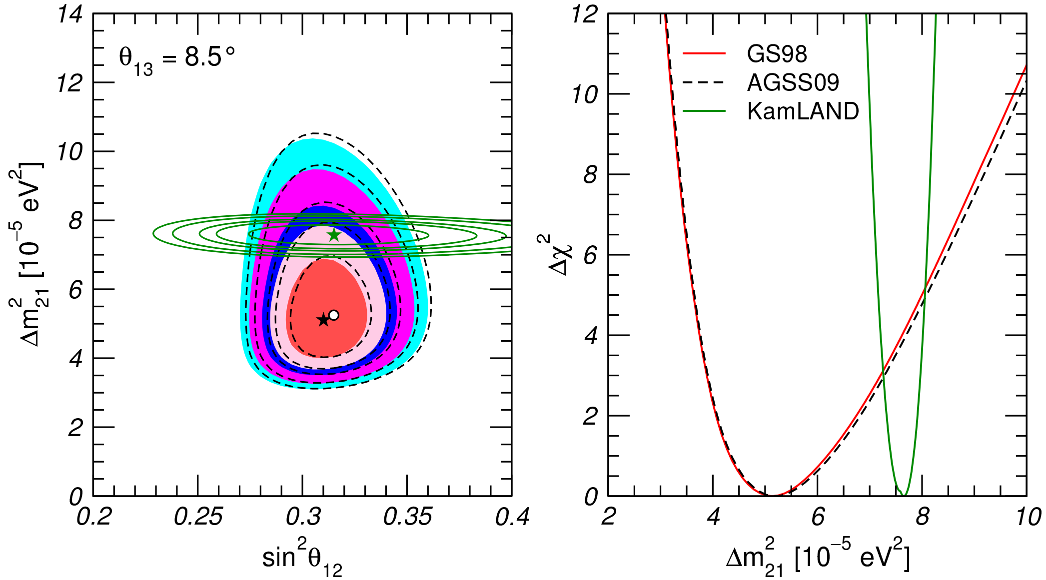


$3\ \nu$ Analysis: Δm^2_{21} KamLAND vs SOLAR

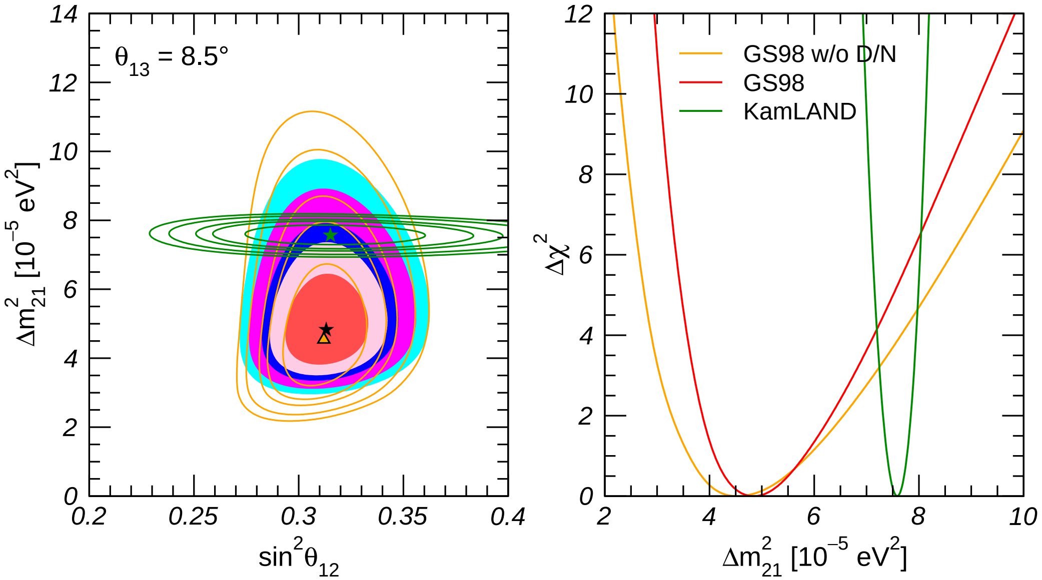
For $\theta_{13} \simeq 9^\circ$ θ_{12} OK. But residual tension on Δm^2_{12}

NuFIT 3.0 (2016)

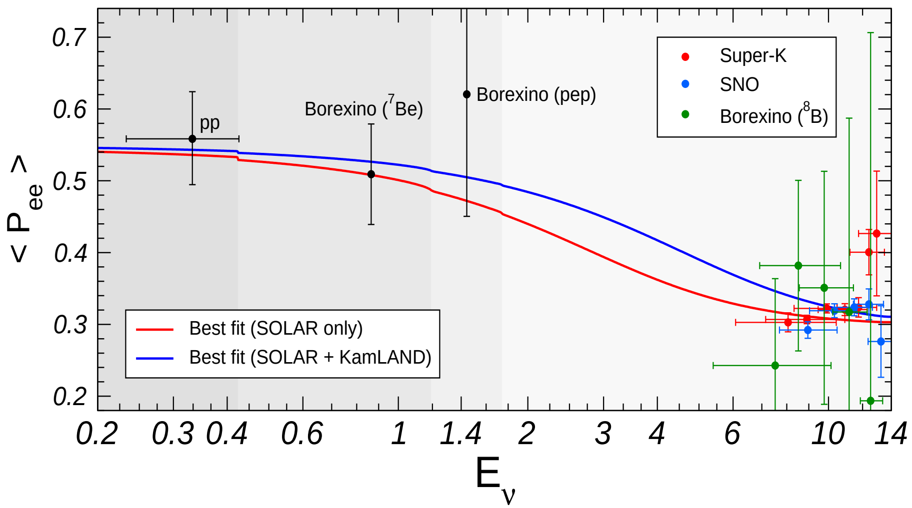


3 ν Analysis: Δm^2_{21} KamLAND vs SOLAR

For $\theta_{13} \simeq 9°$ θ_{12} OK. But residual tension on Δm^2_{12} NuFIT 2.1 (2016)



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? More latter …

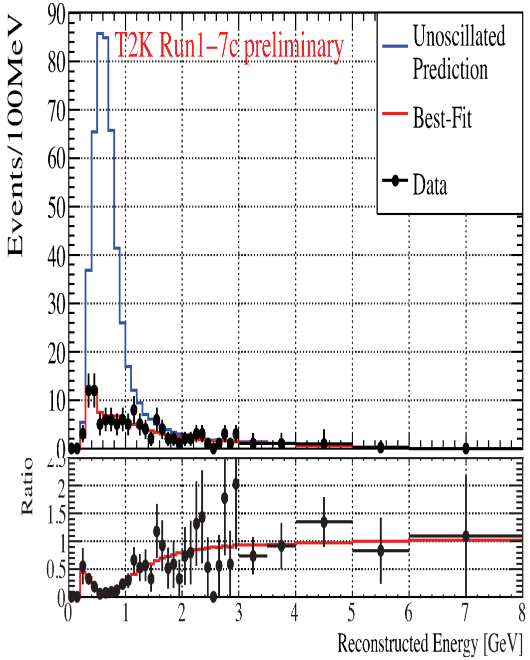
3 ν Analysis: θ_{23}

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

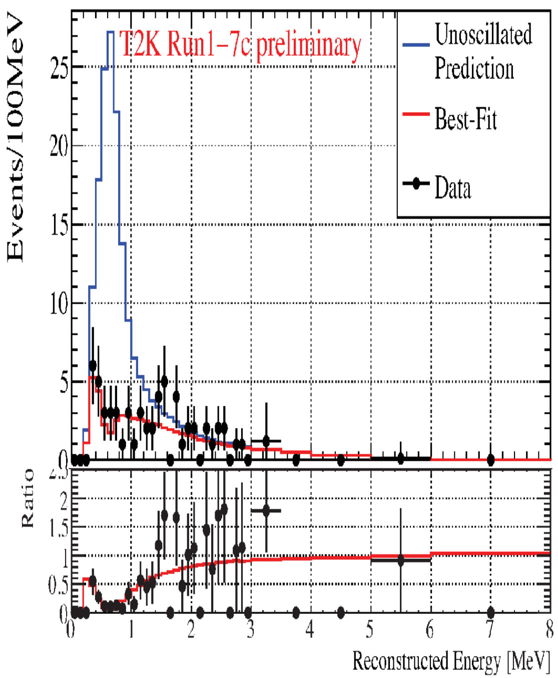
$$P_{\mu\mu} \simeq 1 - (c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \mathcal{O}(\Delta m^2_{21})$$

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

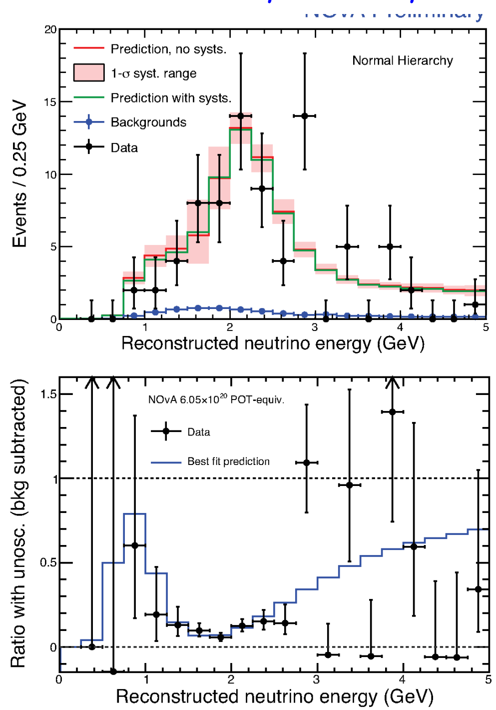
T2K $\nu_\mu \to \nu_\mu$



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



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

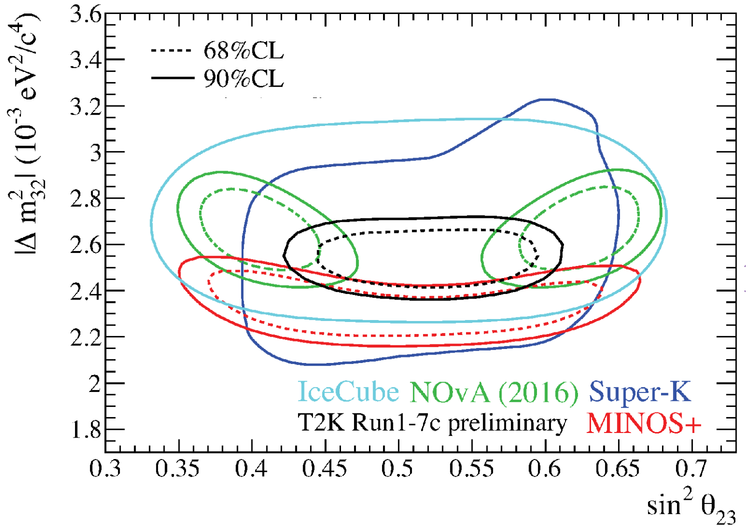


3 ν Analysis: θ_{23}

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

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

- 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)

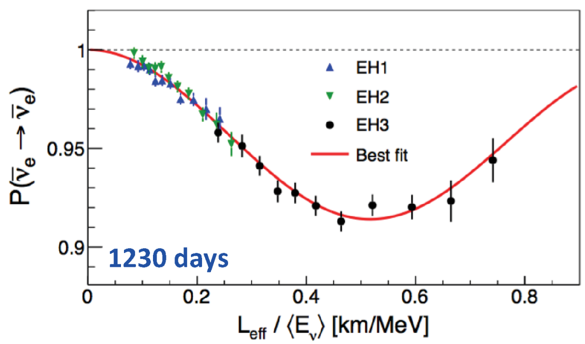
Δm^2_{23} in LBL vs Reactors

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

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



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

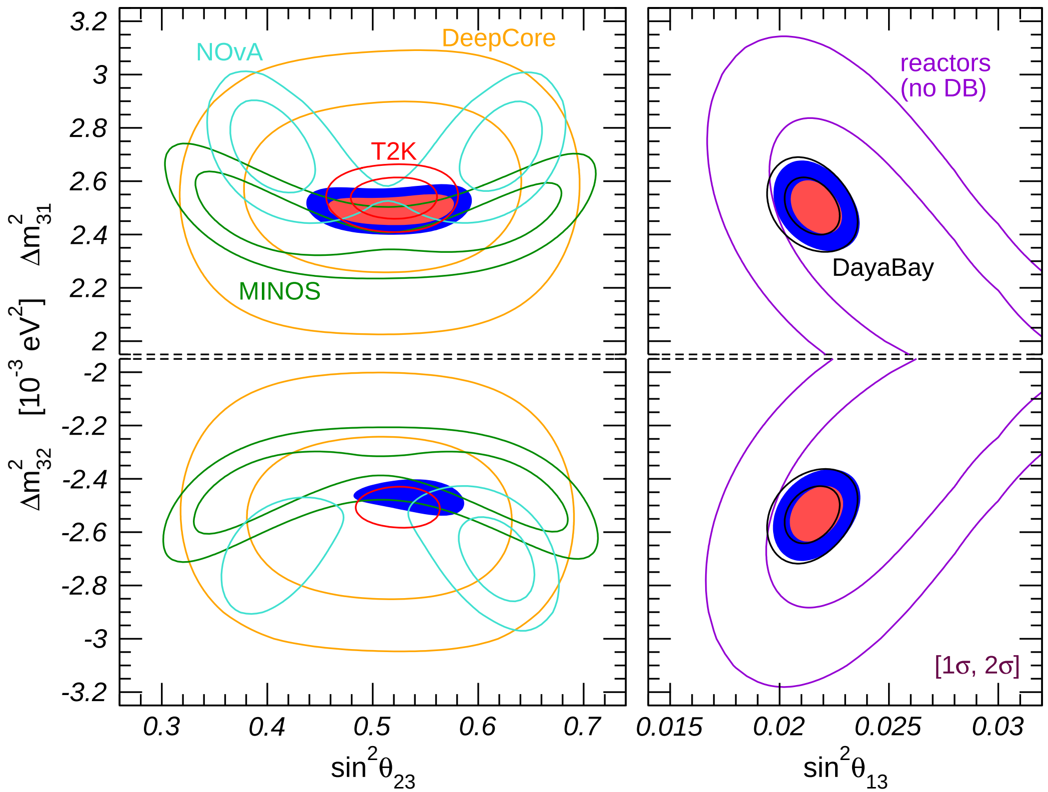
Nunokawa,Parke,Zukanovich (2005)

Δm^2_{23} in LBL vs Reactors: Consistency

- At LBL determined in ν_μ and $\bar{\nu}_\mu$ disappearance spectrum
- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar{\nu}_e$ disapp spectrum

LBL ν_μ disappearance REAC ν_e disappearance

Sept (2017) PRELIM



– Consistent values of $|\Delta m^2_{32}|$

– Hint for non-maximal θ_{23} driven by NOνA and MINOS

– T2K (2017) slight fav $\theta_{23} > 45$

3 ν Analysis: Reactor Flux anomaly and θ_{13}

- The reactor $\bar{\nu}_e$ fluxes was recalculated about 6 yrs ago

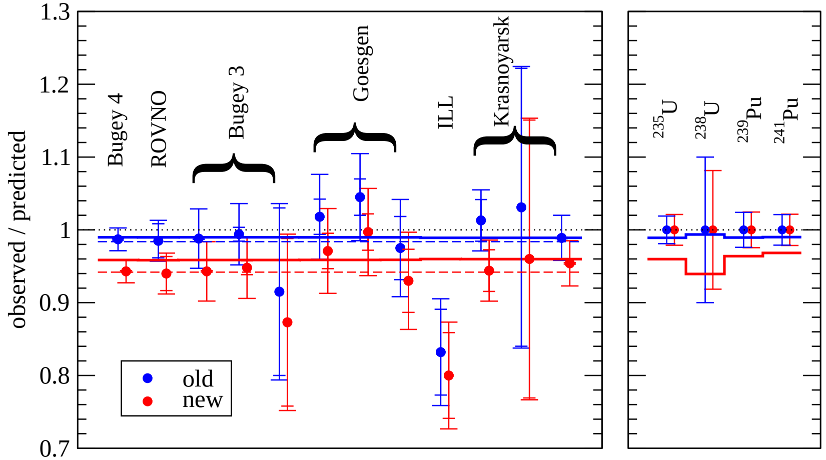
  T.A. Mueller et al.,[arXiv:1101.2663].;P. Huber, [arXiv:1106.0687].

- Both found higher fluxes ~ 3.5 %

$\Rightarrow$ *negative* reactor experiments

at short baselines (RSBL) indeed

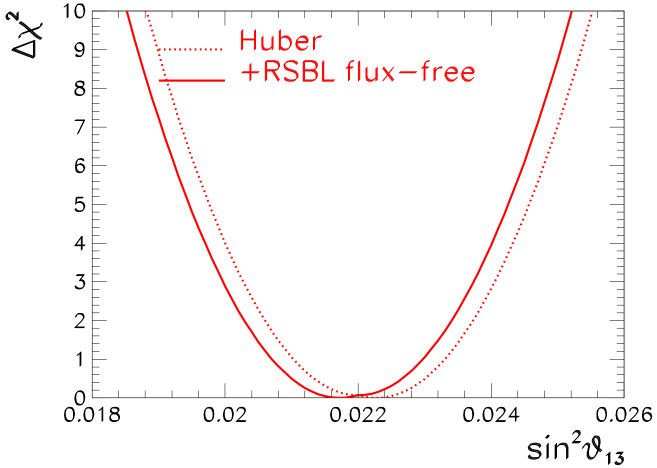
observed a deficit



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

Difference at $\lesssim 0.3\sigma$ level

$\chi^2_{min,a} - \chi^2_{min,b} \sim 7$



Leptonic CP Violation

- Leptonic $\not{C}$P $\Rightarrow P_{\nu_\alpha\to\nu_\beta} \neq P_{\bar\nu_\alpha\to\bar\nu_\beta}$:

$$P_{\nu_\alpha\to\nu_\beta} - P_{\bar\nu_\alpha\to\bar\nu_\beta} \propto J \quad \text{with} \quad J = \mathrm{Im}(U_{\alpha 1} U^*_{\alpha_2} U_{\beta 2} U^*_{\beta_1}) = J^{\max}_{\mathrm{LEP,CP}} \sin\delta_{\mathrm{CP}}$$

$$J^{\max}_{\mathrm{LEP,CP}} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$

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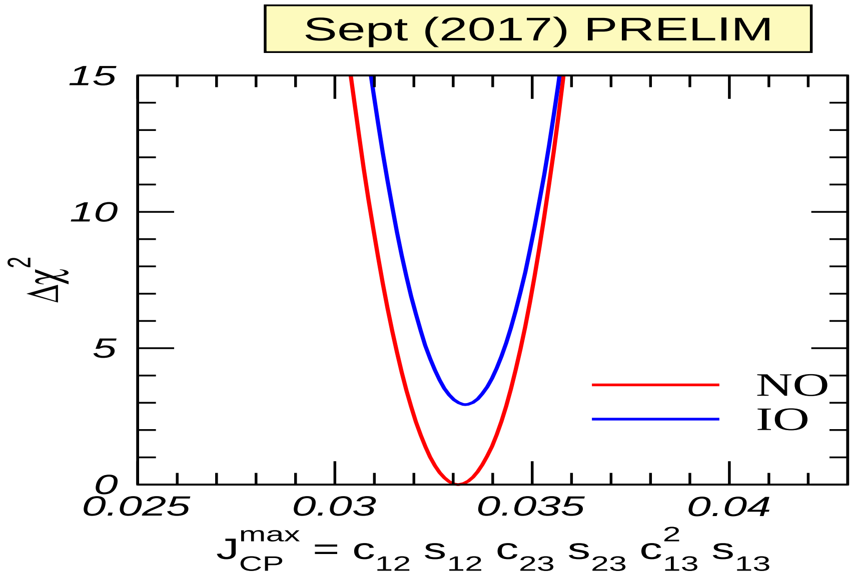
$$J^{\max}_{\text{LEP,CP}} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$

- Maximum Allowed Leptonic CPV:



$J^{\max}_{\text{LEP,CP}} = (3.29 \pm 0.07) \times 10^{-2}$

to compare with

$J_{\text{CKM,CP}} = (3.04 \pm 0.21) \times 10^{-5}$

$\Rightarrow$ Leptonic CPV may be largest CPV in New Minimal SM

if $\sin \delta_{\text{CP}}$ not too small

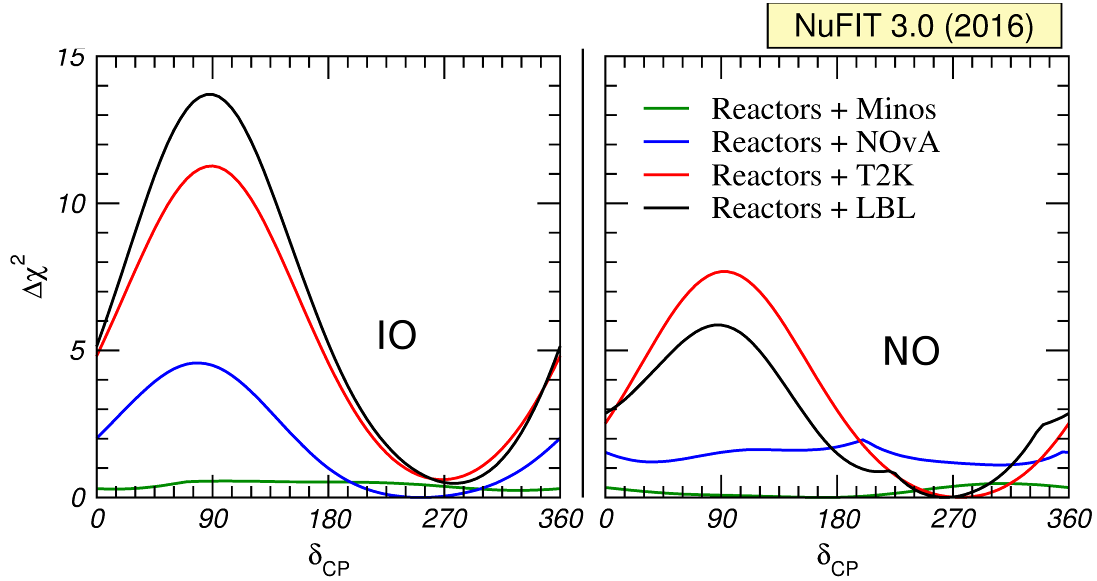
Leptonic CP Phase

- Leptonic CPV Phase: Mainly from $\nu_\mu \to \nu_e$ in LBL (complicated by matter effects)

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

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad J_{\rm LEP,CP}^{\rm max} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$

Before T2K (2017)



– Best fit $\delta_{\rm CP} \sim 270°$

– CP conserv at 70% (NO), 97% (IO)

– Driven by "fluctuation" in T2K

	ν_e		$\bar{\nu}_e$	
Mass hierarchy	Normal	Inverted	Normal	Inverted
$\delta_{CP} = -\pi/2$	28.8	25.5	6.0	6.5
$\delta_{CP} = 0$	24.2	21.2	6.9	7.4
$\delta_{CP} = \pi/2$	19.7	17.2	7.7	8.4
$\delta_{CP} = \pm\pi$	24.2	21.6	6.8	7.4
Data	32		4	

$\Rightarrow$ One concluded :

Significance may not grow soon

Leptonic CP Phase:T2K 2017

Accumulated **14.7x10^{20}** protons-on-target (POT) in neutrino mode and **7.6x10^{20}** POT in antineutrino mode - full data set presented here

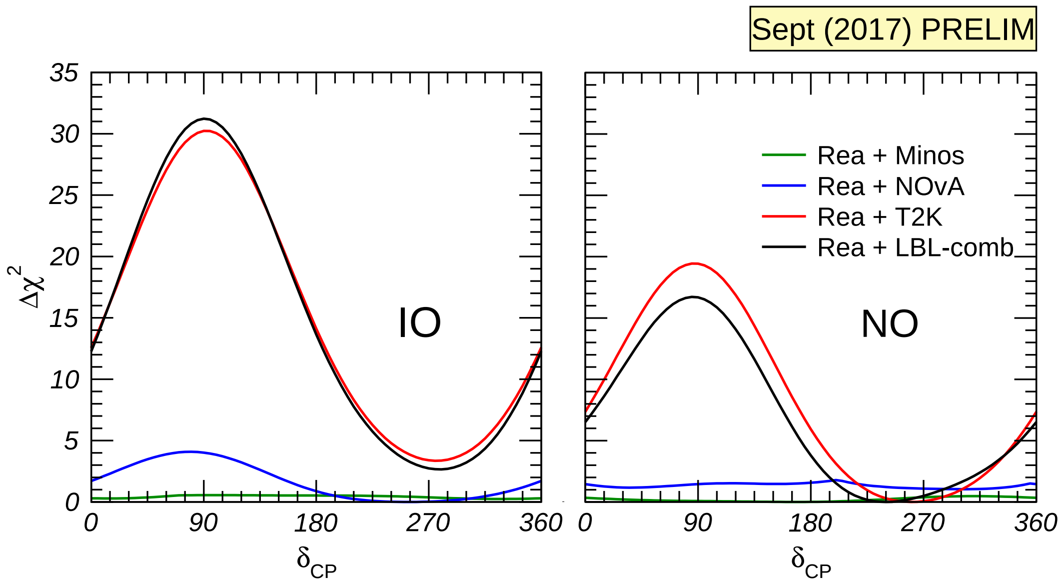
➤ **29% of the approved** T2K POT

	Sample	Predicted Rates δ_{cp}=-π/2	Predicted Rates δ_{cp}=0	Predicted Rates δ_{cp}=π/2	Predicted Rates δ_{cp}=π	Observed Rates
ν_e	CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
ν_e	CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
$\overline{\nu_e}$	CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
ν_μ	CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
$\overline{\nu_\mu}$	CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68

M. Hartz, KeK colloquim, August 2017

Leptonic CP Phase

Including T2K (2017) PRELIMINARY



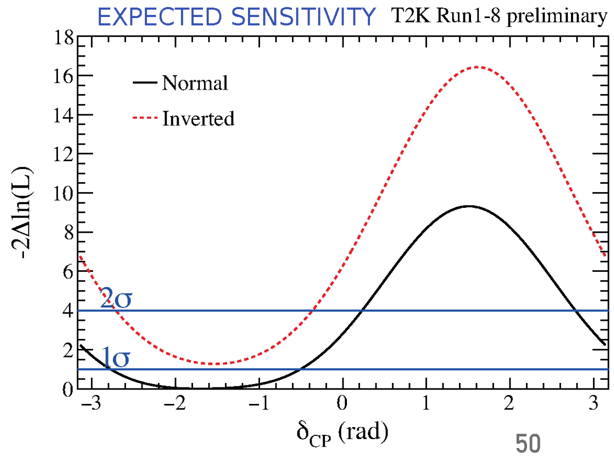
– Best fit at $\delta_{\rm CP} \sim 240°$

– CP conserv at 95% (NO)

– 15°–160° disfavoured at $\Delta\chi^2 > 9$

– Sill more than expected sensitiv in T2K

$-\chi^2_{\rm min,IO} - \chi^2_{\rm min,NO} \simeq 3$



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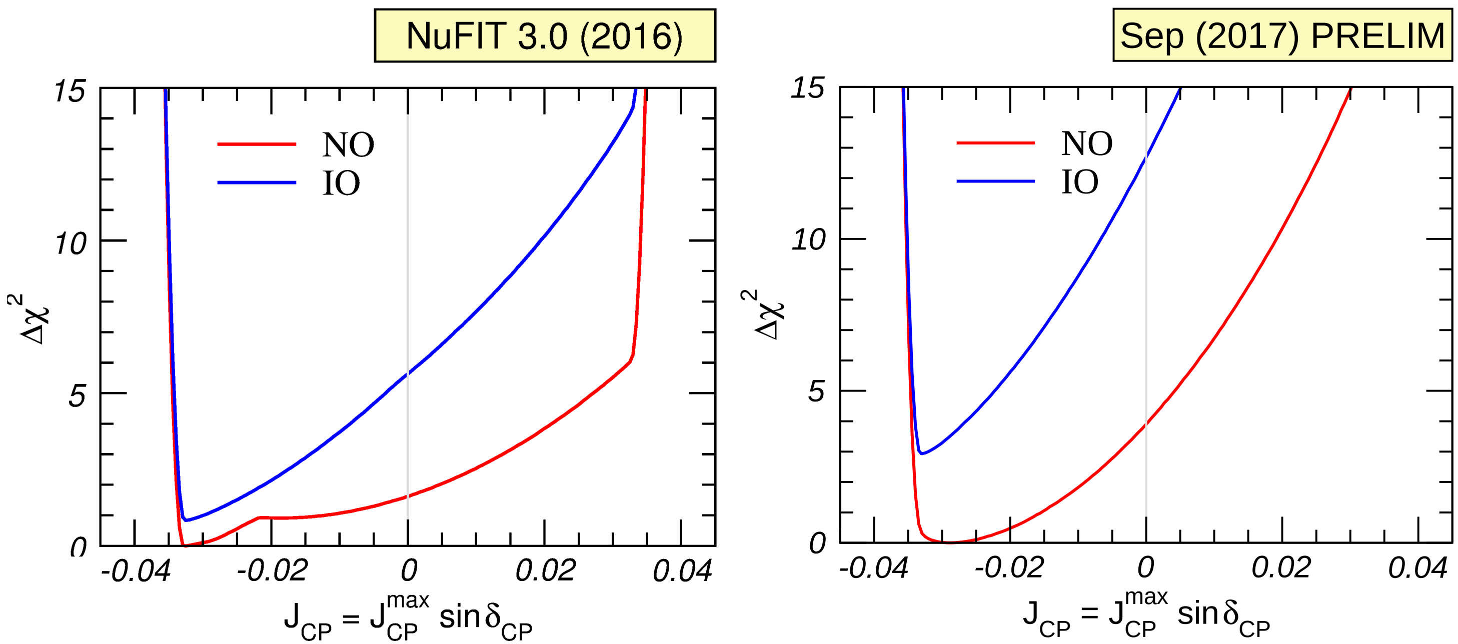
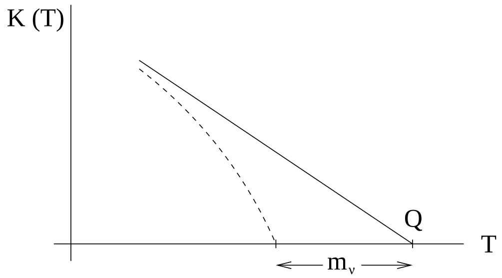
$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad J^{\text{max}}_{\text{LEP,CP}} = \frac{1}{8} c_{13}\sin^2 2\theta_{13}\sin^2 2\theta_{23}\sin^2 2\theta_{12}$$

- Leptonic Jarlskog Invariant : Best fit $J_{\text{LEP,CP}} = -0.030$



Neutrino Mass Scale

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

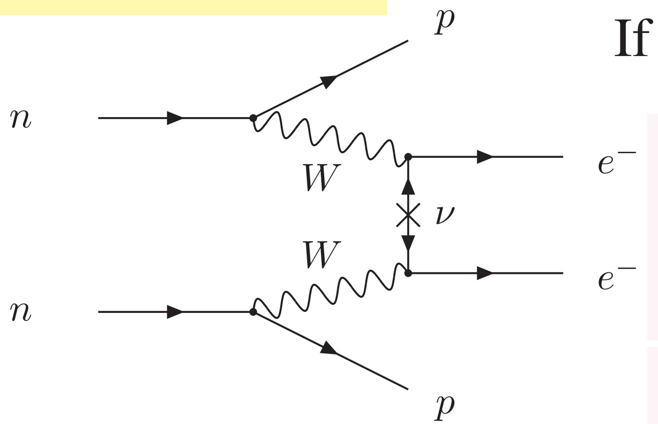


$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = \begin{cases} \text{NO}: \; m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} + \Delta m^2_{31} s^2_{13} \\ \text{IO}: \; m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} - \Delta m^2_{31} c^2_{13} \end{cases}$$

Present bound: $m_{\nu_e} \leq 2.2$ eV (at 95 % CL)

Katrin (20XX???) Sensitivity to $m_{\nu_e} \sim 0.2$ eV

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



If m_ν only source of ΔL $\quad T^{0\nu}_{1/2} = \dfrac{m_e}{G_{0\nu}\, M^2_{\rm nucl}\, m^2_{ee}}$

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

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

$$= f(m_\ell, \text{order}, \text{maj phases})$$

Present Bounds: $m_{ee} < 0.06$–0.76 eV

COSMO for Dirac or Majorana m_ν affect growth of structures

$$\sum m_i = \begin{cases} \text{NO}: \; \sqrt{m_\ell^2} + \sqrt{\Delta m^2_{21} + m_\ell^2} + \sqrt{\Delta m^2_{31} + m_\ell^2} \\ \text{IO} \; \sqrt{m_\ell^2} + \sqrt{-\Delta m^2_{31} - \Delta m^2_{21} - m_\ell^2} + \sqrt{-\Delta m^2_{31} - m_\ell^2} \end{cases}$$

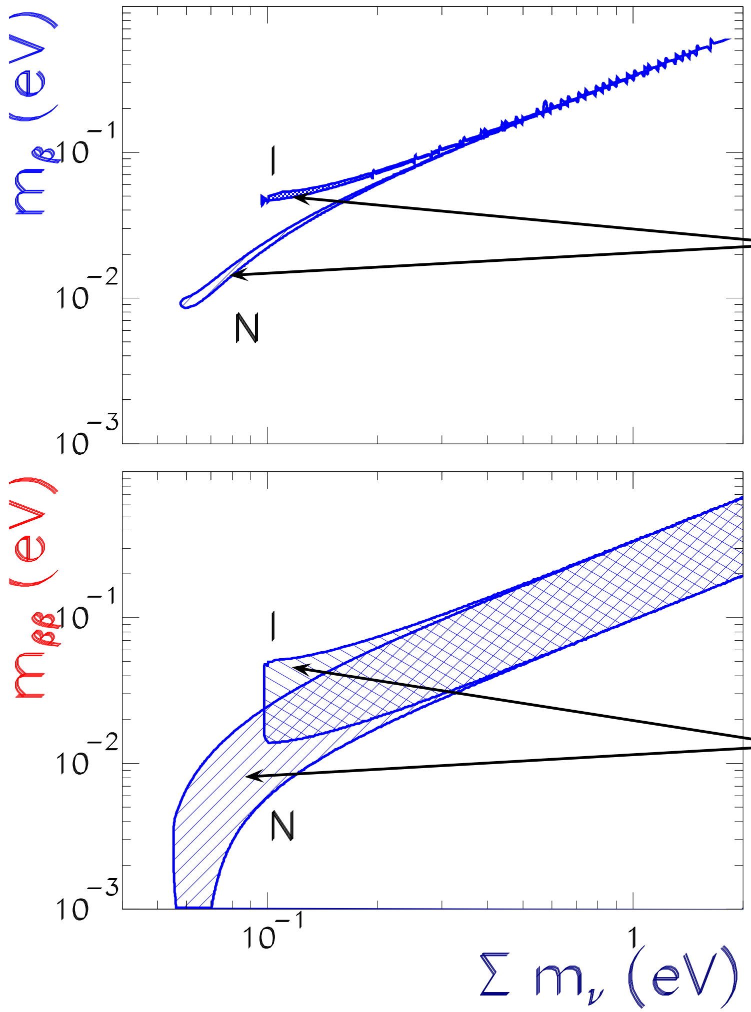
Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

$\Rightarrow$ Correlations m_{ν_e}, m_{ee} and $\sum m_\nu$

(Fogli *et al* (04))

Nufit (95%)



Width due to range in oscillation parameters very narrow

Lower bound on $\sum m_i$ depends on ordering

Wide band due to unknown Majorana phases $\Rightarrow$

Possible Det of Maj phases?

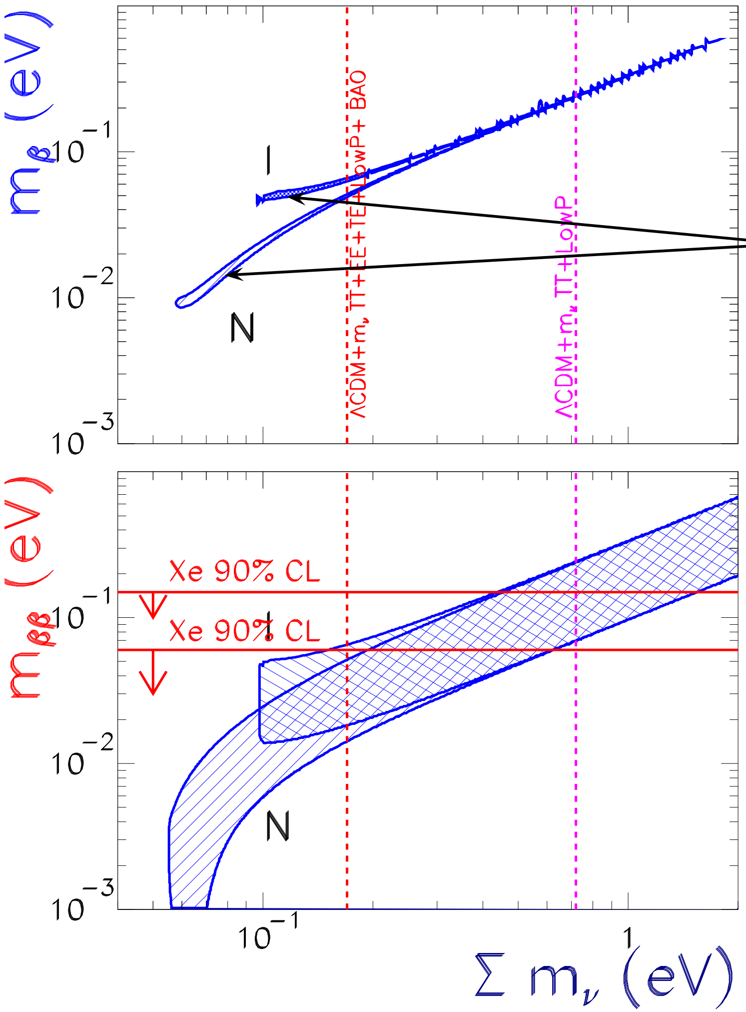
Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis

$\Rightarrow$ Correlations m_{ν_e}, m_{ee} and $\sum m$

(Fogli *et al* (04))

Nufit (95%)



Lower bound on $\sum m_i$ depends on ordering

Precision determination/bound of $\sum m_i$ can give information on ordering ?

Hannestad, Schwetz 1606.04691, Simpson etal 1703.03425, Capozzi etal 1703.04471 ...

Or much ado about nothing?

Cosmo data will only add to N/I likelihood when accuracy on Σm_ν better than 0.02 eV (to see a 2σ N/I difference between 0.06 and 0.1)

Hannestad, Schwetz 1606.04691

Beyond 3 ν Oscillations?

- Three-flavour oscillation scenario very robust

- Most extensions: VLI, Non-Unitarity, CPT viol, eV sterile neutrinos …

  Only allowed to be subdominant

- What about non-standard interactions?

Non Standard ν Interactions

- 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 flavour basis $\vec\nu = (\nu_e, \nu_\mu, \mu_\tau)^T$ the neutrino evolution eq.:

$$i\frac{d}{dx}\vec\nu = H^\nu\vec\nu \quad \text{with} \quad H^\nu = H_{\rm vac} + H_{\rm mat} \quad \text{and} \quad H^{\bar\nu} = (H_{\rm vac} - H_{\rm mat})^*$$

$$H_{\rm mat} = \sqrt{2}G_F N_e(r)\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2}G_F N_e(r)\begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

$\varepsilon_{\alpha\beta}(r) \equiv \sum_{f=ued}\frac{N_f(r)}{N_e(r)}\varepsilon^{fV}_{\alpha\beta}$ $\Rightarrow$ 3ν evolution depends on 6 (vac) + 8 per f (mat)

Non Standard ν Interactions

- Including non-standard neutrino NC interactions with fermion f

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$\varepsilon_{\alpha\beta}(r) \equiv \sum_{f=ued} \frac{N_f(r)}{N_e(r)} \varepsilon^{fV}_{\alpha\beta}$ $\Rightarrow$ 3ν evolution depends on 6 (vac) + 8 per f (mat)

$\Rightarrow$ Parameters degeneracies (some well-known but being rediscovered lately ...)
In particular CPT $\Rightarrow$ invariance under simultaneously:

$$\begin{aligned} &\theta_{12} \leftrightarrow \tfrac{\pi}{2} - \theta_{12}\,, && (\varepsilon_{ee} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2\,, \\ &\Delta m^2_{31} \to -\Delta m^2_{32}\,, && (\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu})\,, \\ &\delta \to \pi - \delta\,, && \varepsilon_{\alpha\beta} \to -\varepsilon^*_{\alpha\beta} \qquad (\alpha \neq \beta)\,, \end{aligned}$$

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

$$H_{\rm mat} = Q_{\rm rel} U_{\rm mat} D_{\rm mat} U_{\rm mat}^\dagger Q_{\rm rel}^\dagger$$

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

Matter Potential/NSI in ATM and LBL

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  Friedland, Lunardini,Maltoni 04

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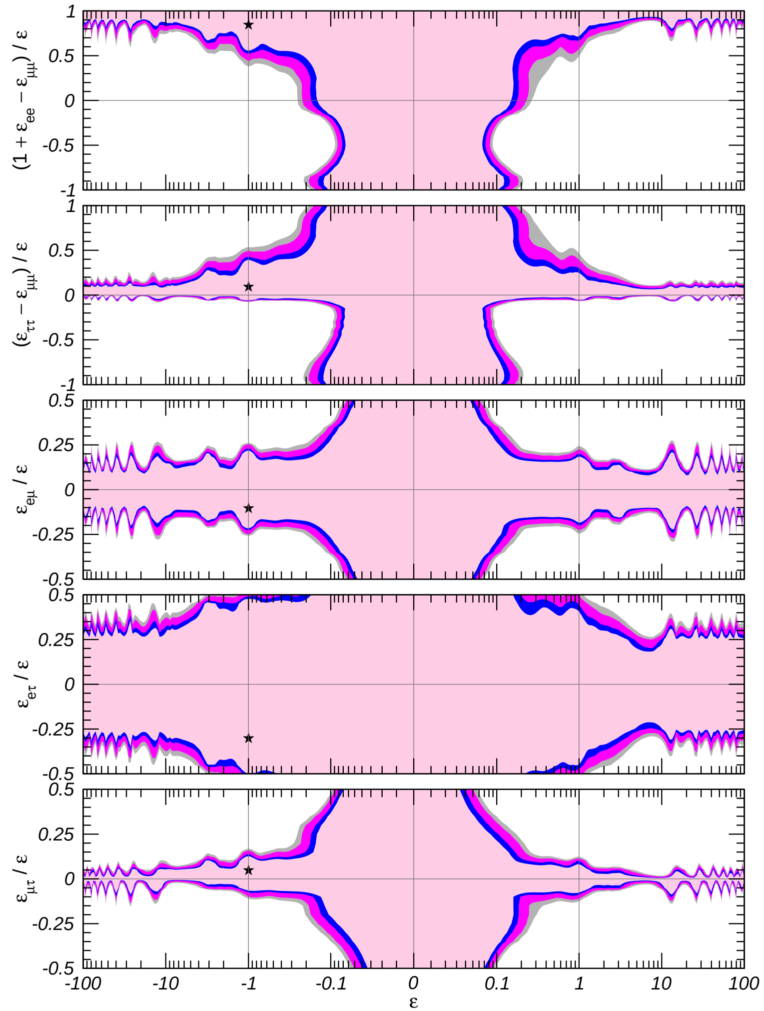
So

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

No bound on ε from ATM+LBL



Maltoni, MCG-G, Salvado ArXiv:1103.4265

Matter Potential/NSI in Solar and KamLAND

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

$$
\begin{aligned}
H^{\rm eff}_{\rm mat} &= \sqrt{2} G_F N_e(r) \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} \\
&+ \sqrt{2} G_F \sum_f N_f(r) \begin{pmatrix} -\varepsilon_D^f & \varepsilon_N^f \\ \varepsilon_N^{f*} & \varepsilon_D^f \end{pmatrix}
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon_D^f &= c_{13} s_{13} {\rm Re}\left[e^{i\delta_{\rm CP}} \left(s_{23}\, \varepsilon_{e\mu}^{fV} + c_{23}\, \varepsilon_{e\tau}^{fV} \right) \right] \\
&- \left(1 + s_{13}^2\right) c_{23} s_{23} {\rm Re}\left(\varepsilon_{\mu\tau}^{fV} \right) \\
&- \frac{c_{13}^2}{2} \left(\varepsilon_{ee}^{fV} - \varepsilon_{\mu\mu}^{fV} \right) \\
&+ \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2} \left(\varepsilon_{\tau\tau}^{fV} - \varepsilon_{\mu\mu}^{fV} \right)
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon_N^f &= c_{13} \left(c_{23}\, \varepsilon_{e\mu}^{fV} - s_{23}\, \varepsilon_{e\tau}^{fV} \right) \\
&+ s_{13} e^{-i\delta_{\rm CP}} \left[s_{23}^2\, \varepsilon_{\mu\tau}^{fV} - c_{23}^2\, \varepsilon_{\mu\tau}^{fV*} \right. \\
&\quad \left. + c_{23} s_{23} \left(\varepsilon_{\tau\tau}^{fV} - \varepsilon_{\mu\mu}^{fV} \right) \right]
\end{aligned}
$$

Matter Potential/NSI in Solar and KamLAND

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

$$H^{\rm eff}_{\rm mat} = \sqrt{2} G_F N_e(r) \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2} G_F \sum_f N_f(r) \begin{pmatrix} -\varepsilon_D^f & \varepsilon_N^f \\ \varepsilon_N^{f*} & \varepsilon_D^f \end{pmatrix}$$

$$\begin{aligned}
\varepsilon_D^f =\ & c_{13} s_{13} \mathrm{Re}\left[e^{i\delta_{\rm CP}} \left(s_{23}\, \varepsilon_{e\mu}^{fV} + c_{23}\, \varepsilon_{e\tau}^{fV} \right) \right] \\
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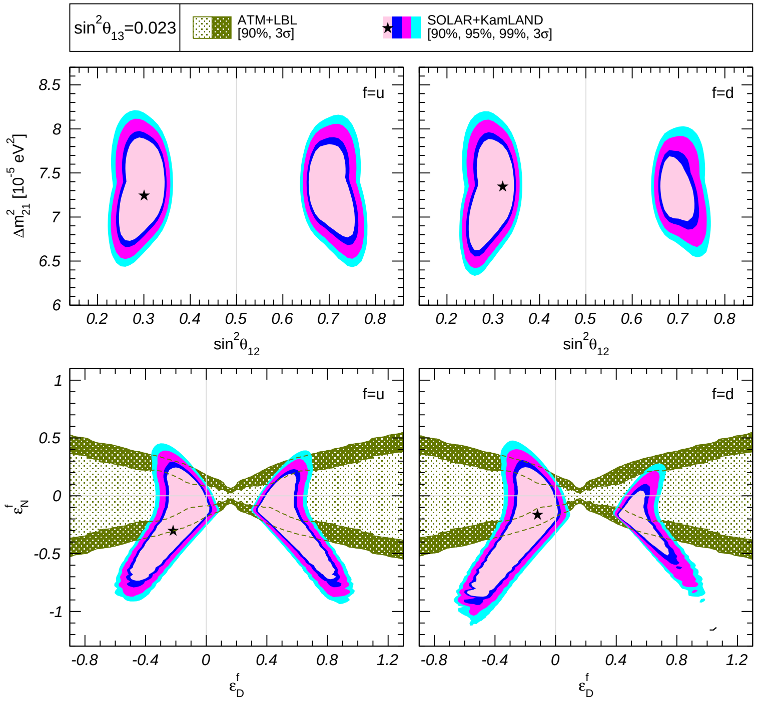
& \left. + c_{23} s_{23} \left(\varepsilon_{\tau\tau}^{fV} - \varepsilon_{\mu\mu}^{fV} \right) \right]
\end{aligned}$$

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

Miranda etal hep-ph/0406280



M.C G-G, M.Maltoni 1307.3092

NSI: Bounds/Degeneracies from/in Oscillation data

M.C G-G, M.Maltoni 1307.3092

		90% CL	
Param.	best-fit	LMA	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	$[-0.01, +0.01]$	$[-0.01, +0.01]$

– Bounds $\mathcal{O}(1-10\%)$

– Except $\varepsilon^{q,V}_{ee} - \varepsilon^{q,V}_{\mu\mu}$

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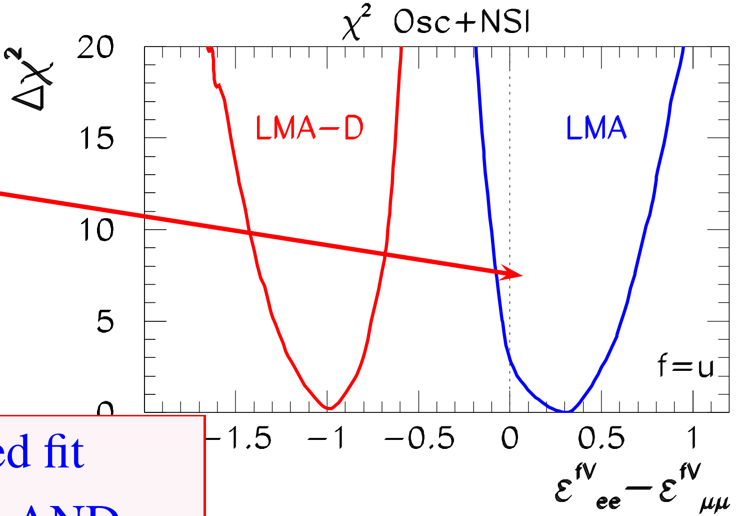

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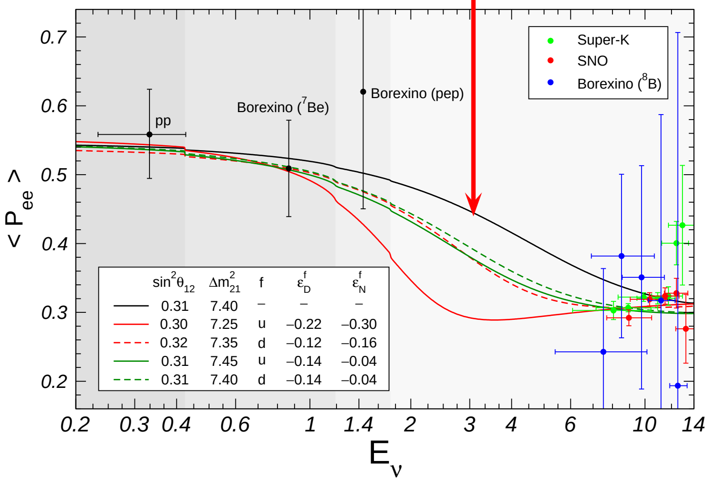
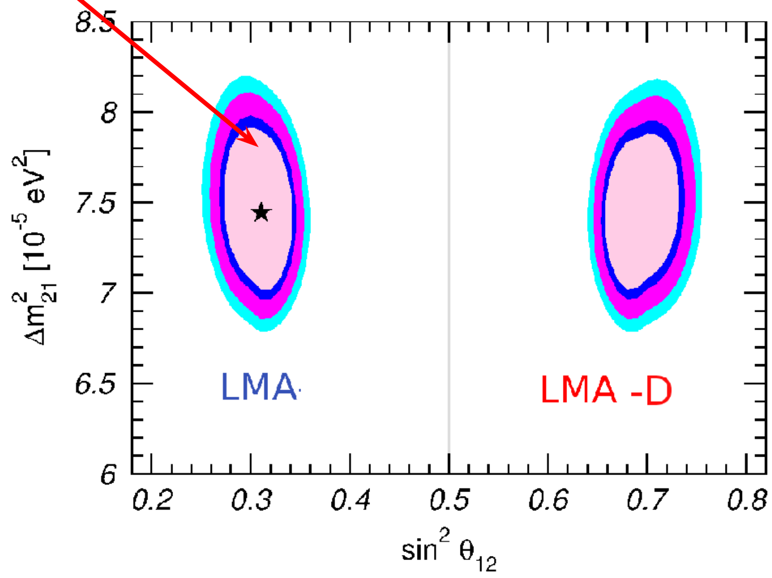
LMA: Improved fit
to Solar+KamLAND





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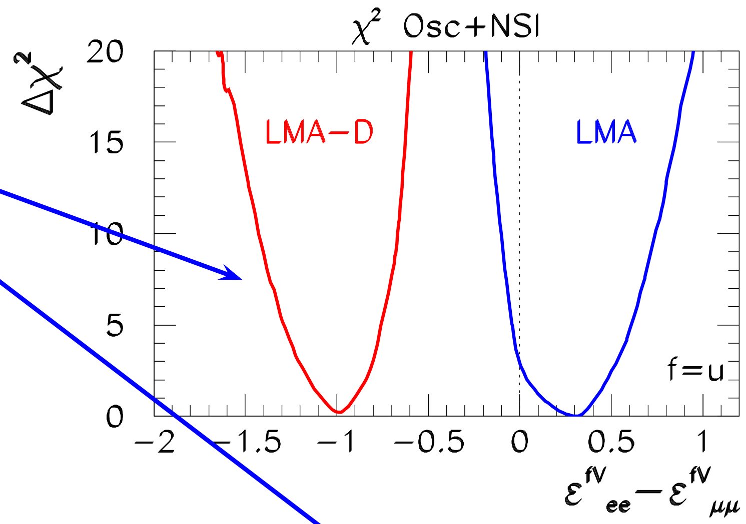


– Bounds $\mathcal{O}(1-10\%)$

– Except $\varepsilon^{q,V}_{ee} - \varepsilon^{q,V}_{\mu\mu}$

Degenerate solution LMA-D ($\theta_{12} > 45°$)

Miranda,Tortola, Valle, hep-ph/0406280

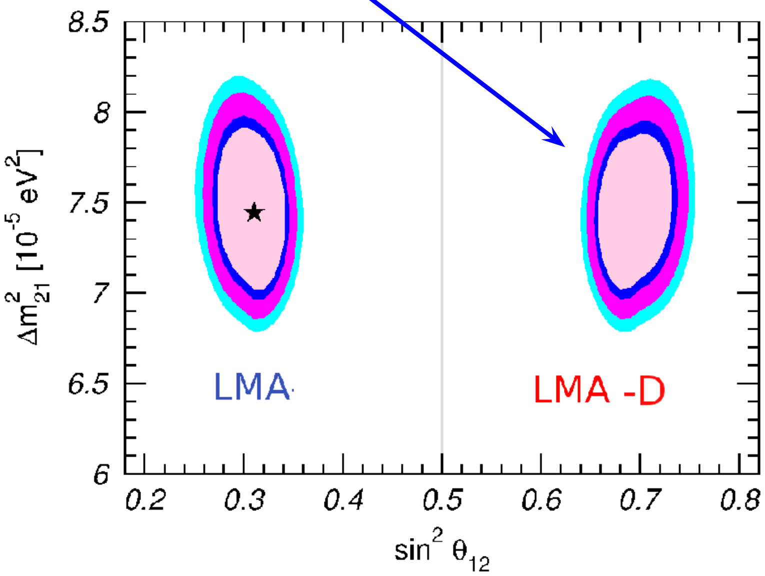
Cannot be resolved with osc-experiments

Requires NC scattering experiments

Coloma etal 1701.04828

Requires NSI $\sim G_F$ (light mediators?)

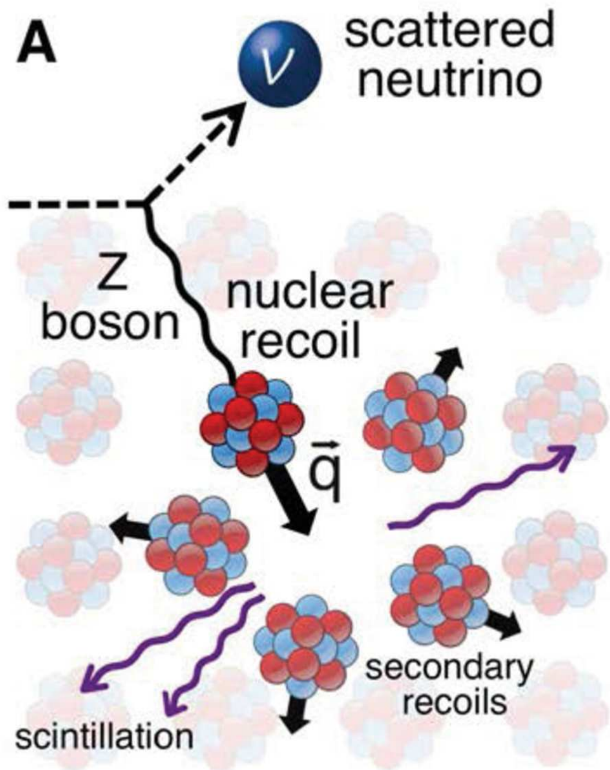
Farzan 1505.06906, and Shoemaker 1512.09147



COHERENT EXPERIMENT

Science 2017 [ArXiv:1708.01294]

- observation of coherent neutrino-nucleus scattering at 6.7σ at CsI[Na] detector
- neutrinos from stopped pion source at Oak Ridge NL
- 142 events observed, in agreement with Standard Model



NSI: Combination with COHERENT data

Coloma, MCGG, Maltoni,Schwetz ArXiv:1708.02899

- COHERENT has detected for first time Coherent νN scattering 1708.01294:
  142(1± 0.28(sys)) observed events over a steady bck of 405
  136(SM) + 6(1± 0.25(sys) beam-on bck) expected

- In presence of NSI: $N_{\rm NSI}(\varepsilon) = \gamma\left[f_{\nu_e} Q^2_{we}(\varepsilon) + (f_{\nu_\mu} + f_{\bar\nu_\mu}) Q^2_{w\mu}(\varepsilon)\right]$

$$Q^2_{w\alpha} \propto \left[Z(g_p^V + 2\varepsilon^{u,V}_{\alpha\alpha} + \varepsilon^{d,V}_{\alpha\alpha}) + N(g_n^V + \varepsilon^{u,V}_{\alpha\alpha} + 2\varepsilon^{d,V}_{\alpha\alpha})\right]^2 + \sum_{\beta\neq\alpha}\left[Z(2\varepsilon^{u,V}_{\alpha\beta} + \varepsilon^{d,V}_{\alpha\beta}) + N(\varepsilon^{u,V}_{\alpha\beta} + 2\varepsilon^{d,V}_{\alpha\beta})\right]^2$$

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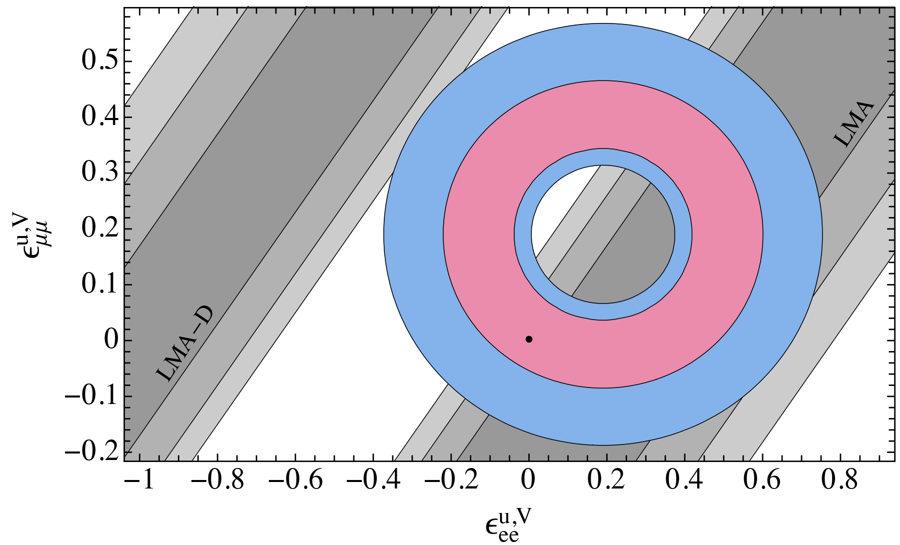
- Impact on LMA-D: Allowed COHERENT region vs LMA-D required range



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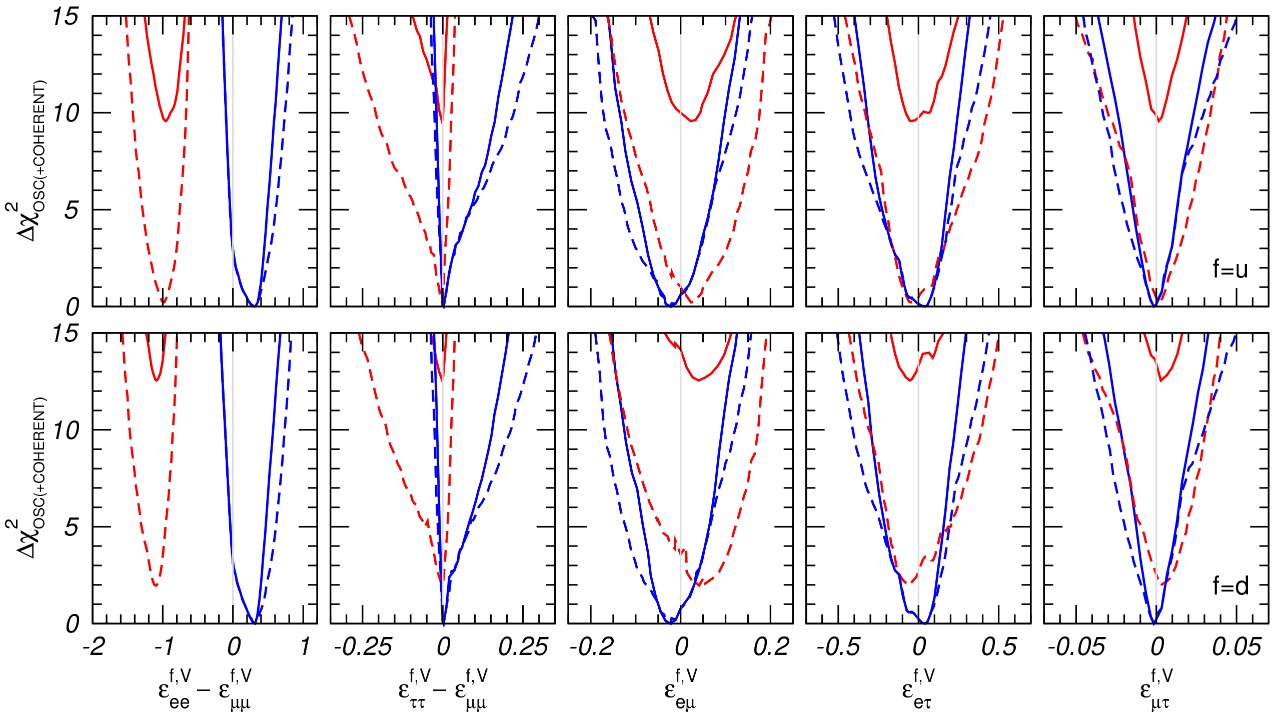
- OSCILLATION + COHERENT ⇒ LMA-D excluded at more than 3.1 (3.6) σ



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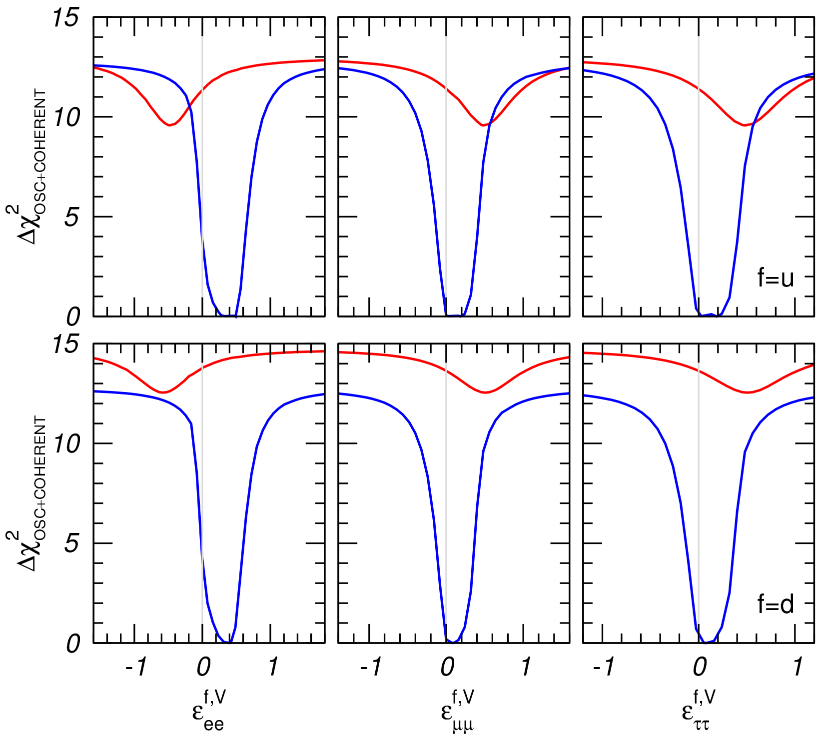
- OSCILLAT+COHERENT bounds on NSI's



	$f = u$	$f = d$
$\epsilon^{f,V}_{ee}$	$[0.028, 0.60]$	$[0.030, 0.55]$
$\epsilon^{f,V}_{\mu\mu}$	$[-0.088, 0.37]$	$[-0.075, 0.33]$
$\epsilon^{f,V}_{\tau\tau}$	$[-0.090, 0.38]$	$[-0.075, 0.33]$
$\epsilon^{f,V}_{e\mu}$	$[-0.073, 0.044]$	$[-0.07, 0.04]$
$\epsilon^{f,V}_{e\tau}$	$[-0.15, 0.13]$	$[-0.13, 0.12]$
$\epsilon^{f,V}_{\mu\tau}$	$[-0.01, 0.009]$	$[-0.009, 0.008]$

Summary

- 3ν oscillation:

  Robust description of all confirmed oscillation data

  CP phase: $\sin\delta_{\rm CP} < 0$ favoured

  CP conservation excluded at 2σ CL

  Hint for NO emerging but still only $\Delta\chi^2 = 3$

- Non-standard neutrino NC interactions:

  Before august possible degeneracies in ordering and octact determination

  New COHERENT results able to exclude LMA-Dark degeneracy

  Bounds of OSC+COHERENT at the few % level.

Thank You

Thank You

Happy Birthday!!

Gauge Inv NSI and Lepton Mixing Non-Unitarity

- Take ν_L mixed with m HEAVY states $U_{\rm LEP} = (K_{l,3\times3}\,, K_{h,3\times m})$ Schechter, Valle (1980)

  And $U_{\rm LEP}U^\dagger_{\rm LEP} = I_{3\times3}$ 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 $K_{L,3\times3}$ (not unitary)
  or equivalently $K_l \simeq (I+\epsilon)U(\theta_{ij},\delta,\eta_i)$

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- But this unitarity violation $\Rightarrow$ Flavour Changing Neutral Currents $\equiv$ NSI's
  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 $|\epsilon_{\alpha j}| \leq \text{few} \times 10^{-3} \Rightarrow$

Too small to have effect in oscillations Blennow *etal* 1609.08637

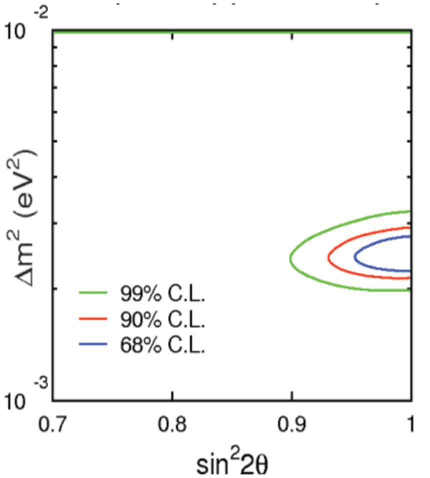
Unless NP is not that heavy (specific models Farzan 1505.06906, and Shoemaker

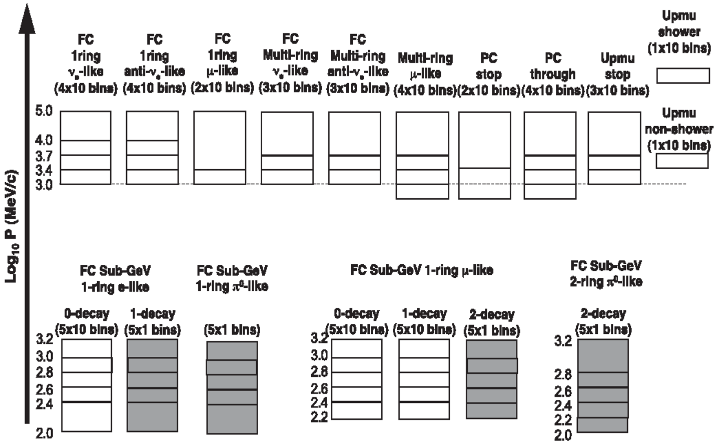
1512.09147)

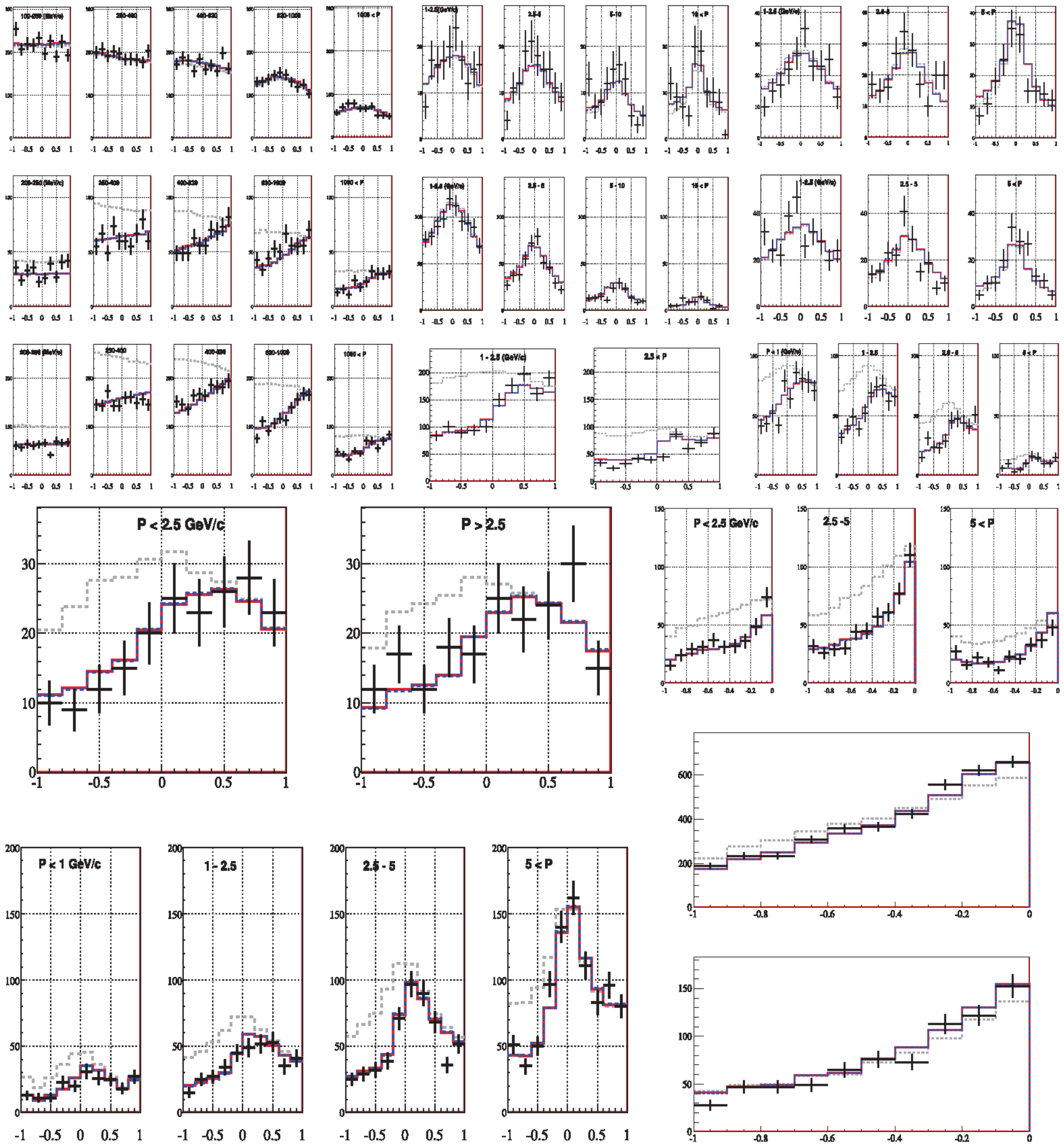
1512.09147)

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: $(\Delta m^2, \theta)$.





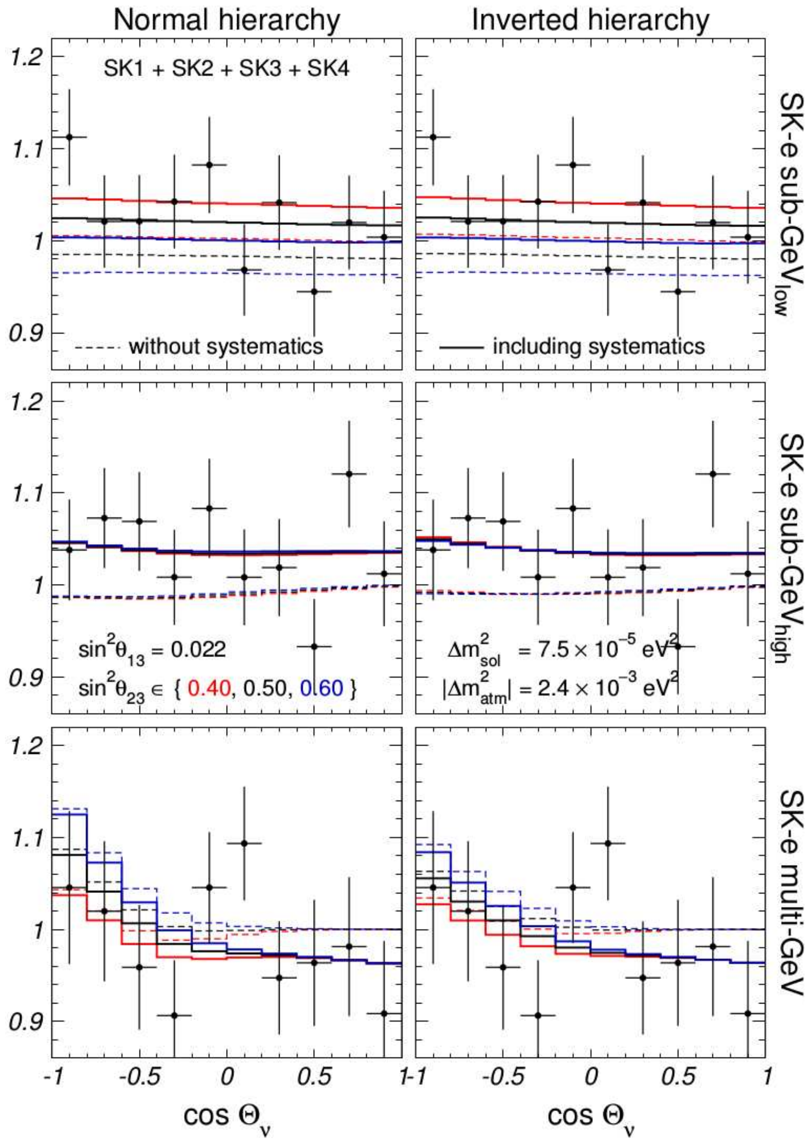


3 ν Analysis: Ordering, $\delta_{\rm CP}$ in ATM

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

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

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



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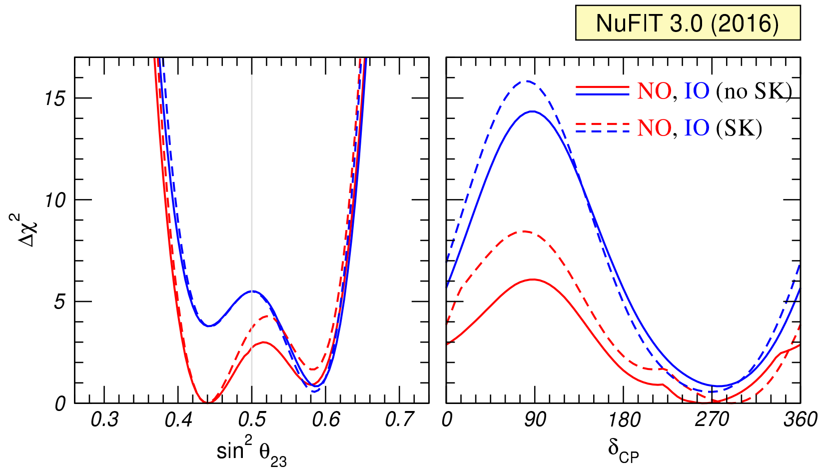
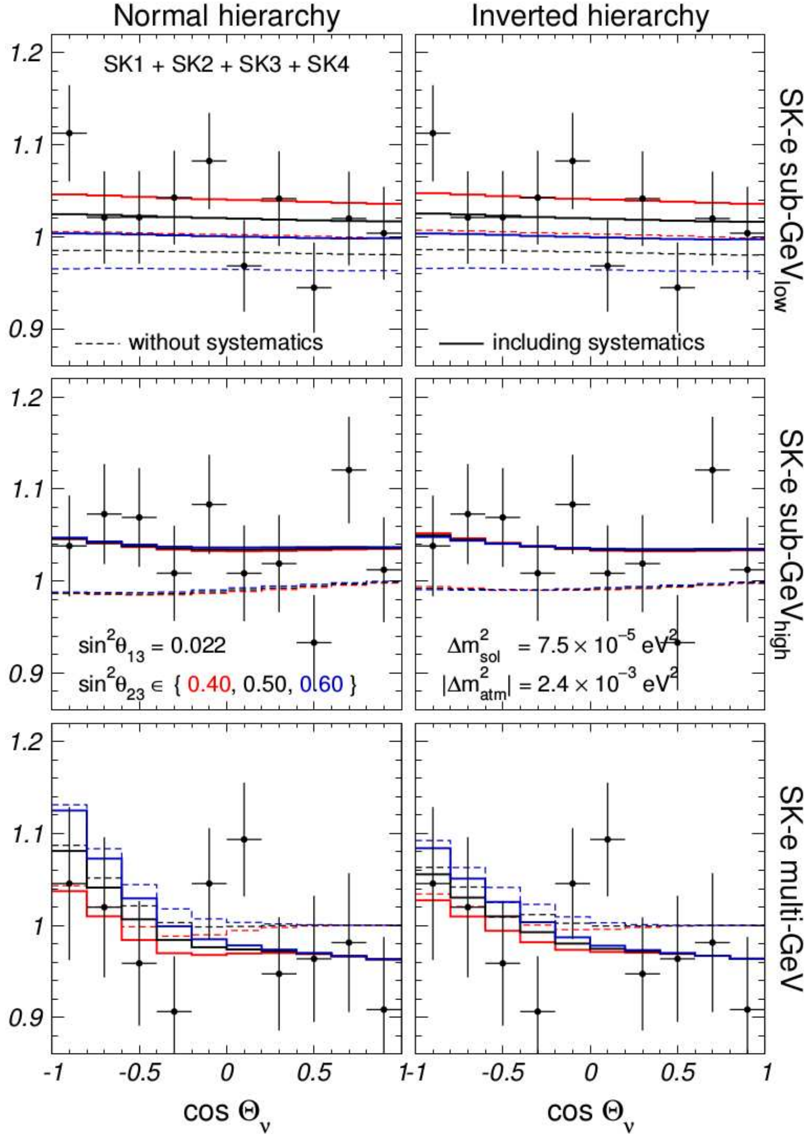
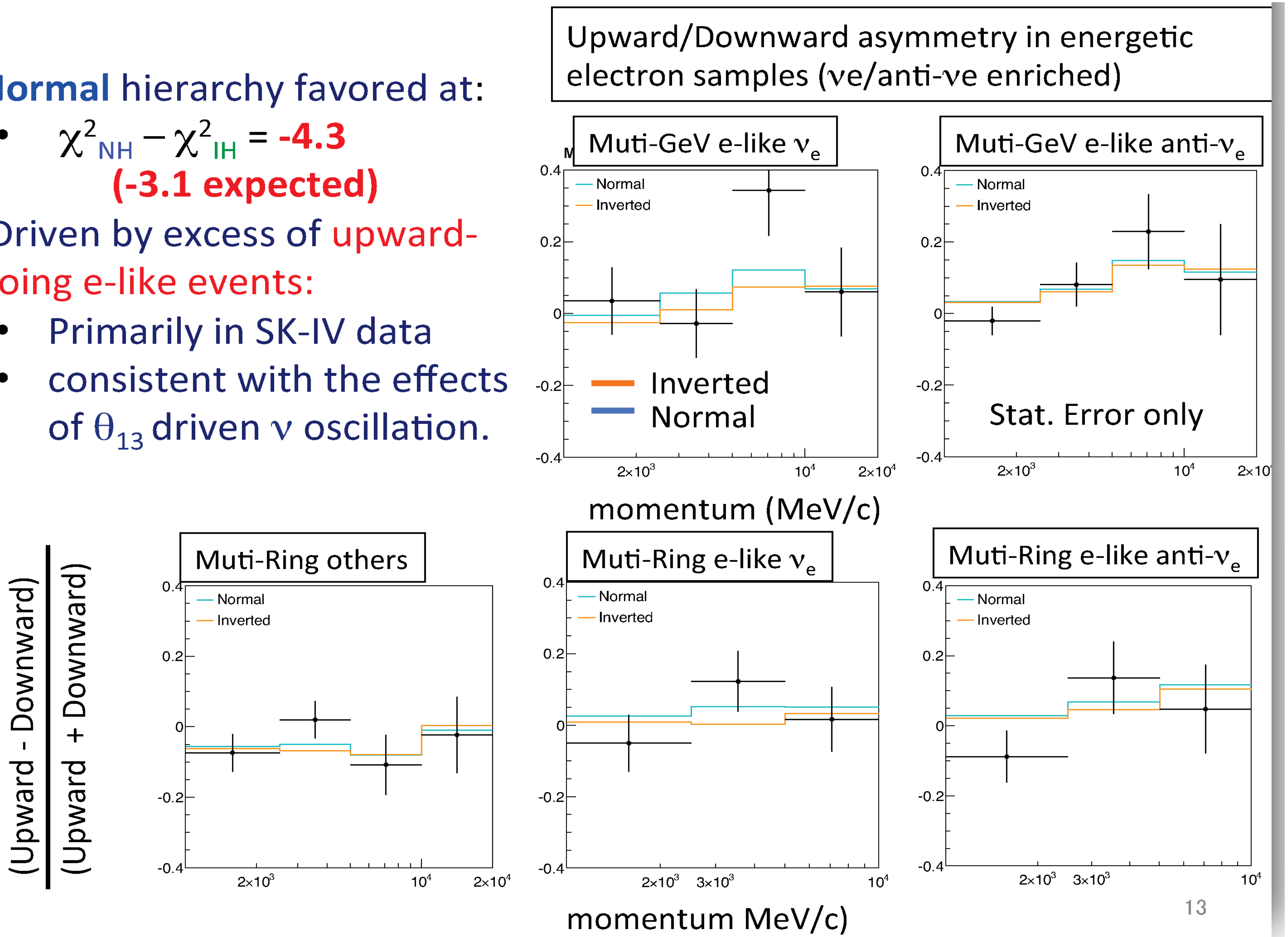
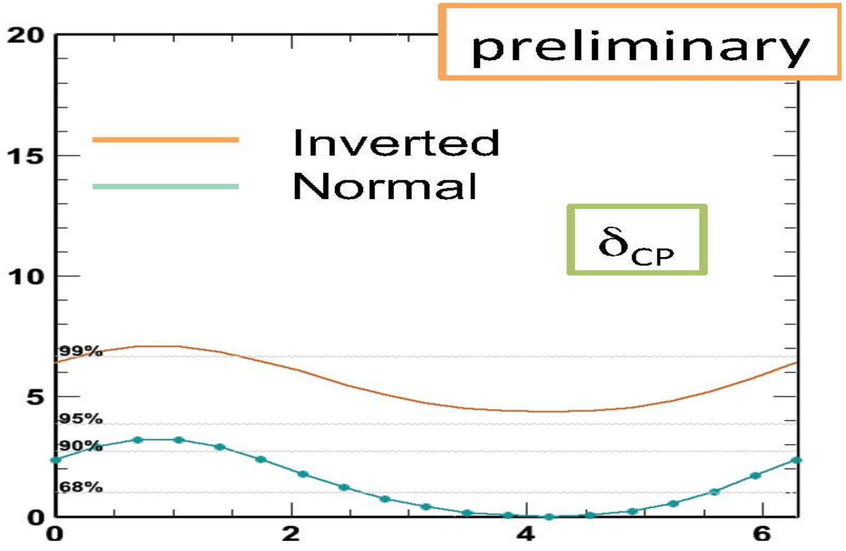




- **Normal** hierarchy favored at:
  - $\chi^2_{NH} - \chi^2_{IH}$ = **-4.3** **(-3.1 expected)**
- Driven by excess of upward-going e-like events:
  - Primarily in SK-IV data
  - consistent with the effects of θ_{13} driven ν oscillation.



J. Kameda (SK) talk at Nufact 2016



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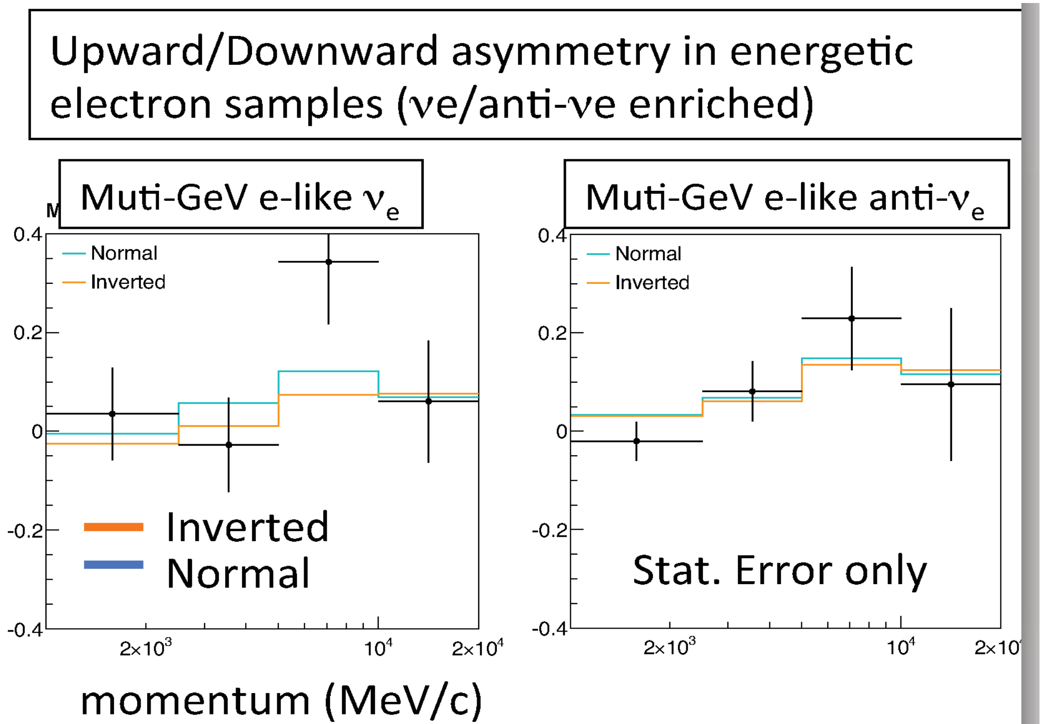

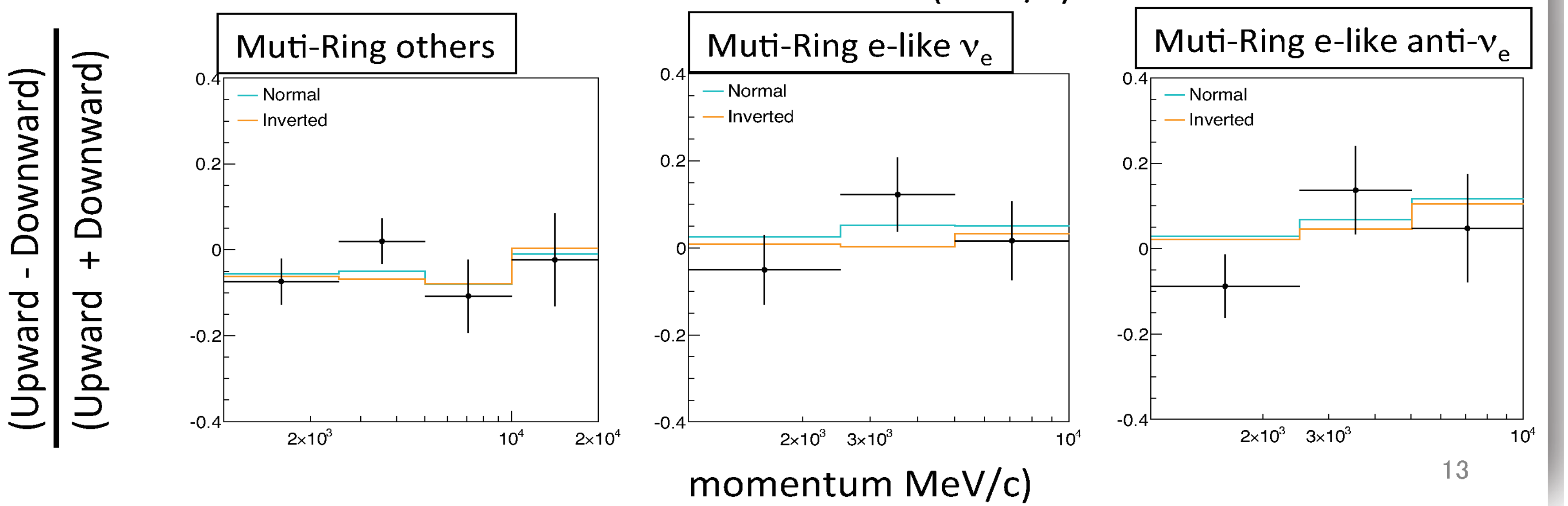

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