Global fit to neutrino oscillation data

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15th MultiDark Consolider Workshop

Zaragoza, April 5th 2019

MultiDark
Multimessenger Approach for Dark Matter Detection
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Parameterization of the mixing matrix

- Neutrino oscillation probability is given by

$$P(\alpha \to \beta; E, L) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{i \frac{\Delta m^2_{kj}}{2E} L}$$

For derivation see for example:
Fundamentals of Neutrino Physics and Astrophysics, C. Giunti, C.W. Kim

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- For a given energy E and distance L the probability depends on:
  - Two mass splittings Δm^2_{21} , Δm^2_{31}
  - The entries of the matrix U

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Parameterization of the mixing matrix

- The mixing matrix can be parameterized as

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

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- There are also two more Majorana phases, but oscillation experiments are blind to them
- Different types of experiments are sensitive to different parameters

Experiment	Dominant measurement	Sub-dominant measurement
Solar Experiments + LBL reactors	θ_{12}, Δm^2_{21}	θ_{13}
Short baseline Reactors	θ_{13}, Δm^2_{31}	θ_{12}, Δm^2_{21}
Atmospheric experiments	θ_{23}, Δm^2_{31}	θ_{13}, δ
LBL accelerator disappearance	θ_{23}, Δm^2_{31}	θ_{13}
LBL accelerator appearance	θ_{13}, δ	θ_{23}

Global fit to neutrino oscillations

Phys.Lett. B782 (2018) 633, P.F. de Salas, D.V. Forero, CAT, M. Tórtola, J.W.F. Valle

https://globalfit.astroparticles.es/

Extracting oscillation parameters

- For the global fit we sum the contribution from all experiments

$$\chi^2_{\mathrm{total}}(\delta, \Delta m^2_{ij}, \theta_{kl}) = \sum_{\mathrm{exp}} \chi^2_{\mathrm{exp}}(\delta, \Delta m^2_{ij}, \theta_{kl})$$

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- From this we can extract the profiles for all parameters, for example

$$\chi^2(\Delta m^2_{31}) = \min_{\Delta m^2_{21}, \theta_{kl}, \delta} \chi^2_{\rm total}(\delta, \Delta m^2_{ij}, \theta_{kl})$$

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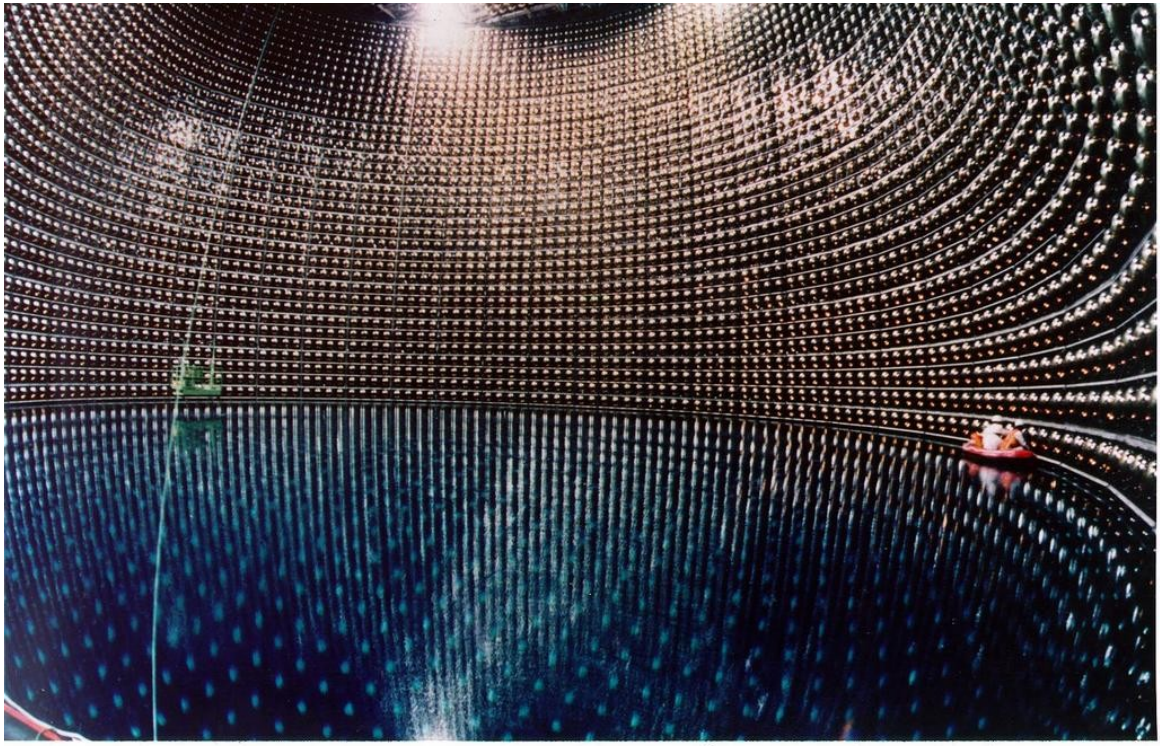
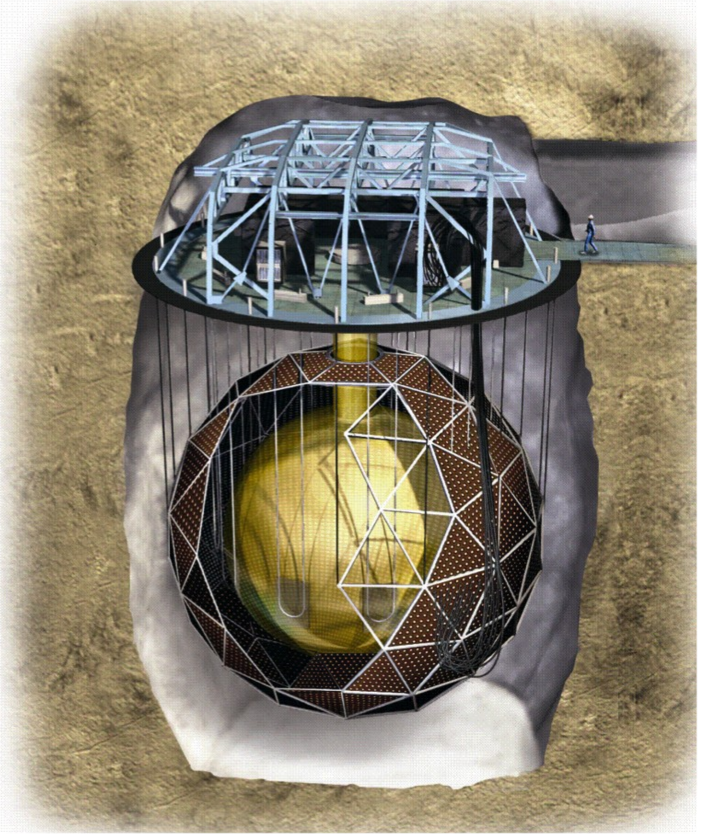
- This means correlations among oscillation parameters are fully taken into account. However, correlations among systematics are not considered

Global fit to neutrino oscillations

- Solar experiments measure disappearance (P_{ee}) and conversion (P_{ex}) of electron neutrinos created in the sun





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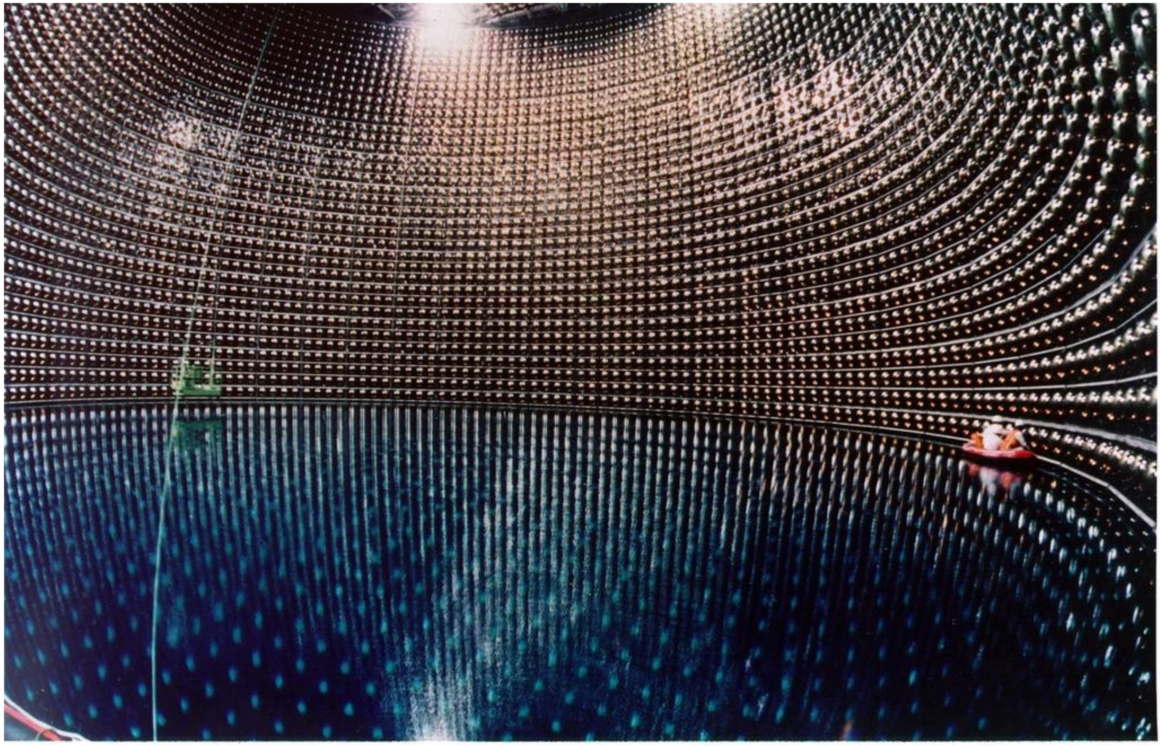

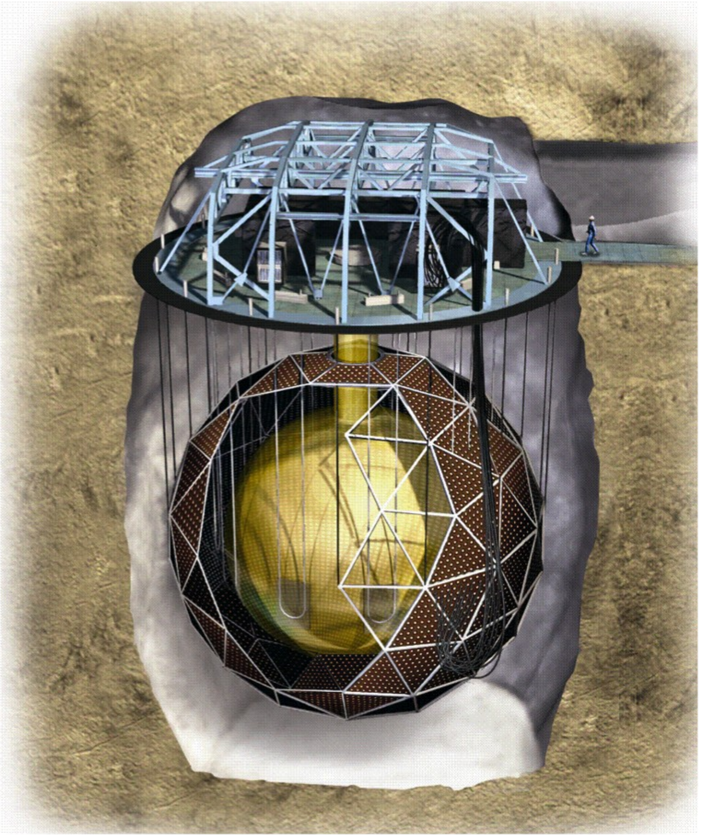

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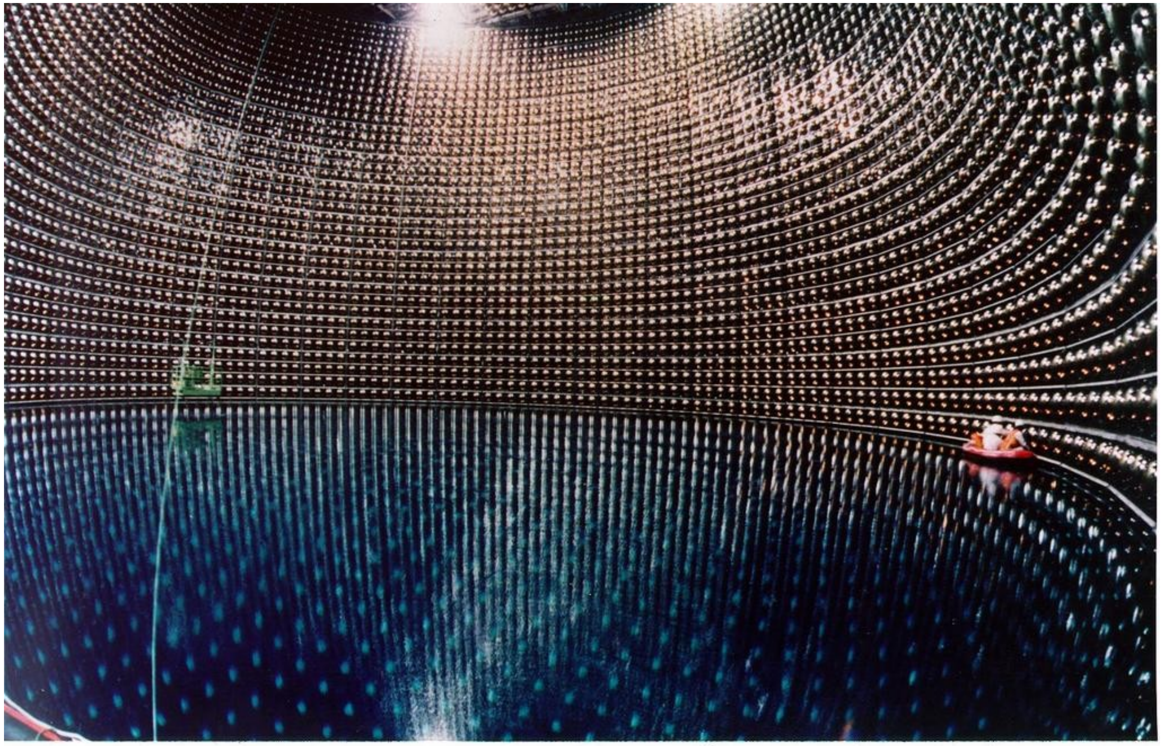
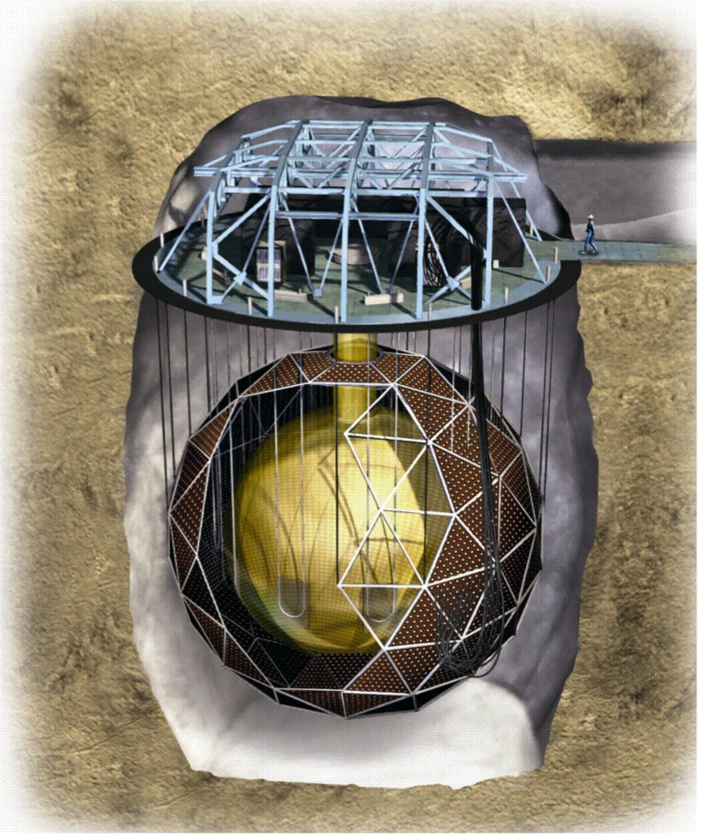
- The solar parameters are measured also by the long baseline reactor experiment KamLAND



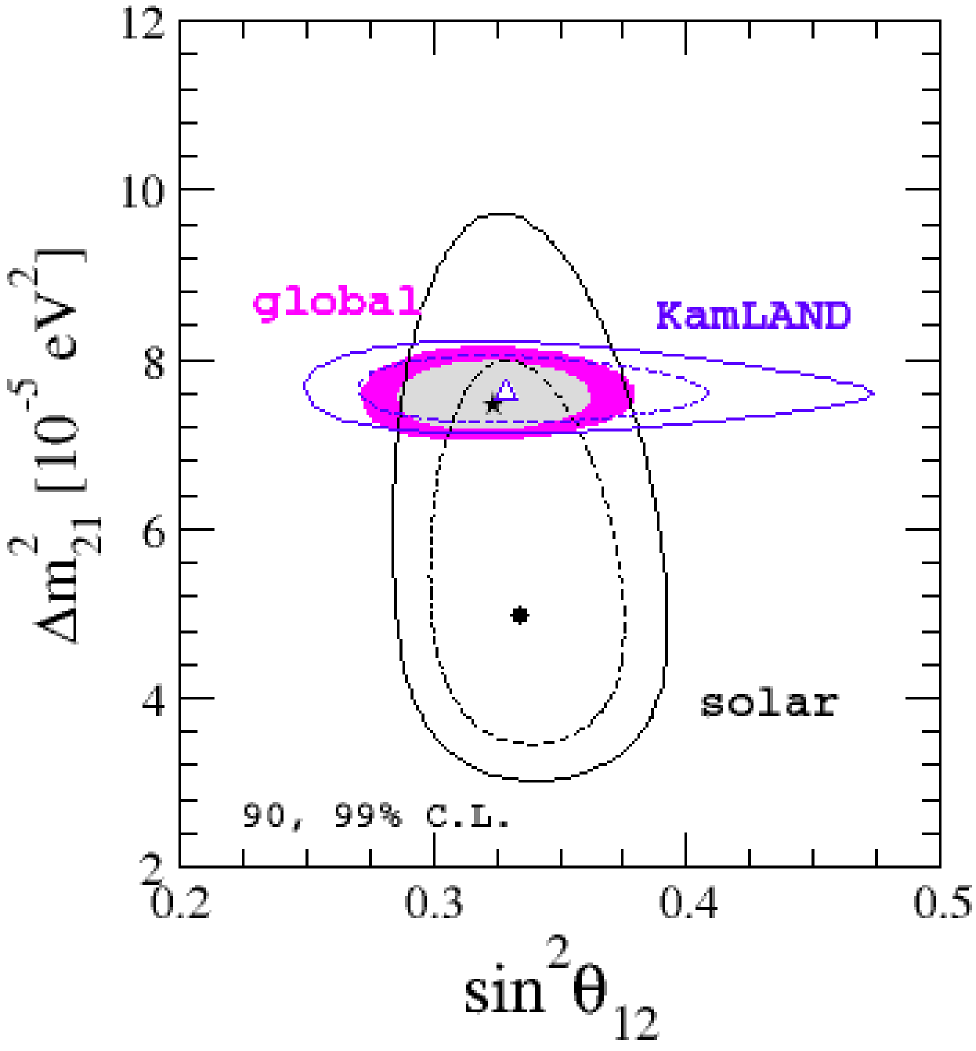


Global fit to neutrino oscillations

- Data included:
  - SK I-IV
  - Borexino: Beryllium data
  - SNO I-III
  - Sage
  - Gallex+GNO
  - Chlorine
  - KamLAND

Global fit to neutrino oscillations

- Result of solar experiments and KamLAND



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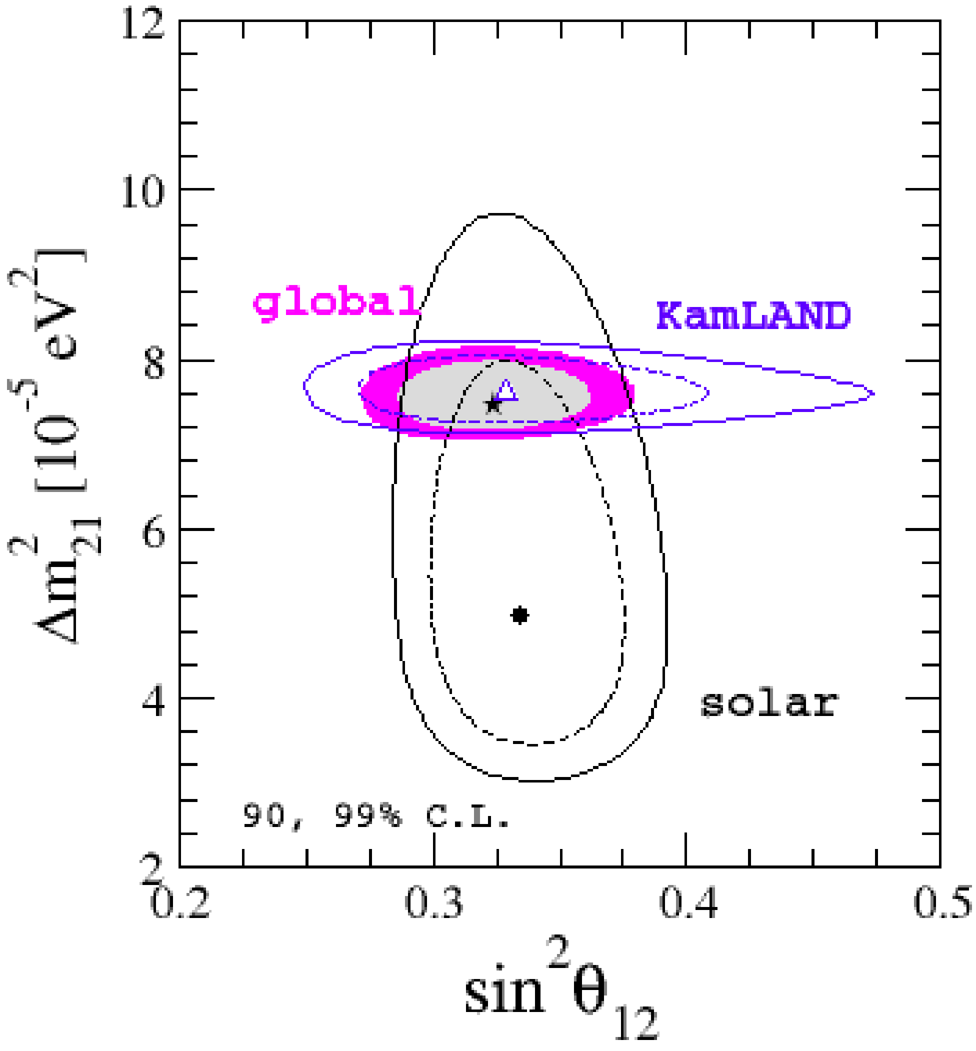

- θ_{12} better measured by solar data

Global fit to neutrino oscillations

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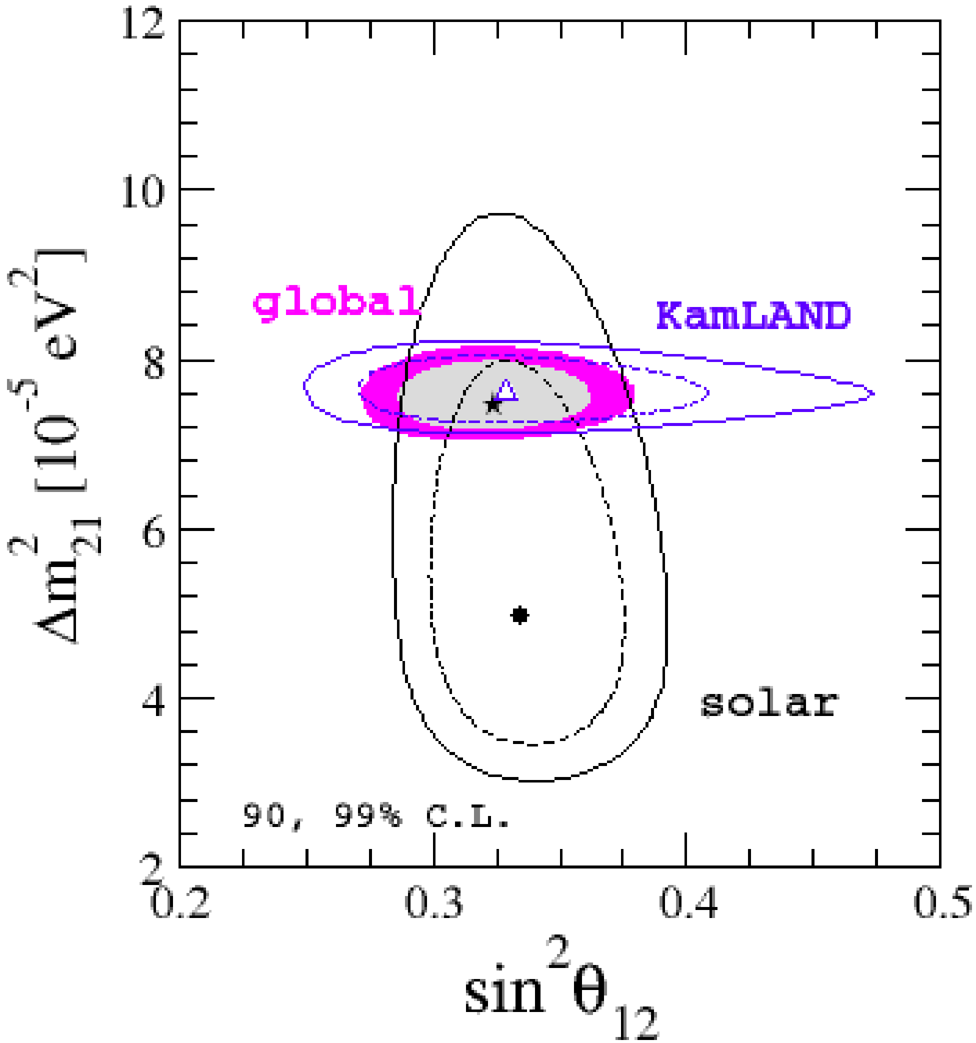

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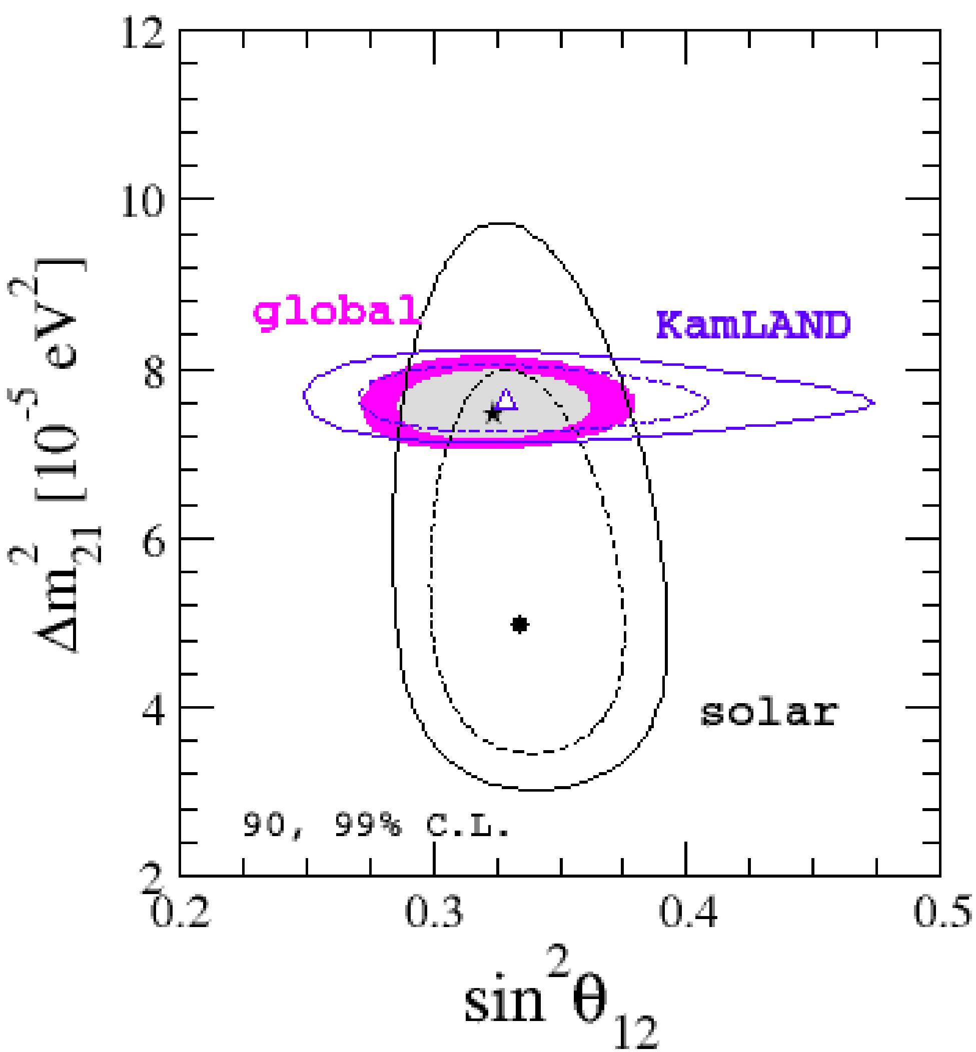

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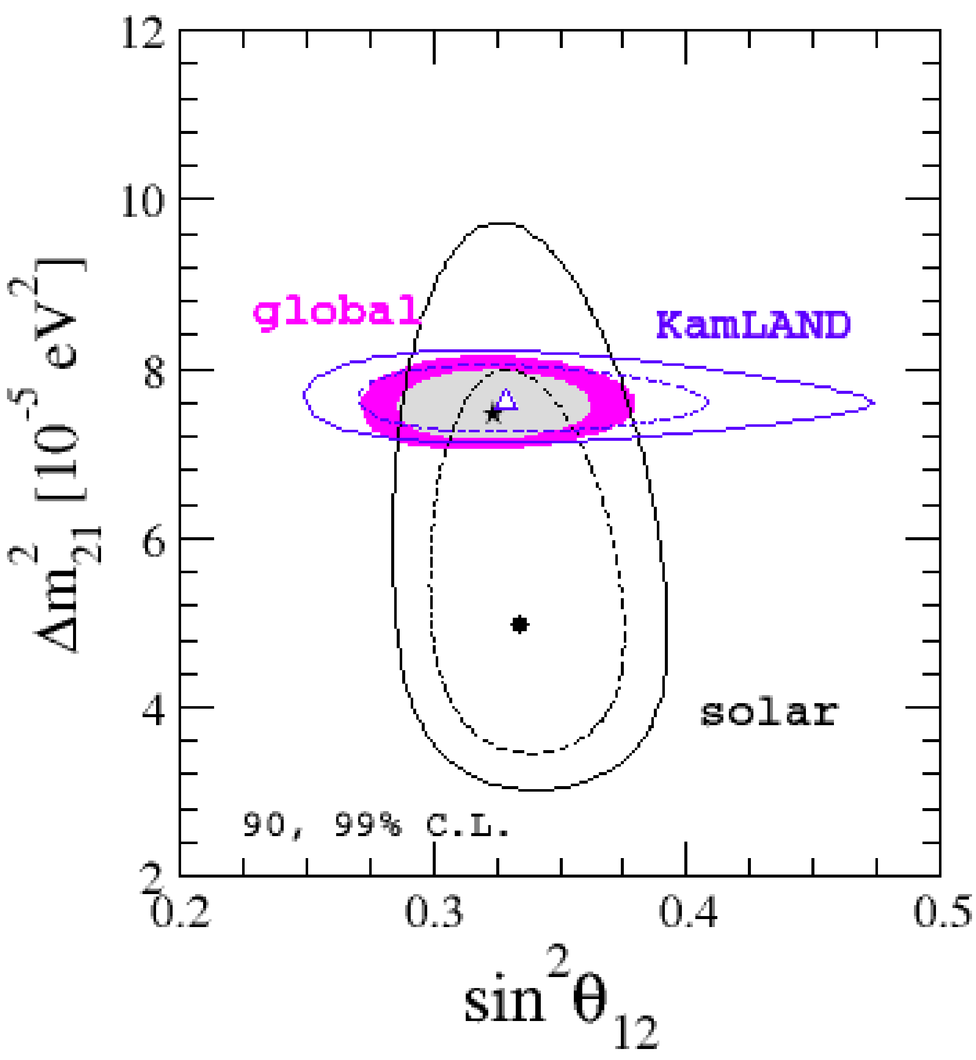

- θ_{12} better measured by solar data
- Δm^2_{21} better measured by KamLAND
- Maximal mixing is highly disfavored
- Mismatch between solar and KamLAND data for mass splitting

Global fit to neutrino oscillations

- Reactor experiments measure disappearance of electron antineutrinos $(P_{\bar{e}\bar{e}})$ created at reactors

Global fit to neutrino oscillations

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- The main dependence of short baseline reactors is on θ_{13} and Δm^2_{31}

Global fit to neutrino oscillations

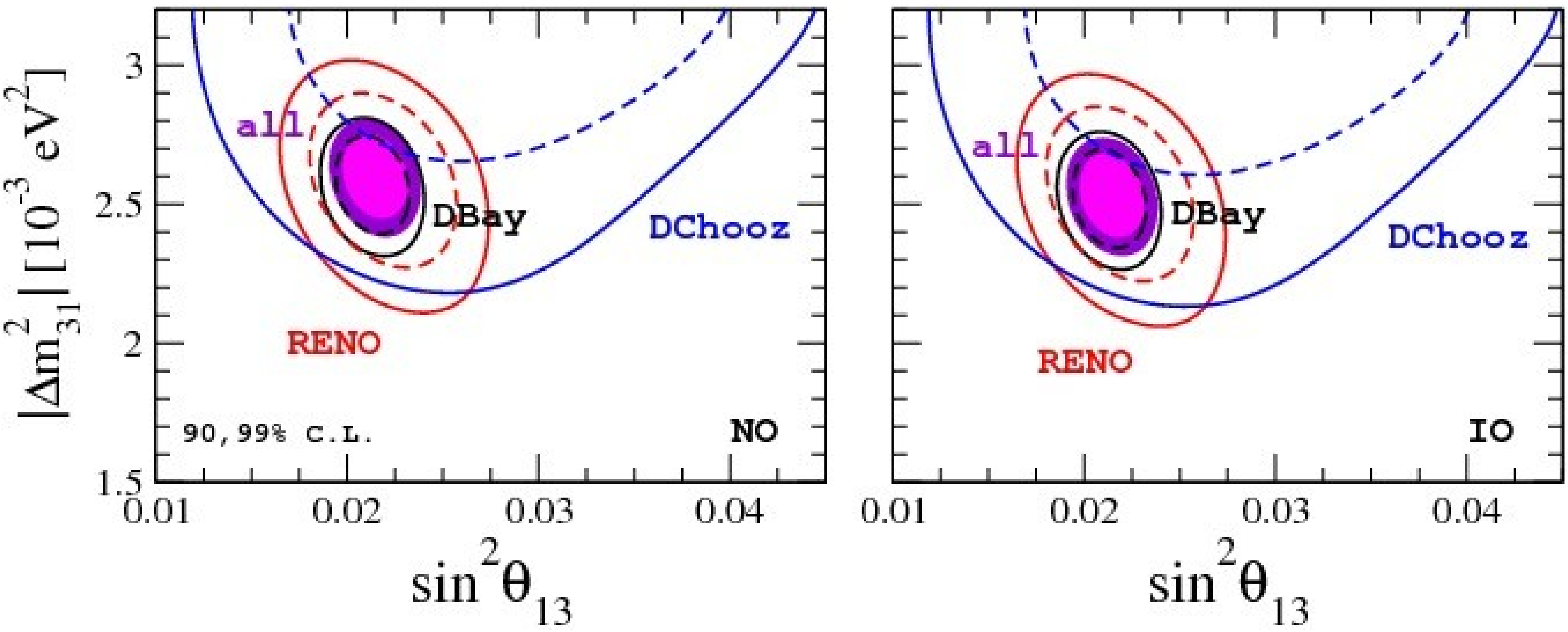
- Data included:
  - 1230 day Daya Bay spectrum
  - 1500 day RENO spectrum
  - 461 day (FI) and 212 day (FII) Double Chooz spectrum

Global fit to neutrino oscillations

- Data included:
  - 1230 day Daya Bay spectrum
  - 1500 day RENO spectrum
  - 461 day (FI) and 212 day (FII) Double Chooz spectrum
- Older reactors are not included, because they only provide upper limits on θ_{13}

Global fit to neutrino oscillations

- Result of reactor experiments



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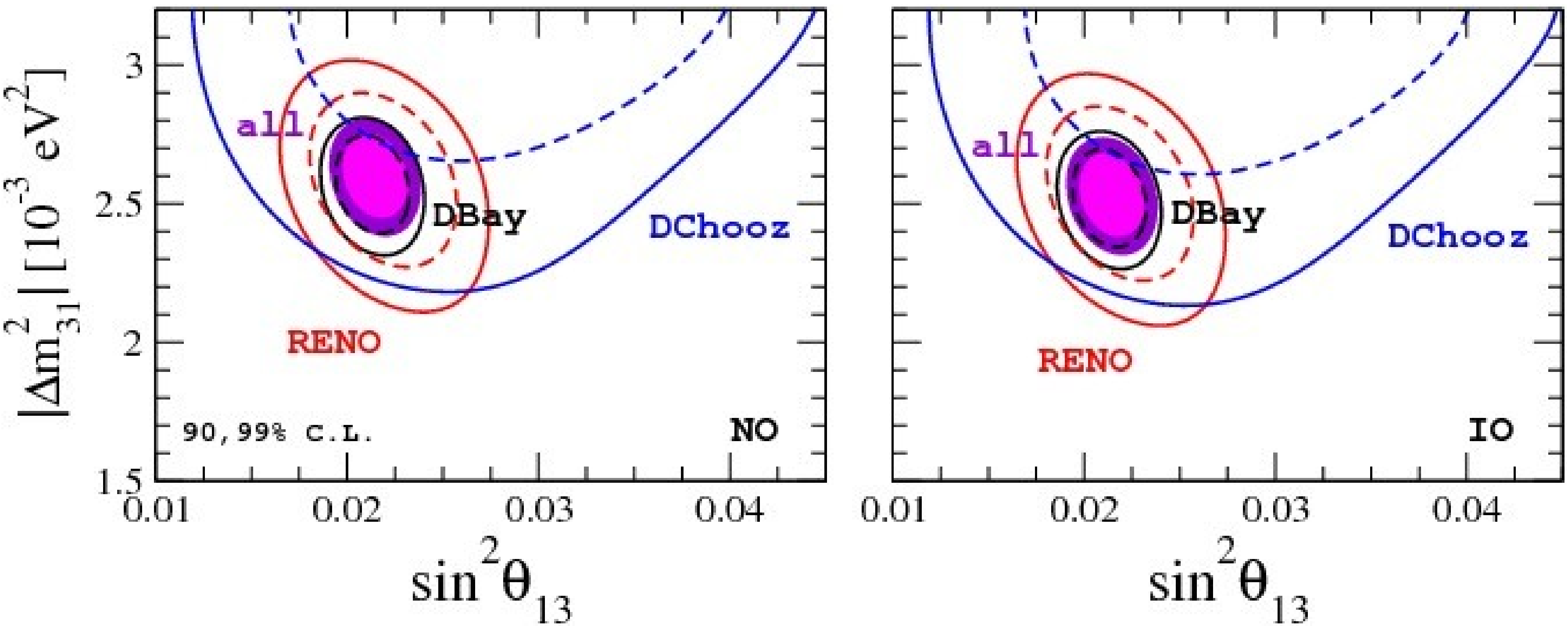

- Reactor analysis is dominated by Daya Bay

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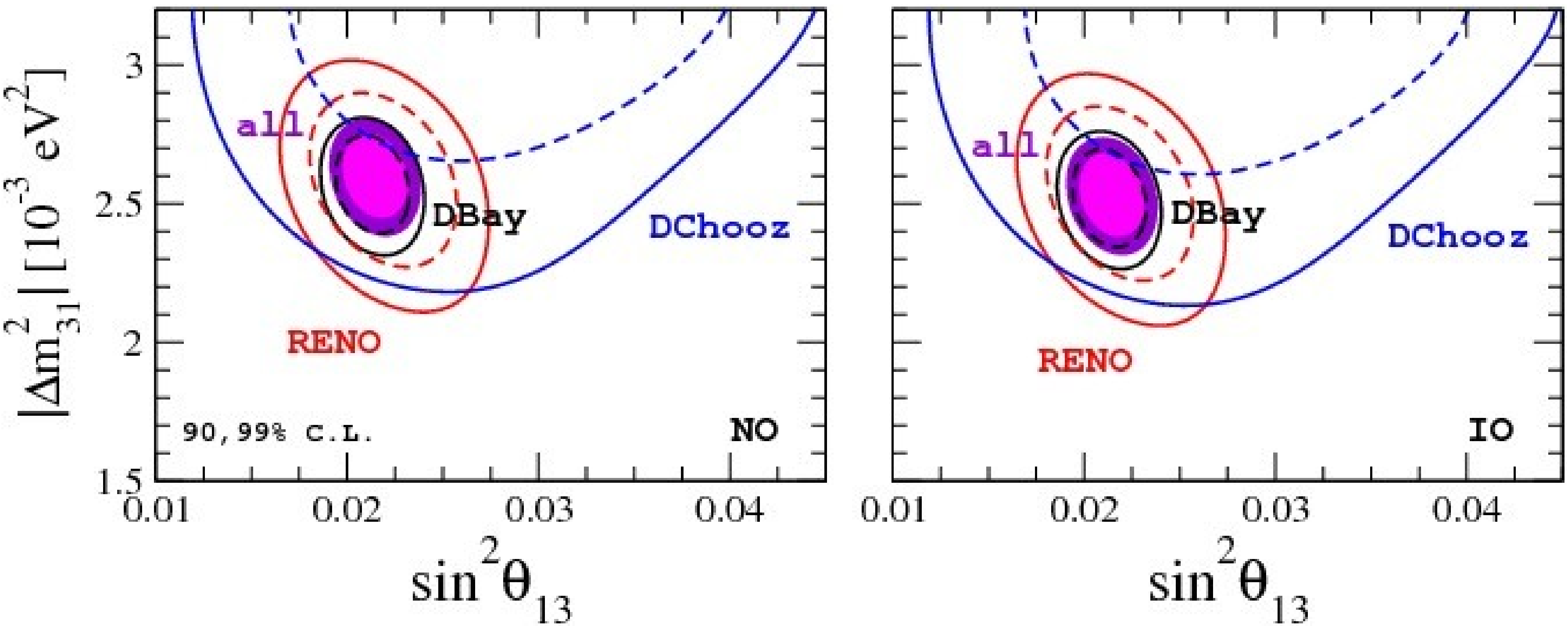
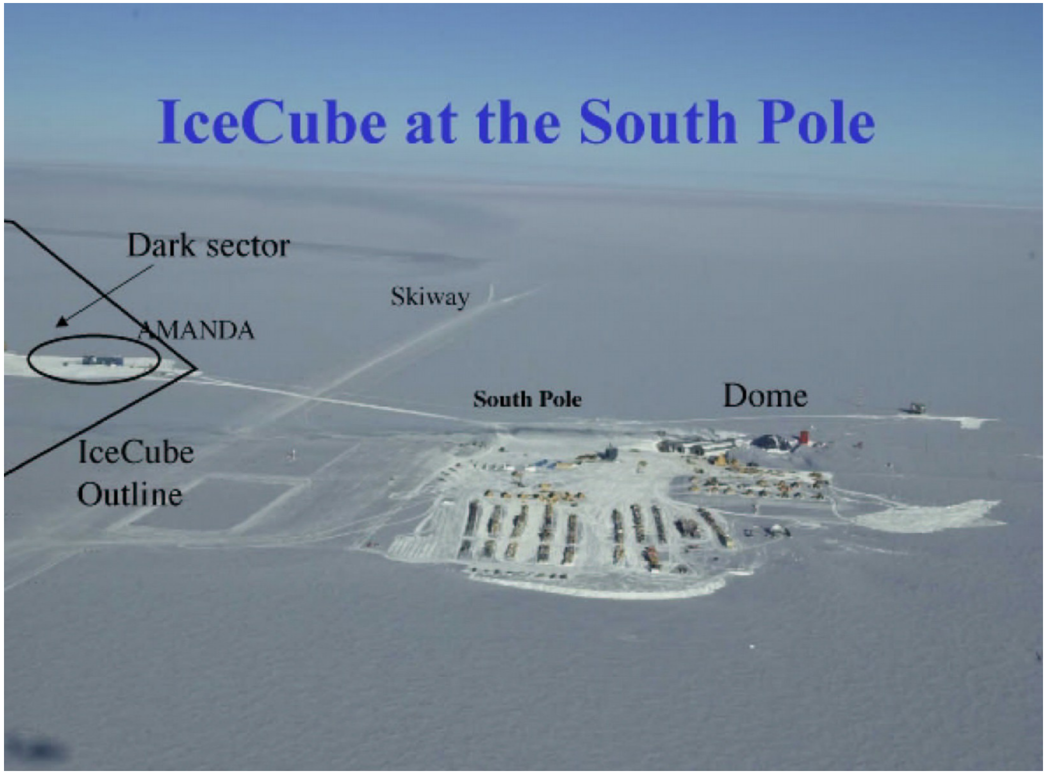
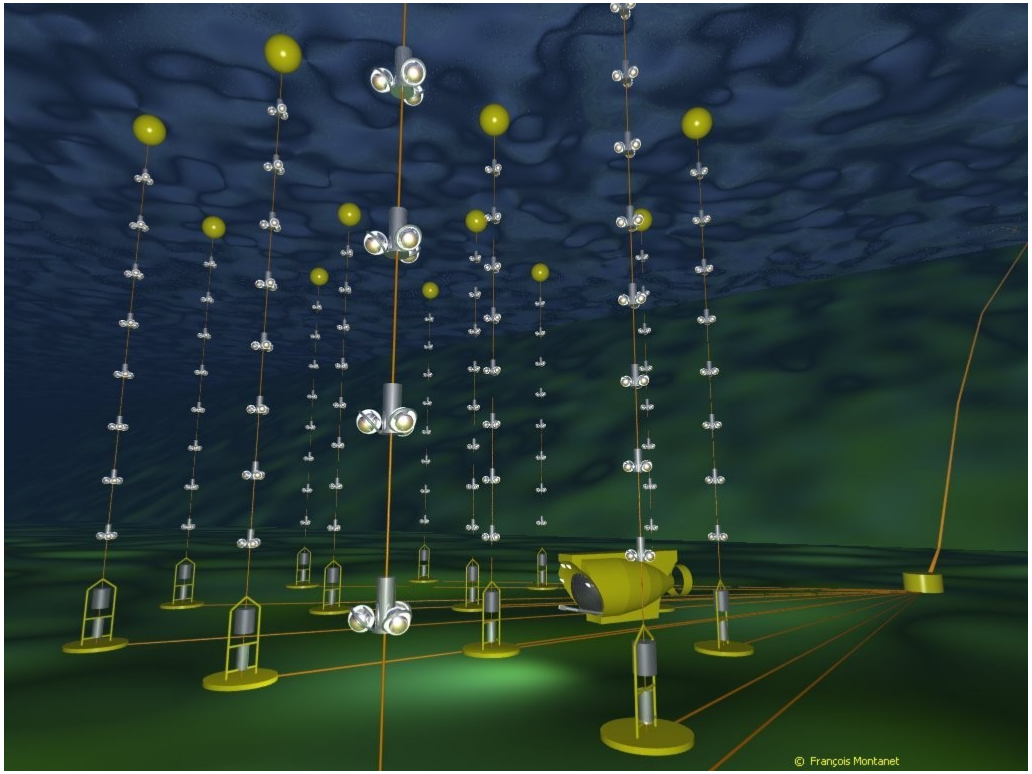


- Reactor analysis is dominated by Daya Bay
- RENO starts being competitive

Global fit to neutrino oscillations

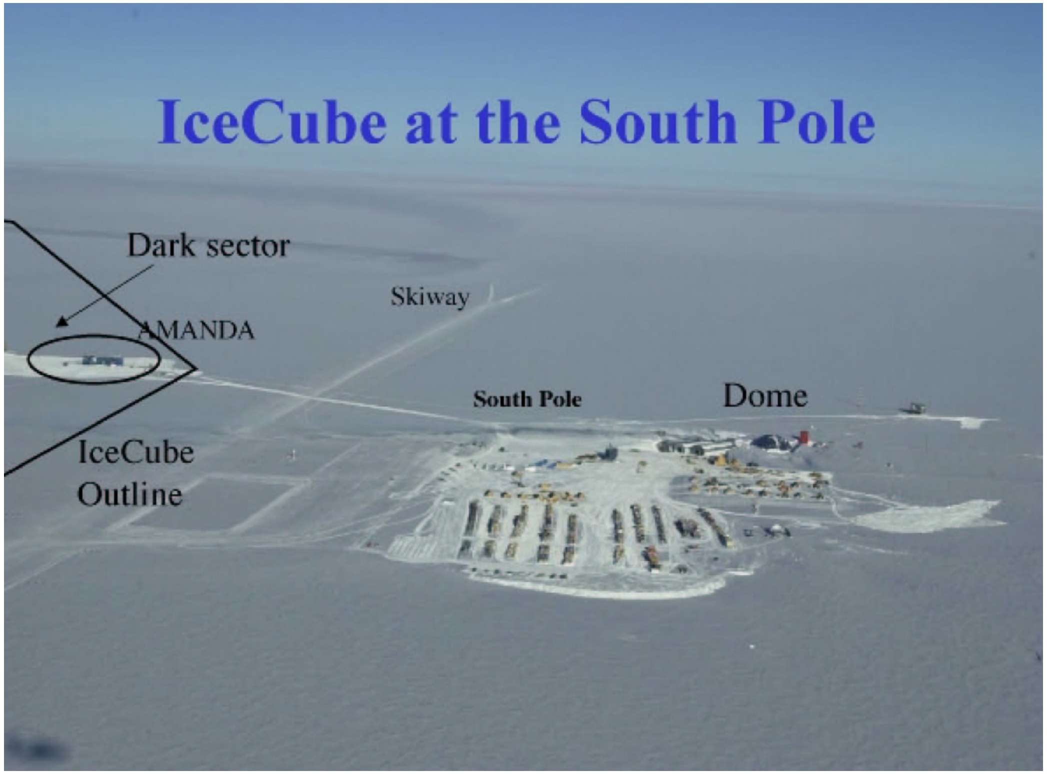
- Atmospheric neutrino experiments are mostly focused on the disappearance of muon neutrinos $(P_{\mu\mu})$ and antineutrinos $(P_{\bar{\mu}\bar{\mu}})$ created in the atmosphere

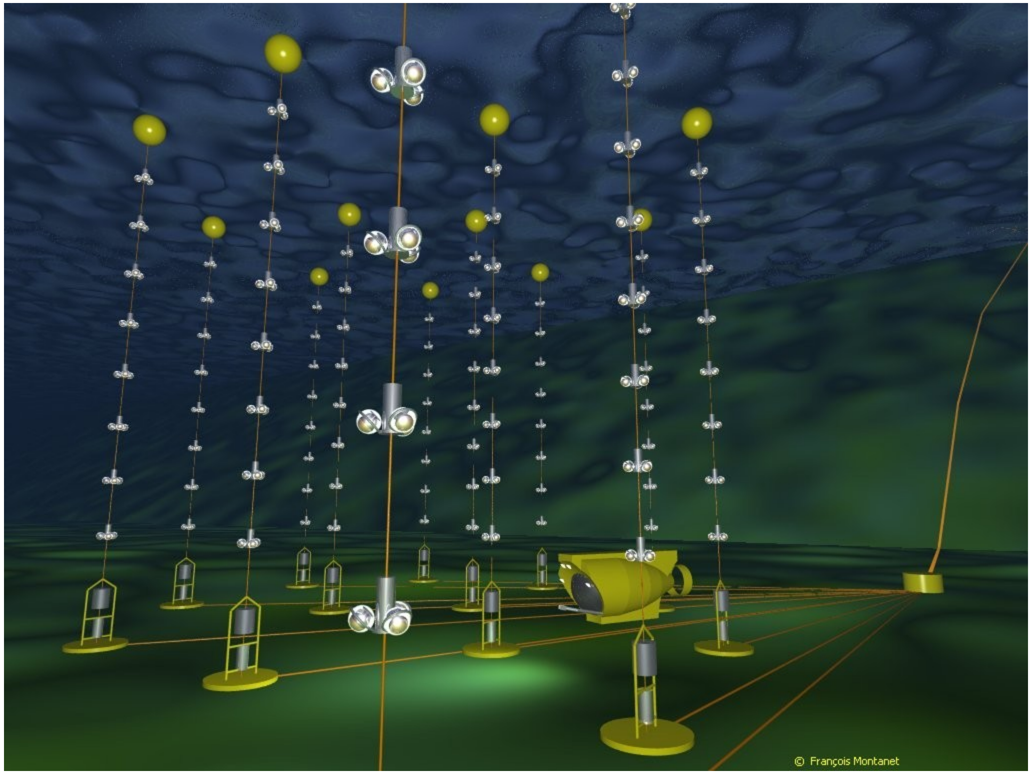




Global fit to neutrino oscillations

- Atmospheric neutrino experiments are mostly focused on the disappearance of muon neutrinos $(P_{\mu\mu})$and antineutrinos $(P_{\bar{\mu}\bar{\mu}})$ created in the atmosphere
- They measure the atmospheric parameters Δm^2_{31} and θ_{23}





Global fit to neutrino oscillations

- Data included:
  - 863 days of ANTARES data
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Global fit to neutrino oscillations

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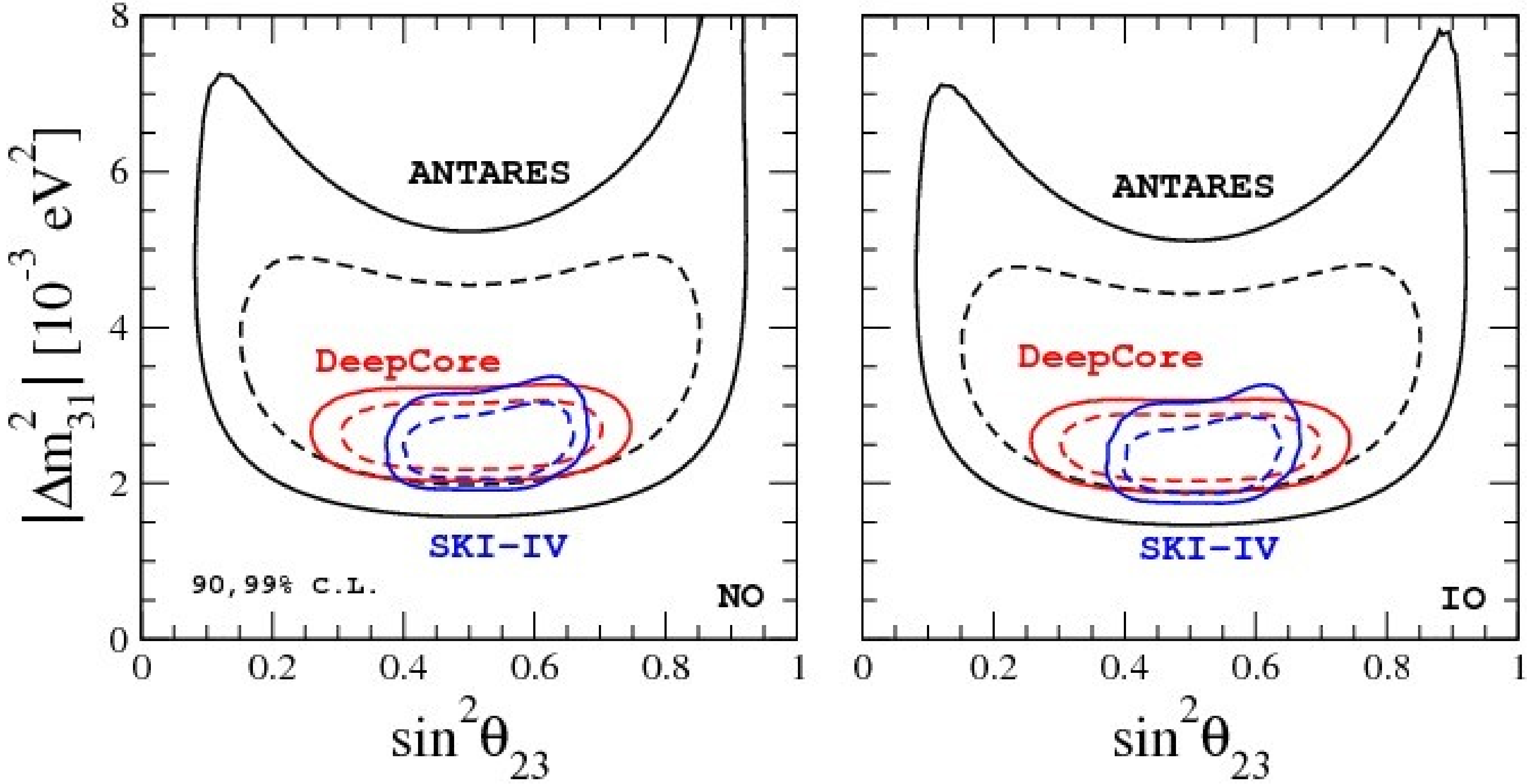
  - 953 days of IceCube DeepCore data
  - SK I-IV
- In the case of SK we add the grid provided by the collaboration
  - 14 datasets, 4 times 520 bins and 155 systematic errors with possible correlations among them, make it impossible to reproduce the results outside the collaboration

Global fit to neutrino oscillations

- Result of atmospheric experiments



Global fit to neutrino oscillations

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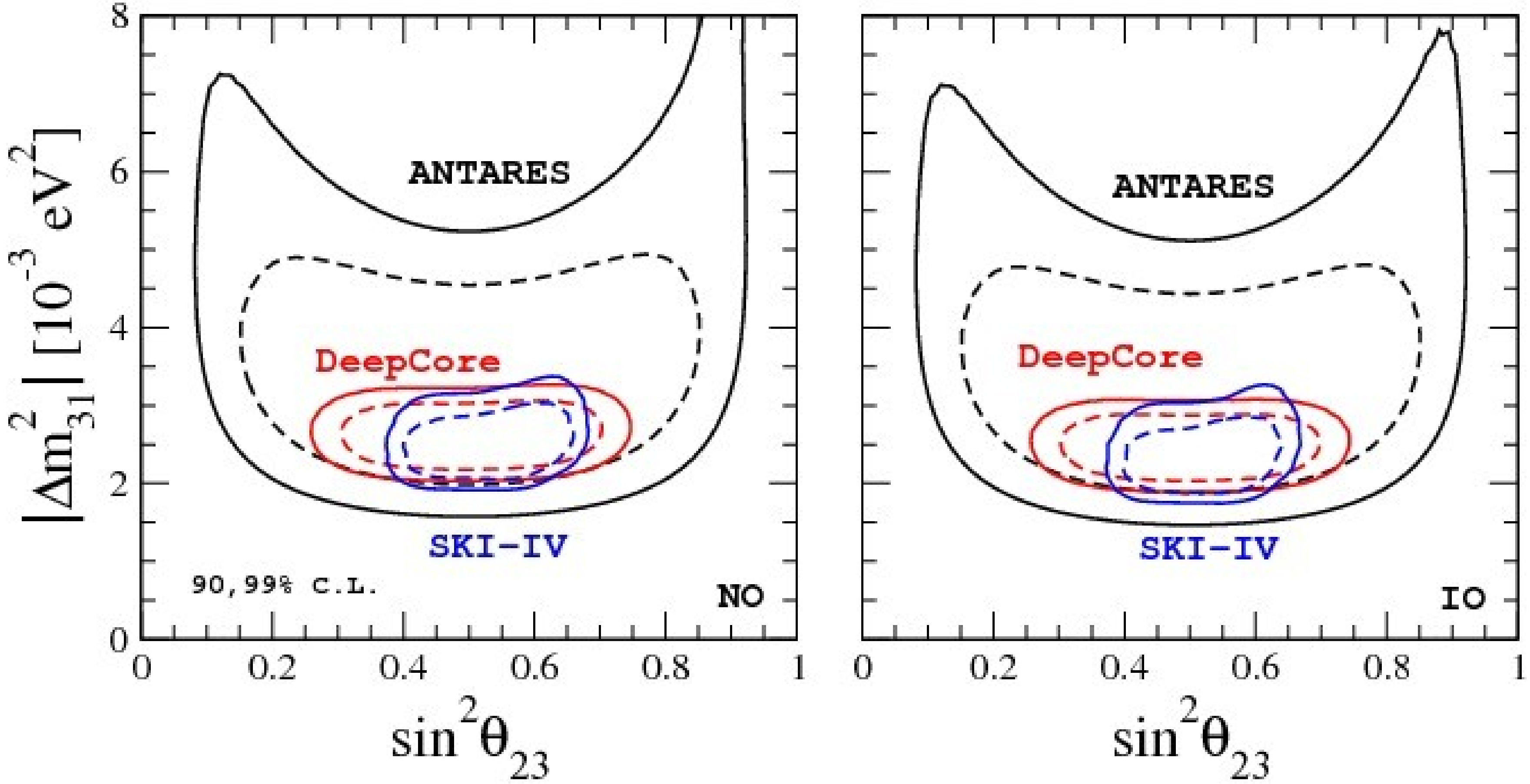
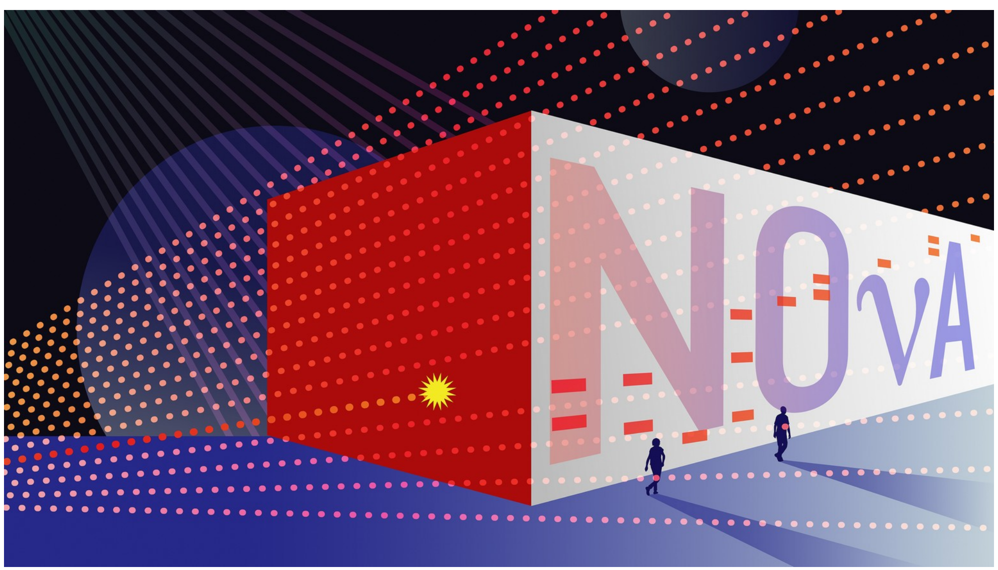
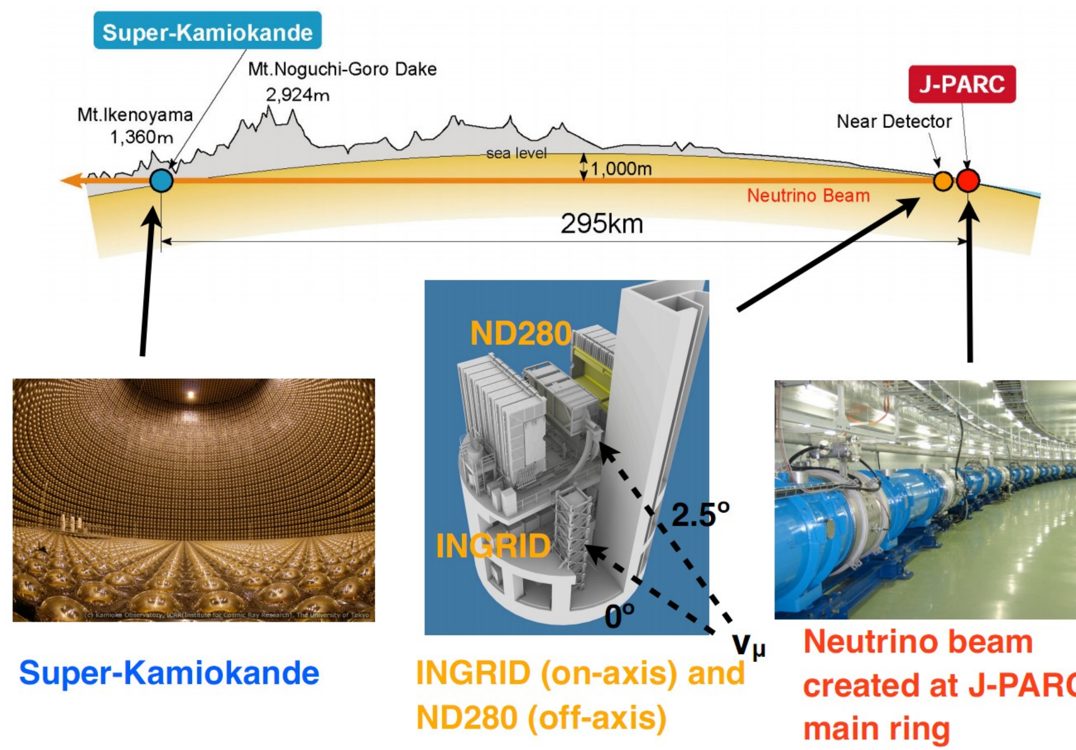


- Atmospheric experiments start to be competitive with long baseline experiments as we will see now

Global fit to neutrino oscillations

- Long baseline experiments measure disappearance of muon neutrinos $(P_{\mu\mu})$ and antineutrinos $(P_{\bar{\mu}\bar{\mu}})$ and appearance of electron neutrinos $(P_{\mu e})$ and antineutrinos $(P_{\bar{\mu}\bar{e}})$ created at accelerator experiments





Global fit to neutrino oscillations

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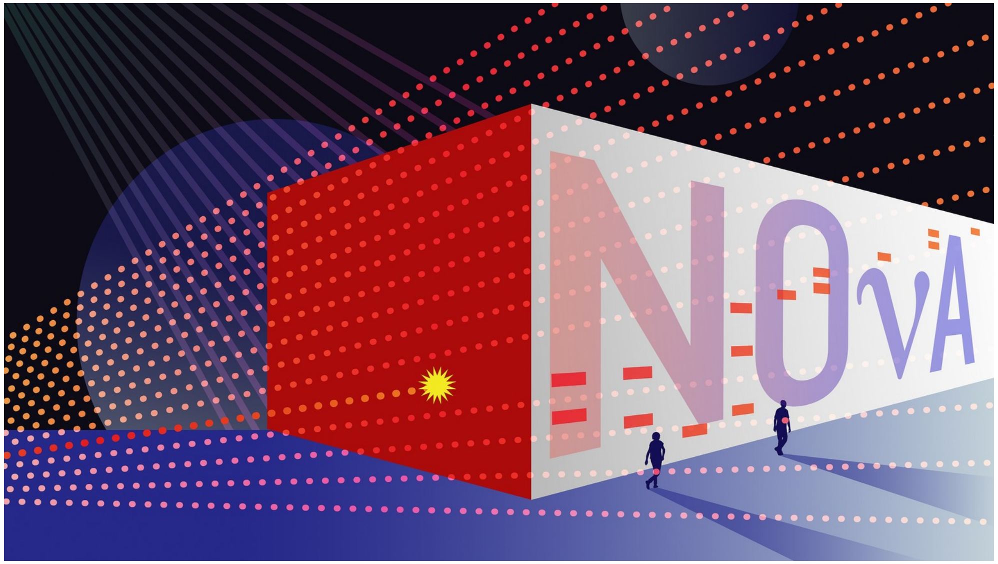
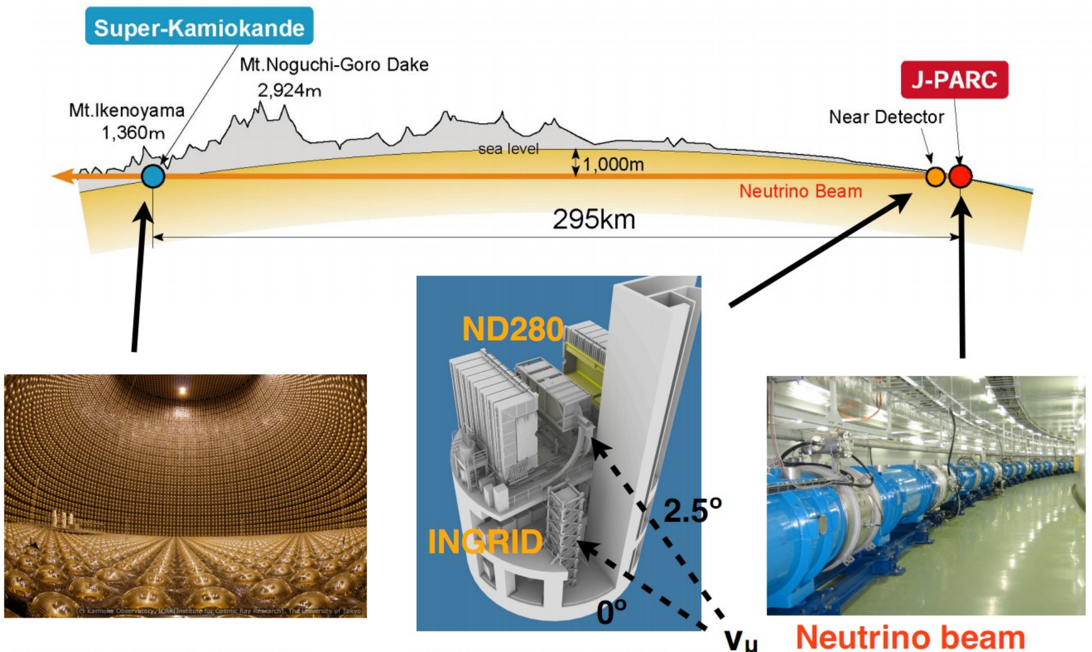
- They measure the parameters $\Delta m^2_{31}, \theta_{23}$, θ_{13} and δ





Super-Kamiokande

INGRID (on-axis) and ND280 (off-axis)

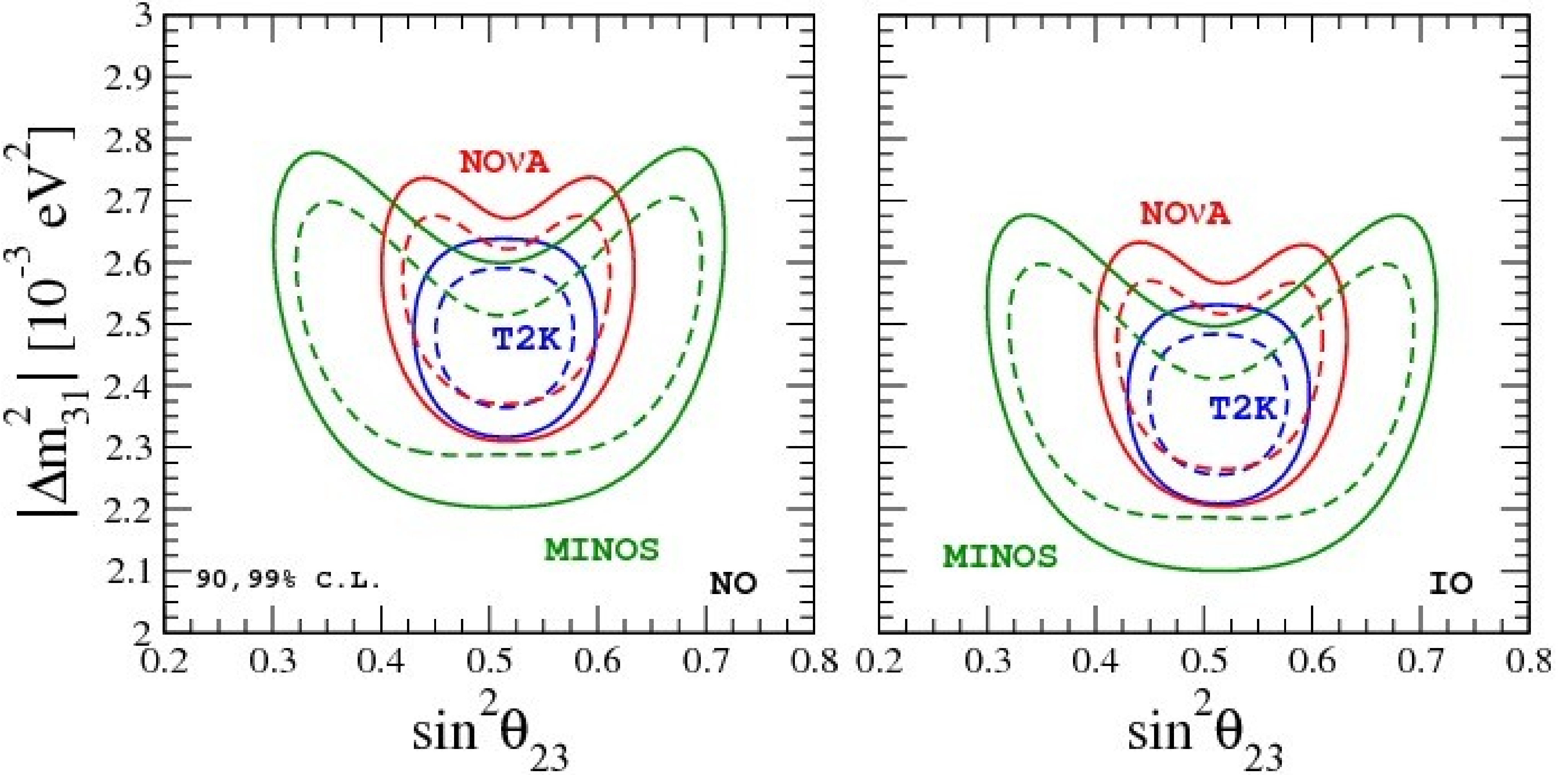
Neutrino beam created at J-PARC main ring

Global fit to neutrino oscillations

- Data included:
  - 14.7 x 10^{20} POT in neutrino mode at T2K
  - 7.6 x 10^{20} POT in antineutrino mode at T2K
  - 8.85 x 10^{20} POT in neutrino mode at NOνA
  - MINOS: full accelerator data set
  - K2K: full data set

Global fit to neutrino oscillations

- Result of long-baseline experiments



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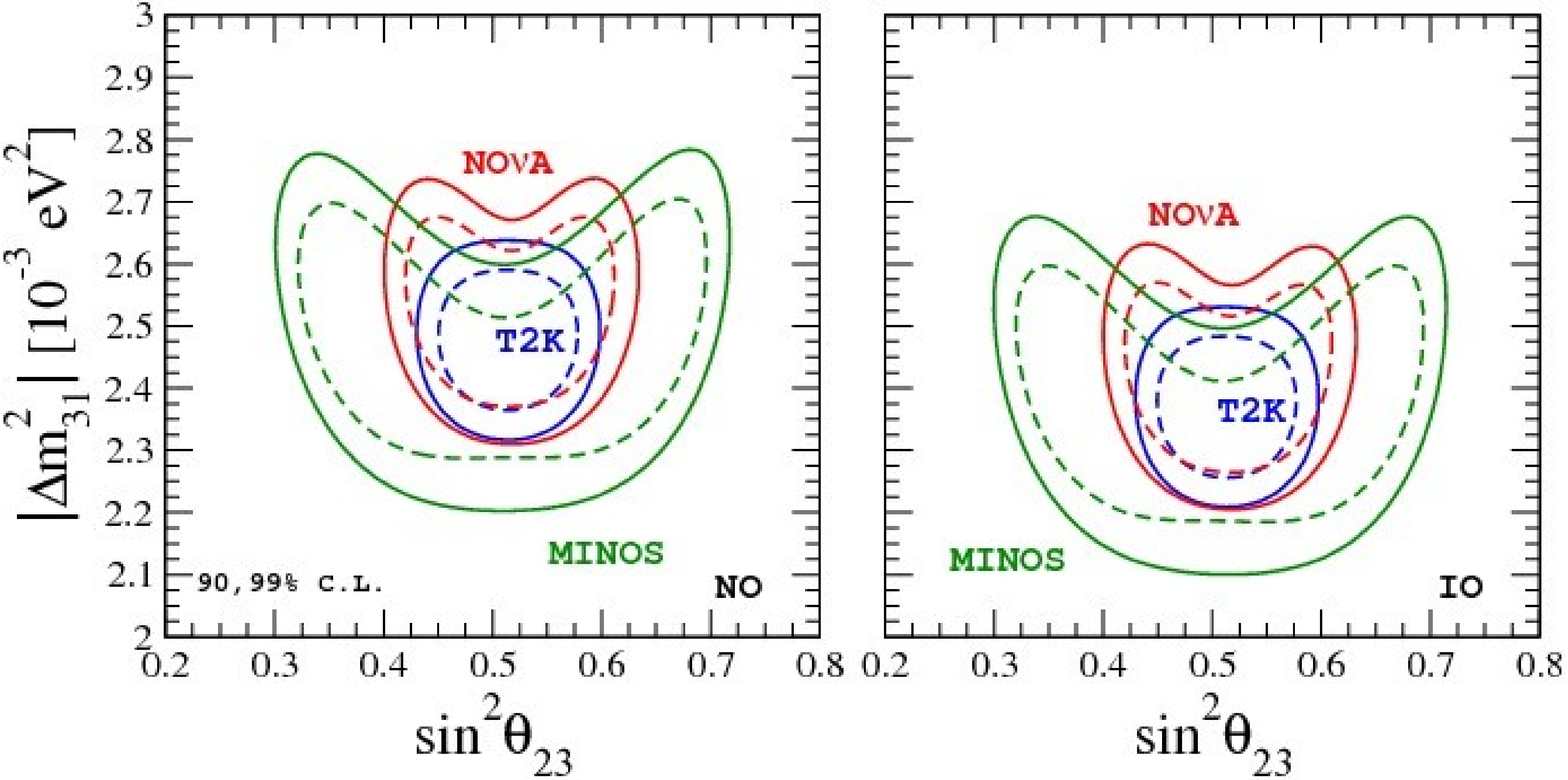
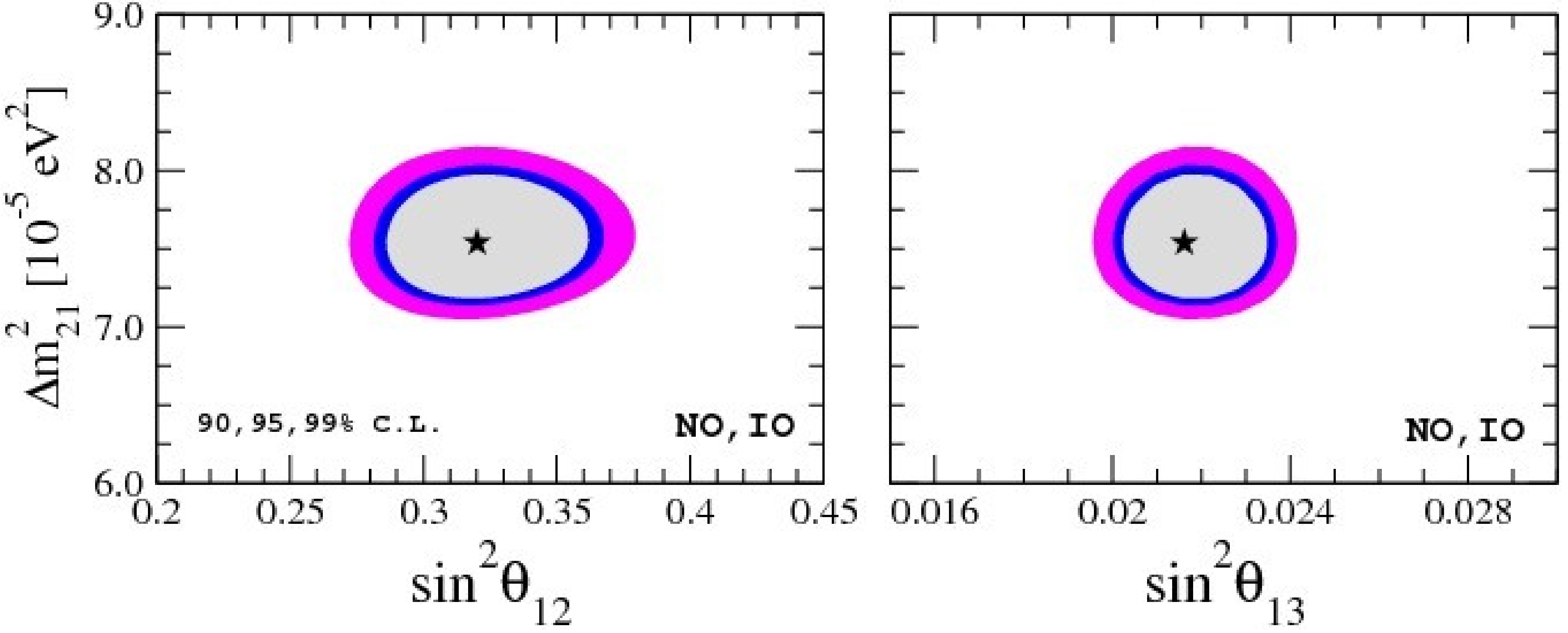


- Analysis dominated by T2K and NOνA

Results of the combined analysis

The solar plane

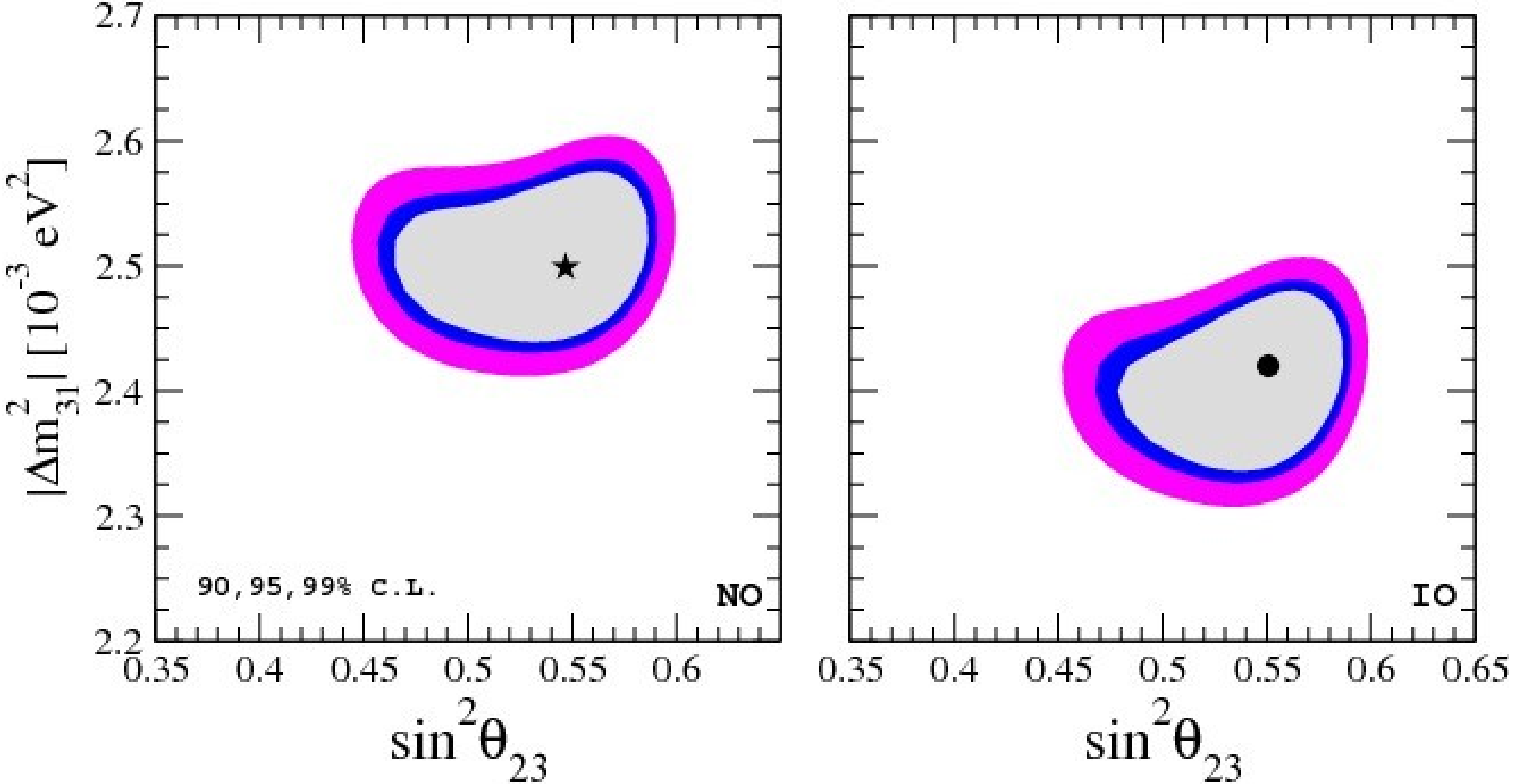
- The solar parameters are measured by solar experiments and KamLAND



- Best fit: $\sin^2\theta_{12} = 0.320, \Delta m^2_{21} = 7.55 \times 10^{-5} \mathrm{eV}^2$

The atmospheric plane

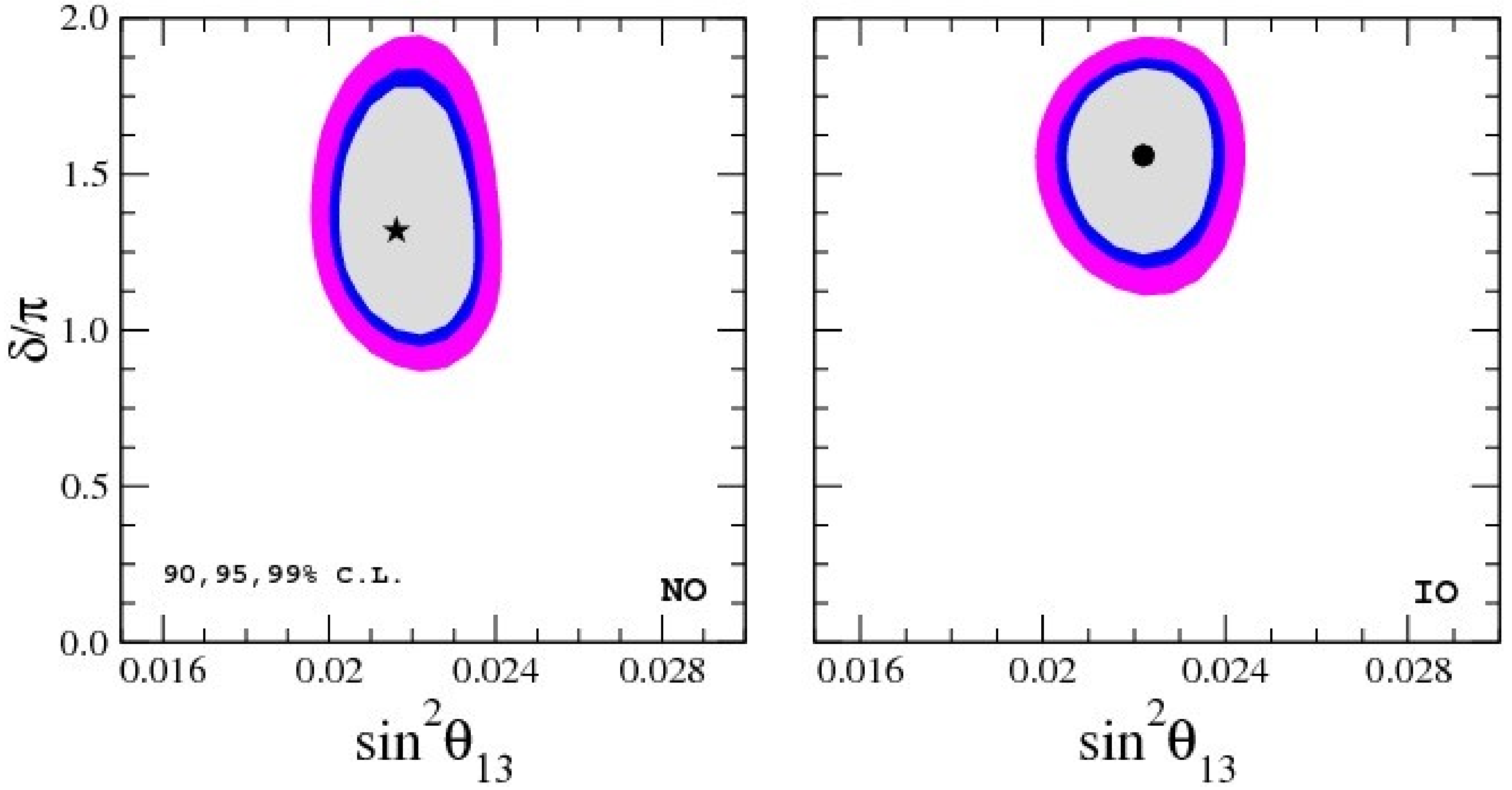
- Measurement of atmospheric parameters dominated by the combination of LBL and reactor experiments



- Best fit: $\sin^2\theta_{23} = 0.547, \Delta m^2_{31} = 2.50 \times 10^{-3}\text{eV}^2(\text{NO})$
  $\sin^2\theta_{23} = 0.551, \Delta m^2_{31} = -2.42 \times 10^{-3}\text{eV}^2(\text{IO})$

The reactor angle and the CP phase

- For the first time we can exclude big part of the parameter space for δ

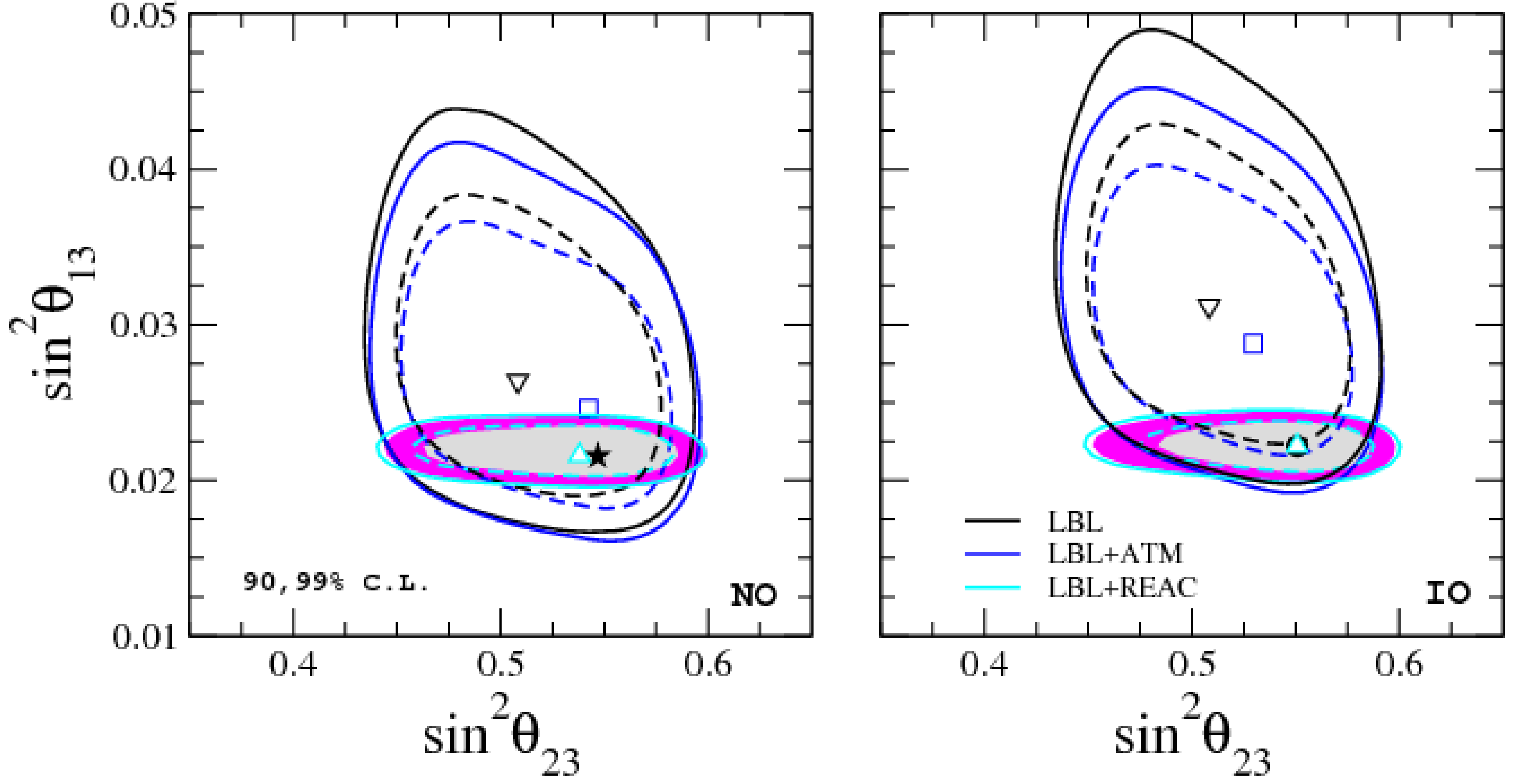


- Best fit: $\sin^2\theta_{13} = 0.0216, \delta = 1.32\pi(\text{NO})$

  $\sin^2\theta_{13} = 0.0222, \delta = 1.56\pi(\text{IO})$

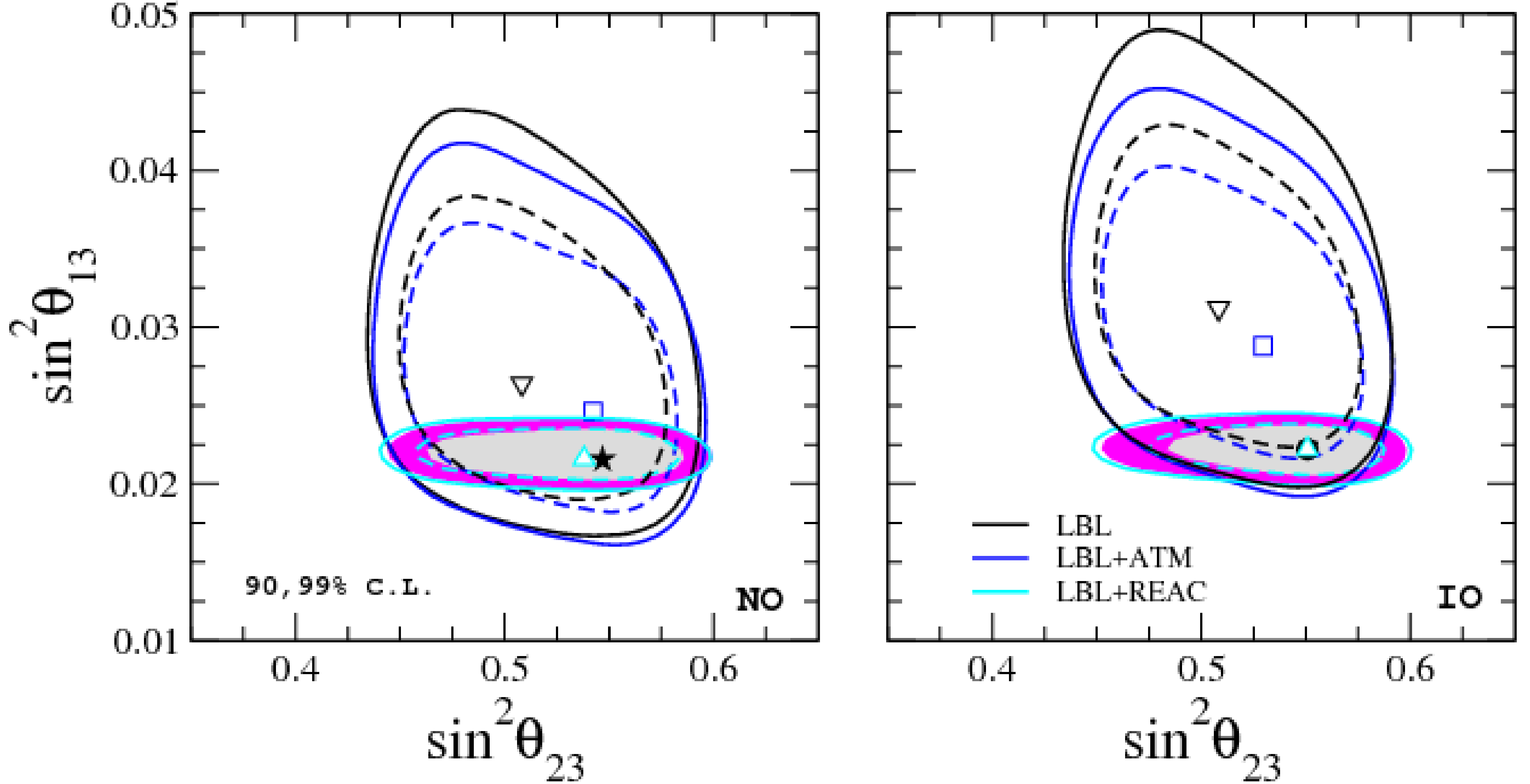
The reactor angle

- The measurement of the reactor angle is dominated by the short baseline reactors

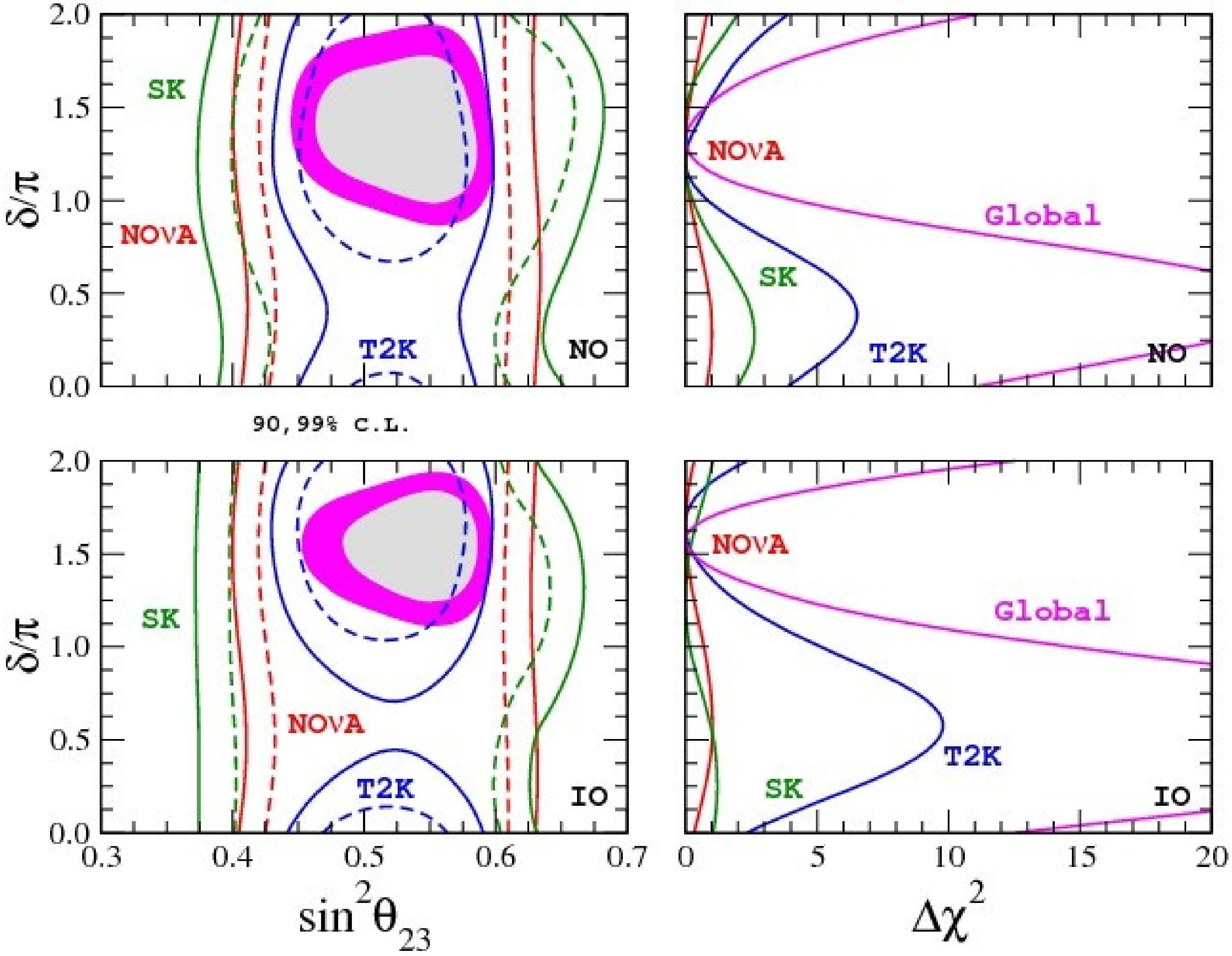


The reactor angle

- The measurement of the reactor angle is dominated by the short baseline reactors
- LBL+ATM might start being competitive in the future

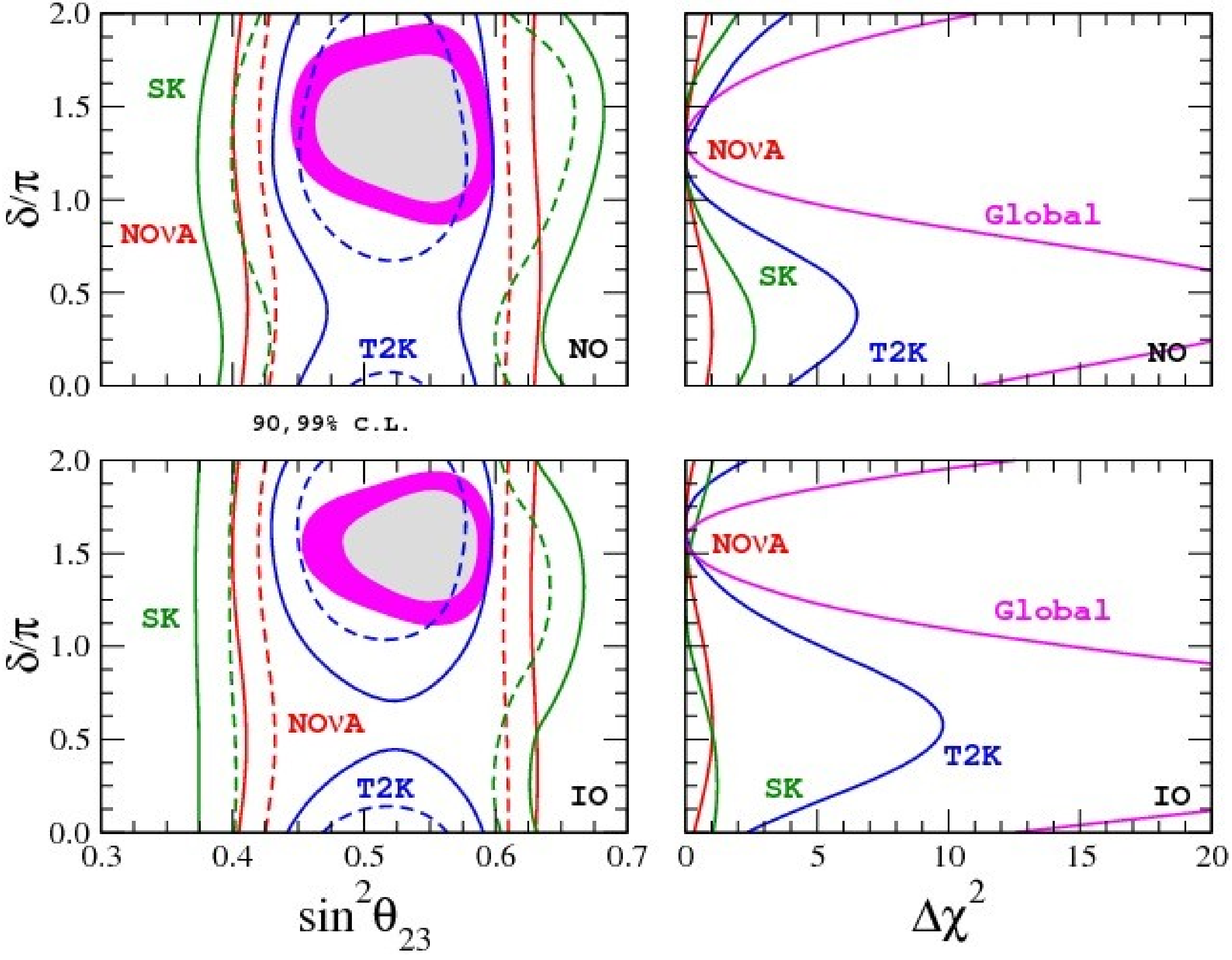


The CP phase



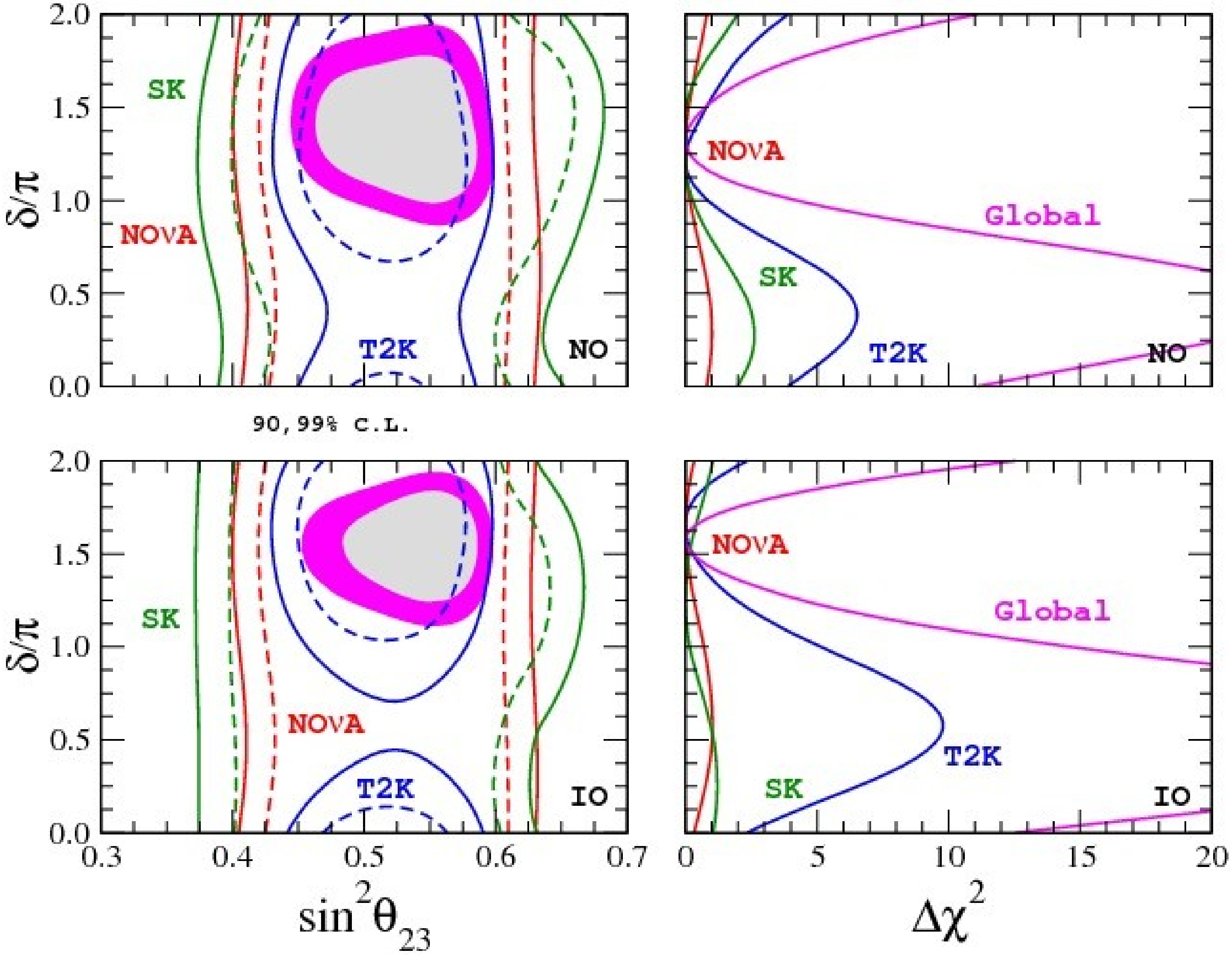
- Best sensitivity to δ comes from T2K

The CP phase



- Best sensitivity to δ comes from T2K
- Constraint on θ_{13} improves sensitivity to δ at all experiments significantly

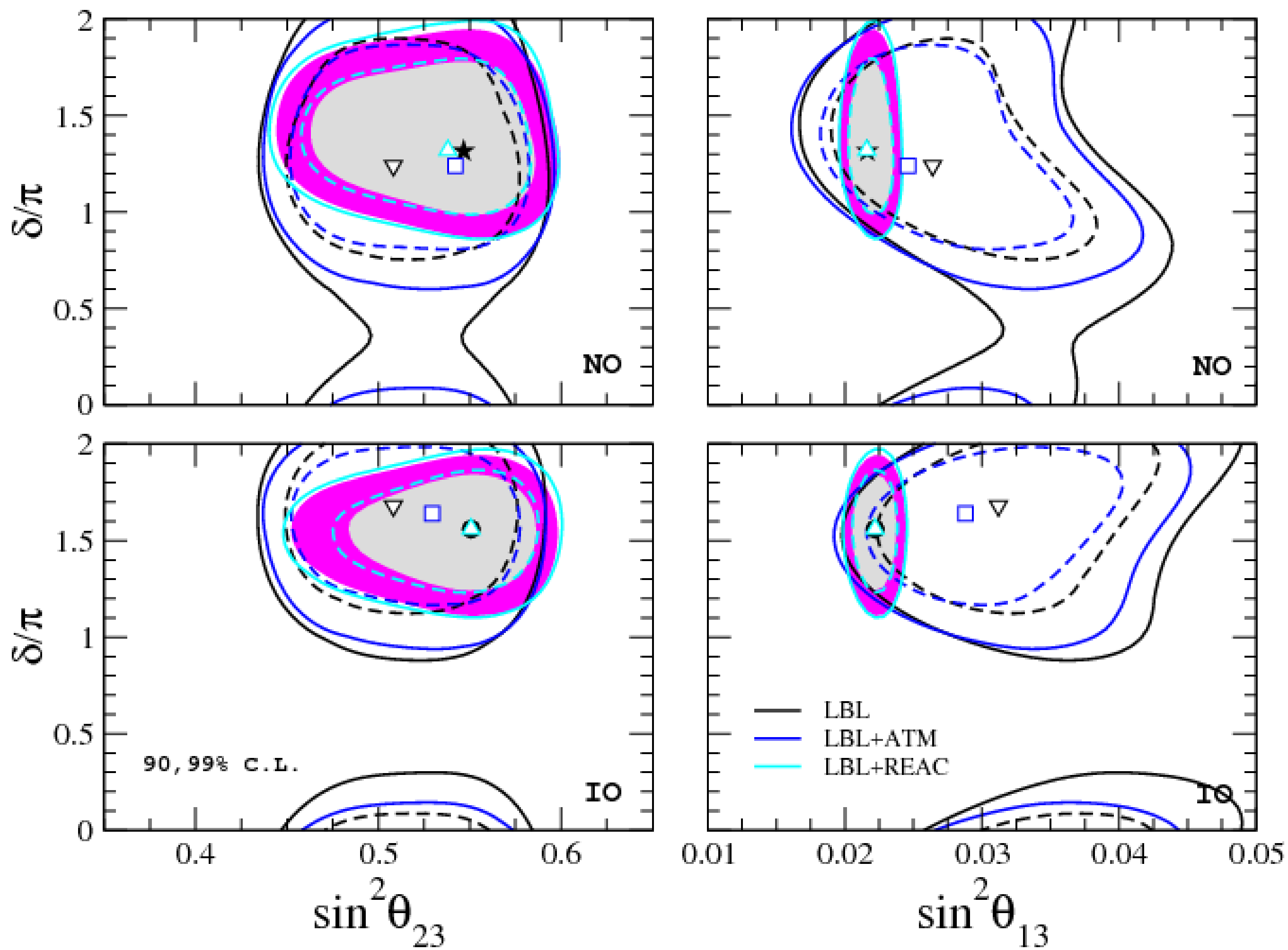
The CP phase



- Best sensitivity to δ comes from T2K
- Constraint on θ_{13} improves sensitivity to δ at all experiments significantly
- This results in exclusion of values around 0.5π at $> 4\sigma$

The mass ordering and the role of SK

- Inverted mass ordering is now disfavored at more than 3σ, with $\Delta\chi^2 = 11.7$



SK does not affect the determination of the oscillation parameters:

The mass ordering and the role of SK

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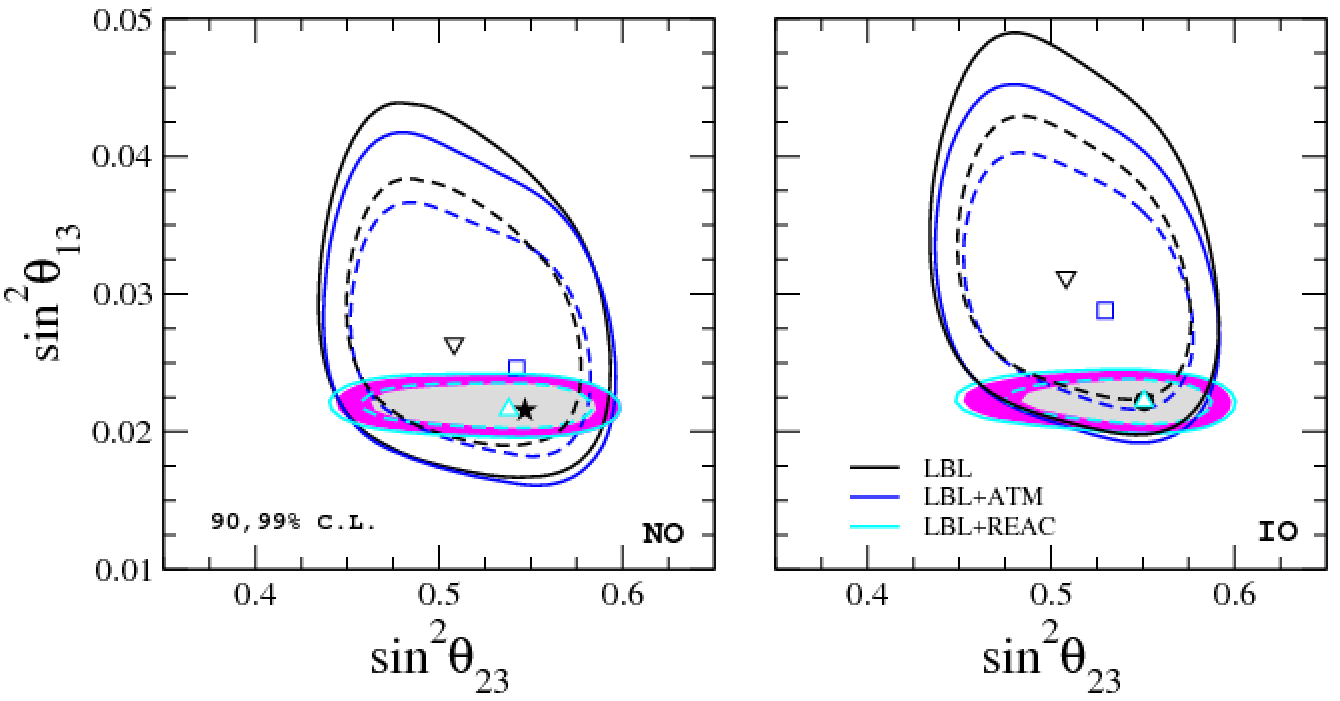

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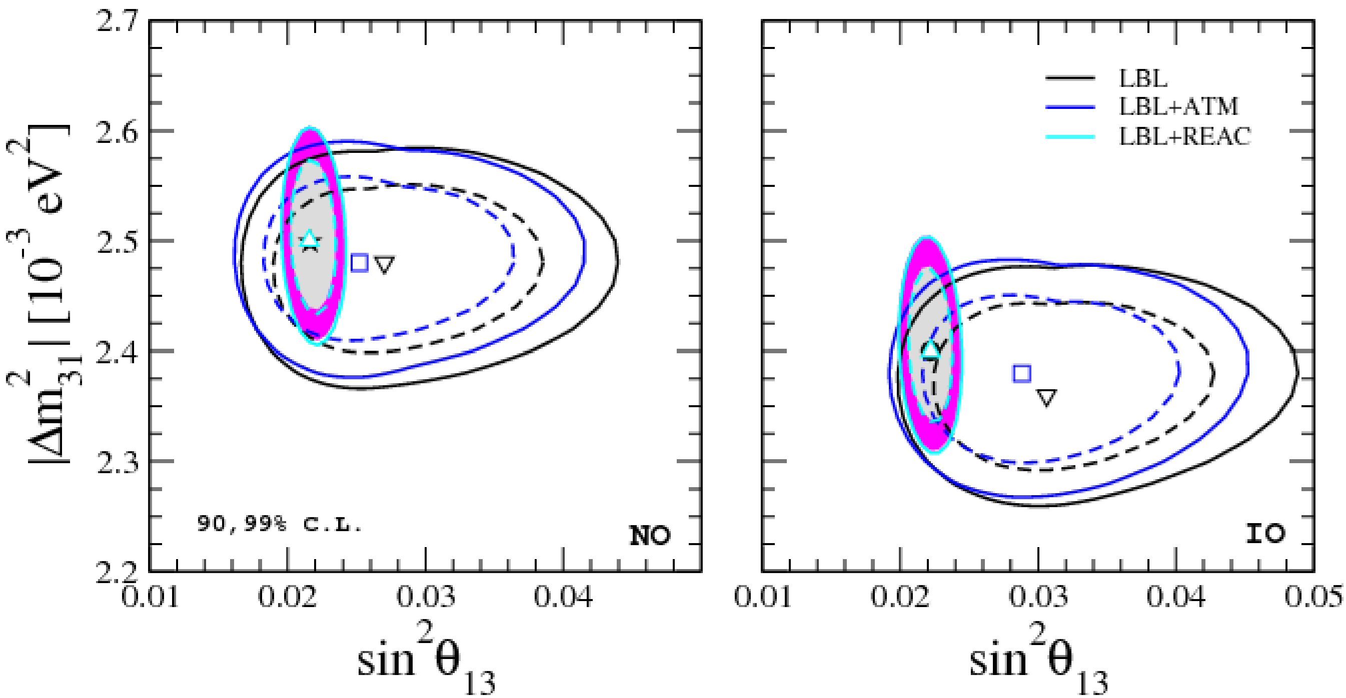

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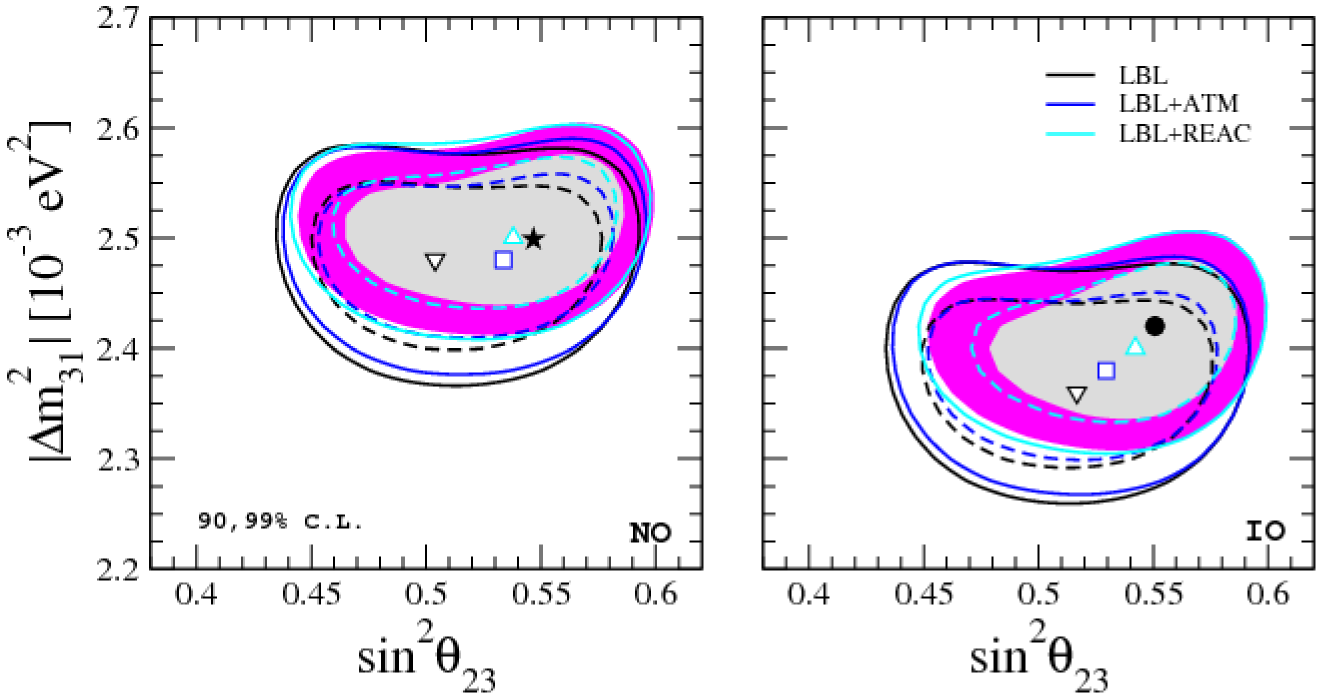
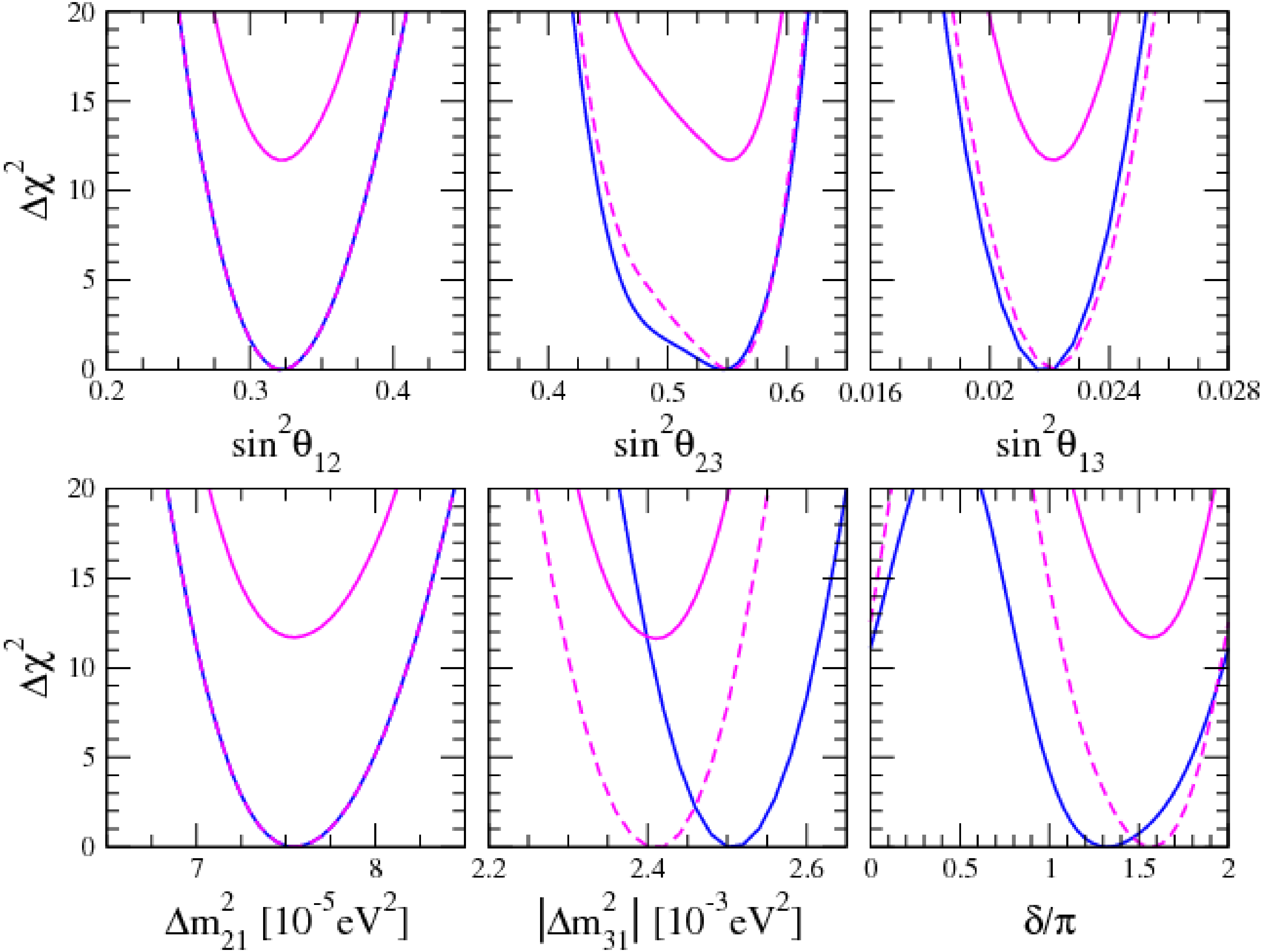
- If we exclude SK from the fit we obtain $\Delta\chi^2 = 7.7$
- This is due to the combination of LBL+Reactors, since LBL alone gives $\Delta\chi^2 = 2.0$
- SK "only" improves the sensitivity to the mass ordering

SK does not affect the determination of the oscillation parameters:



Summary of the global fit



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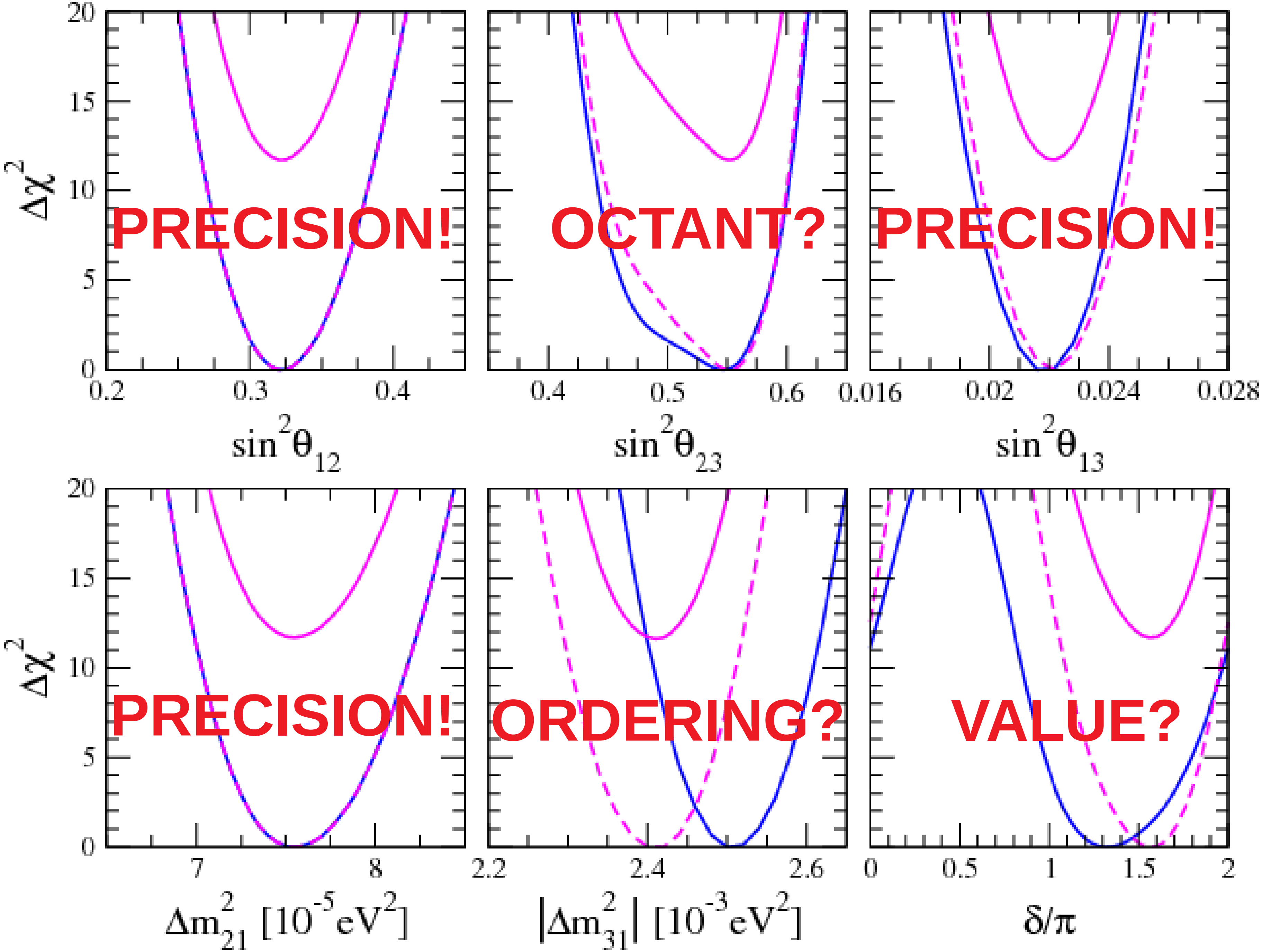

Summary of the global fit

parameter	best fit ± 1σ	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.50±0.03	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

Summary of the global fit

	parameter	best fit ± 1σ	3σ range
~2.6%	Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14
~1.5%	$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.50±0.03	2.41–2.60
	$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
~6.3%	$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
~5.5%	$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
	$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
~3.5%	$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
	$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
~13.5%	δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
	δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

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- The octant problem remains unsolved, although the value now tends towards the second octant
- The combination of all data prefers normal ordering with a significance of 3.4σ

Stay tuned for the future!

DUNE

JUNO

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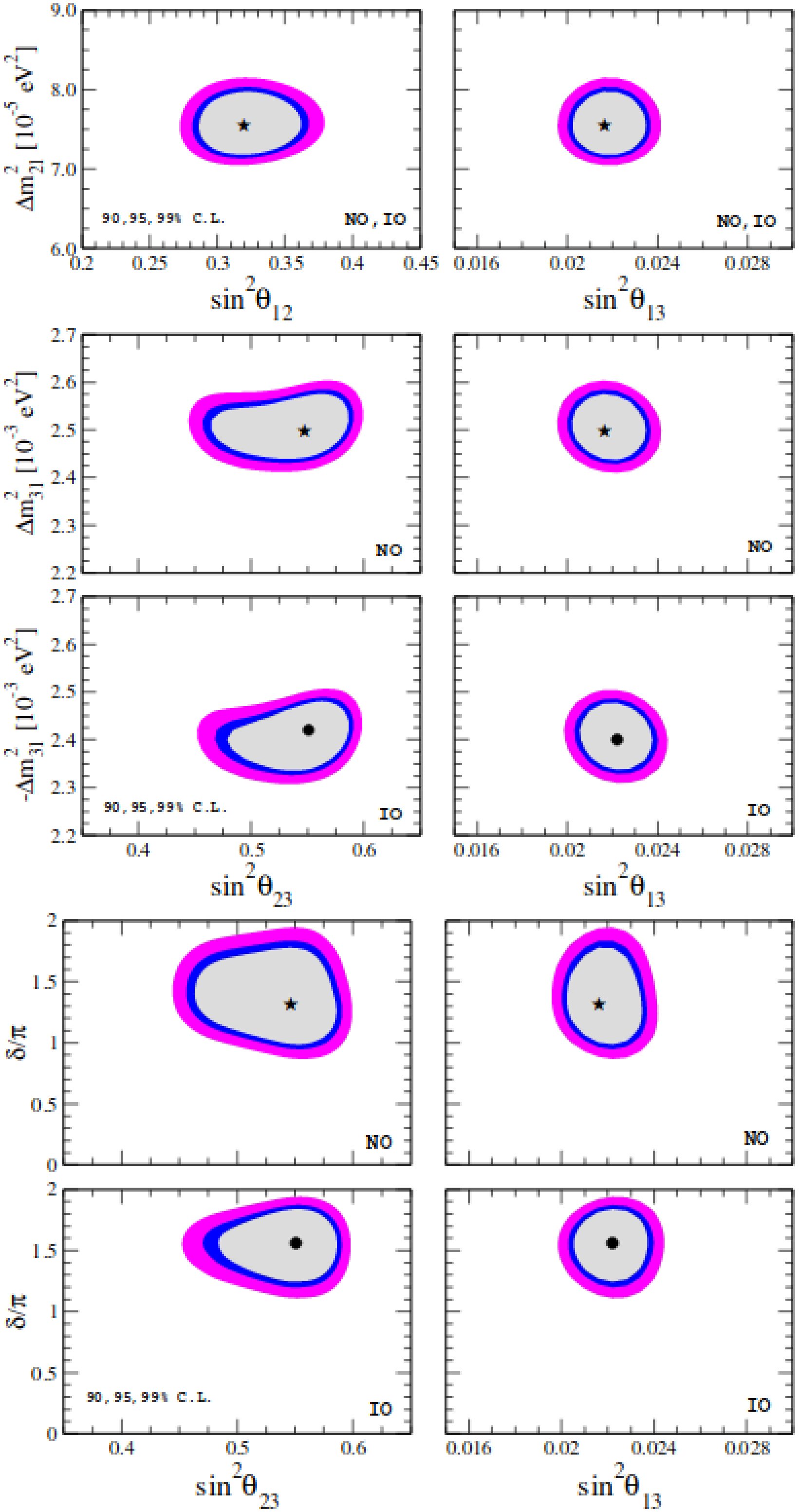
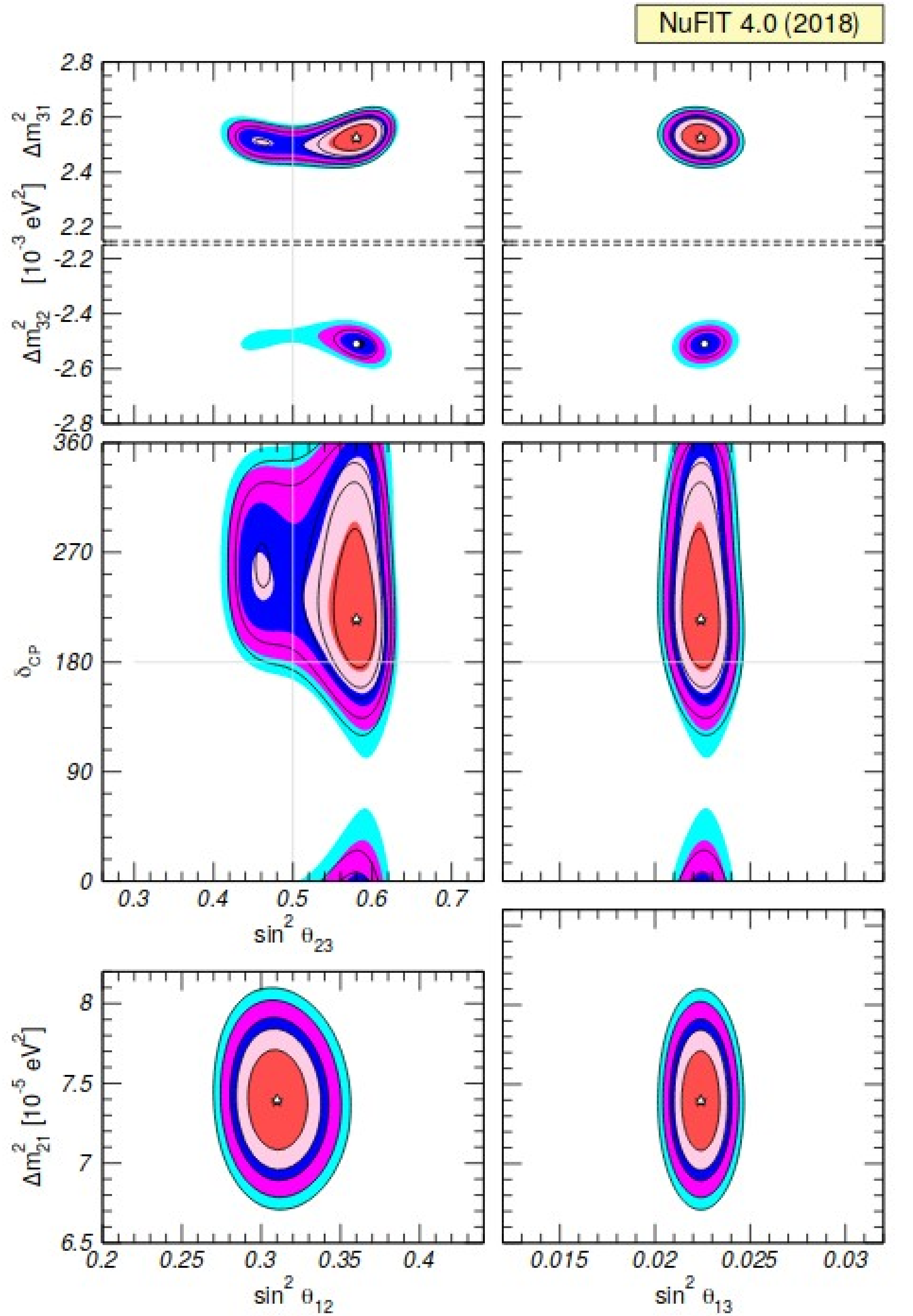
ORCA
KM3NeT

HYPER
K


Gracias!
muon neutrino

Backup





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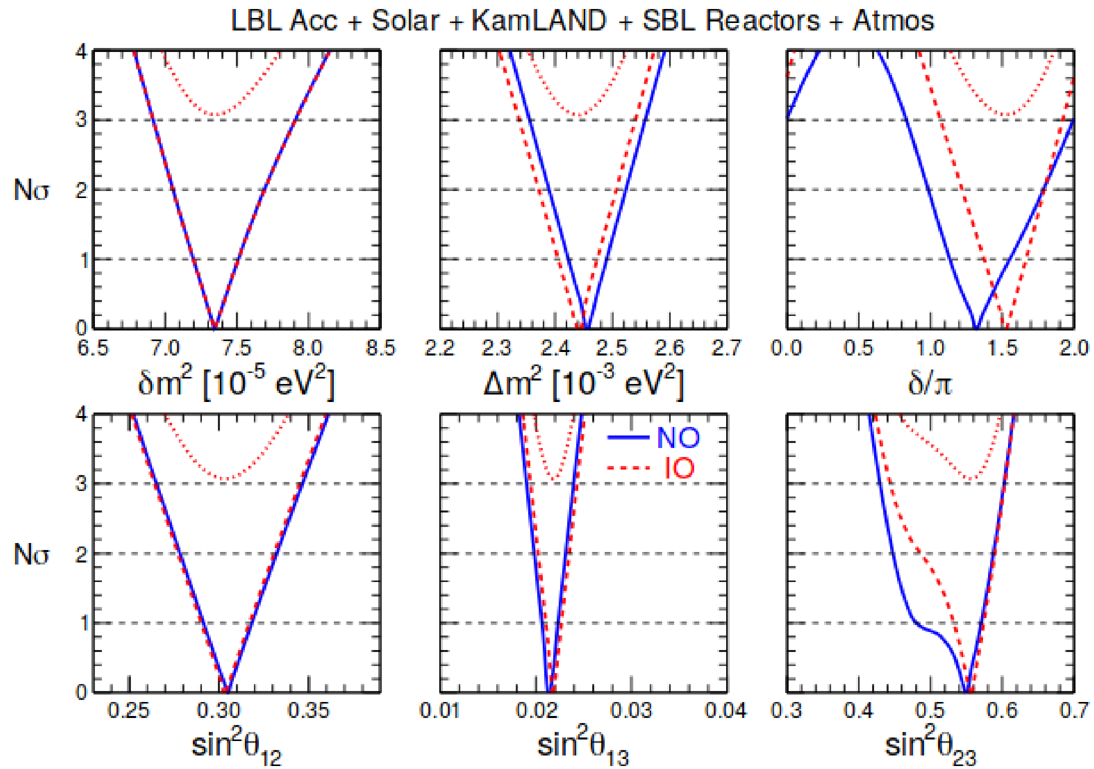

Prog.Part.Nucl.Phys. 102 (2018) 48-72

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