Global fits from Neutrino Oscillation Experiments

NuFact 2014, 25-30 August 2014, Glasgow, UK

Thomas Schwetz

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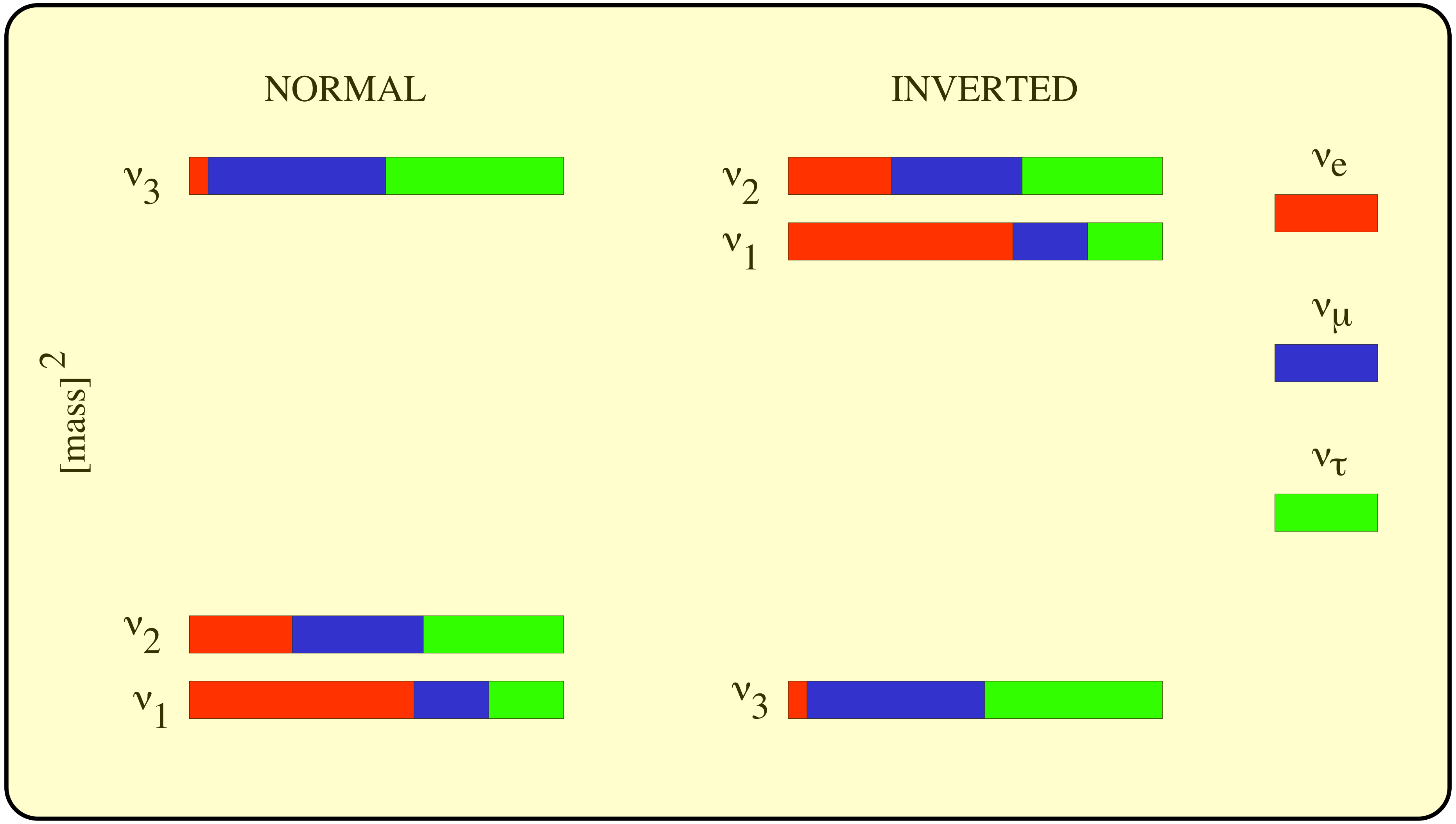
- *Global 3-flavour fit*
  - *Neutrino mass ordering*
  - *CP phase*
  - *Octant of θ_{23}*
- *Sterile neutrinos*

3-flavour oscillations



3-flavour global fit to oscillation data

with C. Gonzalez-Garcia, M. Maltoni

www.nu-fit.org

website with up-to-date restuls from global fit
current version 1.3 (after Neutrino2014)
version 2.0 (plus publication) in preparation

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$	$31.30 \to 35.90$
$\sin^2\theta_{23}$	$0.451^{+0.051}_{-0.026}$	$0.382 \to 0.643$	$0.577^{+0.027}_{-0.035}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.2^{+2.9}_{-1.5}$	$38.2 \to 53.3$	$49.4^{+1.6}_{-2.0}$	$38.6 \to 53.3$	$38.4 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0010}_{-0.0011}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.52^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{\rm CP}/^\circ$	305^{+39}_{-51}	$0 \to 360$	251^{+66}_{-59}	$0 \to 360$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\dfrac{\Delta m^2_{3i}}{10^{-3}\ \rm eV^2}$	$+2.458^{+0.046}_{-0.047}$	$+2.317 \to +2.607$	$-2.448^{+0.047}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

3-flavour global fit to oscillation data

with C. Gonzalez-Garcia, M. Maltoni

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website with up-to-date restuls from global fit
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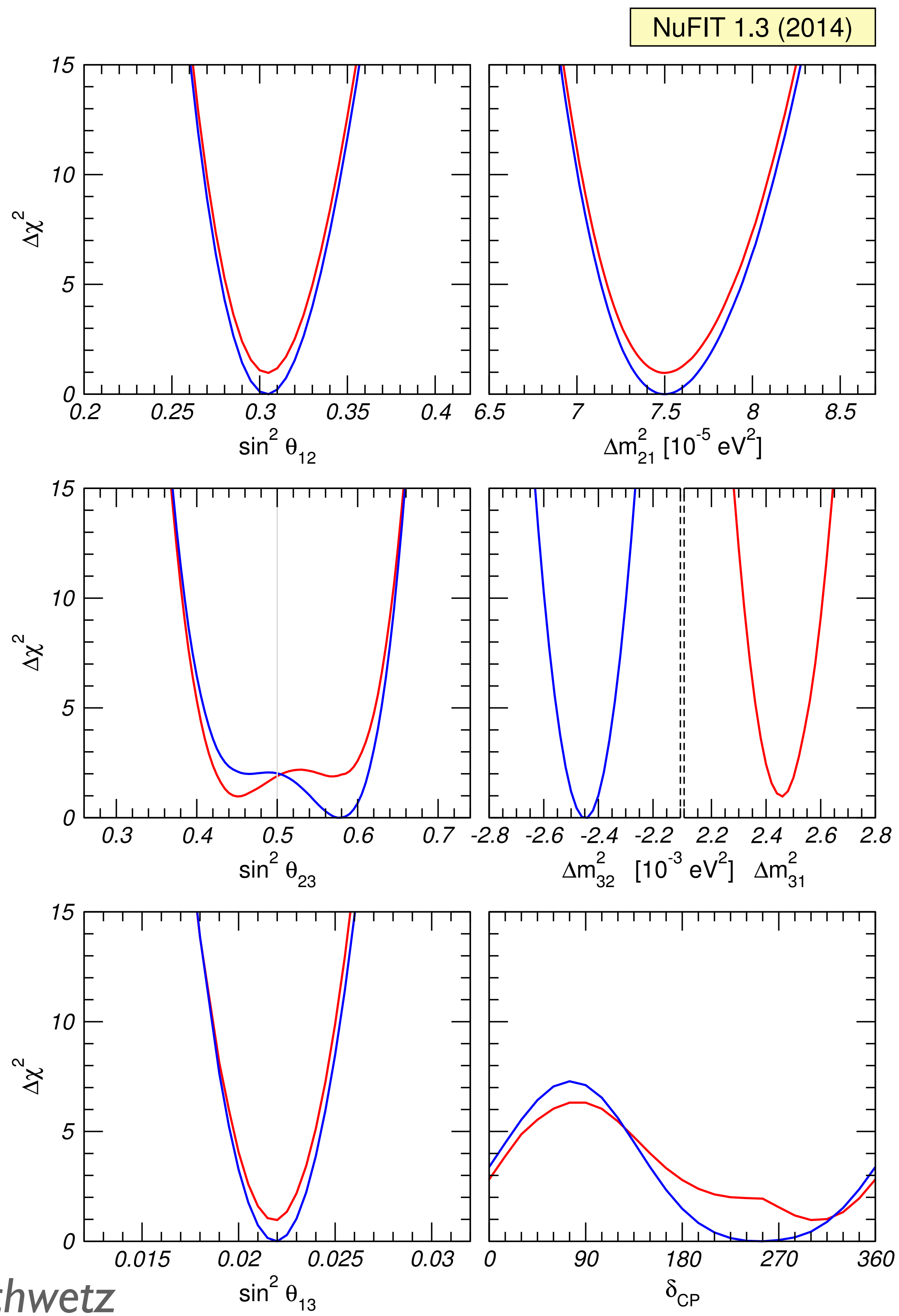
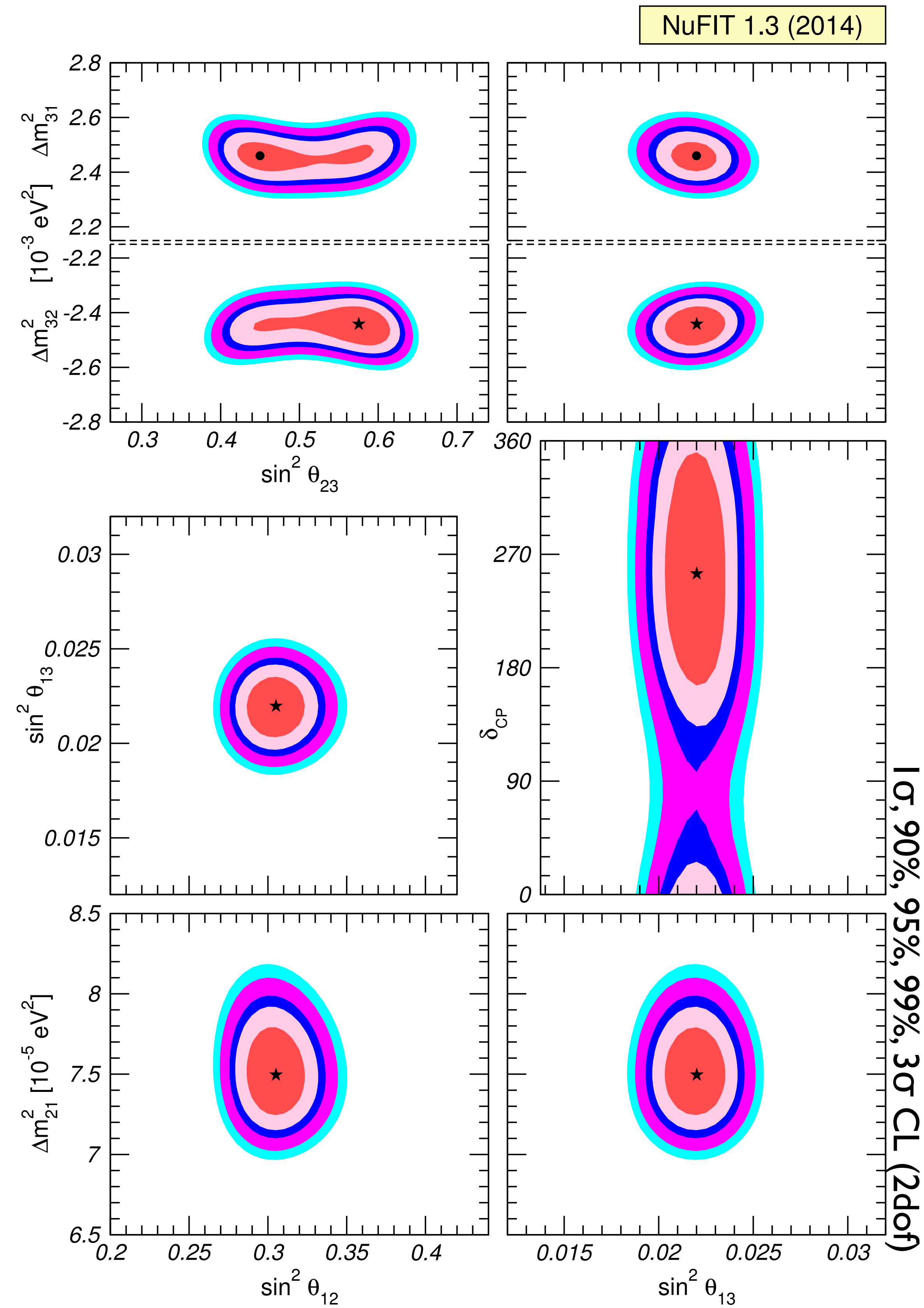
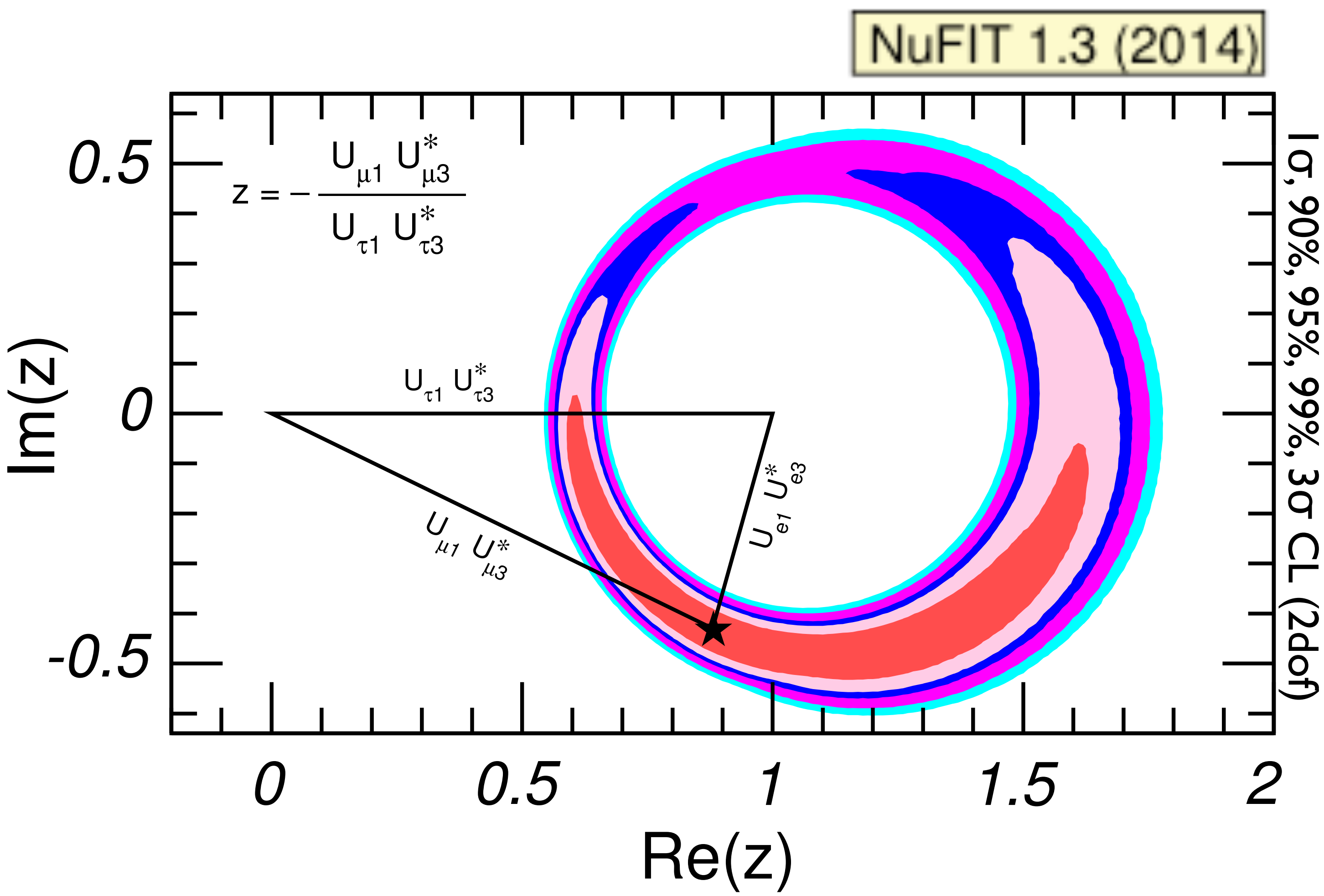
	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering	precision @ 3σ
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range	
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$	4.6° (14%)
$\theta_{12}/^\circ$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$	$31.30 \to 35.90$	
$\sin^2\theta_{23}$	$0.451^{+0.051}_{-0.026}$	$0.382 \to 0.643$	$0.577^{+0.027}_{-0.035}$	$0.389 \to 0.644$	$0.385 \to 0.644$	15° (32%)
$\theta_{23}/^\circ$	$42.2^{+2.9}_{-1.5}$	$38.2 \to 53.3$	$49.4^{+1.6}_{-2.0}$	$38.6 \to 53.3$	$38.4 \to 53.3$	
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0010}_{-0.0011}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$	1.2° (15%)
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.52^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$	
$\delta_{CP}/^\circ$	305^{+39}_{-51}	$0 \to 360$	251^{+66}_{-59}	$0 \to 360$	$0 \to 360$	∞
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$	14%
$\frac{\Delta m^2_{3i}}{10^{-3}\ \mathrm{eV}^2}$	$+2.458^{+0.046}_{-0.047}$	$+2.317 \to +2.607$	$-2.448^{+0.047}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$	11%

3-flavour global fit to oscillation data





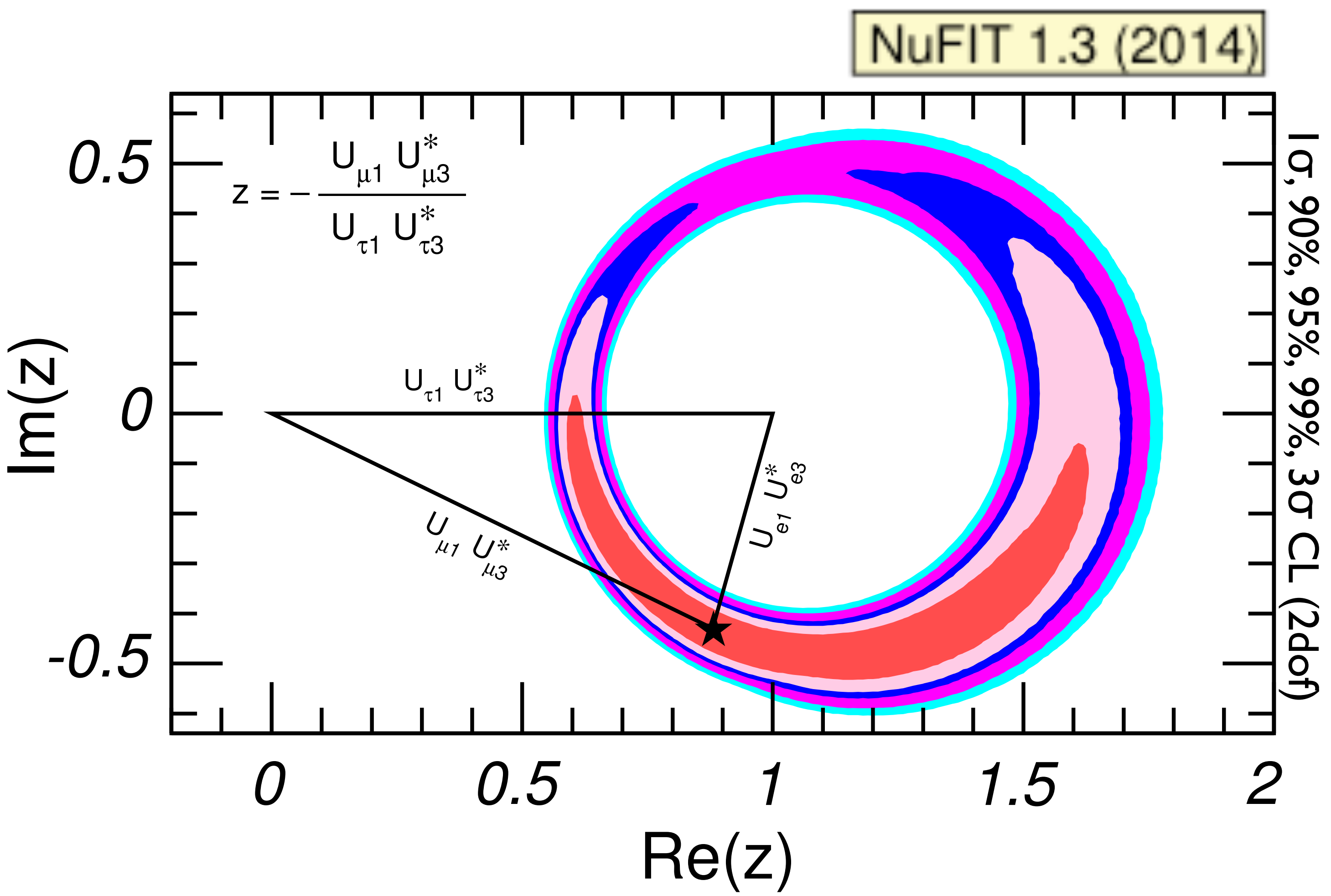
Leptonic unitarity triangle

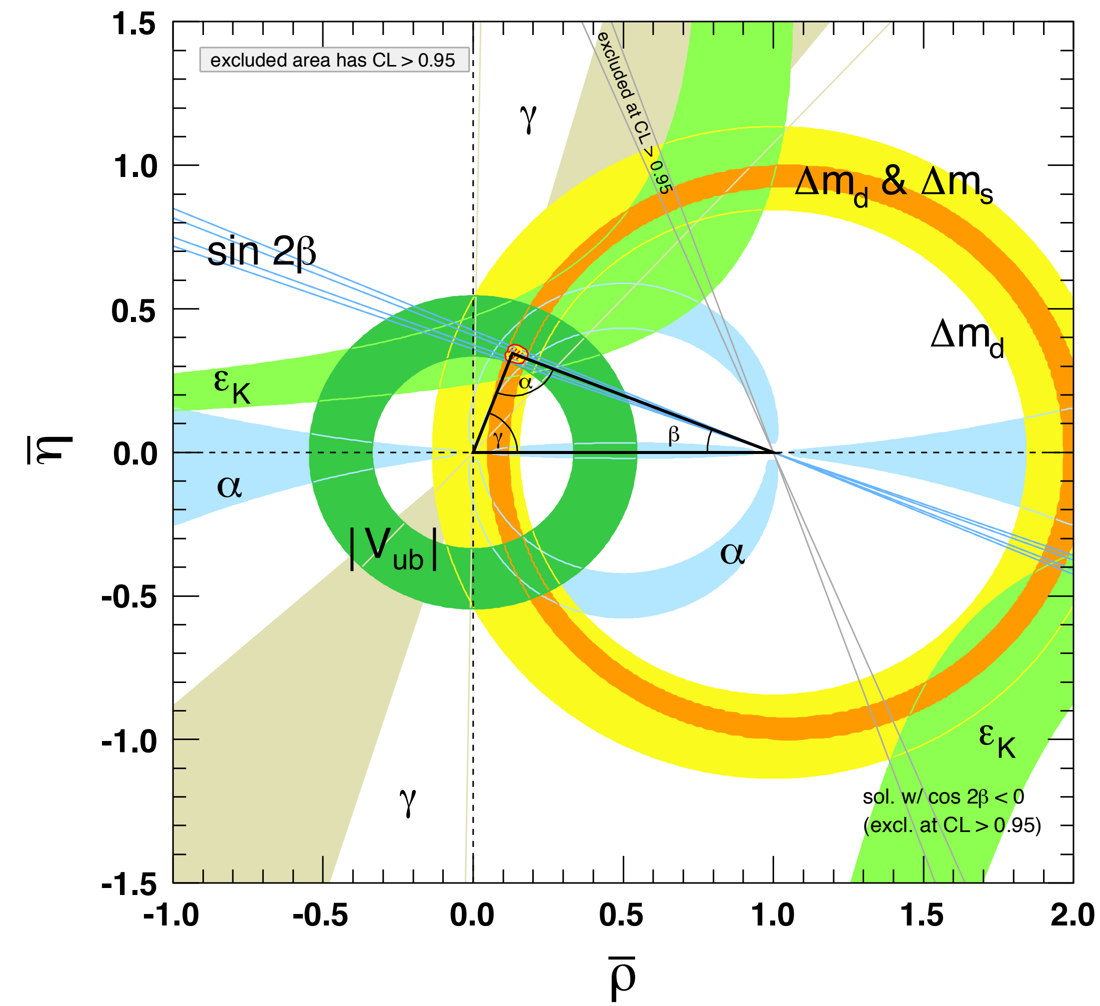


Farzan, Smirnov, hep-ph/0201105
Smirnov, 0810.2668

- *unitarity is always assumed (no test of unitarity!)*

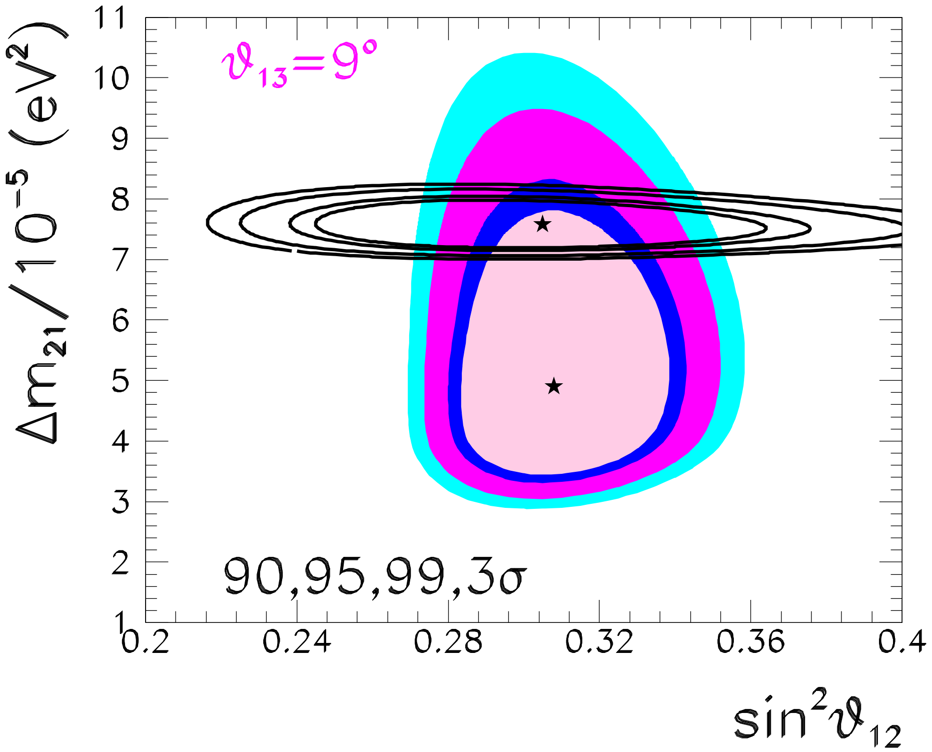
Leptonic unitarity triangle

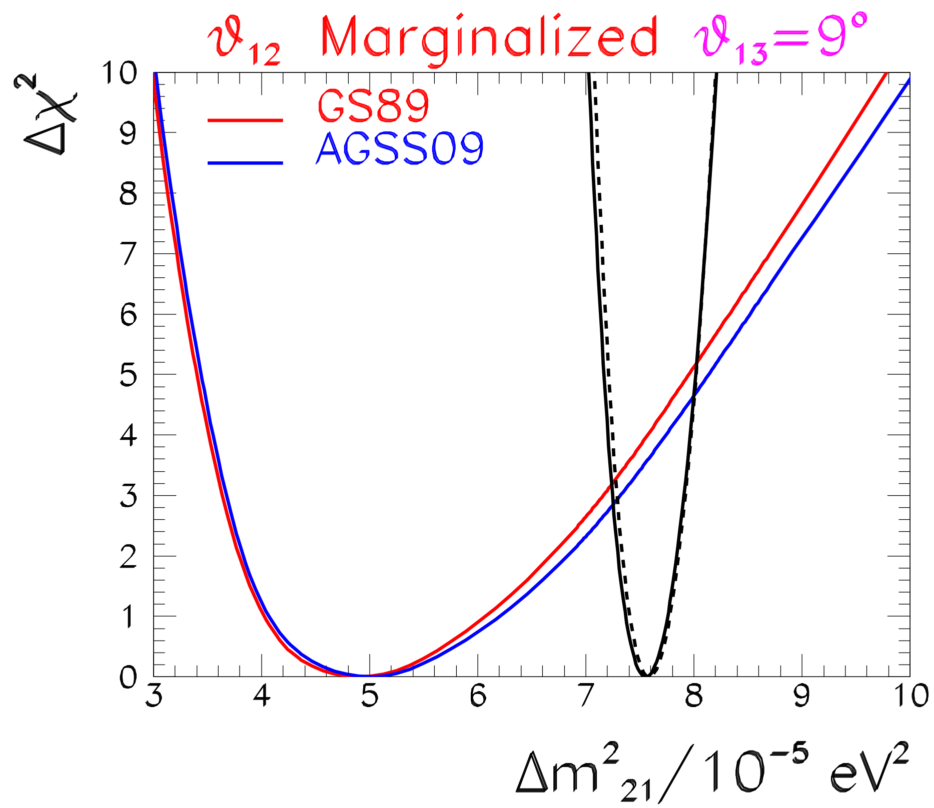


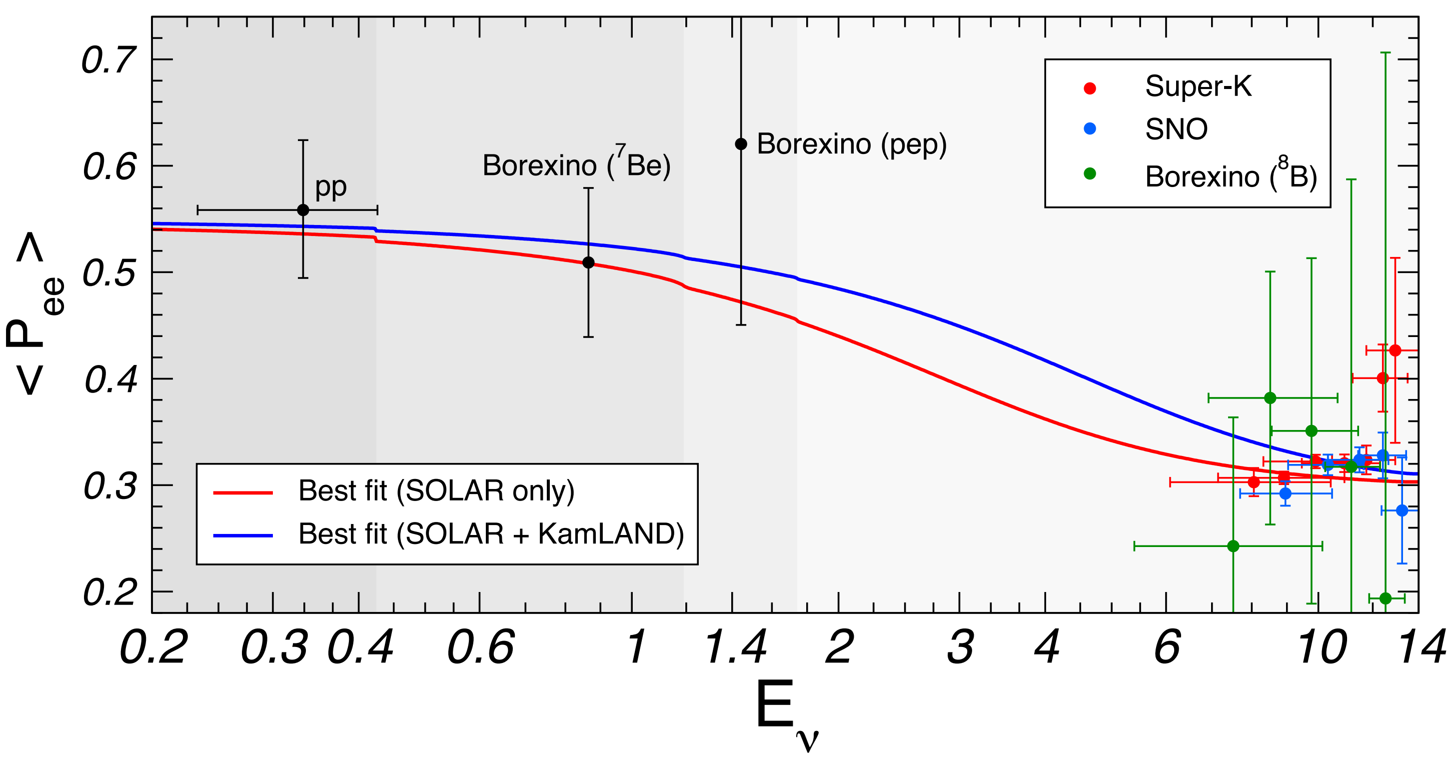


- *still far from knowledge we have on UT in quark sector*

1-2 sector





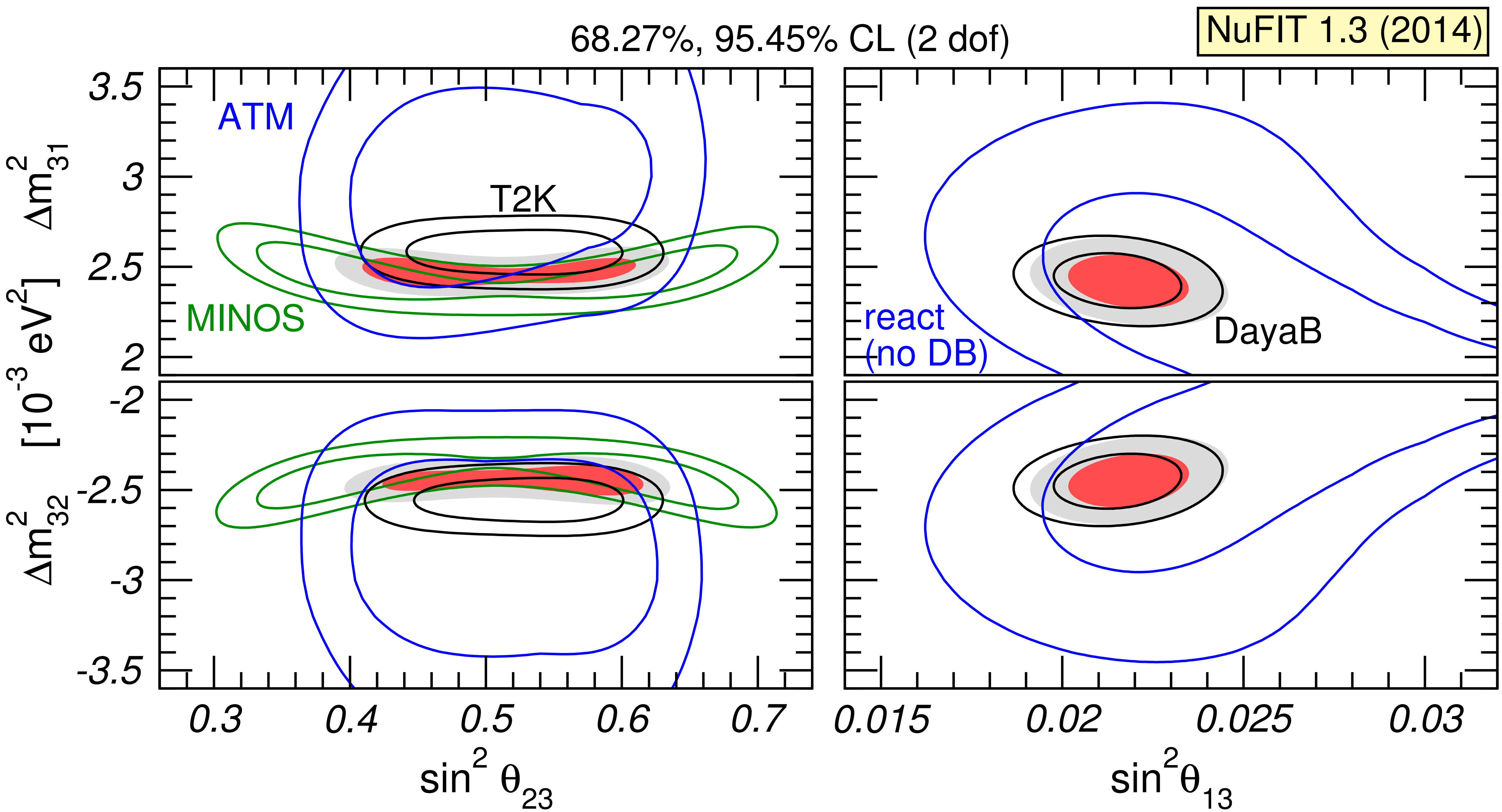


"tension" between solar and Kamland at 2σ level ($\Delta\chi^2$ = 4)

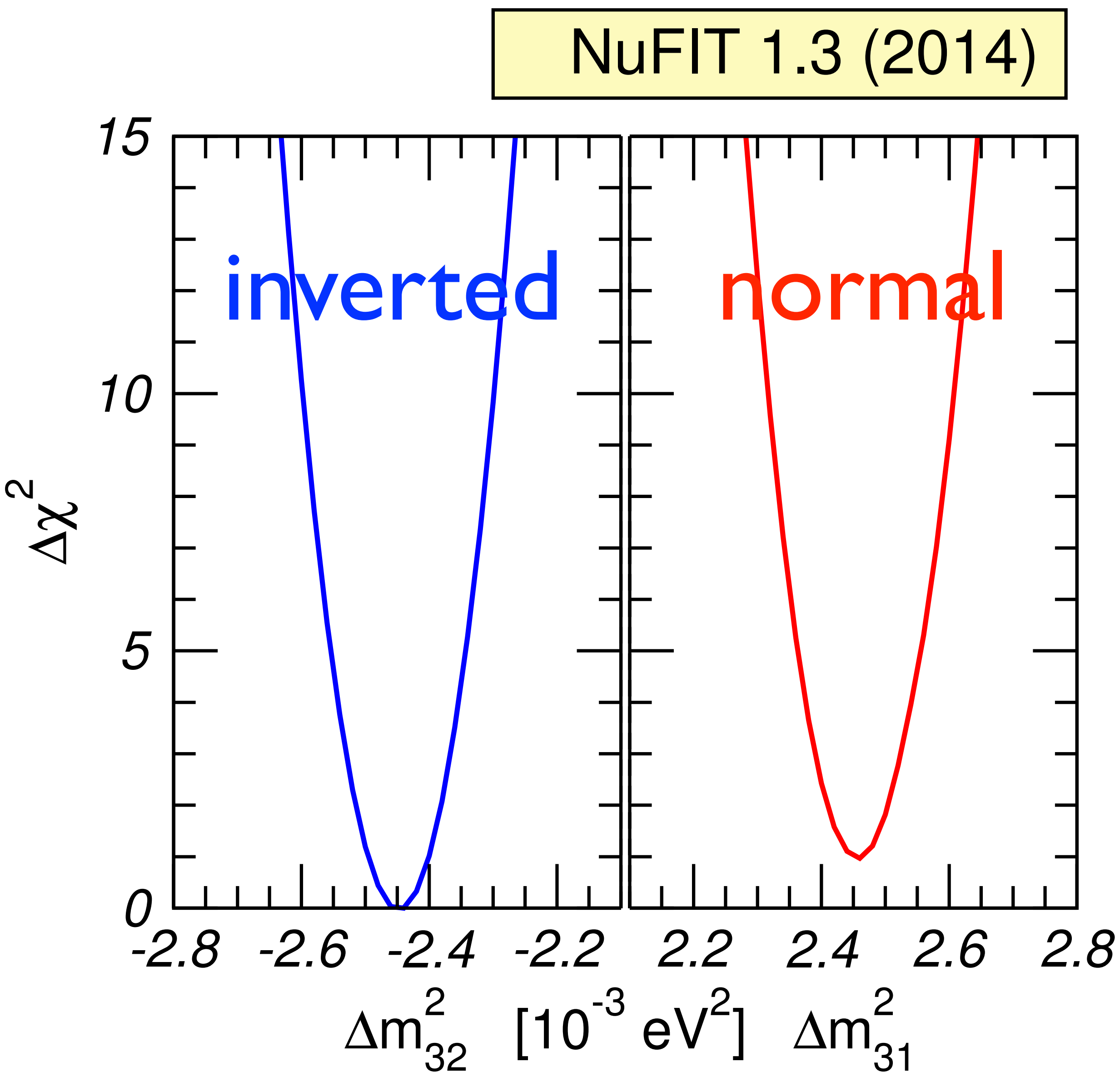
missing up-turn of solar neutrino spectrum in SNO and SK

1-3 sector

consistent determination of $|\Delta m^2_{31}|$ from LBL, ATM, and Daya Bay



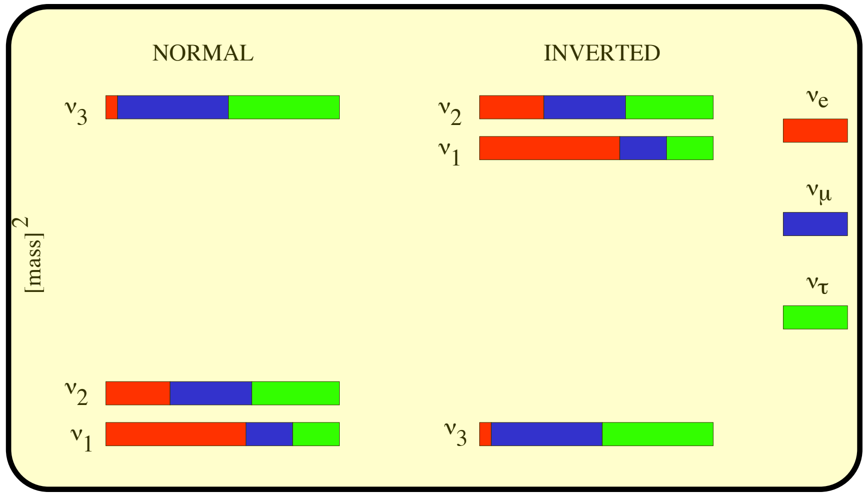
Neutrino mass ordering

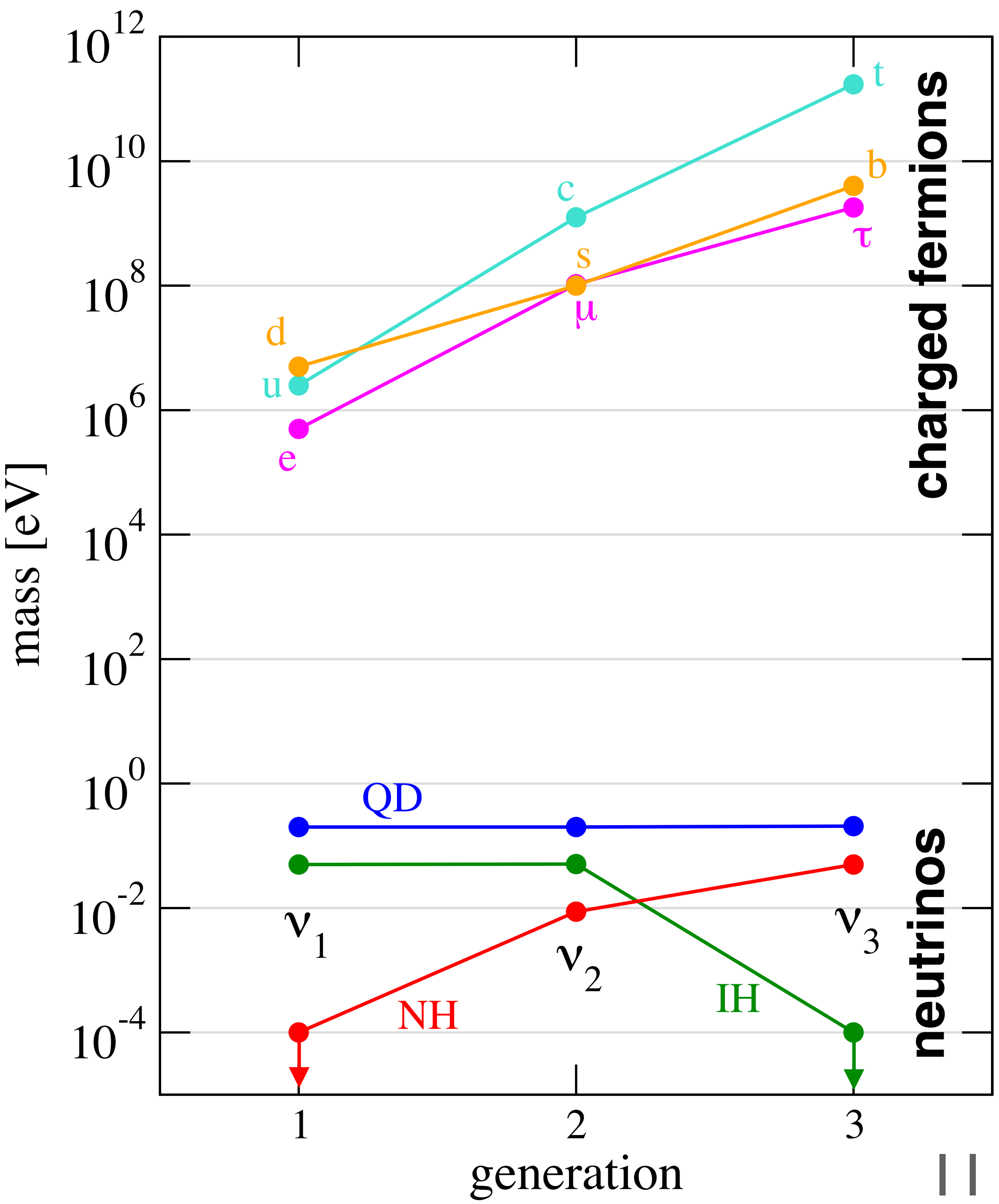


almost complete degeneracy in present data

normal versus abnormal

for inverted ordering lepton mixing is very different from quarks:

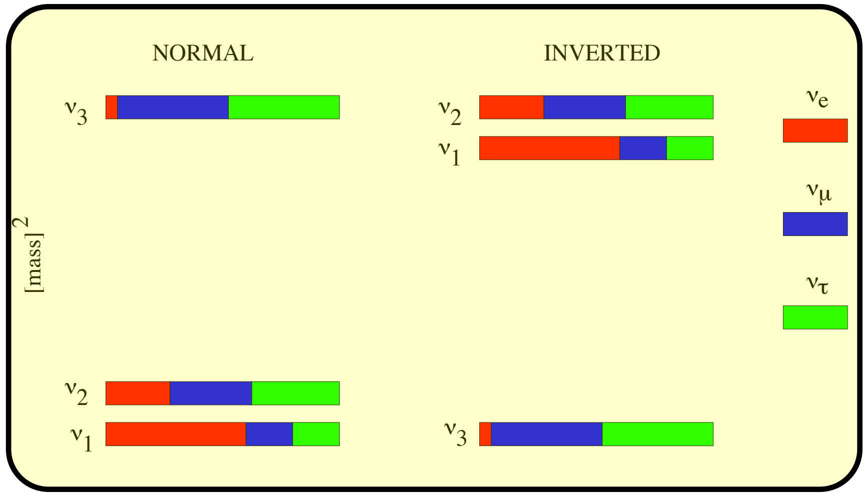


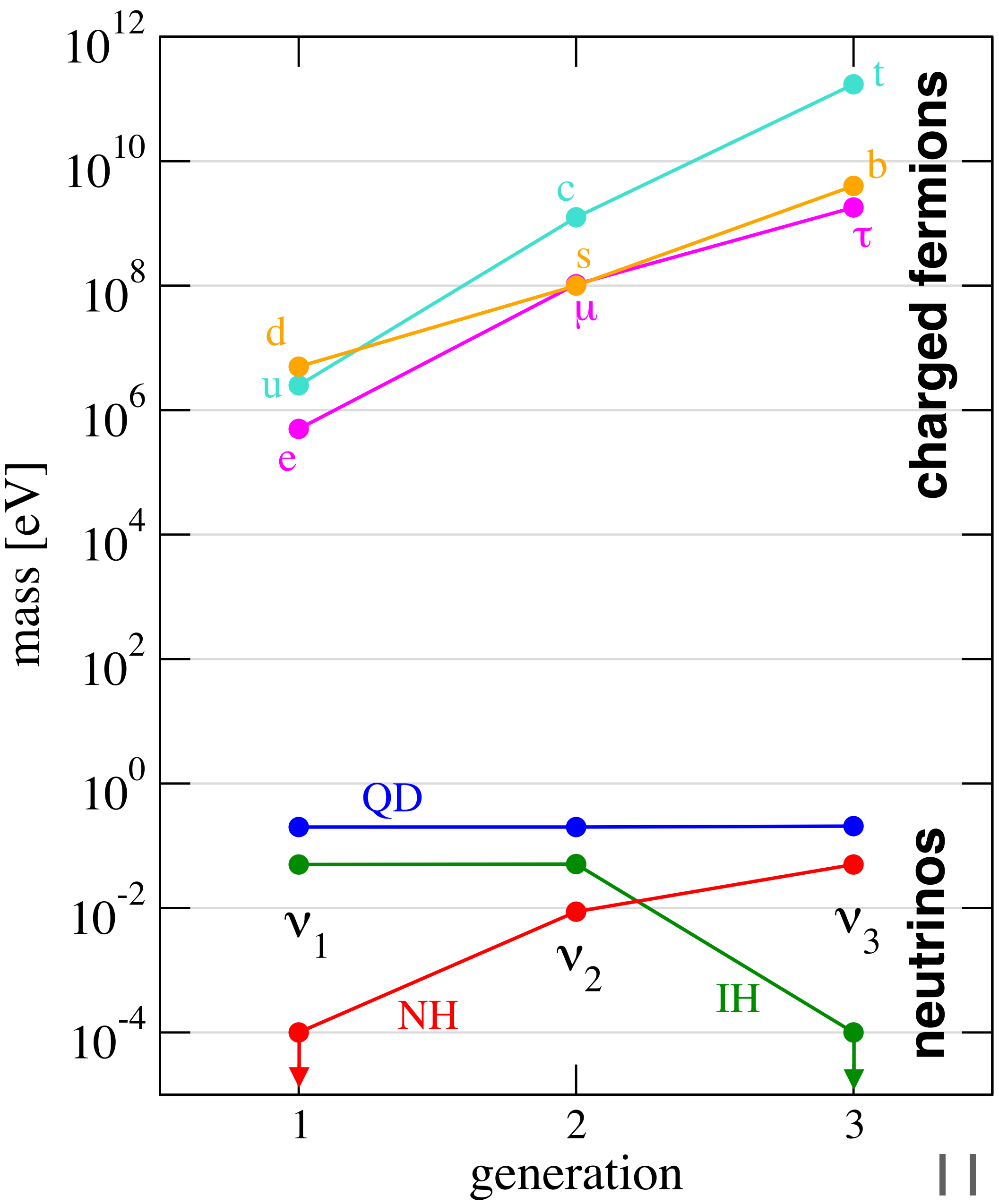


normal versus abnormal

for inverted ordering lepton mixing is very different from quarks:

- *the neutrino mass state mostly related to the 1st generation is not the lightest*





normal versus abnormal

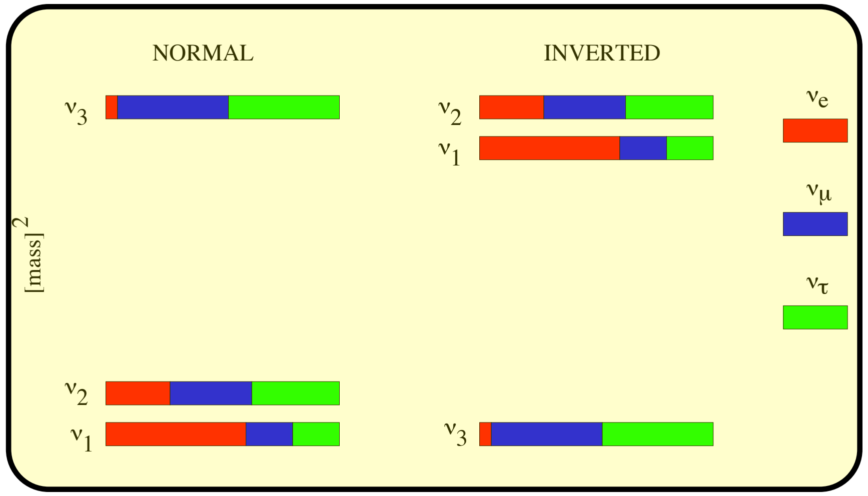
for inverted ordering lepton mixing is very different from quarks:

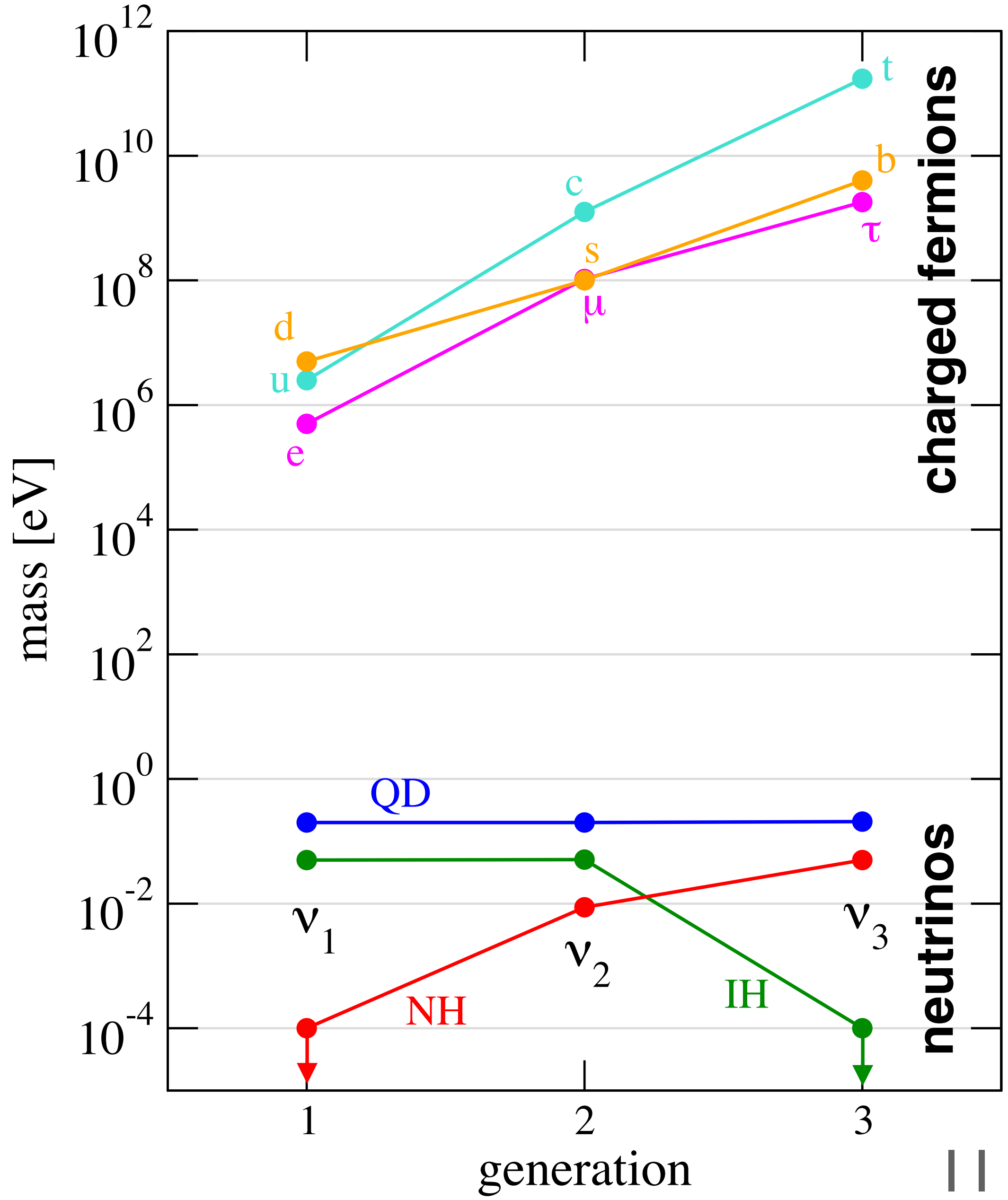
- *the neutrino mass state mostly related to the 1st generation is not the lightest*
- *there is strong degeneracy between at least two mass states*

$$deg \equiv \frac{m_2 - m_1}{\overline{m}} = 2\frac{\Delta m^2_{21}}{(m_1+m_2)^2}$$

$$\approx \frac{1}{2}\frac{\Delta m^2_{21}}{|\Delta m^2_{31}| + m_3^2} \leq \frac{1}{2}\frac{\Delta m^2_{21}}{|\Delta m^2_{31}|}$$

$$1.3 \times 10^{-3}\left(\frac{\sum m_i}{0.5\,\mathrm{eV}}\right)^{-2} \leq deg \leq 1.8 \times 10^{-2}$$





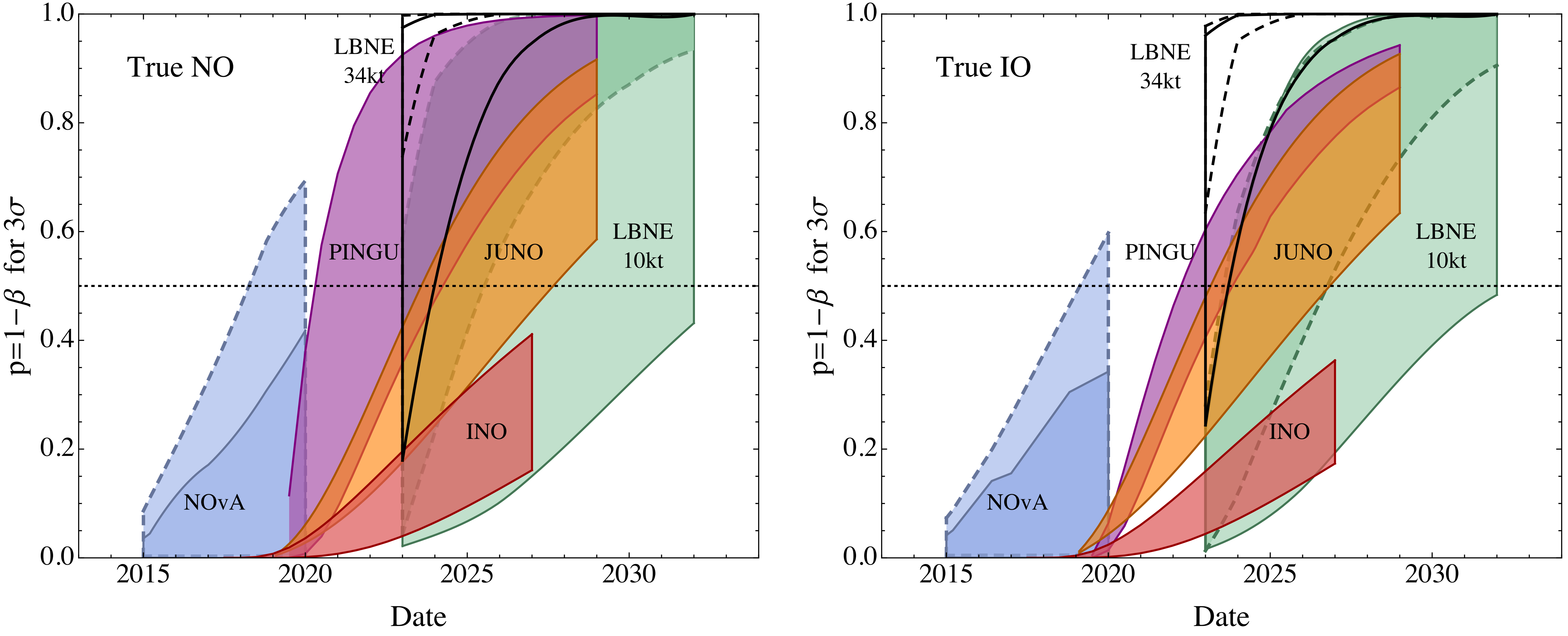
How to determine the mass ordering?

- *Matter effect in the 1-3 sector*
  - *long-baseline accelerator experiments*
    NOvA, LBNE, LBNO, ESS-SB, NuFact
  - *atmospheric neutrinos INO, PINGU, ORCA, HyperK*
- *Interference of oscillations with Δm^2_{21} and Δm^2_{31}*
  - *Reactor experiment at ~60 km JUNO, RENO50*
- *other methods: cosmology, supernova,...*

Sensitivity comparison

Blennow, Coloma, Huber, TS, 1311.1822
talk by M. Blennow, and many more

probability to exclude wrong ordering at 3σ
(“representative” selection of experiments)



Sensitivity comparison

Blennow, Coloma, Huber, TS, 1311.1822
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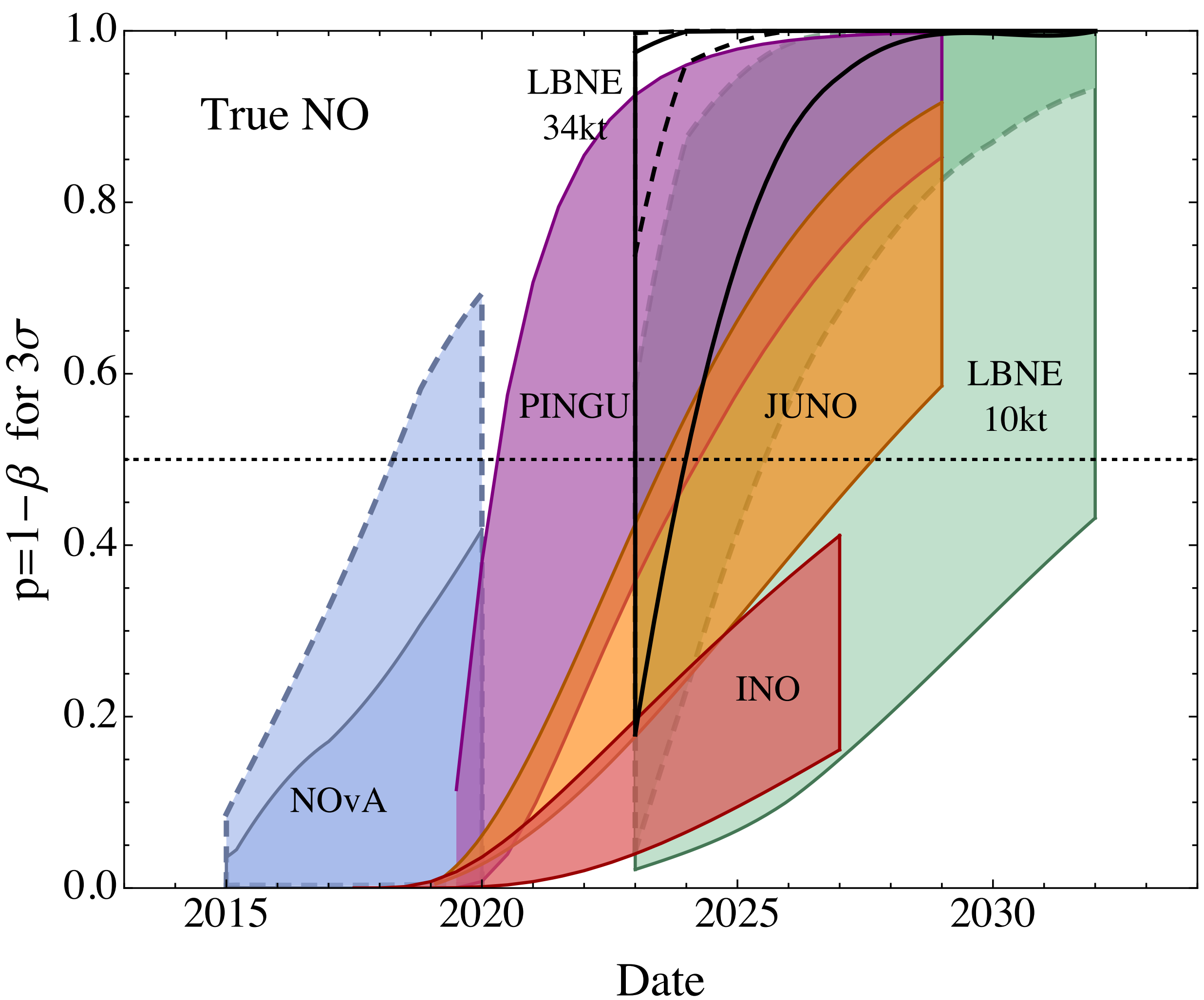
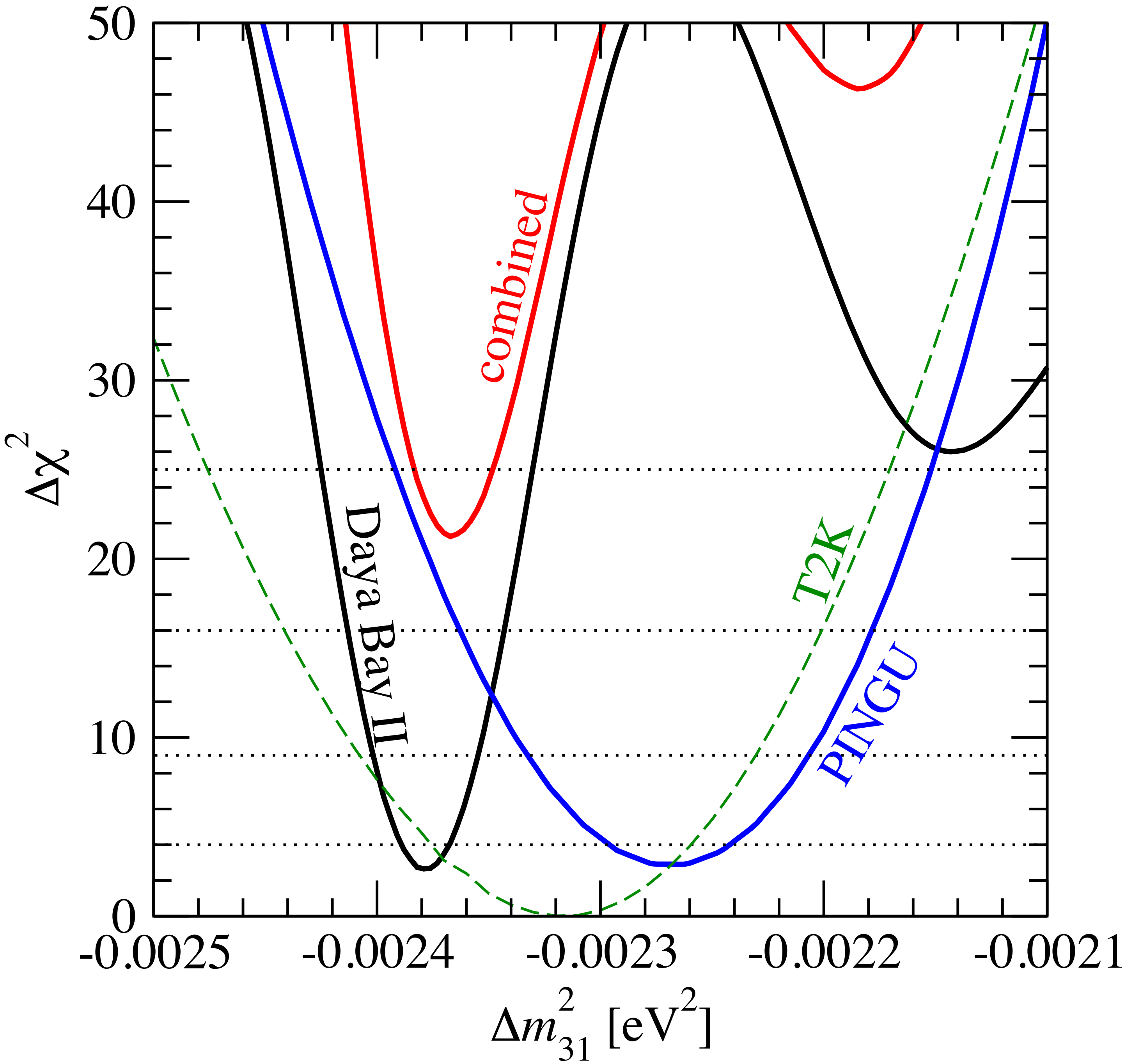


- *experimental parameters (event reconstruction abilities / energy scale) crucial (esp for PINGU, JUNO,...)*
- *LBL experiments: sens. depends on true values of θ_{23} and δ_{CP}*
- *atmospheric neutrino exps.: true value of θ_{23}*

Explore synergy between different experiments

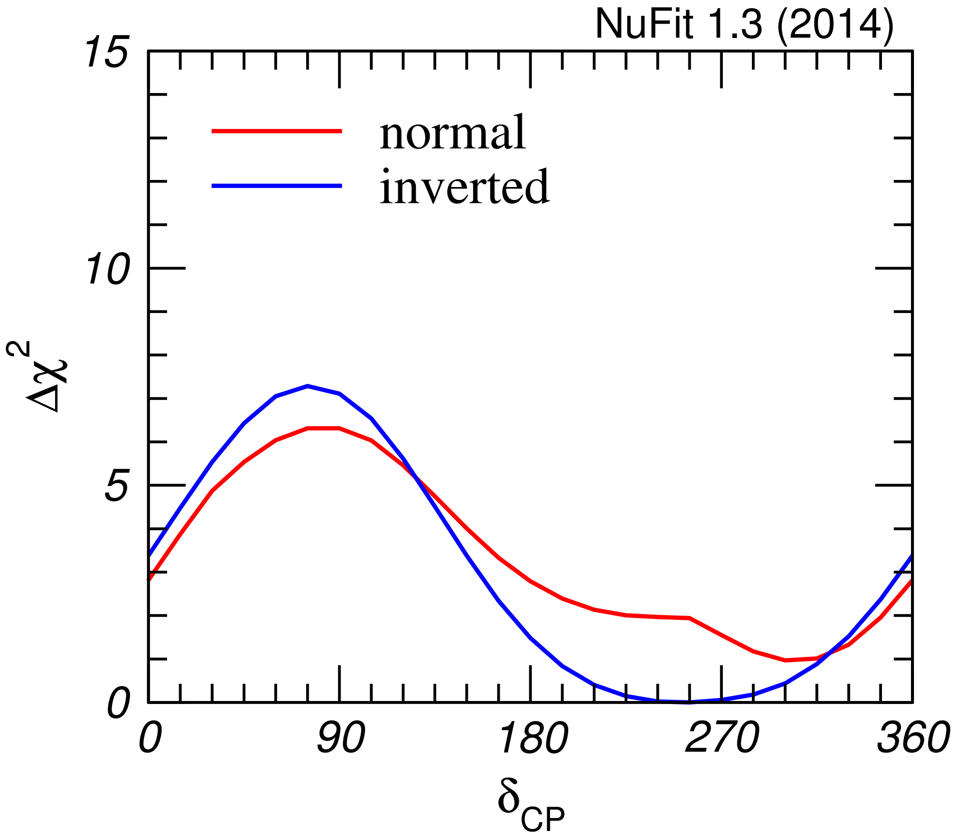


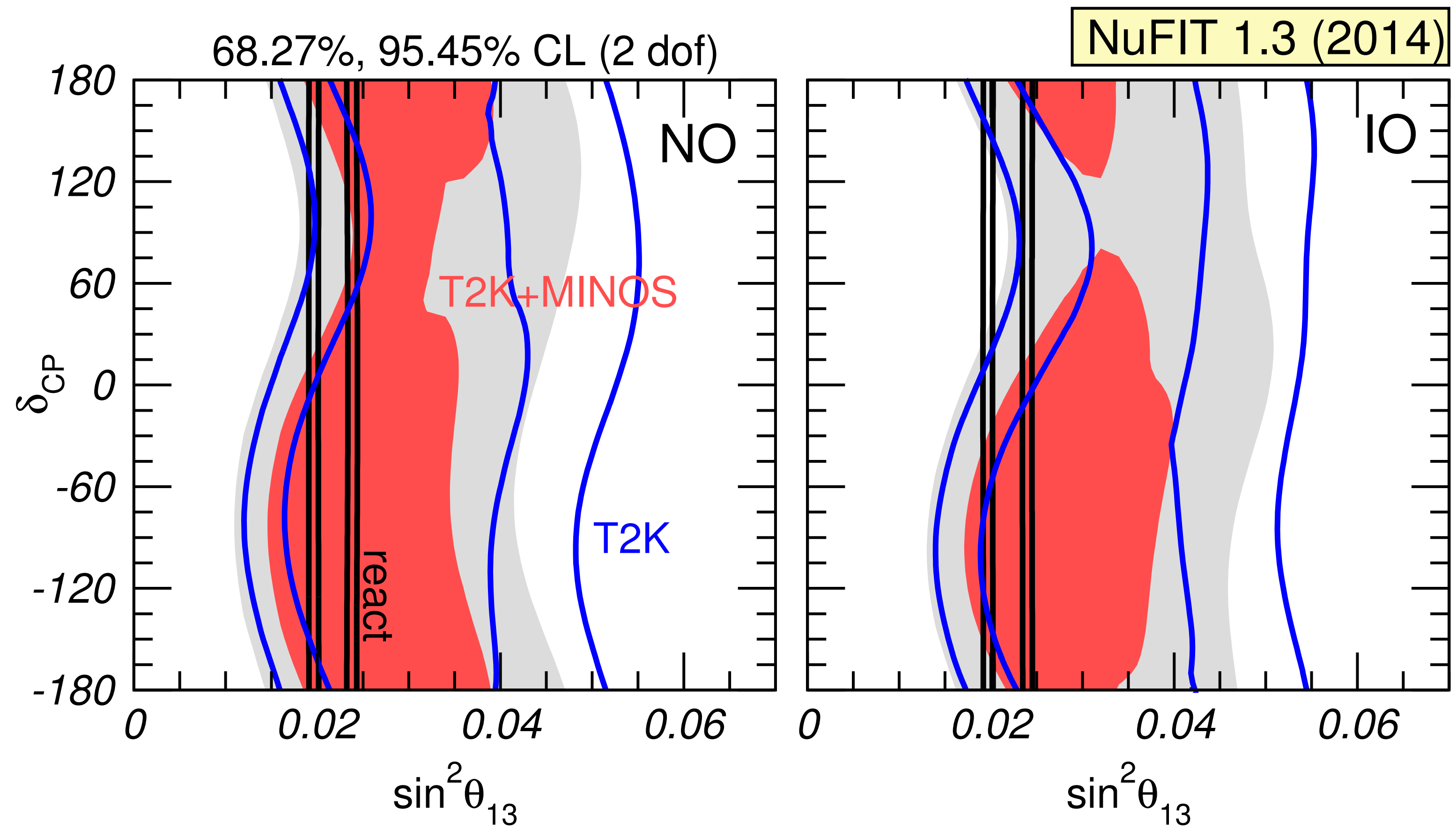
combine measurements of $|\Delta m^2_{31}|$ from PINGU and JUNO

Blennow, Schwetz, arXiv:1306.3988

requires more careful investigations wrt to energy scale uncertainties - both for JUNO and PINGU!

CP phase

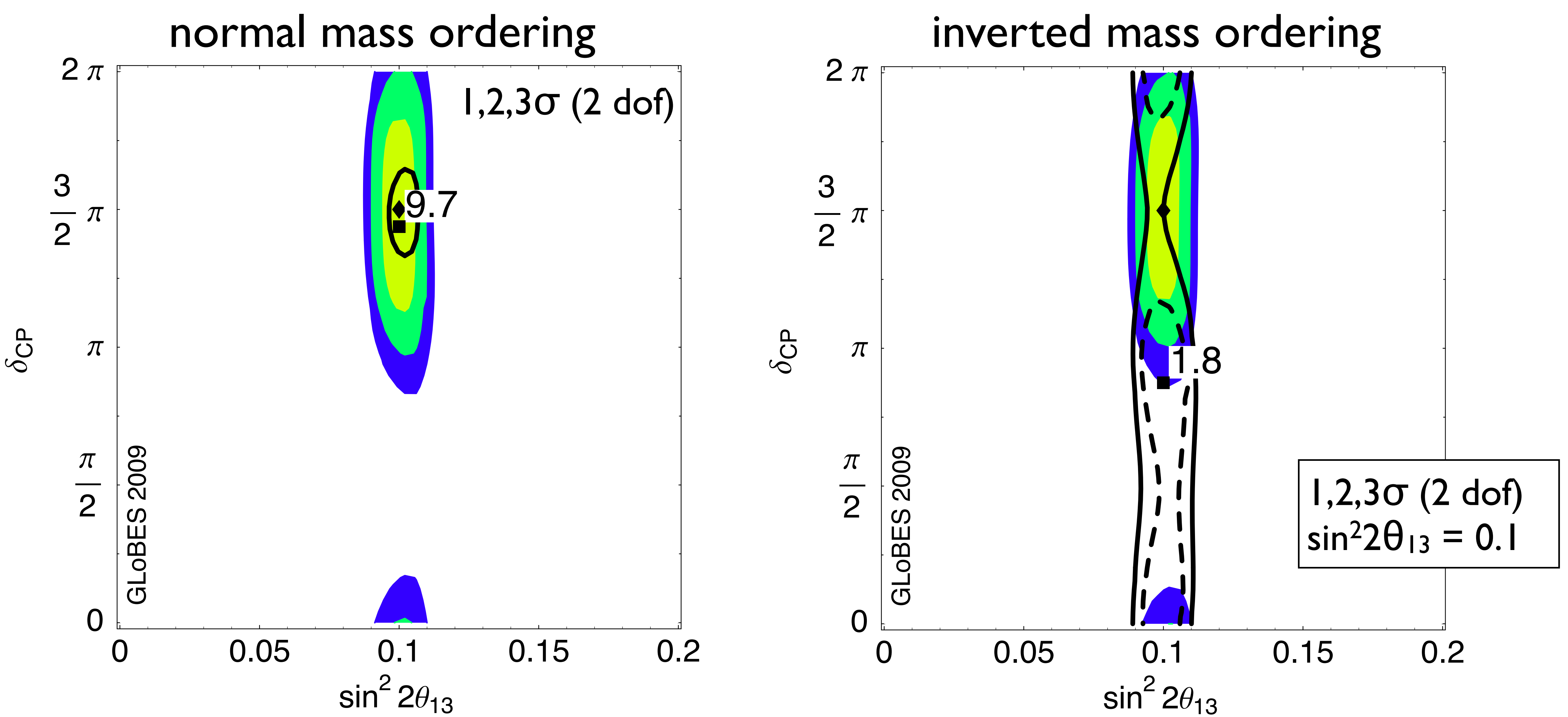




values of δ_{CP} ~ 90° disfavoured with $\Delta\chi^2$ ~ 7 emerges from interplay of T2K and reactor data

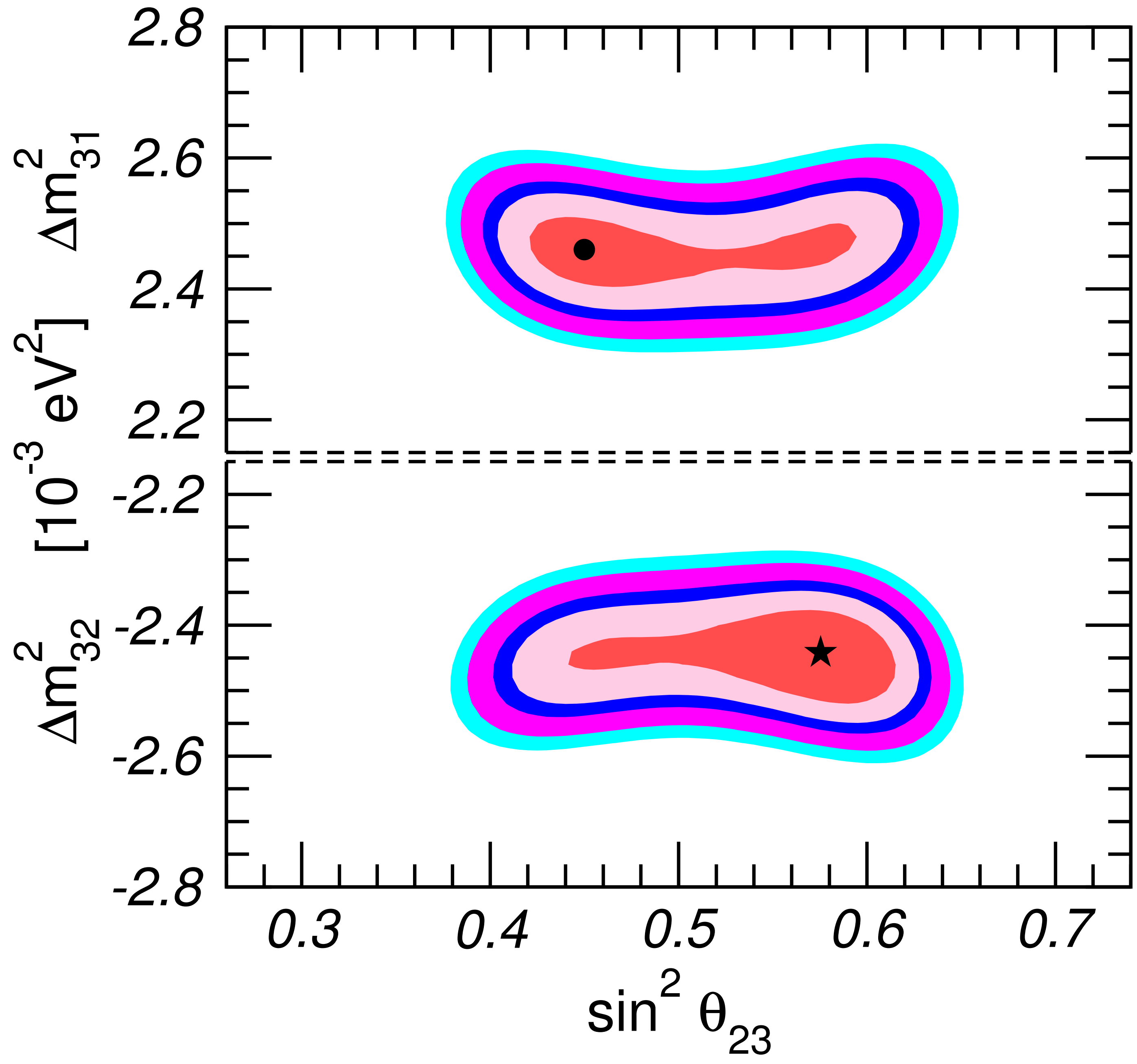
Let's suppose that δ_{CP} = 270°

global fit ~2020: T2K, NOvA, DayaBay



Huber, Lindner, TS, Winter, 0907.1896

Octant of θ_{23}



Interplay of Reactor + LBL appearance data

$$P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{(1-A)^2}$$
$$+ \sin 2\theta_{13}\, \hat{\alpha}\, \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\Delta + \delta_{\rm CP})$$
$$+ \hat{\alpha}^2 \cos^2\theta_{23} \frac{\sin^2 A\Delta}{A^2}$$

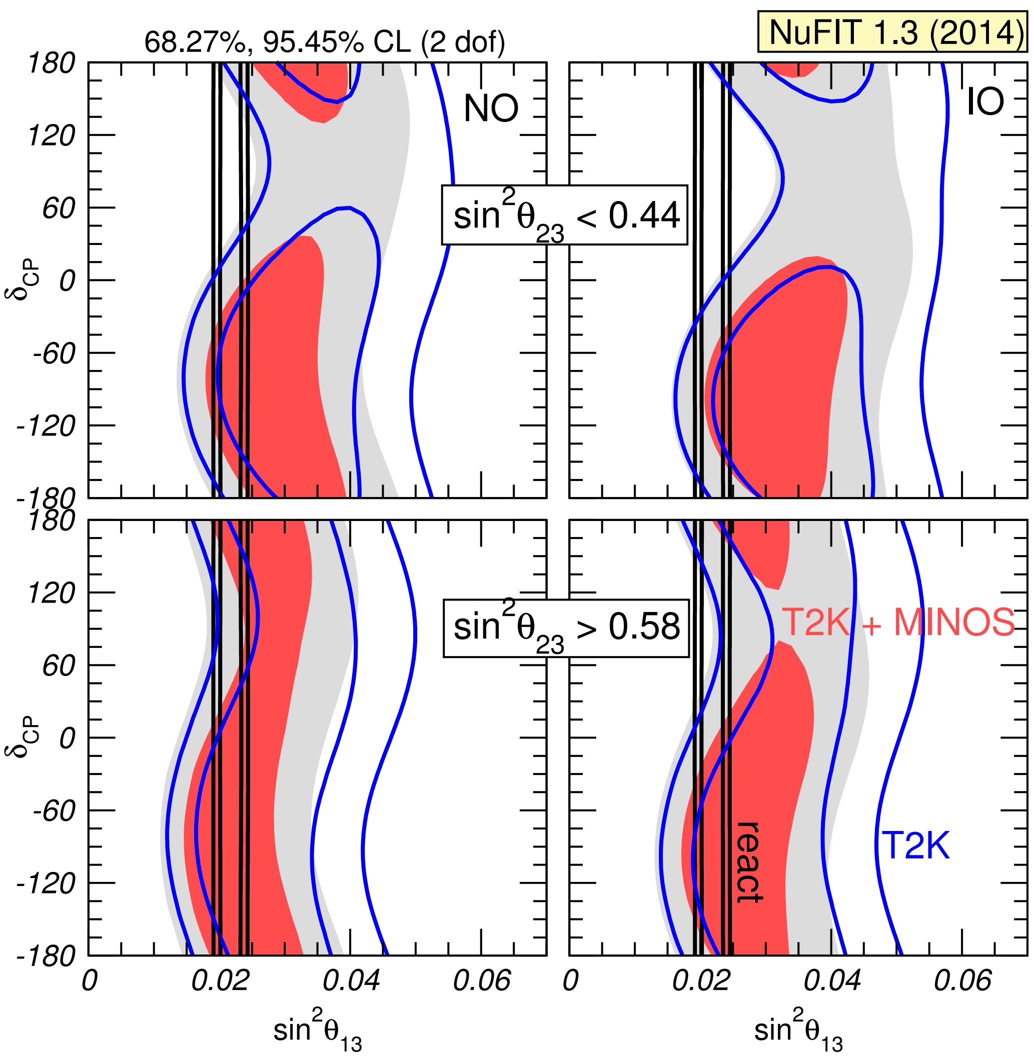
with

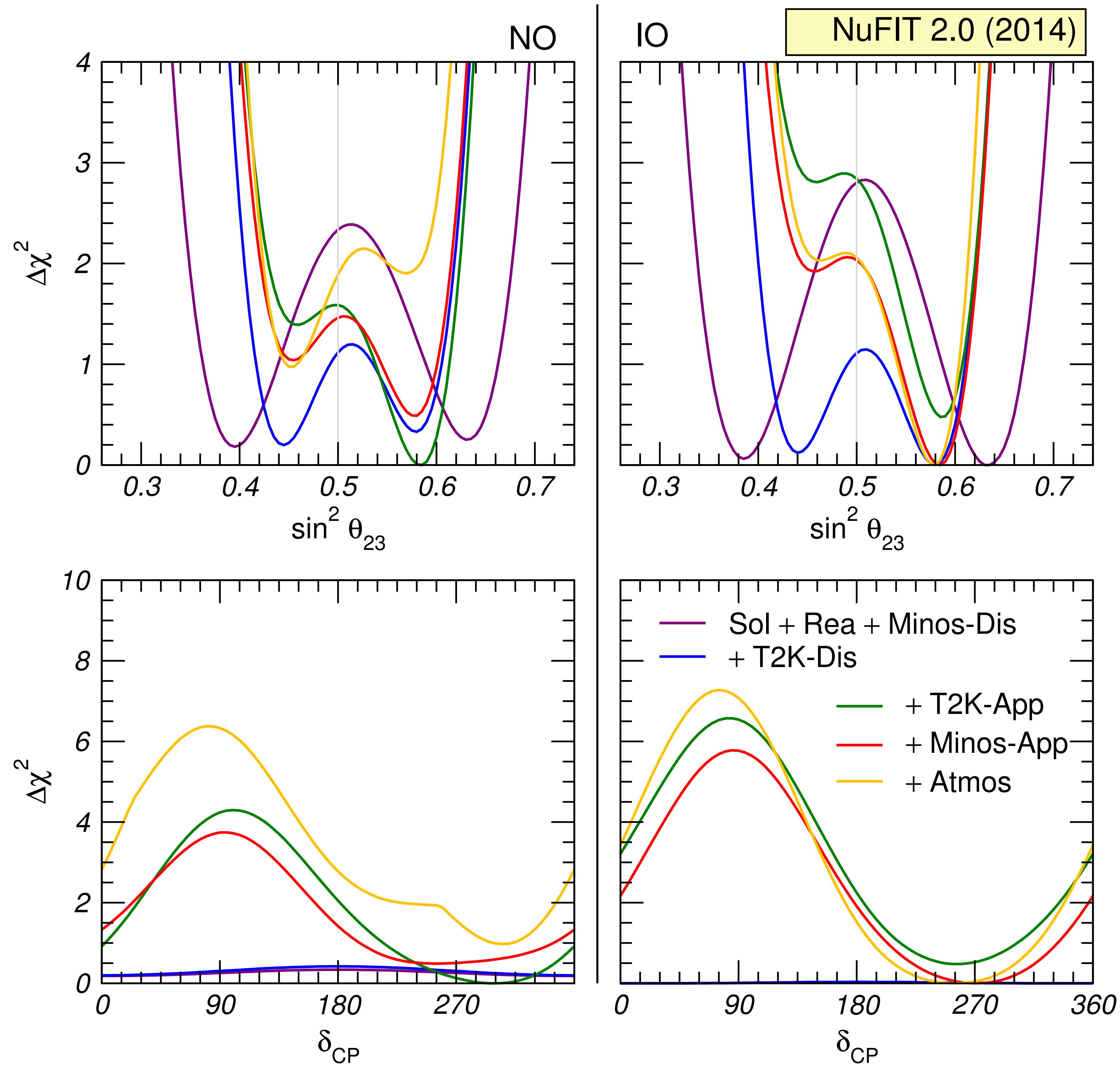
$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}, \quad \hat{\alpha} \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sin 2\theta_{12}, \quad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}$$

- *for large θ_{13} the leading term depends on octant*
- *beam+reactor combination may be sensitive to octant*

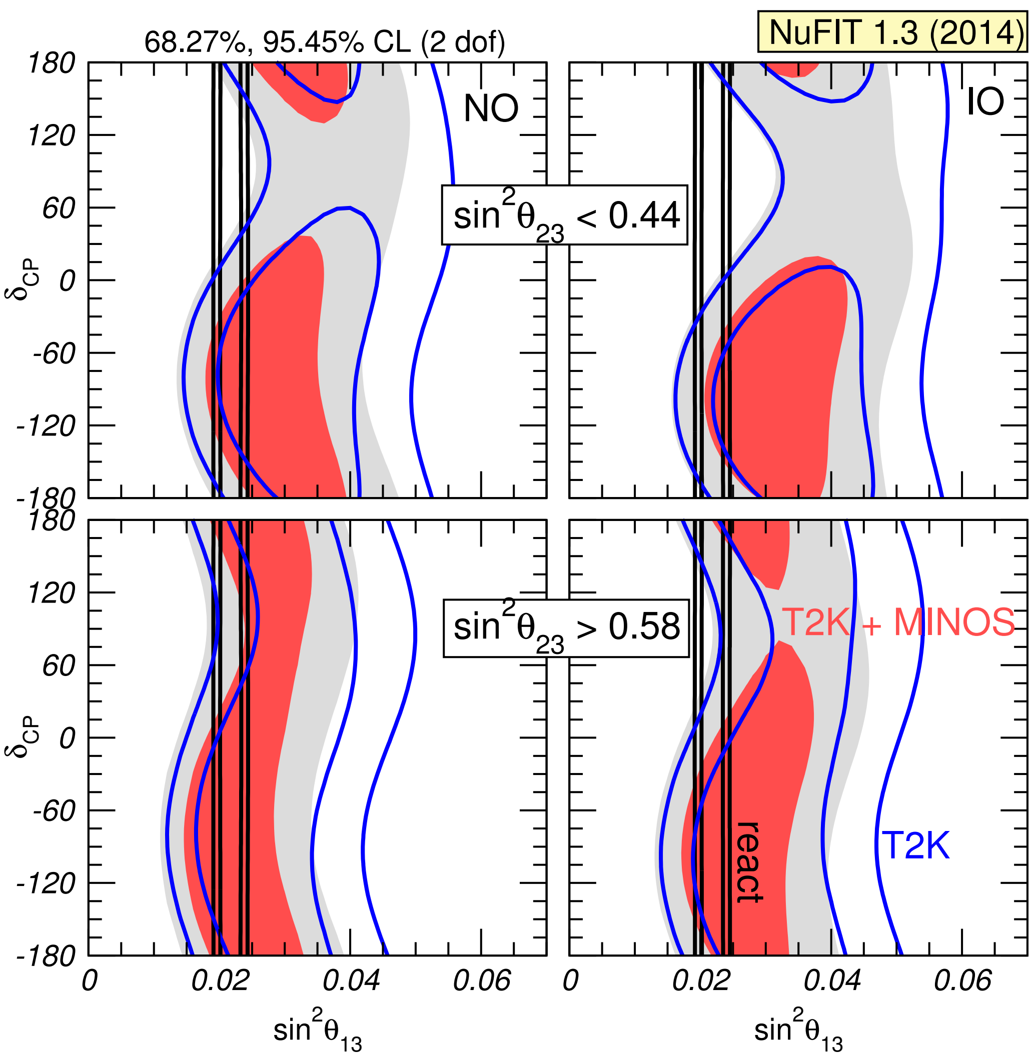
Minakata et al. hep-ph/0211111; McConnel, Shaevitz, hep-ex/0409028

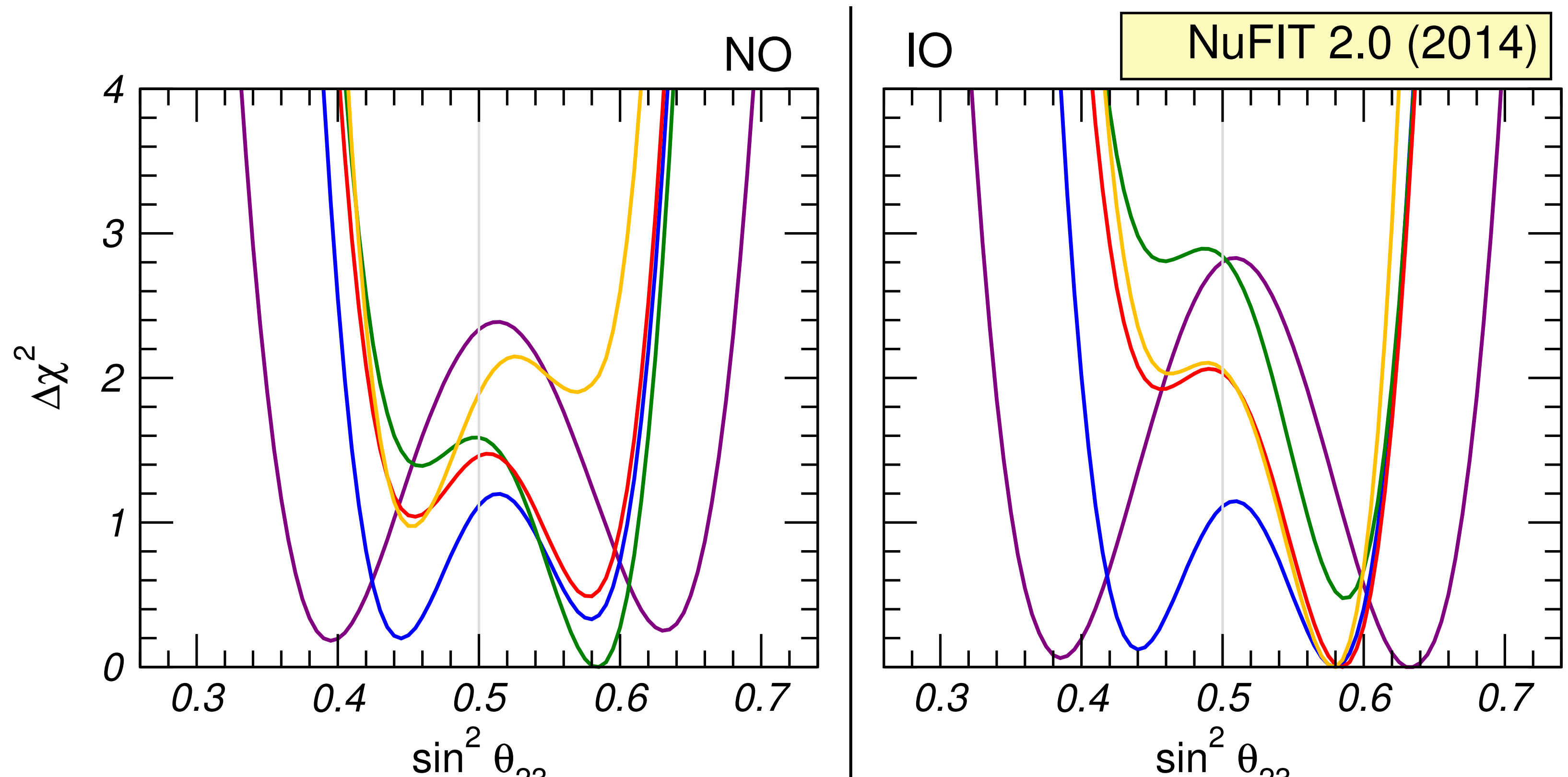
CP phase vs octant of θ_{23}





CP phase vs octant of θ_{23}



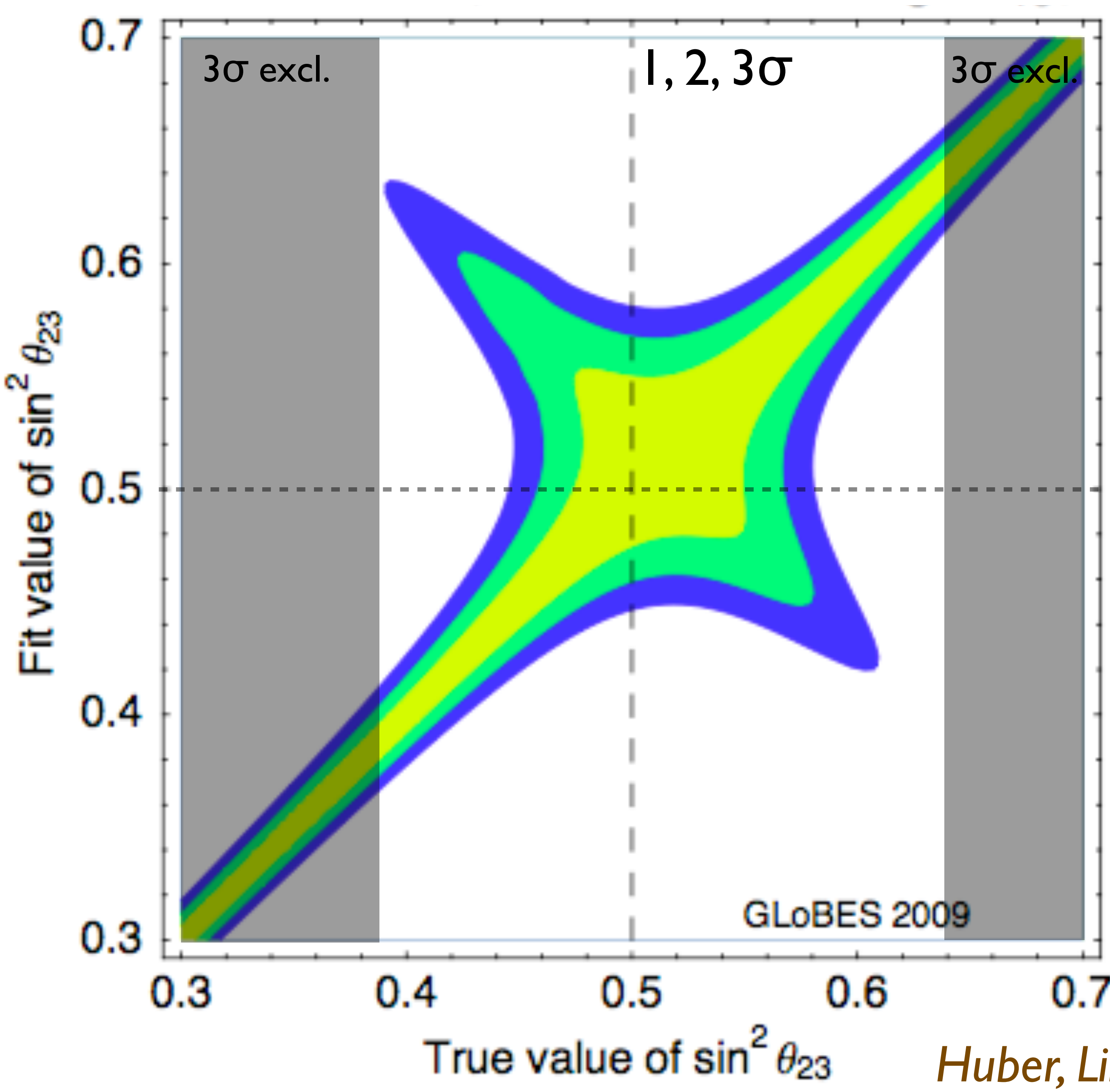


- *some "tendencies" appear at low significance ($\Delta\chi^2 \sim 3$)*
- *Reactor + LBL appearance prefer second octant*
- *for NO atmospheric data pushes best fit point to first octant*

T. Schwetz

Global fit ~2020 - θ_{23} octant

T2K, NOvA, DayaBay

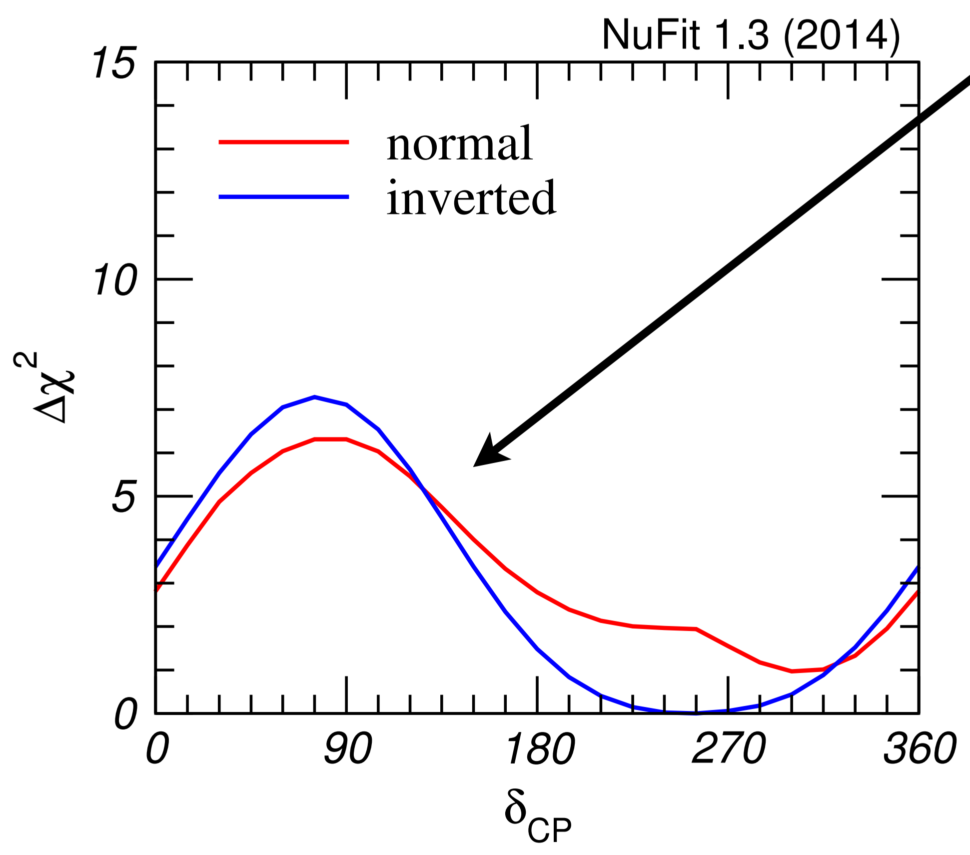


$\sin^2 2\theta_{13} = 0.1$

$\delta_{CP} = 0$
(may change for other values)

Huber, Lindner, TS, Winter, 0907.1896

CP phase - what is the CL?



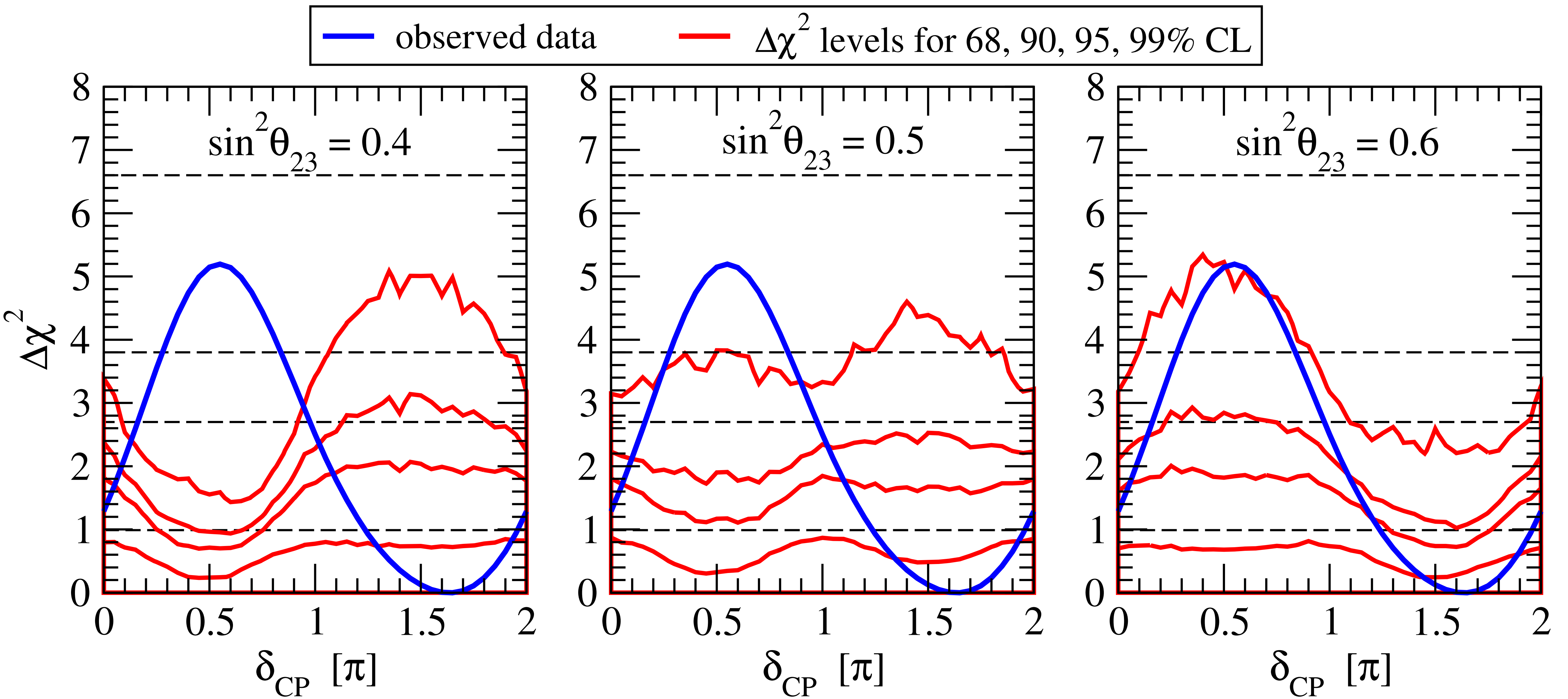
- *complicated non-linear parameter dependence*
- *δ_{CP} is a periodic parameter*
- *poor sensitivity*

usual $\Delta\chi^2$ approximations may not be valid

Schwetz, hep-ph/0612223
Blennow, Coloma, Fernandez-Martinez, 1407.3274
talk by M. Blennow

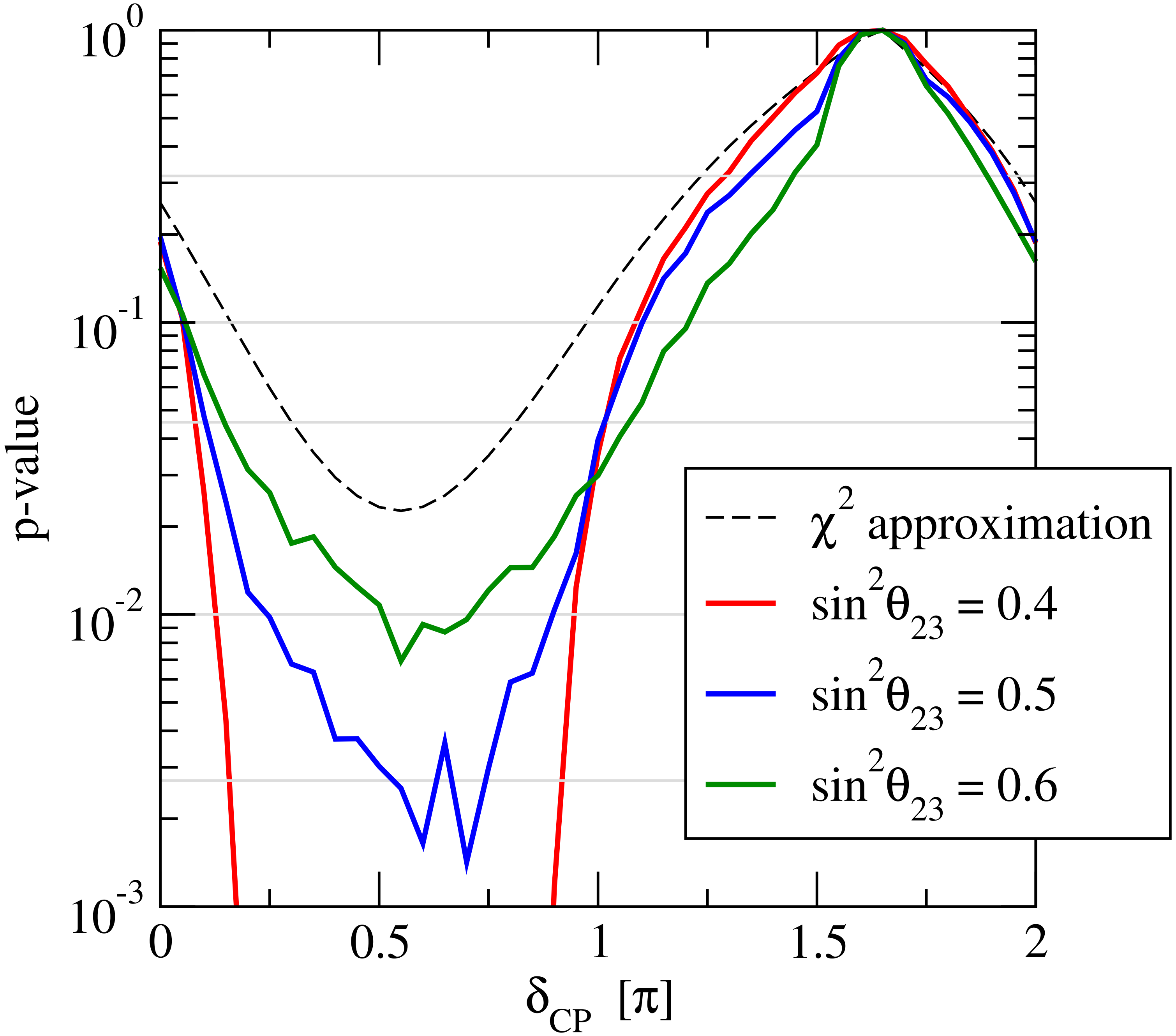
CP phase - what is the CL?

generate pseudo data for T2K (appear + disapp)
check distribution of $\Delta\chi^2$
consider δ_{CP} and θ_{23} as free parameters (all others fixed, incl NO)

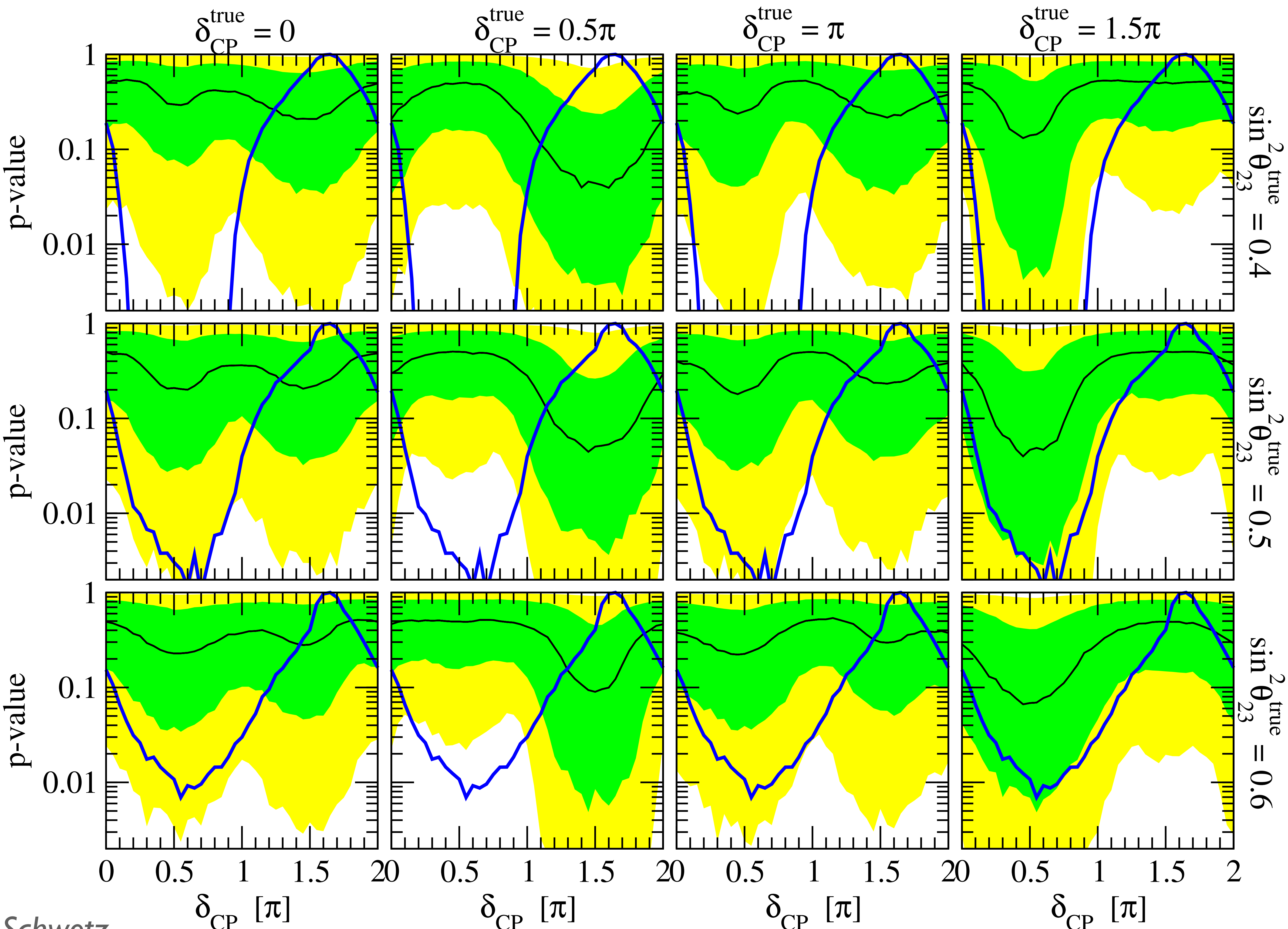


CP phase - what is the CL?

generate pseudo data for T2K (appear + disapp)
check distribution of $\Delta\chi^2$
consider δ_{CP} and θ_{23} as free parameters (all others fixed, incl NO)

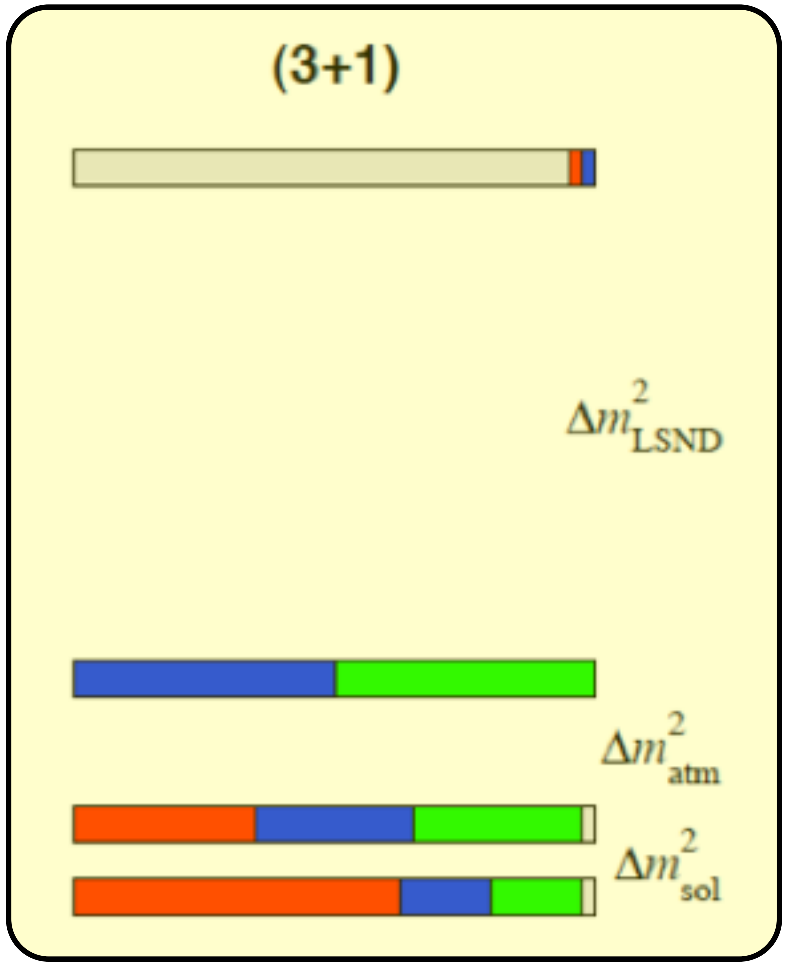


Expected sensitivity



Anomalies at the E/L ~ eV^2 scale

- Reactor anomaly ($\bar{\nu}_e$ disappearance)
- Gallium anomaly (ν_e disappearance)
- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
- MiniBooNE ($\bar{\nu}_\mu \to \bar{\nu}_e$, $\nu_\mu \to \nu_e$ appearance)

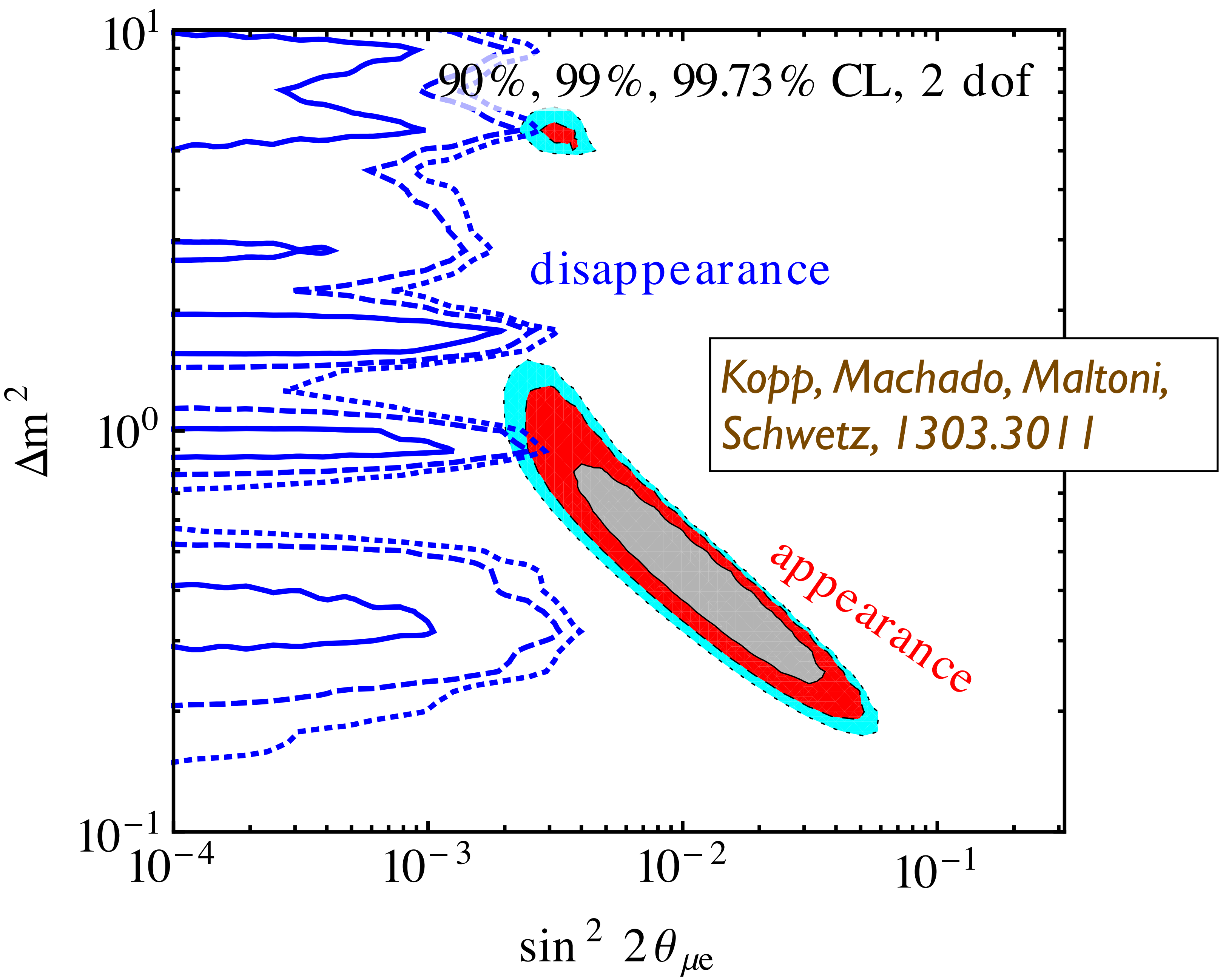


$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

- no hint for ν_μ disappearance
  limits from SK, CDHS, MiniBooNE, MINOS

Strong tension in global data

- *consistency of appearance and disappearance data with p-value 10^{-4}*



expect somewhat increased tension due to recent data from MINOS, SK-atm, ICARUS, OPERA

C. Giunti et al find somewhat better fit: p-value 10^{-3} *1308.5288*

Remark on reactor anomaly

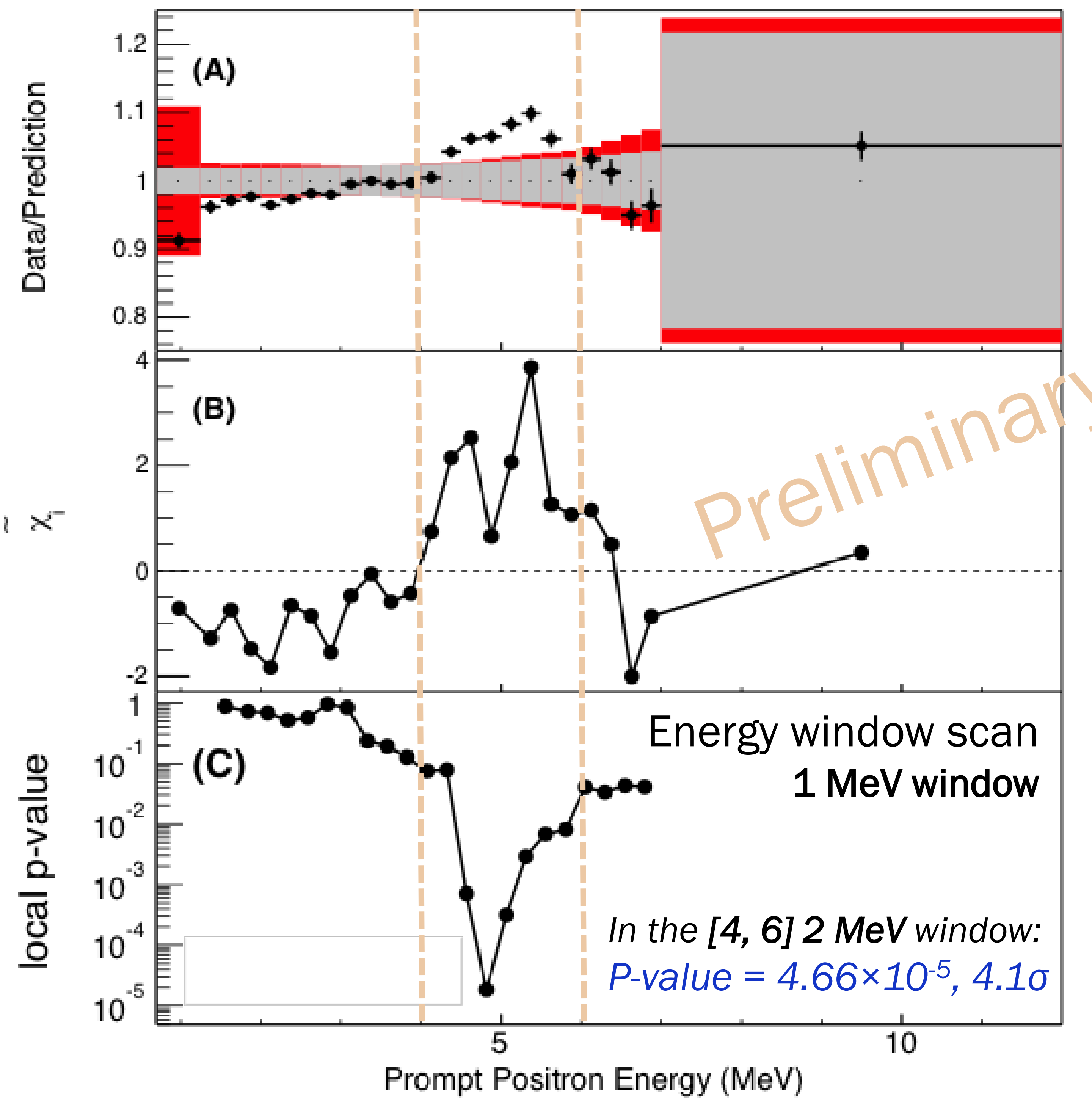
"unexpected" bump in reactor neutrino spectrum

also seen in RENO, DoubleChooz, Chooz

bump seems to be present in ab-initio calculations of the anti-nu spectrum, but problems with beta-spectr?

Dwyer, Langford, 1407.1281

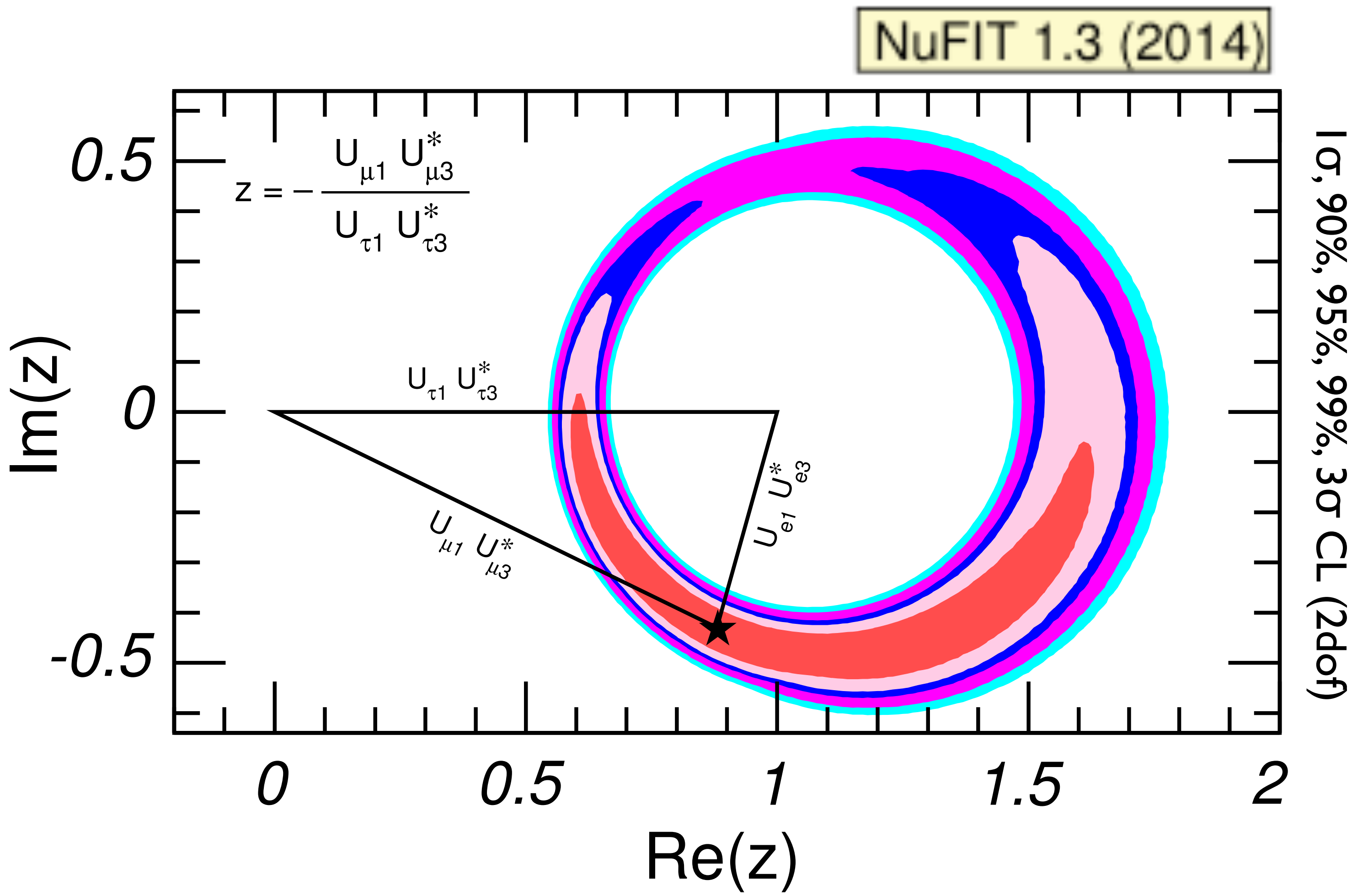
Daya Bay, W. Zhong @ ICHEP 2014



Sterile neutrinos at the eV-scale?

- *It is important to clarify "anomalies"*
- *hints for appearance experiments (LSND, MiniBooNE) are in strong tension with disappearance data*
- *reactor anomaly relies on complicated nuclear physics calculations and/or historical data - seem not under sufficient control to predict neutrino spectrum at %-level precision*

Thank you for your attention!

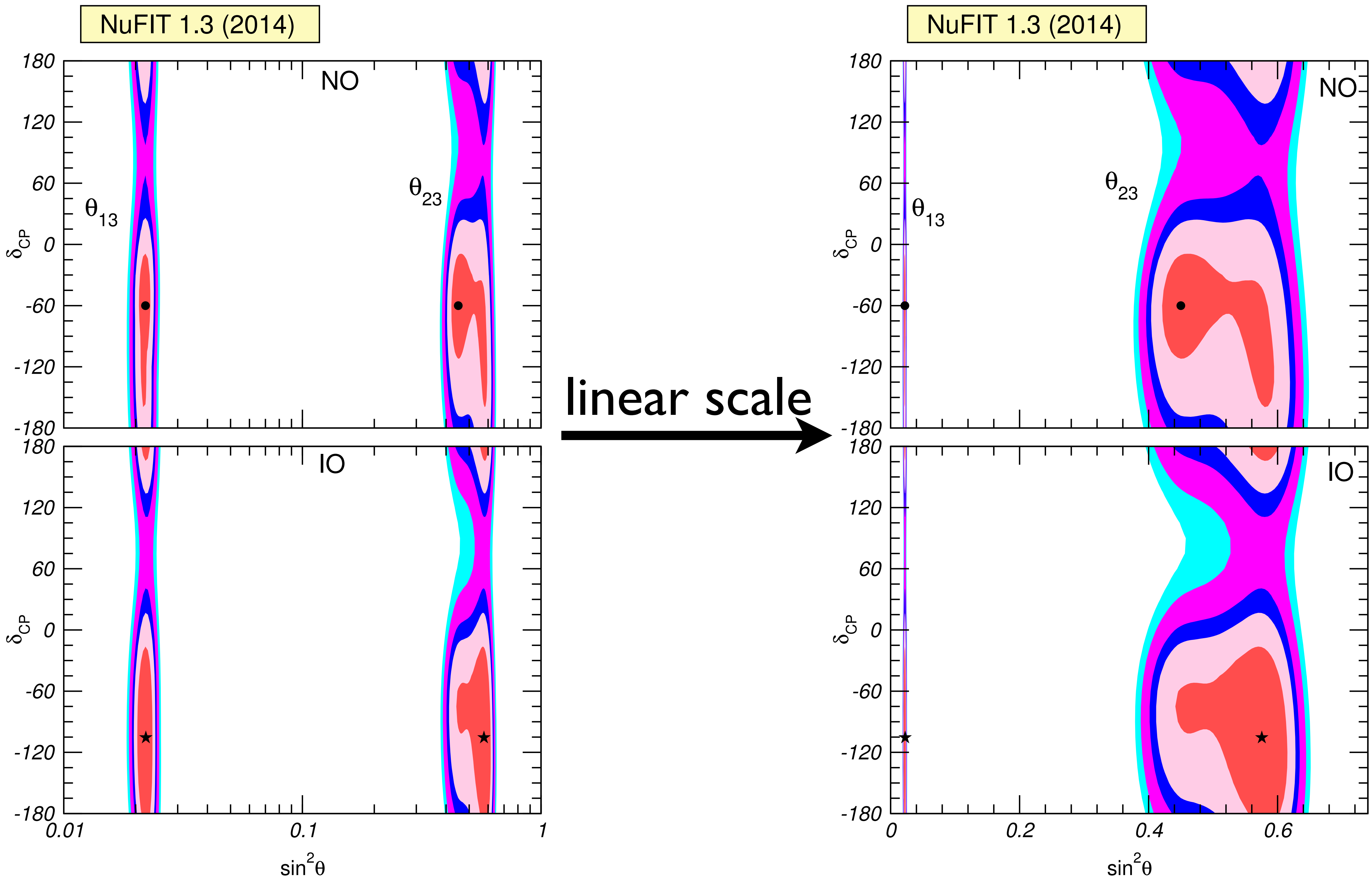


www.nu-fit.org

Additional slides

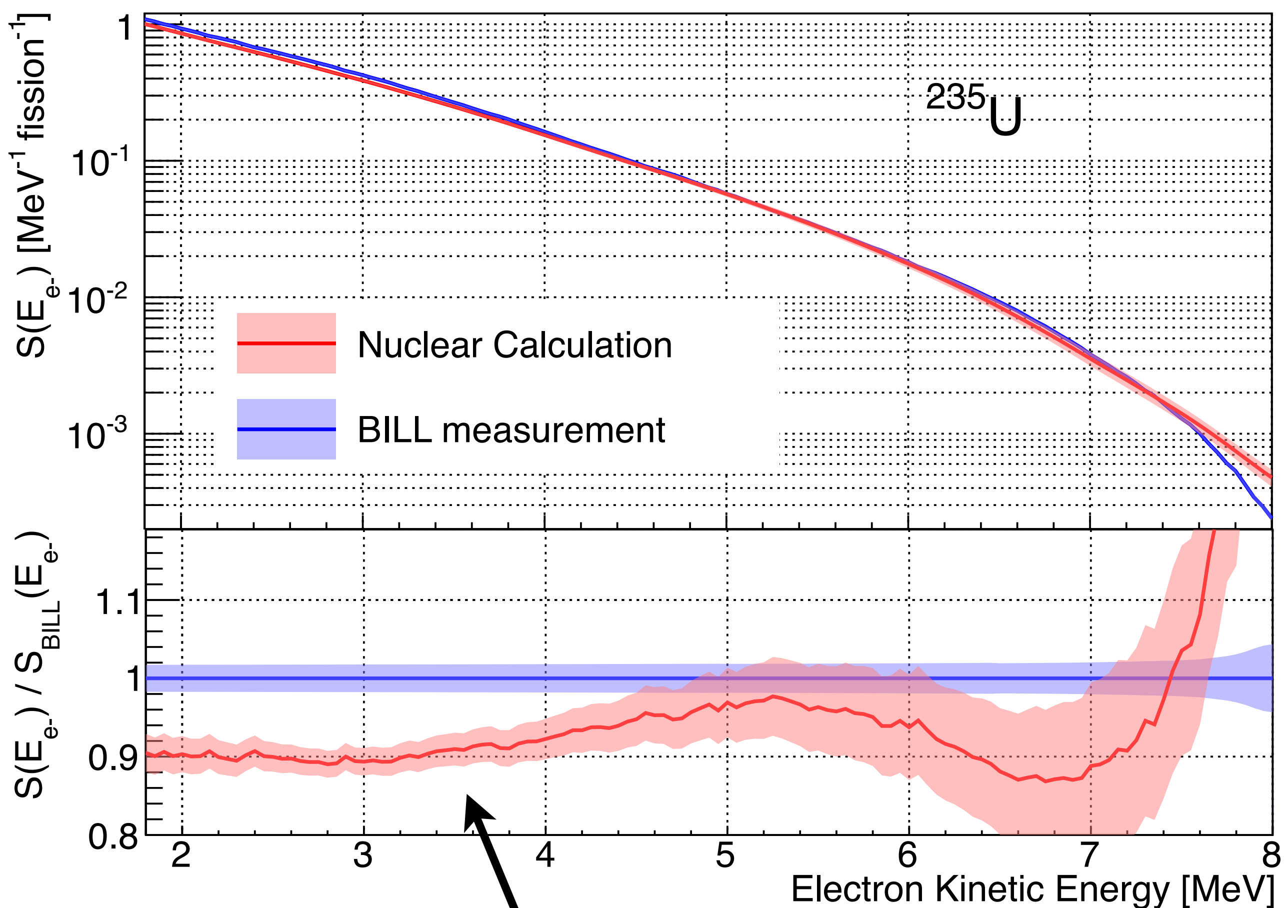
CP phase vs θ_{23}

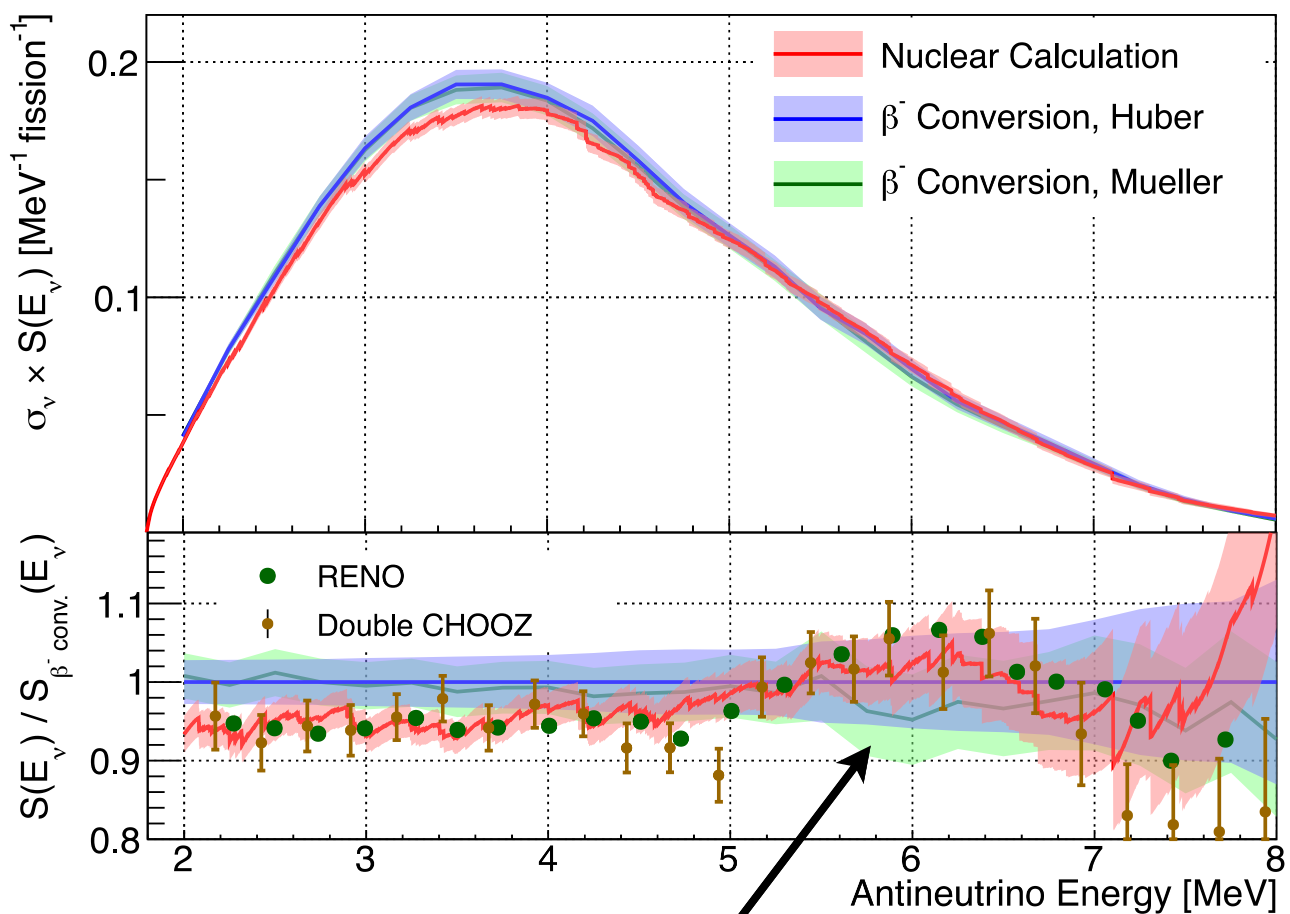
Minakata, Parke, 1303.6178
Coloma, Minakata, Parke, 1406.2551



new ab-initio calculations

Dwyer, Langford, 1407.1281



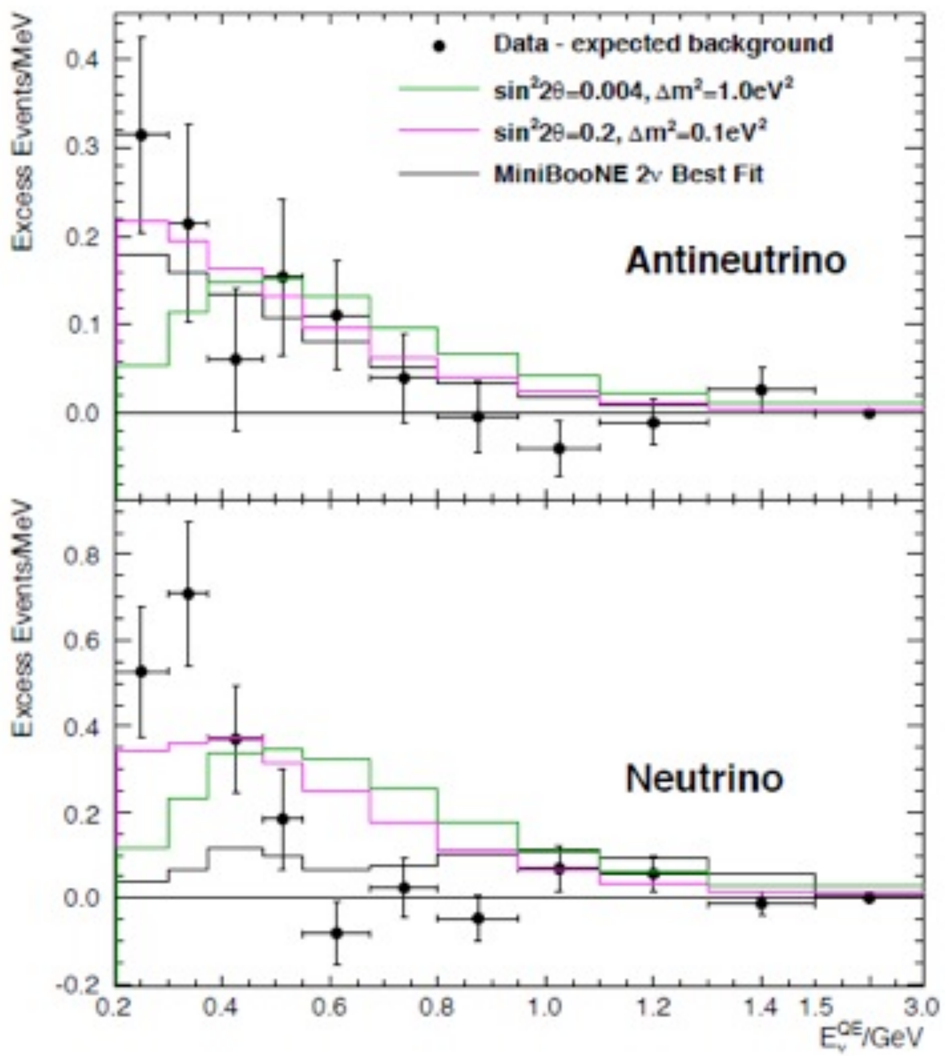


fails to predict beta spectr by ~10%

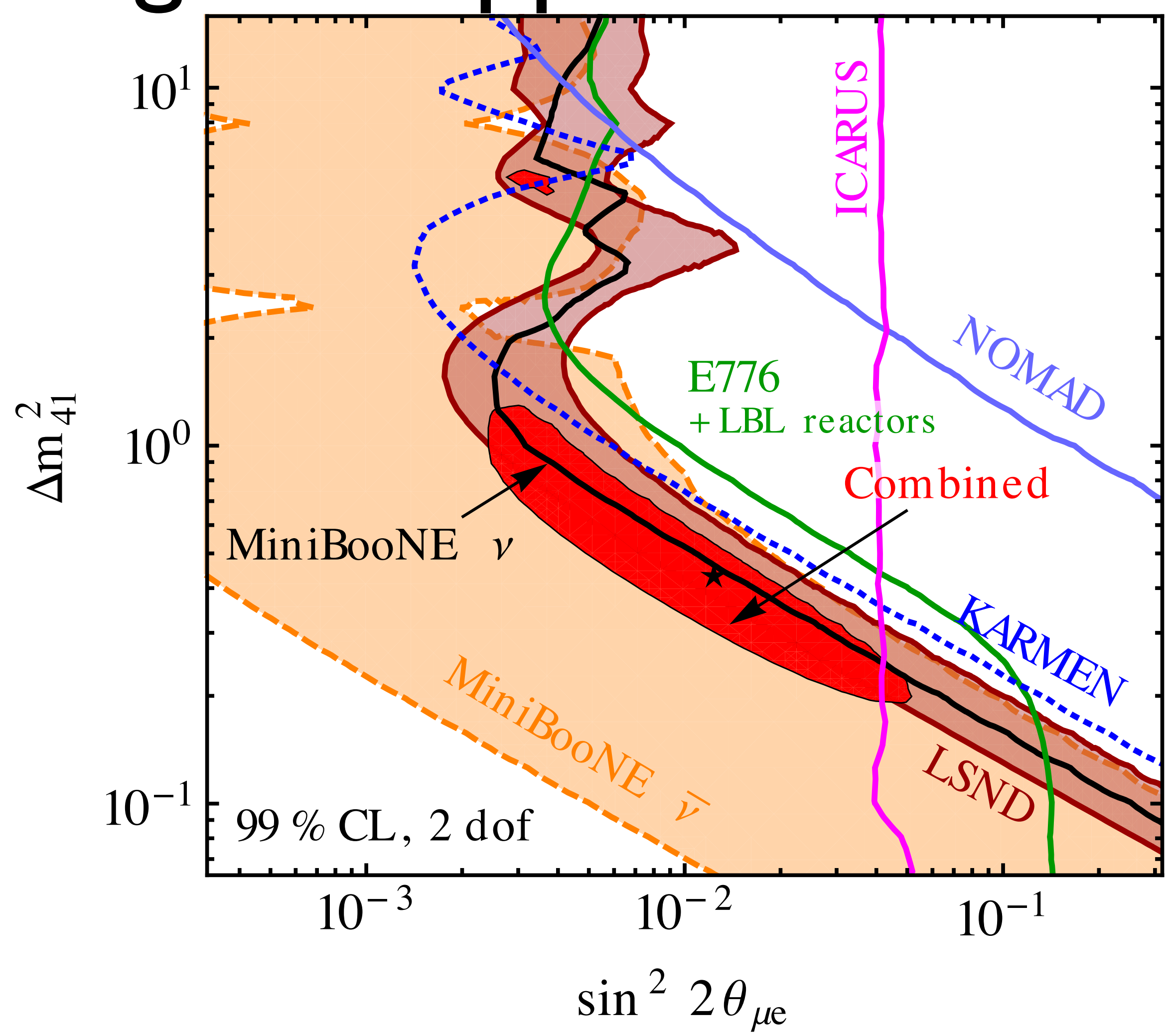
predicts bump around 6 MeV in agreement with data

$\nu_\mu \to \nu_e$ hints from LSND & MiniBooNE

MiniBooNE data



global appearance data



- *LSND signal at 3.8σ*
- *MB antineutrino excess (2.8σ) consistent with oscillations*
- *MB neutrino excess (3.4σ) marginally consistent with osc. (p-value 6.1%)*

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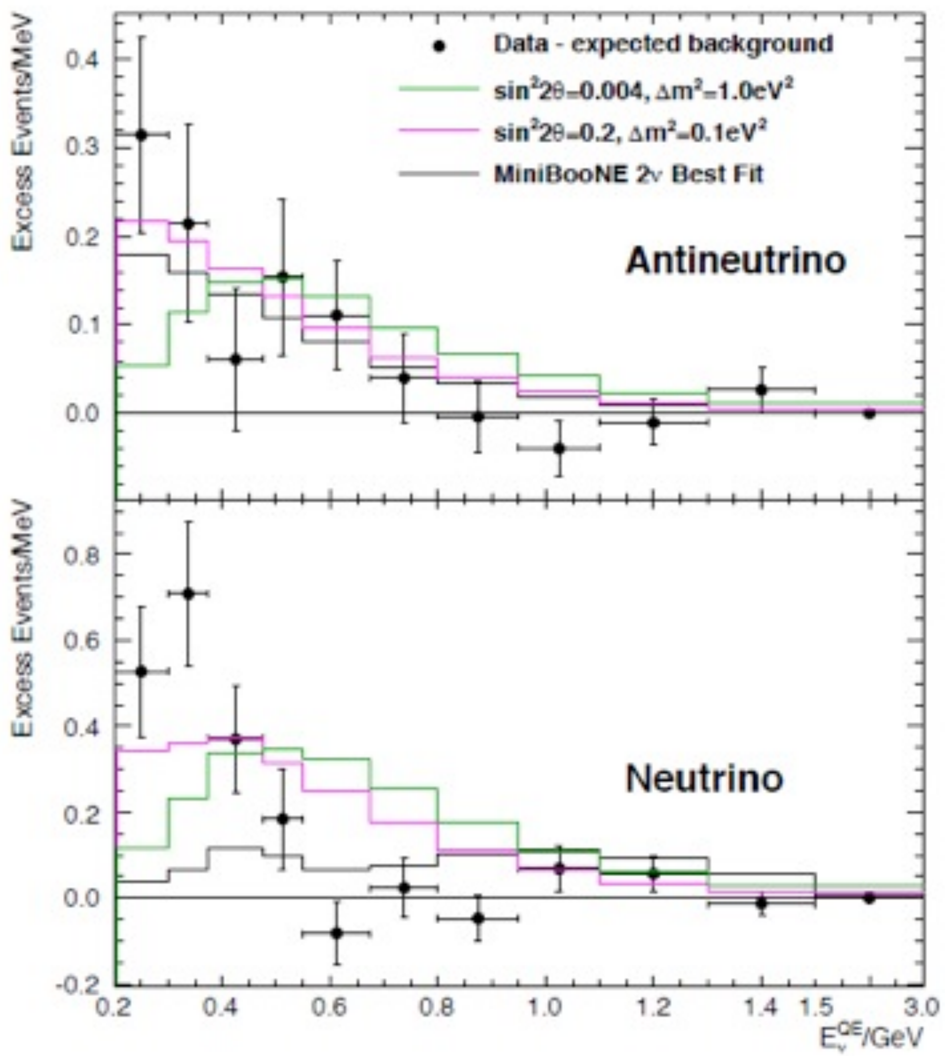

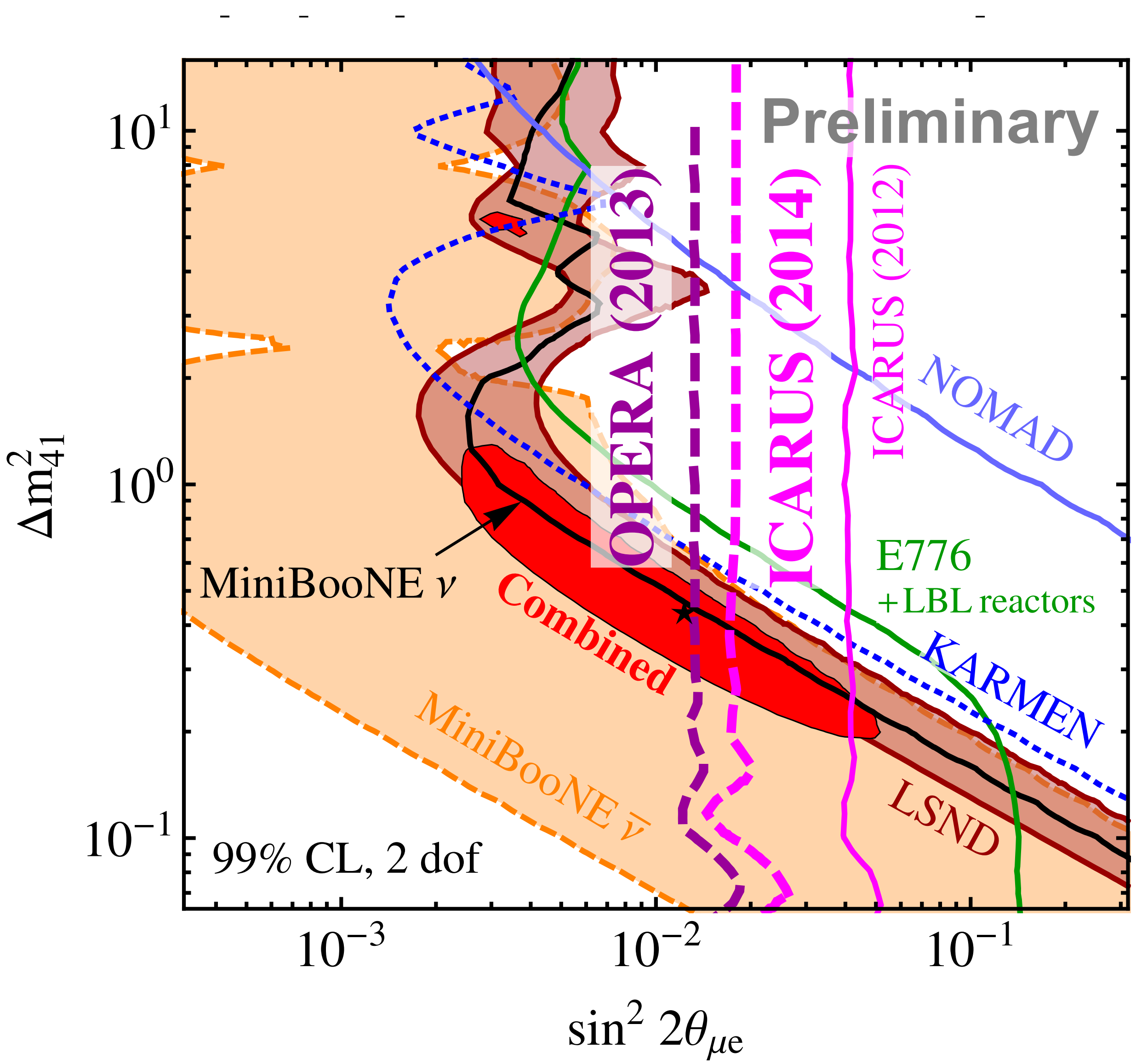

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- SuperK atmospherics
  Bilenky, Giunti, Grimus, TS 99;
  Maltoni, TS, Valle 01
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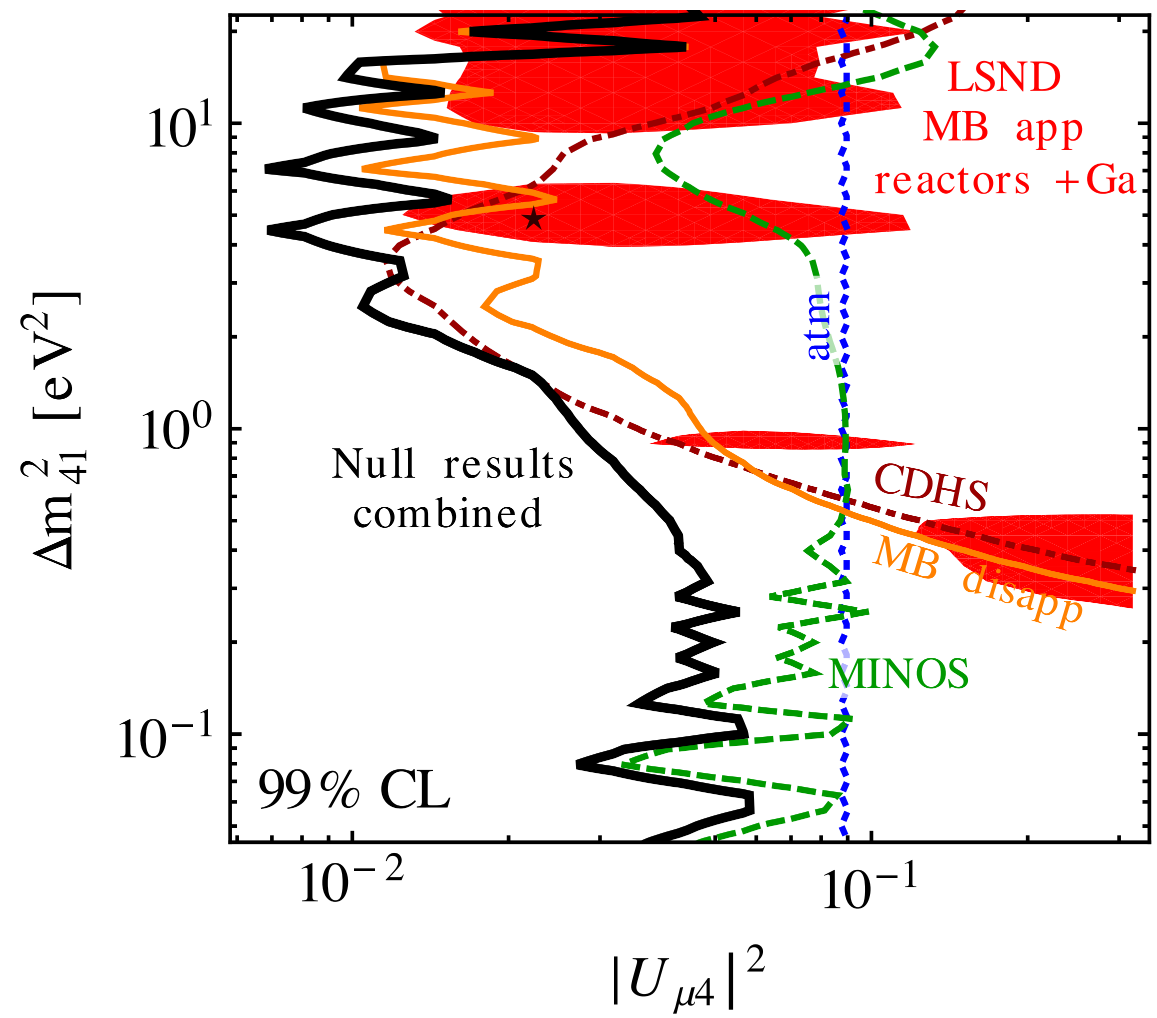
  (CC data most important)
- MiniBooNE $\nu_\mu(\bar{\nu}_\mu)$
  disappearance 1106.5685



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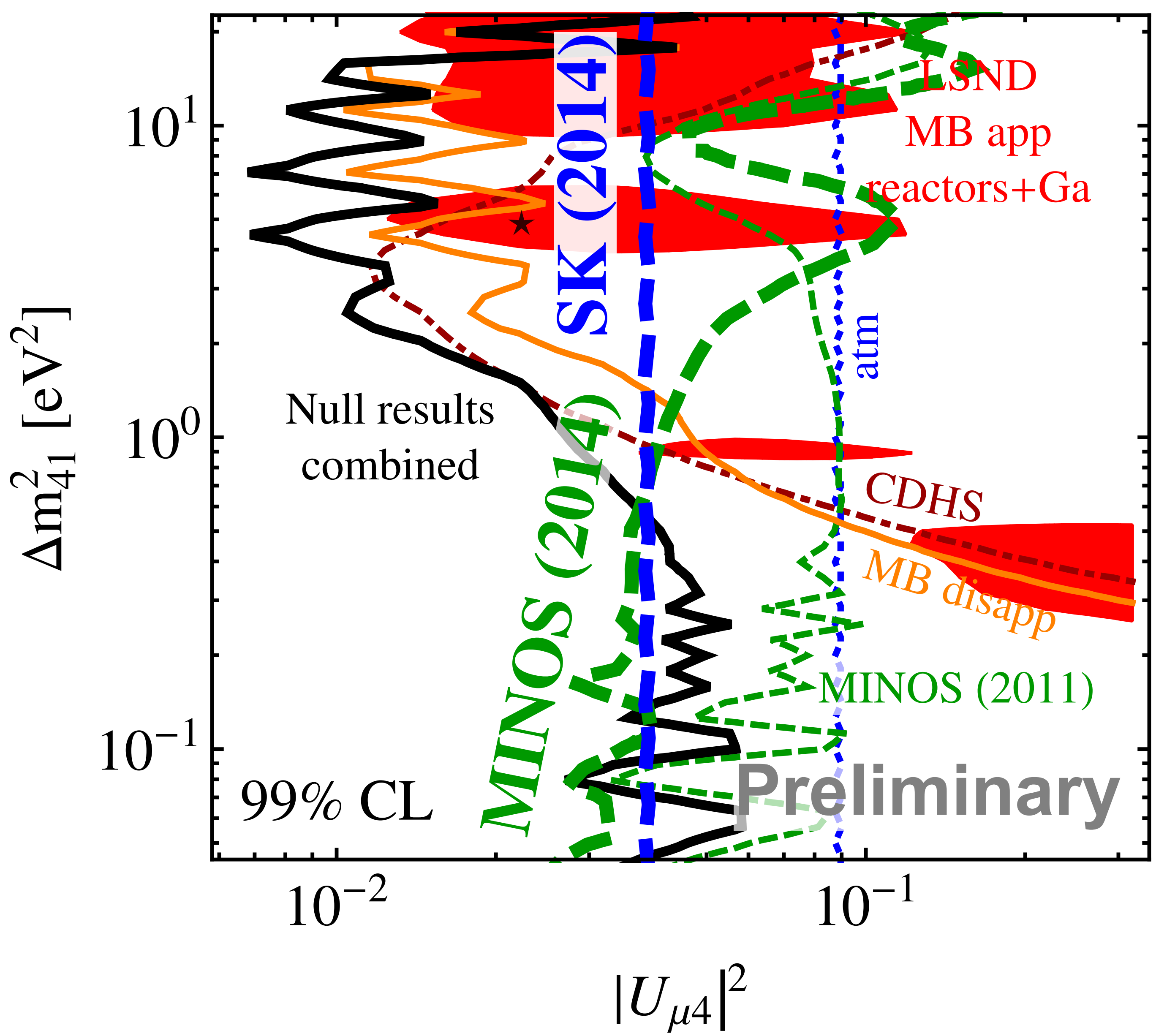

expect somewhat increased tension