MASSIVE NEUTRINOS CIRCA 2017

Concha Gonzalez-Garcia

(YITP Stony Brook & ICREA U. Barcelona)

CERN, March 2017

Global fit to neutrino oscillation data

http://www.nu-fit.org

elusives

neutrinos, dark matter & dark energy physics

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Neutrino Flavour Transition: Data and Interpretation

Some sidetrack in the Sun

My personal list of open questions (today)

Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

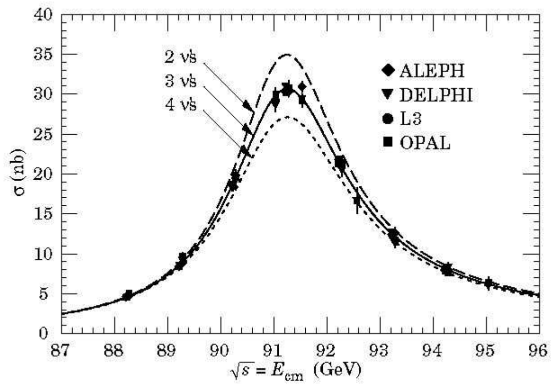
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

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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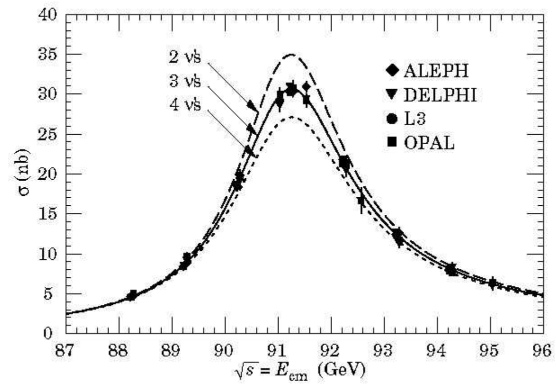

There is no ν_R

$\Downarrow$

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 2016 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

and There is Physics Beyond SM

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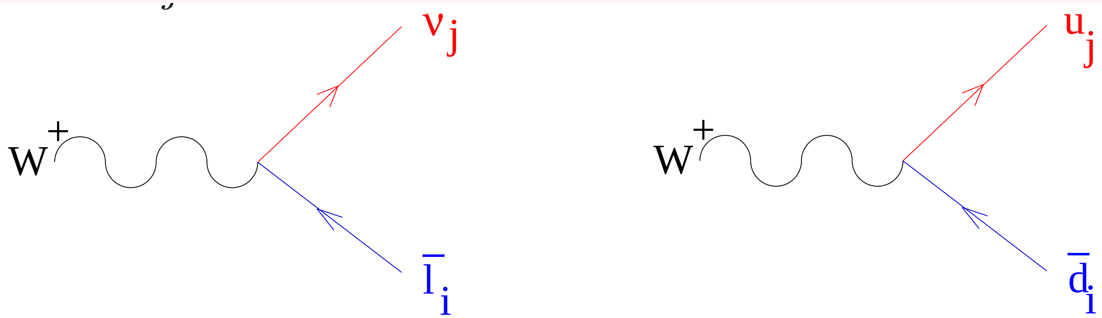
- The charged current interactions of leptons are not diagonal (same as quarks)

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



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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

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

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

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- When osc between 2-ν dominates:

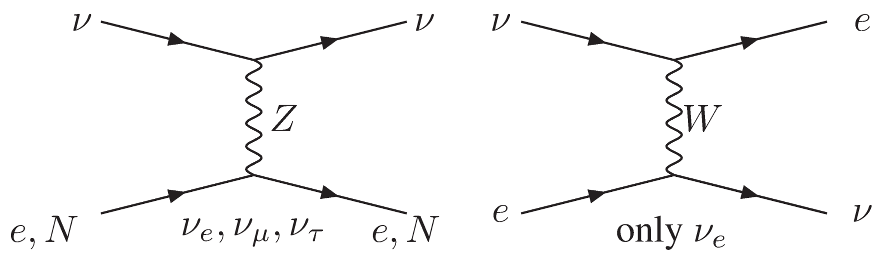
$$P_{\alpha\alpha} = 1 - P_{osc} \quad \text{Disappear}$$

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

Matter Effects

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

  – But Different flavours have different interactions :



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

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

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

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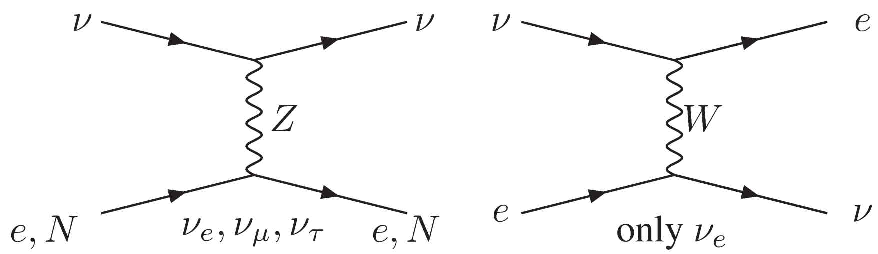

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$\Rightarrow$ *Modification of mixing angle and oscillation wavelength* (MSW)

- Mass difference and mixing in matter:

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

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

$\Rightarrow$ 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

- By 2017 we have observed with high (or good) precision:
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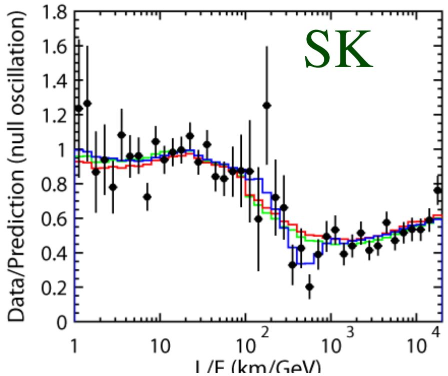
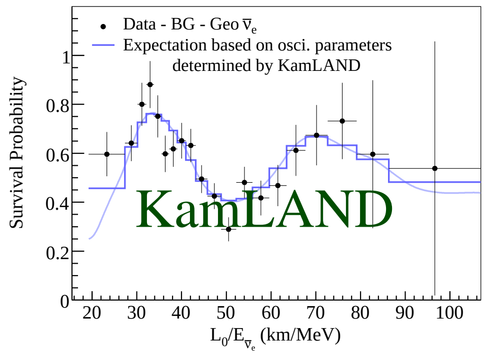
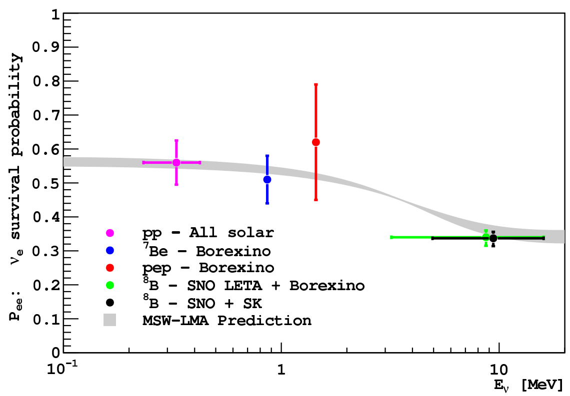
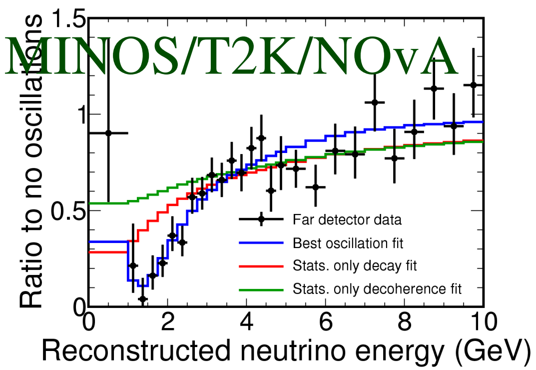
- Confirmed: Vacuum oscillation L/E pattern with 2 frequencies

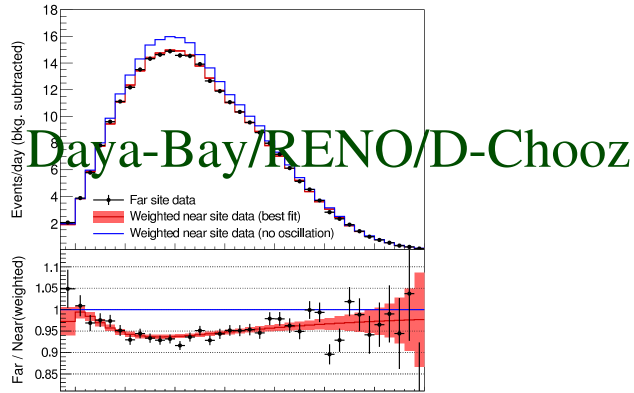




MSW conversion in Sun







3ν Flavour Parameters

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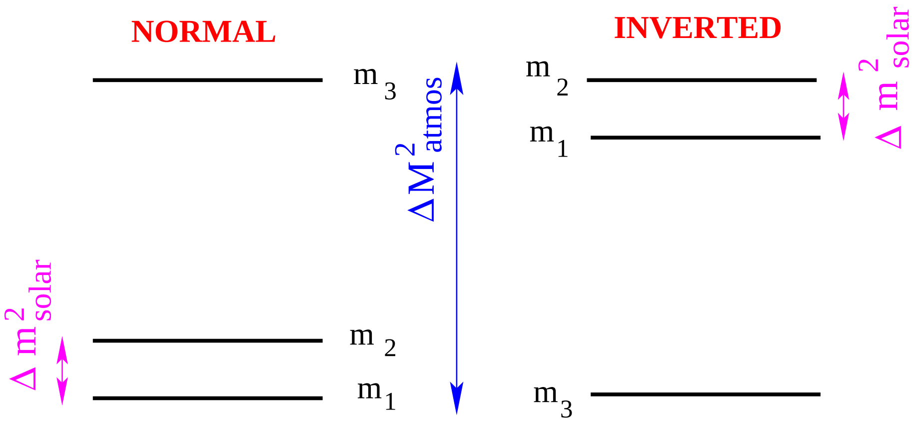
- For for 3 ν's : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

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

- Two Possible Orderings



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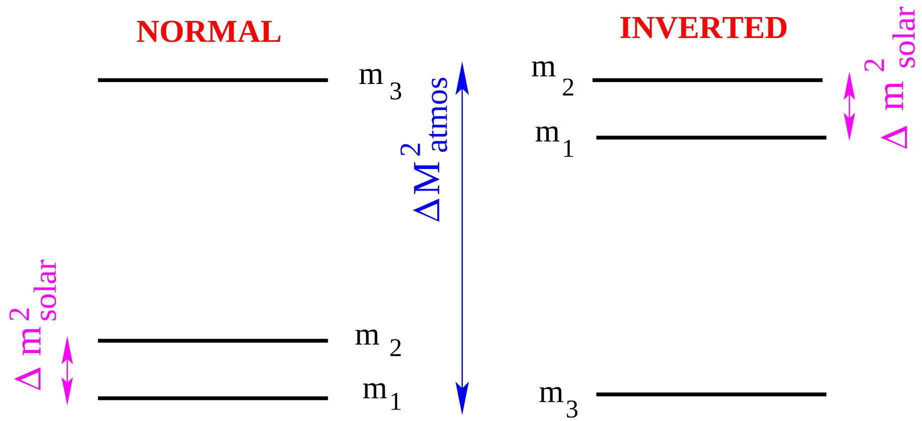
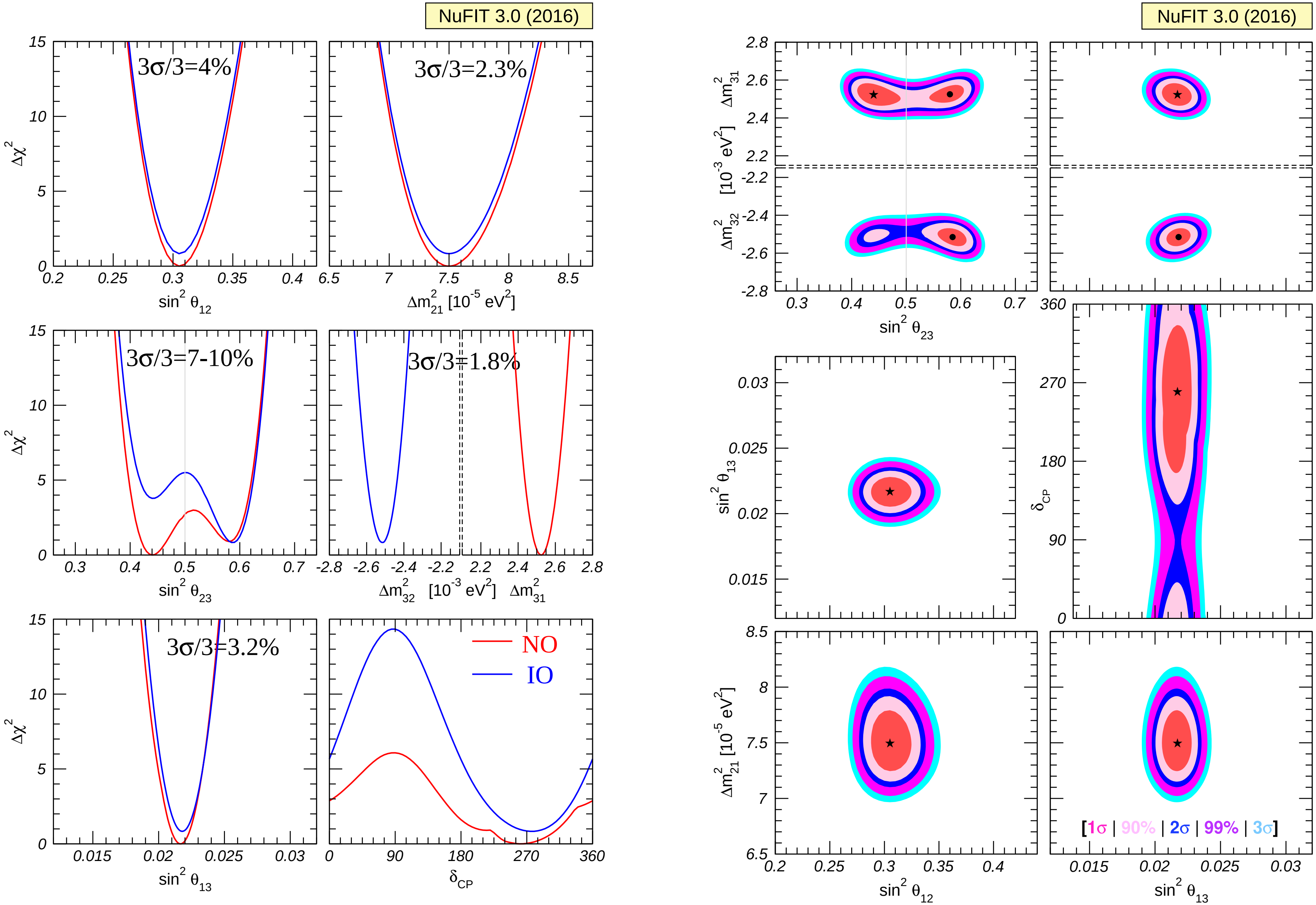


Experiment	Dominant Dependence	Important Dependence
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\rightarrow \theta_{23}$	$\Delta m^2_{\rm atm}$, θ_{13} ,$\delta_{\rm cp}$
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 3/2017

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

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



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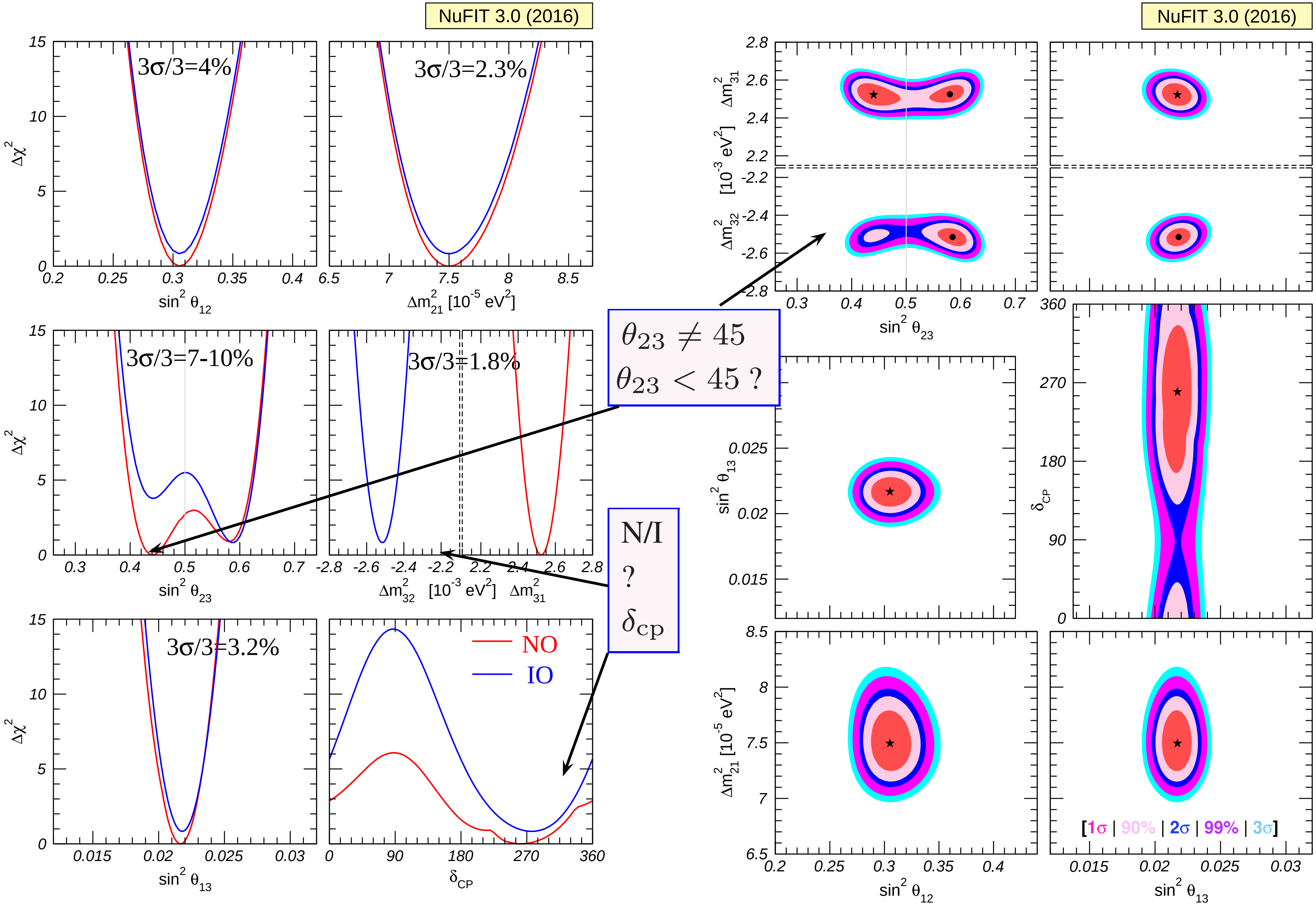
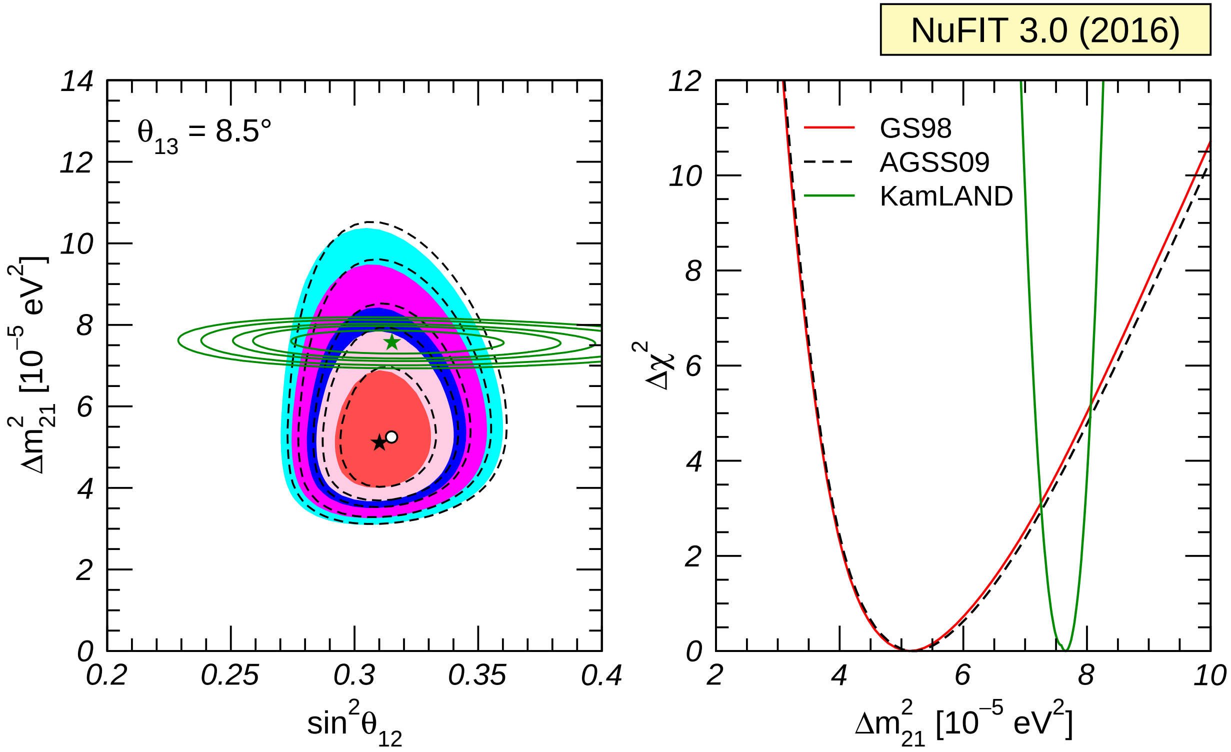


Issues in 3 ν Analysis: Δm^2_{21} KamLAND vs SOLAR

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

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

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



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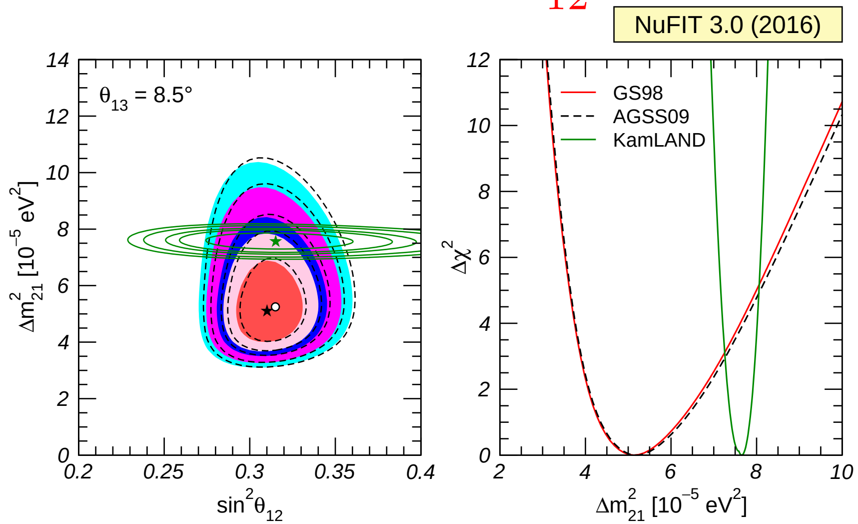
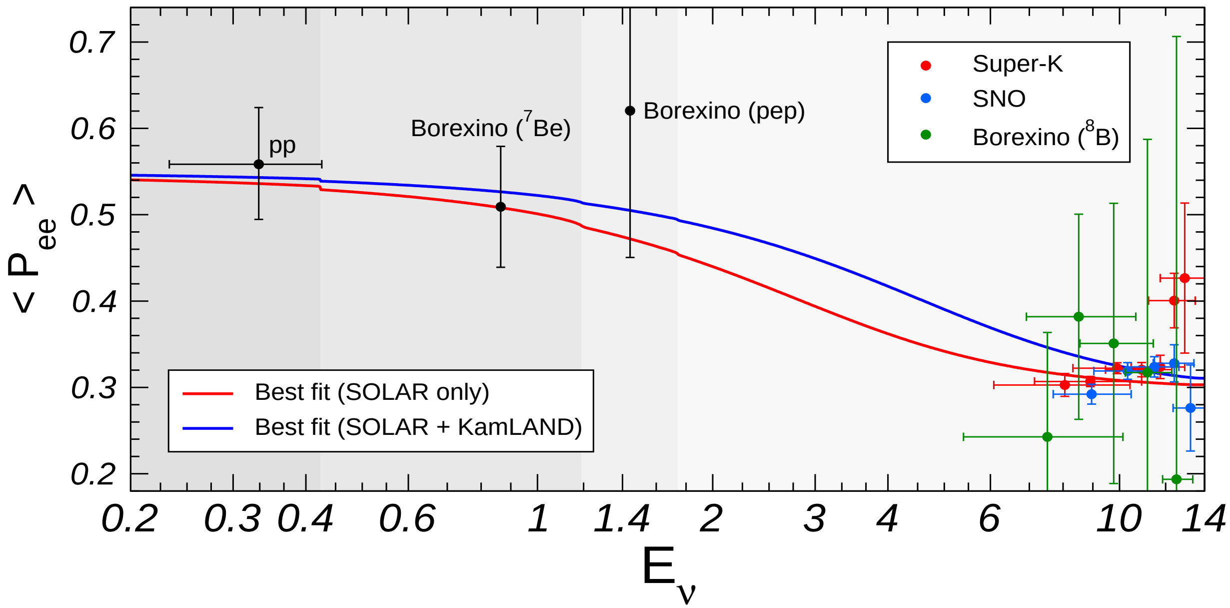


Tension related to: a)"too large" of Day/Night at SK

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



Modified matter potential?

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

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

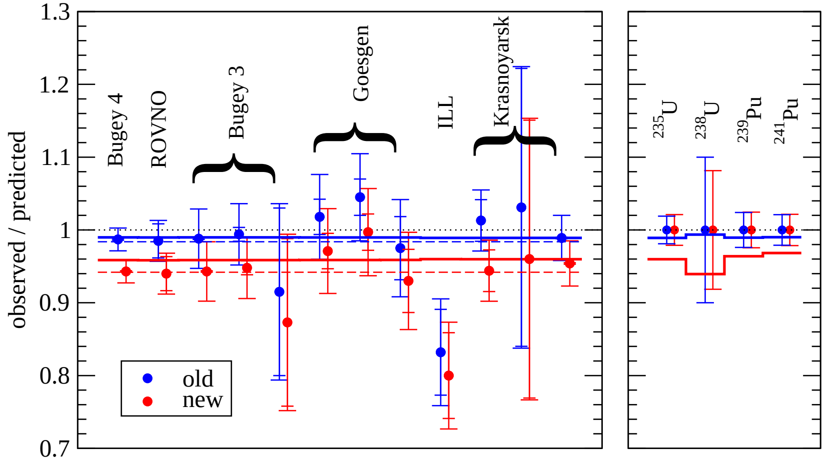
  T.A. Mueller et al.,[arXiv:1101.2663].;P. Huber, [arXiv:1106.0687].

- Both found higher fluxes $\sim$ 3.5 %

$\Rightarrow$ *negative* reactor experiments

at short baselines (RSBL) indeed

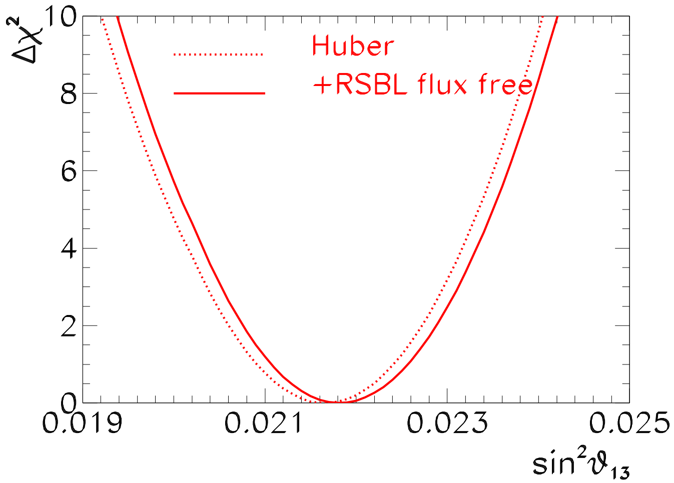
observed a deficit



- 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

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



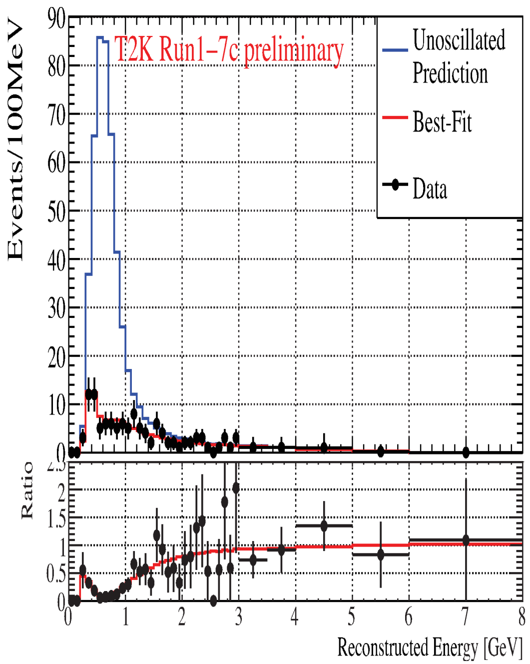
3 ν Analysis: θ_{23}

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

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

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

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



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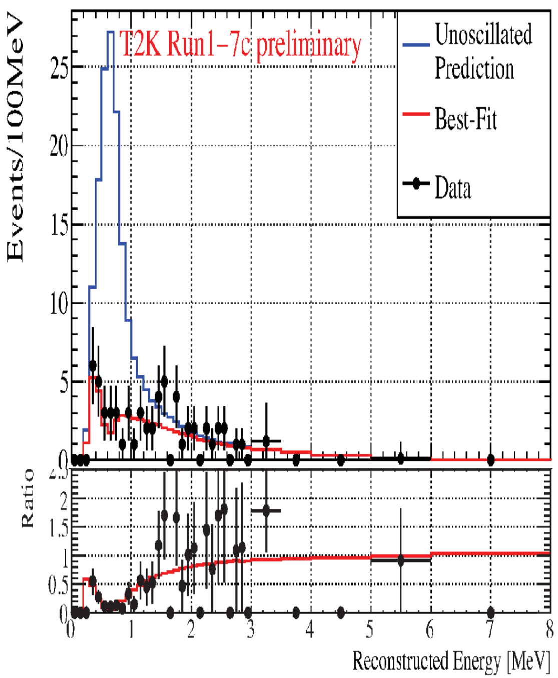
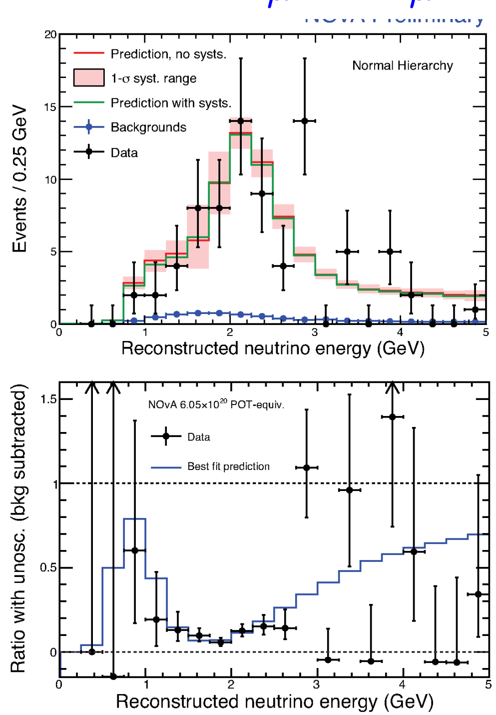


NOvA $\nu_\mu \to \nu_\mu$



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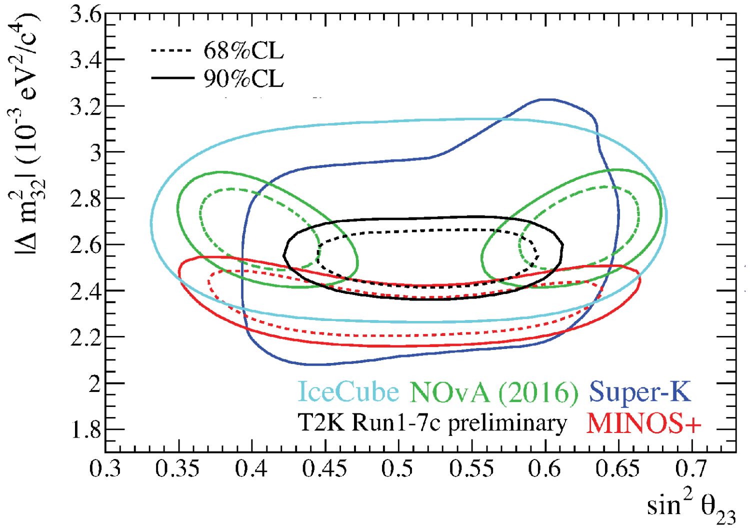
$$P_{\mu\mu} \simeq 1 - (c_{13}^4 \sin^2 2\theta_{23} + s_{23}^2 \sin^2 2\theta_{13}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \mathcal{O}(\Delta m_{21}^2)$$

• 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 $\bar\nu_\mu$ disappearance spectrum

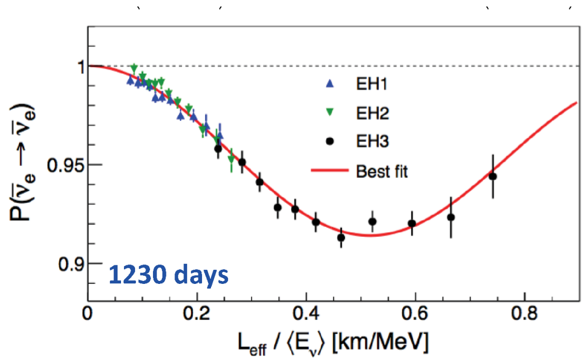
$$P_{\mu\mu} \simeq 1 - (c^4_{13}\sin^2 2\theta_{23} + s^2_{23}\sin^2 2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \mathcal{O}(\Delta m^2_{21})$$

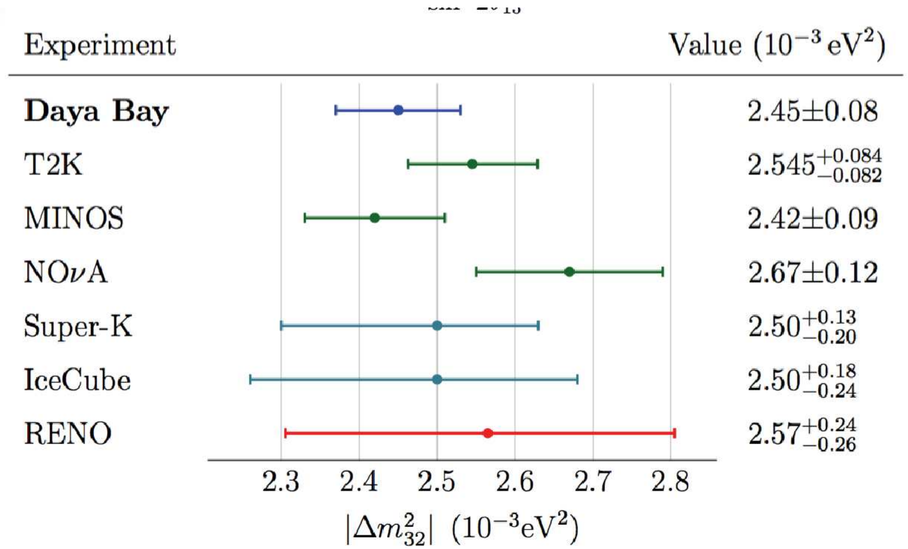
- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar\nu_e$ disapp spectrum

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

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

Nunokawa,Parke,Zukanovich (2005)





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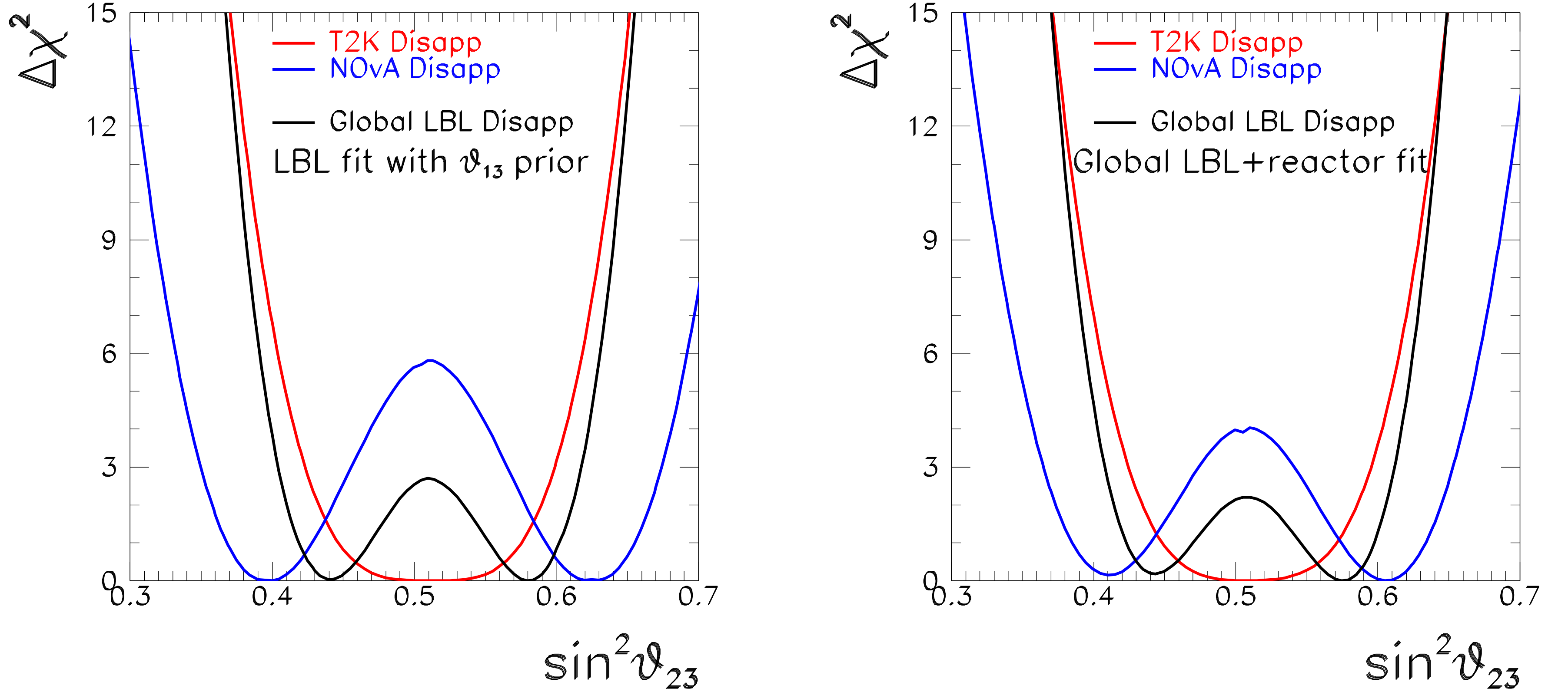
3 ν Analysis: θ_{23}

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

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



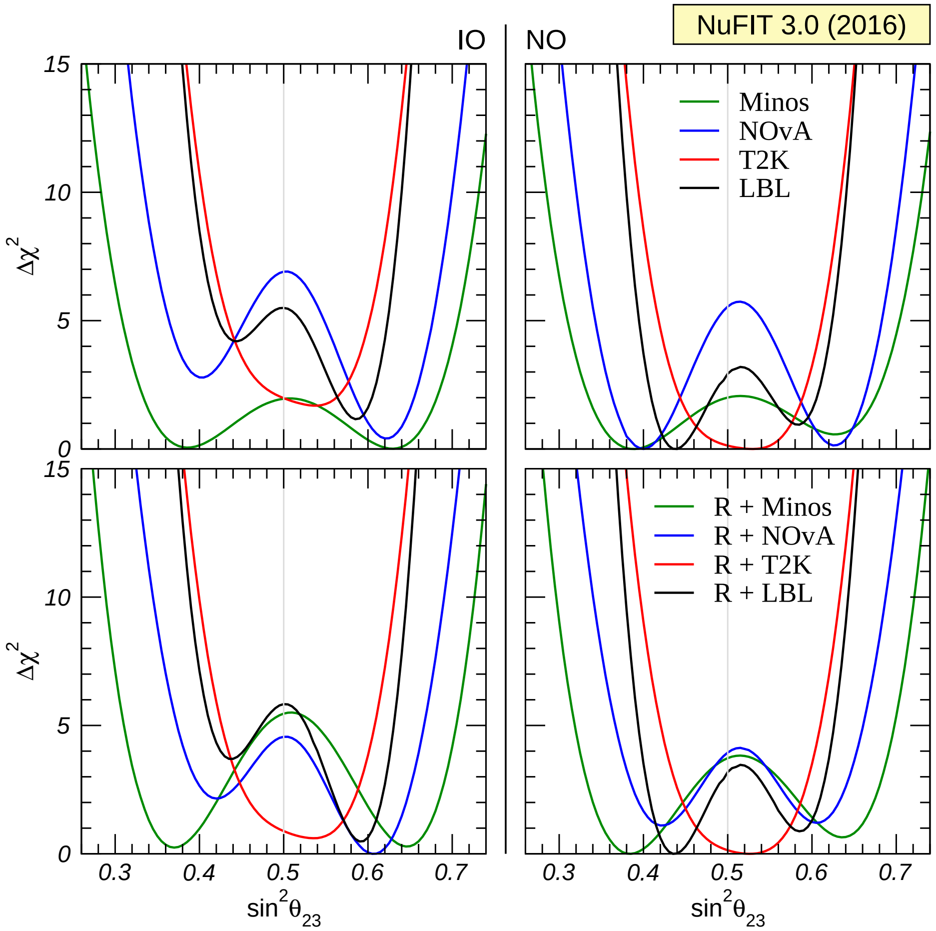
$\Rightarrow$ Impact on CL of non-maximality (also of Ordering and $\delta_{\rm CP}$)

3 ν Analysis: θ_{23} Octant, Ordering in LBL

- Dominant information from ν_e appearance in LBL

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

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



– Upper: LBL+θ_{13} prior from reactors

$\chi^2_{\mathrm{T2K}+\theta_{13}^{\mathrm{REA}}}(\mathrm{IO}) - \chi^2_{\mathrm{T2K}+\theta_{13}^{\mathrm{REA}}}(\mathrm{NO}) \simeq 1.7$

$\chi^2_{\mathrm{NO}\nu\mathrm{A}+\theta_{13}^{\mathrm{REA}}}(\mathrm{IO}) - \chi^2_{\mathrm{NO}\nu\mathrm{A}+\theta_{13}^{\mathrm{REA}}}(\mathrm{NO}) \simeq 0.5$

$\Delta\chi^2_{\mathrm{No}\nu\mathrm{A}+\theta_{13}^{\mathrm{REA}}}(\frac{\pi}{4}) > \Delta\chi^2_{\mathrm{Minos}+\theta_{13}^{\mathrm{REA}}}(\frac{\pi}{4})$

– Lower: LBL+Reactors

$\chi^2_{\mathrm{T2K+REAC}}(\mathrm{NO}) - \chi^2_{\mathrm{T2K+REAC}}(\mathrm{IO}) = 0.6$

$\chi^2_{\mathrm{NO}\nu\mathrm{A+REAC}}(\mathrm{NO}) - \chi^2_{\mathrm{NO}\nu\mathrm{A+REAC}}(\mathrm{IO}) = -1.1$

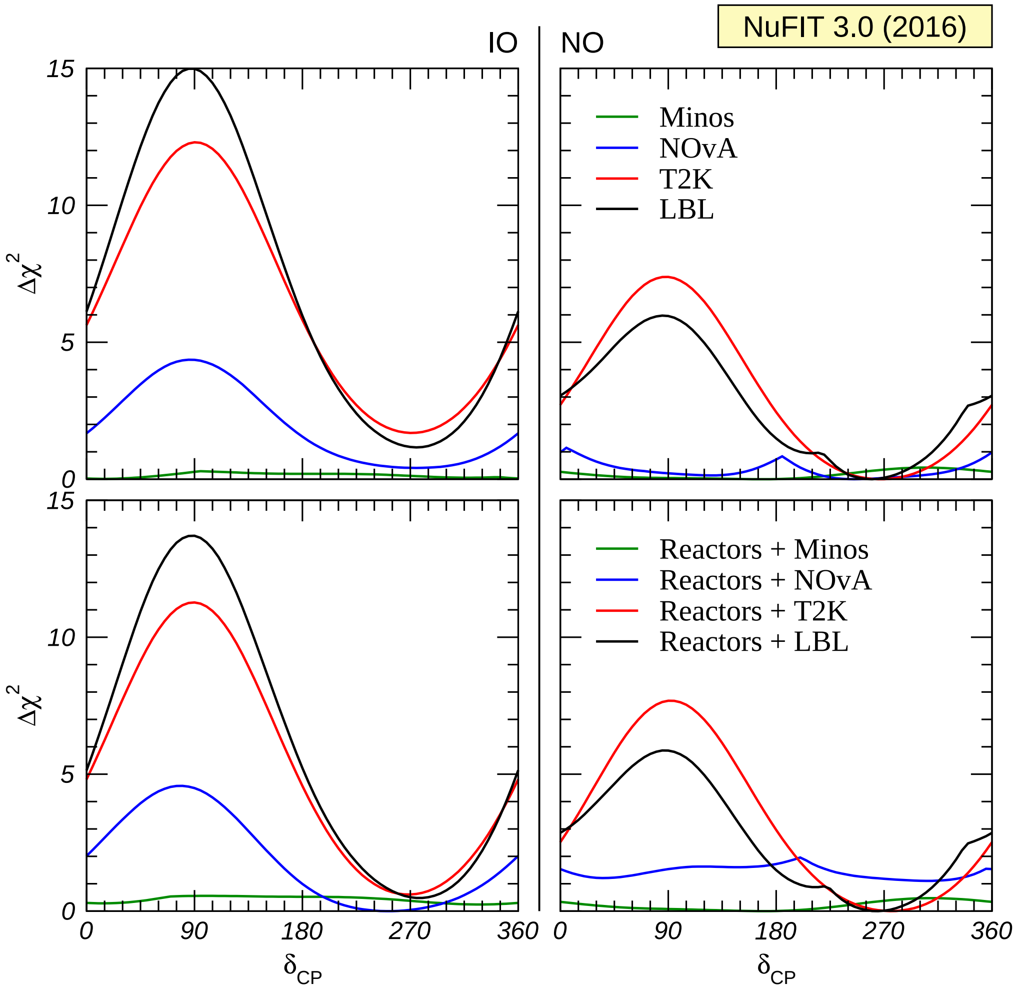
$\Delta\chi^2_{\mathrm{No}\nu\mathrm{A+REAC}}(\frac{\pi}{4}) < \Delta\chi^2_{\mathrm{Minos+REAC}}(\frac{\pi}{4})$

3 ν Analysis: $\delta_{\rm CP}$ and Ordering in LBL

- Dominant information from ν_e appearance in LBL

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

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



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 & $\delta_{\rm CP} = \frac{3\pi}{2} (\equiv -\frac{\pi}{2})$

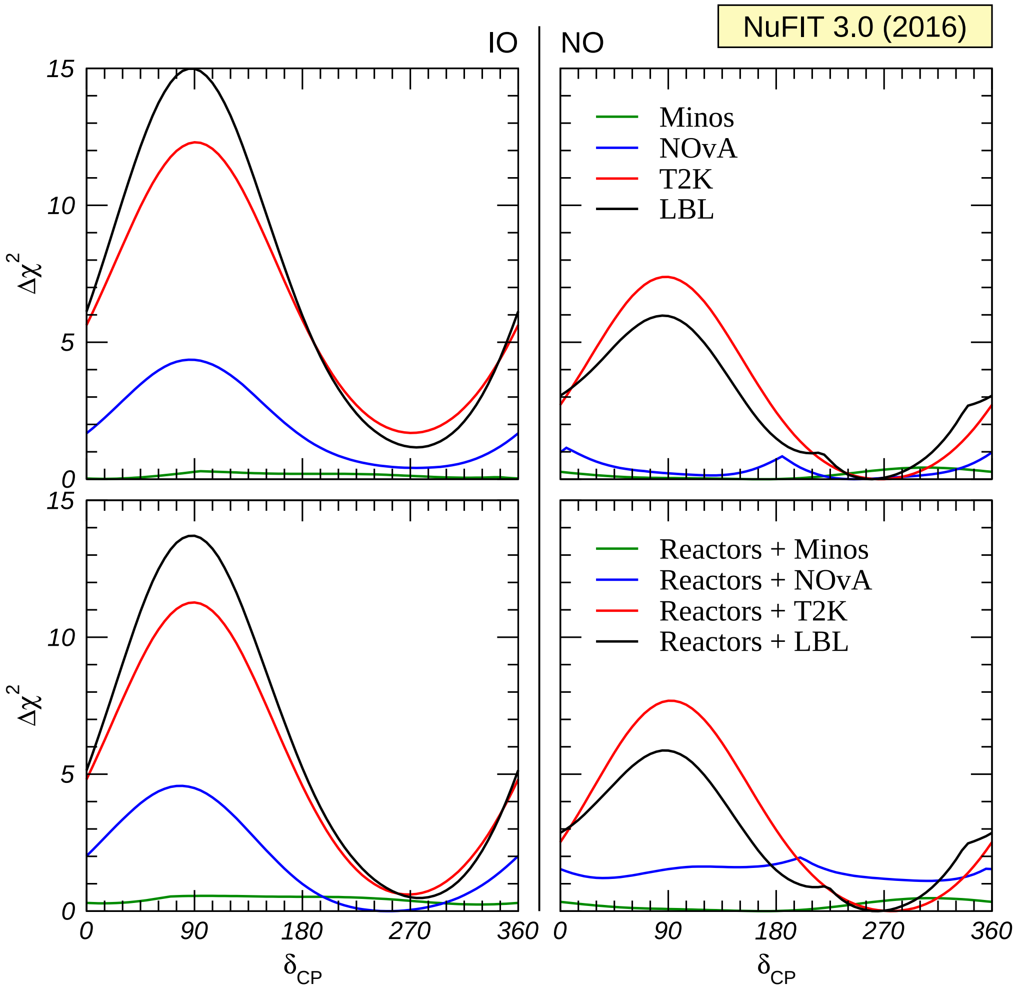
$\Rightarrow$ Significance of $\delta_{\rm CP} = \frac{3\pi}{2}$ and NO larger than expected nzalez-Garcia

3 ν Analysis: $\delta_{\rm CP}$ and Ordering in LBL

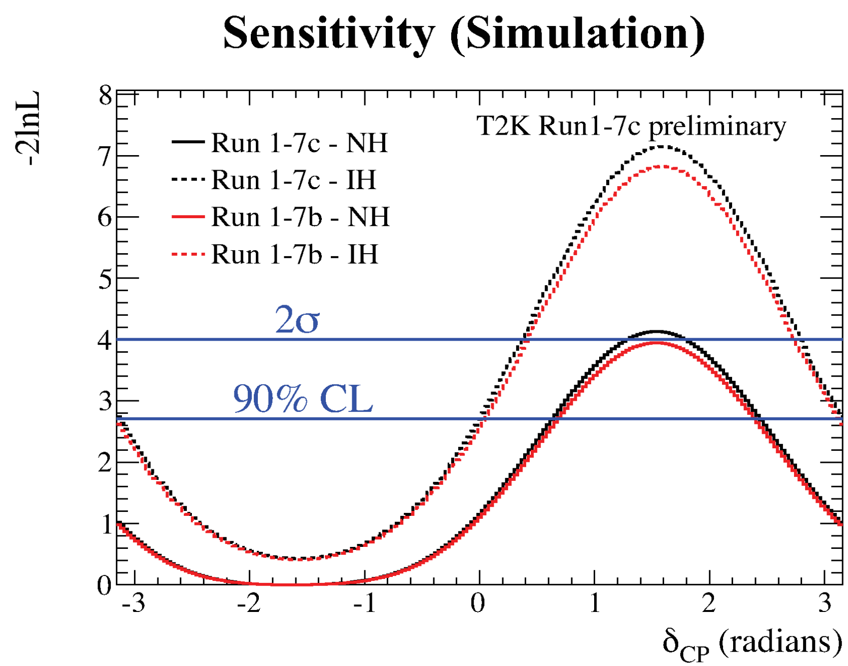
- Dominant information from ν_e appearance in LBL

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

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



In T2K:



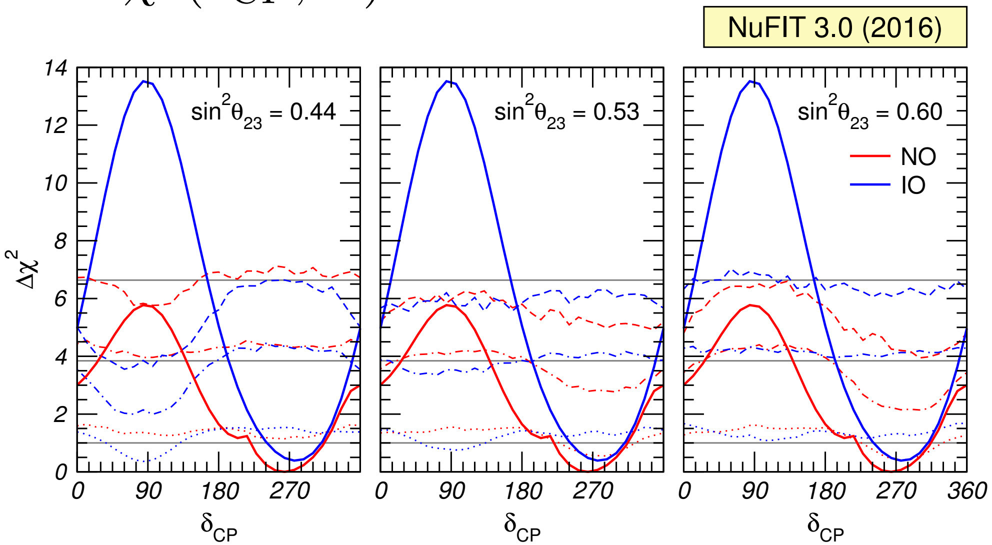
$\Rightarrow$ Significance of $\delta_{\rm CP} = \frac{3\pi}{2}$ and NO

larger than expected

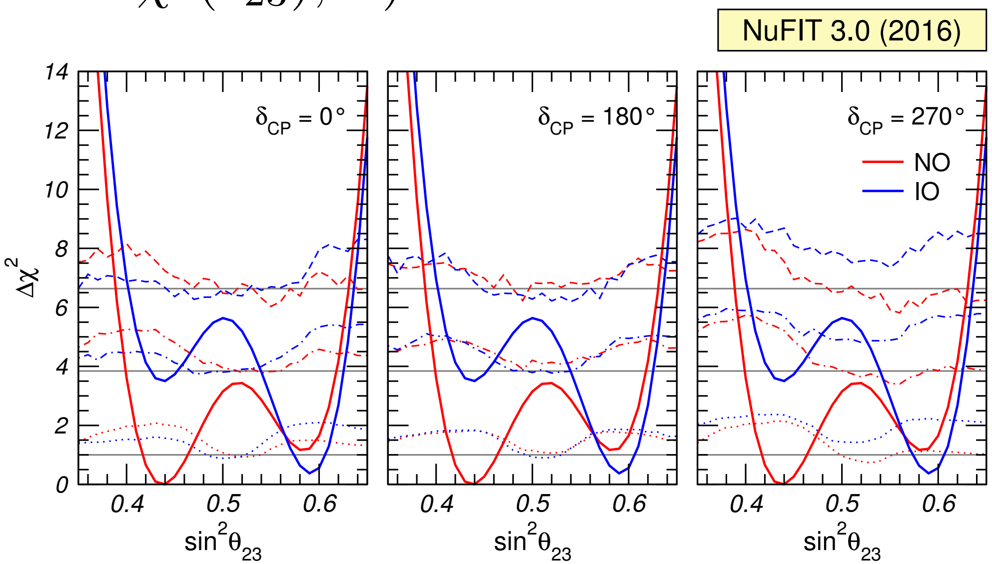
3 ν Analysis: CL of CP, Ordering and Octant hints

MC generation of Prob Distribution of

- $\Delta\chi^2(\delta_{\rm CP}, \mathcal{O})$ for LBL+Reactors



- $\Delta\chi^2(\theta_{23}), \mathcal{O})$ for LBL+Reactors



– Maximal Deviation of Gaussian CL at:

$P_{e\mu}$ max: $\delta_{CP} = 90$, $\theta_{23} < \frac{\pi}{4}$, IO

$P_{e\mu}$ max: $\delta_{CP} = 270$, $\theta_{23} > \frac{\pi}{4}$, NO

– NO/IO favour/reject CL $< 1\sigma$ (30–40%)

– Reject $\theta_{23} = \frac{\pi}{4}$ at $\sim$ 92% CL in NO

$\theta_{23} > \frac{\pi}{4}$ disfavored with 62–70 % for NO

$\theta_{23} < \frac{\pi}{4}$ disfavored with 83–91 % for IO

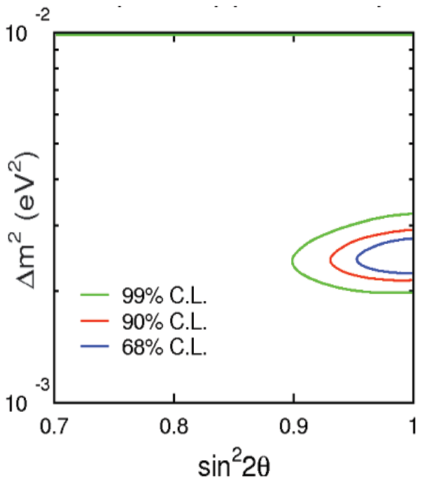
– CP cons disfavoured with 70% for NO

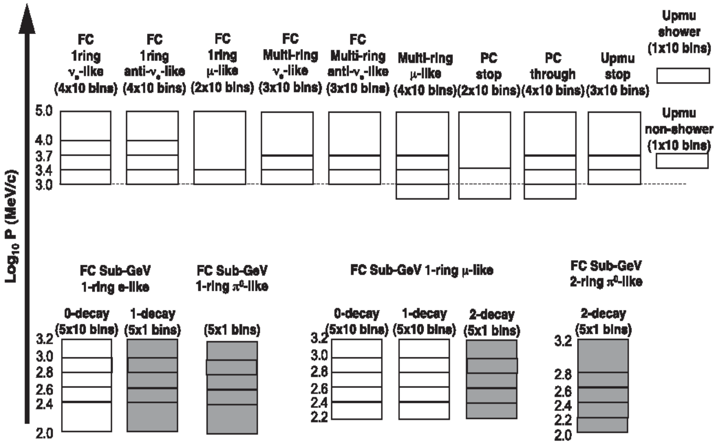
$\delta_{CP} = 90$ disfavoured with $\sim$ 99% CL NO

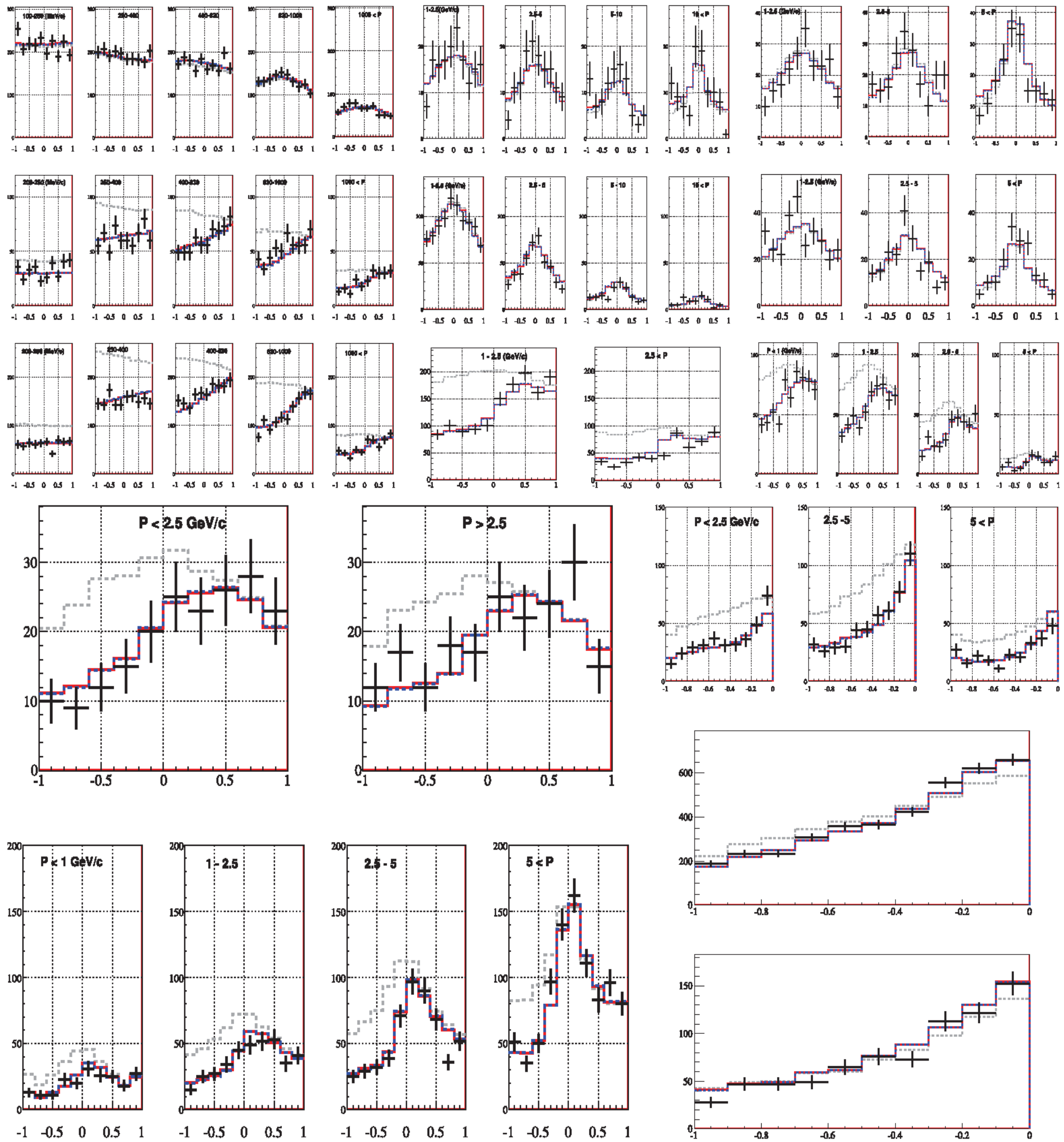
$\delta_{CP} = 90$ disfavoured at $> 3\sigma$ CL for IO

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





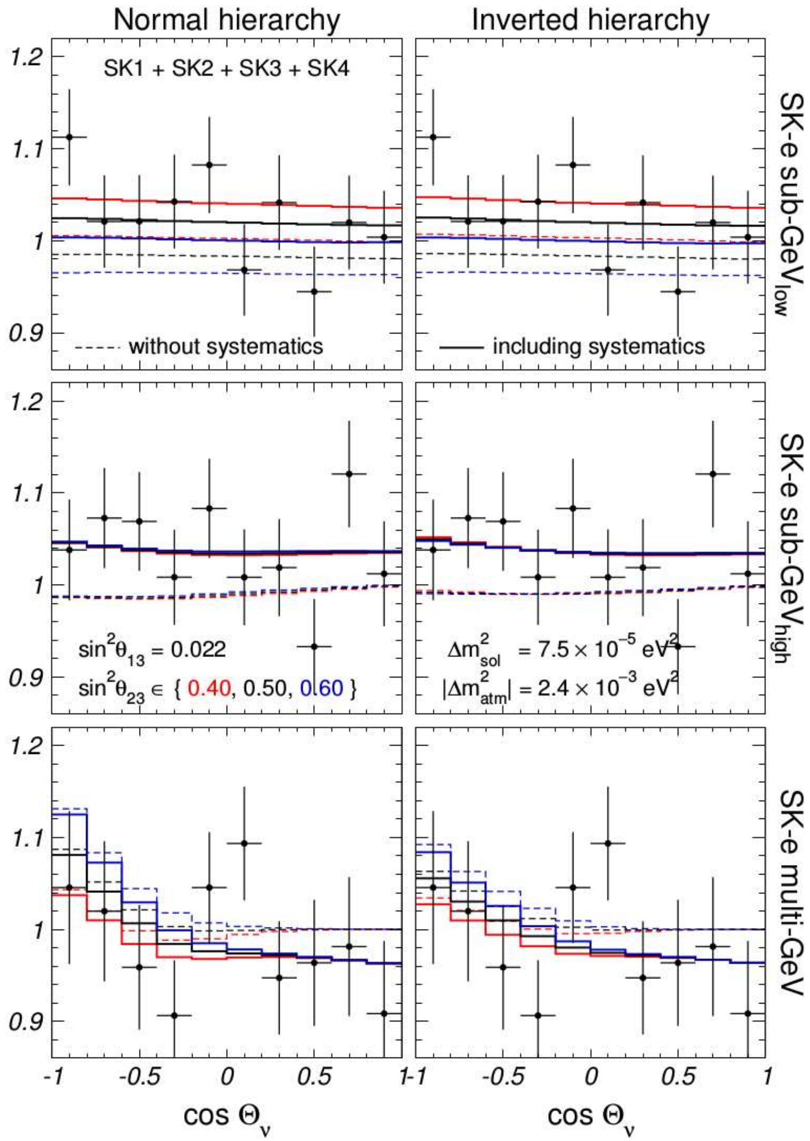


3 ν Analysis: Ordering, $\delta_{\rm CP}$ in ATM

- 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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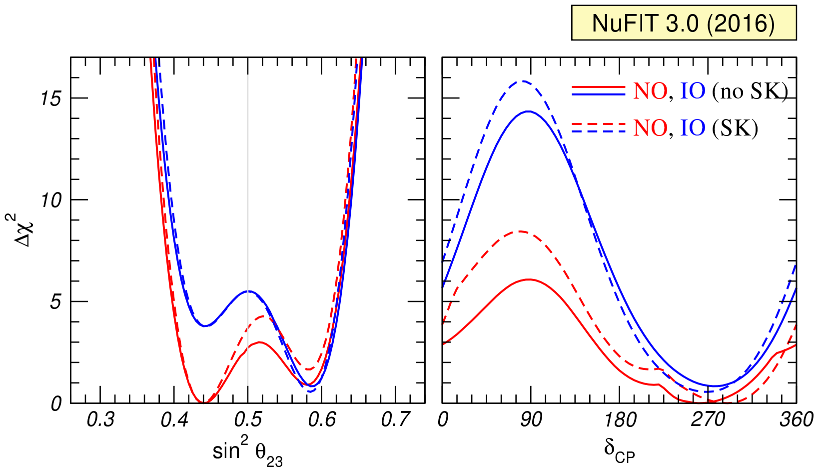
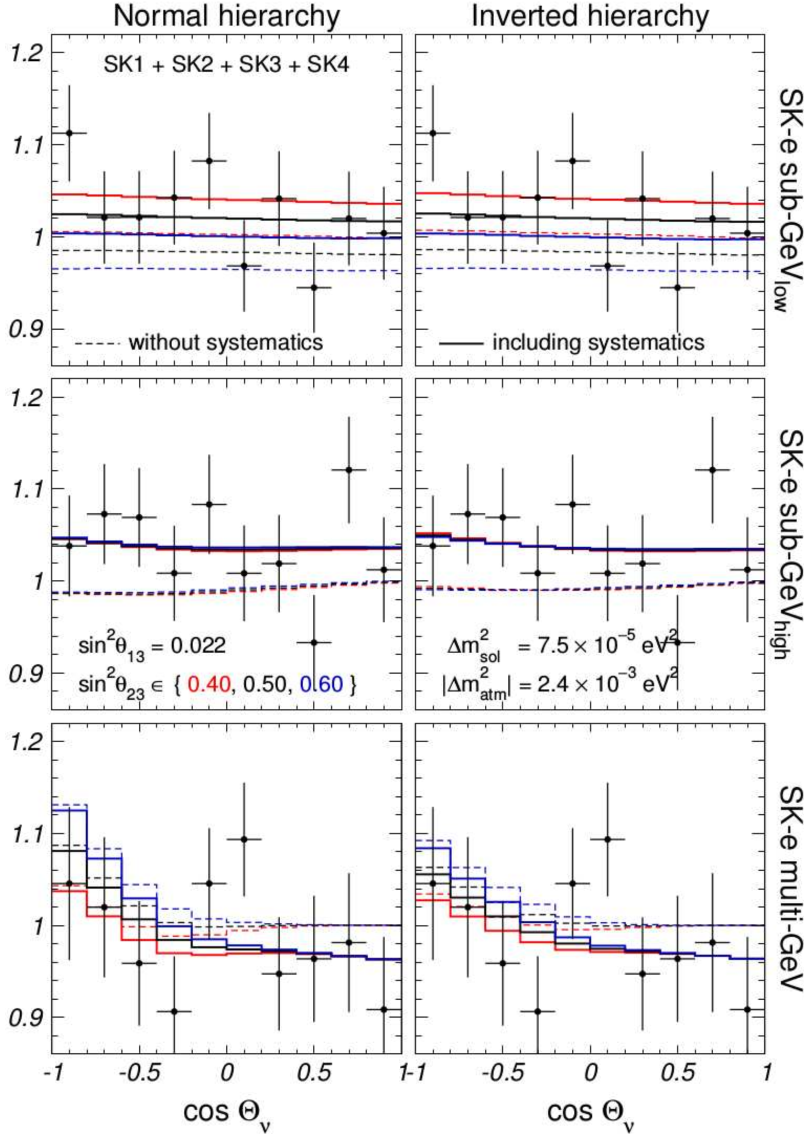
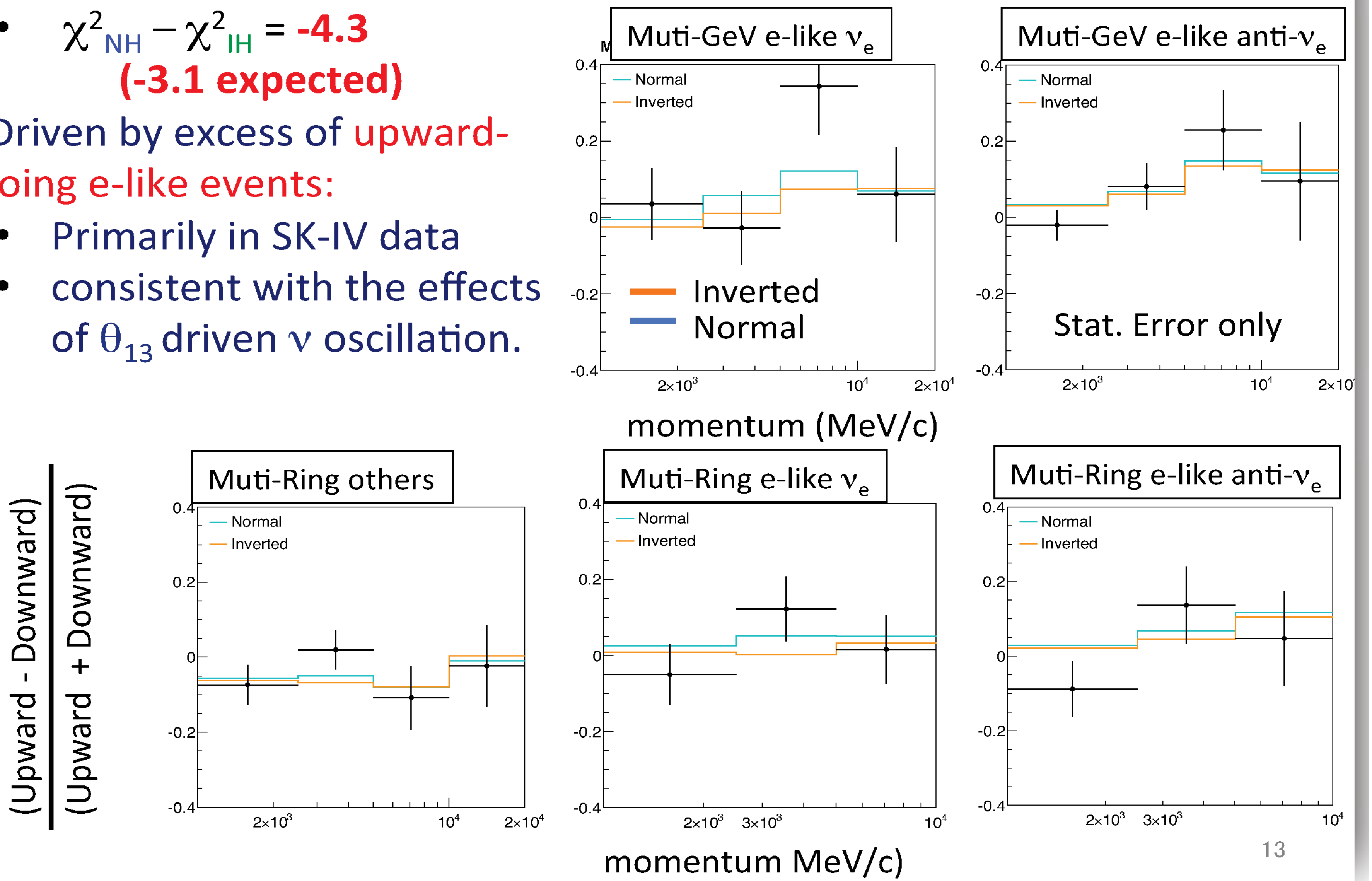


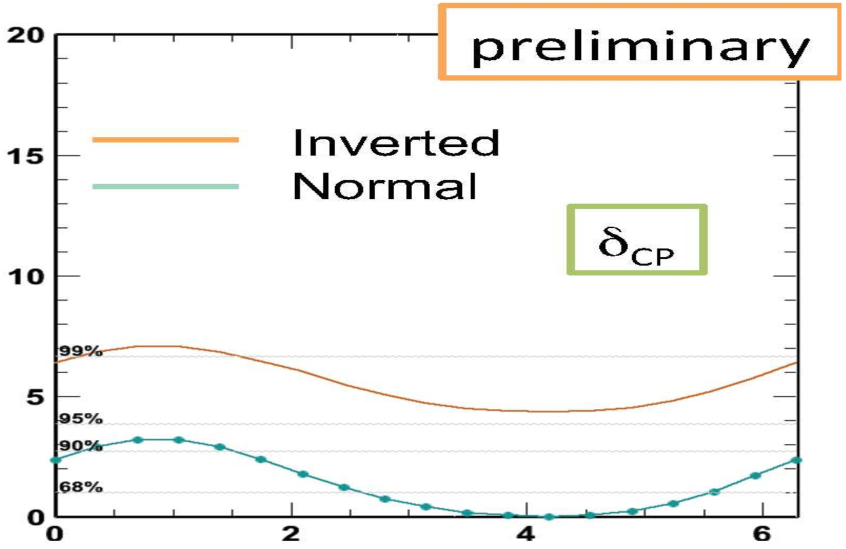


- **Normal** hierarchy favored at:
  - $\chi^2_{NH} - \chi^2_{IH}$ = **-4.3** **(-3.1 expected)**
- Driven by excess of upward-going e-like events:
  - Primarily in SK-IV data
  - consistent with the effects of θ_{13} driven ν oscillation.

Upward/Downward asymmetry in energetic electron samples (νe/anti-νe enriched)



J. Kameda (SK) talk at Nufact 2016



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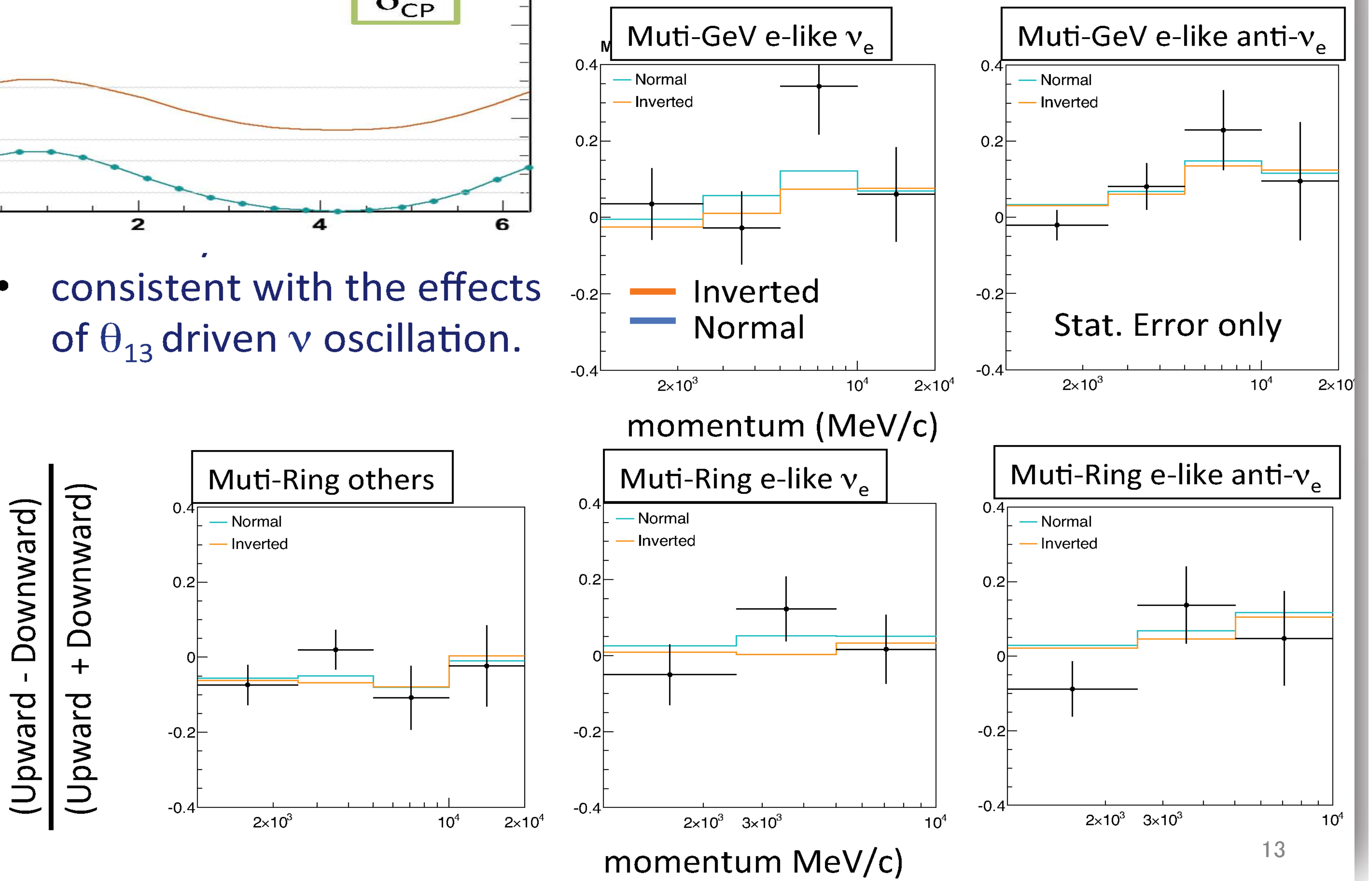
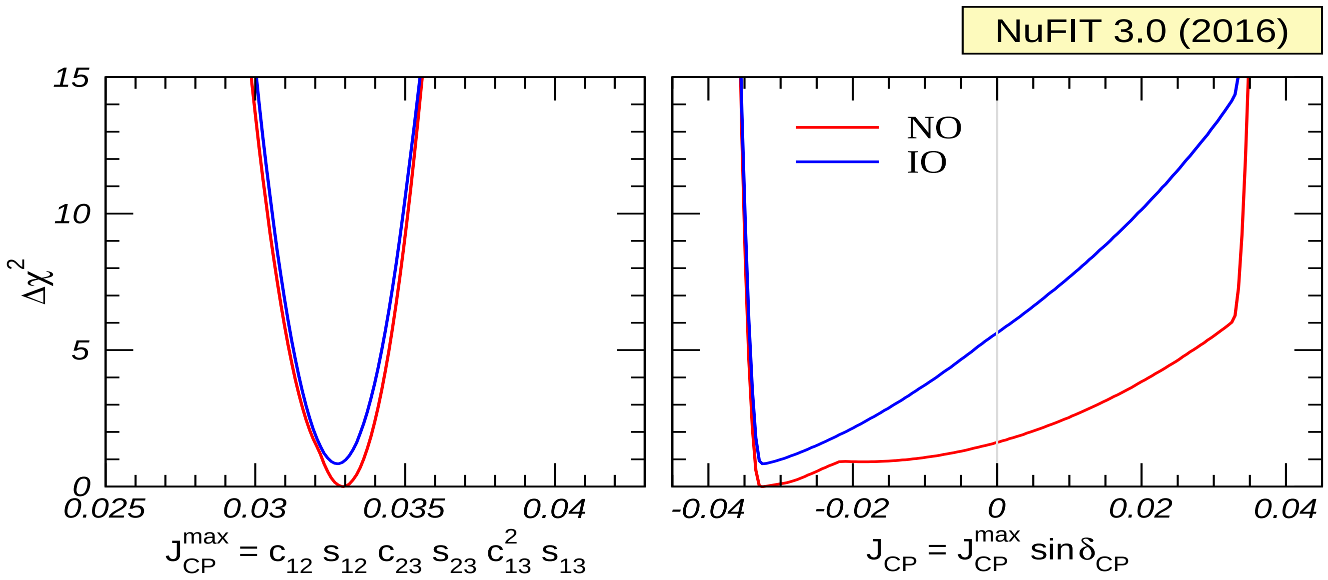


J. Kameda (SK) talk at Nufact 2016

3 ν Analysis: CP violation present status

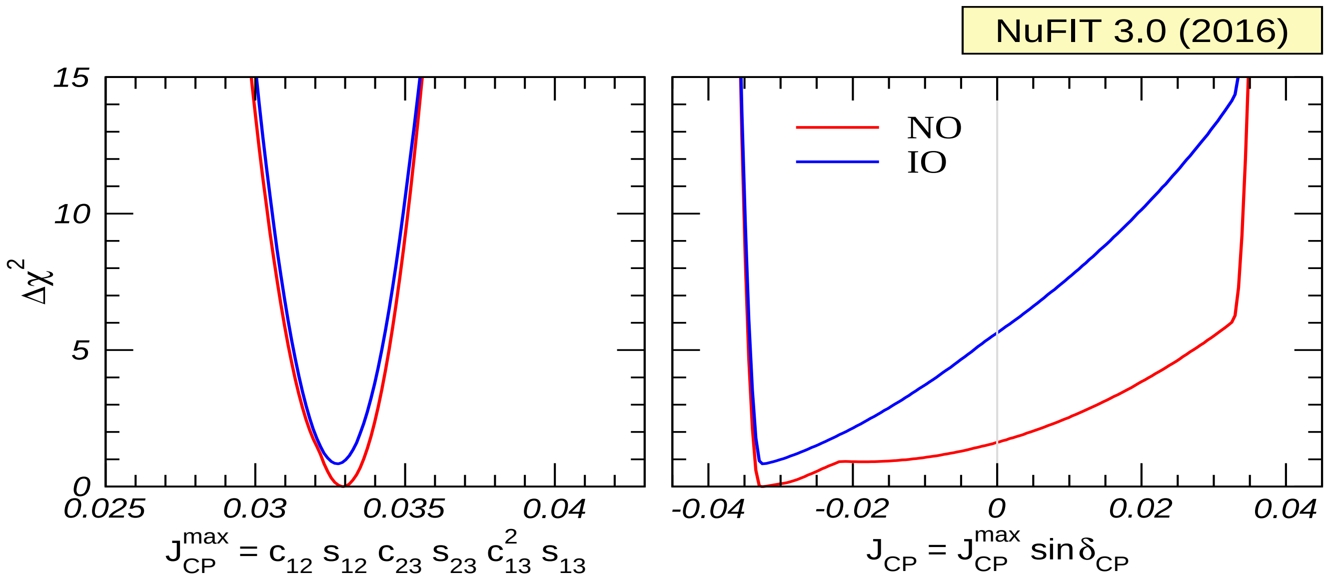


$J_{\rm LEP,CP}^{\rm max} = (3.29 \pm 0.07) \times 10^{-2}$

to compare with

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

3 ν Analysis: CP violation present status



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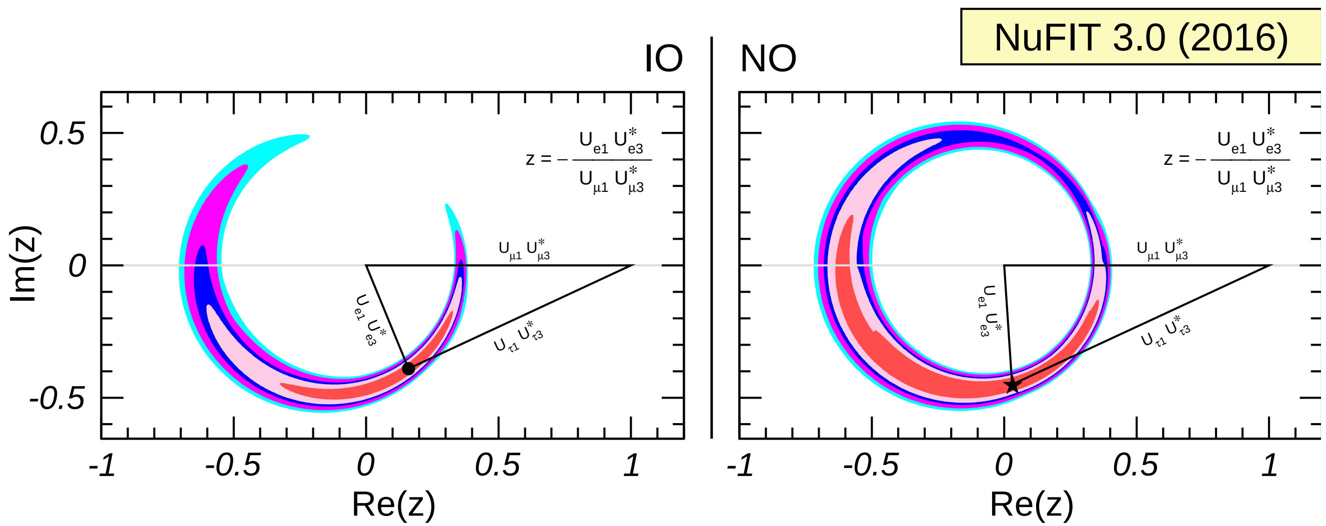
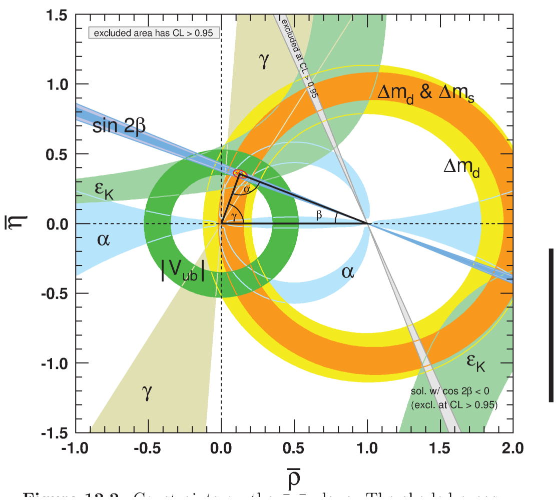
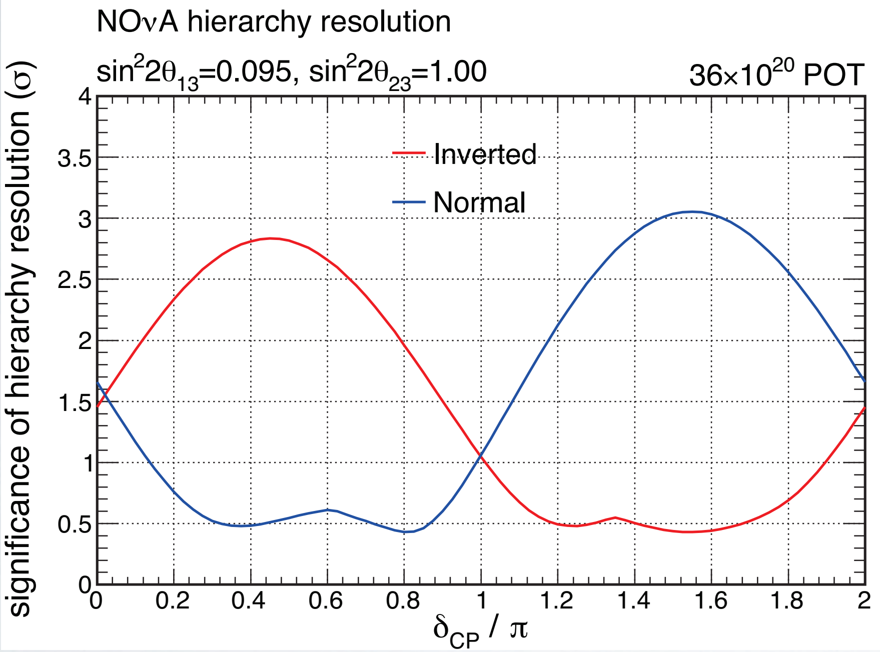
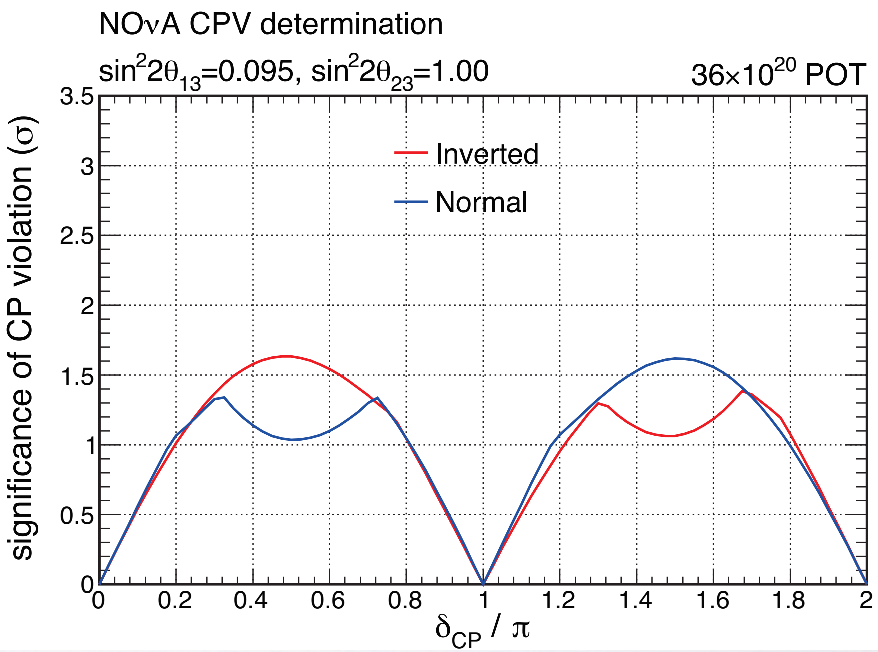




MASS HIERARCHY AND CP-VIOLATION





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

Concha Gonzalez-Garcia

A Detour in the Sun

- Sun=Main sequence star
- Solar Models describes the Sun based on:

Mass:	$M_\odot = 2 \times 10^{33}$ gr
Radius:	$R_\odot = 7 \times 10^{5}$ km
Surf Lum:	$L_\odot = 3.842 \times 10^{33} (1 \pm 0.004)$ erg/sec
Age:	$\tau_\odot = 4.57 \times 10^{9} (1 \pm 0.0044)$ yr

- Basic assumptions:

- The Sun is spherically symmetric
- Some Equation of State

- Incorporate:

- Transport of Energy: Radiative and Convective

$\Rightarrow$ Model of opacities

- Chemical Evolution by Nuclear Reactions

$\Rightarrow$ pp-chain and CNO cycles

- Microscopic Diffusion

- Using inputs from:

- Lab Measurements of Nuclear Rates
- Element Abundance Determination By

$\Rightarrow$ Spectroscopy of Photosphere: C, N, O

$\Rightarrow$ Meteorites: Mg,Si,S,Fe

$\Rightarrow$ Other methods: Ne, Ar

- They Predict Observables:

- Neutrino Flux Spectrum
- Relevant to Helioseismology :

$\Rightarrow$ Surface He Abundance

$\Rightarrow$ Inner Radius of Convective Zone

$\Rightarrow$ Sound Speed Profile

The Solar Composition Problem

– Newer determination of abundances in solar surface give lower values

$\log \epsilon_i \equiv \log N_i/N_H + 12$

Element	GS98	AGSS09met
C	8.52 ± 0.06	8.43 ± 0.05
N	7.92 ± 0.06	7.83 ± 0.05
O	8.83 ± 0.06	8.69 ± 0.05
Mg	7.58 ± 0.01	7.53 ± 0.01
Si	7.56 ± 0.01	7.51 ± 0.01
S	7.20 ± 0.06	7.15 ± 0.02
Fe	7.50 ± 0.01	7.45 ± 0.01
Ar	6.40 ± 0.06	6.40 ± 0.13
Ne	8.08 ± 0.06	7.93 ± 0.10

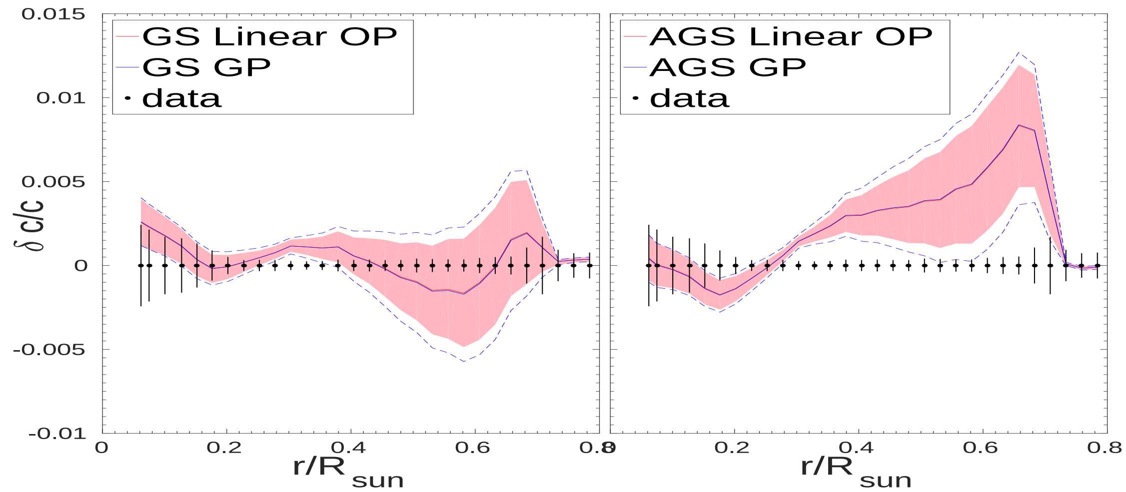
$\Rightarrow$ Two sets of SSM:

Starting from Bahcall *etal* 05, Serenelli *etal* 2016

B16-GS98 with old abund

B16-AGSS09met with new abund

– Solar Models with lower metalicities fail in reproducing helioseismology data



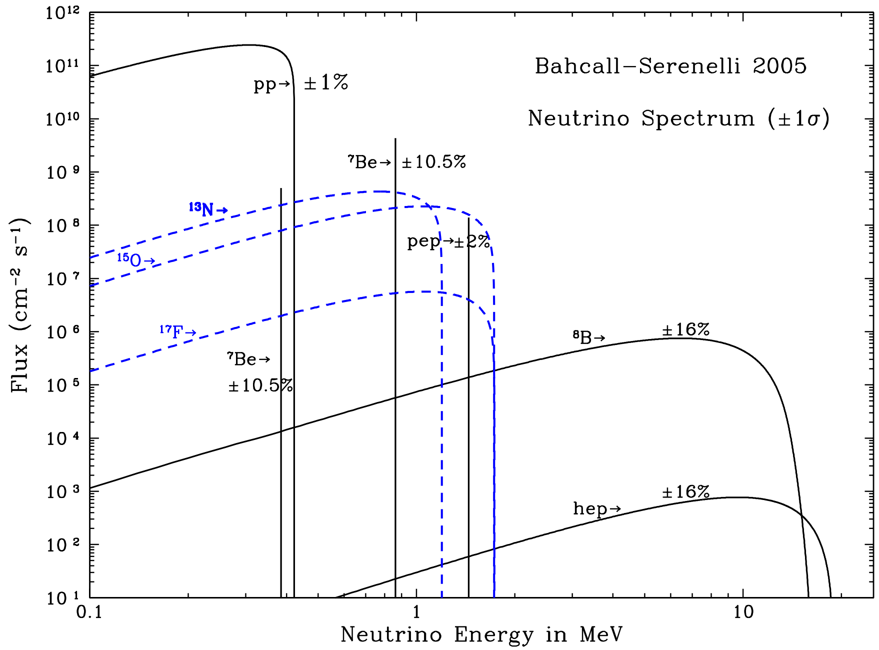
Predictions very strongly correlated

– B16-GS98 (dis)agreement at 2.5 σ

– B16-AGSS09 disagreement 4.7 σ

– Bayes factor B16-AGSS09/B16-GS98<-13 (very strong disfavouring)

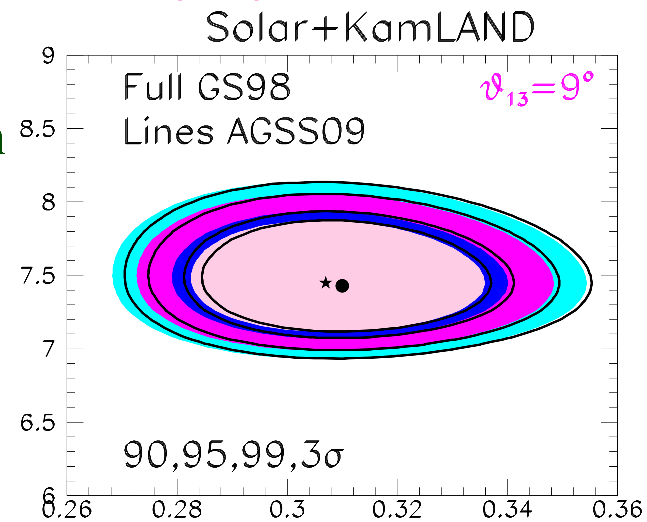
The Neutrino Fluxes



Flux cm^{-2} s^{-1}	B16GS98	B16-AGSS09met	Diff (%)
$pp/10^{10}$	5.98	$6.03\ (1 \pm 0.005)$	0.8
$pep/10^{8}$	1.44	$1.46\ (1 \pm 0.01)$	2.1
$hep/10^{3}$	7.98	$8.25\ (1 \pm 0.30)$	3.4
$^{7}Be/10^{9}$	4.93	$4.40\ (1 \pm 0.06)$	8.8
$^{8}B/10^{6}$	5.46	$4.50\ (1 \pm 0.12)$	17.7
$^{13}N/10^{8}$	2.78	$2.04(1 \pm 0.14)$	**26.7**
$^{15}O/10^{8}$	2.05	$1.44\ (1 \pm 0.16)$	**30.0**
$^{17}F/10^{16}$	5.29	$3.26\ (1 \pm 0.18)$	**38.4**

Most difference in CNO fluxes

– Neglegeable Impact in Osc Parameter Determination



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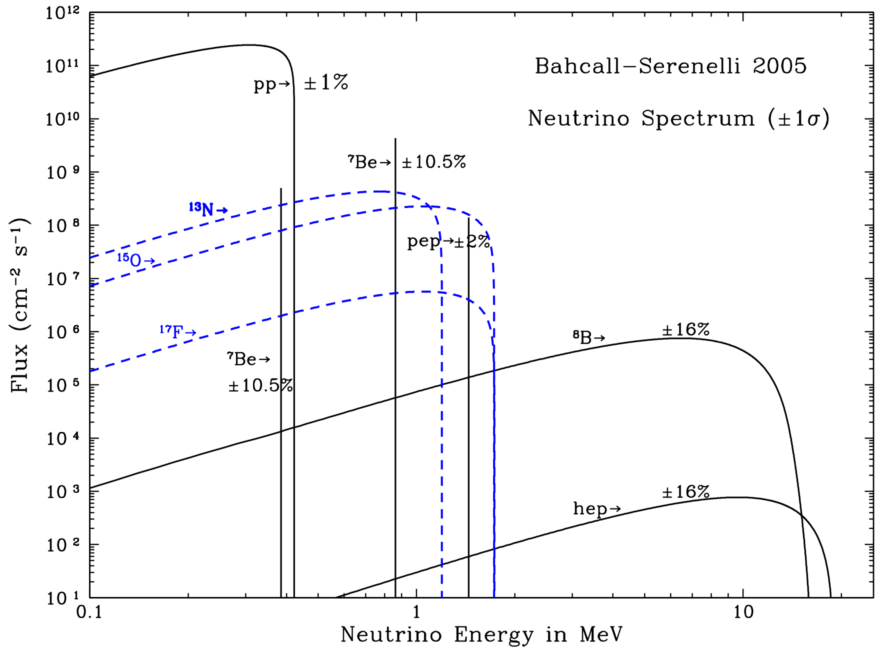
The Neutrino Fluxes



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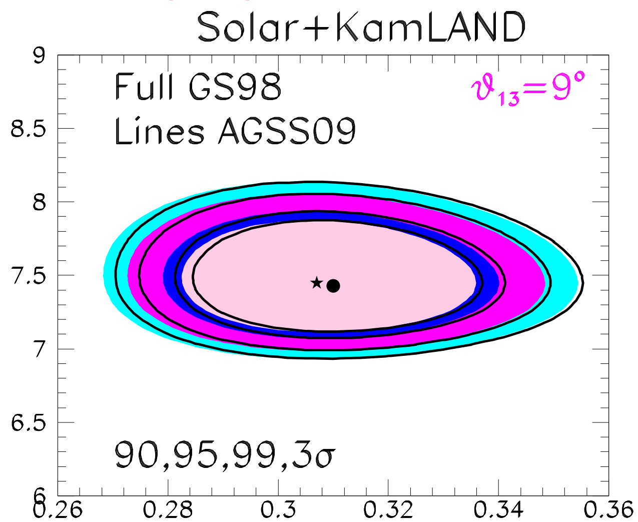
Most difference in CNO fluxes

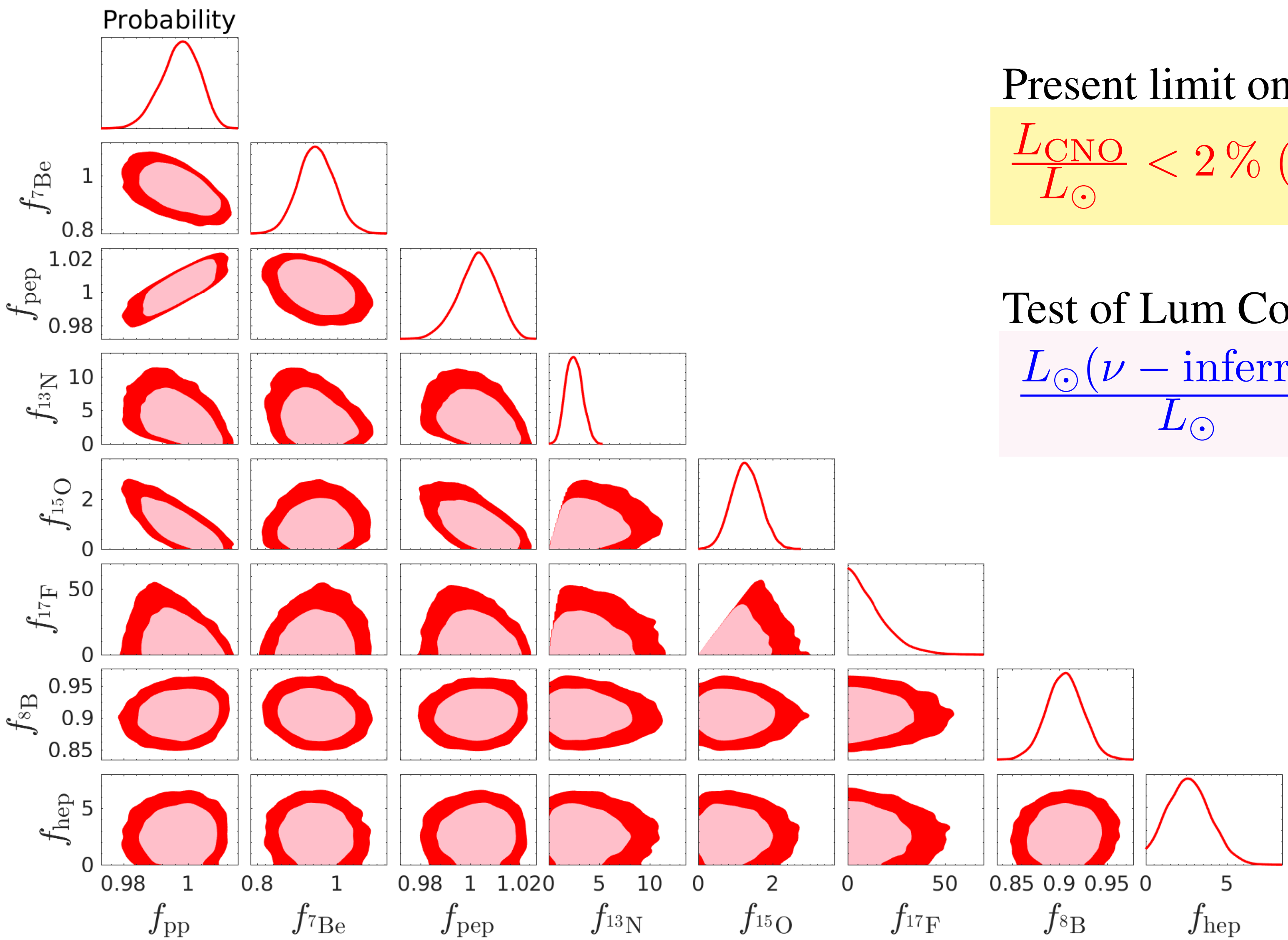
– Neglegeable Impact in Osc Parameter Determination

⇒ Possible to extract fluxes for data



Testing 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:

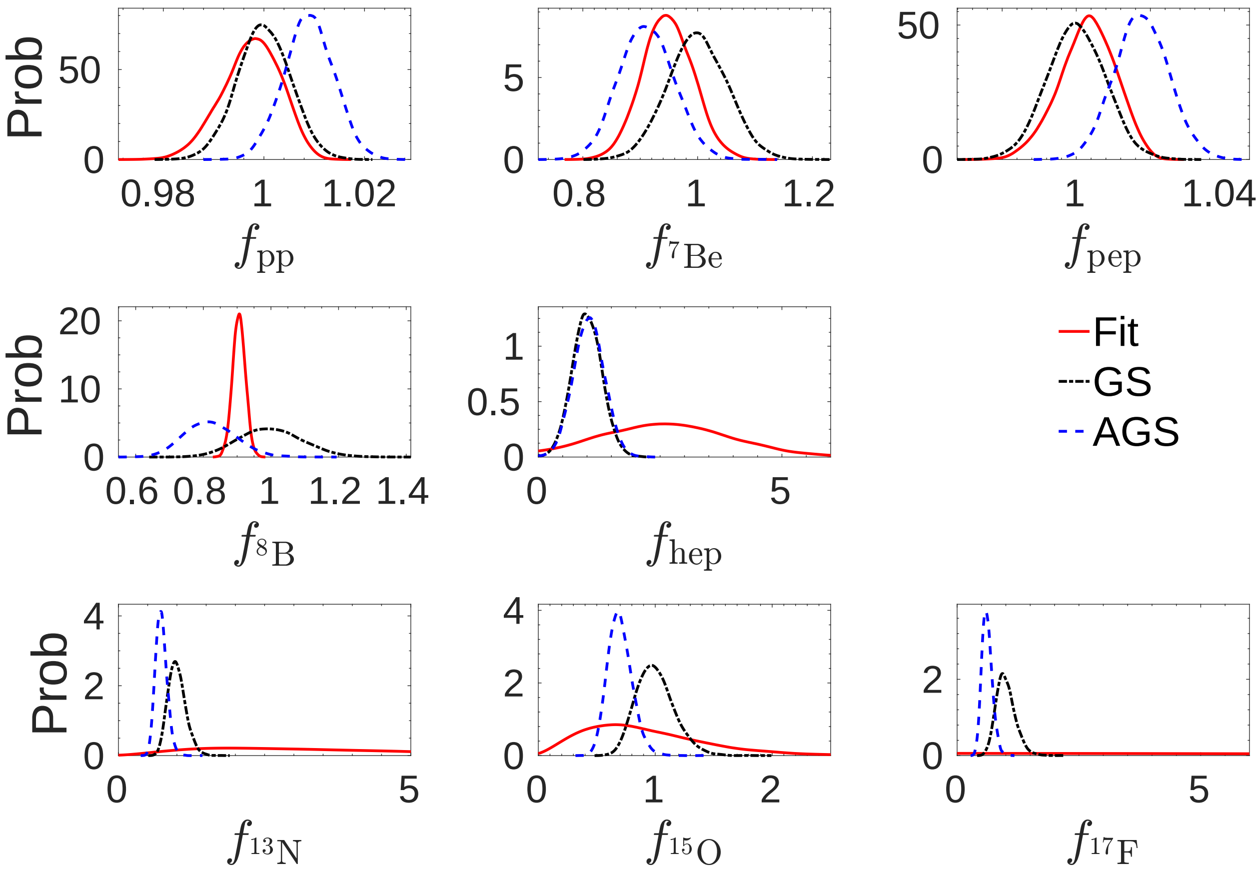
$$\frac{L_{\mathrm{CNO}}}{L_\odot} < 2\,\% \; (3\sigma)$$

Test of Lum Constraint:

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

Fitted Fluxes vs Composition Models

Comparing the empirically determined fluxes with B16-GS98 and B16-AGSS09



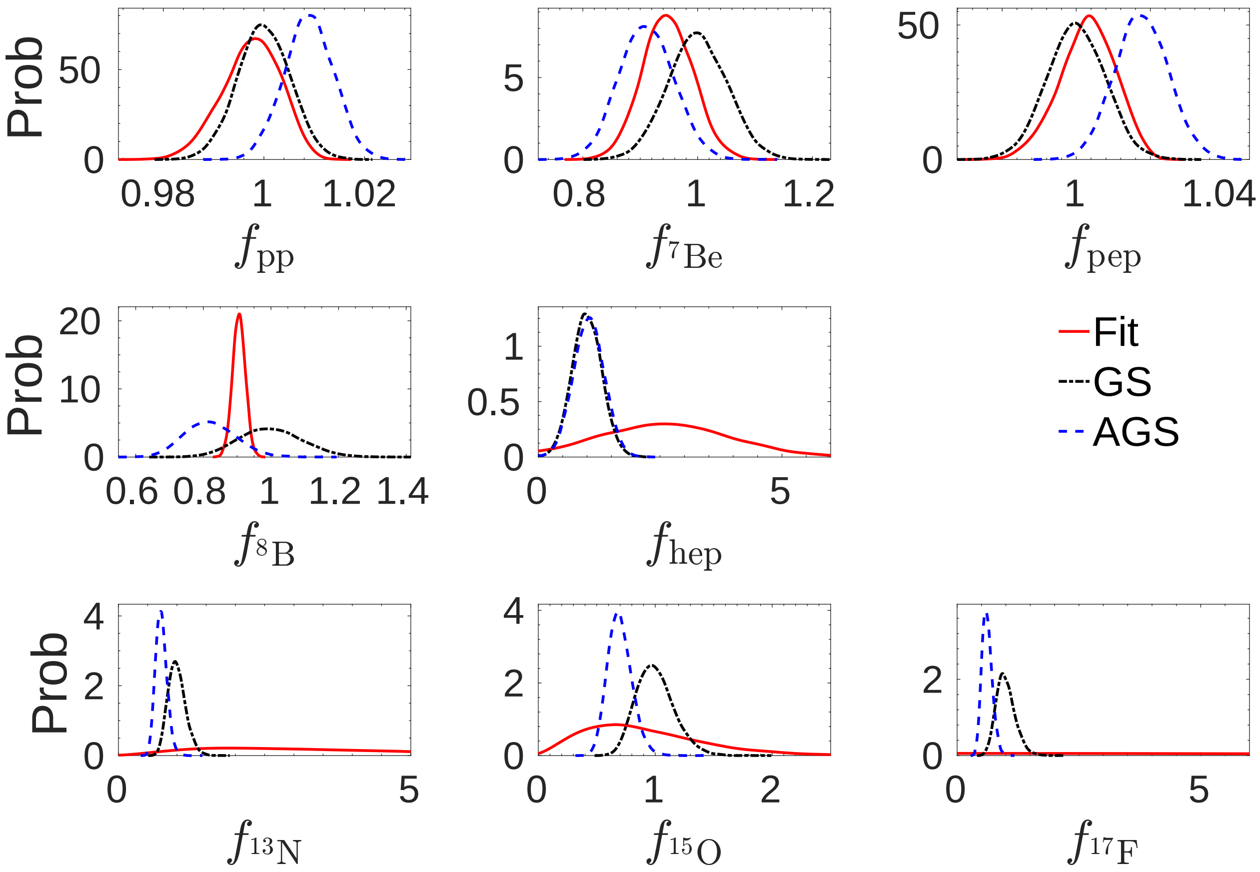
Comparing models and fit ν fluxes:

$\chi^2_{\nu\ \mathrm{flux}}(\mathrm{B16-AGSS09met}) - \chi^2_{\nu\ \mathrm{flux}}(\mathrm{B16-GS98}) = 1.2$

(their Bayes factor $|\ln B| < 0.5$)

Fitted Fluxes vs Composition Models

Comparing the empirically determined fluxes with B16-GS98 and B16-AGSS09



New experiments needed sensitive to CNO fluxes

Using Helioseismic and ν-flux data in Solar Modeling?

MCG-G,Maltoni,Peña-Garay,Serenelli

Song, Vinyoles,Villante in progress

Comparing models and fit ν fluxes:

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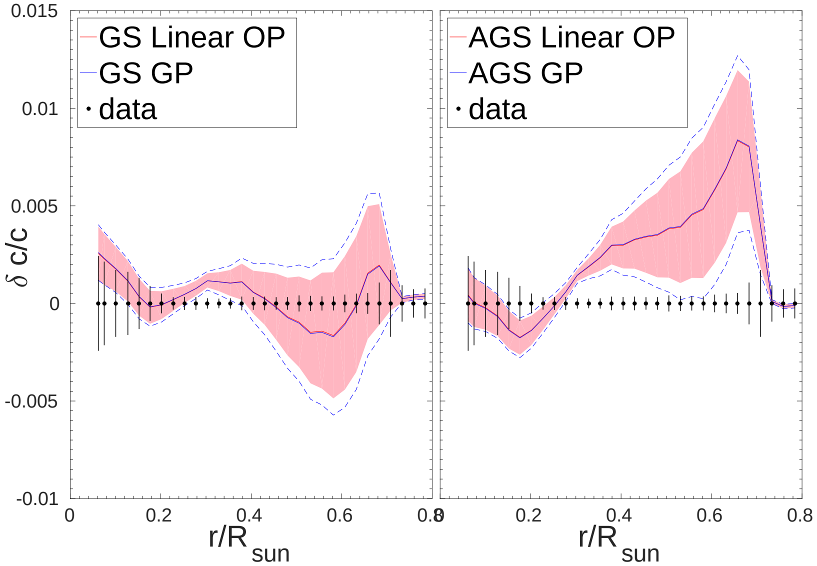
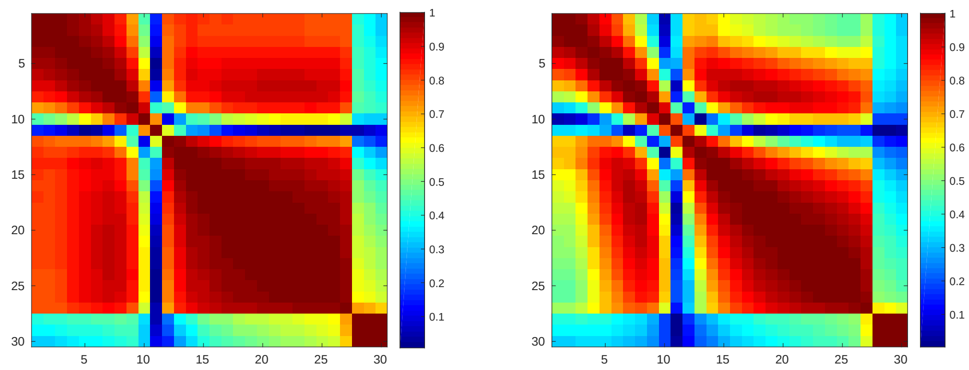
Modeling the uncertainty in the opacity profile

- Opacity is a function $\kappa(T,\rho,X_i = N_i/N_H)$. How to parametrize its uncertainty?
- Generically $(1+\delta\kappa(T))\langle\kappa(T,\rho,X_i)\rangle$
  $\Rightarrow$ Most studies $\delta\kappa(T) = C$ or $\delta\kappa(T) = a + b\log T$ with prior for σ_C (or σ_a,σ_b)
  $\Rightarrow$ only very rigid variations allowed
- Alternative: Gaussian Process anszat with same $\sigma(T)$ but correlation length $L < 1$



Correlations in predictions (blue=0 to red=1)

Linear $\delta\kappa$ | Gaussian Process $\delta\kappa$

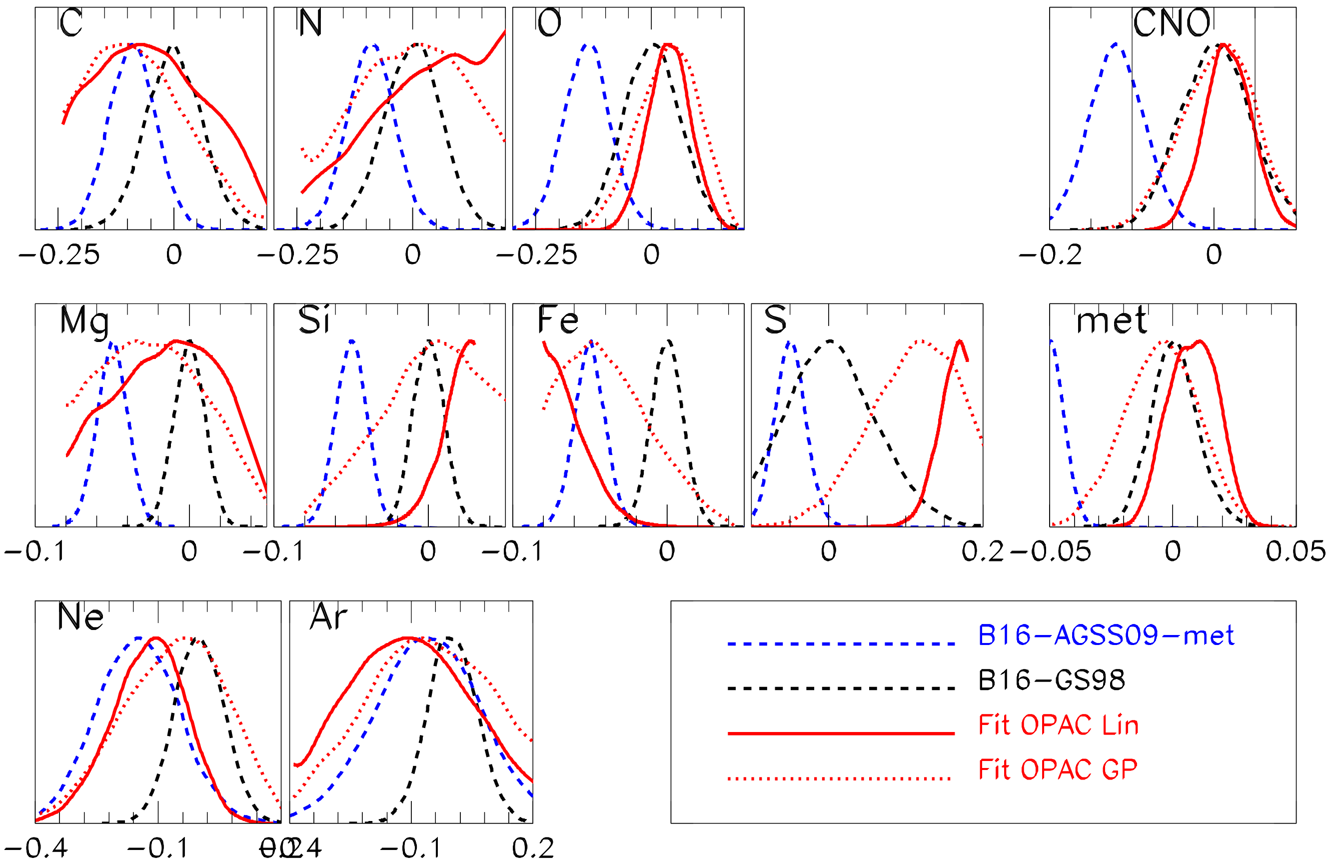


Still, even with GP opacity uncertainty Bayes factor B16-AGSS09/B16-GS98=-4.1
(Moderate to strong disfavour)

Using ν and Helioseismic Data in Sun Modeling

- Proposal: Invert approach and use the ν and helioseismic data in construction of SSM
- Method: Bayesian Inference of Abundance Posterior Distrib (from Uniform Priors)
- Test effects of effects of other modeling aspects (f.e. opacity uncertainty profiles)

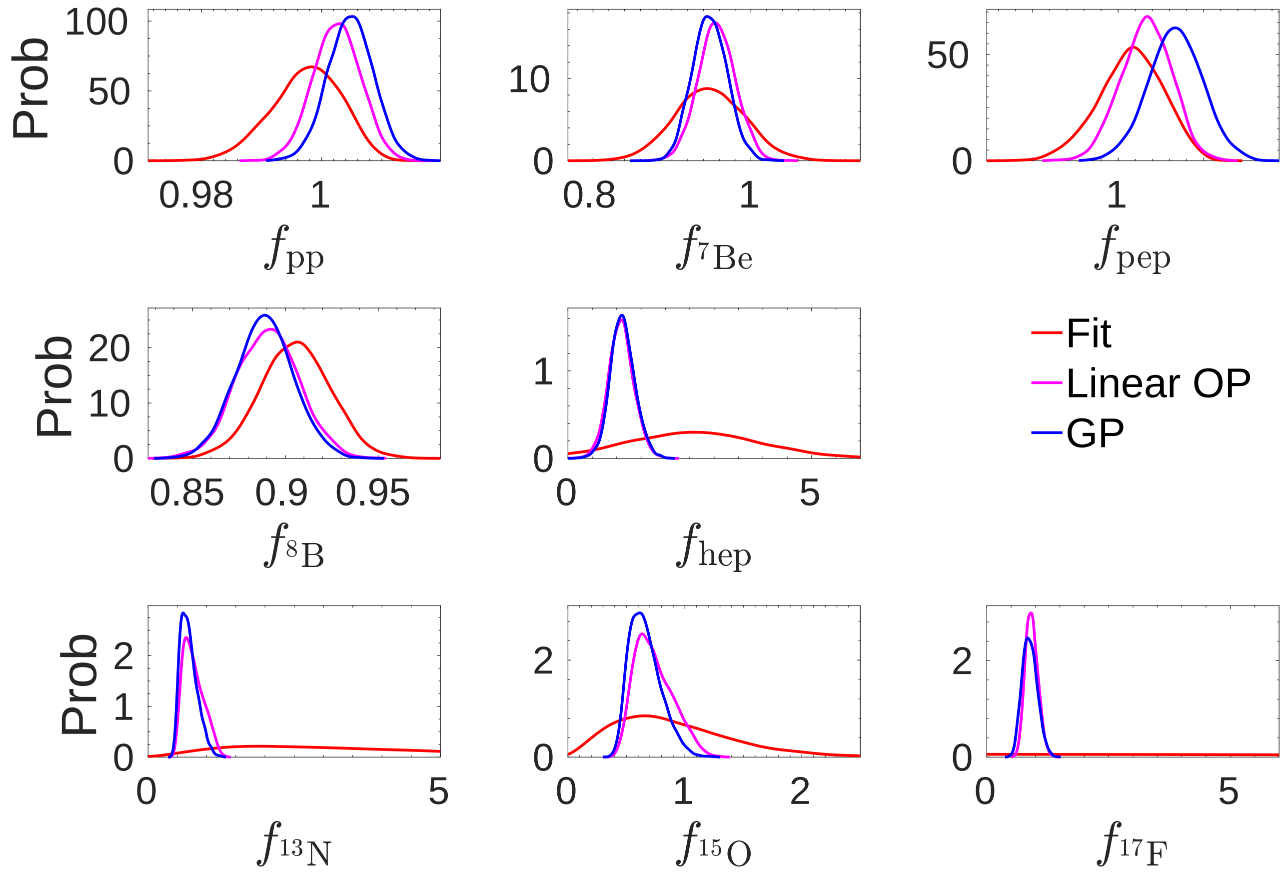
$$x = \ln \frac{N_i}{N_H} - \langle \ln \frac{N_i}{N_H} \rangle_{GS98}$$



MCG-G,Maltoni,Peña-Garay,Serenelli Song, Vinyoles,Villante in preparation

Fitted Fluxes and ν+helioseis data Posteriors

Comparing the empirically determined fluxes with global posteriors



Confirmed Low Energy Picture and MY List of Q&A

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- Three mixing angles are non-zero (and relatively large) $\Rightarrow$ very different from CKM
- Oscillations DO NOT determine the lightest mass
- Oscillations DO NOT distinguish Dirac/Majorana

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Bottom-up: Light ν from *Generic* New Physics

If SM is an effective low energy theory, for $E \ll \Lambda_{\rm NP}$

– The same particle content as the SM and same pattern of symmetry breaking

– But there can be non-renormalizable (dim>4) operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_n \frac{1}{\Lambda_{\rm NP}^{n-4}} \mathcal{O}_n$$

First NP effect $\Rightarrow$ dim=5 operator

There is only one!

$$\mathcal{L}_5 = \frac{Z^{\nu}_{ij}}{\Lambda_{\rm NP}} \left(\overline{L_{L,i}} \tilde{\phi}\right) \left(\tilde{\phi}^T L^C_{L,j}\right)$$

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$$(M_\nu)_{ij} = Z^\nu_{ij} \frac{v^2}{\Lambda_{\rm NP}}$$

Implications:

– It is natural that ν mass is the first evidence of NP

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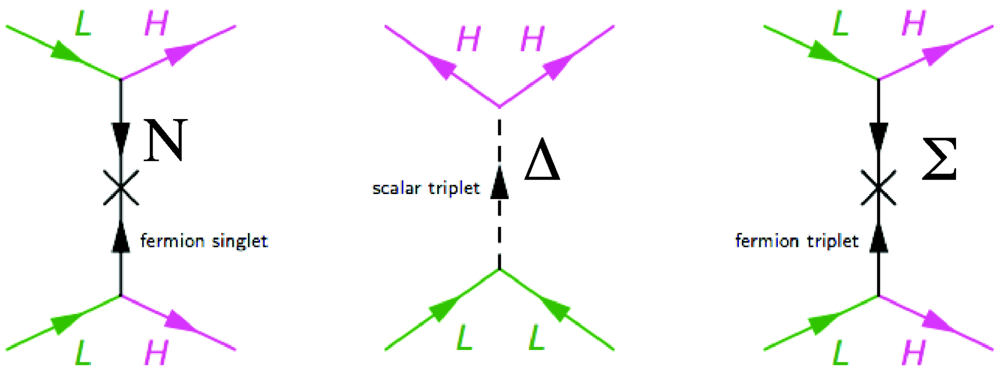
– $m_\nu > \sqrt{\Delta m^2_{\rm atm}} \sim 0.05$ eV for $Z^\nu \sim 1 \Longrightarrow \Lambda_{\rm NP} \sim 10^{15}$GeV $\Longrightarrow$ $\Lambda_{\rm NP} \sim$ GUT scale

$\Rightarrow$ Leptogenesis possible

[But if $Z^\nu \sim (Y_e)^2$ (or more complex NP sector) $\Rightarrow \Lambda_{\rm NP} \sim$ TeV scale]

Model Degeneracy at Low Energy

$\mathcal{O}_5$ is generated for example by tree-level exchange of singlet ($N_i \equiv (1,1)_0$) (Type-I) or triplet fermions ($N_i \equiv \Sigma_i \equiv (1,3)_0$) (Type-III) or a scalar triplet $\Delta \equiv (1,3)_1$ (Type-II)



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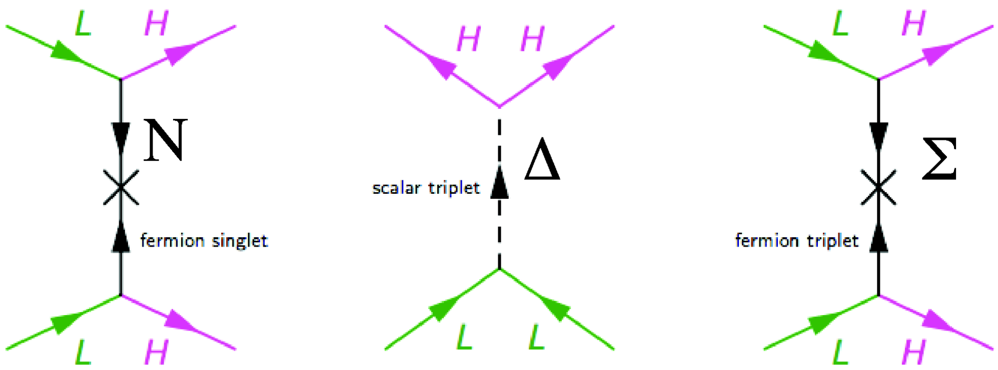

• For fermionic see-saw $\quad -\mathcal{L}_{\rm NP} = -i\overline{N_i}\not{D}N_i + \frac{1}{2}M_{N\,ij}\overline{N_i^c}N_j + \lambda^\nu_{\alpha j}\overline{L_\alpha}\tilde{\phi}N_j[.\tau]$

$$\Rightarrow \mathcal{O}_5 = \frac{(\lambda^{\nu\,T}\lambda^\nu)_{\alpha\beta}}{\Lambda_{\rm NP}}\left(\overline{L_\alpha}\tilde{\phi}\right)\left(\tilde{\phi}^T L^C_\beta\right) \quad \text{with} \quad \Lambda_{\rm NP} = M_N$$

• For scalar see-saw $\quad -\mathcal{L}_{\rm NP} = f_{\Delta\,\alpha\beta}\overline{L_\alpha}\,\Delta\,L^C_\beta\, + M^2_\Delta\,|\Delta|^2\, + \kappa\,\phi^T\,\Delta^\dagger\,\phi\,\ldots$

$$\Rightarrow \mathcal{O}_5 = \frac{f_{\Delta\,\alpha\beta}}{\Lambda_{NP}}\left(\overline{L_\alpha}\tilde{\phi}\right)\left(\tilde{\phi}^T L^C_\beta\right) \quad \text{with} \quad \Lambda_{\rm NP} = \frac{M^2_\Delta}{\kappa}$$

Very different physics, but same ν parameters: How to proceed?

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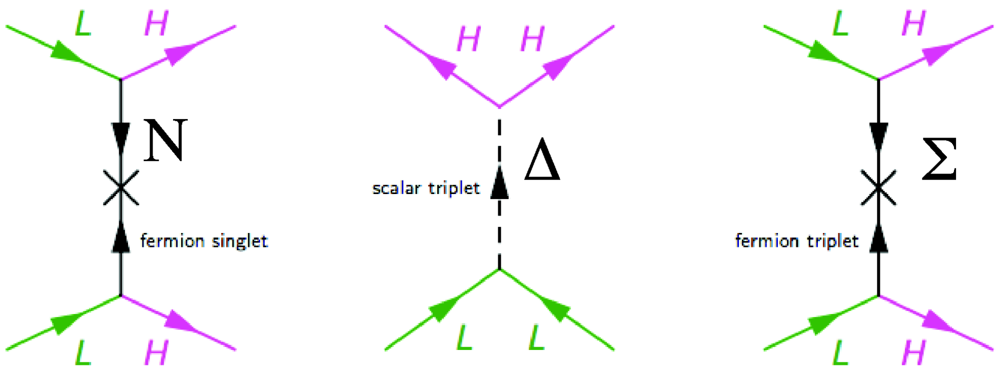

How to proceed?

– Top-down: Assume some specific model and work out the relations

– Still Bottom-up: search for connections to charged LFV, collider signals . . .

Connection to LFV & Collider Signatures?

- ν oscillation $\Rightarrow$ Lepton Flavour is not conserved

  If only $\mathcal{O}_5$ $\Rightarrow Br(\tau \to \mu\gamma) \sim 10^{-41}$ too small!

- But dim=6 operators are LN conserving but LFV (f.e. $O_6 \sim \bar{L}_\alpha \bar{L}_\beta L_\gamma L_\rho$).

  So may be

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_{5\alpha\beta}}{\Lambda_{LN}} \left(\overline{L_\alpha}\tilde{\phi}\right)\left(\tilde{\phi}^T L_\beta^C\right) + \sum_i \frac{c_{6,i}}{\Lambda_{LF}^2} \mathcal{O}_{6,i}$$

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- In general to have observable LFV one needs to *decouple* :

  New Physics scale Λ_{LN} responsible for the small m_ν from

  New Physics scale Λ_{LF} ($\ll \Lambda_{LN}$) controlling of LFV

- Collider signatures if heavy state mass $M \sim \Lambda_{LN} \sim$ TeV and/or $M \sim \Lambda_{LF} \sim$ TeV

  If $M \sim \Lambda_{LF} \sim$ TeV ($\ll \Lambda_{LN}$) motivation of light ν OK

  Furthermore if $c_{6,i} \propto c_5{}^{\text{some power}} \Rightarrow$ LFV and coll signals directly related to M_ν

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Minimal Lepton Flavour Violation

Cirigliano, Grinstein, Isidori, Wise(05); Davidson, Palorini (06); Gavela, Hambye, Hernandez,Hernandez (09)
Alonso, Isidori, Merlo, Munoz, Nardi(11)

MLFV & Collider Signatures

- Minimal Flavour Violation Hypothesis: Chivukula, Georgi (87) Buras, Gambino, Gorbahn, Jager, Silvestrini,(01) d'Ambrosio, Giudice, Isidori, Strumia (02)

  Yukawas are the only source of flavour violation in and beyond SM

  Very predictive and successful to explain quark flavour data

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- Scalar (Type-II) see-saw is MLFV

  $c_{5,\alpha\beta} = f_{\Delta\alpha\beta}\frac{\mu}{M_\Delta}$ $\qquad$ $c_{6,\alpha\beta\gamma\rho} = f^\dagger_{\Delta\alpha\beta} f_{\Delta\gamma\rho}$

- If $M_\Delta \lesssim$ TeV

  $\Rightarrow$ Production of triplet scalars: $H^{\pm\pm}\ H^{\pm},\ A_0,\ H_0$

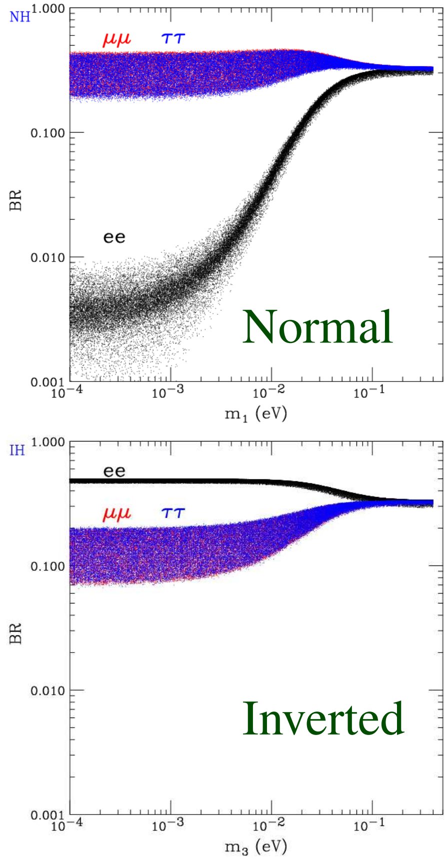
  Striking Signatures

  $pp \to H^{++}H^{--}$

  $pp \to H^{++}H^{-}$

  $\Rightarrow \quad H^{\pm\pm} l_i^\pm l_j^\pm,\ H^\pm \to l_i^\pm \nu_j$

  predicted by neutrino parameters



Akeroyd *et al*, Chao *et al*, Fileviez *et al*

Garayoa *et al*, Han *et al*, Kadastik *et al* ...

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- MLFV Fermionic (I or III) Inverse see-saw

  Gavela, Hambye, Hernandez,Hernandez (09)

  $\rightarrow$ one massless ν & one CP phase α

  $\rightarrow$ Yukawas $\lambda_{\alpha N}$ determined by ν parameters

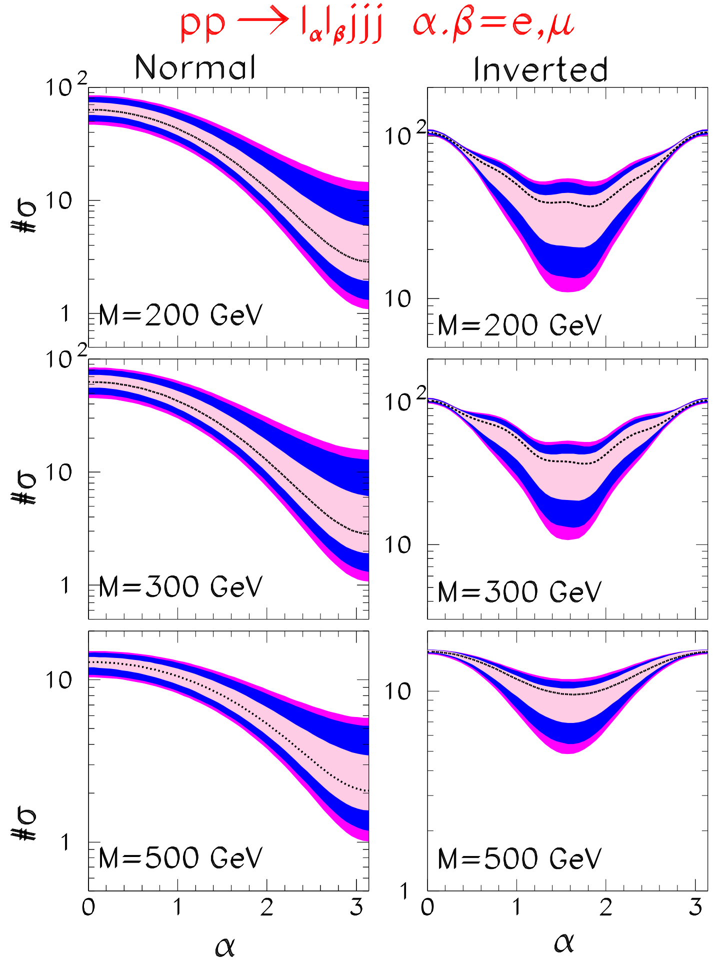
- At LHC: Eboli, Gonzalez-Fraile, MCGG (11) –

Type-I unobservable but Type-III observable

$$pp \to F(\to \ell_\alpha X)F'(\to \ell_\beta X')$$

– Rates predictable in terms of ν parameters

– Difficult but *beatable* SM backgrounds



Eboli, Gonzalez-Fraile, MCGG 1108.0661

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- Turn to "the heavens" (aka Cosmology)?:

Light massive ν in Cosmology

What I found when turning to “the heavens”

Light massive ν in Cosmology

What I found when turning to "the heavens"

"There is a difference between making an observation and making an experiment"

Concha Gonzalez-Garcia

Light massive ν in Cosmology

Relic $\nu's$: Effects in several cosmological observations at several epochs

Mainly via two effects: $\rho_r = \left[1 + \frac{7}{8} \times \left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right] \rho_\gamma$ and $\sum_i m_{\nu_i}$

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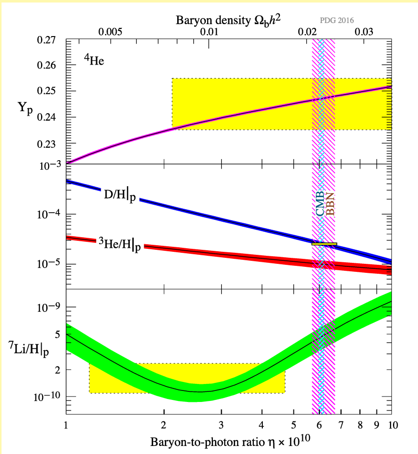
<td>
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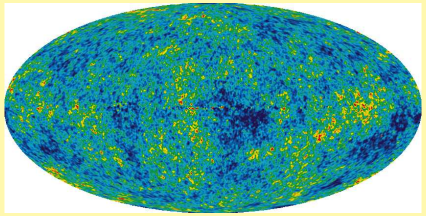
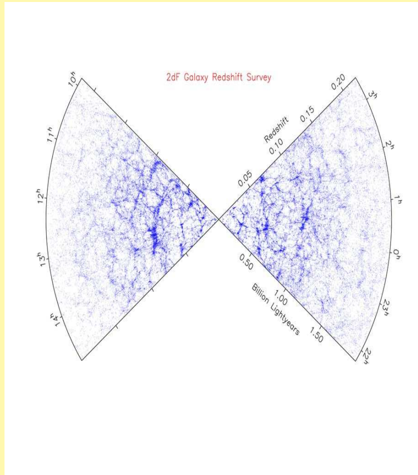
<td></td>
<td>
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BBN</td>
<td>Cosmic Microwave
Background
CMB</td>
<td>Large Scale
Structure Formation
LSS</td>
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<tr>
<td>$T \sim$ MeV</td>
<td colspan="2">$T \lesssim$ eV</td>
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<tr>
<td>Number of $\nu's$ ($N_{\rm eff}$)</td>
<td colspan="2">$N_{\rm eff}$ and $\sum m_\nu$</td>
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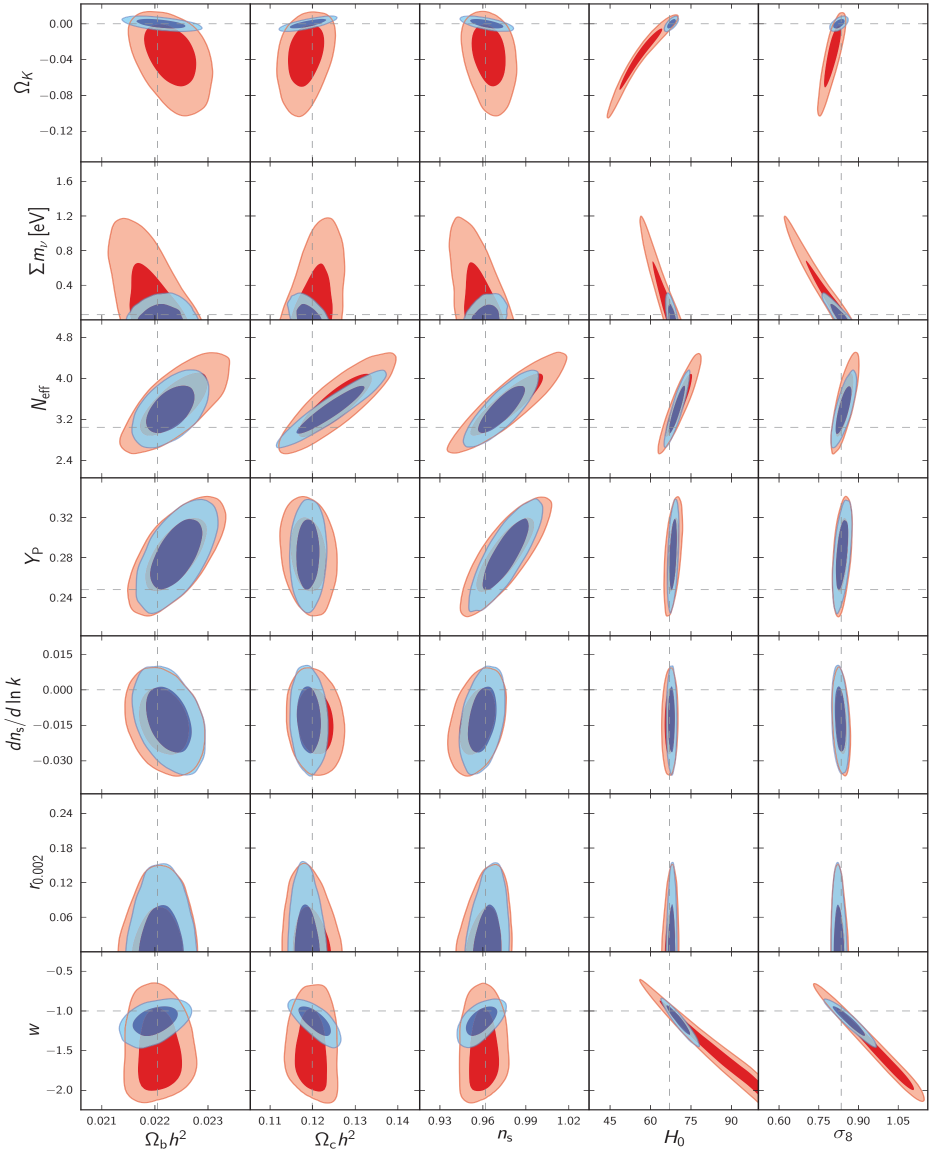
BUT: Observables also depend on all other cosmo parameters (and assumptions)

Concha Gonzalez-Garcia

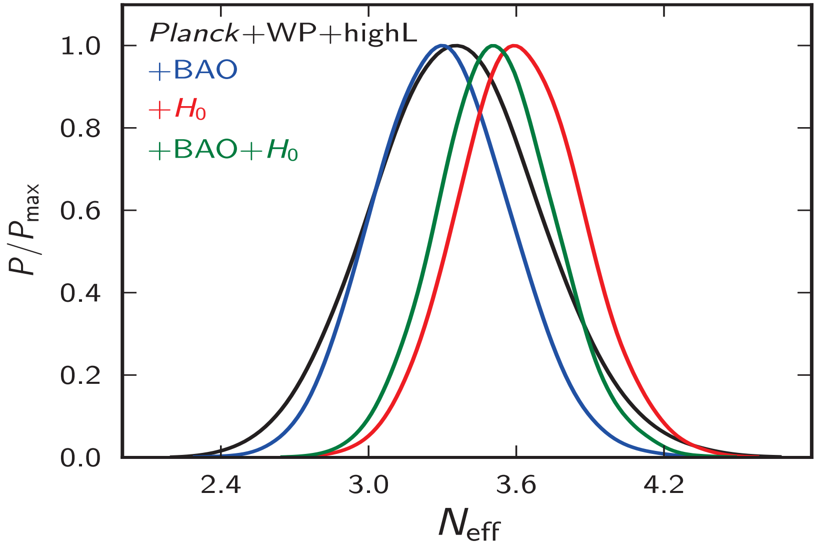
Example: Cosmological Analysis by Planck

arXiv:1502.01589



Range of Bounds in ΛCDM

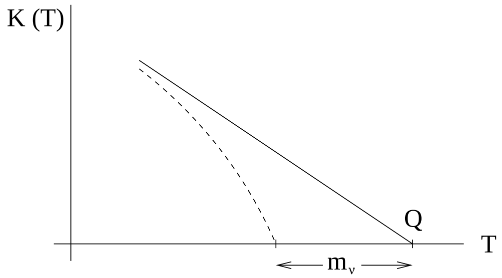
Model	Observables	Σm_ν (eV) 95%
$\Lambda CDM + m_\nu$	Planck TT + lowP	≤ 0.72
$\Lambda CDM + m_\nu$	Planck TT + lowP + lensing	≤ 0.68
$\Lambda CDM + m_\nu$	Planck TT,TE,EE + lowP+lensing	≤ 0.59
$\Lambda CDM + m_\nu$	Planck TT,TE,EE + lowP	≤ 0.49
$\Lambda CDM + m_\nu$	Planck TT + lowP + lensing + BAO + SN + H_0	≤ 0.23
$\Lambda CDM + m_\nu$	Planck TT,TE,EE + lowP+ BAO	≤ 0.17



Neutrino Mass Scale

Concha Gonzalez-Garcia

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

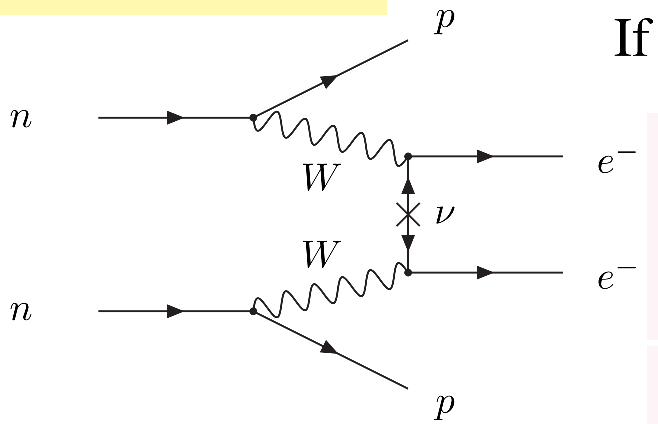


$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = \begin{cases} \text{NO}: & m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} + \Delta m^2_{31} s^2_{13} \\ \text{IO}: & m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} - \Delta m^2_{31} c^2_{13} \end{cases}$$

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: $m_{ee} < 0.06\text{–}0.76$ eV

COSMO for Dirac or Majorana m_ν affect growth of structures

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

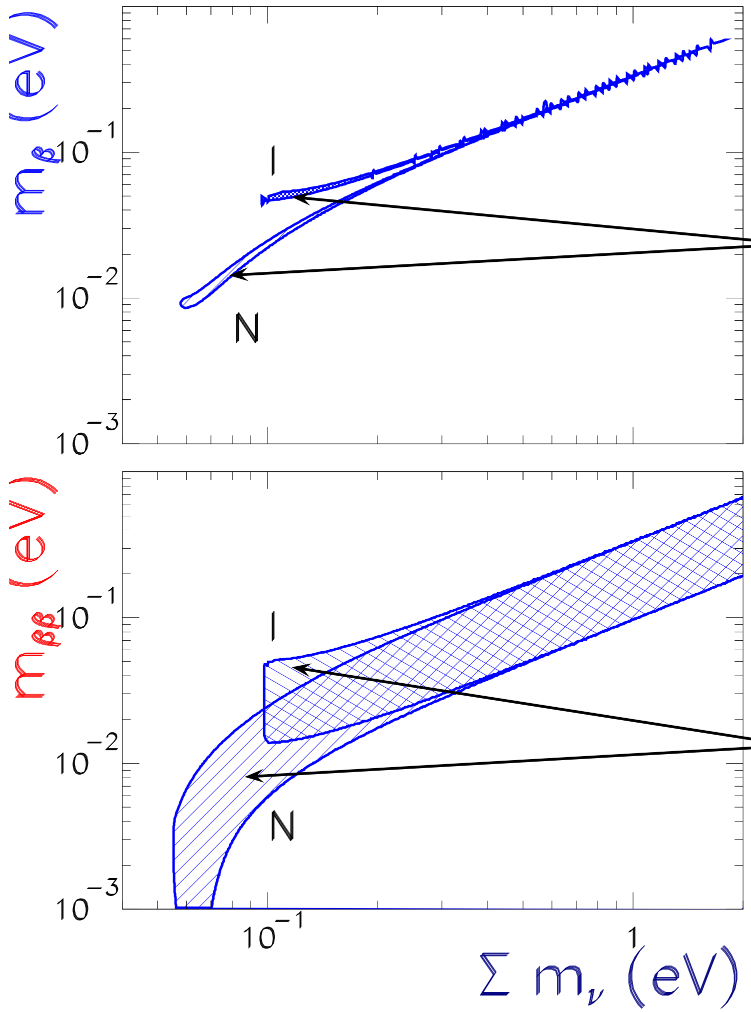
Neutrino Mass Scale: The Cosmo-Lab Connection

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

Wide band due to unknown Majorana phases $\Rightarrow$ Possible Det of Maj phases?

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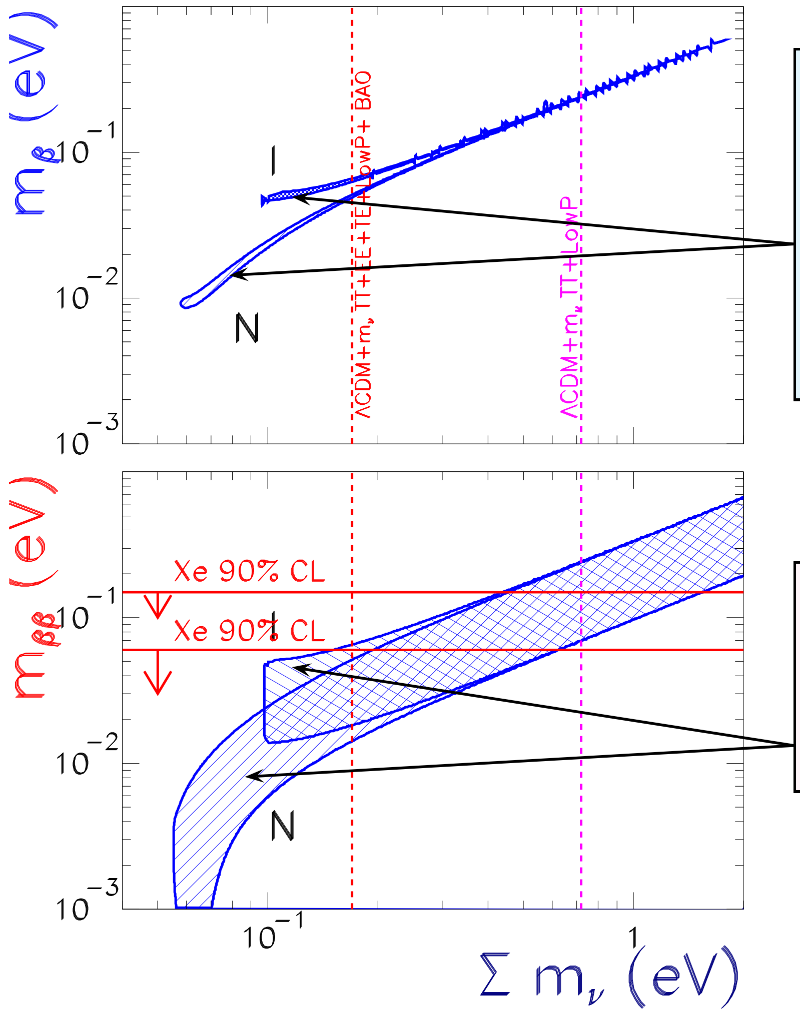
Global oscillation analysis

$\Rightarrow$ 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

Precision determination/bound of m_{ν_e} and $\sum m_i$ can give information on ordering (?)

Only β decay provides model independent information

Wide band due to unknown Majorana phases $\Rightarrow$ Possible Det of Maj phases?

Confirmed Low Energy Picture and MY List of Q&A

- At least two neutrinos are massive $\Rightarrow$ There is NP
- Three mixing angles are non-zero (and relatively large) $\Rightarrow$ very different from CKM
- Oscillations DO NOT determine the lightest mass but β decay: $\sum m_i^2 |U_{ei}|^2 \leq (2.2\text{ eV})^2$

$\Rightarrow$ Heaviest ν is at least $\sim 10^6$ lighter than e^- (which is $\sim 10^6$ ligher than the top...)

- Dirac or Majorana?: We do not know, *anxiously* waiting for ν-less $\beta\beta$ decay

- Only three light states?: Some anomalies and tensions…

- What about a UV complete model which answers?:
  - $*$ Why are neutrinos so light? $\Rightarrow$ The Origin of Neutrino Mass
  - $*$ Why are lepton mixing so different from quark's? $\Rightarrow$ The Flavour Puzzle

  Answer is not going to come from ν osc experiments

  Collider signals? We are going need a break

- Cosmological effects?: Still missing a "signal" and will we ever be convinced it is $\nu's$?

- Should we benefit from decoupling and focus on effective LE Lagrangian for $\nu's$ osc?:

Determination of Matter Potential: Non Standard ν Int

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

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

- The most general matter potential can be parametrized

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

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Deviations from $H^{\rm SM}_{\rm mat} = \sqrt{2} G_F N_e(r) {\rm diag}(1,0,0)$ induced by **NSI**

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

- The 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:

$$\theta_{12} \leftrightarrow \frac{\pi}{2} - \theta_{12}\,, \qquad (\varepsilon_{ee} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2\,,$$

$$\Delta m^2_{31} \to -\Delta m^2_{32}\,, \qquad (\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu})\,,$$

$$\delta \to \pi - \delta\,, \qquad \varepsilon_{\alpha\beta} \to -\varepsilon^*_{\alpha\beta} \qquad (\alpha \neq \beta)\,,$$

Matter Potential/NSI in ATM and LBL

- Weakest constraints when

  2 equal eigenvalues of $H_{\rm mat}$

  Friedland, Lunardini,Maltoni 04

- General parametrization for this case

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

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

So even if $G_F\, \varepsilon\, N_e(r) \gg \Delta m^2_{31}/2E$

– $\nu_\mu \to \nu_\tau$ as vacuum with

$$\tilde{\Delta}_{\rm vac} = \frac{\Delta m^2_{31} L}{4E} \times f(\theta_{ij}, \phi_{ij})$$

– $\nu_e \to \nu_{\mu,\tau}$ matter dominated

$$P_{e\mu} = \cos^2\phi_{13} \sin^2(2\phi_{12}) \sin^2\left(\frac{\sqrt{2} G_F N_e(r) \varepsilon L}{2}\right)$$

$$P_{e\tau} = \cos^2\phi_{12} \sin^2(2\phi_{13}) \sin^2\left(\frac{\sqrt{2} G_F N_e(r) \varepsilon L}{2}\right)$$

Matter Potential/NSI in ATM and LBL

- Weakest constraints when

  $\underline{\text{2 equal eigenvalues of } H_{\text{mat}}}$

  Friedland, Lunardini,Maltoni 04

- General parametrization for <u>this case</u>

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

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

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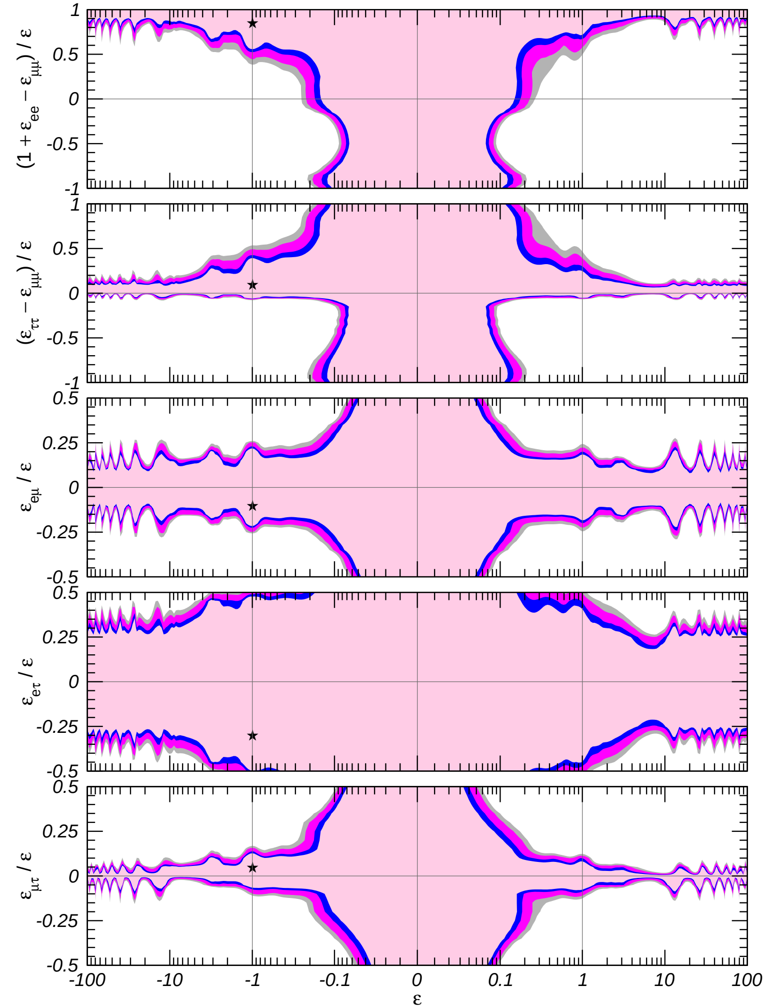
No bound on ε from ATM+LBL



Maltoni, MCG-G, Salvado ArXiv:1103.4265

Matter Potential/NSI in Solar and KamLAND

z-Garcia

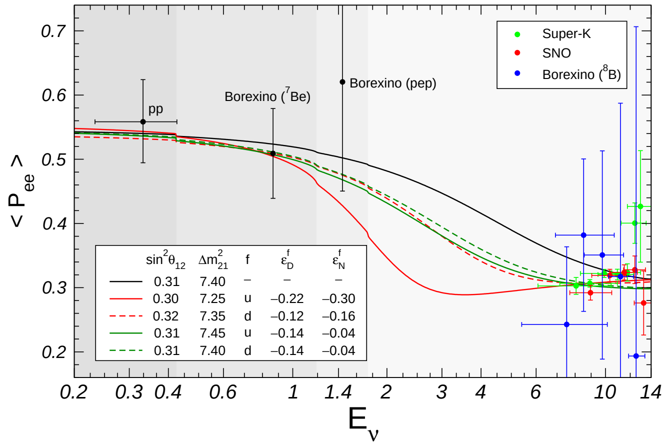
- In $|\Delta m^2_{31}| \to \infty$: $P_{ee} = c^4_{13} P_{\rm eff} + s^4_{13}$

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

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

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

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



Matter Potential/NSI in Solar and KamLAND

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

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

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

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

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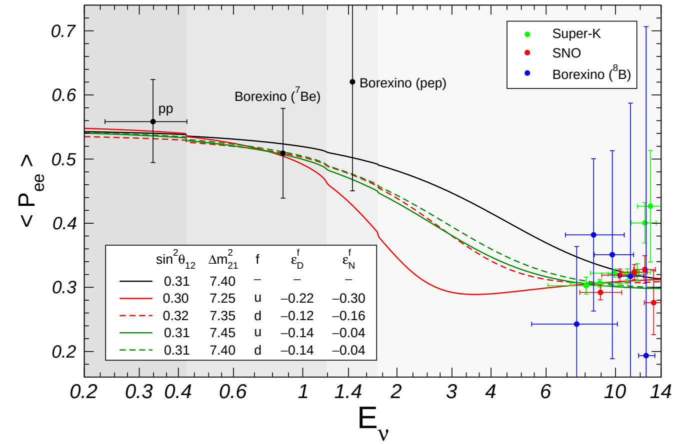
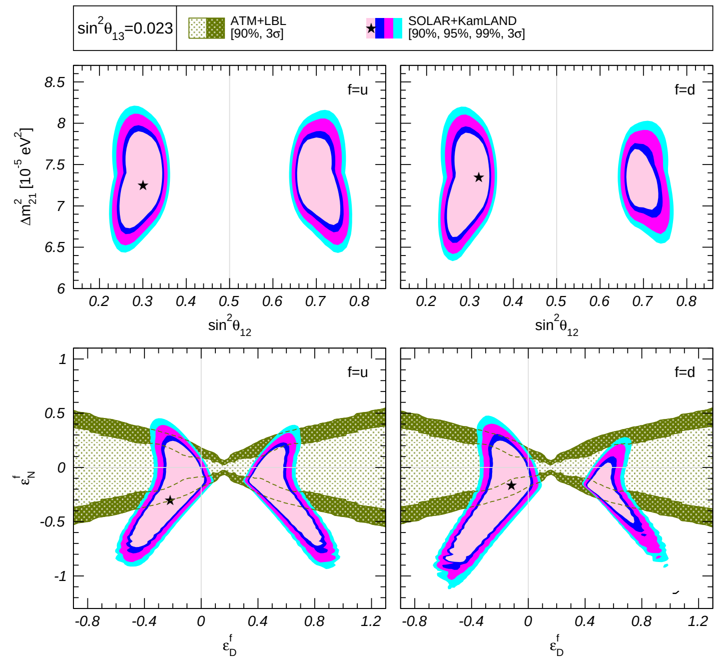


- LMA-D ($\theta_{12} > \frac{\pi}{4}$) allowed

Miranda,Tortola, Valle (2004)

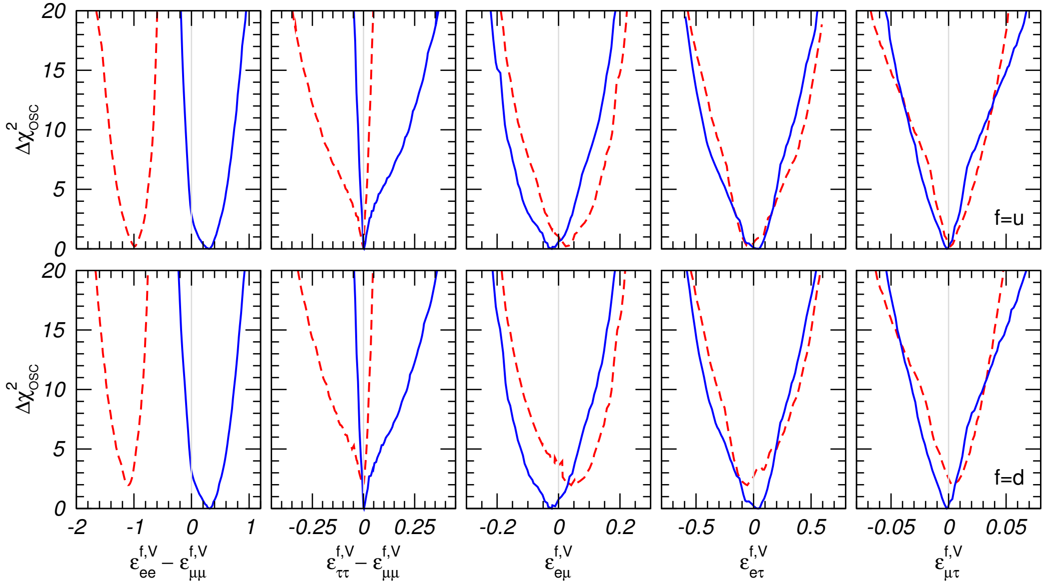


Requires $\varepsilon_{ee} - \varepsilon_{\mu\mu} \sim \mathcal{O}(-1)$

Maltoni, MCG-G, ArXiv:1307.3092

Matter Potential/NSI Global Oscillation Bounds

- All NSI parameters bounded 1-10% (except $\varepsilon_{ee} - \varepsilon_{\mu\mu}$ in LMA-D)
- These bounds should not be ignored in future LBL sensitivity studies



		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	$[-0.01, +0.01]$	$[-0.01, +0.01]$

- Presently LMA-D partly lifted by scattering data (CharmII, NuTeV) depending on:

– Validity of NSI parametrization at $Q^2 \gtrsim \text{GeV}^2$

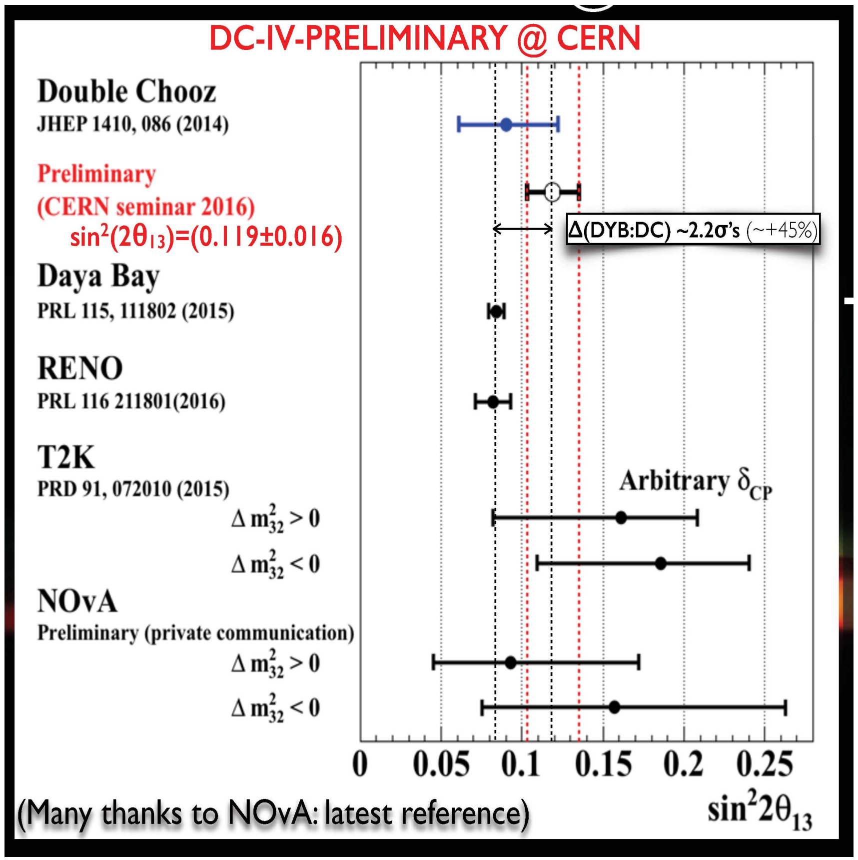
– Treatement of NuTeV Anomaly

Coloma, Denton, MCGG,Maltoni, Schwetz 1701.04828

THANK YOU

Issues in 3 ν Analysis: Consistency of θ_{13}

Daya Bay vs Double Chooz?



From DC (Anatael Cabrera) Talk CERN Sep 16

Allowed regions of DC vs Daya Bay

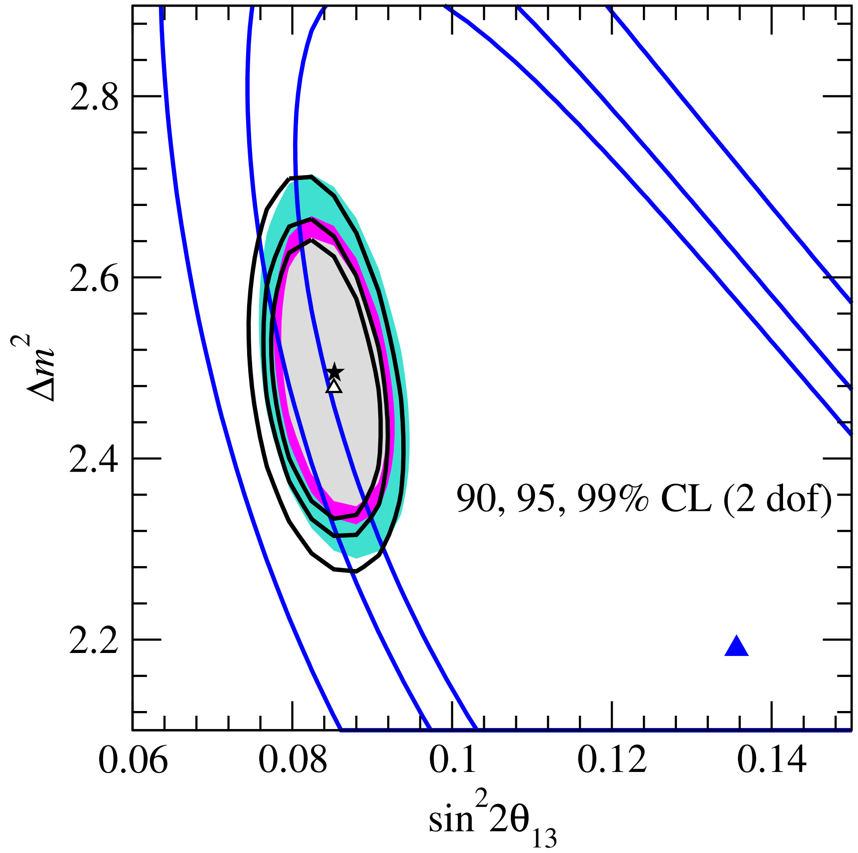


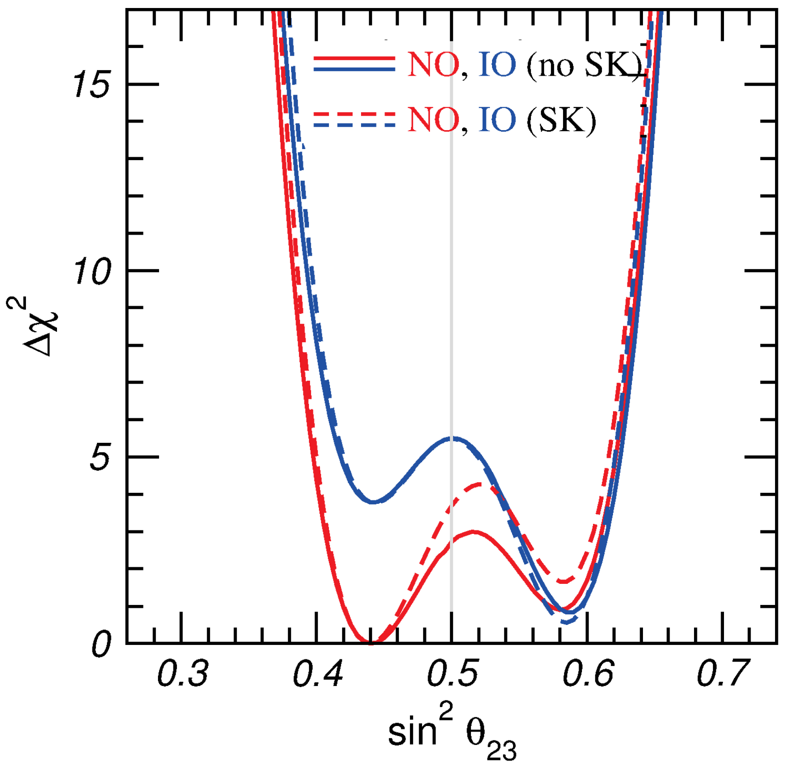
Fig. Courtesy of T. Schwetz

No significant discrepancy

Concha Gonzalez-Garcia

Comparison with Bari group

NuFIT 3.0, Esteban et al., 1611.01514



Cappozzi et al., 1703.04471

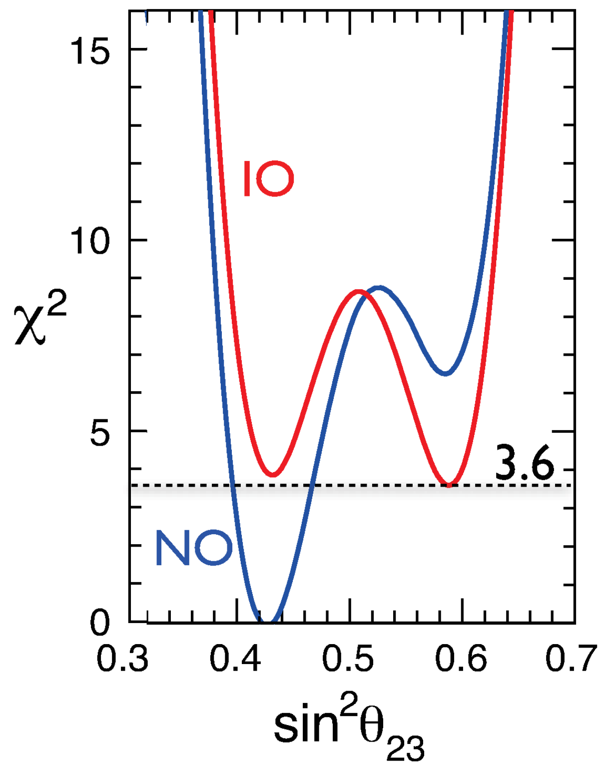


Figure display "borrowed" from T. Schwetz Moriond 17 talk

Main Difference in ATM sensitivity

Both groups use the same reduced number of atm data subsamples

Using these data subsamples SK never found a $\theta_{13} \neq 0$ effect

Flavour Parameters: Present Status

- Finally we have determined (at $\pm$ 3σ/6)

$$\Delta m^2_{21} = 7.50 \times 10^{-5}\ \mathrm{eV}^2\ (2.3\%) \qquad \sin^2\theta_{12} = 0.31\ (4\%)$$

$$\begin{array}{l}\Delta m^2_{31} = 2.52 \times 10^{-3}\ \mathrm{eV}^2 \quad \mathrm{NO} \\ \Delta m^2_{32} = -2.51 \times 10^{-3}\ \mathrm{eV}^2 \quad \mathrm{IO}\end{array}\ (1.8\%) \quad \sin^2\theta_{23} = \begin{array}{c}0.44\\0.59\end{array}\ (7-10\%) \quad \sin^2\theta_{13} = \begin{array}{c}0.0217\\0.0218\end{array}\ (3.2\%)$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

- Good progress but still precision very far from:

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

Near 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)

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

$$J^{\max}_{\rm CP} = c^2_{13} s_{13} c_{23} s_{23} c_{12} s_{12}$$

– 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

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

– Challenge: Energy resolution