NHL'S AND LIGHT OSCILLATING NEUTRINOS IN 2022

Concha Gonzalez-Garcia

(ICREA U. Barcelona & YITP Stony Brook)

FIP's Workshop, CERN, Sept 20, 2022

Global fit to neutrino oscillation data

HIDDeν

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

http://www.nu-fit.org

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OUTLINE

- Introduction: NHL's & Active Neutrino Oscillations
- Status of 3ν global description

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Introduction: The SM of Active Neutrinos

The SM is a gauge theory based on the symmetry group

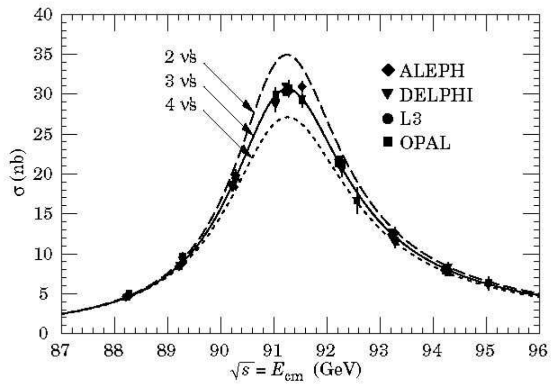
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

With three generation of fermions

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

There is no ν_R

Three and only three



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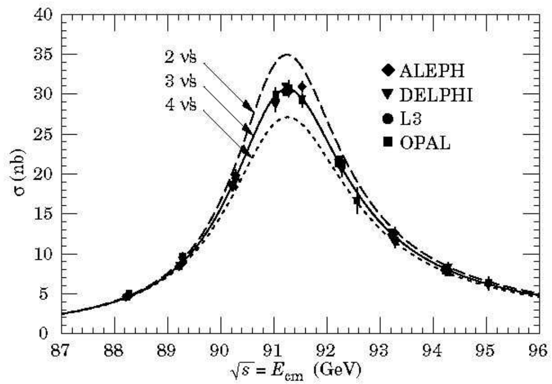

There is no ν_R

$\Downarrow$

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

$\Downarrow$

ν *strictly* massless

Introduction: The need of BSM

- We have confirmed with high/reasonable precision:
  - $*$ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS, **ICECUBE**)
  - $*$ Accel. ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NOνA**)
  - $*$ Some accelerator ν_μ appear as ν_e at $L \sim 300/800$ Km (**T2K**, MINOS,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**)

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All this implies that L_α are violated $\Rightarrow$ SM needs to be extended

Intro: The Minimal SM Extension

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

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

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

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

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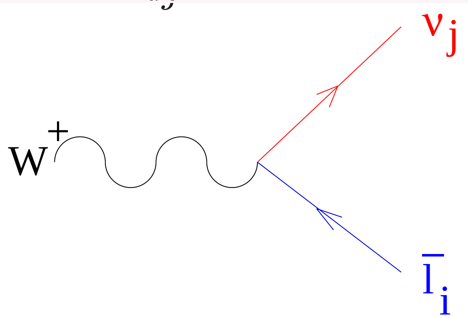
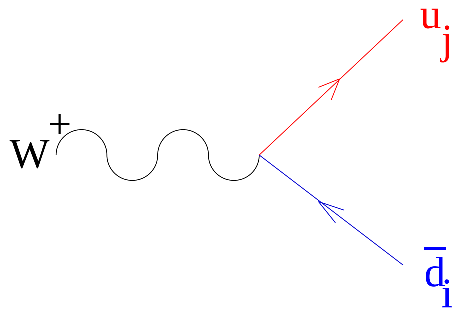
- Charged current interactions of leptons are not diagonal (*similarly* to quarks)

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





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$\Rightarrow$ Flavour Oscillations:

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

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

Intro: Lepton Mixing

- For 3 charged leptons and 3 (ew doublet) + S (ew singlet) neutrinos
  the charged current in the mass basis: $\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \overline{\ell^i_L} \gamma^\mu U^{ij}_{\rm LEP} \nu_j W^+_\mu$

$$U^{ij}_{\rm LEP} = \sum_{k=1}^{3} P^\ell_{ii} {V^\ell_L}^{\dagger\, ik} V^{\nu\, kj} P^\nu_{jj} \qquad\qquad 3 \times (3+S) \text{ matrix}$$

V^ℓ_L : 3×3 Unitary matrix rotating left charged leptons to mass basis

V^ν : $(3+S) \times (3+S)$ Unitary matrix rotating neutrinos to mass basis

P^ℓ_{ii} : 3 phases absorbed in l_i
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- If no other NP in charge lepton sector we can choose $V^\ell_L = I_{3\times 3}$

$$\Rightarrow V^\nu = \begin{array}{c|cc} \text{dim} & 3 & S \\ \hline 3 & (K_l & K_h) \equiv U_{\rm LEP} \\ S & \tilde{K}_h & \tilde{K}_H \end{array}$$

$K_{l,3\times 3}$ and $K_{h,3\times S}$ non-unitary

Valle and Schechter PRD22 (1980)

Intro: Lepton Mixing Unitarity

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$$\mathcal{L}_{NC} = -\frac{g}{2} \left(\overline{\nu_l}\gamma^\mu K_l^\dagger K_l\, \nu_l + \overline{\nu_l}\gamma^\mu K_l^\dagger K_h\, N + \overline{N}\gamma^\mu K_h^\dagger K_l\, \nu_l + \overline{N}\gamma^\mu K_h^\dagger K_h\, N\right) Z_\mu$$

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- $V^\nu V^{\nu\dagger} = \begin{pmatrix} K_l K_l^\dagger + K_h K_h^\dagger & \dots \\ \dots & \dots \end{pmatrix} = \begin{pmatrix} I_{3\times 3} & 0 \\ 0 & I_{S\times S} \end{pmatrix}$

$$\Rightarrow \; U_{\rm LEP} U_{\rm LEP}^\dagger = K_l K_l^\dagger + K_h K_h^\dagger = I_{3\times 3}$$

[But $U_{\rm LEP}^\dagger U_{\rm LEP} \neq I_{(3+S)\times(3+S)}$]

$K_l K_l^\dagger + K_h K_h^\dagger = I_{3\times 3} \Rightarrow$ *generic* relation between NHL couplings and unitarity violation in ν_l oscillations

- Convenient parametrization:

Xing arXiv:1110.0083; Escrihuela *etal* arXiv:1503.08879, Blennow *etal* arXiv:1609.08637

$$K_l = \left[I_{3\times3} - \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{e\mu} & \alpha_{\mu\mu} & 0 \\ \alpha_{e\tau} & \alpha_{\mu\tau} & \alpha_{\tau\tau} \end{pmatrix} \right] U_{3\times3}$$

$$U_{3\times3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{\rm cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{\rm cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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- Canonical type-I see-saw: $M_\nu = \begin{pmatrix} 0 & D_{3\times S} \\ D^T_{S\times3} & M_{S\times S} \end{pmatrix} \qquad D \equiv \frac{Y^\nu}{\sqrt{2}}\, v$

$$\text{Diagonalizing } M_\nu \Rightarrow \begin{cases} 3\,\nu_l's: & m_{\nu_l} \sim D^T\, M^{-1}\, D \\ \text{S NHL's}: & M_N \sim M \gg \text{TeV} \\ \alpha \sim \left(\frac{D}{M}\right)\left(\frac{D}{M}\right)^\dagger & \sim \frac{m_{\nu_l}}{M_N} \text{ unobservable} \end{cases}$$

Convenient parametrization:

$$K_l = \left[I_{3\times3} - \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{e\mu} & \alpha_{\mu\mu} & 0 \\ \alpha_{e\tau} & \alpha_{\mu\tau} & \alpha_{\tau\tau} \end{pmatrix} \right] U_{3\times3}(\theta_{12}, \theta_{13}, \theta_{23}, \delta; \eta_1, \eta_2) \qquad K_h \sim \mathcal{O}(\sqrt{\alpha})$$

- In more general see-saw-I scenarios: Bounds on $\alpha' s$ depend on NHL mass range

Blennow *etal* arXiv:1609.08637

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– for all $M_N \lesssim 10$ eV :

- 3+S $\nu' s$ in oscillation experiments {
  - $M_N \sim$ eV $\Rightarrow$ some SBL anomaly explained
  - Fit to all other osc data $\Rightarrow$ $\alpha' s \lesssim$ 0.1-0.01

– For 10 eV $\lesssim M_N \ll$ EW scale :

- M_N oscillations mostly averaged in osc experiments
- Searches for N's at beam-dump experiments

} $\Rightarrow$ stronger bounds on $\alpha' s$

– For $M_N \gtrsim$ EW scale $\Rightarrow$ Unitarity and Universality violation in EWPD

$\Rightarrow$ $\alpha' s \lesssim 10^{-3}$ - 10^{-4}

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$\Rightarrow$ Unitarity violation can be ignored in present $3\nu_l$ oscillation analysis

Partial 3ν-osc analysis w/o unitarity Hu *etal* 2008.09730; Denton,Gehrlein 2109.14575

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$K_l K_l^\dagger + K_h K_h^\dagger = I_{3\times3} \Rightarrow$ *generic* relation between NHL effects and ν_l unit. violat.

– Theoretical prejudice & Experimental bounds:

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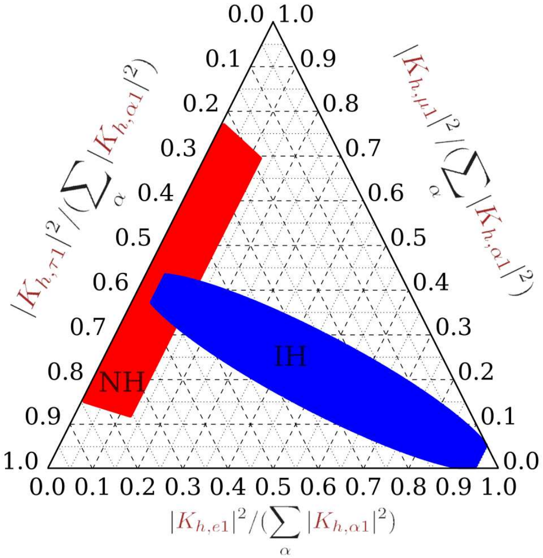
Minimal (Lepton Flavour Violating) Type I see-saws: Gavela *etal* 0906.1461



$\Rightarrow K_h$ dominantly determined by $3\nu_l$ osc parameters [up to overall normalization & Maj phase(s)]

$\Rightarrow$ Maximal corrrelation between $3\nu_l$ osc parameters and expected NHL effects

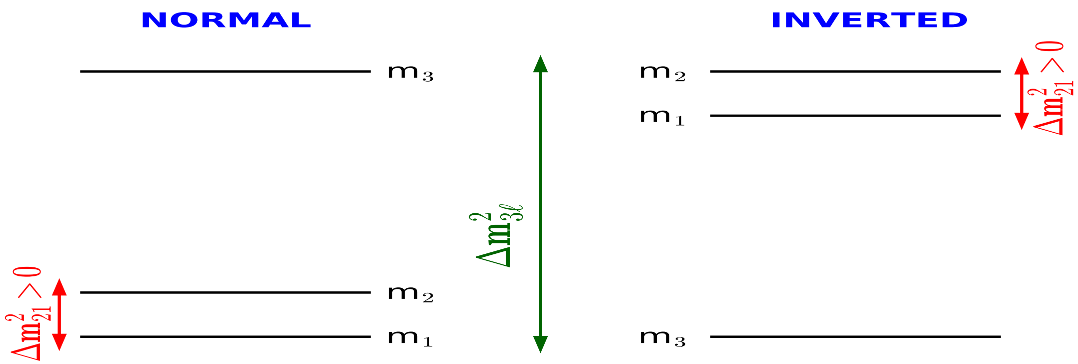
Caputo *etal* 1704.08721

Active 3ν Flavour Parameters

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

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

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



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

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

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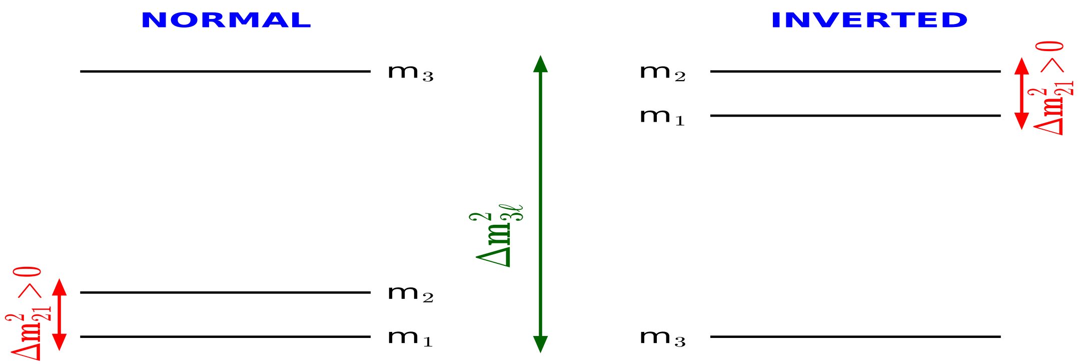
oncha Gonzalez-Garcia

- 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: $0 \le \theta_{ij} \le 90^\circ$ $\quad 0 \le \delta \le 360^\circ$ $\quad \Rightarrow$ 2 Orderings



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

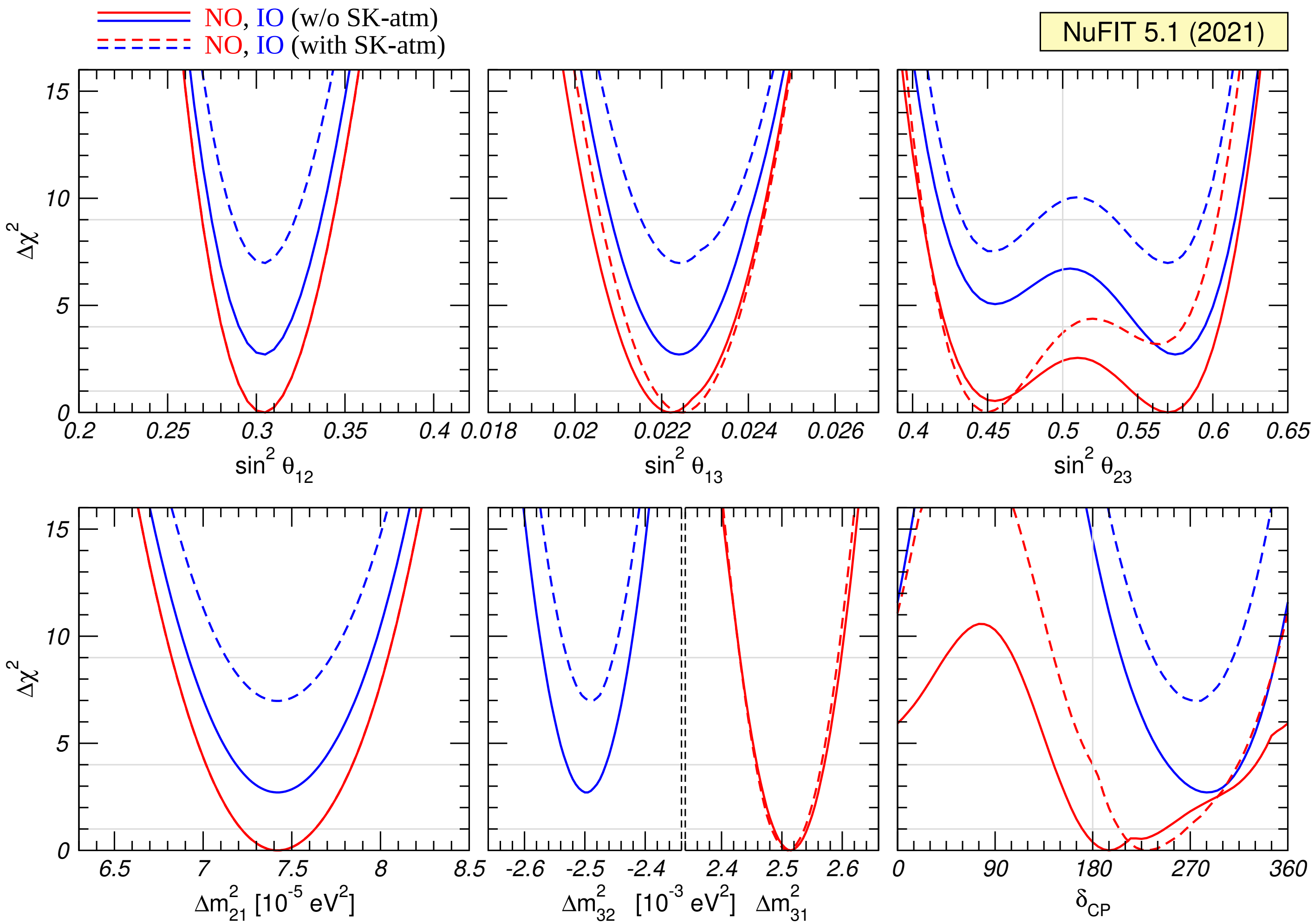
$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases}$$

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}

Summary: Global 3 ν Flavour Parameters

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

Esteban, G-G, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792], G-G, Maltoni, Schwetz, 2111.03086



SK-atm $\equiv$ χ^2 table from SK1-4 for 372 kton-years

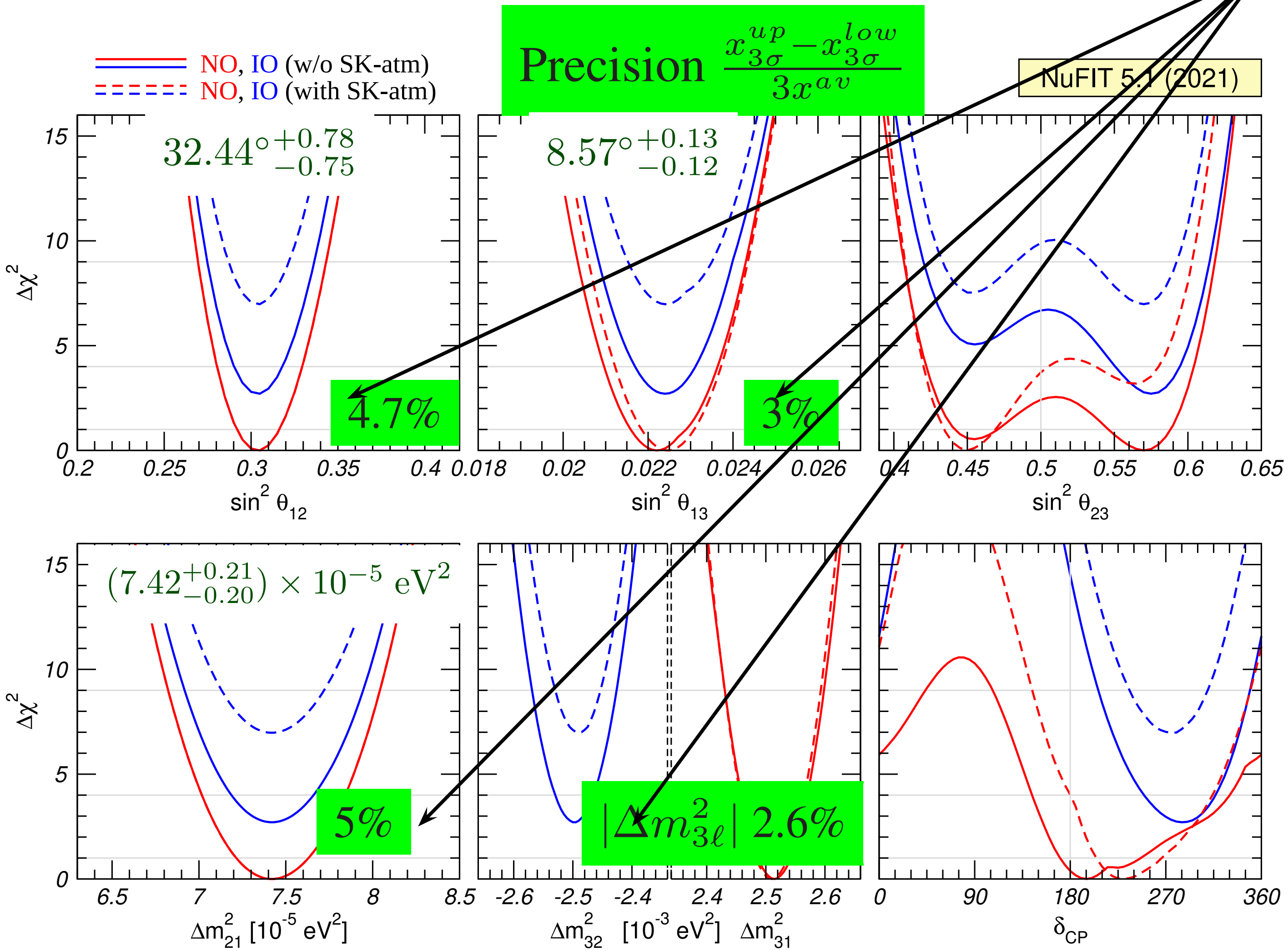
Summary: Global 3 ν Flavour Parameters

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

Esteban, G-G, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792], G-G, Maltoni, Schwetz, 2111.03086

- 4 well-known parameters:

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



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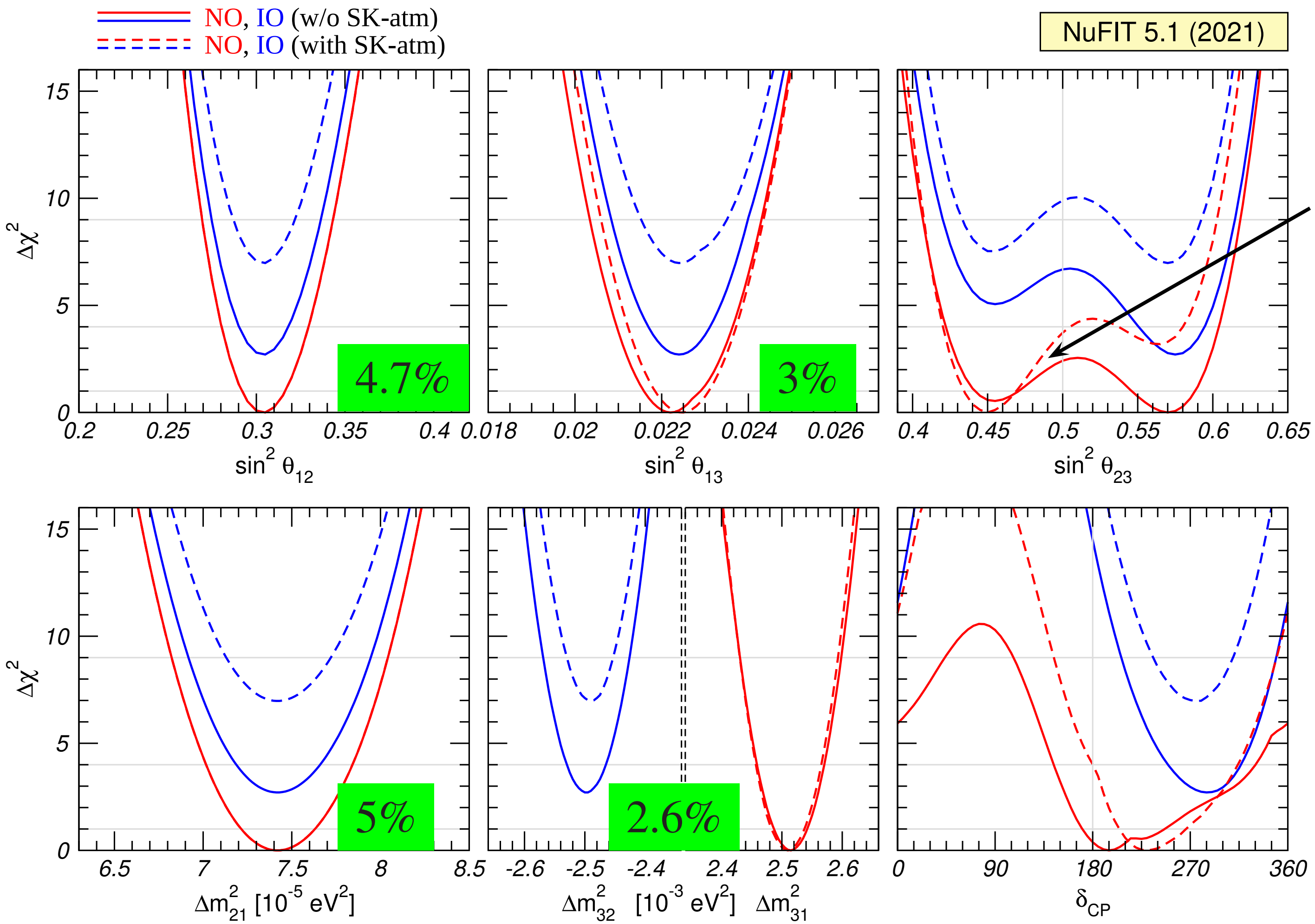
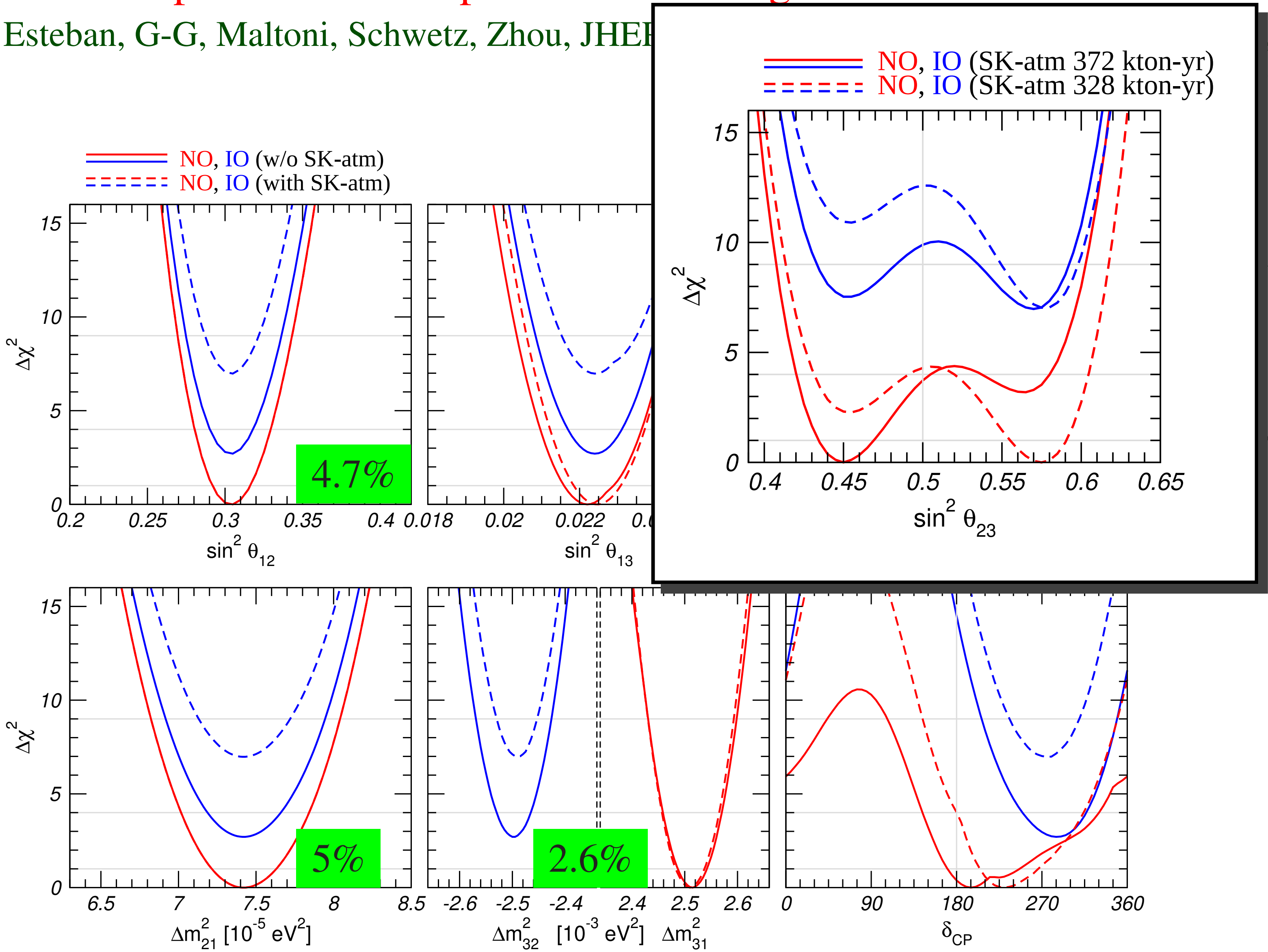


- 4 well-known parameters:
  θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$
  Δm^2_{21} Solar vs KLAND
  Tension Resolved
- θ_{23}: Least known angle
  Maximal? Octant?
  non-robust wrt ATM

Summary: Global 3 ν Flavour Parameters

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

Esteban, G-G, Maltoni, Schwetz, Zhou, JHE… , 2111.03086



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Solar vs KLAND

on Resolved

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Summary: Global 3 ν Flavour Parameters

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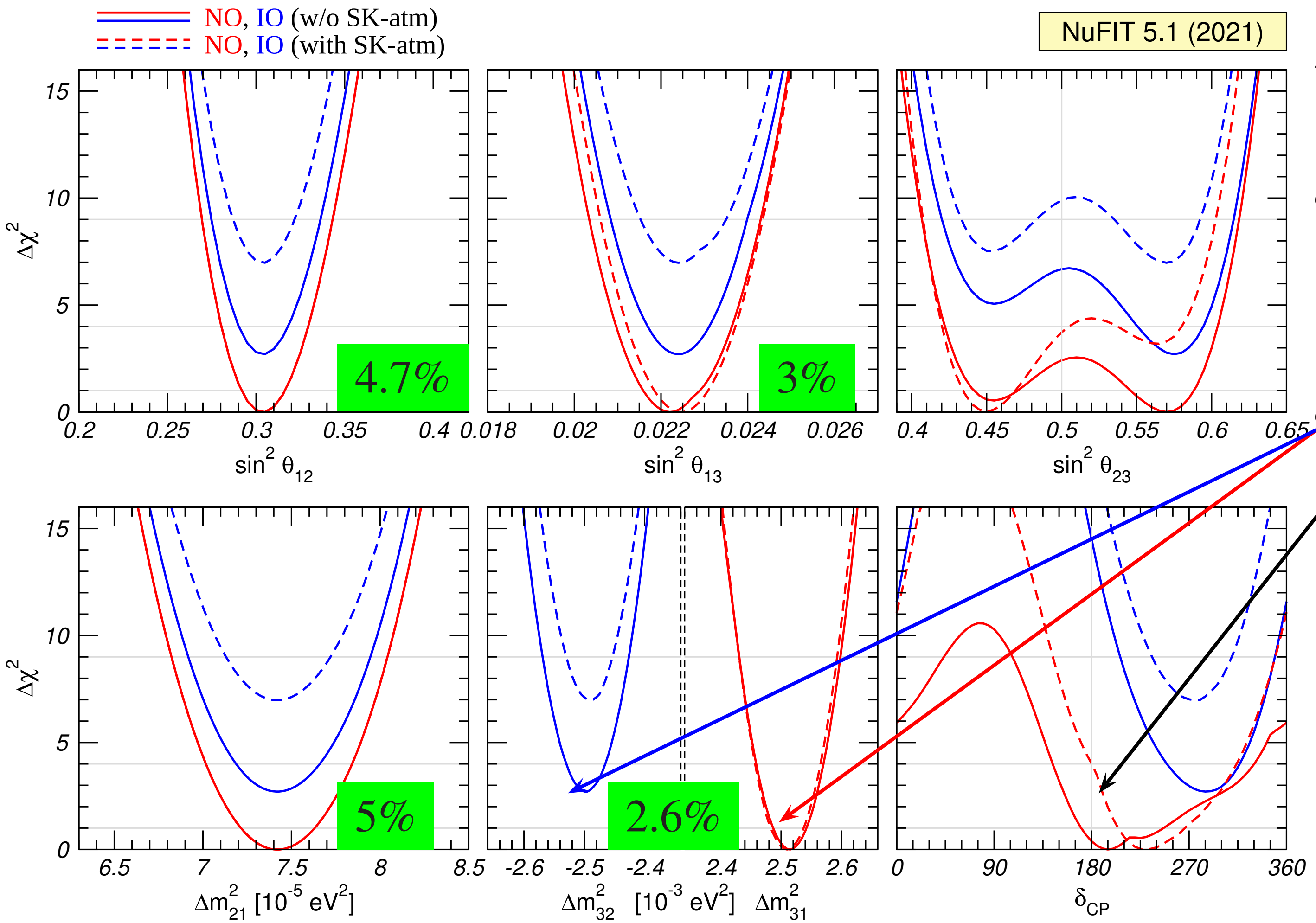


- 4 well-known parameters:

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

  Δm^2_{21} Solar vs KLAND

  Tension Resolved
- θ_{23}: Least known angle

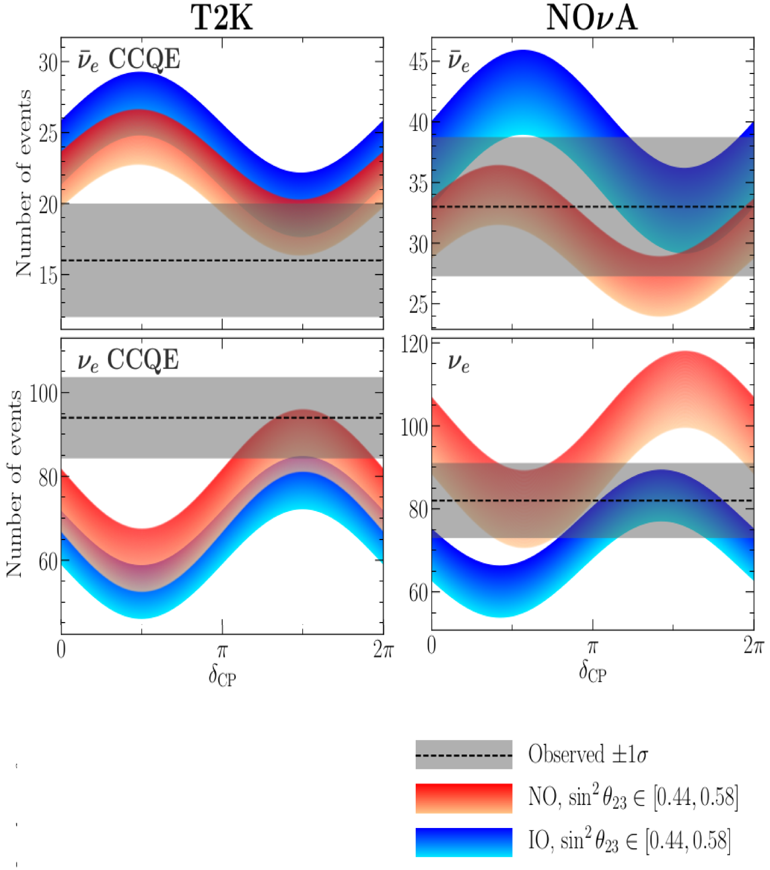
  Maximal? Octant?

  non-robust wrt ATM
- Ordering NO or IO?

  CPV?:

CPV and Ordering in LBL: ν_e appearace

ν_e and $\overline{\nu}_e$ apperance events



$\Rightarrow$ Each T2K and NOνA favour NO

CPV and Ordering in LBL: ν_e appearace

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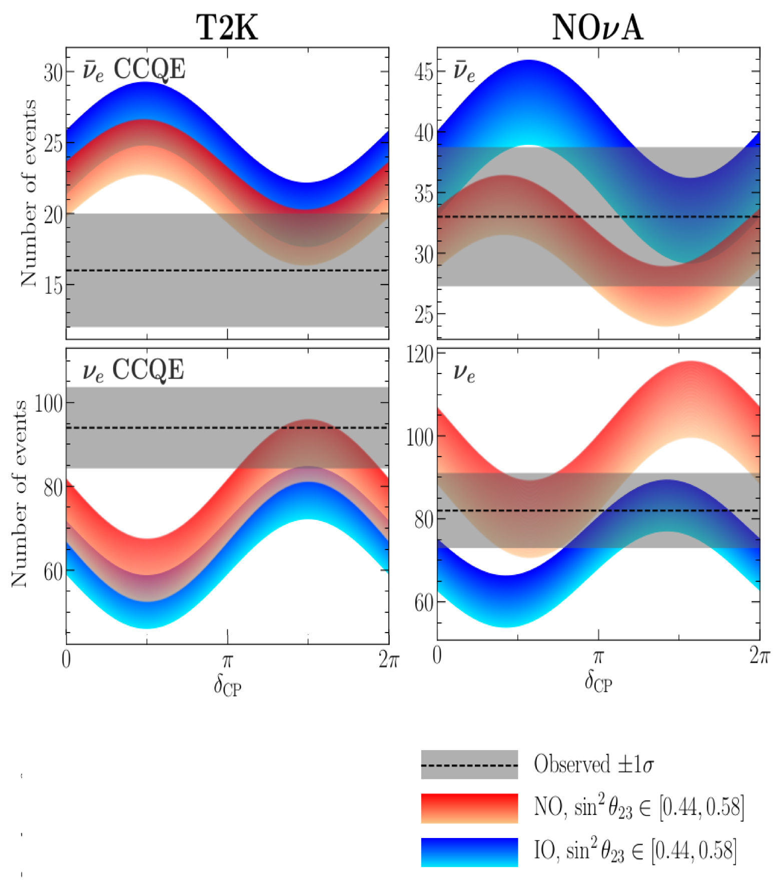
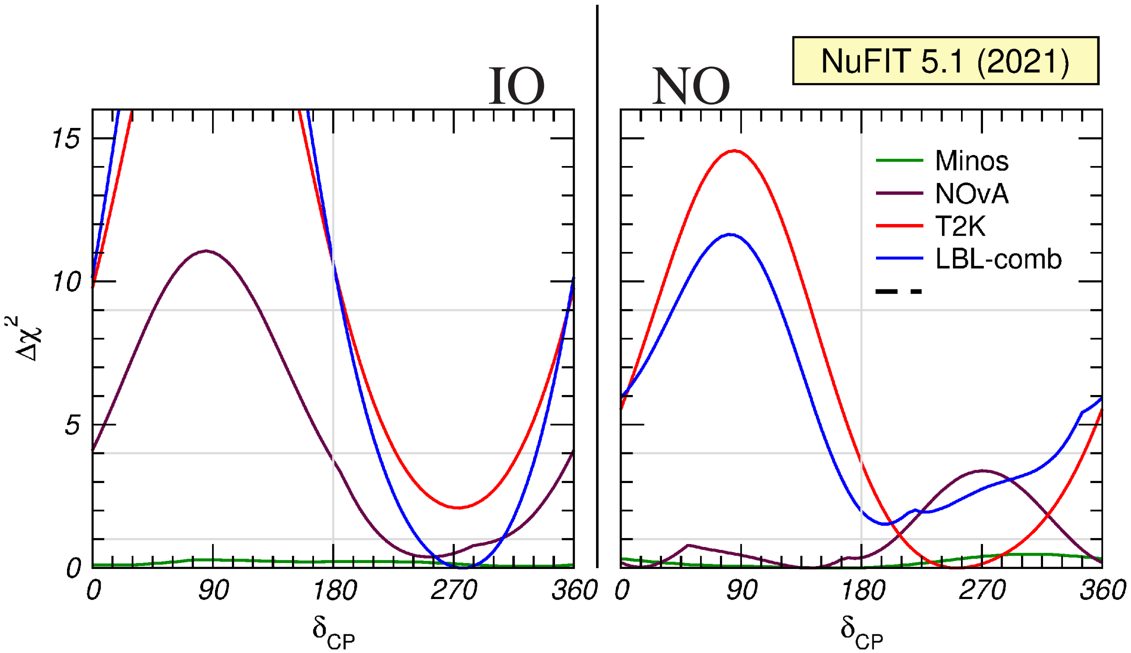


But tension in favoured values of δ_{CP} in NO

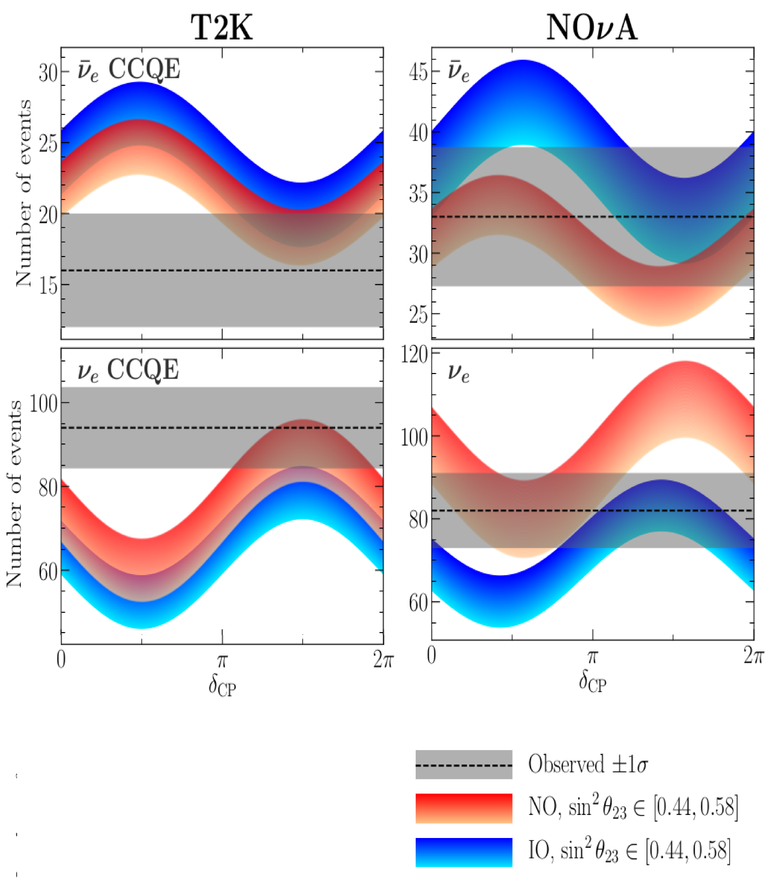


$\Rightarrow$ IO best fit in LBL combination

$\Rightarrow$ Each T2K and NOνA favour NO nzalez-Garcia

CPV and Ordering in LBL: ν_e appearace

ν_e and $\overline{\nu}_e$ apperance events



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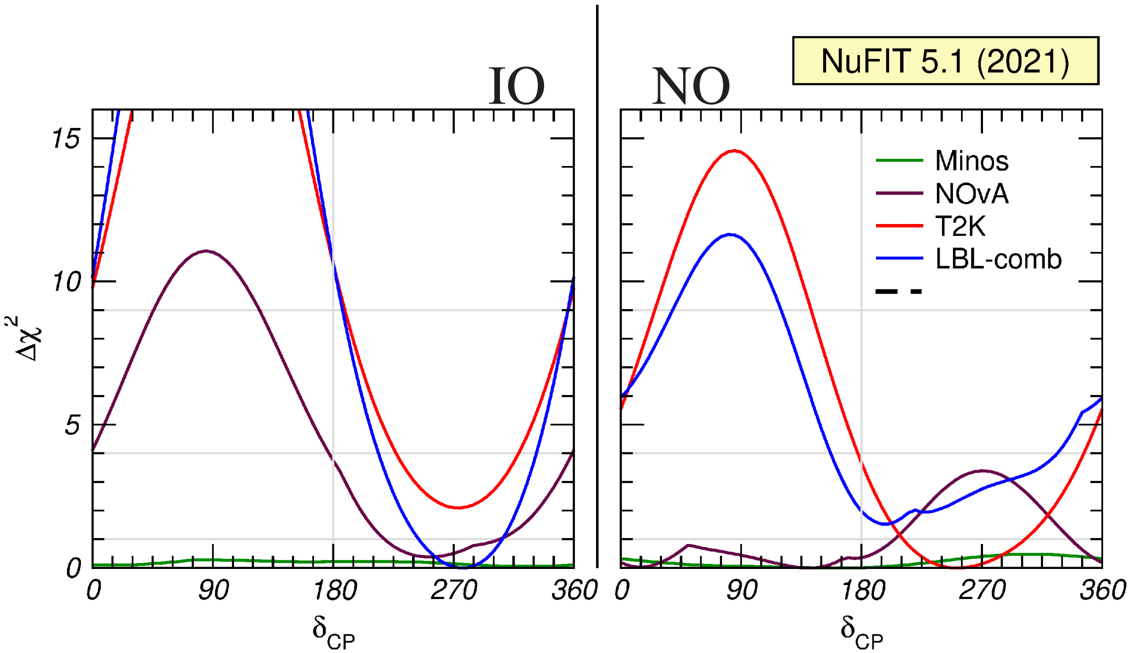

$\Rightarrow$ IO best fit in LBL combination

- Parameter goodness-of-fit (PG) test:

	normal ordering			inverted ordering		
	χ^2_{PG}/n	p-value	$\#\sigma$	χ^2_{PG}/n	p-value	$\#\sigma$
T2K vs NOvA (θ_{13} free)	6.7/4	0.15	1.4σ	3.6/4	0.46	0.7σ
T2K vs NOvA (θ_{13} fix)	6.5/3	0.088	1.7σ	2.8/3	0.42	0.8σ

No significant incompatibility

Ordering in LBL & Reactors

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

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

- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar{\nu}_e$ disapp spectrum

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

Nunokawa,Parke,Zukanovich (2005)

$\Rightarrow$ Contribution to NO/IO from combination of LBL with reactor data

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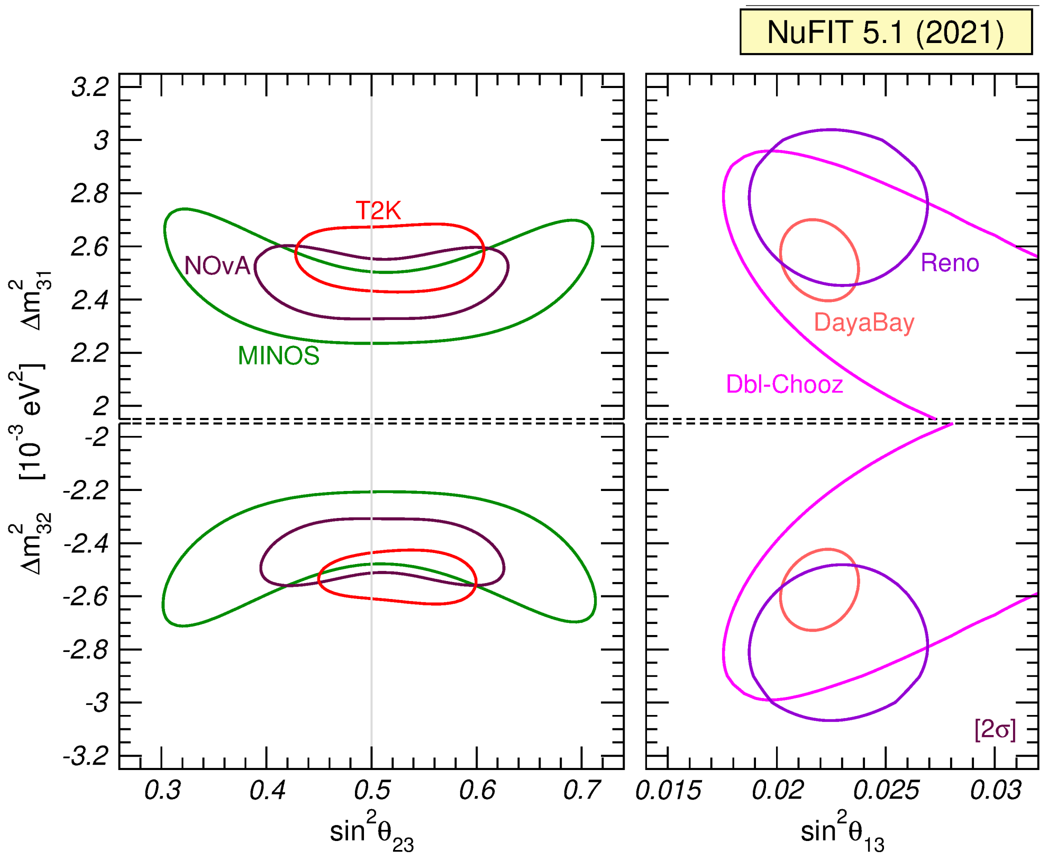

Ordering: LBL + Reactors

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

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

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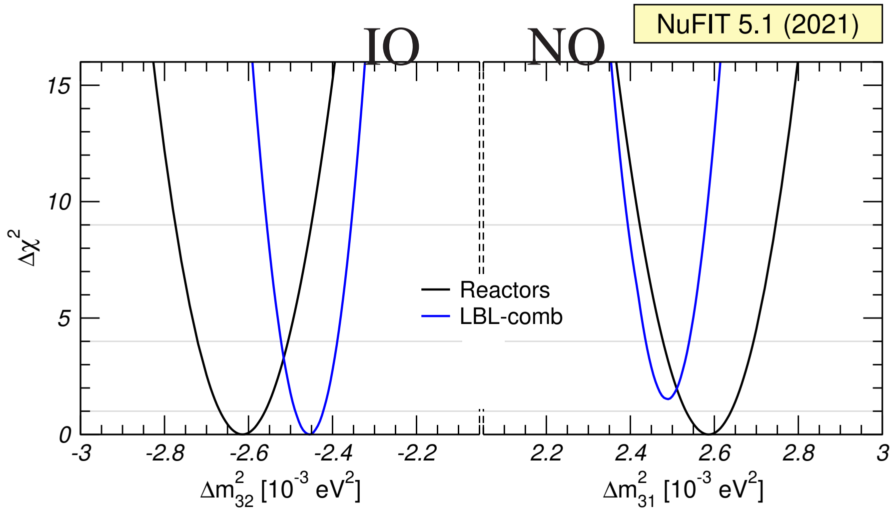

- T2K and NOνA more compatible in IO $\Rightarrow$IO best fit in LBL combination
- LBL/Reactor complementarity in $\Delta m^2_{3\ell}$ $\Rightarrow$ NO best fit in LBL+Reactors

Ordering & CPV: LBL + Reactors

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

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

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

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

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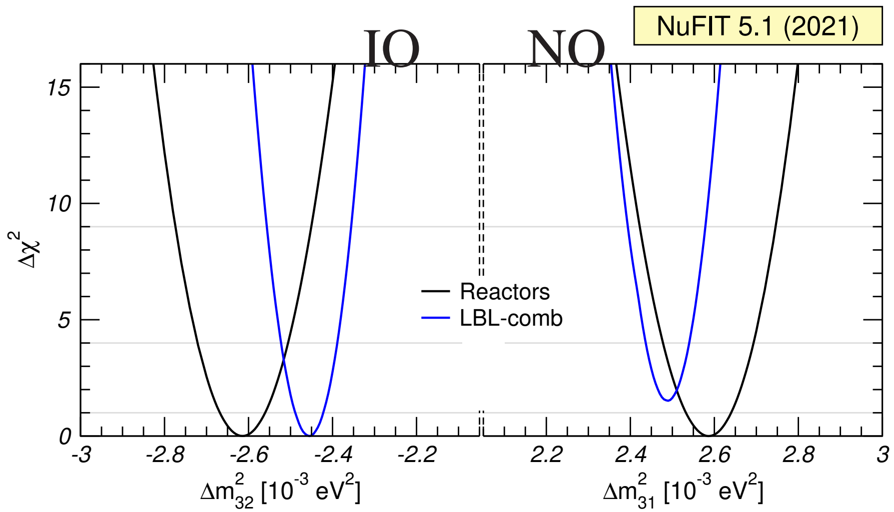
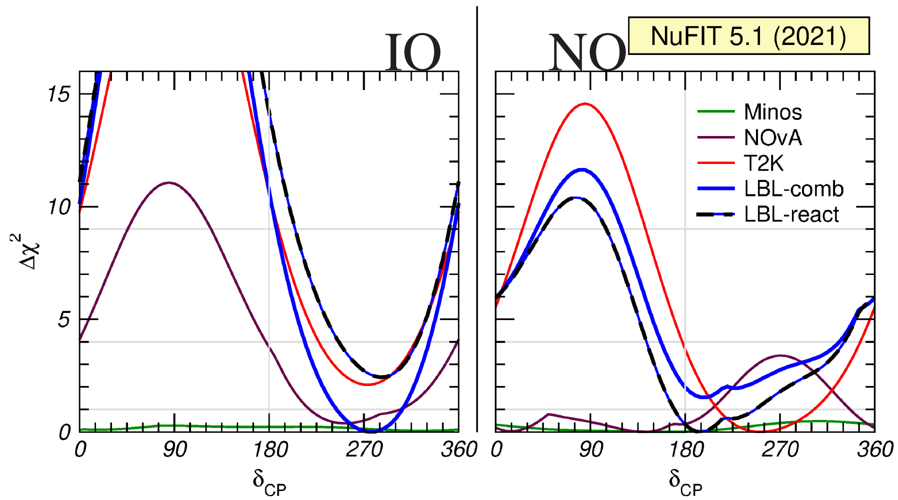


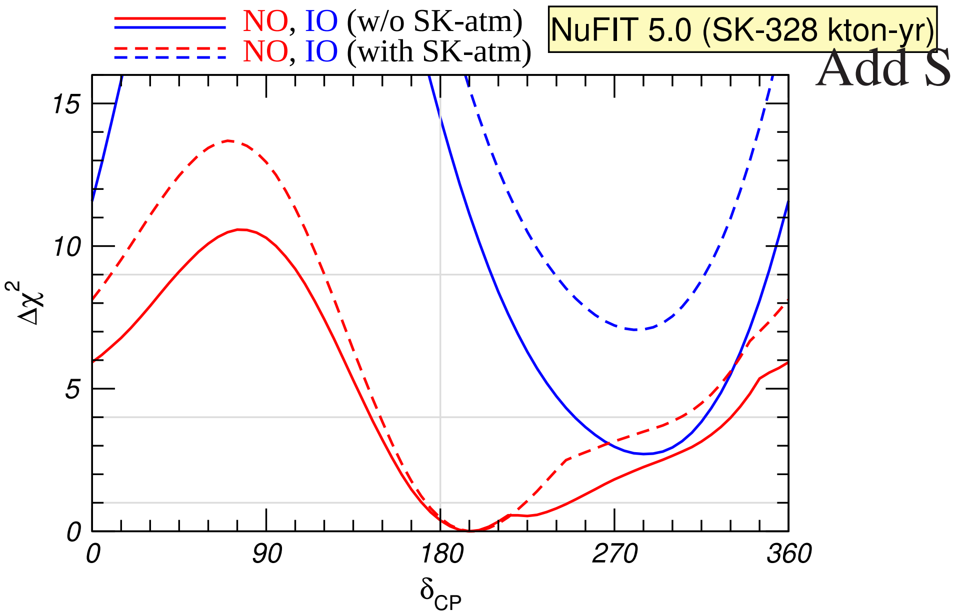


- T2K and NOνA more compatible in IO $\Rightarrow$IO best fit in LBL combination
- LBL/Reactor complementarity in $\Delta m^2_{3\ell}$ $\Rightarrow$ NO best fit in LBL+Reactors
- in NO: b.f $\delta_{CP} = 195°$ $\Rightarrow$ CPC allowed at 0.6 σ
- in IO: b.f $\delta_{CP} \sim 270°$ $\Rightarrow$ CPC disfavoured at 3 σ

Ordering & CPV including ATM

ATM results added to global fit using SK χ^2 tables

- NUFIT 5.0: included SK I-IV 328 kton-years table
- NUFIT 5.1: include SK I-IV 372.8 kton-years table



Add SK-atm table⇒ favouring of NO:

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

$$\Delta\chi^2_{\mathrm{NO-IO,with\,SK-atm}} = 7.1$$

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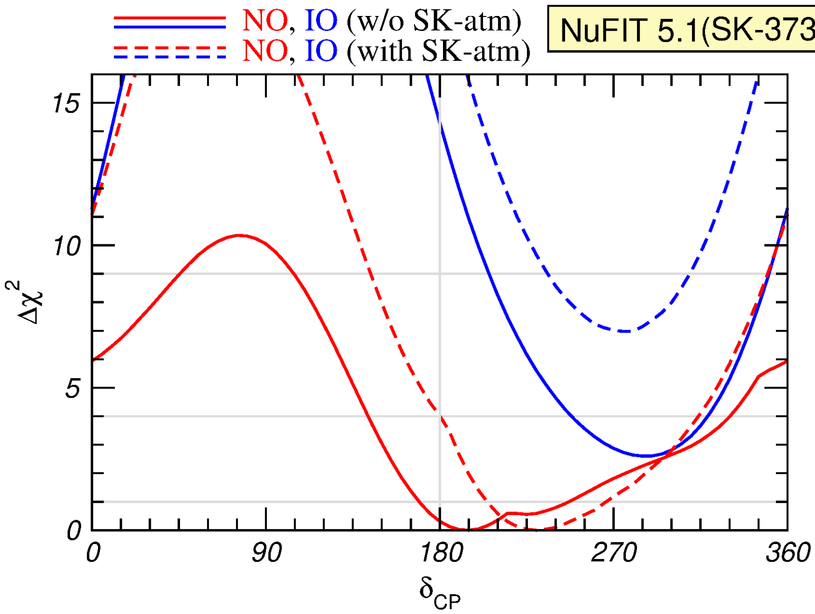

Add either SK-atm table⇒ favouring of NO:

$$\Delta\chi^2_{\mathrm{NO-IO,w/o\ SK-atm}} = 2.7$$
$$\Delta\chi^2_{\mathrm{NO-IO,with\ SK-atm}} = 7.1$$

Add new table ⇒ slight increase of significance of CPV in NO

w/o SK-Atm b.f $\delta_{\mathrm{CP}} = 195^\circ$ CPC at 0.6σ

with SK-Atm: b.f $\delta_{\mathrm{CP}} = 230^\circ$ CPC at 2σ

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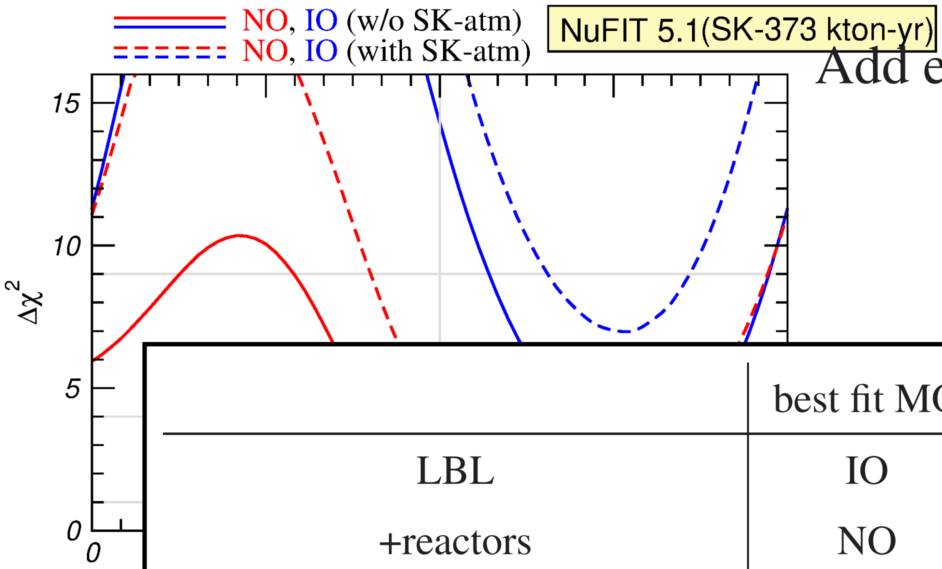

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	best fit MO	$\Delta\chi^2$(MO)	best fit δ_{CP}	$\Delta\chi^2$(CPC)	oct.θ_{23}	$\Delta\chi^2$(oct)
LBL	IO	1.5	275°	2.0	2nd	2.2
+reactors	NO	2.7	195°	0.4	2nd	0.5
+ SK-Atm 328 kt-y (NuFIT 5.0)	NO	7.1	197°	0.5	2nd	2.5
+ SK-Atm 373 kt-y (NuFIT 5.1)	NO	7.0	230°	4.0	1st	3.2

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)

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

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

  – Challenge: Parameter degeneracies, Normalization uncertainty, E_ν reconstruction

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

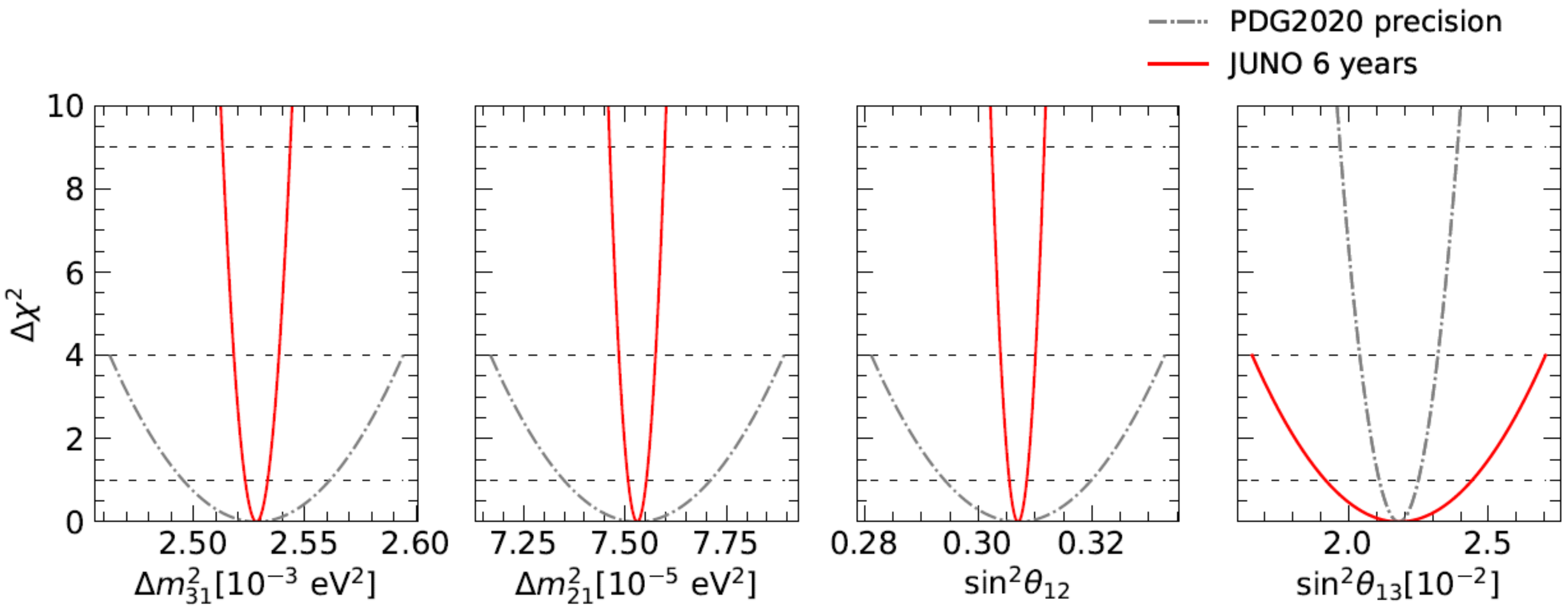
$$P_{\nu_e,\nu_e} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]$$

  – Challenge: Energy resolution/scale

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

JUNO: Sensitivity to Oscillation Parameters

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)



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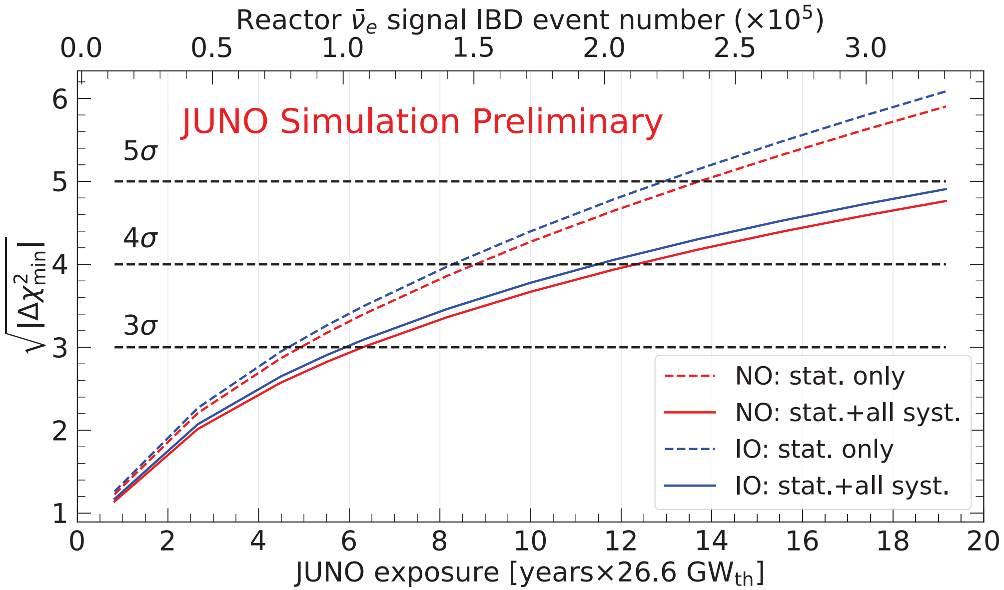
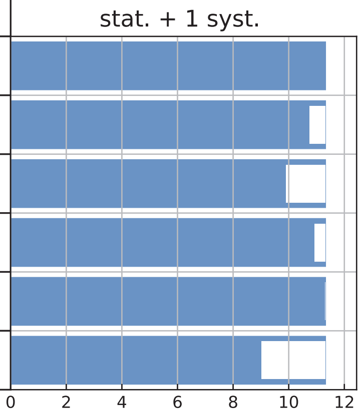
Sensitivity to Neutrino Mass Ordering



- ✓ JUNO+TAO, 6 years×26.6 GW exposure: $\sim 3\sigma$
- ✓ +1% external constrain on Δm^2_{32}: $> 4\sigma$
- ✓ combined with accelerator/atmospheric experiment: $> 5\sigma$
  ↪ sensitivity boost due to tension for wrong ordering

Impact of systematics:

	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0

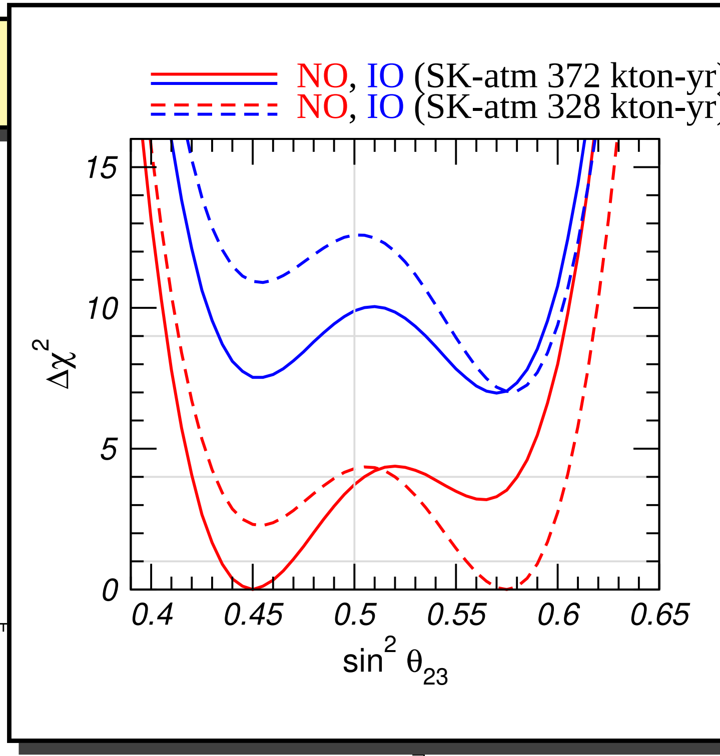


JUNO Simulation Preliminary

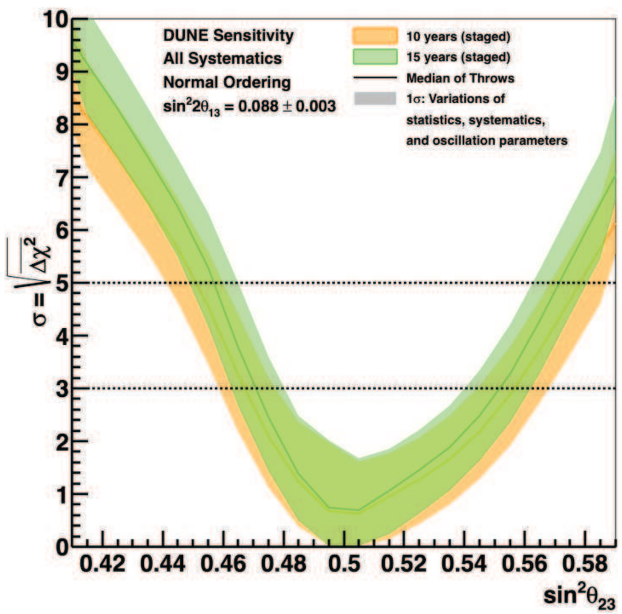
- Paper under preparation.
- Combination of reactor and atmospheric channels within JUNO is investigated.

Extra [2008.11280], JUNO+IceCube [1911.06745]

DUNE & Hyper-Kamiokande: θ_{23}

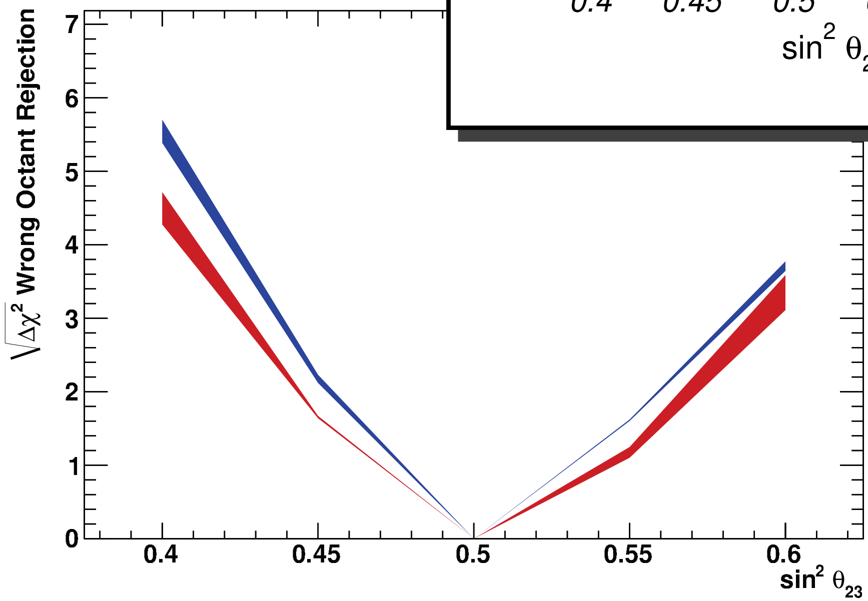


θ_{23} octant: future sensitivities



$\sim 3-5\sigma$

DUNE 2002.03005



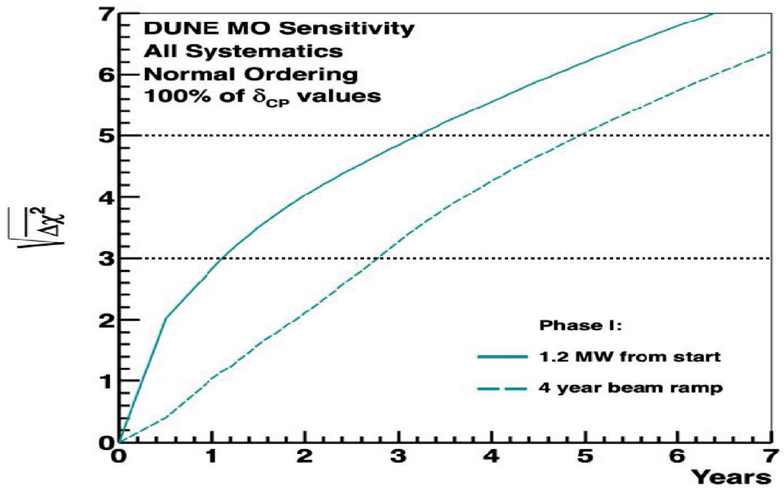
Beam+Atm$\Rightarrow\sim 3-6\sigma$

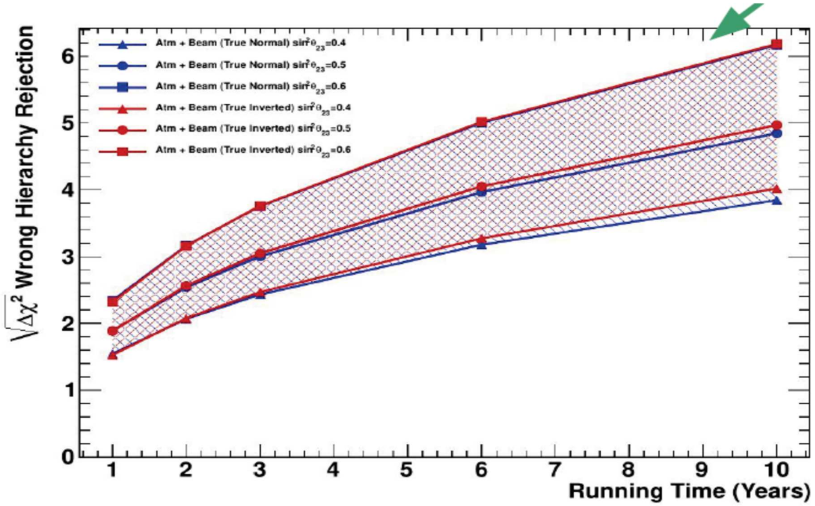
HK 1805.04163

DUNE & Hyper-Kamiokande: CPV and MO

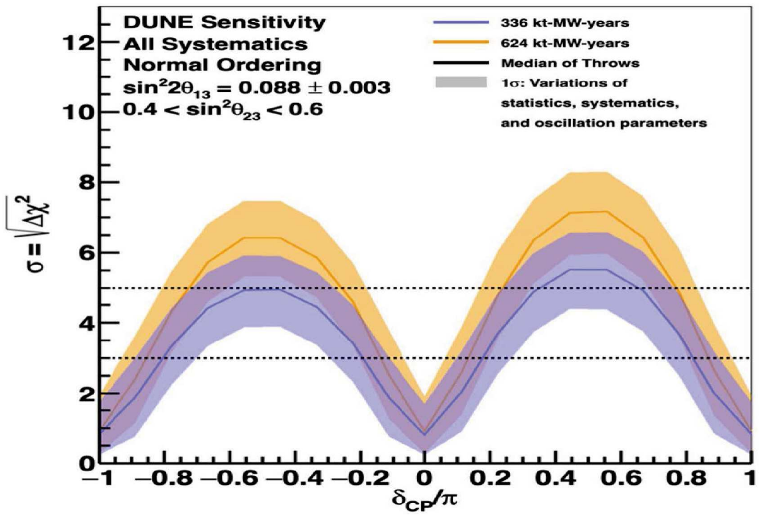
DUNE | Hyper-Kamiokande

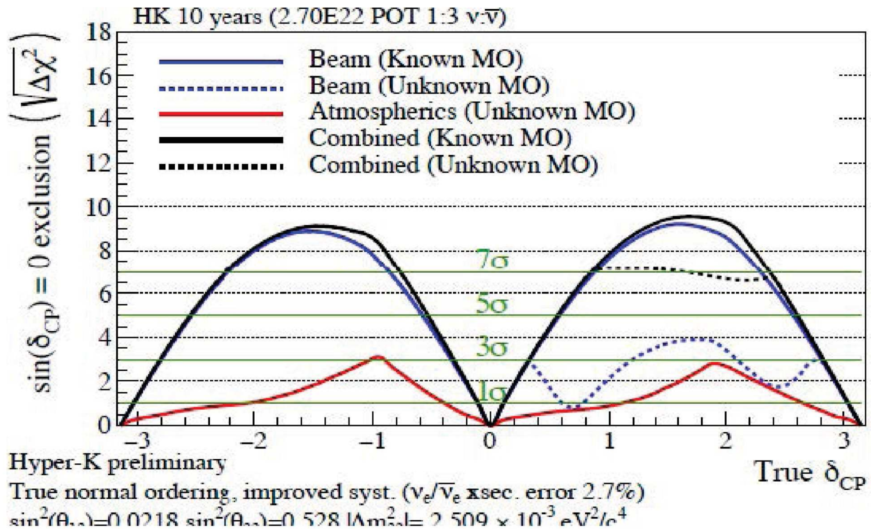
Mass Ordering





CPV





Summary

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- SM extension with additional singlets
  - Lepton-mixing Unitarity: $K_l K_l^\dagger + K_h K_h^\dagger = I_{3\times3} \Rightarrow$ *generic* relation between NHL couplings (K_h) and flavour param. and unit. violation of active ν_l (K_l)
  - Canonical see-saw: Unitarity violation in the light sector unobservably small
  - In more general see-saw-I scenarios: Experimental bounds
    $\Rightarrow$ Unitarity violation can still be ignored in present $3\nu_l$ oscillation analysis
  - Model dependent correlation between $3\nu_l$ parameters and NHL couplings
    Maximal correlation in minimal (Lepton Flavour Violating) See-saws

- Status of 3ν fit
  - Robust determination of θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$
  - Mass ordering, θ_{23} Octant, CPV depend on subdominant 3ν-effects
    $\Rightarrow$ interplay of LBL/reactor/ATM results

	best fit MO	$\Delta\chi^2$(MO)	best fit δ_{CP}	$\Delta\chi^2$(CPC)	oct.θ_{23}	$\Delta\chi^2$(oct)
LBL	IO	1.5	275°	2.0	2nd	2.2
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+ SK-Atm 373 kt-y (NuFIT 5.1)	NO	7.0	230°	4.0	1st	3.2

$\Rightarrow$ not statistically significant yet

$\Rightarrow$ definitive answer from upcoming experiments

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Summary: Global 3 ν Flavour Parameters

Evolution of global 3 flavour fit

Gonzalez-Garcia, Maltoni, TS [arXiv:2111.03086]

	2012 NuFIT 1.0	2014 NuFIT 2.0	2016 NuFIT 3.0	2018 NuFIT 4.0	2021 NuFIT 5.1	
θ_{12}	15%	14%	14%	14%	14%	**1.07**
θ_{13}	30%	15%	11%	8.9%	9.0%	**3.3**
θ_{23}	43%	32%	32%	27%	27%	**1.6**
Δm^2_{21}	14%	14%	14%	16%	16%	**0.88**
$\|\Delta m^2_{3\ell}\|$	17%	11%	9%	7.8%	6.7% [6.5%]	**2.5**
δ_{CP}	100%	100%	100%	100% [92%]	100% [83%]	**1 [1.2]**
$\Delta\chi^2_{\text{IO-NO}}$	± 0.5	-0.97	$+0.83$	$+4.7$ [$+9.3$]	$+2.6$ [$+7.0$]	

w/o [w] SK atm data

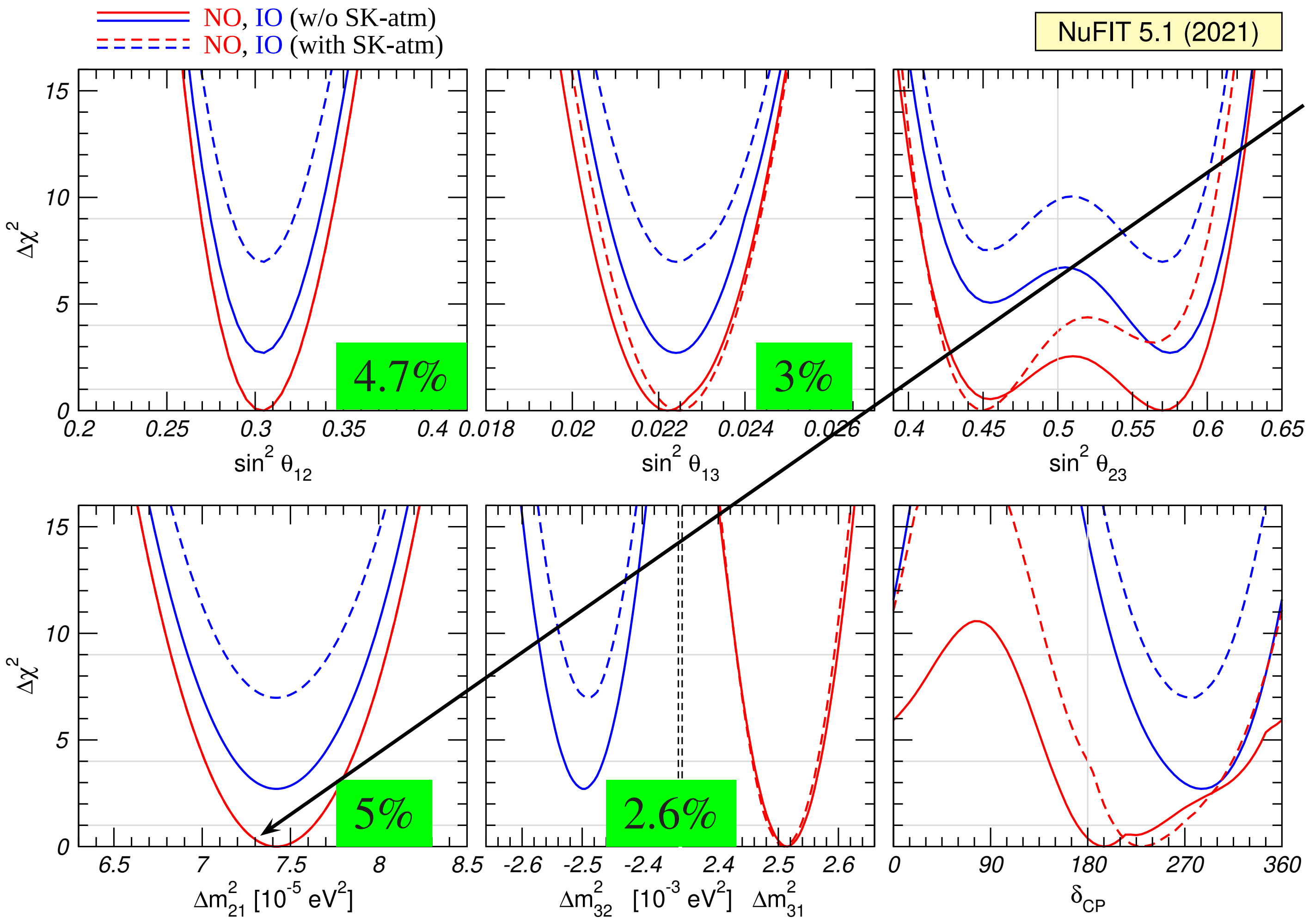
relat. precision at 3σ : $\frac{2(x^+ - x^-)}{(x^+ + x^-)}$

improvement factor from 2012 to 2021

Summary: Global 3 ν Flavour Parameters

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

Esteban, G-G, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792], G-G, Maltoni, Schwetz, 2111.03086



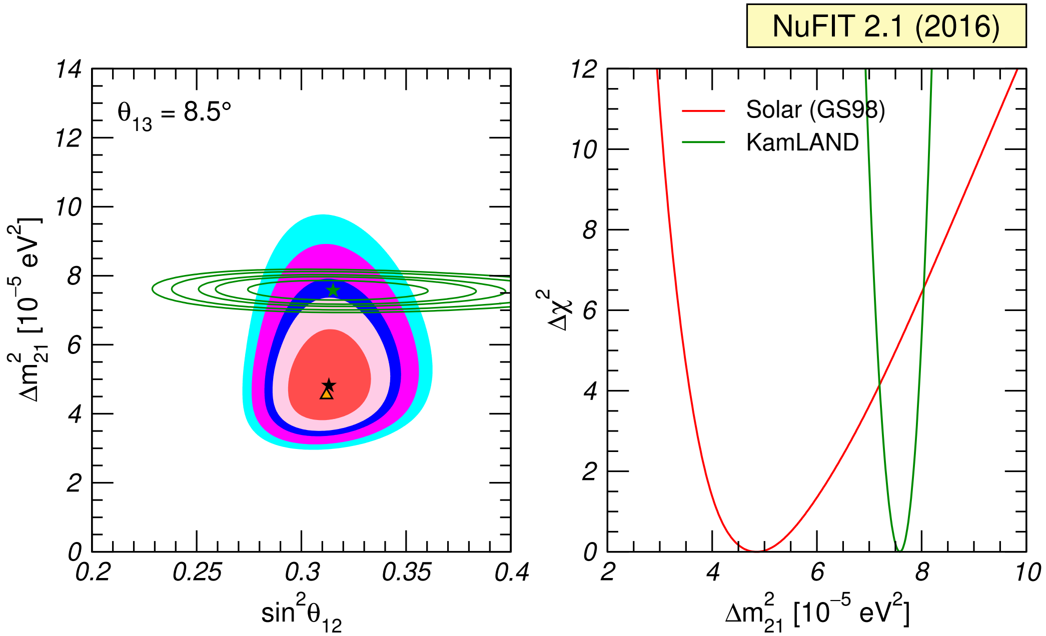
- 4 well-known parameters:

  θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$

  Δm^2_{21} Solar vs KLAND

  Tension Resolved

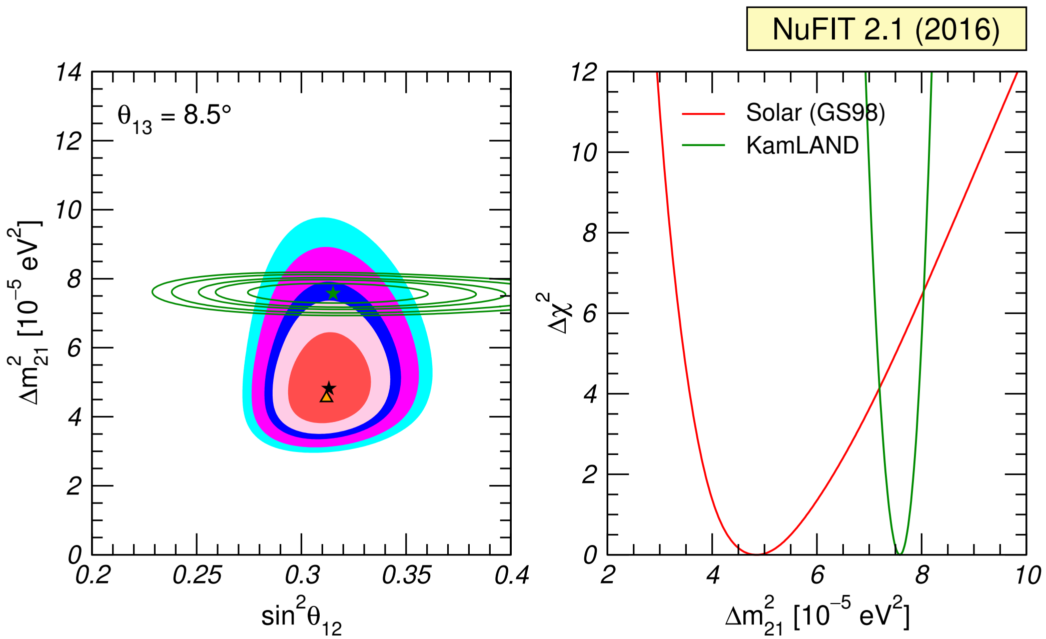
- Last decade: after including $\theta_{13} \simeq 9^\circ$ the comparison of KamLAND vs Solar



θ_{12} better than 1σ agreement

But $\sim 2\sigma$ tension on Δm^2_{12}

- Last decade: after including $\theta_{13} \simeq 9^\circ$ the comparison of KamLAND vs Solar



θ_{12} better than 1σ agreement

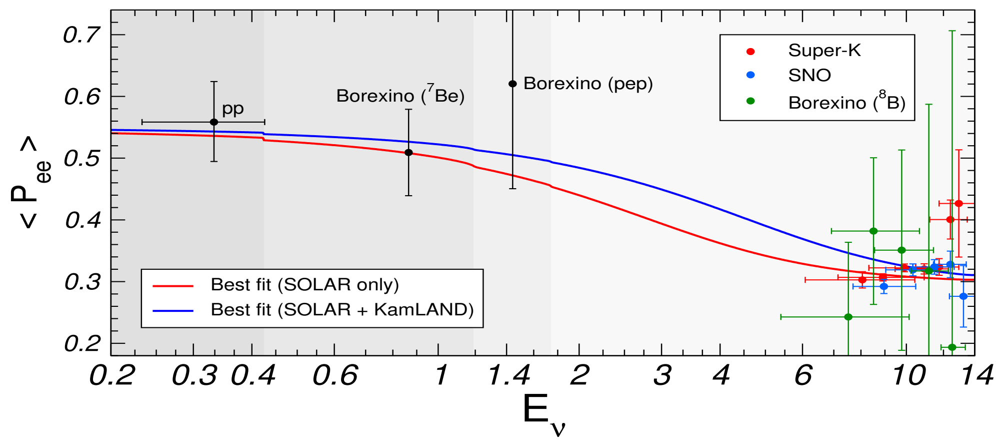
But $\sim 2\sigma$ tension on Δm^2_{12}

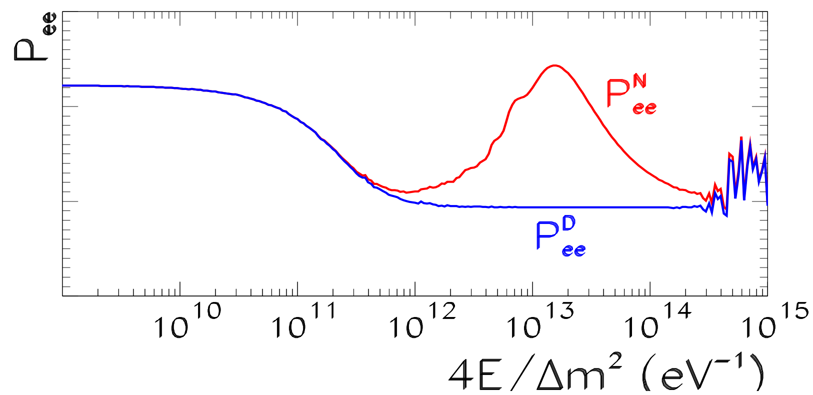
- Tension arising from:

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

"too large" of Day/Night at SK

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





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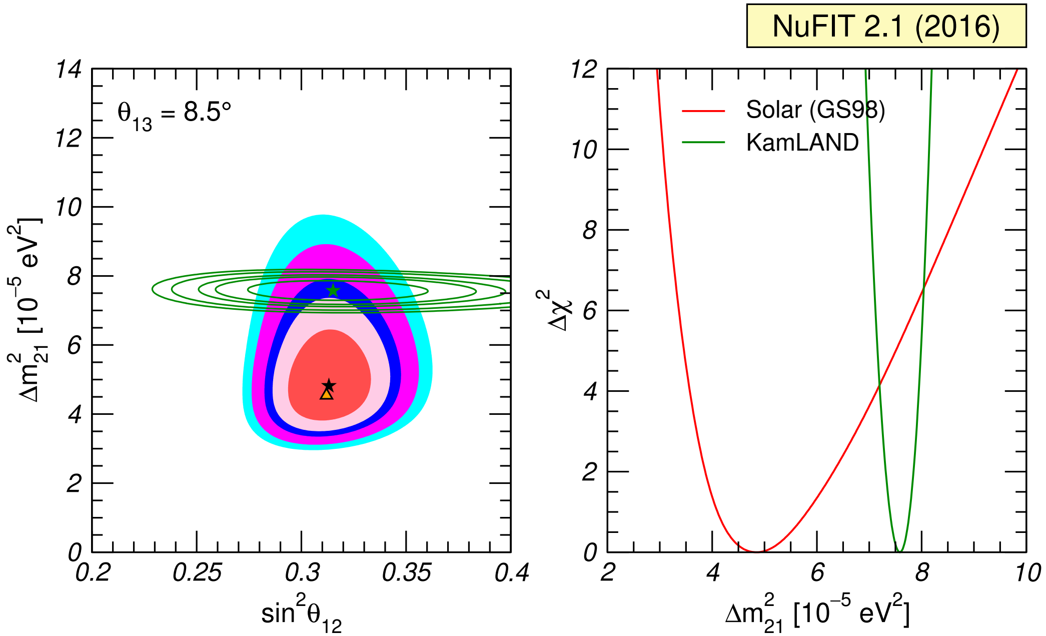

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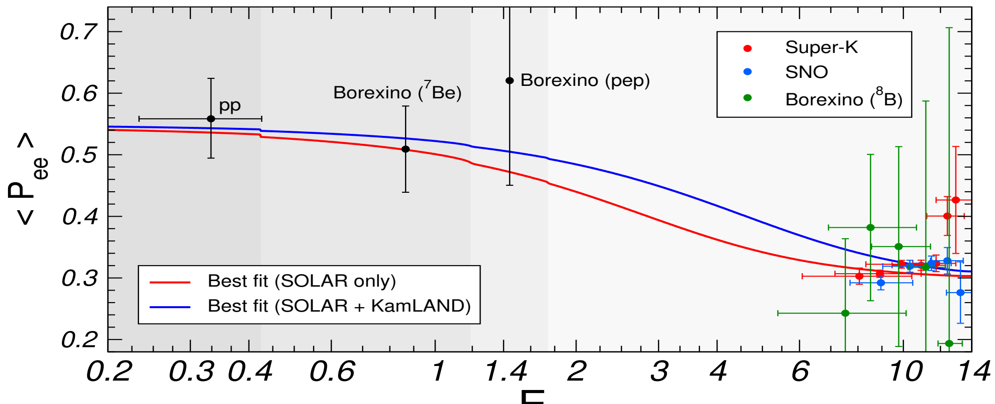
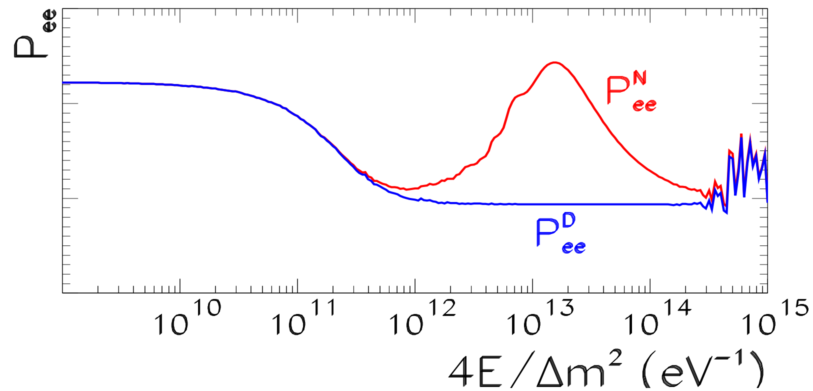
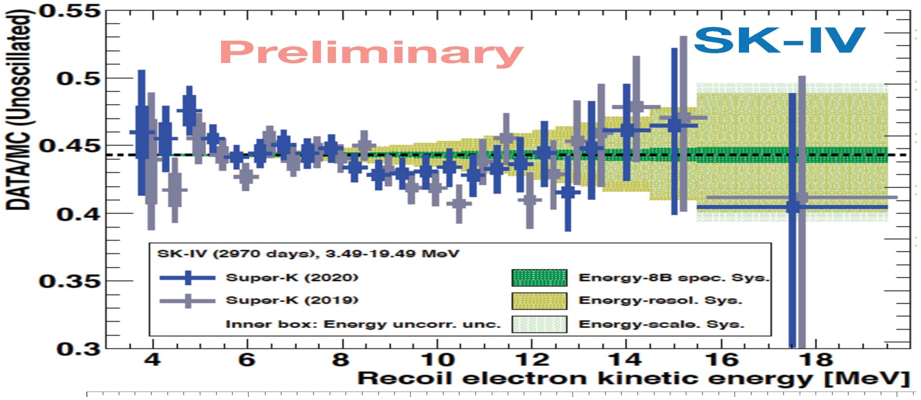




$\Rightarrow$ "hint" of NP in propagation: NSI?

- AFTER NU2020: With SK4 2970 days data

Slightly more pronounced low-E turn-up

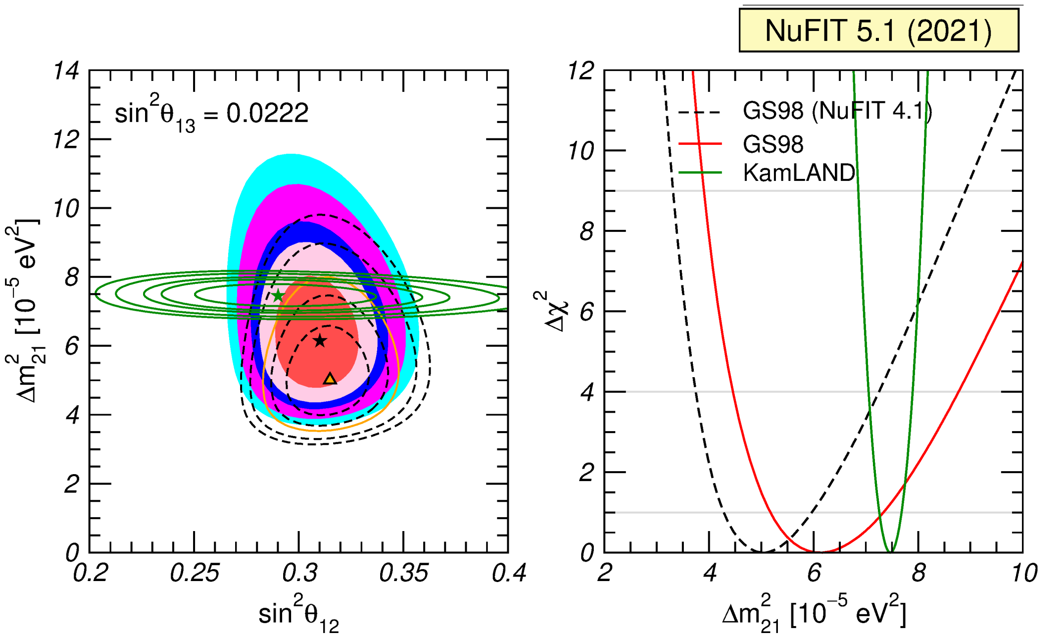


Smaller of Day/Night at

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

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

- In NuFIT 5.1

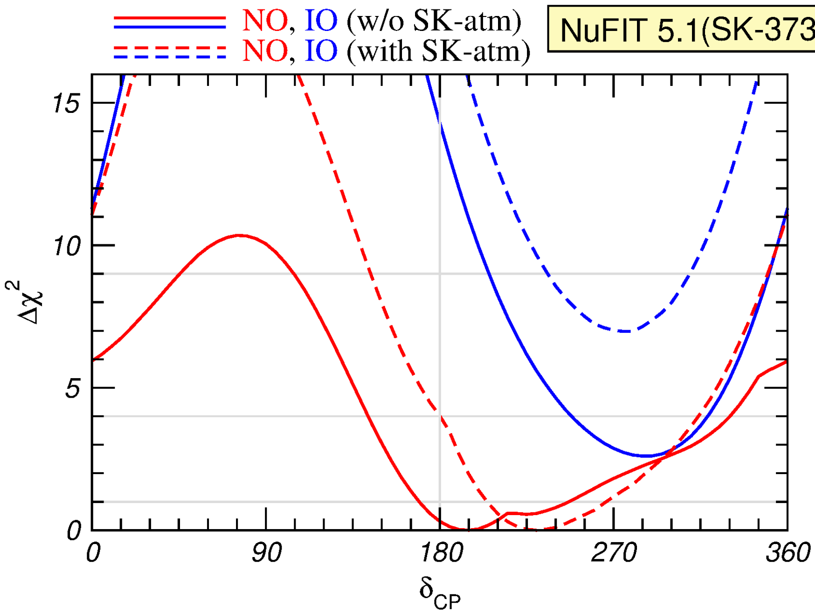


$\Rightarrow$ Agreement of Δm^2_{21} between solar and KamLAND at 1 σ

Ordering & CPV including ATM

ATM results added to global fit using SK χ^2 tables

- NUFIT 5.0: included SK I-IV 328 kton-years table
- NUFIT 5.1: include SK I-IV 372.8 kton-years table



Add either SK-atm table$\Rightarrow$ favouring of NO:

$$\Delta\chi^2_{\rm NO-IO,w/o\,SK-atm} = 2.7$$
$$\Delta\chi^2_{\rm NO-IO,with\,SK-atm} = 7.1$$

Add new table $\Rightarrow$ slight increase of significance of CPV in NO

w/o SK-Atm b.f $\delta_{\rm CP} = 195^\circ$ CPC at 0.6σ

with SK-Atm: b.f $\delta_{\rm CP} = 230^\circ$ CPC at 2σ

Ordering & CPV including ATM

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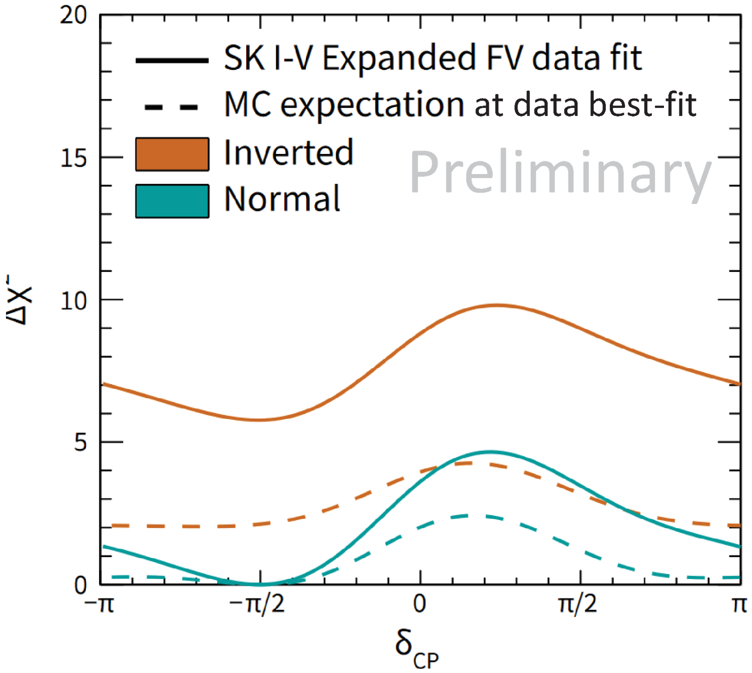
Expected impact of SK-V

(373 $\rightarrow$ 484 kt.yr)



Favouring of NO and CPV increases beyond expectation

yr)

either SK-atm table$\Rightarrow$ favouring of NO:

$$\Delta\chi^2_{\rm NO-IO,w/o\ SK-atm} = 2.7$$
$$\Delta\chi^2_{\rm NO-IO,with\ SK-atm} = 7.1$$

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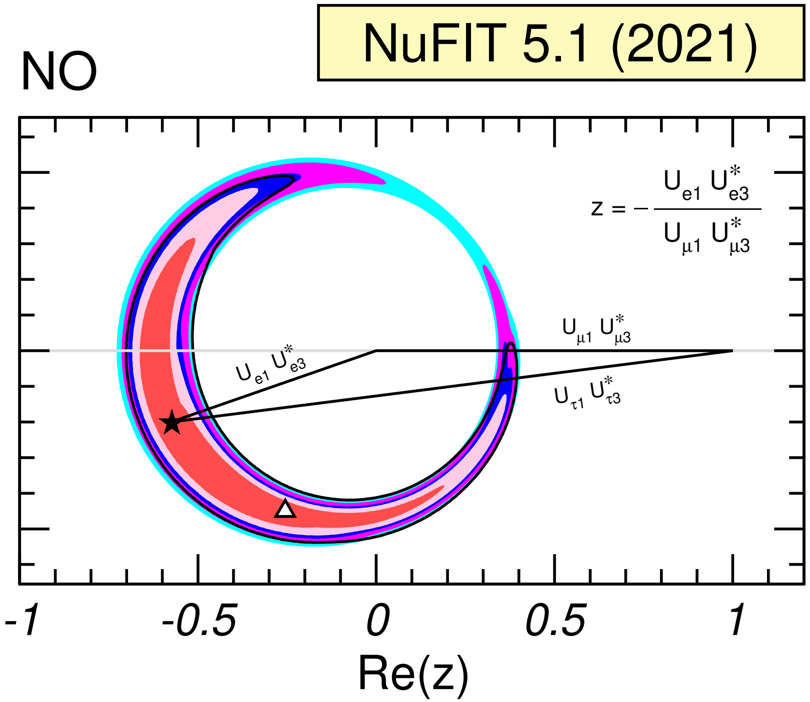
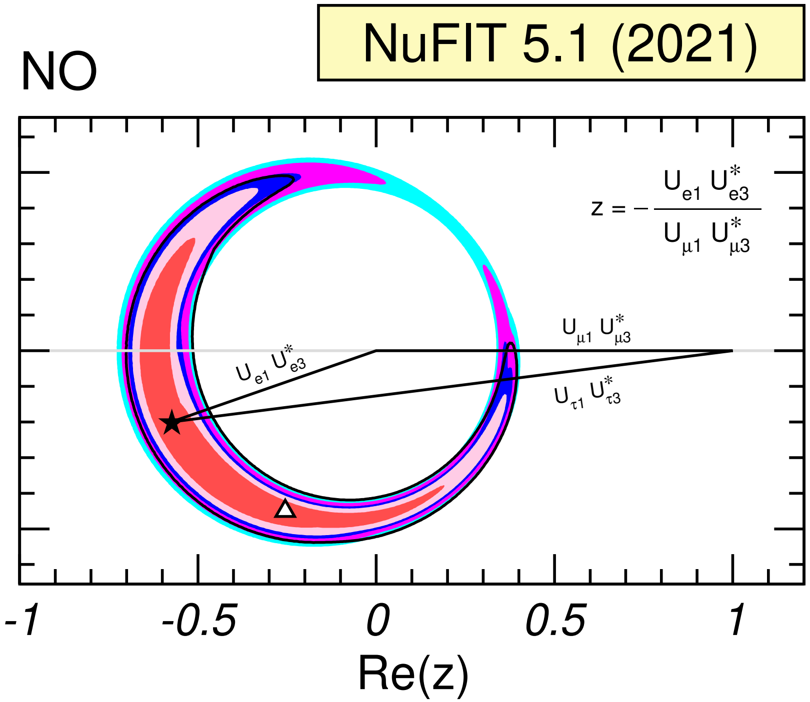
3ν Mixing: Leptonic Unitarity Triangle

Unitarity triangle in lepton sector

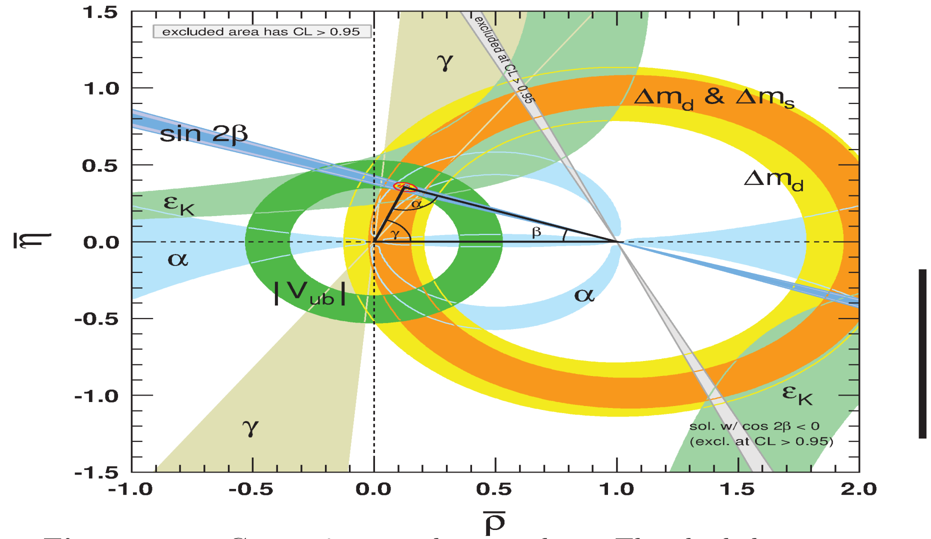


3ν Mixing: Leptonic Unitarity Triangle

Unitarity triangle in lepton sector

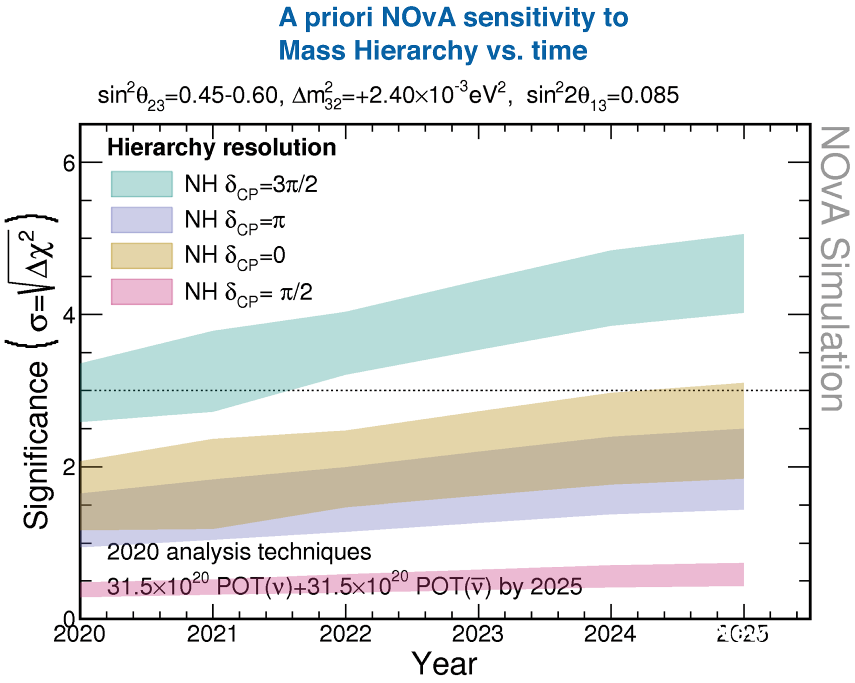


The equivalent in the quark sector



"Near Future" for CPV and Ordering

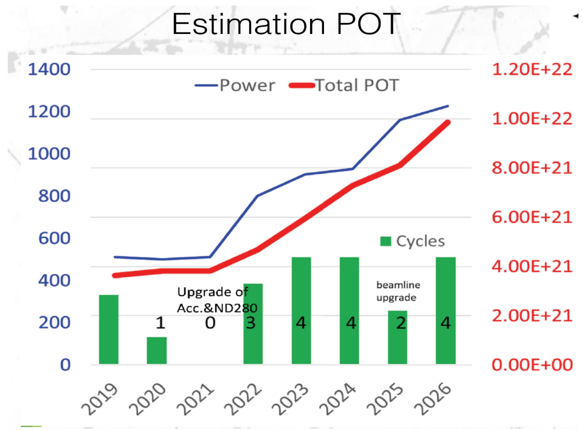
NOνA: Ordering

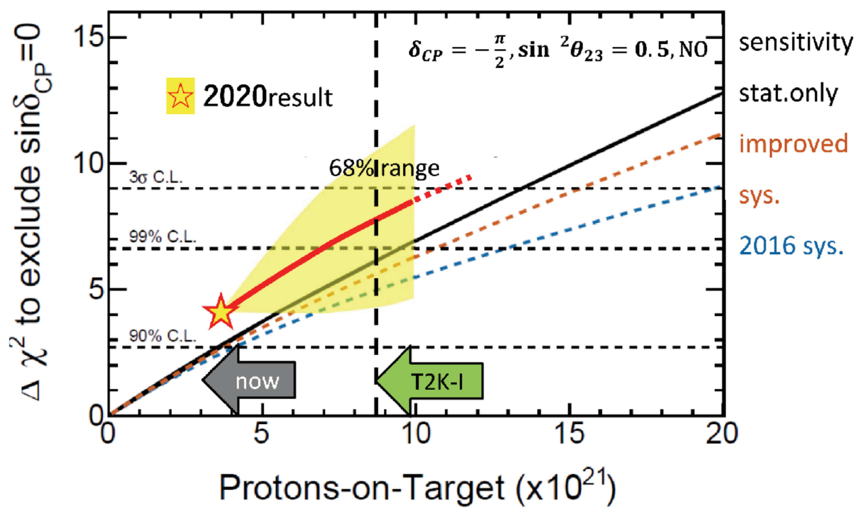


NOvA reaches 3 sigma sensitivity for between 30% and 50% of δ_{CP} values, depending on MH and $\sin^2(\theta_{23})$

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.

From F.Sanchez snowmass talk