Global Analysis of Neutrino Oscillation Data Circa Autumn 2018

NuTheories: Beyond the 3×3 Paradigm, Pittsburgh

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6th November 2018

www.nu-fit.org

Standard Model

The Standard Model is a gauge theory based on

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

and three fermion generations

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

with no $\nu_R \Longrightarrow$ lepton flavours are *accidentally* conserved and $\boldsymbol{m_\nu = 0}$.

There is New Physics in the lepton sector

We have observed neutrino flavour changes:

- Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear, most likely to ν_τ (SK, MINOS, ICECUBE).
- Accelerator ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ km (K2K, T2K, MINOS, NOνA).
- Some accelerator ν_μ & $\bar{\nu}_\mu$ appear as ν_e at $L \sim 300/800$ km (T2K, MINOS, NOνA).
- Some accelerator ν_μ appear as ν_τ at $L \sim 300/800$ km (OPERA).
- Solar ν_e convert to ν_μ & ν_τ (Cl, Ga, SK, SNO, Borexino).
- Reactor $\bar{\nu}_e$ disappear at $L \sim 200$ km (KamLAND).
- Reactor $\bar{\nu}_e$ disappear at $L \sim 1$ km (D-Chooz, Daya Bay, Reno).

Each of the lepton numbers is violated: **there is physics beyond the SM**.

Introduction

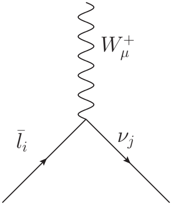
There is New Physics in the lepton sector

We have observed neutrino flavour changes (Sun, atmosphere, human-made). The minimal way of explaining them is giving neutrinos a mass.

- Dirac mass term: $-M_\nu^D \bar{\nu}_L \nu_R$ introduce ν_R and enforce L conservation.
- Majorana mass term: $-M_\nu^M \bar{\nu}_L \nu_L^C$, effectively-generated, violates L.

As a consequence, leptons mix:

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(\boldsymbol{U_{ij}^{\text{lep}}} \bar{l}_{iL} \gamma^\mu \nu_{jL} + U_{ij}^{\text{CKM}} \bar{u}_{iL} \gamma^\mu d_{jL} \right) + \text{h.c.}$$



Neutrino flavour oscillations

We need to parametrise the new physics: **flavour oscillations** are a unique experimental window.

$$|\nu_\alpha(0)\rangle = \sum_i {U^{\text{lep}}_{\alpha i}}^* |\nu_i\rangle \Rightarrow |\nu_\alpha(L)\rangle \simeq \sum_i {U^{\text{lep}}_{\alpha i}}^* e^{-i\frac{m_i^2 L}{2E}} |\nu_i\rangle$$

Due to $|\nu_i\rangle$ interference:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} \mathrm{Re}\left[U^{\text{lep}}_{\alpha i} U^{\text{lep}*}_{\beta i} U^{\text{lep}*}_{\alpha j} U^{\text{lep}}_{\beta j}\right] \sin^2 \frac{\Delta m_{ij}^2 L}{4E} + 2\sum_{i<j}^{n} \mathrm{Im}\left[U^{\text{lep}}_{\alpha i} U^{\text{lep}*}_{\beta i} U^{\text{lep}*}_{\alpha j} U^{\text{lep}}_{\beta j}\right] \sin \frac{\Delta m_{ij}^2 L}{2E}$$

For 2 ν, $P_{\text{osc}} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = 1 - P_{\text{surv}}$, **insensitive to θ octant and Δm^2 sign**.

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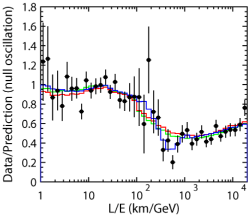
Travelling in matter, ν_e get a potential $V_{\nu_e} = \sqrt{2} G_F n_e$,

$$i\frac{d}{dx}\begin{pmatrix}|\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle\end{pmatrix} = H_{\text{eff}}\begin{pmatrix}|\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle\end{pmatrix} \; ; \; H_{\text{eff}} = \begin{pmatrix}\sqrt{2}G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0\end{pmatrix} + \frac{1}{2E} U^{\text{lep}} \begin{pmatrix} m_1^2 & 0 & \\ 0 & m_2^2 & \\ & & \ddots \end{pmatrix} U^{\text{lep}\dagger}$$

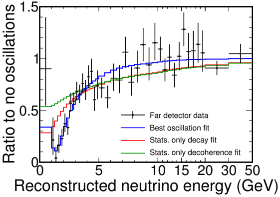
Matter effects break the 2 $\boldsymbol{\nu}$ $\boldsymbol{\theta}$ and $\boldsymbol{\Delta m^2}$ symmetries.

Experimental knowledge

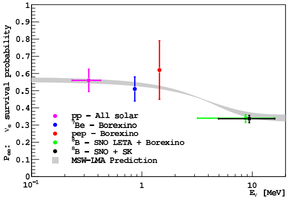
We need 3 light neutrinos



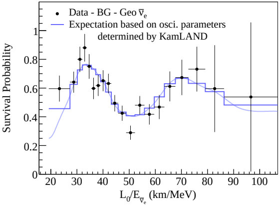
Atmospheric ν in SK



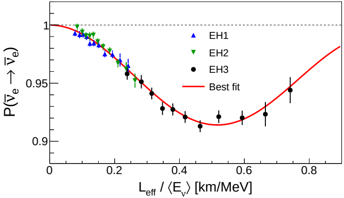
Accelerator ν in MINOS (L=735 km)



Solar ν (MSW conversion)



Reactor $\bar{\nu}$ in KamLAND



Reactor $\bar{\nu}$ in Daya Bay

Experimental knowledge

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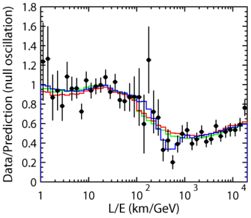

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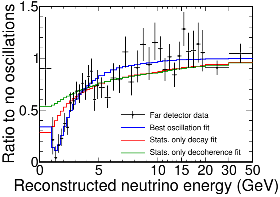

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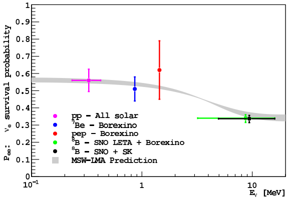

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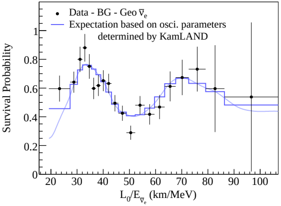

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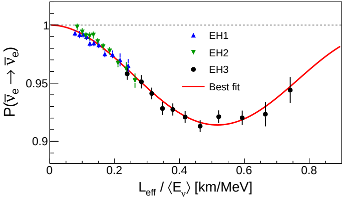


Reactor $\bar{\nu}$ in Daya Bay

Sun $\begin{cases} \Delta m^2 \sim 10^{-5}\text{eV}^2 \\ \theta \sim 30^\circ \end{cases}$

Atm. Accel. $\begin{cases} \Delta m^2 \sim 10^{-3}\text{eV}^2 \\ \theta \sim 45^\circ \end{cases}$

Reac. $\begin{cases} \Delta m^2 \sim 10^{-5}\text{eV}^2 \\ \theta \sim 30^\circ \end{cases}$ $\begin{cases} \Delta m^2 \sim 10^{-3}\text{eV}^2 \\ \theta \sim 9^\circ \end{cases}$

Experimental knowledge

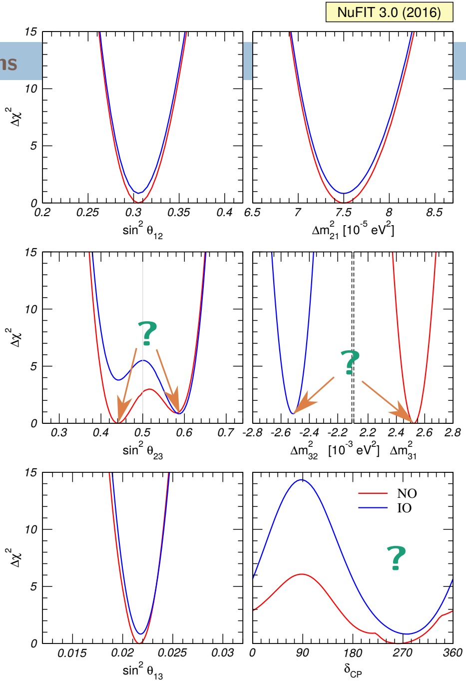
Parametrisation and open questions

M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, T. Schwetz, IE

JHEP **01** (2017) 087. NuFIT 3.0 (2016), www.nu-fit.org.

We need at least 3 light neutrino mixing parametrised by:

Δm^2_{21}	θ_{12}	δ_{CP}
Δm^2_{32}	θ_{13}	
$\Delta m^2_{31} = \Delta m^2_{32} - \Delta m^2_{21}$	θ_{23}	



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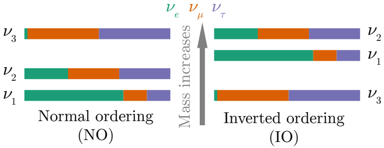
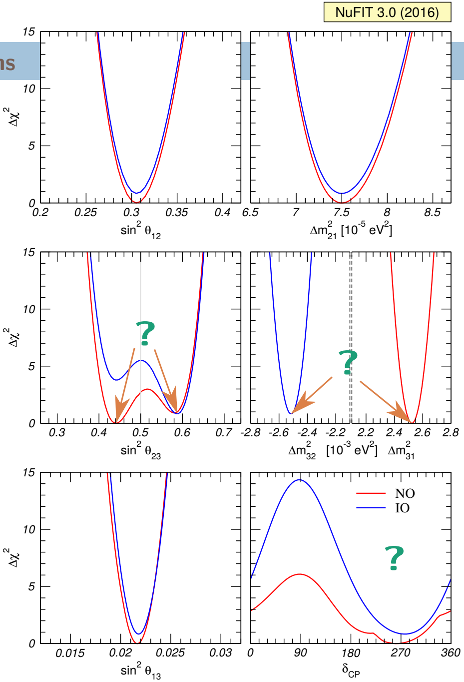
There are still open questions:

- 

- $\theta_{23} < 45°$? $\theta_{23} > 45°$?
- CP violation?

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \propto$$

$$J_{\text{lep}} = c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta_{CP} = (0.0330 \pm 0.0007) \sin\delta_{CP}$$



Experimental knowledge

What is new?

Reactor experiments:

- Daya Bay: 1230 days $\rightarrow$ 1958 days.
- RENO: 1500 days $\rightarrow$ 2200 days.

Accelerator experiments:

- T2K $\bar{\nu}$: $7.6 \cdot 10^{20}$ POT $\rightarrow 11.2 \cdot 10^{20}$ POT.
- NOνA $\bar{\nu}$: $\emptyset \rightarrow 6.9 \cdot 10^{20}$ POT.
- T2K ν systematic reevaluation.

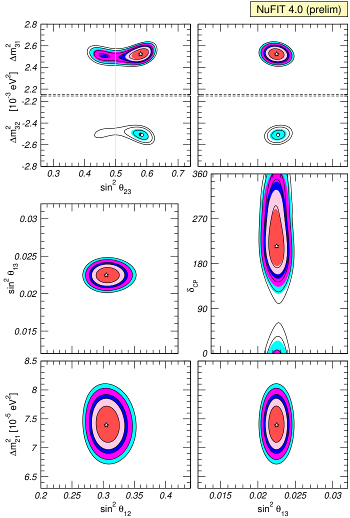
Atmospheric experiments:

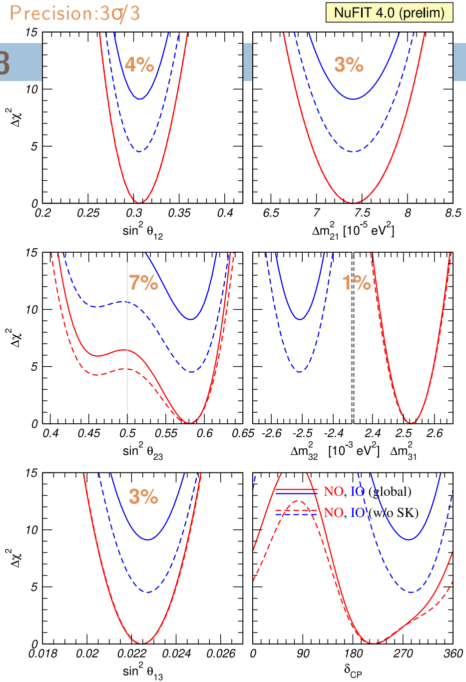
- SK: *external* χ^2 table.

Experimental knowledge

Status as of Autumn 2018

M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, T. Schwetz, IE

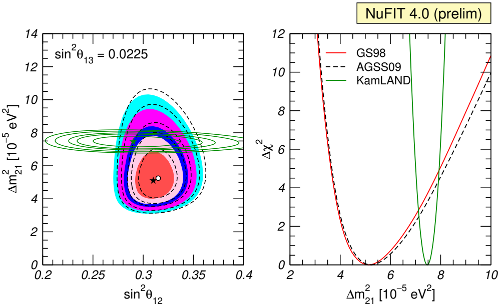


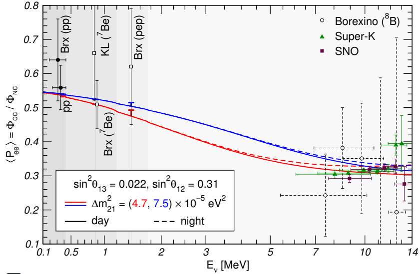


The Solar-KamLAND tension

θ_{12} and Δm^2_{21} are determined in Solar experiments + KamLAND:

$$P_{ee} \simeq \cos^4\theta_{13} \times \begin{cases} \sin^2\theta_{12} & \text{Solar, high E} \\ 1 - \frac{1}{2}\sin^2 2\theta_{12} & \text{Solar, low E} \\ 1 - \sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21} L}{4E} & \text{KamLAND} \end{cases}$$





M. Maltoni and A. Yu. Smirnov , "Solar neutrinos and neutrino physics", *Eur. Phys. J.* **A52** no. 4, (2016) 87, `arXiv:1507.05287 [hep-ph]`.

1-2 sector

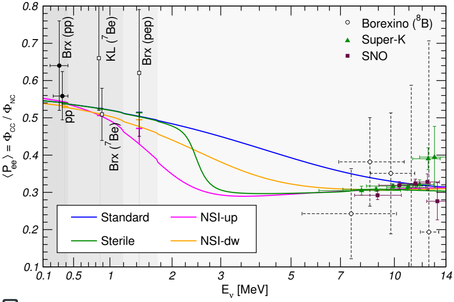
Future perspectives

Solar-KamLAND tension:

- JUNO: $\sigma_{\Delta m^2_{21}} / \Delta m^2_{21} \sim 6\%$
- SNO+: spectral measurement of the "upturn"
- Hyper-Kamiokande: improvements in day-night asymmetry

Or maybe there is a modified matter potential...

$$H_{\text{mat}} = \sqrt{2} G_F n_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$



M. Maltoni and A. Yu. Smirnov , arXiv:1507.05287 [hep-ph].

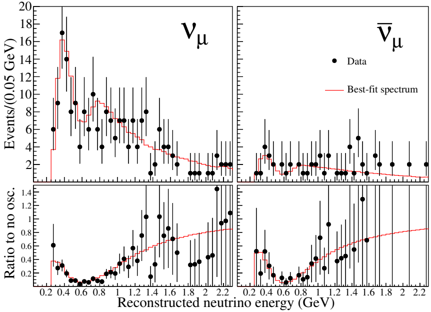
2-3 sector: status after Neutrino 2018

θ_{23}

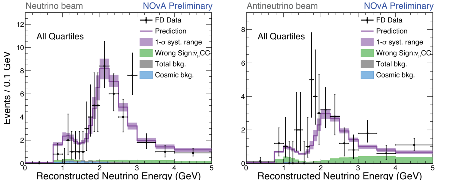
It is mostly determined through

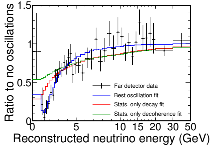
$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right) + \text{subleading } 3\nu \text{ effects}$$

At the oscillation maximum, $\sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right) = 1$, so $P_{\mu\mu} \simeq 0$ for $\theta_{23} \simeq 45^\circ$.



Taichiro Koga, PhD thesis





NOνA (Neutrino 2018) & MINOS

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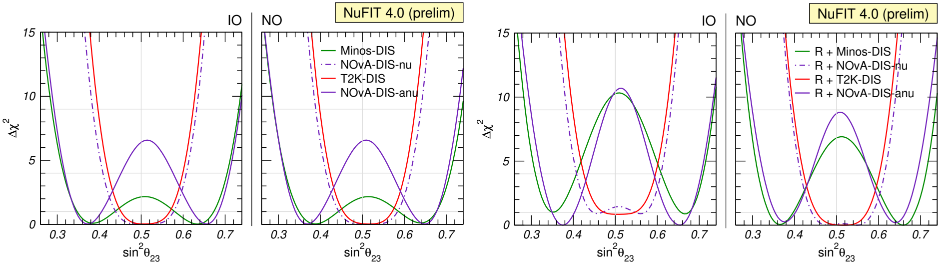

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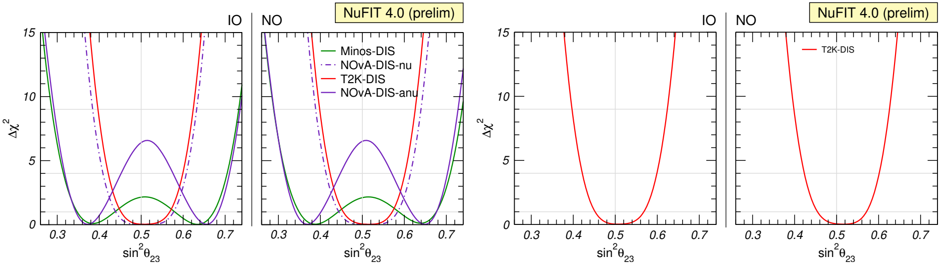

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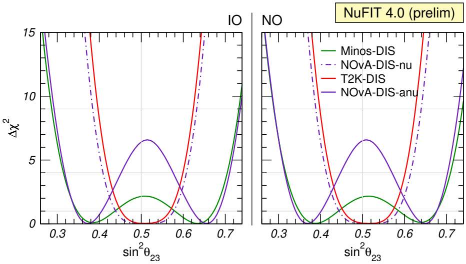

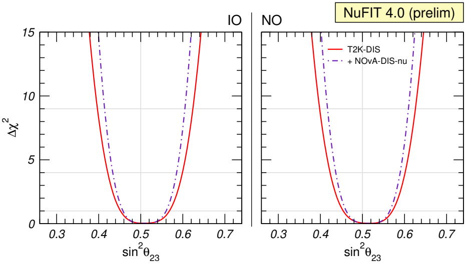

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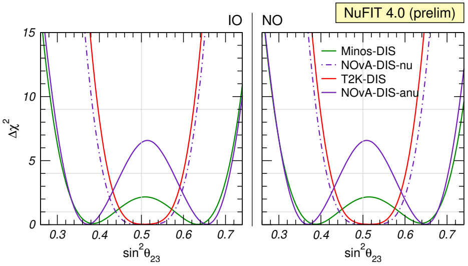

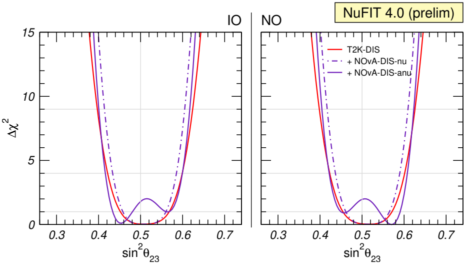

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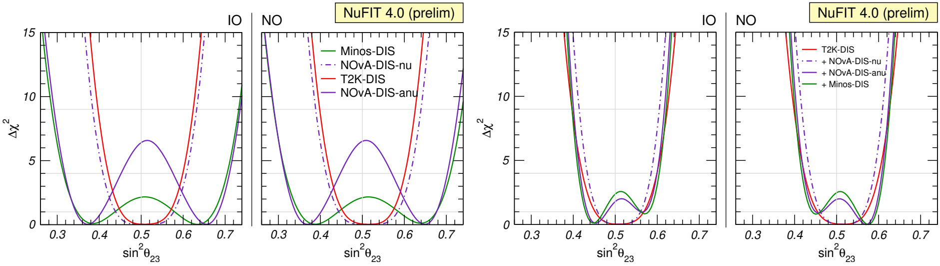

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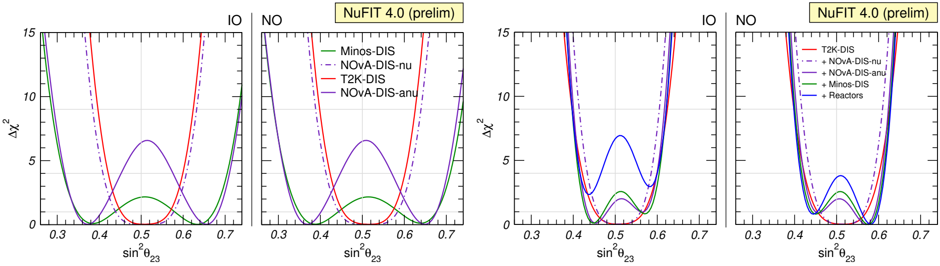

2-3 sector: status after Neutrino 2018

$|\Delta m^2_{32}|$

We can determine it in

- LBL, through $\nu_\mu \to \nu_\mu$
$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{\mu\mu} L}{4E}\right)$$
- Reactors, through $\bar{\nu}_e \to \bar{\nu}_e$
$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$$

with

$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{cases} -\cos^2\theta_{12}\Delta m^2_{21} & \text{for NO} \\ \sin^2\theta_{12}\Delta m^2_{21} & \text{for IO} \end{cases}$$

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H. Nunokawa, S. J. Parke, and R. Zukanovich Funchal, "Another possible way to determine the neutrino mass hierarchy", *Phys. Rev.* **D72** (2005) 013009, arXiv:hep-ph/0503283 [hep-ph].

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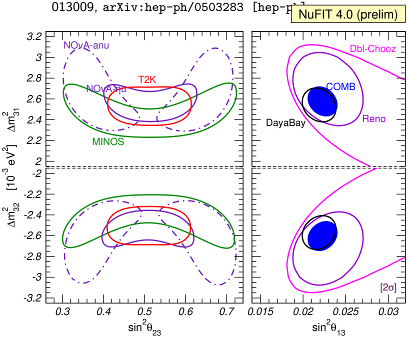
H. Nunokawa, S. J. Parke, and R. Zukanovich Funchal, "Another possible way to determine the neutrino mass hierarchy", *Phys. Rev.* **D72** (2005) 013009, arXiv:hep-ph/0503283 [hep-ph].



2-3 sector: status after Neutrino 2018

$|\Delta m^2_{32}|$

We can determine it in

- LBL, through $\nu_\mu \to \nu_\mu$
$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{\mu\mu} L}{4E} \right)$$
- Reactors, through $\bar{\nu}_e \to \bar{\nu}_e$
$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{ee} L}{4E} \right)$$

with

$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{cases} -\cos^2\theta_{12}\Delta m^2_{21} & \text{for NO} \\ \sin^2\theta_{12}\Delta m^2_{21} & \text{for IO} \end{cases} \qquad \Delta m^2_{ee} \simeq \Delta m^2_{3l} + \begin{cases} -\sin^2\theta_{12}\Delta m^2_{21} & \text{for NO} \\ \cos^2\theta_{12}\Delta m^2_{21} & \text{for IO} \end{cases}$$

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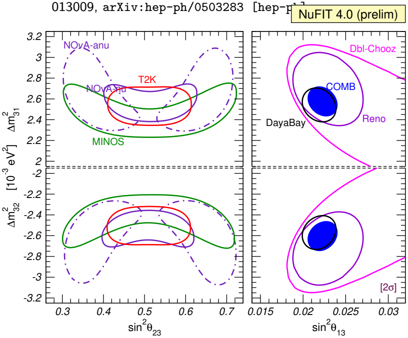
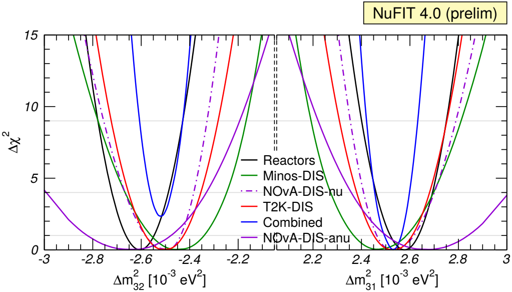


$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| \simeq \pm \Delta m^2_{21} \cos 2\theta_{12}$$



2-3 sector: status after Neutrino 2018

Mass ordering, θ_{23} octant, and CP violation

They are mostly determined through $\nu_\mu \to \nu_e$ in accelerators,

$$P_{\mu e} = \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 \Delta_{31}(1-A)}{(1-A)^2} + \frac{\Delta_{21}}{\Delta_{31}} 8 J_{\rm lep}^{\rm max} \cos(\Delta_{31} + \delta_{\rm CP}) \frac{\sin \Delta_{31} A}{A} \frac{\sin \Delta_{31}(1-A)}{(1-A)} + \mathcal{O}\left(\frac{\Delta_{21}}{\Delta_{31}}\right)^2$$

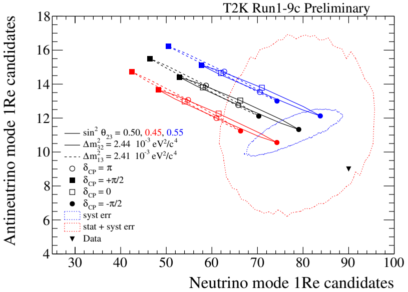
$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

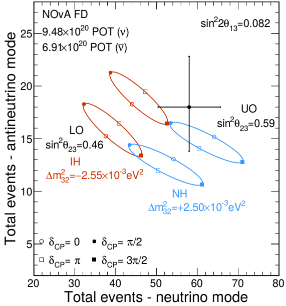
$$(\Delta_{31} \sim 1,\ \Delta_{21} \sim 10^{-2})$$

$$A = 2\sqrt{2} G_F n_e \frac{E}{\Delta m^2_{31}}$$

$$J_{\rm lep}^{\rm max} = \frac{1}{8} c_{13}^2 s_{13} c_{12} s_{12} c_{23} s_{23}$$

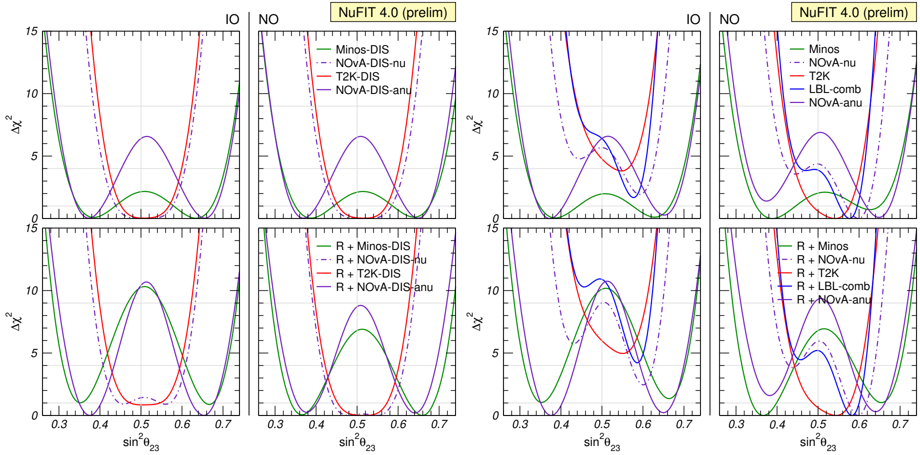
Strongly correlated: we need as much data and independent determinations as possible!





2-3 sector: status after Neutrino 2018

θ_{23} octant



$P_{\mu e} \propto \sin^2\theta_{23} \Rightarrow$ more $\nu/\bar{\nu}$ events favours second octant, particularly for IO.

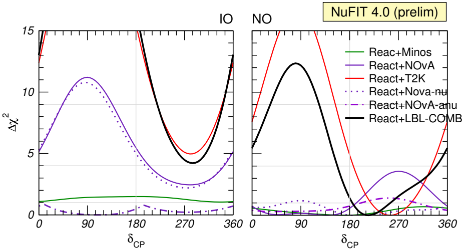
For NO, MINOS and T2K preferences $\sim$ cancel, so the octant preference is dominated by NOνA.

2-3 sector: status after Neutrino 2018

CP violation

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \propto J_{\text{lep}} = J_{\text{lep}}^{\text{max}} \sin\delta_{\text{CP}} = (0.0333 \pm 0.0007) \sin\delta_{\text{CP}}$$

Compare to $J_{\text{quark}} = 0.000030 \pm 000002$. If $\sin\delta_{\text{CP}}$ is not small, **main source of CP violation in the model**.



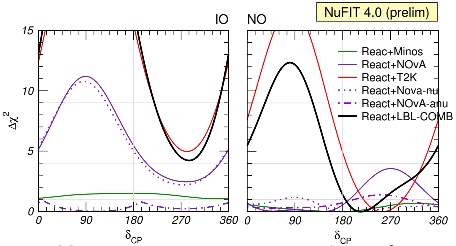
The T2K preference is driven by *a statistical fluctuation*: their result is more restricting than their sensitivity.

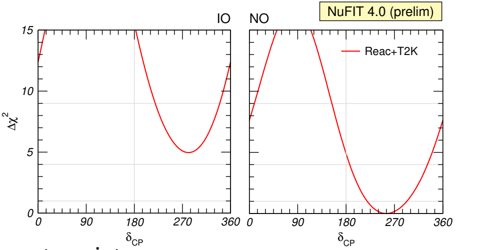
SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
FHC 1Rμ	268.5	268.2	268.5	268.9	243
FHC 1Re 0 decay-e	73.8	61.6	50.0	62.2	75
FHC 1Re 1 decay-e	6.9	6.0	4.9	5.8	15
RHC 1Rμ	95.5	95.3	95.5	95.8	102
RHC 1Re 0 decay-e	11.8	13.4	14.9	13.2	9

"p-value for up/down fluctuation in 1 of 5 samples is $\sim$ 5% (1% with single sample)"
T2K, neutrino 2018

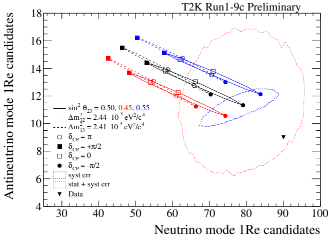
2-3 sector: status after Neutrino 2018

CP violation



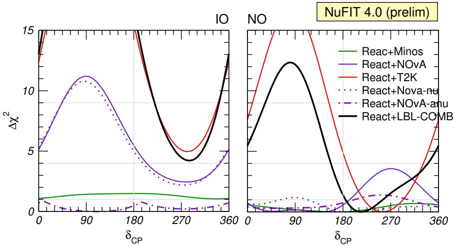


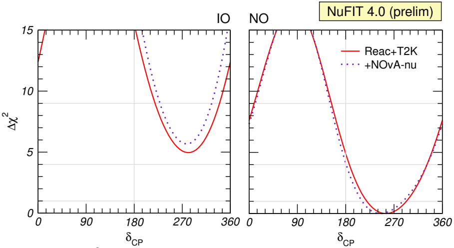
- T2K: too many ν_e events and too few $\bar{\nu}_e$ events point towards maximal CP violation.



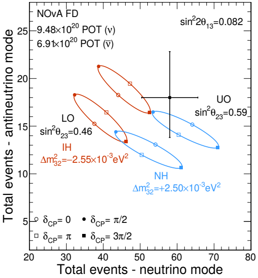
2-3 sector: status after Neutrino 2018

CP violation



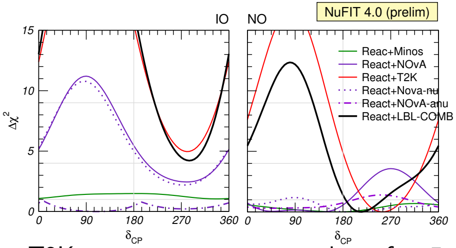


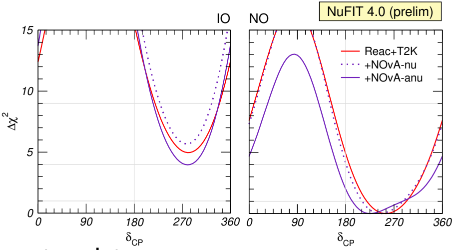
- T2K: too many ν_e events and too few $\bar{\nu}_e$ events point towards maximal CP violation.
- +NOvA-nu: there are not so many ν_e events, but still compatible with large CP violation.



2-3 sector: status after Neutrino 2018

CP violation





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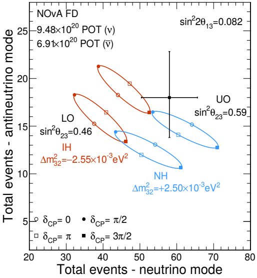
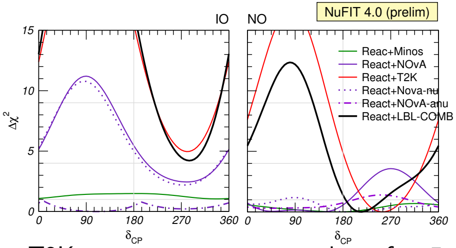
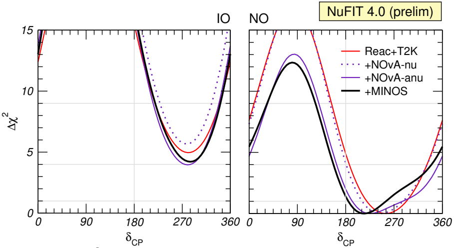
- +NOvA-nu: there are not so many ν_e events, but still compatible with large CP violation.
- +NOvA-anu: there are not so few $\bar{\nu}_e$ events. Furthermore, non-maximal θ_{23} increases ν_e events in previous experiments without needing maximal CP violation.



2-3 sector: status after Neutrino 2018

CP violation





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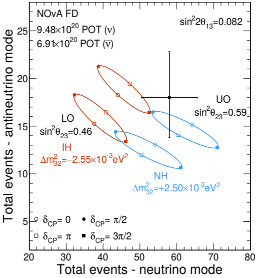
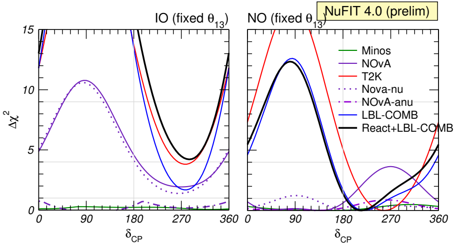
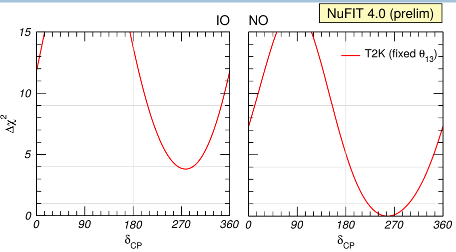
- +MINOS: same effect as NOvA-anu.



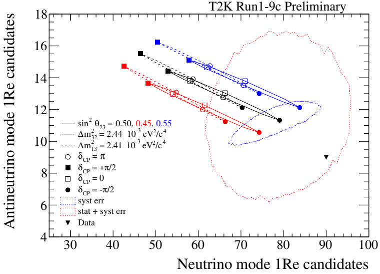
2-3 sector: status after Neutrino 2018

Mass ordering



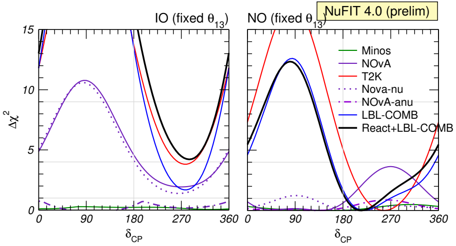


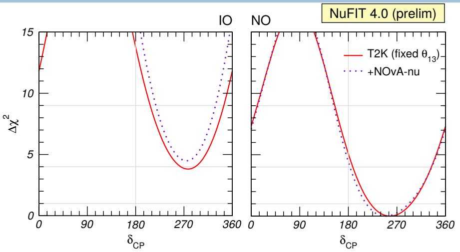
- T2K: too many ν_e events and too few $\bar{\nu}_e$ events point towards NO ($\Delta\chi^2 \sim 4$).



2-3 sector: status after Neutrino 2018

Mass ordering





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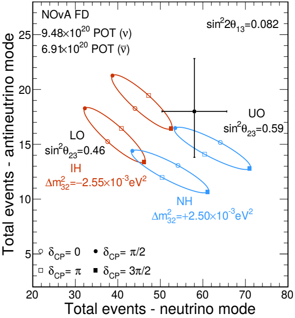
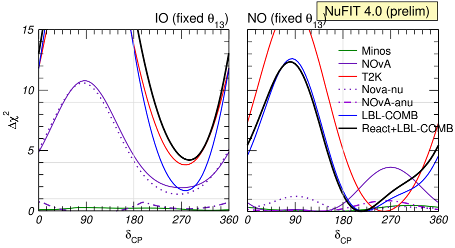
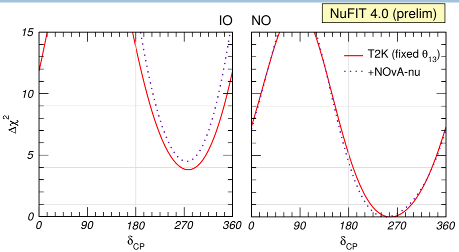


2-3 sector: status after Neutrino 2018

Mass ordering





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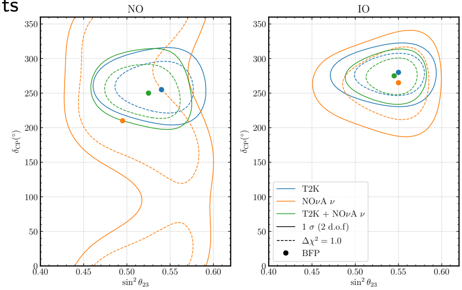
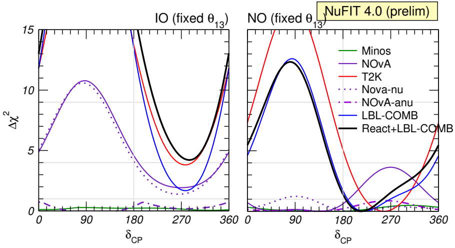
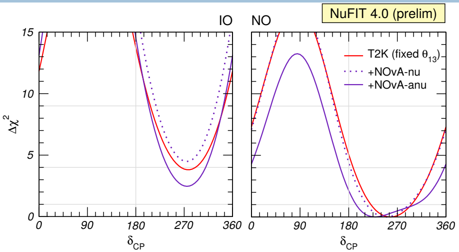


2-3 sector: status after Neutrino 2018

Mass ordering





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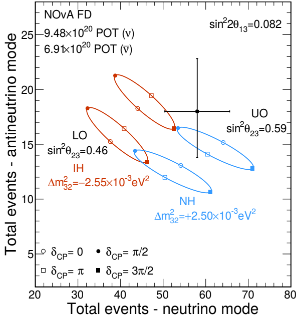
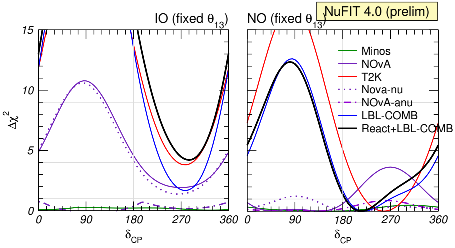
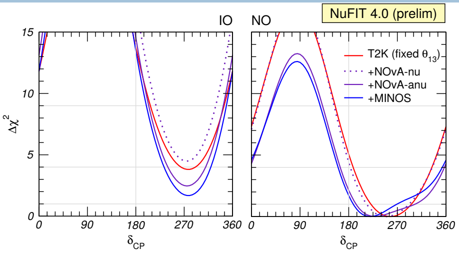
- $+$NOvA-anu: the δ_{CP} tension decreases the significance for NO.



2-3 sector: status after Neutrino 2018

Mass ordering





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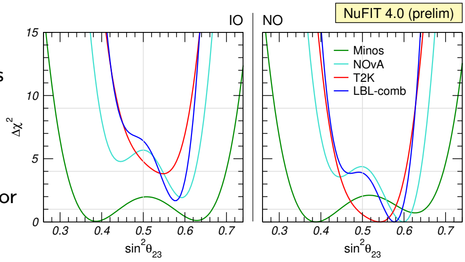
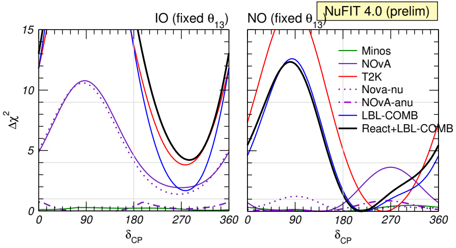
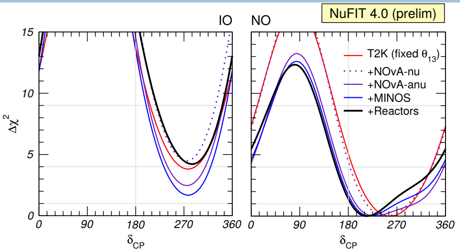


2-3 sector: status after Neutrino 2018

Mass ordering





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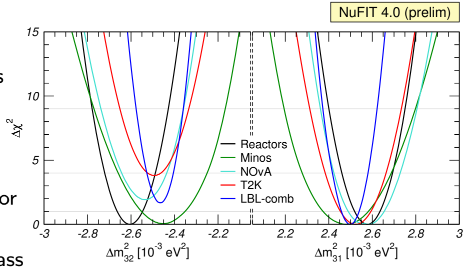
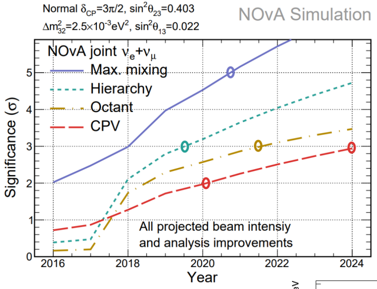
- +NOvA-anu: the δ_{CP} tension decreases the significance for NO.
- +MINOS: MINOS disfavours second octant for NO.
- +Reactors: Reactors allow to measure the mass ordering through $\Delta m^2_{\mu\mu}$ vs Δm^2_{ee}.

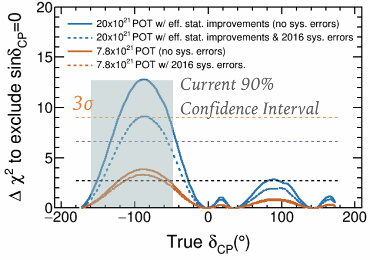


Mass ordering, θ_{23} octant, and CP violation

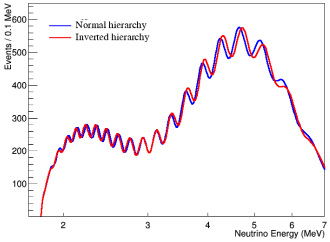
Future prospects: short term ($\sim$ 3 years)



NOνA



T2K



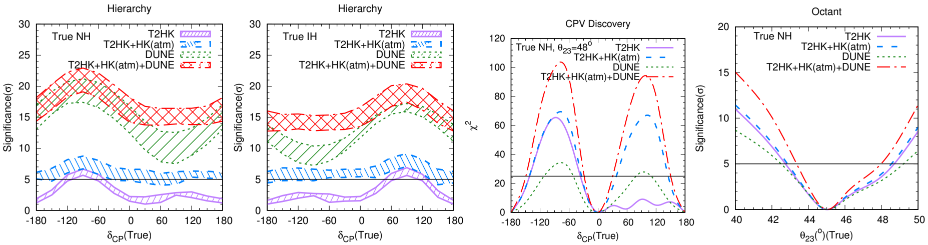
JUNO ($\Delta\chi^2_{\text{MO}} \sim 16$)

Mass ordering, θ_{23} octant, and CP violation

Future prospects: long term ($\sim$ 10 years)

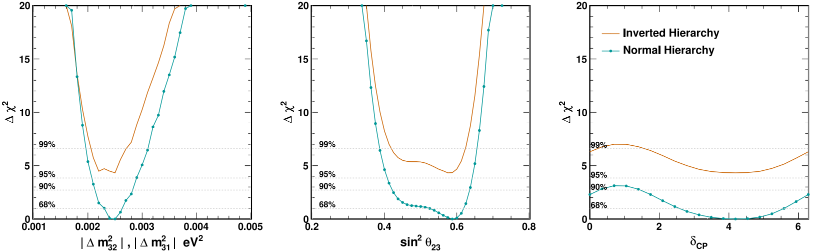
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Hyper-Kamiokande



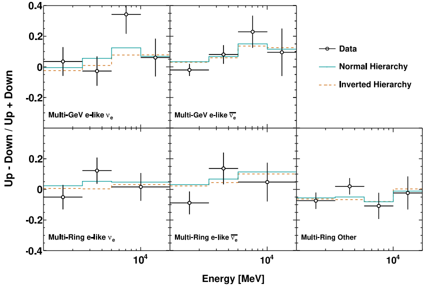
O. Yasuda, S. Fukasawa, and M. Ghosh, "Complementarity Between Hyperkamiokande and DUNE" , in *18th International Workshop on Neutrino Factories and Future Neutrino Facilities Search (NuFact16) Quy Nhon, Vietnam, August 21-27, 2016*. `arXiv:1610.09971 [hep-ph]`.

Atmospheric SK results



Super-Kamiokande Collaboration, K. Abe *et al.*, "Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV", *Phys. Rev.* **D97** no. 7, (2018) 072001, arXiv:1710.09126 [hep-ex].

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



- No phenomenological group can reproduce these results.
- The only possibility is to use a χ^2 table.

Conclusions

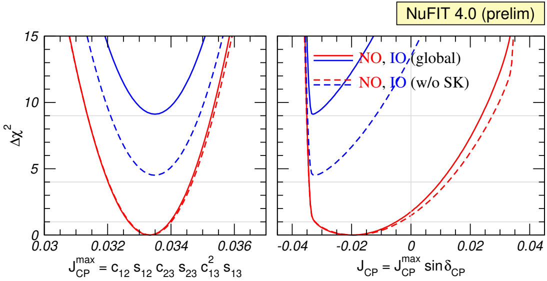
- 3ν oscillations can robustly and precisely describe oscillation data, the low-energy parametrisation of our first evidence of New Physics.
- After Neutrino 2018,
  - best fit at $\delta_{\rm CP} \sim 215^\circ$ — maximal CP violation disfavoured with $> 1\sigma$.
  - CP conservation allowed within $\sim 1\sigma$.
  - NO favoured at $\sim 2\sigma$, $> 3\sigma$ after including SK.
  - maximal 2-3 mixing disallowed at $\gtrsim 2\sigma$.
- T2K effects are driven by a statistical fluctuation: they observe more ν_e than expected.
- All the effects are quite sensitive to, and diluted by, tensions with other LBL experiments (particularly NOνA antineutrino data).
- The combination of reactor and LBL disappearance results is providing a *complementary* measurement of the mass ordering other than ν_e appearance.
- New data will continue appearing: stay tuned!

I would like to acknowledge the rest of the NuFIT collaboration: M.C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, T. Schwetz. And thanks to the great work by the experimental collaborations!

Thanks!

Backup

Leptonic Jarlskog invariant

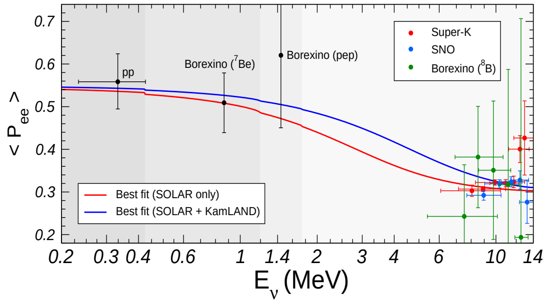


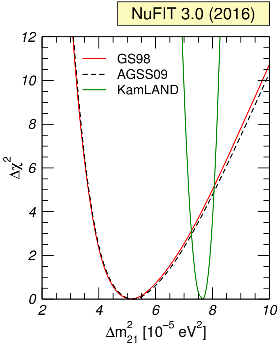
Backup

1-2 sector

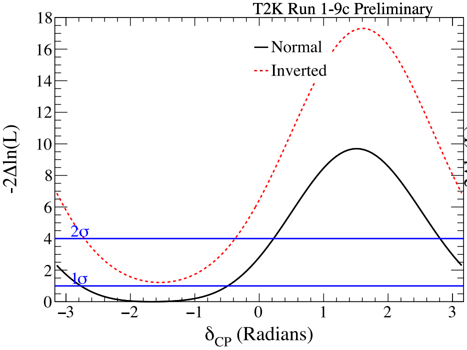
Sun, Δm^2_{21} through matter effects $\begin{cases} \Delta m^2_{\text{eff}} = \Delta m^2 \sqrt{\left(\cos 2\theta - 2\sqrt{2} G_F n_e \frac{E}{\Delta m^2}\right)^2 + (\sin 2\theta)^2} \\ \sin(2\theta_{\text{eff}}) = \sin 2\theta \frac{\Delta m^2}{\Delta m^2_{\text{eff}}} \end{cases}$

KamLAND, $P_{ee} \sim 1 - \frac{1}{2} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{2E}$

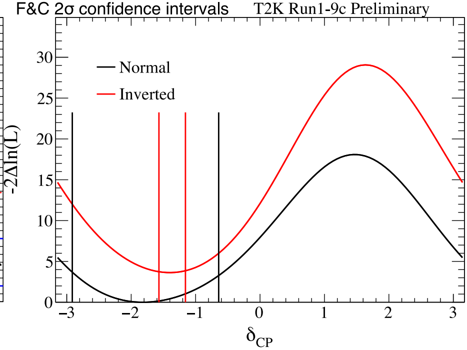




T2K: sensitivity vs data



Sensitivity



Fit (notice the different vertical scale!)