Global fits to neutrino oscillations: current status and robustness

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ASTROPARTICLES Astroparticles and High Energy Physics Group IFIC INSTITUT DE FISICA CORPUSCULAR CSIC VNIVERSITAT DE VALÈNCIA EXCELENCIA SEVERO OCHOA GENERALITAT VALENCIANA

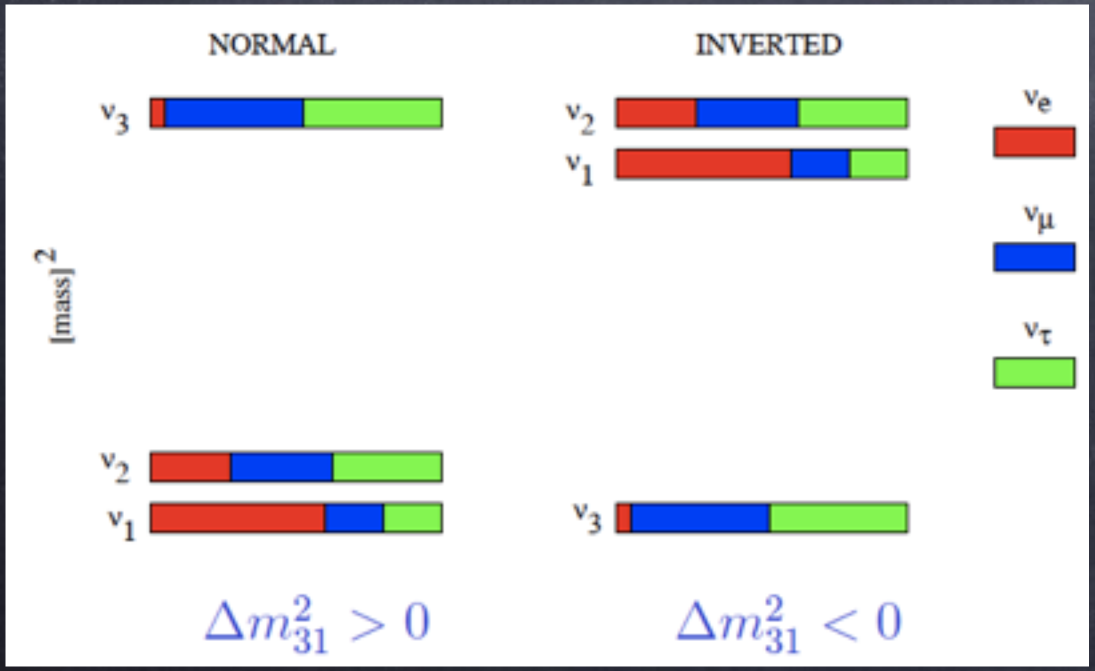
Neutrino masses and mixings

- Three-neutrino mixing is described by 3 mixing angles and 1 Dirac (+2 Majorana) CP violating phase.

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

atmospheric + LBL disapp   SBL reactor + LBL app   solar + KamLAND

- two possible mass orderings:



measured parameters:

θ_{12}, θ_{23}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{31}|$

unknown quantities:

sign(Δm^2_{31}), θ_{23}-octant, δ_{CP}

two-neutrino approximation:

$\boxed{\Delta m^2_{21} \ll \Delta m^2_{31}}$ θ_{13} small → 3-flavour effects suppressed: 2ν approx

$\theta_{12}, \Delta m^2_{21}$

solar + KamLAND

$\theta_{13}, \Delta m^2_{31}$

SBL reactor

$\theta_{23}, \Delta m^2_{31}$

atmospheric + LBL

Precision measurements of parameters require full 3-nu analysis

three-neutrino analysis:

$\theta_{12}, \Delta m^2_{21}, \theta_{13}$

$\theta_{13}, \Delta m^2_{31}, \theta_{12}$

$\theta_{23},$
$\Delta m^2_{31}, \theta_{13},$

all data samples are connected → a global 3ν analysis is required.

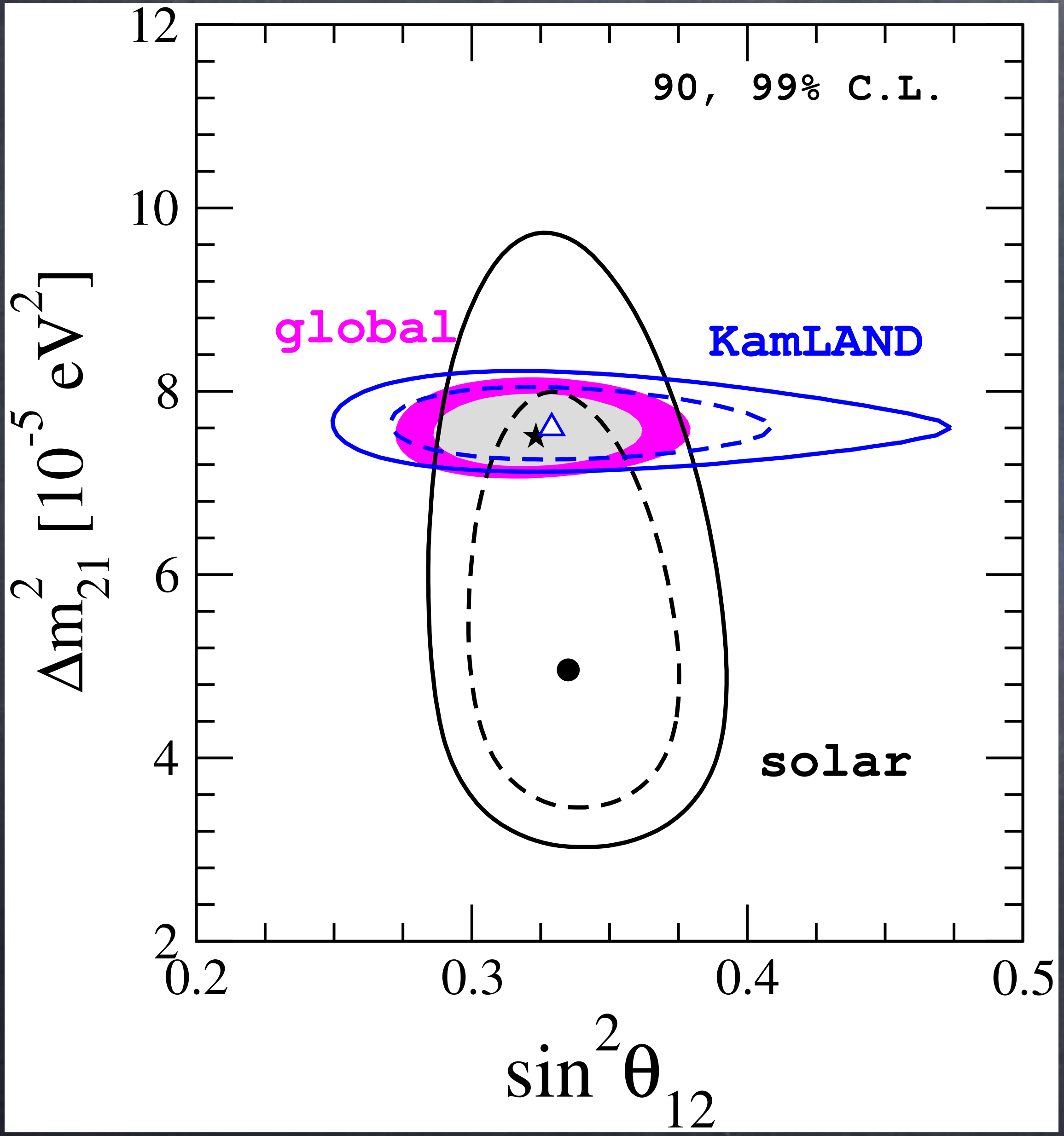
Global analysis of 3-flavour neutrino oscillations

Solar sector

Previous fit: Cl, Ga, SNO, Borexino, SK-I-III

New data: 2055-day D/N spectrum SK-IV

Nakano, PhD Thesis



Best fit point:

$\sin^2\theta_{12} = 0.321^{+0.018}_{-0.016}$

$\Delta m^2_{21} = 7.56 \pm 0.19 \times 10^{-5}$ eV^2

- max. mixing excluded at > 7σ
- θ_{12} determined by solar data
- Δm^2_{21} dominated by KamLAND.
- mismatch between Δm^2_{21} from solar and KamLAND

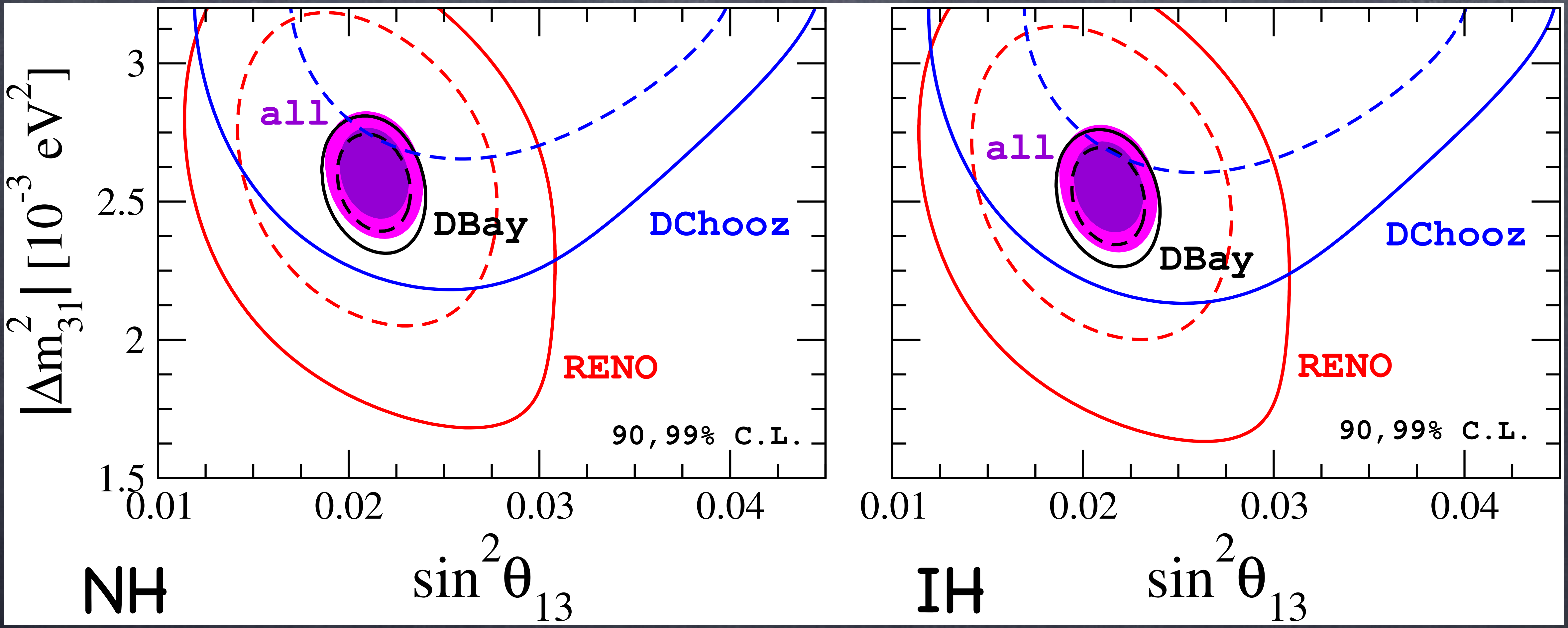
de Salas et al, 2017

no significant change wrt global fit in 2014

Reactor sector

New data: 1230d Daya Bay and 500d RENO $\bar{\nu}_e$ spectrum, 461d (FI) + 212d (FII) Double Chooz event spectrum

de Salas et al, 2017

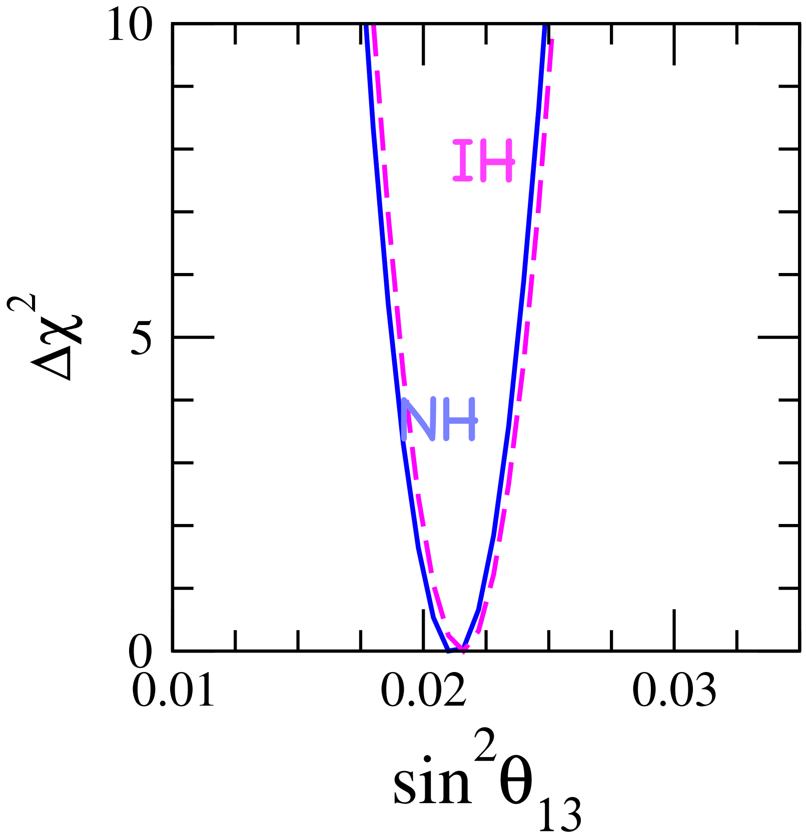


RENO favours lower value of θ_{13}

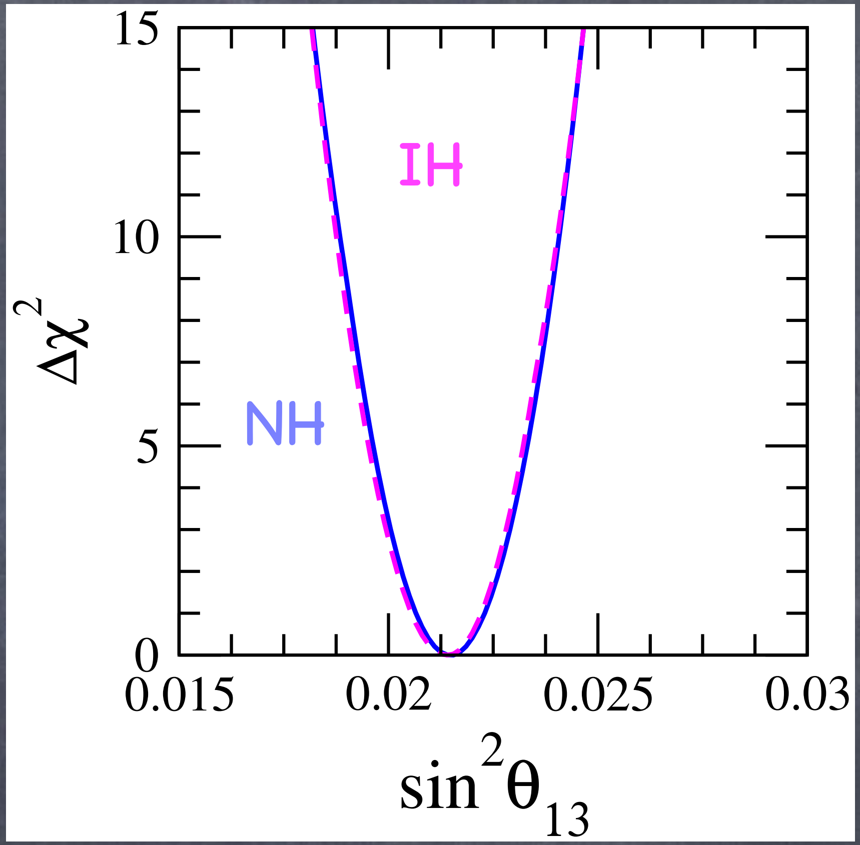
Daya Bay increase precision on θ_{13}

Impact of new data over θ_{13}

Forero, MT, Valle 2014



de Salas et al, 2017



- NH: $\sin^2\theta_{13} = 0.0226 \pm 0.0012$
- IH: $\sin^2\theta_{13} = 0.0229 \pm 0.0012$

~5%

- NH: $\sin^2\theta_{13} = 0.02155^{+0.00090}_{-0.00075}$
- IH: $\sin^2\theta_{13} = 0.02155^{+0.00076}_{-0.00092}$

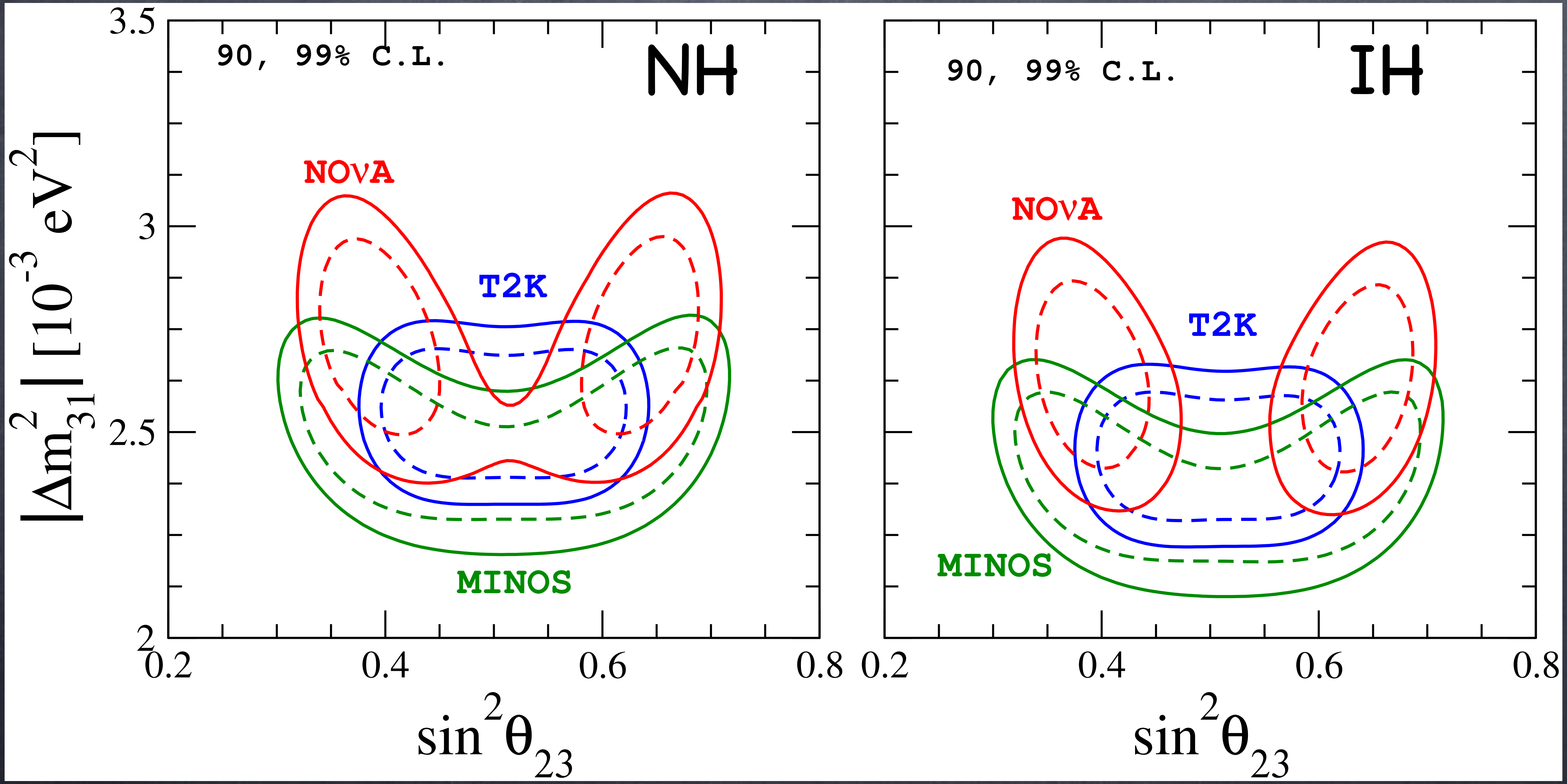
~3.9%

Precision dominated by Daya Bay

Accelerator LBL experiments

Previous fit: K2K, MINOS, T2K neutrino data

New data: T2K antineutrino data + latest NOνA data



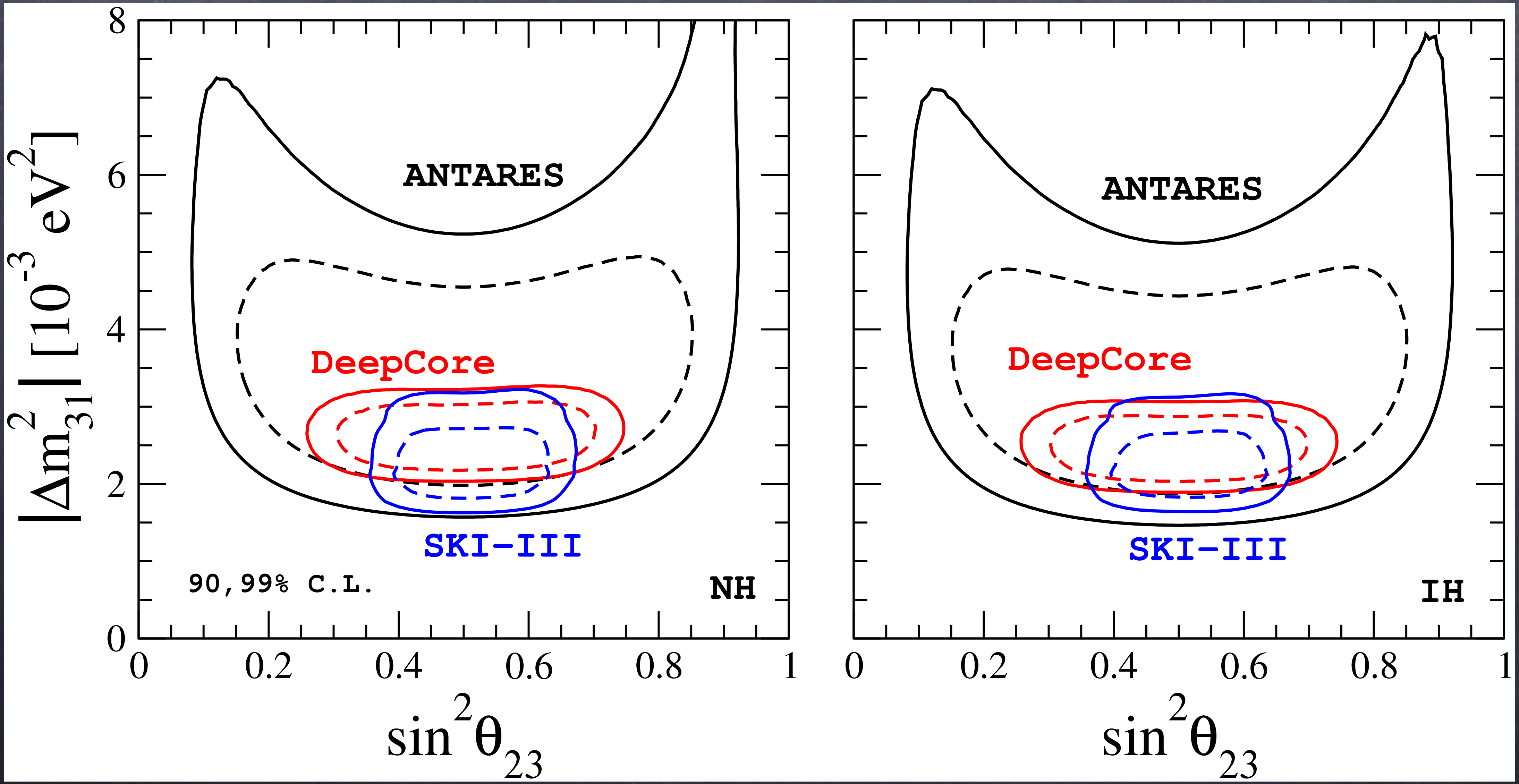
T2K prefers maximal mixing while NOvA disfavours θ_{23} = 45 at more than 2σ

Atmospheric neutrino data

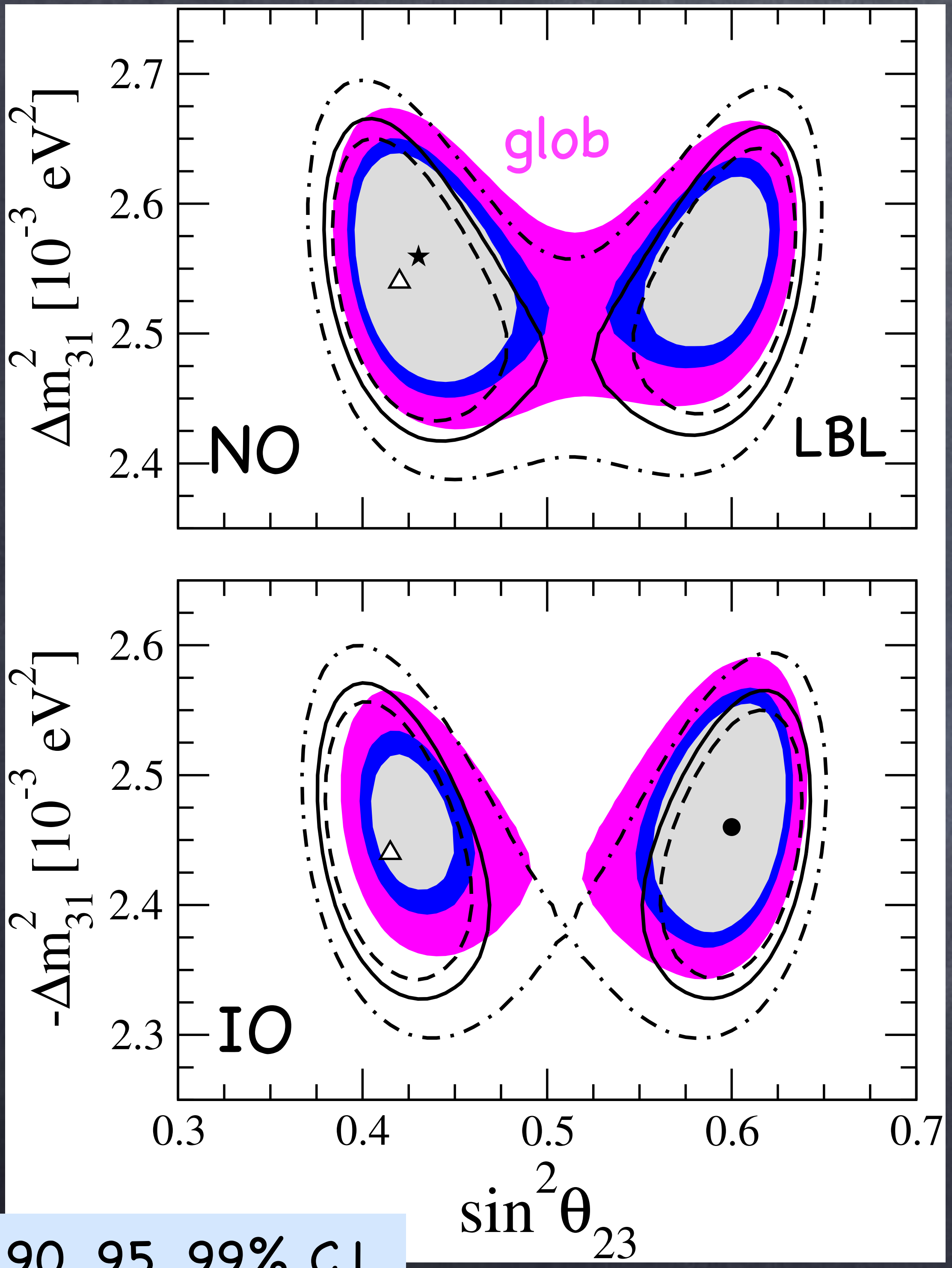
Previous fit: Super-K I to III — Wendell et al, PRD81 (2010)

New data: 3-year data IC-DeepCore — Aartsen et al, arXiv:1410.7227

+ 863-day ANTARES — Adrián-Martínez et al, PLB 2012



Atmospheric parameters



90, 95, 99% C.L.

- atmospheric parameters are mostly constrained by LBL data.
- maximal mixing allowed at 99%CL in NO, and disfavoured at more than 3σ for IO.
- best fit values:

NO

$$\Delta m^2_{31} = (2.55 \pm 0.04) \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.430^{+0.020}_{-0.018}$$

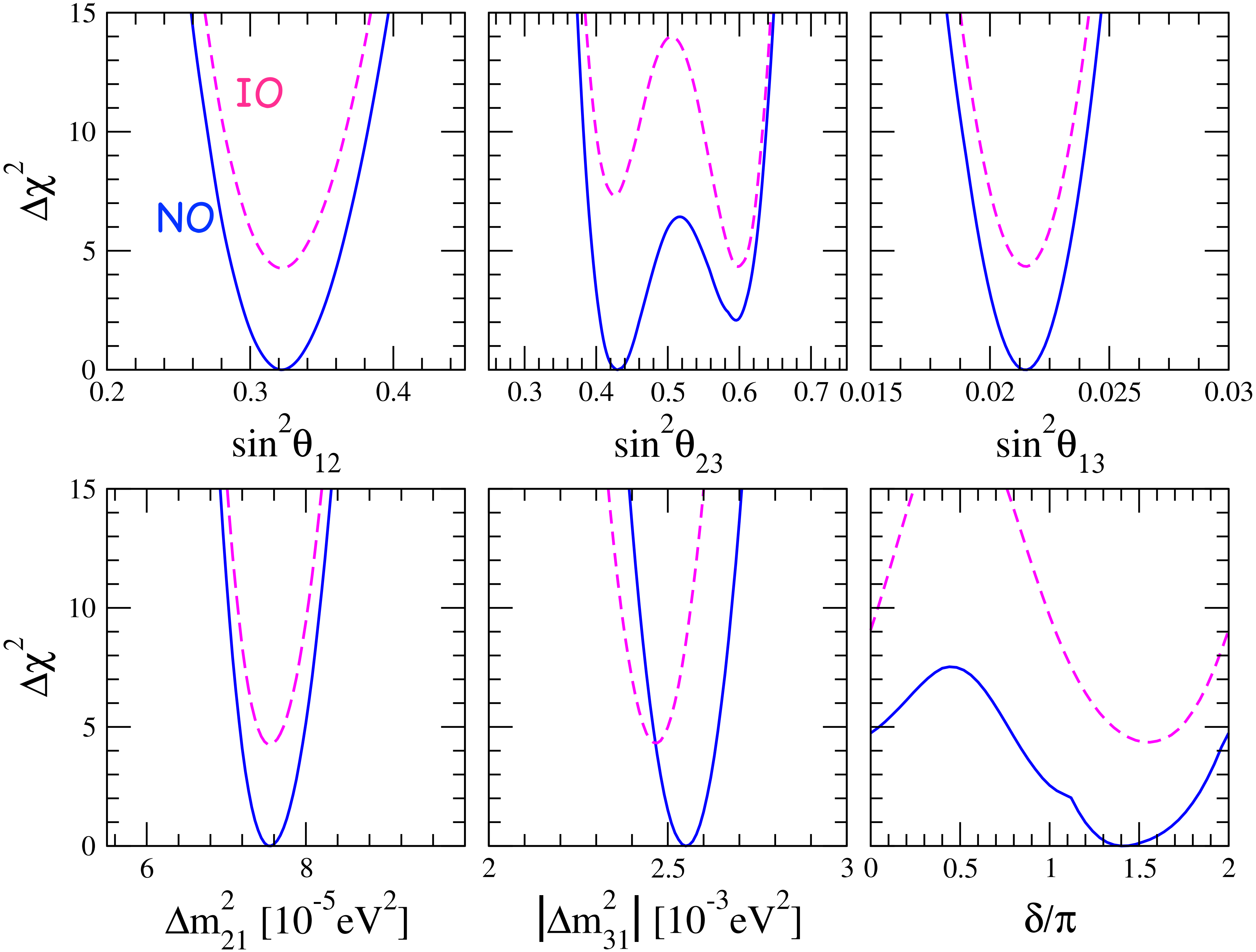
IO

$$\Delta m^2_{31} = -(2.47^{+0.04}_{-0.05}) \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.598^{+0.017}_{-0.015}$$

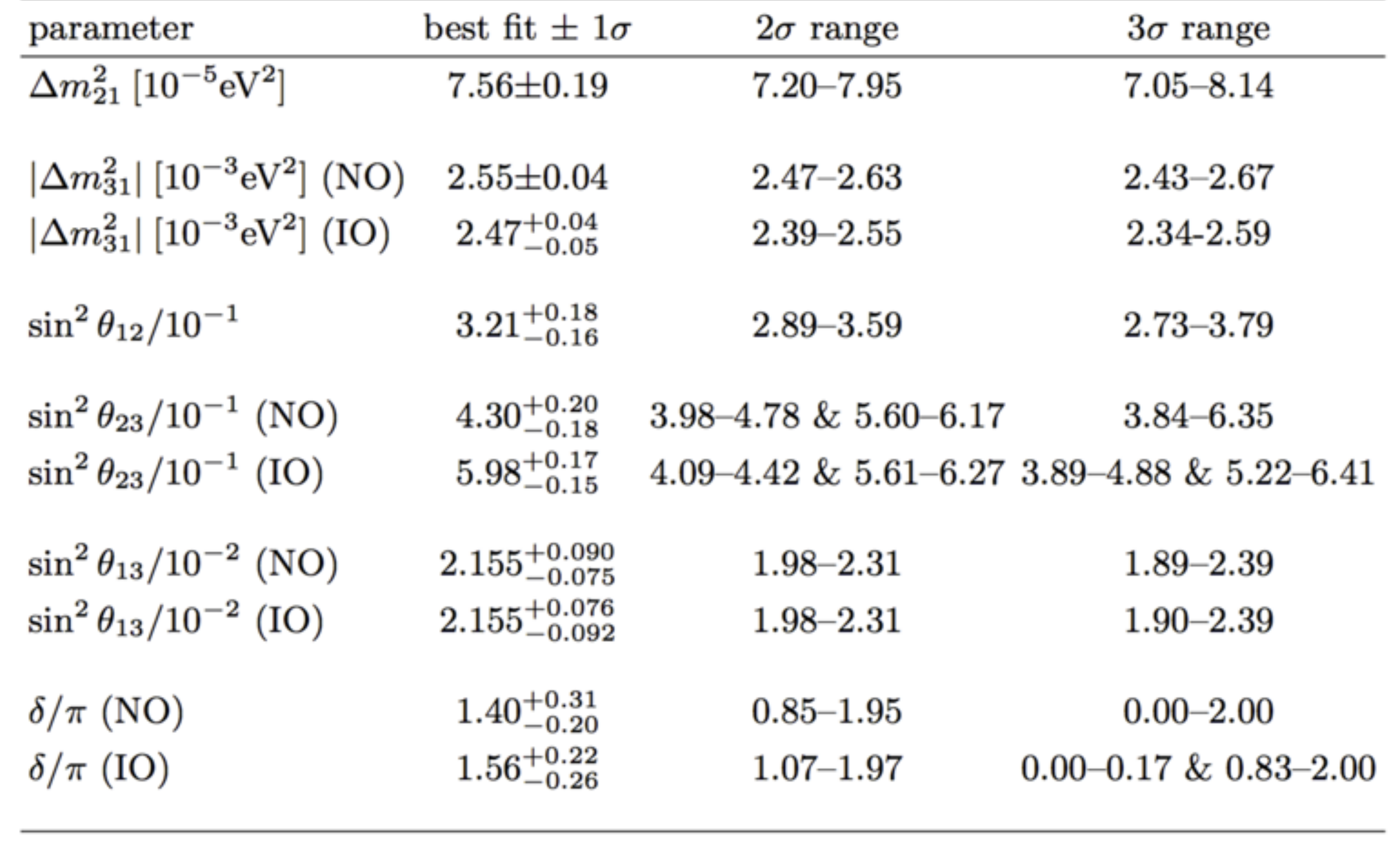
de Salas et al, 2017

Updated global fit summary



- slight preference for Normal Ordering: $\Delta\chi^2(\text{IO-NO}) = 4.3$

Updated global fit summary



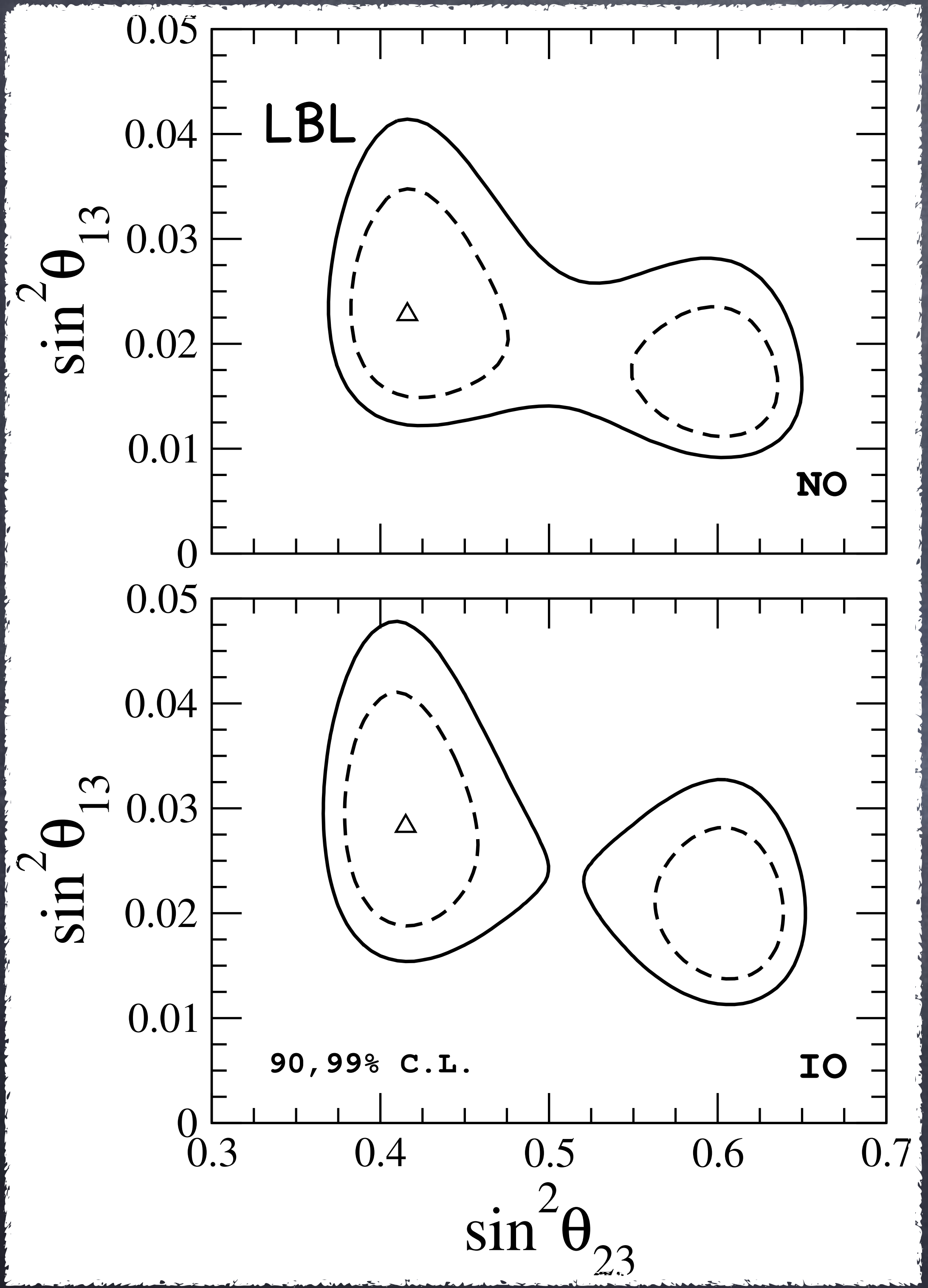
parameter	best fit ± 1σ	2σ range	3σ range	relative 1σ
Δm^2_{21} [10^{-5}eV^2]	7.56±0.19	7.20–7.95	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.55±0.04	2.47–2.63	2.43–2.67	1.6%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	$2.47^{+0.04}_{-0.05}$	2.39–2.55	2.34-2.59	
$\sin^2\theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$	2.89–3.59	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$	3.98–4.78 & 5.60–6.17	3.84–6.35	9.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.98^{+0.17}_{-0.15}$	4.09–4.42 & 5.61–6.27	3.89–4.88 & 5.22–6.41	7.0%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.155^{+0.090}_{-0.075}$	1.98–2.31	1.89–2.39	3.9%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.155^{+0.076}_{-0.092}$	1.98–2.31	1.90–2.39	
δ/π (NO)	$1.40^{+0.31}_{-0.20}$	0.85–1.95	0.00–2.00	
δ/π (IO)	$1.56^{+0.22}_{-0.26}$	1.07–1.97	0.00–0.17 & 0.83–2.00	

**IO ranges: calculated wrt local minimum

NO
local min. at 2nd octant, $\Delta\chi^2$ = 2.1

IO
local min. at 1st octant, $\Delta\chi^2$ = 3.0

The octant of the atmospheric angle

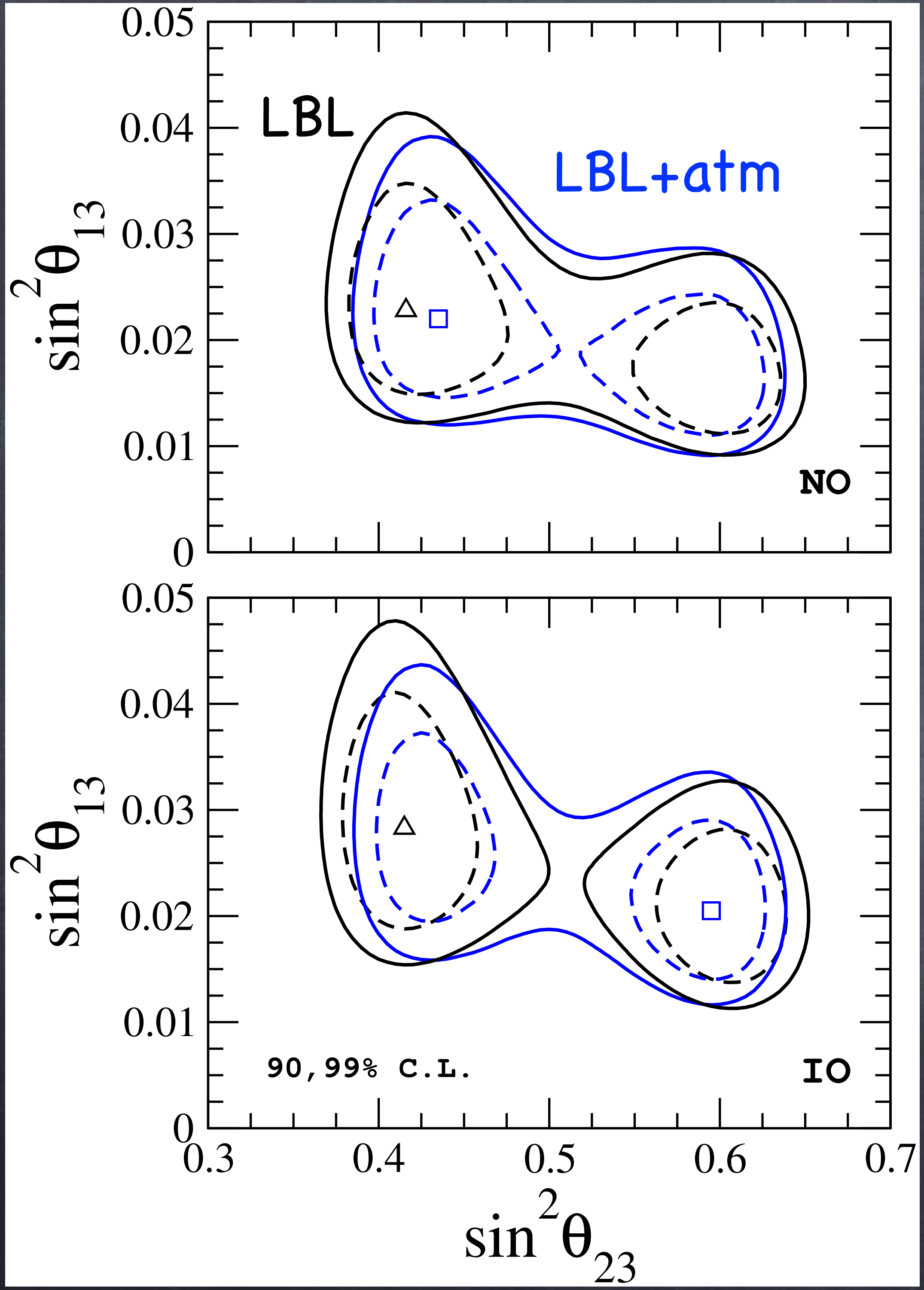


de Salas et al, 2017

- LBL data analysis show a degeneracy in θ_{13}-θ_{23} plane due to appearance prob:

$$P_{\mu e} \propto \sin^2\theta_{23}\sin^2(2\theta_{13})$$

The octant of the atmospheric angle



- LBL data analysis show a degeneracy in θ_{13}–θ_{23} plane due to appearance prob:

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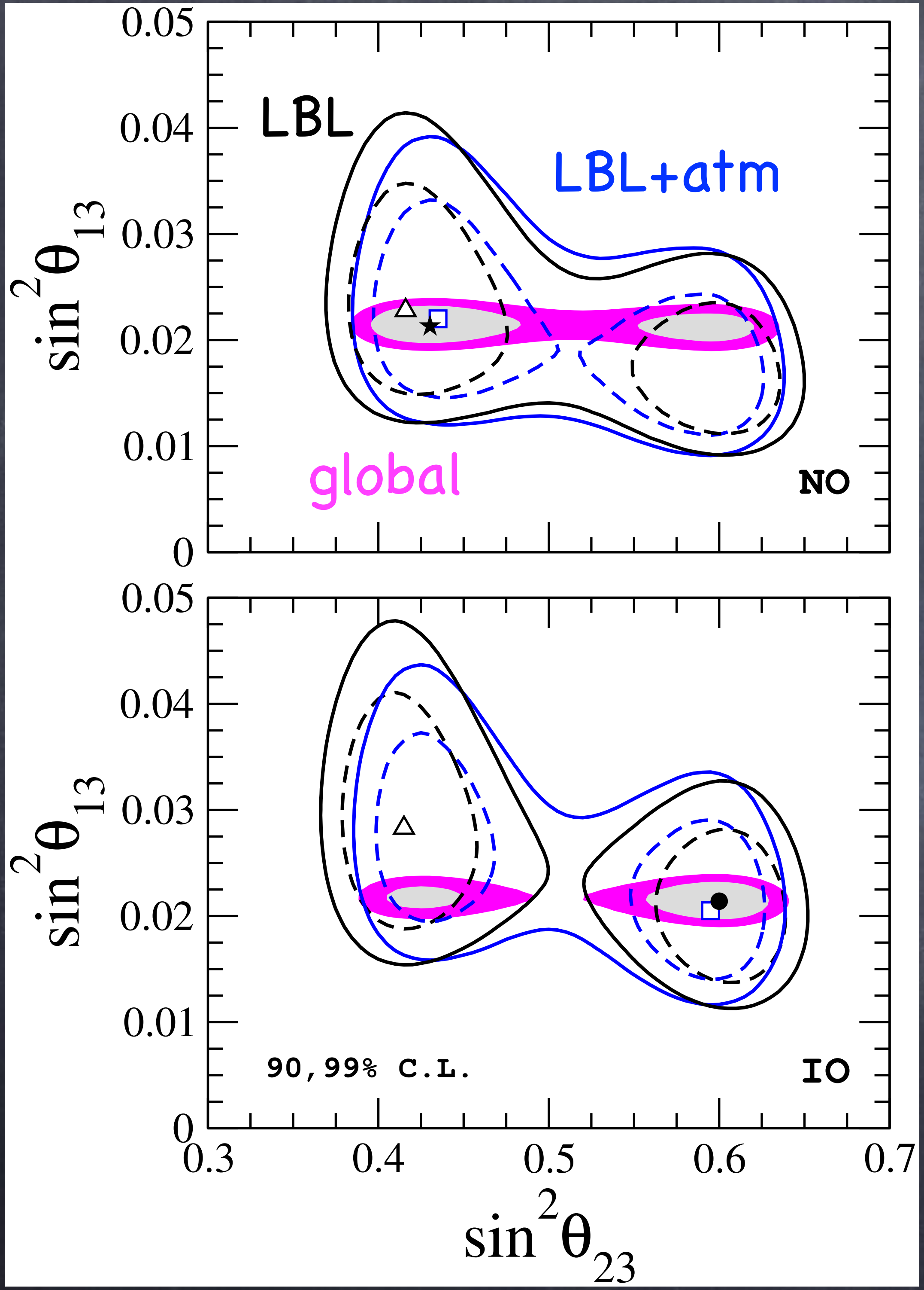
- atm data improve status of maximal mixing and fix θ_{23} preferred octant

de Salas et al, 2017

The octant of the atmospheric angle



de Salas et al, 2017

- LBL data analysis show a degeneracy in θ_{13}–θ_{23} plane due to appearance prob:

$$P_{\mu e} \propto \sin^2\theta_{23}\sin^2(2\theta_{13})$$

- atm data improve status of maximal mixing and fix θ_{23} preferred octant
- reactor θ_{13} measurement confirms preferred θ_{23} octant for NO (1st) and IO (2nd)

NO

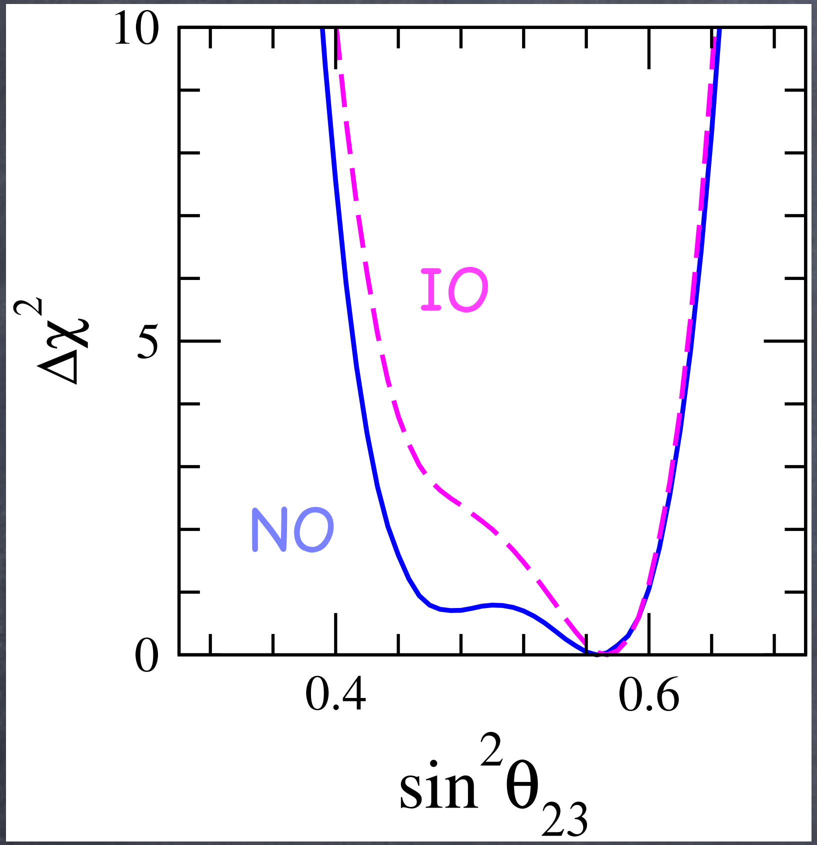
local min. at 2nd octant, $\Delta\chi^2 = 2.1$

IO

local min. at 1st octant, $\Delta\chi^2 = 3.0$

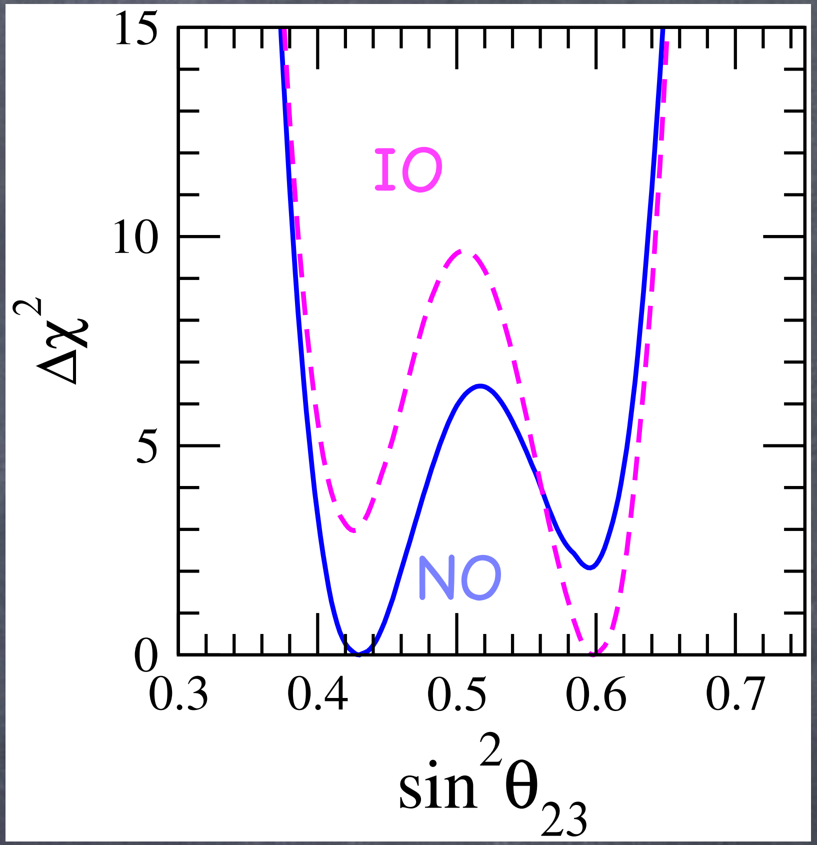
Impact of new data over θ_{23} octant

Forero, MT, Valle 2014



- NO: local min. at 1st octant with $\Delta\chi^2 = 0.71$
- IO: 1st octant allowed with $\Delta\chi^2 > 2.0$

de Salas et al, 2017

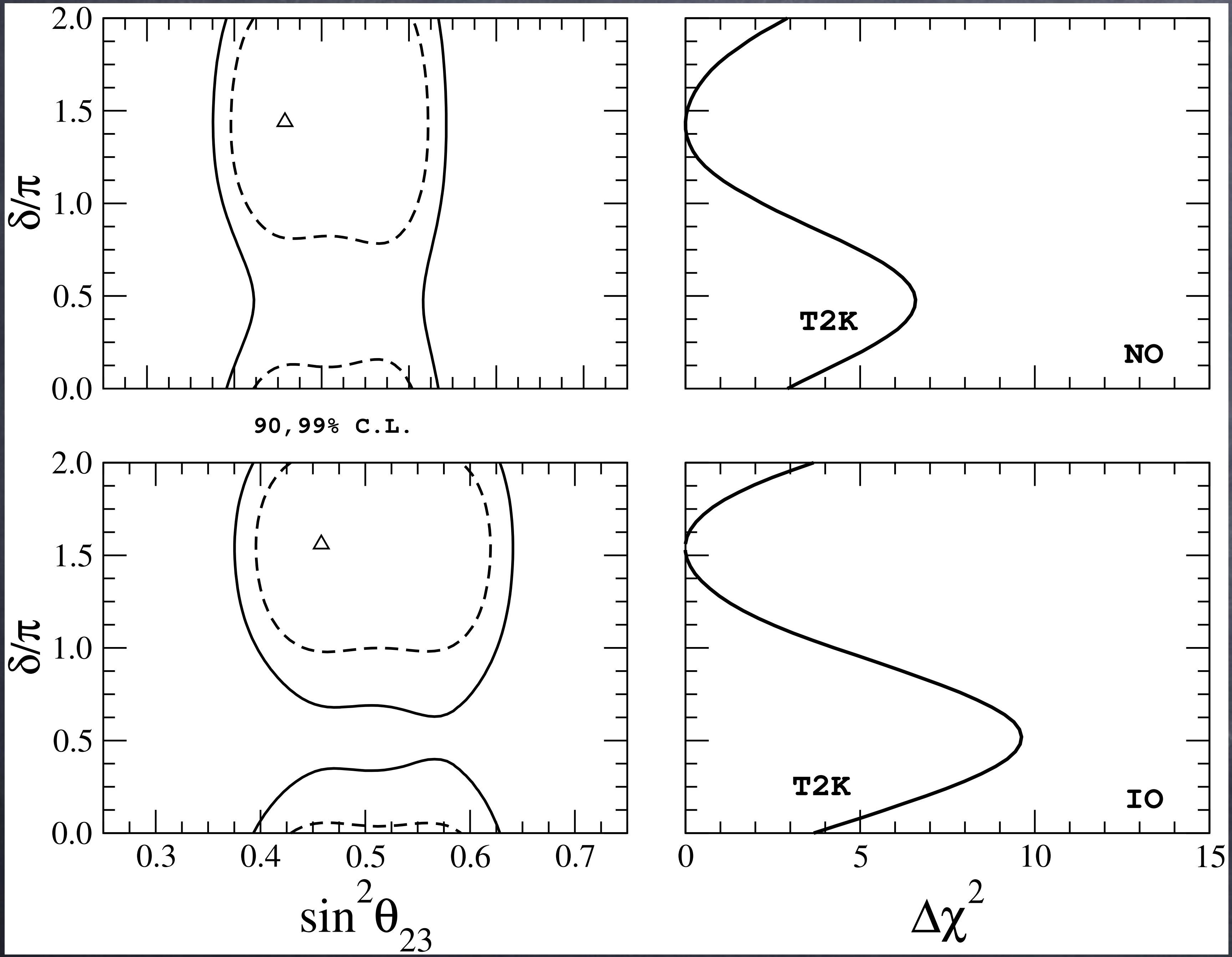


- NO: local min at 2nd octant with $\Delta\chi^2 = 2.1$
- IO: local min at 1st octant with $\Delta\chi^2 = 3.0$

reactor and atmos. data select θ_{23} octant for NO (1st) and IO (2nd)

Sensitivity to the CP phase

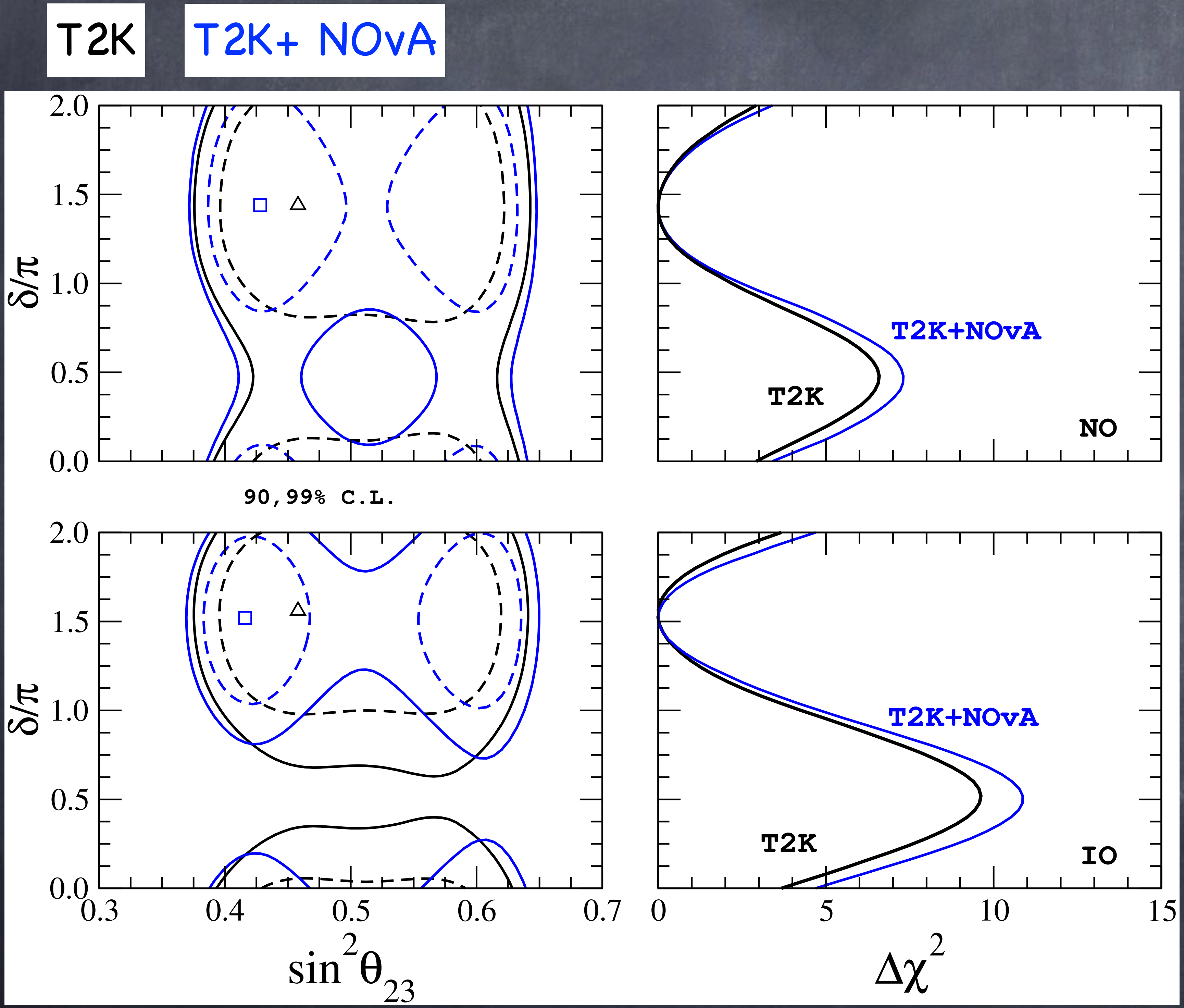
T2K



- T2K shows improved sensitivity to δ_{CP} thanks to ν-$\bar{\nu}$ data

de Salas et al, 2017

Sensitivity to the CP phase

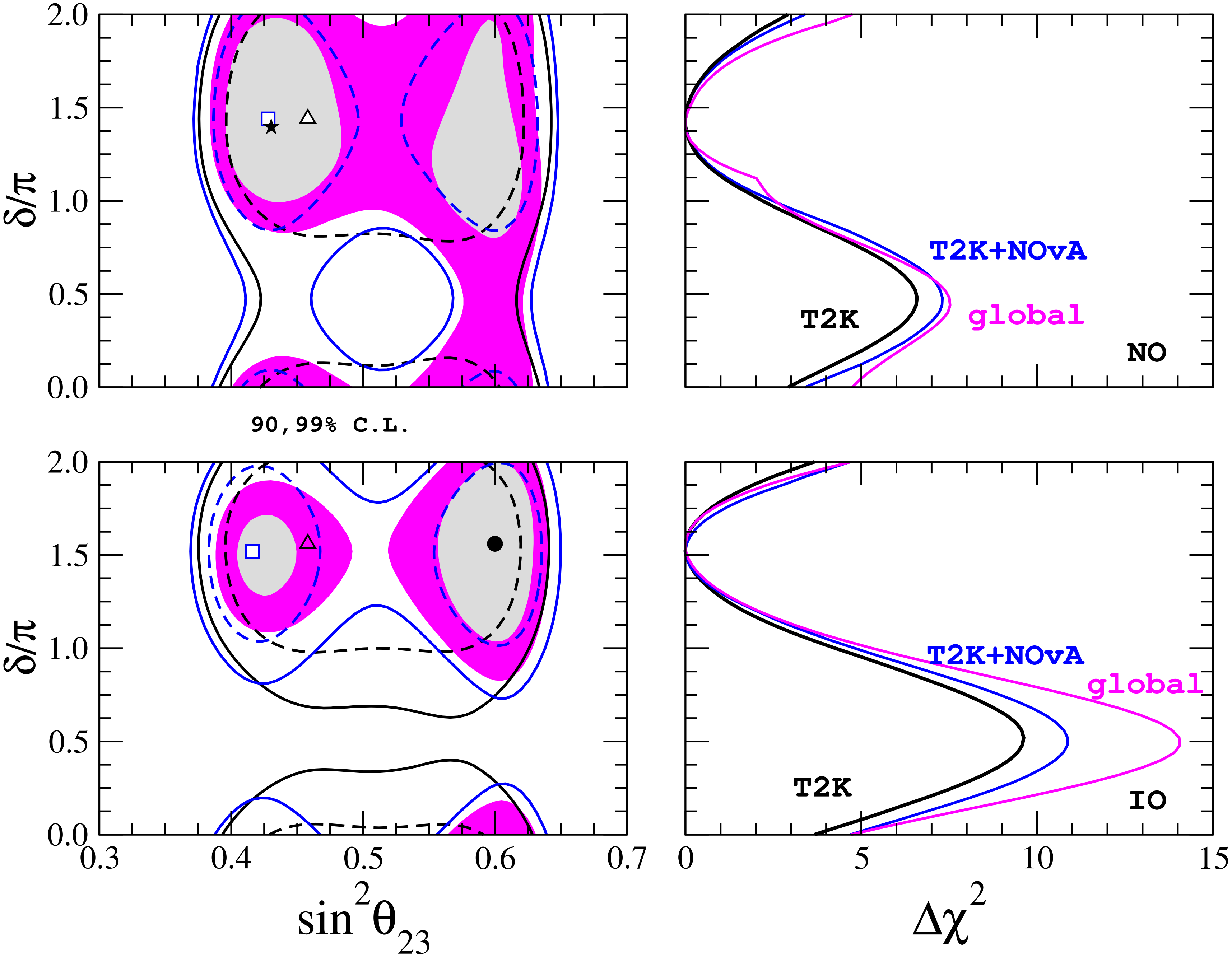


- T2K shows improved sensitivity to δ_{CP} thanks to ν-$\bar{\nu}$ data
- NOνA improves the rejection against π/2

de Salas et al, 2017

Sensitivity to the CP phase

T2K   T2K+ NOvA   global



- T2K shows improved sensitivity to δ_{CP} thanks to ν-$\bar{\nu}$ data
- NOνA improves the rejection against π/2
- reactor data further disfavour π/2 for IO
- best fit values:

$$\delta/\pi = 1.40^{+0.31}_{-0.20} \quad \text{(NO)}$$

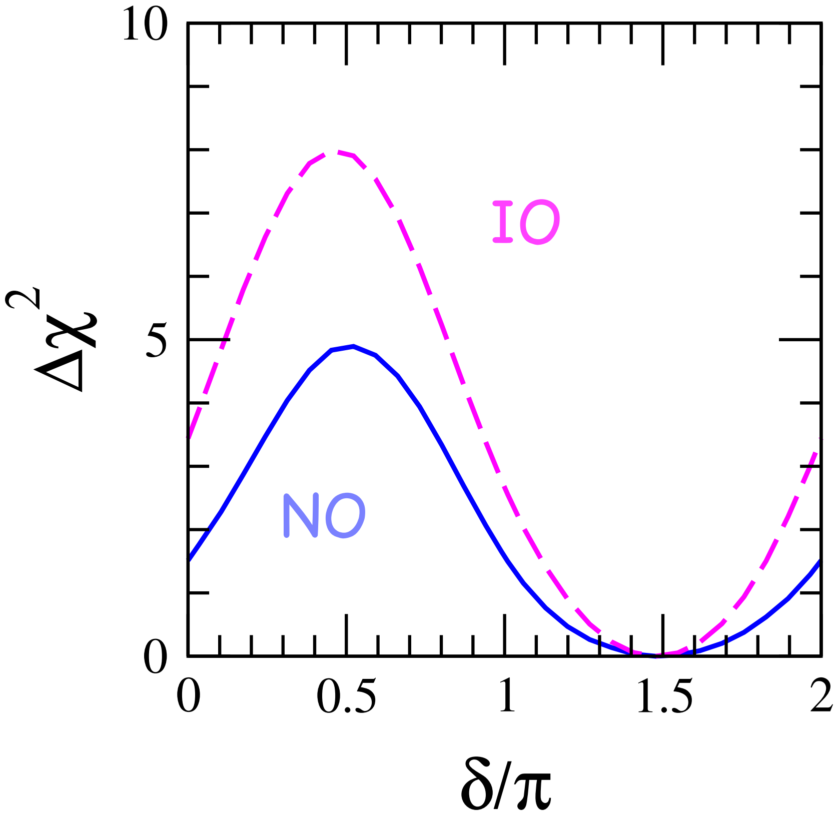
$$\delta/\pi = 1.56^{+0.22}_{-0.26} \quad \text{(IO)}$$

de Salas et al, 2017

δ = π/2 disfavoured at 2.7σ (3.7) for NO (IO)

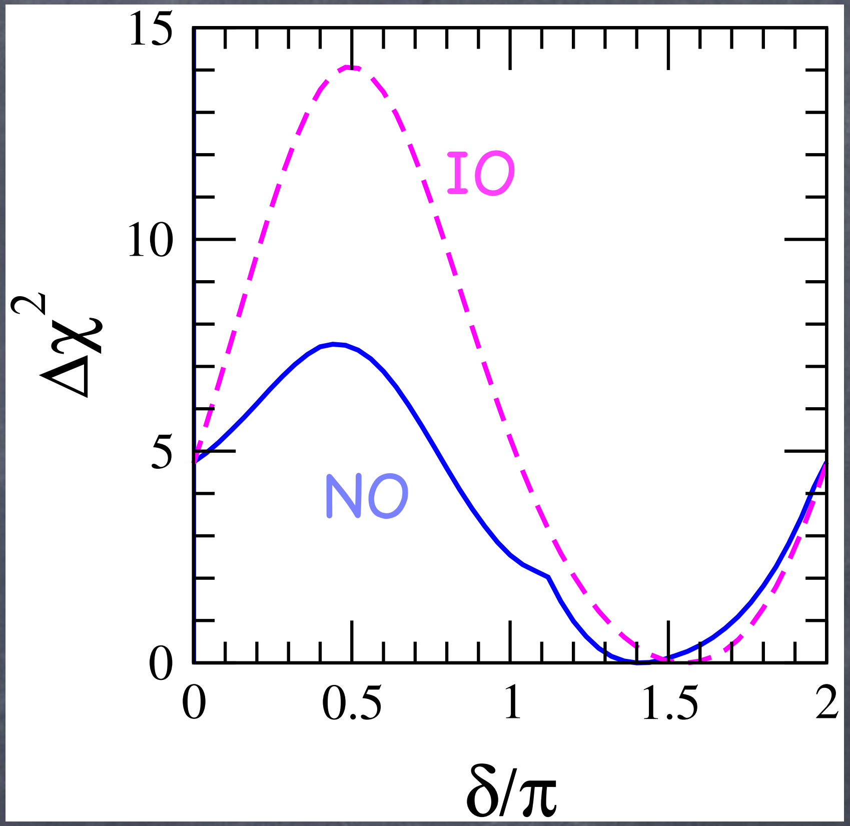
Impact of new data over δ_{CP} phase

Forero, MT, Valle 2014



- Best fit: δ ~ 1.5**π** for NO and IO
- NO: δ ~ **π**/2 disfavoured at 2.2σ
- IO: δ ~ **π**/2 disfavoured at 2.8σ

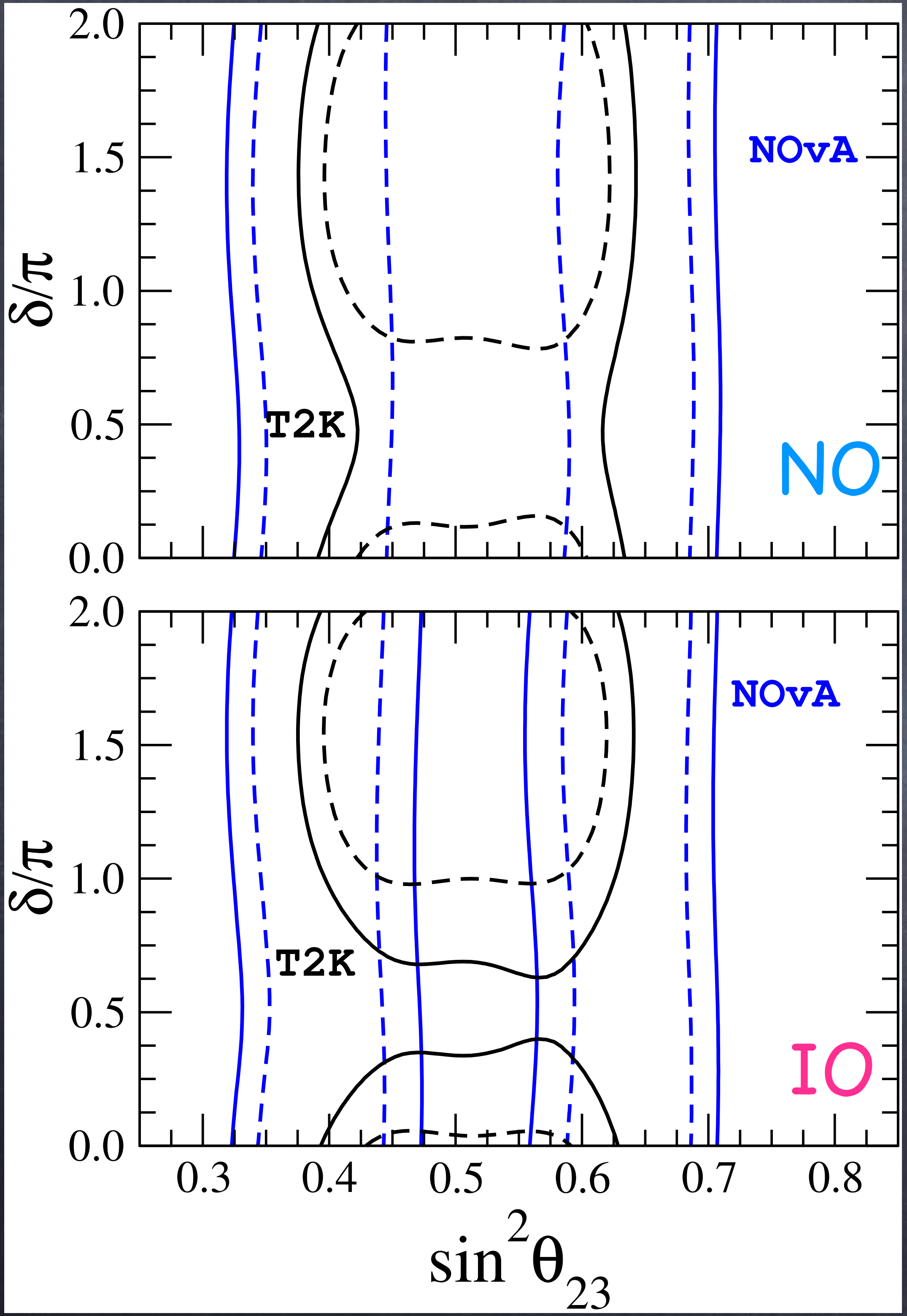
de Salas et al, 2017



- Best fit: δ ~ 1.5**π** for NO and IO
- NO: δ ~ **π**/2 disfavoured at 2.7σ
- IO: δ ~ **π**/2 disfavoured at 3.7/4.3σ

Full range [0,2**π**] allowed at 3σ for NO, disfavoured regions for IO

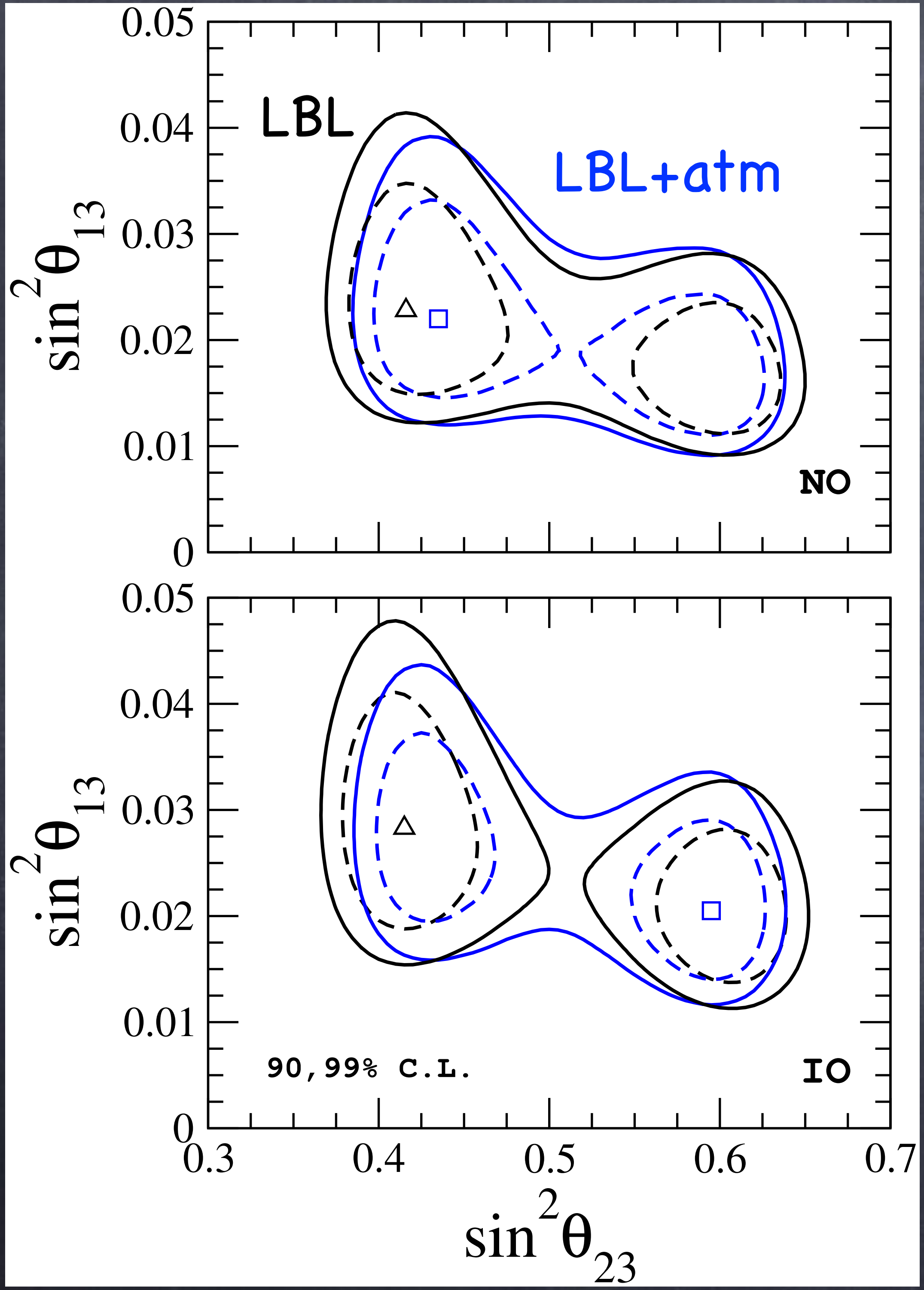
Sensitivity to the mass ordering



90, 99% C.L.

- $\Delta\chi^2 = 3.6$ from the combination of T2K + NOvA, due to the tension in θ_{23}, stronger for IO

Sensitivity to the mass ordering

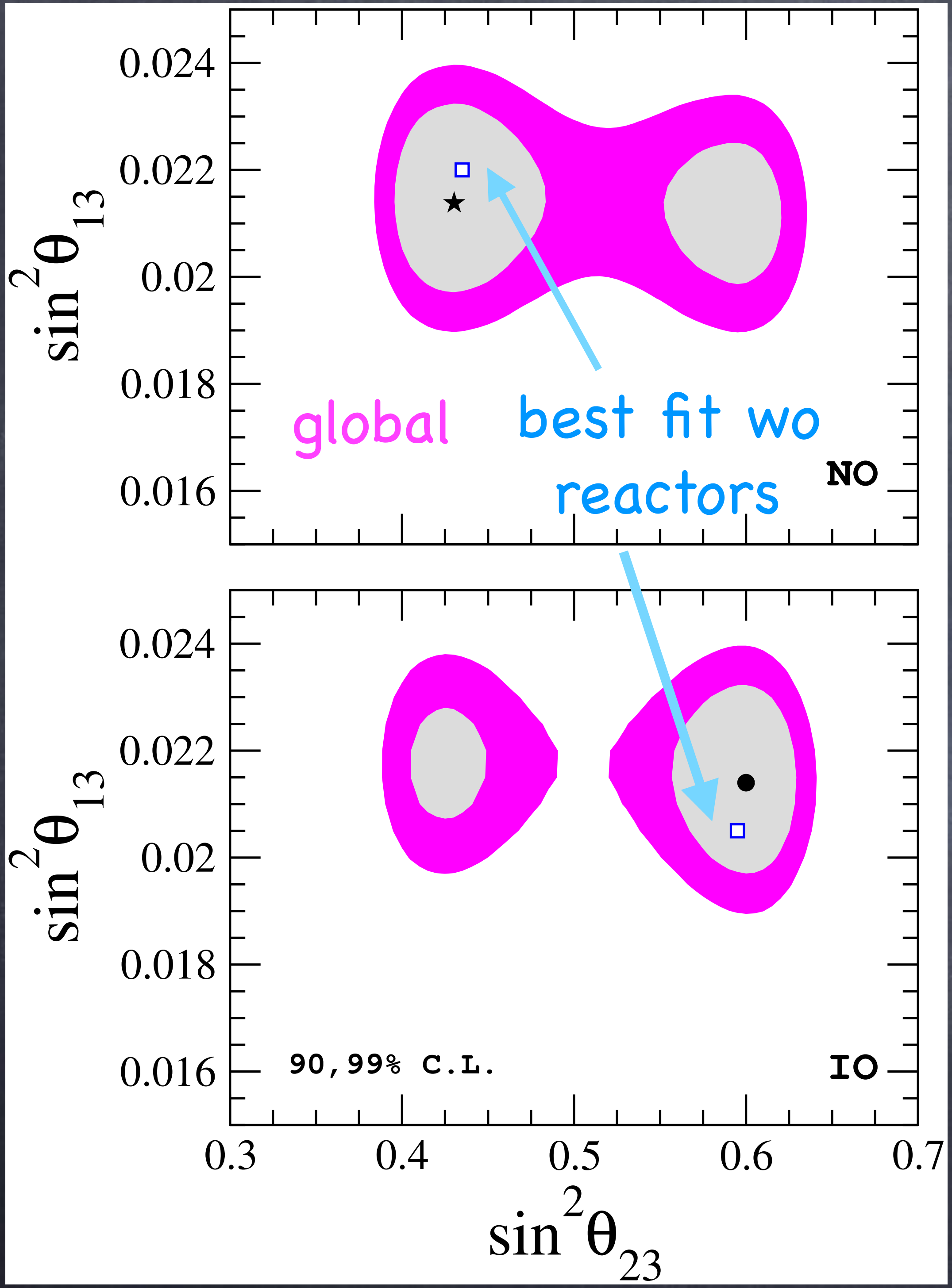


- $\Delta\chi^2 = 3.6$ from the combination of T2K + NOvA, due to the tension in θ_{23}, stronger for IO

- atm data improve max mixing and relax the tension down to $\Delta\chi^2 = 3.1$

90, 99% C.L.

Sensitivity to the mass ordering



- $\Delta\chi^2 = 3.6$ from the combination of T2K + NOvA, due to the tension in θ_{23}, stronger for IO

- atm data improve max mixing and relax the tension down to $\Delta\chi^2 = 3.1$

- combination with reactors worsens status of IO up to $\Delta\chi^2 = 4.3$, due to better agreement with θ_{13} for NO.

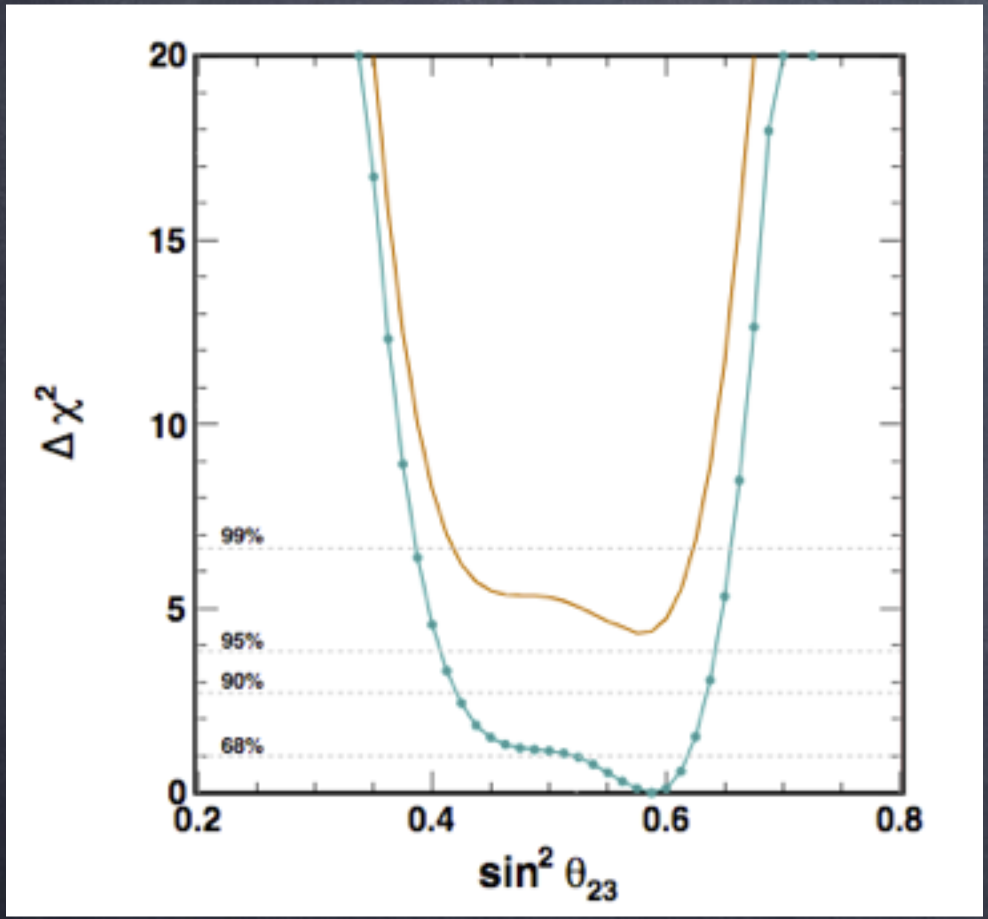
90, 99% C.L.

Global: $\Delta\chi^2$ (IO-NO) = 4.3

New data

Super-K IV atmos.

Abe et al, arXiv:1710.09126

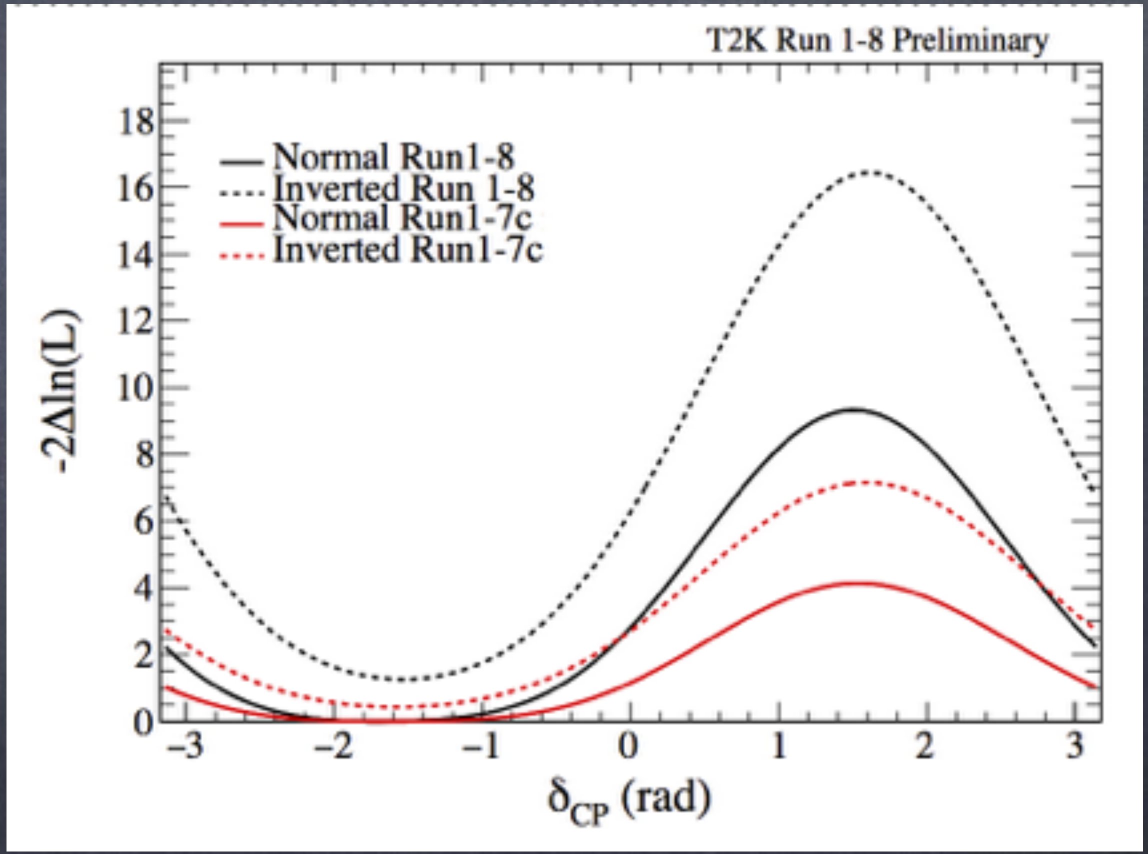


- 2nd octant for NO and IO
- preference for NO with $\Delta\chi^2 = 4.34$

T2K August 2017

M. Hartz, KEK seminar

(preliminary)



- improved CP sensitivity
- preference for NO and 2nd octant

Beyond 3-neutrino oscillations

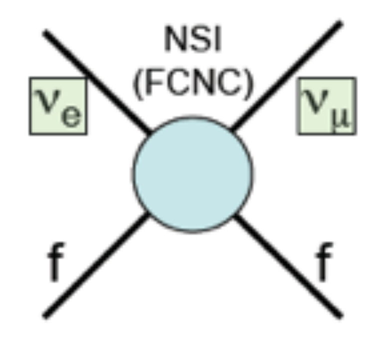
Beyond 3-neutrino oscillations

- Oscillations in presence of NSI
- Non-unitary neutrino mixing

Non-standard neutrino interactions

- NC interactions predicted in extensions of the SM:

  flavour-changing: $\nu_\alpha \, f \rightarrow \nu_\beta \, f$ non-universal: $\nu_\alpha \, f \rightarrow \nu_\alpha \, f$



- effective 4-fermion operator:

$$\mathcal{L}_{\rm NSI} = -\varepsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F (\bar\nu_\alpha \gamma_\mu L \nu_\beta)(\bar f \gamma^\mu P f)$$

- NSI may affect neutrino production, propagation and detection:

Wolfenstein 78, Valle 87, Roulet 91, Guzzo et al, 91

$$\mathcal{H}_F = \frac{1}{2E}\left\{ U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger + a_{\rm CC} \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ (\epsilon^m_{e\mu})^* & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ (\epsilon^m_{e\tau})^* & (\epsilon^m_{\mu\tau})^* & \epsilon^m_{\tau\tau} \end{pmatrix} \right\}$$

- bounds on NSI come mainly from:
  - ν scattering: LSND, CHARM, reactor exp. Barranco et al., 2005, 2007
  - $e^- e^+ \rightarrow \nu \, \nu \, \gamma$ at LEP Berezhiani & Rossi, 2002
  - atmospheric data Fornengo et al., 2002; Friedland et al., 2004, Maltoni 2008

NSI in solar ν propagation

$$L_{NSI} = -\varepsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F \left(\bar{\nu}_\alpha \gamma_\mu P \nu_\beta\right)\left(\bar{f}\gamma^\mu P f\right)$$

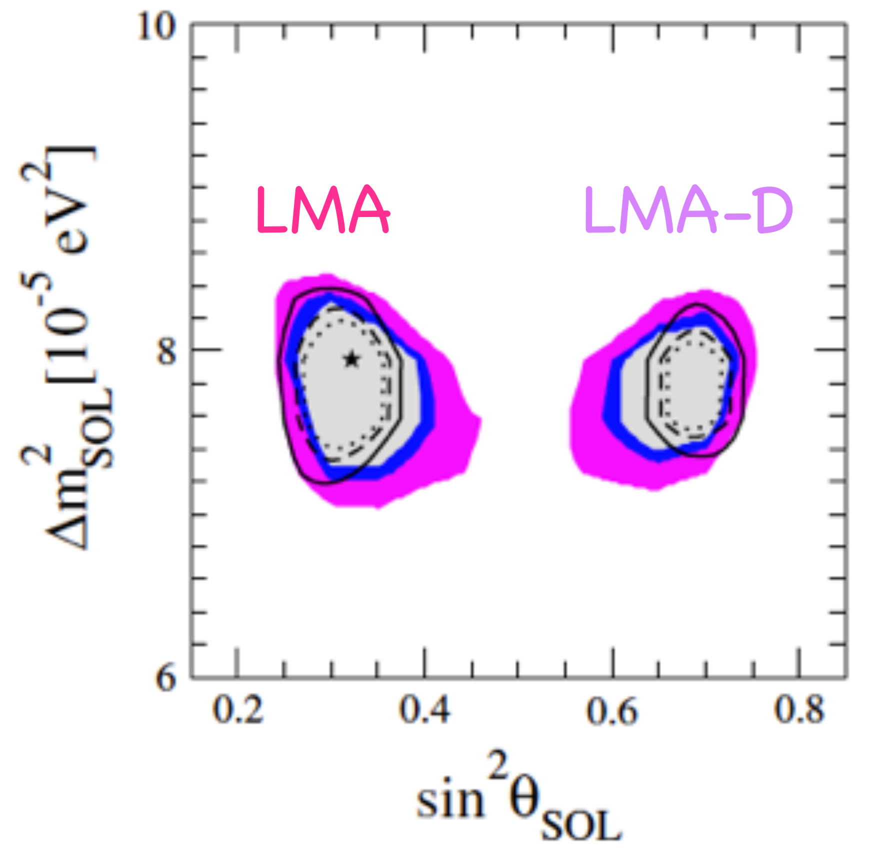
$$H_{NSI} = \sqrt{2} G_F N_f \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}$$

$$\varepsilon = -\sin\theta_{23}\, \varepsilon^{fV}_{e\tau}$$

$$\varepsilon' = \sin^2\theta_{23}\, \varepsilon^{fV}_{\tau\tau} - \varepsilon^{fV}_{ee}$$

- strong bounds on ε
- large ε′ allowed

⇒ degenerate solution $\theta_{SOL} > \pi/4$



degeneracy (θ_{sol}, ε′)

new solution for solar ν oscillations: LMA-Dark

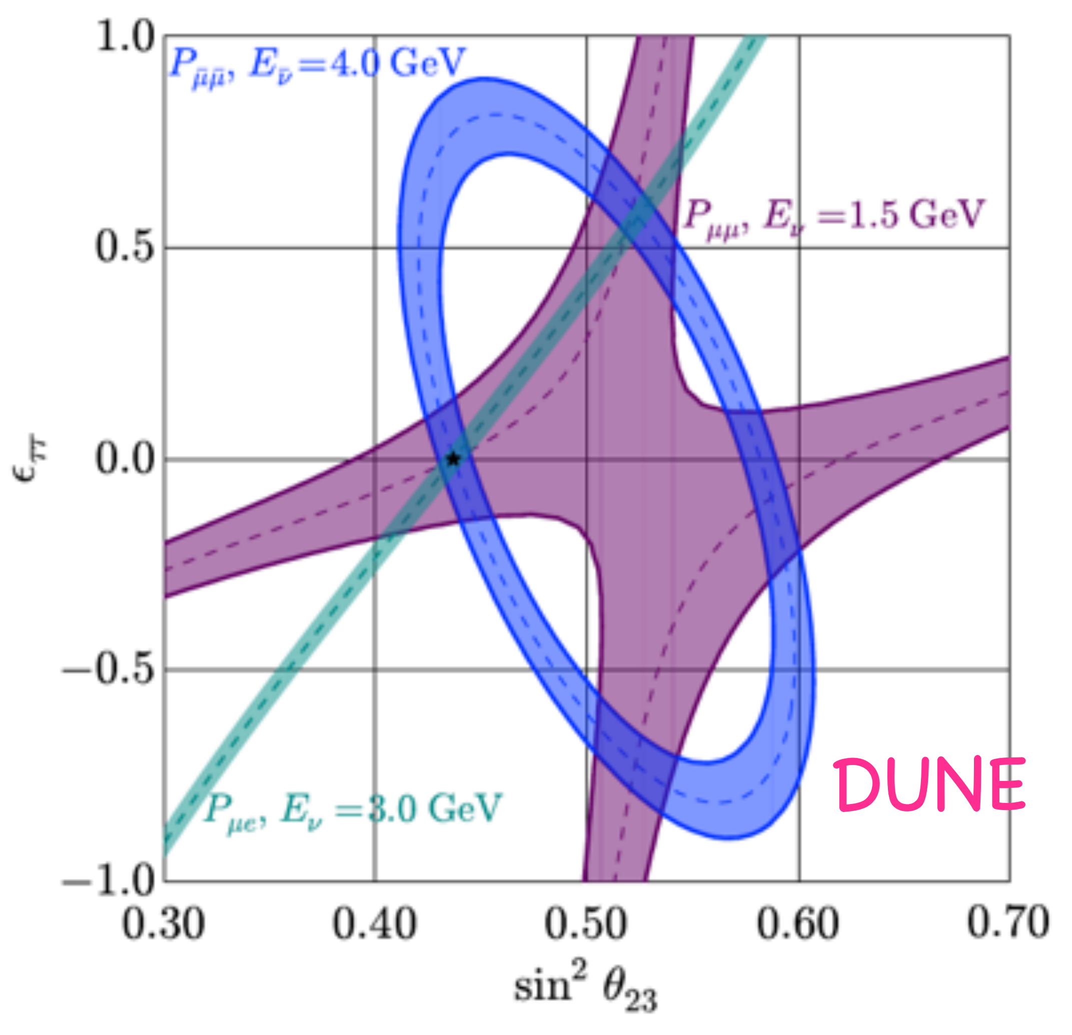
Miranda et al., JHEP 2006

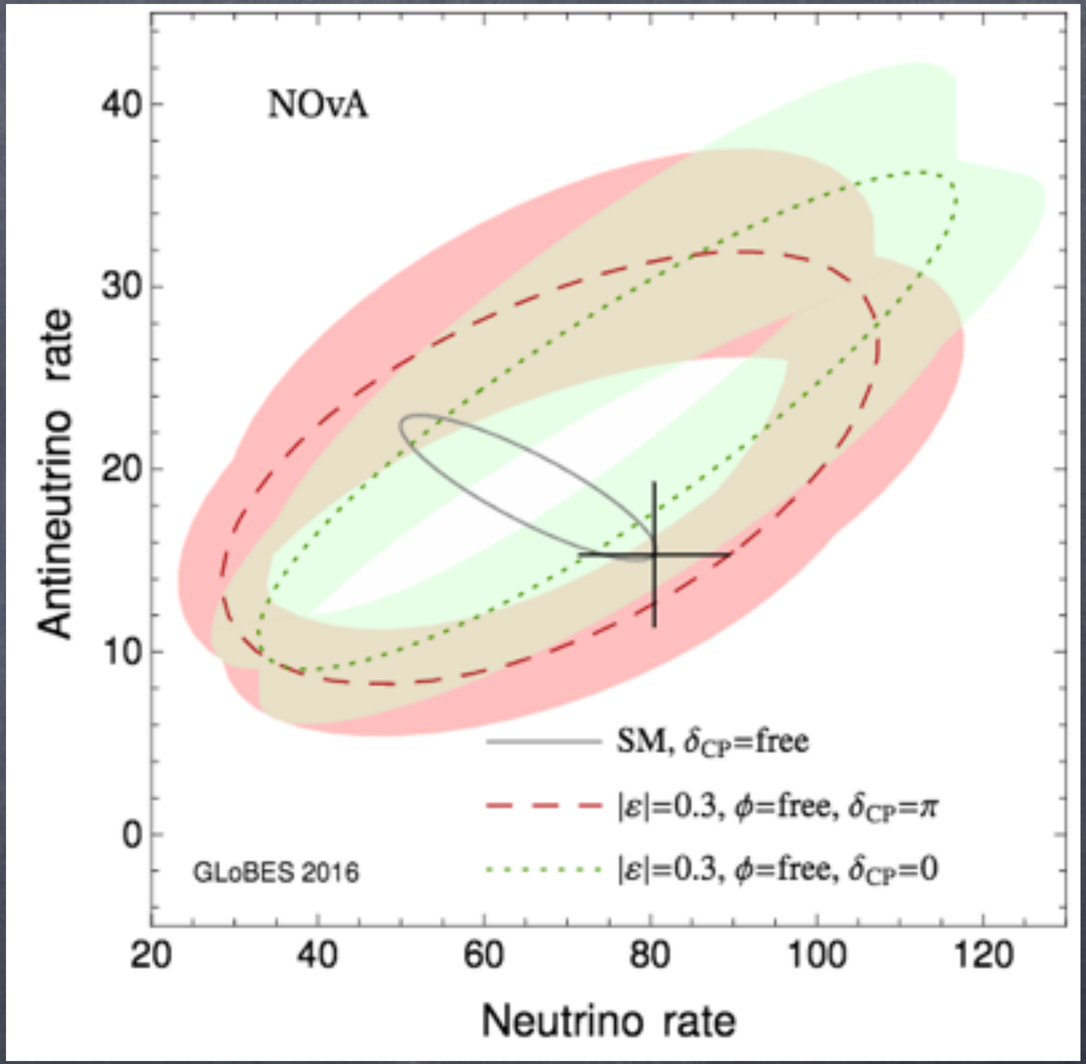
Escrihuela et al, PRD80 2009

generalized mass ordering degeneracy

Coloma and Schwetz, PRD94 2016

Other degeneracies in presence of NSI





degeneracy (θ_{23}, $\varepsilon_{\tau\tau}$)

degeneracy (δ_{CP}, ϕ)

Gouvea and Kelly, NPB908, 2016

Coloma, JHEP 1603, 2016

Forero and Huber, PRL117, 2016

NSI in reactor experiments

- CC-like NSI at the production / detection processes in Daya Bay may affect the robustness of the recent θ_{13} determination

$$
\begin{aligned}
P_{\bar{\nu}_e^s \to \bar{\nu}_e^d} \simeq\ & \underbrace{1 - \sin^2 2\theta_{13}\left(c_{12}^2 \sin^2\Delta_{31} + s_{12}^2 \sin^2\Delta_{32}\right) - c_{13}^4 \sin^2 2\theta_{12} \sin^2\Delta_{21}}_{\text{Standard Model terms}} \\
& + \underbrace{4|\varepsilon_e|\cos\phi_e + 4|\varepsilon_e|^2 + 2|\varepsilon_e|^2\cos 2\phi_e + 2|\varepsilon_\mu|^2 + 2|\varepsilon_\tau|^2}_{\text{non}-\text{oscillatory NSI terms}} \\
& - \underbrace{4\{s_{23}^2|\varepsilon_\mu|^2 + c_{23}^2|\varepsilon_\tau|^2 + 2s_{23}c_{23}|\varepsilon_\mu||\varepsilon_\tau|\cos(\phi_\mu - \phi_\tau)\}\sin^2\Delta_{31}}_{\text{oscillatory NSI terms}} \\
& - \underbrace{4\{2s_{13}[s_{23}|\varepsilon_\mu|\cos(\delta - \phi_\mu) + c_{23}|\varepsilon_\tau|\cos(\delta - \phi_\tau)]\}\sin^2\Delta_{31}}_{\text{oscillatory NSI terms}}.
\end{aligned}
$$

shift in θ_{13}:

$$
\begin{aligned}
s_{13}^2 \to\ & s_{13}^2 + s_{23}^2|\varepsilon_\mu|^2 + c_{23}^2|\varepsilon_\tau|^2 + 2s_{23}c_{23}|\varepsilon_\mu||\varepsilon_\tau|\cos(\phi_\mu - \phi_\tau) \\
& + 2s_{13}\left[s_{23}|\varepsilon_\mu|\cos(\delta - \phi_\mu) + c_{23}|\varepsilon_\tau|\cos(\delta - \phi_\tau)\right]
\end{aligned}
$$

Leitner et al, JHEP 2011

previous bounds: $|\varepsilon_{e,\tau}| < 0.041\,,\ |\varepsilon_\mu| < 0.026\,,\ (90\%\,\text{C.L.})$

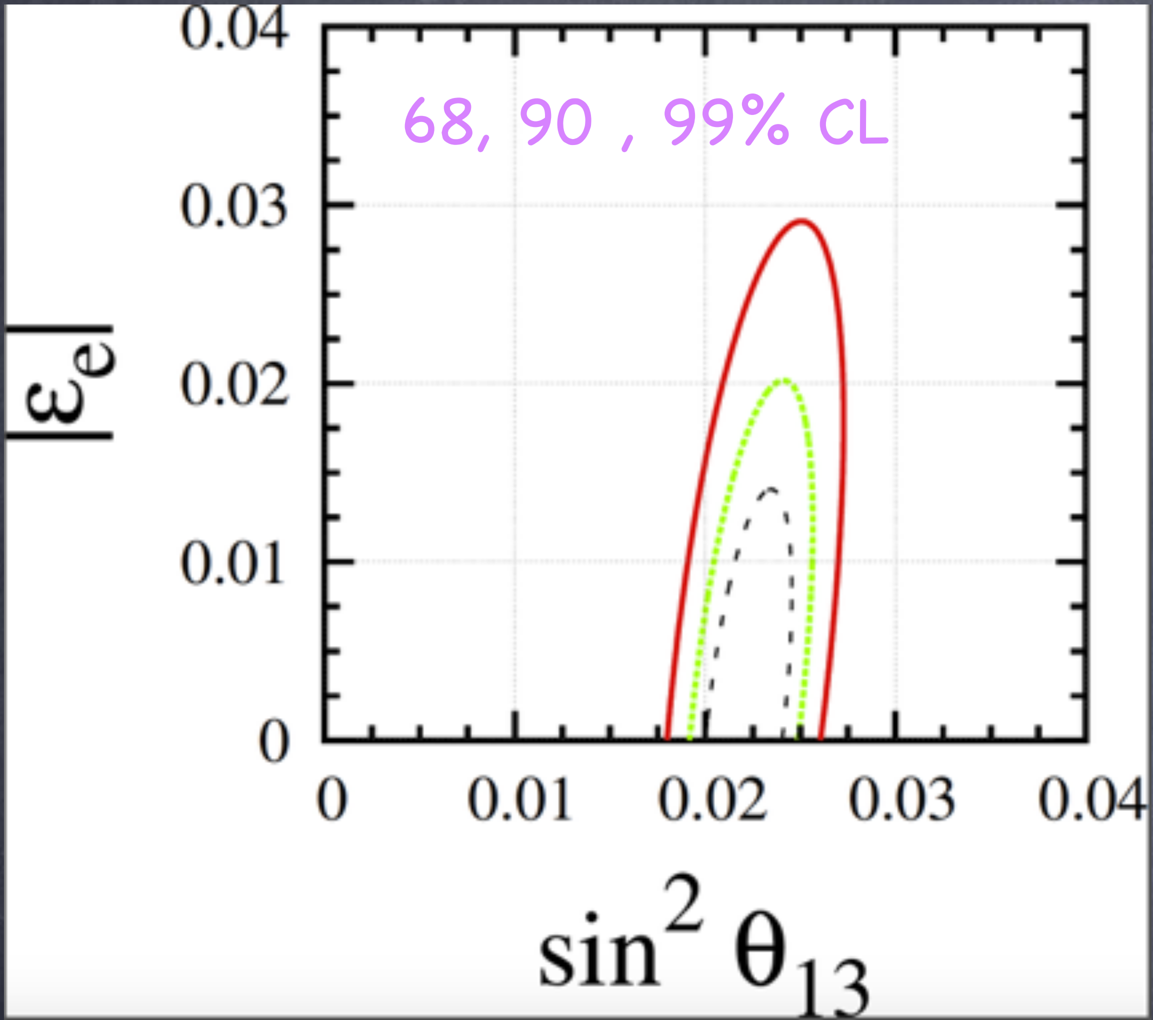
Biggio et al, JHEP 2009

→ study robustness of θ_{13} measurement

→ derive bounds on NSI couplings with Daya Bay data

NSI in Daya Bay

621 days rate

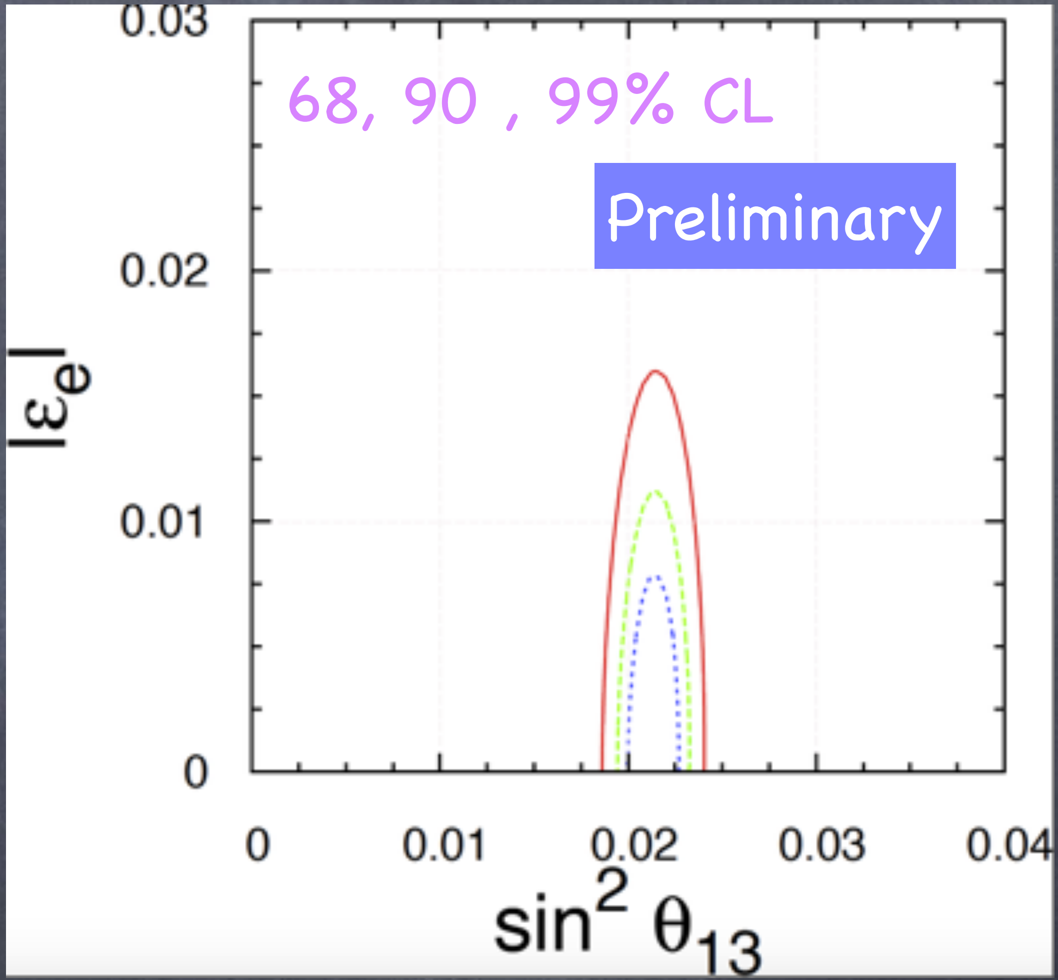


5% uncert on flux

$$|\varepsilon_e| < 0.015\,(90\%\,\text{C.L.})$$

improved bound on ε_e

1230 days spectrum



2% uncert on flux

$$|\varepsilon_e| < 0.007\,(90\%\,\text{C.L.})$$

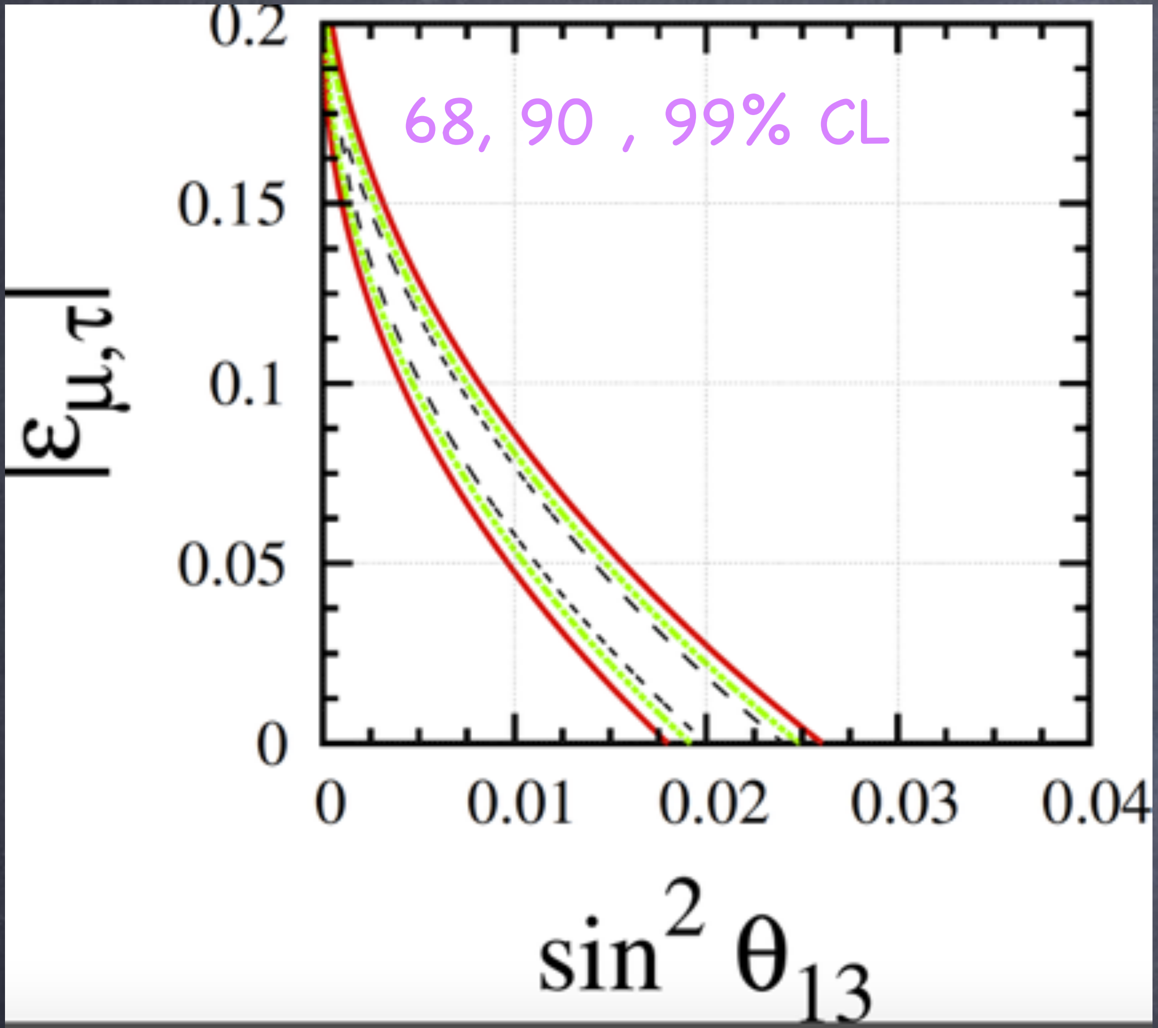
robust θ_{13} determination

Agarwalla et al, JHEP 2015

Agarwalla et al, in progress

NSI in Daya Bay

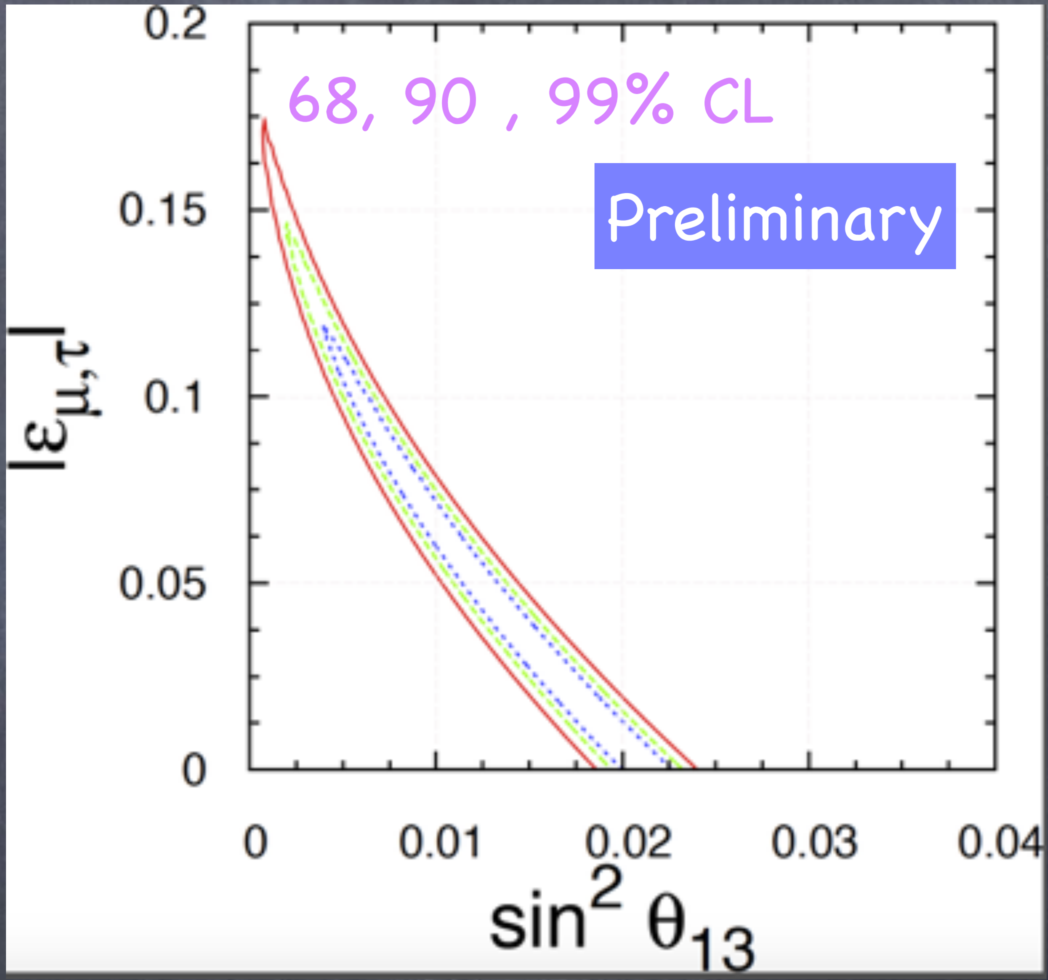
621 days rate



5% uncert on flux

$$|\varepsilon_{\mu,\tau}| < 0.176\,(90\%\,\text{C.L.})$$

1230 days spectrum



2% uncert on flux

$$|\varepsilon_{\mu,\tau}| < 0.12\,(90\%\,\text{C.L.})$$

θ_{13} determination may be affected by NSI

Agarwalla et al, JHEP 2015

Agarwalla et al, in progress

Beyond 3-neutrino oscillations

- Oscillations in presence of NSI
- Non-unitary neutrino mixing

Non-unitary light neutrino mixing

- Most models of neutrino masses -> extra heavy states

Ex: type I seesaw, inverse seesaw

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

$$\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

Minkowski 1977, Gell-Mann Ramond Slanski 1979,
Yanagida 1979, Mohapatra Senjanovic 80,
Schechter Valle 1980.

Mohapatra-Valle, 86

- NxN mixing matrix with:

N(N-1)/2 mixing angles and (N-1)(N-2)/2 Dirac CP phases

$\rightarrow$ (3x3) light neutrino mixing matrix non-unitary in general

General parameterization of NU mixing

- NxN mixing matrix:

Okubo, PTP1962

$$U^{n\times n} = \omega_{n-1\,n}\,\omega_{n-2\,n}\,\ldots\,\omega_{1\,n}\,\omega_{n-2\,n-1}\,\omega_{n-3\,n-1}\,\ldots\,\omega_{1\,n-1}\,\ldots\,\omega_{2\,3}\,\omega_{1\,3}\,\omega_{1\,2}$$

ω_{ij} ≡ complex rotation matrix in the i-j plane

$$\omega_{13} = \begin{pmatrix} c_{13} & 0 & e^{-i\phi_{13}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\phi_{13}} s_{13} & 0 & c_{13} \end{pmatrix}$$

→ $$U^{n\times n} = \begin{pmatrix} N & W \\ V & T \end{pmatrix}$$

Hettmansperger et al, JHEP2011

and the (3x3) light block:

$$N = N^{NP}\,U^{3\times3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times3}$$

See Xing, PRD2012 for n=6

Escrihuela et al, PRD92 (2015)

See also Fernandez-Martinez et al, PLB2007

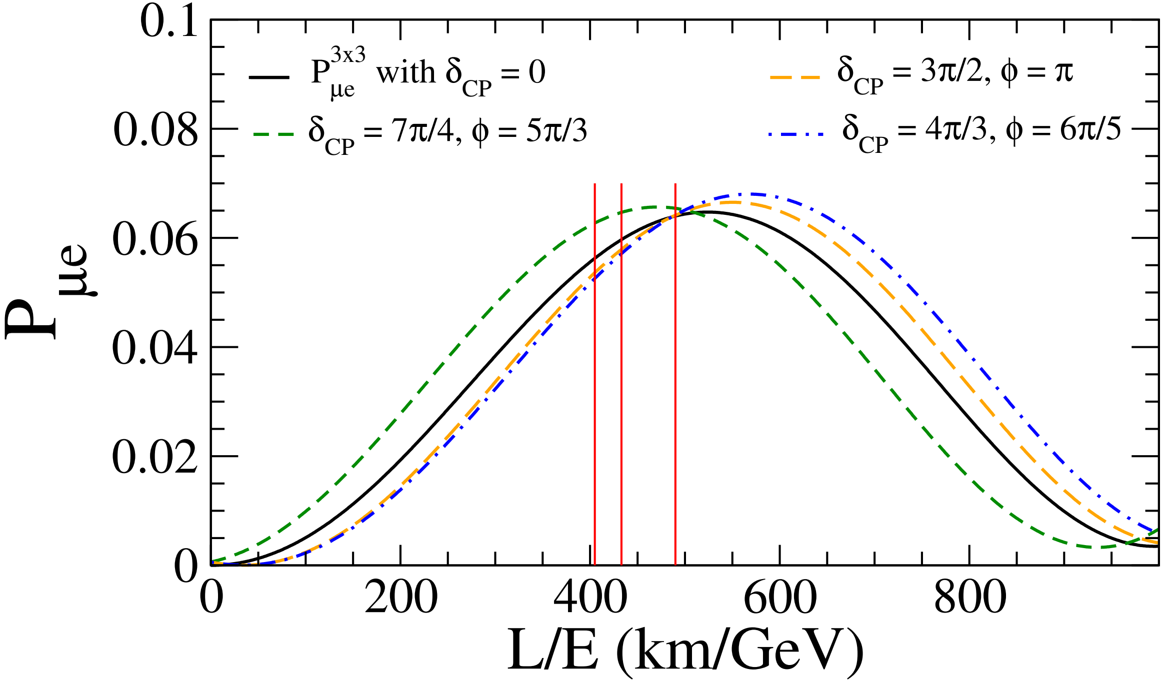
CP degeneracies in Pμe with NU

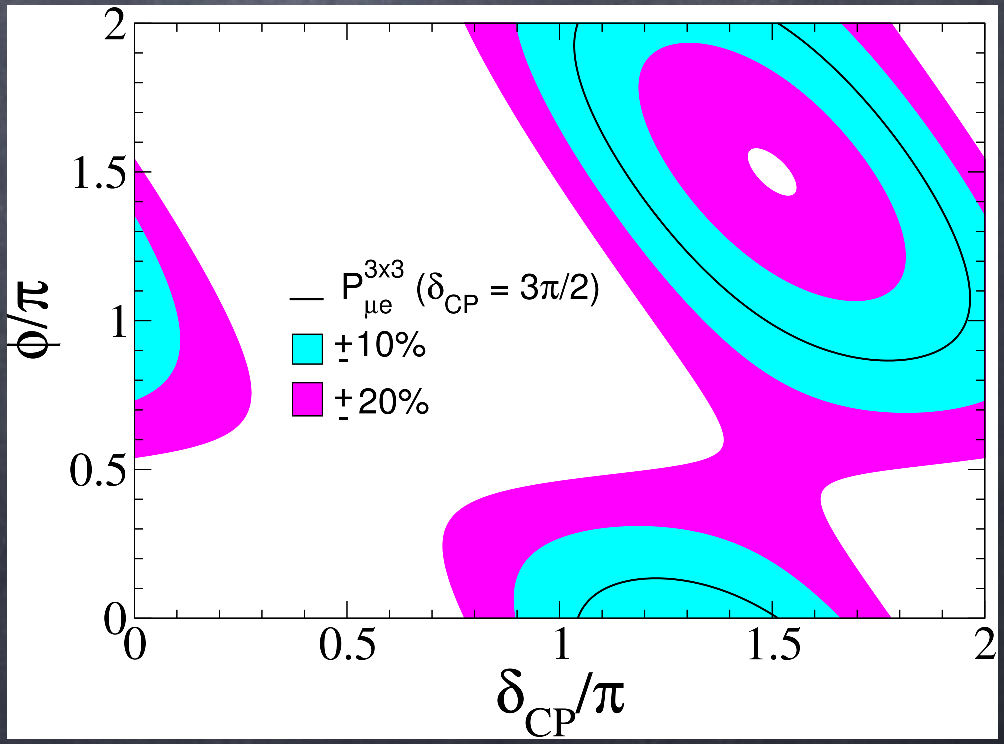
$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P^{3\times 3}_{\mu e} + \alpha_{11}^2\alpha_{22}|\alpha_{21}|P^{I}_{\mu e} + \alpha_{11}^2|\alpha_{21}|^2$$

$$\begin{array}{rcl} P^{3\times 3}_{\mu e} & = & 4\left(\cos^2\theta_{12}\cos^2\theta_{23}\sin^2\theta_{12}\sin^2\Delta_{21} + \cos^2\theta_{13}\sin^2\theta_{13}\sin^2\theta_{23}\sin^2\Delta_{31}\right) \\ & + & \sin 2\theta_{12}\sin\theta_{13}\sin 2\theta_{23}\sin 2\Delta_{21}\sin\Delta_{31}\cos\left(\Delta_{31} + \delta_{\mathrm{CP}}\right) \end{array}$$

$$\begin{array}{rcl} P^{I}_{\mu e} = & - & 2\sin 2\theta_{13}\sin\theta_{23}\sin\Delta_{31}\sin\left(\Delta_{31} + \delta_{CP} + \phi\right) \\ & - & \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}\sin 2\Delta_{21}\sin\phi \end{array}$$

→ degeneracies in the (δ, ϕ) plane



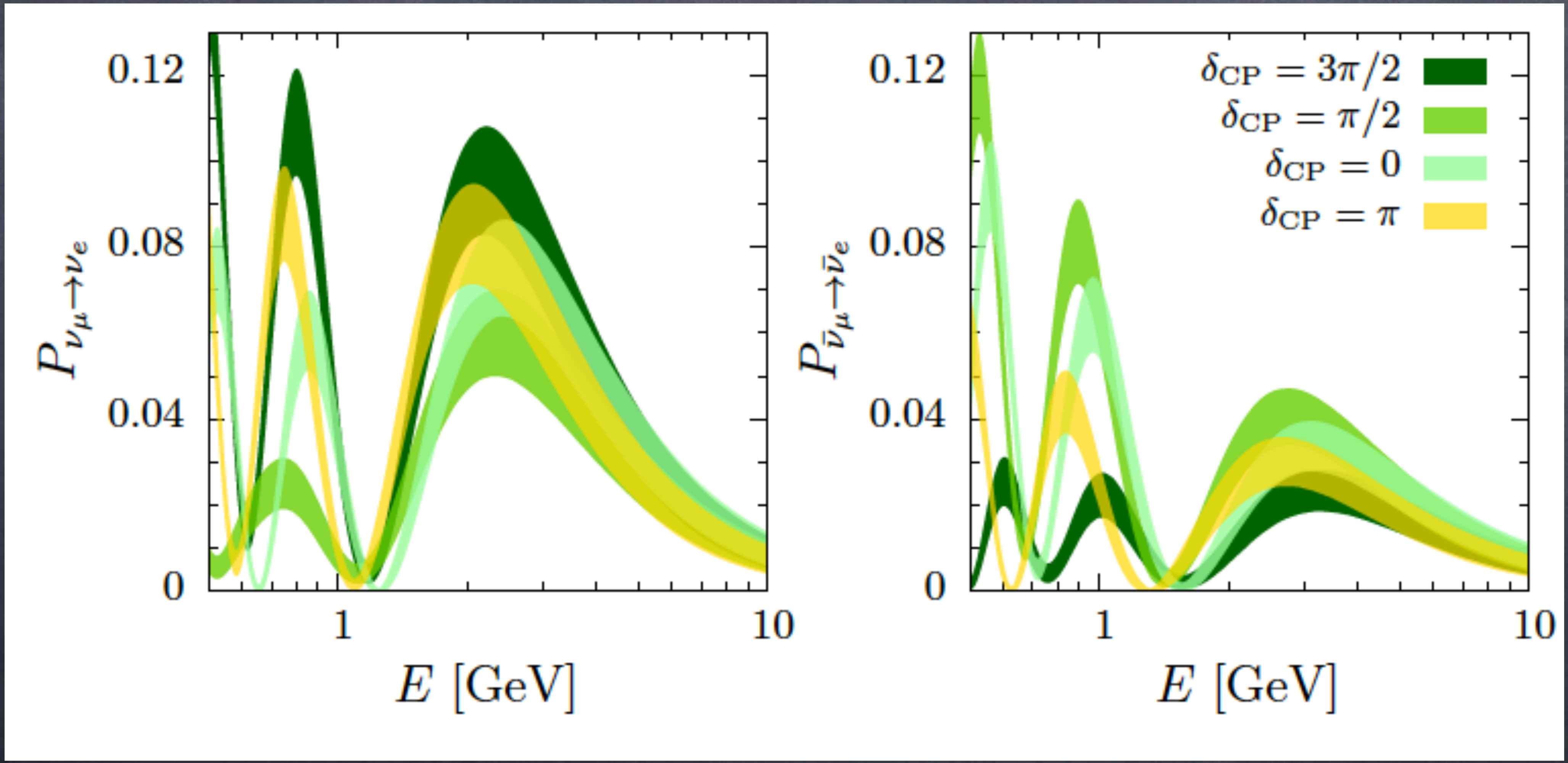


Miranda, MT, Valle, PRL 117 (2016)

NU neutrino oscillations in DUNE

The standard oscillation picture in DUNE gets modified due to NU

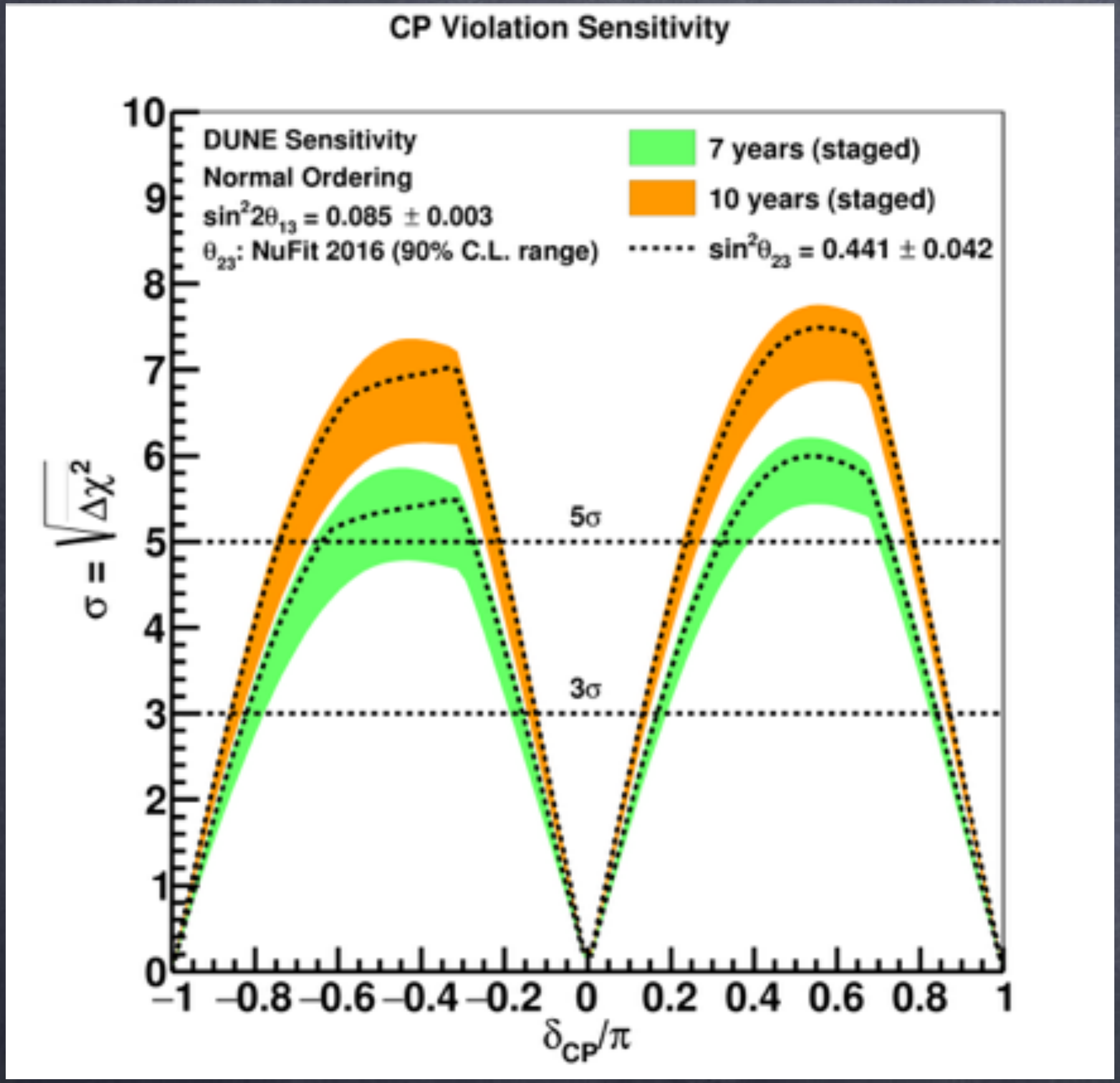
Here: α_{ii} = 1, $|\alpha_{21}|$ = 0.02, ϕ free (α_{3i} enter in $P_{\mu e}$ through matter effects)

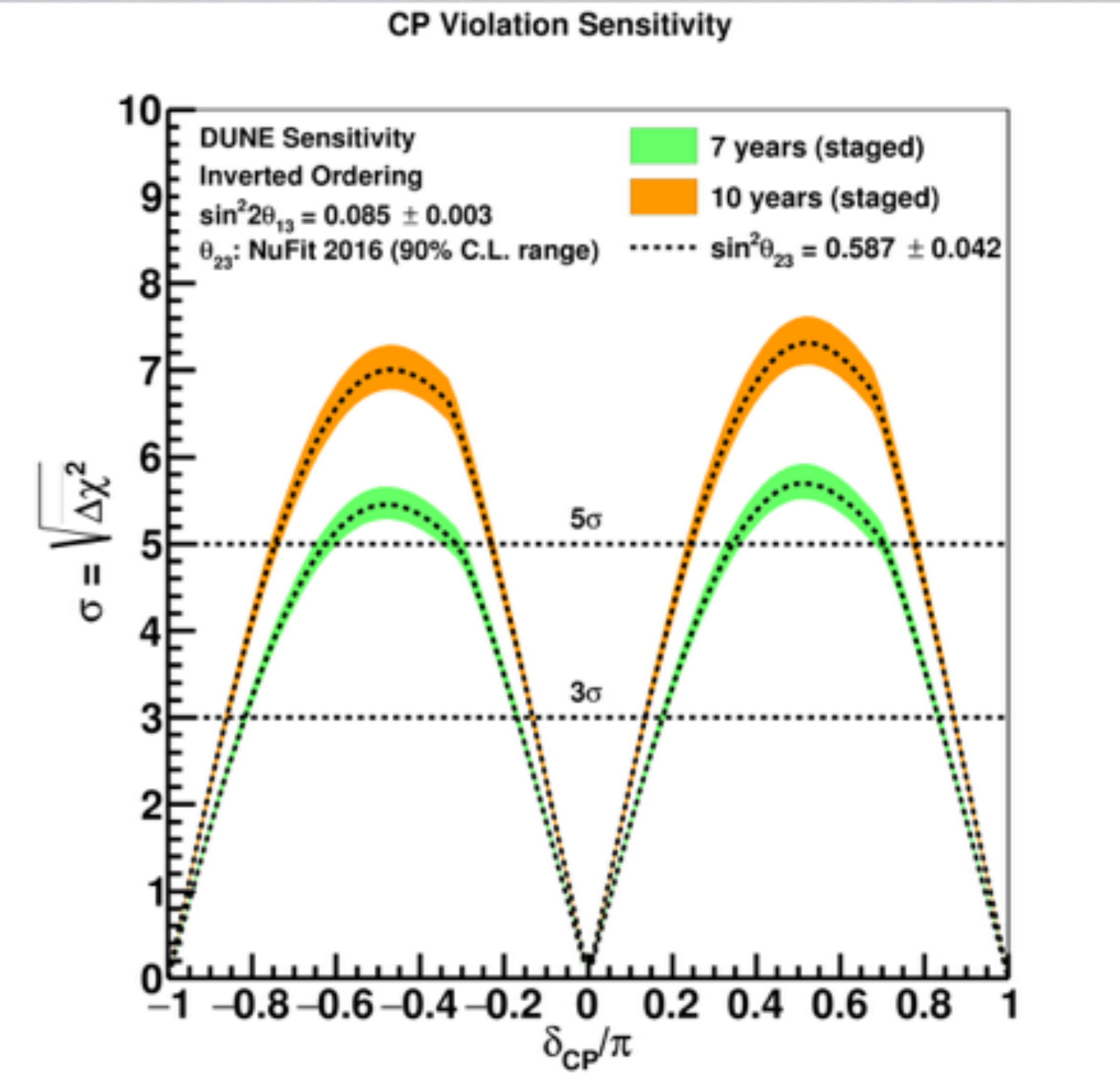


→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E≳ 3 GeV in both channels

Escrihuela et al, NJP 2017

CP violation searches in DUNE

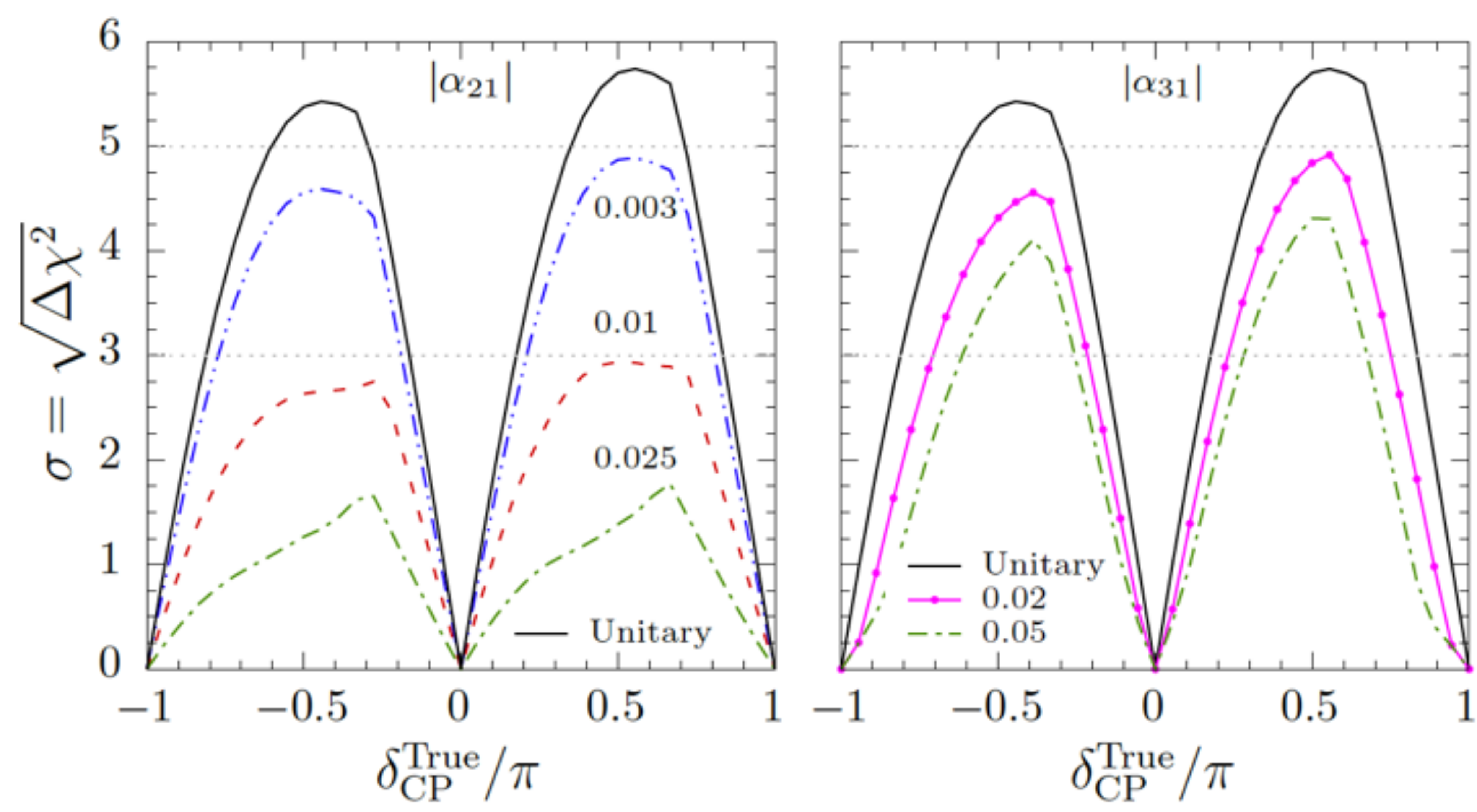




$> 5\sigma$ sensitivity for some fraction of δ_{CP}

E. Worcester, DUNE Collaboration

DUNE CP sensitivity with NU



Escrihuela et al, NJP 2017

- ➡ probing maximal CP violation may be a challenge for large α_{21}.
- ➡ the impact of α_{31} and α_{32} is less relevant.
- ➡ weaker effect wrt probability analysis due to wide beam in DUNE

Summary

- The precision in the determination of the “known” oscillation parameters has improved thanks to the last LBL and reactor data.
- The sensitivity to the mass ordering, the octant of atmospheric angle and the CP violation phase has increased in the last years, although we are still far from a measurement.
- The presence of new physics beyond the Standard Model may affect significantly the current picture of neutrino oscillations.
- Neutrino NSI with matter or Non-unitary neutrino mixing expected in models of neutrino masses may reduce the sensitivity of current and future reactor and LBL experiments.