Three-flavour neutrino oscillations and beyond

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ASTROPARTICLES Astroparticles and High Energy Physics Group IFIC INSTITUT DE FISICA CORPUSCULAR CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS 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

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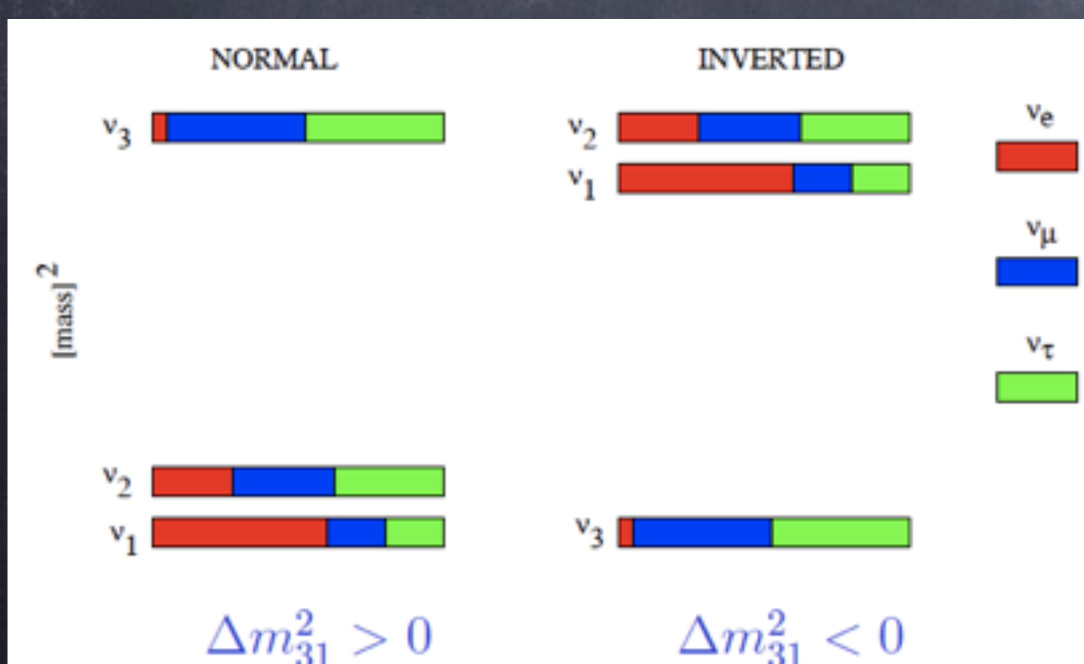
- two possible mass orderings:



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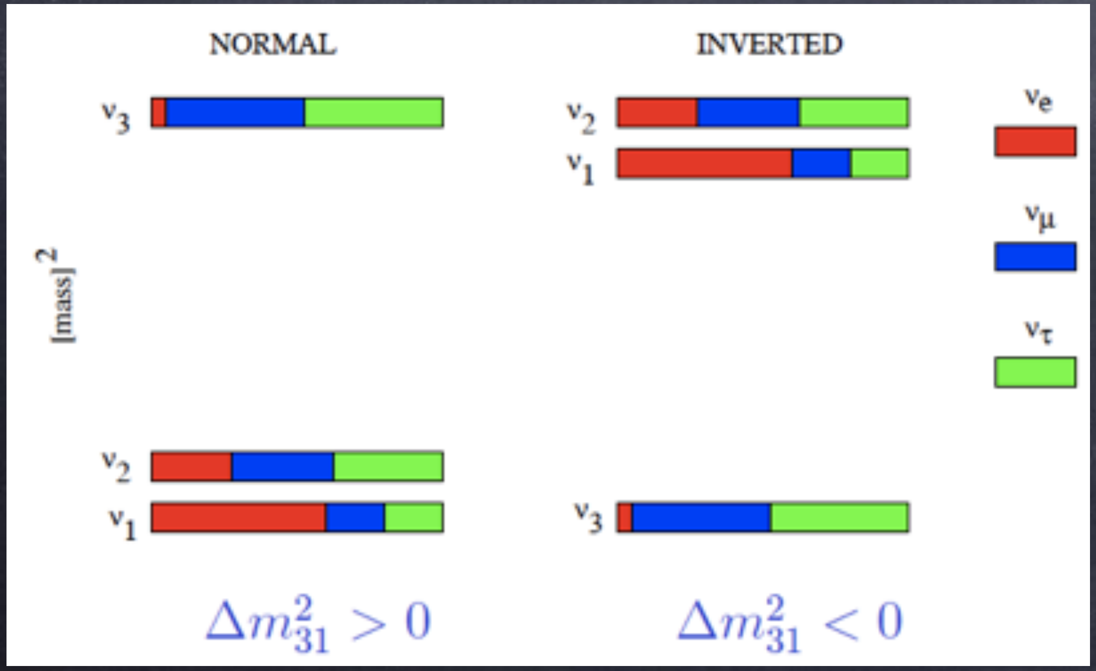

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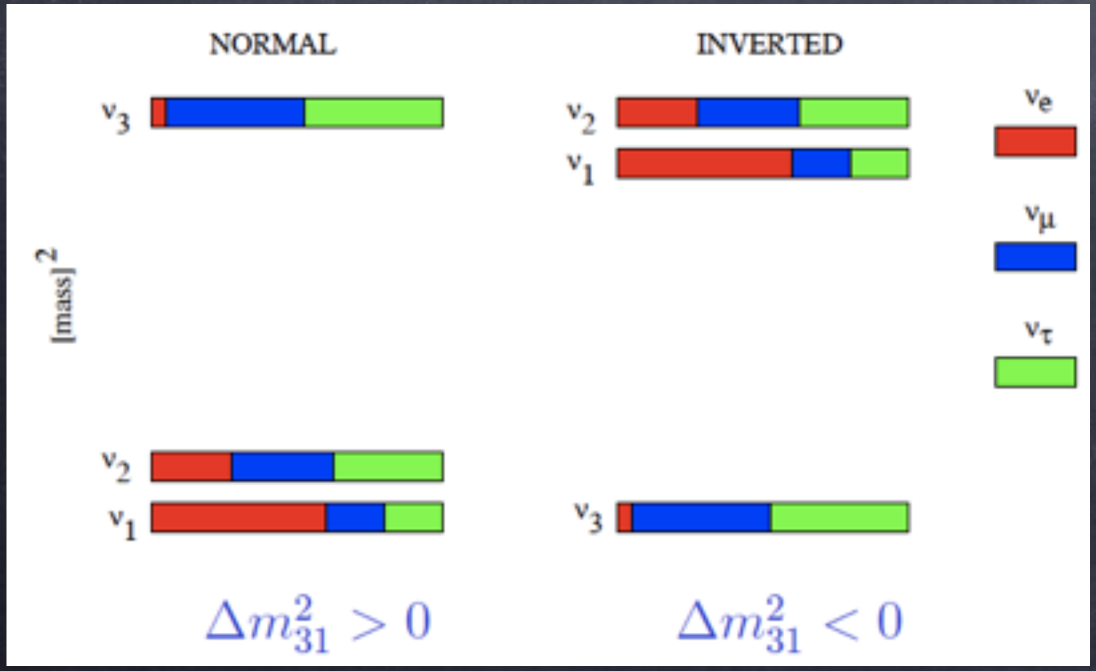

measured parameters:
θ_{12}, θ_{23}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{31}|$

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

two-neutrino approximation:

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

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

solar + KamLAND

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

SBL reactor

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three-neutrino analysis:

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

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

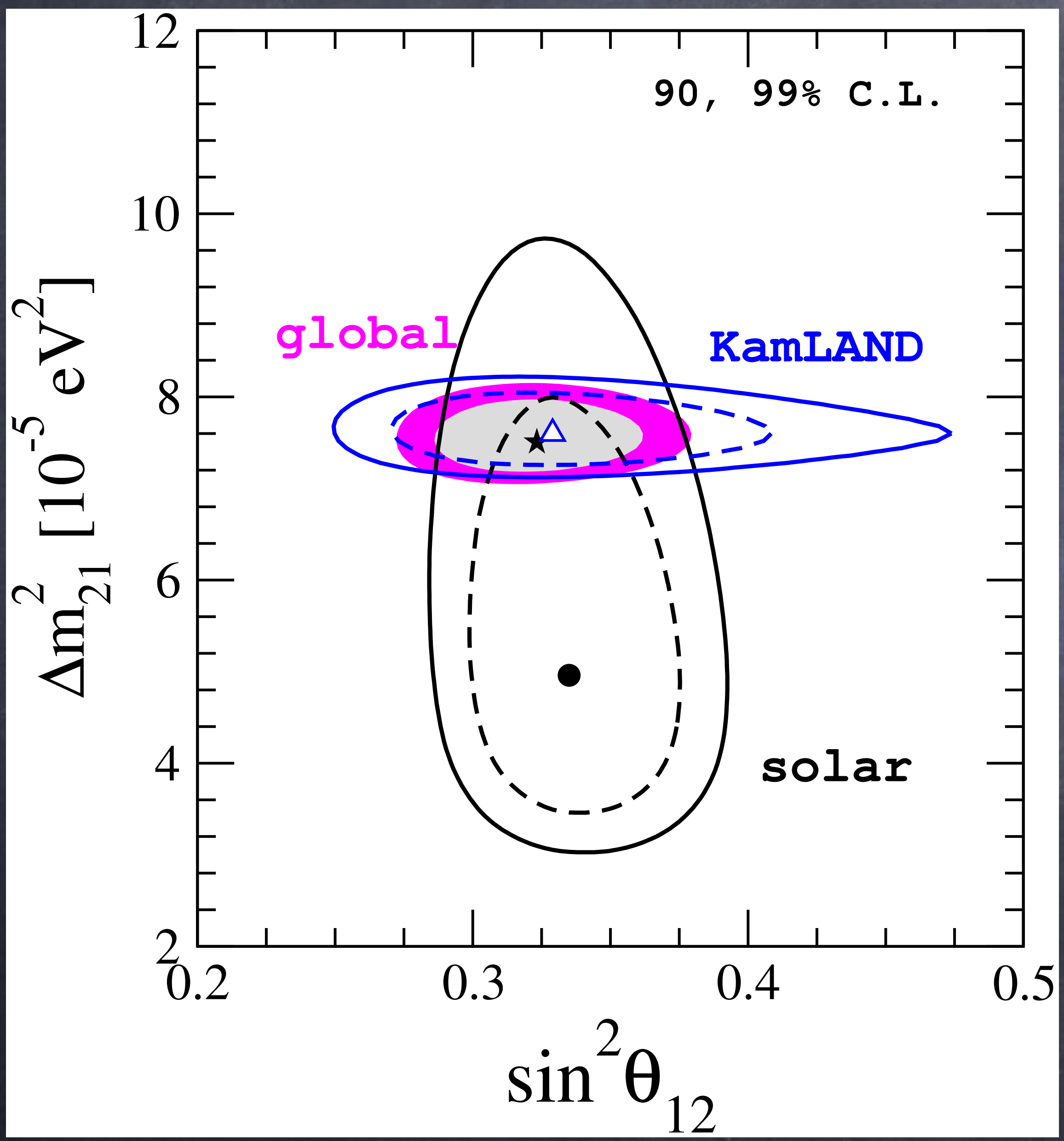
$\theta_{23}, \Delta m^2_{31}, \theta_{13},$

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

Global analysis of 3-flavour neutrino oscillations

Solar sector

New data: 2055-day D/N spectrum SK-IV   Nakano, PhD Thesis



de Salas et al, 2017

Best fit point:

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

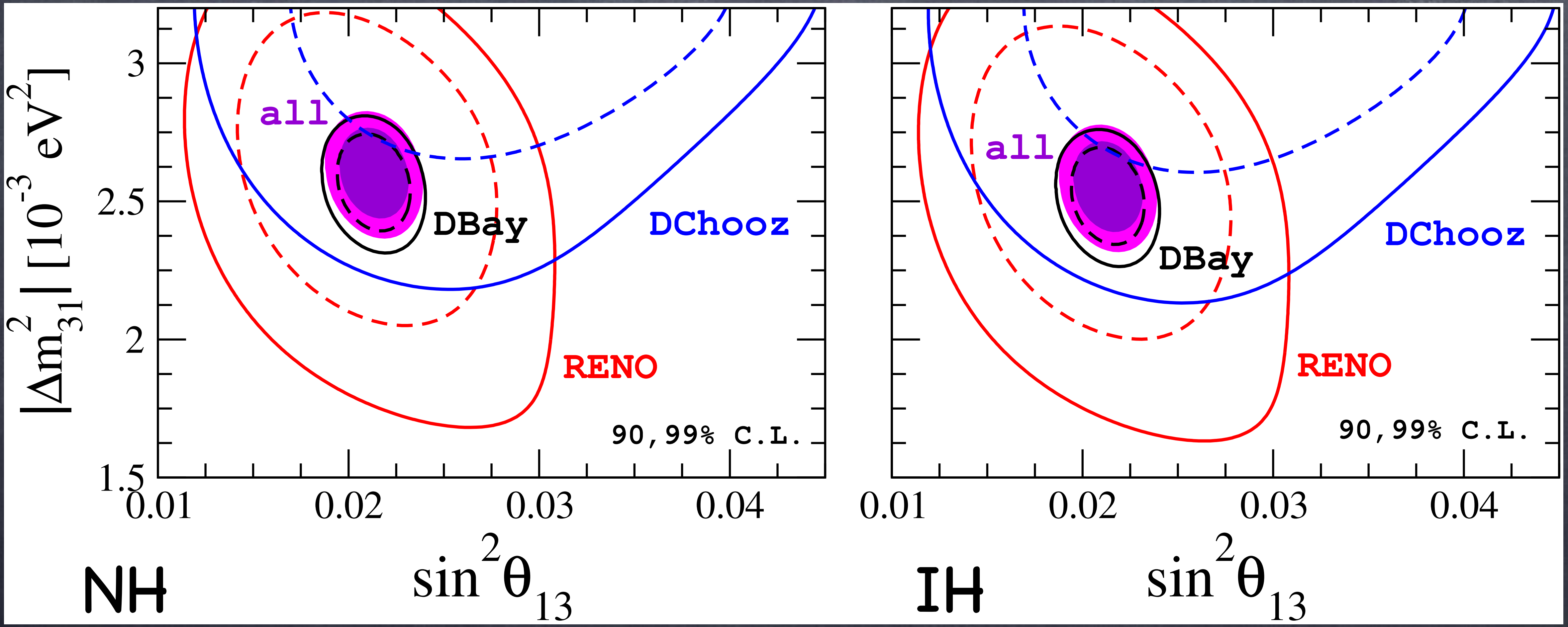
$\Delta m^2_{21} = 7.56 \pm 0.19 \times 10^{-5}$ eV^2

- 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

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



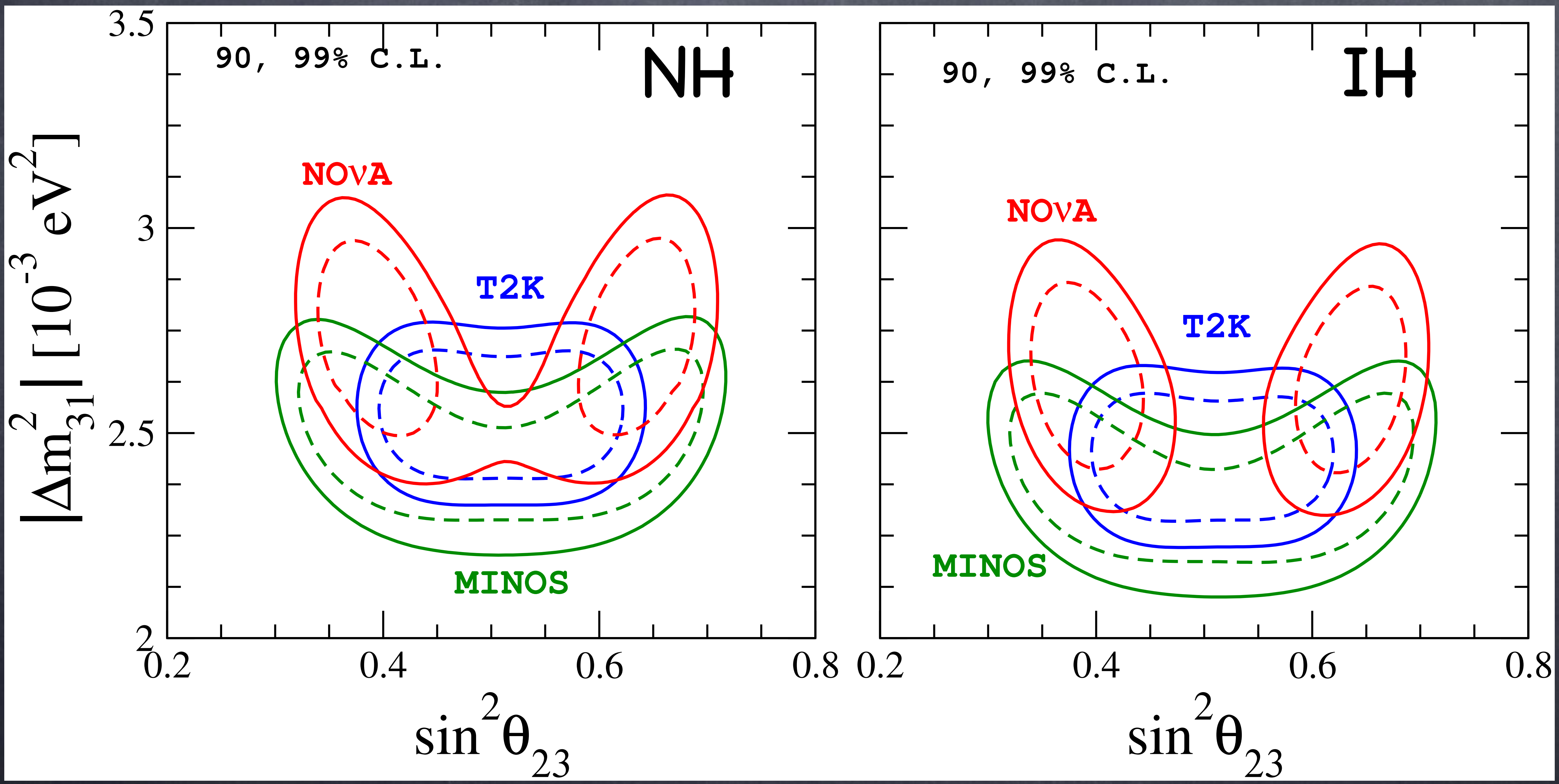
Best Fit: $\sin^2\theta_{13} = 0.02155^{+0.00090}_{-0.00075}$ $\sin^2\theta_{13} = 0.02140^{+0.00082}_{-0.00085}$

RENO favours lower value of θ_{13}

Daya Bay increase precision on θ_{13}

Accelerator LBL experiments

New data: T2K antineutrino data + latest NOνA data

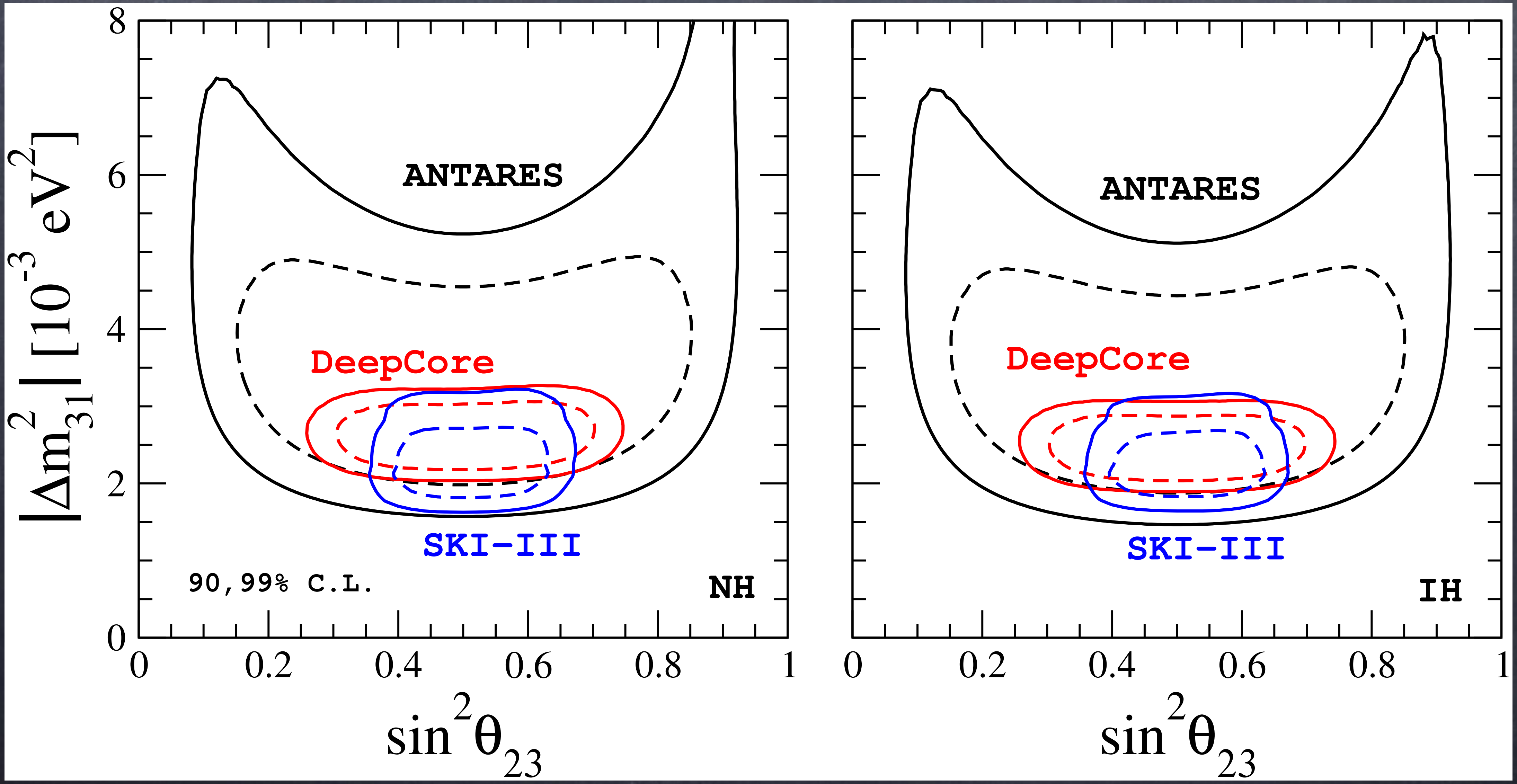


T2K prefers maximal mixing while NOvA disfavours θ_{23} = 45 at more than 2σ

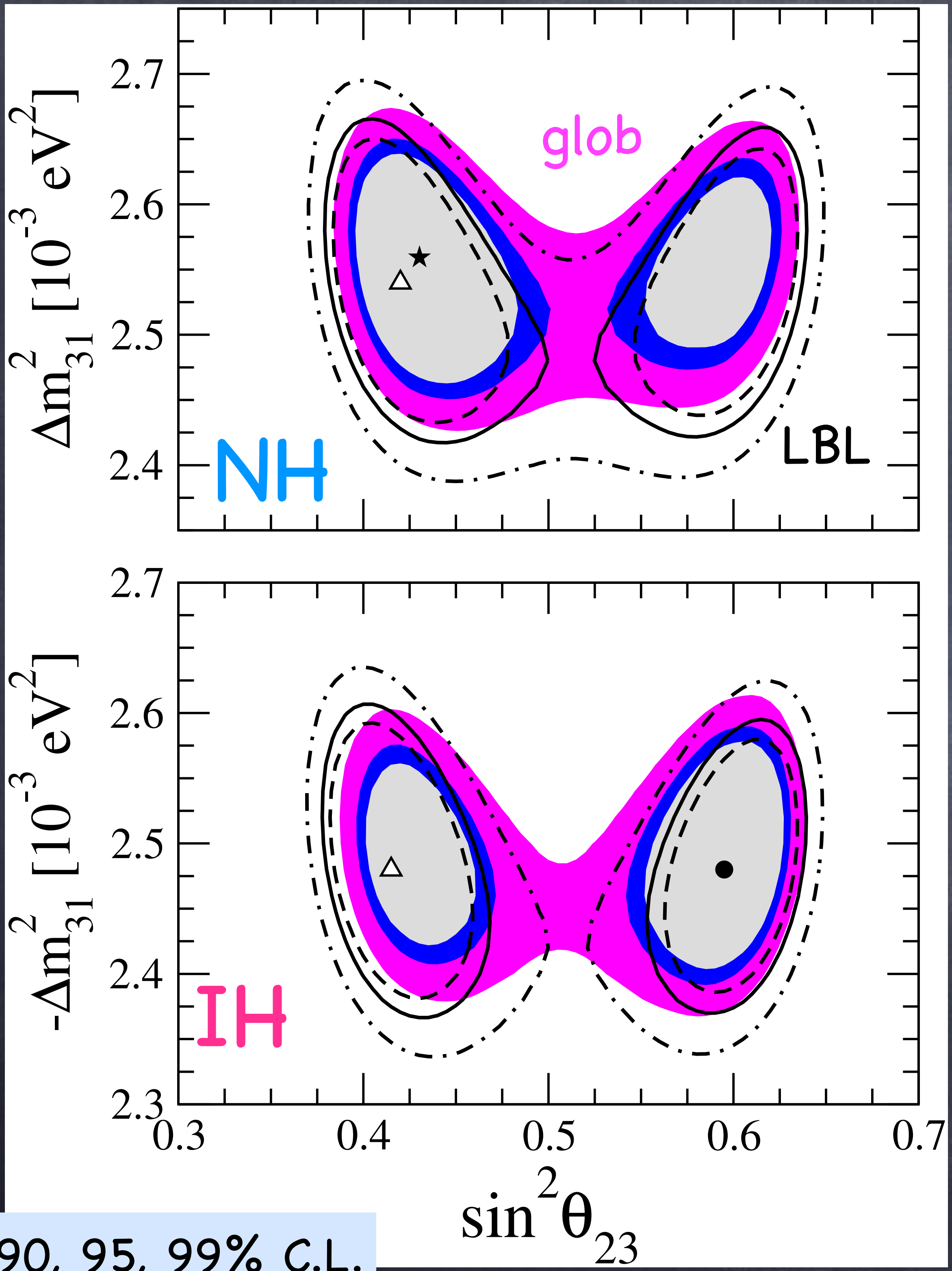
Atmospheric sector

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.

de Salas et al, 2017

- atmospheric parameters are essentially constrained by LBL data.

- maximal mixing allowed at 99%CL due to NOvA data

- best fit values:

NH

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

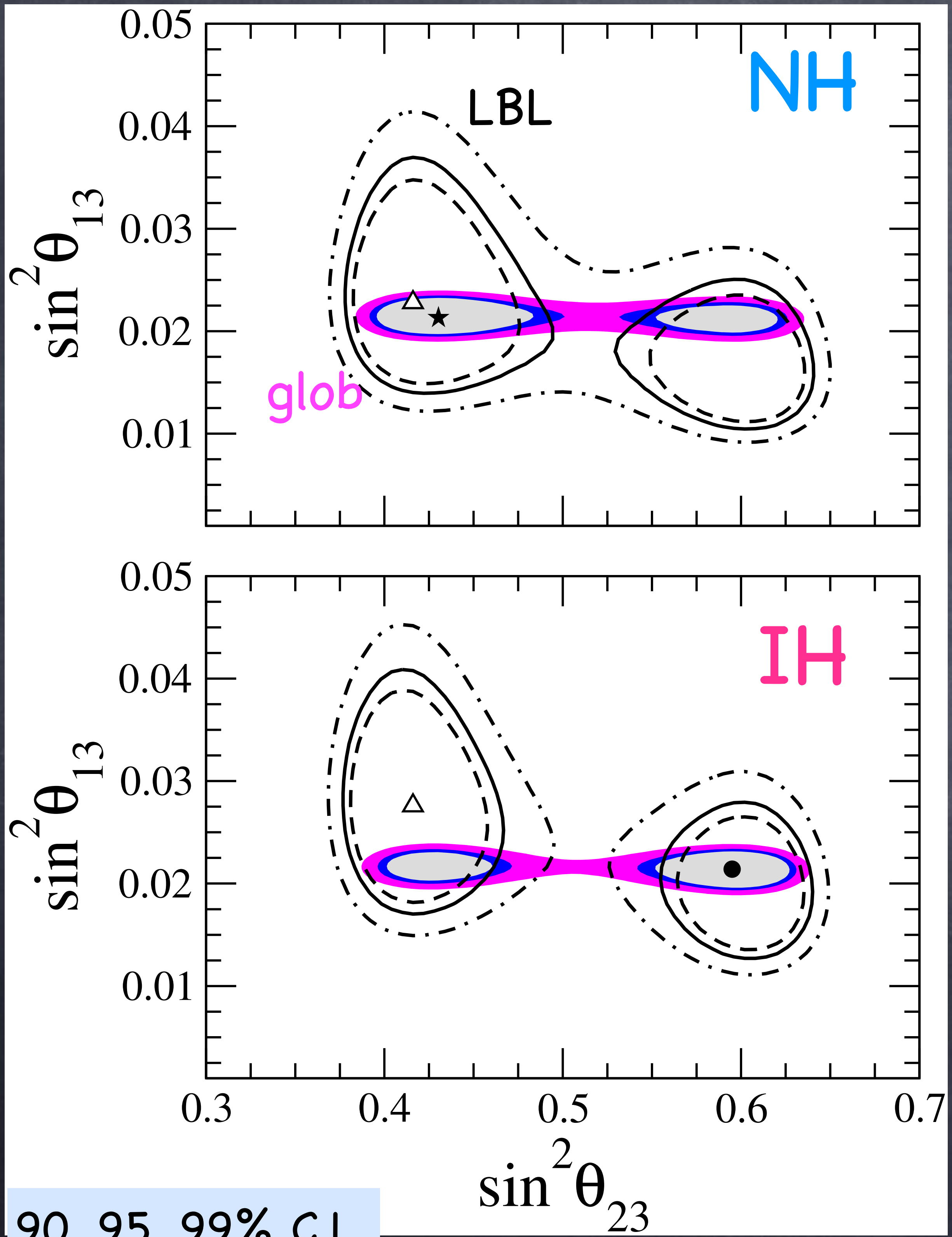
$$\sin^2\theta_{23} = 0.430^{+0.020}_{-0.018}$$

IH

$$\Delta m^2_{31} = -(2.40 \pm 0.04) \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.596^{+0.017}_{-0.018}$$

The octant of the atmospheric angle



90, 95, 99% C.L.

- Appearance probability at LBL:

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

→ degeneracy in θ_{13}–θ_{23} plane

- reactor θ_{13} measurement selects preferred θ_{23} octant for NH (1st) and IH (2nd)

NH

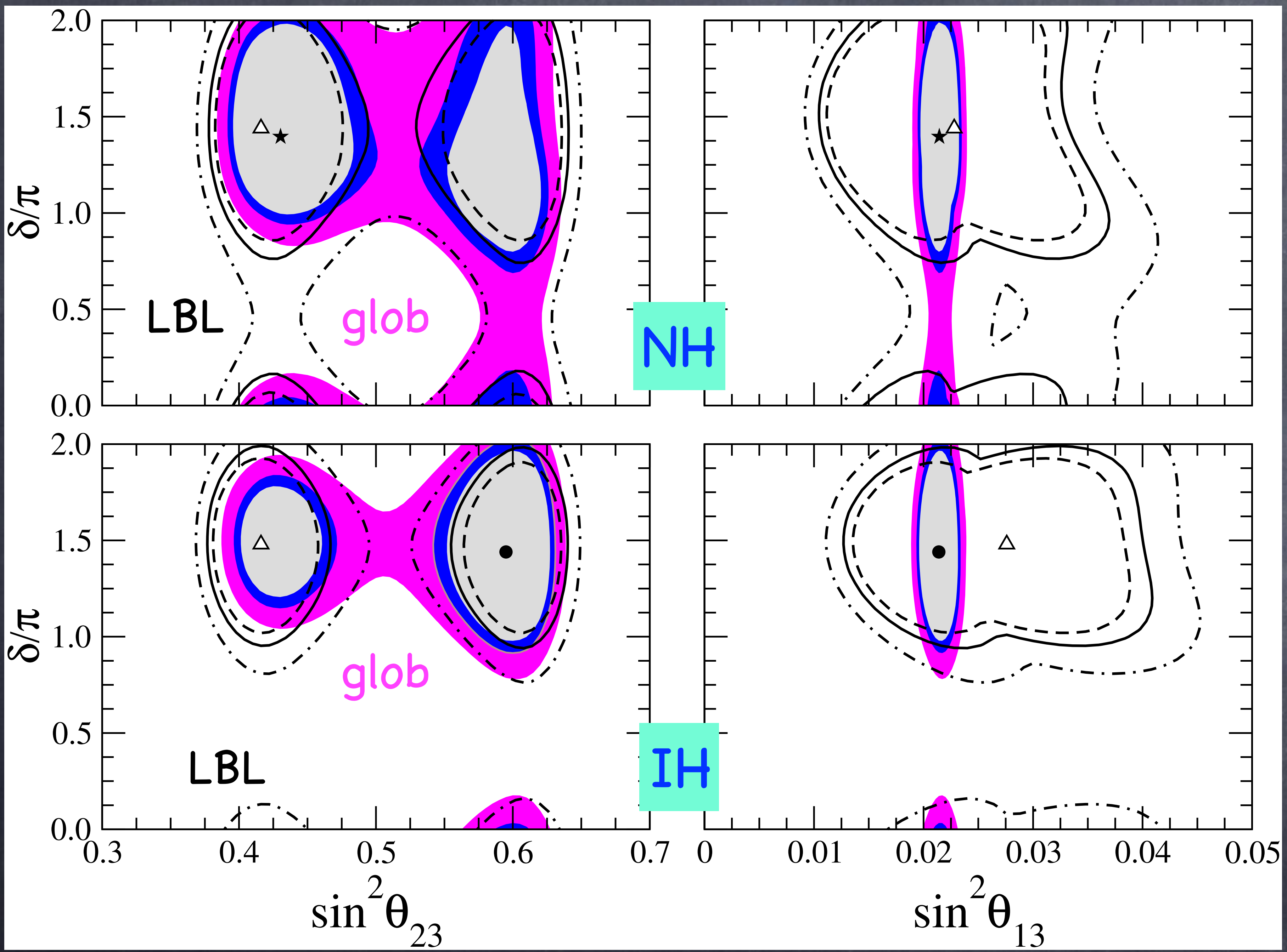
local min. at 2nd octant, $\Delta\chi^2 = 2.1$

IH

local min. at 1st octant, $\Delta\chi^2 = 1.7$

de Salas et al, 2017

Sensitivity to the CP phase



→ LBL exp. show improved sensitivity to δ_{CP} thanks to ν-$\bar{\nu}$ T2K data.

→ NOνA disfavours 1st octant with IH

→ best fit values:

$$\delta/\pi = 1.40^{+0.31}_{-0.20} \quad \text{(NH)}$$

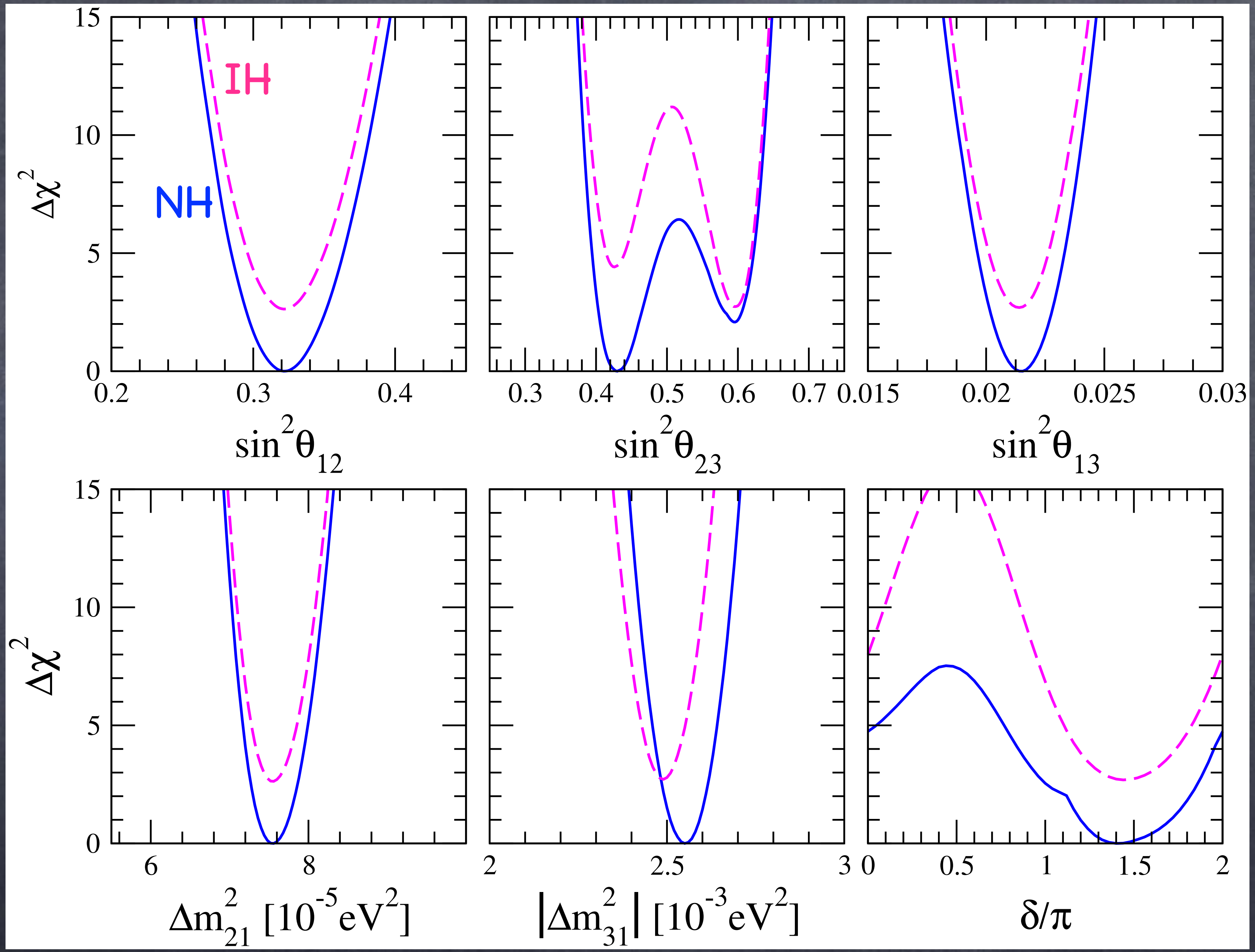
$$\delta/\pi = 1.44^{+0.26}_{-0.23} \quad \text{(IH)}$$

90, 95, 99% C.L.

δ = 0.5**π** disfavoured at 2.7σ (3.7) for NH (IH)

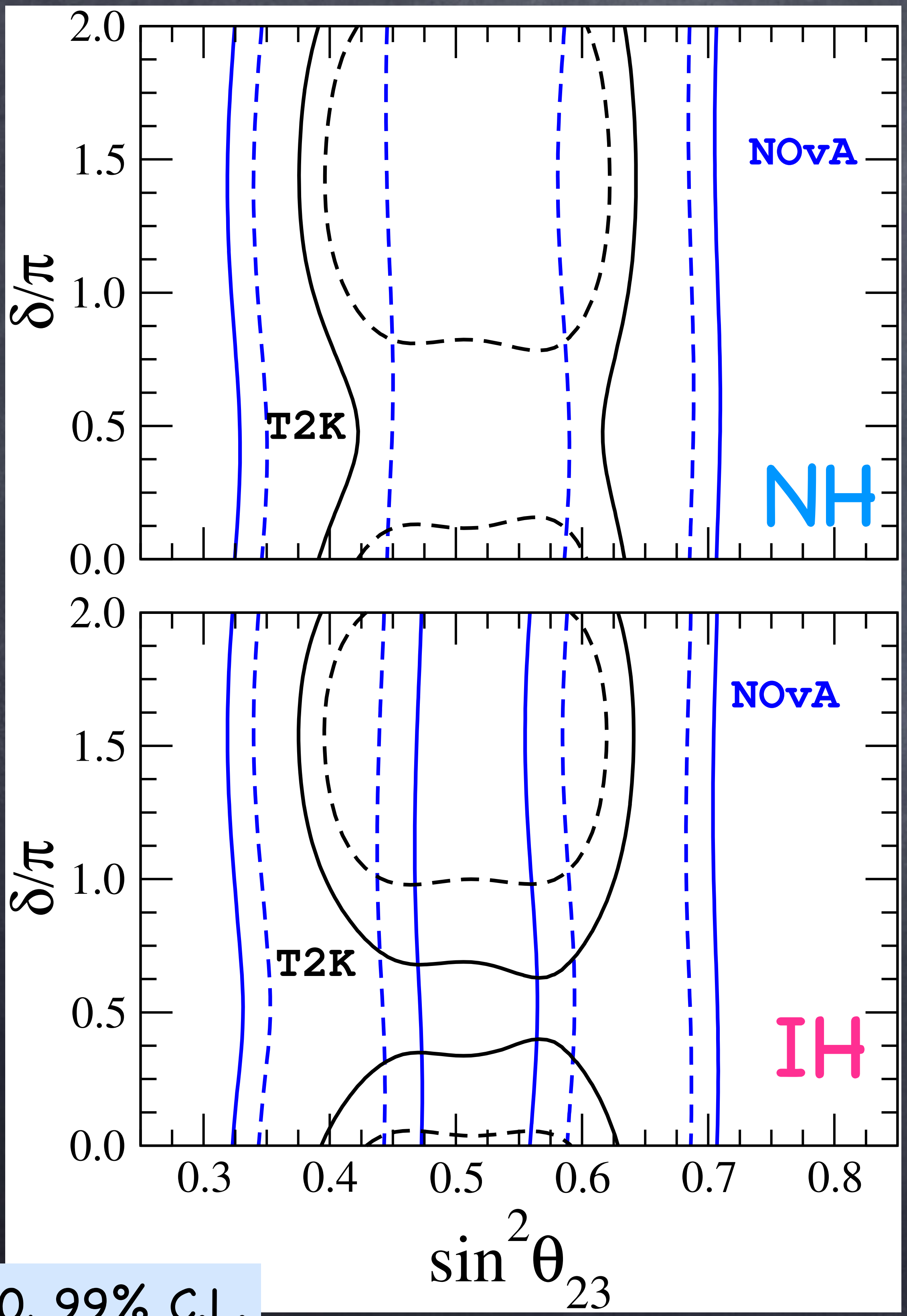
de Salas et al, 2017

Updated global fit summary



- slight preference for Normal Ordering: $\Delta\chi^2\ (\text{IH-NH}) = 2.7$

Sensitivity to the mass ordering

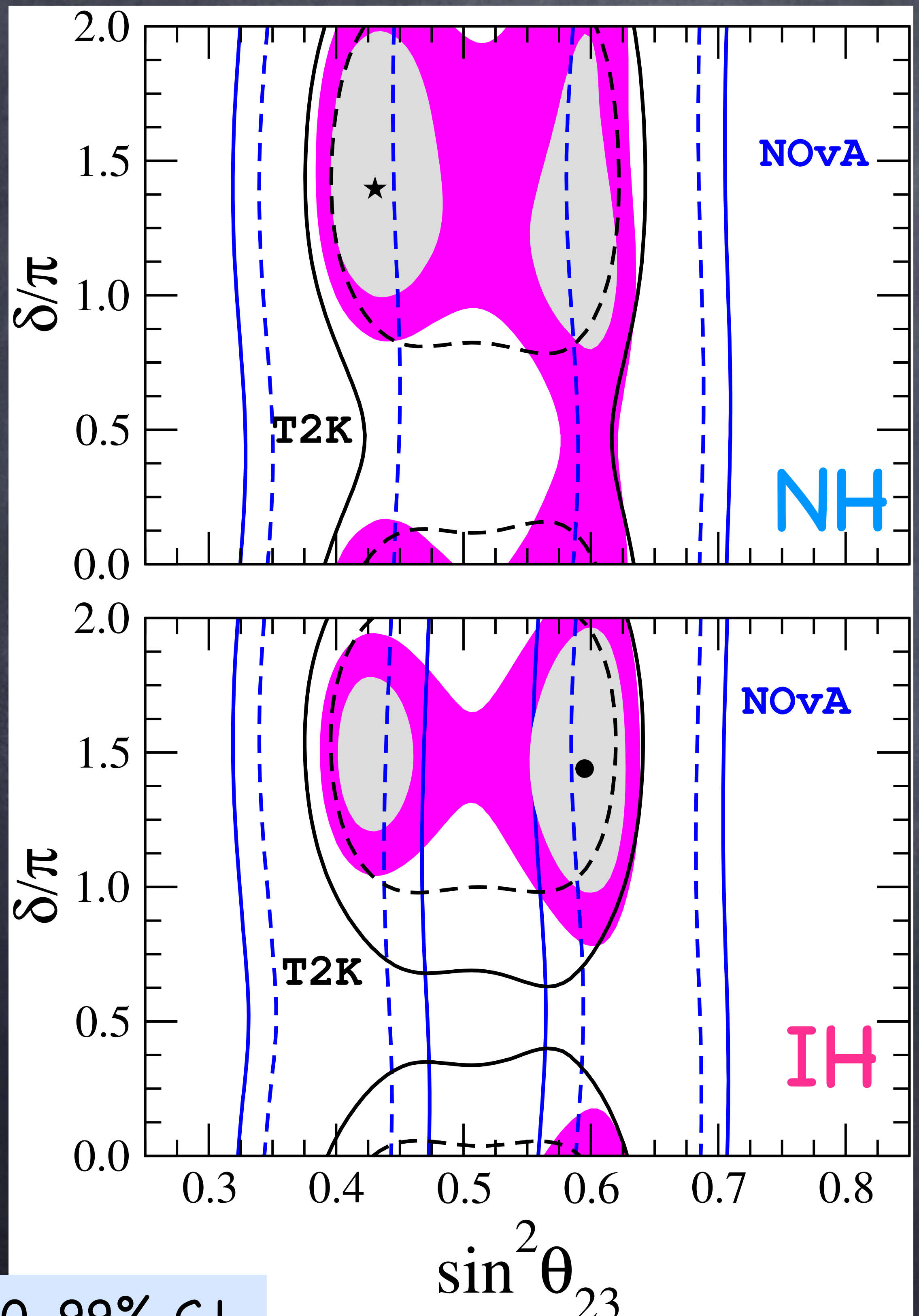


90, 99% C.L.

$\Delta\chi^2 \sim 0.4$ from DeepCore and Antares atm data

$\Delta\chi^2 \sim 3.6$ from the combination of T2K and NOvA, due to the stronger mismatch in preferred θ_{23} for IH (diluted to 2.2 after combining with MINOS)

Sensitivity to the mass ordering



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Global Fit: $\Delta\chi^2 \sim 2.7$

Updated global fit summary

parameter	best fit ± 1σ	2σ range	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.56±0.19	7.20–7.95	7.05–8.14
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NH)	2.55±0.04	2.47–2.63	2.43–2.67
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (IH)	2.49±0.04	2.41–2.57	2.37-2.61
$\sin^2\theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$	2.89–3.59	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NH)	$4.30^{+0.20}_{-0.18}$ [a]	3.98–4.78 & 5.60–6.17	3.84–6.35
$\sin^2\theta_{23}/10^{-1}$ (IH)	$5.96^{+0.17}_{-0.18}$ [b]	4.04–4.56 & 5.56–6.25	3.88–6.38
$\sin^2\theta_{13}/10^{-2}$ (NH)	$2.155^{+0.090}_{-0.075}$	1.98–2.31	1.89–2.39
$\sin^2\theta_{13}/10^{-2}$ (IH)	$2.140^{+0.082}_{-0.085}$	1.97–2.30	1.89–2.39
δ/π (NH)	$1.40^{+0.31}_{-0.20}$	0.85–1.95	0.00–2.00
δ/π (IH)	$1.44^{+0.26}_{-0.23}$	1.01–1.93	0.00–0.17 & 0.79–2.00

relative 1σ

2.4%

1.6%

5.5%

9.7%

7.0%

3.9%

**IH ranges: calculated wrt local minimum

NH	IH
local min. at 2nd octant, $\Delta\chi^2 = 2.1$	local min. at 1st octant, $\Delta\chi^2 = 1.7$

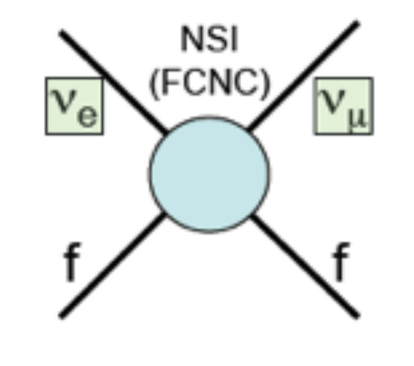
Beyond 3-neutrino oscillations

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: $\nu_\alpha\ f \to \nu_\beta\ f$ non-universal: $\nu_\alpha\ f \to \nu_\alpha\ f$



- effective 4-fermion operator:

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

- NSI may affect neutrino production, propagation and detection:

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

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

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

NSI in solar ν propagation

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

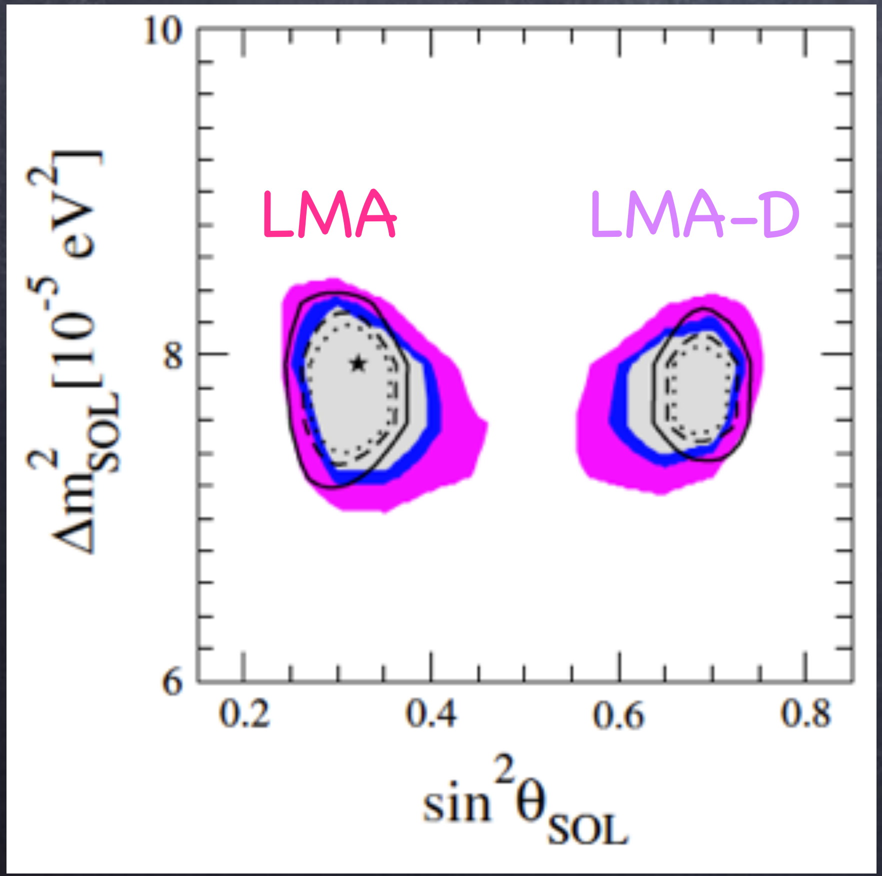
$$H_{NSI} = \sqrt{2} G_F N_f \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}$$

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

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

- 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

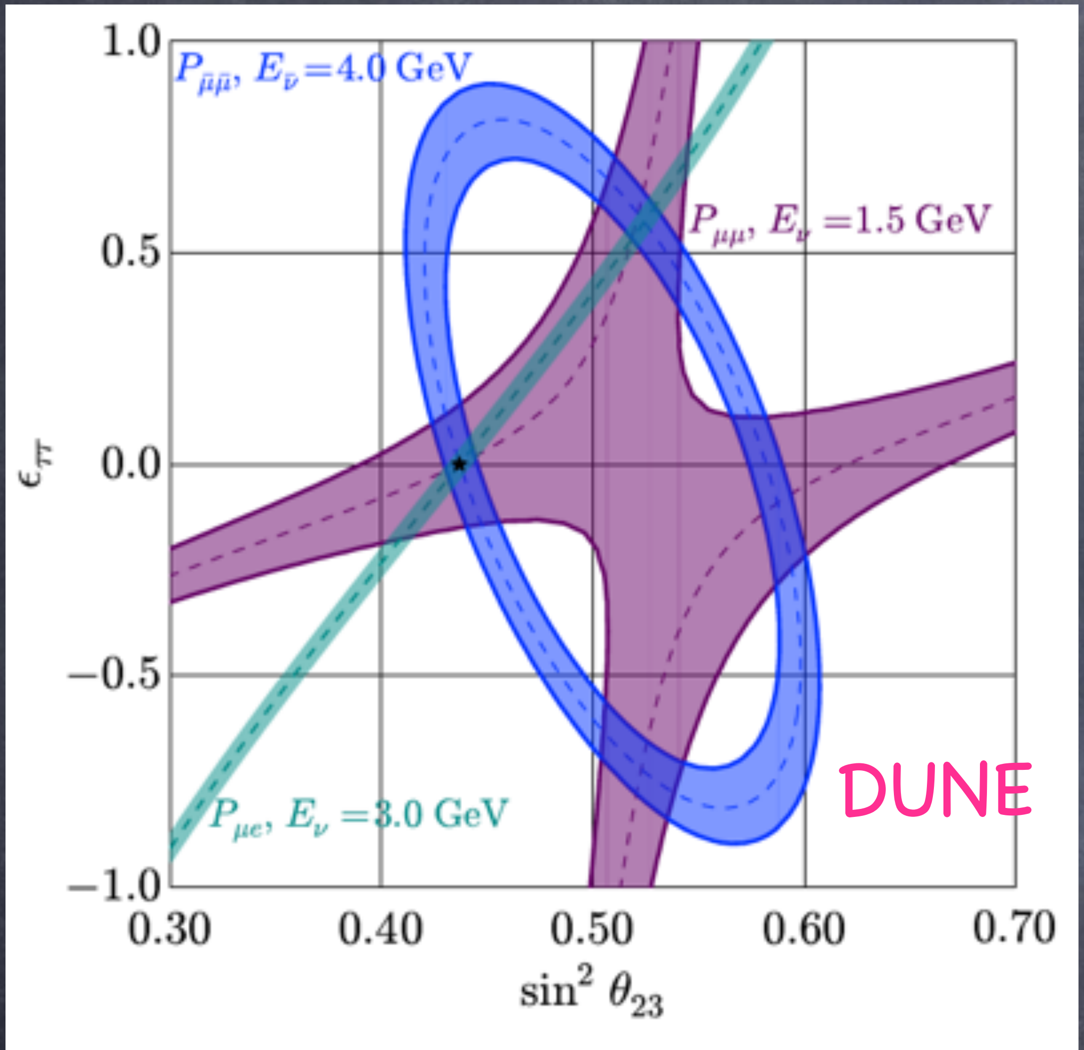
Miranda et al., JHEP 2006

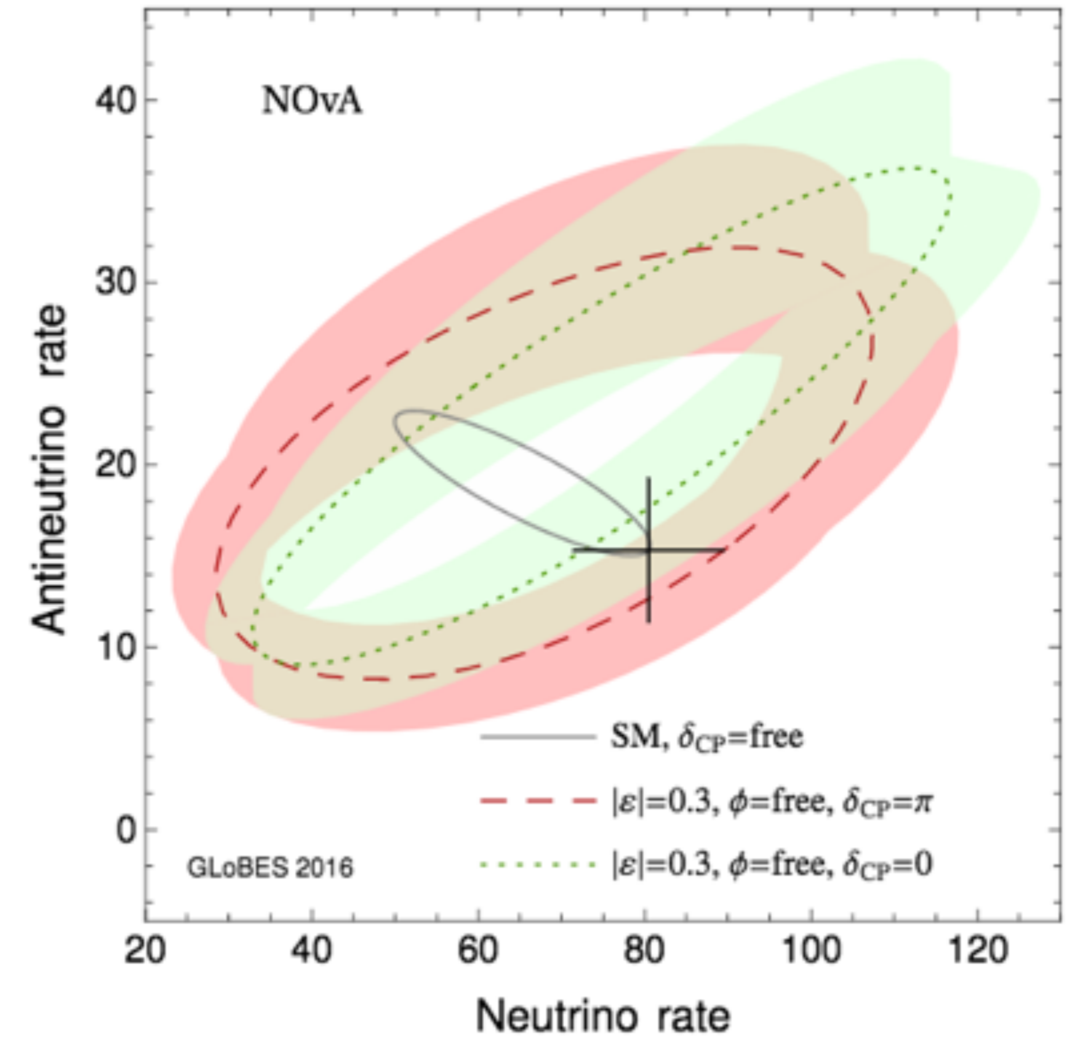
Escrihuela et al, PRD80 2009

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

θ_{13}-NSI degeneracy in Daya Bay

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

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

NSI induce a shift in θ_{13}

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

→ study robustness of θ_{13} measurement

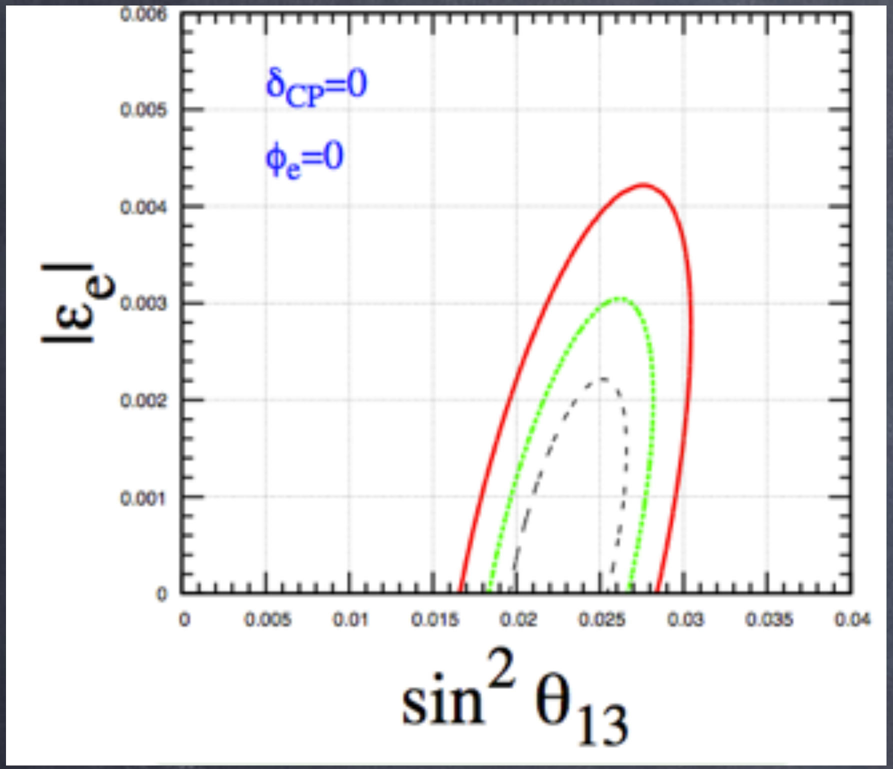
→ derive bounds on NSI couplings with Daya Bay data

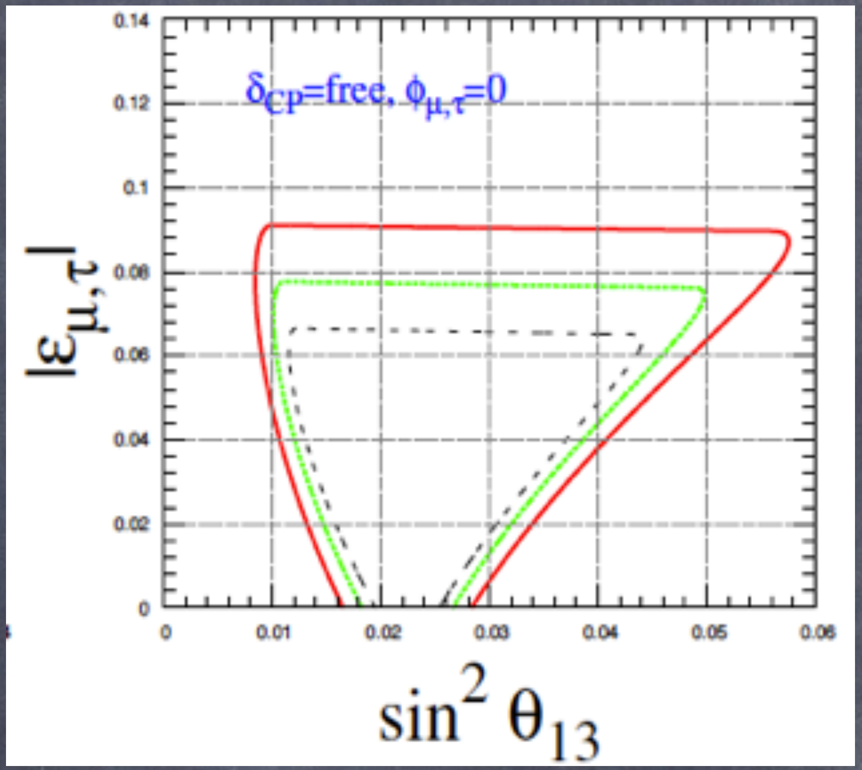
Agarwalla et al, JHEP 2015

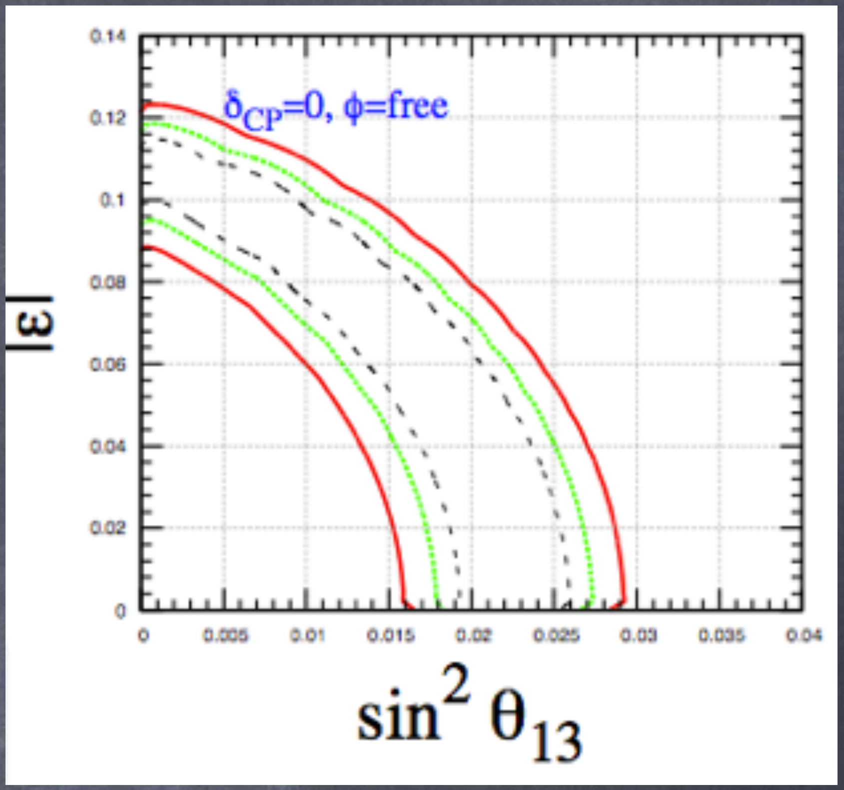
θ_{13}–NSI degeneracy in Daya Bay

$0.020 \leq \sin^2\theta_{13} \leq 0.024$ (90% CL)

some examples:







$0.020 \leq \sin^2\theta_{13} \leq 0.024$

$|\varepsilon_e| < 1.2 \times 10^{-3}$

$0.013 \leq \sin^2\theta_{13} \leq 0.036$

$|\varepsilon_{\mu,\tau}| < 5.2 \times 10^{-2}$

$\sin^2\theta_{13} \leq 0.024$

$|\varepsilon| < 1.1 \times 10^{-1}$

→ strong ε_e bound

→ robust θ_{13} determination

→ weaker bounds on NSI

→ θ_{13} determination affected by NSI

Agarwalla et al, JHEP 2015

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

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

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

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

Hettmansperger et al, JHEP2011

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

and the (3x3) light block:

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

See Xing, PRD2012 for n=6

Escrihuela et al, PRD92 (2015)

See also Fernandez-Martinez et al, PLB2007

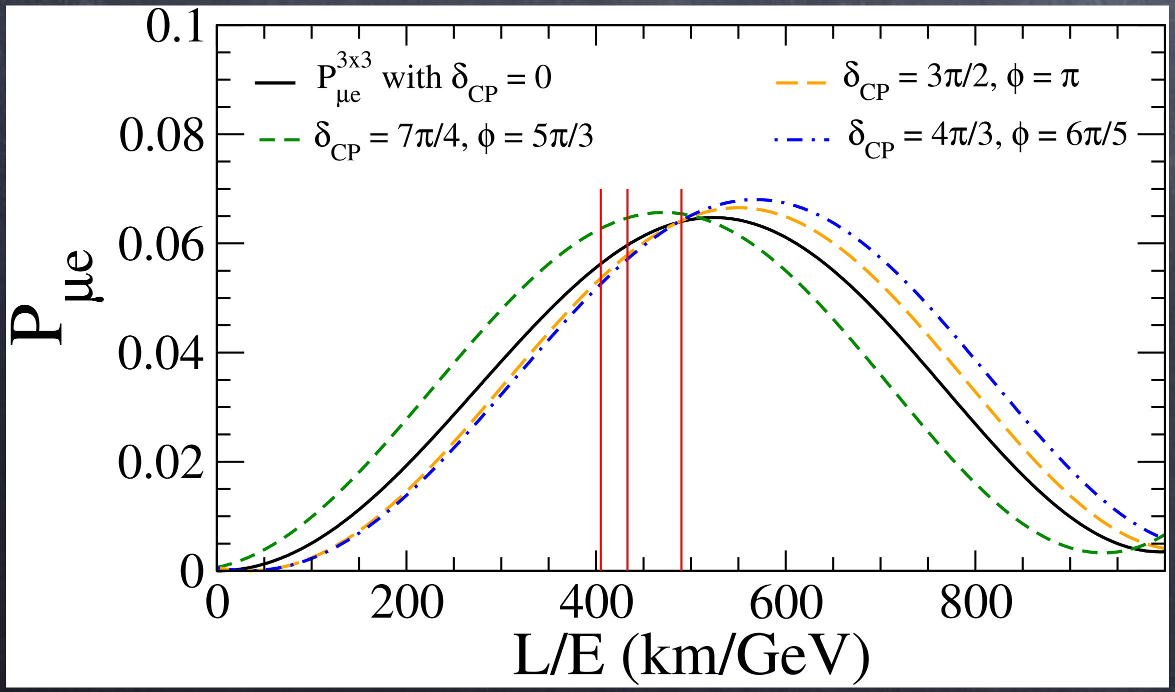
CP degeneracies in Pμe with NU

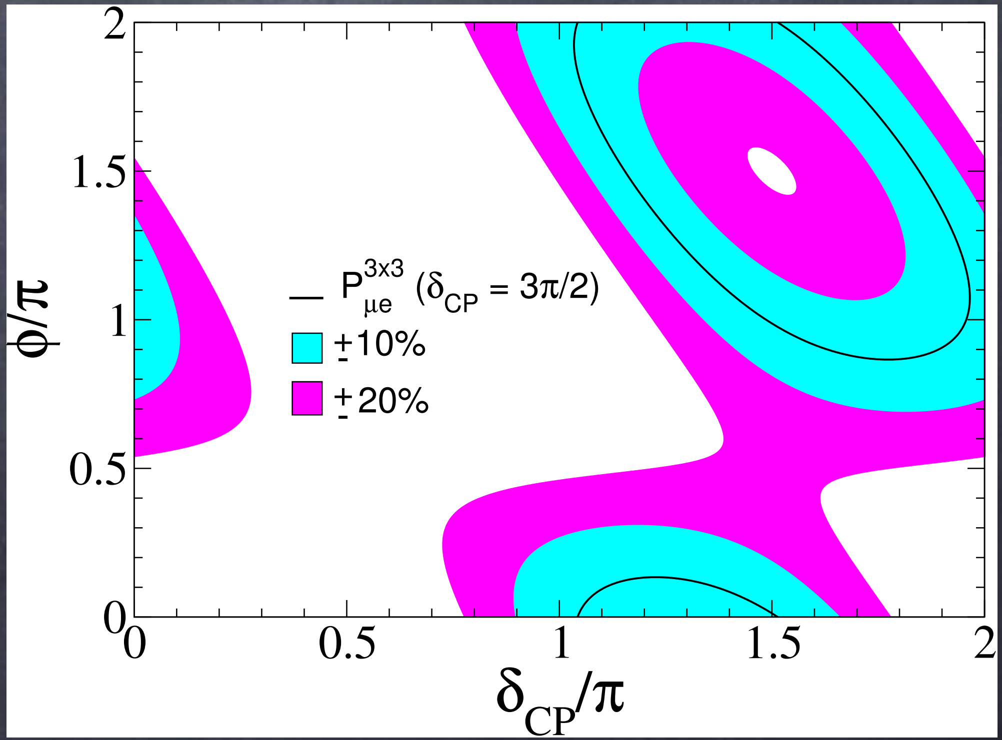
$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P_{\mu e}^{3\times 3} + \alpha_{11}^2\alpha_{22}|\alpha_{21}|P_{\mu e}^I + \alpha_{11}^2|\alpha_{21}|^2$$

$$\begin{aligned} P_{\mu e}^{3\times 3} &= 4\left(\cos^2\theta_{12}\cos^2\theta_{23}\sin^2\theta_{12}\sin^2\Delta_{21} + \cos^2\theta_{13}\sin^2\theta_{13}\sin^2\theta_{23}\sin^2\Delta_{31}\right) \\ &+ \sin 2\theta_{12}\sin\theta_{13}\sin 2\theta_{23}\sin 2\Delta_{21}\sin\Delta_{31}\cos\left(\Delta_{31}+\delta_{\rm CP}\right) \end{aligned}$$

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

→ degeneracies in the (δ, ϕ) plane



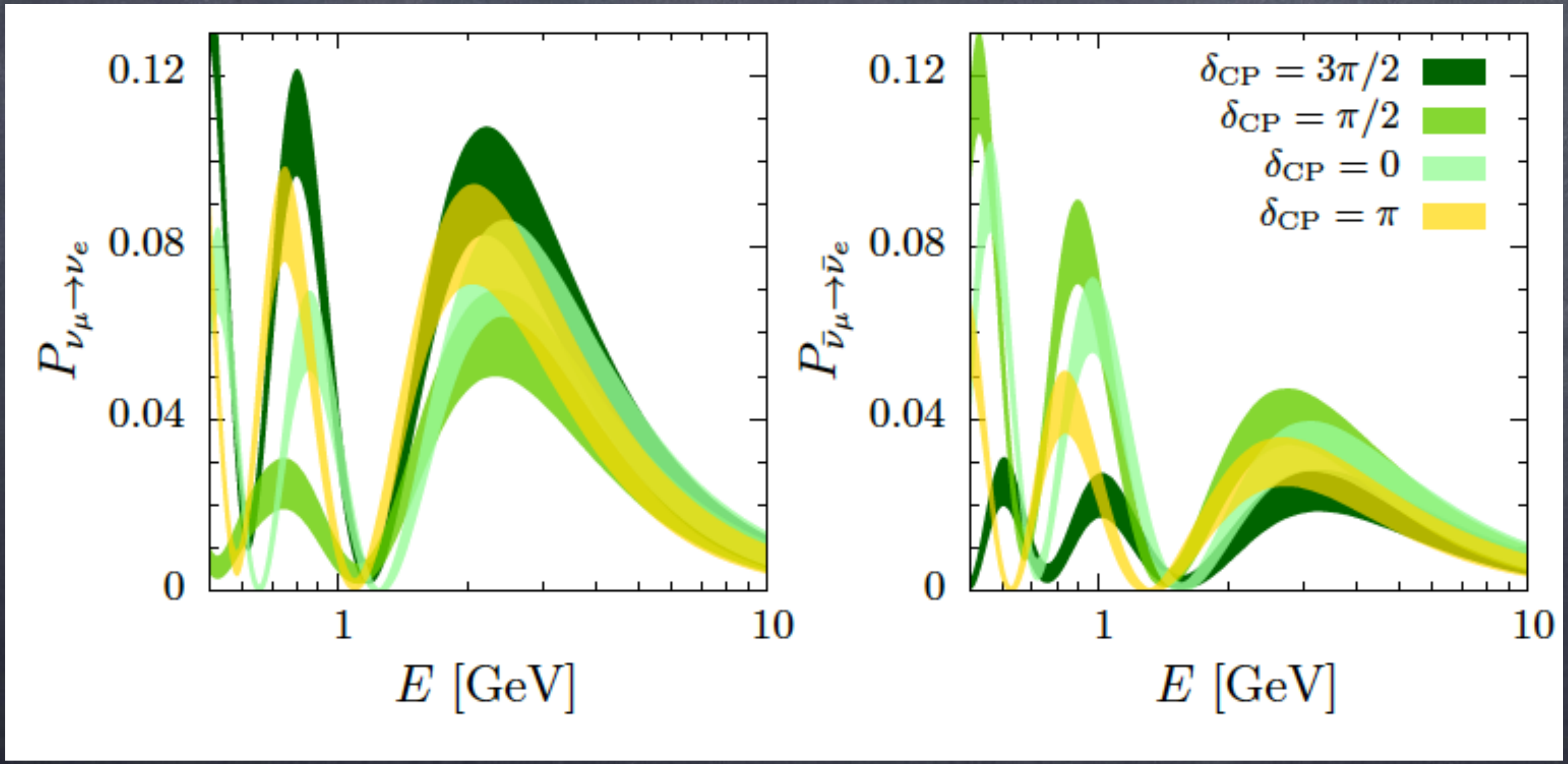


Miranda, MT, Valle, PRL 117 (2016)

NU neutrino oscillations in DUNE

The standard oscillation picture in DUNE gets modified due to NU

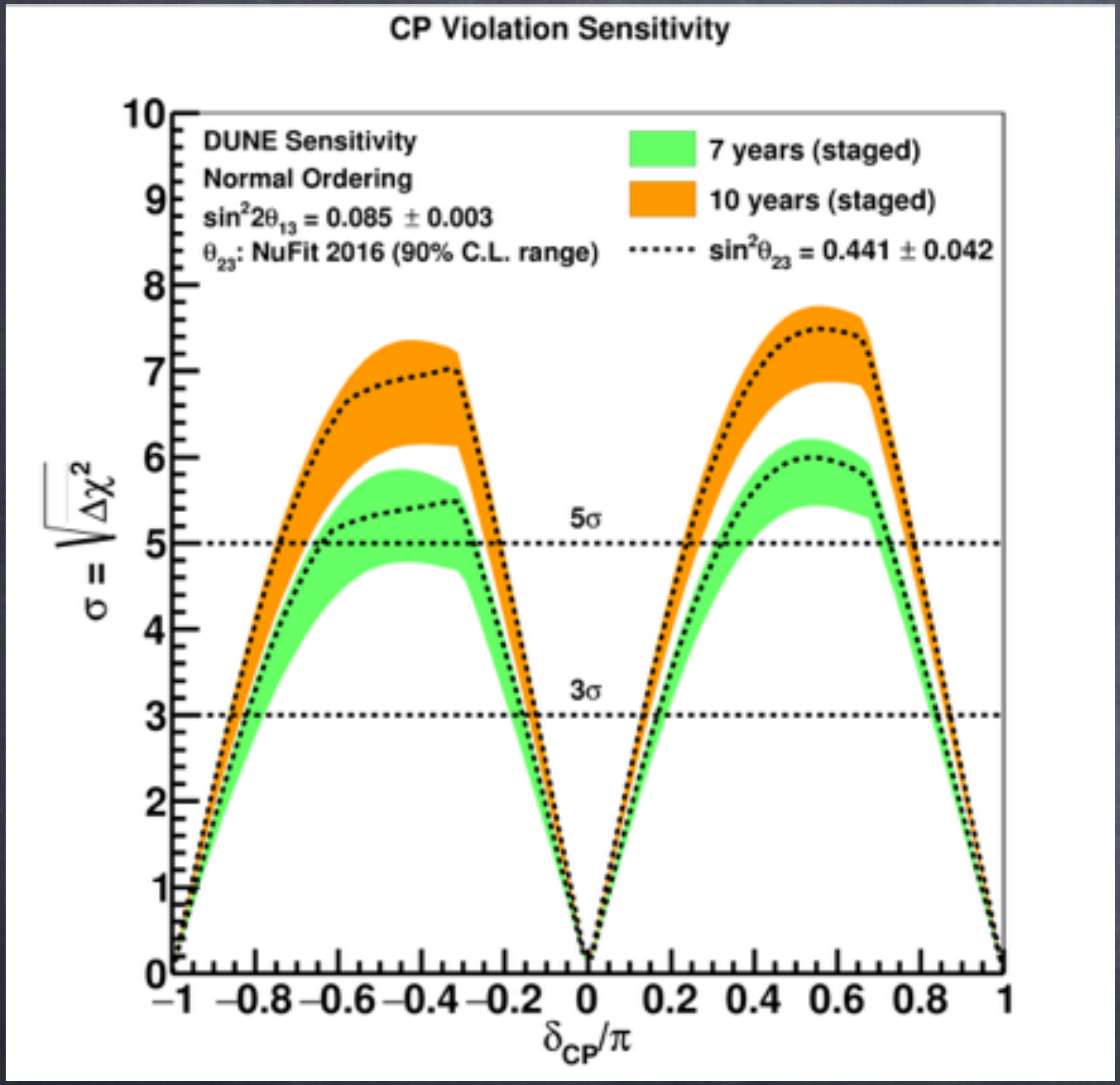
Here: α_{ii} = 1, $|\alpha_{21}|$ = 0.02, ϕ free (α_{3i} enter in $P_{\mu e}$ through matter effects)

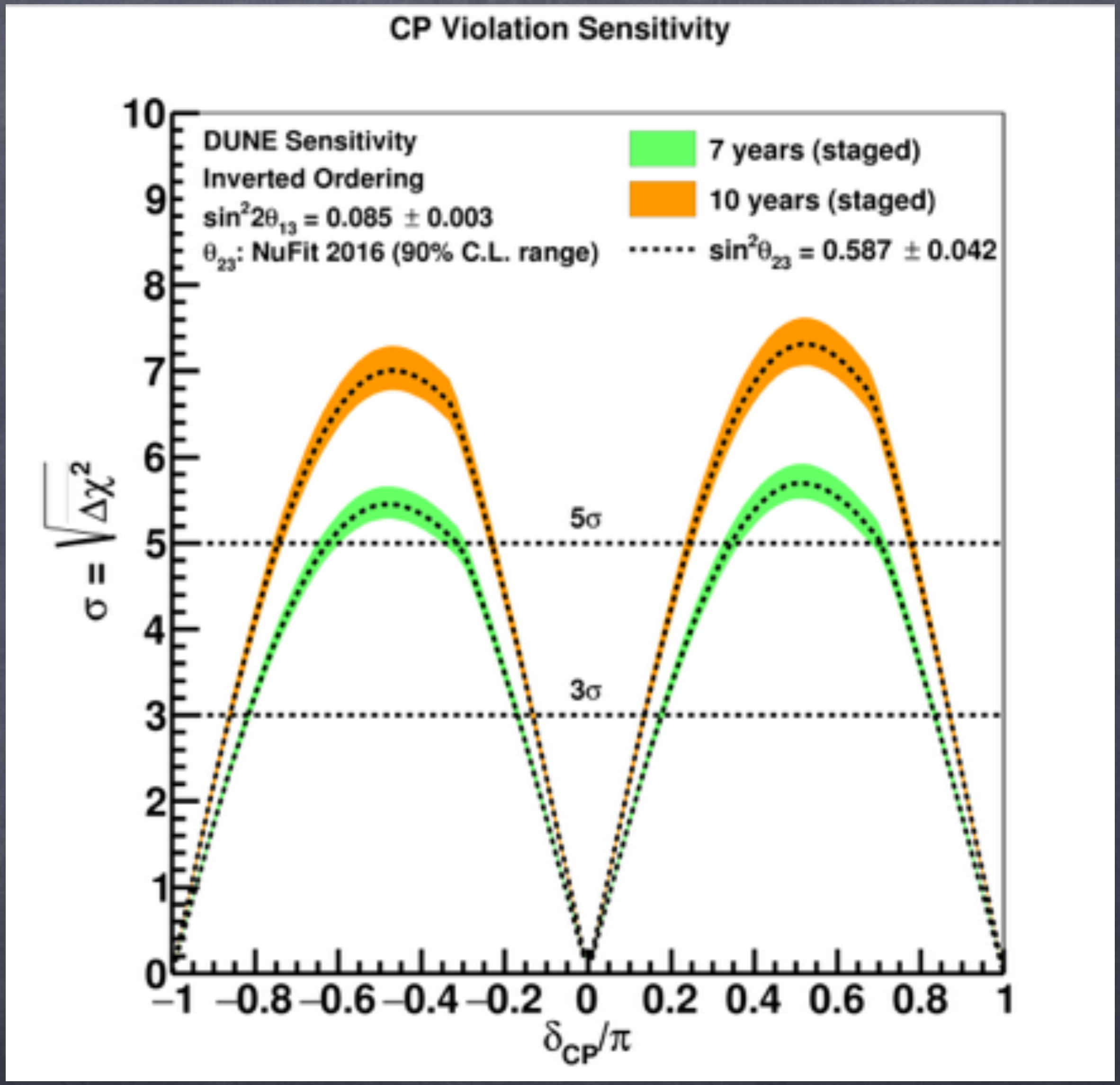


→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E≳ 3 GeV in both channels

Escrihuela et al, arXiv:1612.07377 [hep-ph]

CP violation searches in DUNE

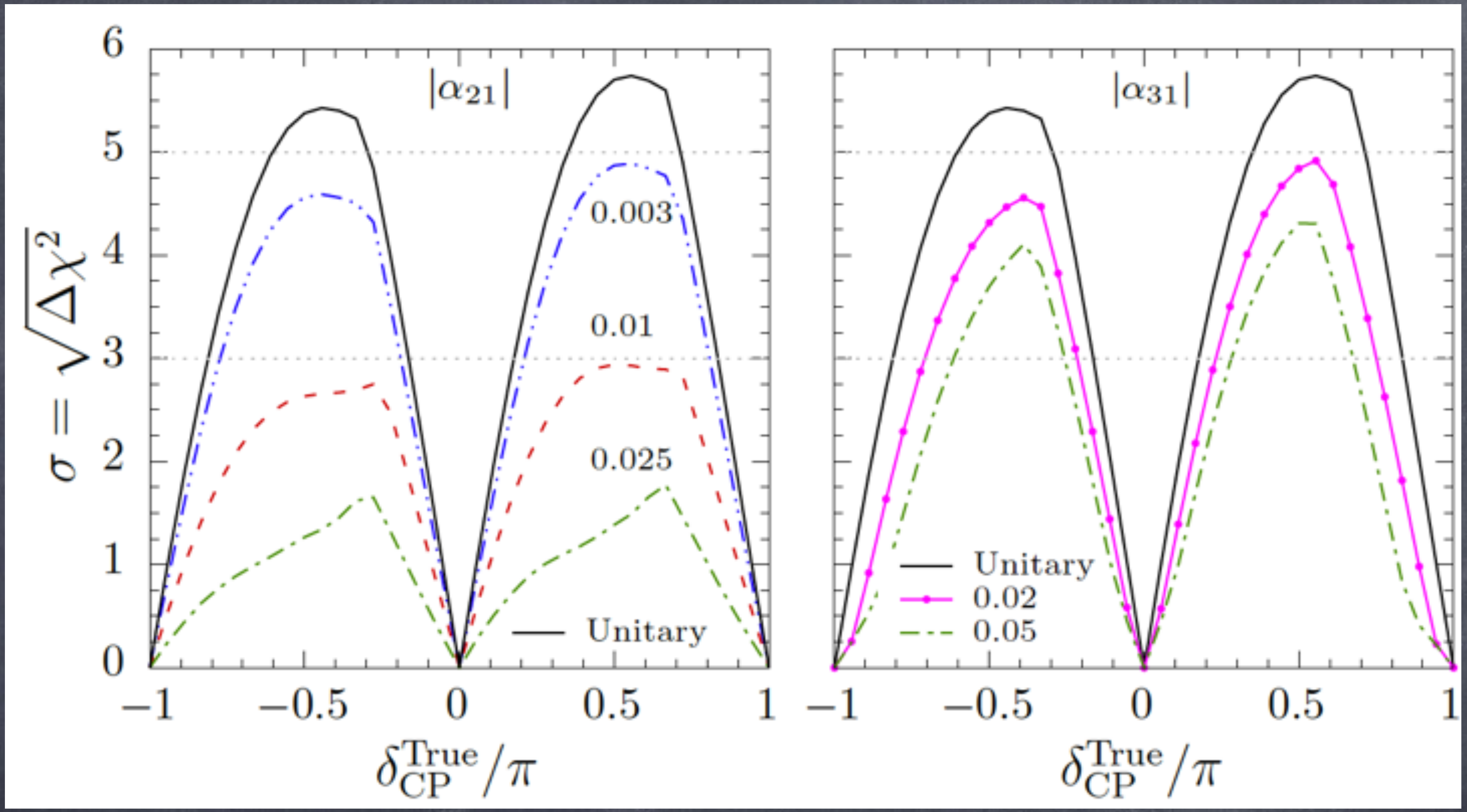




> 5σ sensitivity for some fraction of δ_{CP}

E. Worcester, DUNE Collaboration

DUNE CP sensitivity with NU



Escrihuela et al, arXiv:1612.07377 [hep-ph]

- ➡ 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 mass ordering, octant of atmospheric angle and CP violation has been increased, 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 LBL experiments.