Sensitivity of oscillation experiments to the neutrino mass hierarchy

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Based on the work

M. Blennow, P. Coloma, P. Huber and T. Schwetz,

JHEP03(2014) 028, 1311.1822 [hep-ph]

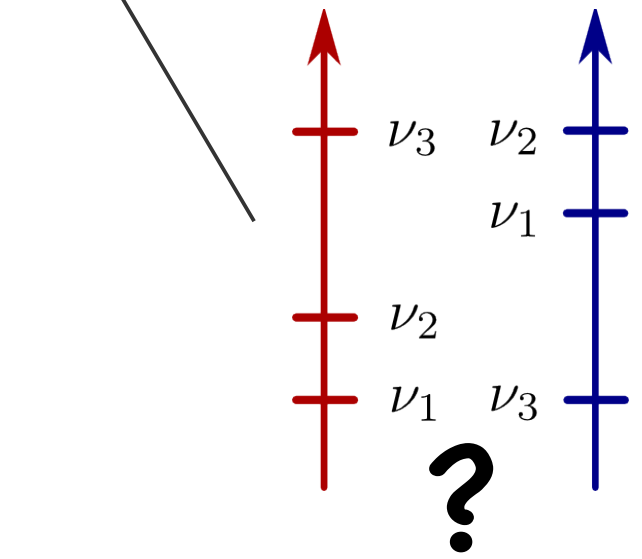
Rencontres de Moriond EW 2014

La Thuile, Aosta Valley, Italy

Mar 17, 2014

The two-family approximation

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{\alpha\alpha} L}{4E}\right)$$



$$\begin{aligned} \Delta m^2_{21} &= 7.5 \times 10^{-5} \mathrm{eV}^2 \\ |\,\Delta m^2_{31}\,| &= 2.47 \times 10^{-3} \mathrm{eV}^2 (\text{for NH}) \end{aligned}$$

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, 1209.3023 [hep-ph]

(See also Fogli et al, 1205.5254 [hep-ph], Forero et al, 1205.4018 [hep-ph] and Capozzi et al, 1312.2878 [hep-ph])

Motivation

- An unknown hierarchy may lead to a reduced ability to observe CP violation

Minakata, Nunokawa, hep-ph/0108085

Barger, Marfatia, Whisnant, hep-ph/0112119

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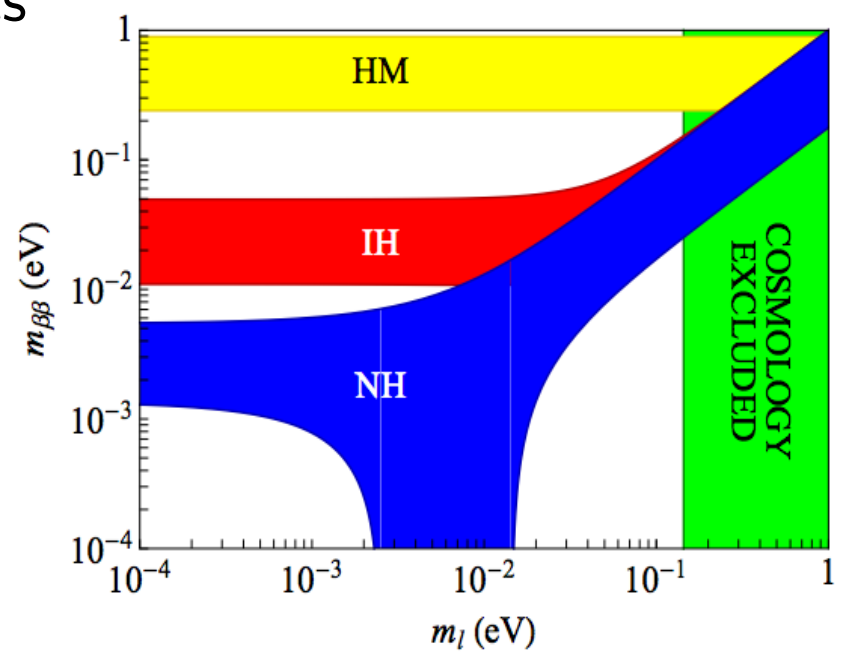
- An independent measurement of the hierarchy is extremely useful as a double-check of $0\nu\beta\beta$ and new physics

(see, for instance,
Blennow et al, 1005.3240 [hep-ph])

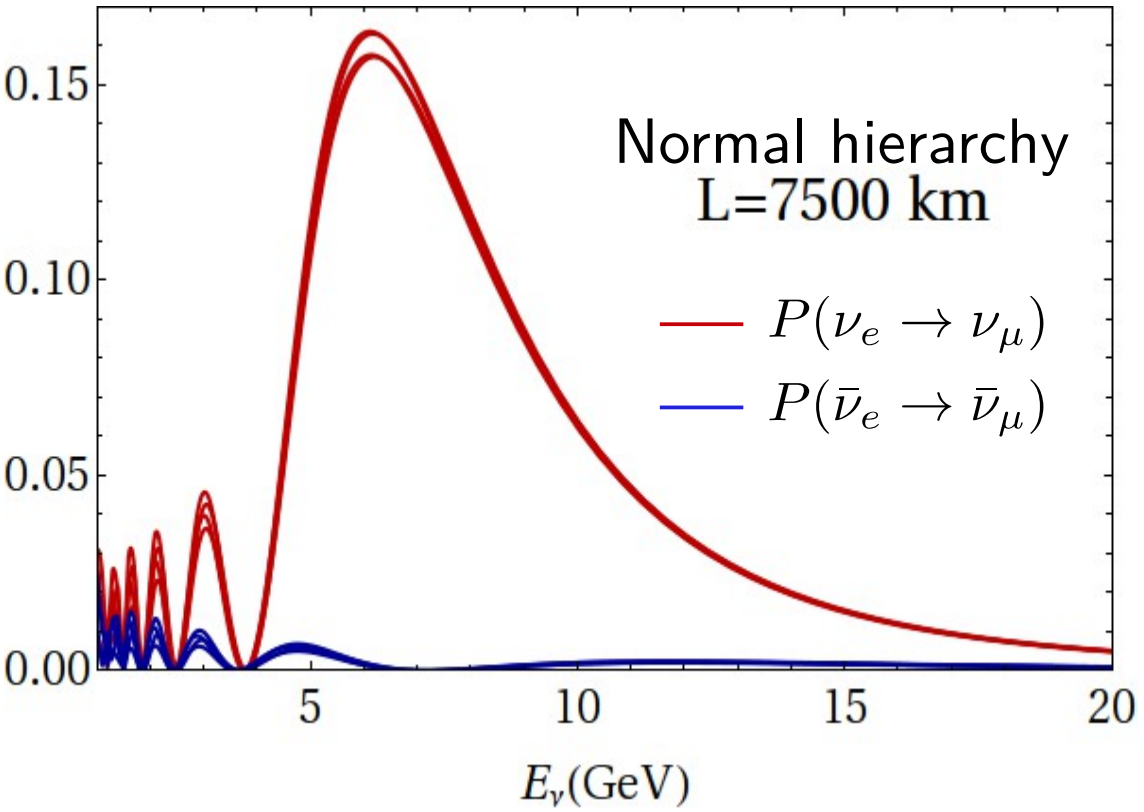


Experimental possibilities

i. Matter effects

In appearance $\rightarrow$ beams (T2K, NOvA, LBNE, LBNO, ...)

Wolfenstein ('78), Barger et al ('80), Mikheev and Smirnov ('85)



Experimental possibilities

i. Matter effects

In appearance $\rightarrow$ beams (T2K, NOvA, LBNE, LBNO, ...)

Wolfenstein ('78), Barger et al ('80), Mikheev and Smirnov ('85)

In disappearance $\rightarrow$ atmospheric neutrinos (PINGU, ORCA, ICAL@INO, Hyper-Kamiokande, ...)

Petcov, hep-ph/9805262

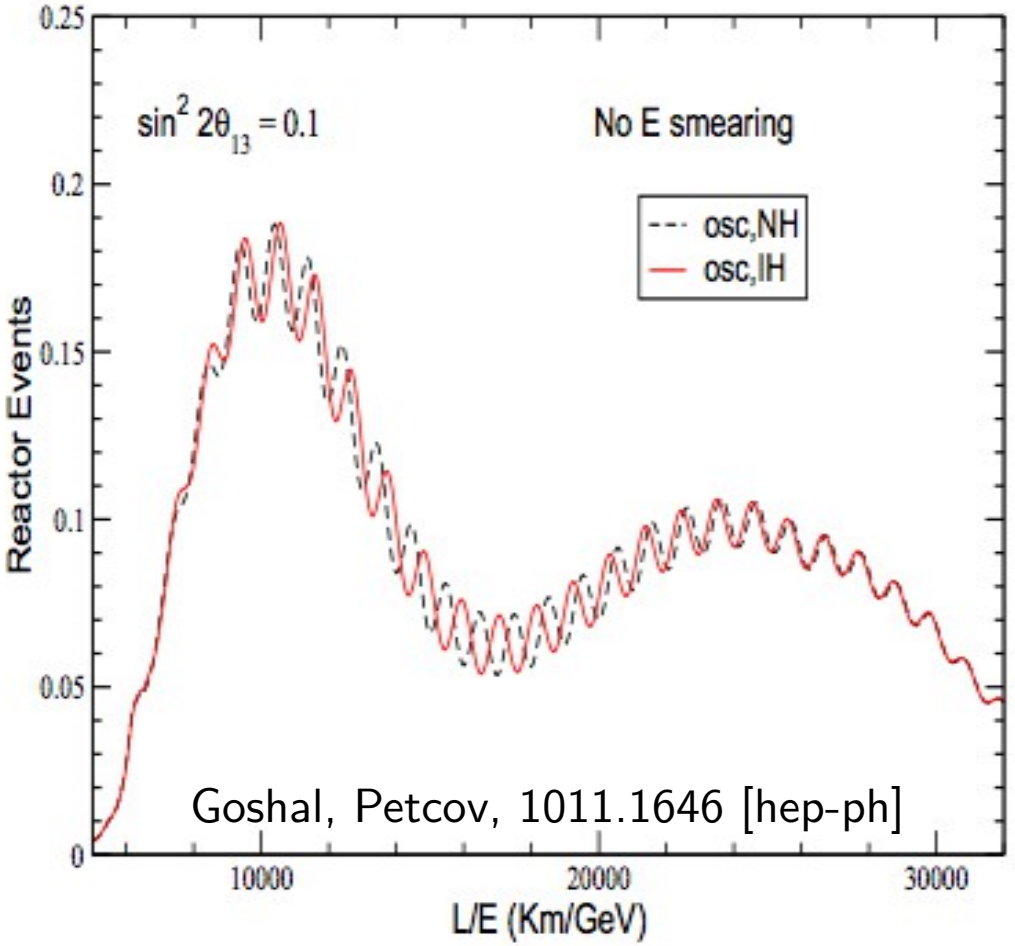
Akhmedov, hep-ph/9805272

Akhmedov, Dighe, Lipari, Smirnov, hep-ph/9808270

Experimental possibilities

ii. Interference effects between solar and atmospheric oscillations

$\rightarrow$ reactors at medium baselines (JUNO, RENO50)



Petcov, Piai, hep-ph/0112074

Choubey, Petcov, Piai, hep-ph/0306017

Statistical issues

Statistical issues with mass ordering

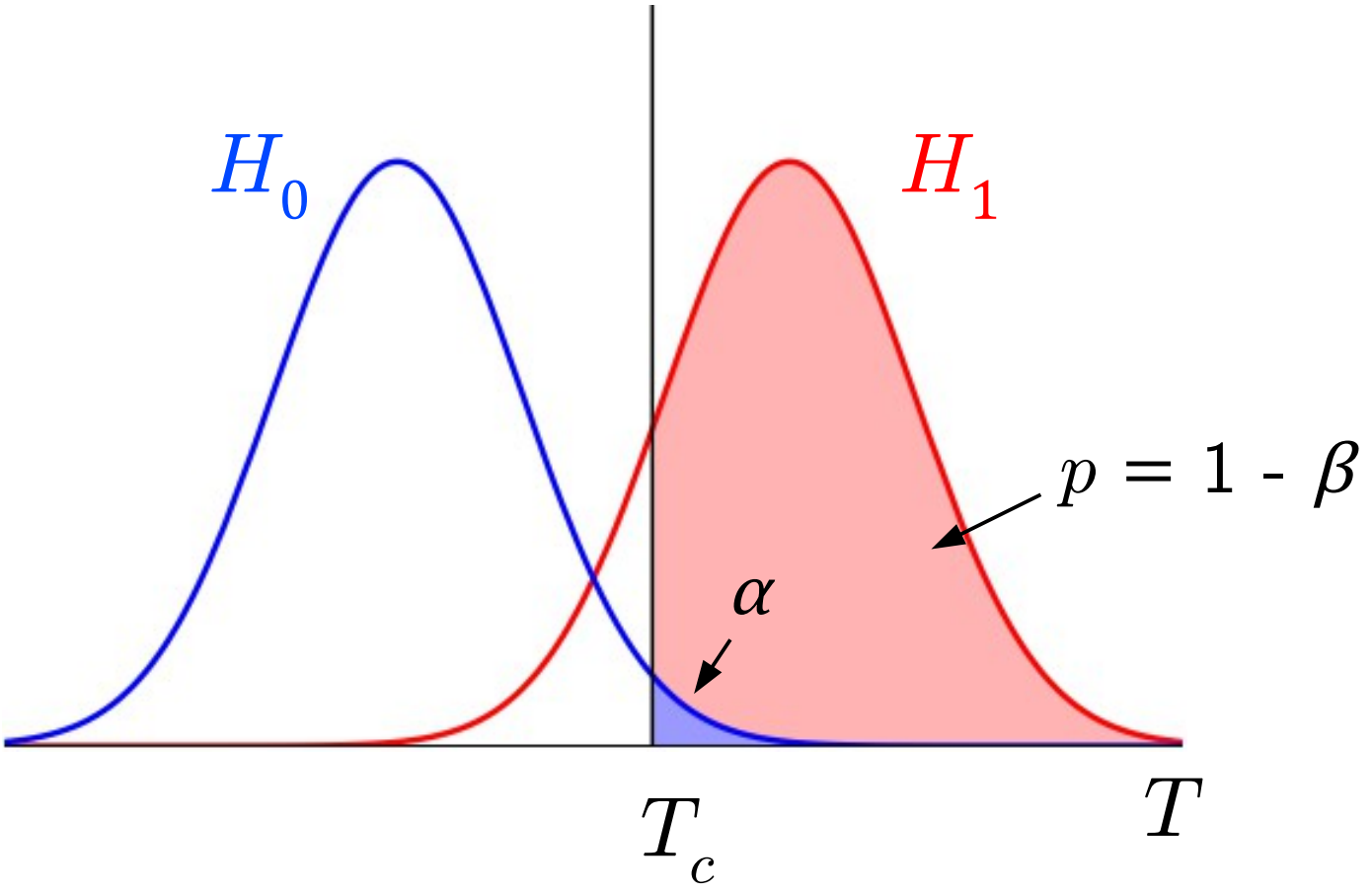
One of the requirements of Wilks' theorem is that the parameter begin tested needs to be continuous, but the mass ordering is not!

$\rightarrow$ What happens then?

Qian et al, 1210.3651 [hep-ph]
Ge, Hagiwara, Okamura, Takaesu, 1210.8141 [hep-ph]
Ciuffoli, Evslin and Zhang, 1305.5150 [hep-ph]
Capozzi, Lisi and Marrone, 1309.1638 [hep-ph]
Vittels and Read, 1311.4076 [hep-ex]
Blennow, 1311.3183 [hep-ph]
LBNO collaboration, 1312.6520 [hep-ph]

(See also talk by F. Capozzi)

Hypothesis testing



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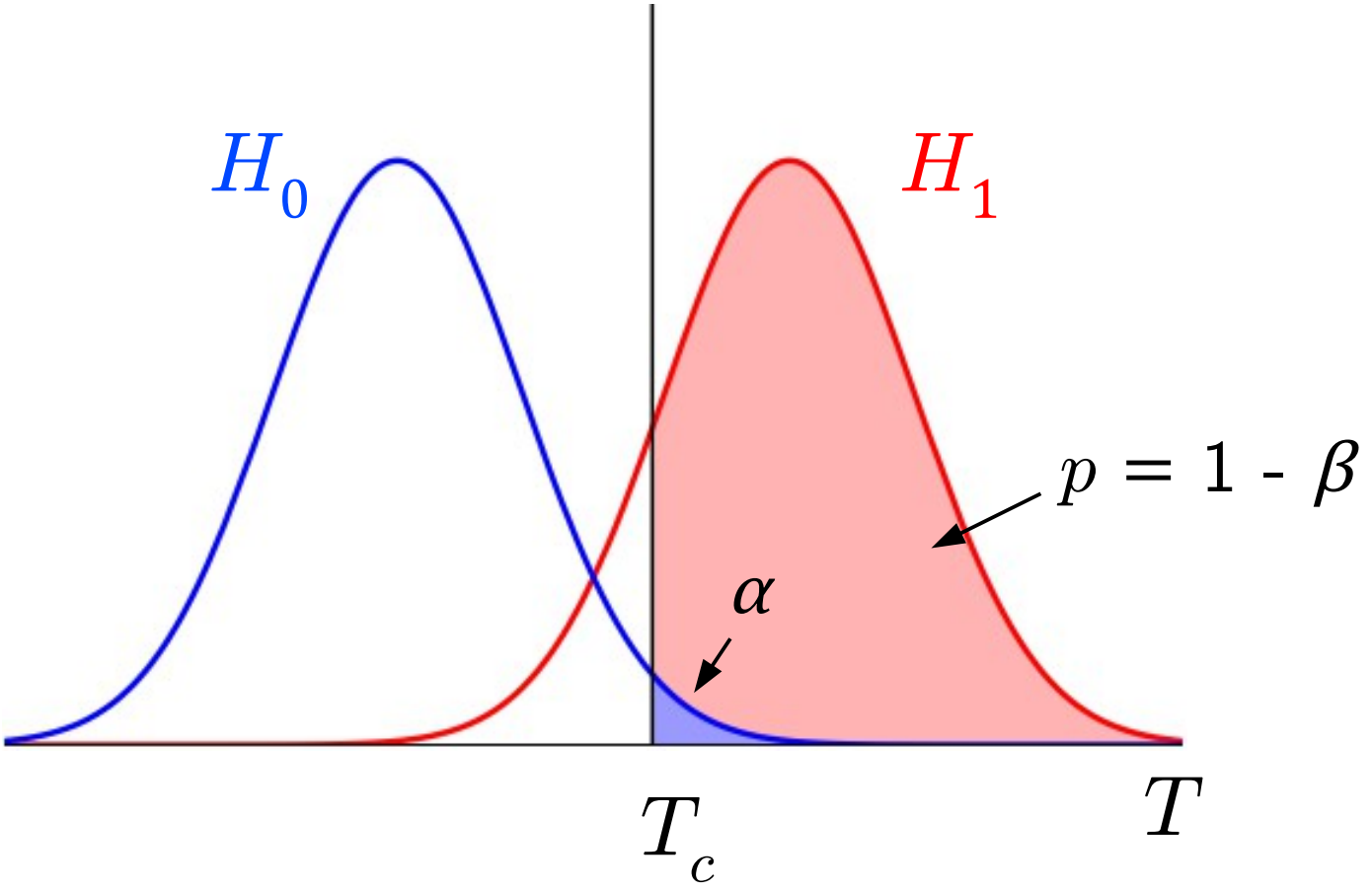

$$T = \chi^2_{\mathrm{IO}} - \chi^2_{\mathrm{NO}}$$

Gaussian approximation

- Under the gaussian approximation:

$$T = \mathcal{N}\left(\pm T_0, 2\sqrt{T_0}\right)$$

One can obtain simple expressions for type I and type II error rates as a function of T_0, which turns into a relation between α and β.

Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

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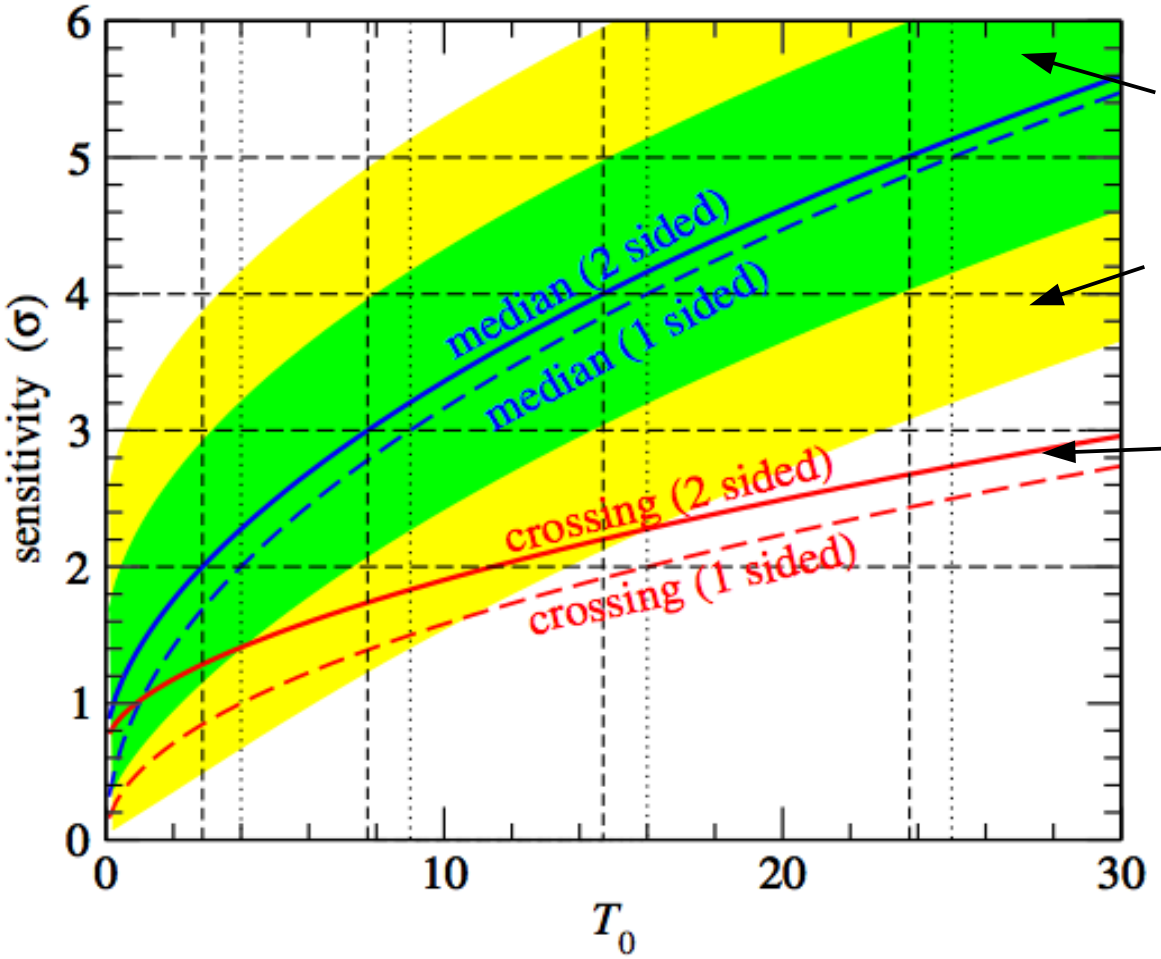
- Then, setting β=0.5 one can then get the expression for the number of sigmas for the median experiment in the gaussian case:

$$n = \sqrt{2}\mathrm{erfc}^{-1}\left(\frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{T_0}{2}}\right)\right)$$

Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

Gaussian approximation



$$\beta = \frac{1}{2} \pm \frac{0.6827}{2}$$

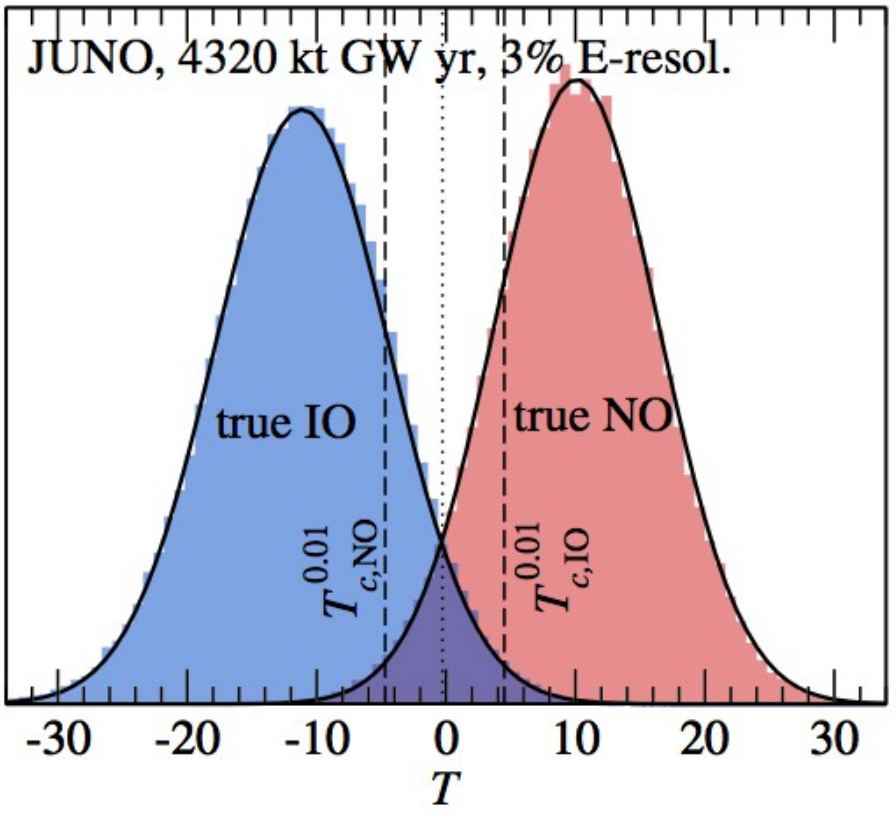
$$\beta = \frac{1}{2} \pm \frac{0.9545}{2}$$

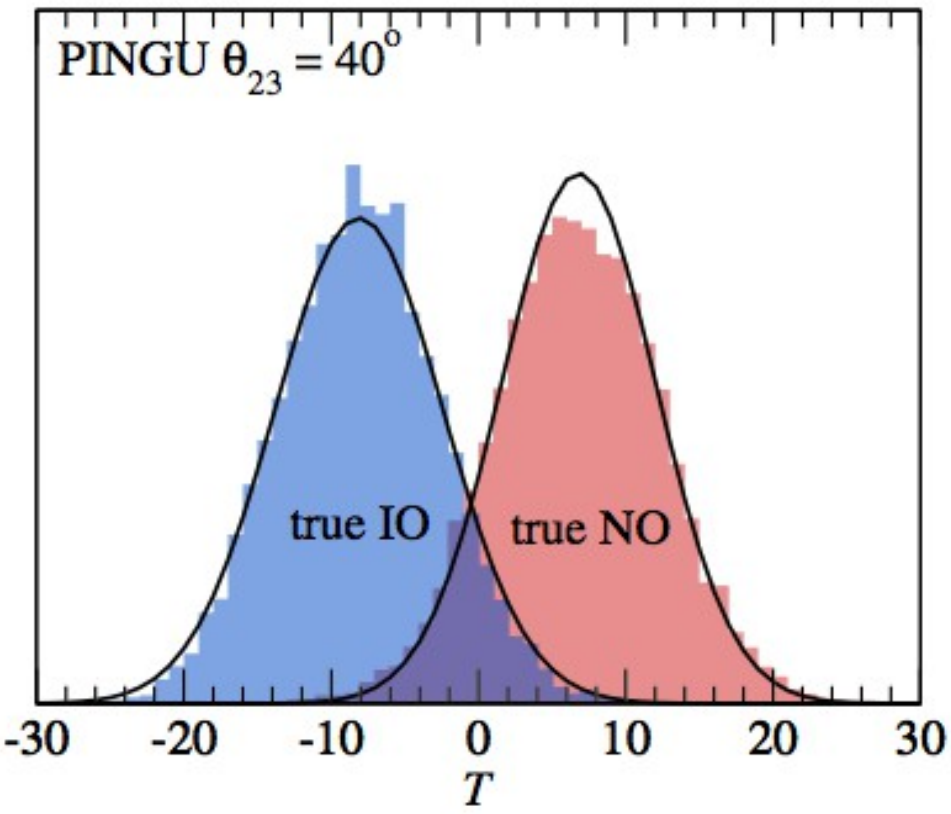
$$\beta = \alpha$$

Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

Does the gaussian approximation hold for a real experiment?

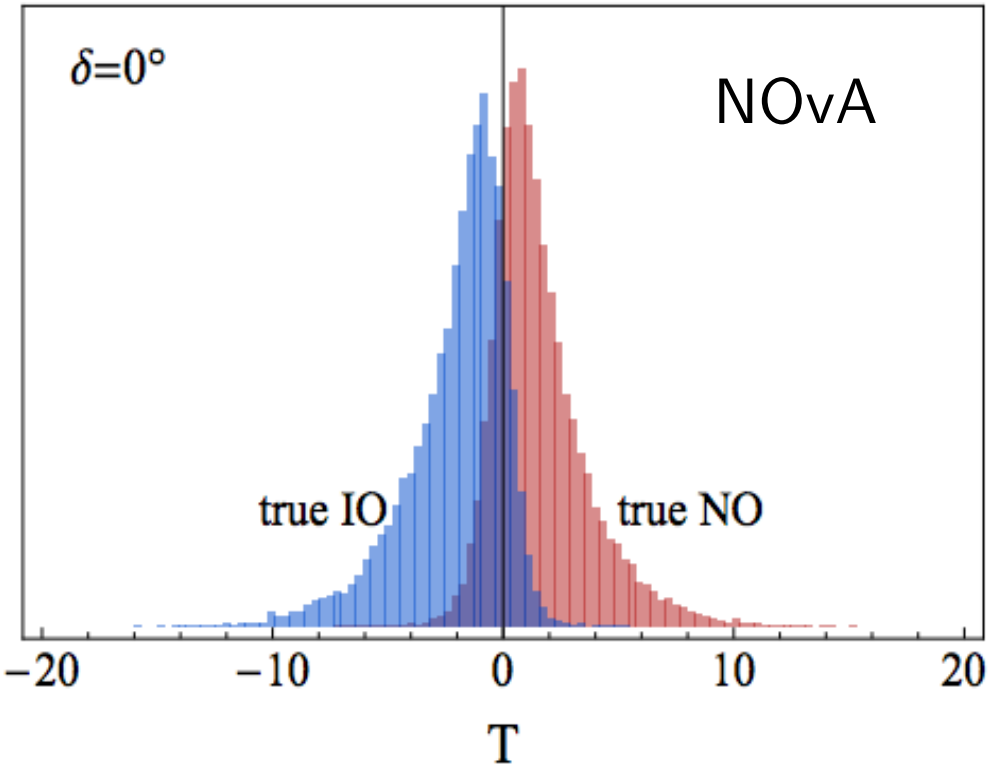
Distributions of T

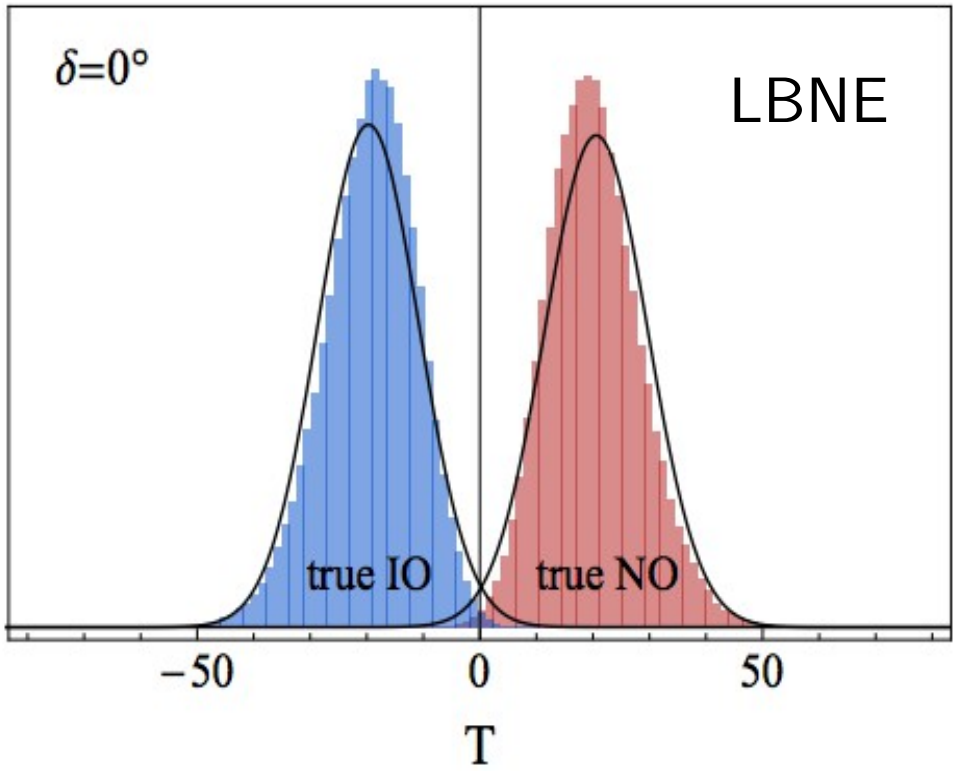




Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

Long-baseline experiments





Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

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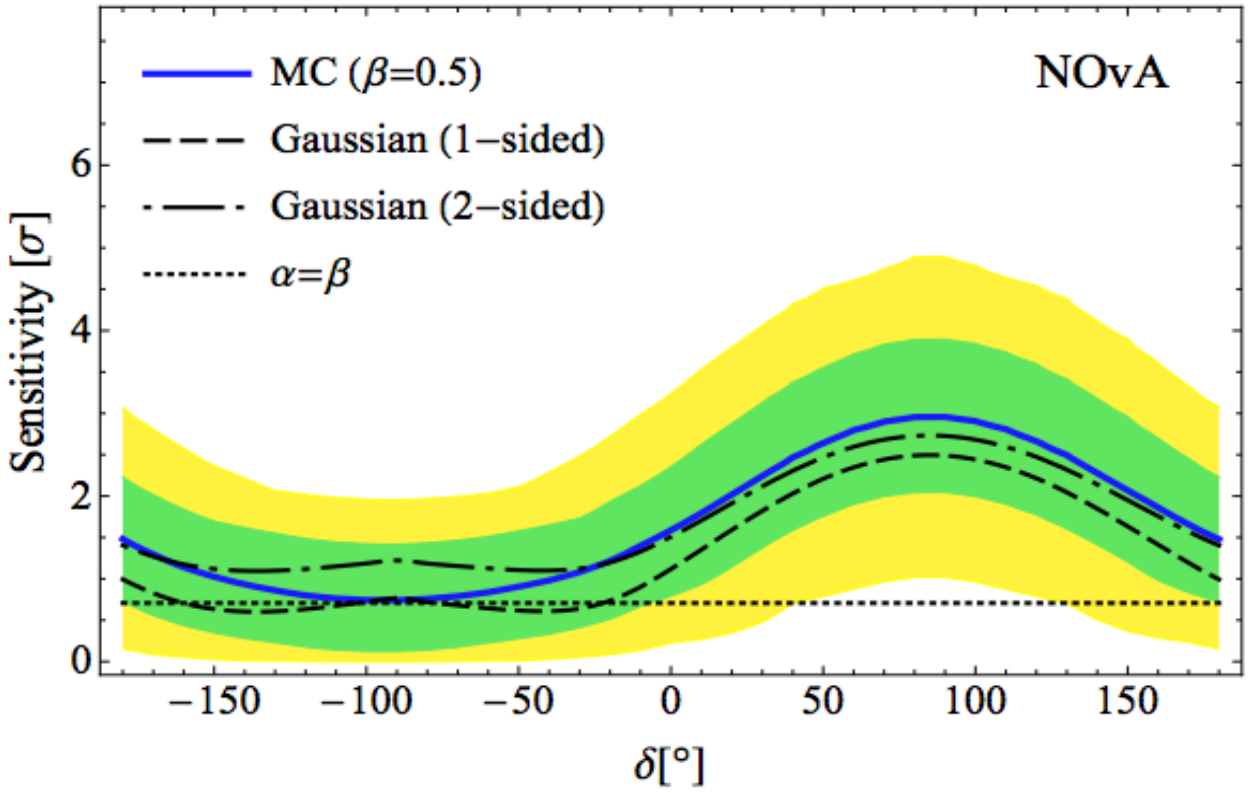
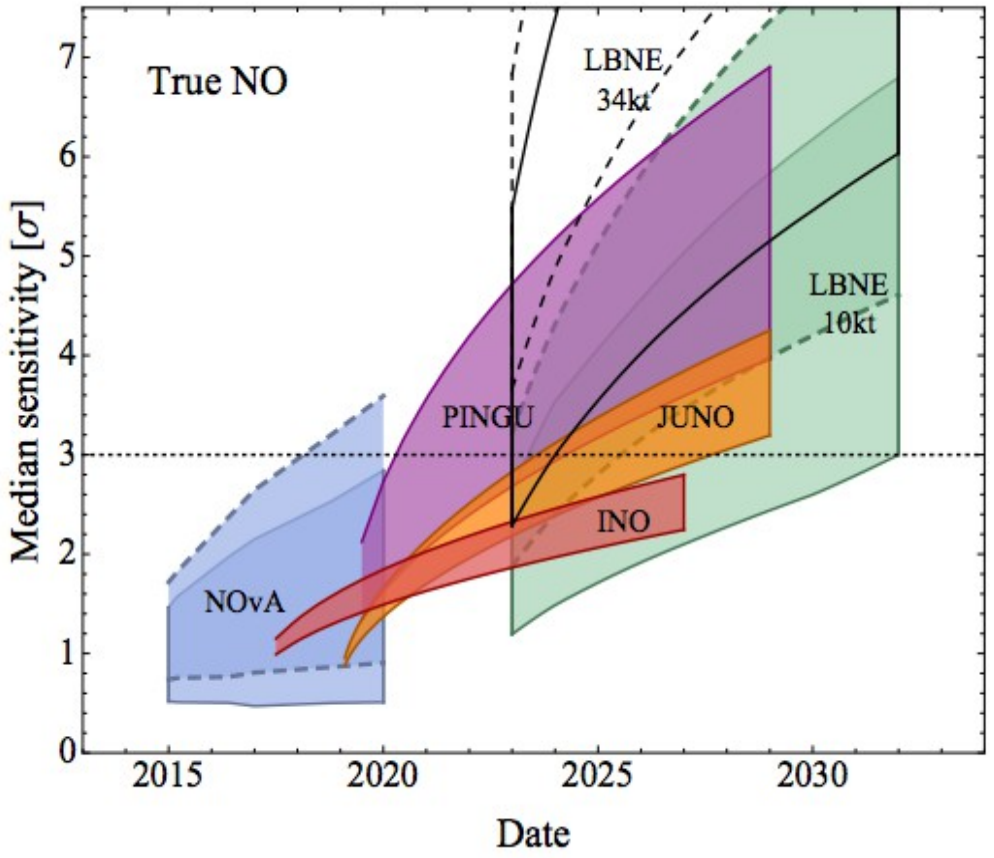
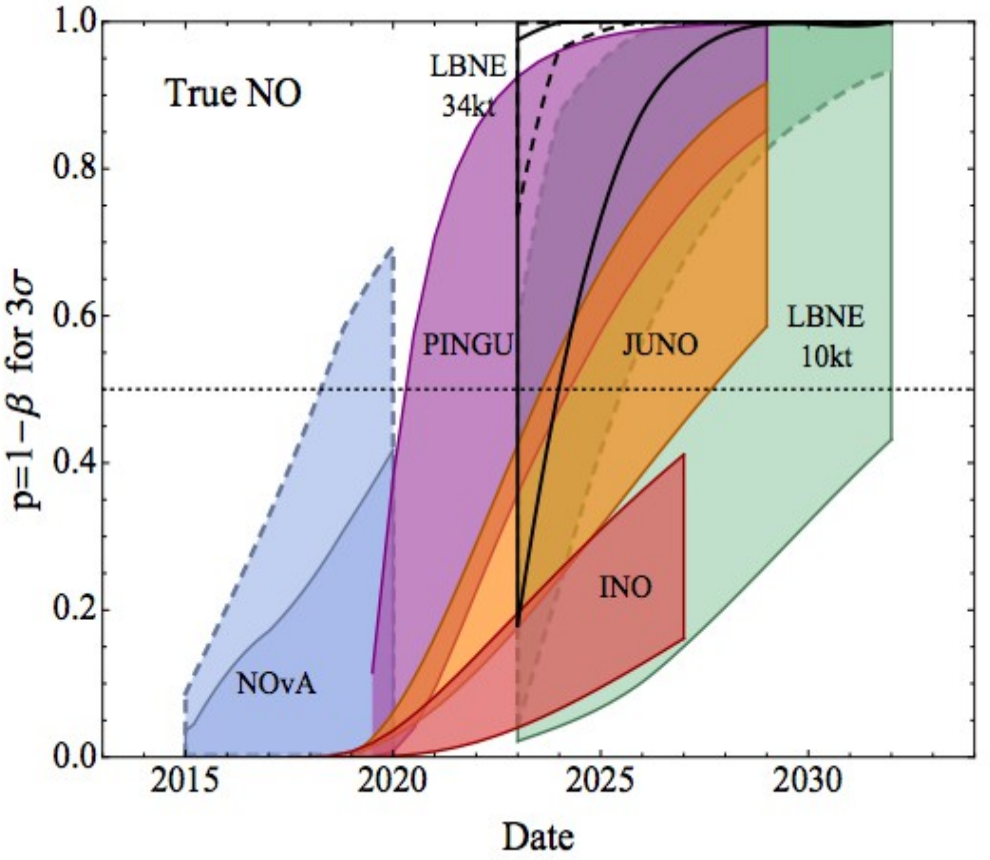


Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

Future prospects





Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

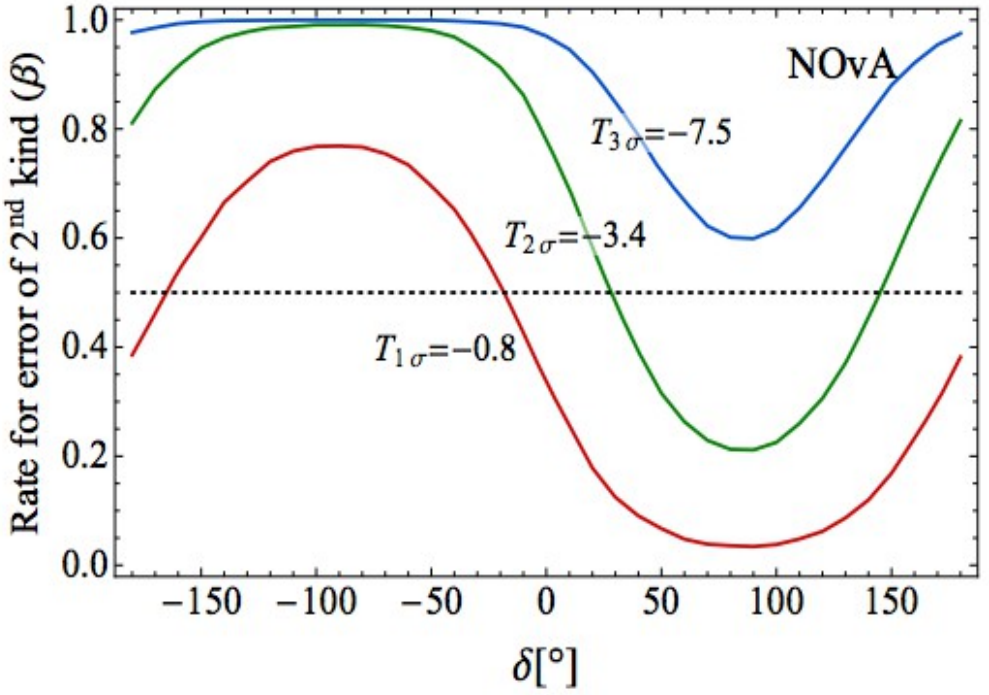
Conclusions

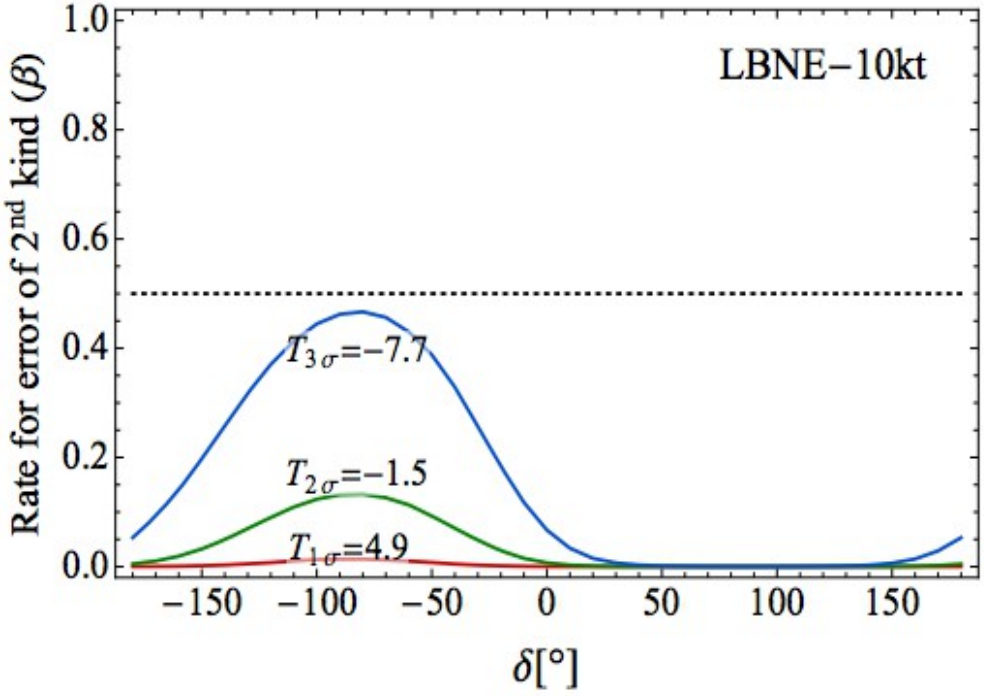
- The large value of θ_{13} recently measured has open a door to determine the hierarchy in many different ways
- Huge number of possibilities (short-, mid- and long-term): PINGU, ORCA, HyperK, JUNO, RENO50, ICAL, NOvA, LBNE,...
- The usual sensitivity estimates for the *median* experiment are valid, even for experiments which show large deviations from gaussianity

Thank you!

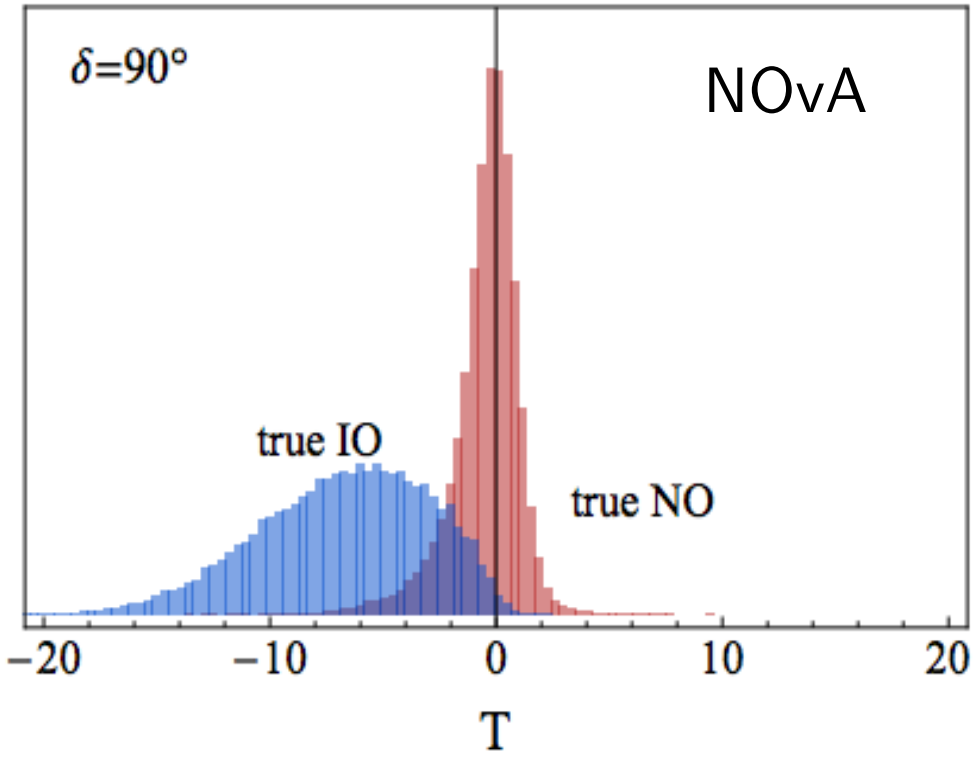
Backup

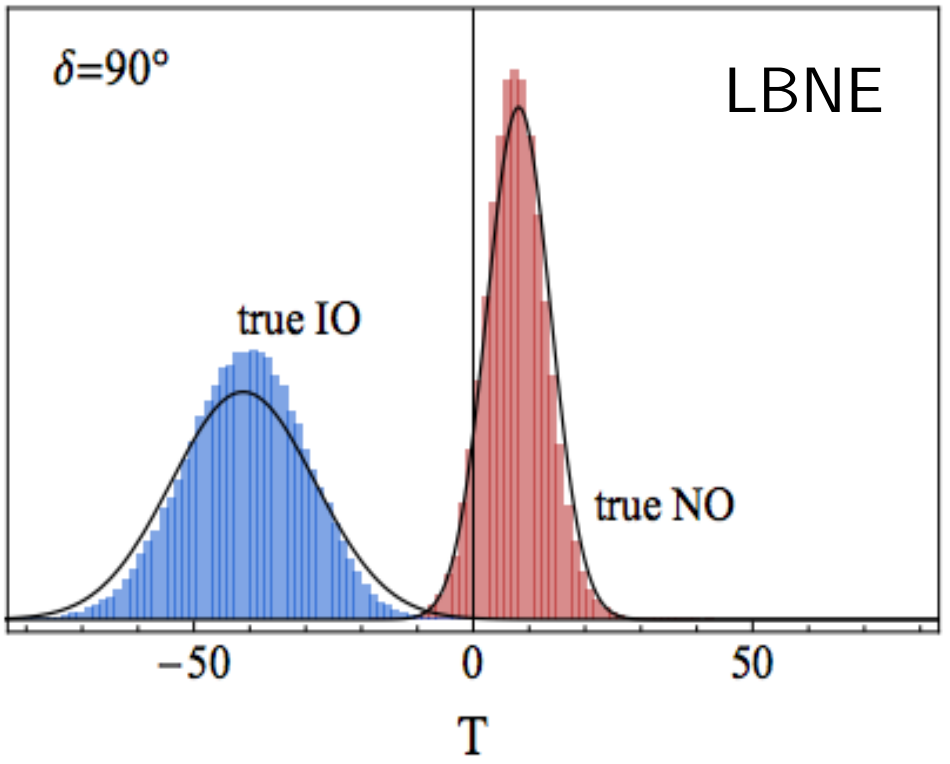
Long-baseline experiments





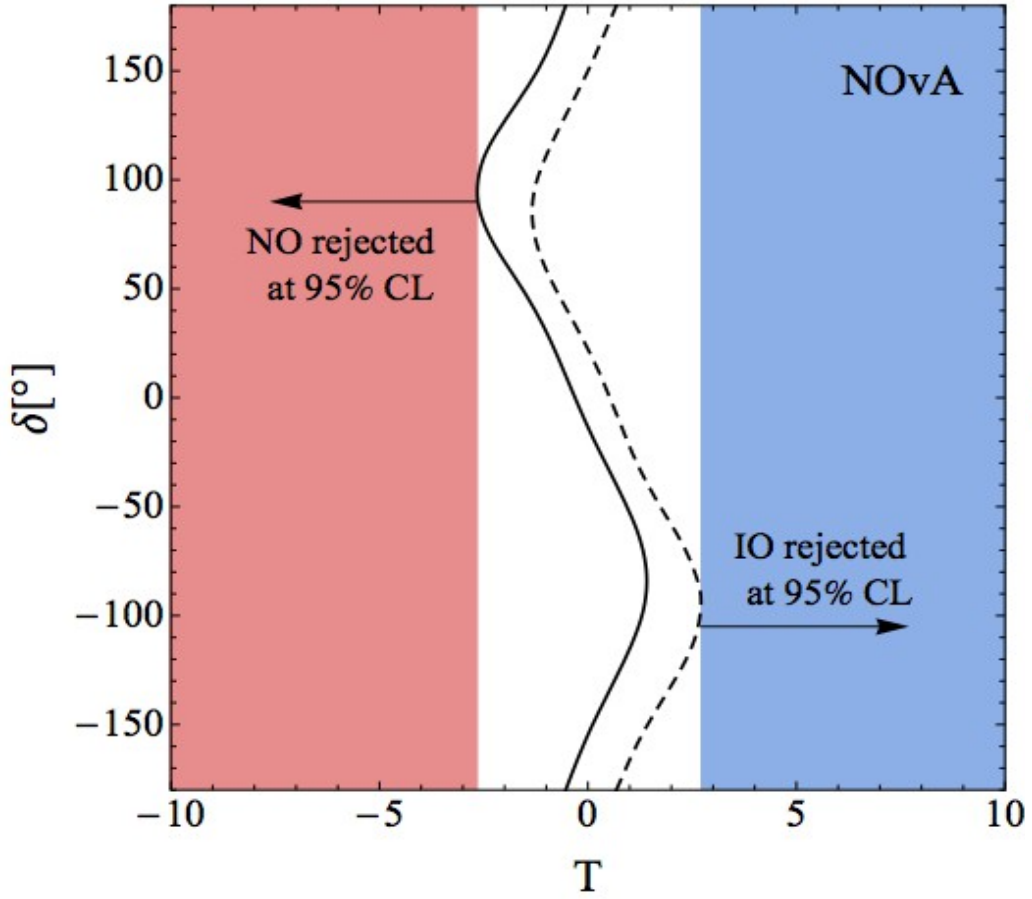
Long-baseline experiments

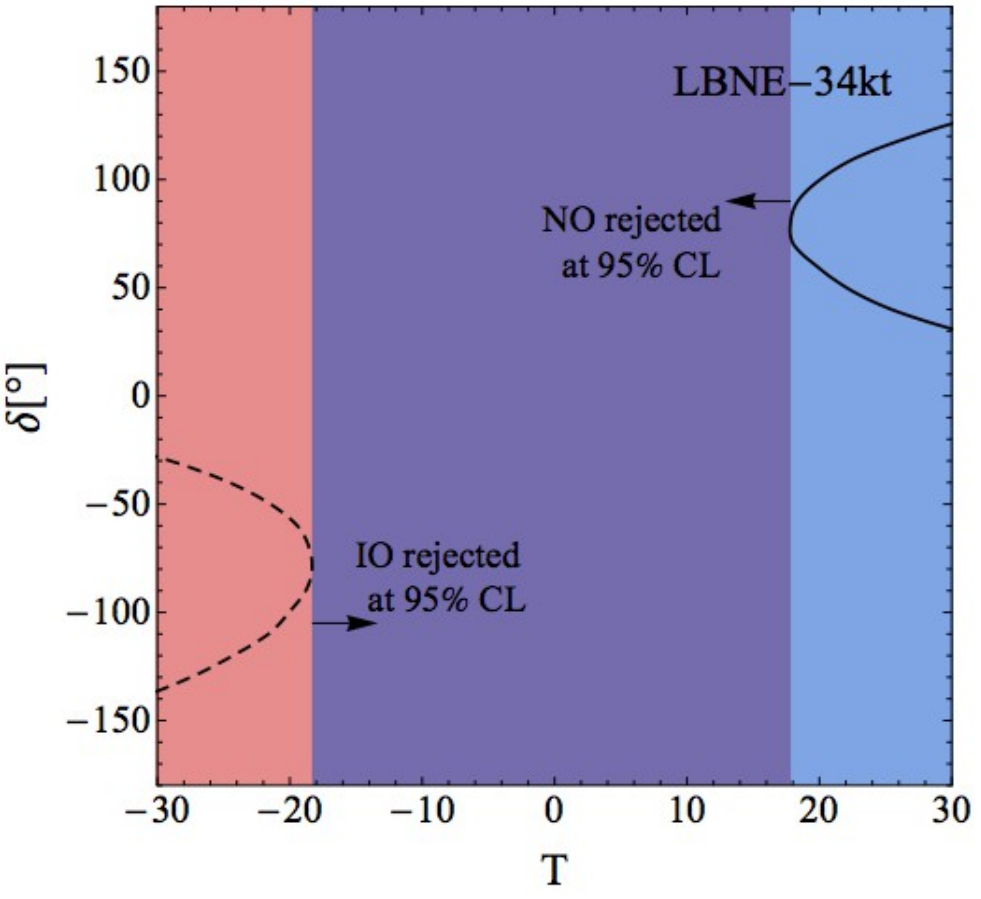




Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

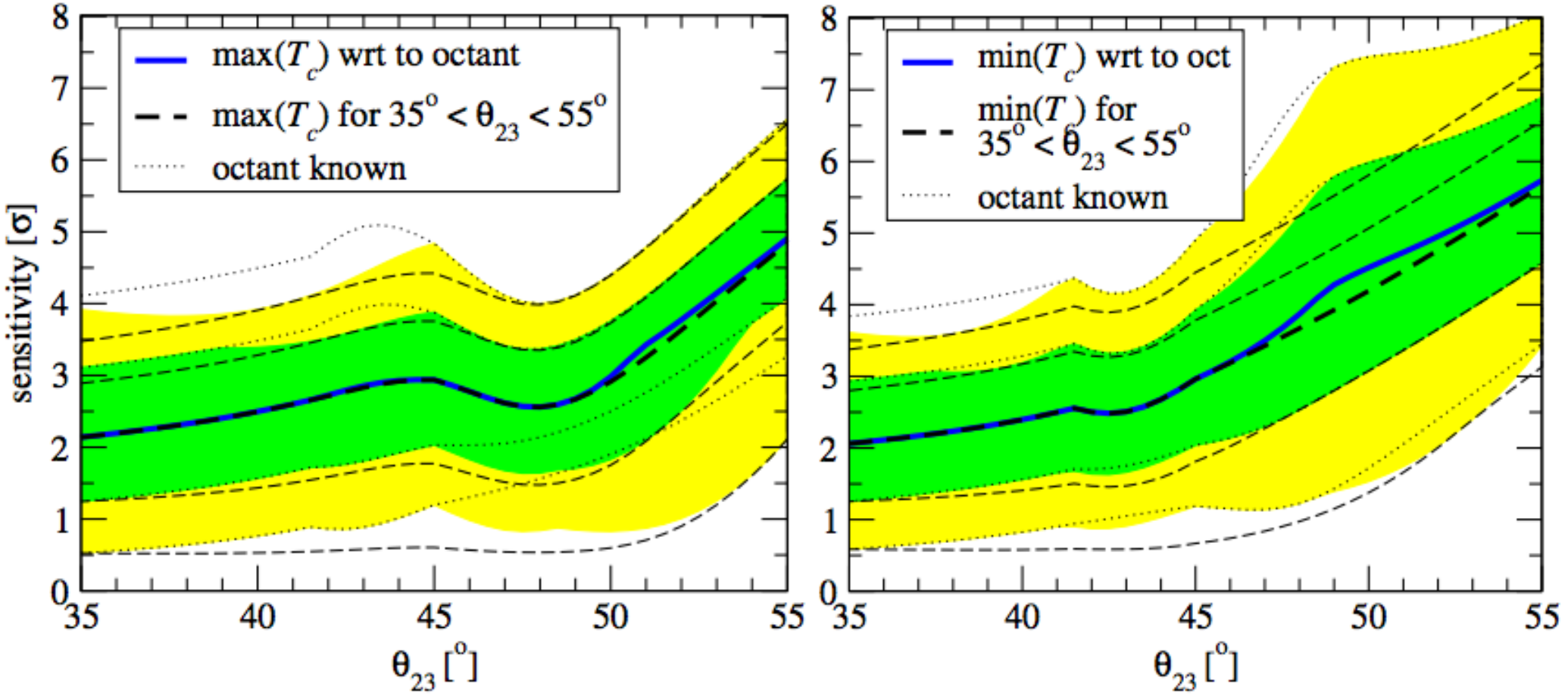
Long-baseline experiments





Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

PINGU: dependence with θ_{23}



Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

JUNO:

energy resolution	$3\%\sqrt{1\,\mathrm{MeV}/E}$		$3.5\%\sqrt{1\,\mathrm{MeV}/E}$	
	normal	inverted	normal	inverted
T_0 ($\sqrt{T_0}\sigma$)	10.1 (3.2σ)	11.1 (3.3σ)	5.4 (2.3σ)	5.9 (2.4σ)
median sens.	7.3×10^{-4} (3.4σ)	4.3×10^{-4} (3.5σ)	1.0×10^{-2} (2.5σ)	7.5×10^{-3} (2.7σ)
crossing sens.	5.2% (1.9σ)		12% (1.6σ)	

	σ_{E_ν}	σ_{θ_ν}	exposure	T_0^{NO} (med. sens.)	T_0^{IO} (med. sens.)
INO	$0.1E_\nu$	10°	10 yr × 50 kt	5.5 (2.6σ)	5.4 (2.6σ)
PINGU	$0.2E_\nu$	$29^\circ/\sqrt{E_\nu/\mathrm{GeV}}$	5 yr	12.5 (3.7σ)	12.0 (3.6σ)

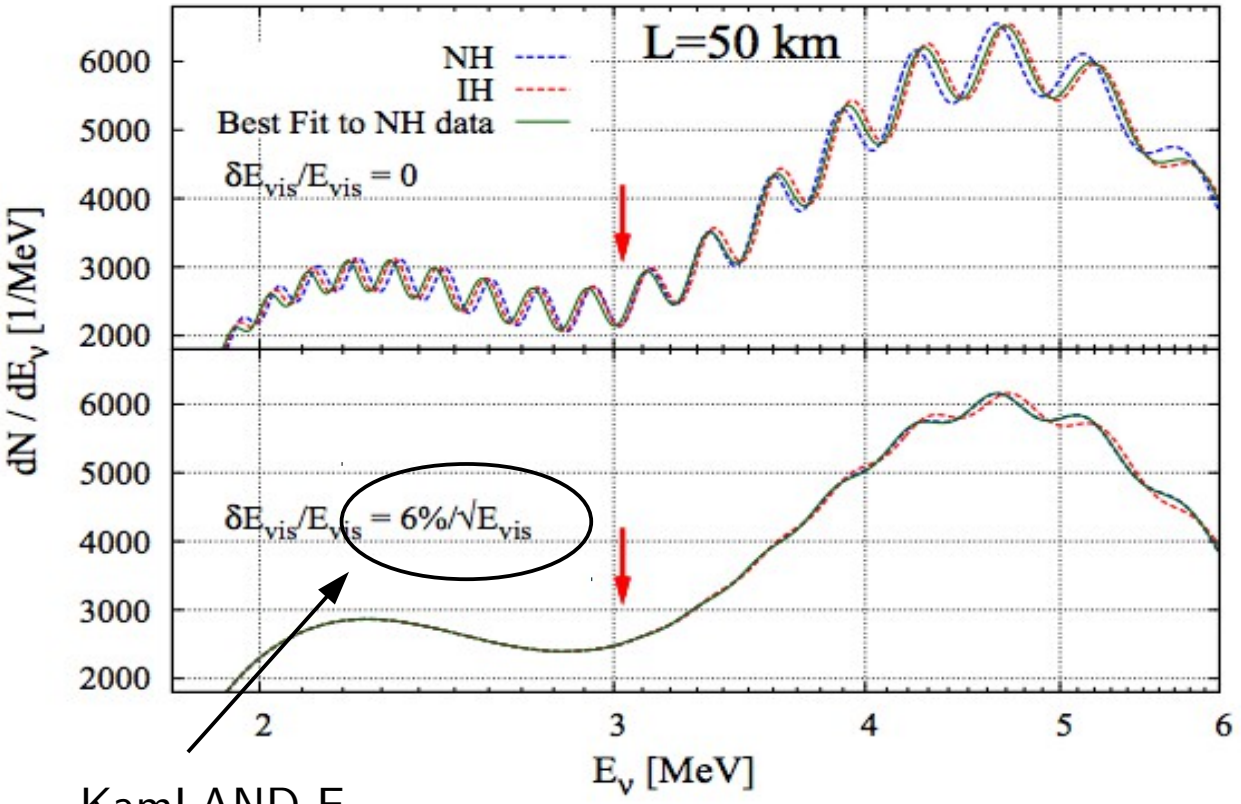
	L (km)	Off-axis angle	ν flux peak	Detector	M(kt)	Years $(\nu,\bar{\nu})$
NOνA	810	14 mrad	2 GeV	TASD	13 kt	(3,3)
LBNE-10(34) kt	1290	–	2.5 GeV	LAr	10(34) kt	(5,5)

(ii) Reactor experiment at medium baseline

Two major proposals: RENO-50 and JUNO

Technical challenges:

- energy resolution
- energy non-linearity
- reactor distribution



KamLAND E_{res}

(~1 kton)

Ge, Hagiwara, Okamura, Takaesu, 1210.8141 [hep-ph]

See also:

Zhan et al, 0807.3203, 0901.2976

Qian et al, 1208.1551

Kettell et al, 1307.7419

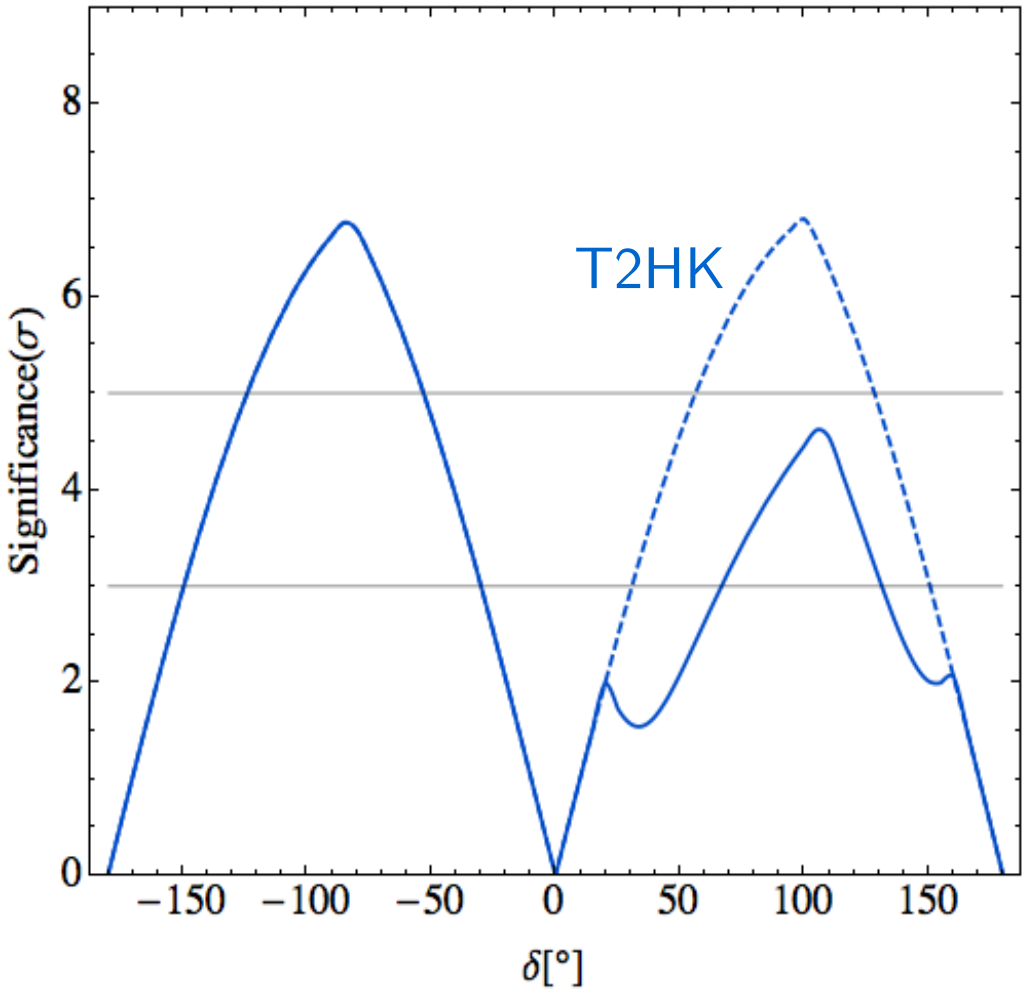
Learned et al, hep-ex/0612022

Ciuffoli et al, 1209.2227,1308.0591

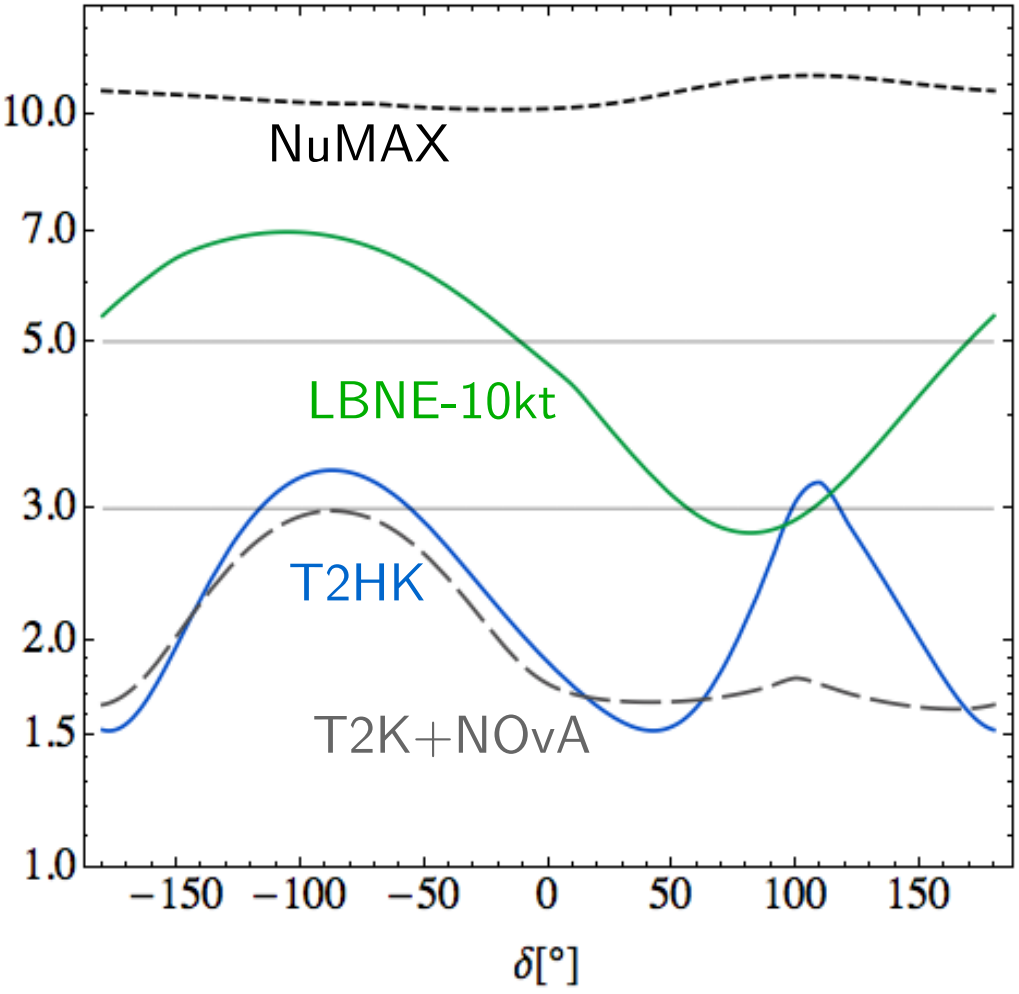
...

(i-a) Matter effects in appearance (beams)

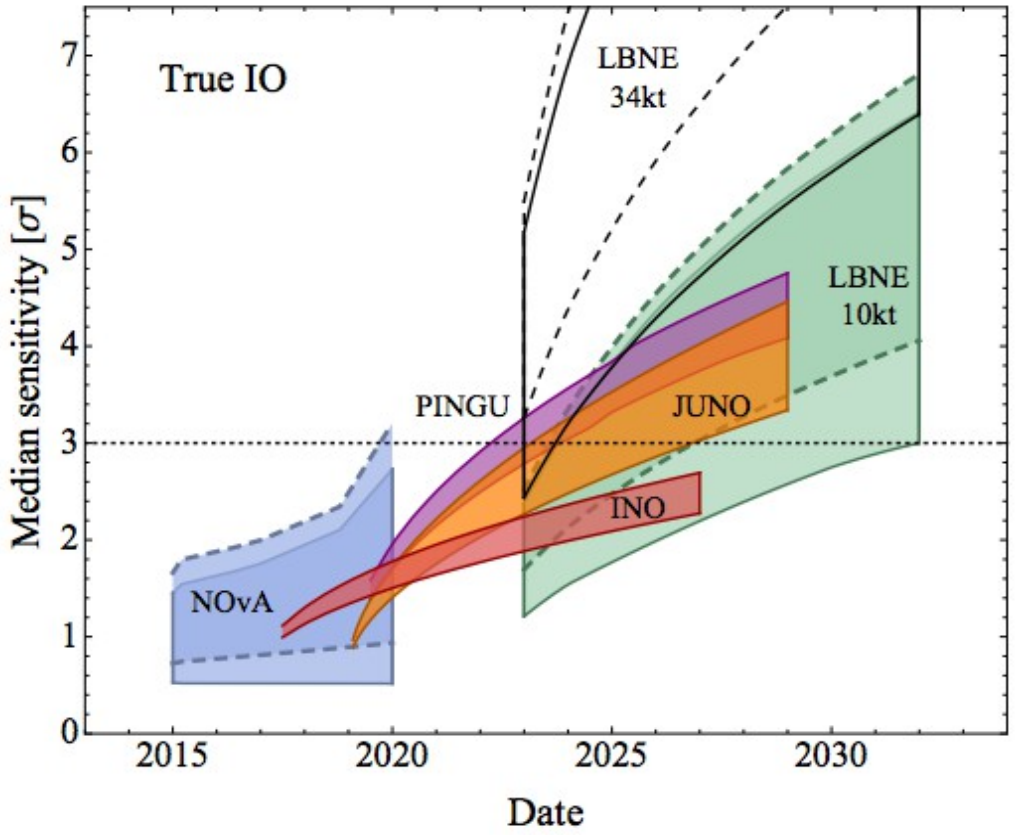
CP violation

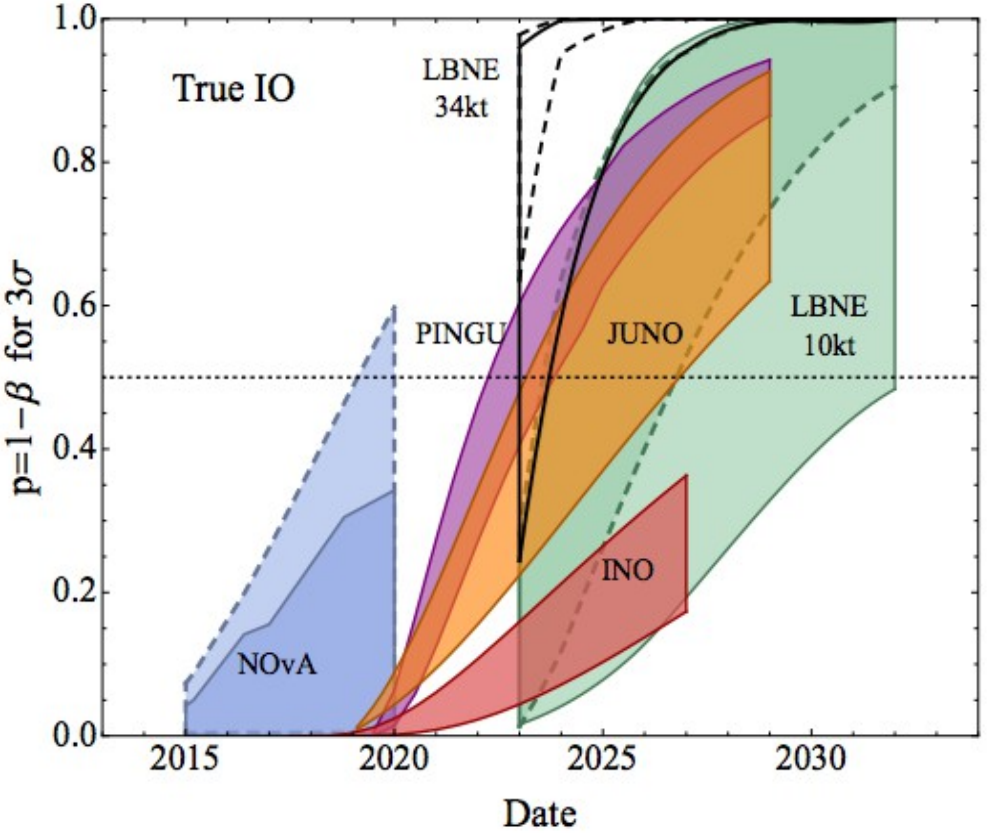


Mass ordering



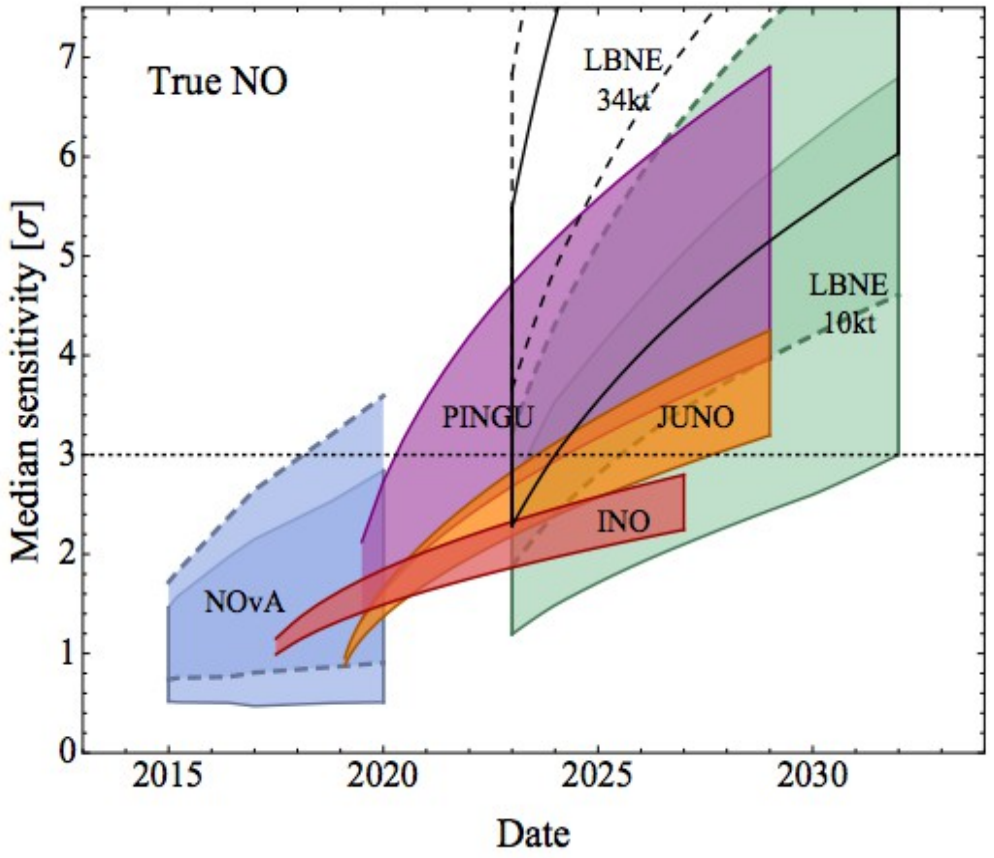
Present and future prospects

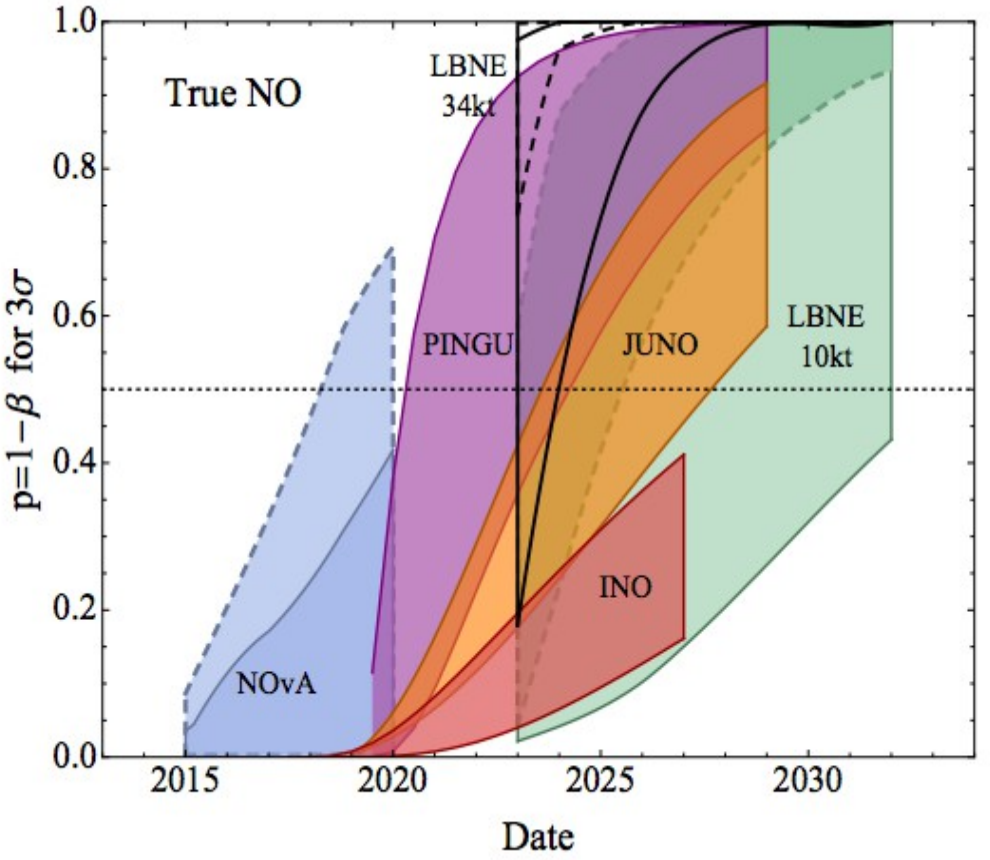




Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

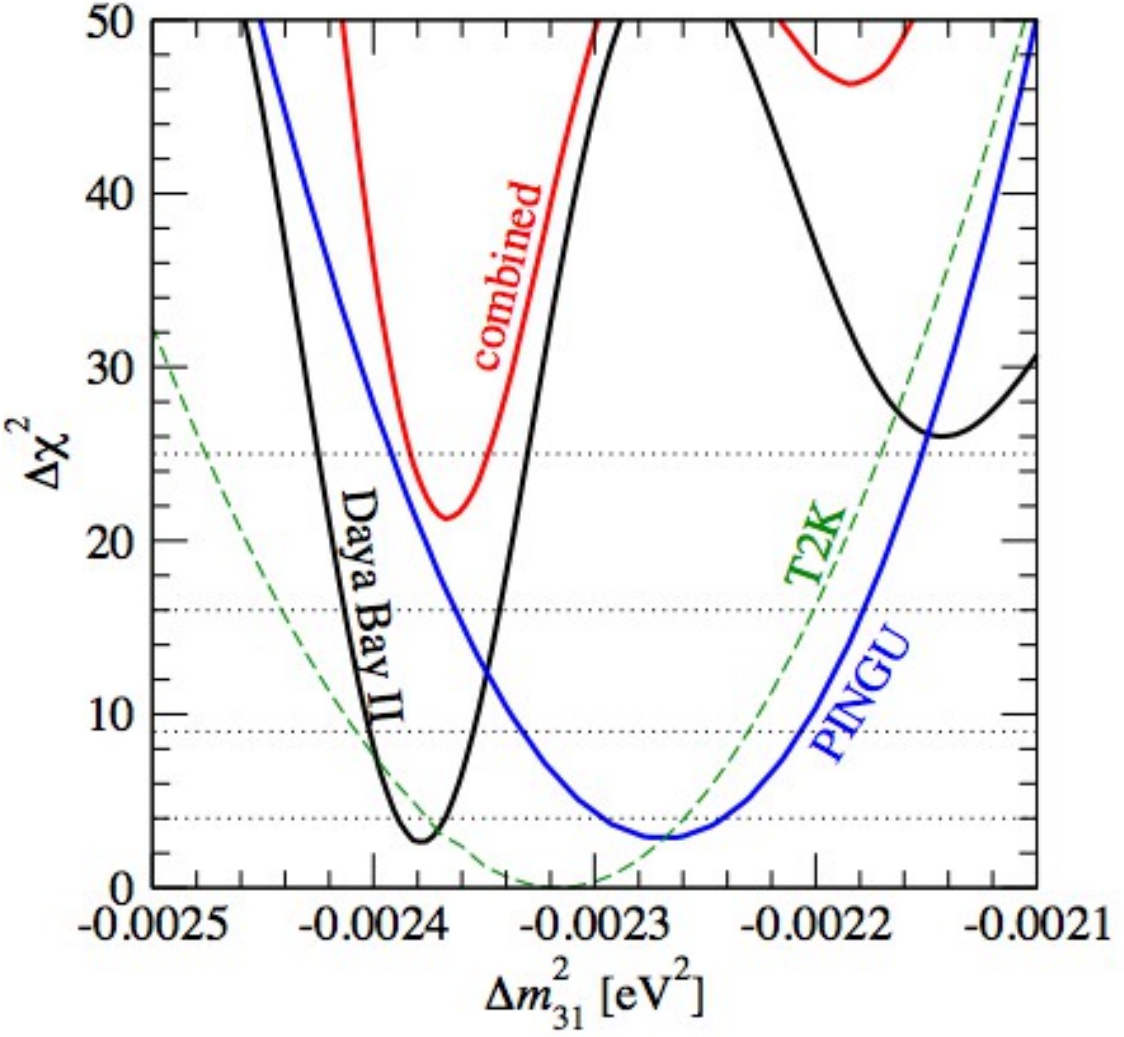
Future prospects





Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]

(iii) Precise measurements of mass splittings



Blennow, Schwetz, 1306.3988 [hep-ph]

(see also Li *et al*, 1303.6733 [hep-ph], for instance)

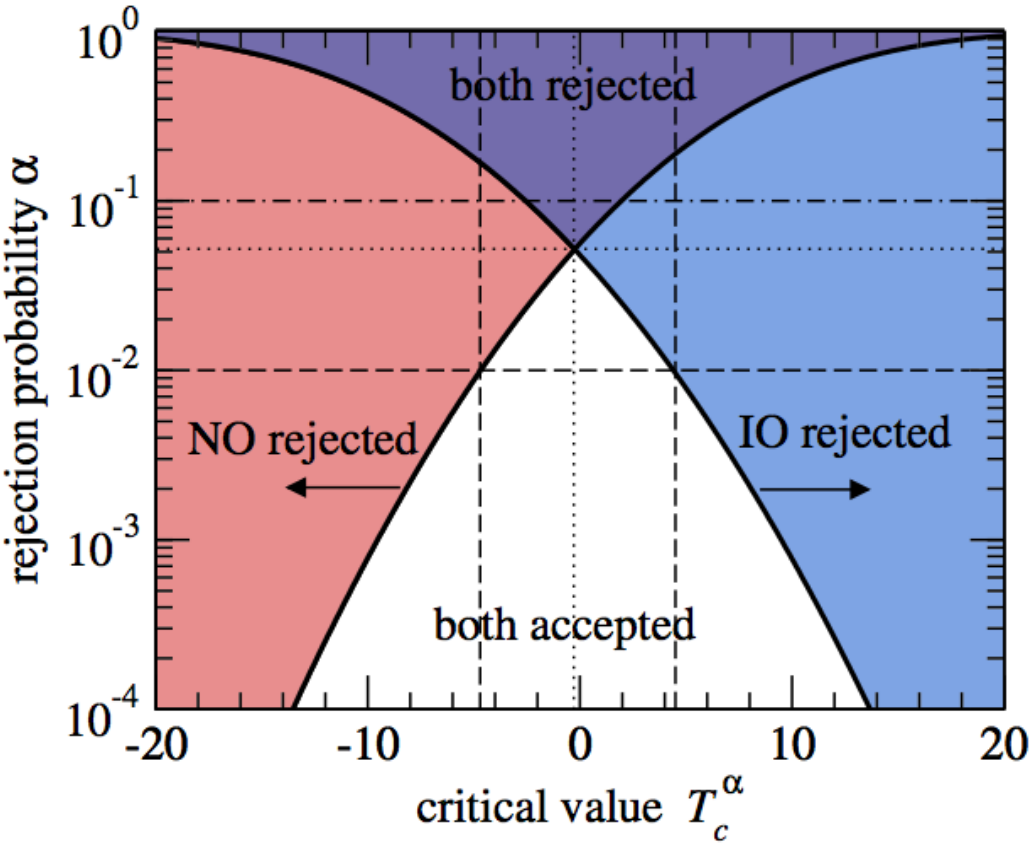
Hypothesis testing

Three possible outcomes are in principle possible:

1) Reject exactly one hypothesis

2) Reject both hypotheses

3) Accept both hypotheses



Blennow, Coloma, Huber and Schwetz, 1311.1822 [hep-ph]