Neutrino Oscillations for large θ_{13}

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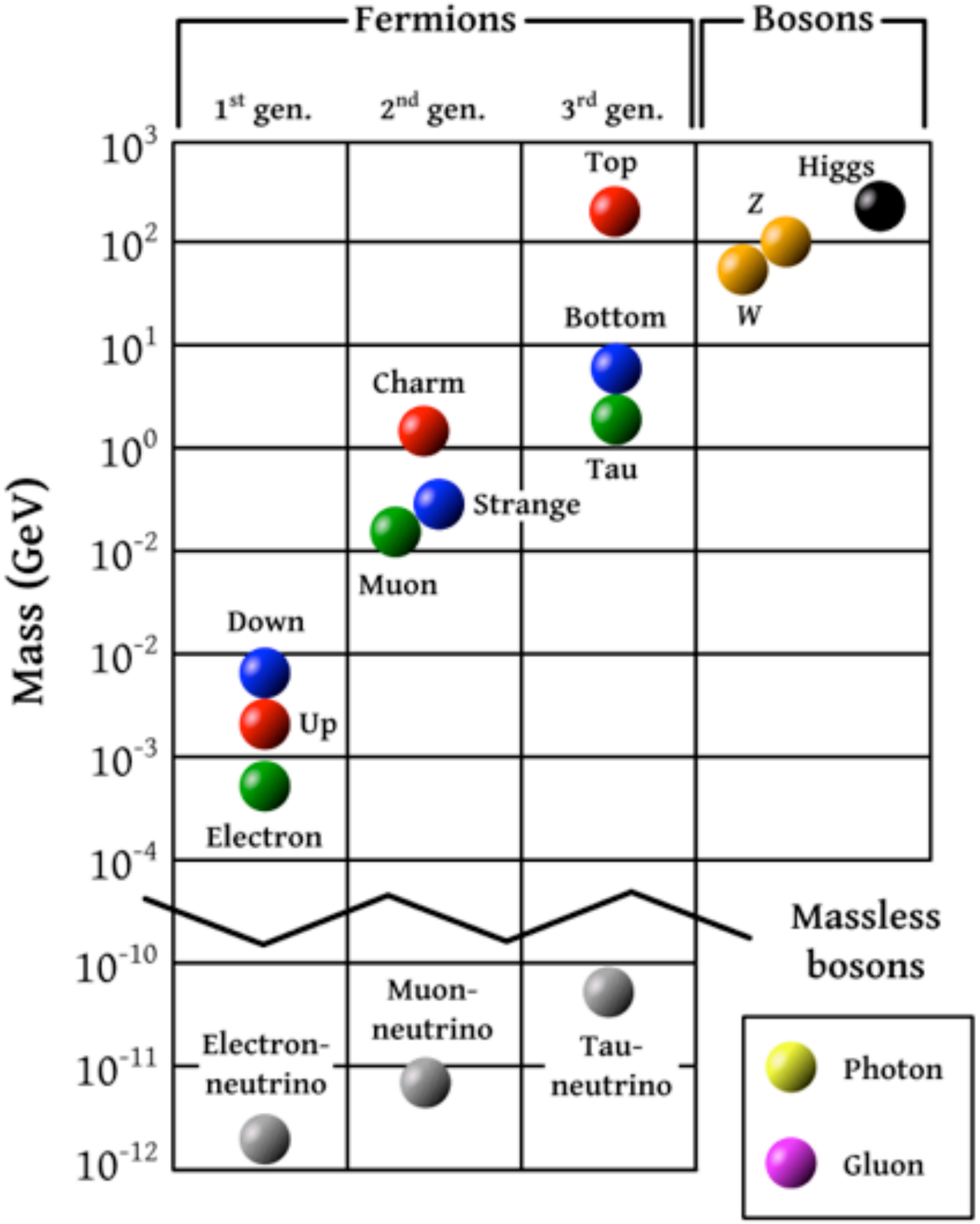
Invent the Future

Fermilab, April 12, 2012

Outline

- Introduction to neutrino oscillations
- Present and future facilities: where are we
- The 1^{st} and 2^{nd} oscillation maxima
- Precision at future oscillation facilities
- Conclusions

Are ν masses different?



The Dawn of Particle Physics Beyond the Standard Model,
Gordon Kane (Scientific American, 2003)

$$\mathcal{L}^{\nu}_{mass} \sim \quad Y \bar{L}_L \tilde{\phi} \nu_R + \frac{1}{2} M \bar{\nu}^c_R \nu_R$$

If no M, there may be a profound reason

Is B-L gauge?

Small M implies extra sterile neutrinos

SBL anomalies? cosmology?

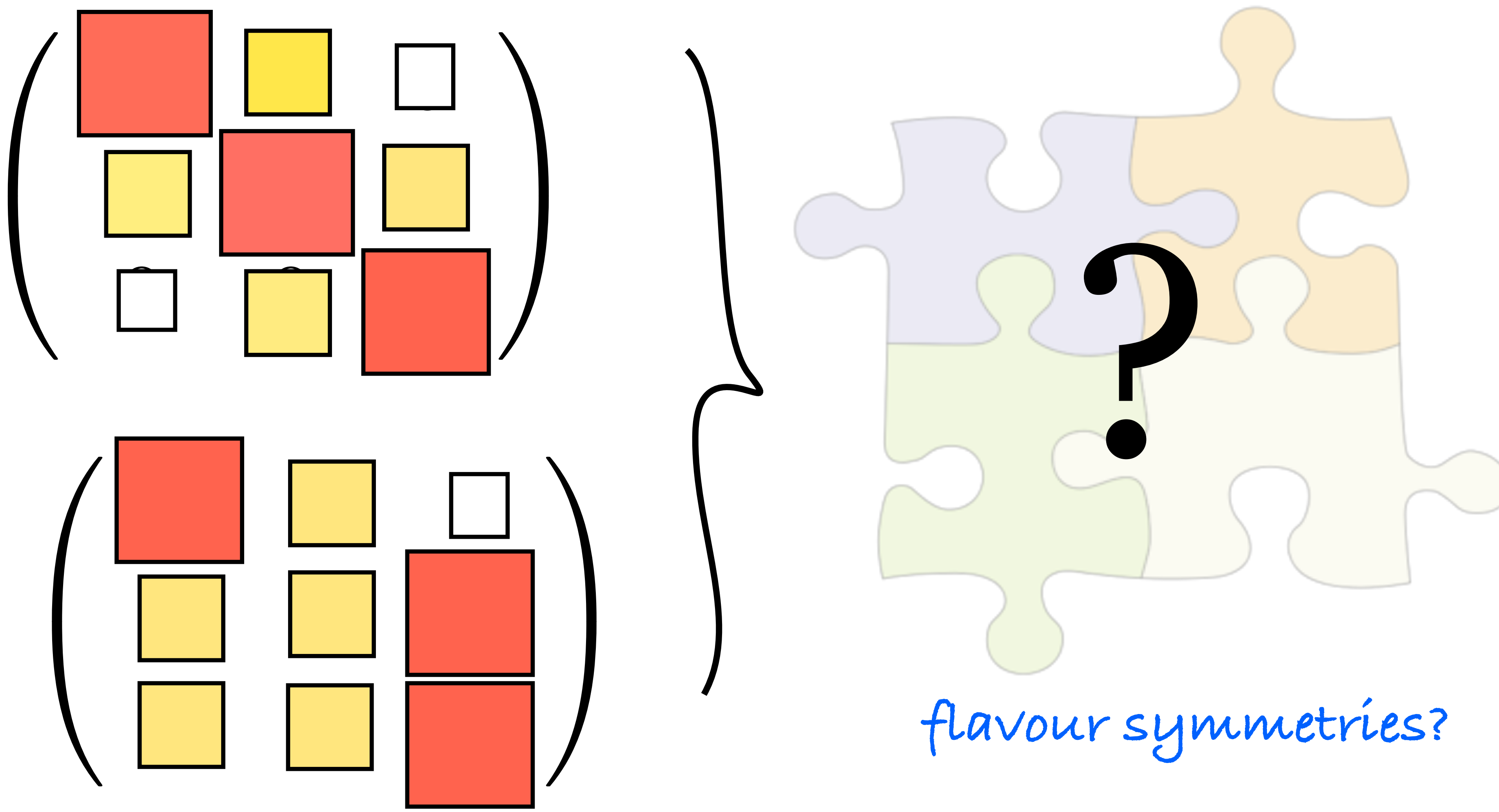
Large M opens a window to a higher scale of NP

leptogenesis?

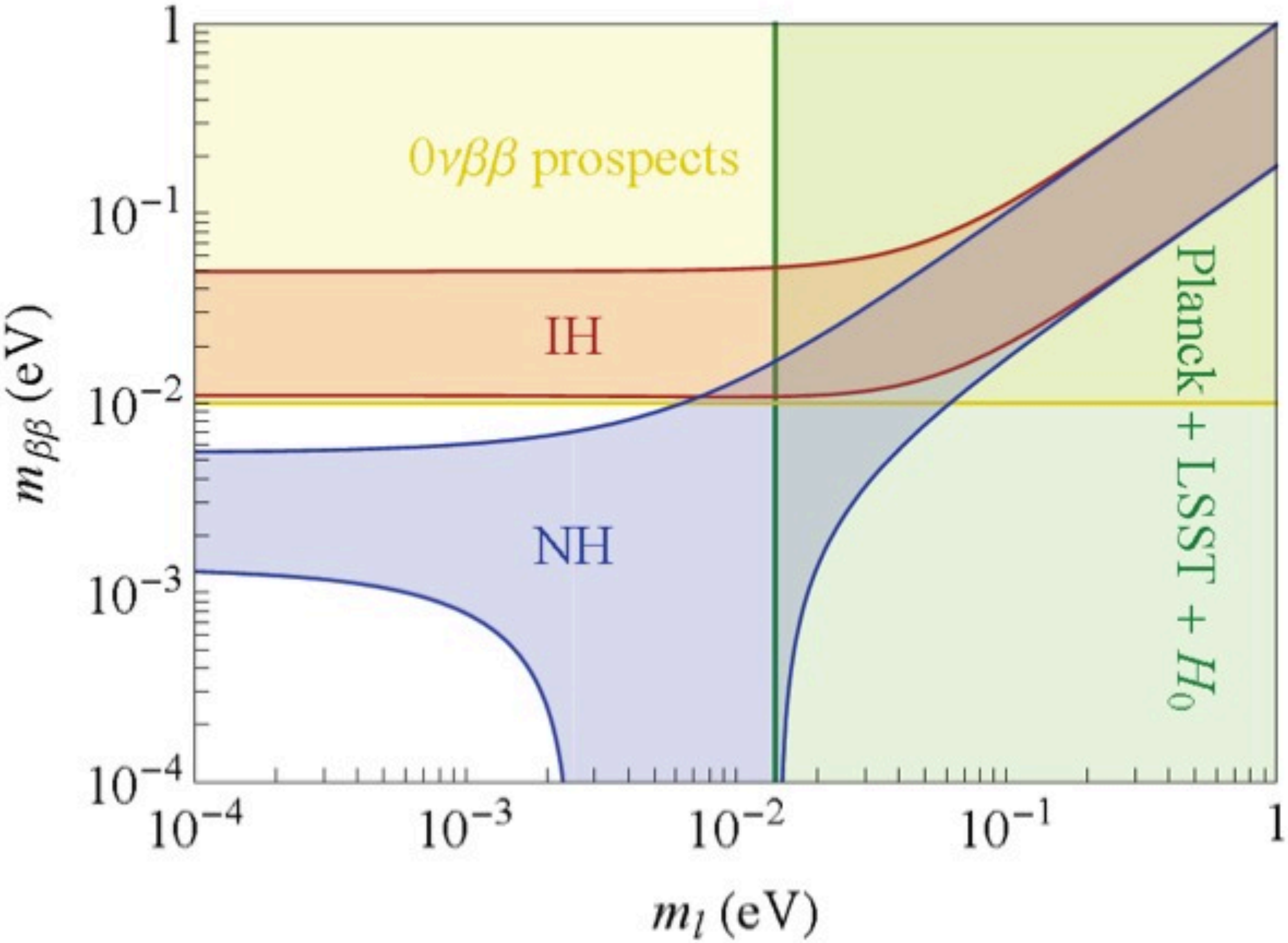
Are ν masses different?

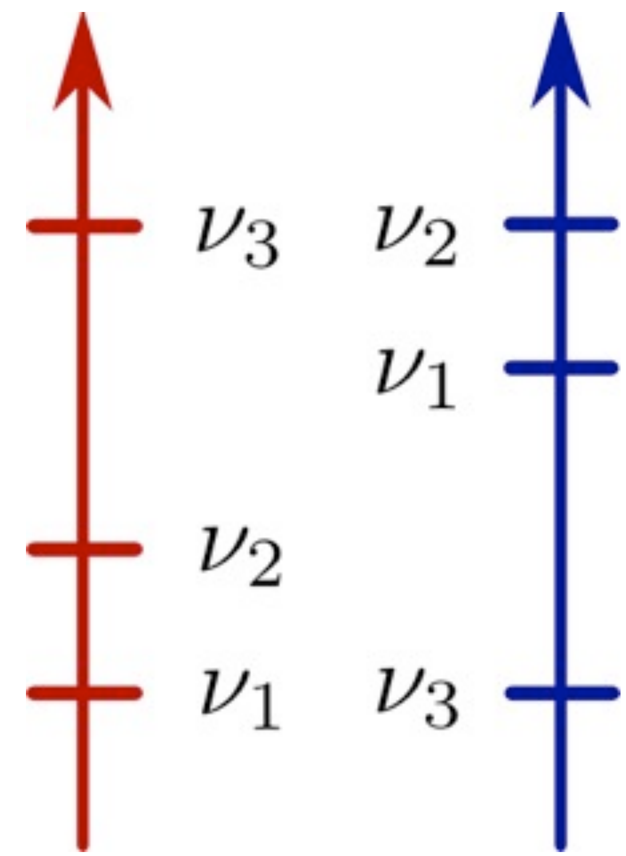
$V_{CKM} \sim$

$U_{PMNS} \sim$



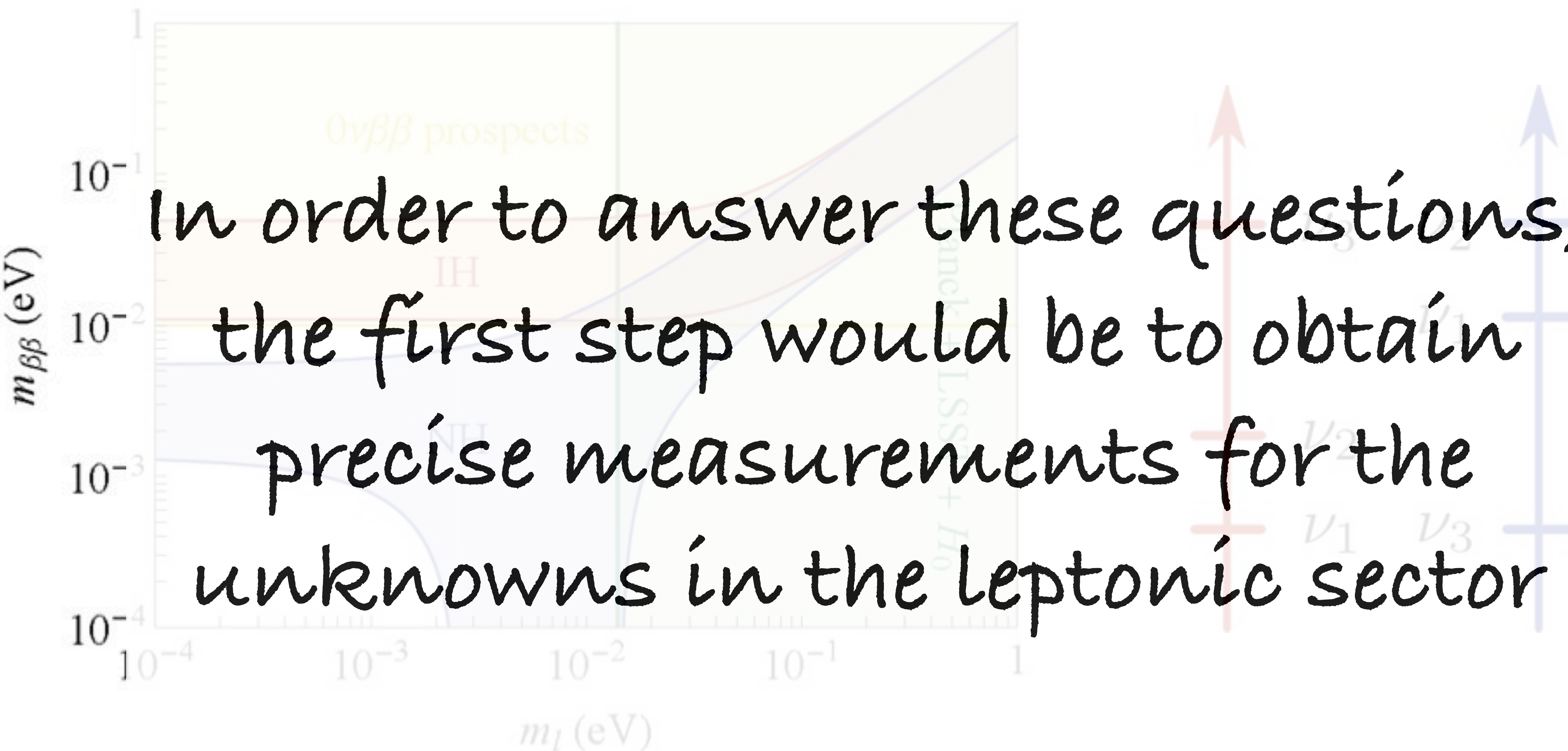
Are ν masses different?





Courtesy of E. Fernández-Martínez

Are ν masses different?



In order to answer these questions, the first step would be to obtain precise measurements for the unknowns in the leptonic sector

Courtesy of E. Fernández-Martínez

Neutrino oscillations

CC interactions mix charged leptons and neutrinos

$$\mathcal{L}_{CC}^{\nu} \sim U_{i\alpha}^{*} \left(\bar{l}_{\alpha}\, \gamma_L^{\mu}\, \nu_i W_{\mu}^{+} + h.c.\right)$$

Neutrinos are produced as a superposition of mass eigenstates. During propagation, each wave packet evolves independently:

$$|\nu_i(L,t)\rangle = e^{-i(E_i t - p_i L)}|\nu_i\rangle$$

Neutrino oscillations

CC interactions mix charged leptons and neutrinos

$$\mathcal{L}_{CC}^{\nu} \sim U_{i\alpha}^{*} \left(\bar{l}_{\alpha}\, \gamma_{L}^{\mu}\, \nu_{i} W_{\mu}^{+} + h.c. \right)$$

Neutrinos are produced as a superposition of mass eigenstates. During propagation, each wave packet evolves independently:

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

(In two families)

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

$$\sin^2\theta_{23} = 0.52^{+0.06}_{-0.07}$$

$$\Delta m^2_{31} = \begin{array}{c} 2.50^{+0.09}_{-0.16} \\ -(2.40^{+0.08}_{-0.09}) \end{array} \times 10^{-3}\text{eV}^2$$

$$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}$$

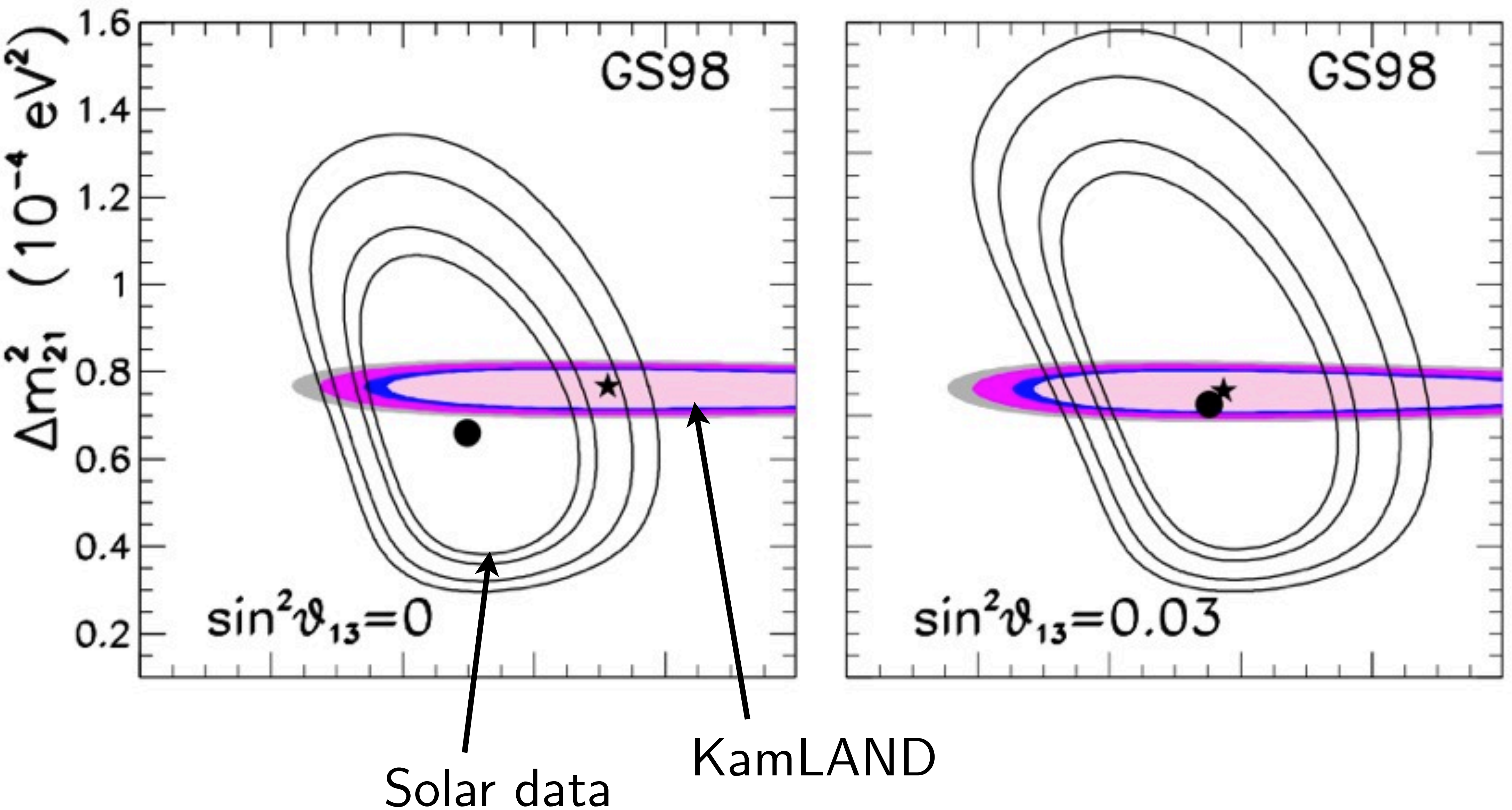
$$\Delta m^2_{12} = (7.59^{+0.20}_{-0.18}) \times 10^{-5}\,\text{eV}^2$$

Schwetz, Tortola, Valle, 1108.1376

The shopping list

Previous hints

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

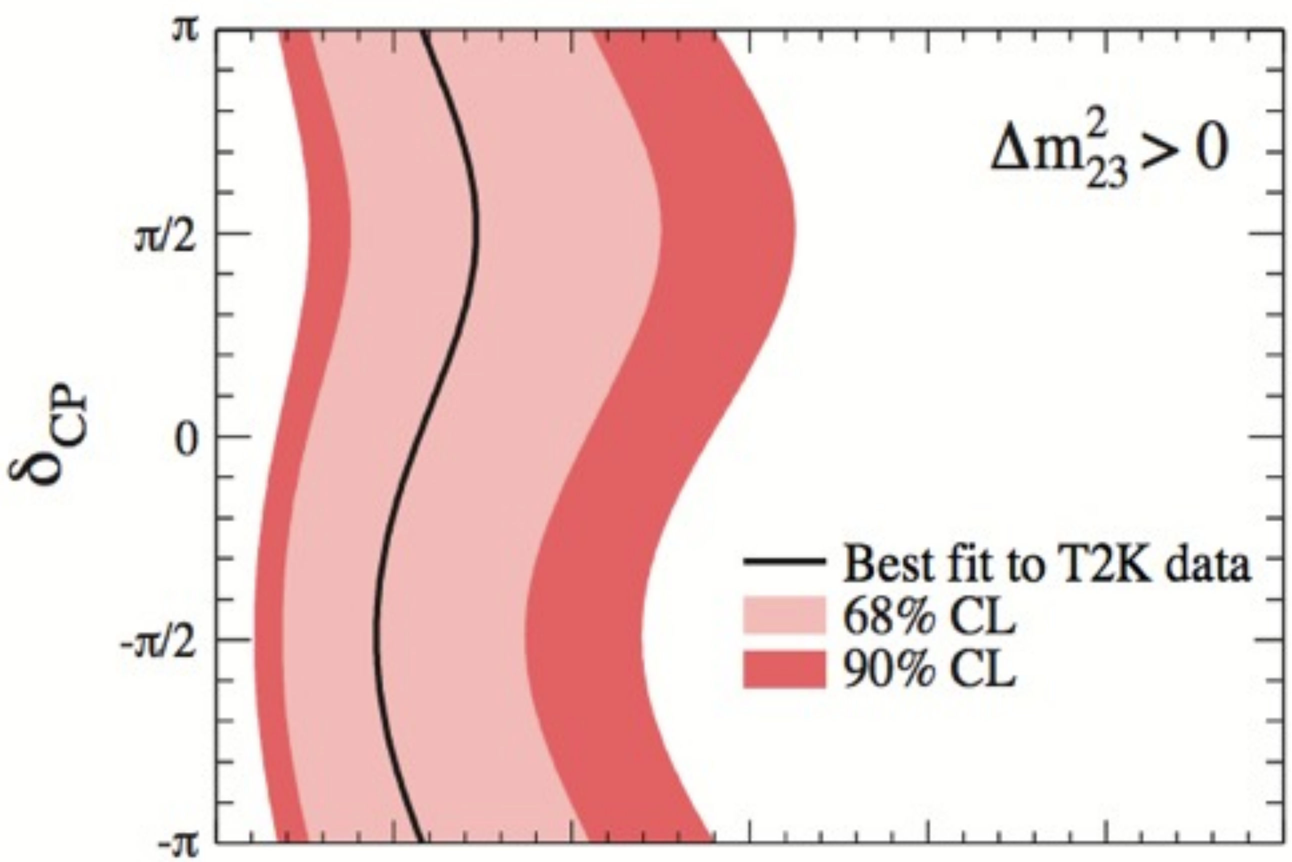


González-García, Maltoni,Salvado, 1001.4524 [hep-ph]

Long baseline beams

T2K

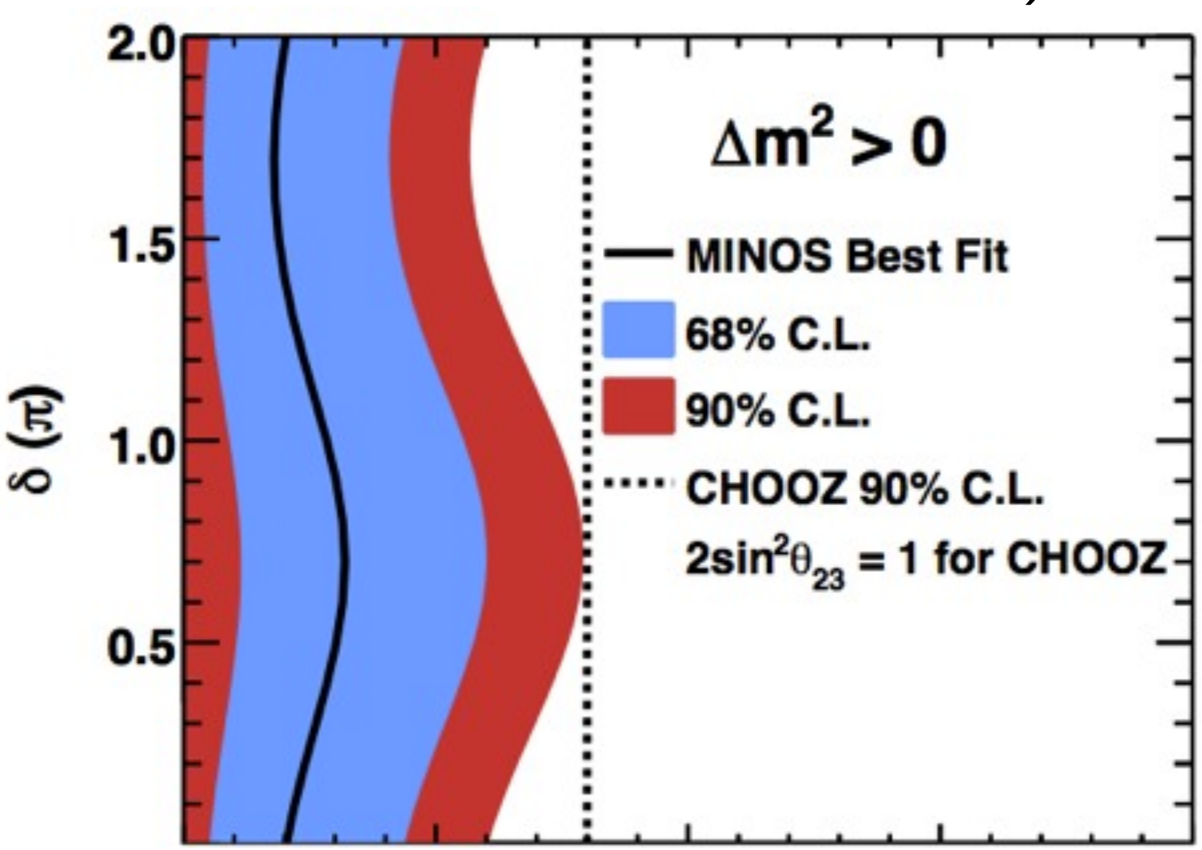
(295 km, 22.5 kt WC,
2.5° OA, E~0.6 GeV)



1106.2822 [hep-ex]

MINOS

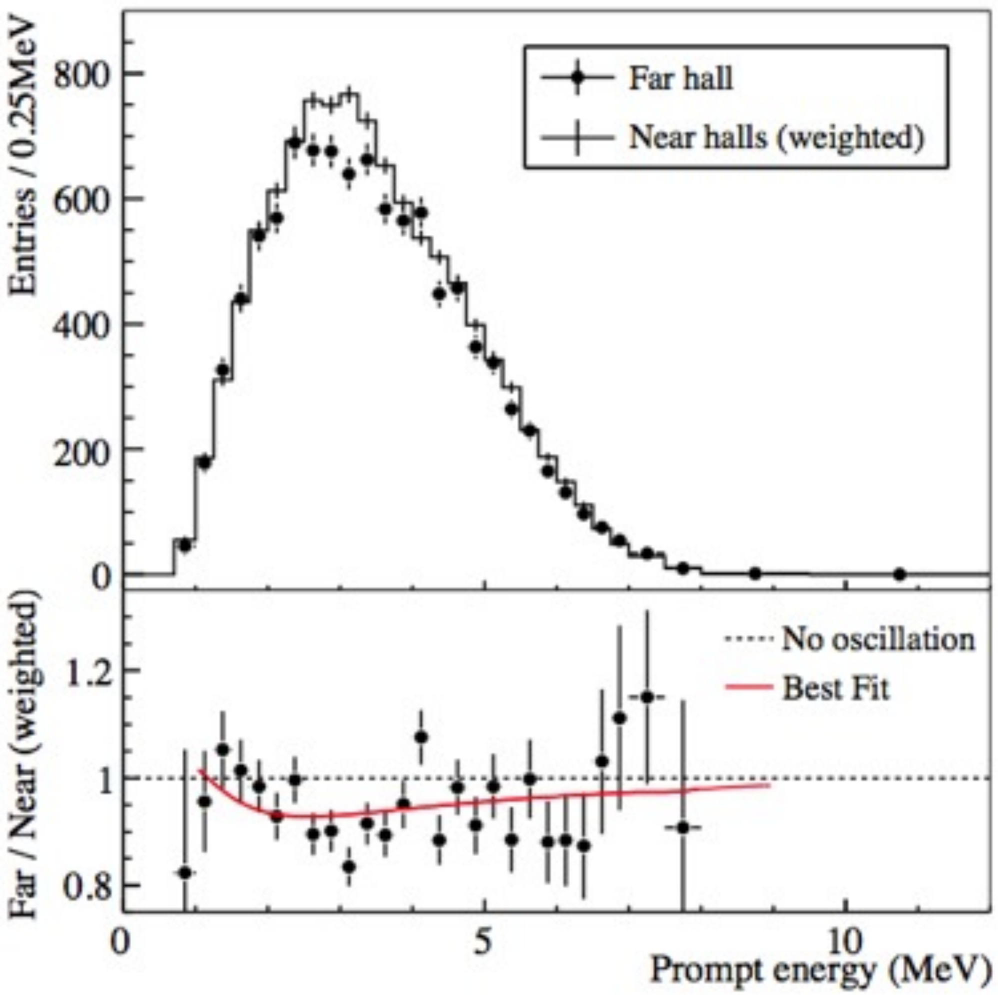
(735 km, 5.4 kt magnetized
tracking calorimeter,
on axis, E~4.5 GeV)



1108.0015 [hep-ex]

Reactors

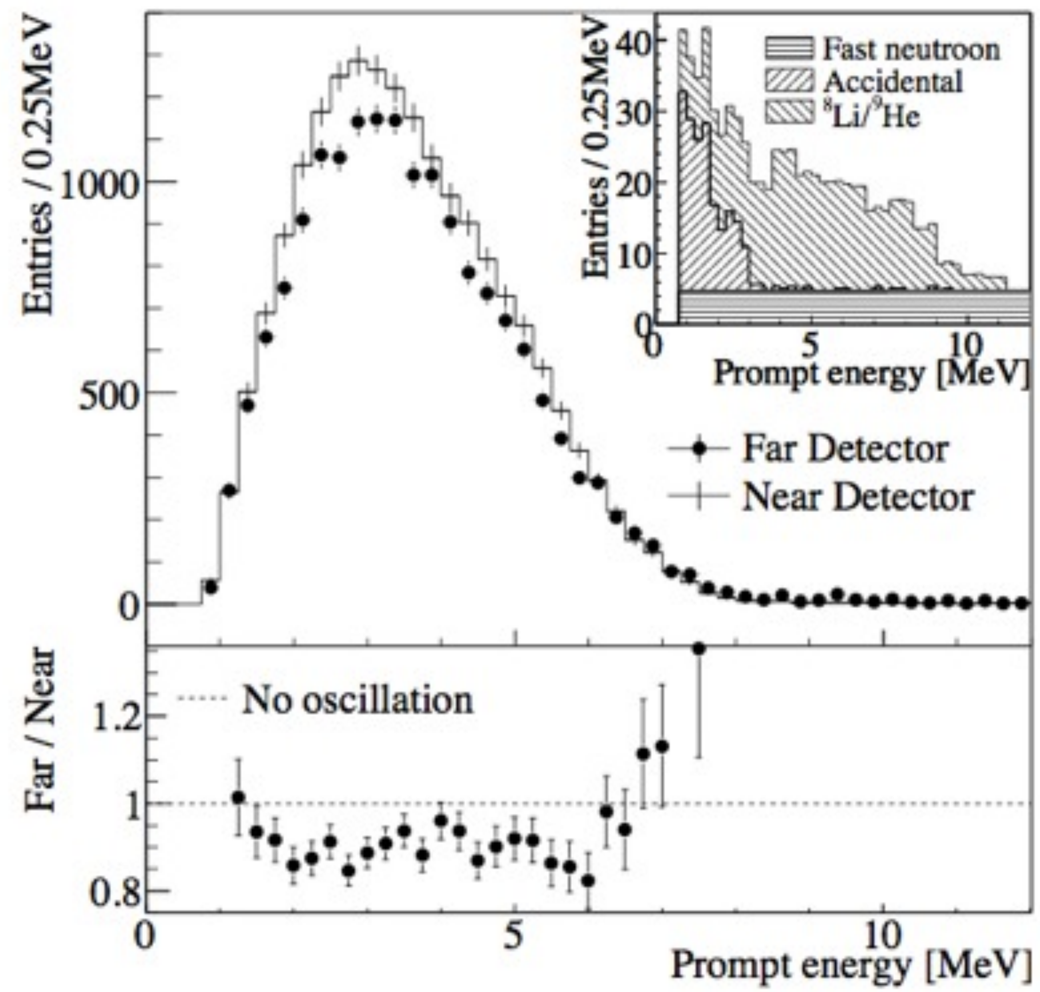
Daya Bay (5.3 σ)



$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$$

1203.1669 [hep-ex]

RENO (6.3 σ)



$$\sin^2 2\theta_{13} = 0.103 \pm 0.013 \pm 0.011$$

1204.0626 [hep-ex]

Plus a previous hint at 90% CL from Double Chooz, 1112.6353 [hep-ex]

Does this change anything?

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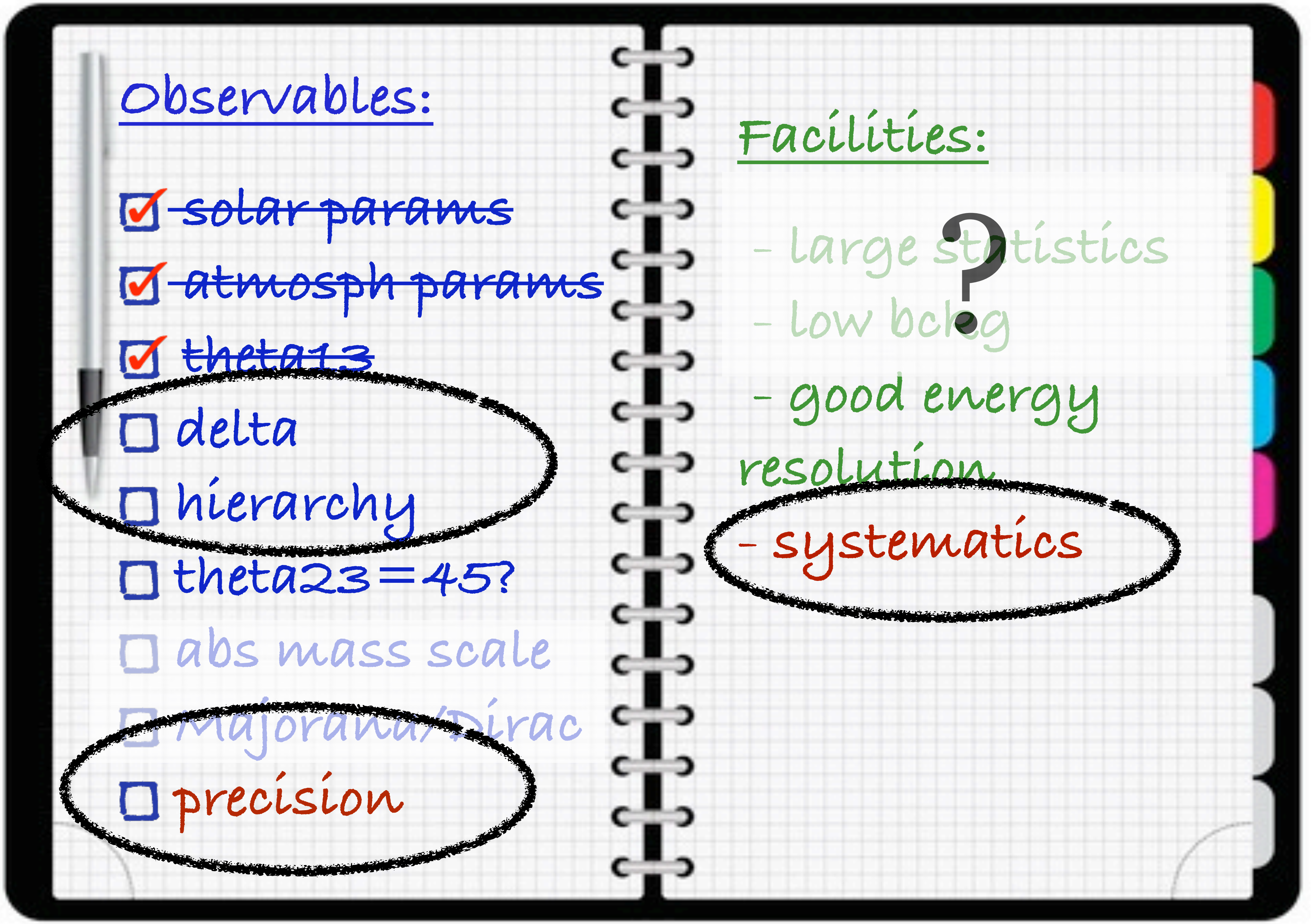
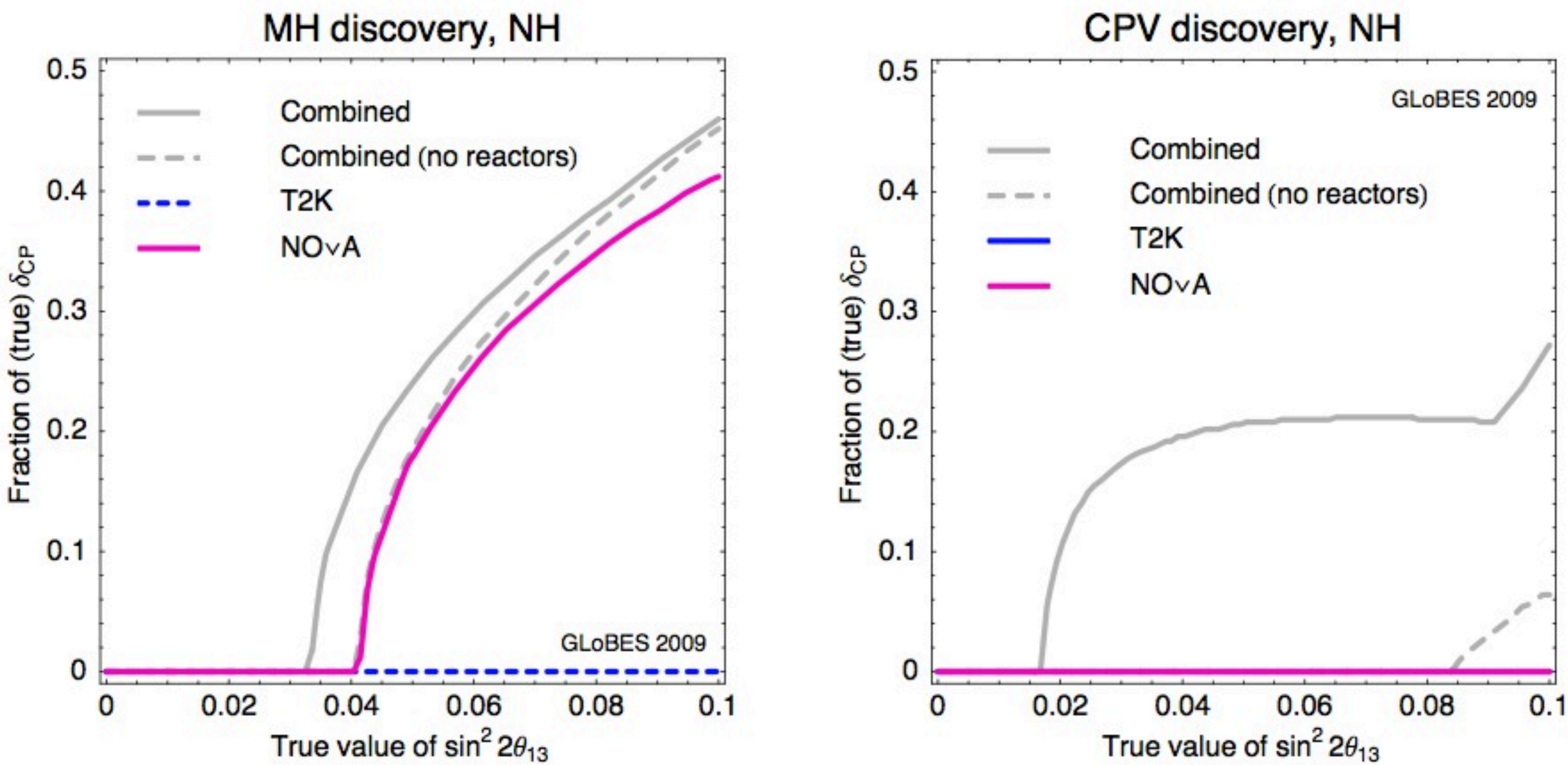


Present oscillation facilities

Discovery potential at the 90% CL

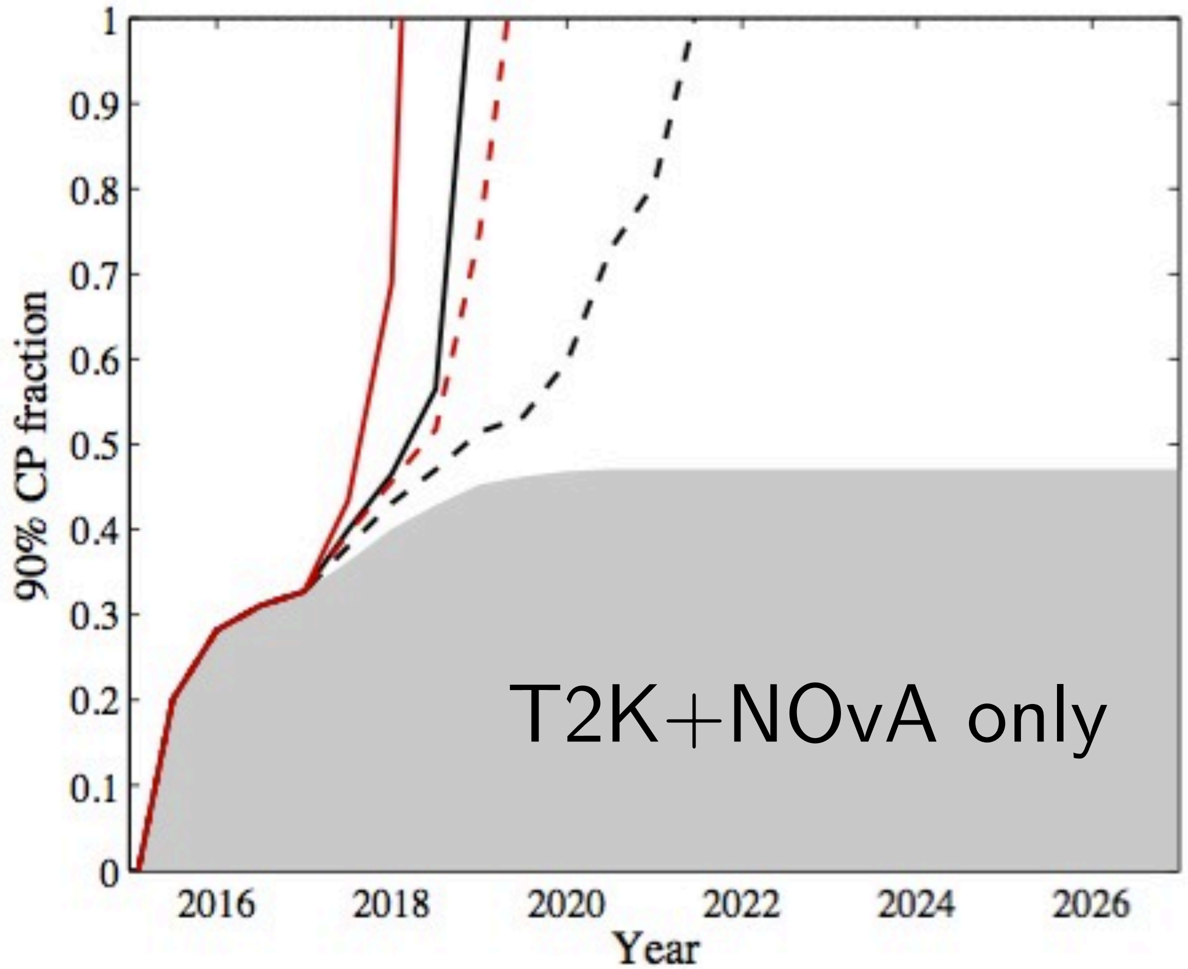


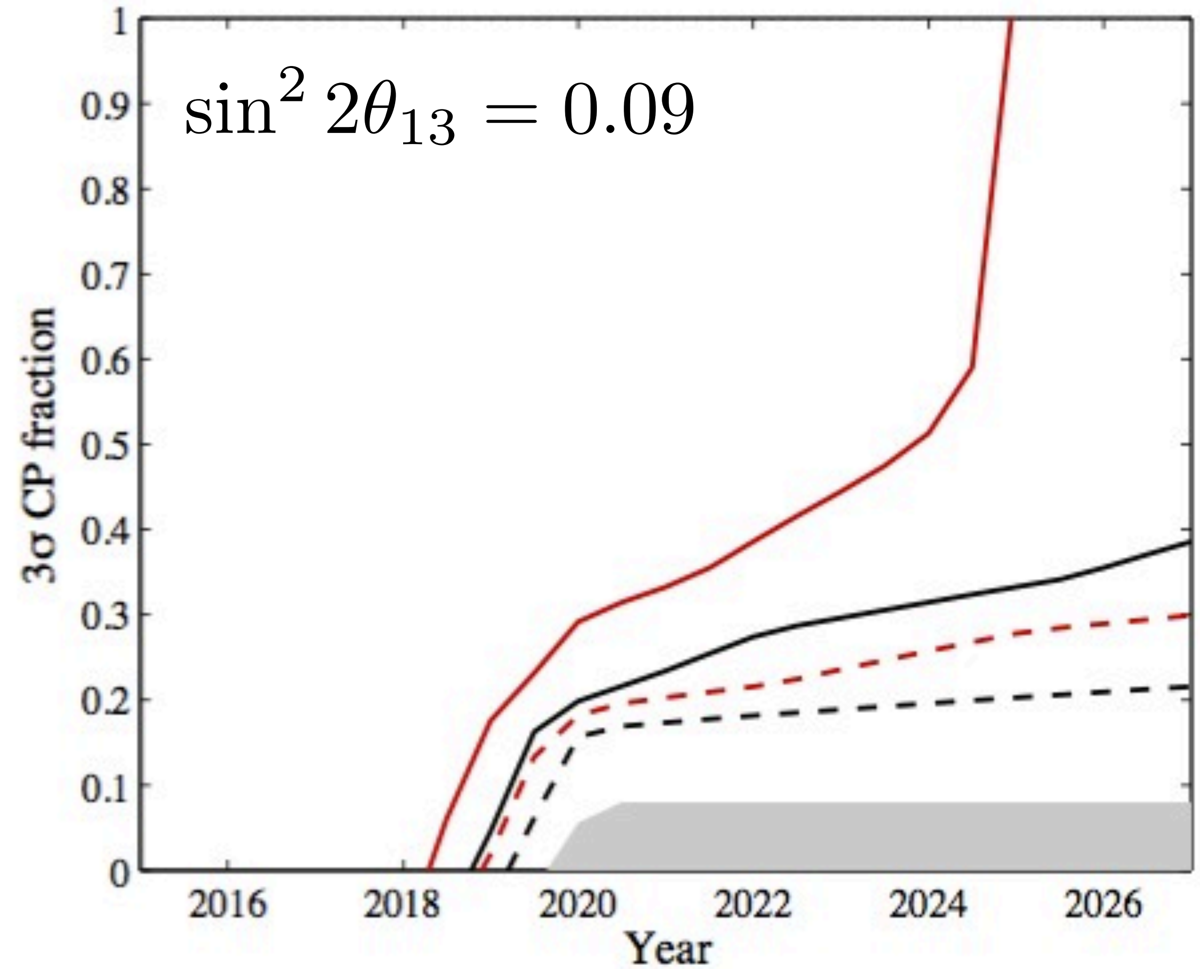
Huber, Lindner, Schwetz, Winter, 0907.1896 [hep-ph]

Present oscillation facilities

T2K+NOvA+INO

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





Blennow, Schwetz, 1203.3388 [hep-ph]

Future oscillation facilities

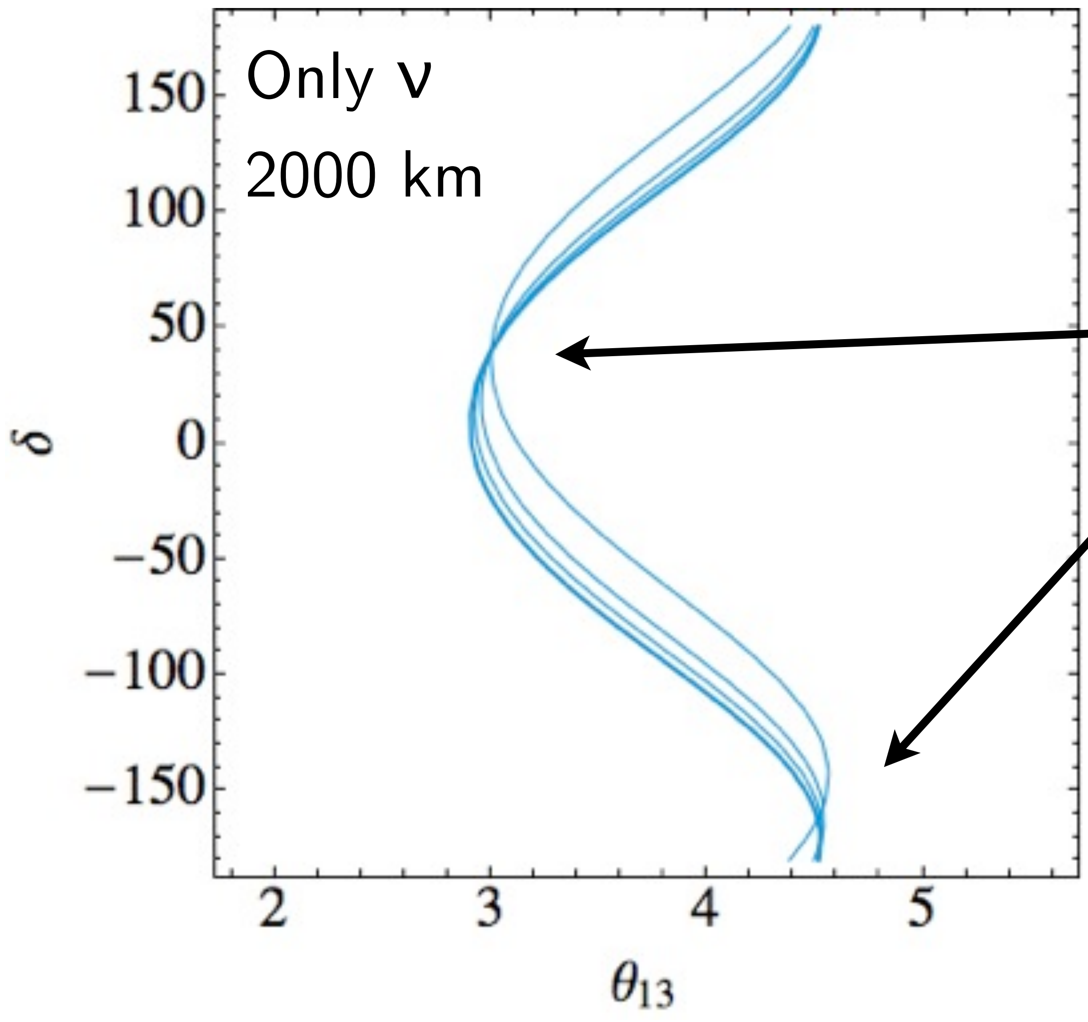
- Super-Beams
  - Japan: T2HK
  - USA: NOvA, LBNE
  - Europe: LAGUNA-LBNO (C2P? SPL?)
- Beta-Beams
  - Low gamma ($\gamma \sim 100$)
  - High gamma ($\gamma \sim 350$ - 580)
- Neutrino Factories
  - High energy ($E_\mu = 25$ - 50 GeV)
  - Low energy ($E_\mu = 4.5$ - 10 GeV)

The golden channel

$$P_{e\mu}^{\pm} = X_{\pm} \sin^2 2\theta_{13} + Z$$

$$+ Y_{\pm} \cos\theta_{13} \sin 2\theta_{13} \cos\left(\pm\delta - \frac{\Delta_{31} L}{2} \right)$$

Cervera et al, hep-ph/0002108



Degeneracy problem: several pairs of values are able to fit the same data

Burguet-Castell et al., hep-ph/0103258

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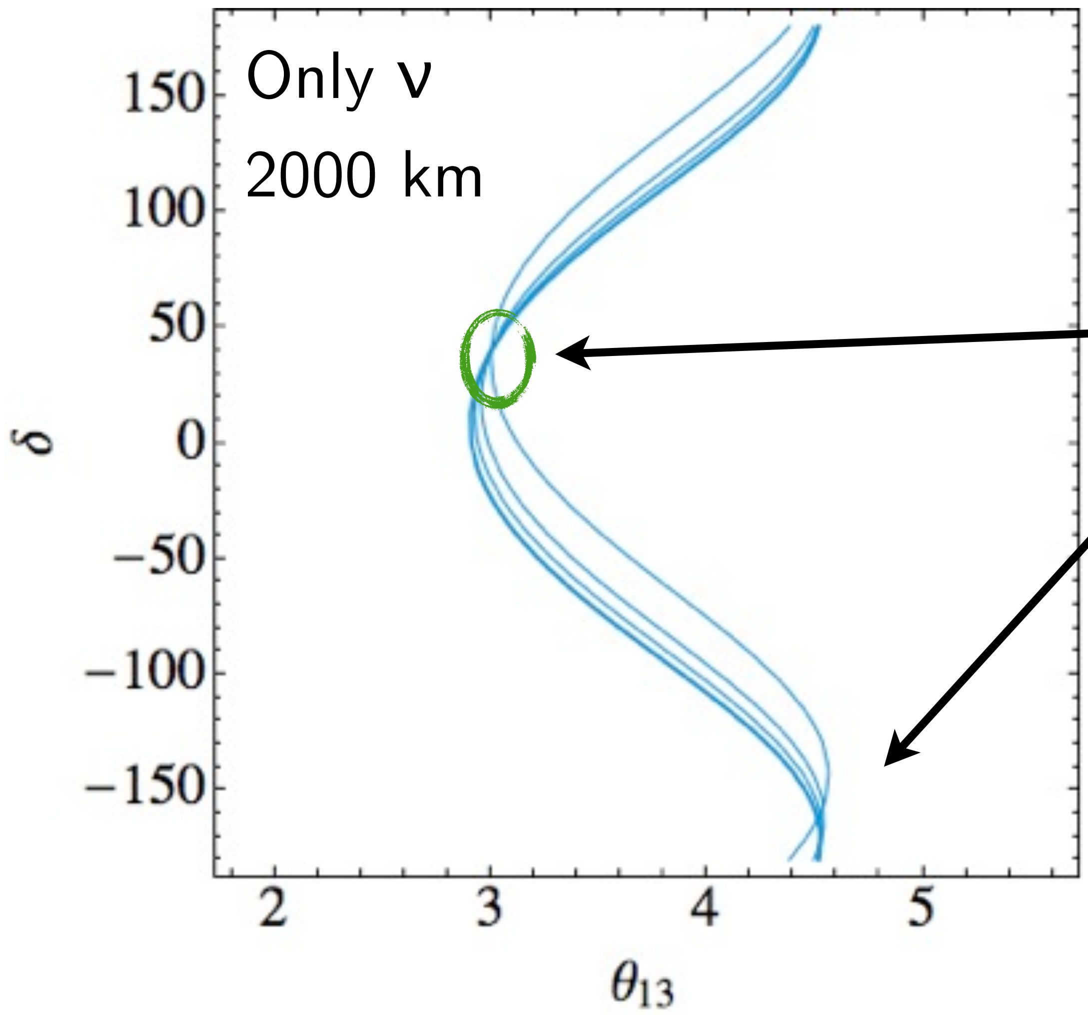

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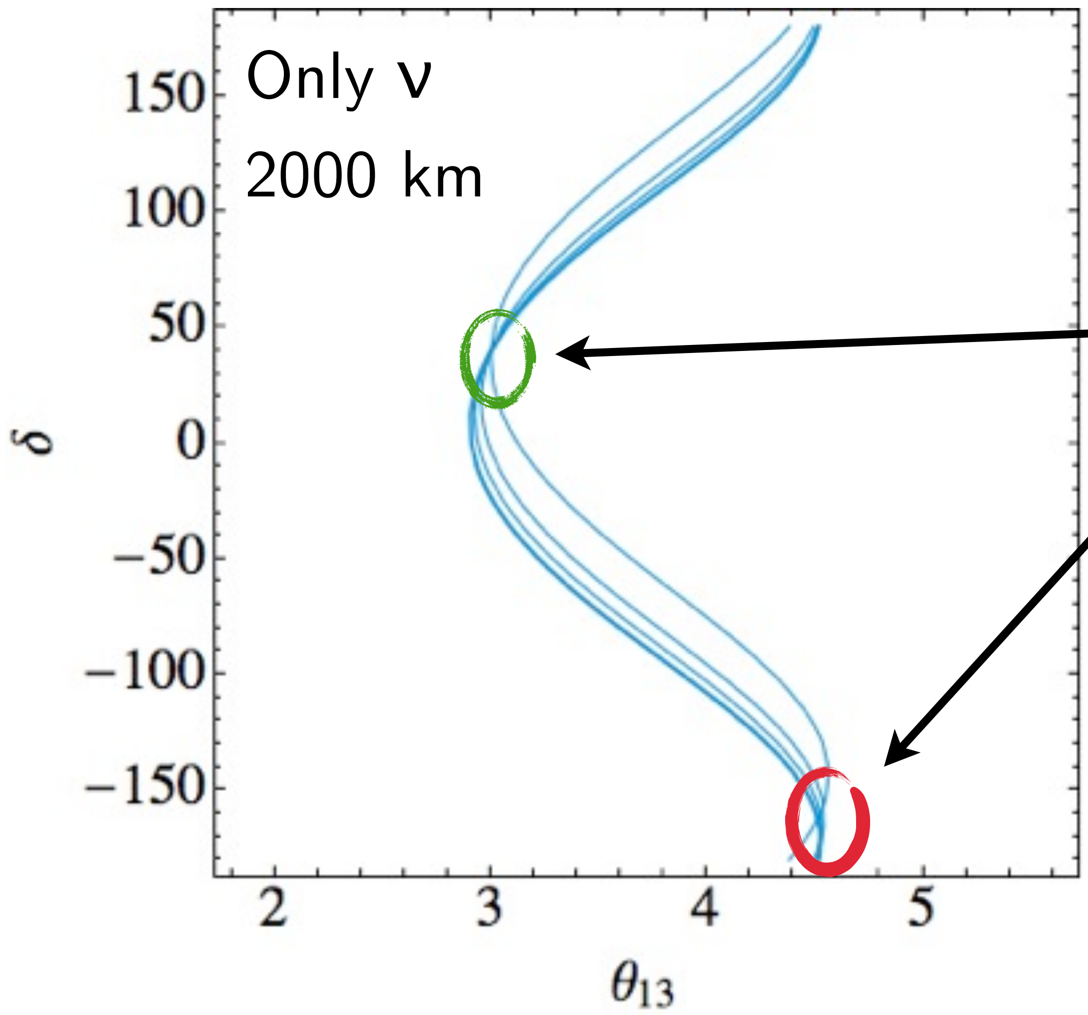

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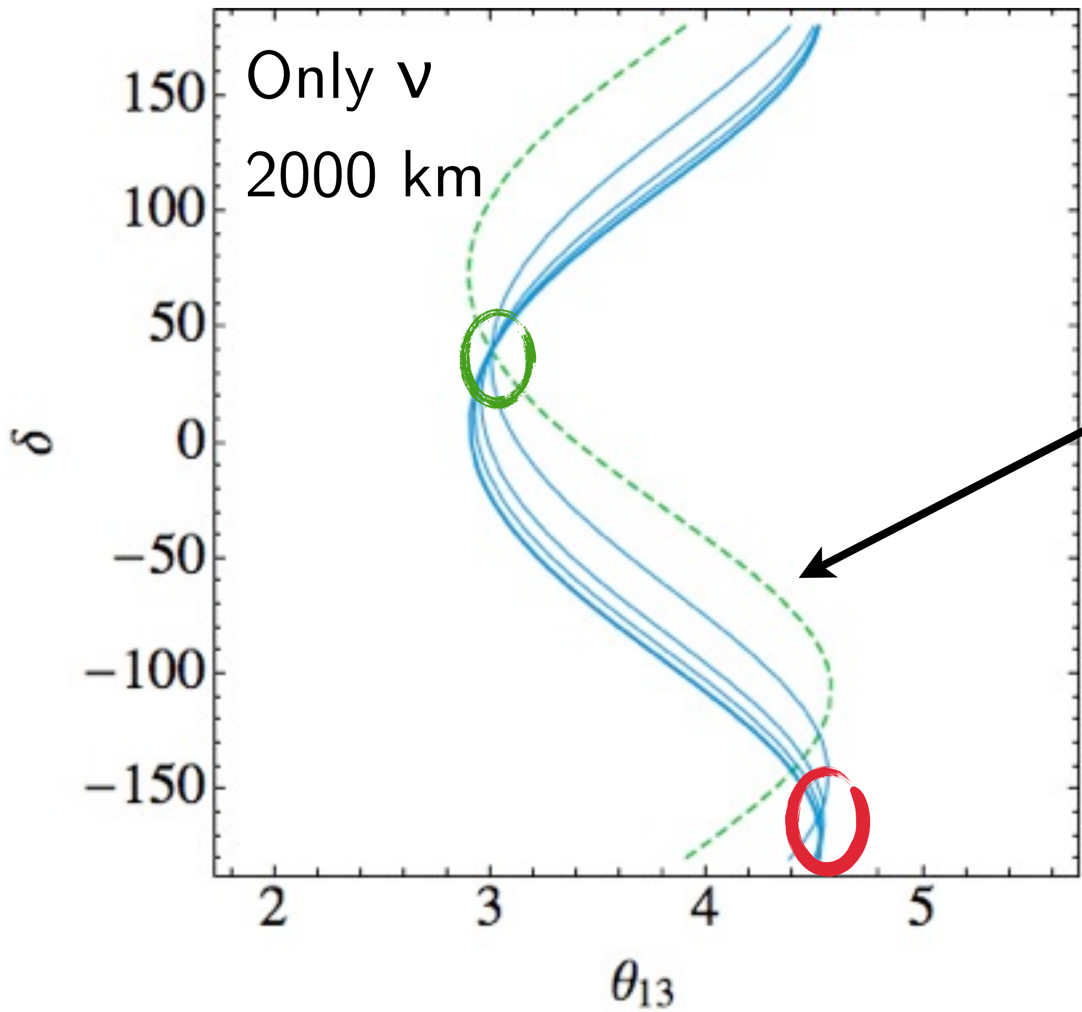

This can be solved in several ways, such as including information at different neutrino energies

Matter effects

$$P_{e\mu}^{\pm} = X_{\pm} \sin^2 2\theta_{13} + Z$$
$$+ Y_{\pm} \cos\theta_{13} \sin 2\theta_{13} \cos\left(\pm\delta - \frac{\Delta_{31} L}{2}\right)$$

In vacuum, this is the only dependence on the hierarchy...

Matter effects

$$P_{e\mu}^{\pm} = X_{\pm} \sin^2 2\theta_{13} + Z$$

$$+ Y_{\pm} \cos\theta_{13} \sin 2\theta_{13} \cos\left(\pm\delta - \frac{\Delta_{31} L}{2}\right)$$

In matter, these are modified differently for NH/IH

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$$+ Y_{\pm} \cos\theta_{13} \sin 2\theta_{13} \cos\left(\pm\delta - \frac{\Delta_{31} L}{2}\right)$$

In matter, these are modified differently for NH/IH

General landscape

BB100,BB350:
hep-ph/0406132
hep-ph/0503021

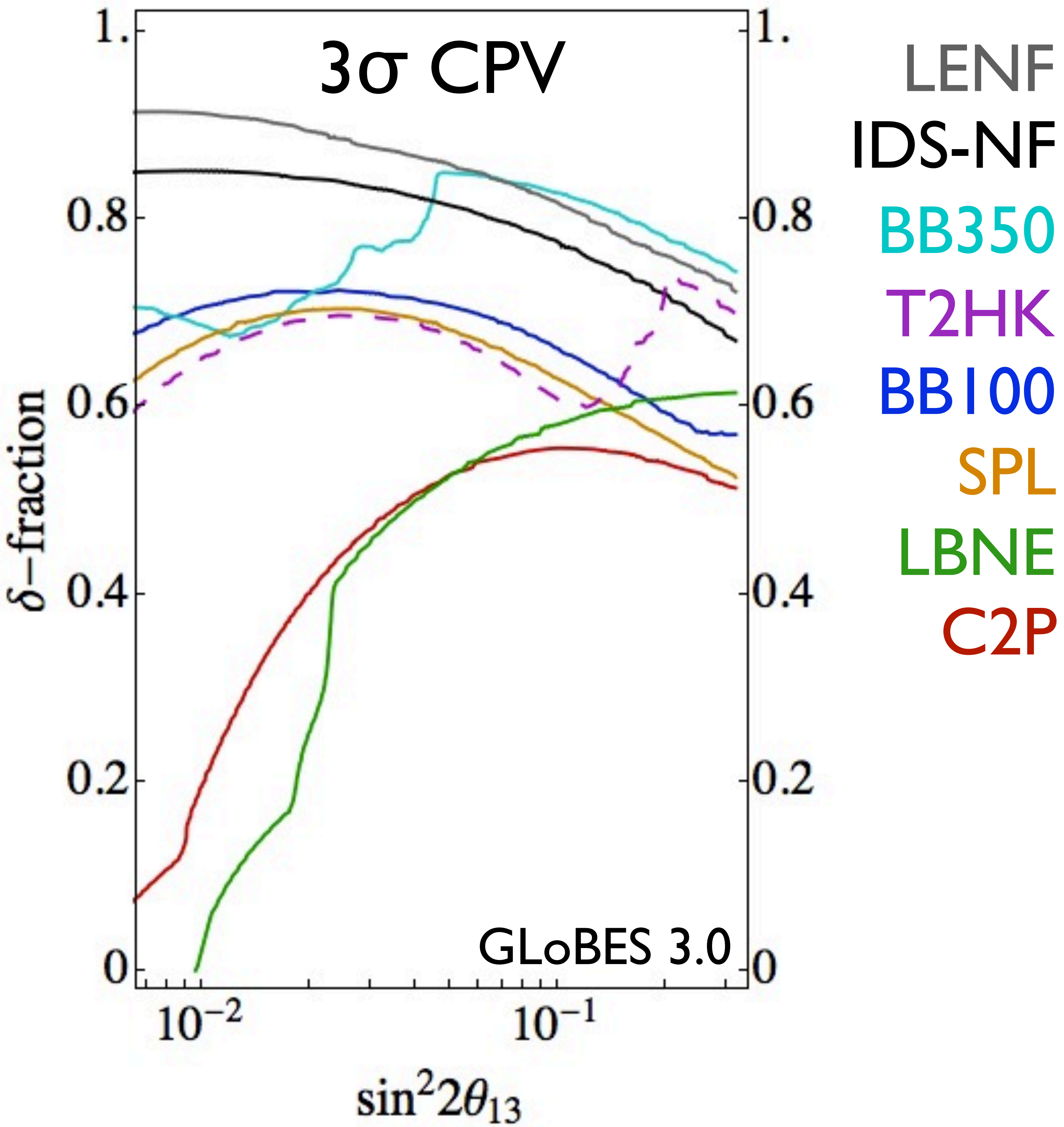
T2HK: hep-ex/0106019

C2P, SPL:
1001.0077 [physics.ins-det]
hep-ex/0411062
1106.1096 [physics.acc-ph]

LENF: 1012.1872 [hep-ph]

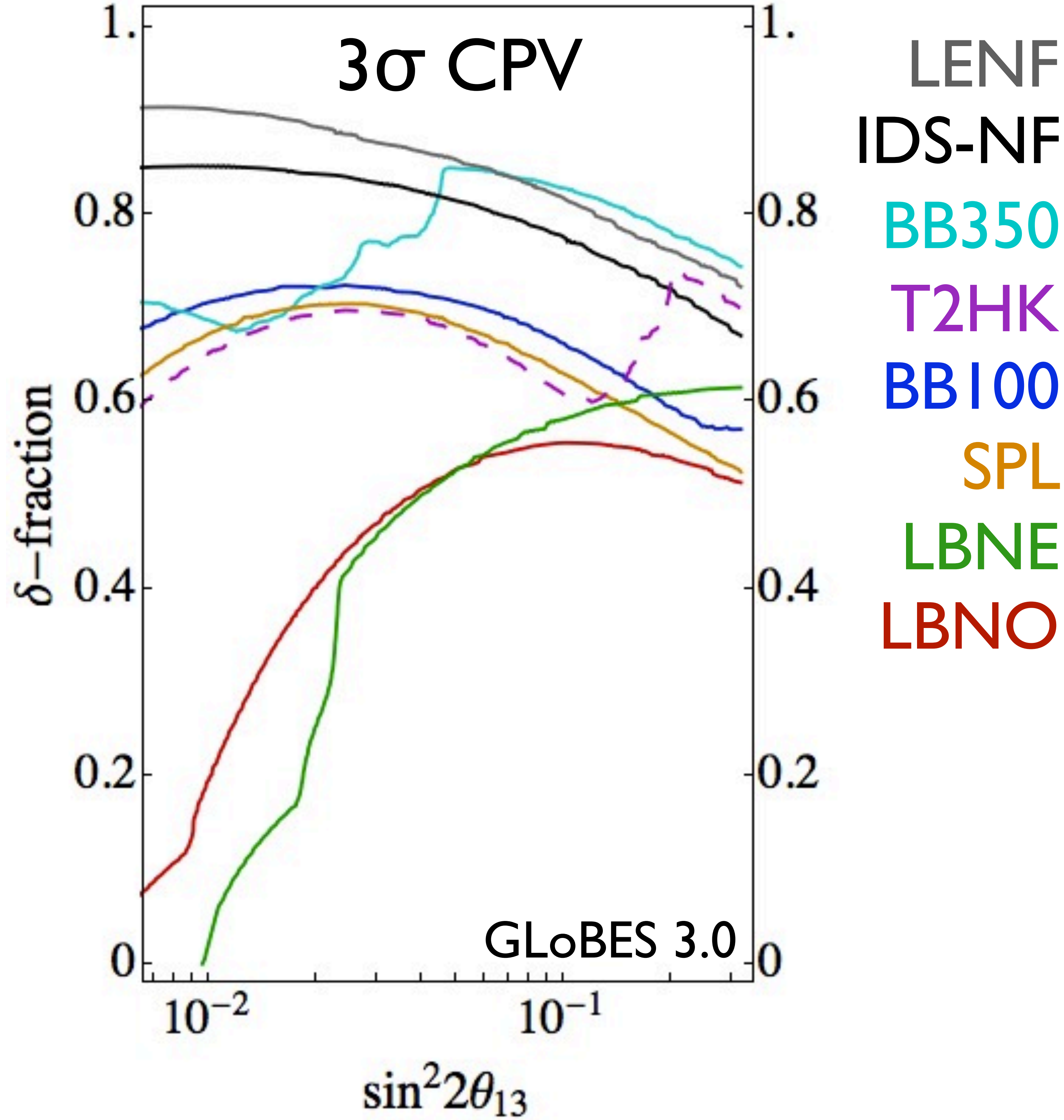
LBNE: 1110.6249 [hep-ex]

IDS: 1112.2853 [hep-ex]



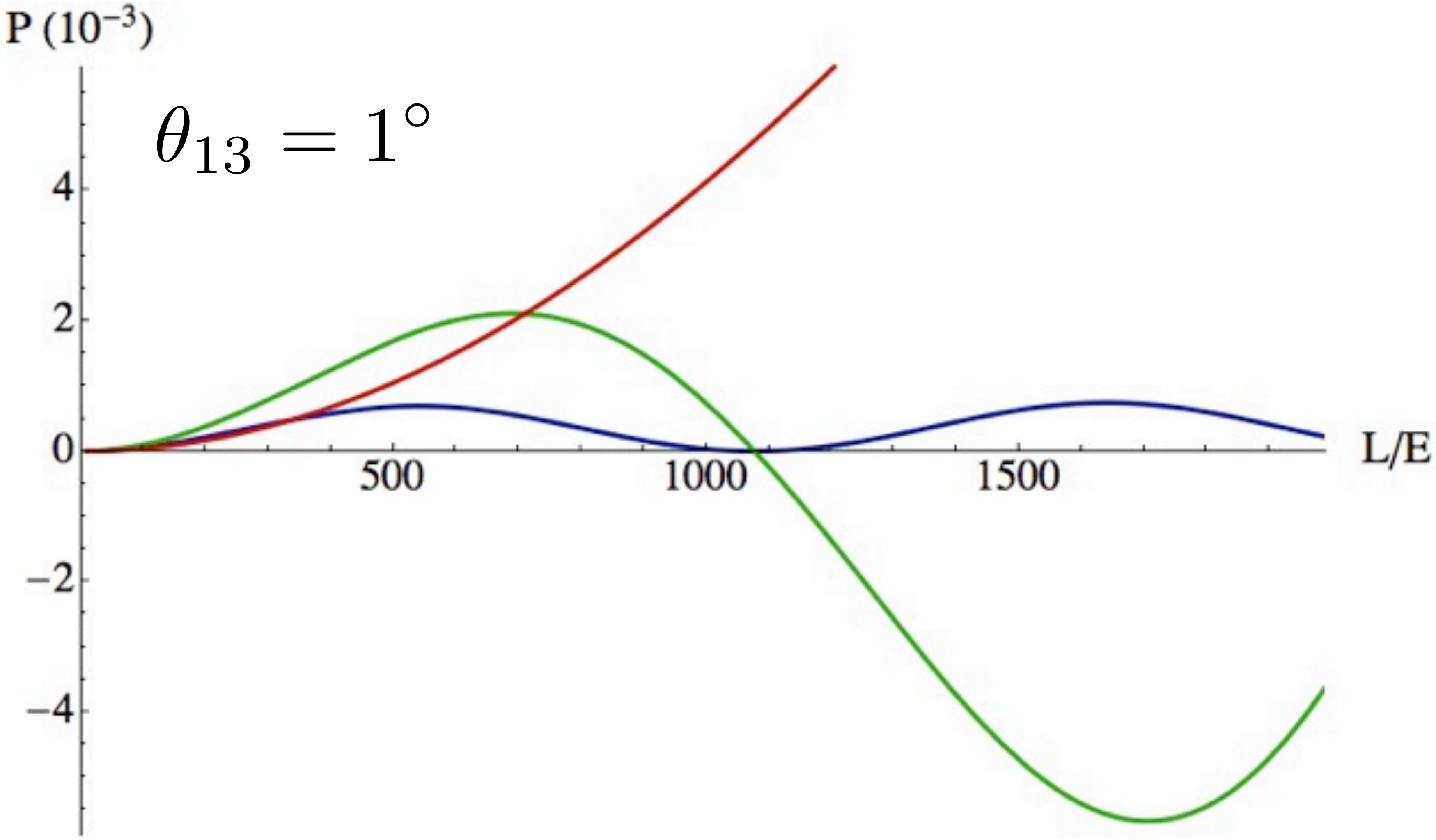
The 1^{st} and 2^{nd} oscillation maxima

Motivation


3σ CPV
1.
0.8
0.6
0.4
0.2
0
δ−fraction
10^{-2}
10^{-1}
$\sin^2 2\theta_{13}$
GLoBES 3.0
LENF
IDS-NF
BB350
T2HK
BB100
SPL
LBNE
LBNO

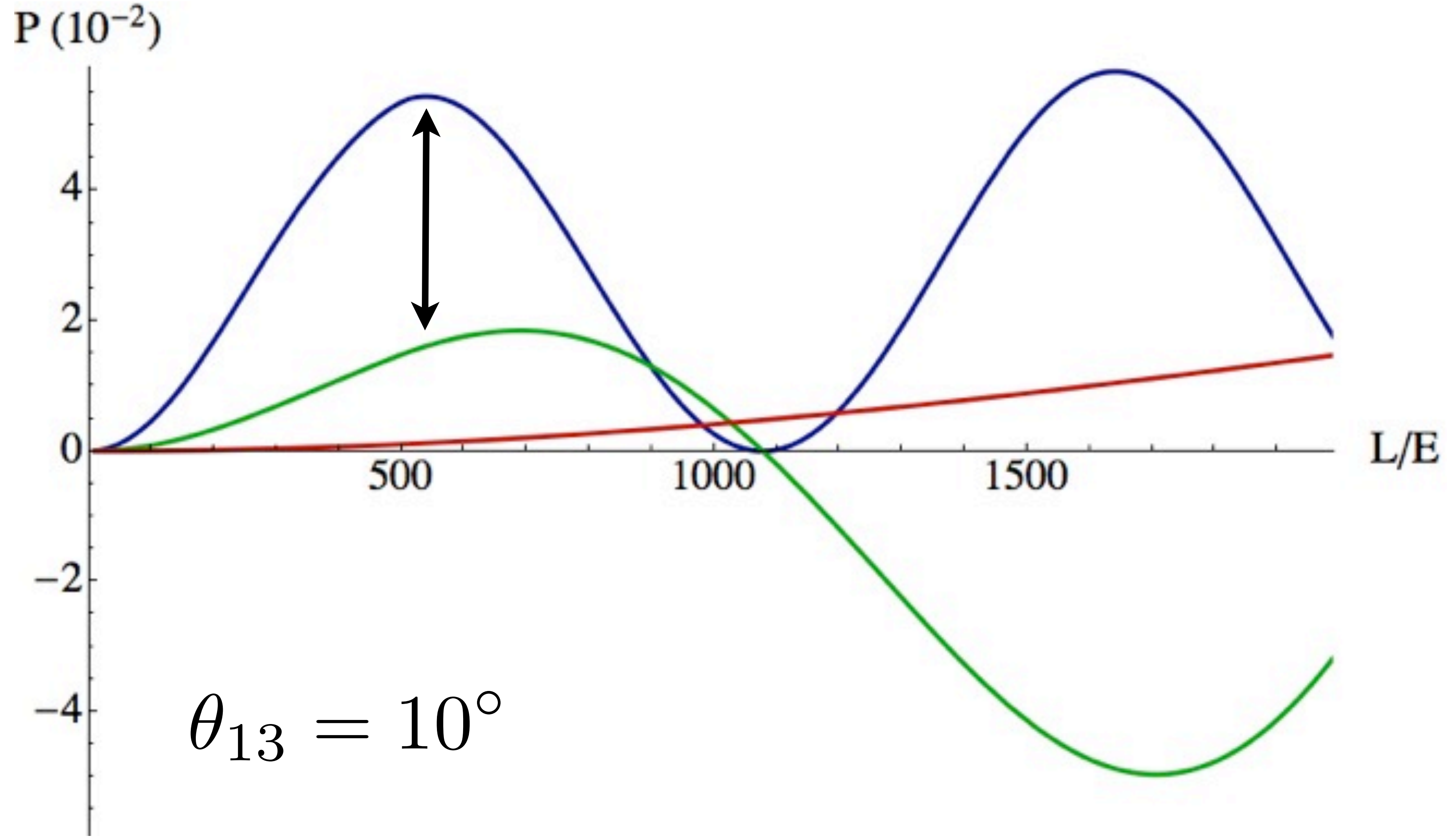
Motivation

$$P_{e\mu}^{\pm}(\theta_{13},\delta) = X_{\pm}\sin^2 2\theta_{13} + Z + Y_{\pm}\cos\theta_{13}\sin 2\theta_{13}\cos\left(\pm\delta - \frac{\Delta_{31}L}{2}\right)$$



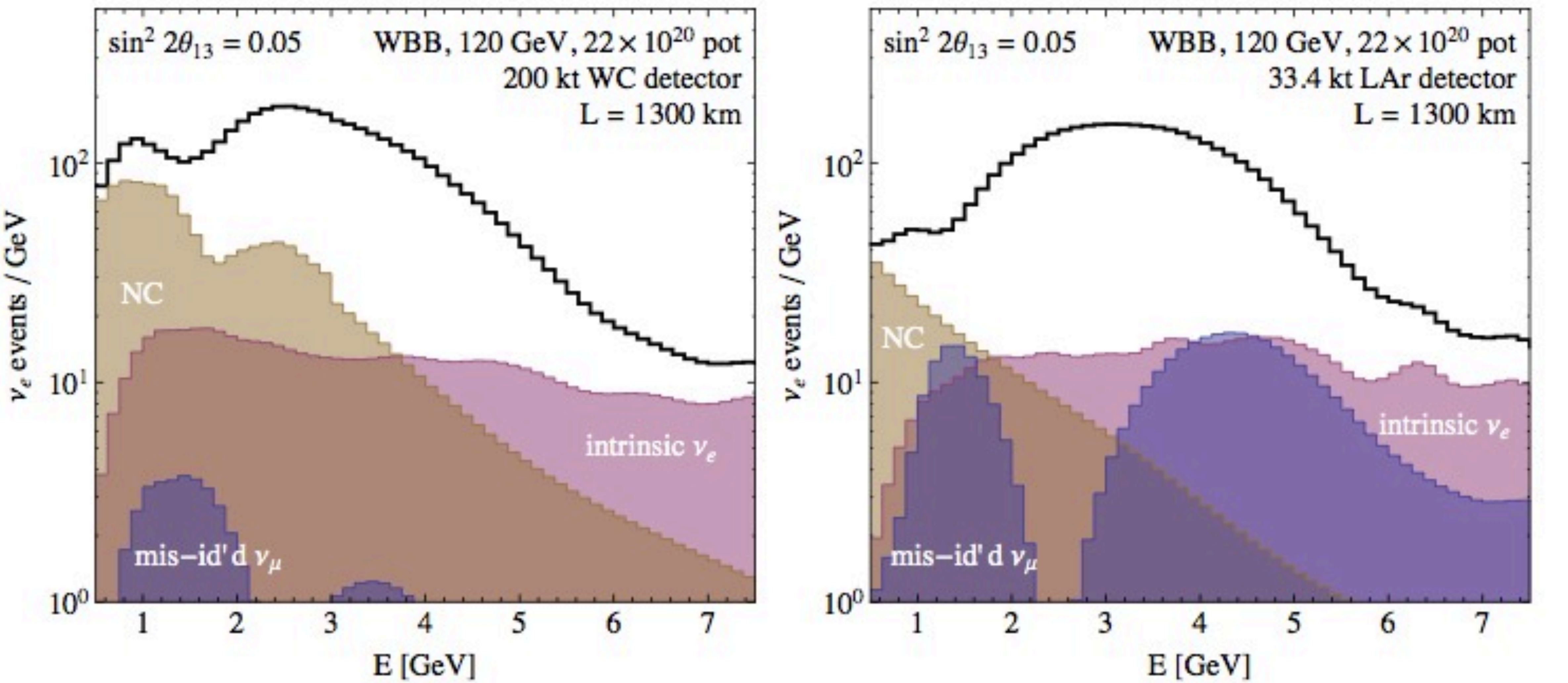
Motivation

$$P^{\pm}_{e\mu}(\theta_{13}, \delta) = X_{\pm} \sin^2 2\theta_{13} + Z$$
$$+ Y_{\pm} \cos\theta_{13} \sin 2\theta_{13} \cos\left(\pm\delta - \frac{\Delta_{31} L}{2}\right)$$



Combining $1^{st}+2^{nd}$ peaks

The 2^{nd} maximum was already studied for LBNE
but it was of little help...



Huber and Kopp, 1010.3706 [hep-ph]

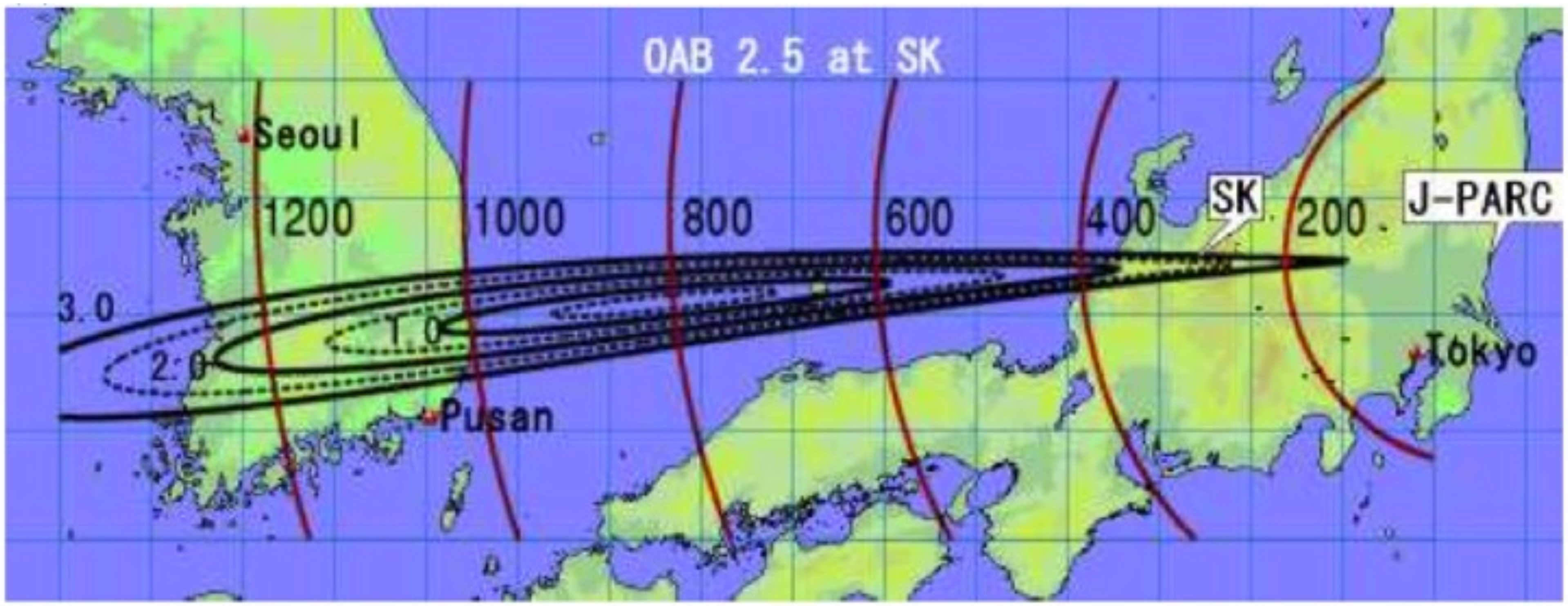
The 2nd oscillation peak

- The T2KK proposal considered the 2nd maximum in combination with the 1st for an off-axis beam, at L~1000 km and L~650 km

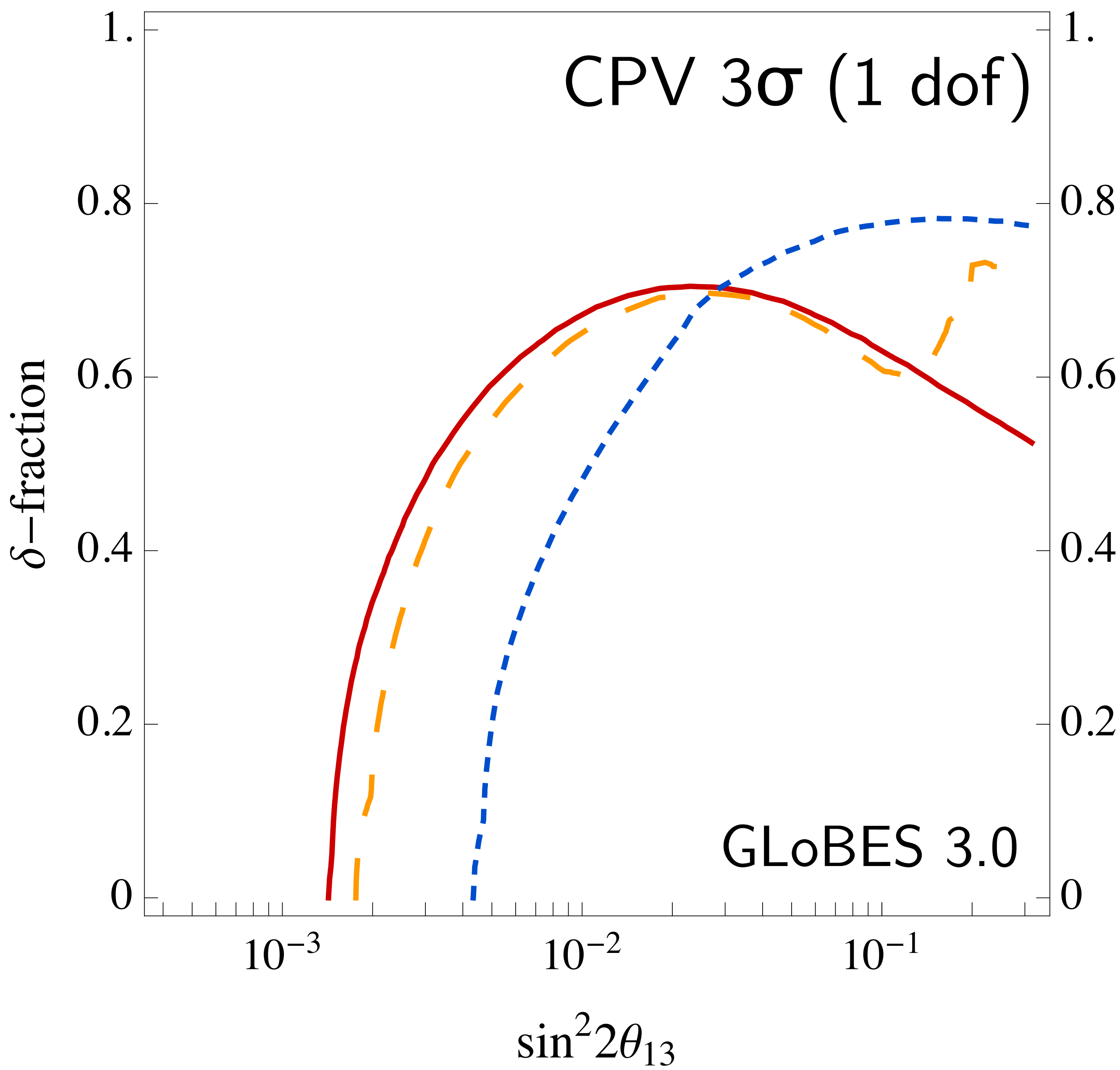
hep-ph/0504026

0901.1517 [hep-ph]

0801.4035 [hep-ph]



The 2nd oscillation peak



T2HK: 4 MW, 440 kton WC, 295 km

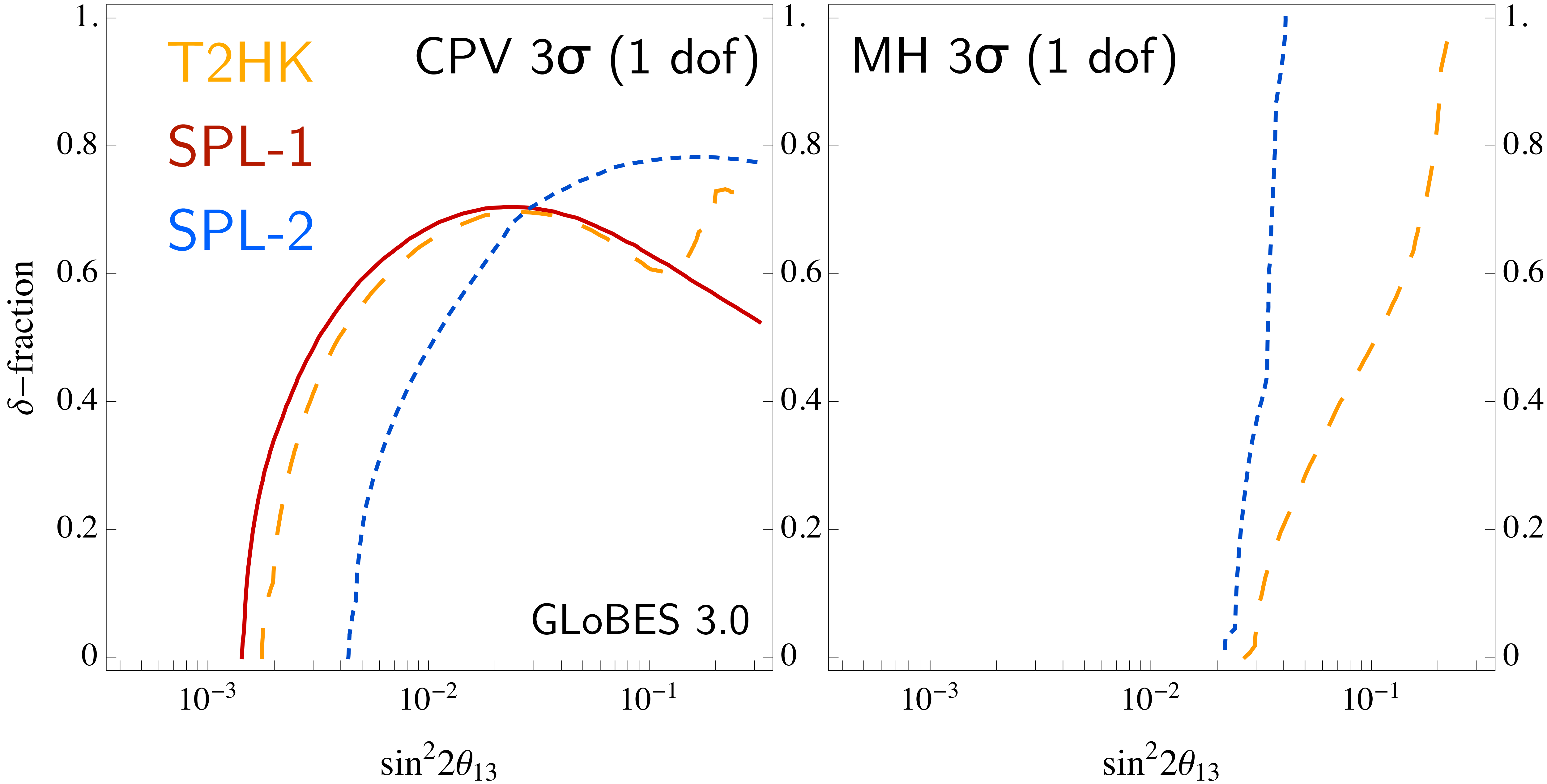
SPL-1: 4 MW, 440 kton WC, 130 km

SPL-2: 4 MW, 440 kton WC, 650 km

(Sys errors: 5% sig, 10% bg)

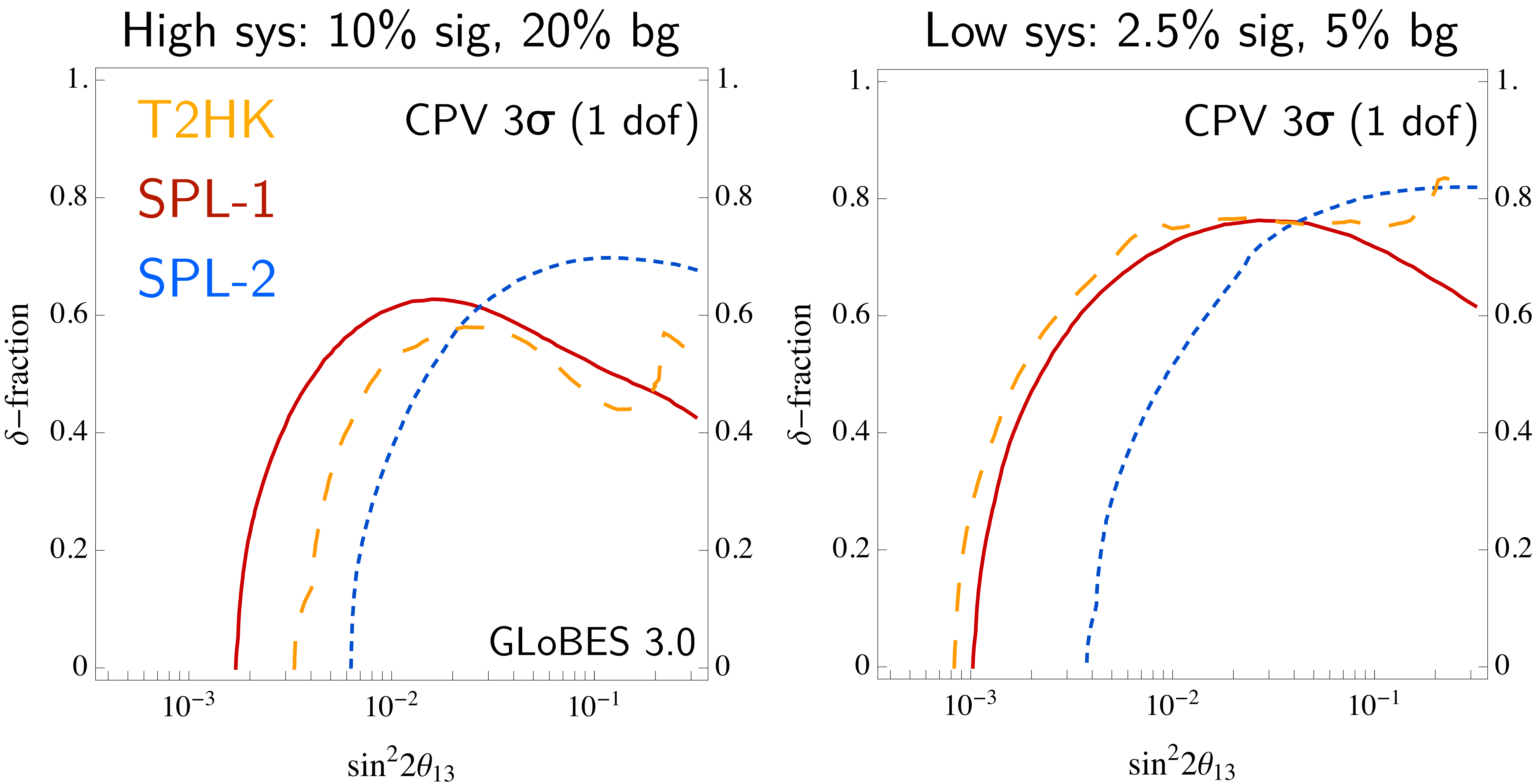
Coloma, Fernandez-Martinez, 1110.4583 [hep-ph]

The 2nd oscillation peak



Coloma, Fernandez-Martinez, 1110.4583 [hep-ph]

Effect of systematics

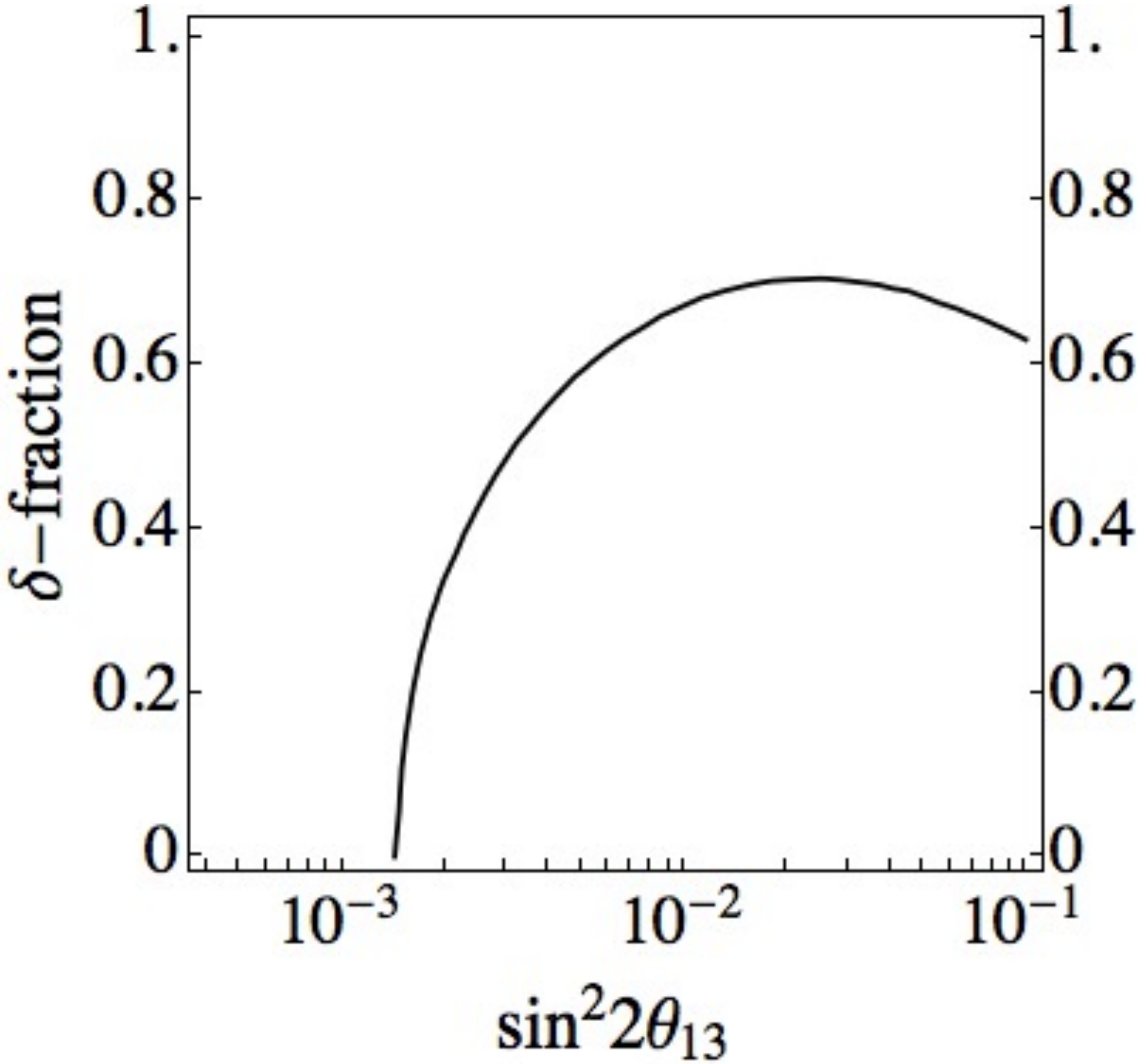


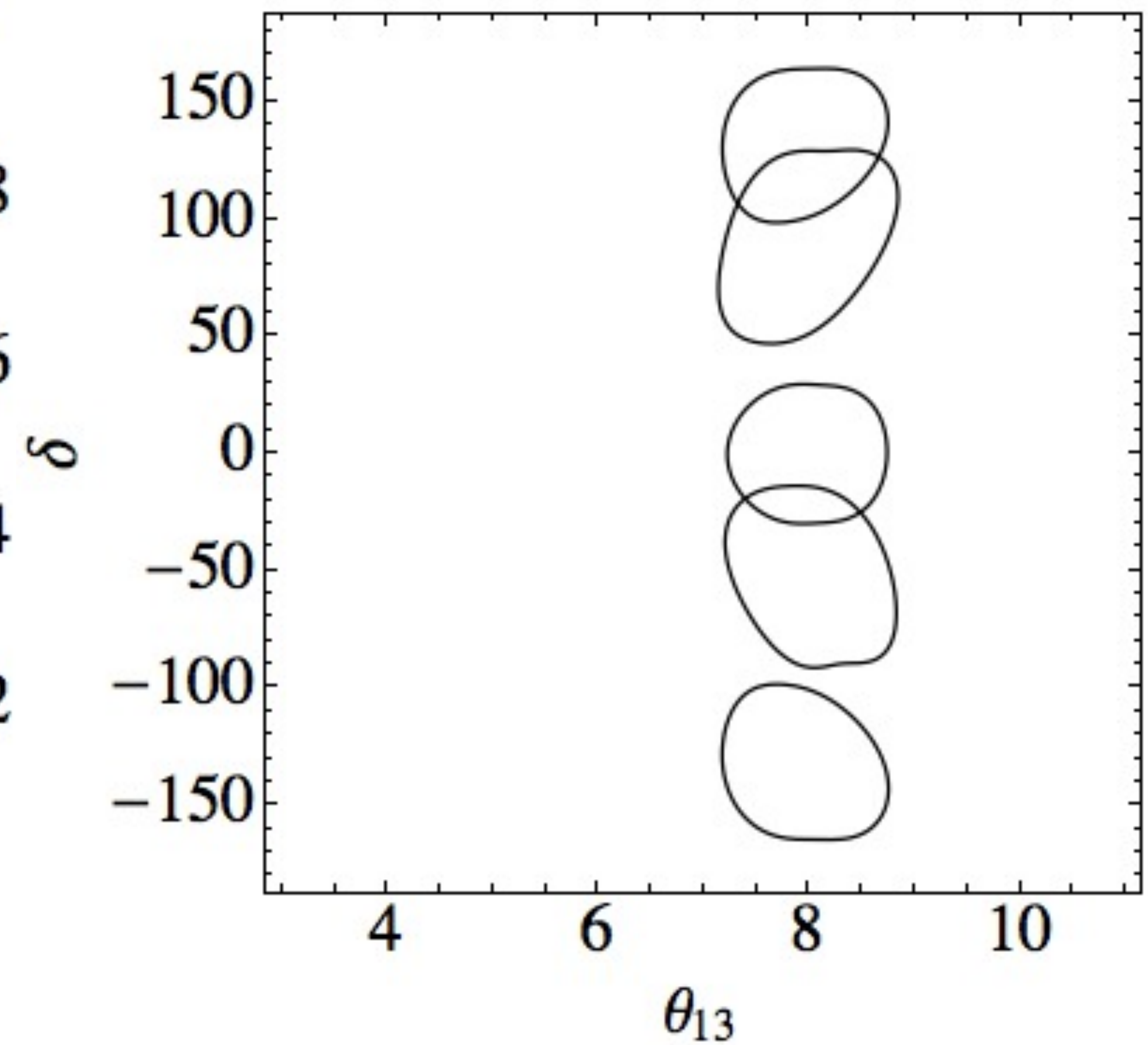
Coloma, Fernandez-Martinez, 1110.4583 [hep-ph]

Precision

Motivation

Discovery potential vs precision:





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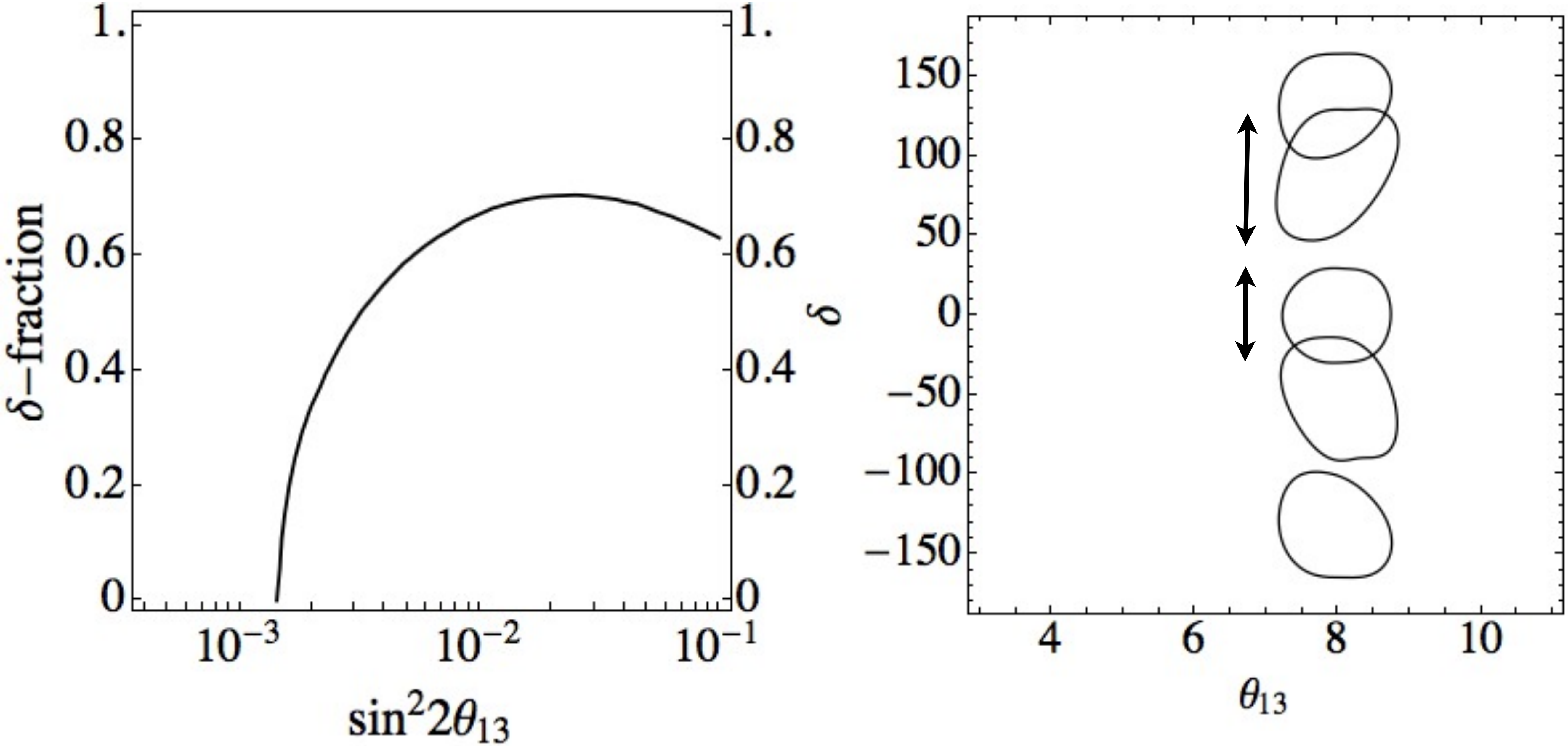
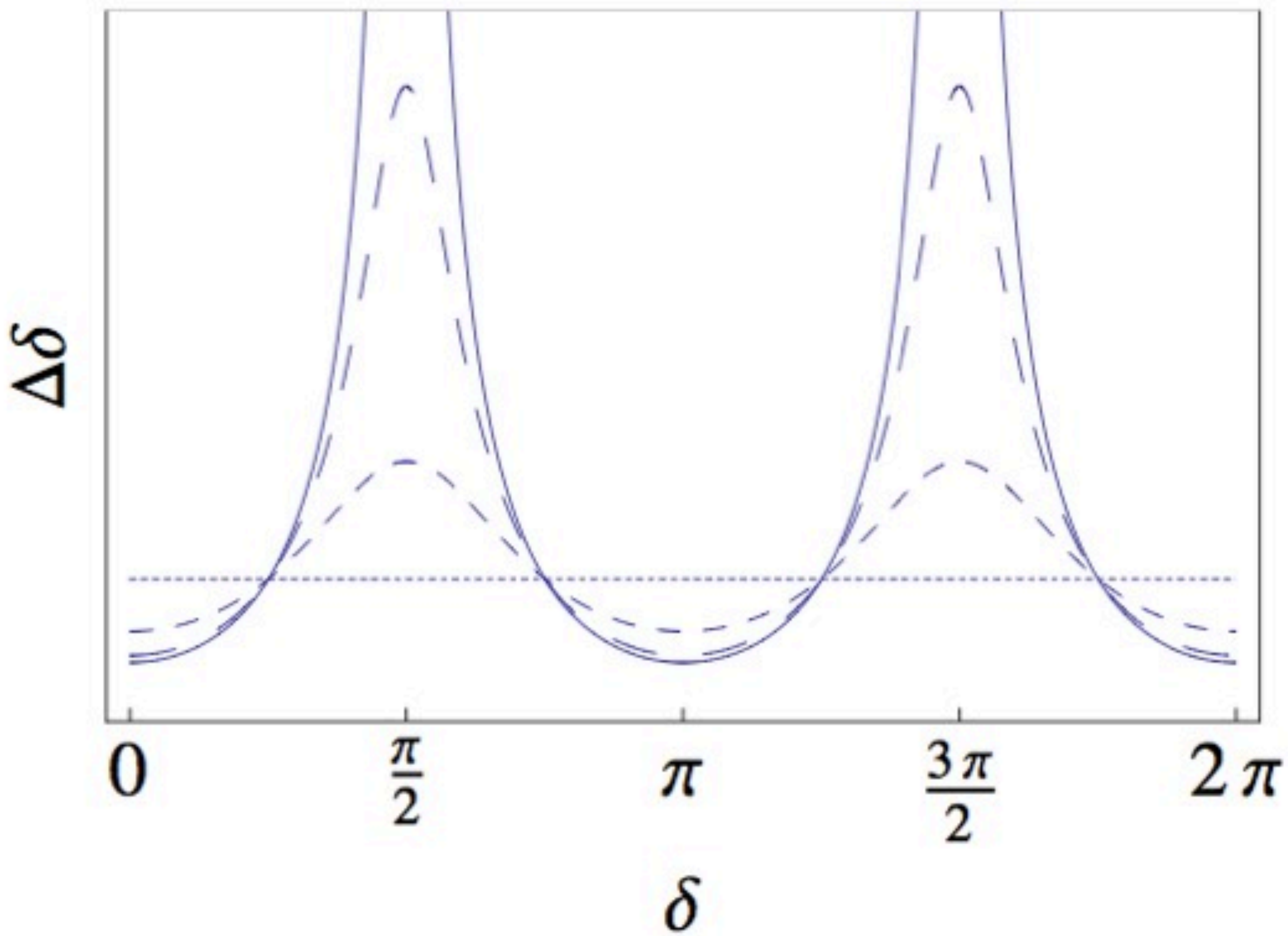
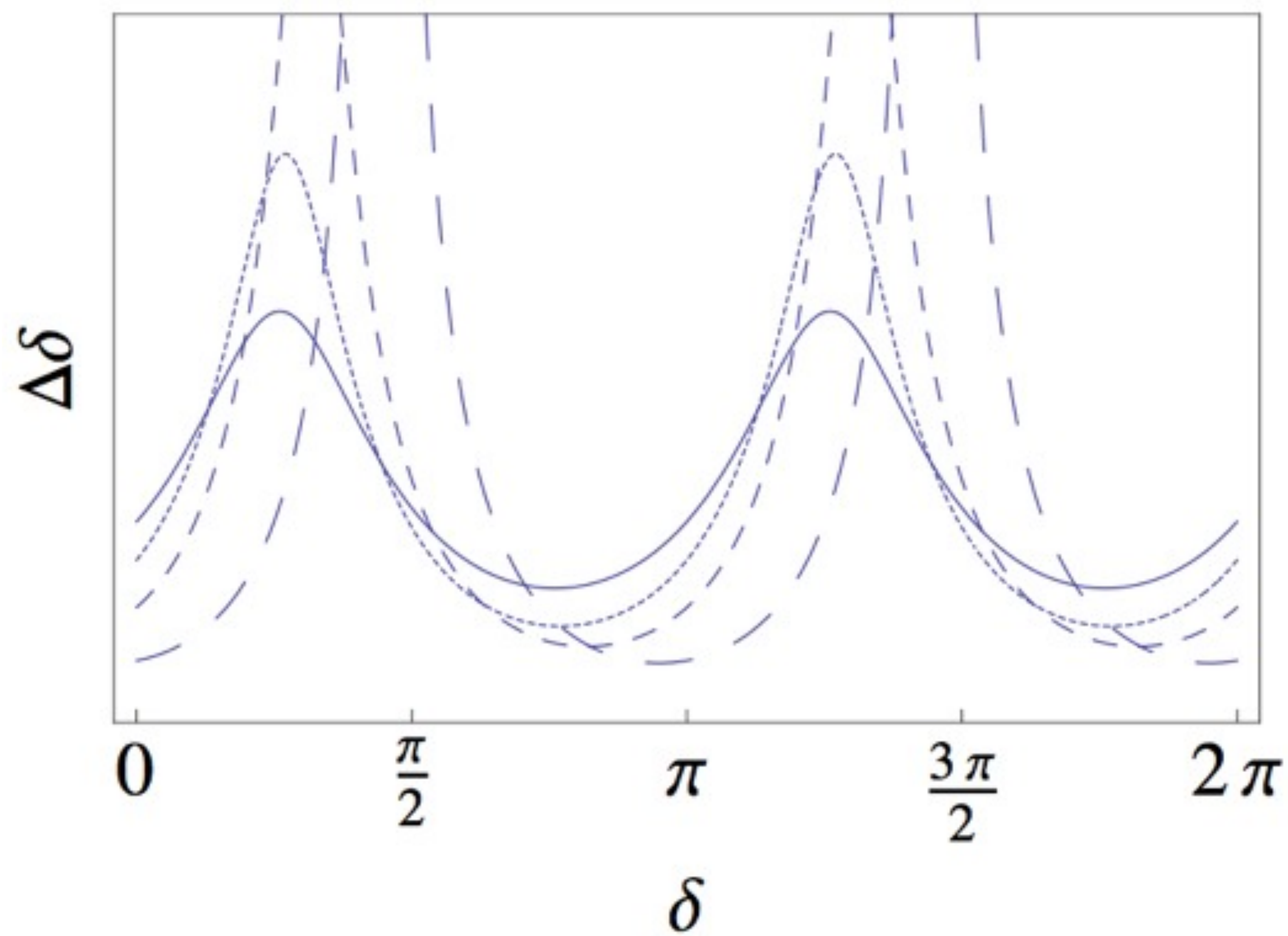


On/Off peak (vacuum)



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

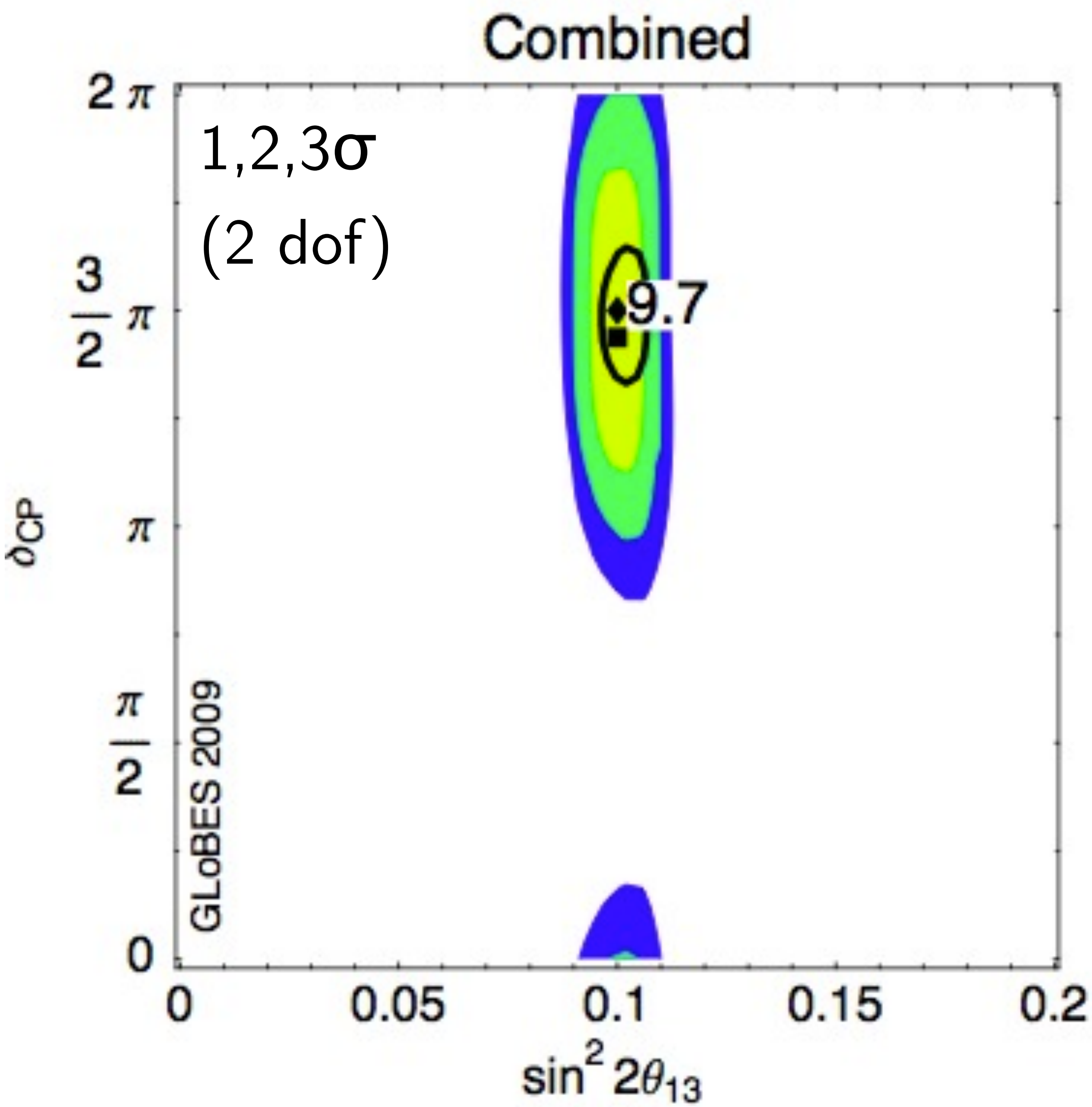
Importance of matter effects



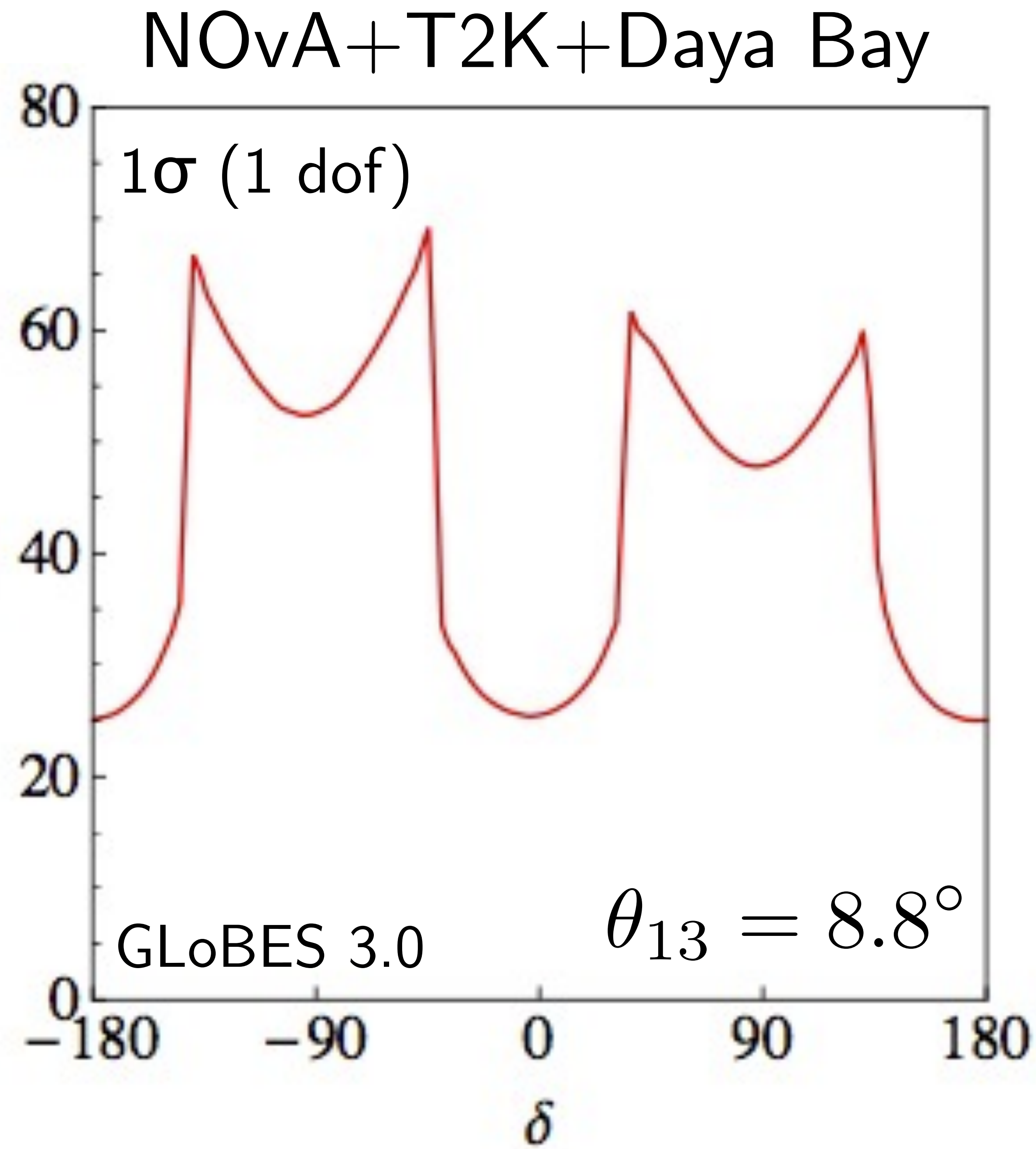
$$(\Delta\delta)_\pm \propto \frac{1}{\sin\left(\frac{\pi}{2}\frac{1}{(1\mp\hat{A})} \mp \delta\right)}$$

$$\left(\hat{A} \equiv \frac{\sqrt{2}G_F n_e L}{2\Delta}\right)$$

The starting point

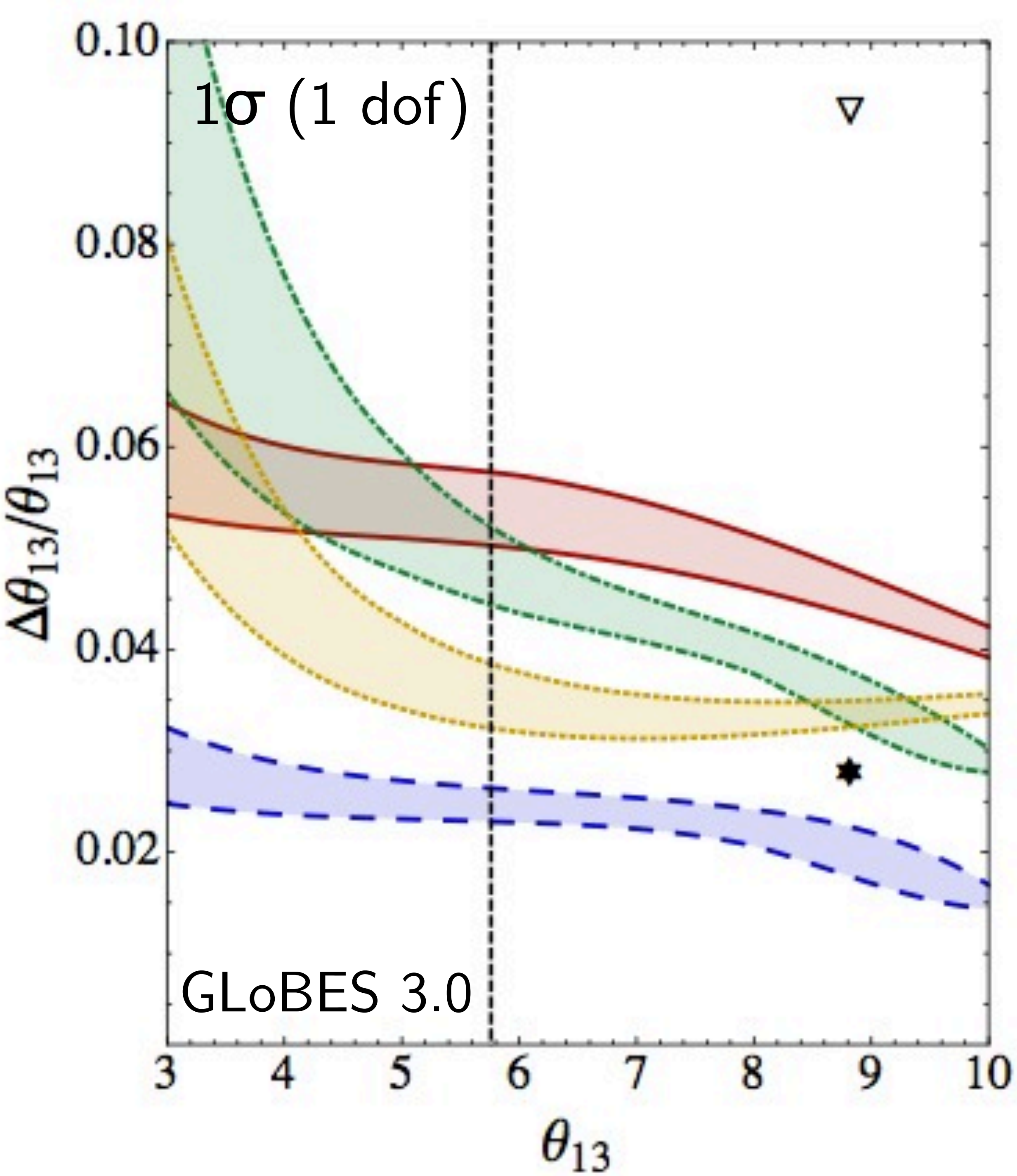


Huber, Lindner, Schwetz, Winter, 0907.1896 [hep-ph]



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

Precision



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

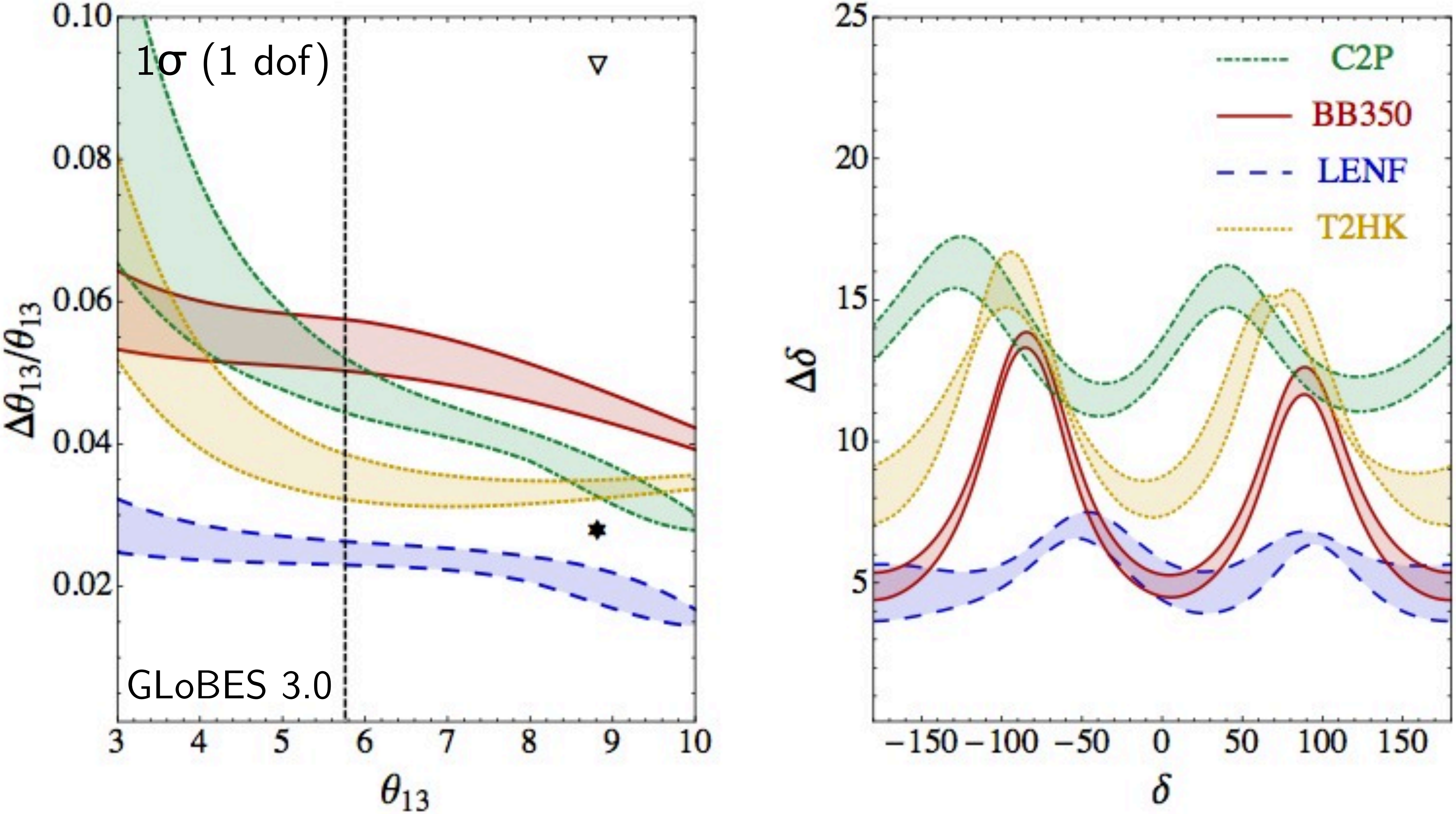
T2HK: 4 MW, 500 kton WC, 295 km, 5% sys

C2P: 800 kW, 100 kton LAr, 2300 km, 5% sys

BB350: 1.1(2.8) x10^{18} ions, 500 kton WC, 650 km, 2.5% sys

LENF: 1.4x10^{21} μ decays 100 kton MIND, 2000 km, 2.5% sys

Precision



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

Conclusions

- We are in the middle of an important change
- Now that we know that t13 is large, priorities may need to be revised
  - Possible optimization of some facilities: go to 2nd peak
  - Precision becomes relevant:
    - not all facilities with good discovery potential are necessarily going to be good in precision too
    - combination of matter+vacuum may be a good option
- Effect of systematics should be studied in detail:
    - for CPV, it might be good to go to 2nd peak; for precision, a ND is needed

Thank you!