What can be done for CP violation in the next 10 years?

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in collaboration with:
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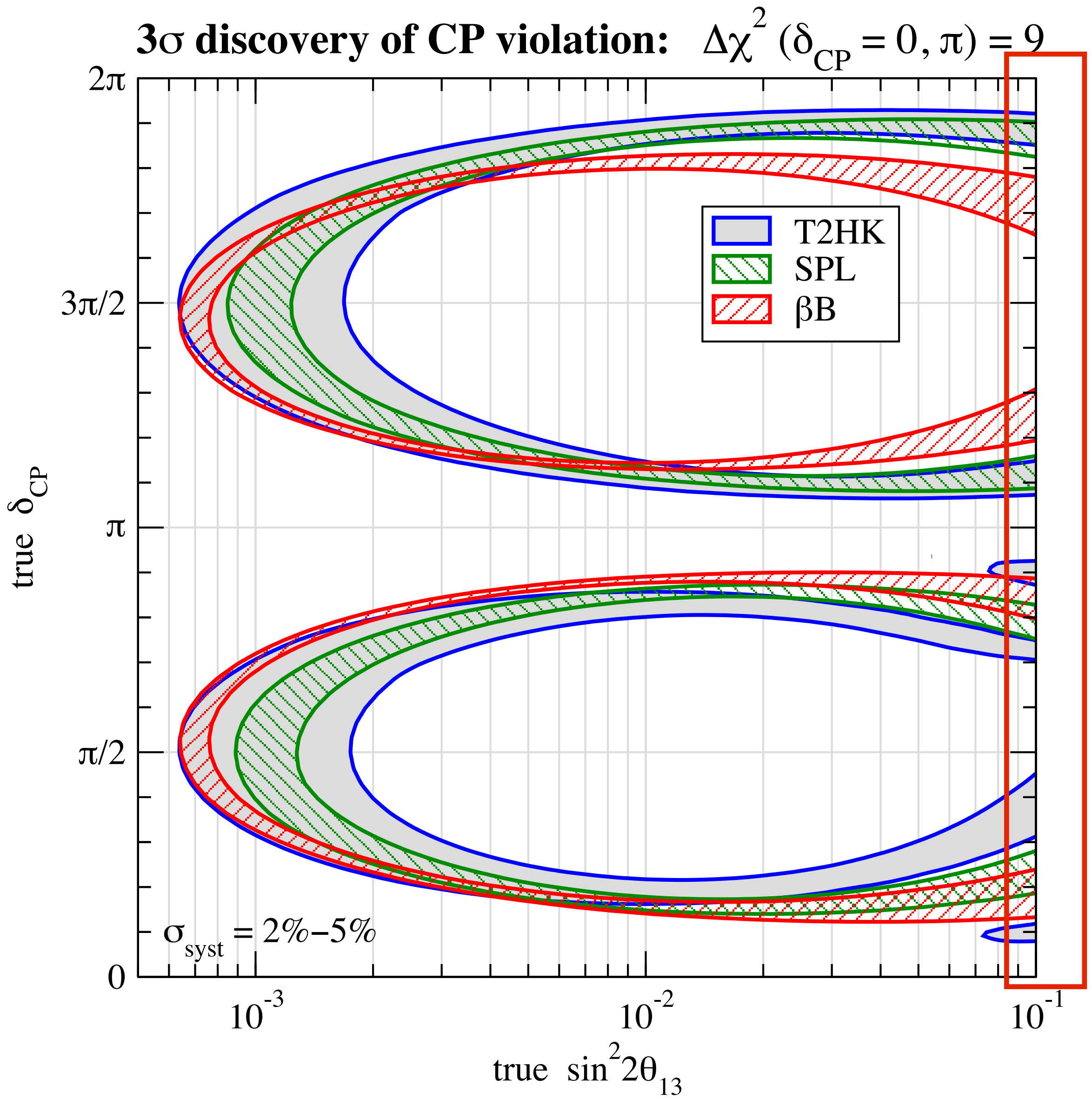
arXiv:1307.3248

Things change...

After θ_{13}, the experimental strategies should be re-thought...

Do we need a neutrino factory? A β-beam?

Can T2K and NOvA help us in probing δ_{cp}?



Campagne et al JHEP 0704 (2007) 003

Why δ_{cp}?

Last unknown in neutrino mixing

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Is observable CP violation confined to hadrons?

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Last unknown in neutrino mixing

Is observable CP violation confined to hadrons?

Glashow, Particle Physics in the United States - A Personal Point of view 1305.5482

"I would assign very high priority to experiments that could demonstrate the existence of CP violating effects."

"The other important mass-related issue is the binary choice between two orderings of neutrino masses. [...] The result is also relevant to the design of experiments to search for CP violation in neutrino oscillations."

Model building, leptogenesis, etc...

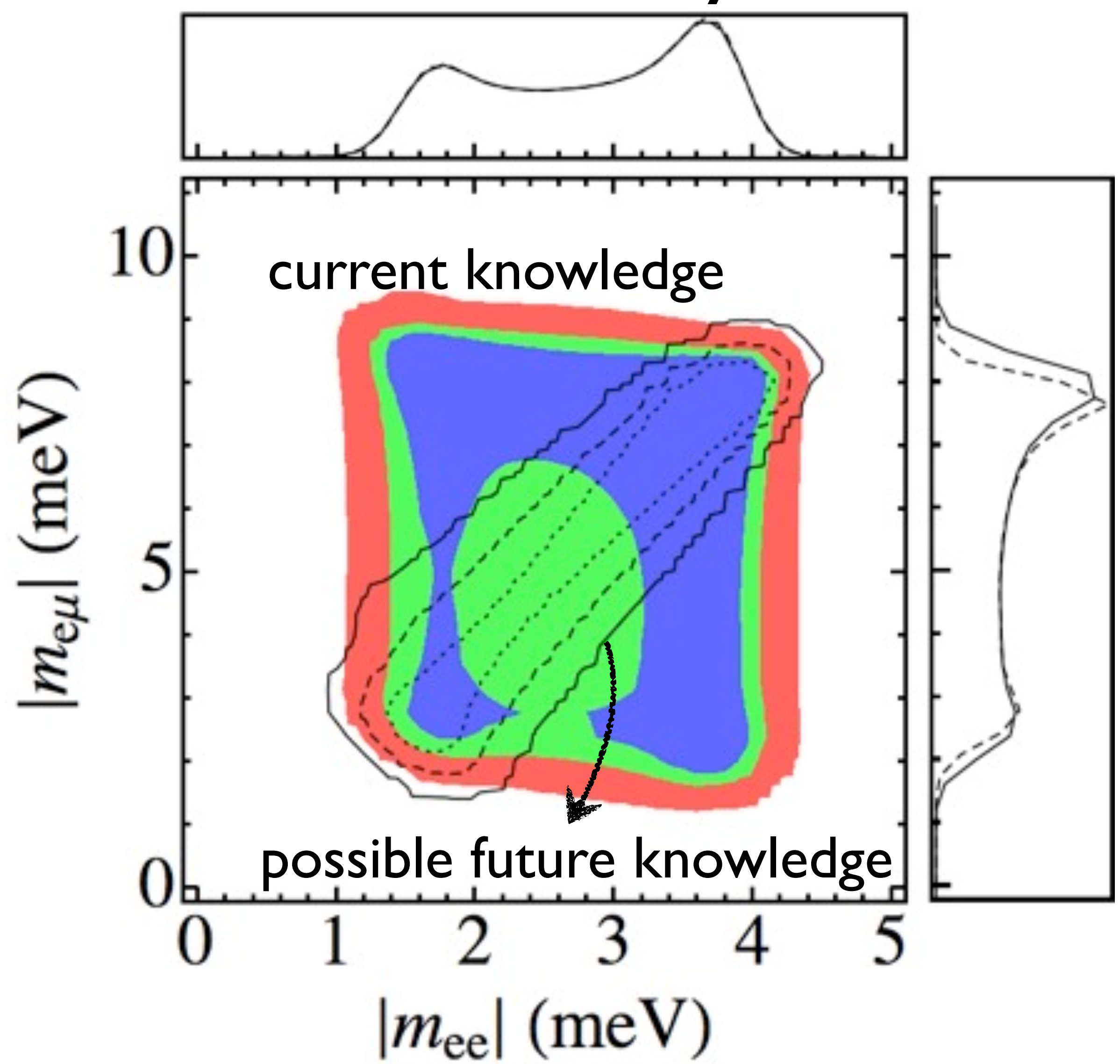
Why δ_{cp}?

What do we know about the mass matrix and its correlations?

Monte Carlo simulation based on pdfs of global fits Gonzalez-Garcia, Maltoni, Salvado, Schwetz 1209.3023

(δ_{cp} = 0, 10° error)

Normal hierarchy, $m_0 = 0$



E Bertuzzo, PANM, R Zukanovich Funchal 1302.0653

Why in the next 10 years?

Measuring the CP phase is tough

Let's combine reactor and accelerator experiments

Take a look at the probabilities:

Arafune et al PRD 56 3093 (1997)

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{\rm atm} L}{4E}\right)$$

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$$P[\nu_\mu \to \nu_{\rm e}(\bar{\nu}_\mu \to \bar{\nu}_{\rm e})]$$

$$= \sin^2 2\theta_{13} s_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \frac{1}{2} s_{12}^2 \sin^2 2\theta_{13} s_{23}^2 \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right)$$

$$+ 2J_r \cos\delta \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \mp 4J_r \sin\delta \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$\pm \cos 2\theta_{13} \sin^2 2\theta_{13} s_{23}^2 \left(\frac{4Ea(x)}{\Delta m_{31}^2}\right) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$\mp \frac{a(x)L}{2} \sin^2 2\theta_{13} \cos 2\theta_{13} s_{23}^2 \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta m_{21}^2 L}{4E}\right)^2$$

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$$J_r = c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23}$$

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$$a(x) = \sqrt{2} G_{\rm F} N_e(x)$$

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Arafune et al PRD 56 3093 (1997)

leading

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Arafune et al PRD 56 3093 (1997)

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intrinsic CPC

intrinsic CPV

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leading, solar

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intrinsic CPC, intrinsic CPV

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matter CPV, solar

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We need dedicated machines to measure it!

But it will take ~ 10 years (or more?) to start these!!!

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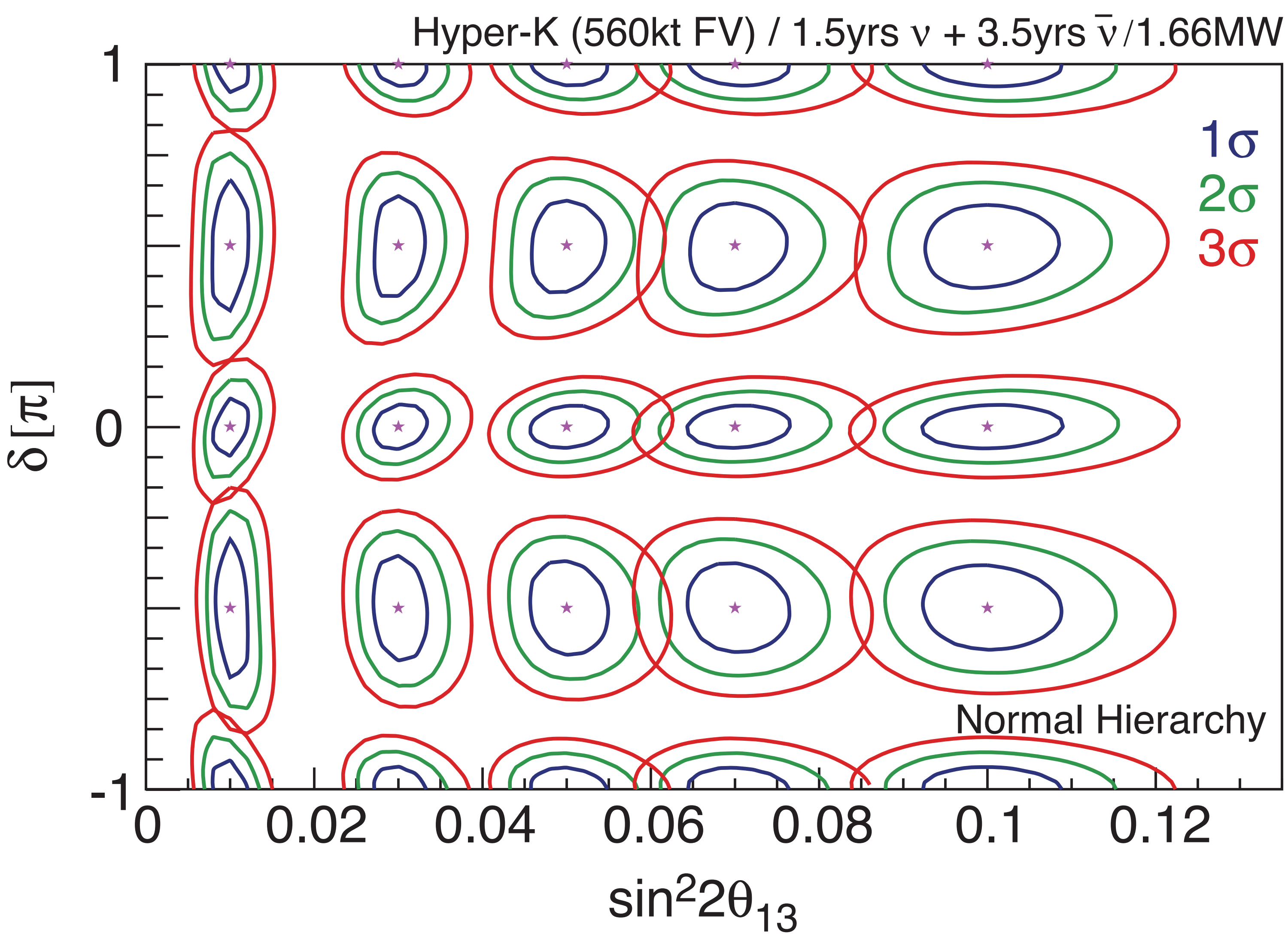
So, the question is
"How can an experiment that is not actually capable of observing CP violation due to δ_{CP} help us to pave the way to a final discovery?"

What has been done so far

1) Allowed regions in δ_{CP} x $\sin^2\theta_{13}$ or δ_{CP} x $\sin^2\theta_{23}$



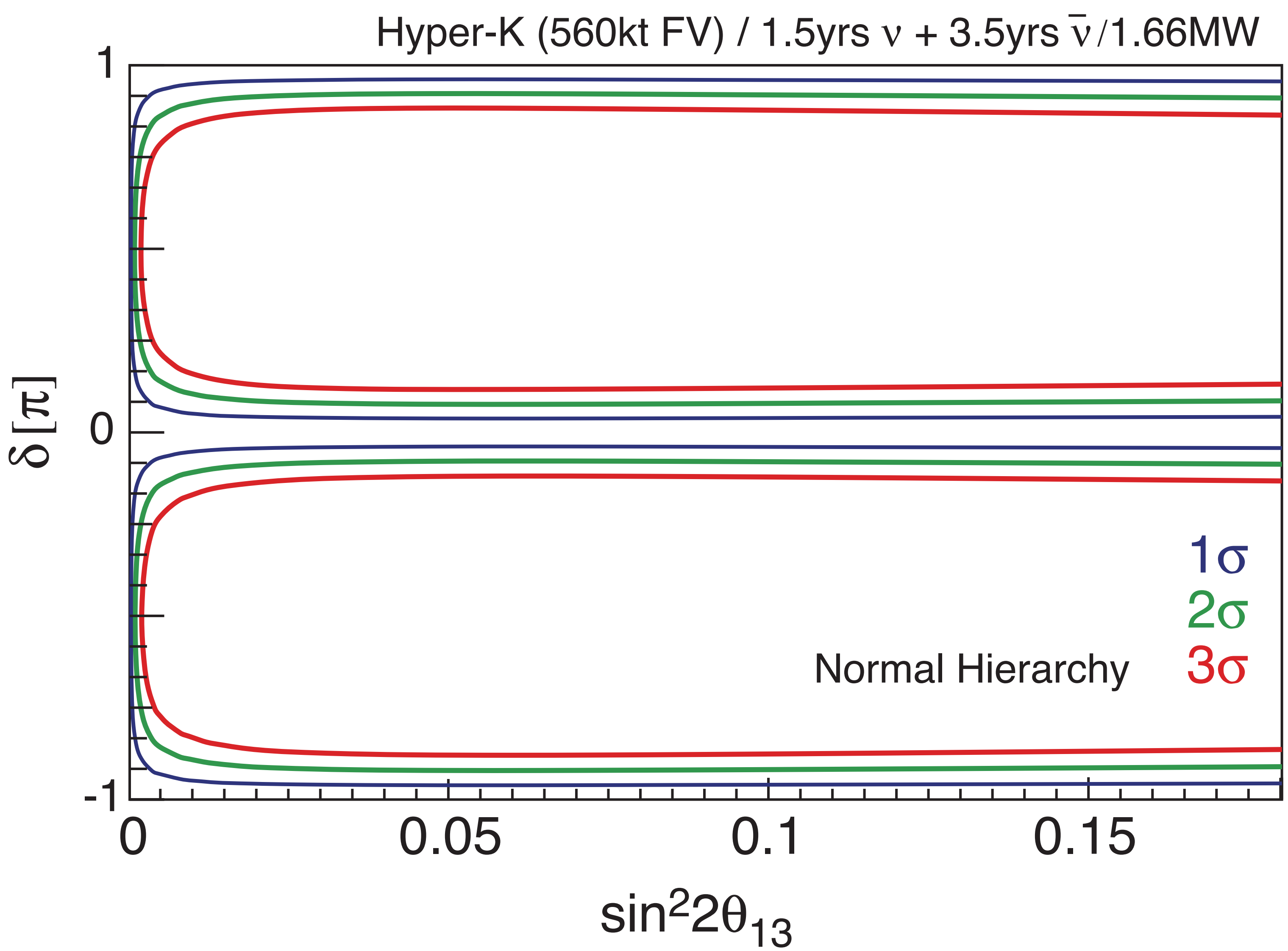
Hyper-Kamiokande Letter of Intent 1109.3262

Pros:
simple, straightforward interpretation

Cons:
local, misses global picture

What has been done so far

2) CP violation fraction - $\sin^2\theta_{13}$ ($\sin^2\theta_{23}$?)



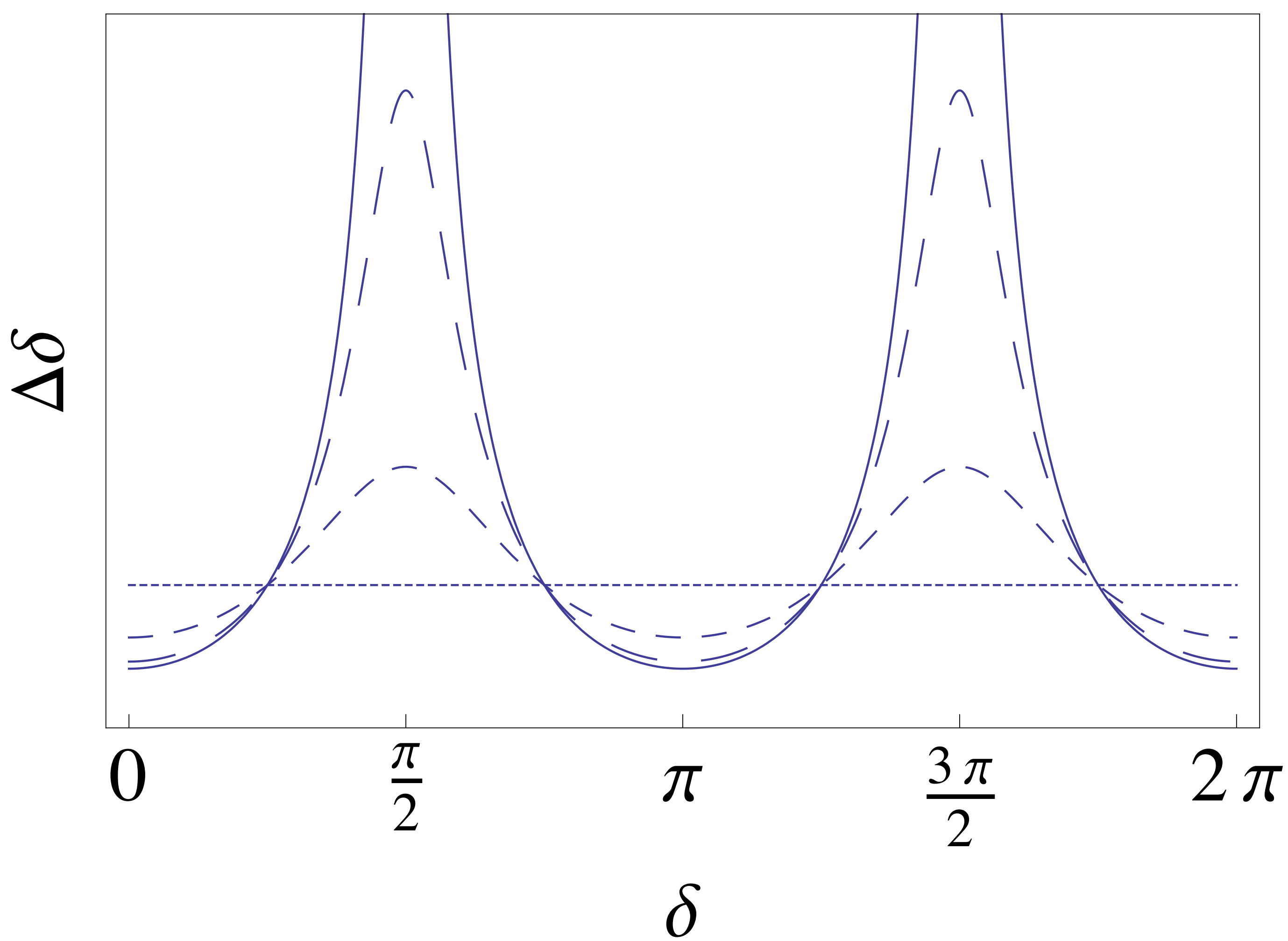
Hyper-Kamiokande Letter of Intent 1109.3262

Pros:
global, clear "yes or no" message for CPV

Cons:
"bias" for $\delta_{cp} = 0,\pi$

What has been done so far

3) Achievable uncertainty in δ_{cp}



Coloma et al 1203.5651

Pros:
global quantification of δ_{cp} sensitivity

Cons:
only appropriate for powerful experiments

The CP exclusion fraction

Our original proposal is very simple

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Winter hep-ph/0310307
Huber, Lindner, Winter hep-ph/0412199

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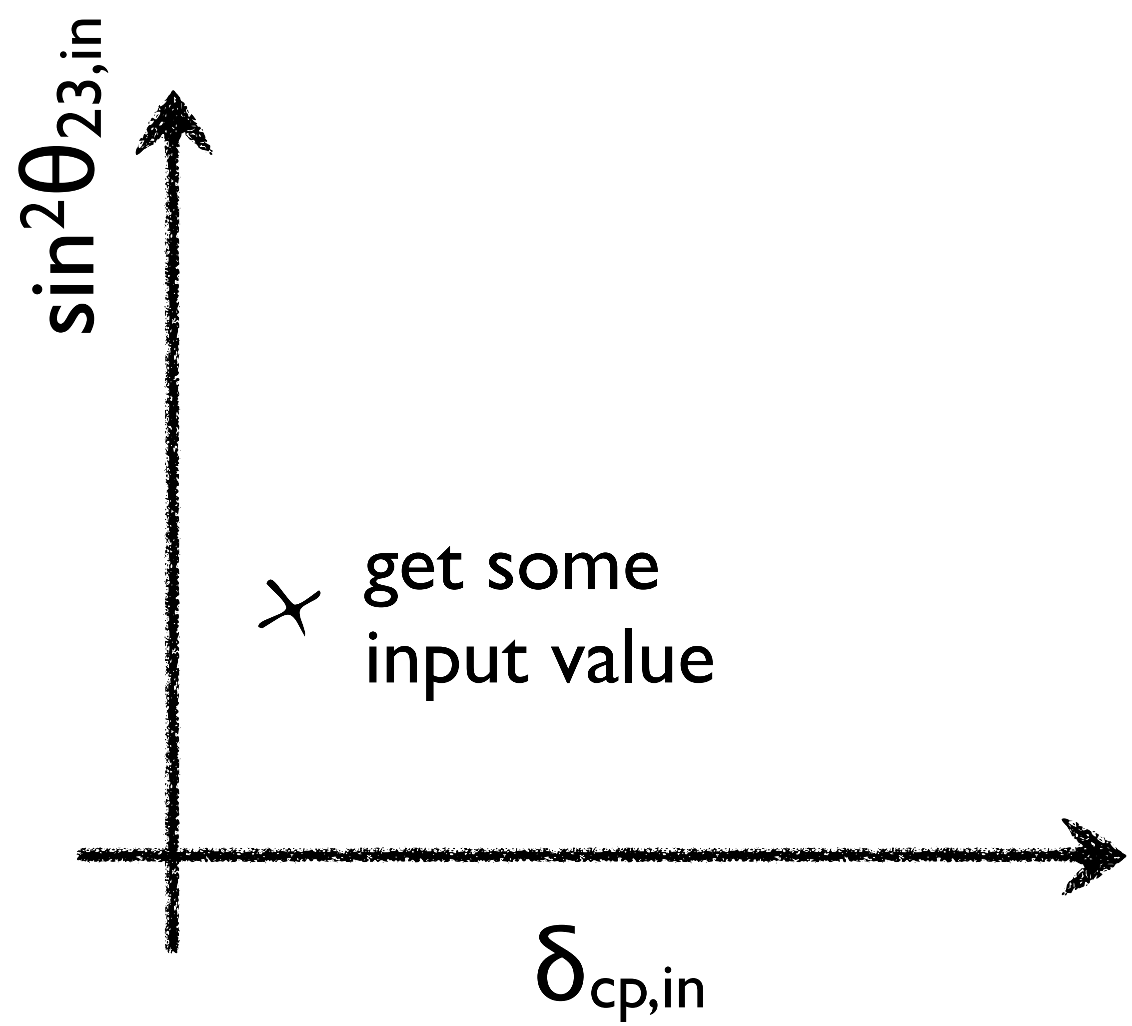

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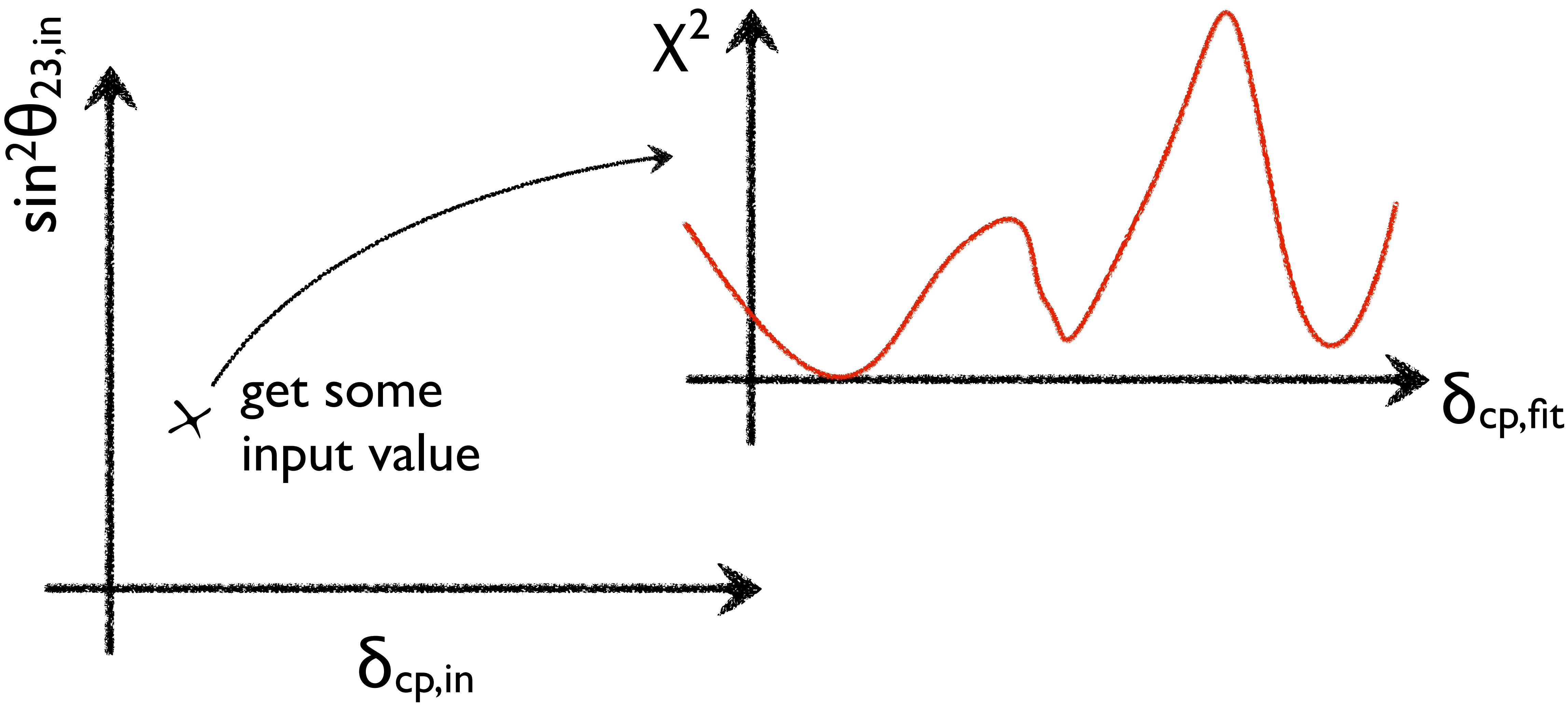

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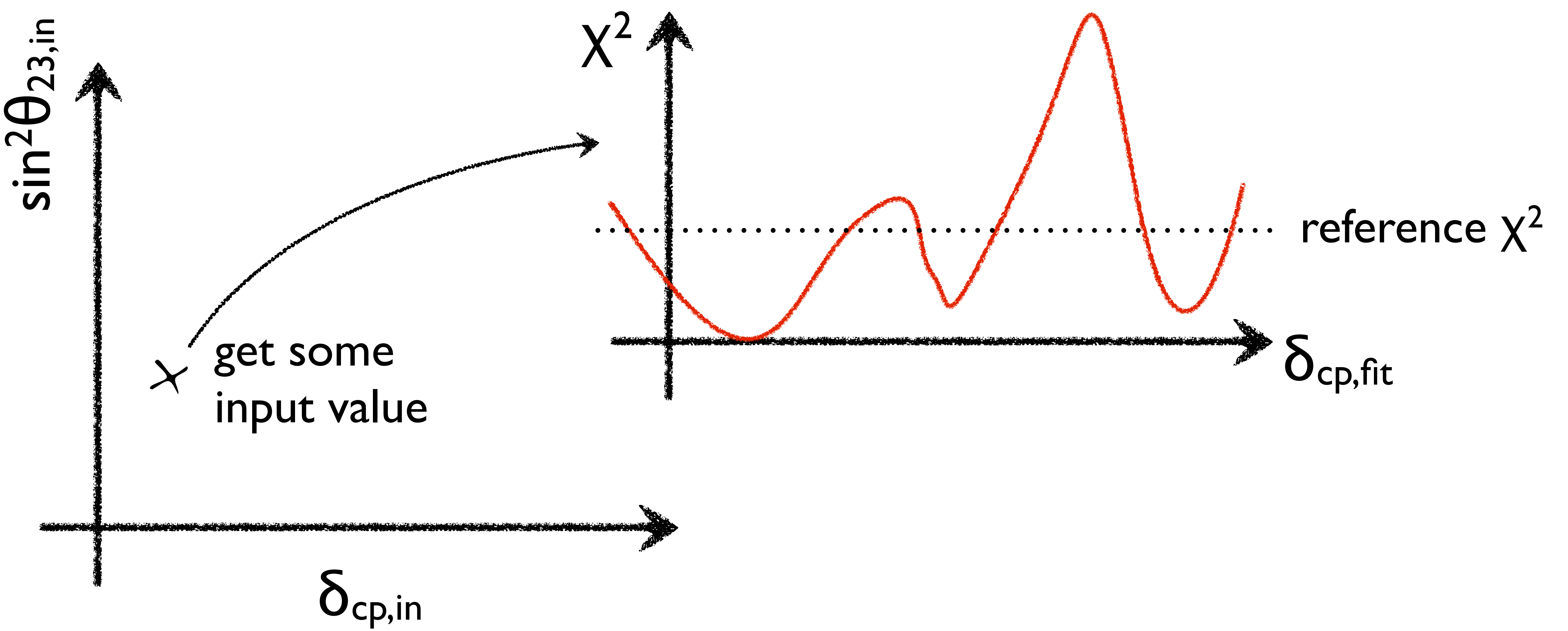

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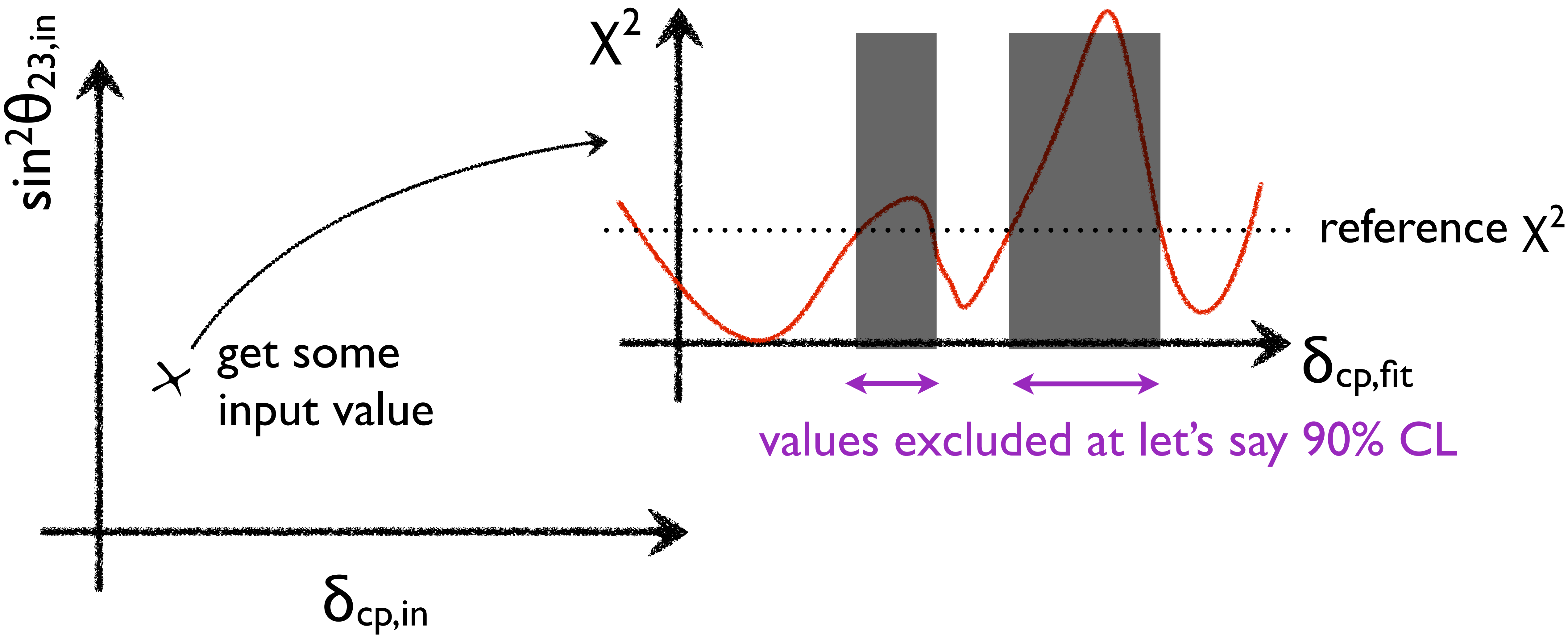
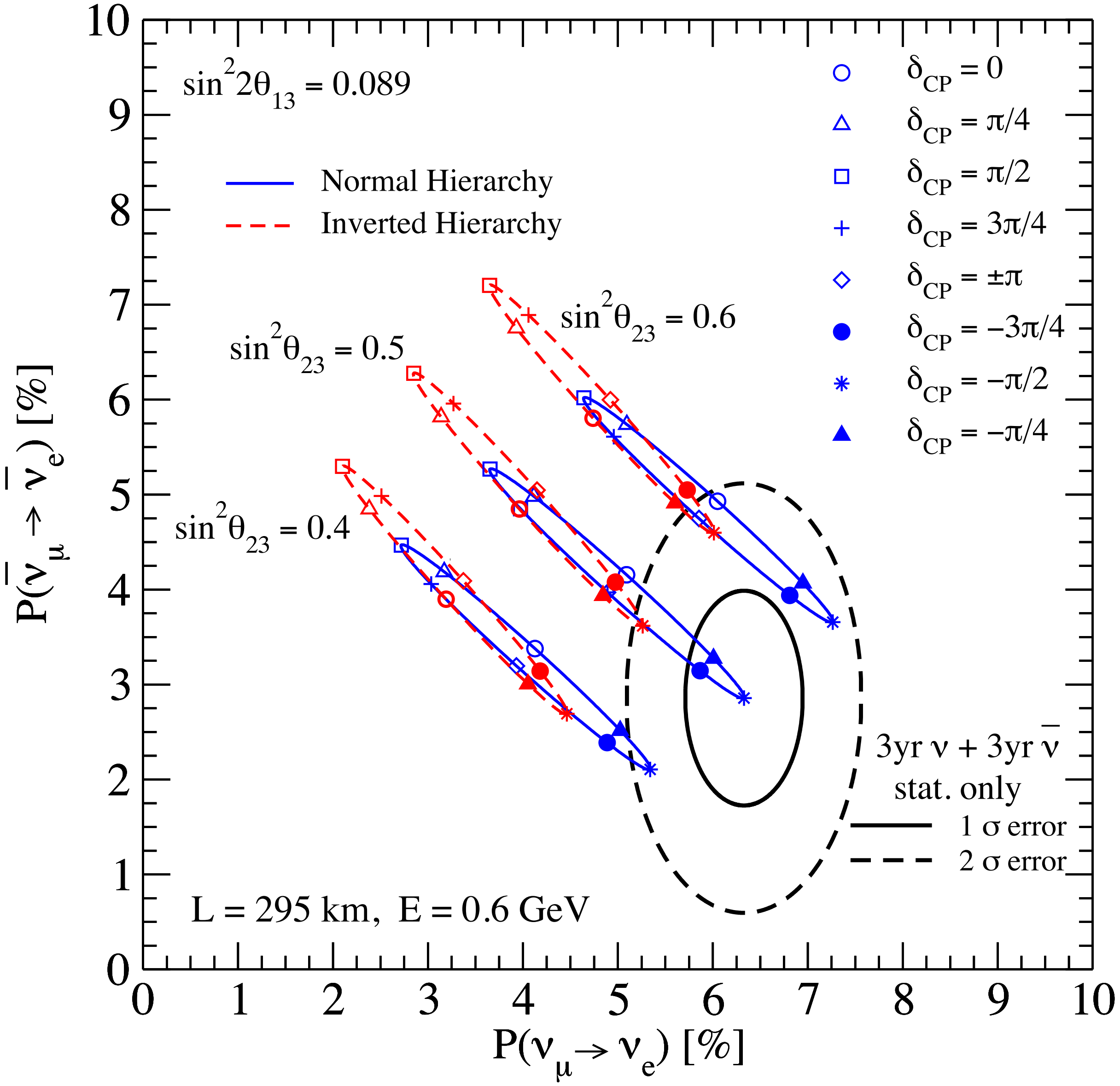
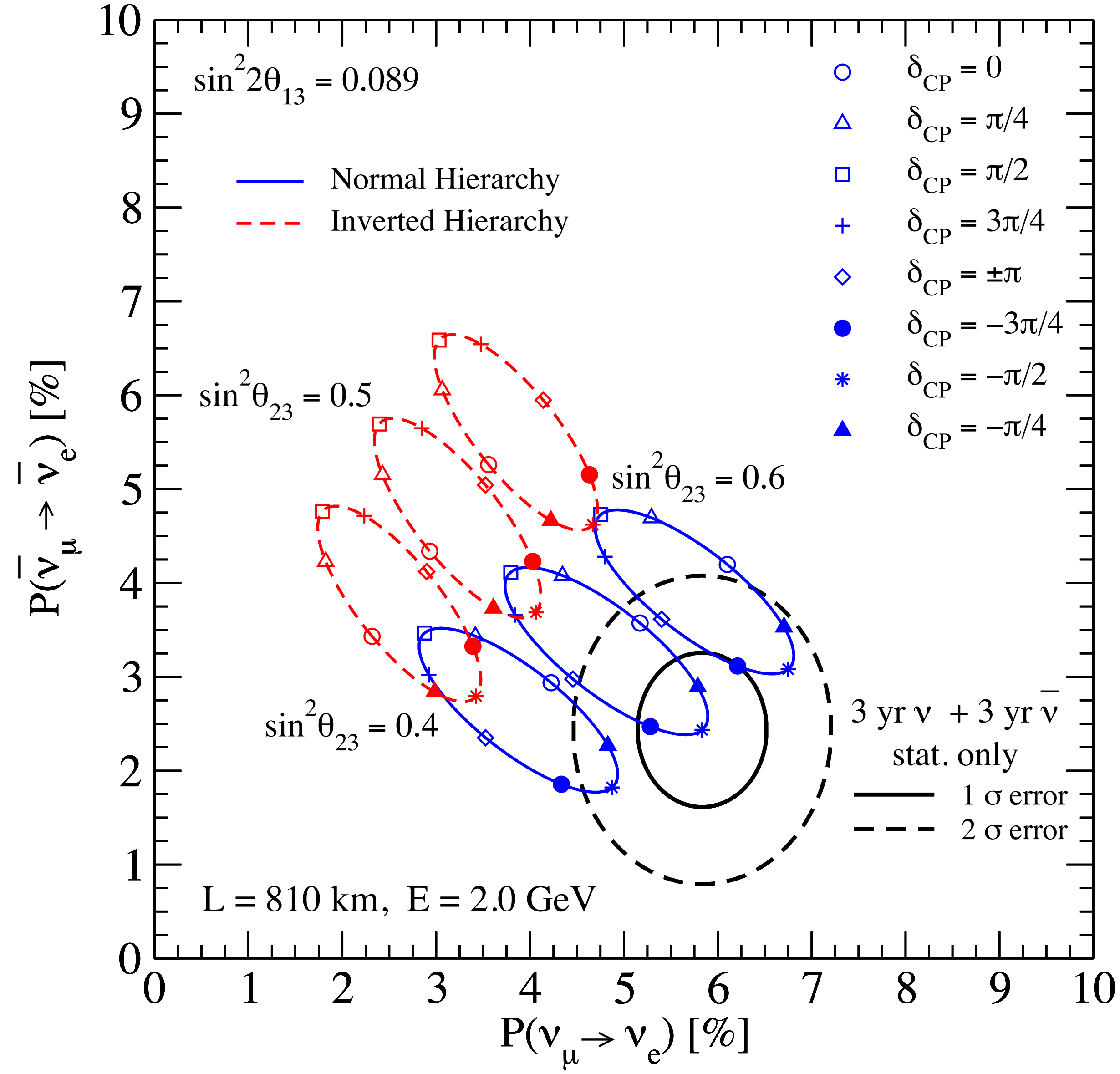


Qualitatively





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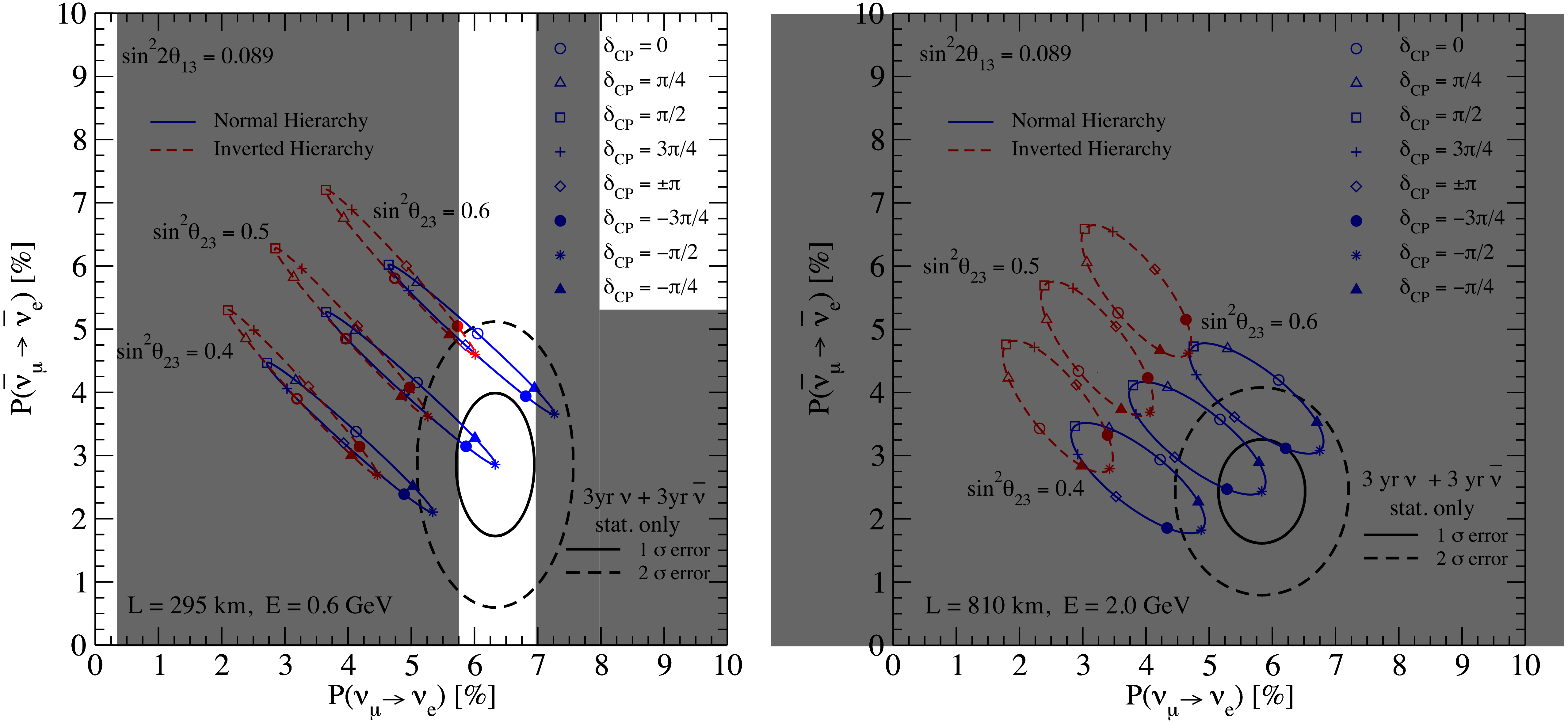

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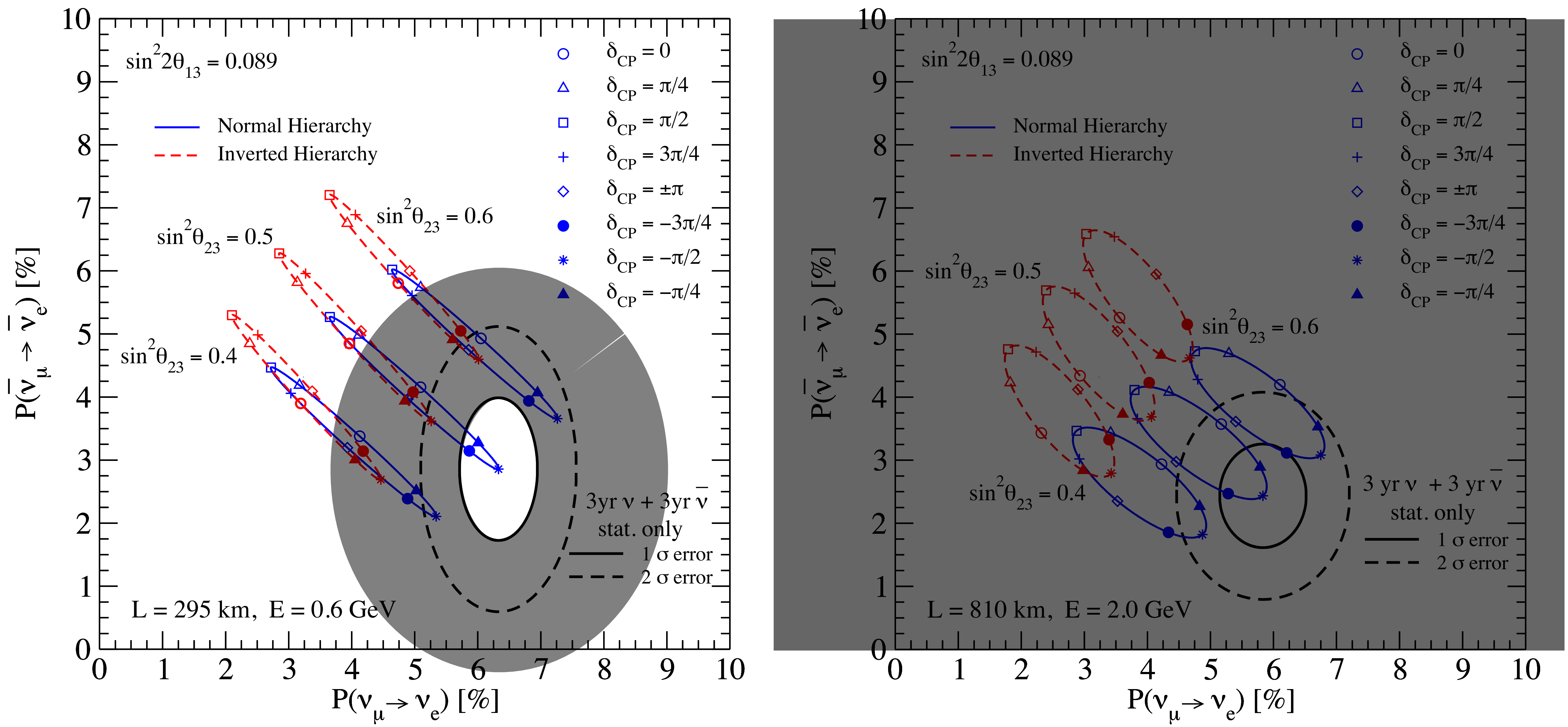
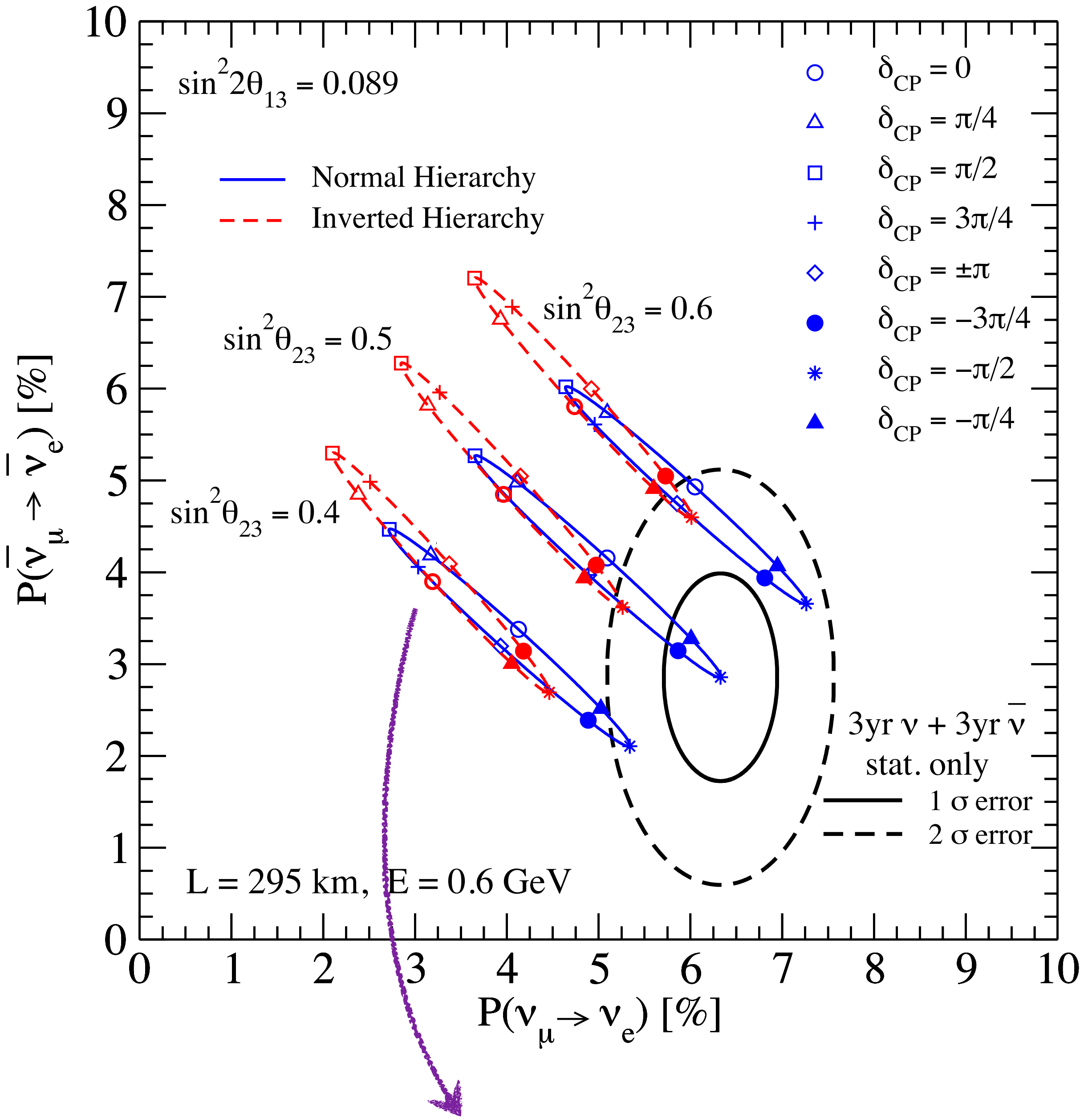
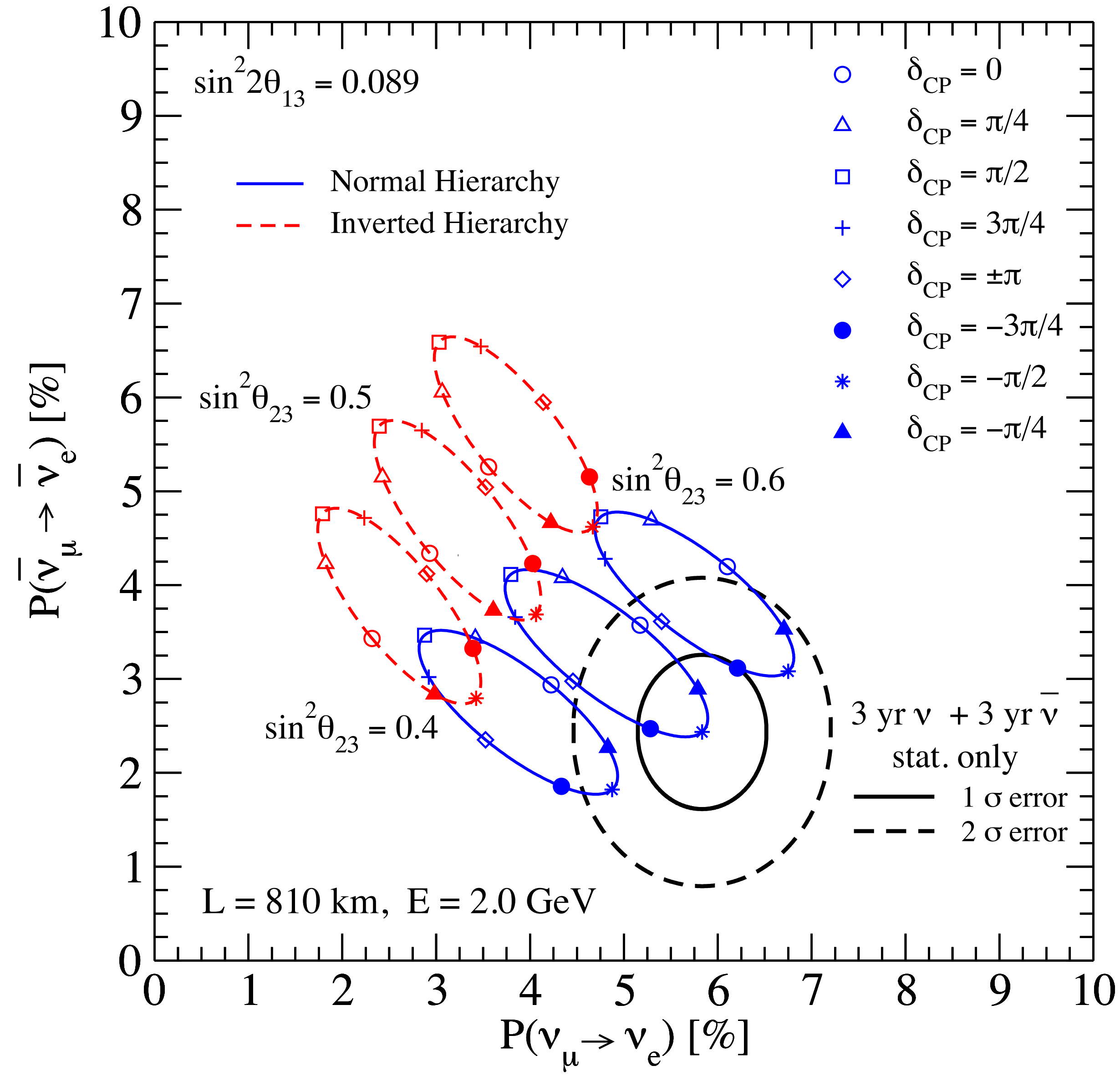


Of course, antineutrinos help!

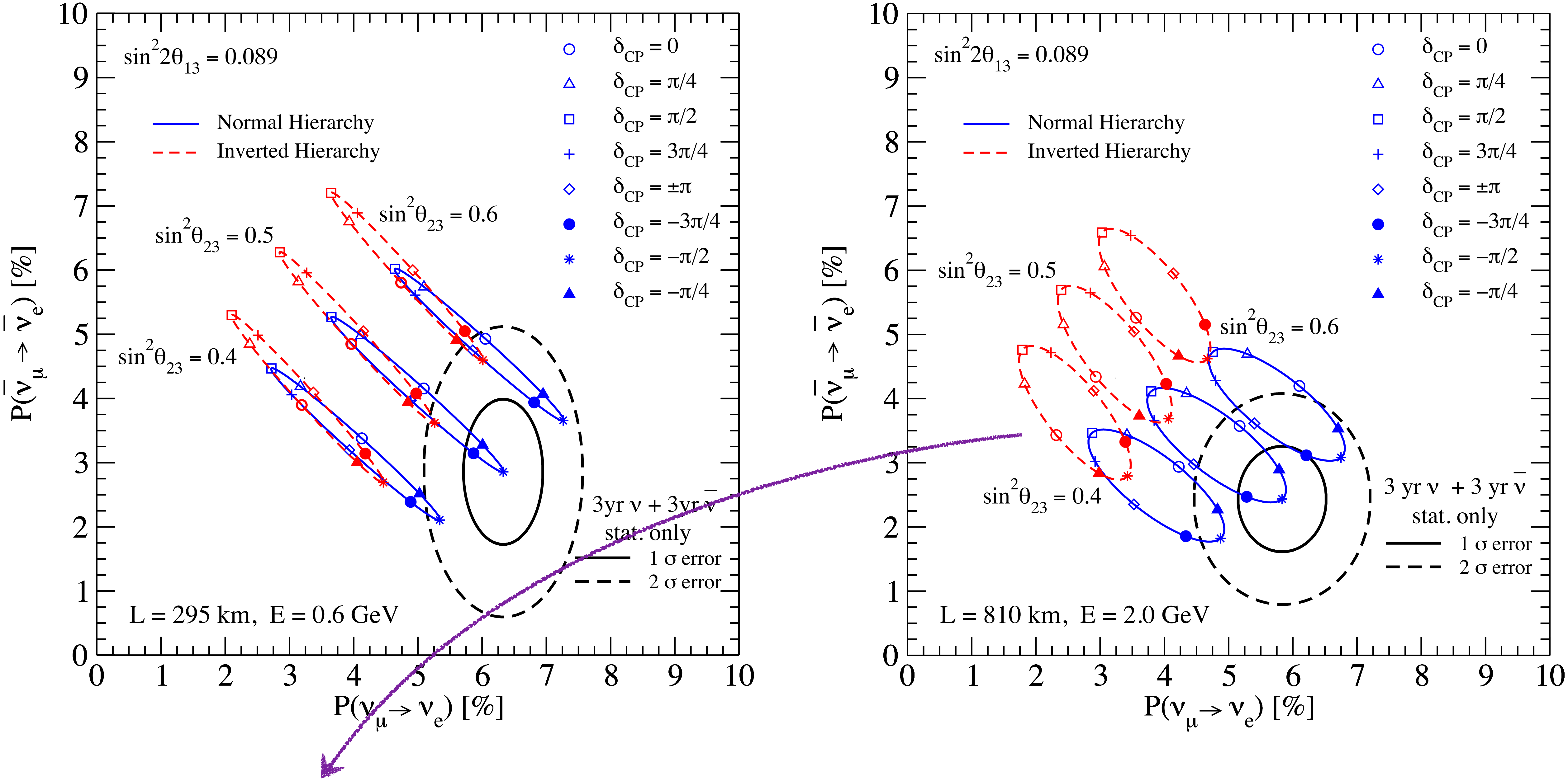
Qualitatively





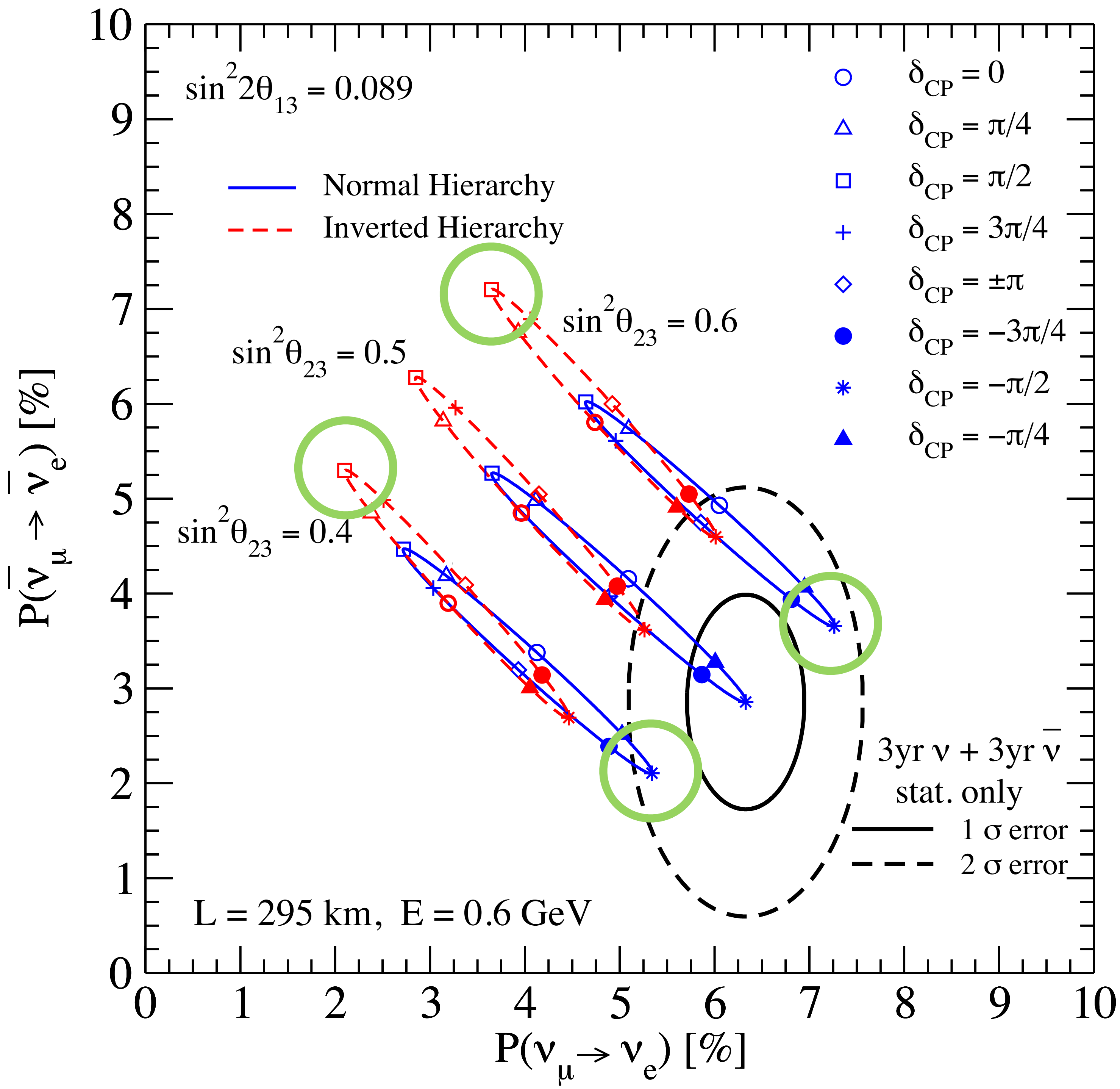
Thinner ellipses: spectrum is peaked in oscillation maximum

Qualitatively



Larger separation between hierarchies: more matter effects

Qualitatively



Better f_{cpx} (δ_{cp}, $\sin^2\theta_{23}$)

NH

$-\pi/2$, 0.4

$-\pi/2$, 0.6

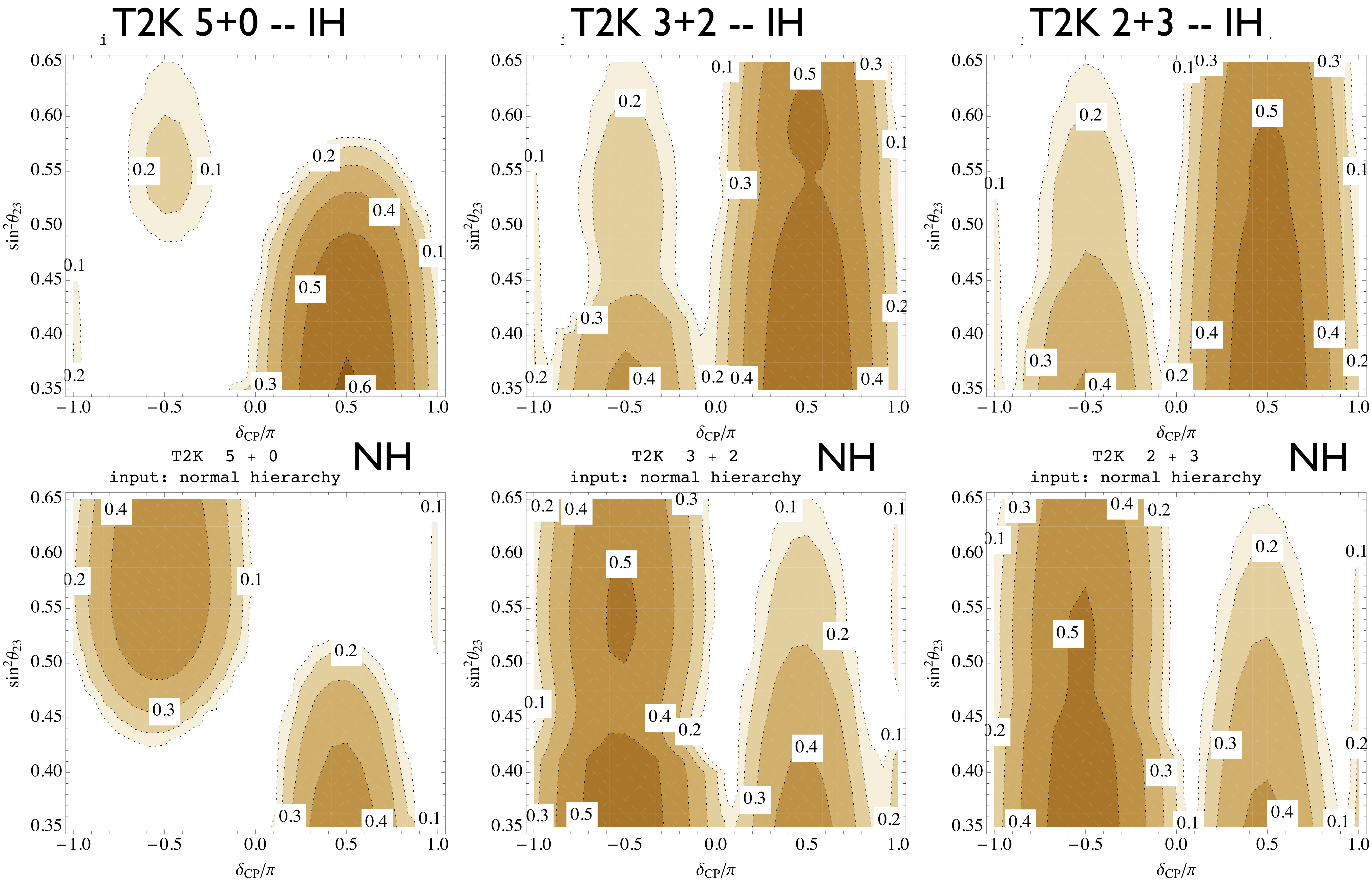
IH

$+\pi/2$, 0.4

$+\pi/2$, 0.6

Also, lower $\sin^2\theta_{23}$ is easier!

T2K 5 years (5x10^{21} POT)



PAN Machado

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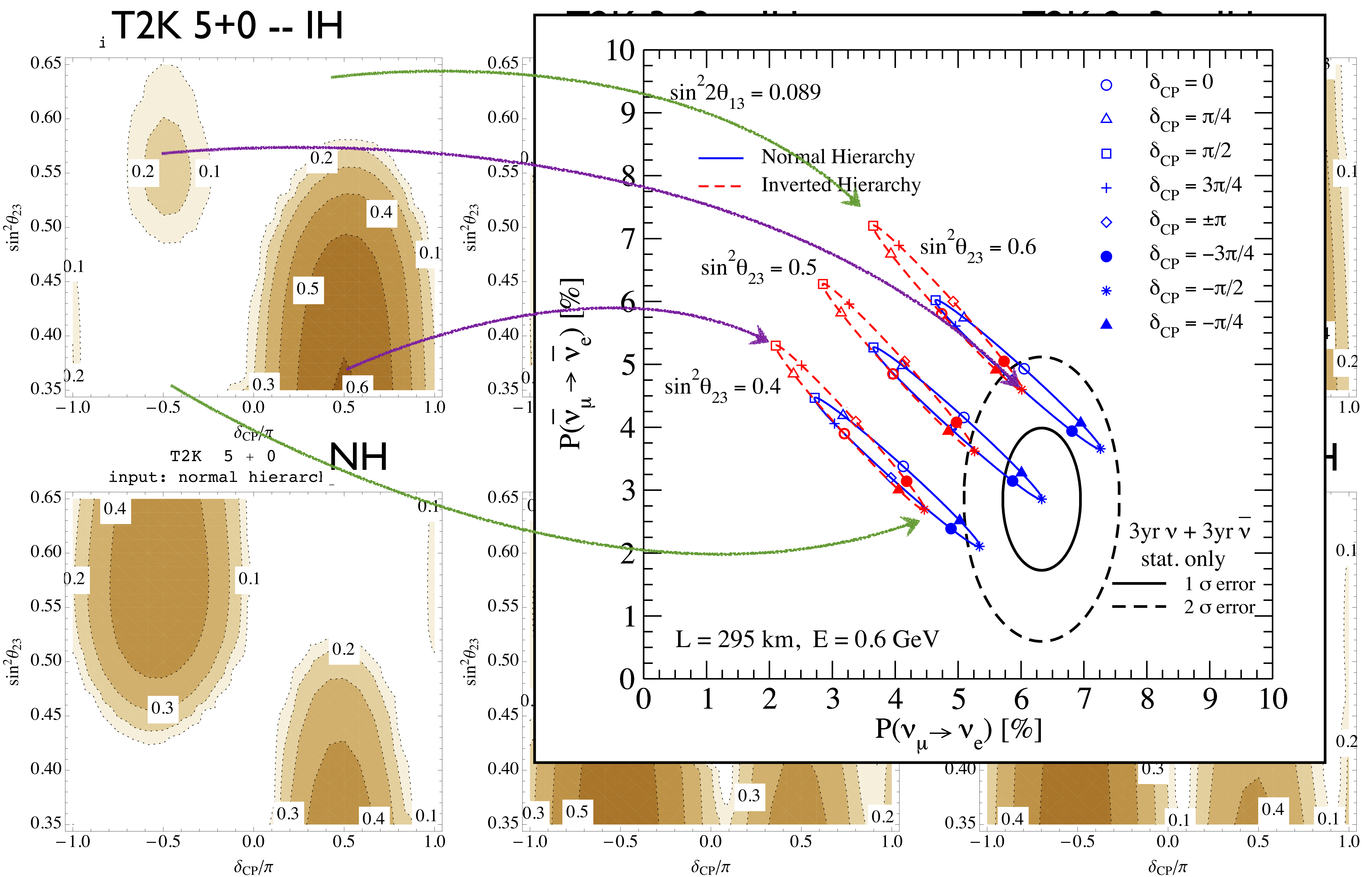

Invisibles Jul-2013

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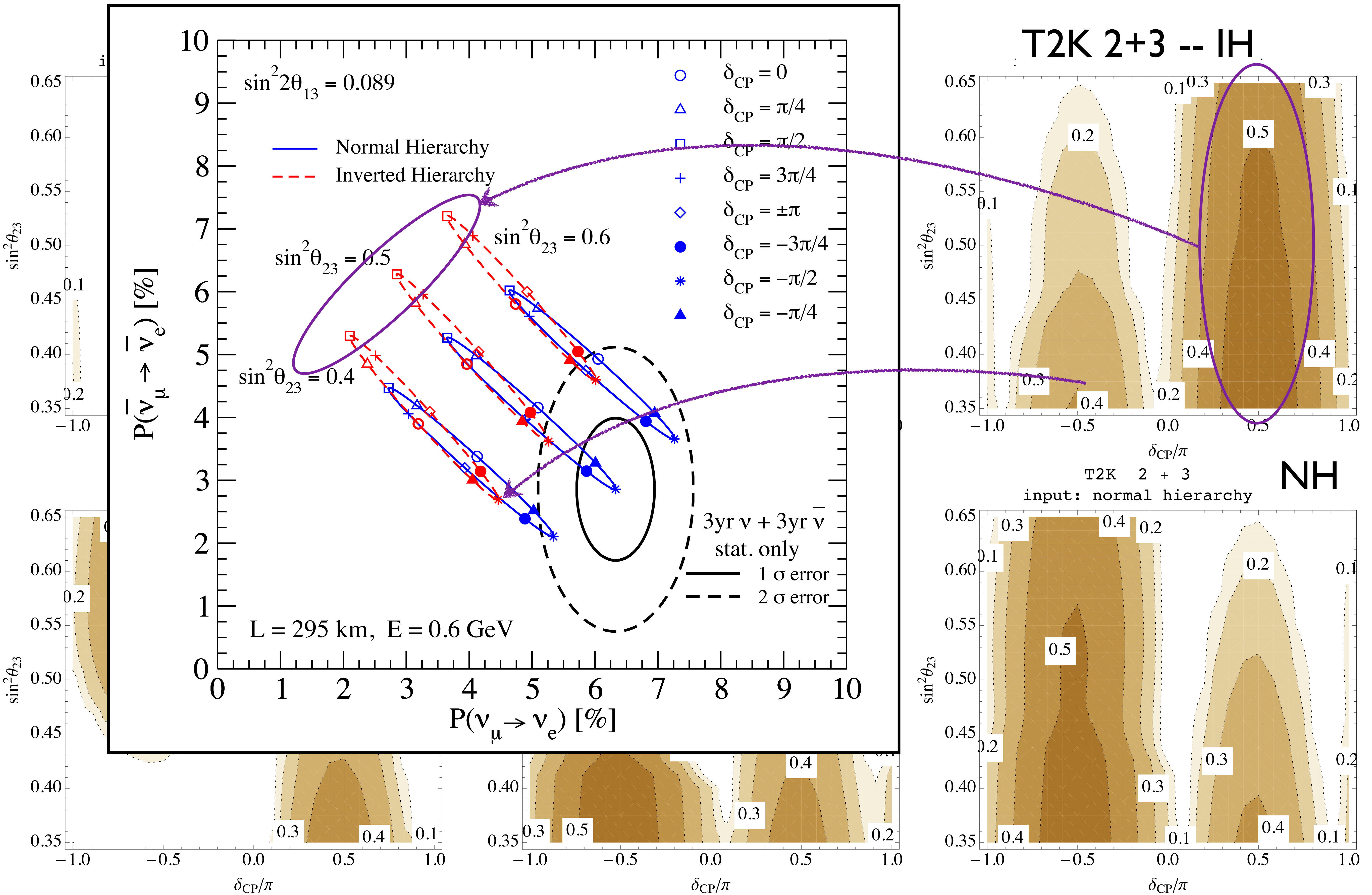

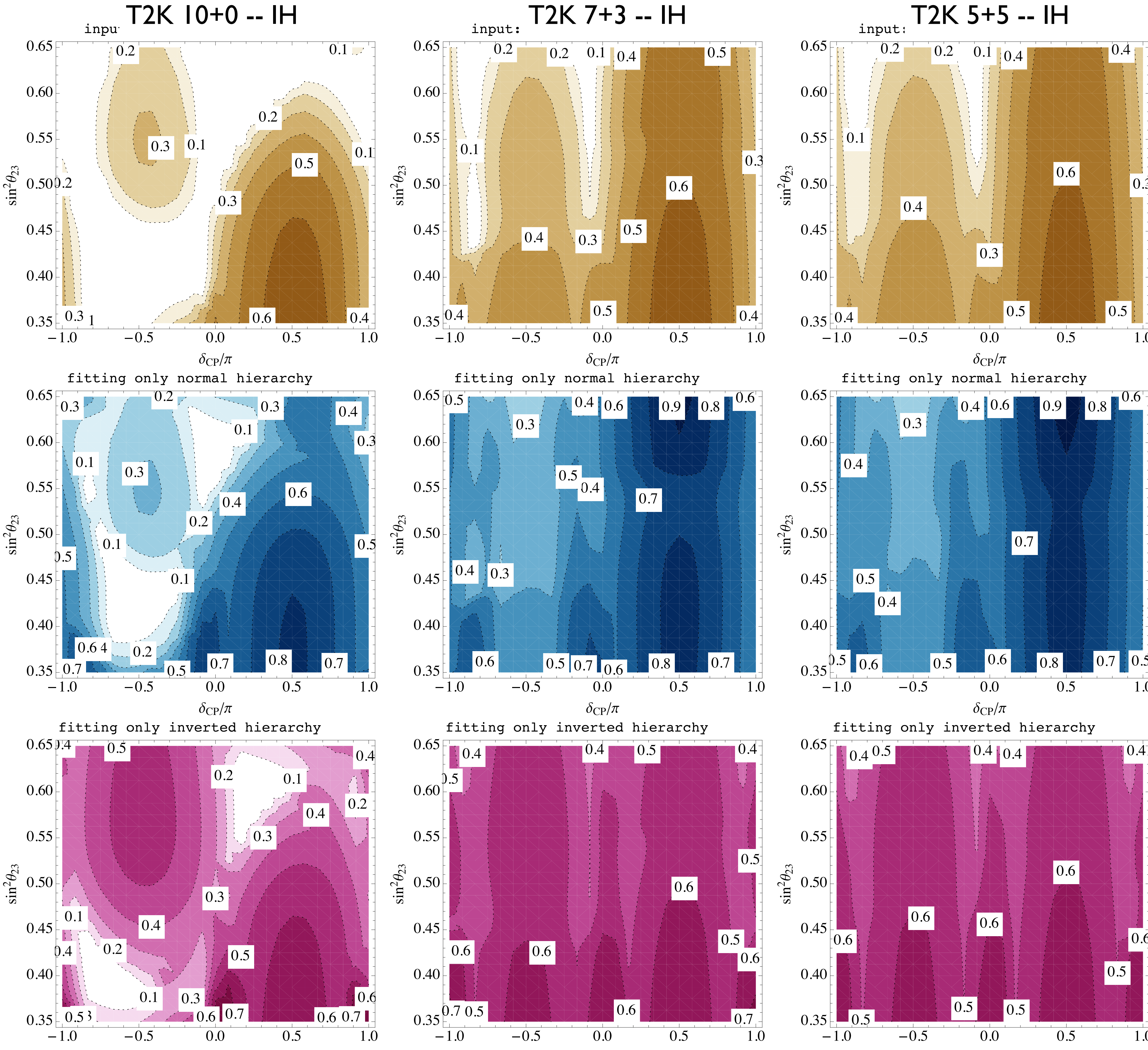

T2K 10 y (10^{22} POT)

fitting NH

fitting IH

Invisibles Jul-2013

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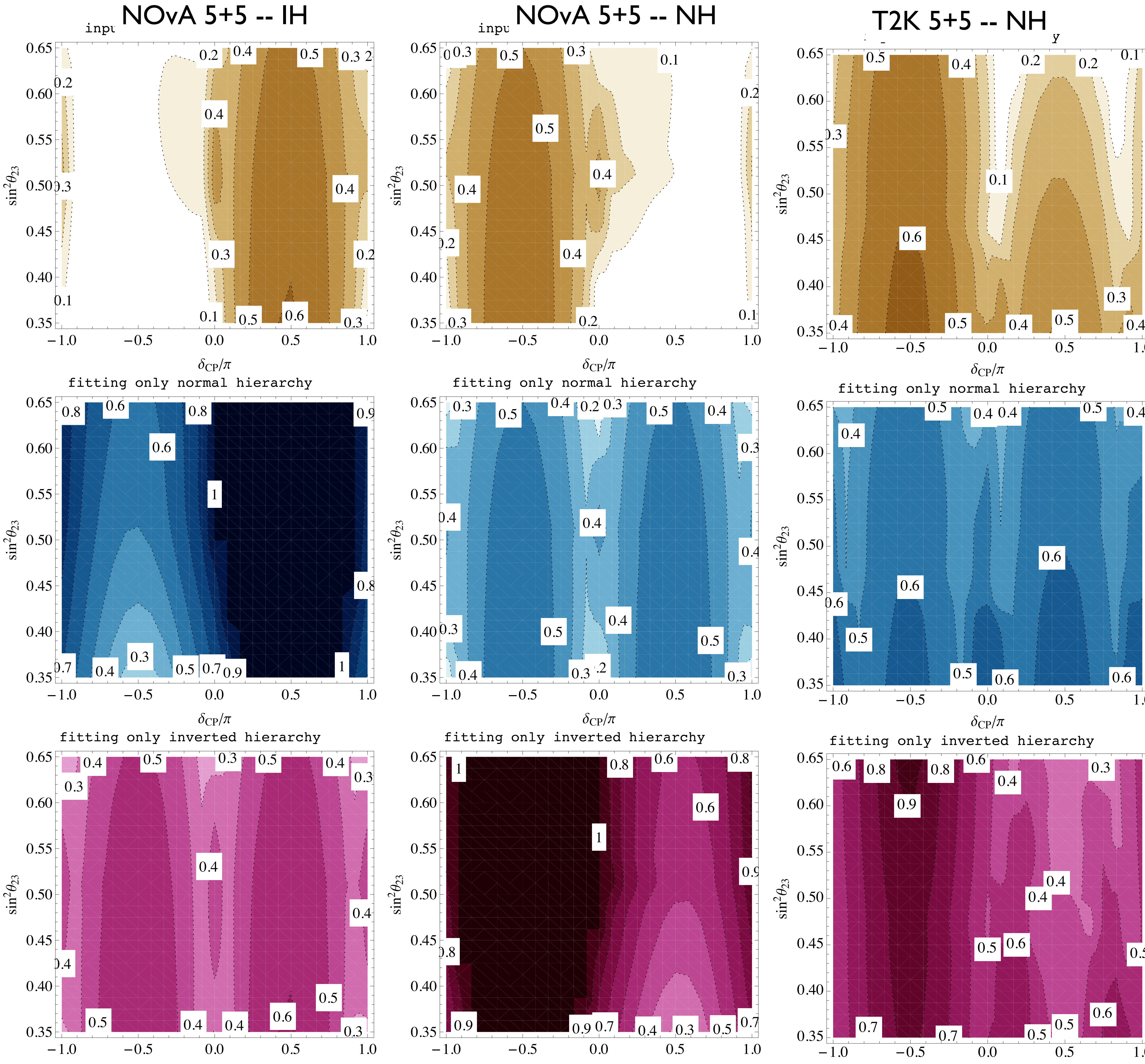

NOvA 10 y
(6×10^{21} POT)

T2K 10 y
(10^{22} POT)

fitting NH

fitting IH

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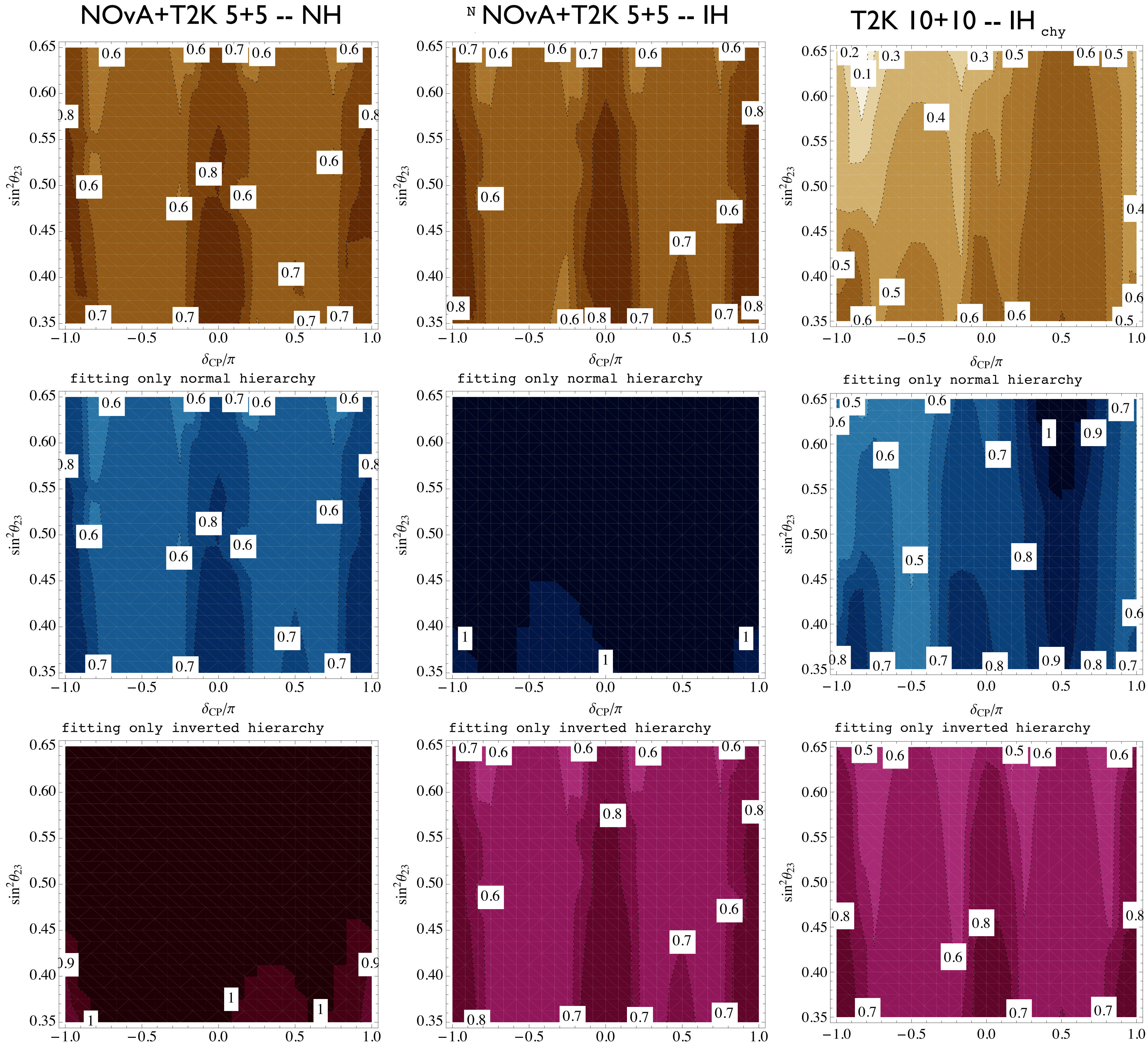

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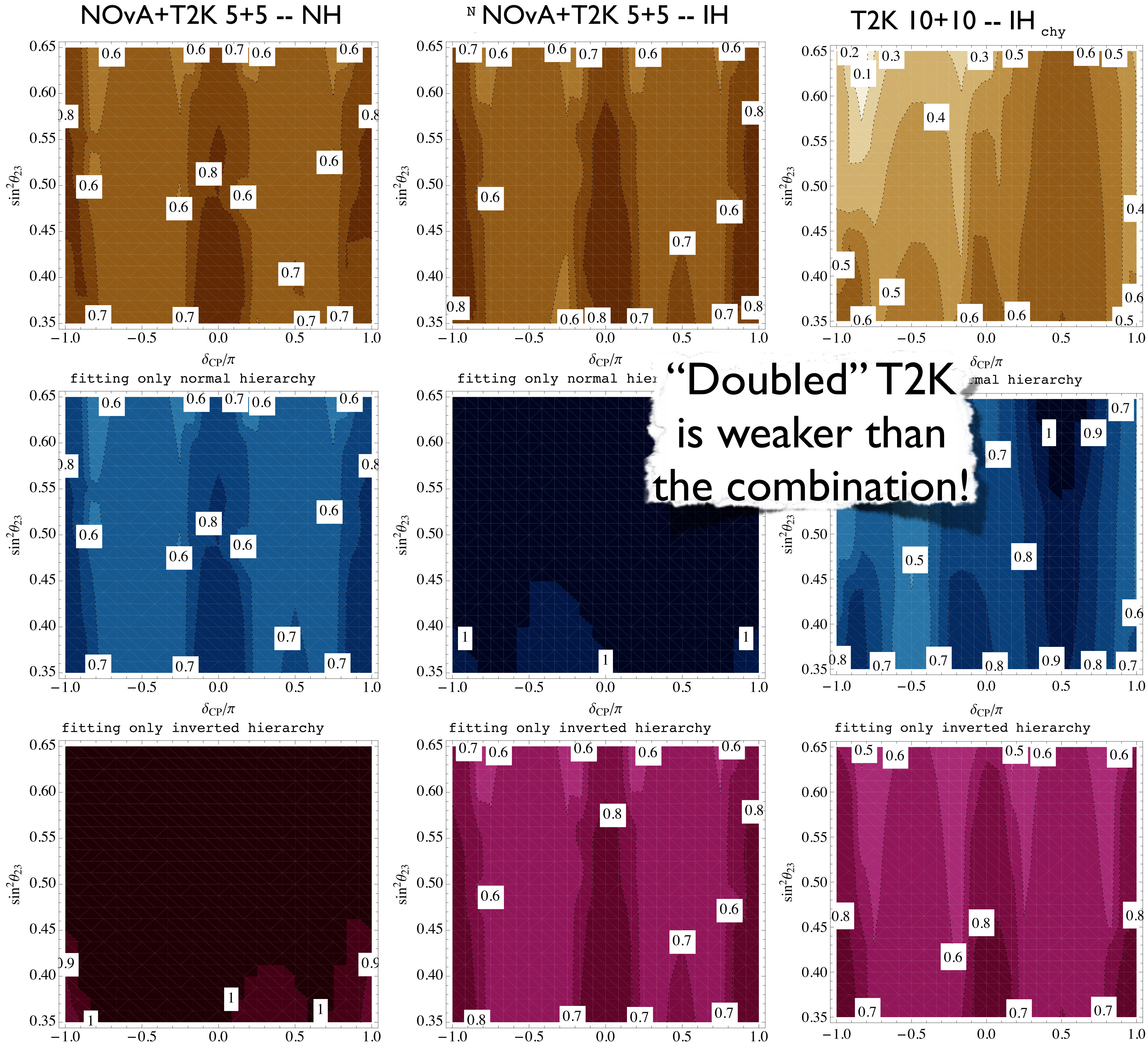

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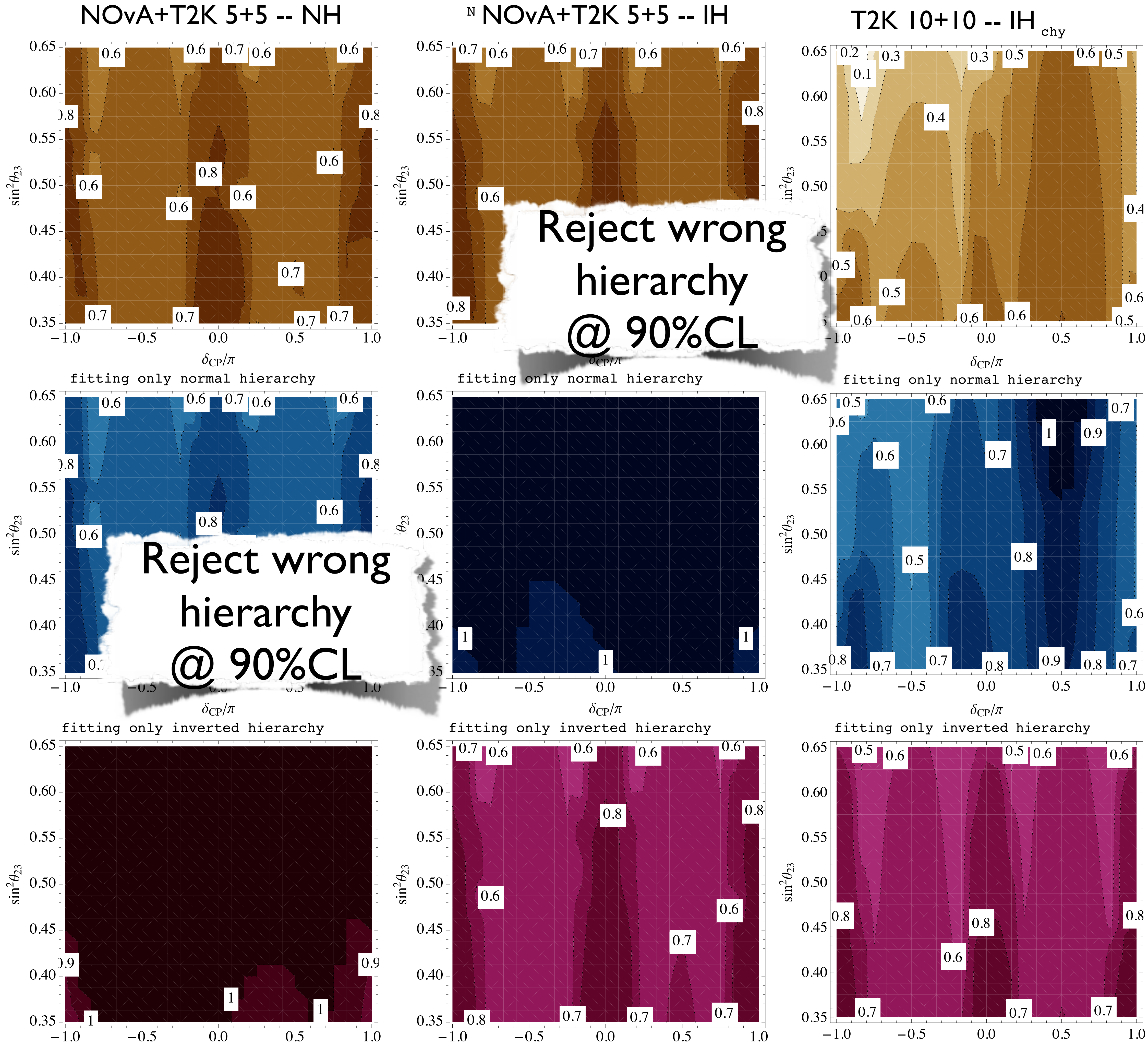

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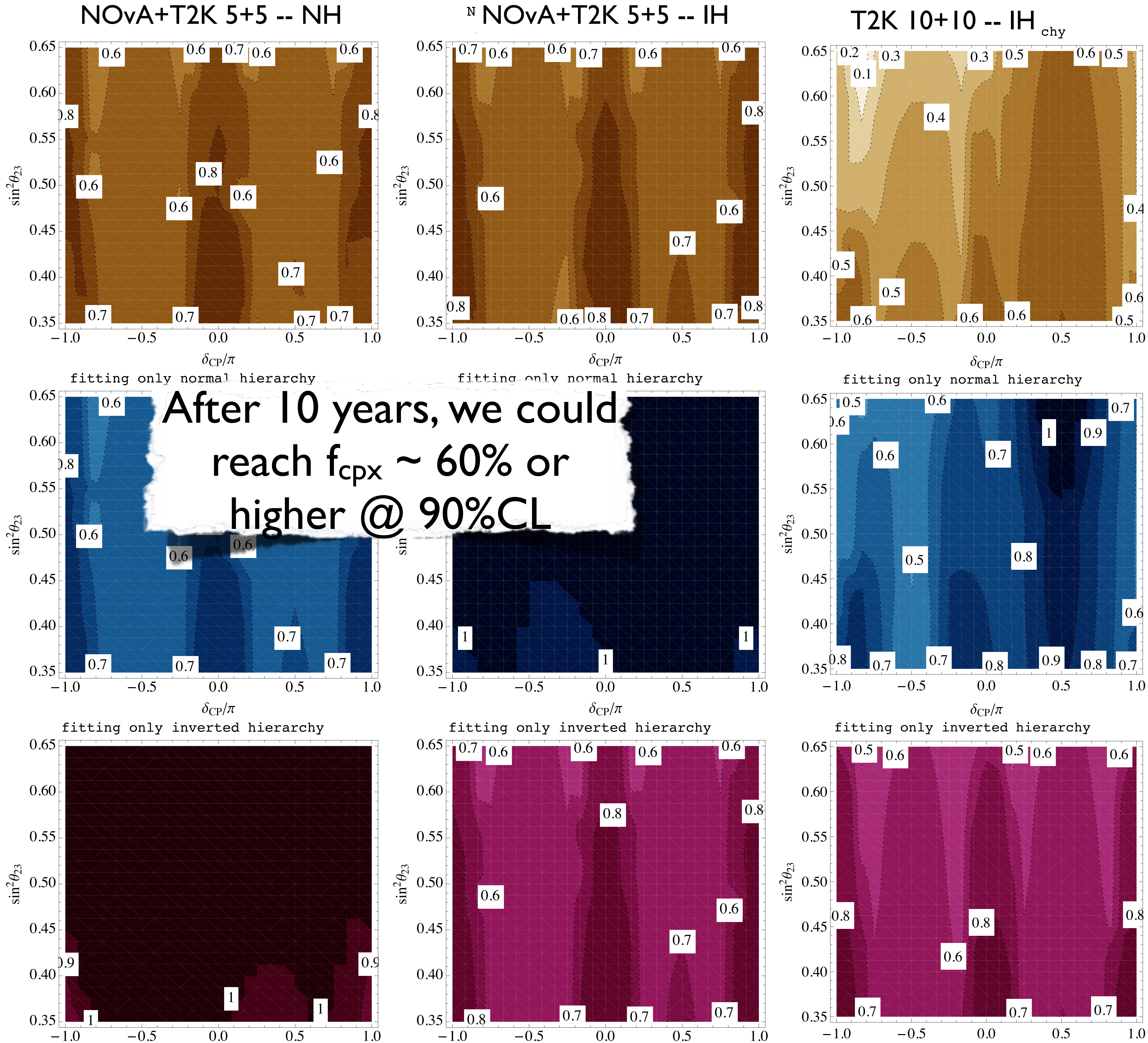

After 10 years, we could reach f_{cpx} ~ 60% or higher @ 90%CL

fitting NH

fitting IH

Invisibles Jul-2013

PAN Machado

Summary I

We do not expect to measure δ_{cp} in the following 10 years

Right now, we do not have any strong indication of δ_{cp}

Hence, it is important to question what we can learn from T2K and NOvA about the CP phase

We tried to answer what would be the best experimental strategy for T2K and NOvA regarding the CP phase

Summary II

A way of characterizing the sensitivity to δ_{cp}, appropriate for non-conclusive experiments, the CP exclusion fraction

and we can also learn about the hierarchy with this

T2K alone can exclude 50% or more of δ_{cp} values in half $\delta_{CP} \times \sin^2\theta_{23}$ plane independently of the hierarchy

NOvA is not as powerful for CP, but can exclude a larger portion of the parameter space for the wrong hierarchy

The synergy between these experiments makes possible to exclude 60% or more of δ_{cp} values by combining them!

We checked that the θ_{23} octant determination strategy is much more permissive (backup slides!)

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Thank you!

BACKUP

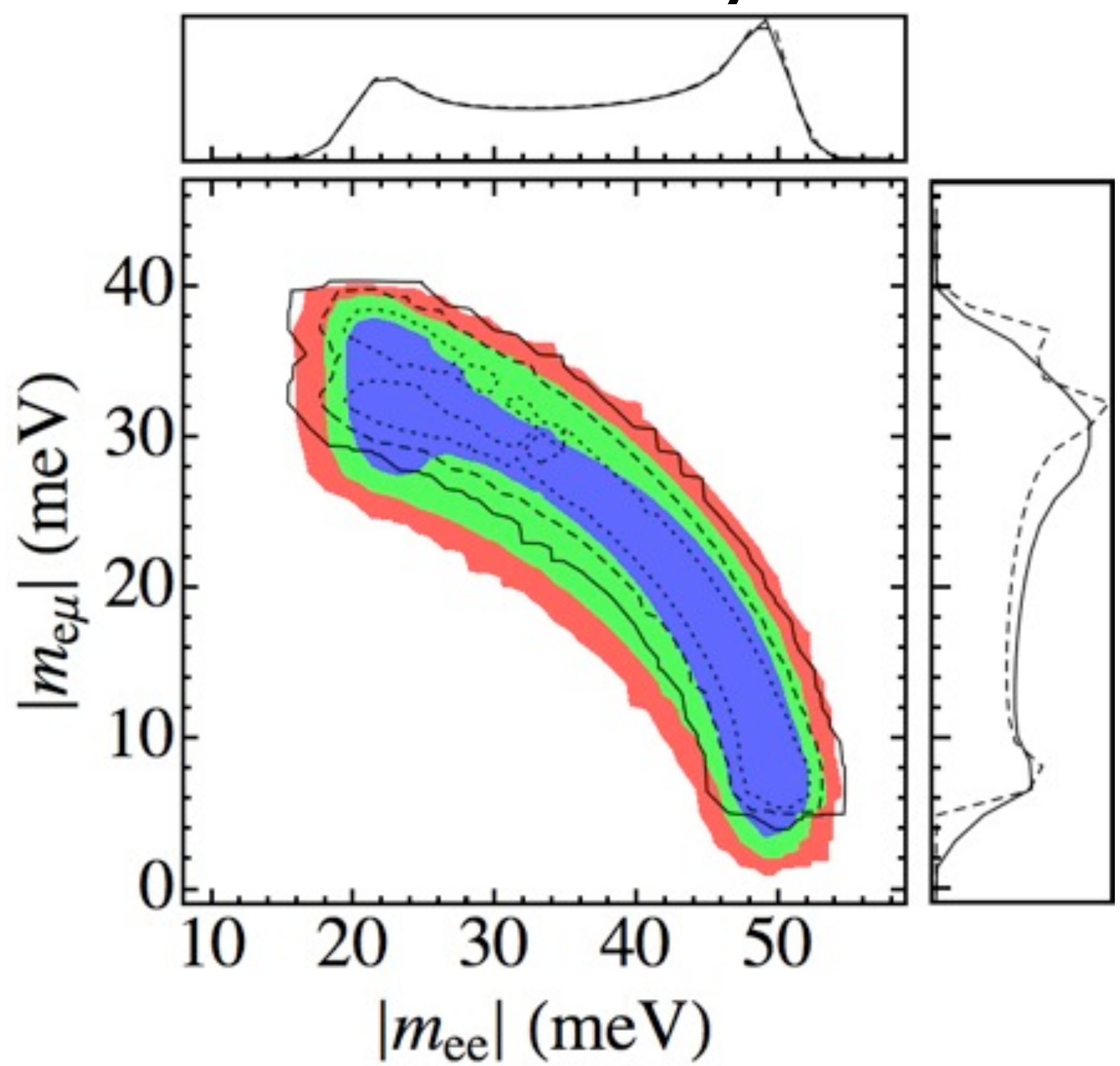
Why δ_{cp}?

What do we know about the mass matrix and its correlations?

Monte Carlo simulation based on pdfs of global fits Gonzalez-Garcia, Maltoni, Salvado, Schwetz 1209.3023

(δ_{cp} = 0, 10° error)

Inverted hierarchy, m_0 = 0



E Bertuzzo, PANM, R Zukanovich Funchal 1302.0653

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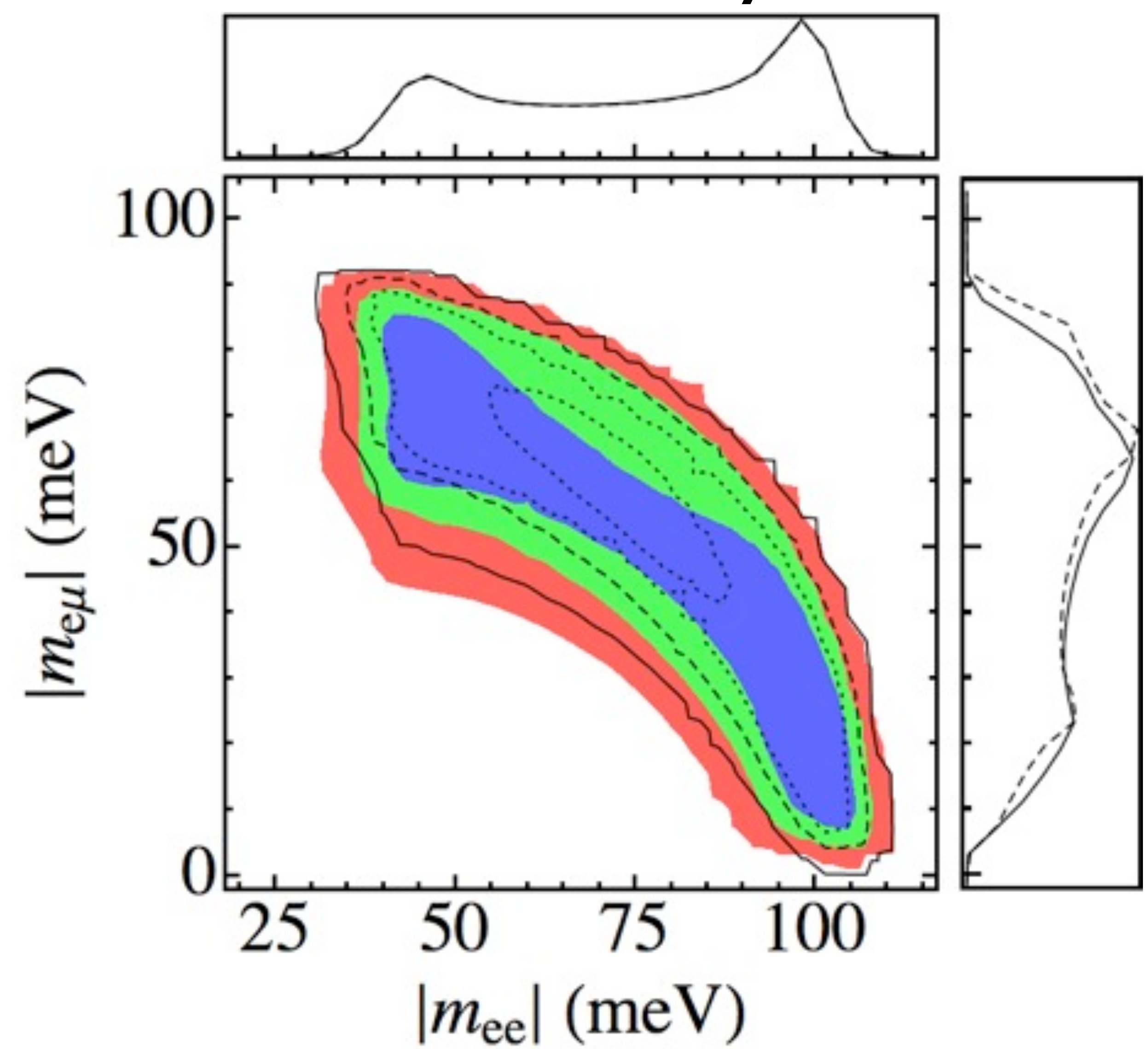
(δ_{cp} = 0, 10° error)

Normal hierarchy, m_0 = 0.1 eV



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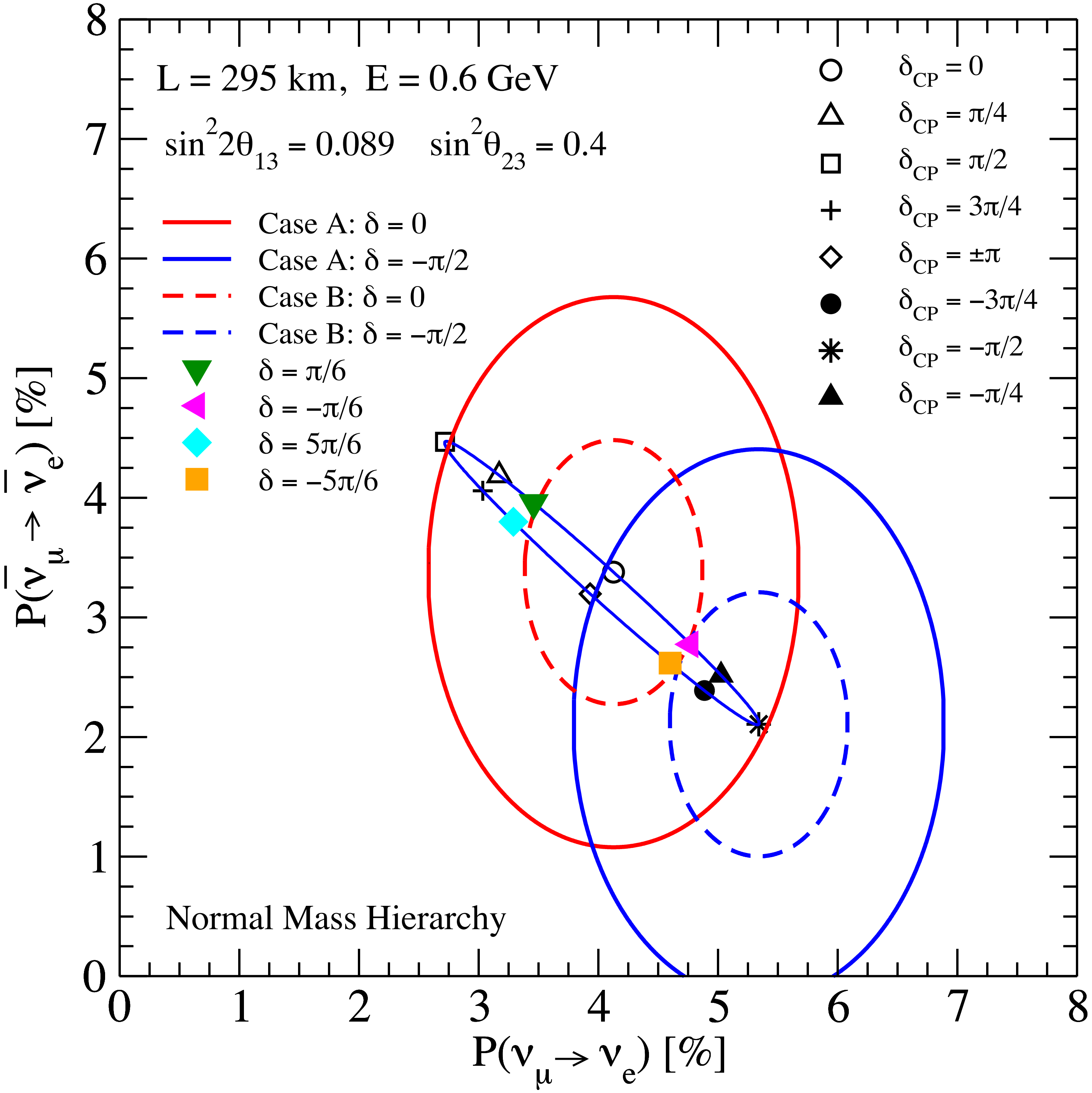
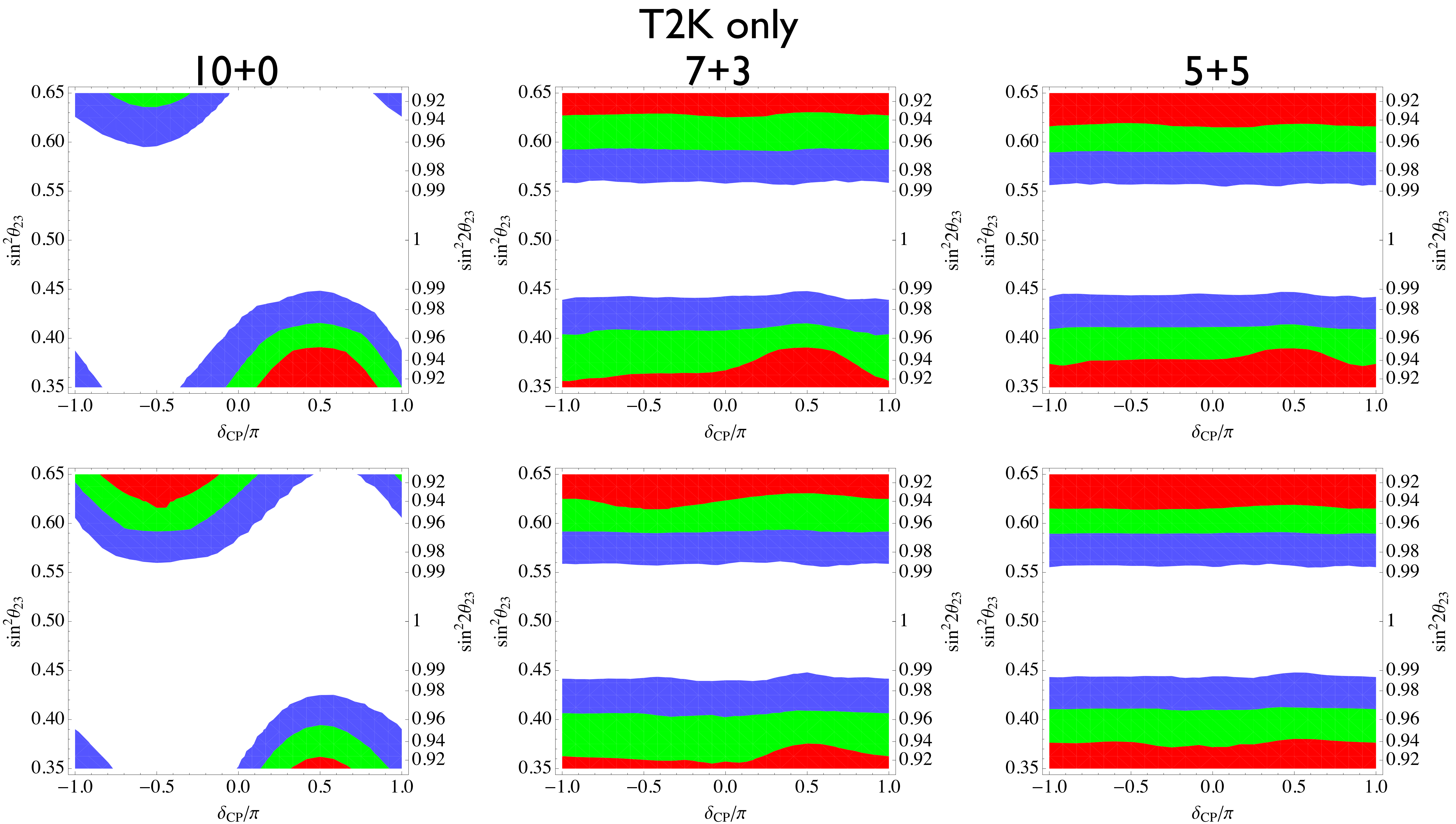
Qualitatively



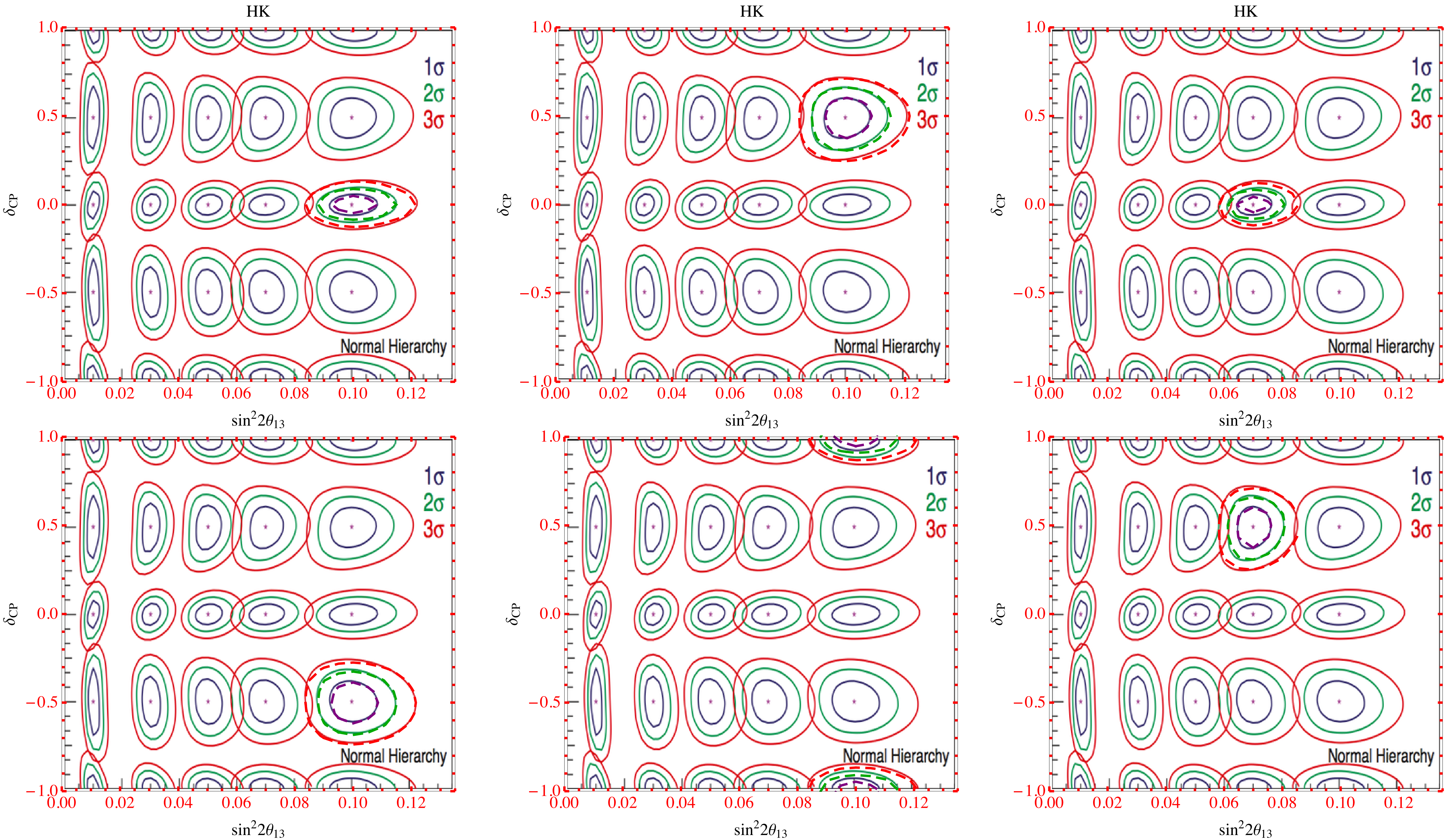
θ_{23} octant determination



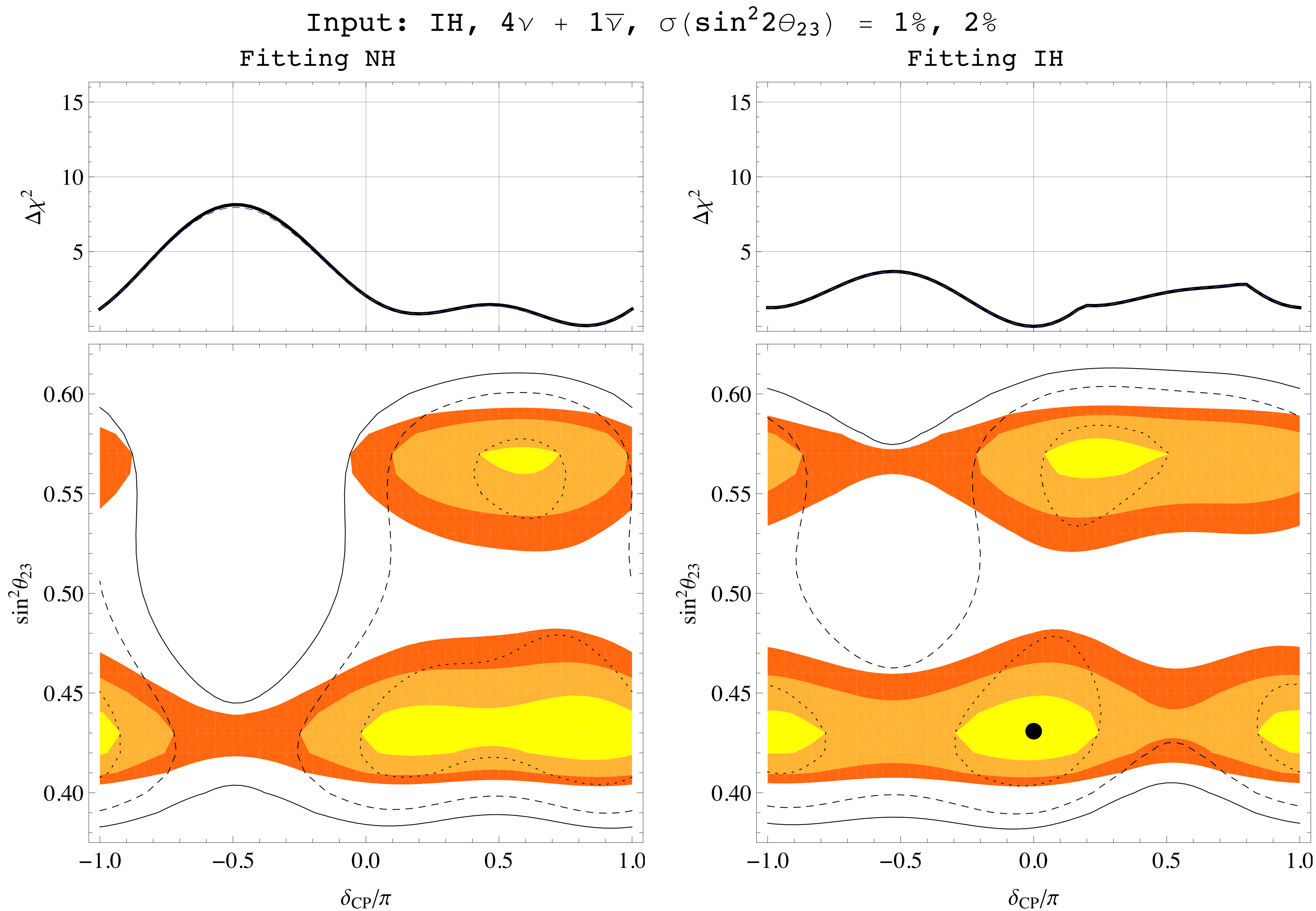
Invisibles Jul-2013

PAN Machado

T2K simulation



T2K



Input: IH, 4ν + 1ν̄, σ(sin²2θ23) = 1%, 2%
Fitting NH
Fitting IH
Δχ²
sin²θ23
δCP/π