Determination of the θ_{23} octant within and beyond the Standard Model

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Physics of Fundamental Interactions

Neutrino Physics Parallel Sessions
15:15 - 15:30, 8th June, 2017

NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

Some open questions

- What is the order of neutrino masses?
- Is there CP violation among neutrinos?
- Which octant does θ_{23} belong to?

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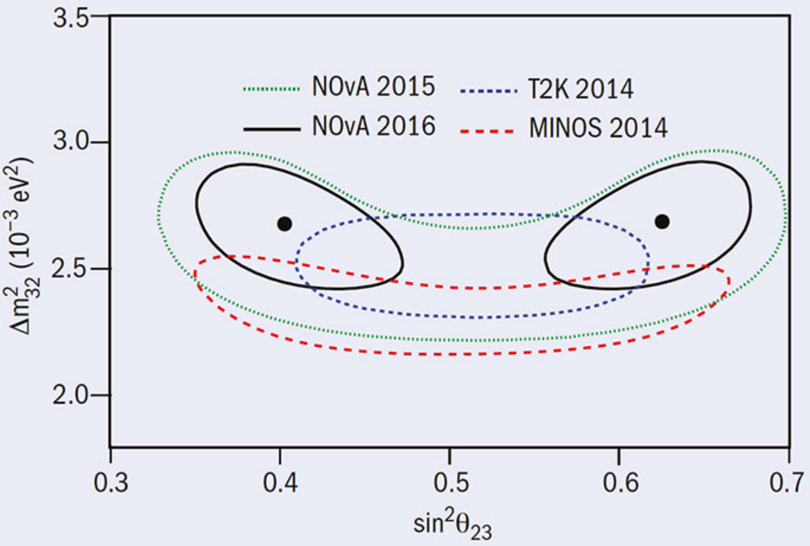

What we say!

- Standard Model is one of the most successful stories in particle physics.
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Some other open questions

- Why are neutrino masses so small?
- Why are CP and P violated?
- Why do we have anomalies in the reactor, gallium and short-baseline data?

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.... beyond Standard Model physics is needed!

Beyond the Standard Model

Most attempts to find answer to the origin of the neutrino masses involve:

- Sterile neutrinos
- Non-standard interactions
- Majorana nature of neutrino

In case of one sterile neutrino

$$U_{4\times4} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

the 3×3 matrix is no longer unitary.

Nonunitary mixing

- A convenient way to parameterize nonunitarity:

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} \times U_{PMNS}$$

$$H = \frac{1}{2E_\nu} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}$$

$$+ \quad N^\dagger \times \begin{pmatrix} V_{CC} + V_{NC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix} \times N$$

F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola and J.W.F. Valle,
Phys. Rev. **D92**, 053009 (2015) and arXiv:1612.07377.

- Nonunitary mixing bounds:
  (Example from Escrihuela et al.)

Nonunitary parameter	Bound at 90% C.L.
α_{11}	0.9974
α_{22}	0.9994
α_{33}	0.9988
$\|\alpha_{21}\|$	2.6×10^{-2}
$\|\alpha_{31}\|$	2.0×10^{-3}
$\|\alpha_{32}\|$	1.5×10^{-2}

Nonunitary mixing

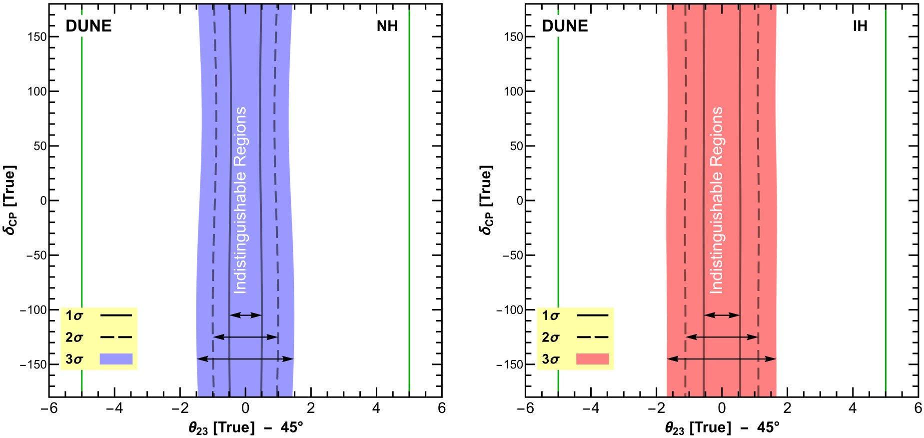
- Another way to parameterize nonunitarity:

$$H = \frac{1}{2E_\nu}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} + \frac{V_{CC}}{2} U^\dagger \times \begin{pmatrix} 2-2\alpha_{ee} & \alpha^*_{\mu e} & \alpha^*_{\tau e} \\ \alpha_{\mu e} & 2\alpha_{\mu\mu} & \alpha^*_{\tau\mu} \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 2\alpha_{\tau\tau} \end{pmatrix} \times U$$

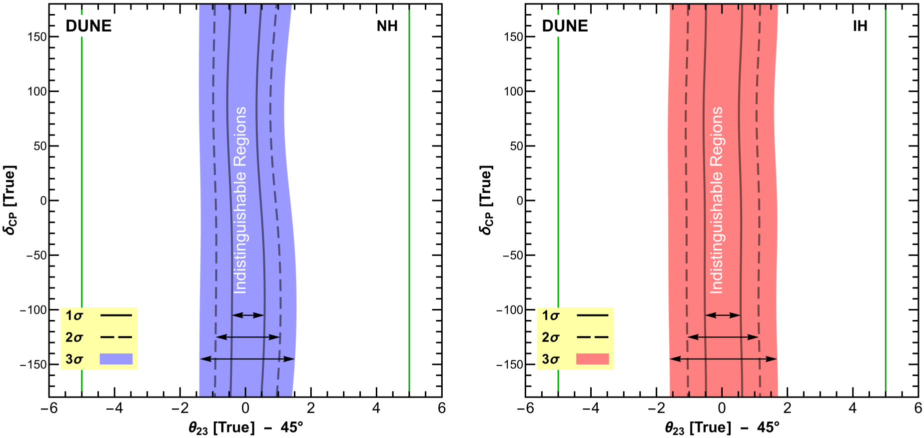
M. Blennow, P. Coloma, E. Fernandez-Martinez, J. Hernandez-Garcia and J. Lopez-Pavon, J. High Energ. Phys. **04**, 153 (2017).

- Both notations are equivalent when calculating the Hamiltonian and oscillation probabilities.

Standard Model case (3 active neutrinos and nothing else)



Nonunitary mixing (3 active and 3 sterile neutrinos, Blennow et al. bound)



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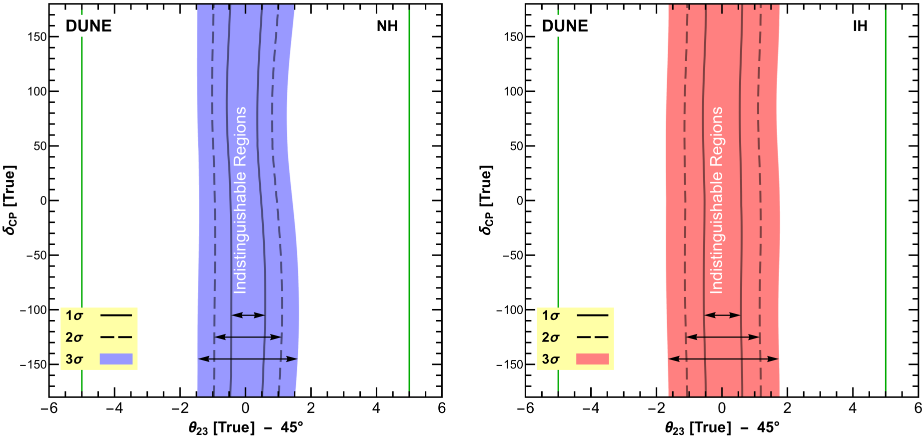
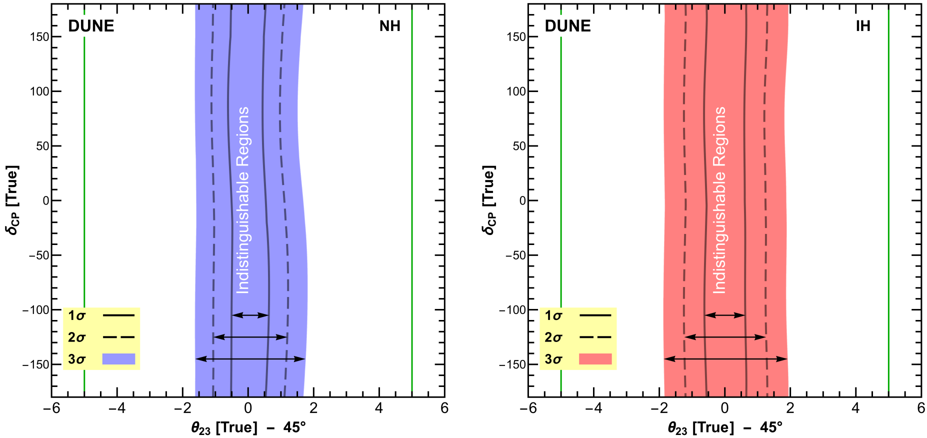
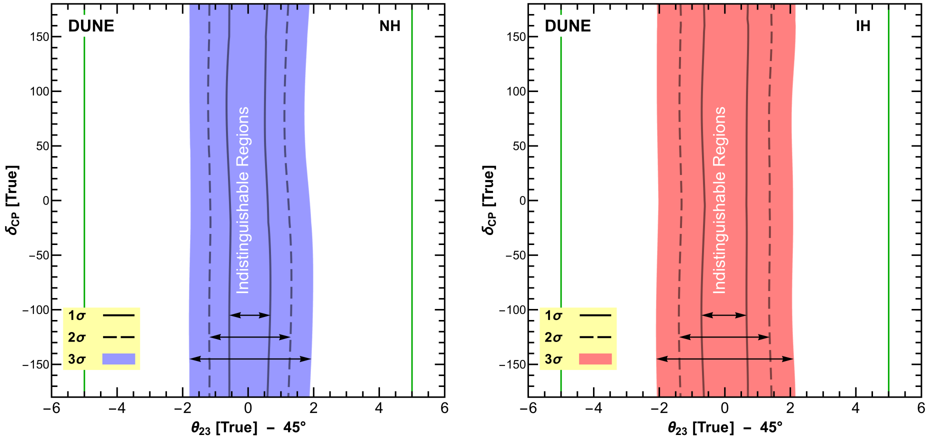


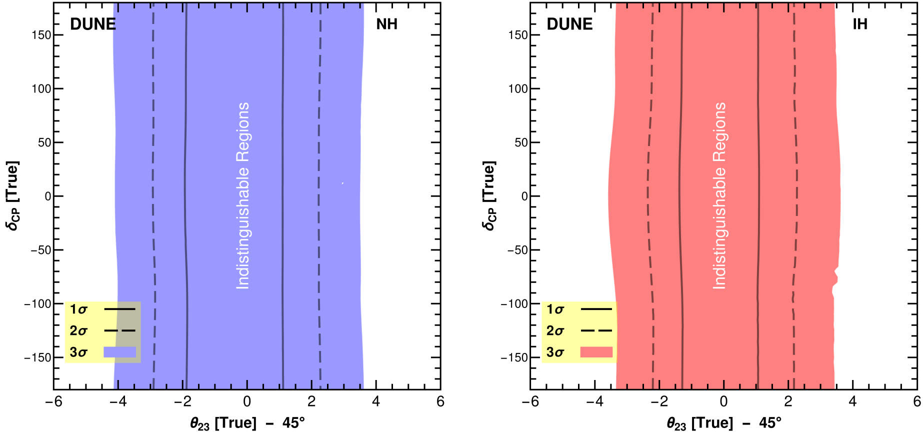
Light sterile neutrino
(3 active and 3 sterile neutrinos,
$0.1\ \text{eV}^2 < \Delta m_{41}^2 < 1\ \text{eV}^2$, Blennow et al. bound)



Light sterile neutrino
(3 active and 3 sterile neutrinos,
$\Delta m^2_{41} > 100$ eV^2, Blennow et al. bound)



Nonunitary mixing
(Unconstrained αs)



$|\alpha_{21}|$ dependency plot