PHENOMENOLOGY OF NEUTRINO OSCILLATIONS IN 2020

Concha Gonzalez-Garcia

(ICREA U. Barcelona & YITP Stony Brook)

SnowMass2021:TF11: Neutrino Theory Workshop. Sept 2qt, 2020

Global fit to neutrino oscillation data http://www.nu-fit.org

Concha Gonzalez-Garcia

Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

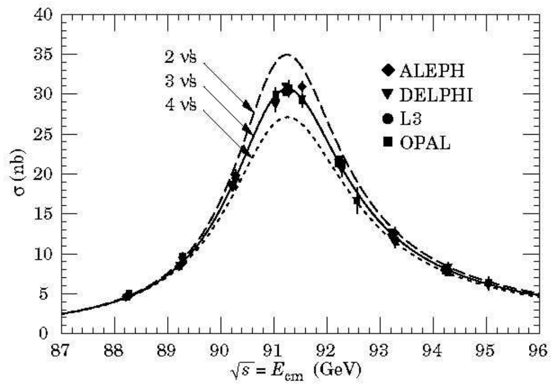
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

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



Concha Gonzalez-Garcia

Neutrinos in the Standard Model

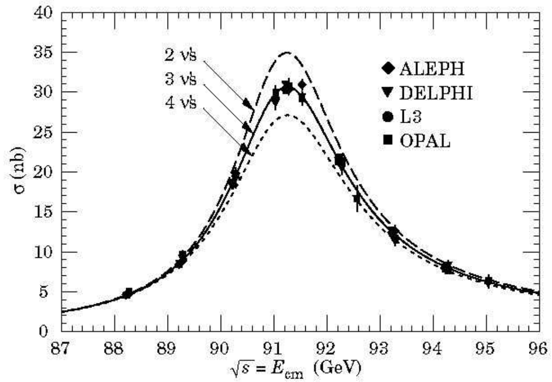
The SM is a gauge theory based on the symmetry group

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

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

Three and only three



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 2020 we have precisely observed (**relevant new results in** ν2020)
  - $*$ 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, MINOS **T2K, NOνA**)
  - $*$ Accel. ν_μ & $\bar{\nu}_\mu$ appear as ν_e and $\bar{\nu}_e$ at $L \sim 300/800$ Km (MINOS **T2K, NOνA**)
  - $*$ Solar ν_e convert to ν_μ/ν_τ (Cl, Ga, **SK**, SNO, Borexino)
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km (KamLAND)
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 1$ Km (**D-Chooz**, Daya Bay, **Reno**)

All this implies that L_α are violated

and There is Physics Beyond SM

- By 2020 we have precisely observed (**relevant new results in** ν2020)

  - $*$ 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, MINOS **T2K, NOνA**)
  - $*$ Accel. ν_μ & $\bar{\nu}_\mu$ appear as ν_e and $\bar{\nu}_e$ at $L \sim 300/800$ Km (MINOS **T2K, NOνA**)
  - $*$ Solar ν_e convert to ν_μ/ν_τ (Cl, Ga, **SK**, SNO, Borexino)
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km (KamLAND)
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 1$ Km (**D-Chooz**, Daya Bay, **Reno**)

All this implies that L_α are violated

and There is Physics Beyond SM

- 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 $\nu = \nu^c$

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

The New Minimal Standard Model

- Minimal Extension to allow for LFV ⇒ give Mass to the Neutrino

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

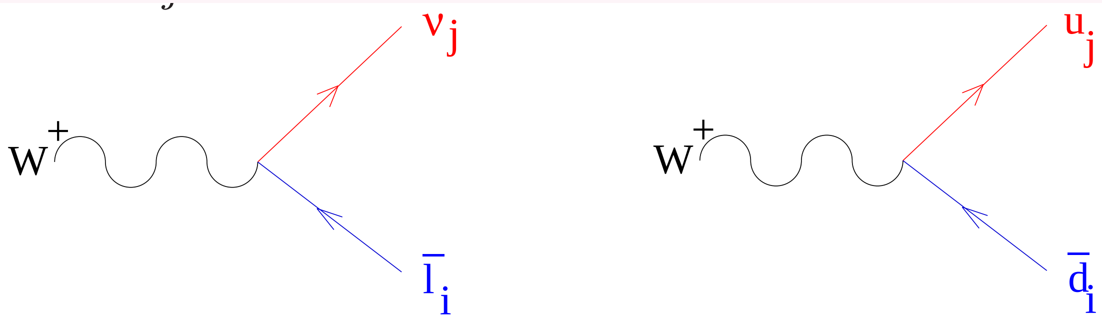
$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  $*$ NOT impose L conservation ⇒ 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)

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



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 $\nu = \nu^c$

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

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

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

$\Rightarrow$ Flavour Oscillations:

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

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

No information on ν mass scale nor Majorana versus Dirac

Flavour Osc in Vaccum vs Transitions in Matter

- In Vaccum

  when osc between 2-ν 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(Δm^2)) nor octact of θ

$\Rightarrow$ For $L \gg E/\Delta m^2$, (oscillation averaged) $\Rightarrow P_{\alpha\alpha} > \frac{1}{2}$

Flavour Osc in Vaccum vs Transitions in Matter

- In Vaccum
  when osc between 2-ν dominates:

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

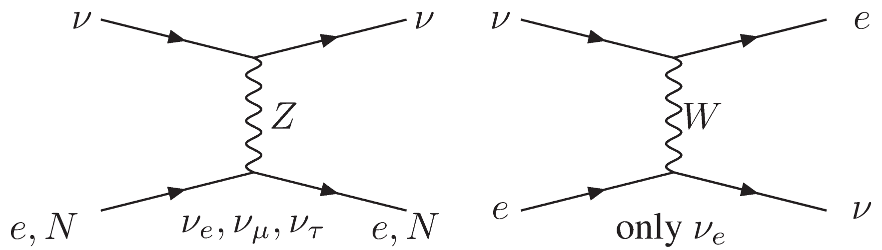
$P_{\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$ Appear

$\Rightarrow$ No information on Ordering of states (i.e sign(Δm^2)) nor octact of θ

$\Rightarrow$ For $L \gg E/\Delta m^2$, (oscillation averaged) $\Rightarrow P_{\alpha\alpha} > \frac{1}{2}$

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

  – And Different flavours
    have different interactions :



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

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

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

Flavour Osc in Vaccum vs Transitions in Matter

- In Vaccum
  when osc between 2-ν dominates:

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

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

$\Rightarrow$ No information on Ordering of states (i.e sign(Δm^2)) nor octact of θ

$\Rightarrow$ For $L \gg E/\Delta m^2$, (oscillation averaged) $\Rightarrow P_{\alpha\alpha} > \frac{1}{2}$

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

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

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

- Mass difference and mixing in matter:

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

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

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

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

Dependence on θ octant

$\Rightarrow$ In LBL terrestrial experiments

Dependence on sign of Δm^2

and θ octant

3ν Flavour Parameters

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

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

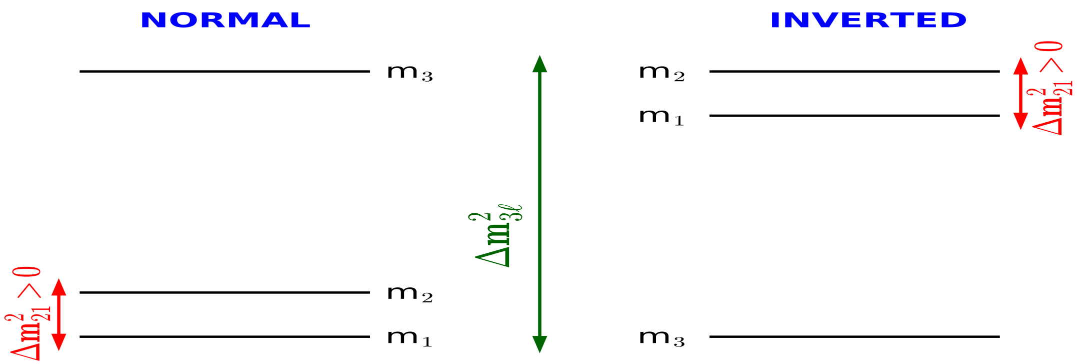
3ν Flavour Parameters

Concha Gonzalez-Garcia

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

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

- Convention: $0 \leq \theta_{ij} \leq 90°$ $\quad 0 \leq \delta \leq 360°$ $\quad \Rightarrow$ 2 Orderings



$\Delta m^2_{21} > 0$ by convention

$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases}$$

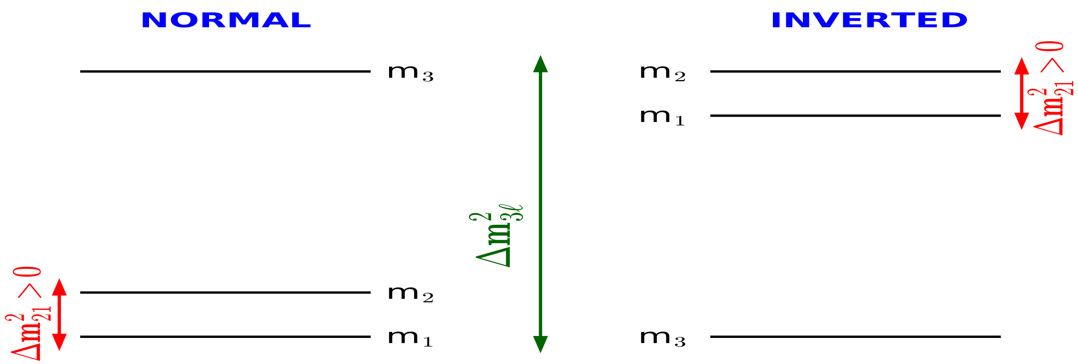
3ν Flavour Parameters

Concha Gonzalez-Garcia

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

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

- Convention: $0 \leq \theta_{ij} \leq 90°$ $\quad 0 \leq \delta \leq 360°$ $\quad \Rightarrow$ 2 Orderings



$\Delta m^2_{21} > 0$ by convention

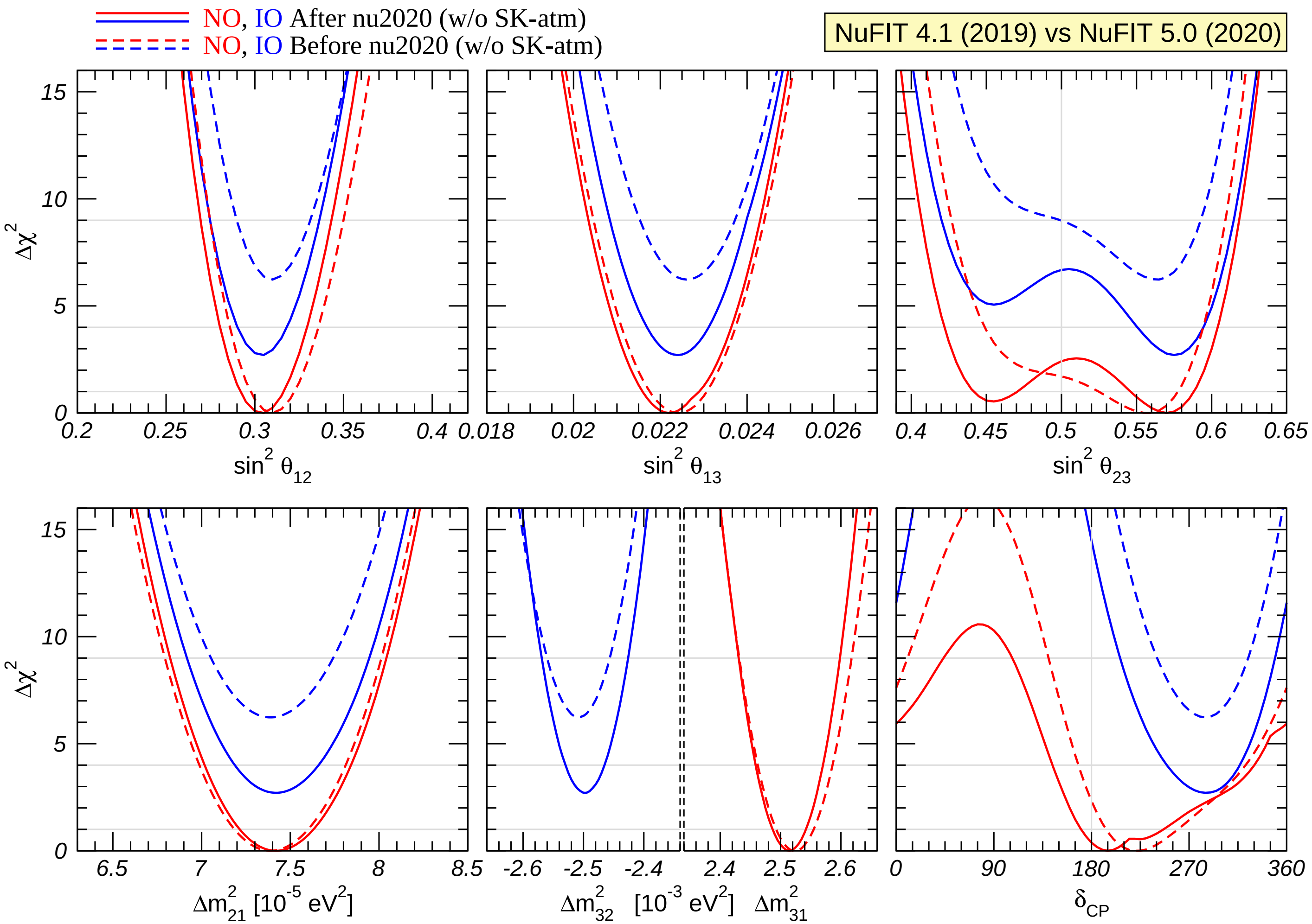
$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases}$$

Experiment	Dominant Dependence	Important Dependence
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	θ_{13} $\Delta m^2_{3\ell}$	
Atmospheric Experiments (SK,IC)		θ_{23}, $\Delta m^2_{3\ell}$, θ_{13} ,$\delta_{\rm cp}$
Acc LBL ν_μ Disapp (Minos,T2K,NOvA)	$\Delta m^2_{3\ell}$ θ_{23}	
Acc LBL ν_e App (Minos,T2K,NOvA)	$\delta_{\rm cp}$	θ_{13}, θ_{23}

Status 9/2020: Global 3 ν Flavour Parameters

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

Esteban, Maltoni, Schwetz, Zhou, MCG-G ArXiv:2007.14792 (to appear in JHEP)



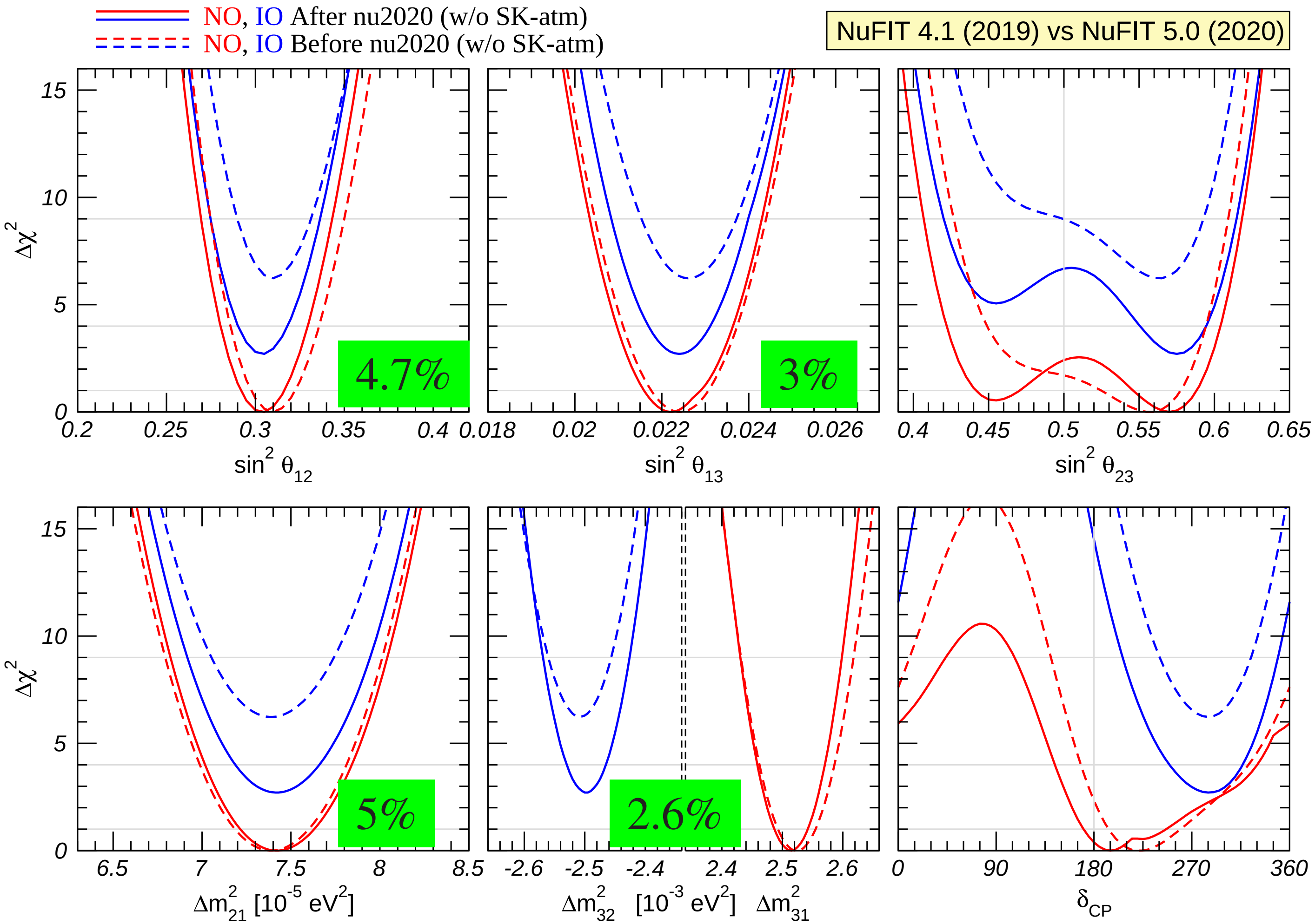
Concha Gonzalez-Garcia

Status 9/2020: Global 3 ν Flavour Parameters

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

Esteban, Maltoni, Schwetz, Zhou, MCG-G ArXiv:2007.14792 (to appear in JHEP)

Precision $\frac{x^{up}_{3\sigma}-x^{low}_{3\sigma}}{3x^{av}}$



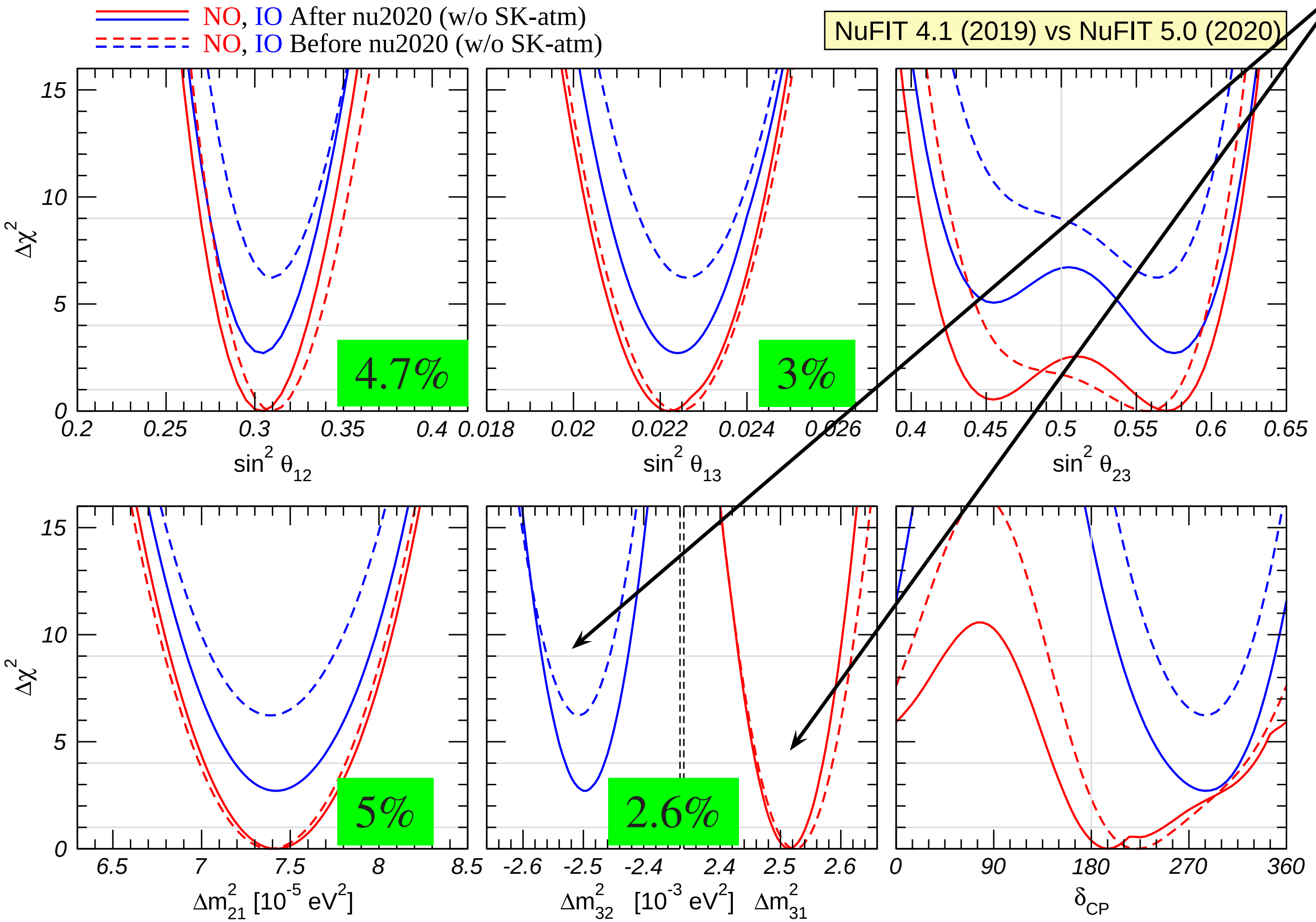
Concha Gonzalez-Garcia

Status 9/2020: Global 3 ν Flavour Parameters

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

Esteban, Maltoni, Schwetz, Zhou, MCG-G ArXiv:2007.14792 (to appear in JHEP)

Precision $\frac{x_{3\sigma}^{up} - x_{3\sigma}^{low}}{3x^{av}}$



- Decrease NO favouring

	$\Delta\chi^2_{\rm NO-IO}$
T2K	2.1
NOνA	0.4
LBL-Comb	-1.5
LBL+Reac	2.7
Glob w/o SK-atm	2.7
Glob w SK-atm	7.1

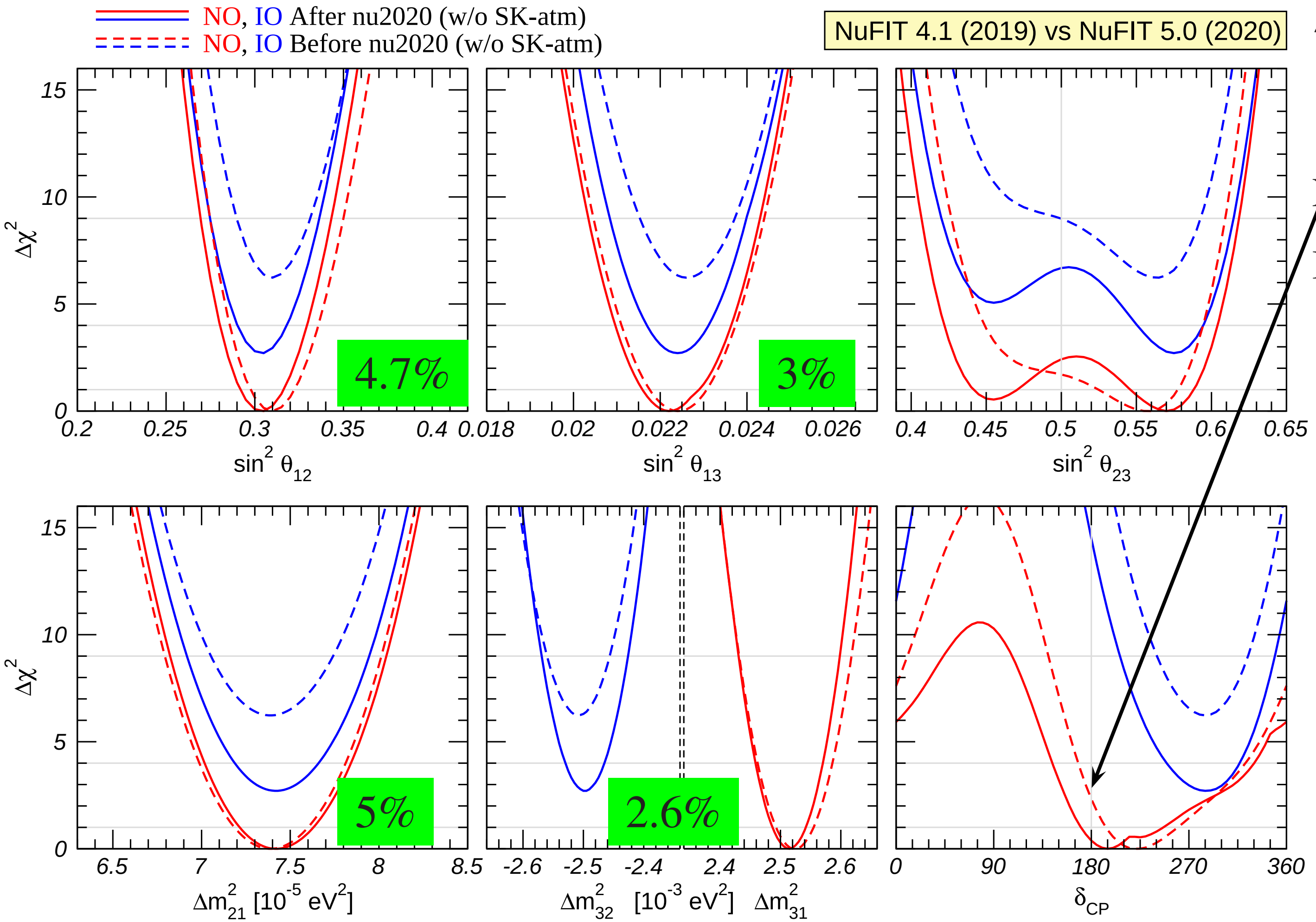
See Talk by I. Esteban for details

Status 9/2020: Global 3 ν Flavour Parameters

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

Esteban, Maltoni, Schwetz, Zhou, MCG-G ArXiv:2007.14792 (to appear in JHEP)

Precision $\frac{x^{up}_{3\sigma} - x^{low}_{3\sigma}}{3x^{av}}$



- Mass Ordering

$\Delta\chi^2_{\rm NO-IO, w/o\ SK-atm} = 2.7$

- CPV: CPC better

NO: b.f $\delta_{\rm CP} = 195^\circ$ CPC at 0.6σ

IO: b.f $\delta_{\rm CP} = 286^\circ$ CPC at 3σ

See Talk by I. Esteban for details

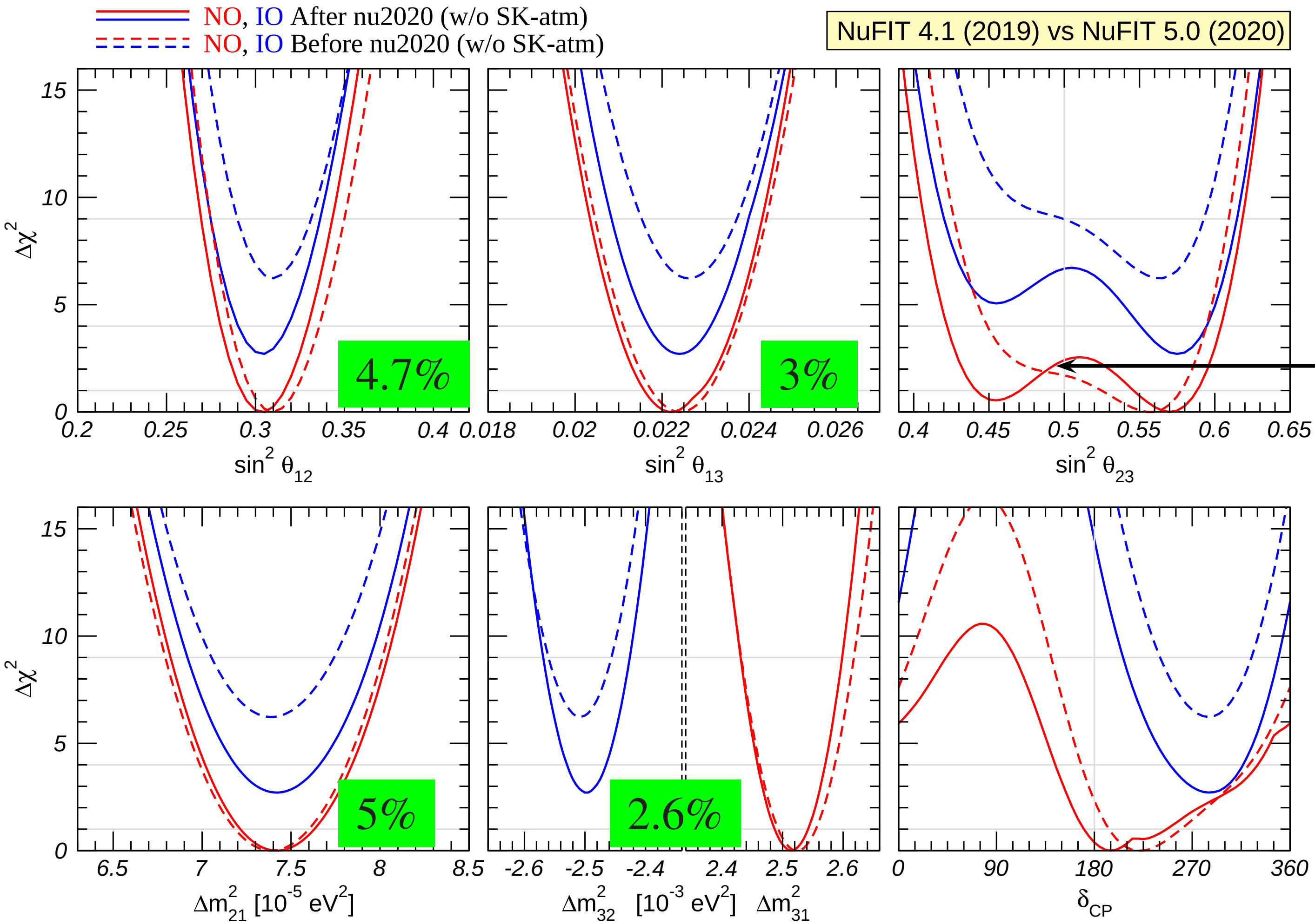
Concha Gonzalez-Garcia

Status 9/2020: Global 3 ν Flavour Parameters

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

Esteban, Maltoni, Schwetz, Zhou, MCG-G ArXiv:2007.14792 (to appear in JHEP)

Precision $\frac{x_{3\sigma}^{up} - x_{3\sigma}^{low}}{3x^{av}}$



- Mass Ordering

$\Delta\chi^2_{\rm NO-IO,w/o\ SK-atm} = 2.7$

- CPV:

NO: b.f $\delta_{\rm CP} = 195^\circ$ CPC at 0.6σ

IO: b.f $\delta_{\rm CP} = 286^\circ$ CPC at 3σ

- θ_{23}:

NO: bf $s^2_{23} = 0.57$

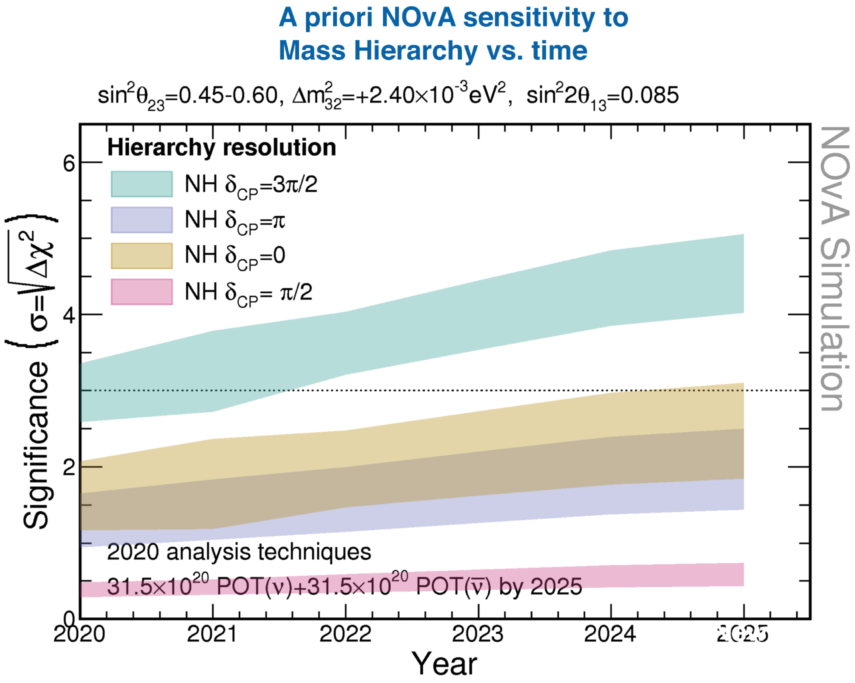
$\Delta\chi^2_{\rm w/o\ SK-atm}(\rm 1st\ oct) = 0.53$

$\Delta\chi^2_{\rm w/o\ SK-atm}(\rm Maxmix) = 2.4$

See Talk by I. Esteban for details

“Near Future” for CPV and Ordering

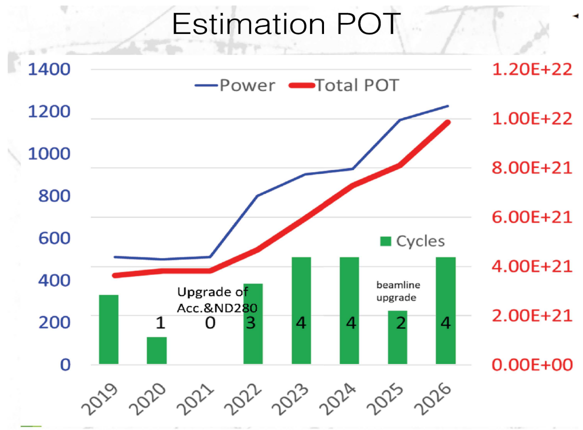
NOνA: Ordering

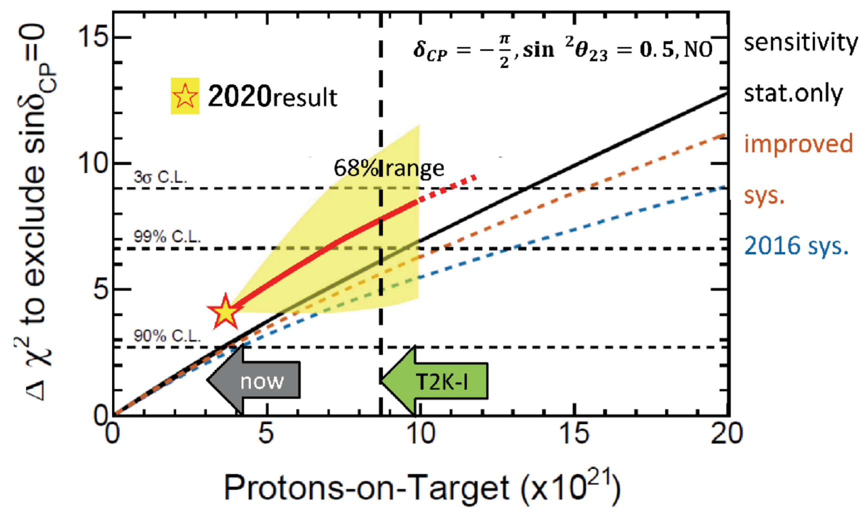


NOvA reaches 3 sigma sensitivity for between 30% and 50% of δ_{CP} values, depending on MH and $\sin^2(\theta_{23})$

03 Sep 2020 P. Shanahan I The NOvA Physics Program

T2K: CPV





To be further improved by ND280 upgrade etc.
If CP is maximally violated, we have a good chance to reach 3σ.

F.Sanchez Sep 3rd talk

Confirmed LE Picture and today's 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" fading . . .

  CPC close to best fit
- Ordering: NO preference fading . . .

  Definite answers most likely only with upcoming experiments

Confirmed LE Picture and today's List of Q&A

- At least two neutrinos are massive ⇒ There is NP
- Three mixing angles are non-zero (and relatively large) ⇒ very different from CKM
- Leptonic CP: "Hint" driven by T2K "fluctuation" fading ...

  CPC close to best fit
- Ordering: NO preference fading ...

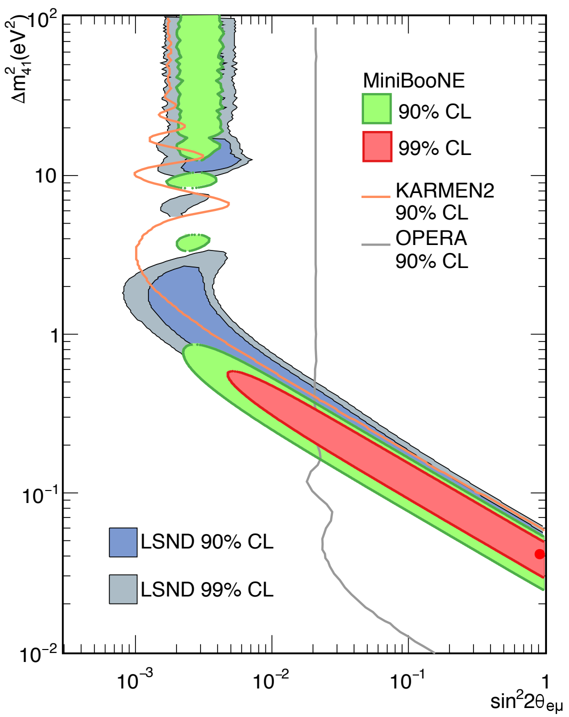
  Definite answers most likely only with upcoming experiments
- Only three light states?

Beyond 3ν's: Light Sterile Neutrinos

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

LSND, MiniBoone

$\nu_\mu \to \nu_e$ and $\bar\nu_\mu \to \bar\nu_e$



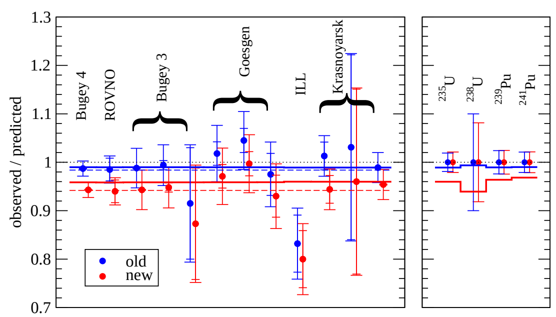
From LSND mid 90's
to MiniBoone 1805.12028

Reactor Anomaly

Huber, 1106.0687
Mention *etal* ,1101.2755

New reactor flux calculation

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



Explained as $\bar\nu_e$ disappearance

2.3 σ with updated fluxes

Berryman, Huber, 1909.09267

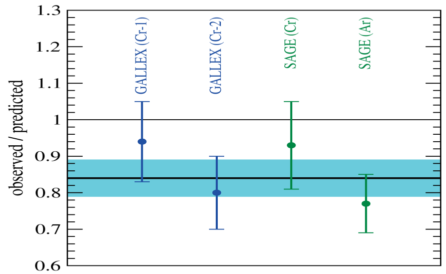
Gallium Anomaly

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 ν_e disappearance

Dimish significance to 2.3 σ

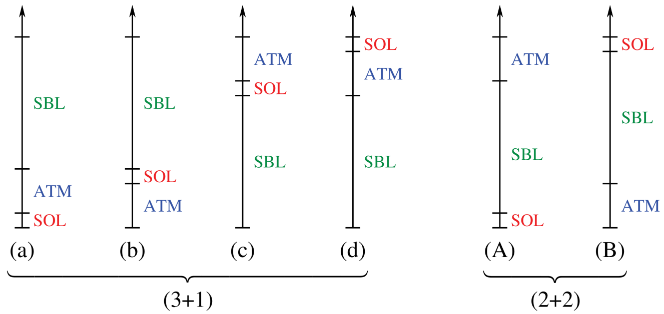
with new nuclear shell-model wave func

Kostensale etal 2019

Light Sterile Neutrinos

Concha Gonzalez-Garcia

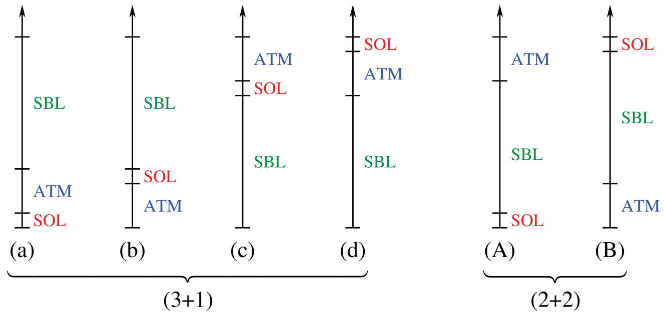
- These explanations require $\mathcal{O}$(eV) mass ν_s



Light Sterile Neutrinos

Concha Gonzalez-Garcia

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

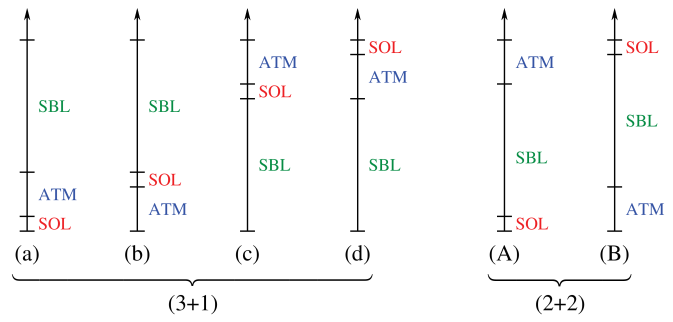


- 2+2: Ruled out by solar and atm data ($\gtrsim 5\sigma$) Maltoni *etal* NPB 02

Light Sterile Neutrinos

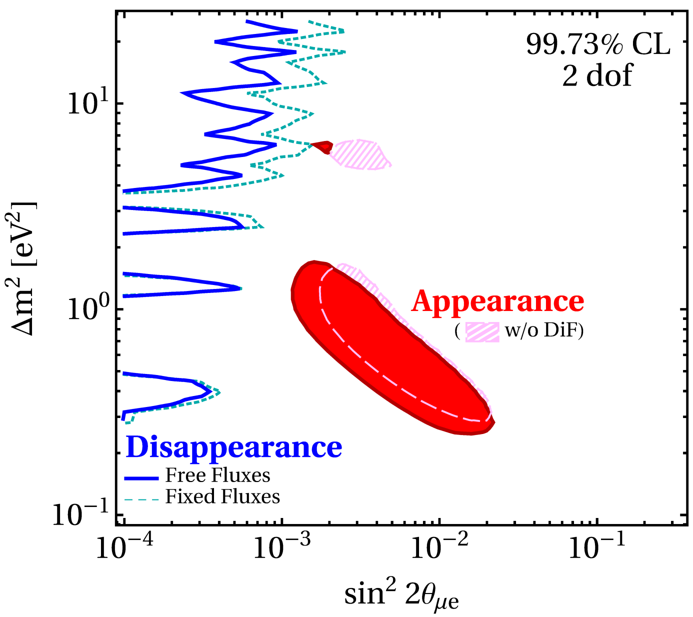
Concha Gonzalez-Garcia

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



- 2+2: Ruled out by solar and atm data ($\gtrsim 5\sigma$) Maltoni *etal* NPB 02

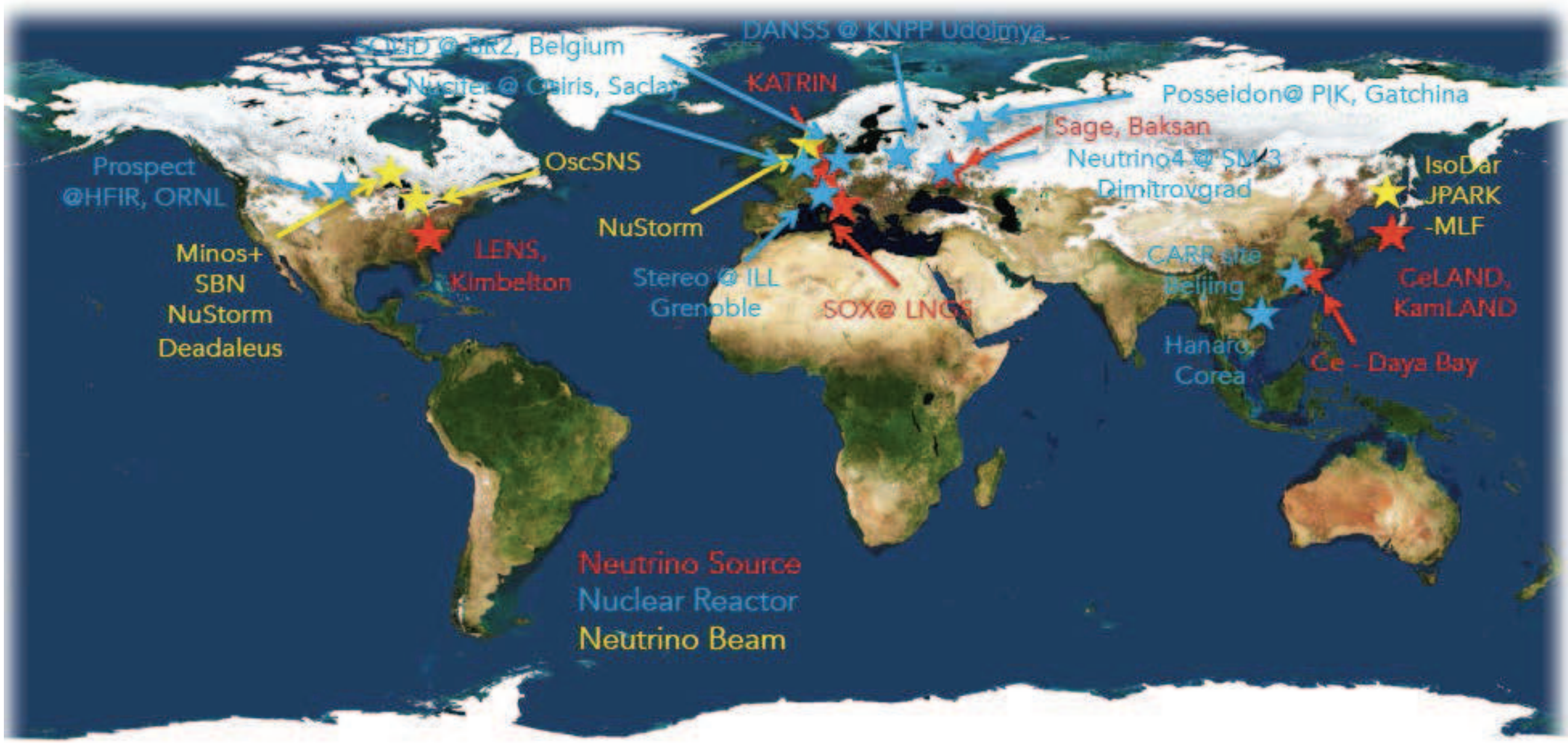
- 3+1: Generically appearance $P_{e\mu} \sim |U^*_{ei} U_{\mu i}| \begin{cases} |U_{ei}| \text{ constrained by } P_{ee} \text{ disapp data} \\ |U_{\mu i}| \text{ constrained by } P_{\mu\mu} \text{ disapp data} \end{cases}$



Dentler etal, 1803.10661

4.7 σ tension betwen disapp and app

Searches for eV sterile neutrinos



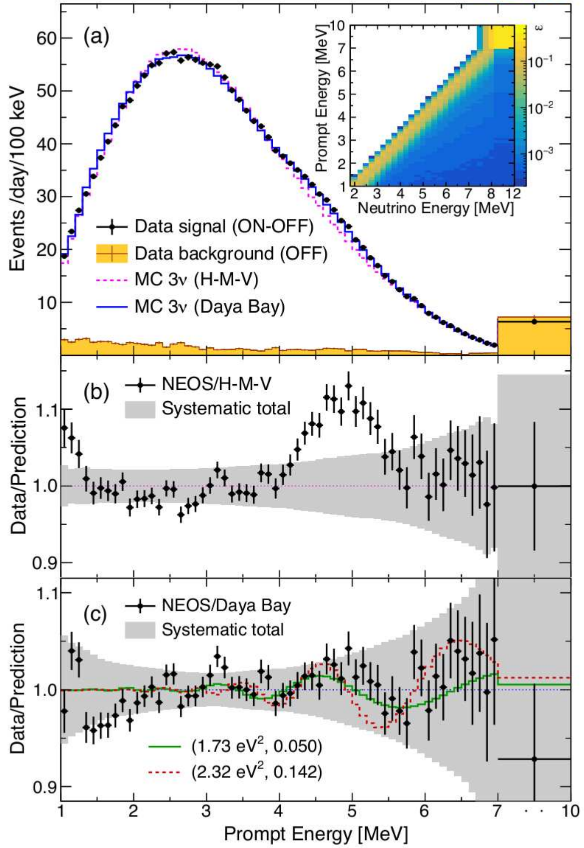
This talk: (anti-) ν_e disapearance only

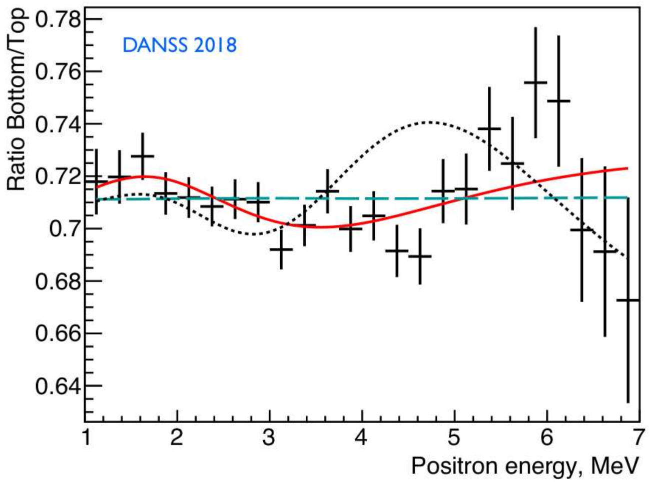
$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$

Reactor antineutrino anomaly

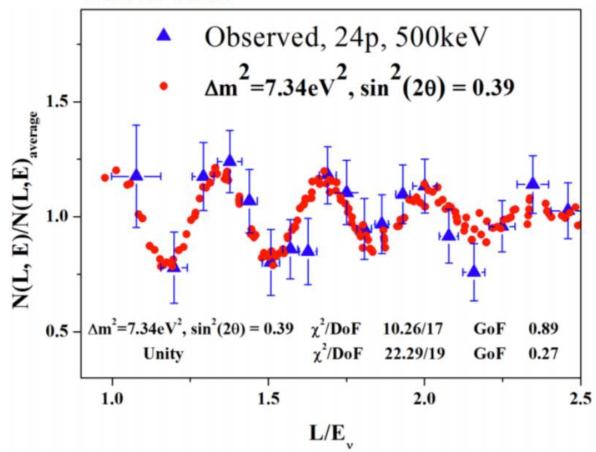
Wiggles in the data???

NEOS 2016





Neutrino-4 2020



Statistics of small wiggles may not be χ^2 distributed!

MC simulation and calibration of test statistics is necessary to state confidence level of claims

se e.g. Giunti 2004.07577

Prospect+Stereo on Neutrino-4:
- statistics may be an issue
- systematics may be an issue

2006.13147

And more data presented in ν2020 .....

Confirmed LE Picture and today's List of Q&A

- At least two neutrinos are massive ⇒ There is NP
- Three mixing angles are non-zero (and relatively large) ⇒ very different from CKM
- Leptonic CP: "Hint" driven by T2K "fluctuation" fading …

  CPC close to best fit
- Ordering: NO preference fading …
- Only three light states?

  App and disapp results in severe tension in 4th ν_s interpretation

  New VSBL reactor data? I take the 5th

Confirmed LE Picture and today's List of Q&A

- At least two neutrinos are massive ⇒ There is NP
- Three mixing angles are non-zero (and relatively large) ⇒ very different from CKM
- Leptonic CP: "Hint" driven by T2K "fluctuation" fading ...
  CPC close to best fit
- Ordering: NO preference fading ...
- Only three light states?
  App and disapp results in severe tension in 4th ν_s interpretation
  New VSBL reactor data? I take the 5th
- Other NP at play?

Alternative Oscillation Mechanisms

- Oscillations are due to:
  - Misalignment between CC-int and propagation states: Mixing $\Rightarrow$ Amplitude
  - Difference phases of propagation states $\Rightarrow$ Wavelength. For Δm^2-OSC $\lambda = \dfrac{4\pi E}{\Delta m^2}$

Alternative Oscillation Mechanisms

- Oscillations are due to:
  - Misalignment between CC-int and propagation states: Mixing $\Rightarrow$ Amplitude
  - Difference phases of propagation states $\Rightarrow$ Wavelength.

For Δm^2-OSC $\lambda = \frac{4\pi E}{\Delta m^2}$

- ν masses are not the only mechanism for oscillations

Violation of Equivalence Principle (VEP): Gasperini 88, Halprin,Leung 01

Non universal coupling of neutrinos $\gamma_1 \neq \gamma_2$ *to gravitational potential* ϕ

$$\lambda = \frac{\pi}{E|\phi|\delta\gamma}$$

Violation of Lorentz Invariance (VLI): Coleman, Glashow 97

Non universal asymptotic velocity of neutrinos $c_1 \neq c_2 \Rightarrow E_i = \frac{m_i^2}{2p} + c_i p$

$$\lambda = \frac{2\pi}{E\Delta c}$$

Interactions with space-time torsion: Sabbata, Gasperini 81

Non universal couplings of neutrinos $k_1 \neq k_2$ *to torsion strength* Q

$$\lambda = \frac{2\pi}{Q\Delta k}$$

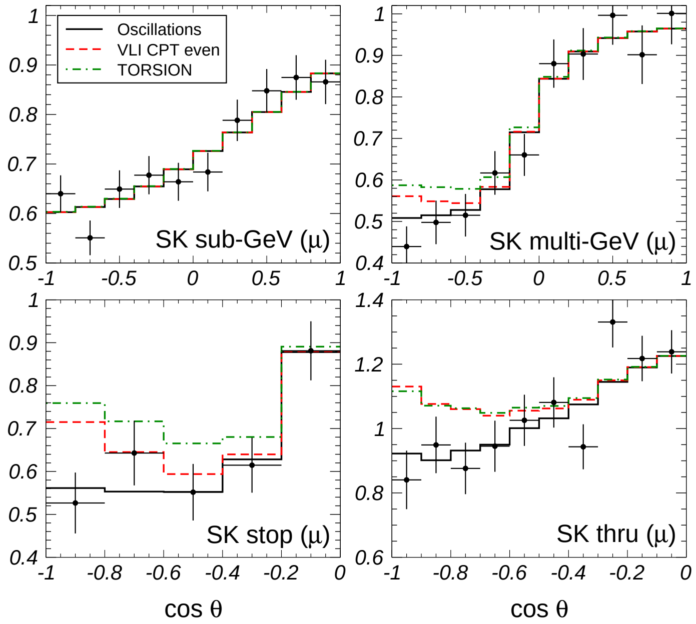
Violation of Lorentz Invariance (VLI) Colladay, Kostelecky 97; Coleman, Glashow 99

due to CPT violating terms: $\bar{\nu}_L^\alpha b_\mu^{\alpha\beta} \gamma_\mu \nu_L^\beta \Rightarrow E_i = \frac{m_i^2}{2p} \pm b_i$

$$\lambda = \pm\frac{2\pi}{\Delta b}$$

Alternative Mechanisms vs ATM ν's

- Severly constrained (MCG-G, M. Maltoni PRD 04,07)



At 90% CL:

$$\frac{|\Delta c|}{c} \leq 1.2 \times 10^{-24}$$

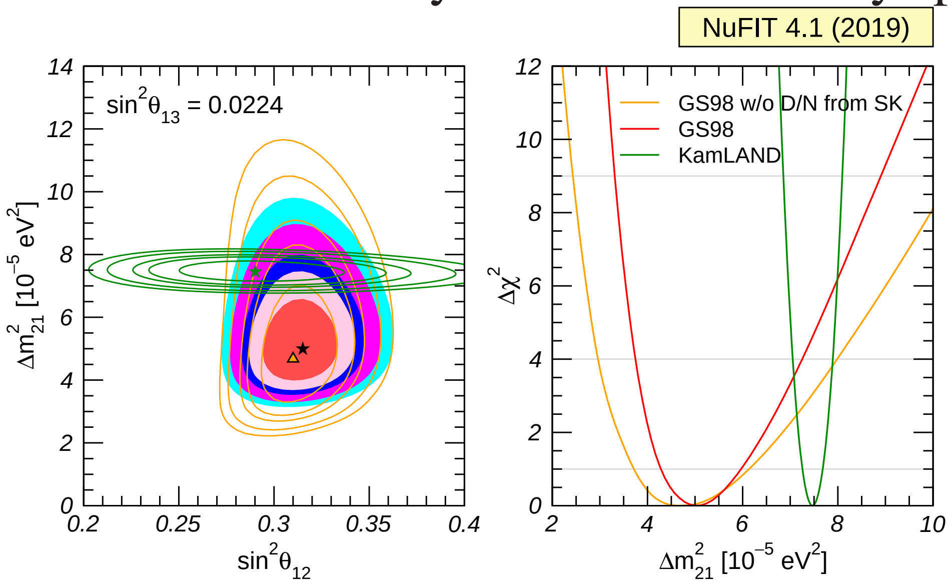
$$|\phi\,\Delta\gamma| \leq 5.9 \times 10^{-25}$$

$$|Q\,\Delta k| \leq 4.8 \times 10^{-23}\ \text{GeV}$$

$$|\Delta b| \leq 3.0 \times 10^{-23}\ \text{GeV}$$

NP Hint?: Δm^2_{21} KamLAND vs SOLAR

- BEFORE NU2020: With SK4 2055 days D/N and 2860 day spectrun

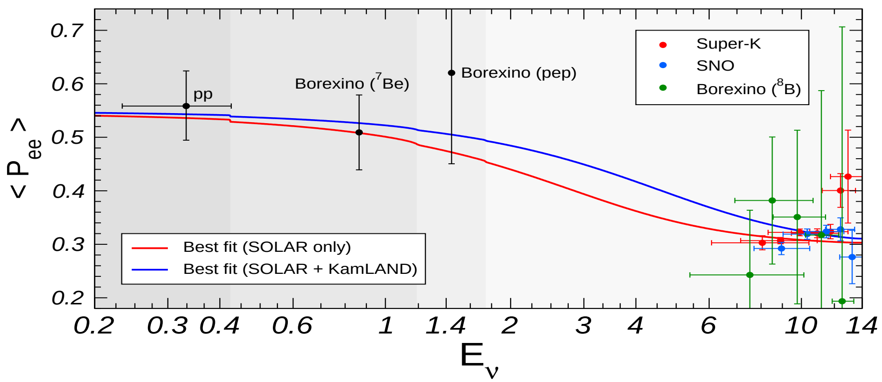


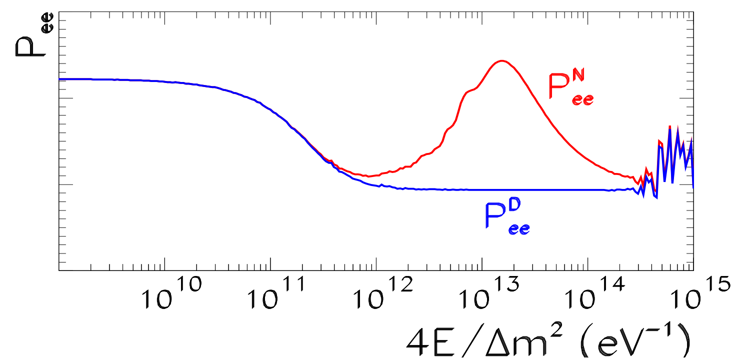
- Tension arising from:

Smaller-than-expected low-E turn-up in SK/SNO from MSW at global b.f.

"too large" of Day/Night at SK

$A_{\rm D/N,SK4-2055} = [-3.1 \pm 1.6({\rm stat.}) \pm 1.4({\rm sys.})]\%$

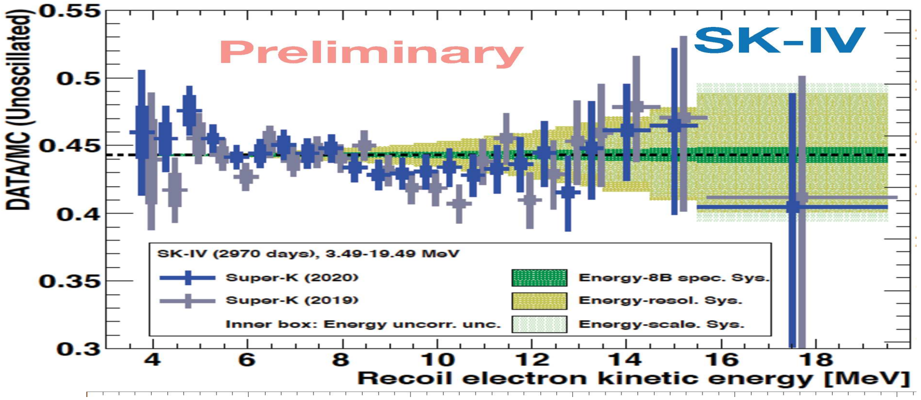




$\Rightarrow$ "hint" of NP in propagation: NSI?

- AFTER NU2020: With SK4 2970 days data

Slightly more pronouncced low-E turn-up



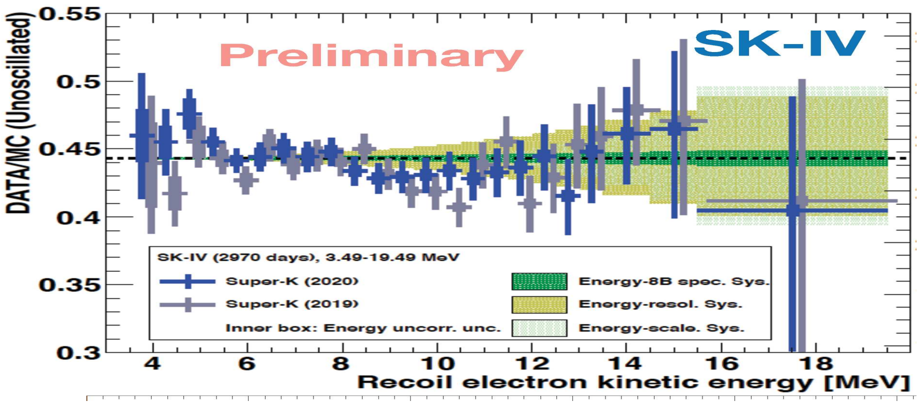
Smaller of Day/Night at

$$A_{\rm D/N,SK4-2055} = [-3.1 \pm 1.6({\rm stat.}) \pm 1.4({\rm sys.})]\%$$

$$A_{\rm D/N,SK4-2970} = [-2.1 \pm 1.1]\%$$

• AFTER NU2020: With SK4 2970 days data

Slightly more pronouncced low-E turn-up

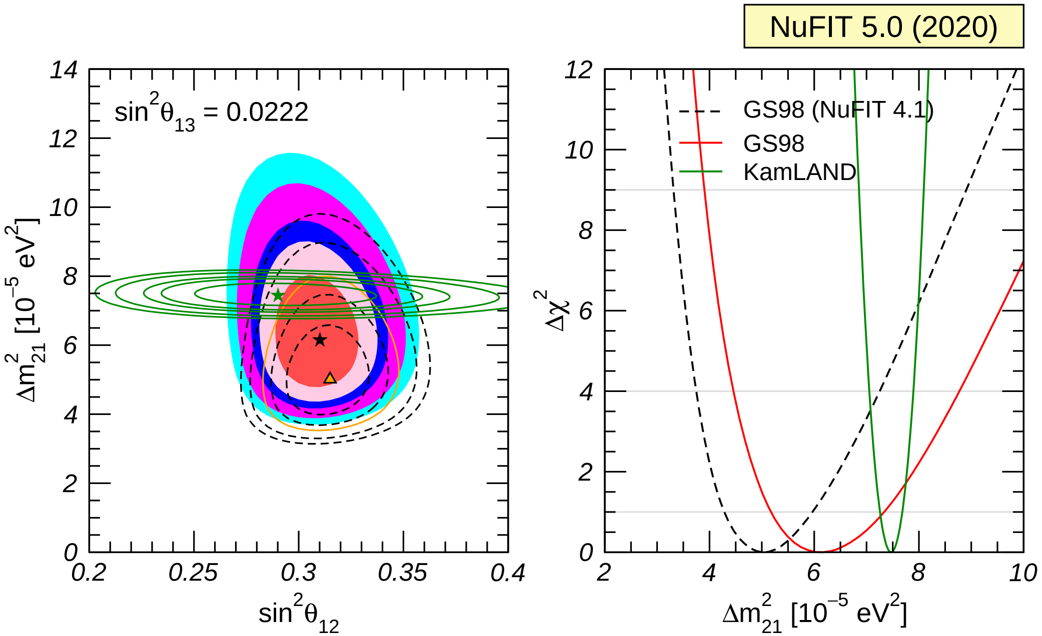


Smaller of Day/Night at

$$A_{\mathrm{D/N,SK4-2055}} = [-3.1 \pm 1.6(\mathrm{stat.}) \pm 1.4(\mathrm{sys.})]\%$$

$$A_{\mathrm{D/N,SK4-2970}} = [-2.1 \pm 1.1]\%$$

• In NuFIT 5.0



$\Rightarrow$ Agreement of Δm^2_{21} between solar and KamLAND at 1 σ