# PRESENT STATUS AND FUTURE OUTLOOK OF NEUTRINO THEORY

Concha Gonzalez-Garcia

*(YITP Stony Brook & ICREA U. Barcelona )*

**Brookhaven Forum 2019, Sept 27th, 2019**

Global fit to neutrino oscillation data

http://www.nu-fit.org

elusives neutrinos, dark matter & dark energy

invisiblesPlus neutrinos, dark matter & dark energy physics

# MASSIVE NEUTRINOS CIRCA 2019

Concha Gonzalez-Garcia
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Neutrino Flavour Transition: Data and Interpretation

Some comments on Status of :

- *Leptonic CP violation*
- *Determination of mass Ordering*
- *Light Sterile neutrinos*
- *Mass scale*
- *Degeneracies with NC-NSI*

# Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

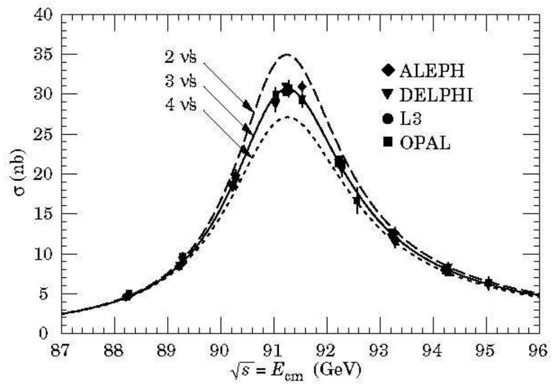
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

With three generation of fermions

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

There is no $\nu_R$

Three and only three



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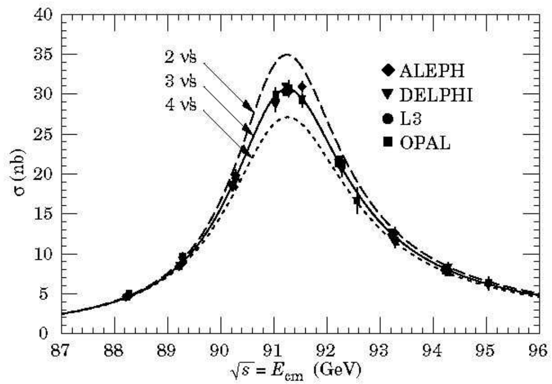


There is no $\nu_R$

$\Downarrow$

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

$\Downarrow$

$\nu$ *strictly* massless

- By 2019 we have observed with high (or good) precision:
  - ∗ Atmospheric $\nu_\mu$ & $\bar{\nu}_\mu$ disappear most likely to $\nu_\tau$ (**SK**,MINOS, ICECUBE)
  - ∗ Accel. $\nu_\mu$ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NO$\nu$A**)
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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 $\nu_R$ AND impose $L$ conservation $\Rightarrow$ Dirac $\nu \neq \nu^c$:

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

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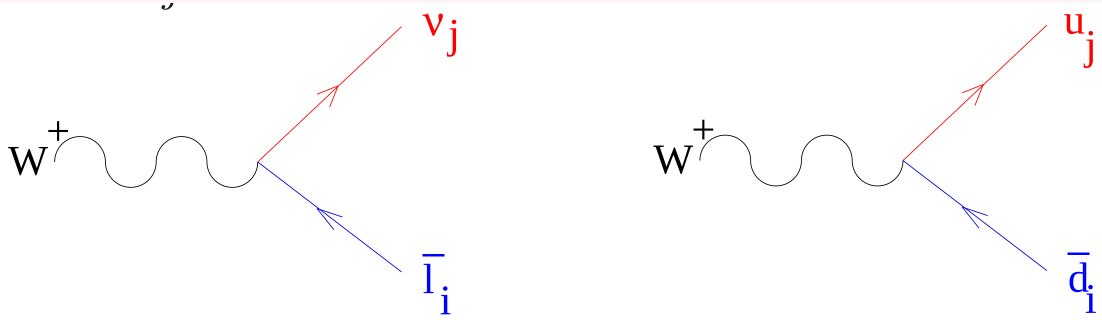
- The charged current interactions of leptons are not diagonal (same as quarks)

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



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⇒ Flavour Oscillations:

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

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

No information on $\nu$ mass scale nor Majorana versus Dirac

# Flavour Osc in Vaccum vs Transitions in Matter

- In Vaccum
  when osc between 2-$\nu$ dominates:

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

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

$\Rightarrow$ No information on Ordering of states ( i.e sign$(\Delta m^2)$) nor octact of $\theta$

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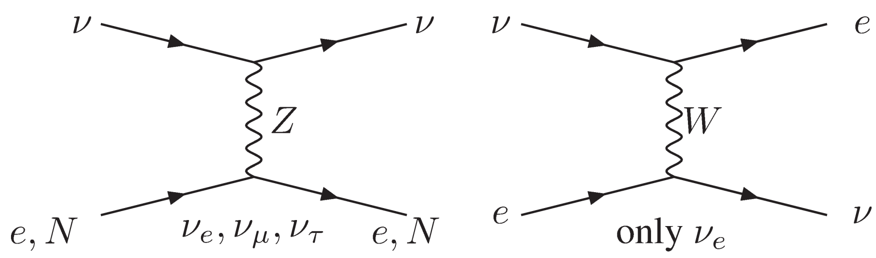
- If $\nu$ cross matter regions (Sun, Earth...) it interacts *coherently*

  – And Different flavours
    have different interactions :




$\Rightarrow$ Effective potential in $\nu$ 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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- 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

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

Dependence on $\theta$ octant

$\Rightarrow$ In LBL terrestrial experiments
Dependence on sign of $\Delta m^2$
and $\theta$ octant

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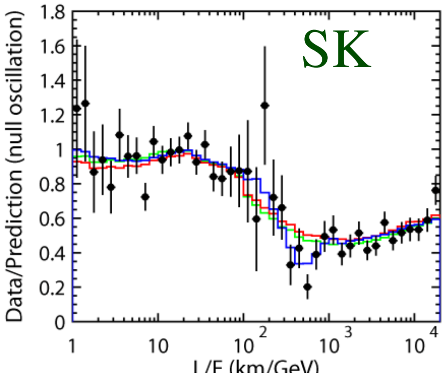
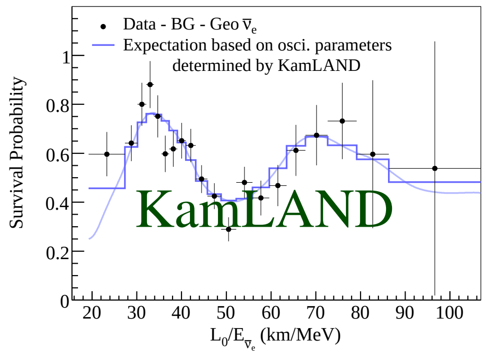
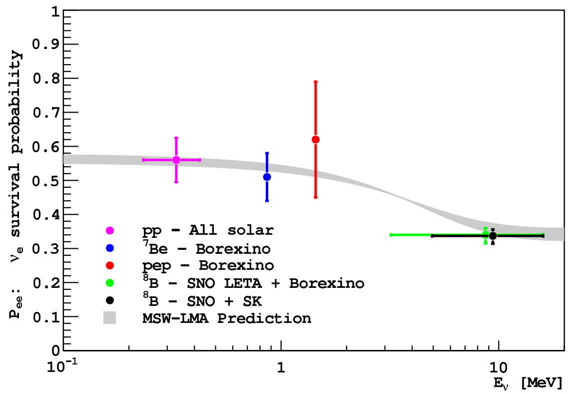
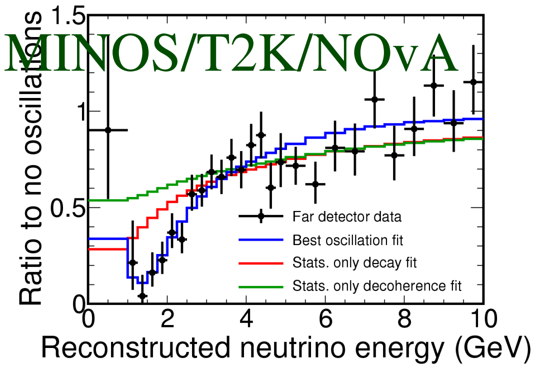
- Confirmed: Vacuum oscillation $L/E$ pattern with 2 frequencies

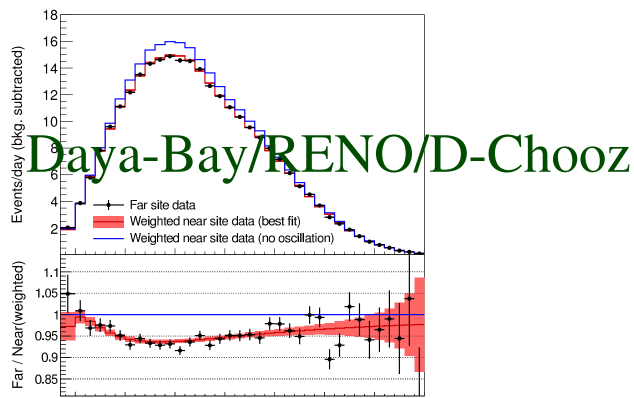
MSW conversion in Sun



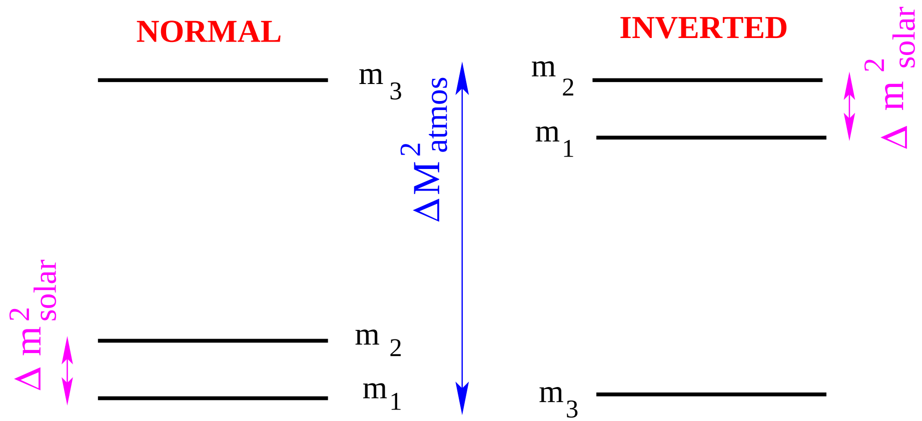
# $3\nu$ Oscillations



- For for 3 $\nu$'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

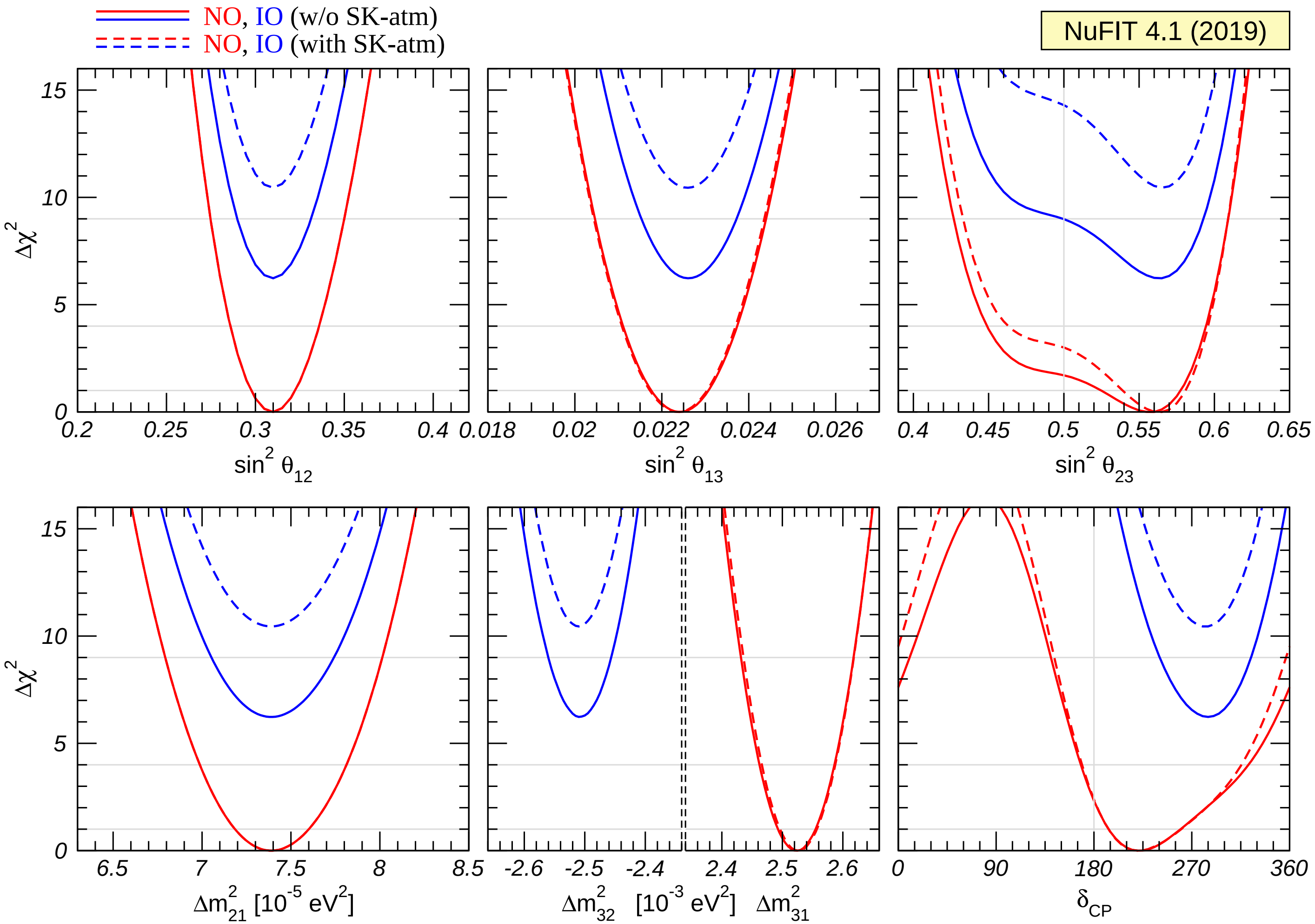



| Experiment | Dominant Dependence | Important Dependence |
|---|---|---|
| Solar Experiments | $\rightarrow \theta_{12}$ | $\Delta m^2_{21}$ , $\theta_{13}$ |
| Reactor LBL (KamLAND) | $\rightarrow \Delta m^2_{21}$ | $\theta_{12}$ , $\theta_{13}$ |
| Reactor MBL (Daya Bay, Reno, D-Chooz) | $\rightarrow \theta_{13}$ | $\Delta m^2_{3\ell}$ |
| Atmospheric Experiments | $\rightarrow \theta_{23}$ | $\Delta m^2_{3\ell}$, $\theta_{13}$ ,$\delta_{\rm cp}$ |
| Acc LBL $\nu_\mu$ Disapp (Minos,T2K,NOvA) | $\rightarrow \Delta m^2_{3\ell}$ | $\theta_{23}$ |
| Acc LBL $\nu_e$ App (Minos,T2K,NOvA) | $\rightarrow \theta_{13}$ | $\delta_{\rm cp}$ , $\theta_{23}$ |

# 3 $\nu$ Flavour Parameters: Present Status

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

Esteban, Hernandez-Cabezudo,Maltoni, Schwetz, MCG-G ArXiv:1811.05487



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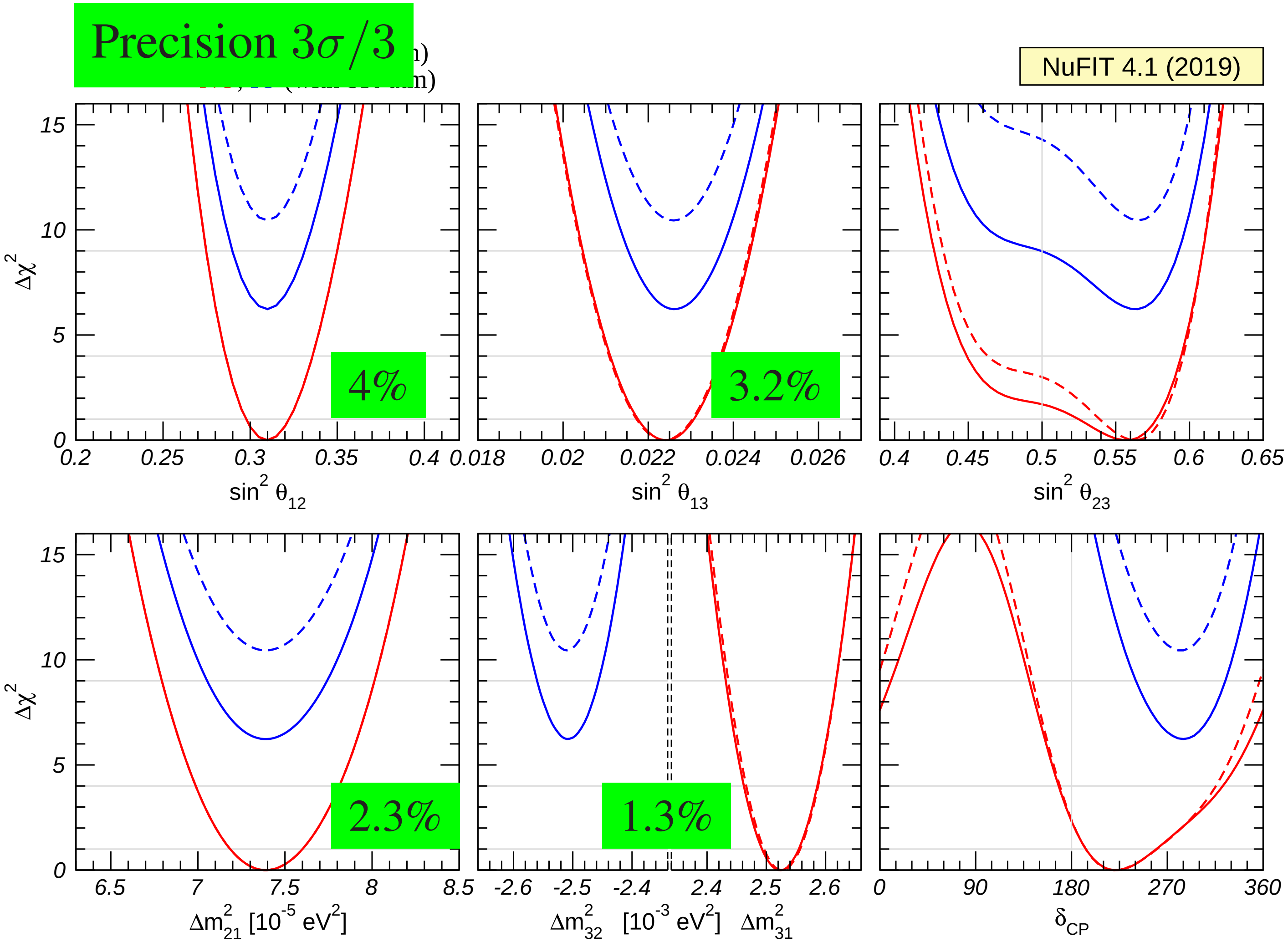


- Best determined:

  $\theta_{12}$, $\theta_{13}$,$\Delta m^2_{21}$, $|\Delta m^2_{3l}|$

  $[\Delta m^2_{3l} = \Delta m^2_{31} > 0$ (NO)

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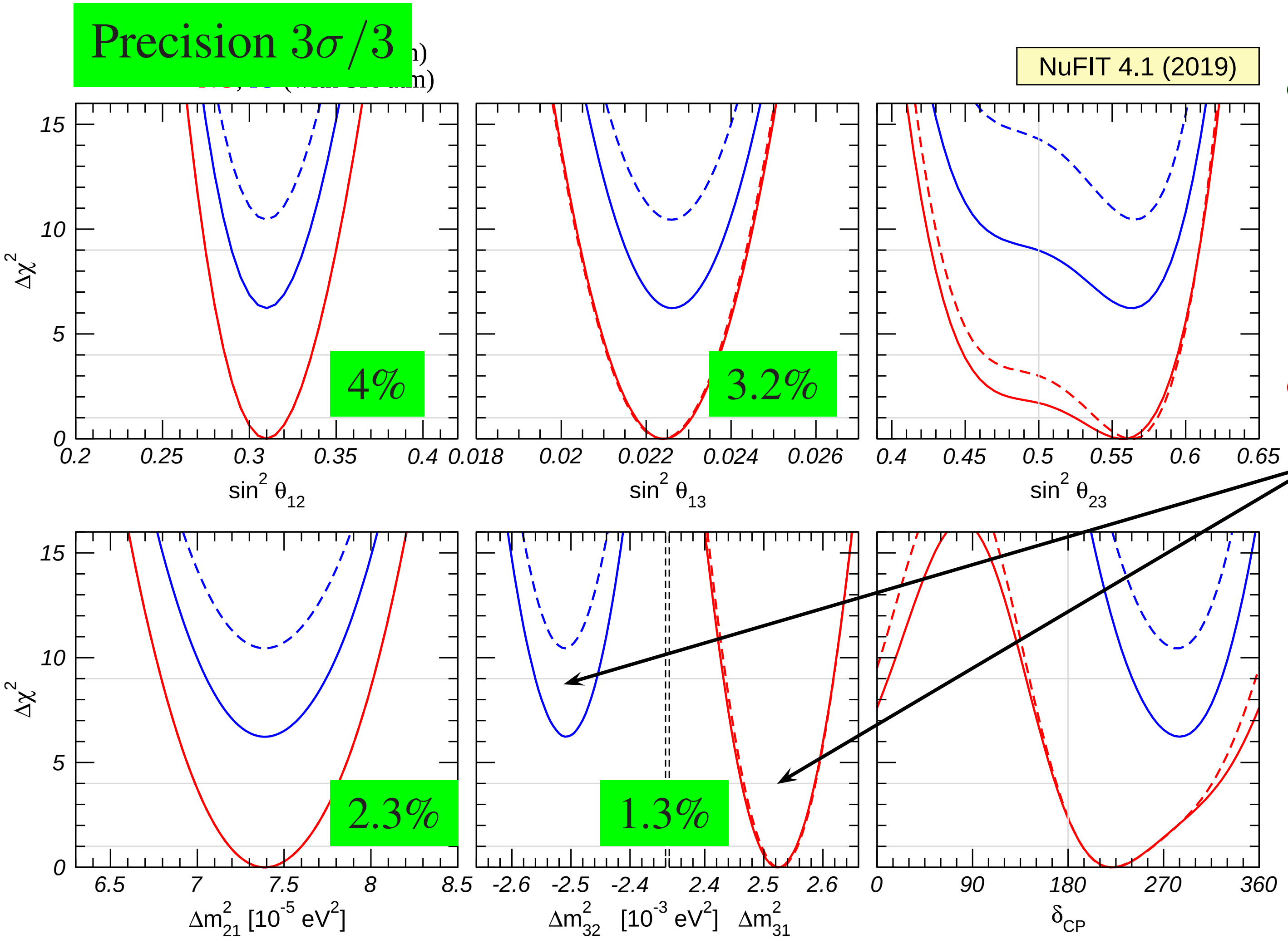


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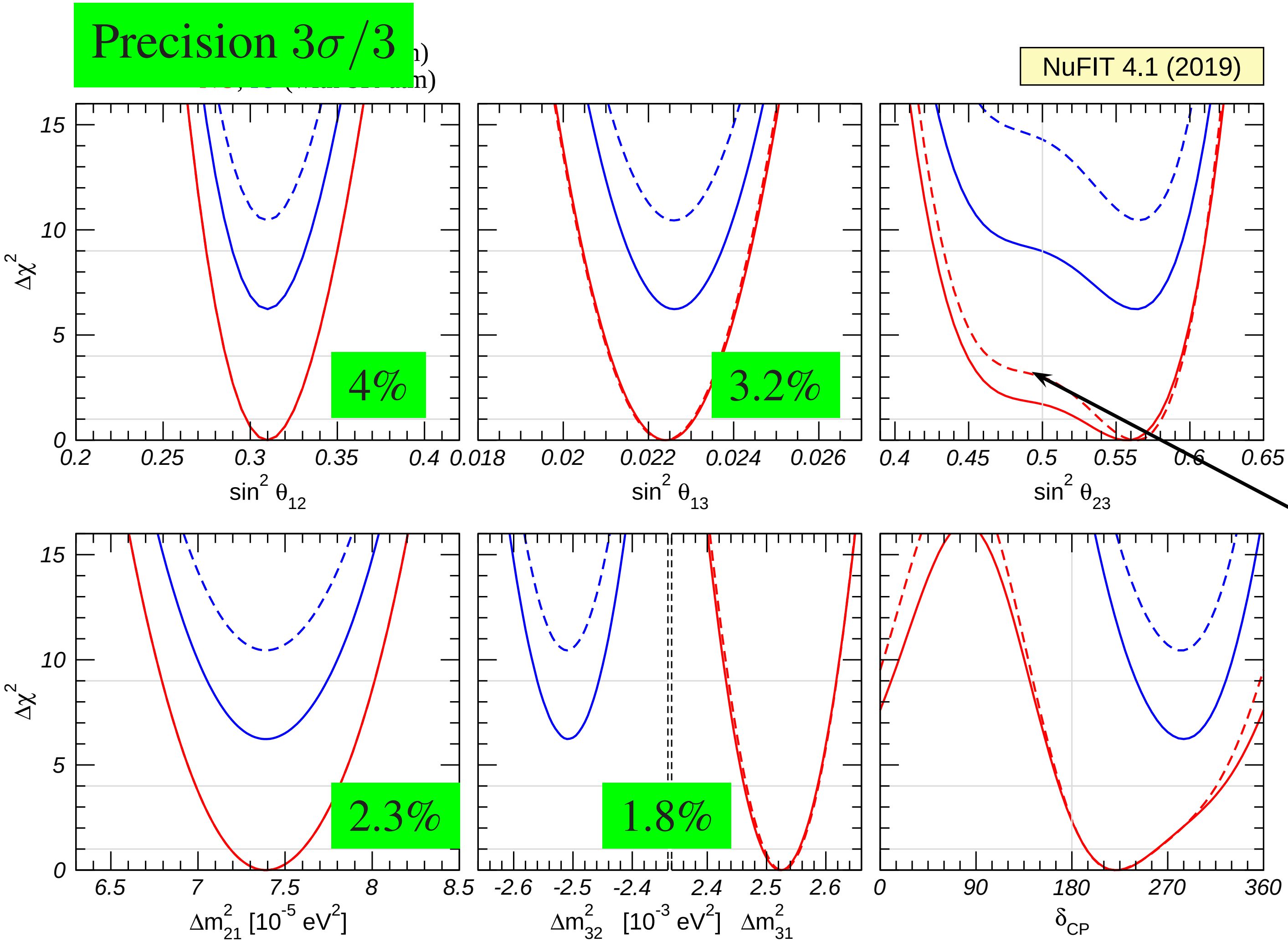


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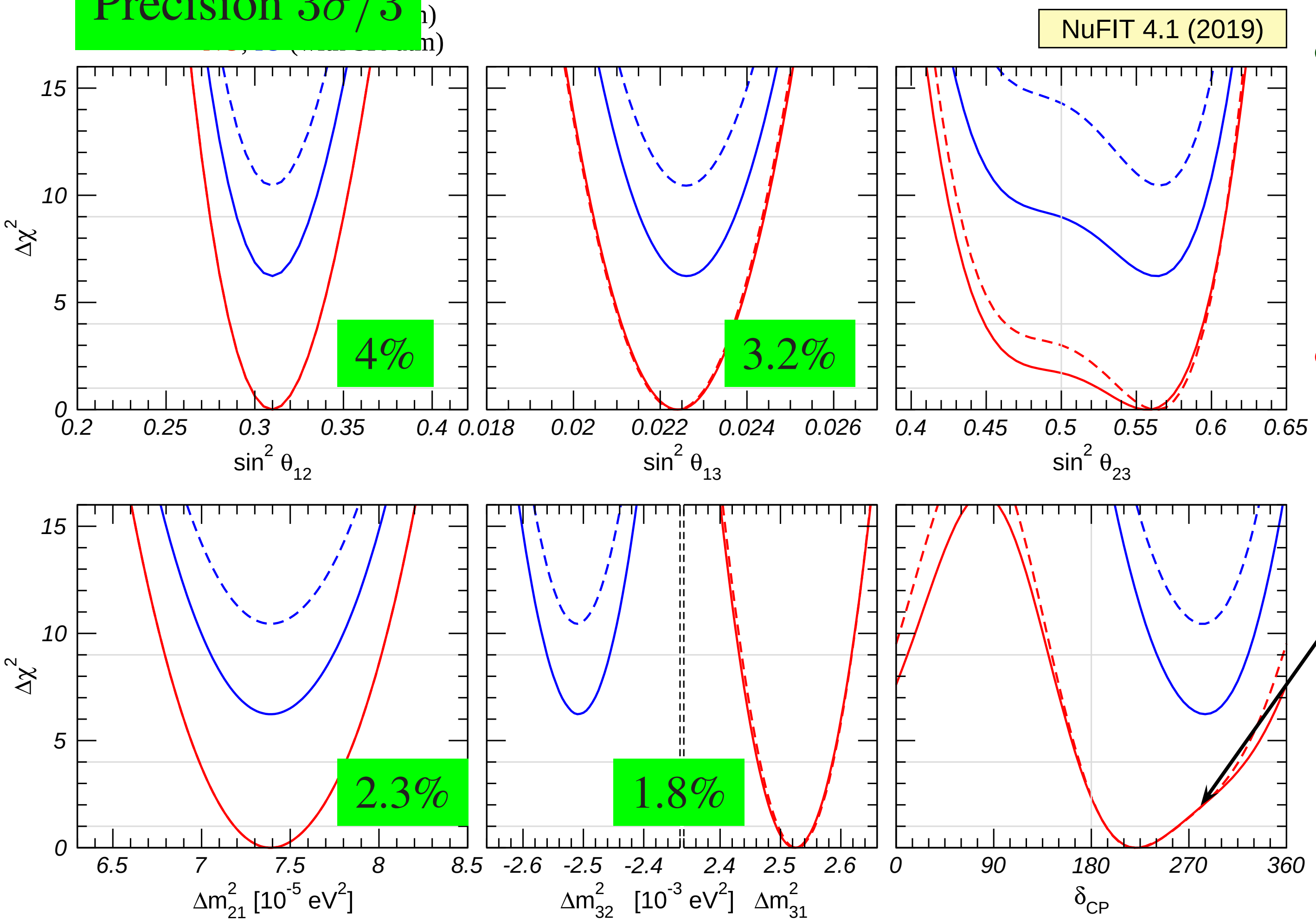
Precision $3\sigma/3$

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  $*$ CP phase: $> \pi$?

# Flavour Parameters: Mixing Matrix

- Finally we have the three leptonic mixing angles determined (at $\pm 3\sigma/6$)

$$|U|_{3\sigma} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.233 \to 0.495 & 0.448 \to 0.679 & 0.639 \to 0.783 \\ 0.287 \to 0.532 & 0.486 \to 0.706 & 0.604 \to 0.754 \end{pmatrix}$$

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

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- Also very different flavour mixing of leptons vs quarks

# 3 $\nu$ Analysis: $\theta_{23}$

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

$$P_{\mu\mu} = P_{\bar\mu\bar\mu} \approx 1 - \sin^2 2\theta_{\mu\mu}\, \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E_\nu} \simeq 1 - c^2_{13} \sin^2 2\theta_{23}\, \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}(s^2_{13}, \Delta m^2_{21})$$

$*$ Irrelevant matter effects

$*$ $E$ spectrum of events:

– *Location* of osc minimum:

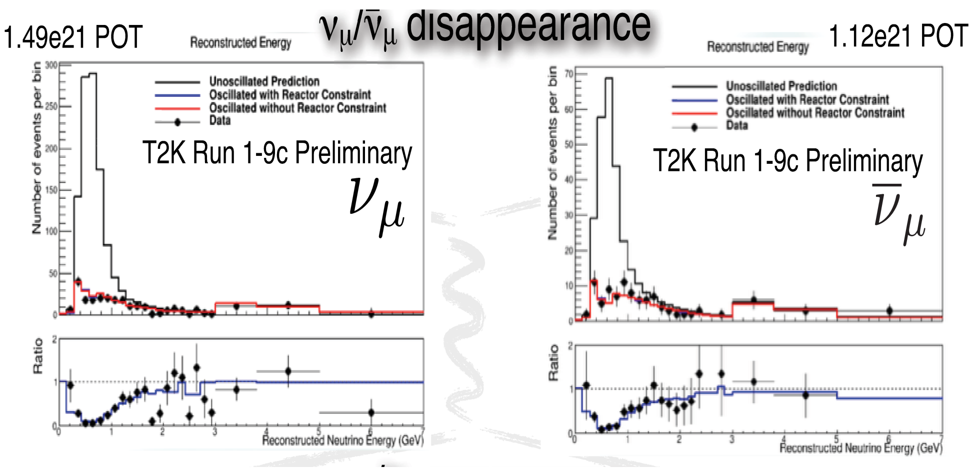
$\Rightarrow$ Determination of $|\Delta m^2_{32}| \simeq |\Delta m^2_{31}|$

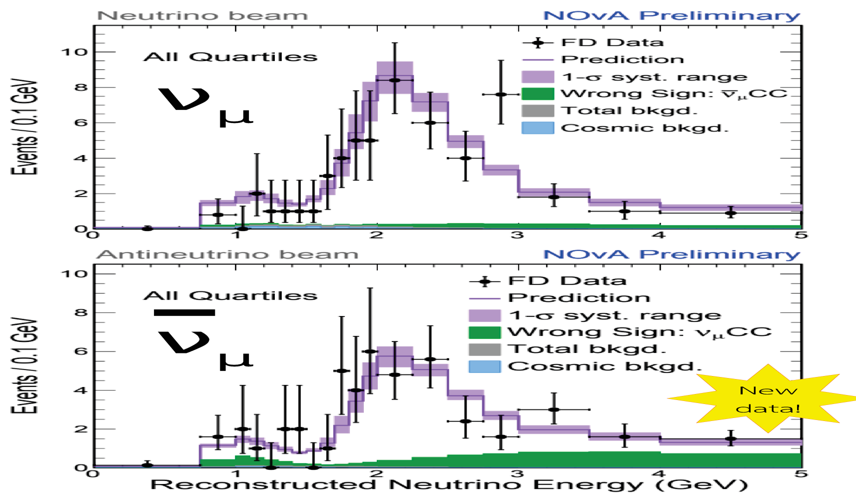
– *Depth* at osc minimum:

$\Rightarrow$ Determination of $\theta_{23}$ up to octant

$$P_{\mu\mu}(\theta_{23}) \simeq P_{\mu\mu}(\tfrac{\pi}{2} - \theta_{23})$$

(At osc min $P_{\mu\mu}(\theta_{23} \simeq \frac{\pi}{4}) \sim 0$)



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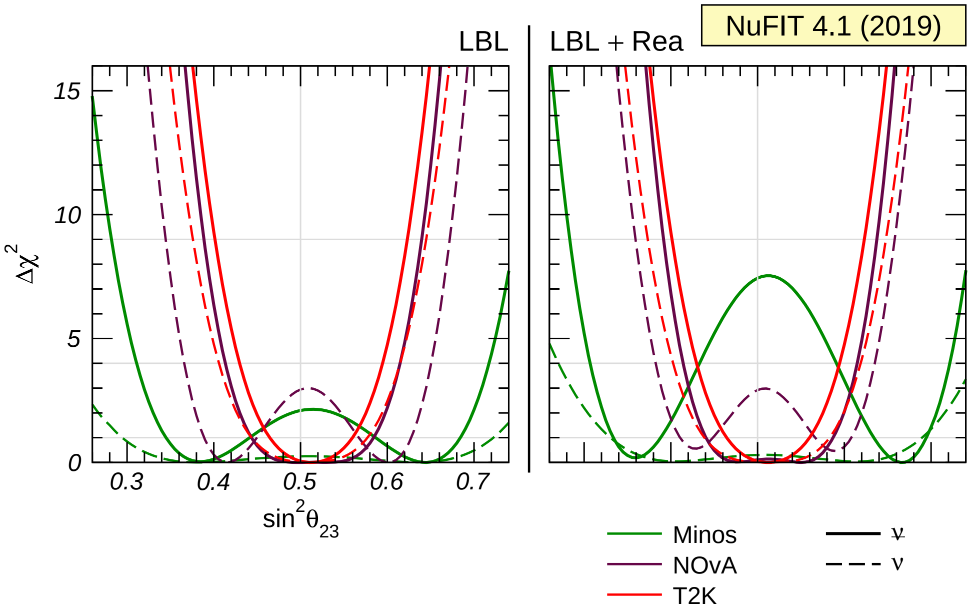
• In $3\nu$ scenario the relevant survival probability

$$P_{\mu\mu} = P_{\bar\mu\bar\mu} \approx 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E_\nu} \simeq 1 - c^2_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}(s^2_{13}, \Delta m^2_{21})$$




∗ Left panel use prior $\theta_{13}$ from reactors (procedure in LBL experment analysis)

∗ Right panel: full combination with $\chi^2_{\rm react}(\theta_{13}, \Delta m^2_{31})$

⇒ Non-maximality driven by NO$\nu$A $\bar\nu$ and MINOS

⇒ More significant when full comb with React

# 3 $\nu$ Analysis: $\Delta m^2_{3l}$ in LBL vs Reactors

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

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

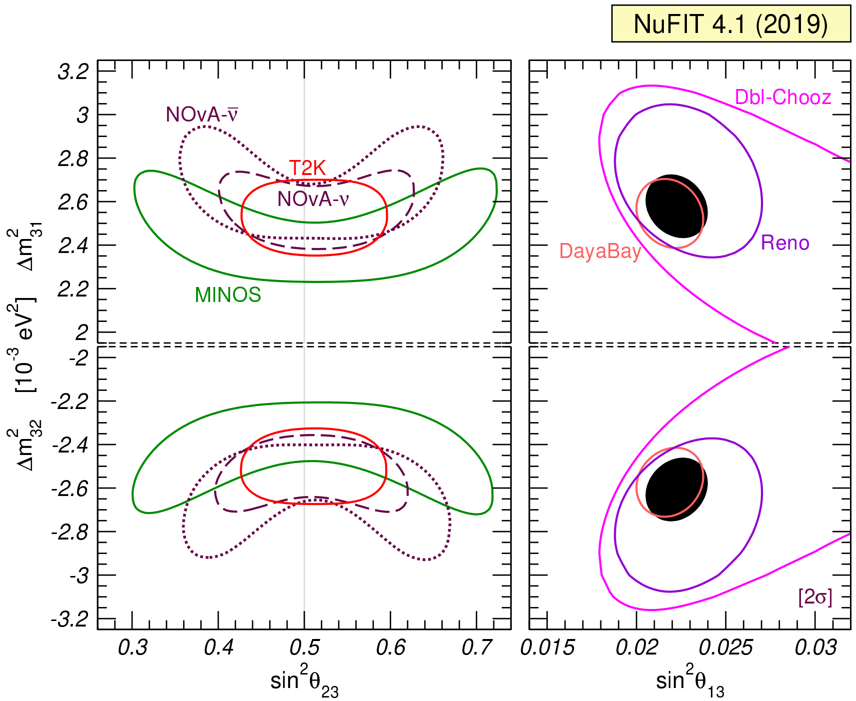
$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{matrix} c^2_{12}\Delta m^2_{21} & \text{NO} \\ s^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix} + \dots$$

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

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) + \mathcal{O}[(\Delta m^2_{21})^2]$$

$$\Delta m^2_{ee} \simeq \Delta m^2_{3l} + \begin{matrix} s^2_{12}\Delta m^2_{21} & \text{NO} \\ c^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix}$$

Nunokawa,Parke,Zukanovich (2005)




$\Rightarrow$ Small contribution to NO/IO from disapp data

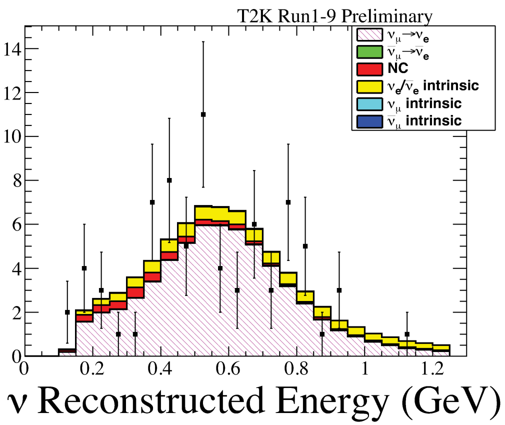
# 3 $\nu$ Analysis: $\theta_{23}$ Octant, Ordering, $\delta_{CP}$ in LBL

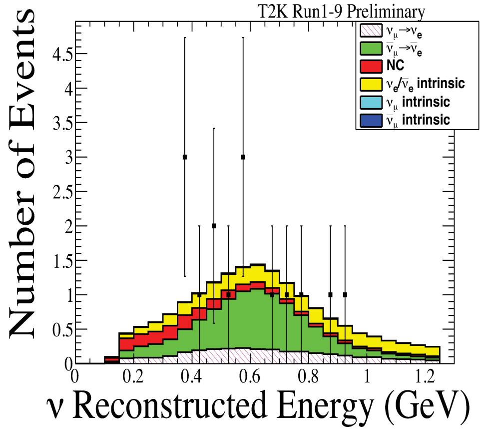
- Dominant information from $\nu_e$ apperance in LBL

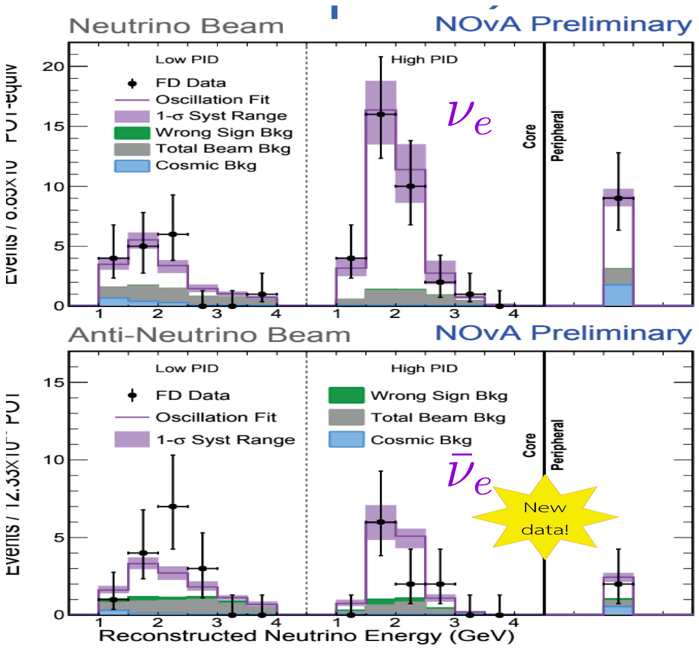
$$P_{\mu e} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) + \tilde{J}\,\frac{\Delta_{21}}{V_E}\,\frac{\Delta_{31}}{B_\mp}\,\sin\left(\frac{V_E L}{2}\right)\sin\left(\frac{B_\mp L}{2}\right)\cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

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

T2K $\nu_\mu \to \nu_e$ $\qquad$ $\bar{\nu}_\mu \to \bar{\nu}_e$ $\qquad$ NOvA




| | | Observed | $\delta = -\pi/2$ | $\delta = 0$ | $\delta = +\pi/2$ | $\delta = \pi$ |
|---|---|---|---|---|---|---|
| $\nu_e$ | *e*-like $\nu$ mode | 75 | 74.4 | 62.2 | 50.6 | 62.7 |
| $\nu_e$ | *e*-like+1$\pi^+$ $\nu$ mode | 15 | 7.0 | 6.1 | 4.9 | 5.9 |
| $\bar{\nu}_e$ | *e*-like $\bar{\nu}$ mode | 15 | 17.1 | 19.4 | 21.7 | 19.3 |
| $\nu_\mu$ | $\mu$-like $\nu$ mode | 243 | 272.4 | 272.0 | 272.4 | 272.8 |
| $\bar{\nu}_\mu$ | $\mu$-like $\bar{\nu}$ mode | 140 | 139.2 | 139.2 | 139.5 | 139.9 |

in NO

| | |
|---|---|
| Data neutrino candidates | 58 |
| Best fit total prediction | 59 |

| | |
|---|---|
| Data antineutrino candidates | 27 |
| Best fit total prediction | 27 |

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

- Dominant information from $\nu_e$ apperance in LBL

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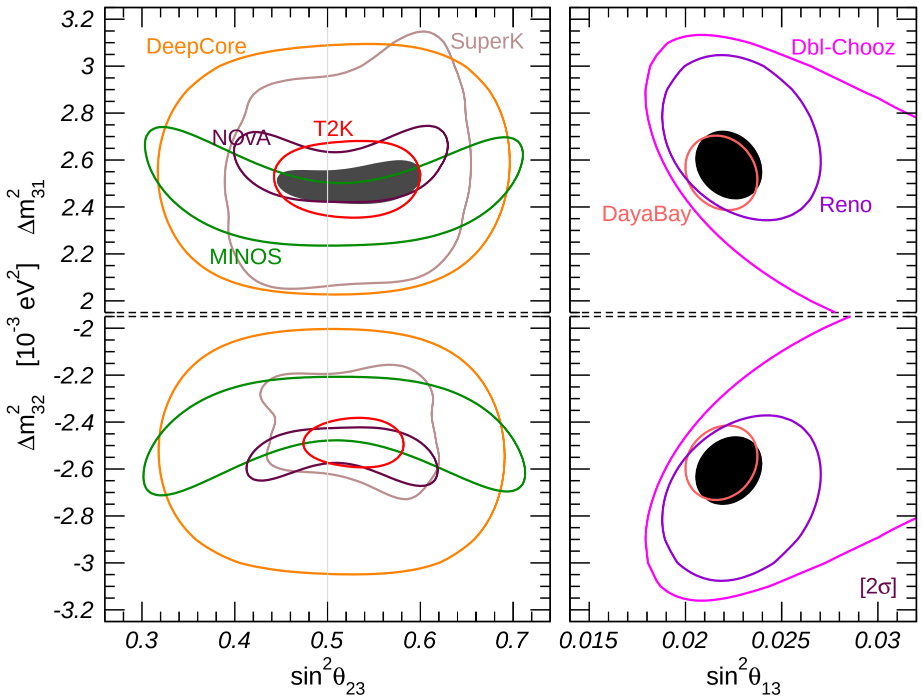


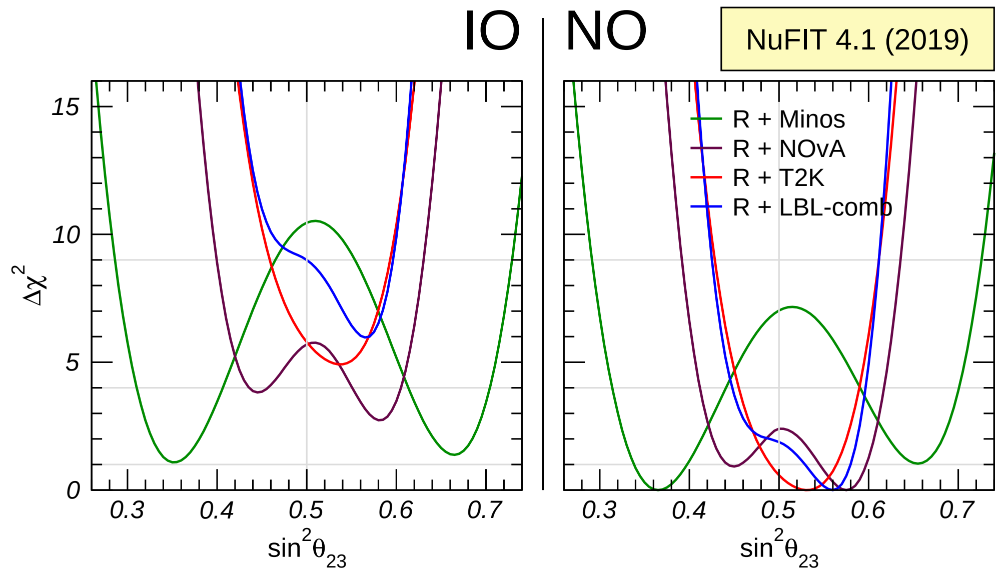


REAC+LBL-COMB:

$*$ In both orderings best fit $\sin^2\theta_{23} \sim 0.58$

$*$ $\theta_{23} = \frac{\pi}{4}$ at$\Delta\chi^2 \sim 2(4)$ of b.f. in NO(IO)

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



- Dominant information from $\nu_e$ apperance in LBL

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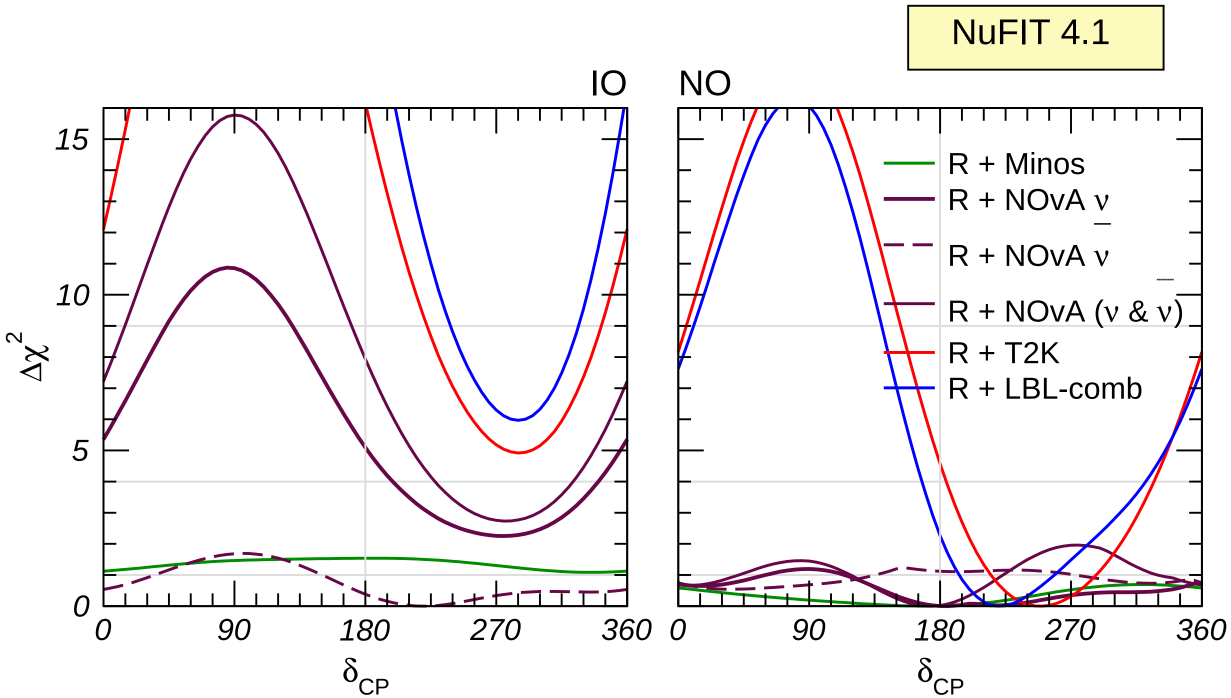


$*$ IO disfavoured at $\Delta\chi^2 \sim 6$

$*$ NO: CP conservation ($\delta_{CP} = 180^\circ$ allowed at $\Delta\chi^2 \sim 3$

$*$ NO: $-40 \lesssim \delta_{CP} \lesssim 160$ ($20 \lesssim \delta_{CP} \lesssim 135$) disfavoured at $2\sigma$ ($3\sigma$)

# Leptonic CPV in 3$\nu$ Mixing: Jarlskog Invariant

- Leptonic $\not{C}$P $\Rightarrow P_{\nu_\alpha \to \nu_\beta} \neq P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}$
- In 3$\nu$ always

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

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

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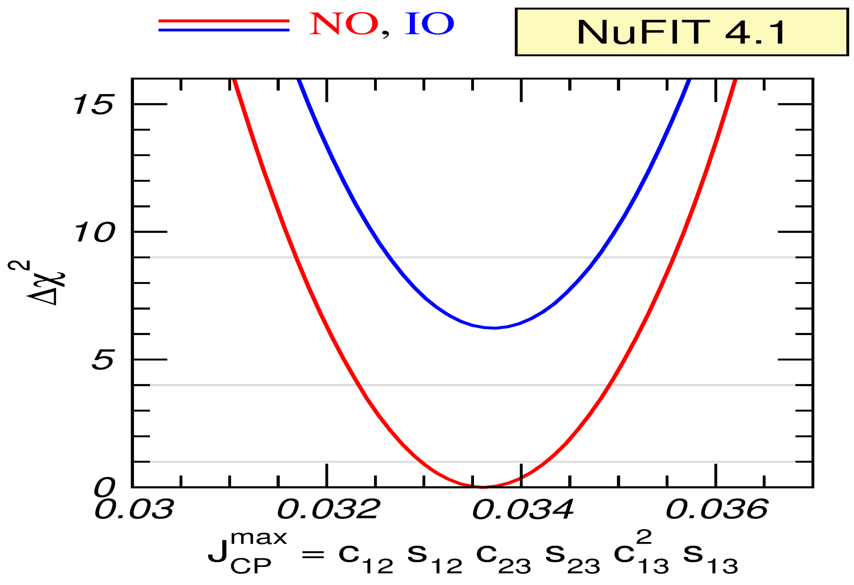
- Maximum Allowed Leptonic CPV:




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

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 CPV in 3$\nu$ Mixing: Jarlskog Invariant

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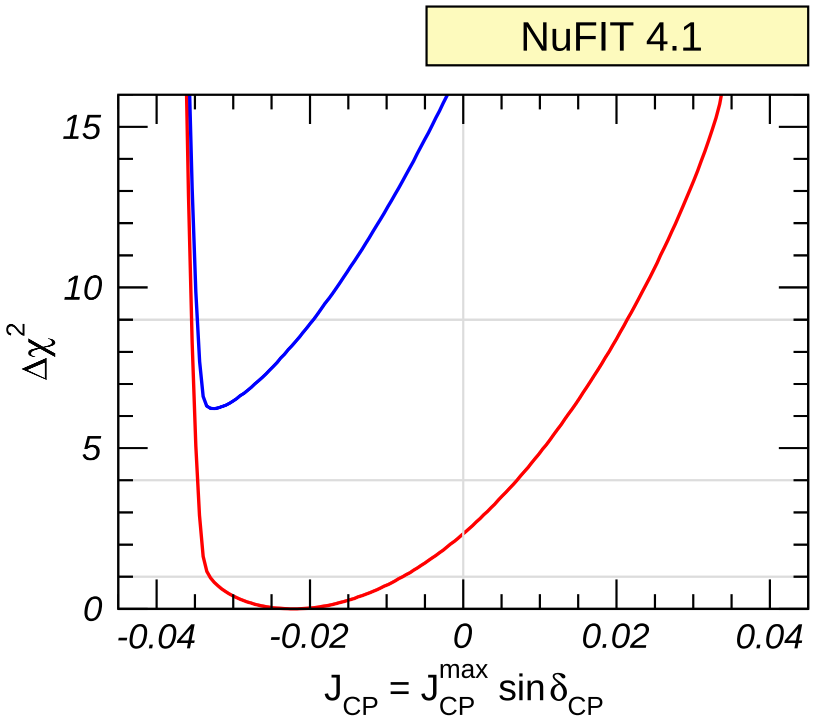
- Present determination of $J$:



# $3\nu$ Mixing: Leptonic Unitarity Triangles

- $U$ unitary $\Rightarrow$ any pair of rows or columns verify

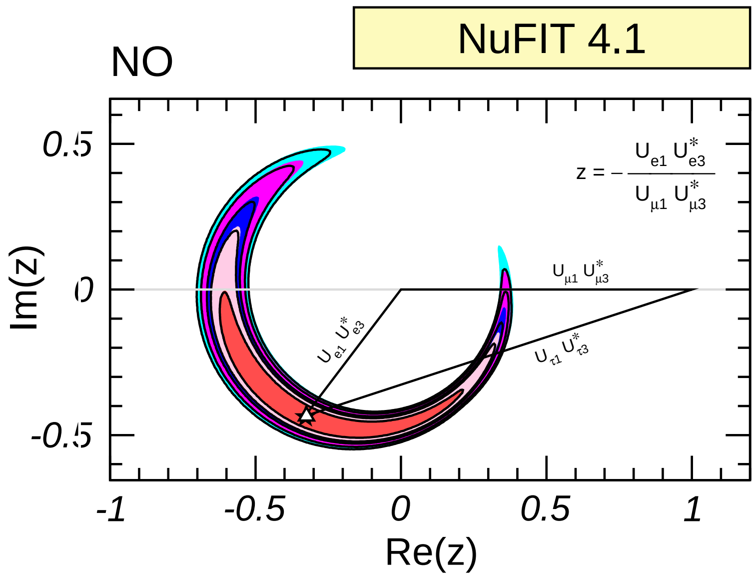
$$\sum_{i=1,2,3} U_{\alpha i} U^*_{\beta i} = 0 \quad \text{with } \alpha \neq \beta \qquad \text{or} \qquad \sum_{\alpha=e,\mu,\tau} U_{\alpha i} U^*_{\alpha j} = 0 \quad \text{with } i \neq j$$

$\Rightarrow$ Each condition represent a triangle in complex plane

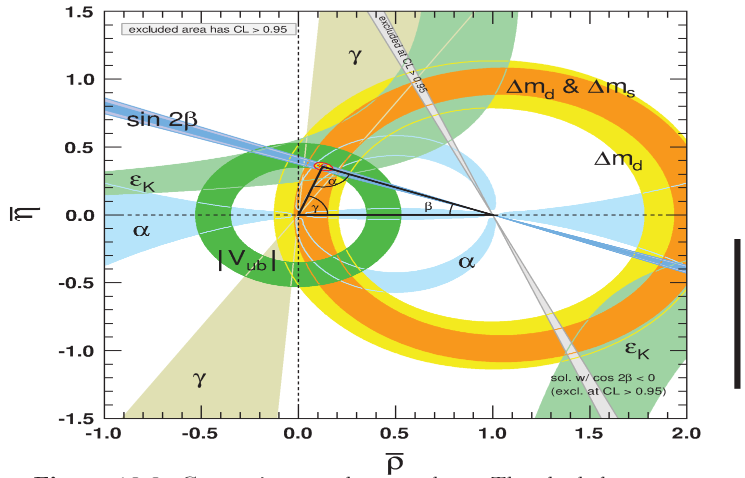
- All 6 triangles are equivalent
- CPV $\Rightarrow$ triangles are not "flat"

- Convenient define a complex variable $z = -\frac{U_{\alpha i} U^*_{\beta i}}{U_{\alpha k} U^*_{\beta k}}$ or $z = -\frac{U_{\alpha i} U^*_{\alpha j}}{U_{\gamma i} U^*_{\gamma j}}$

$\Rightarrow$ two triangle vertices at $(0,0)$ and $(1,0)$ in complex $z$ plane.




The equivalent triangle in quark sector



# *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)

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

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

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

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- Earth matter effects in large statistics ATM $\nu_\mu$ disapp : HK,INO, PINGU,ORCA ...
  – Challenge: ATM flux contains both $\nu_\mu$ and $\bar\nu_\mu$, ATM flux uncertainties

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

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

  – Challenge: Energy resolution

# *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
- Leptonic CP: "Hint" driven by T2K "fluctuation". Diluted in combination with NOvA.

  CP conservation at 90% CL
- Ordering: IO disfavoured at 99%CL ($3.3\sigma$) without (with) SK ATM

  Definite answers most likely only with upcoming experiments

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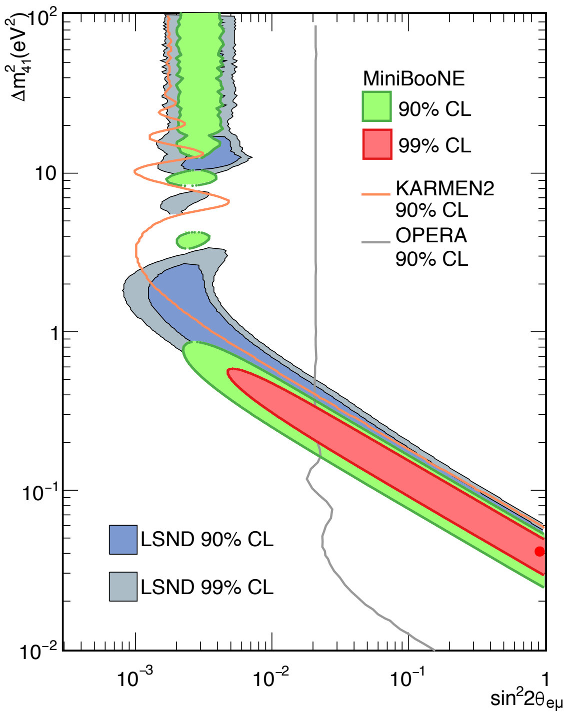
  Definite answers most likely only with upcoming experiments
- Only three light states?

# Beyond 3$\nu$'s: Light Sterile Neutrinos

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

## LSND, MiniBoone

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



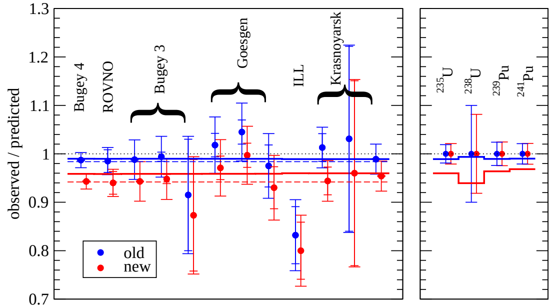

From LSND mid 90's
to MiniBoone 1805.12028

## Reactor Anomaly

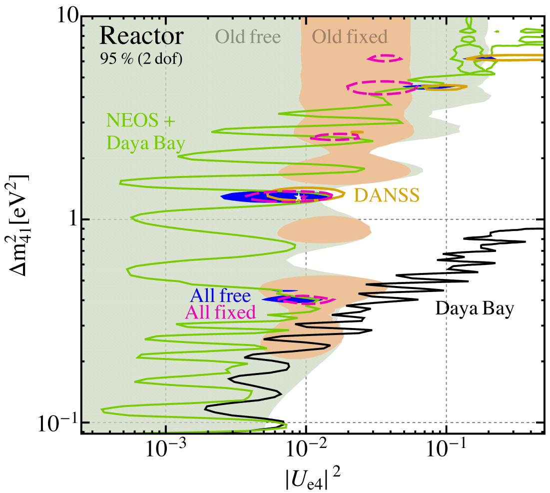
Huber, 1106.0687
Mention *etal* ,1101.2755

New reactor flux calculation

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




Explained as $\nu_e$ disappearance




Dentler etal, 1803.10661

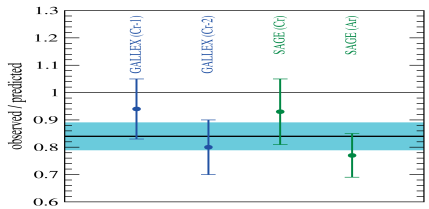
## Gallium Anomaly

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

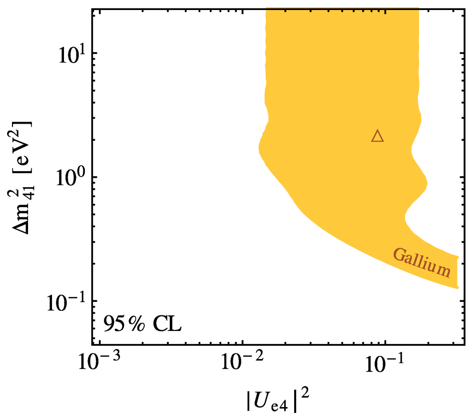
Radioactive Sources ($^{51}$Cr, $^{37}$Ar)
in calibration of Ga Solar Exp;

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

Give a rate lower than expected



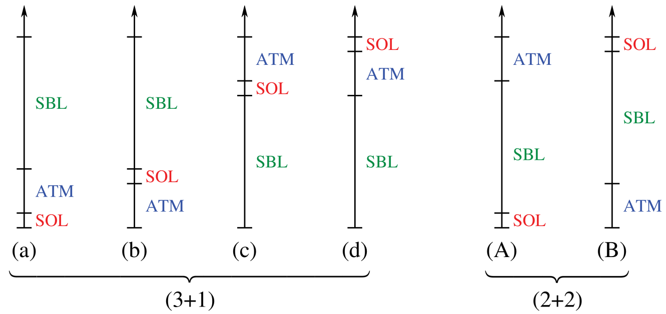

Explained as $\nu_e$ disappearance



# Light Sterile Neutrinos



- These explanations require $\mathcal{O}$(eV) mass $\nu_s$



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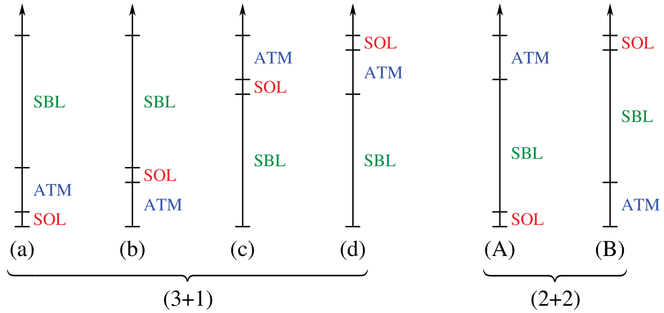
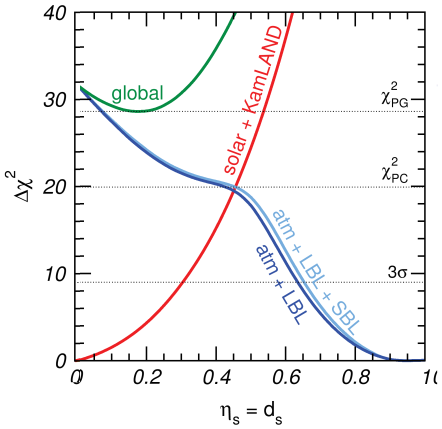



- 2+2:




Ruled out by solar and atm data ($\gtrsim 5\sigma$)

Maltoni *etal* NPB 02

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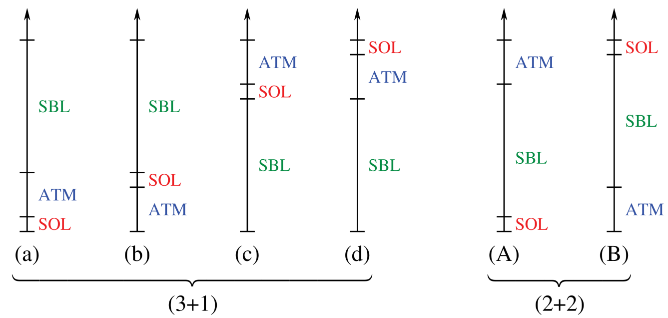
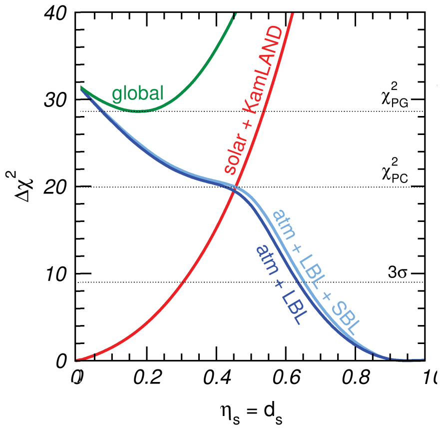



- 2+2:

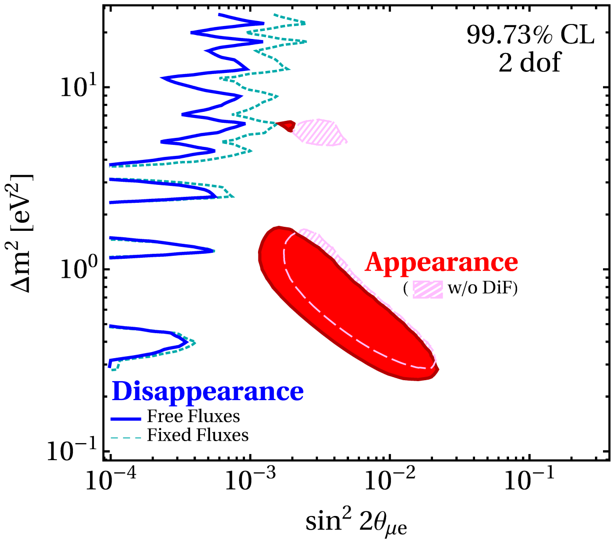



Ruled out by solar and atm data ($\gtrsim 5\sigma$)

Maltoni *etal* NPB 02

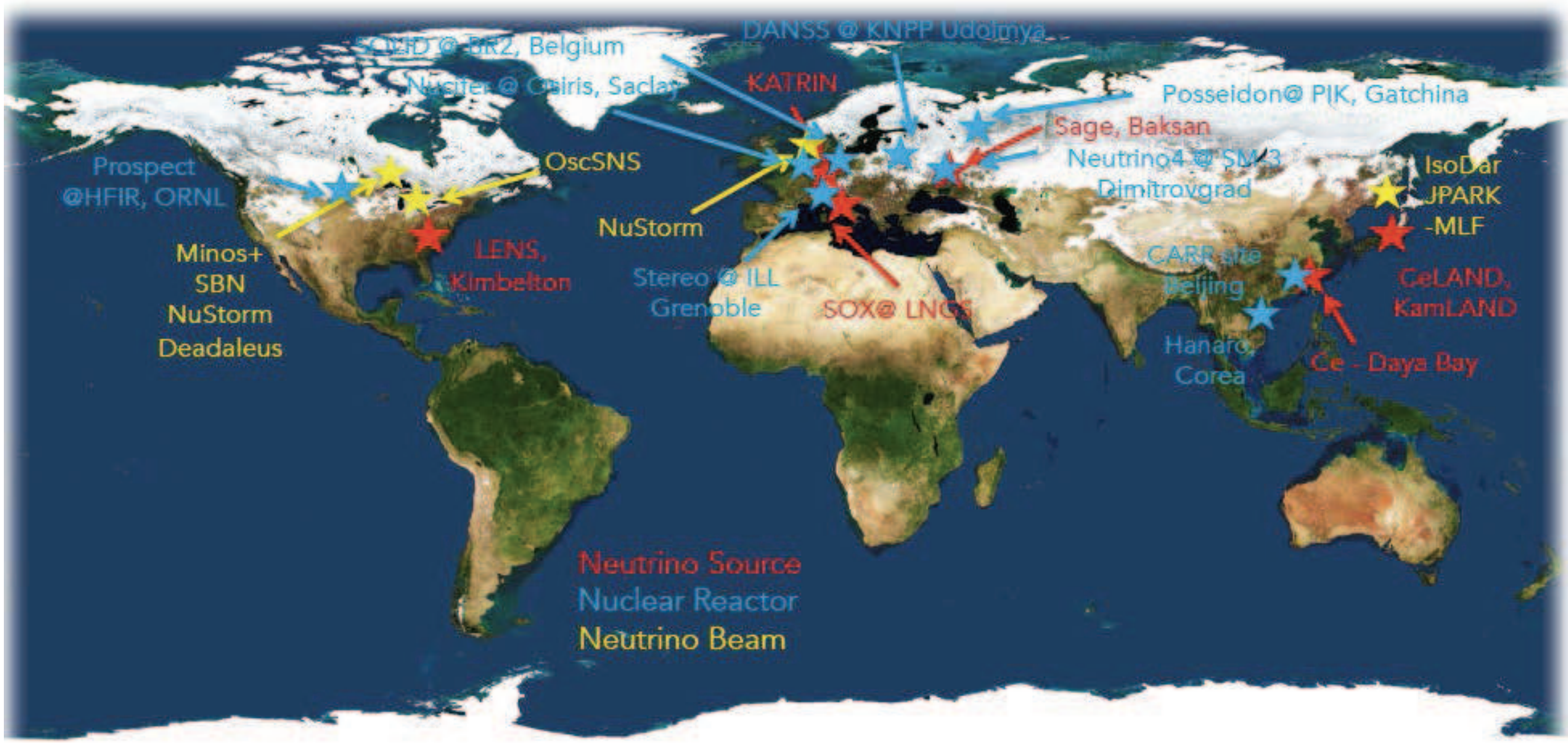
- 3+1: Generically appearance $P_{e\mu} \sim |U^*_{ei} U_{\mu i}|$ $\begin{cases} |U_{ei}| \text{ constrained by } P_{ee} \text{ disapp data} \\ |U_{\mu i}| \text{ constrained by } P_{\mu\mu} \text{ disapp data} \end{cases}$

*




Dentler etal, 1803.10661

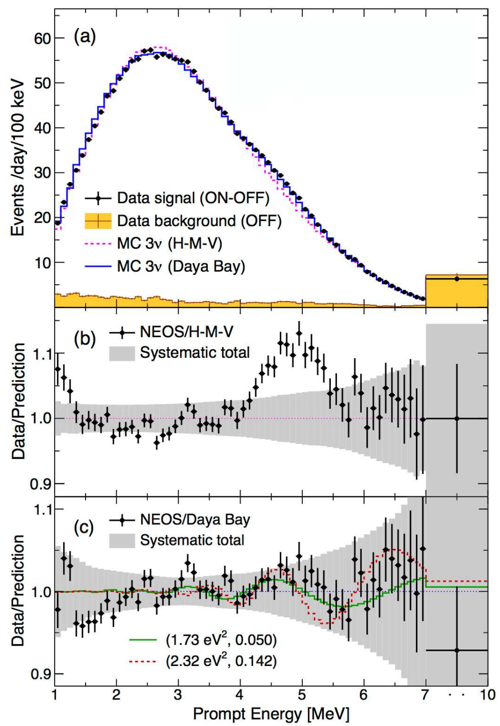
# Searches for eV sterile neutrinos



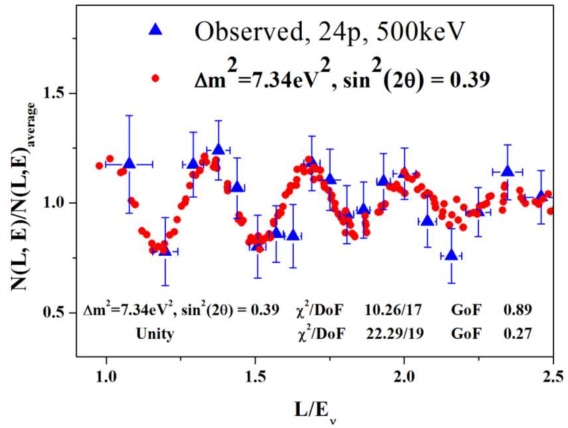

This talk: (anti-) $\nu_e$ disapearance only

$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$

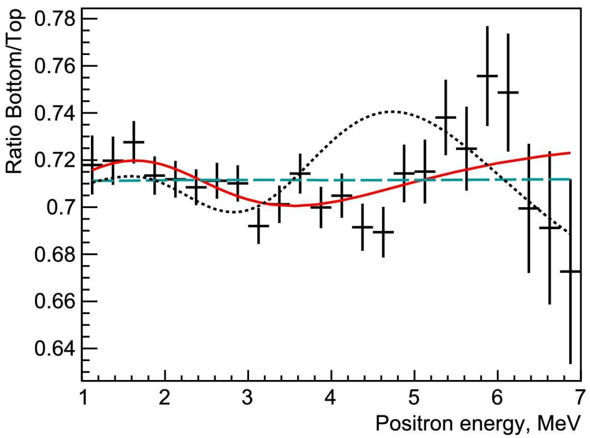
# NEOS (Bounds)



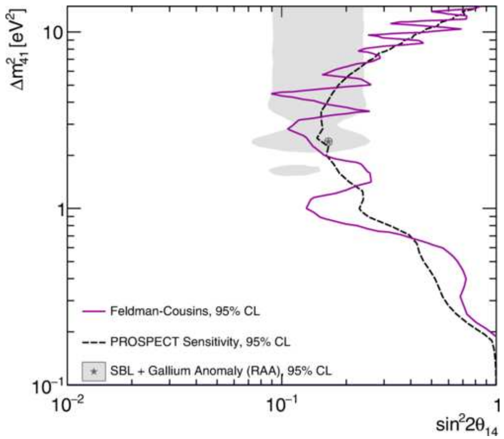

# Neutrino4 Results (Signal?)



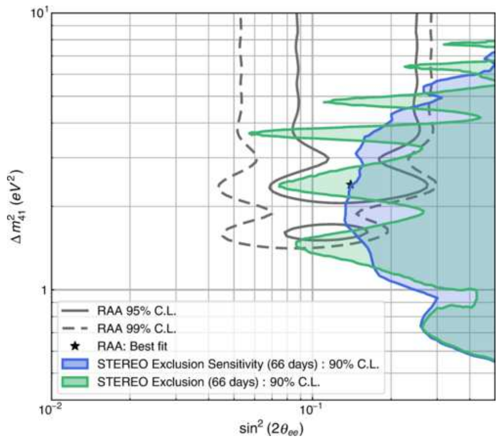

# DANS (Bounds)




# Prospect (Bounds)




# Stereo (Bounds)




Figures from Boser *eta* arXiv:1906.01739

# *Confirmed* Low Energy Picture and MY List of Q&A

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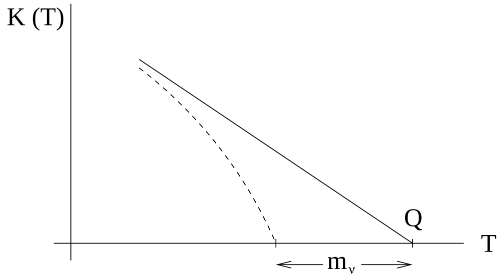
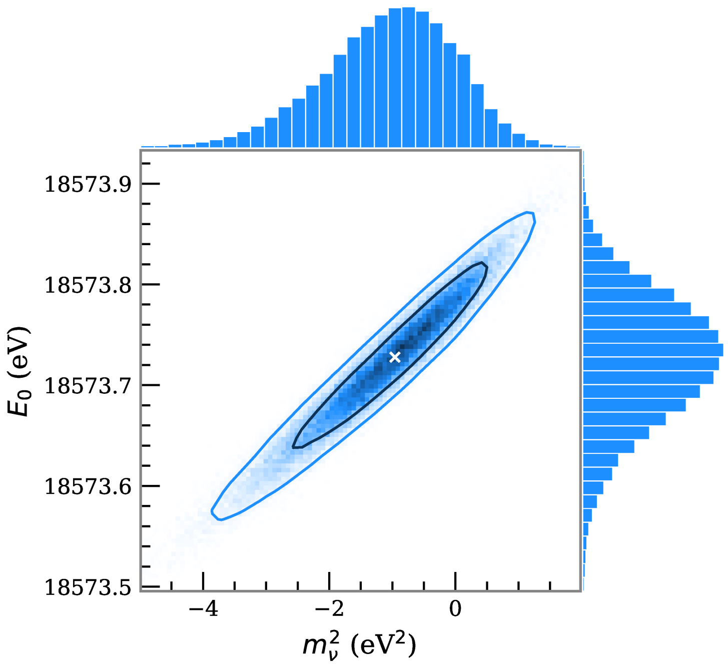
# Neutrino Mass Scale: $\beta$ Decay

**Single $\beta$ decay** : Dirac or Majorana $\nu$ mass modify spectrum endpoint




$$m^2_{\nu_e} = \sum m^2_j |U_{ej}|^2 = c^2_{13} c^2_{12} m^2_1 + c^2_{13} s^2_{12} m^2_2 + s^2_{13} m^2_3$$

Purely kinematics $\Rightarrow$ Only model independent probe $\nu$-mass scale



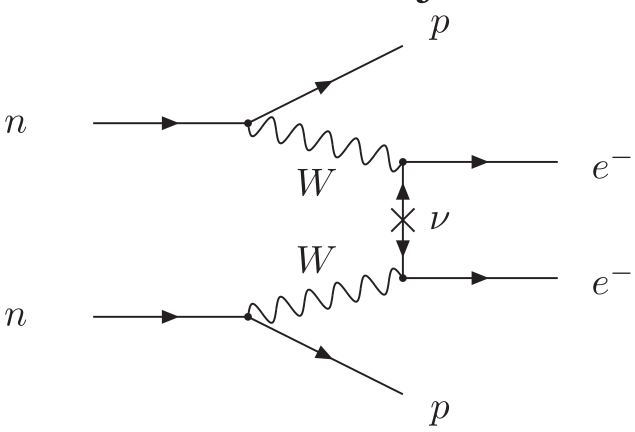

**KATRIN NEW:** $m_{\nu_e} \leq 1.1$ eV **(at 90 % CL)**

arXiv:1909.96048

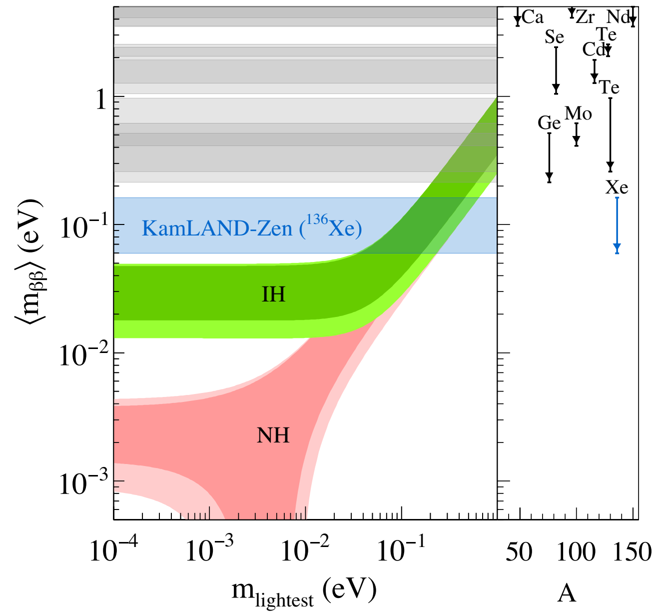
Future Katrin Sensitivity to $m_{\nu_e} \sim 0.2$ eV

# Majorana or Dirac: $0\nu\beta\beta$ Decay

$0\nu\beta\beta \Rightarrow$ L violation $\Leftrightarrow$ Majorana $\nu$




At present only bounds from $^{136}$Xe (EXO and KamLAND-ZEN) $^{76}$Ge (Gerda) and $^{130}$Te (Cuore-0)




If $m_\nu$ only source of $\Delta L$

$$T^{0\nu}_{1/2} = \frac{m_e}{G_{0\nu}\, M^2_{\rm nucl}\, m^2_{ee}}$$

KamLAND-Zen Coll. ArXiv:1605.02889

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

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

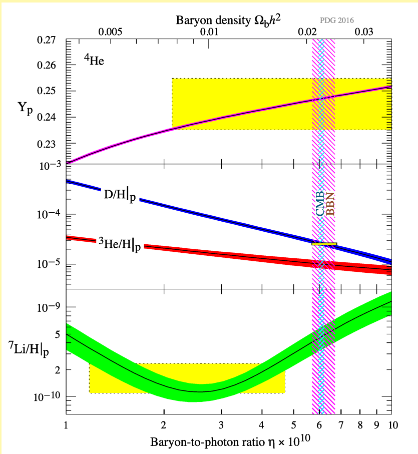
$$= f(m_\ell, \text{order}, \text{maj phases})$$

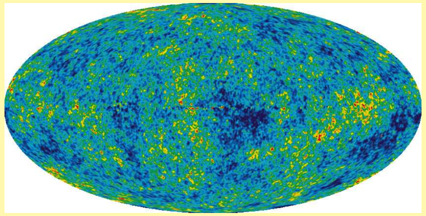
$$m_{ee} \lesssim 0.061 - 0.165 \text{ (90\% CL)}$$

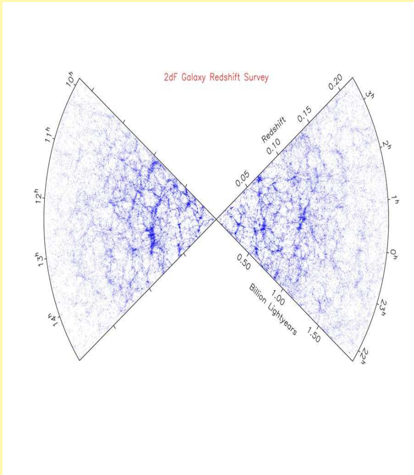
# Light massive $\nu$ in Cosmology

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 $\sum_i m_{\nu_i}$



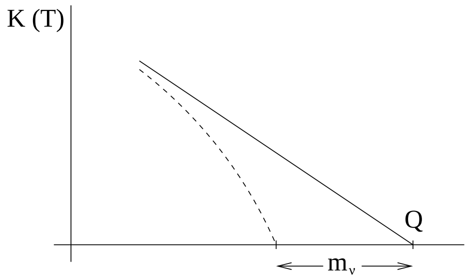



| | | |
|---|---|---|
| Primordial Nucleosynthesis BBN | Cosmic Microwave Background CMB | Large Scale Structure Formation LSS |
| $T \sim$ MeV | $T \lesssim$ eV | |
| Number of $\nu's$ ($N_{\rm eff}$) | $N_{\rm eff}$ and $\sum m_\nu$ | |

BUT: Observables also depend on all other cosmo parameters (and assumptions)

# Probes of Mass Scale in 3$\nu$-mixing

**Single $\beta$ decay** : Pure kinematics, Dirac or Majorana $\nu$'s, only model independent

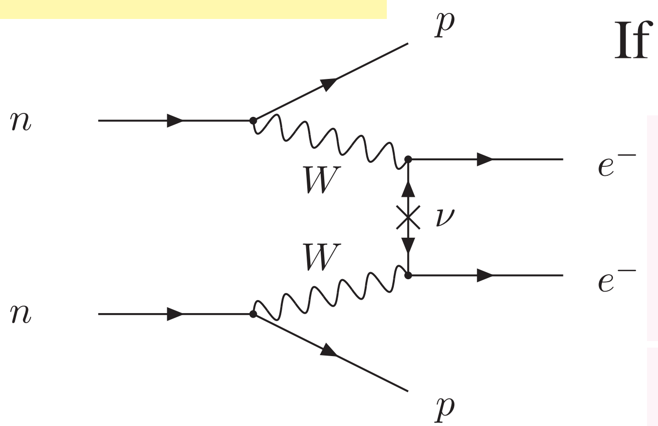



$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = \begin{cases} \text{NO}: \; m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} + \Delta m^2_{31} s^2_{13} \\ \text{IO}: \; m_\ell^2 + \Delta m^2_{21} c^2_{13} s^2_{12} - \Delta m^2_{31} c^2_{13} \end{cases}$$

Present bound: $m_{\nu_e} \leq 1.1$ eV (90% CL KATRIN 2019)

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

**$\nu$-less Double-$\beta$ decay:** $\Leftrightarrow$ Majorana $\nu' s$




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

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

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

**COSMO** for Dirac or Majorana
$m_\nu$ 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⇒ Correlations $m_{\nu_e}$, $m_{ee}$ and $\sum m_\nu$( Fogli *et al* (04))

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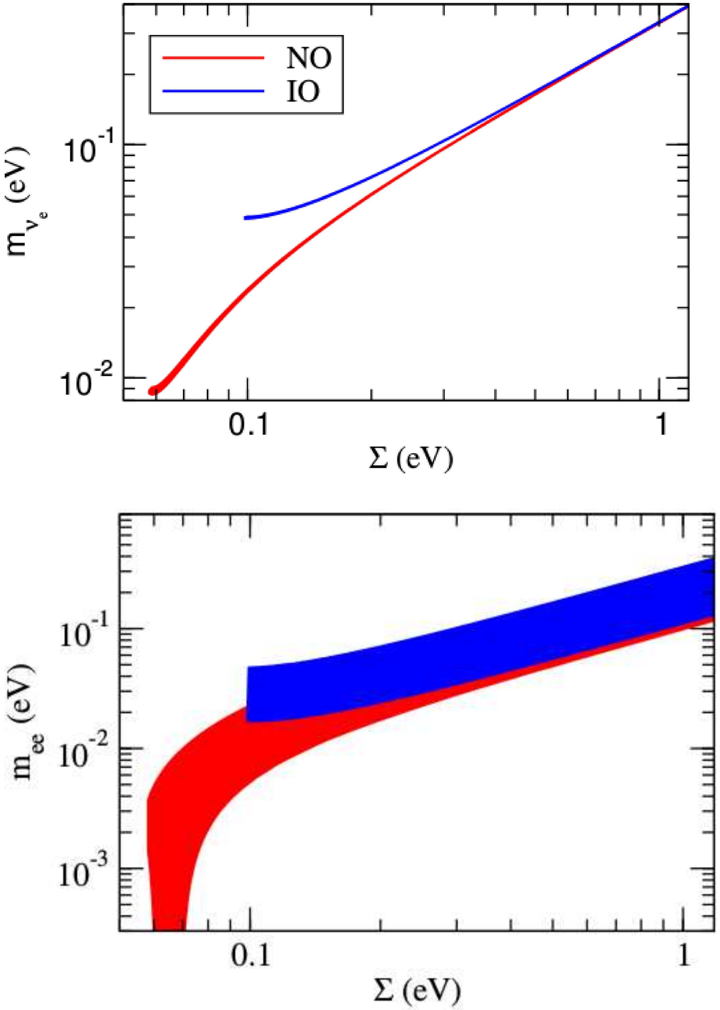
NuFIT 4.1 (2019)



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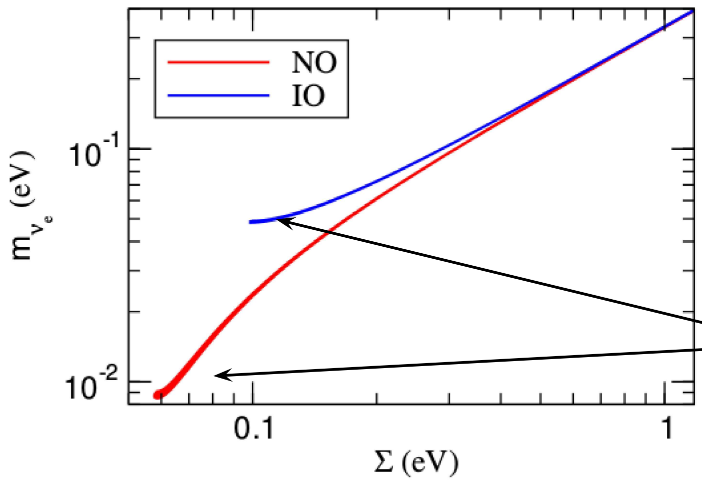
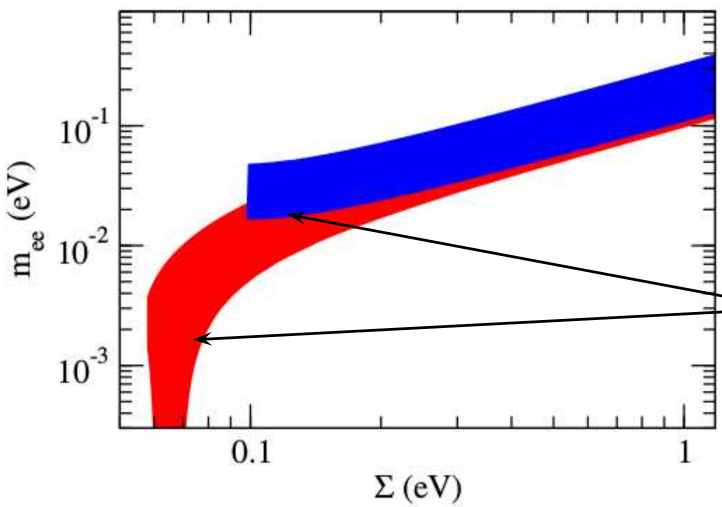



Width due to range in oscillation parameters very narrow

Lower bound on $\sum m_i$ depends on ordering




Wide band due to unknown Majorana phases ⇒

Possible Det of Maj phases?

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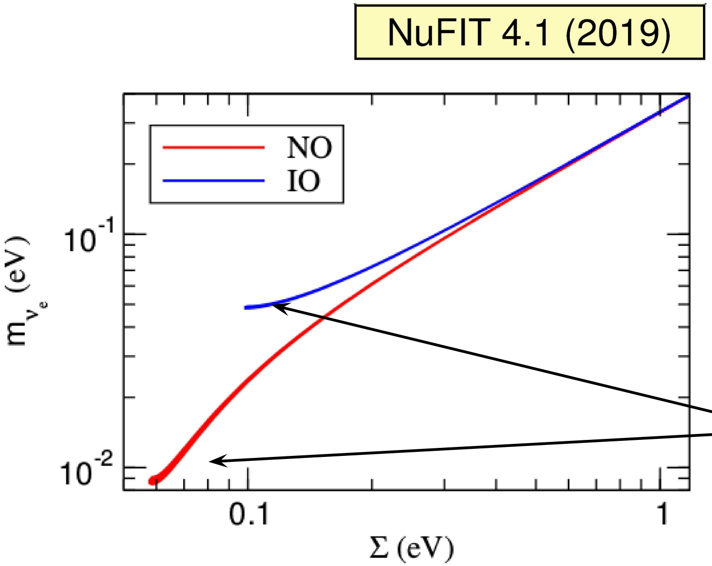
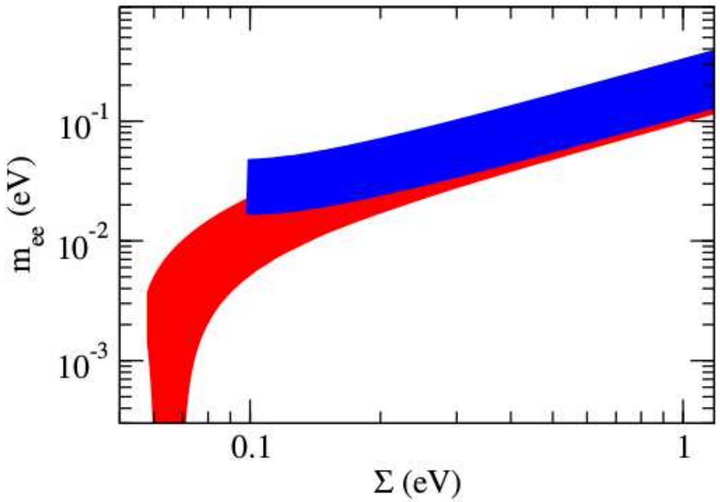



Lower bound on $\sum m_i$ depends on ordering

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

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

Cosmo data will only add to N/I likelihood when accuracy on $\Sigma m_\nu$ better than 0.02 eV (to see a $2\sigma$ N/I difference between 0.06 and 0.1)

Hannestad, Schwetz 1606.04691

# Ordering: The Cosmo-Lab Connection

## Other inputs for mass ordering?

ν-oscillations: $\Delta m^2_{ij}$

cosmology: $\Sigma m_i$

$0\nu\beta\beta$: $m_{\beta\beta}$

**Case A**

$(m_1, m_2, m_3)$

**Case B**

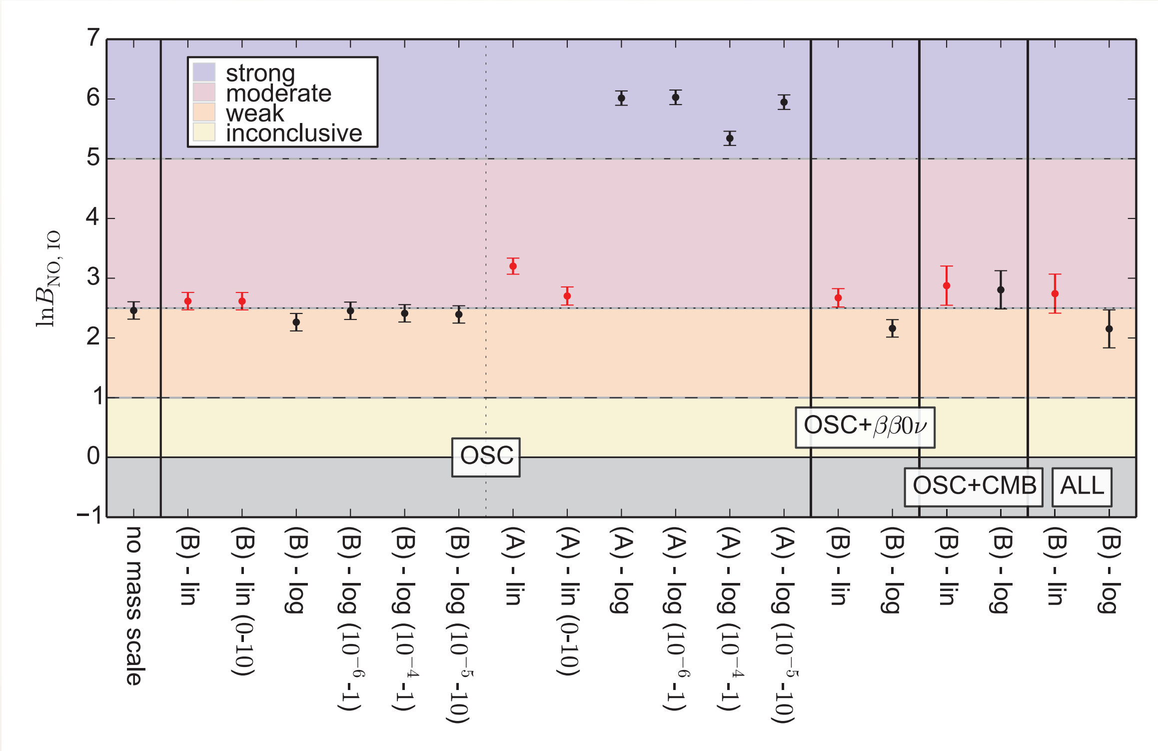
$(m_0, \Delta m^2_{21}, \Delta m^2_{31})$

- $m_j$: linear / log prior
- $\Delta m^2_{ij}$: always linear

⇒ case A: choice of priors is very relevant

⇒ preference for NO driven by oscillation data

⇒ cosmology can not contribute to determine MO yet




Gariazzo et al, JCAP03 (2018) 11

Using global fit-2017, wo SK I-IV, old LBL

Slide from M. Tortola Talk at $\nu$2018

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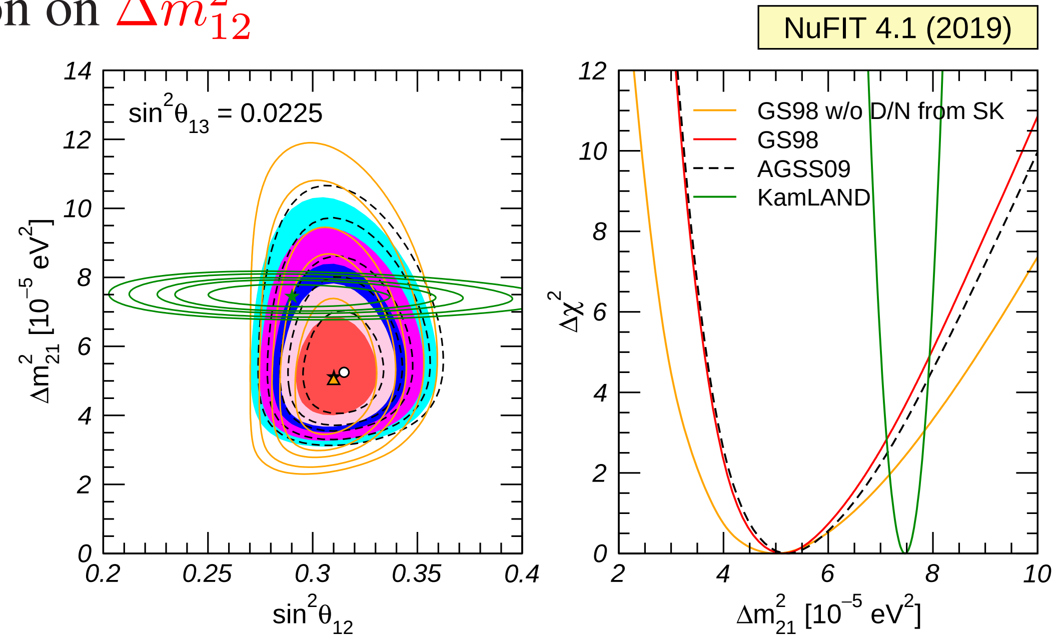
- Cosmological effects?: Still missing a "signal" and will we ever be convinced it is $\nu's$?
- Other NP at play?

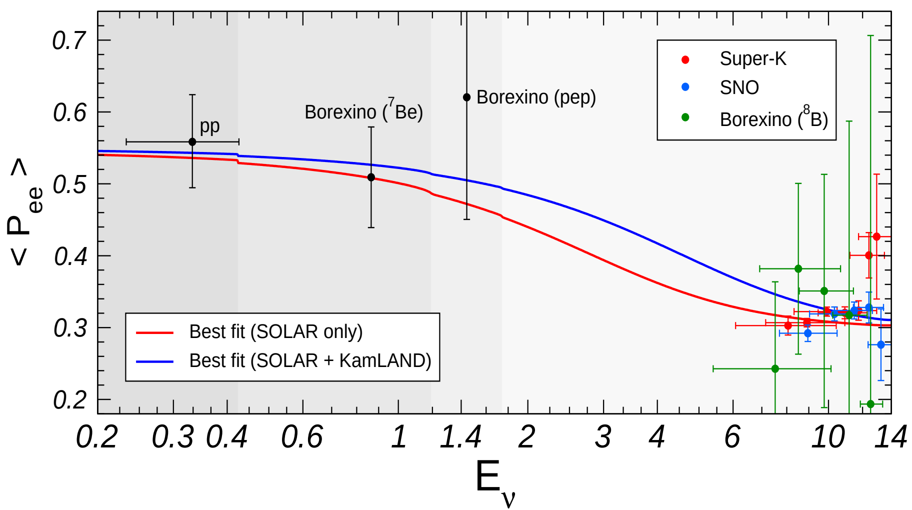
# Motivation: $\Delta m^2_{21}$ KamLAND vs SOLAR

For $\theta_{13} \simeq 8.5°$ agreement on $\theta_{12}$ OK between Solar and KamLAND is perfect.

But residual tension on $\Delta m^2_{12}$




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




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

Modified matter potential?

# Non Standard $\nu$ 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.:

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

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

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

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

In particular CPT $\Rightarrow$ invariance under simultaneously:

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

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

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

# NSI: Bounds/Degeneracies from/in Oscillation data

M.C G-G, M.Maltoni JHEP 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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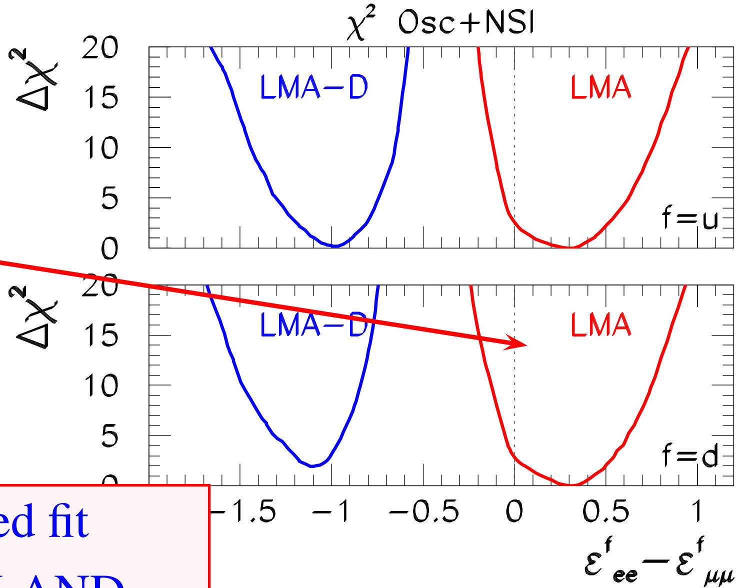


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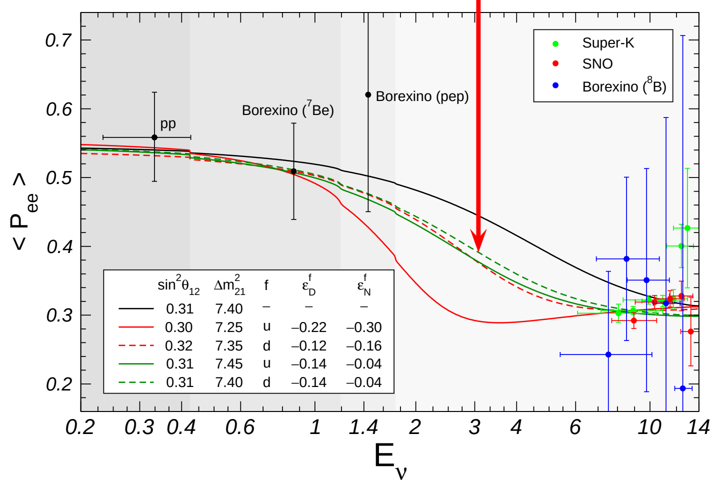
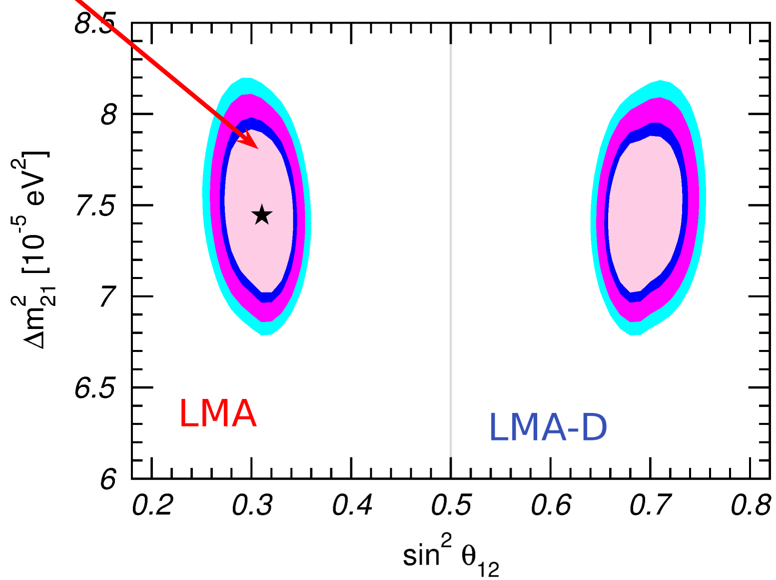
LMA: Improved fit
to Solar+KamLAND



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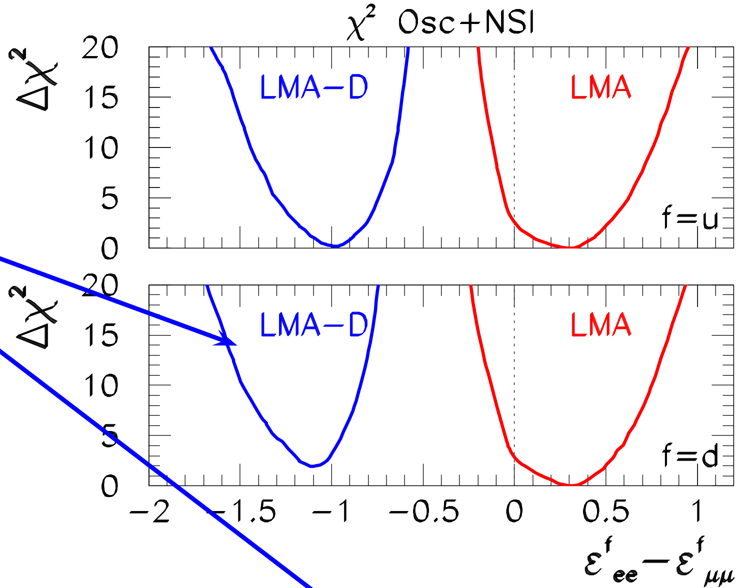



– Bounds $\mathcal{O}(1-10\%)$

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

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

Miranda,Tortola, Valle, hep-ph/0406280

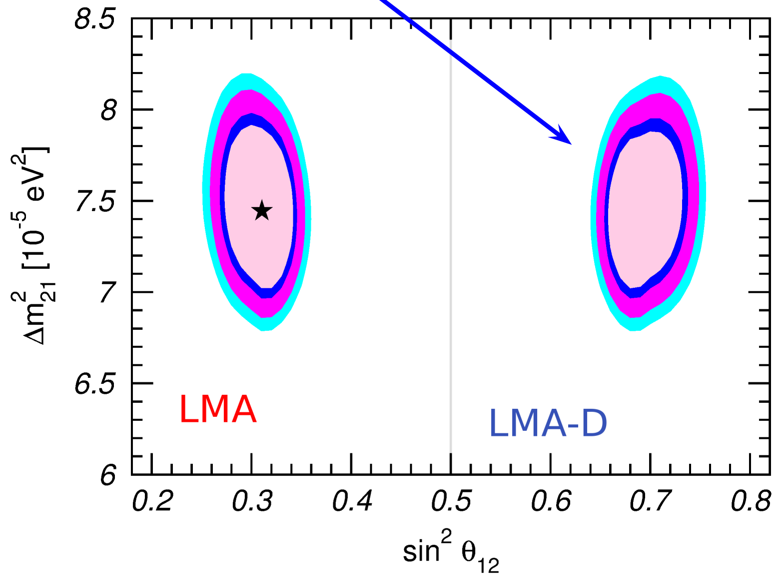
Cannot be resolved with osc-experiments

Requires NC scattering experiments

Coloma etal 1701.04828

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

Farzan 1505.06906, and Shoemaker 1512.09147



# NSI: Combination with COHERENT

Coloma, MCGG, Maltoni,Schwetz ArXiv:1708.02899

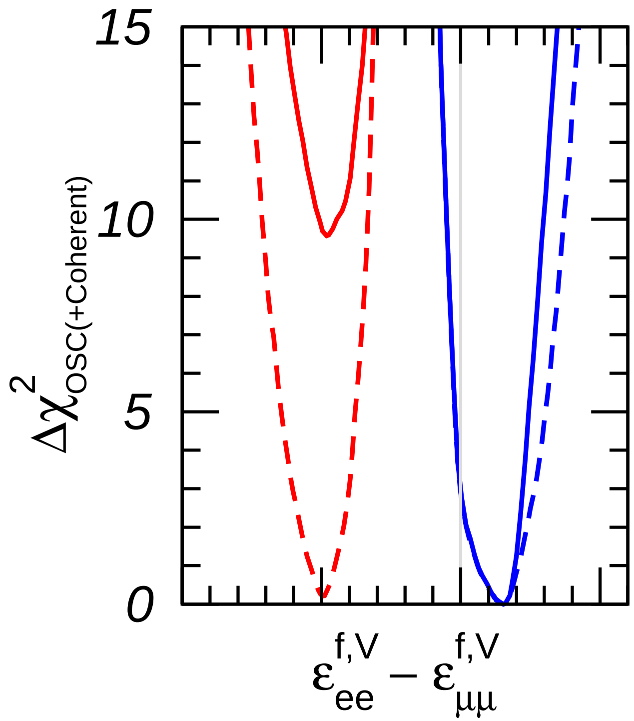
- COHERENT has detected for first time Coherent $\nu N$ scattering 1708.01294:
  142(1$\pm$ 0.28(sys)) observed events over a steady bck of 405
  136(SM) + 6(1$\pm$ 0.25(sys) beam-on bck) expected
- In presence of NSI: $N_{\rm NSI}(\varepsilon) = \gamma\left[f_{\nu_e} Q^2_{we}(\varepsilon) + (f_{\nu_\mu} + f_{\bar\nu_\mu}) Q^2_{w\mu}(\varepsilon)\right]$

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

- OSCILLATION + COHERENT $\Rightarrow$ LMA-D excluded at more than 3.1 $\sigma$
  for NSI with f=up or f=down

All NSI's constrained

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



# NSI: Combination with COHERENT

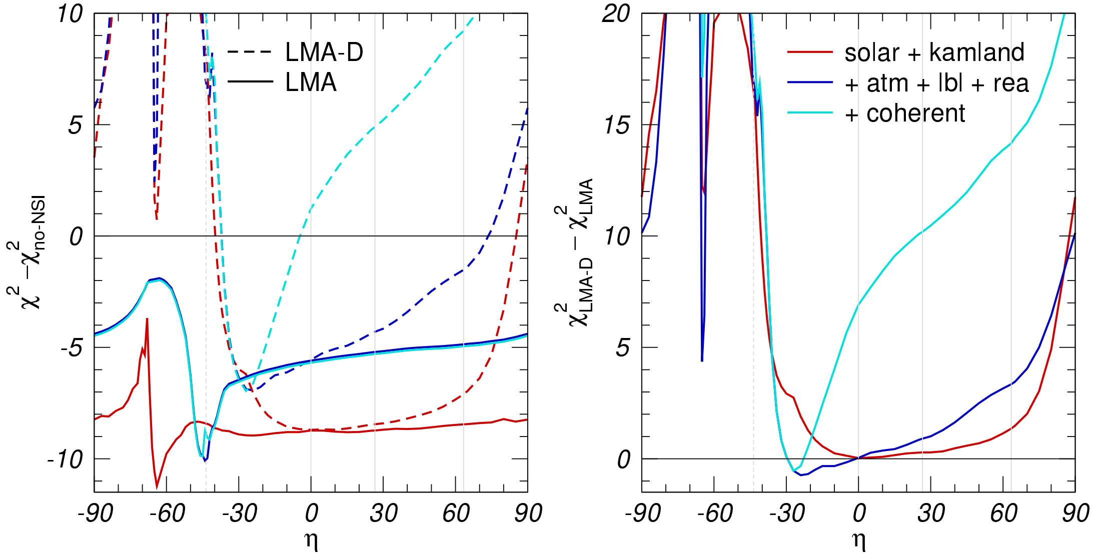
Coloma, MCGG, Maltoni,Schwetz ArXiv:1708.02899

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

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

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

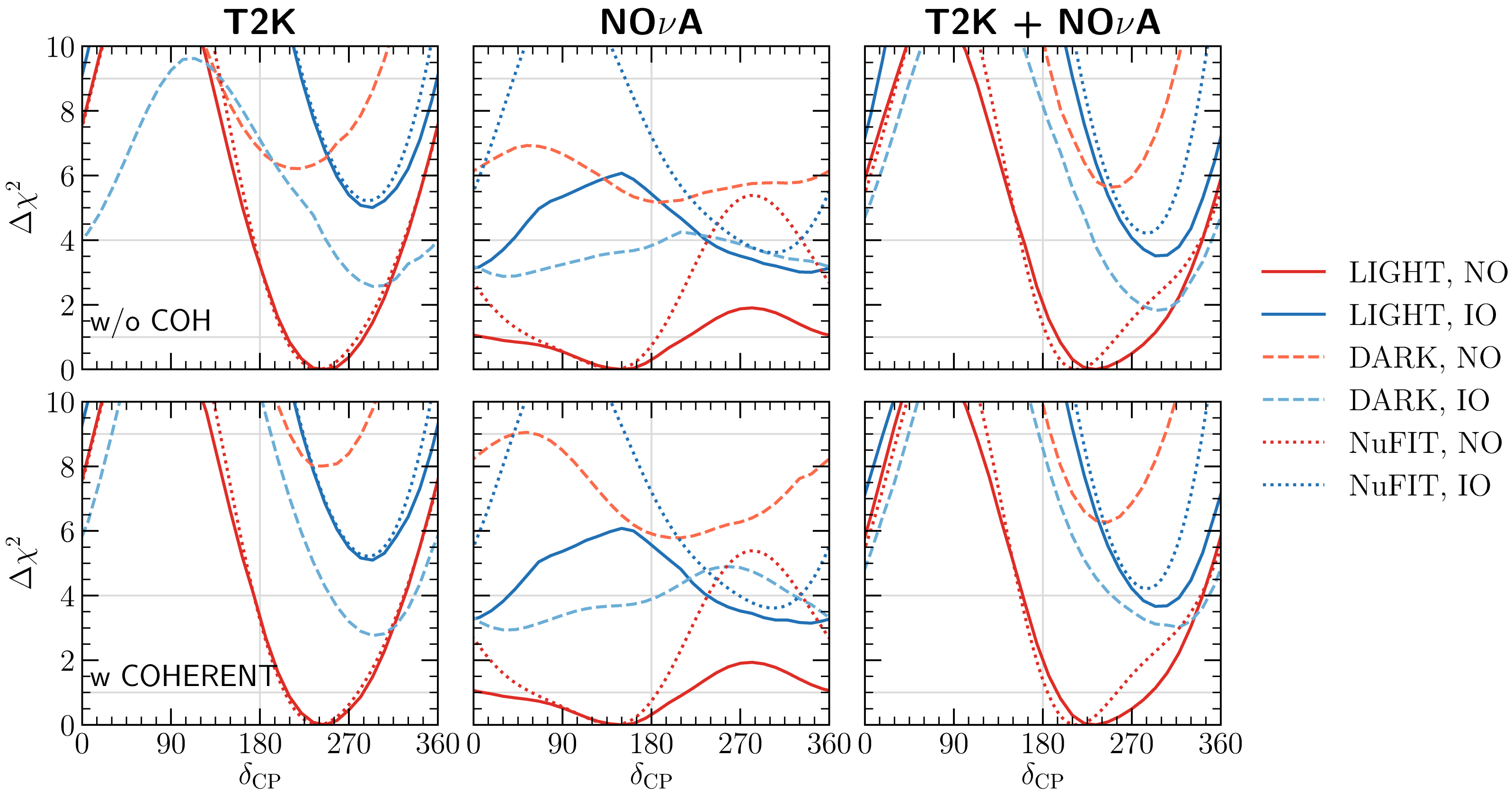
- OSCILLATION + COHERENT:
  Update with more general NSI's: $\varepsilon^u_{\alpha\beta} \propto (2\cos\eta - \sin\eta)\varepsilon^\eta_{\alpha\beta}$ $\quad \varepsilon^d_{\alpha\beta} \propto (2\sin\eta - \cos\eta)\varepsilon^\eta_{\alpha\beta}$




LMA-D Still allowed at 3$\sigma$ for
$-40^\circ \lesssim \eta \lesssim 15^\circ$

Esteban etal, ArXiv:1805.04530

# MAXIMUM EFFECT IN PRESENT LBL




Esteban,Maltoni, MCG-G ArXiv:1905.05203

– "Hints" of CPV in T2K and in combination with NOvA robust

– Preference for NO lost

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- At least two neutrinos are massive ⇒ There is NP
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  CP conservation at 90% CL
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- What about a UV complete model which answers?:
  - ∗ Why are neutrinos so light? ⇒ The Origin of Neutrino Mass
  - ∗ Why are lepton mixing so different from quark's? ⇒ The Flavour Puzzle

# Bottom-up: Light $\nu$ 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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which after symmetry breaking induces a $\nu$ Majorana mass

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

## Implications:

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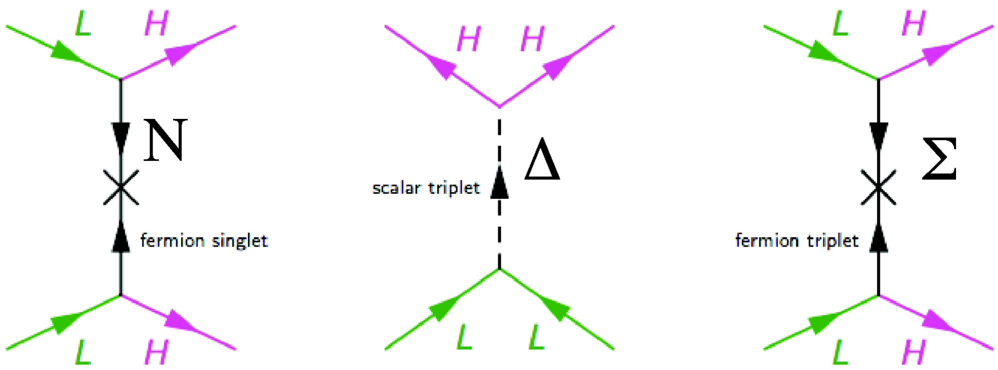
– $m_\nu > \sqrt{\Delta m^2_{\rm atm}} \sim 0.05$ eV for $Z^\nu \sim 1 \Longrightarrow \Lambda_{\rm NP} \sim 10^{15}$GeV $\Longrightarrow$ $\Lambda_{\rm NP} \sim$ GUT scale

$\Rightarrow$ Leptogenesis possible

[ But if $Z^\nu \sim (Y_e)^2 \Rightarrow \Lambda_{\rm NP} \sim$ 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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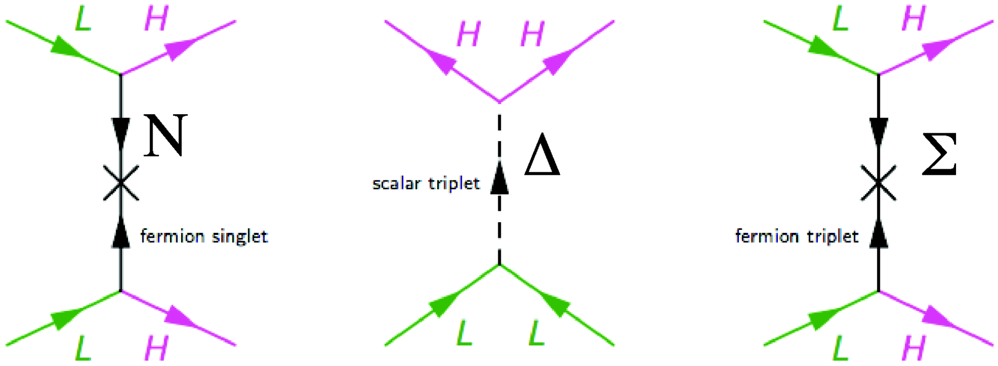


- For fermionic see-saw $-\mathcal{L}_{\rm NP} = -i\overline{N_i}\not{D} N_i + \frac{1}{2} M_{N\,ij} \overline{N_i^c} N_j + \lambda^\nu_{\alpha j} \overline{L_\alpha} \tilde{\phi} N_j [.\tau]$

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

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

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

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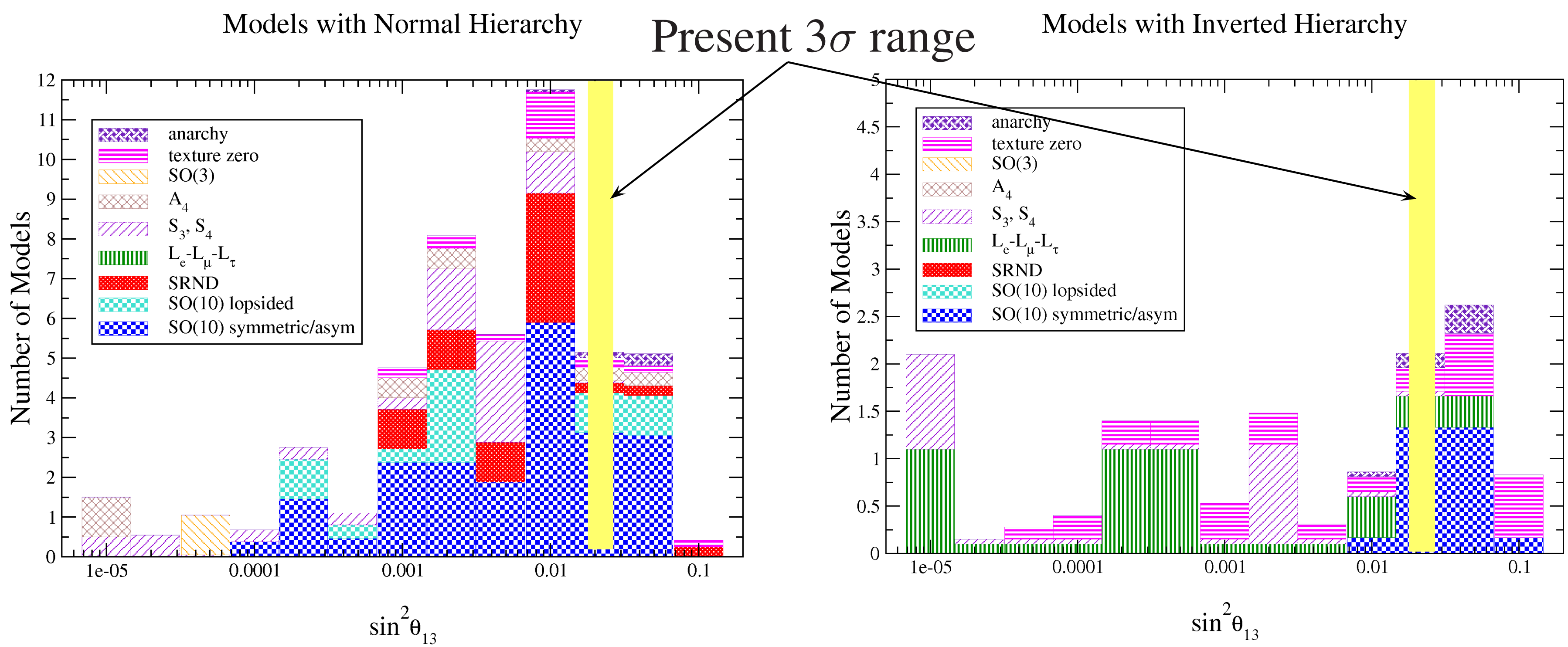
Same $\mathcal{O}_5$ can be generated by very different High Energy physics

Very different physics, but same $\nu$ parameters: How to proceed?

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

# Modeling Lepton Flavour: 2006 to 2019

- Survey of 63 $\nu$ mass models in 2006 (Albright, M-C Chen,hep-ph/0608136)




– Determination of $\theta_{13}$ has given us important handle in flavour modeling

– Next *frontier* is the ordering

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– Hope/Wait for additional information from charged LFV, collider signals . . .

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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* :

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- 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 $\nu$ OK

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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)

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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

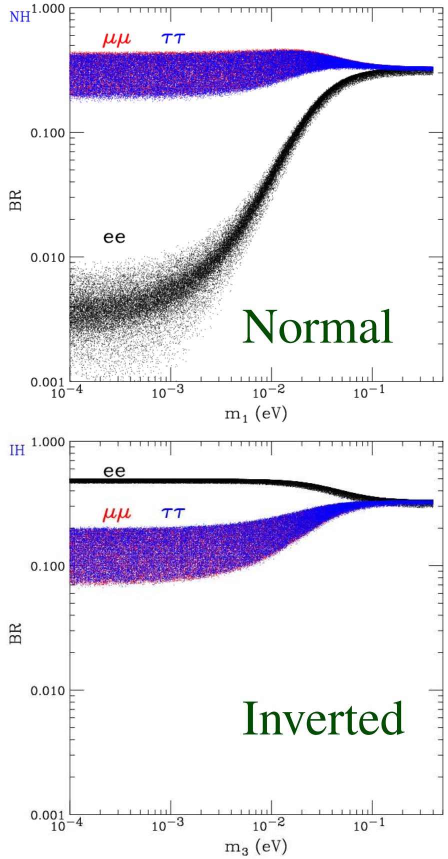
$\Rightarrow$ Production of triplet scalars: $H^{\pm\pm}\ H^\pm,\ A_0,\ H_0$

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* ...

# MLFV & Collider Signatures

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

  Gavela, Hambye, Hernandez,Hernandez (09)

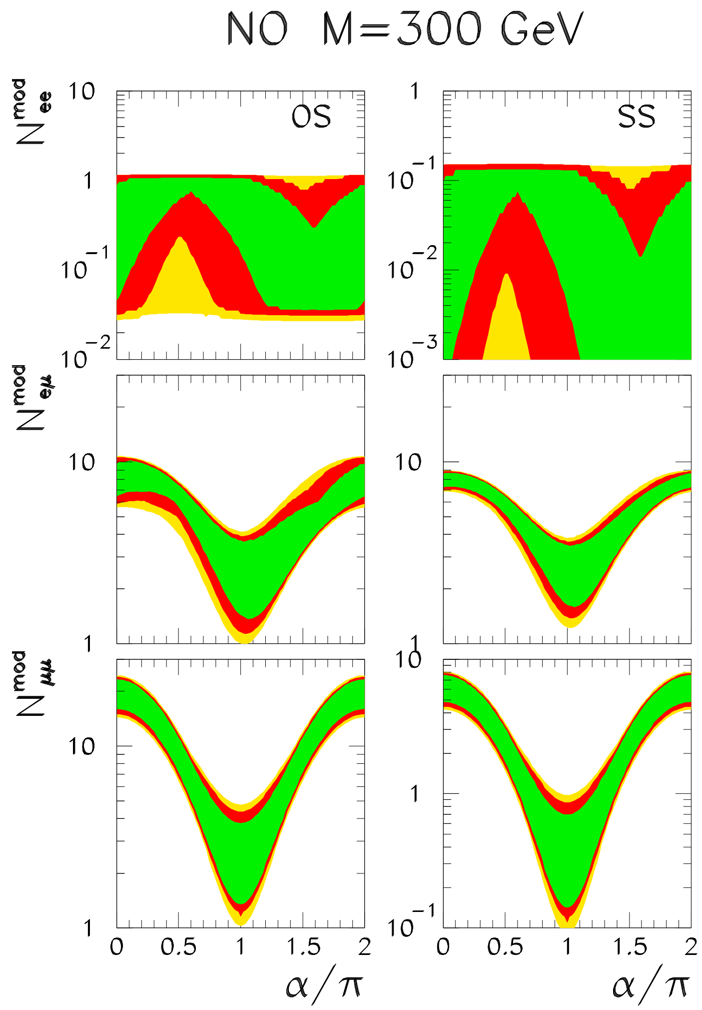
  $\rightarrow$ one massless $\nu$ & one CP phase $\alpha$

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

- At LHC:
  - Type-I unobservable but Type-III observable

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

  - Rates predictable in terms of $\nu$ parameters
  - Unambiguous constraints from existing data
  - Best with final state flavour and charge info




Rosa-Agostinho,Eboli, MCGG 1708.08456

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  Dilution of present ordering preference
- What about a UV complete model for $\nu$ mass BSM?:
  Will need complementary information from other sectors

# III. Sterile neutrino models and $\nu_\mu$ disappearance



## (3+1): robustness of the result

- The tension cannot be eliminated by discarding any *individual* experiment.

| Analysis | $\chi^2_{\text{min,global}}$ | $\chi^2_{\text{min,app}}$ | $\Delta\chi^2_{\text{app}}$ | $\chi^2_{\text{min,disapp}}$ | $\Delta\chi^2_{\text{disapp}}$ | $\chi^2_{\text{PG}}$/dof | PG |
|---|---|---|---|---|---|---|---|
| Global | 1120.9 | 79.1 | 11.9 | 1012.2 | 17.7 | 29.6/2 | $3.7\times10^{-7}$ |
| **Removing anomalous data sets** | | | | | | | |
| w/o LSND | 1099.2 | 86.8 | 12.8 | 1012.2 | 0.1 | 12.9/2 | $1.6\times10^{-3}$ |
| w/o MiniBooNE | 1012.2 | 40.7 | 8.3 | 947.2 | 16.1 | 24.4/2 | $5.2\times10^{-6}$ |
| w/o reactors | 925.1 | 79.1 | 12.2 | 833.8 | 8.1 | 20.3/2 | $3.8\times10^{-5}$ |
| w/o gallium | 1116.0 | 79.1 | 13.8 | 1003.1 | 20.1 | 33.9/2 | $4.4\times10^{-8}$ |
| **Removing constraints** | | | | | | | |
| w/o IceCube | 920.8 | 79.1 | 11.9 | 812.4 | 17.5 | 29.4/2 | $4.2\times10^{-7}$ |
| w/o MINOS(+) | 1052.1 | 79.1 | 15.6 | 948.6 | 8.94 | 24.5/2 | $4.7\times10^{-6}$ |
| w/o MB disapp | 1054.9 | 79.1 | 14.7 | 947.2 | 13.9 | 28.7/2 | $6.0\times10^{-7}$ |
| w/o CDHS | 1104.8 | 79.1 | 11.9 | 997.5 | 16.3 | 28.2/2 | $7.5\times10^{-7}$ |
| **Removing classes of data** | | | | | | | |
| $\overset{(-)}{\nu}_e$-dis vs app | 628.6 | 79.1 | 0.8 | 542.9 | 5.8 | 6.6/2 | $3.6\times10^{-2}$ |
| $\overset{(-)}{\nu}_\mu$-dis vs app | 564.7 | 79.1 | 12.0 | 468.9 | 4.7 | 16.7/2 | $2.3\times10^{-4}$ |
| $\overset{(-)}{\nu}_\mu$-dis+solar vs app | 884.4 | 79.1 | 13.9 | 781.7 | 9.7 | 23.6/2 | $7.4\times10^{-6}$ |

# The New Minimal Standard Model

- Minimal Extension to allow for LFV $\Rightarrow$ give Mass to the Neutrino

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

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

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

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

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

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

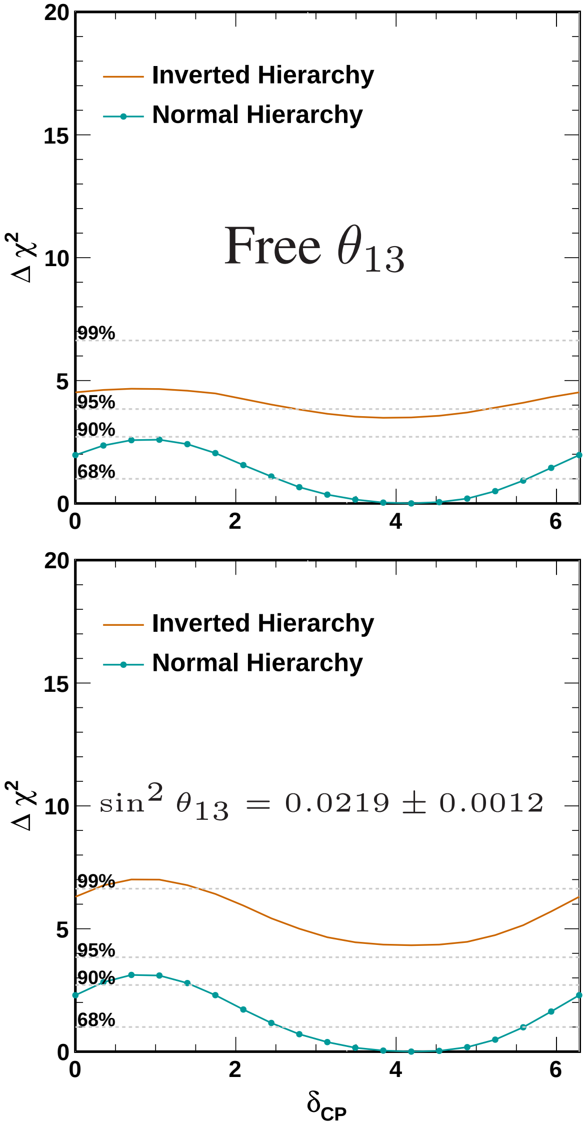
- In general for $N = 3 + s$ massive neutrinos $U_{\rm LEP}$ is $3 \times N$ matrix

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

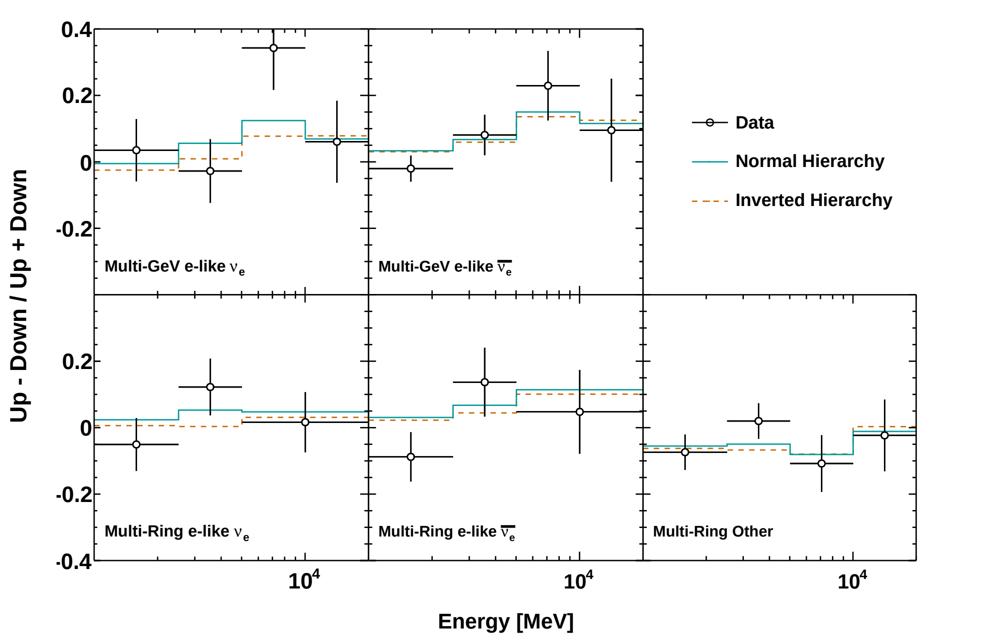
- $U_{\rm LEP}$: $3 + 3s$ angles + $2s + 1$ Dirac phases + $s + 2$ Majorana phases

# $\theta_{23}$, CP & Ordering: Effect in SK ATM

Latest SK analysis (PRD 2018) yelds:




From SK paper: *"Small excesses seen between a few and ten GeV in the Multi-GeV e-like $\nu_e$ and the Multi-Ring e-like $\nu_e$ and $\bar{\nu}_e$ samples drive these preferences".*




– No pheno group reproduces SK analysis

– Only possibility is combine with SK $\chi^2$ tables