Theta-13 after Daya Bay

Pedro A N Machado[1,2]

in collaboration with:
Hisakazu Minakata[3], Hiroshi Nonukowa[4],
and Renata Zukanovich Funchal[1]

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[3]Tokyo Metropolitan Univ., [4]PUC-Rio

arXiv:1111.3330

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and RENO!

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A quest for θ_{13}

The oscillation probabilities

A quest for θ_{13}

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4c_{13}^2 s_{13}^2 \left[c_{12}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) \right]$$
$$- 4s_{12}^2 c_{12}^2 c_{13}^4 \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

A quest for θ_{13}

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A quest for θ_{13}

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A quest for θ_{13}

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

A quest for θ_{13}

The dependence in θ_{13} is simple, there is no CP phase involved

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

A quest for θ_{13}

Approximately (for atmospheric distances),

Arafune et al PRD 56 3093 (1997)

$$P[\nu_\mu \to \nu_e(\bar{\nu}_\mu \to \bar{\nu}_e)]$$

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

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

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

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

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

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

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

$$a(x) = \sqrt{2} G_F N_e(x)$$

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

A quest for θ_{13}

Approximately (for atmospheric distances),

$$P[\nu_\mu \to \nu_e(\bar{\nu}_\mu \to \bar{\nu}_e)]$$

leading

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

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A quest for θ_{13}

Approximately (for atmospheric distances),

$$P[\nu_\mu \to \nu_e(\bar{\nu}_\mu \to \bar{\nu}_e)]$$

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

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intrinsic CPC

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

intrinsic CPV

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

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matter CPV

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

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matter CPV

A quest for θ_{13}

Approximately (for atmospheric distances),

$$P[\nu_\mu \to \nu_e(\bar{\nu}_\mu \to \bar{\nu}_e)]$$

leading solar

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

intrinsic CPC intrinsic CPV

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

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solar

matter CPV

A quest for θ_{13}

Approximately (for atmosph

There is an interplay between θ_{13} and δ_{CP}

$$P[\nu_\mu \to \nu_e(\bar{\nu}_\mu \to \bar{\nu}_e)]$$

leading

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

intrinsic CPC

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

intrinsic CPV

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matter CPV

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

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matter CPV

solar

A quest for θ_{13}

Approximately (for atmosph

$P[\nu_\mu \to \nu_e(\bar{\nu}_\mu \to \bar{\nu}_e)]$

leading

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

intrinsic CPC

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

intrinsic CPV

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

matter CPV

$\pm \cos 2\theta_{13} \sin^2 2\theta$ $\left(\frac{\Delta m_{31}^2 L}{}\right)$

$\mp$ $\left(\frac{\Delta m_{21}^2 L}{4E}\right)^2$

matter CP

There is an interplay between θ_{13} and δ_{CP}

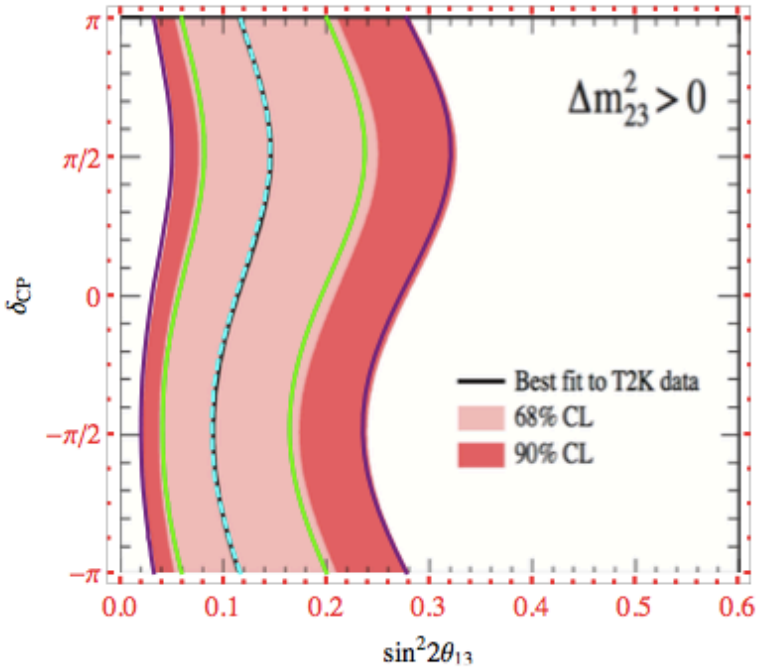
Reactor and accelerator neutrinos are complementary

A quest for θ_{13}

The experiments

A quest for θ_{13}

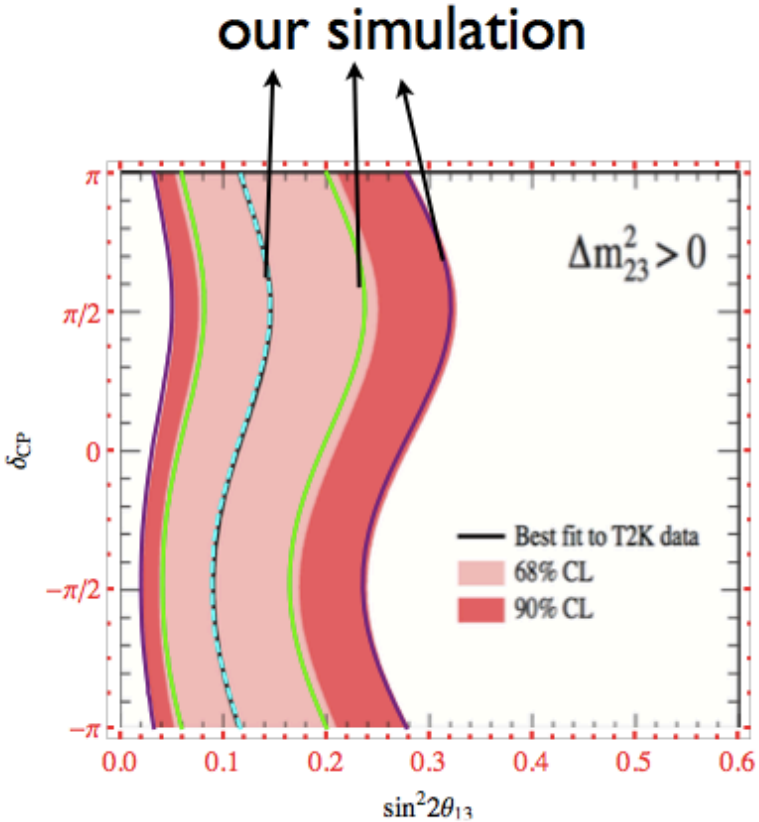
T2K



T2K Collaboration PRL 107 (2011) 041801

A quest for θ_{13}

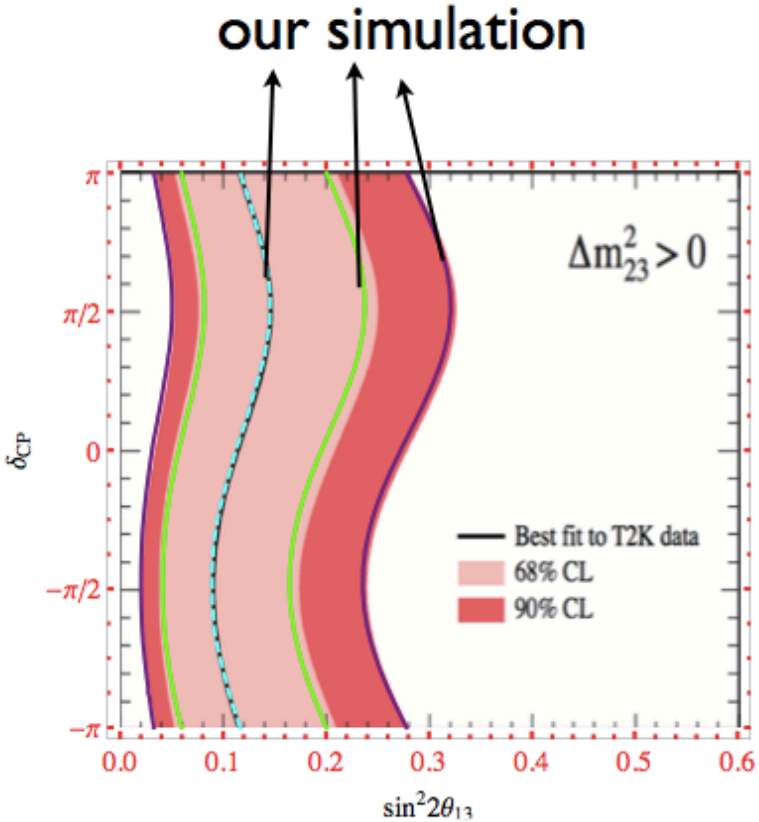
T2K



T2K Collaboration PRL 107 (2011) 041801

A quest for θ_{13}

T2K



Technical details:

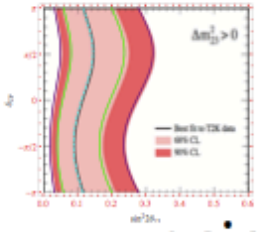
- We tried to reproduce each experiment as faithfully as possible

- In the final fit, we let all oscillation parameters vary

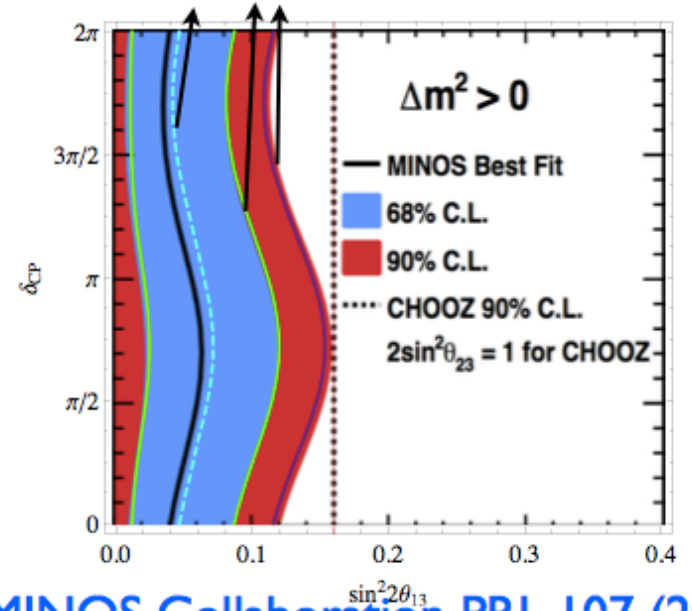
- We assumed SK atmospheric result as a prior for θ_{23}, MINOS for Δm^2_{atm}, and Kamland + Solar for θ_{12} and Δm^2_{sol}

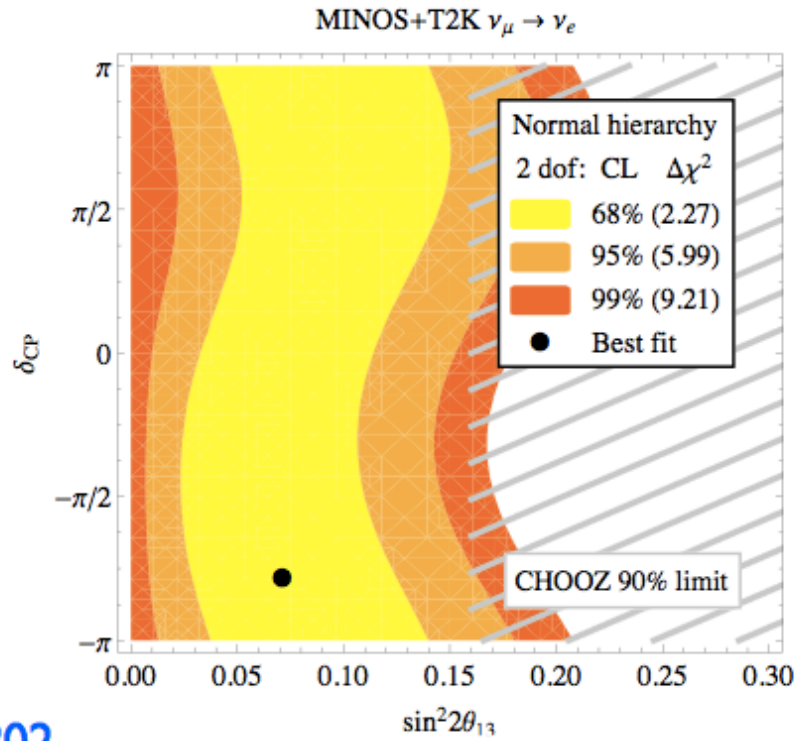
A quest for θ_{13}

T2K+MINOS



our simulation

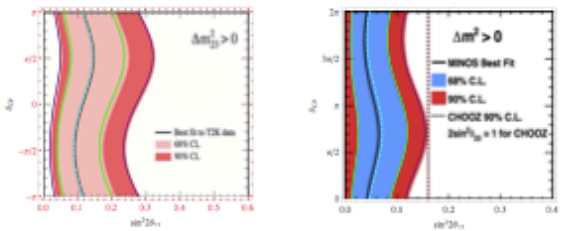


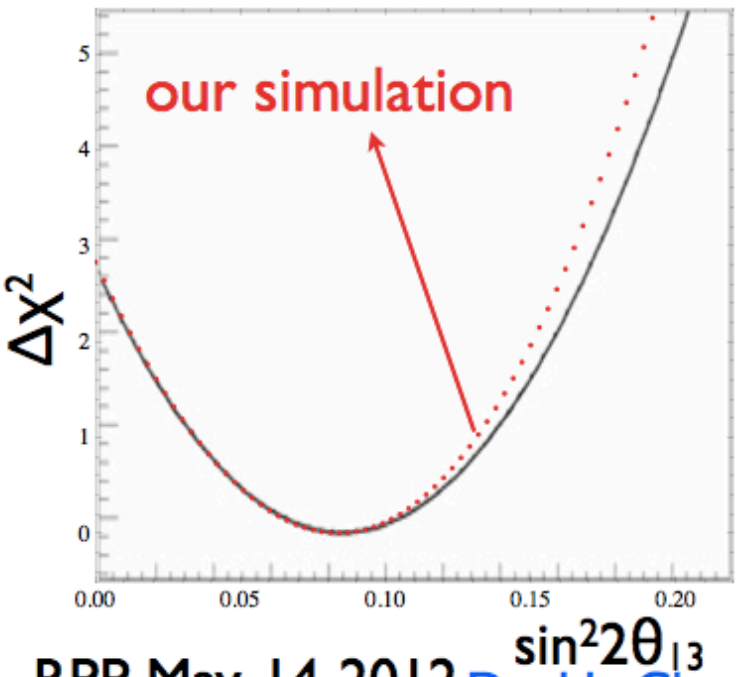


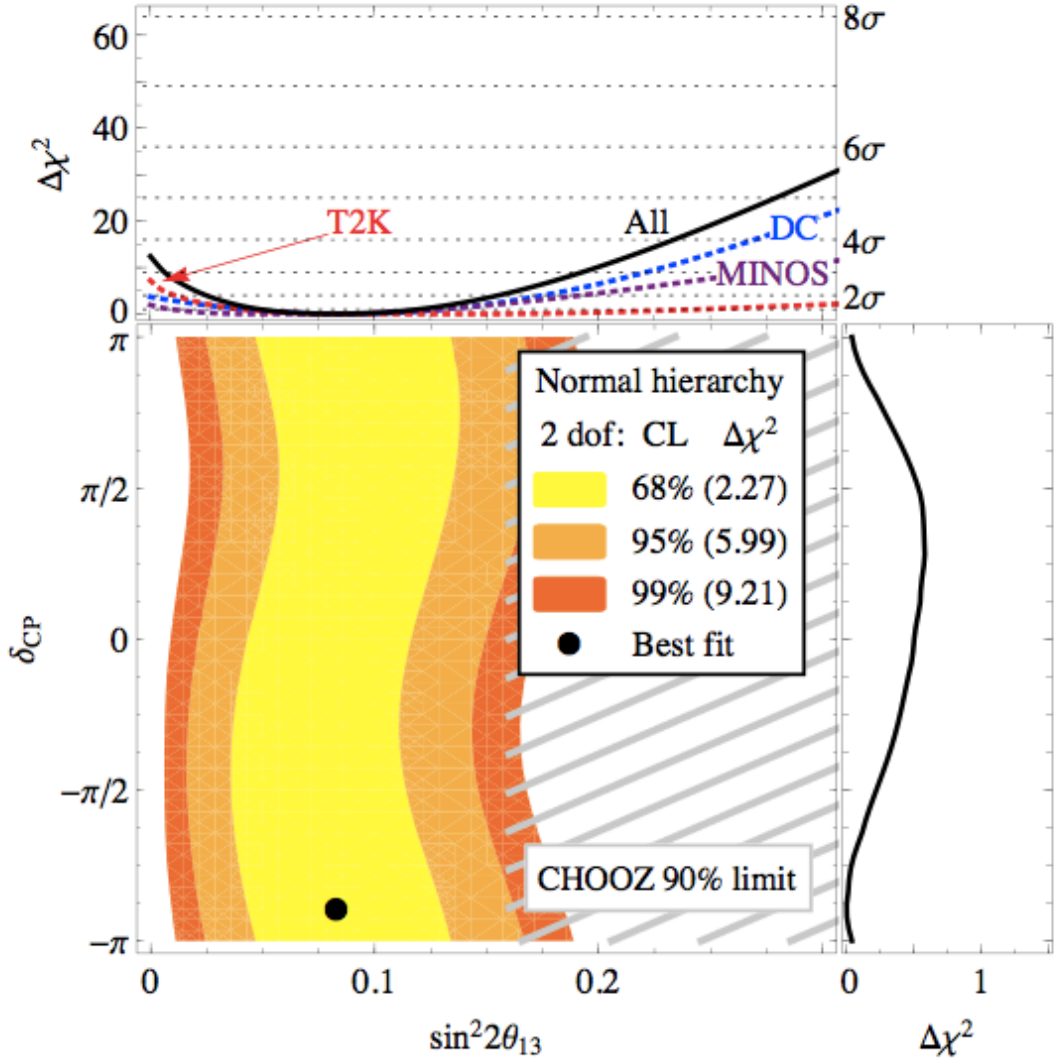
MINOS Collaboration PRL 107 (2011) 181802

A quest for θ_{13}

T2K+MINOS+DC







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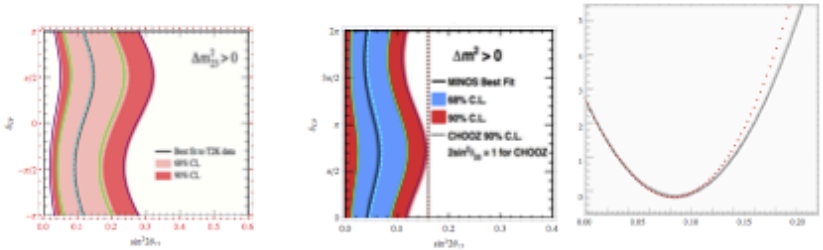
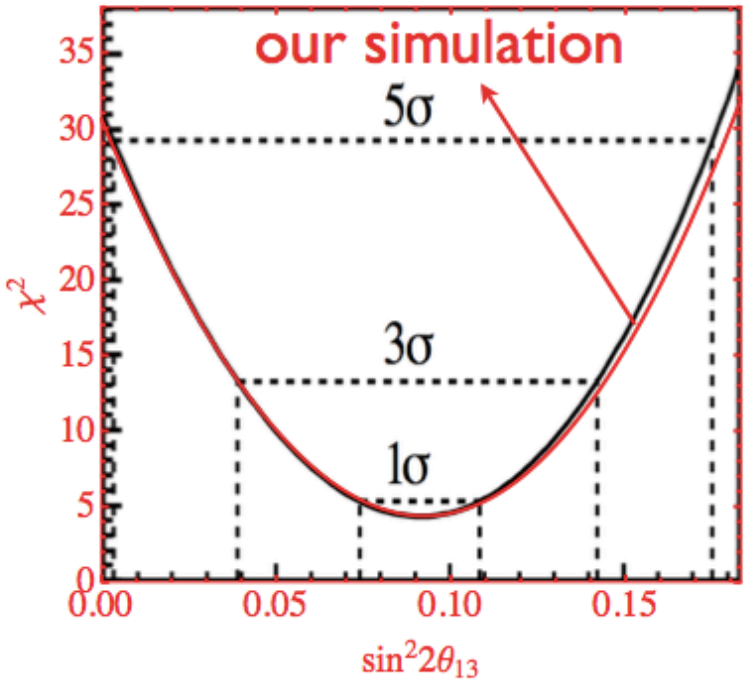
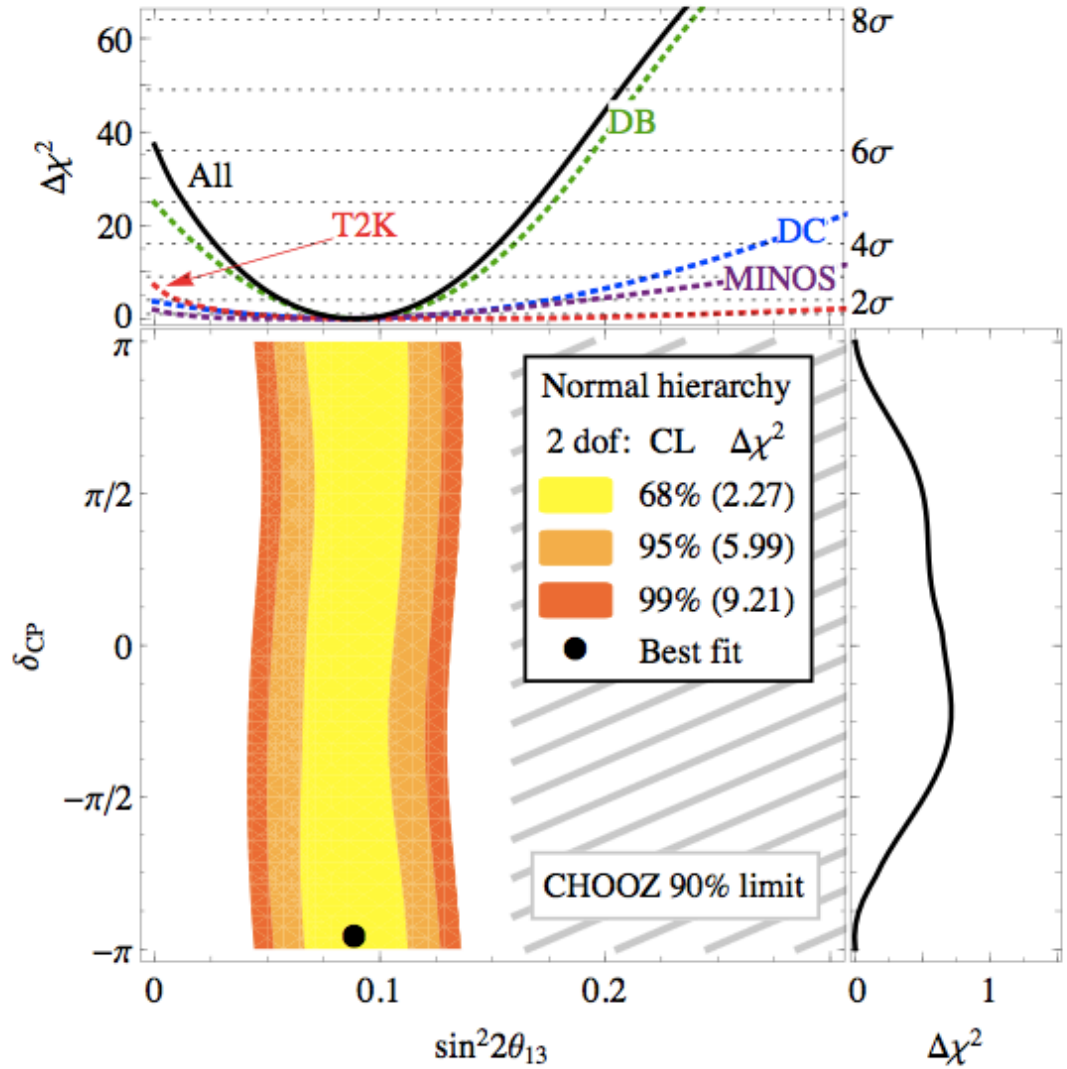
A quest for θ_{13}

T2K+MINOS+DC+DB







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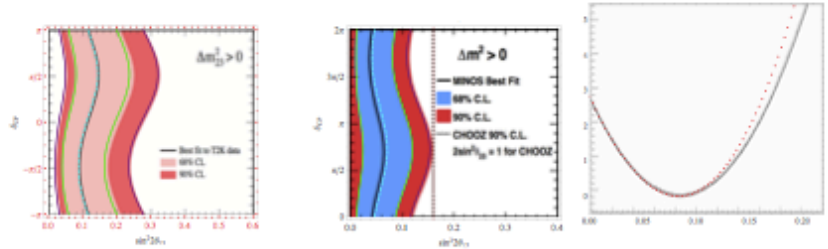
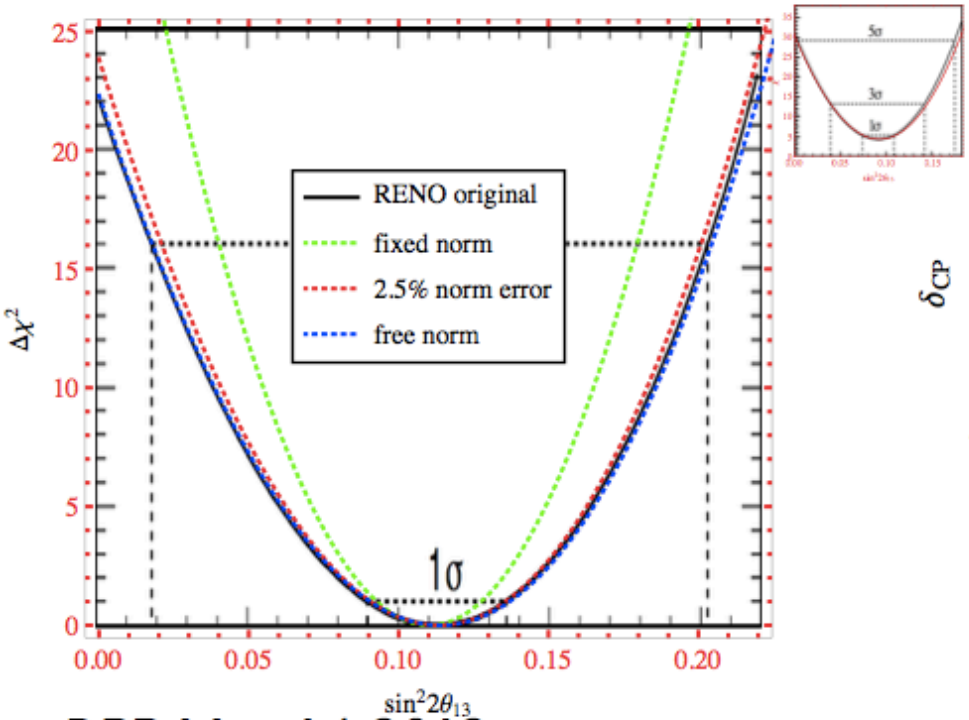
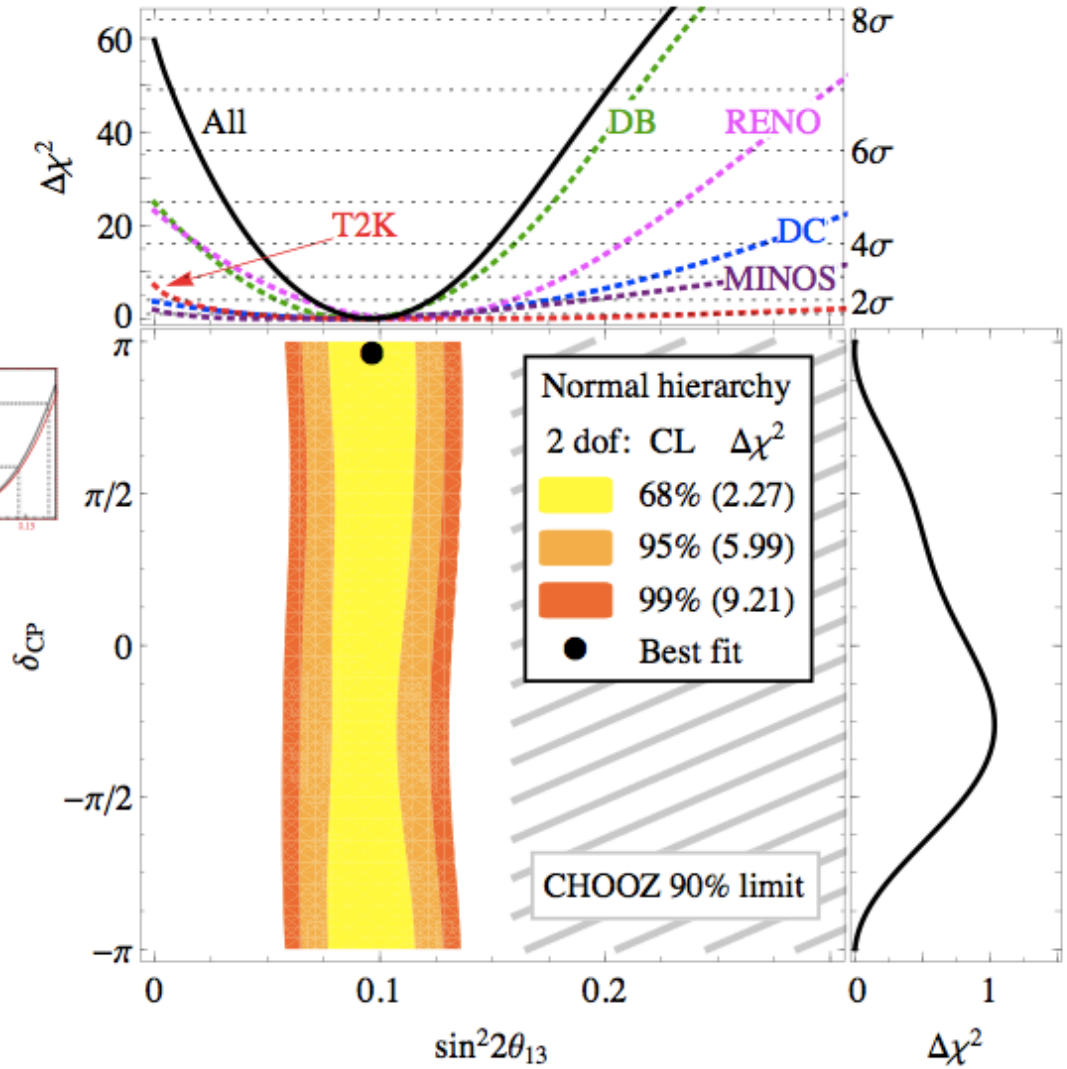
A quest for θ_{13}

T2K+MINOS+DC+DB







RPP May-14-2012 RENO Coll. 1204.0626

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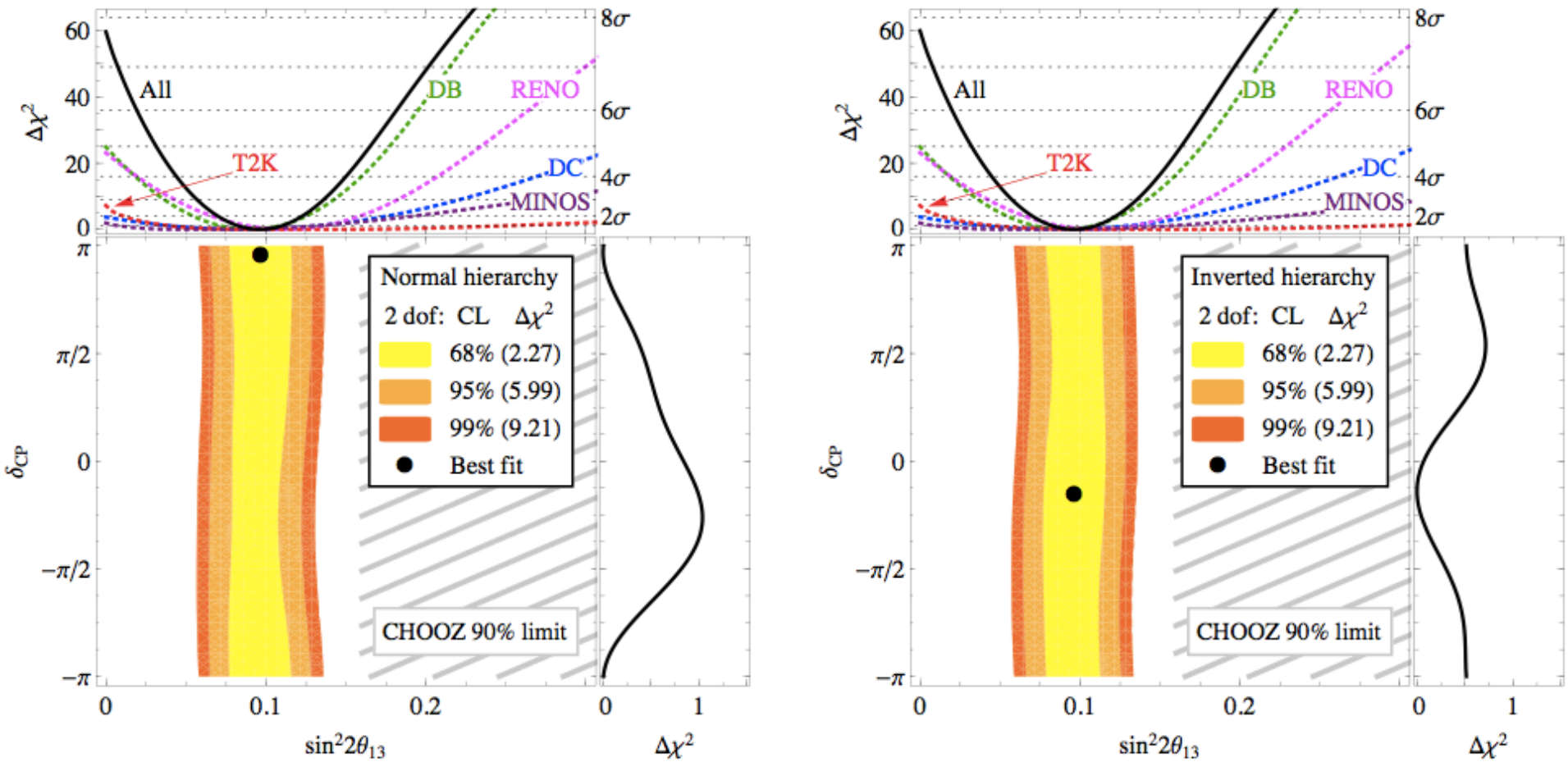
A quest for θ_{13}



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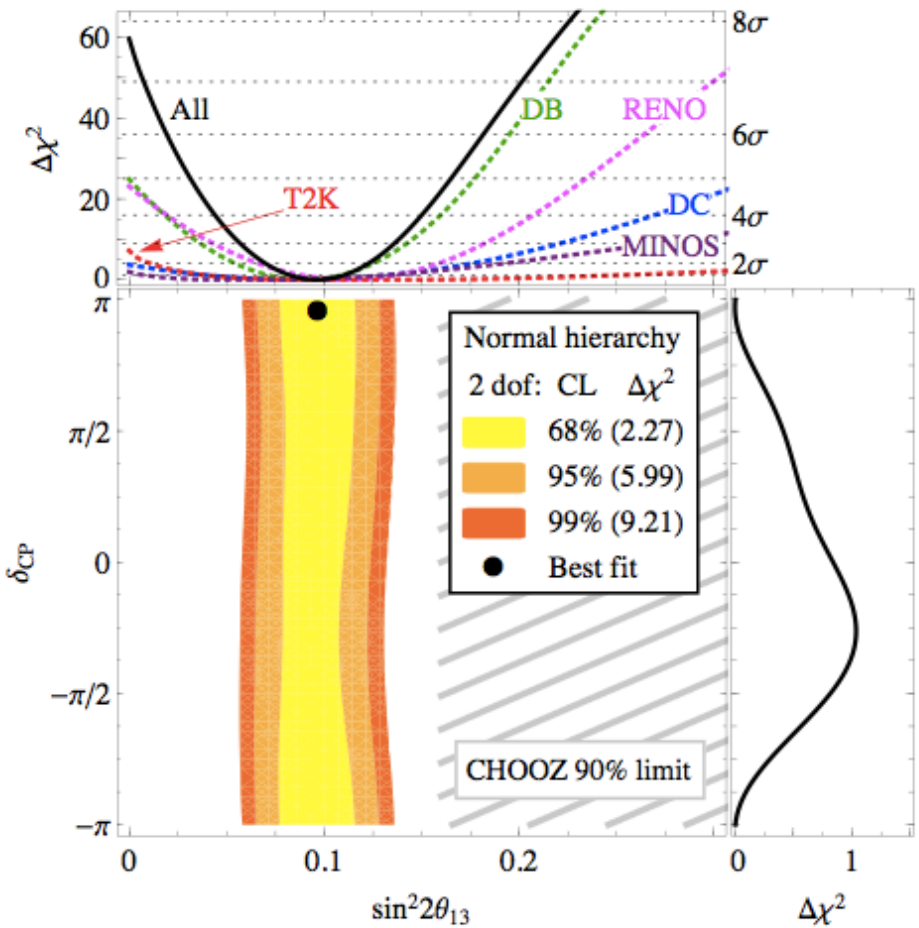
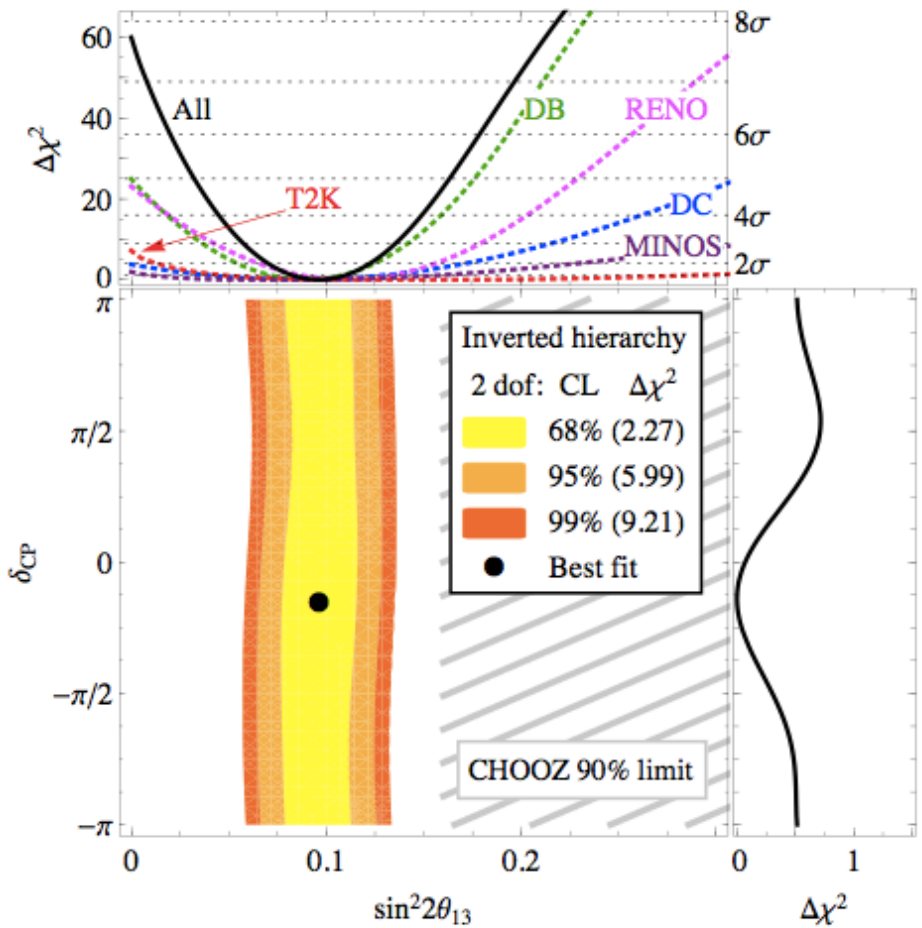
A quest for θ_{13}





$\sin^2 2\theta_{13} = 0.096 \pm 0.013\ (\pm 0.040)$ @ 1σ (3σ)

$\delta = 0.97\pi\ (-0.14\pi)$ $\theta_{13} \neq 0$ @ 7.7σ

$\theta_{13} = 9.02° = 0.1575$ rad

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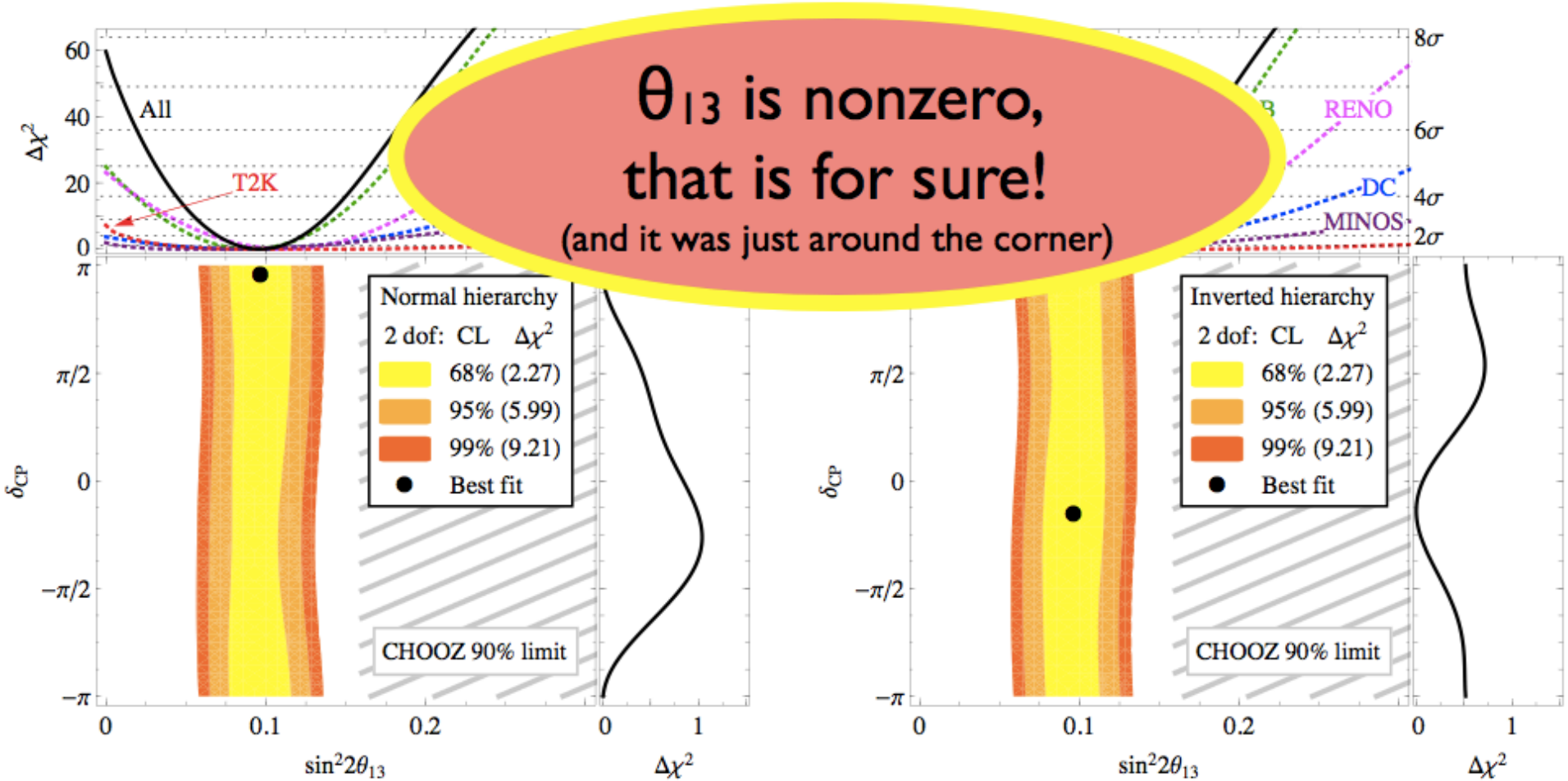
A quest for θ_{13}



θ_{13} is nonzero,
that is for sure!
(and it was just around the corner)

$\sin^2 2\theta_{13} = 0.096 \pm 0.013\ (\pm 0.040)$ @ 1σ (3σ)
$\delta = 0.97\pi\ (-0.14\pi)$ $\theta_{13} \neq 0$ @ 7.7σ

$\theta_{13} = 9.02° = 0.1575$ rad

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A few questions

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- Does the reactor anomaly affect the determination of theta-13? see Giunti Laveder PRD 85 (2012) 031301

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- How does the precision on theta-13 evolves?

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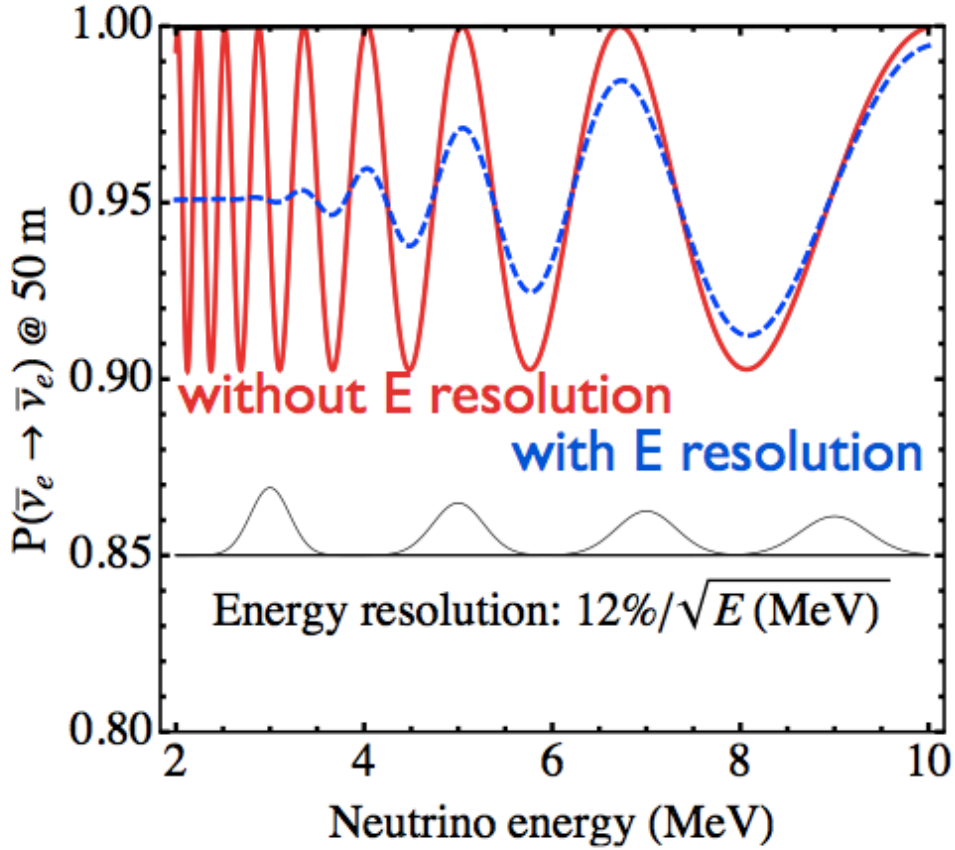
- How does the precision on theta-13 evolves?

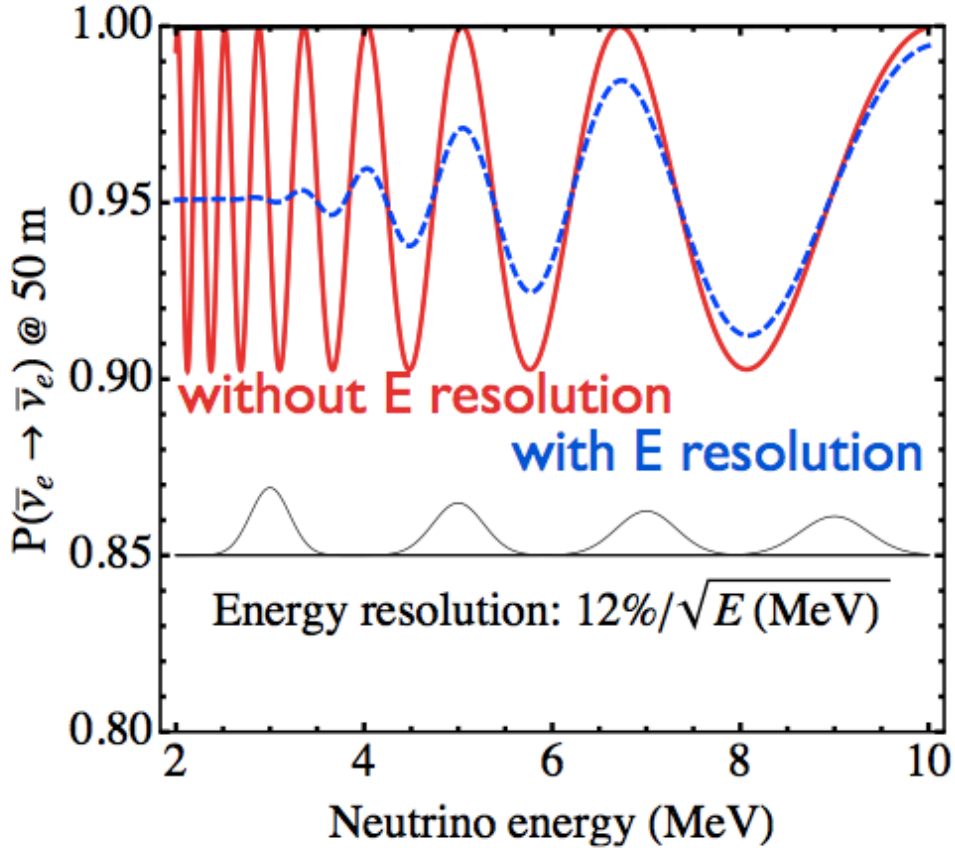
- What does a large theta-13 change? What does it mean?

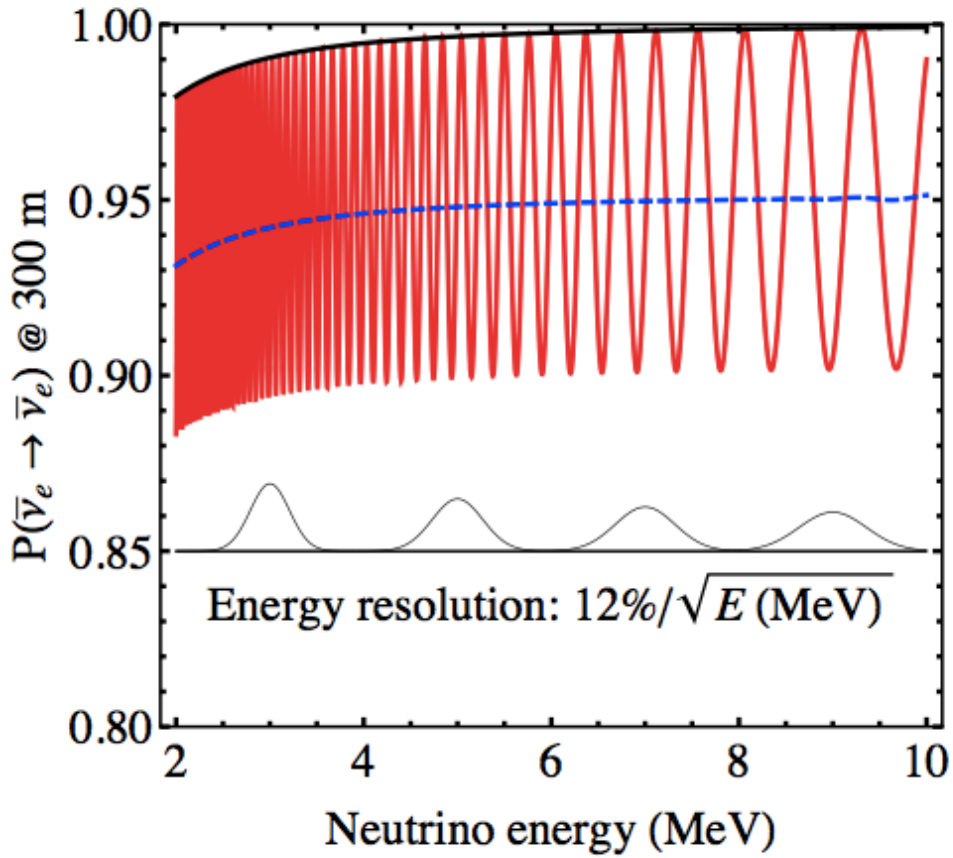
θ_{13} vs Reactor anomaly



$\Delta m^2_{RAA} = 1\ eV^2 \qquad \sin^2 2\theta_{RAA} = 0.10$

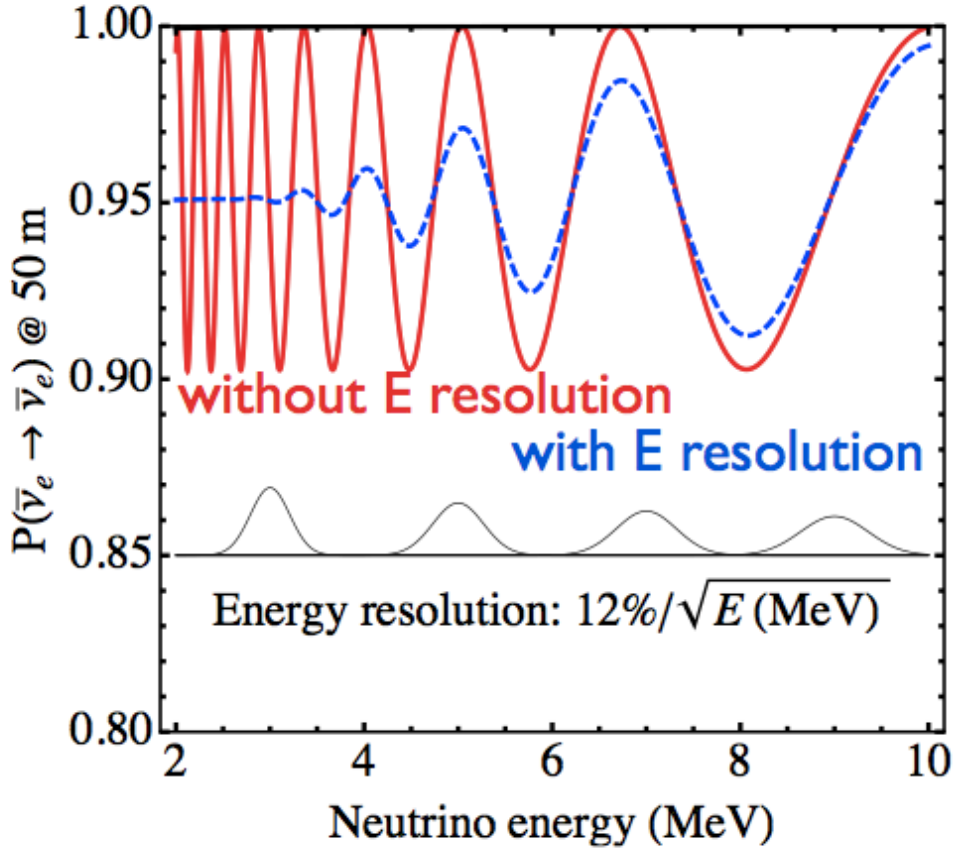
θ_{13} vs Reactor anomaly

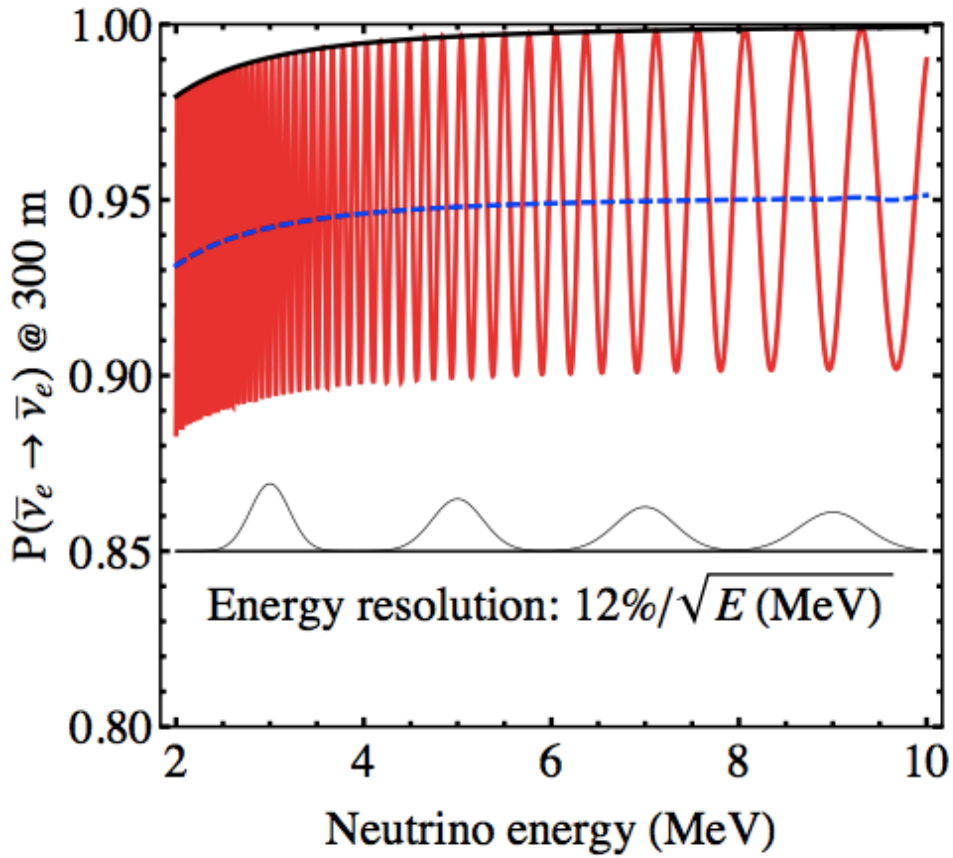




$\Delta m^2_{sterile} = 1\ eV^2$ $\sin^2 2\theta_{sterile} = 0.10$

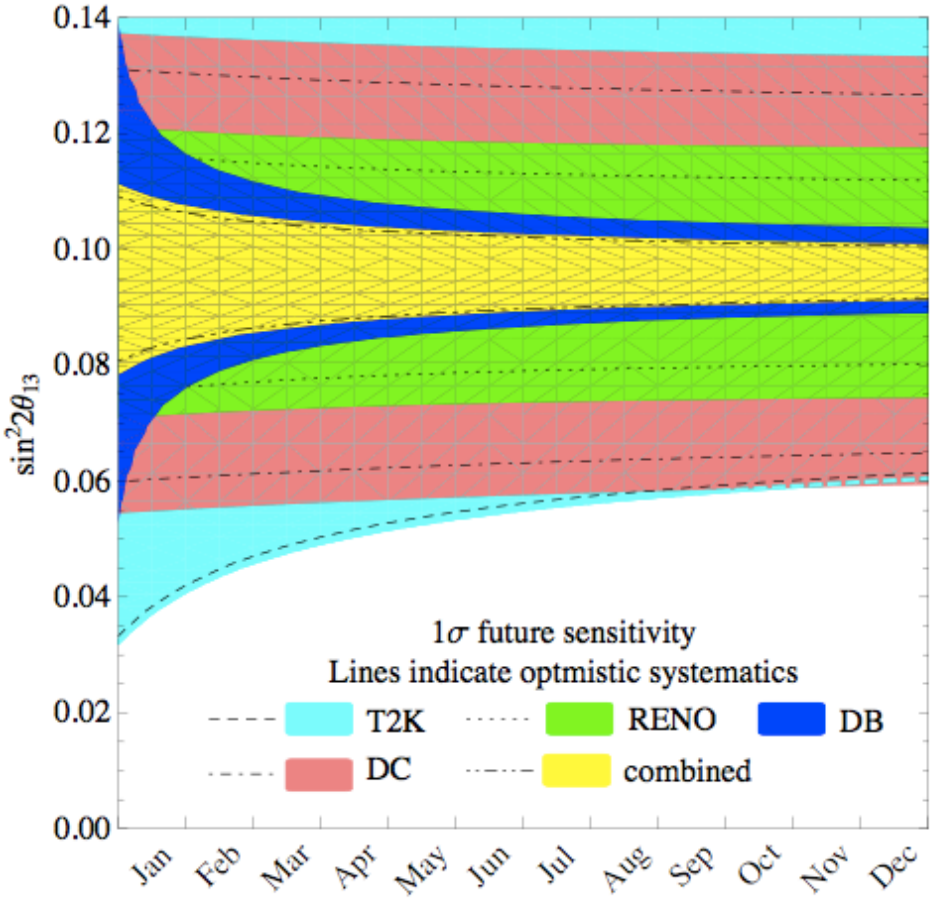
θ_{13} vs Reactor anomaly

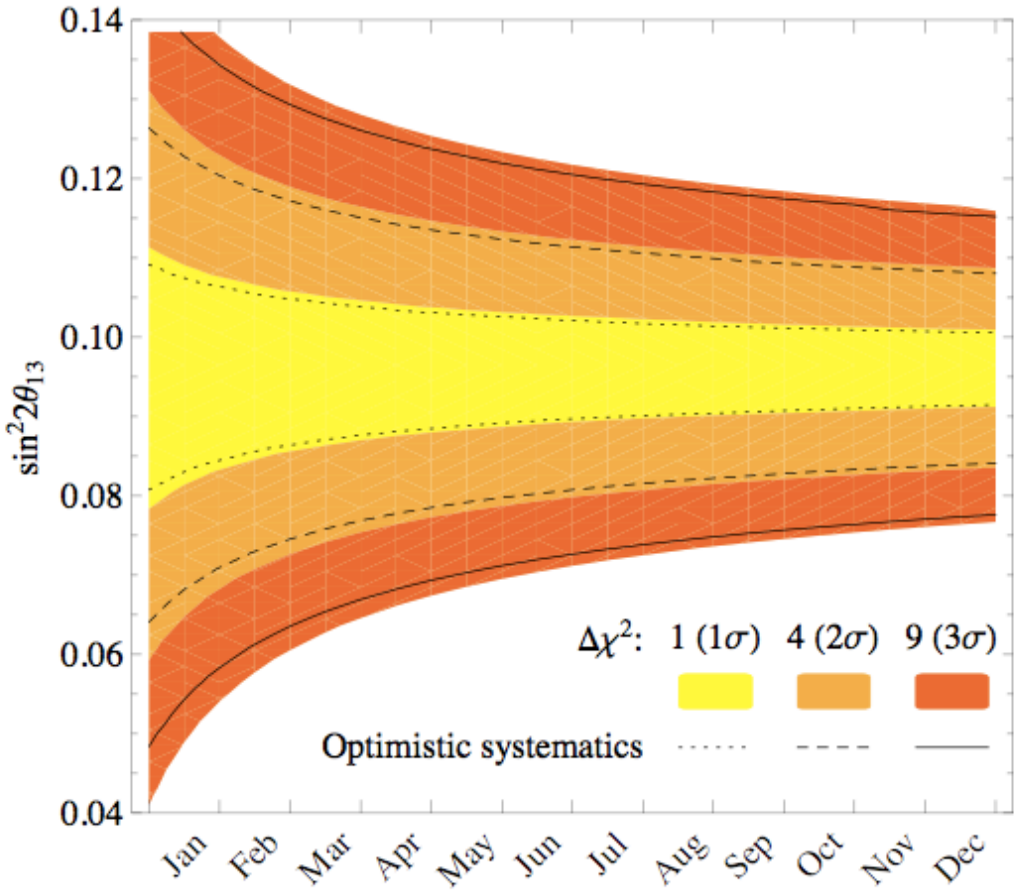




It can affect Double Chooz but not RENO and Daya Bay

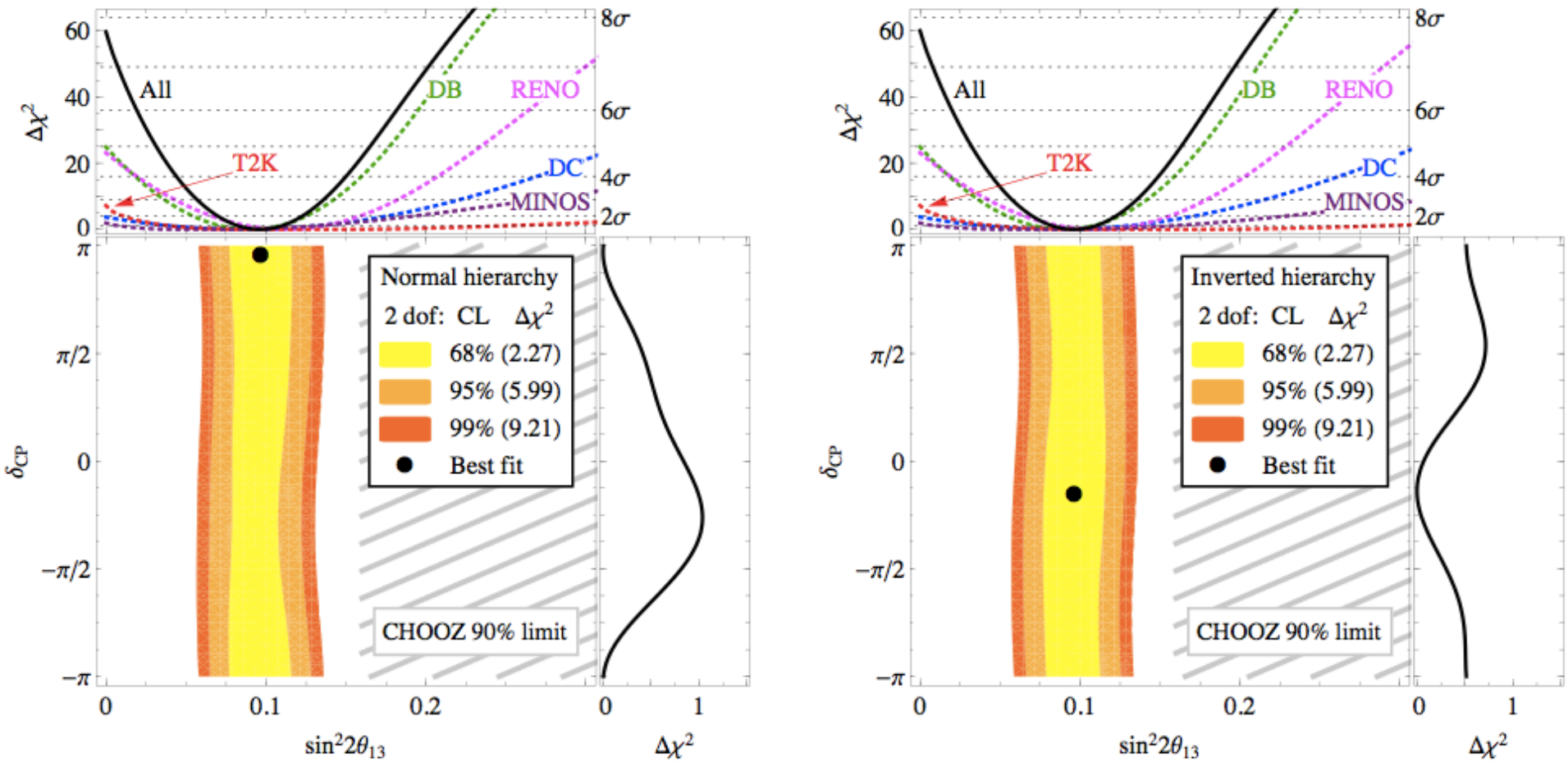
θ_{13} precision





see the paper for details (1111.3330)

θ_{13} precision

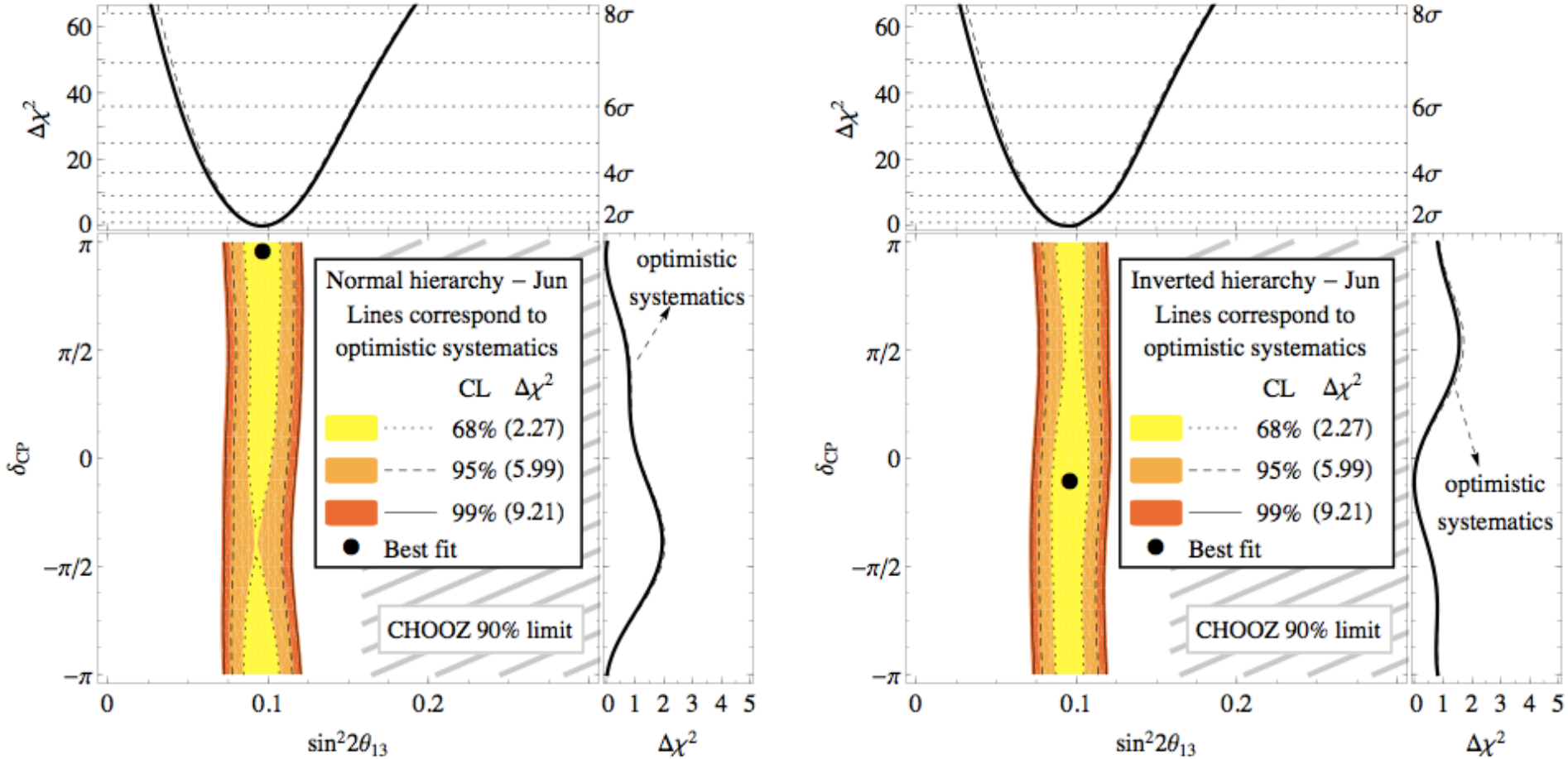


Present: $\sin^2 2\theta_{13} = 0.096 \pm 0.013\ (\pm\ 0.040)$ @ 1σ (3σ)

RPP May-14-2012

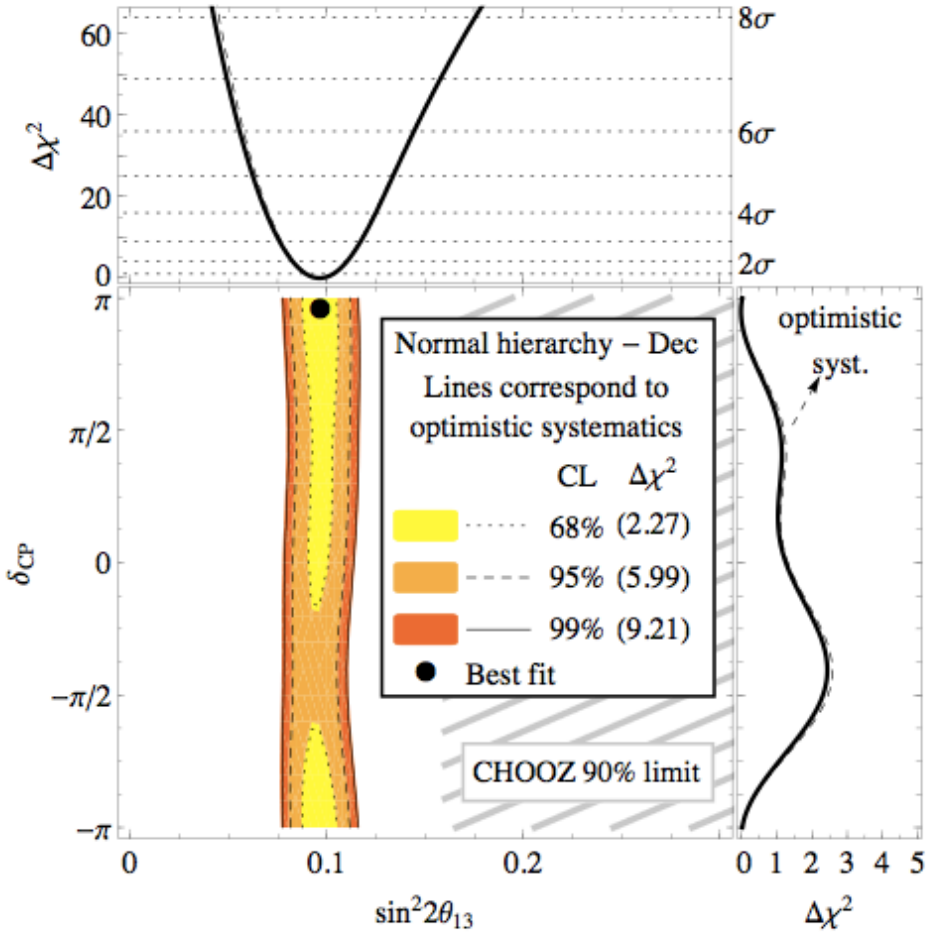
PAN Machado

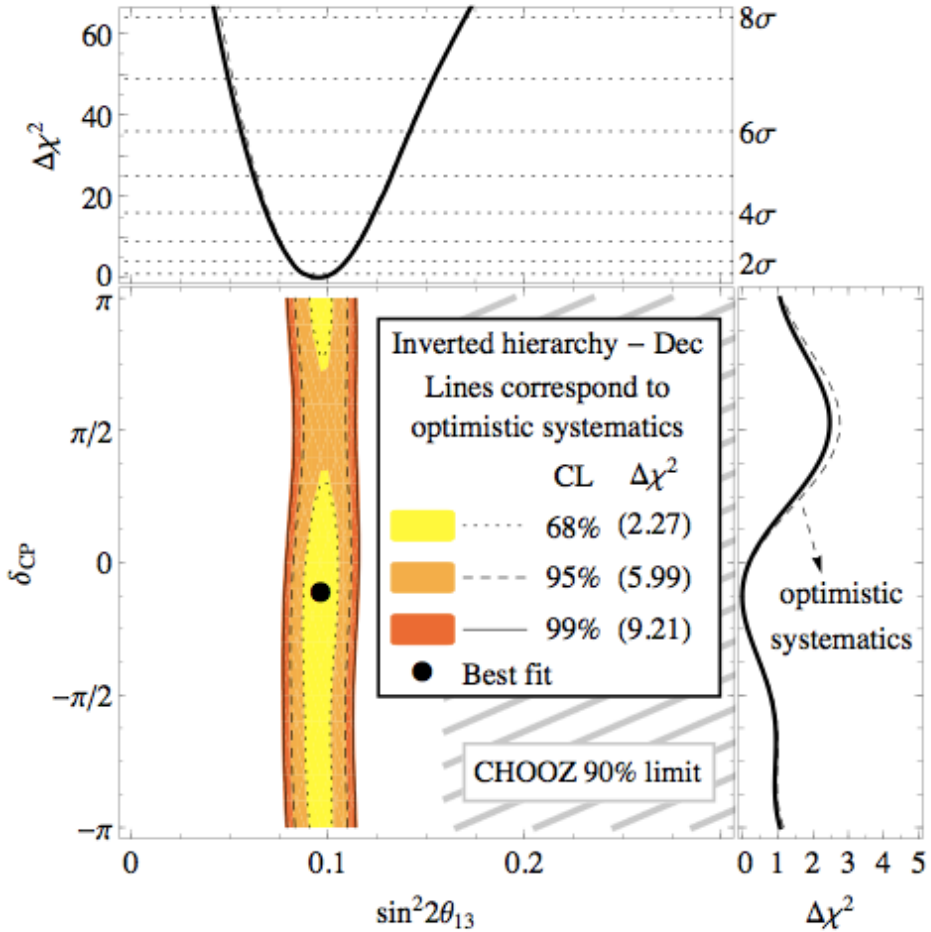
θ_{13} precision



June 2012: $\sin^2 2\theta_{13} = 0.096 \pm 0.007\ (\pm\ 0.025)$ @ 1σ (3σ)

θ_{13} precision





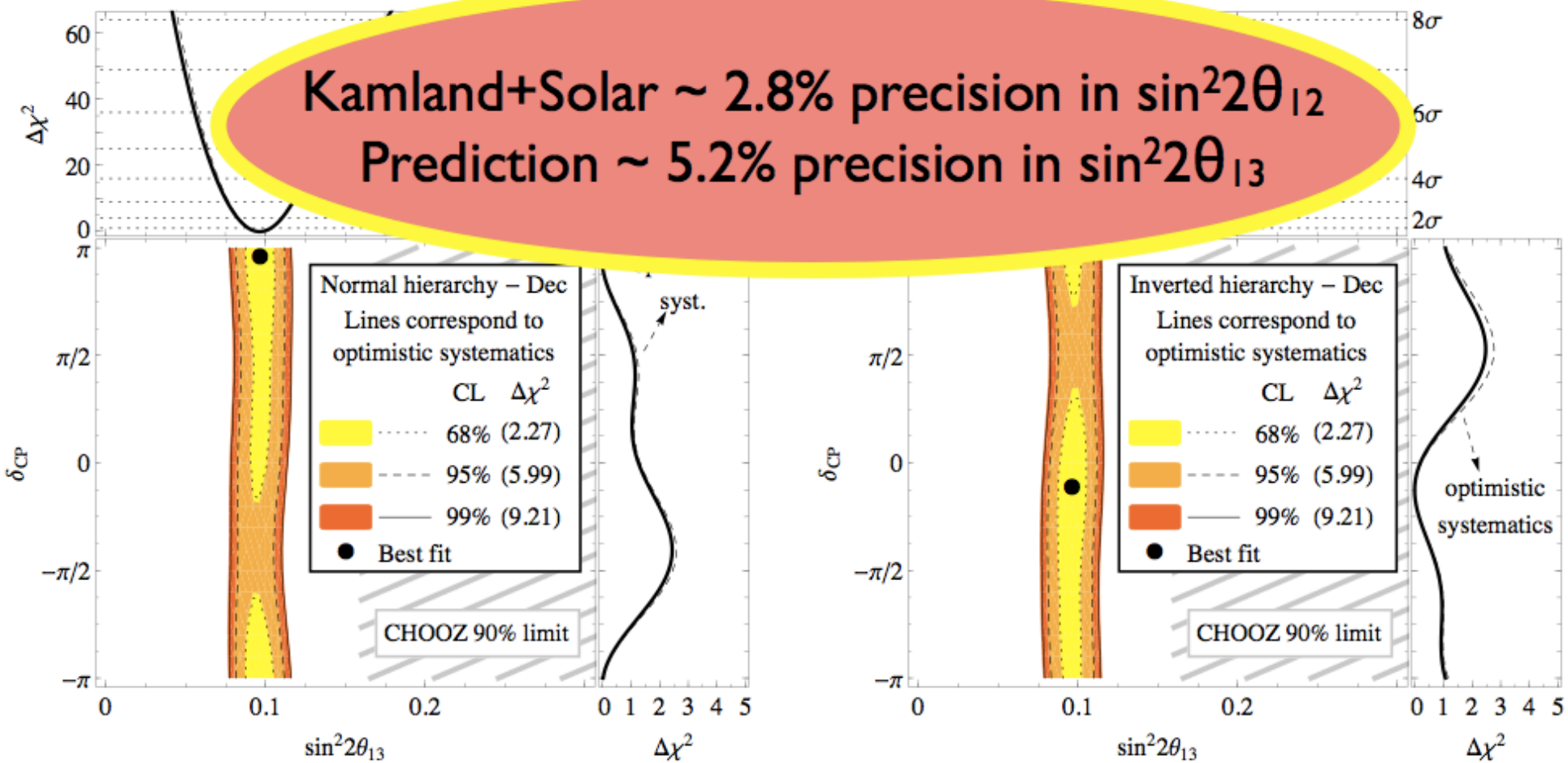
Dec 2012: $\sin^2 2\theta_{13} = 0.096 \pm 0.005\ (\pm\ 0.020)$ @ 1σ (3σ)

RPP May-14-2012

PAN Machado

θ_{13} precision

Kamland+Solar ~ 2.8% precision in $\sin^2 2\theta_{12}$
Prediction ~ 5.2% precision in $\sin^2 2\theta_{13}$



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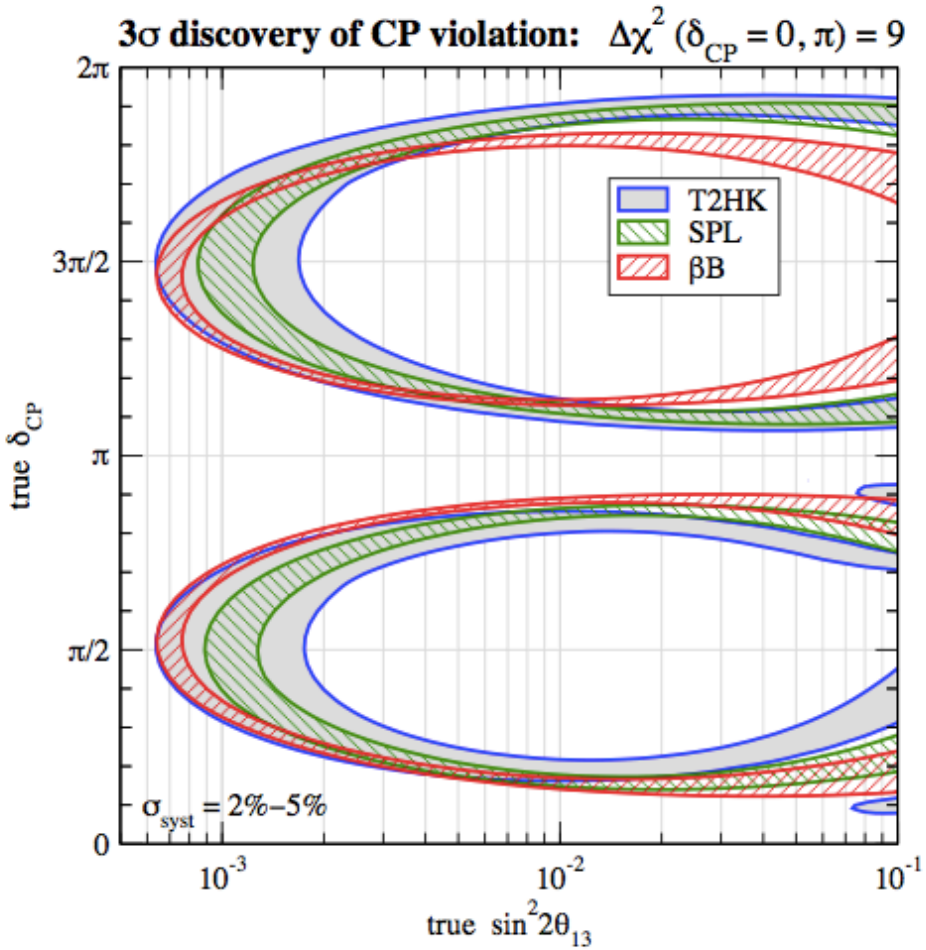
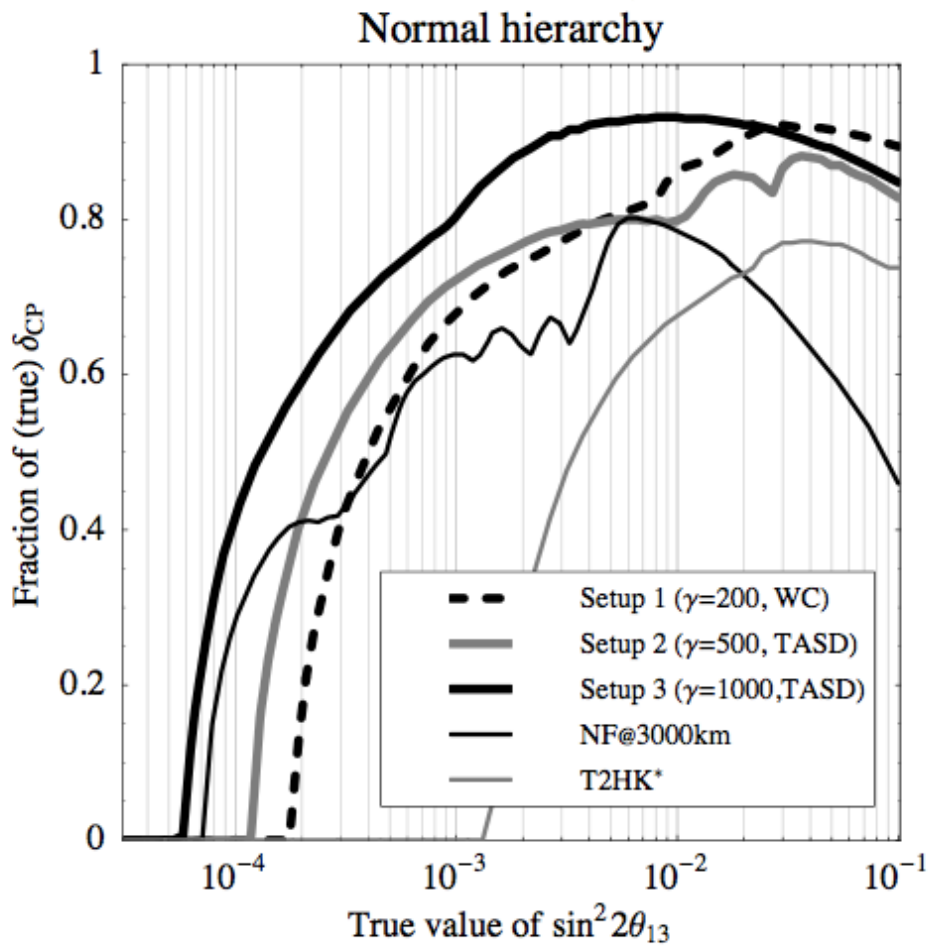
What does a large θ_{13} change?

What does a large θ_{13} chan

Future strategy



Campagne et al JHEP 0704 (2007) 003



Huber et al PRD 73 (2006) 053002

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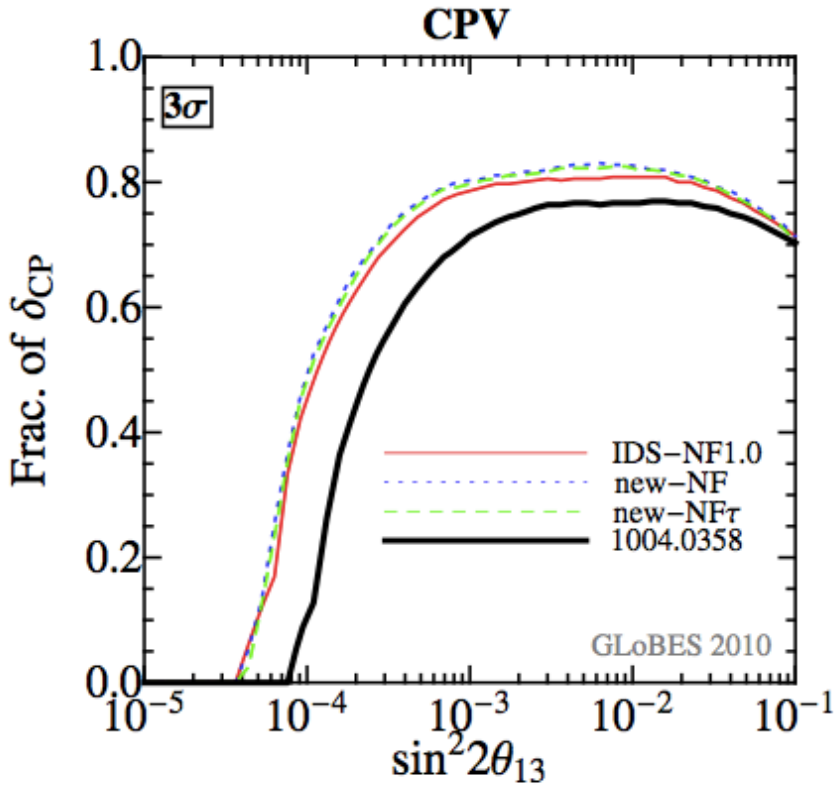
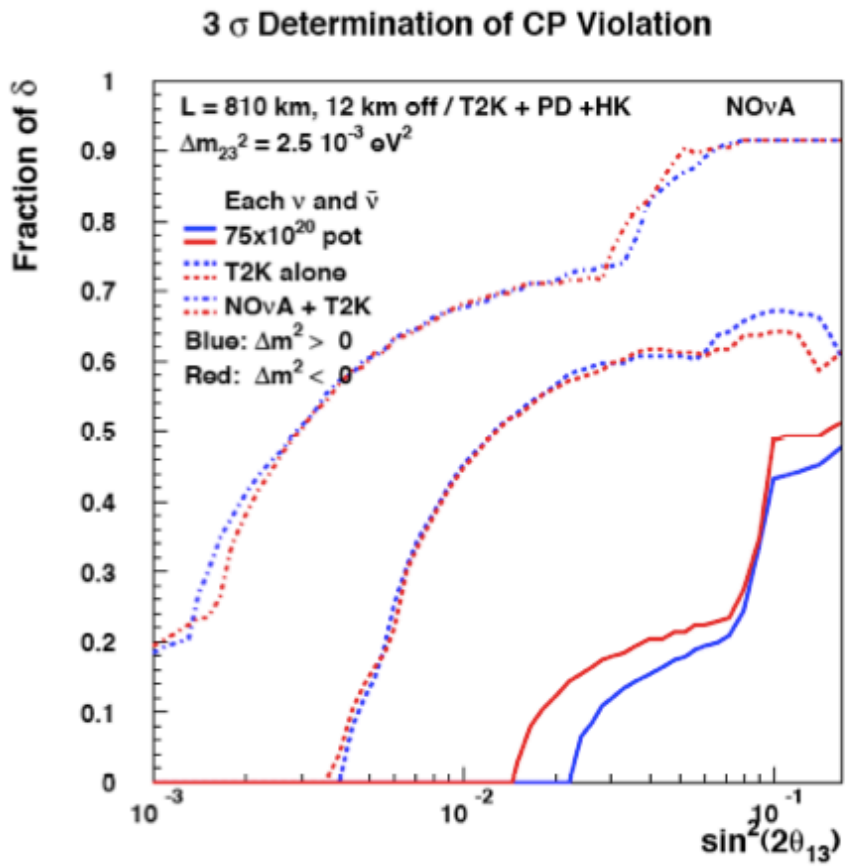


Agarwalla et al JHEP 01 (2011) 120



NOvA proposal

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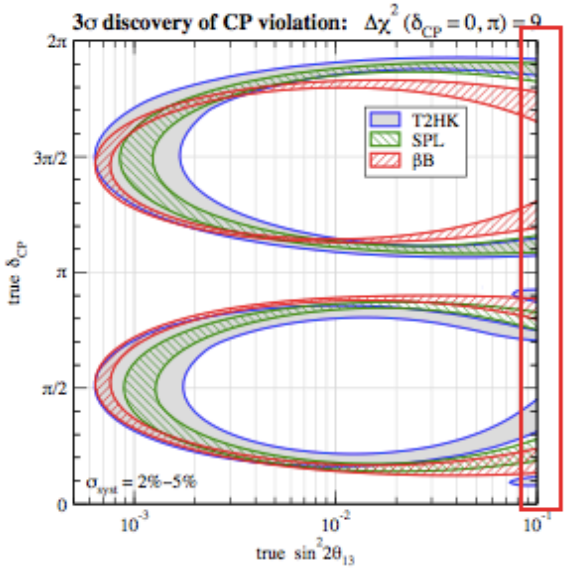

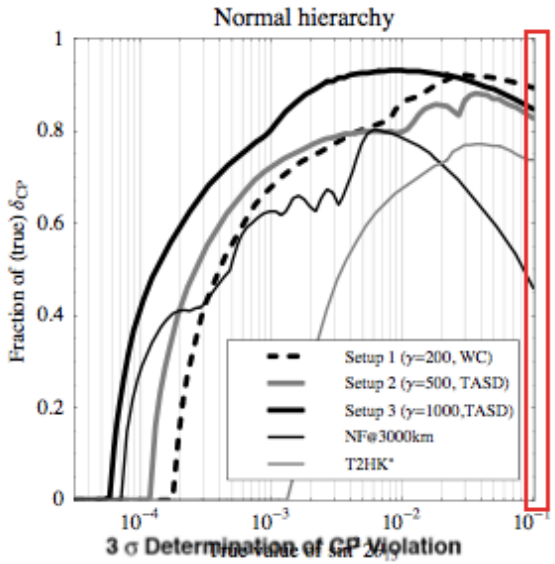

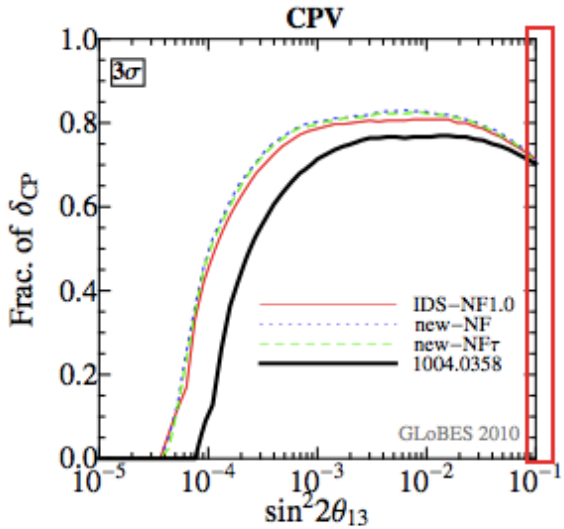

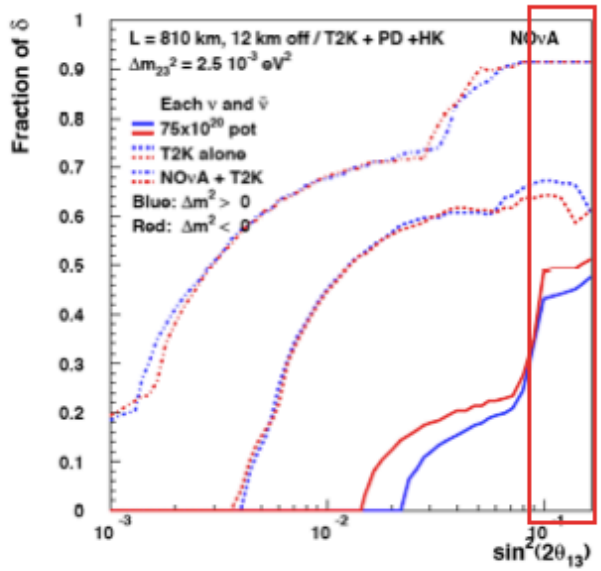

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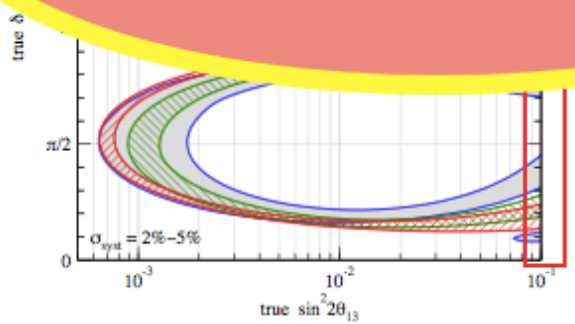

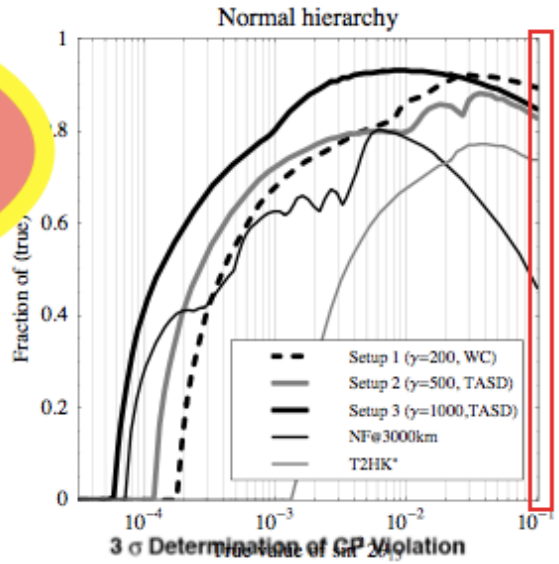

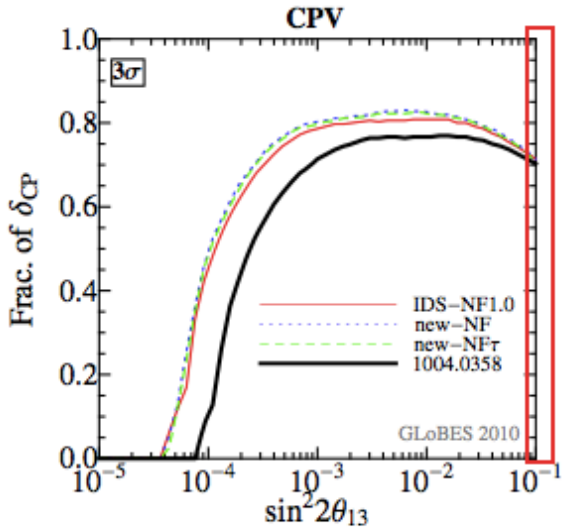

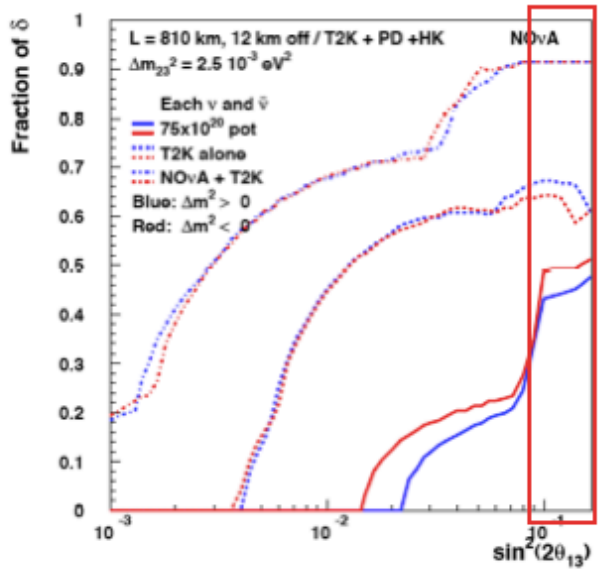

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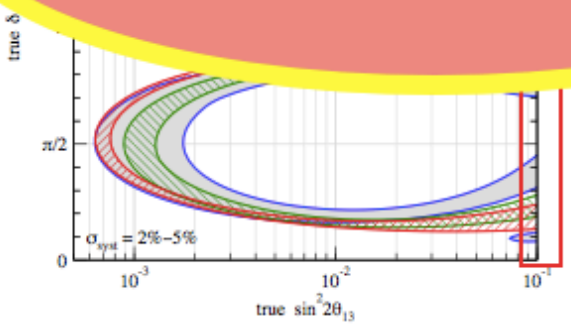
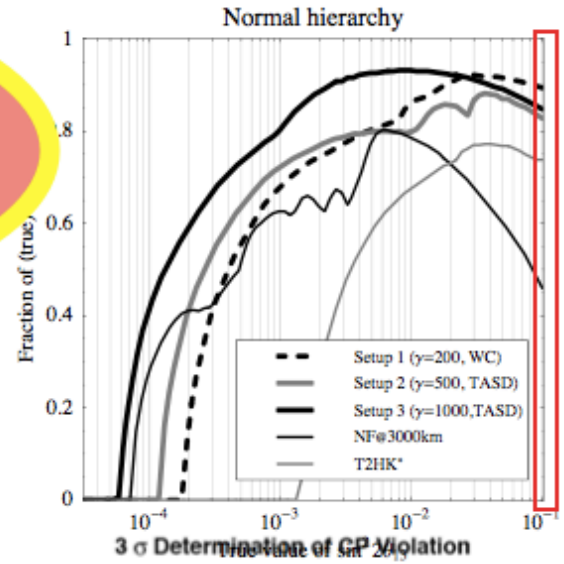
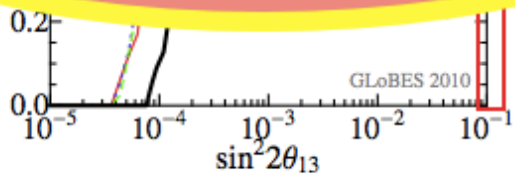
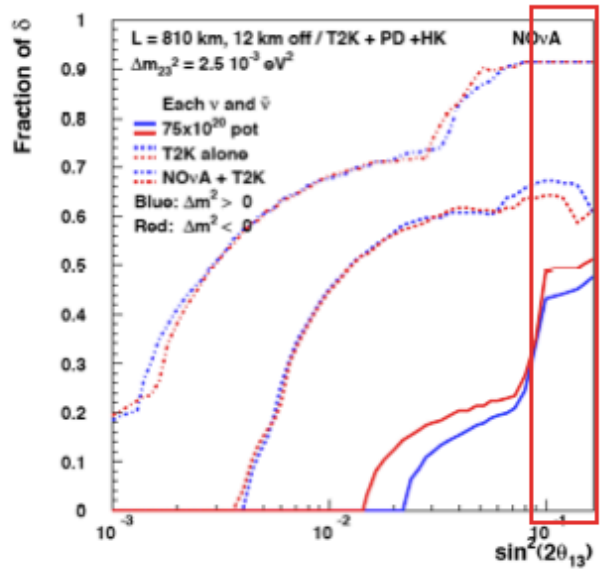




Do we need a neutrino factory? A β-beam?





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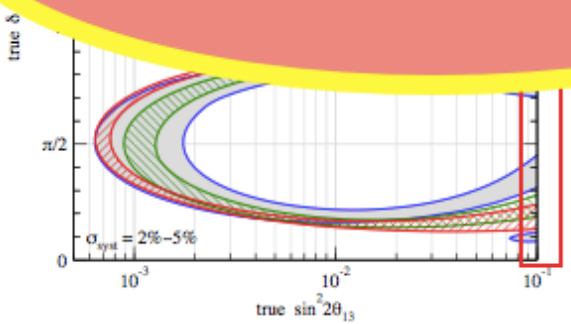

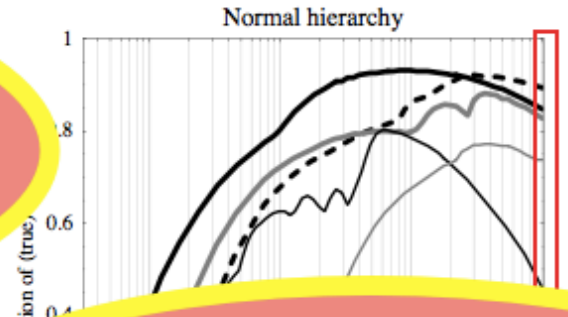

Is it possible now to have an all-in-one experiment?

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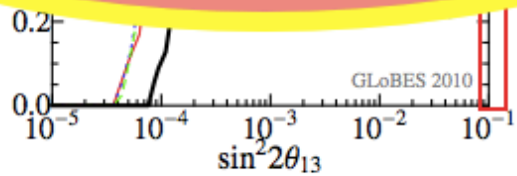

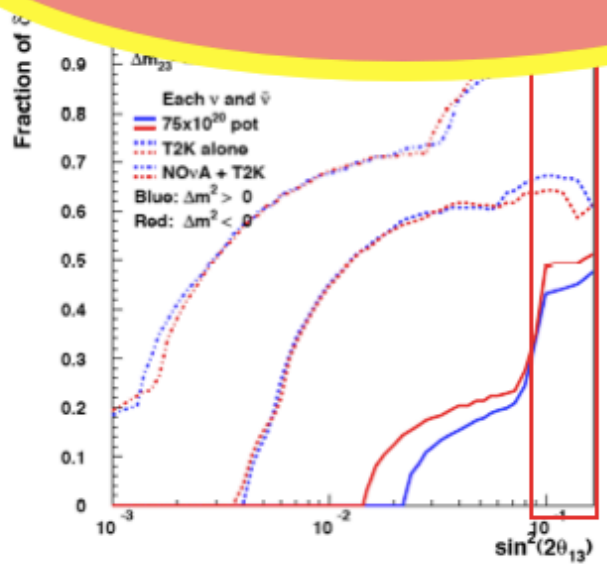

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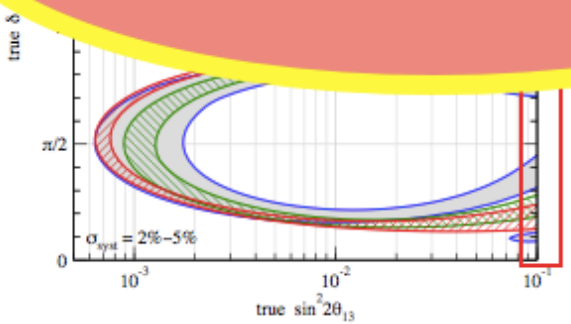

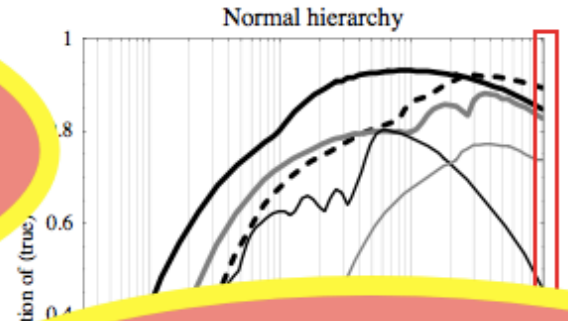

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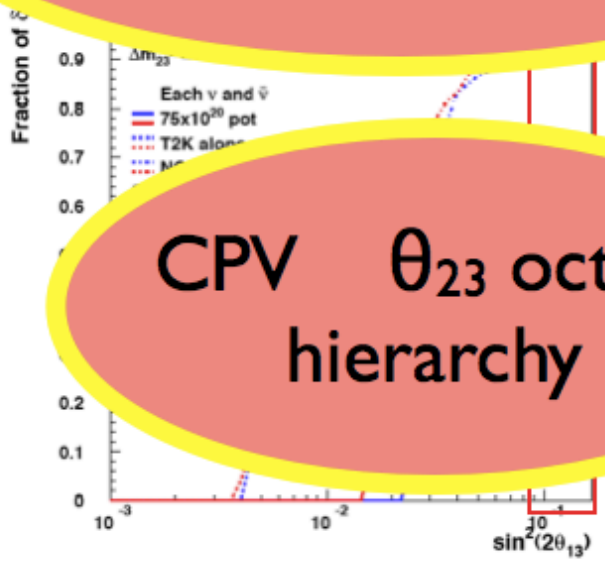
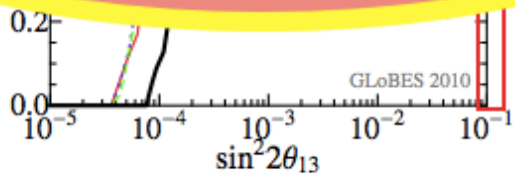




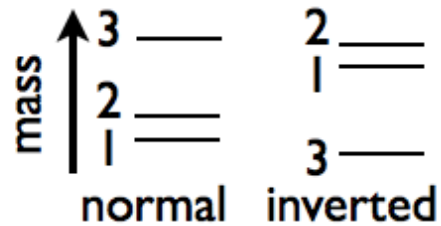
CPV θ_{23} octant hierarchy

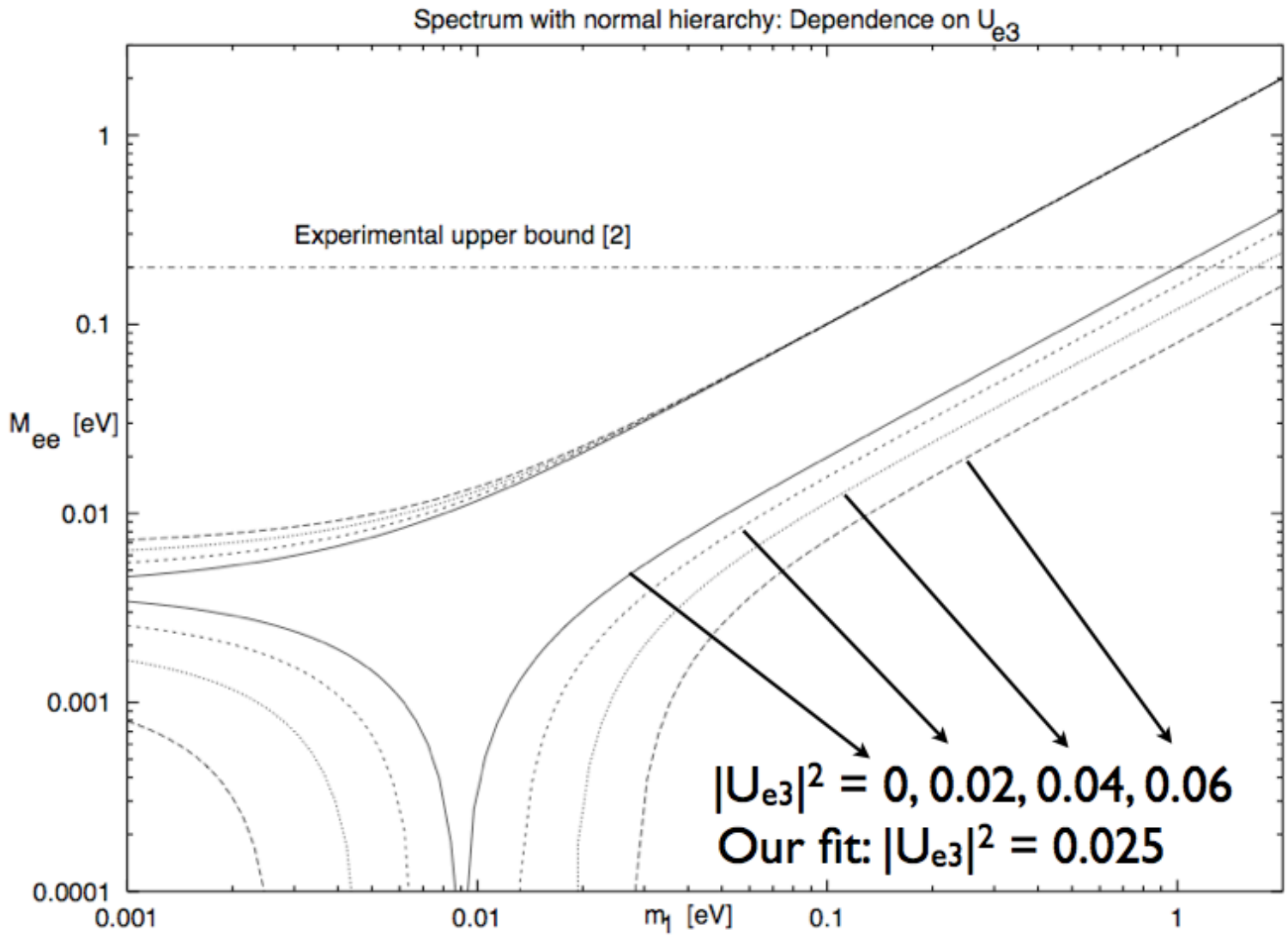
What does a large θ_{13} change?

$0\nu\beta\beta$

Vissani JHEP 9906 (1999) 022

$M_{ee} = |U_{ei}^2 m_i|$





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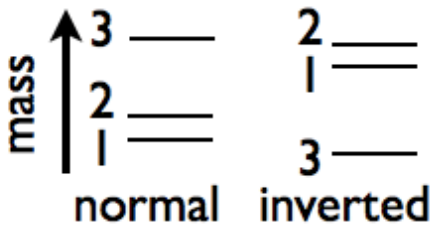
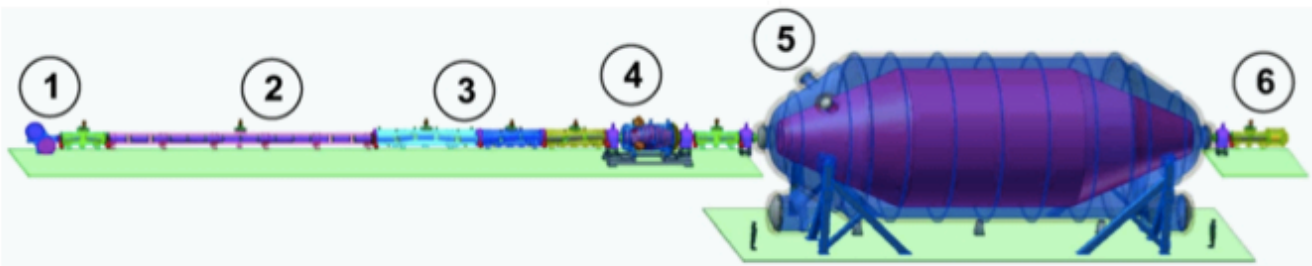
β decay

$$m^2(\nu_e) = \sum_i |U_{ei}^2| m_i^2$$





KATRIN: $m(\nu_e) < 0.2$ eV

Eitel Nucl NPB (PS) 143 (2005)

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If the hierarchy is normal,
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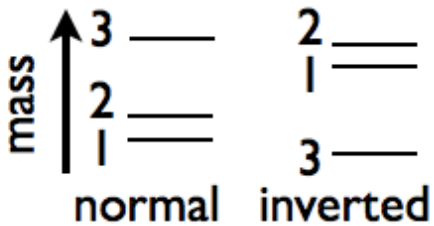

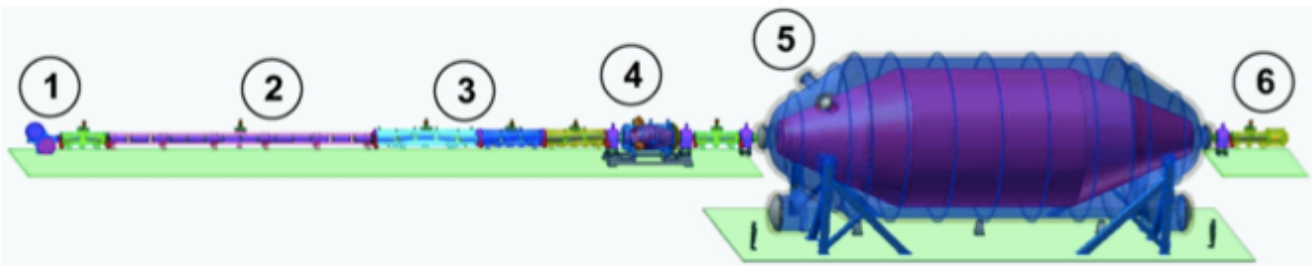

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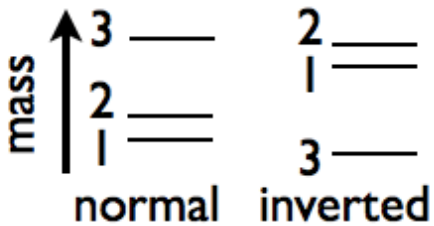

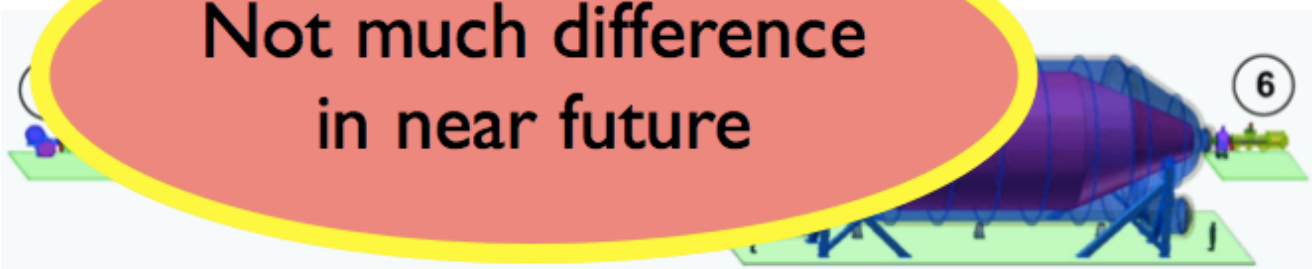

Not much difference
in near future

KATRIN: $m(\nu_e) < 0.2$ eV

Eitel Nucl NPB (PS) 143 (2005)

But what does it mean?

But what does it mean?

Is tribimaximal ~~dead~~ disfavored?

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Is tribimaximal ~~dead~~ disfavored?

Is there physics behind a large theta-13?

But what does it mean?

Is tribimaximal ~~dead~~ disfavored?

Anarchy?
De Gouvêa, Murayama 1204.1249

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$\theta_{13} \neq 0$ @ 7.7σ

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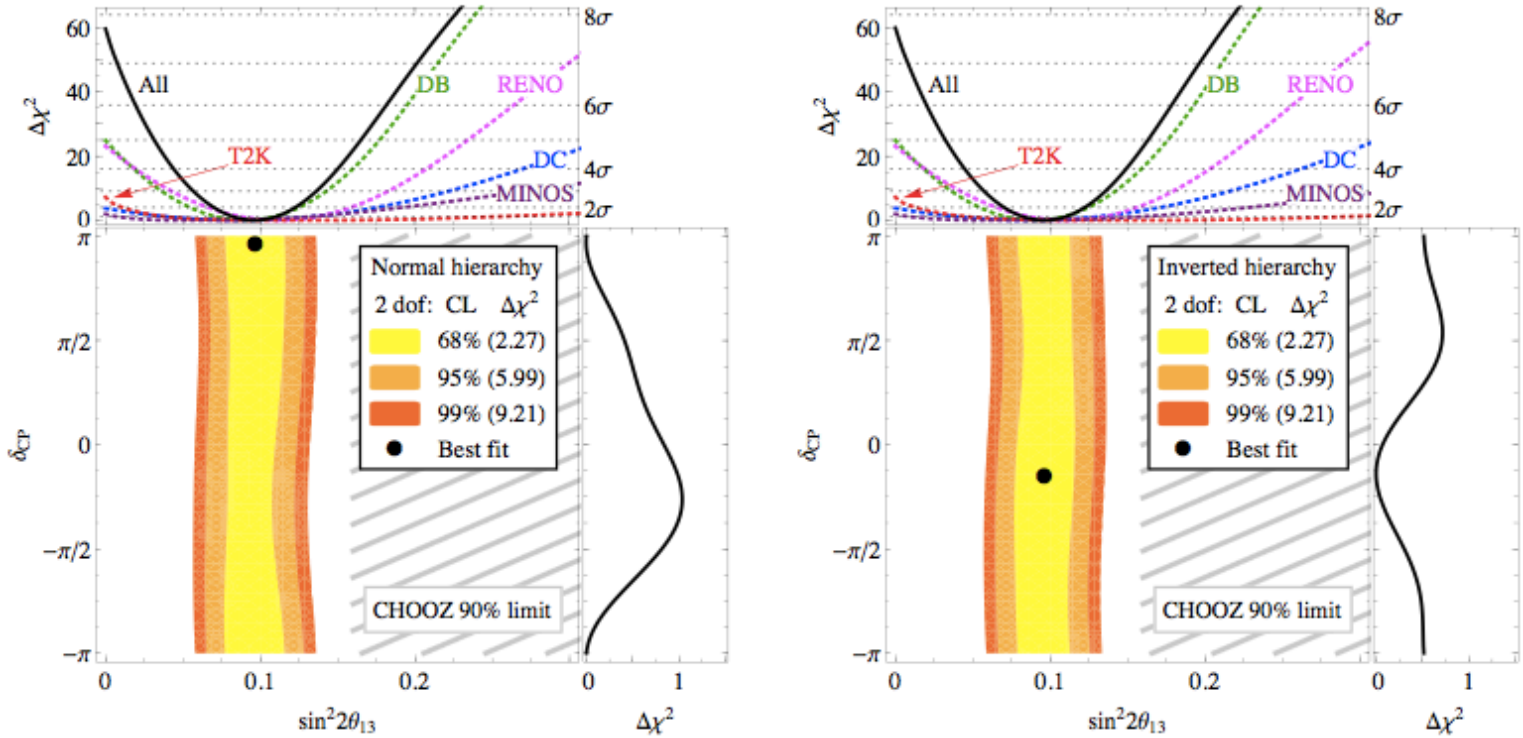

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Thank you!