Beyond the Standard Model and neutrino precision test

C.R. Das, J. Maalampi, J. Pulido and S. Vihonen

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“Modern Problems in Nuclear and Elementary Particle Physics”
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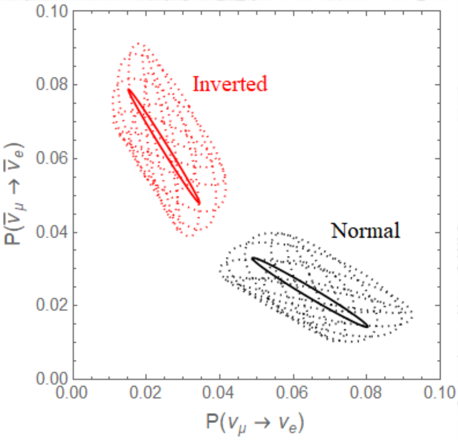
Although neutrinos are among the most abundant particles in the Universe, many of their basic properties are still unknown.

Gossip in the corridor

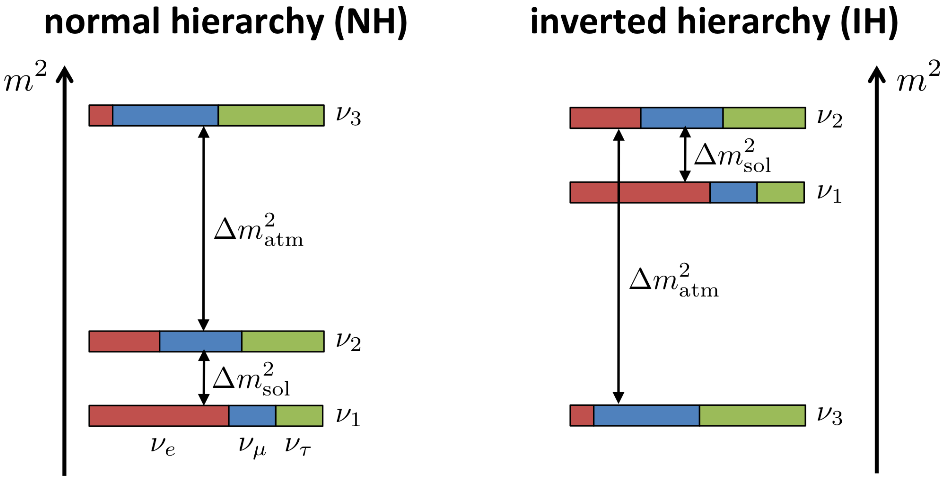
Neutrinos may have tipped the balance in favour of matter over anti-matter in the Universe!



Detecting CP Violation in the Presence of Non-Standard Neutrino Interactions, Jeffrey M. Hyde (Goucher Coll.), arXiv: 1809.11128

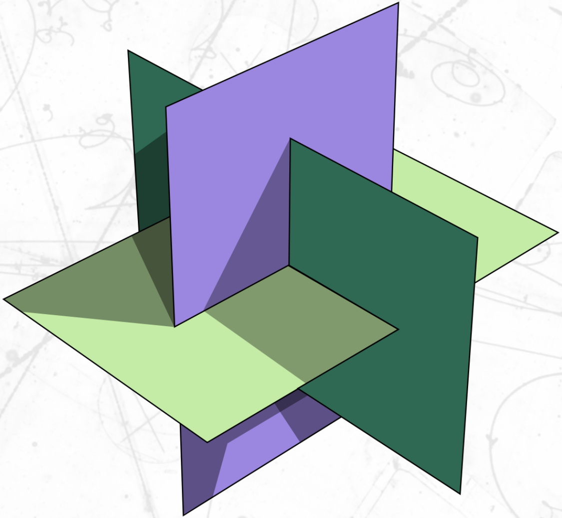
Gossip in the corridor

Which one is heaviest ν_2 or ν_3?



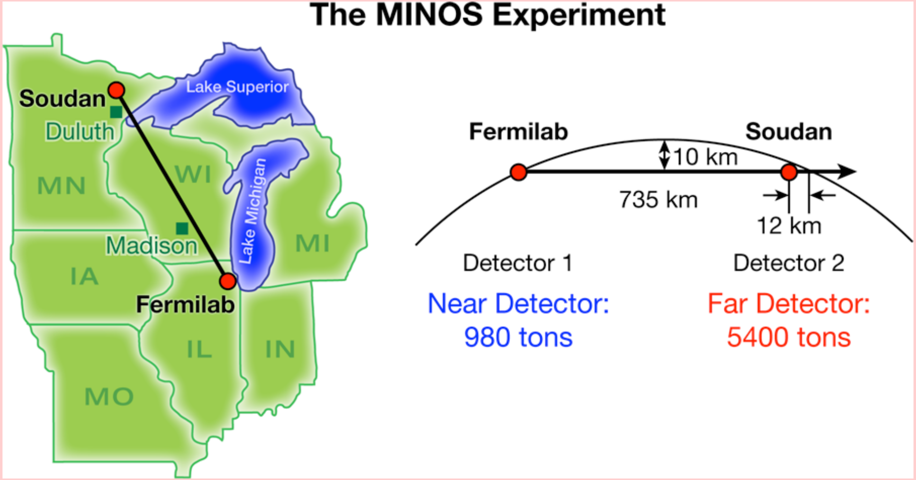
No gossip in the corridor

In which octant θ_{23} is sitting?



Preliminaries (Physics with long baseline)

MINOS and MINOS+ (Main injector neutrino oscillation search)



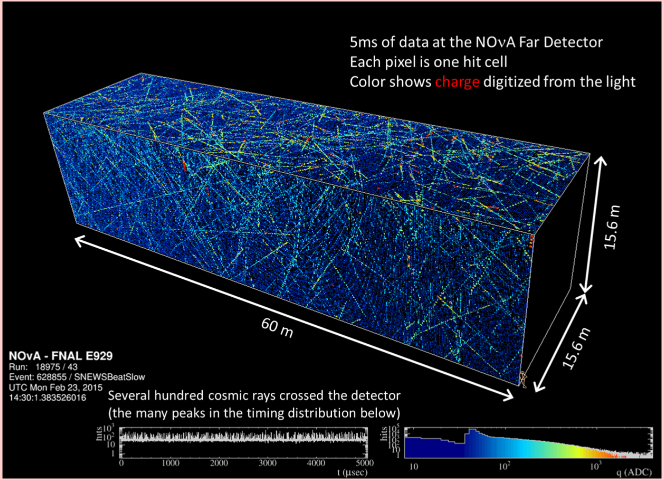
Preliminaries (Physics with long baseline)

MINOS, MINOS+ and NOvA

Cross section of the earth showing Fermilab, MINOS and NOvA, to scale.
The red line is the central axis of the NuMI beam.

Preliminaries (Physics with long baseline)

NOvA (NuMI Off-Axis ν_e Appearance)

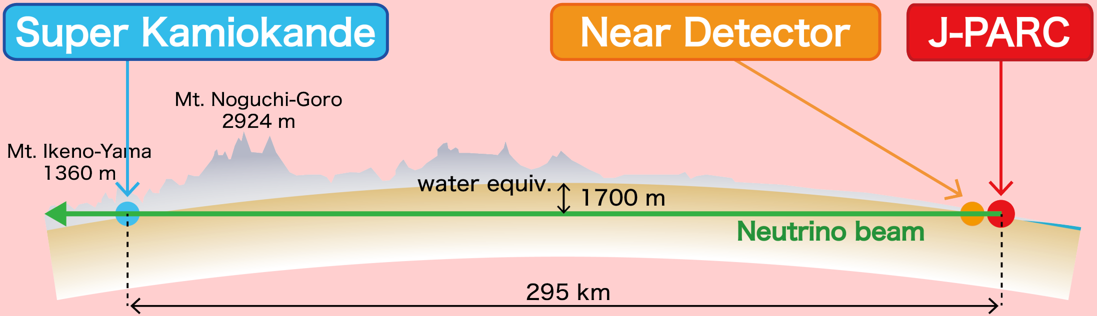


Preliminaries (Physics with long baseline)

NOvA (NuMI Off-Axis ν_e Appearance)

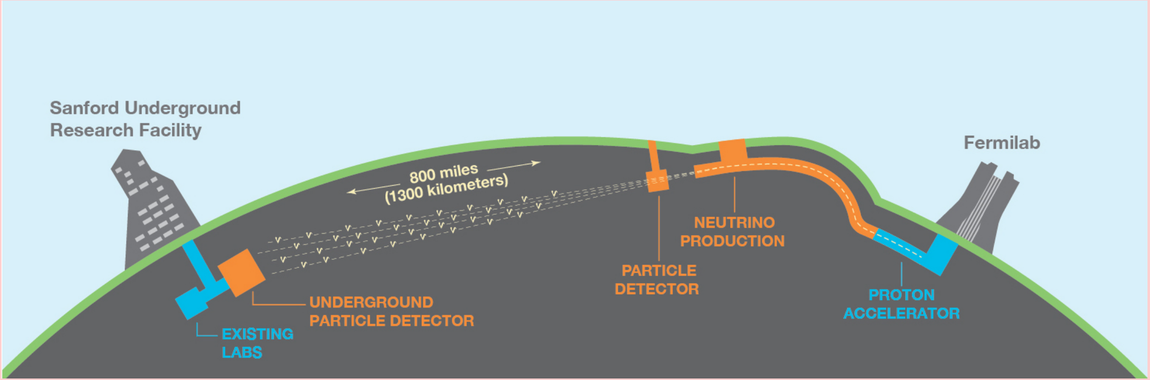
Preliminaries (Physics with long baseline)

T2K (Tokai to Kamioka, Japan)



Preliminaries (Physics with long baseline)

DUNE (Deep Underground Neutrino Experiment)



	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
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$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
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NuFIT 3.2 (2018)

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- Is there any CP violation among neutrinos?
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- Which octant does θ_{23} belong to?

The problem of θ_{23} octant

The conversion probability formula is given by:

$$\begin{aligned}
P_{\mu e} \quad \approx \quad & \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\frac{\sin^2(\Delta_{31}-a\,L)}{(\Delta_{31}-a\,L)^2}\,\Delta_{31}^2 \\
& + \sin 2\theta_{23}\,\sin 2\theta_{13}\,\sin 2\theta_{12}\,\frac{\sin(\Delta_{31}-a\,L)}{\Delta_{31}-a\,L}\,\Delta_{31} \\
& \times \frac{\sin(a\,L)}{a\,L}\,\Delta_{21}\,\cos(\Delta_{31}+\delta_{\mathrm{CP}}) \\
& + \cos^2\theta_{23}\,\sin^2 2\theta_{12}\,\frac{\sin^2(a\,L)}{(a\,L)^2}\,\Delta_{21}^2,
\end{aligned}$$

where $\Delta_{ij} = \frac{L\,\Delta m_{ij}^2}{4\,E}$ and $a = \frac{G_F\,N_e}{\sqrt{2}}$.

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Tests of three-flavour mixing in long-baseline neutrino oscillation experiments, G.L. Fogli and E. Lisi, Phys. Rev. D **54**, 3667-3670 (1996); arXiv: hep-ph/9604415

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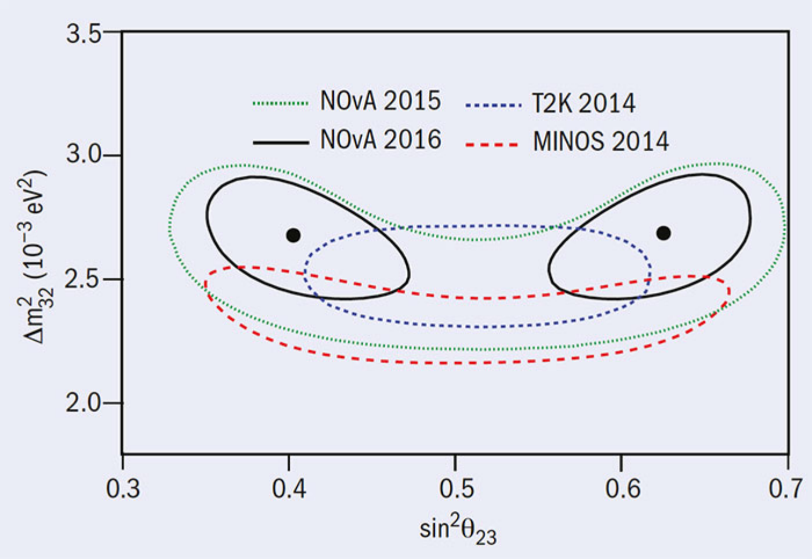

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P.F. de Salas, S. Gariazzo, O. Mena, C.A. Ternes and M. Tórtola,
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The hint of normal hierarchy suggests the atmospheric mixing angle might reside in the high octant.

- I. Esteban, M.C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni and T. Schwetz, JHEP **01**, 106 (2019); arXiv: 1811.05487

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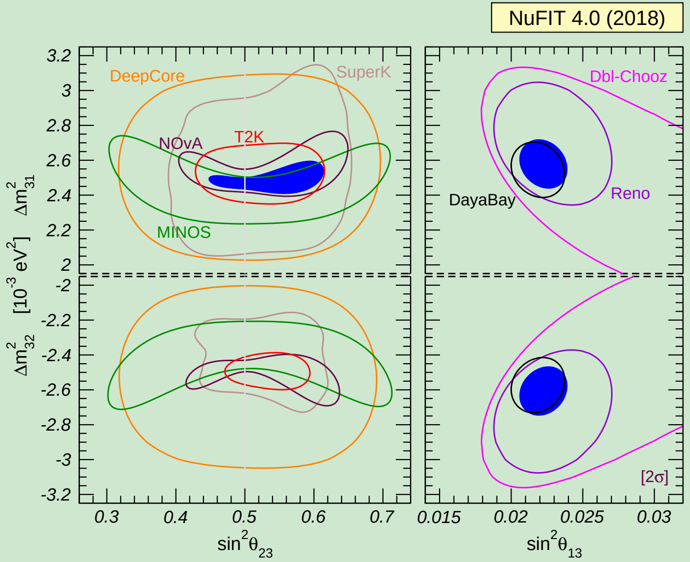

Matter effects and octant determination

Matter effects revisited:

$$
\begin{aligned}
P^m_{\mu\mu} \approx\ & 1 - \cos^2\theta^m_{13}\,\sin^2 2\theta_{23}\,\sin^2\left(C\,\frac{L}{E}\left(\frac{\Delta m^2_{31} + A + (\Delta m^2_{31})_m}{2}\right)\right) \\
& - \sin^2\theta^m_{13}\,\sin^2 2\theta_{23}\,\sin^2\left(C\,\frac{L}{E}\left(\frac{\Delta m^2_{31} + A - (\Delta m^2_{31})_m}{2}\right)\right) \\
& - \sin^4\theta_{23}\,\sin^2 2\theta^m_{13}\,\sin^2\left(C\,\frac{L}{E}\,(\Delta m^2_{31})_m\right),
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where $A = 2\,E\,V$, $C = 1.27$ and $V = 2\sqrt{2}\,G_F\,N_e$.

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$$(\Delta m^2_{31})_m = \sqrt{(\Delta m^2_{31}\ \cos 2\theta_{13} - A)^2 + (\Delta m^2_{31}\ \sin 2\theta_{13})^2},$$

$$\sin 2\theta^m_{13} = \frac{\Delta m^2_{31}}{(\Delta m^2_{31})_m}\ \sin 2\theta_{13},$$

and

$$\cos 2\theta^m_{13} = \frac{\Delta m^2_{31}}{(\Delta m^2_{31})_m}\,(\cos 2\theta_{13} - A).$$

Matter effects and octant determination

Matter effects revisited:

Neglecting the last term, this expression is also octant-degenerate:

$$P^m_{\mu\mu}(\theta_{23}) = P^m_{\mu\mu}(\pi/2 - \theta_{23})$$

- The $P^m_{\mu\mu}$ expression derived for the survival probability, given here, does have a subleading term (the last term) that is octant sensitive, however.
- This term is also subject to matter resonant effects, and therefore could also contribute to the determination of the θ_{23} octant.

Matter effects and octant determination

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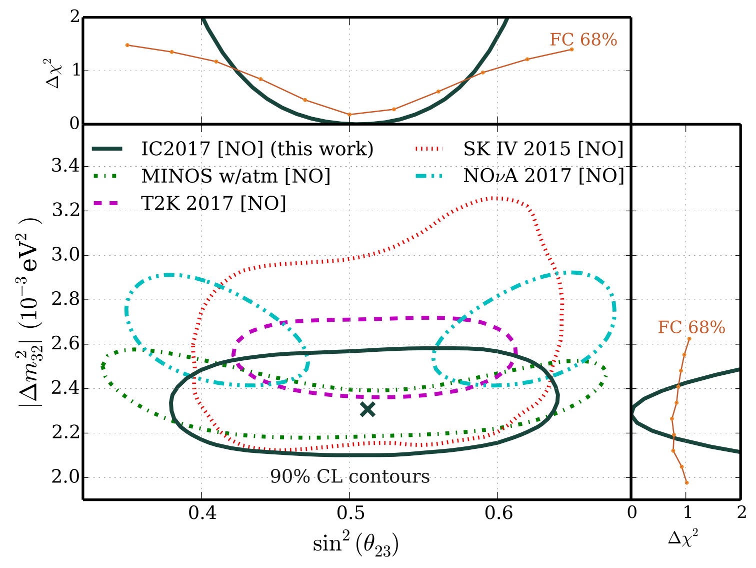
- C.R. Das, J. Maalampi, J. Pulido and S. Vihonen, J. Phys.: Conf. Ser. **888**, 012219 (2017); arXiv: 1606.02504

- A. Chatterjee, P. Ghoshal, S. Goswami and S.K. Raut, JHEP **1306**, 010 (2013); arXiv: 1302.1370

This is Shrek!



How to free octants from its clutch!

Simulation examples:

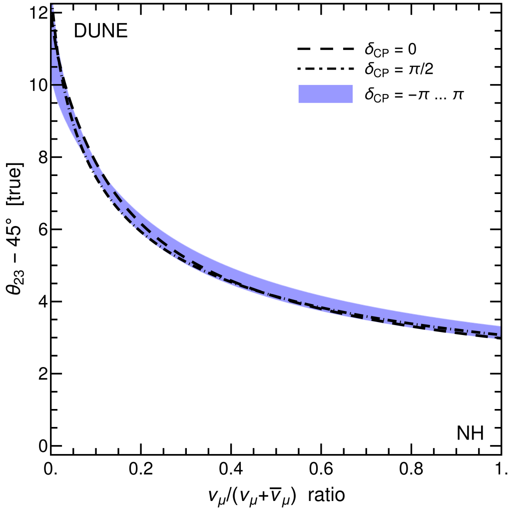
DUNE

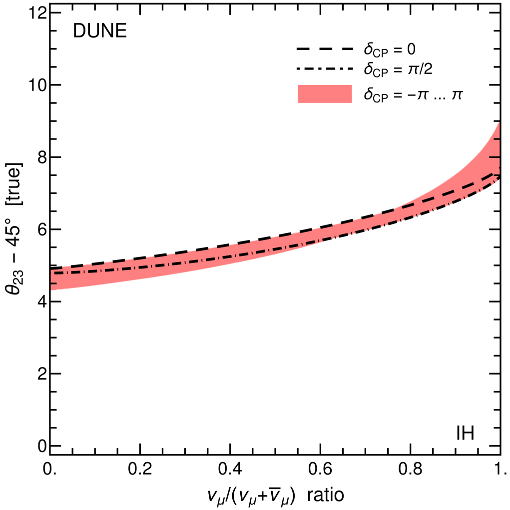
1. 1300 km baseline
2. oscillation maximum at ~ 2 GeV
3. wide-band beam

T2HK

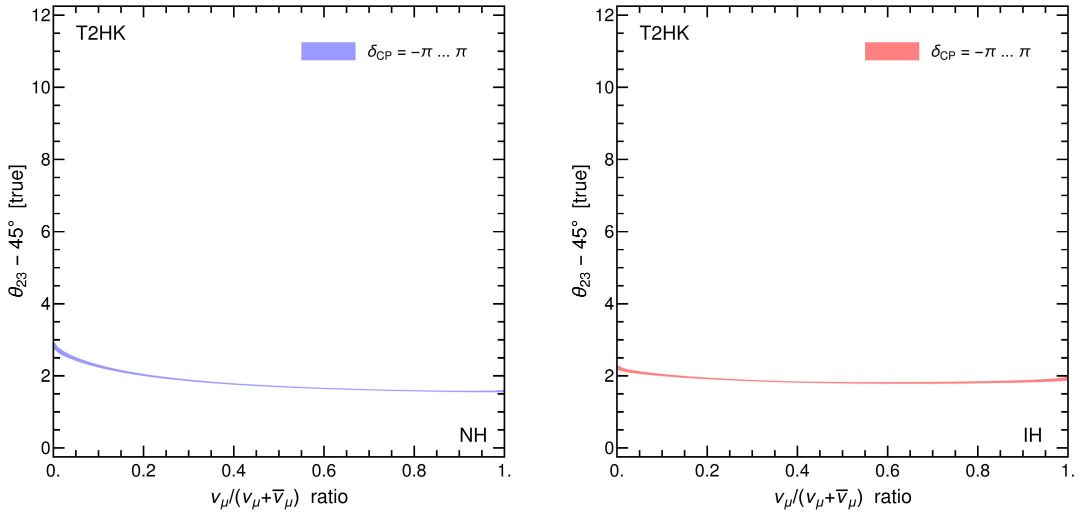
1. 295 km baseline
2. oscillation maximum at ~ 0.6 GeV
3. off-axis experiment

Octant determination in DUNE:





Octant determination in T2HK:



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  This is because the $\nu_\mu \to \nu_\mu$ survival probability is mostly octant-degenerate and $\nu_\mu \to \nu_e$ is the one that tells us about the octant.

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If θ_{23} is very near to maximal,
it will be very difficult to ascertain the octant through long-baseline experiments.

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The apparent conflict between T2K and NOvA results can also be an indication of new physics:

- Non-standard interactions, sterile neutrinos and decoherence effects are few examples.

Midpoint summary

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Beyond the Standard Model

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In case of one sterile neutrino

$$U_{4\times 4} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

the 3×3 matrix is no longer unitary.

Non-unitary mixing

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

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

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

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F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola and J.W.F. Valle, Phys. Rev. **D92**, 053009 (2015) and New J. Phys. **19**, 093005 (2017)

- Non-unitary mixing bounds:
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Non-unitary parameter	Bound at 90% C.L.
α_{11}	0.9974
α_{22}	0.9994
α_{33}	0.9988
$\lvert\alpha_{21}\rvert$	2.6×10^{-2}
$\lvert\alpha_{31}\rvert$	2.0×10^{-3}
$\lvert\alpha_{32}\rvert$	1.5×10^{-2}

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M. Blennow, P. Coloma, E. Fernandez-Martinez, J. Hernandez-Garcia and J. Lopez-Pavon, J. High Energ. Phys. **04**, 153 (2017); arXiv:1609.08637

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

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	Non-Unitarity	Sterile neutrinos	
	$(m > \text{EW})$	$\Delta m^2 \gtrsim 100\ \text{eV}^2$	$\Delta m^2 \sim 0.1 - 1\ \text{eV}^2$
α_{ee}	$1.3 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$	$1.0 \cdot 10^{-1}$	$1.0 \cdot 10^{-1}$
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$2.5 \cdot 10^{-2}$	$1.7 \cdot 10^{-2}$
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$5.3 \cdot 10^{-2}$

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- In this case, the average-out effect will be the same in both near and far detectors, and they will find no difference in the event rates that are measured in the far detector and extrapolated from the near detector.

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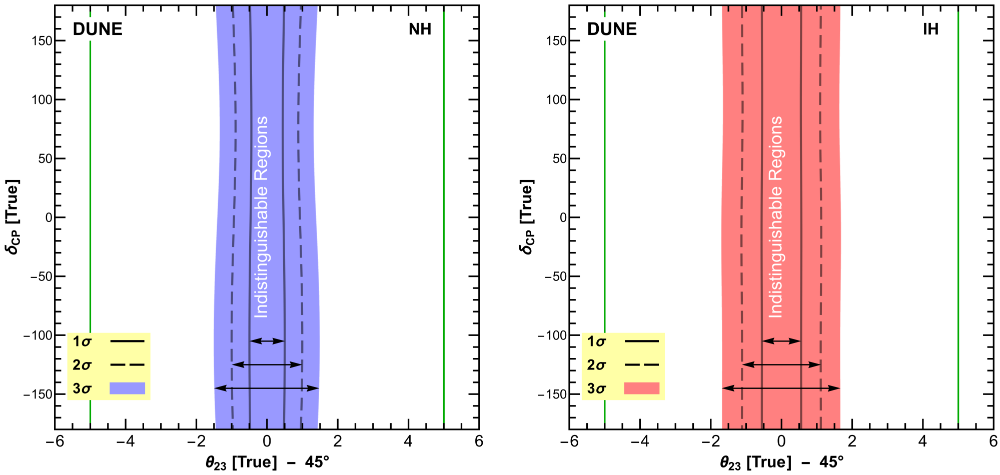
- This is the reason why the bounds are calculated differently and sorted into two mass ranges.

Standard Model case
(3 active neutrinos and nothing else)
(3.5 years + 3.5 years)



Non-unitary mixing
(3 active and 3 sterile neutrinos, Blennow et al. bound)
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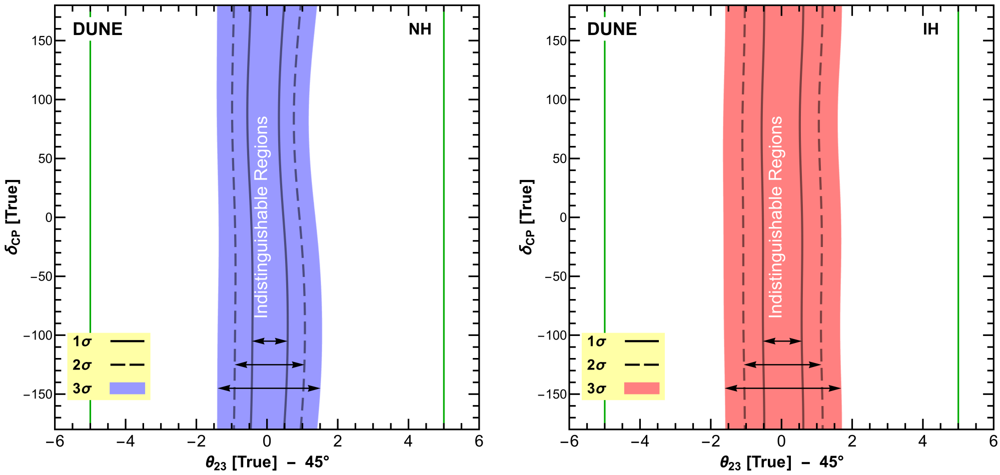

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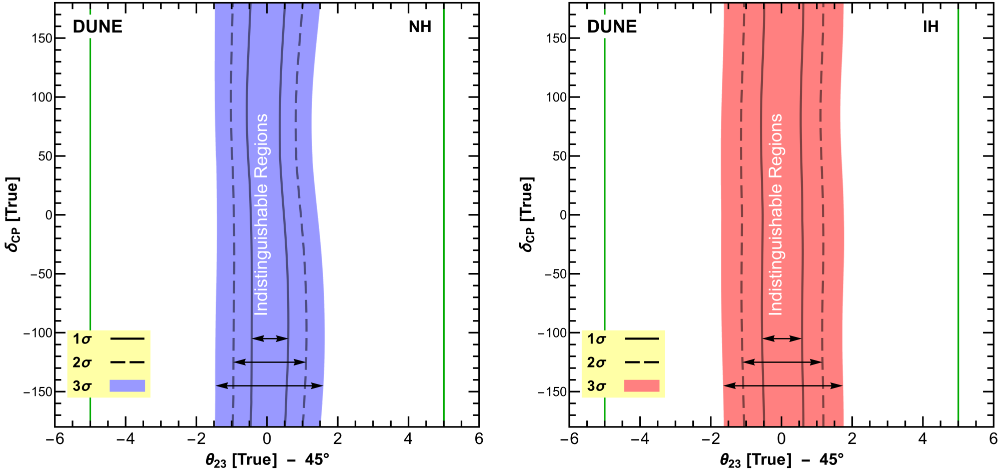
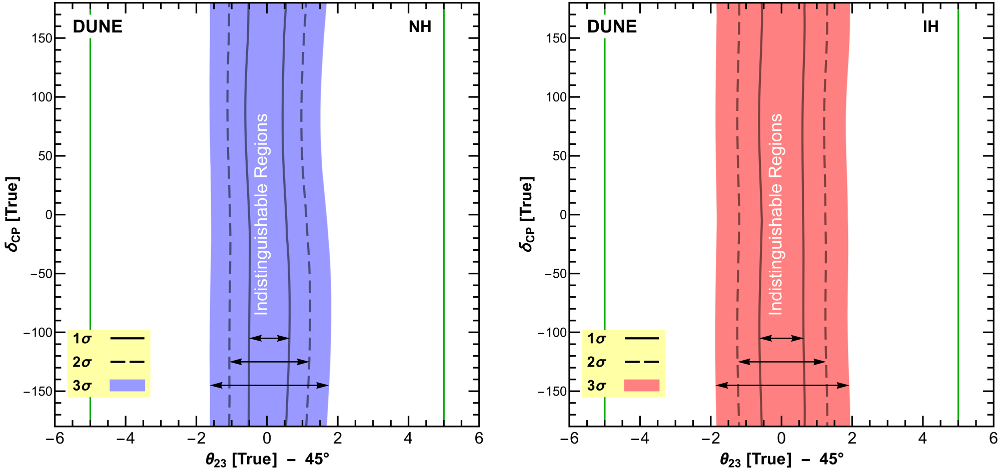


Light sterile neutrino
(3 active and 3 sterile neutrinos, 0.1 eV^2 $< \Delta m^2_{41} <$ 1 eV^2, Blennow et al. bound)
(3.5 years + 3.5 years)



Light sterile neutrino
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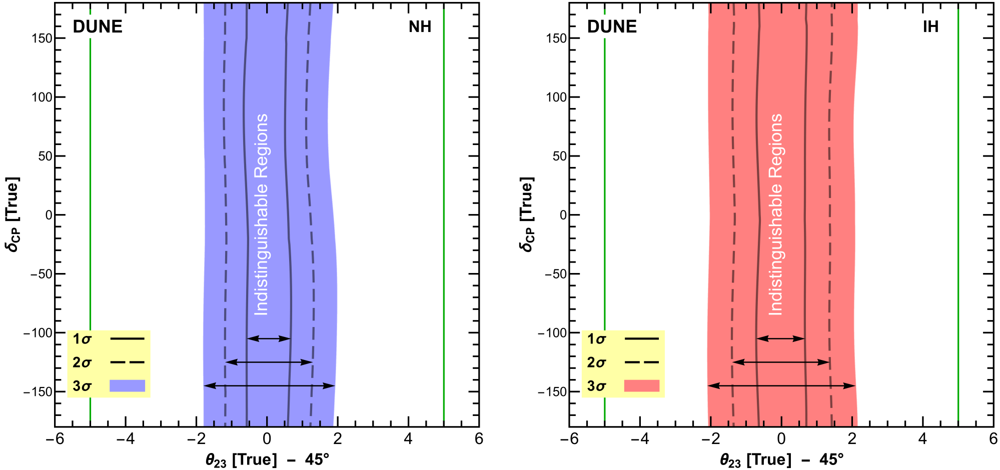

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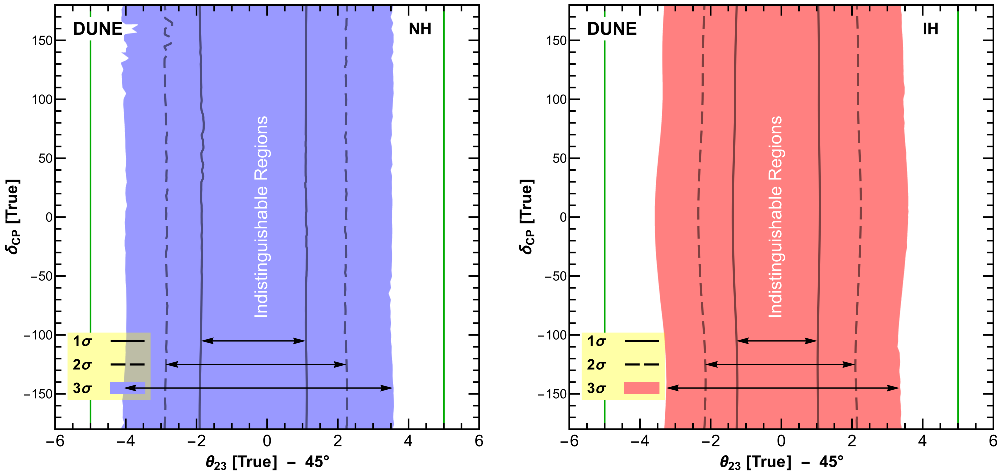
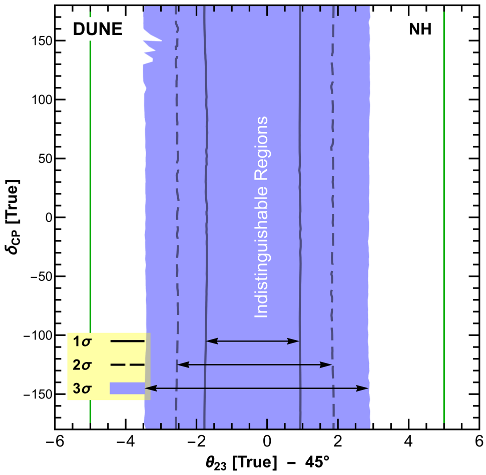
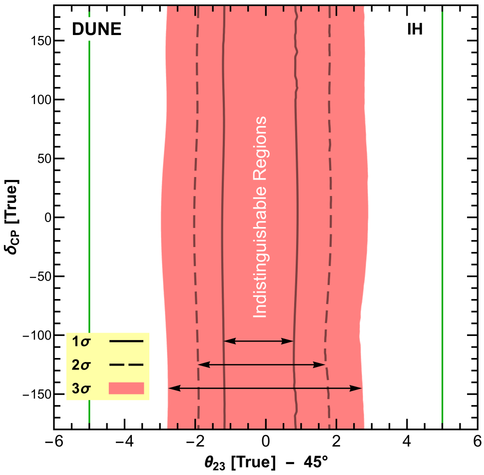
What will happen if αs are unconstrained?

Non-unitary mixing
(Unconstrained αs)
(3.5 years + 3.5 years)

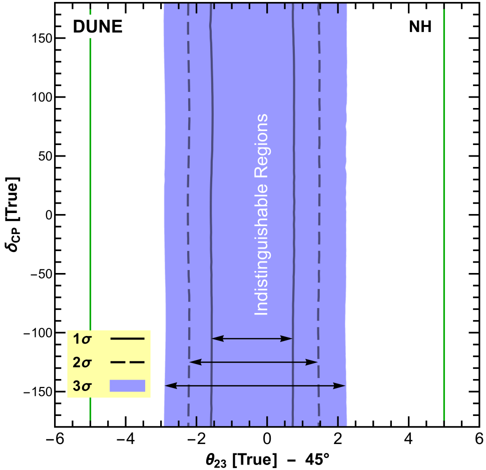


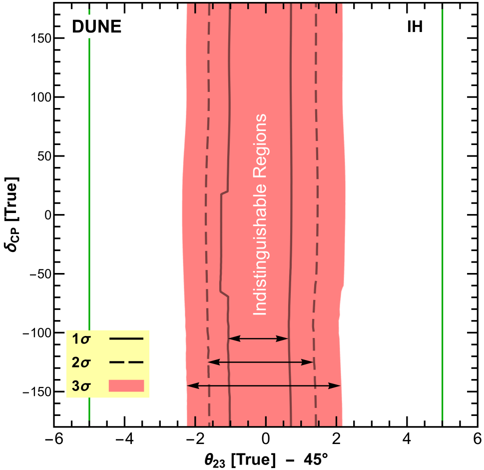
Non-unitary mixing (Unconstrained αs) (5 years + 5 years)



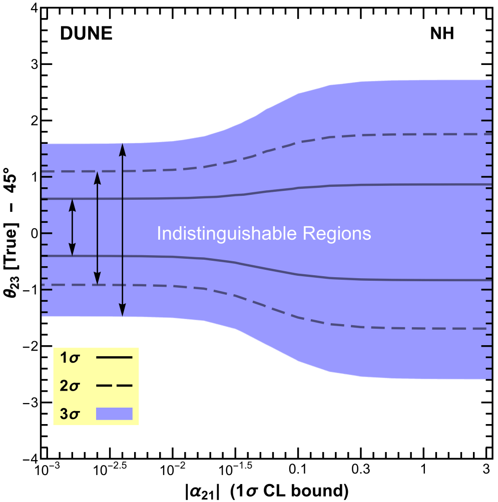


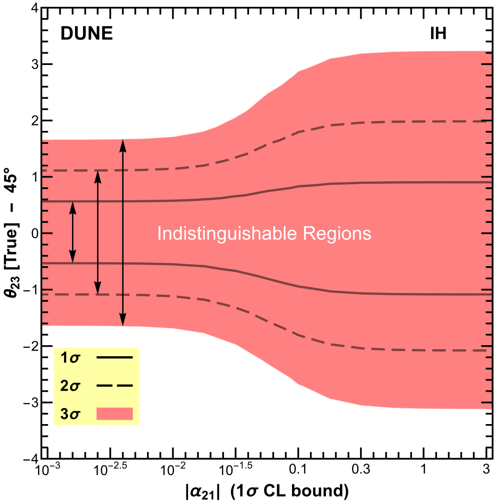
Non-unitary mixing (Unconstrained αs) (8 years + 8 years)





$|\alpha_{21}|$ dependency plot (3.5 years + 3.5 years)





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If you don't know anything about BSMs, don't worry, try to increase the events!

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- This non-unitarity do not appear yet in the leading order, so the effects turn out to be negligible. If one is to recalibrate the whole neutrino experimental data which is available today, the non-unitarity corrections would be so small that the new best-fits would easily fall within the current experimental bounds.

Summary

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Please see articles by C.R. Das, J. Maalampi, J. Pulido and S. Vihonen:

arXiv: 1712.07343

DOI: 10.1088/1742-6596/888/1/012219

DOI: 10.1103/PhysRevD.97.035023

DOI: 10.22323/1.283.0030

arXiv: 1606.02504

DOI: 10.1007/JHEP02(2015)048

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Experimental parameters:

Parameter	Value
Beam power [SPS] (10^{20} POT/yr)	1.125
Beam power [HPPS] (10^{21} POT/yr)	3.0
Baseline length (km)	2288
Running times (yr)	5+5
Detection efficiency (%)	90
ν_μ NC rejection (%)	99.5
ν_μ CC rejection (%)	99.5
Energy resolution (GeV)	$0.15 \times \sqrt{E}$
Energy window (GeV)	[0.1, 10.0]
Number of bins	80
Bin width (GeV)	0.125

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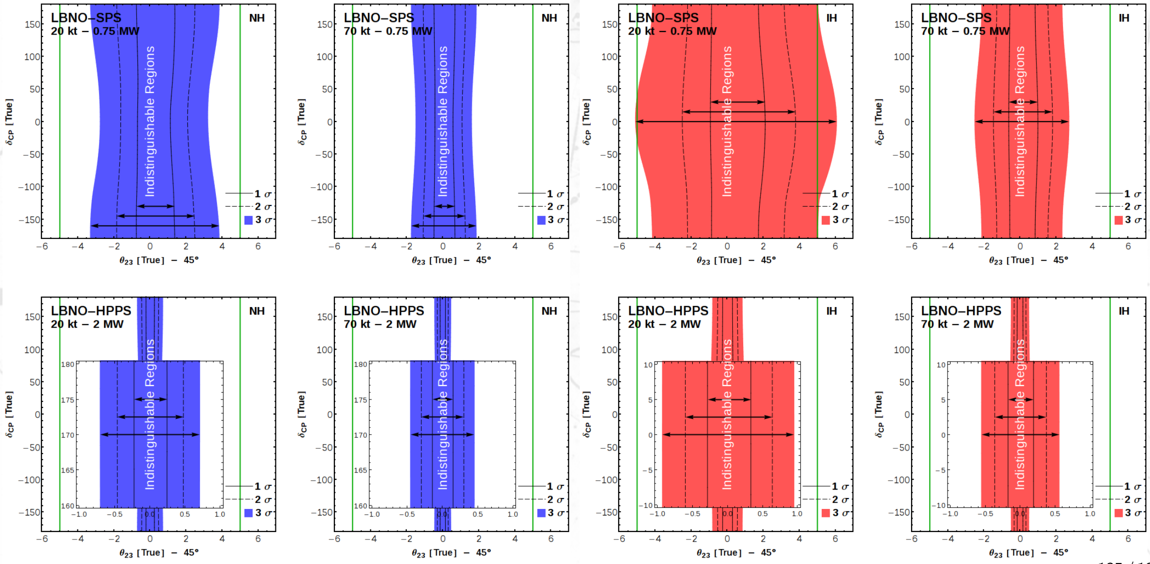
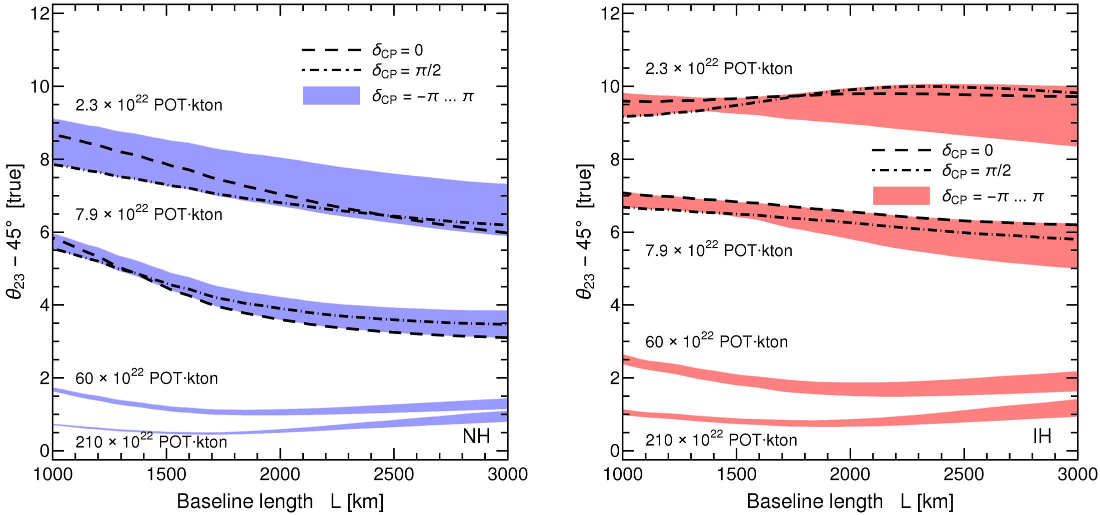
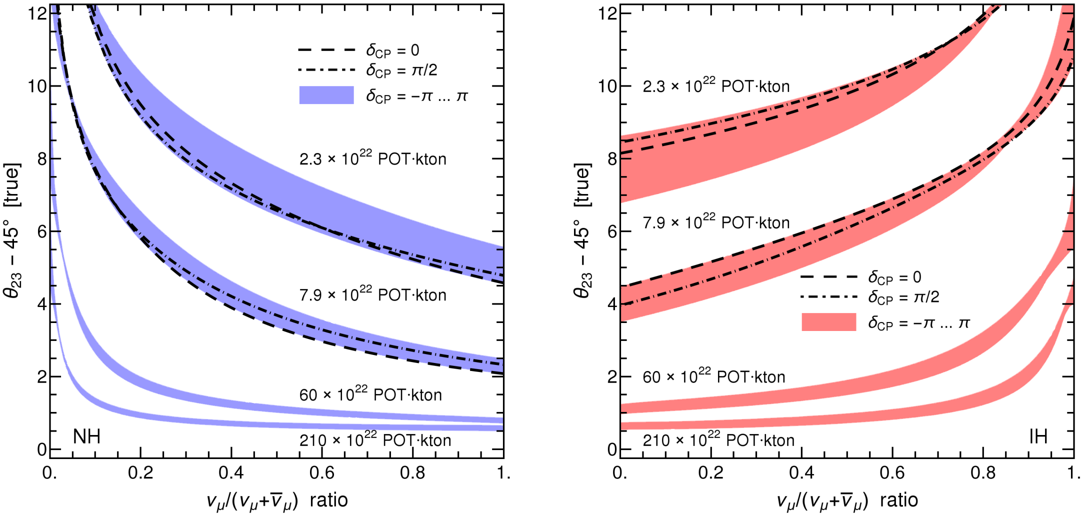


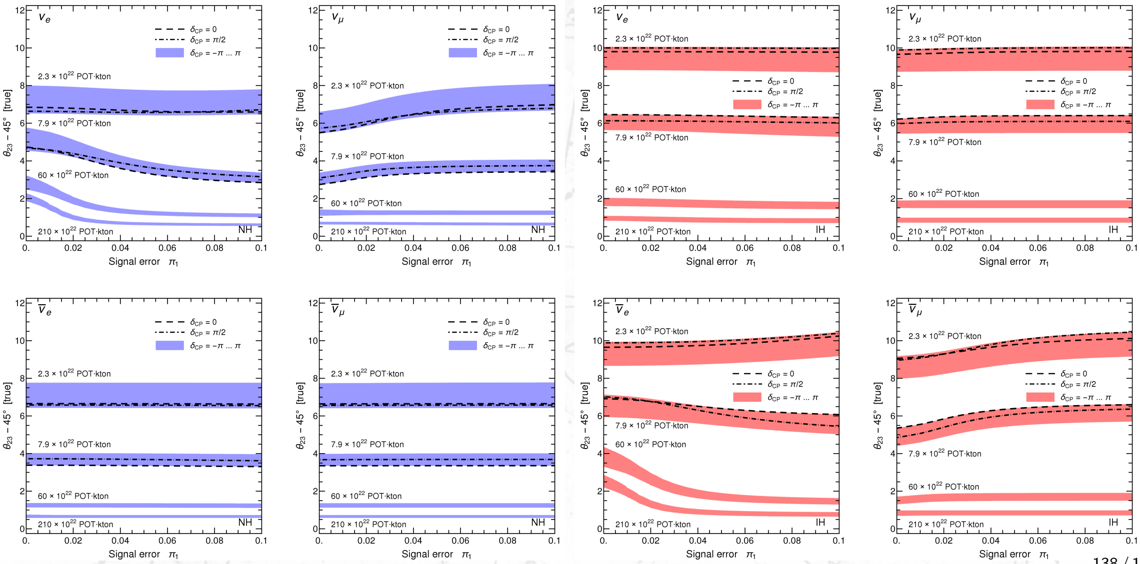
Back stories: 5σ discovery

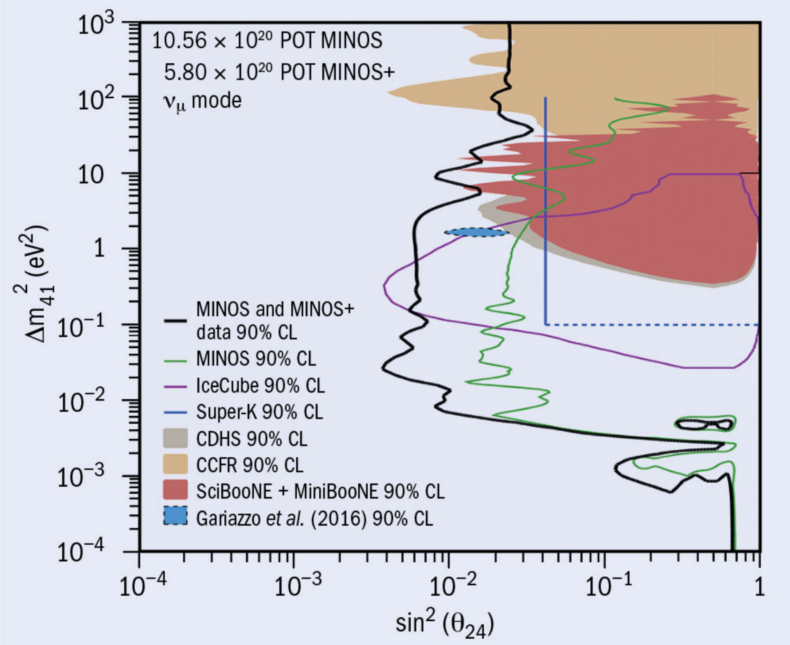


Back stories: 5σ discovery



Back stories: 5σ discovery





10.56 × 10²⁰ POT MINOS
5.80 × 10²⁰ POT MINOS+
ν_μ mode
MINOS and MINOS+ data 90% CL
MINOS 90% CL
IceCube 90% CL
Super-K 90% CL
CDHS 90% CL
CCFR 90% CL
SciBooNE + MiniBooNE 90% CL
Gariazzo *et al.* (2016) 90% CL
Δm^2_{41} (eV^2)
$\sin^2(\theta_{24})$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3

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GLoBES
General Long Baseline Experiment Simulator

GLoBES is a sophisticated software package for the simulation of long baseline neutrino oscillation experiments. Main features are:

- Full incorporation of correlations and degeneracies in the oscillation parameter space.
- Advanced routines for the treatment of arbitrary systematical errors
- AEDL, the **A**bstract **E**xperiment **D**efinition **L**anguage provides an easy way to define experimental setups.
- User-defined priors allow the inclusion of arbitrary external physical information
- Interface for the simulation of non-standard physics
- Predefined setups are available for many experiments: Superbeams, Beta Beams, Neutrino factories, Reactors, various detector technologies, ...
- Extensive documentation and examples are available for download.

The latest stable release of GLoBES, version 3.0 is available for download.

NEW: We now offer also the latest, frequently updated, development releases for download.

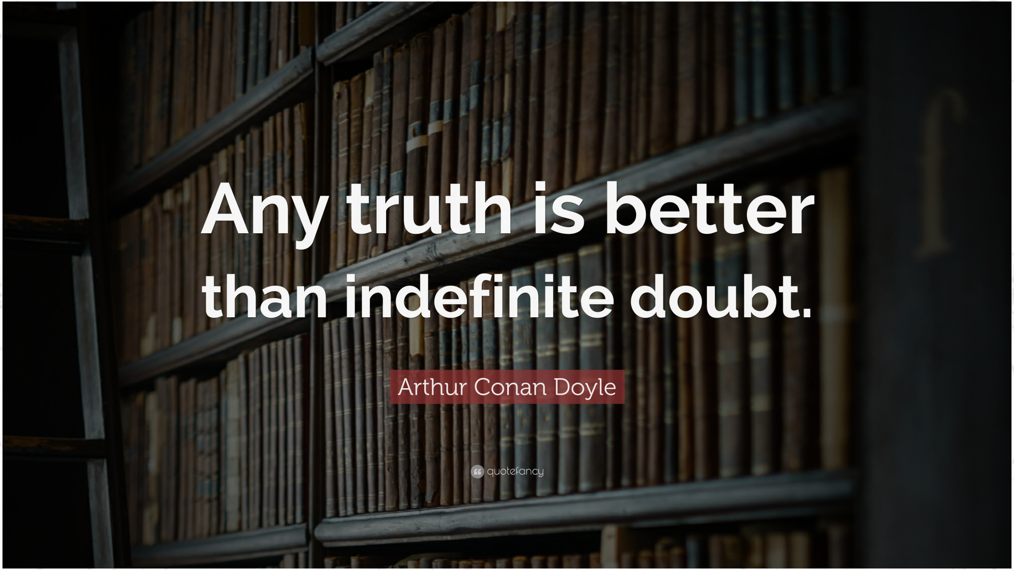
NEW: A collection of additional tools for degeneracy finding, new physics simulation, etc. is now available for download.

GLoBES is maintained by **Patrick Huber**, **Joachim Kopp**, **Manfred Lindner**, and **Walter Winter** (globes@mpi-hd.mpg.de).

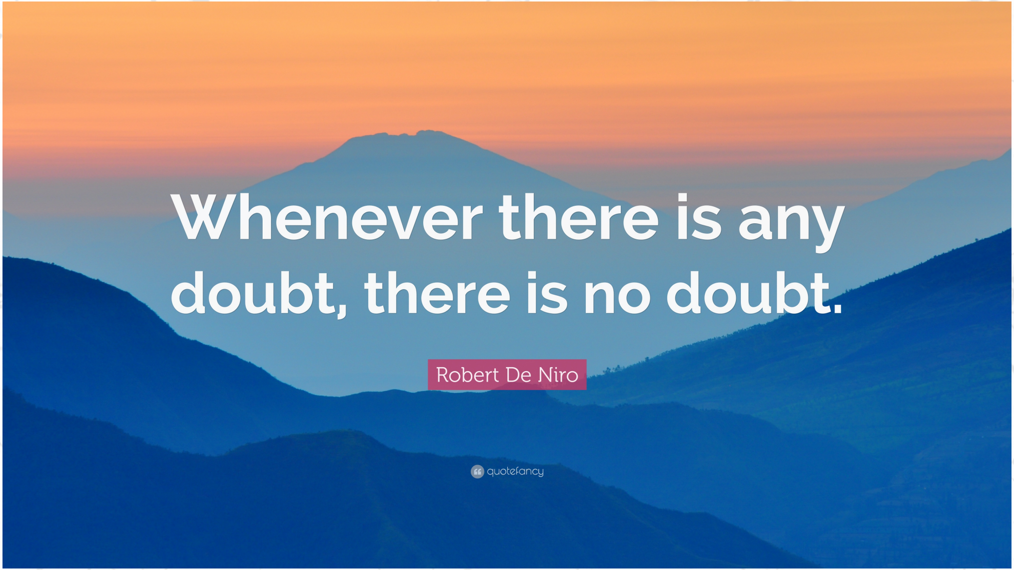
Last modified: 14 May 2018, 19:00 CET , Impressum , Datenschutzhinweis

How to say THANK YOU in various European languages

Any doubts?


Any truth is better than indefinite doubt.
Arthur Conan Doyle
quotefancy

Any doubts?


Whenever there is any doubt, there is no doubt.
Robert De Niro
quotefancy

We have to learn many things about BSM in the future!

O friend, there is injustice and loyal in your love ...
There is also chance of death and life ...
There is also loss and profit ...
I am not daring to meet you, my heart becomes comfortless ...
Moving with difficulty in your pain, there is also remedy and happiness ...
Wondering how to hide this essence within me ...
The beauty is obvious, also visible and clear ...
Only the beloved of the lover is the target ...
You are the treatment of love, there is also healing and remedy ...
Wherever you live, in the ancient world, o clear foundation ...
There is also a glimpse of hope!

... Love for SM