Precision at future long baseline oscillation facilities

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Work in collaboration with
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arXiv: 1203.5651 [hep-ph]

NuFact12, July 24th 2012
W&M, Williamsburg, VA

Outline

- Present status of the U_{PMNS} matrix and θ_{13}
- Why precision?
- General landscape: discovery vs precision
- Simulation details
- Analytical approach and phenomenology
- Results:
  - for θ_{13}
  - for delta
- Summary and conclusions

Present status on θ_{13}

- Global analyses, 2008:

0808.2016 [hep-ph]
0806.2649 [hep-ph]

$$\sin^2 2\theta_{13} = 0.06 \pm 0.04$$

- T2K, 2011:

$$\sin^2 2\theta_{13} = 0.11^{+0.17}_{-0.08} (90\%)$$

1106.2822 [hep-ex]

$$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$$

Nakaya's talk at
Neutrino 2012

- MINOS, 2011:

$$\sin^2 2\theta_{13} = 0.041^{+0.047}_{-0.031} (90\%)$$

1108.0015 [hep-ex]

- Global analyses, 2011:

1106.6028 [hep-ex]
1108.1376 [hep-ph]

$$\sin^2 2\theta_{13} = 0.098 \pm 0.027$$

Present status on θ_{13}

- D-Chooz, 2011:

$$\sin^2 2\theta_{13} = 0.109 \pm 0.030 \pm 0.025$$

Ishitsuka's talk at Neutrino 2012

- Daya Bay, 2012:

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$$

Dwyer's talk at Neutrino 2012

- RENO, 2012:

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013 \pm 0.019$$

1204.0626 [hep-ex]

The leptonic mixing matrix

Pontecorvo, 1957

Maki, Nakagawa, Sakata, 1962

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric | Interference | Solar

$$\Delta m^2_{31} = 2.47 \times 10^{-3} \mathrm{eV}^2$$

$\sin^2\theta_{23} = 0.386$ (for NH)

$$\Delta m^2_{21} = 7.54 \times 10^{-5} \mathrm{eV}^2$$

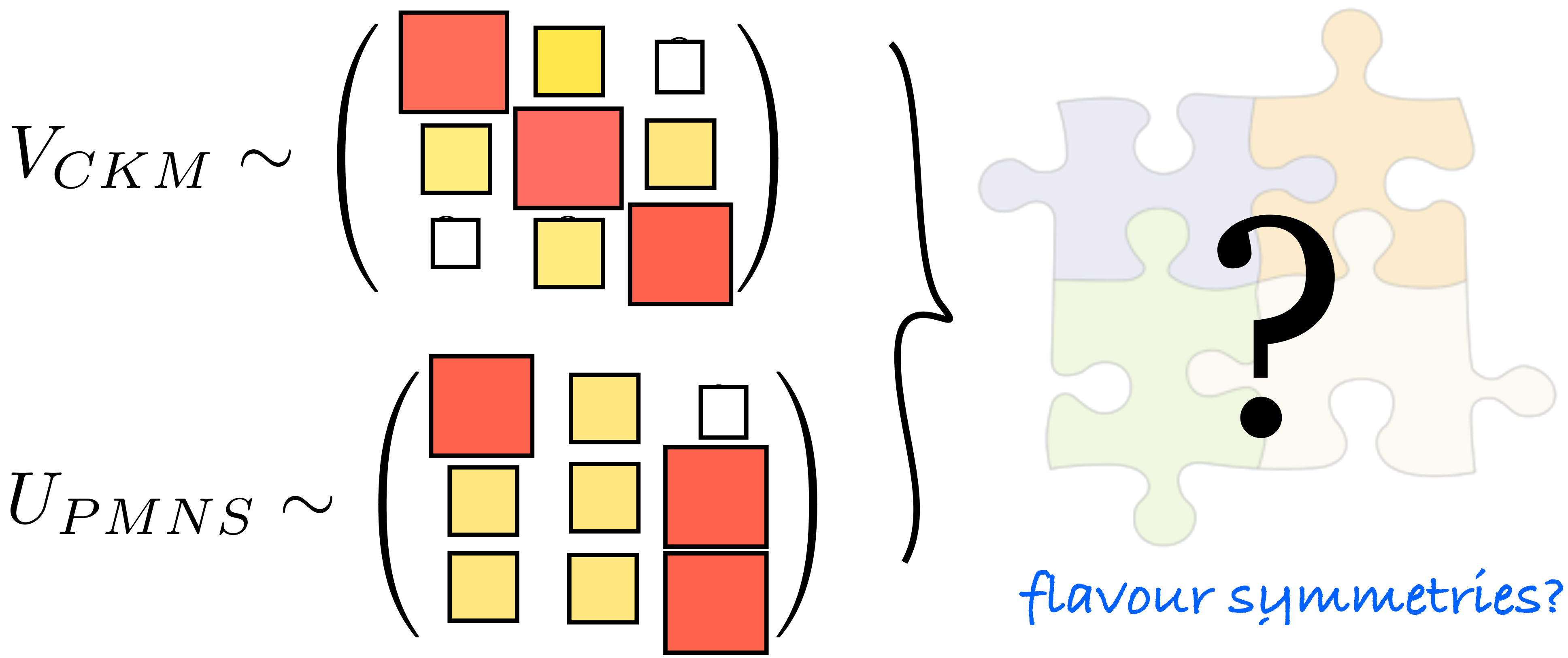
$$\sin^2\theta_{12} = 0.307$$

$\sin^2\theta_{13} = 0.0241$ (for NH)

Fogli et al., 1205.5254 [hep-ph]

(see also Forero et al, 1205.4018 [hep-ph])

Why precision?



Parameter	Value (neutrino PMNS matrix)	Value (quark CKM matrix)
θ_{12}	$34 \pm 1^\circ$	$13.04 \pm 0.05^\circ$
θ_{23}	$43 \pm 4^\circ$	$2.38 \pm 0.06^\circ$
θ_{13}	$9 \pm 1^\circ$	$0.201 \pm 0.011^\circ$
Δm^2_{21}	$+(7.58 \pm 0.22) \times 10^{-5}$ eV^2	
$\lvert\Delta m^2_{32}\rvert$	$(2.35 \pm 0.12) \times 10^{-3}$ eV^2	$m_3 >> m_2$
δ_{CP}	unknown	$67 \pm 5^\circ$

Table from Bishai's talk at PXPS

The setups

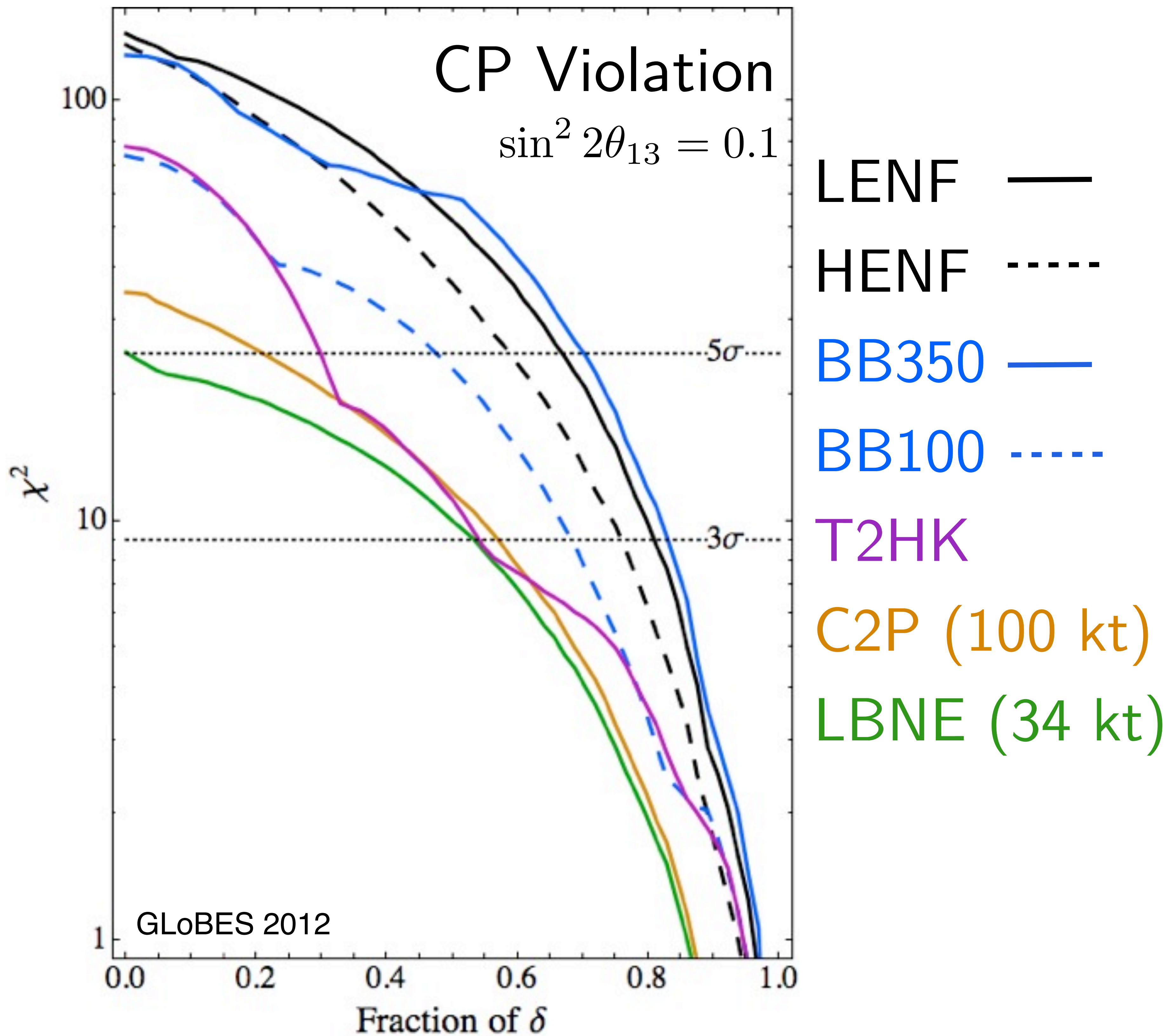
- T2HK (1109.3262 [hep-ex]): 4 MW, 8 years (4+4), 500 kton WC simulated as in hep-ph/0204352, L=295 km
- C2P (1001.0077 [physics.ins-det]): 800 kW, fluxes from PoS ICHEP2010 (2010) 325, 10 years (5+5), 100 kton LAr, L=2300 km
- LBNE (1110.6249 [hep-ex]): 700 kW, 10 years (5+5), 34 kton LAr, L=1290 km
- SPL (detector as in hep-ph/0603172, fluxes from 1106.1096 [physics-acc.ph]): 4 MW, 10 years (2+8), 500 kton WC, L=130 km

The setups

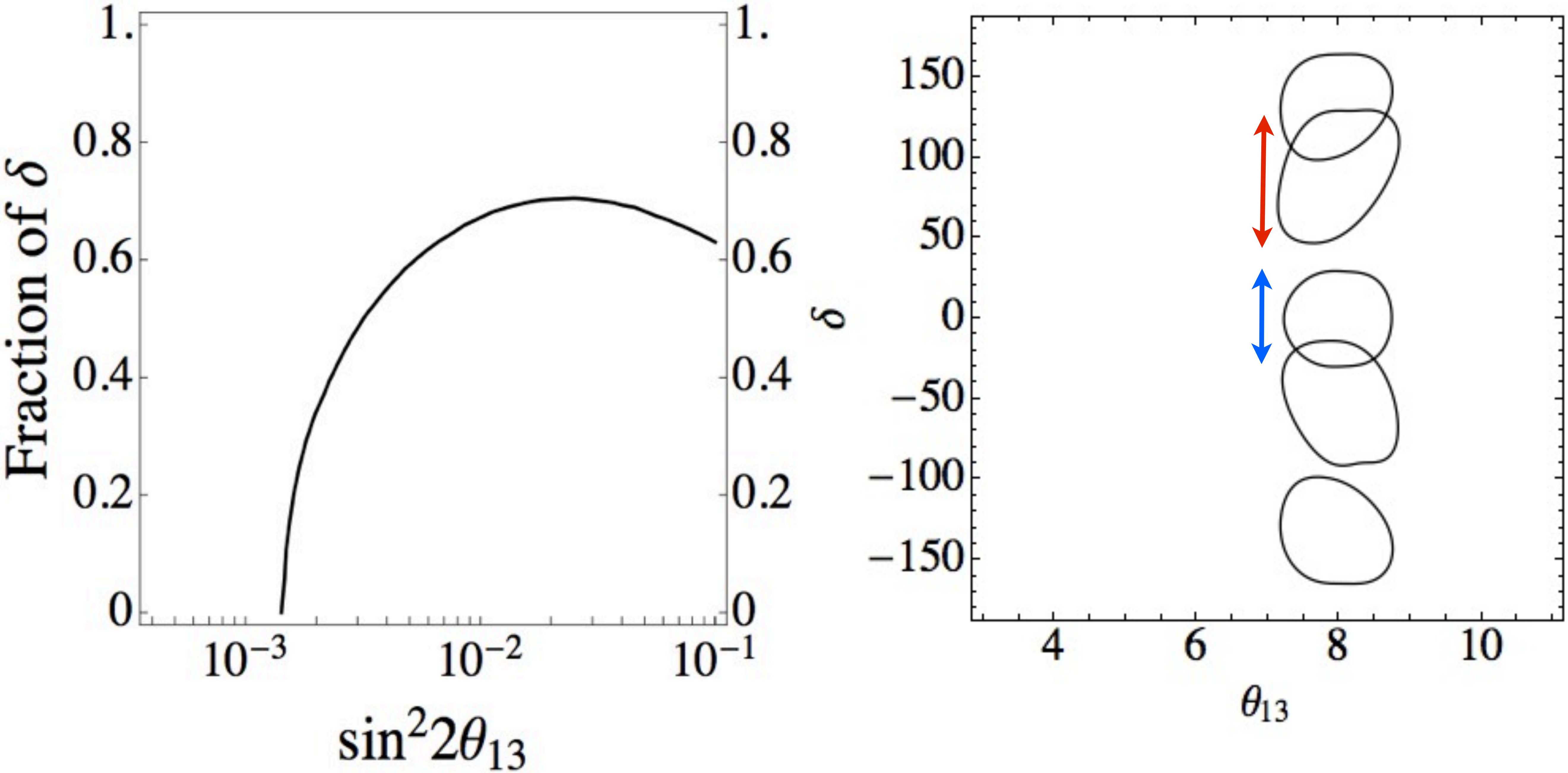
- BB350/100 (hep-ph/0312068, hep-ph/0503021): γ=350, 1.1(2.8)e18 useful ^{18}Ne(^{6}He) ion decays per year, 10 years (5+5), 500 kton WC, L=650/130 km

- LENF/IDS1B (1012.1872 [hep-ph],): 10/25 GeV muons, 1.4e21 useful muon decays per year, 10 years (5+5), 100 kton MIND, L=2000/4000 km

General landscape

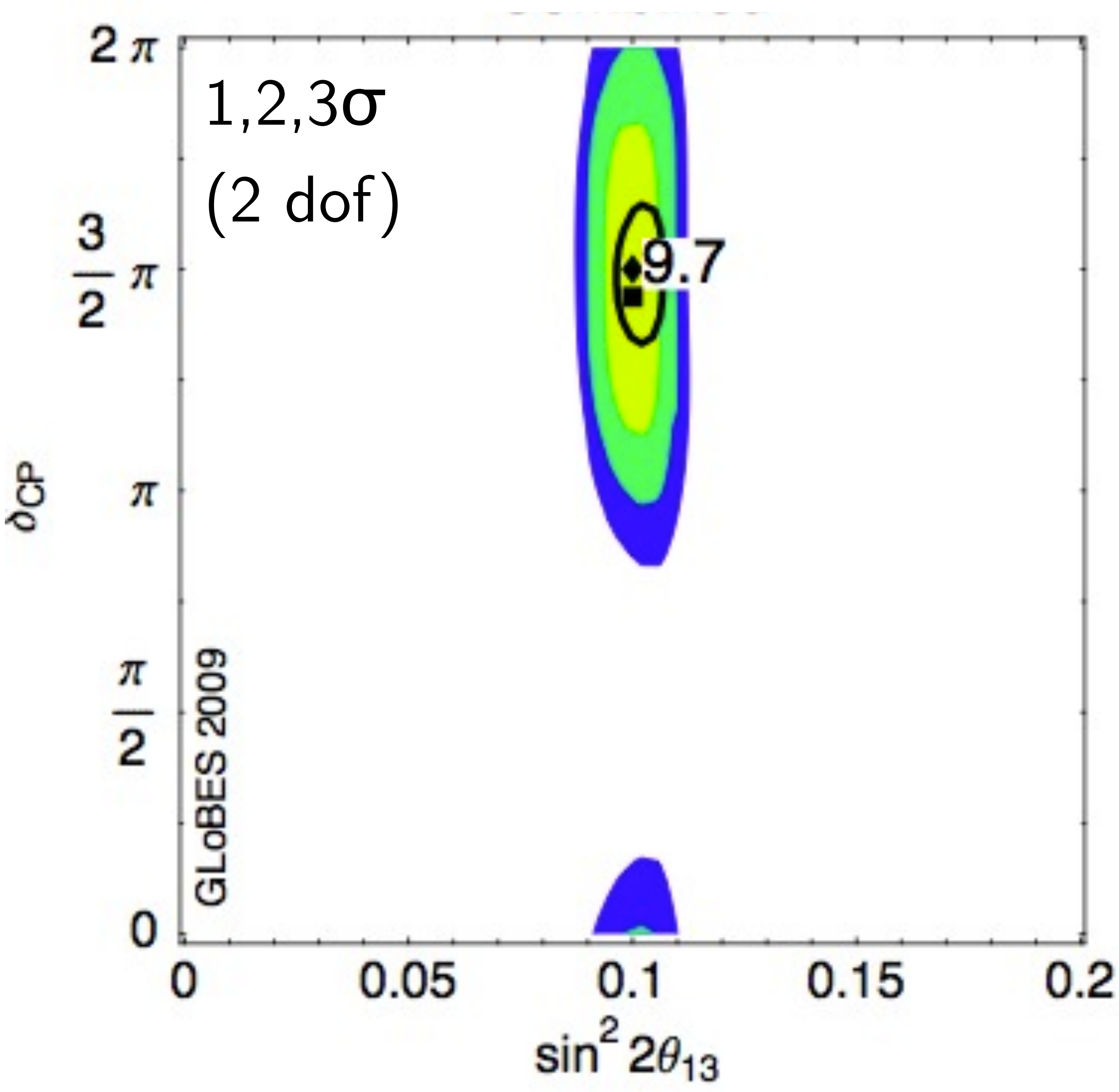


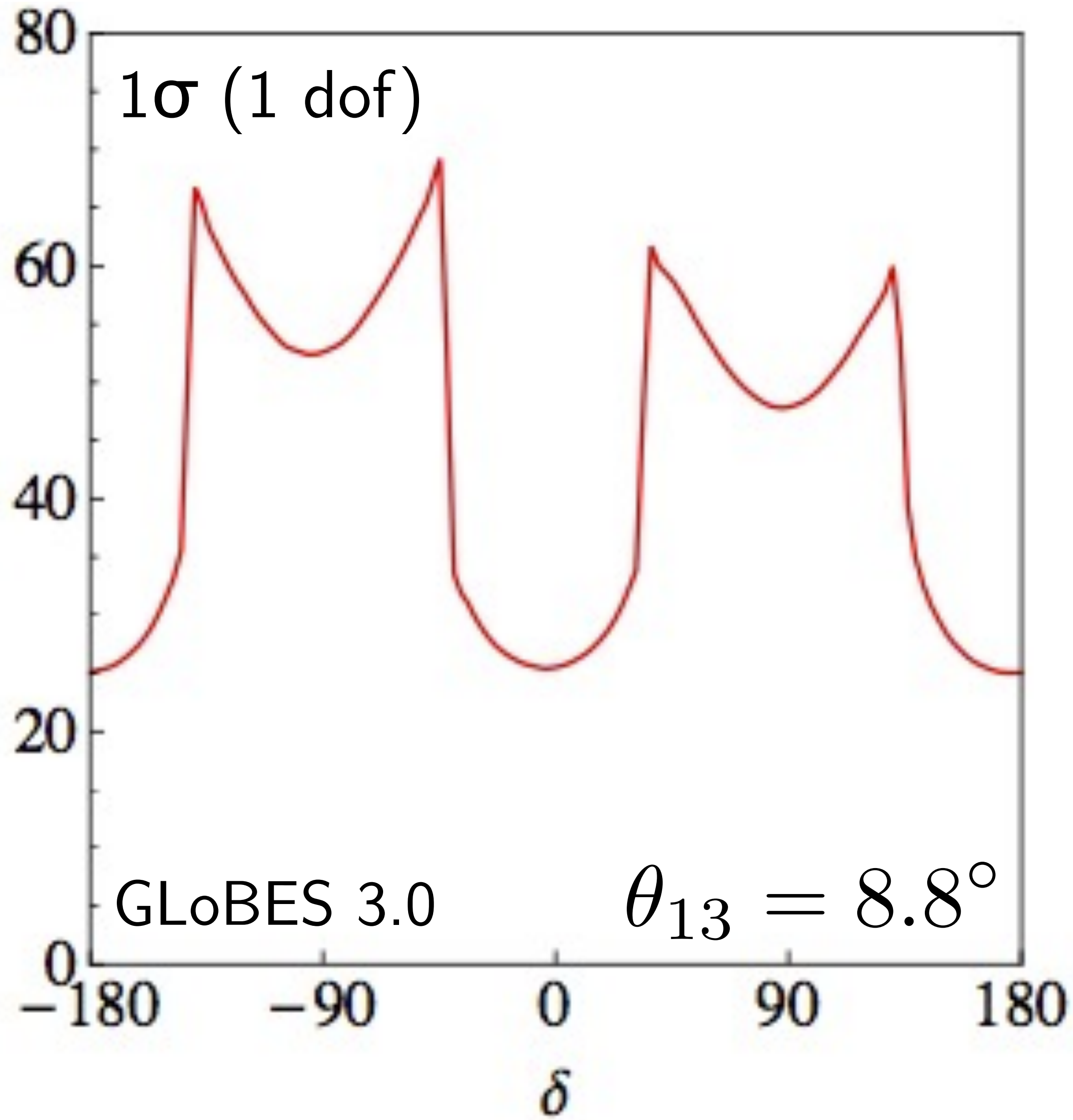
Discovery vs precision



The starting point

NOvA+T2K+Daya Bay





Huber, Lindner, Schwetz, Winter, 0907.1896 [hep-ph]

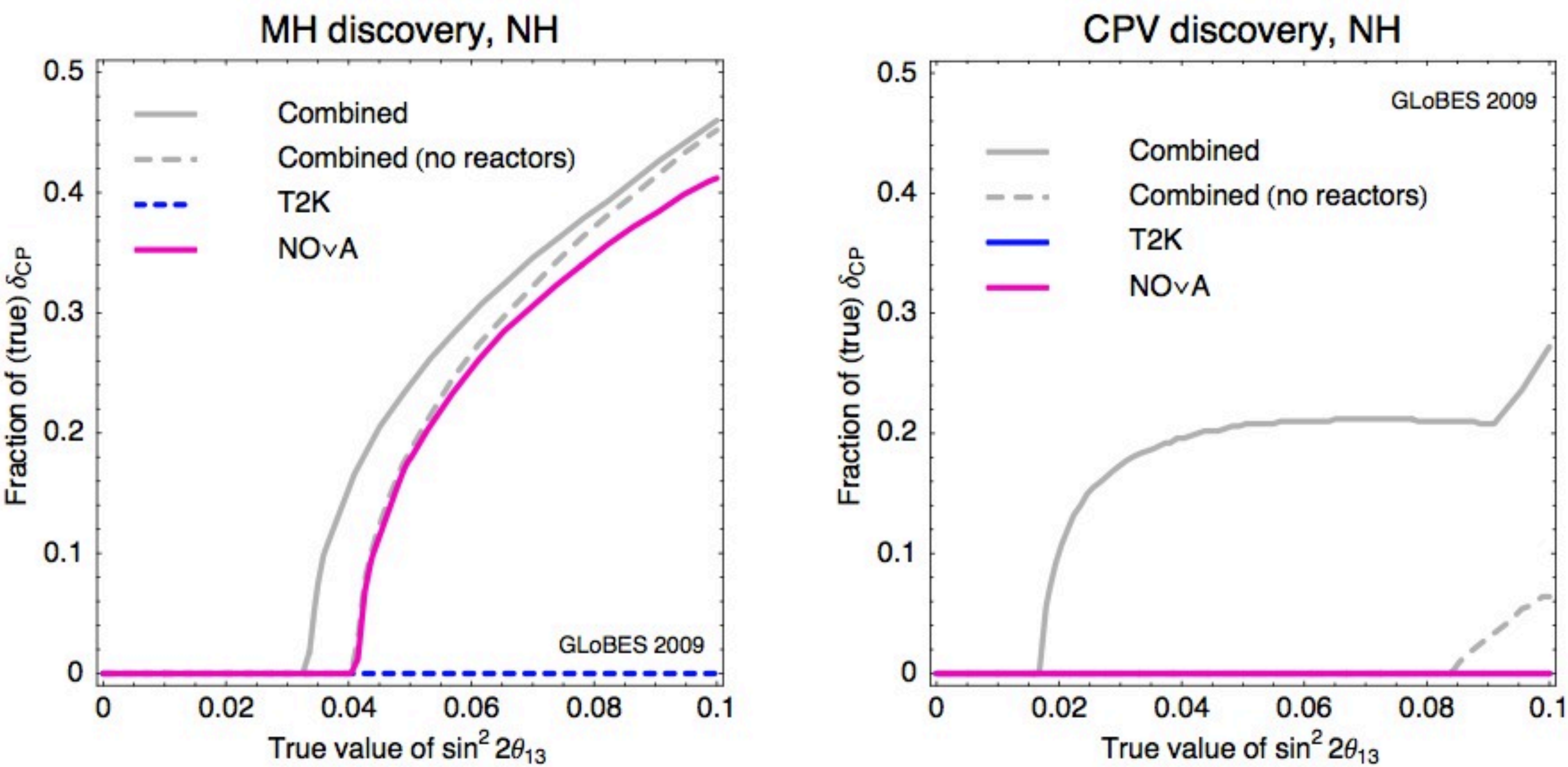
Coloma, Donini, Fernández-Martínez, Hernández, 1203.5651 [hep-ph]

Simulation details

- GLoBES software used — hep-ph/0407333, hep-ph/0701187
- Input values in agreement with best fits — 1205.5254 [hep-ph], 1205.4018 [hep-ph]
- Marginalization over solar and atmospheric params performed assuming 1σ gaussian priors — 1108.1376 [hep-ph]
- θ_{13} varied in the 3σ range allowed by Daya Bay, around their best fit in March 2012 — 1203.1669 [hep-ex]
- 1σ (1 dof) unless stated otherwise
- No degeneracies have been accounted for: atmospheric angle set to maximal, normal hierarchy

Mass hierarchy

Discovery potential at the 90% CL

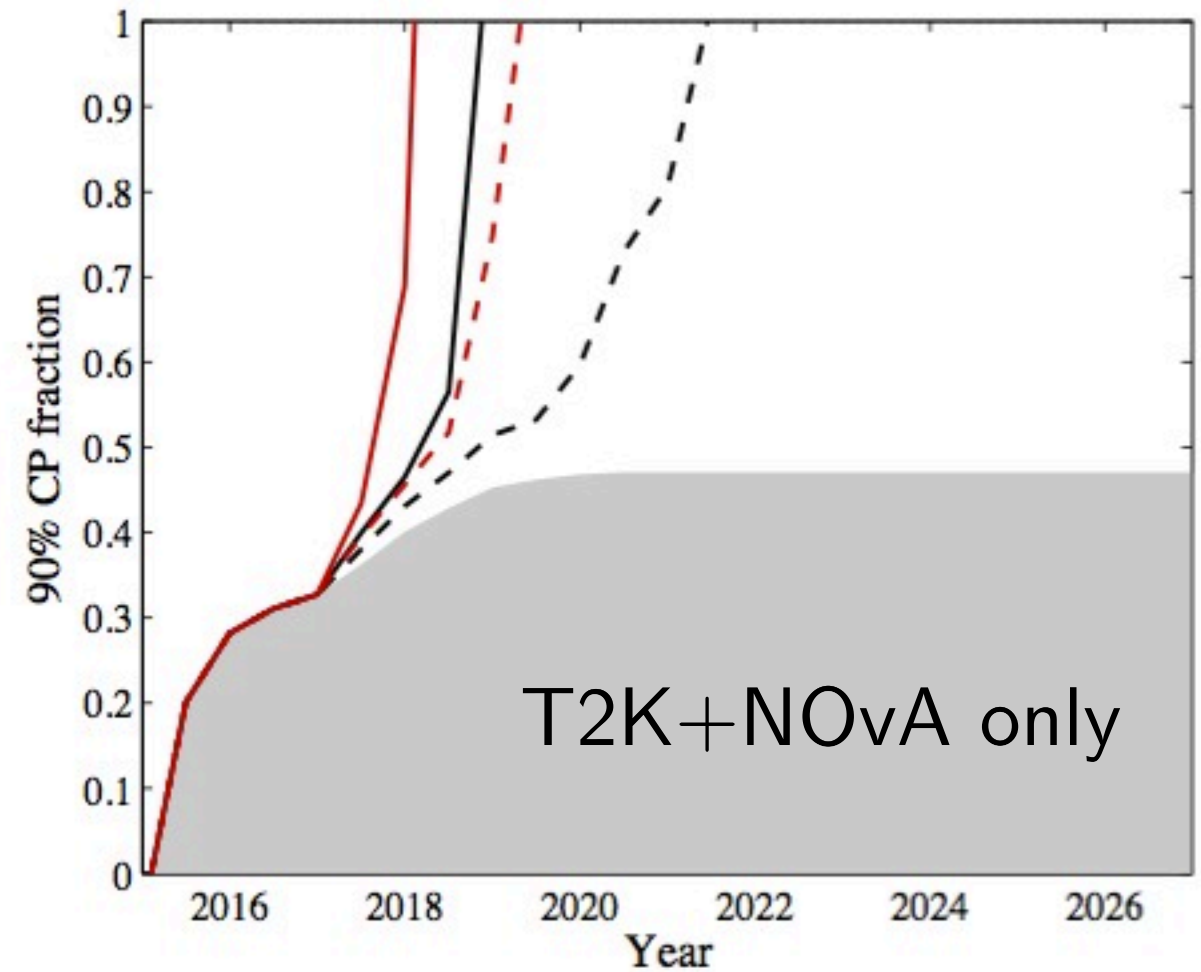


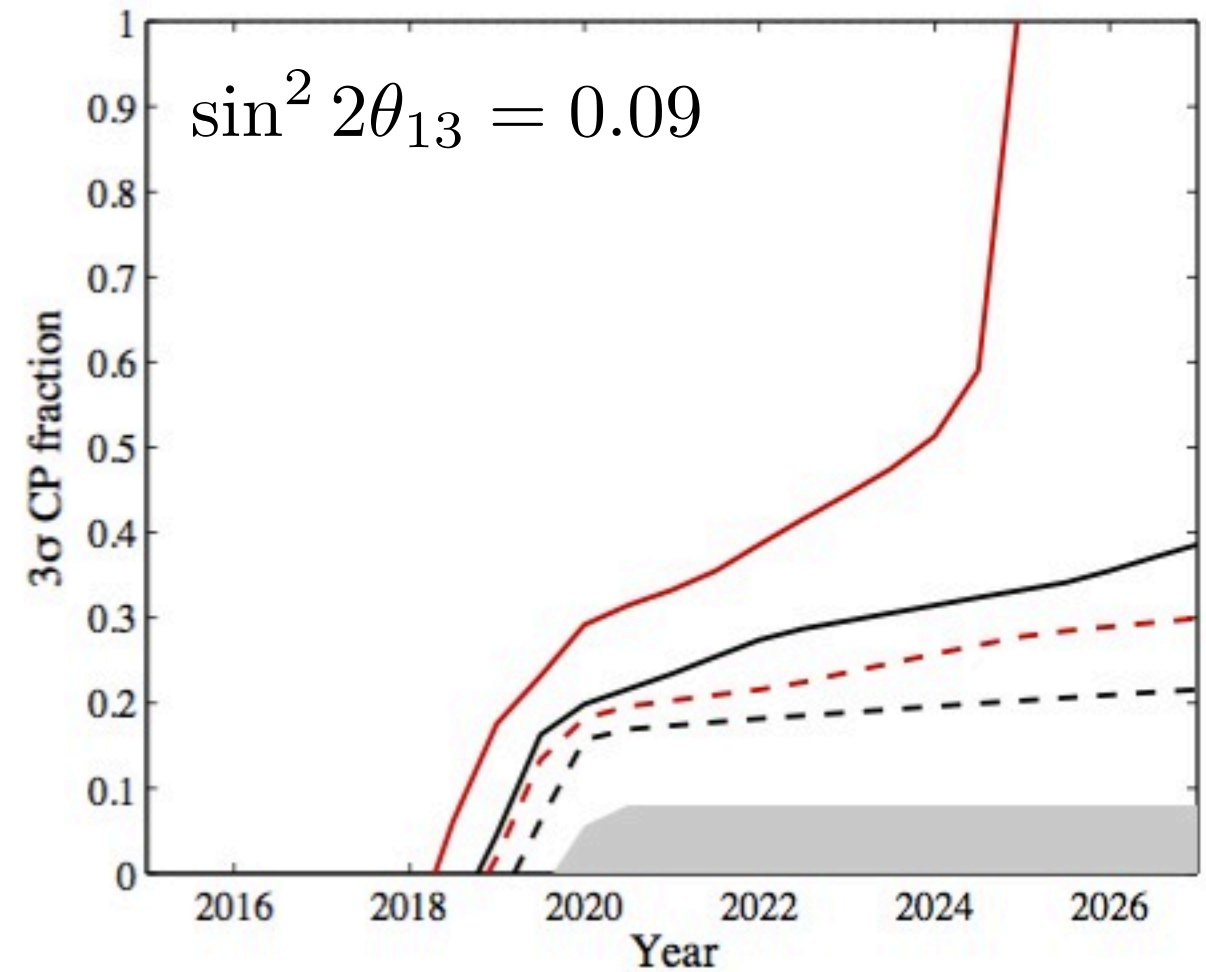
Huber, Lindner, Schwetz, Winter, 0907.1896 [hep-ph]

Mass Hierarchy

T2K+NOvA+INO

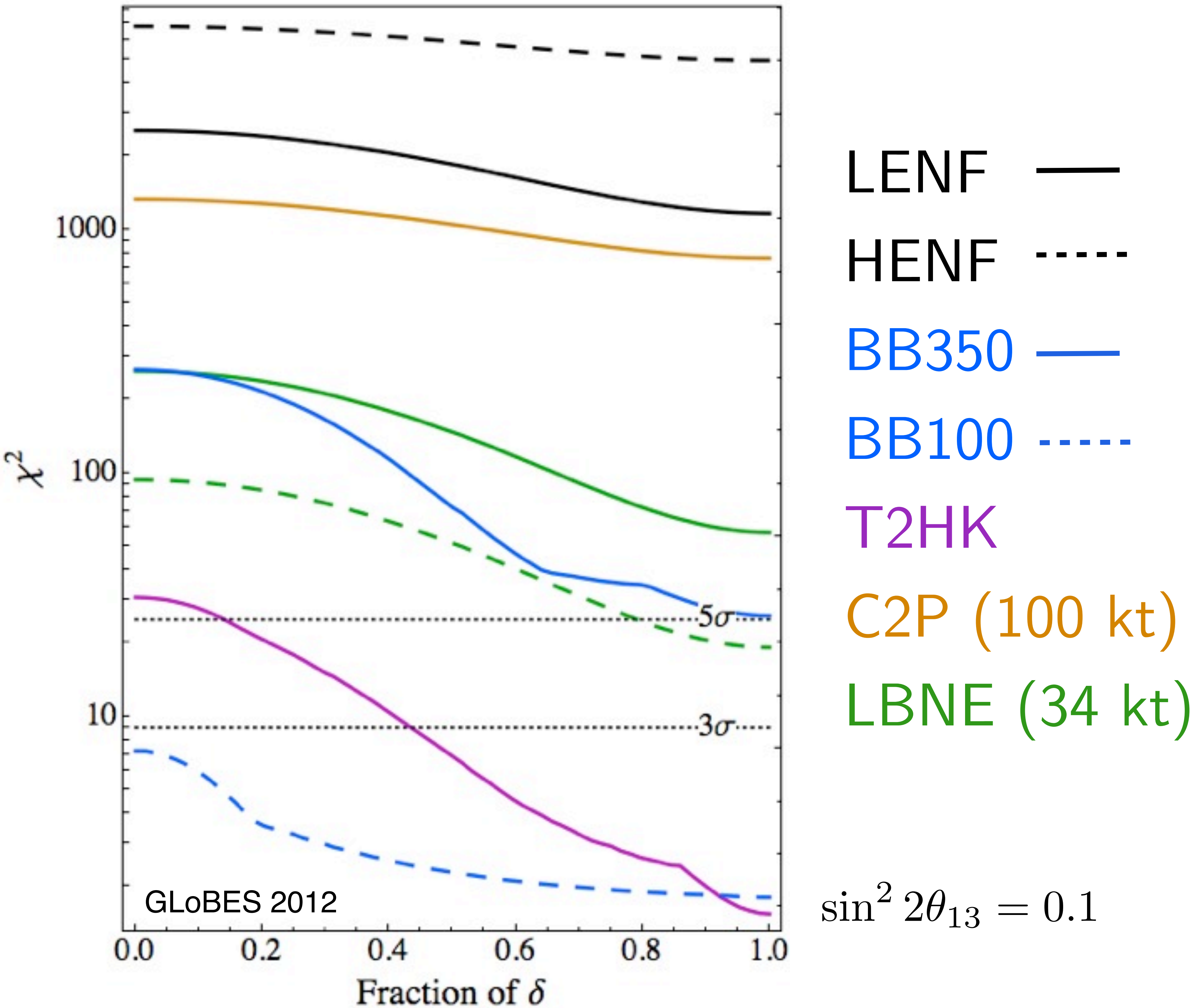
(50kt/100kt; low/high res)





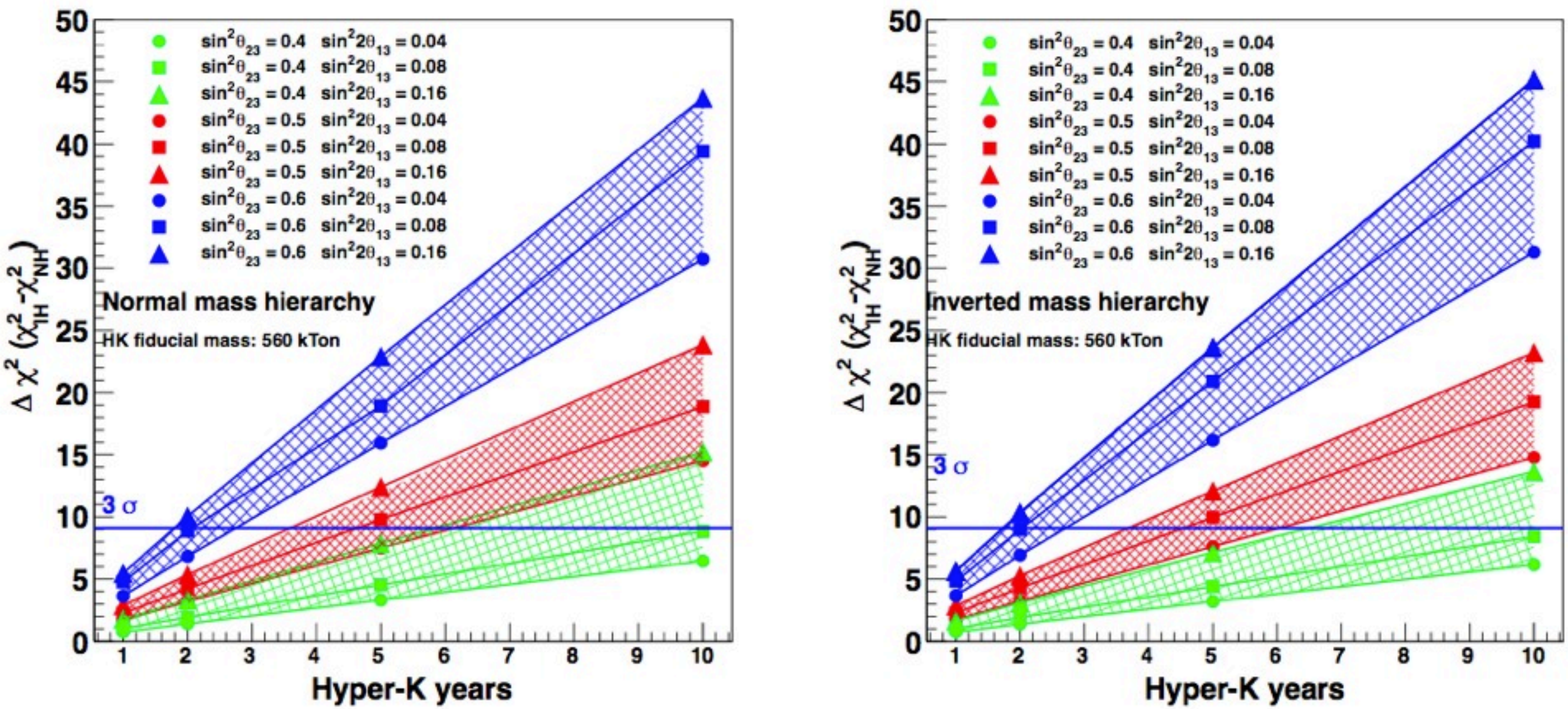
Blennow, Schwetz, 1203.3388 [hep-ph]

Mass hierarchy



$\sin^2 2\theta_{13} = 0.1$

Mass Hierarchy



HK LoI, 1109.3262 [hep-ex]

Precision in theta13

Error propagation

$$\Delta N_{\pm} = \left| \frac{\partial N_{\pm}}{\partial \theta_{13}} \right| (\Delta \theta_{13})_{\pm}$$

neutrino/antineutrino

Error propagation

$$\Delta N_{\pm} = \left|\frac{\partial N_{\pm}}{\partial \theta_{13}}\right| (\Delta\theta_{13})_{\pm} \propto \theta_{13} \frac{\sin^2((1 \mp \hat{A})\Delta)}{(1 \mp \hat{A})^2} (\Delta\theta_{13})_{\pm} + \ldots$$

$$\hat{A} \equiv \frac{\sqrt{2} G_F n_e L}{2\Delta} \,;\, \Delta \equiv \frac{\Delta m^2_{13} L}{4E}$$

The final error would be:

$$(\Delta\theta_{13}) \simeq \left(\sqrt{\frac{1}{(\Delta\theta_{13})^2_+} + \frac{1}{(\Delta\theta_{13})^2_-}}\right)^{-1}$$

Error propagation

$$(\Delta\theta_{13})_\pm \propto \left[\frac{(1\mp\hat{A})^2}{\sin^2((1\mp\hat{A})\Delta)}\right]\frac{1}{\theta_{13}}\Delta N_\pm$$

Statistical limit:

$$\Delta N_\pm \propto \sqrt{N_\pm} \quad \propto \theta_{13} \longrightarrow (\Delta\theta_{13})_\pm \propto const$$

Systematics on the signal:

$$\Delta N_\pm \propto N_\pm \quad \propto \theta_{13}^2 \longrightarrow (\Delta\theta_{13})_\pm \propto \theta_{13}$$

Background error:

$$\Delta N_\pm \propto const \longrightarrow (\Delta\theta_{13})_\pm \propto 1/\theta_{13}$$

Precision in θ_{13}

Statistical limit:

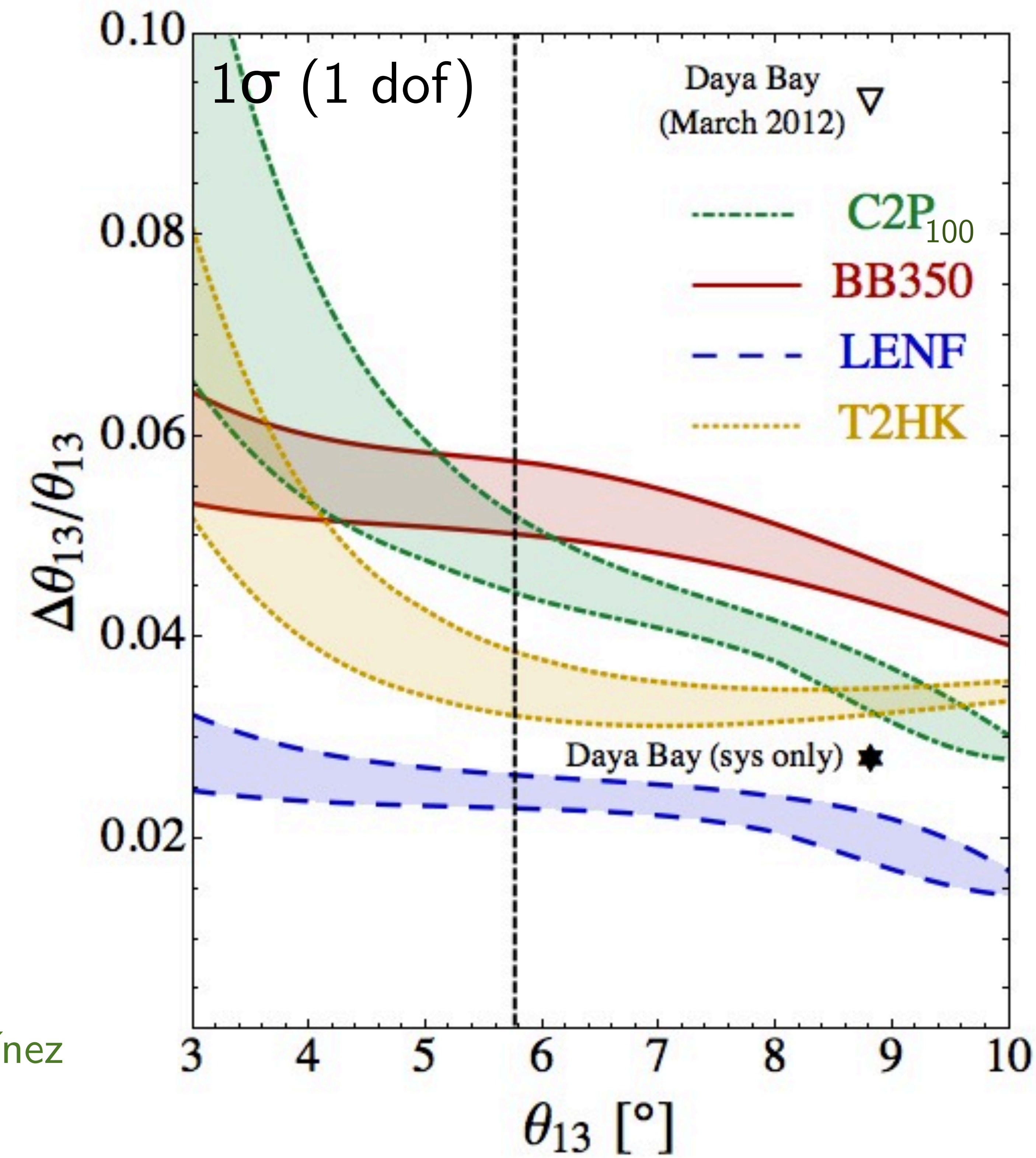
$$\frac{\Delta\theta_{13}}{\theta_{13}} \propto \frac{1}{\theta_{13}}$$

Systematics on the signal:

$$\frac{\Delta\theta_{13}}{\theta_{13}} \propto const$$

Background error:

$$\frac{\Delta\theta_{13}}{\theta_{13}} \propto \frac{1}{\theta_{13}^2}$$



P. Coloma, A. Donini, E. Fernández-Martínez and P. Hernández, 1203.5651 [hep-ph]

Precision in delta

Precision in δ

Error propagation:

$$(\Delta\delta)_{\pm} \propto \left| \frac{\hat{A}\Delta}{\sin \hat{A}\Delta \sin(\Delta \mp \delta)} \right|$$

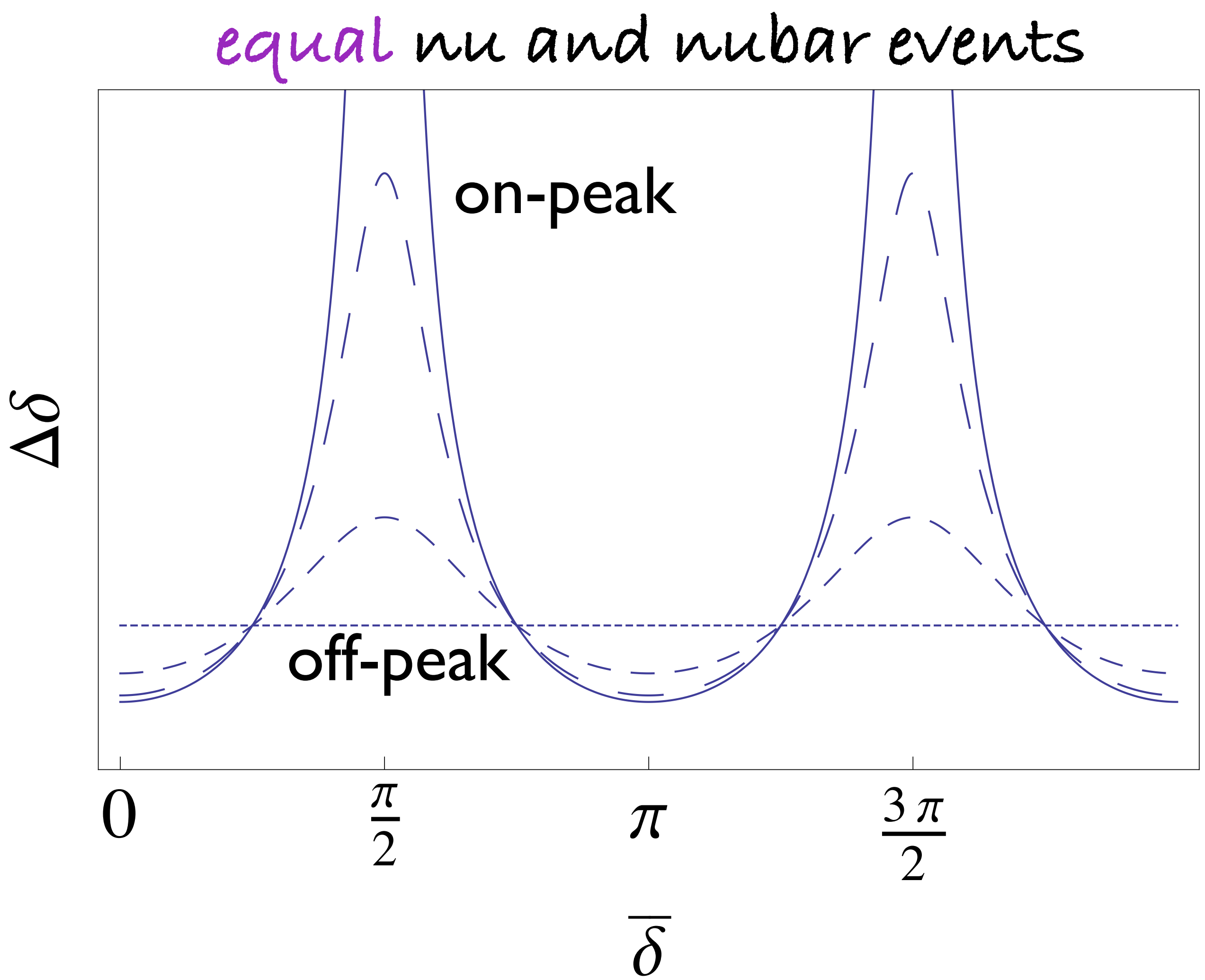
position of maxima depend both
on delta and the matter effects

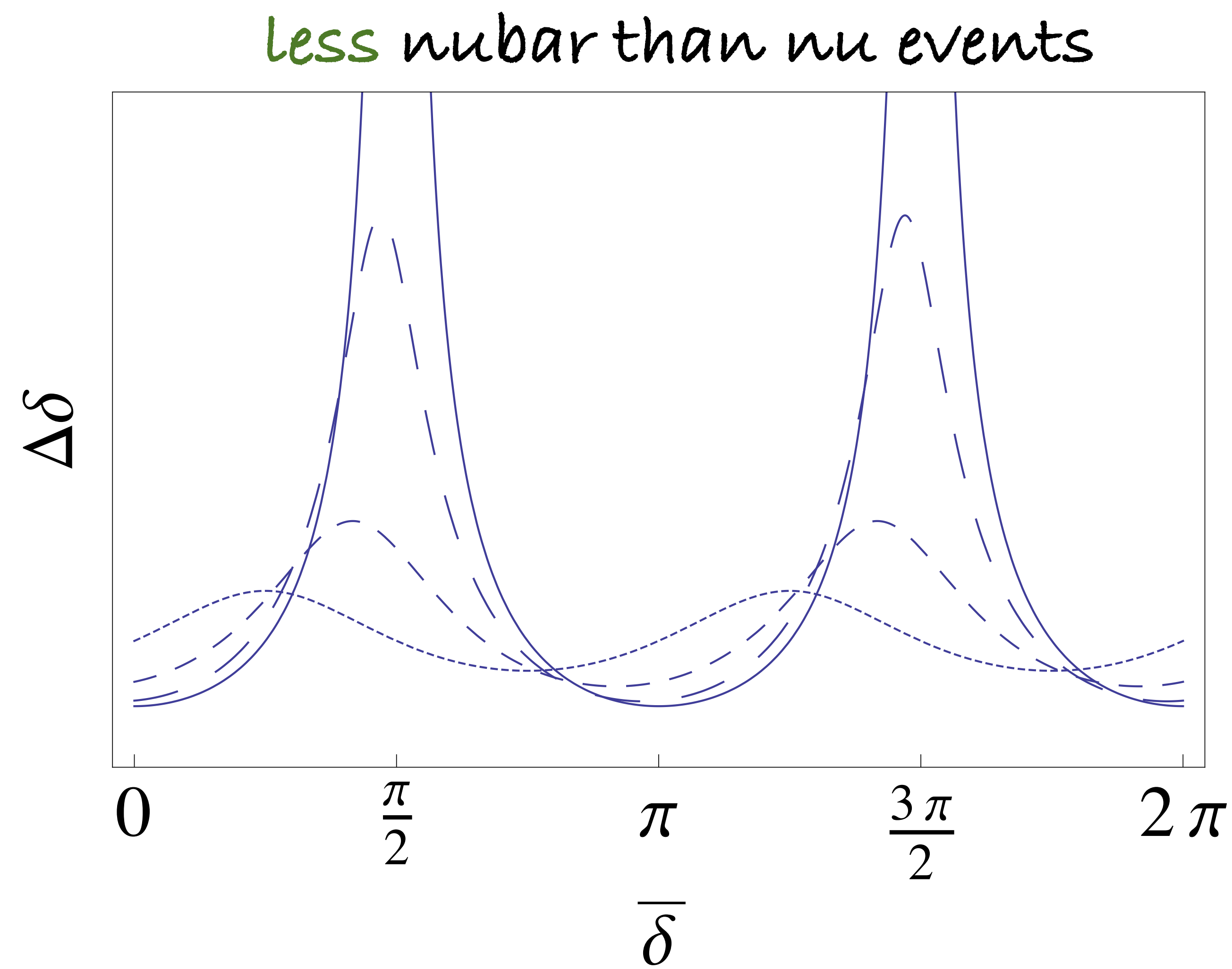
$$(\Delta\delta) \simeq \left(\sqrt{\frac{1}{(\Delta\delta)_{+}^{2}} + \frac{1}{(\Delta\delta)_{-}^{2}}} \right)^{-1}$$

Precision in δ

VACUUM

$$(\Delta\delta)_{\pm} \propto f[\Delta] \frac{1}{\sin\left(\frac{\pi}{2} \mp \delta\right)}$$





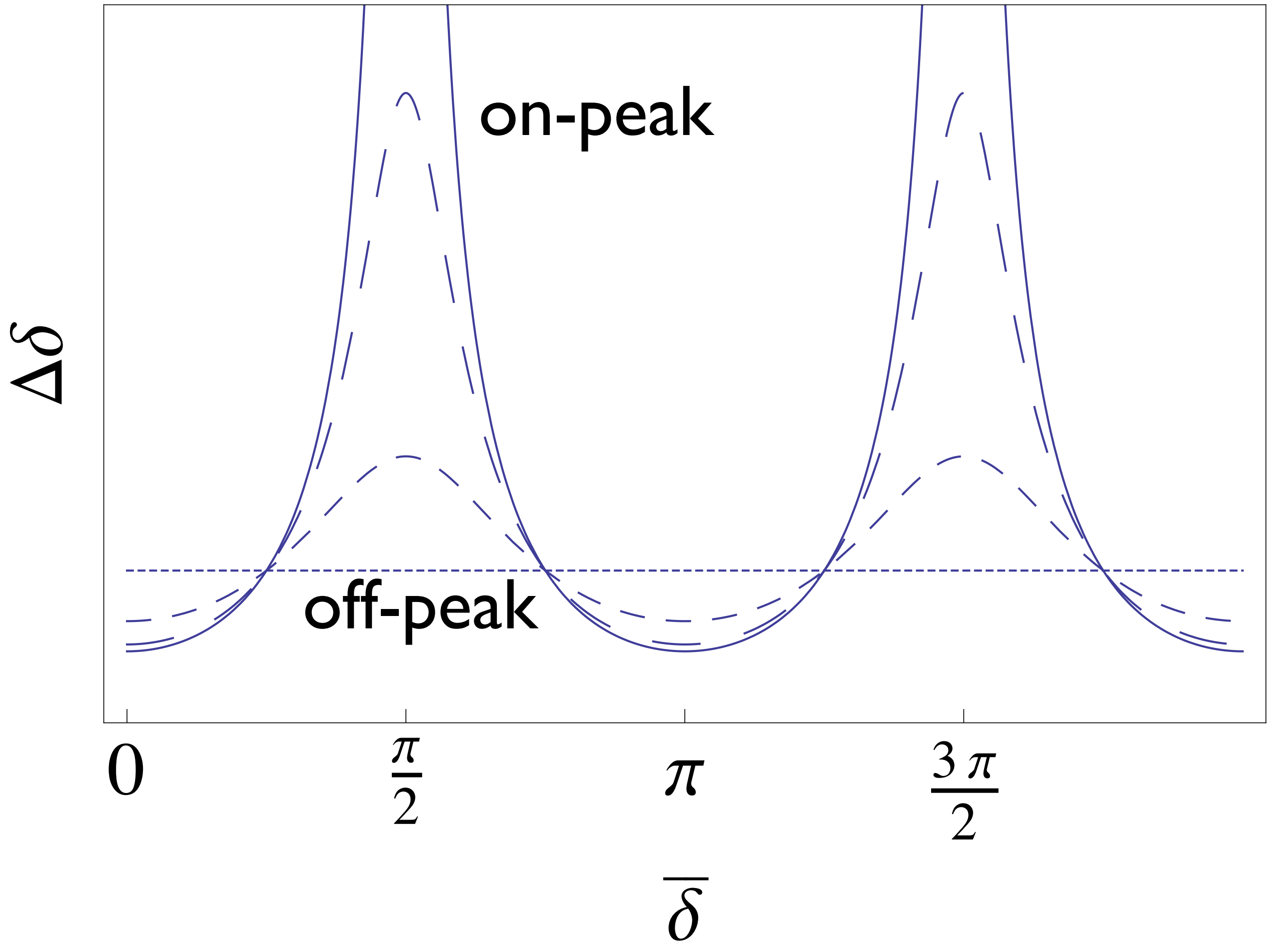
Precision in δ

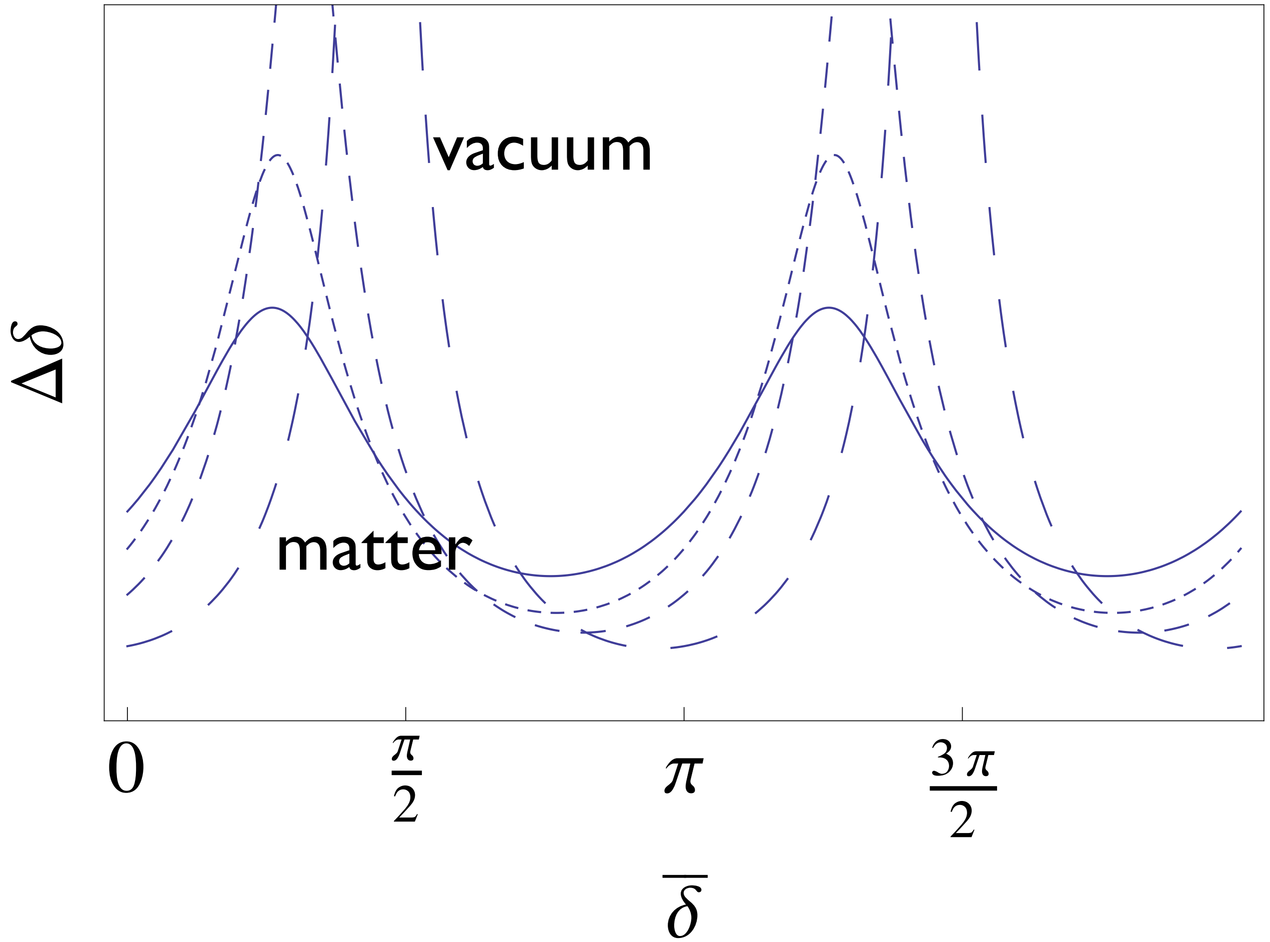
VACUUM

$$(\Delta\delta)_\pm \propto f[\Delta]\frac{1}{\sin\left(\frac{\pi}{2} \mp \delta\right)}$$

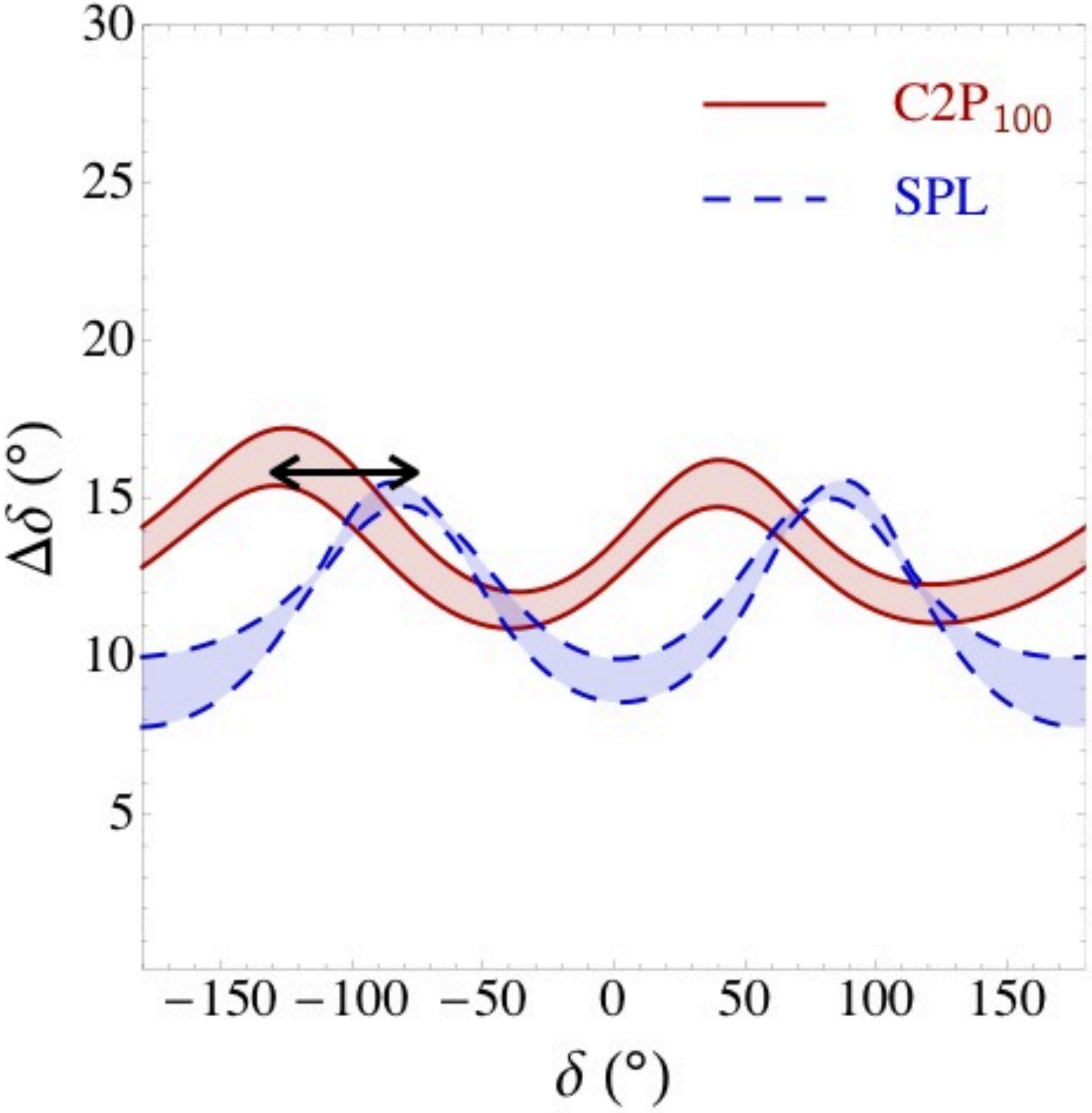
MATTER

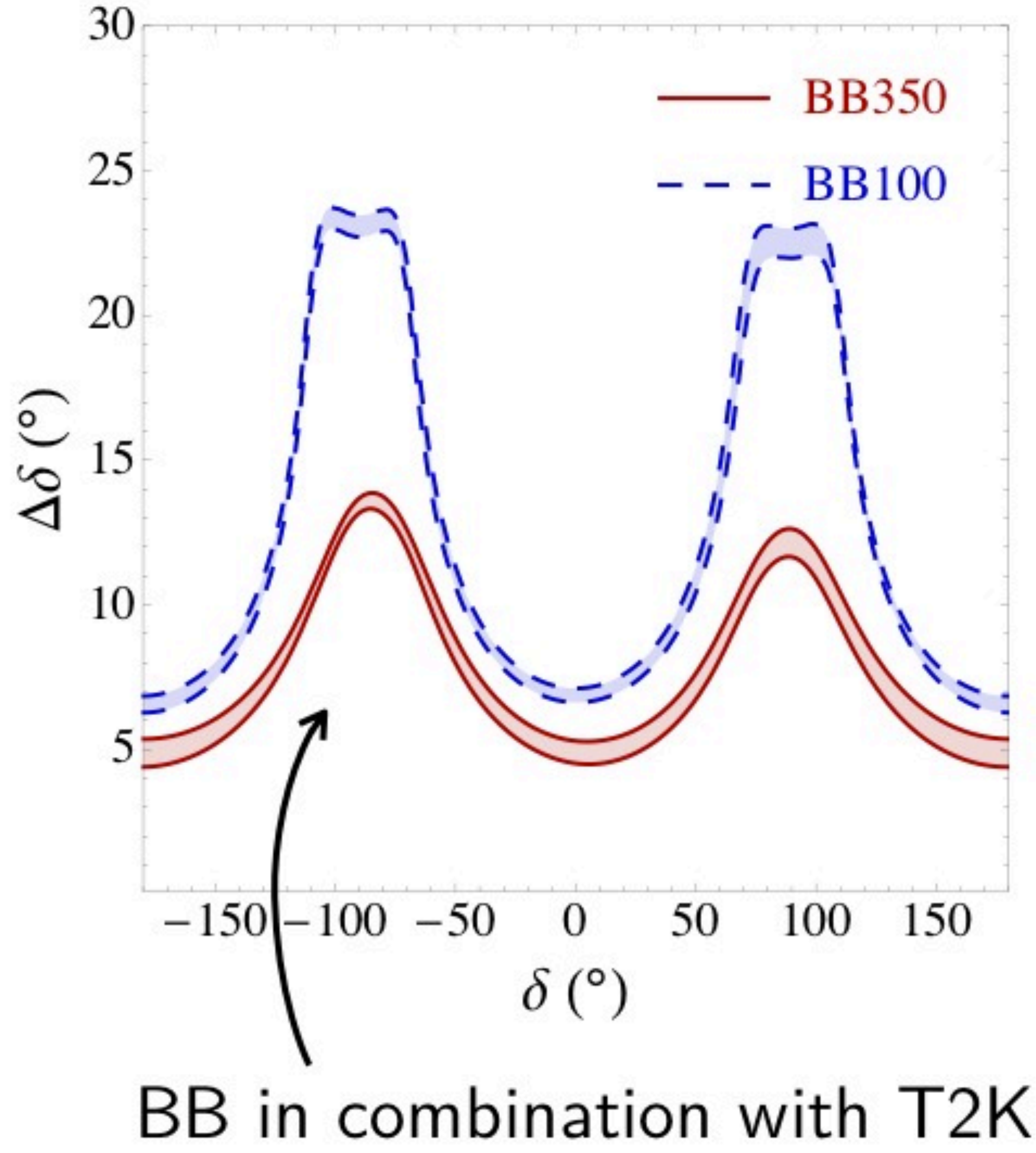
$$(\Delta\delta)_\pm \propto \tilde{f}[\Delta, \hat{A}]\frac{1}{\sin\left(\frac{\pi}{2}\frac{\hat{A}}{(1\mp\hat{A})} \mp \delta\right)}$$





Precision in δ



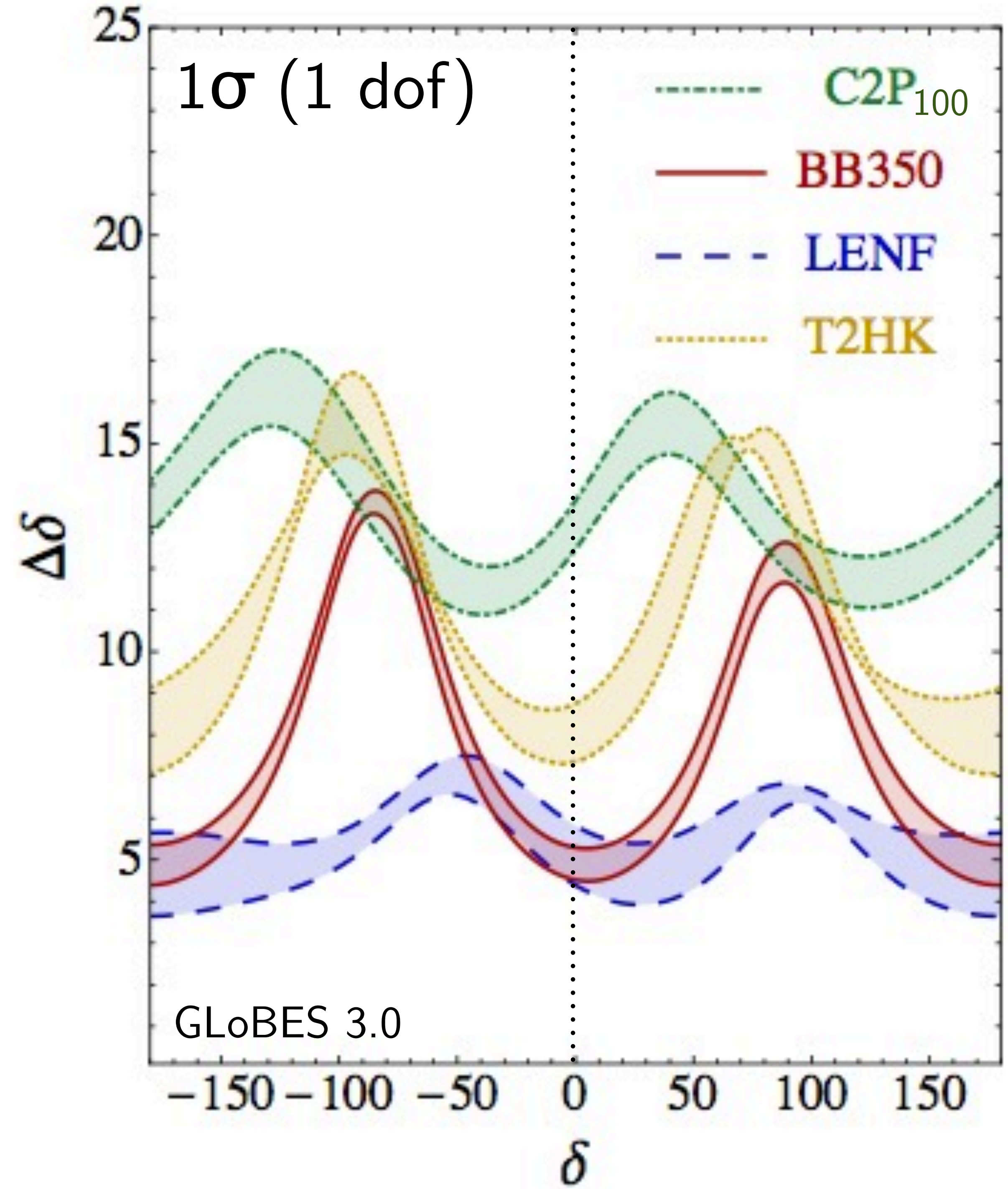


Precision in δ

1) Mild θ_{13} dependence

2) Strong delta dependence for BB350 due to no disappearance data

3) CPV discovery potential related to precision around 0,π: more favorable for setups in vacuum and with similar number of nu/nubar events



Coloma, Donini, Fernández-Martínez, Hernández, 1203.5651 [hep-ph]

Conclusions

- Precision in θ_{13}:
  - reactors can only be beaten by a NuFact
- Precision in delta:
  - beta-beams suffer from lack of disappearance data (need to be combined with T2K)
  - BB100 suffers from intrinsic degeneracies: this could be alleviated from a refined analysis or from its combination with SPL
  - Facilities in vacuum have very good precision around $0,\pi$ but a strong delta dependence
  - Matter effects help to smooth this dependence out

Backup

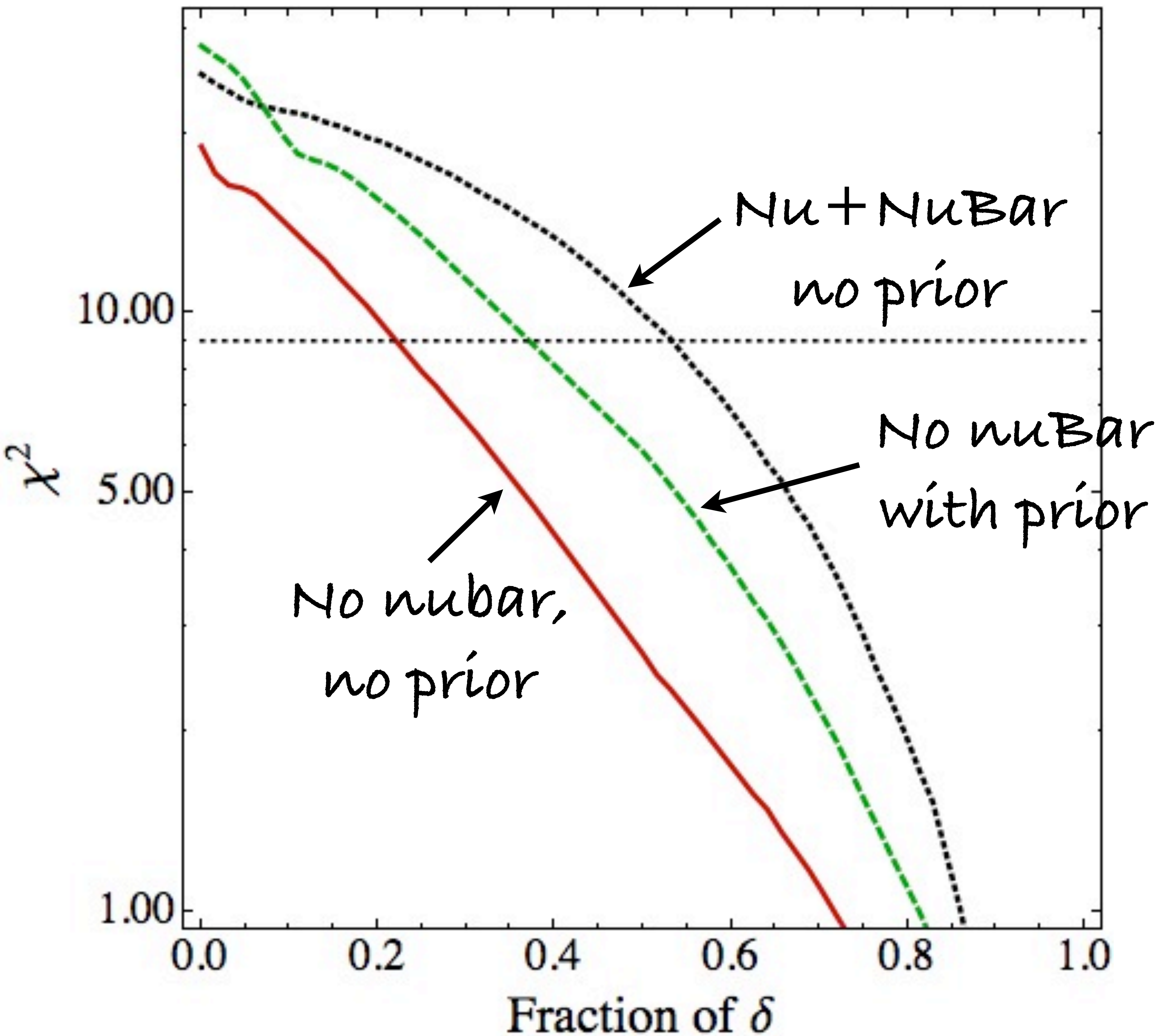
	L	$N_\nu/N_{\bar{\nu}}$	$B_\nu/B_{\bar{\nu}}$	$\langle E_\nu\rangle/\langle E_{\bar{\nu}}\rangle$	$\delta E_\nu/\delta E_{\bar{\nu}}$	$\hat{A}$
T2K	295	$2.6/0 \times 10^3$	46/0	0.72/–	0.27/–	0.02
NOνA	810	$1.1/0.7 \times 10^3$	10/11	2.02/2.04	0.43/0.42	0.14
T2HK	295	$4.3/1.3 \times 10^5$	$4.3/1.5 \times 10^3$	0.79/0.80	0.18/0.18	0.022
LBNE	1290	$2.3/0.9 \times 10^4$	302/201	3.55/3.50	1.38/1.33	0.30
SPL	130	$2.5/1.6 \times 10^5$	$1.1/1.2 \times 10^3$	0.59/0.57	0.20/0.21	0.017
C2P	2300	$2.4/1.1 \times 10^4$	210/129	5.04/5.15	1.65/1.59	0.48
BB100	130	$2.9/4.4 \times 10^4$	$0.6/1.2 \times 10^3$	0.47/0.45	0.18/0.18	0.013
BB350	650	$5.0/9.2 \times 10^4$	372/432	1.53/1.61	0.45/0.45	0.11
LENF	2000	$8.1/5.3 \times 10^5$	48/81	6.75/6.78	1.81/1.79	0.63
IDS1b	4000	$1.9/1.2 \times 10^6$	154/196	16.85/16.86	4.57/4.55	1.65

Setup details

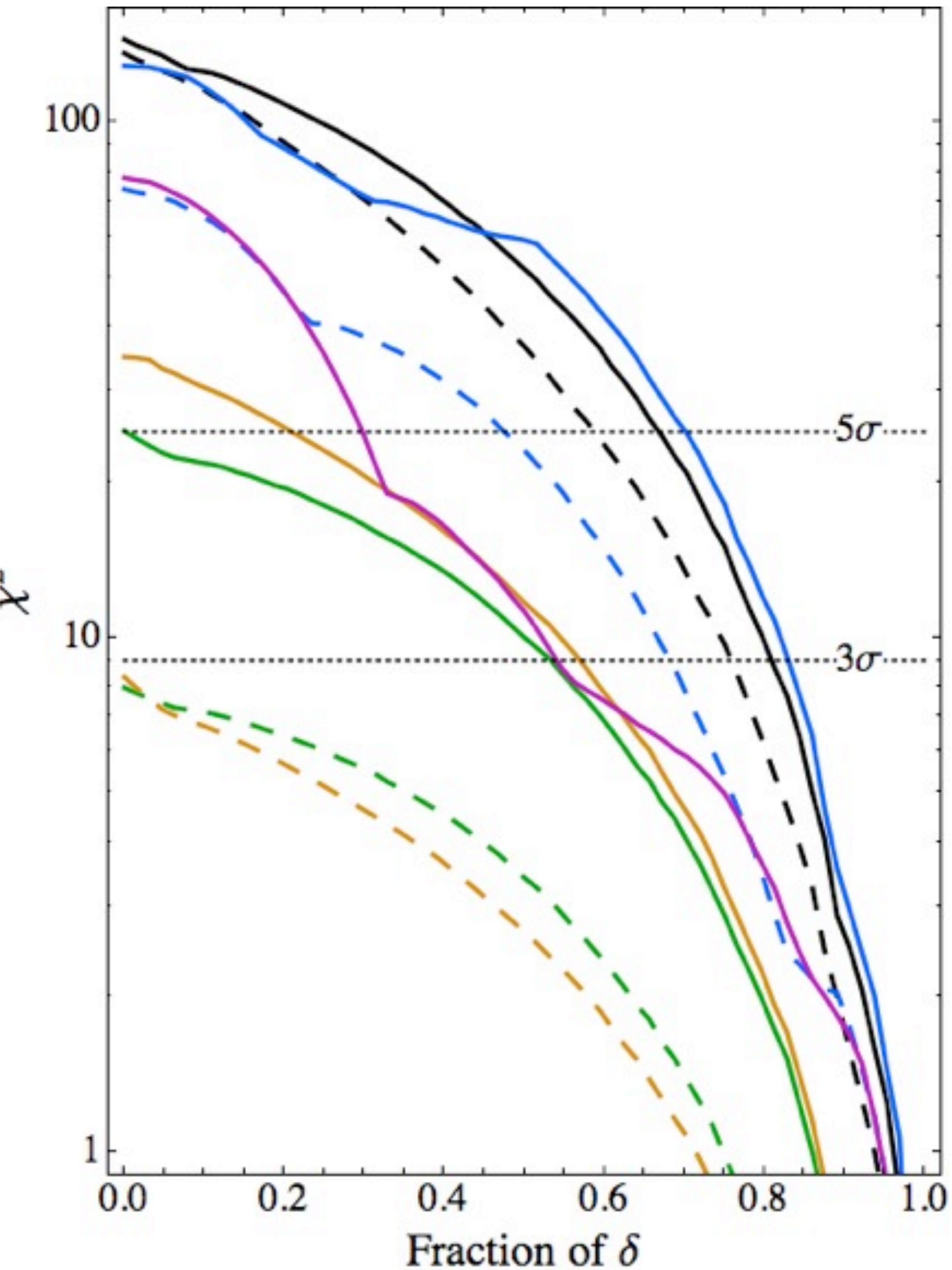
	L (km)	Det. (kton)	MW	$(t_\nu, t_{\bar{\nu}})$	Refs.
T2K	295	WC (22.5)	0.75	(5,0)	[79–83]
NOνA	810	TASD (15)	0.7	(3,3)	
T2HK	295	WC (500)	4.0	(4,4)	[38, 84, 85]
LBNE	1290	LAr (33.4)	0.7	(5,5)	[33, 86, 87]
SPL	130	WC (440)	4.0	(2,8)	[16, 36]
C2P	2300	LAr (100)	0.8	(5,5)	[33, 88, 89]

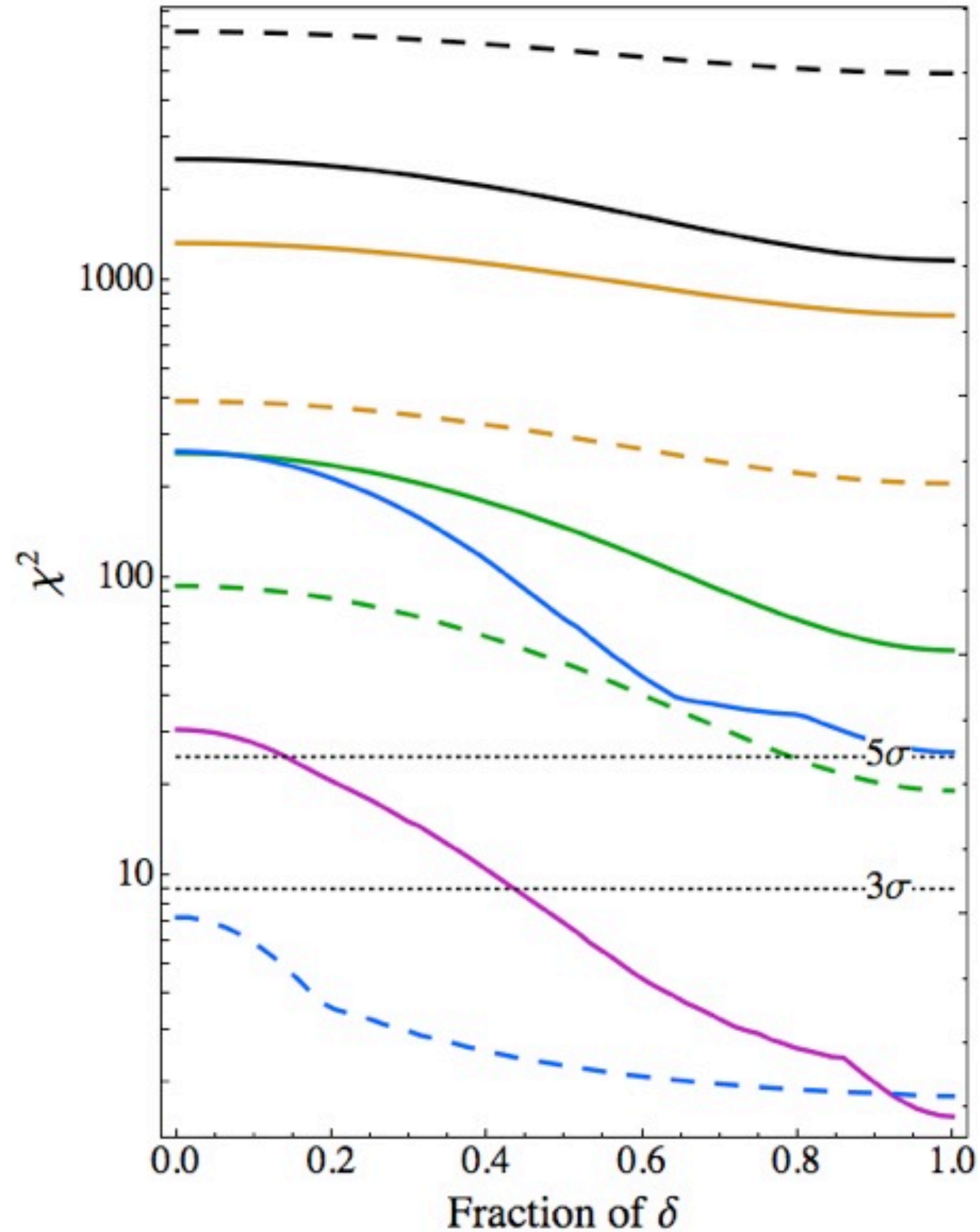
Table 2: Summary of the main details for the conventional beam and super-beam setups that have been presented in the comparison. From left to right, each column indicates the baseline, the detector technology (Water Čerenkov, Totally Active Scintillator Detector, or Liquid Argon) and its fiducial mass, the beam power, the number of years that the experiment would be running in ν and $\bar{\nu}$ modes, and the references which have been followed in order to simulate each setup. It should be noted that the numbers quoted in this table correspond to the values stated in the cited references, where the beam power in each case has been computed according to a certain number of useful seconds per year (which in general do not coincide): T2K and T2HK assume 130 useful days per year (1.12×10^7 secs, approx.); NOνA assumes 1.7×10^7 sec$\times$yr^{-1}; LBNE assumes 2×10^7 sec$\times$yr^{-1}; and SPL and C2P assume 10^7 sec$\times$yr^{-1}.

Effect of th13 prior on CPV



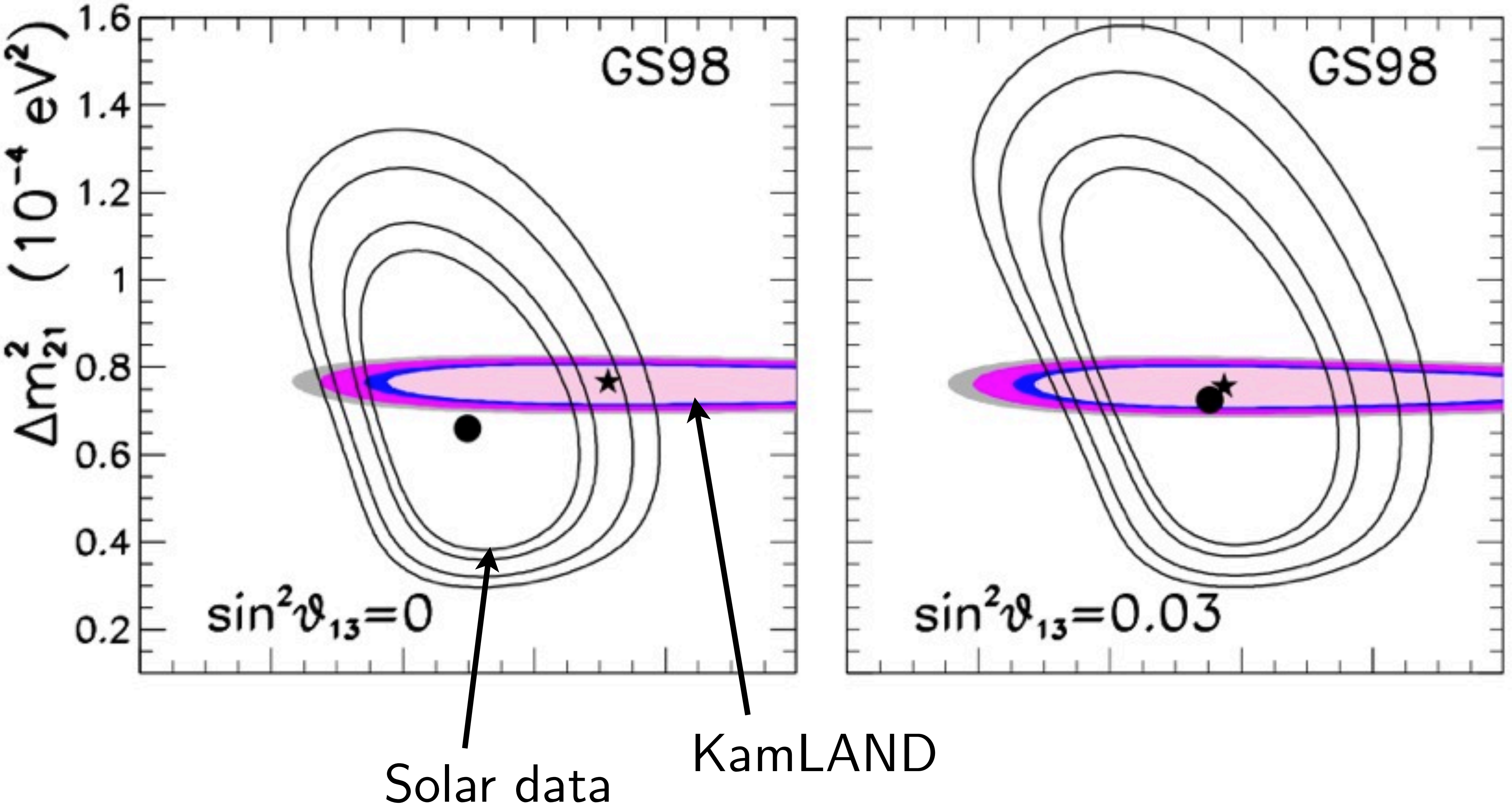
Mass hierarchy and CPV





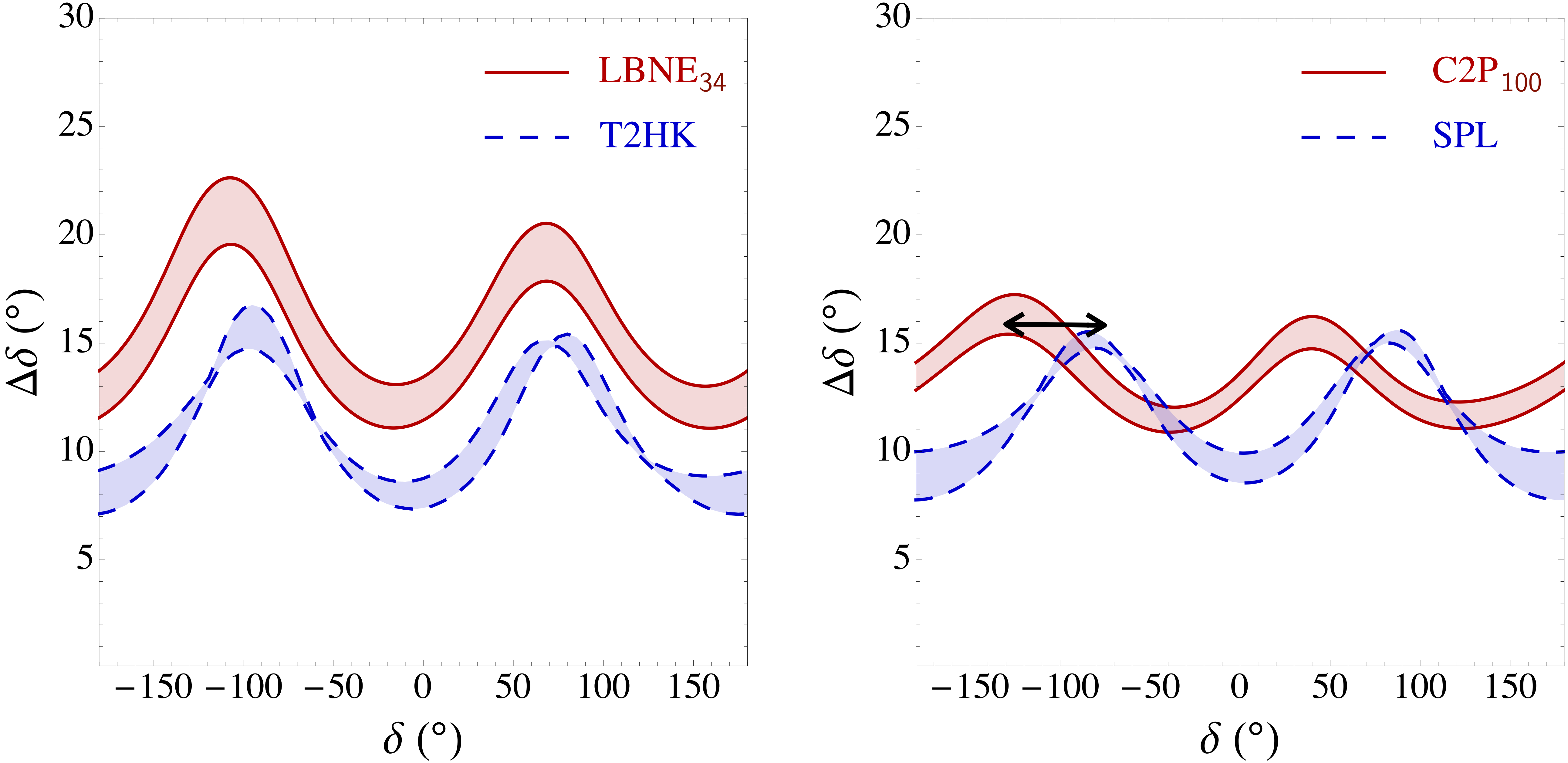
Previous hints on θ_{13}

Previous hints from global fits pointed to nonzero θ_{13}...

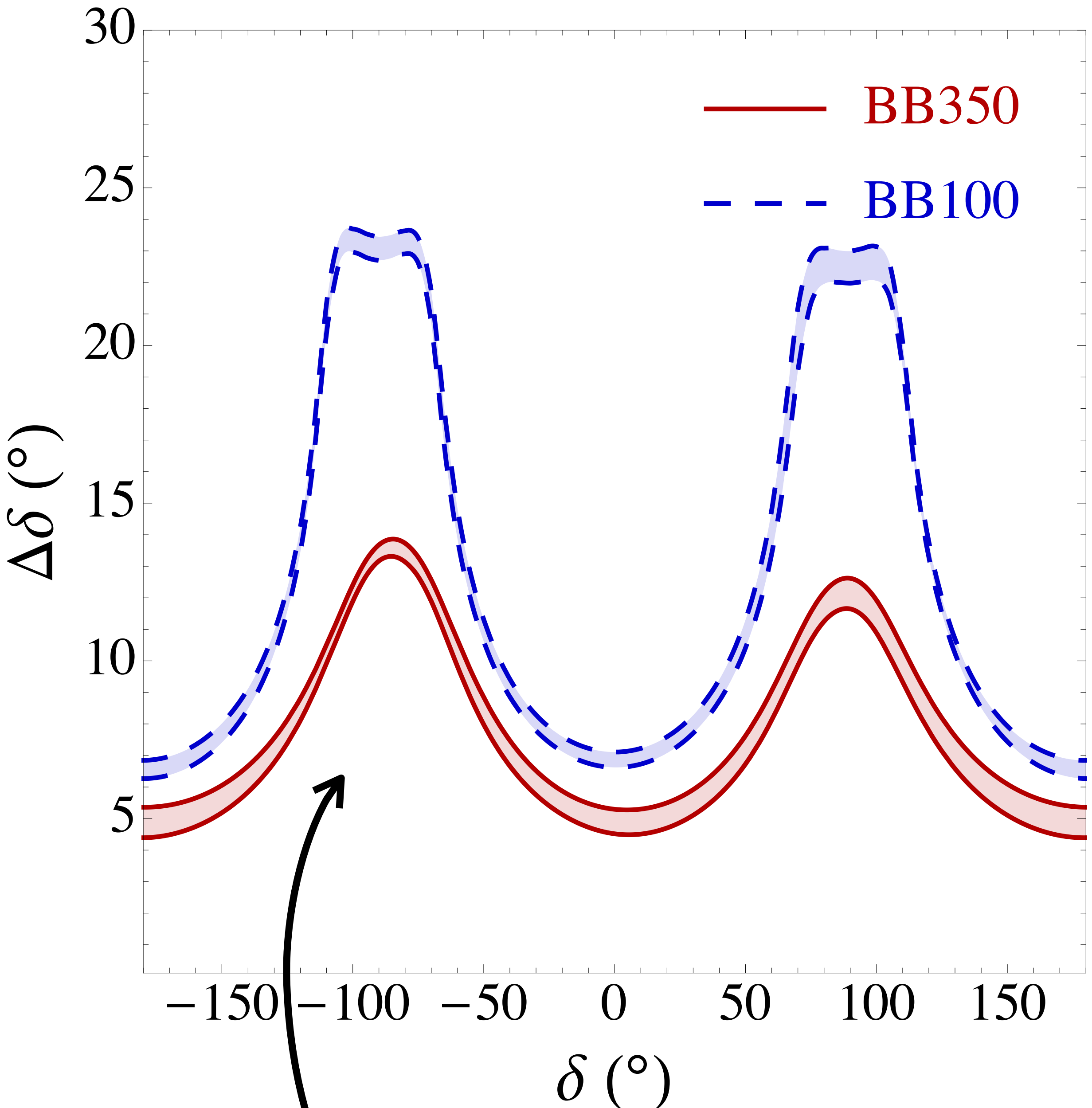


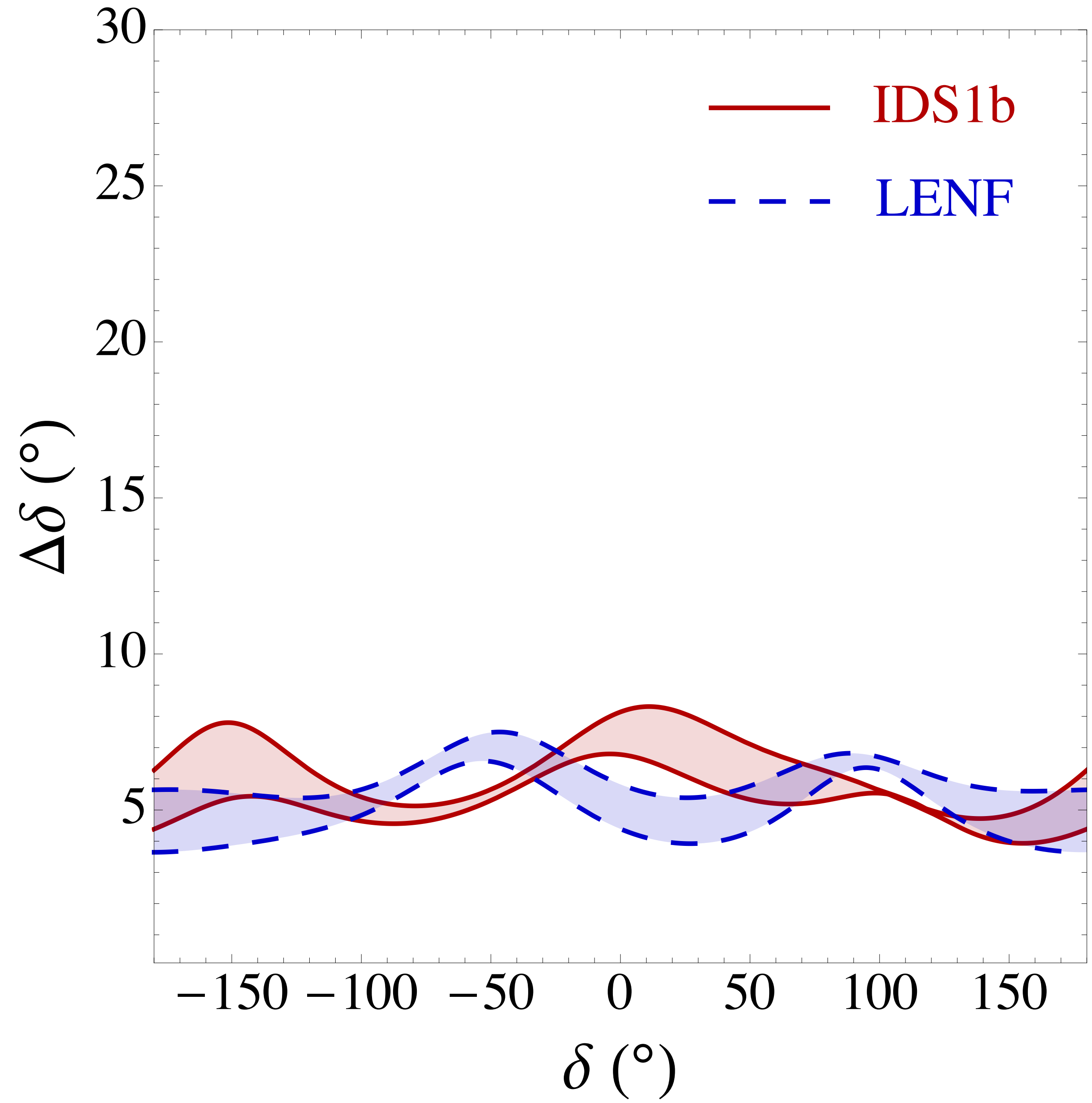
González-García, Maltoni,Salvado, 1001.4524 [hep-ph]

Precision in δ



Precision in δ





BB in combination with T2K data

The leptonic mixing matrix

Pontecorvo, 1957

Maki, Nakagawa, Sakata, 1962

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric | Interference | Solar

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$$\sin^2\theta_{12} = 0.307$$

$\sin^2\theta_{13} = 0.0241$ (for NH)

$$\delta = 1.08\pi$$

Fogli et al., 1205.5254 [hep-ph]

(see also Forero et al, 1205.4018 [hep-ph])

Precision at 2nd peak