

# GLOBAL STATUS OF NEUTRINO OSCILLATION PARAMETERS

DAVID VANEGAS FORERO ([D.V. Forero](#))  
dvanegas@udemedellin.edu.co

7<sup>th</sup> ComHEP  
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# OUTLINE

- 1 INTRODUCTION
- 2 NEUTRINO OSCILLATION DATA
- 3 PARTIAL FIT RESULTS
- 4 GLOBAL FIT RESULTS
- 5 COMPARISON WITH OTHER GLOBAL-FITS
- 6 SUMMARY & CONCLUSIONS

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1 INTRODUCTION

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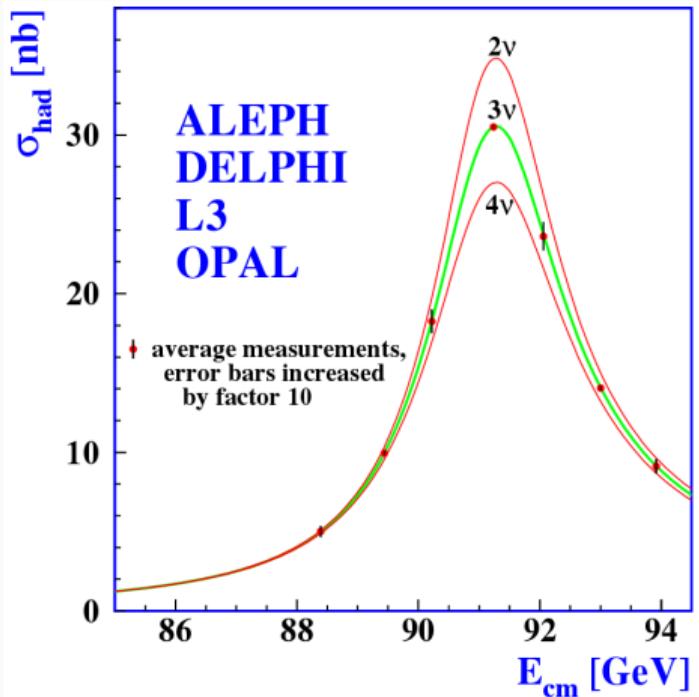
6 SUMMARY & CONCLUSIONS

# Known facts about the neutrino ( $\nu$ )

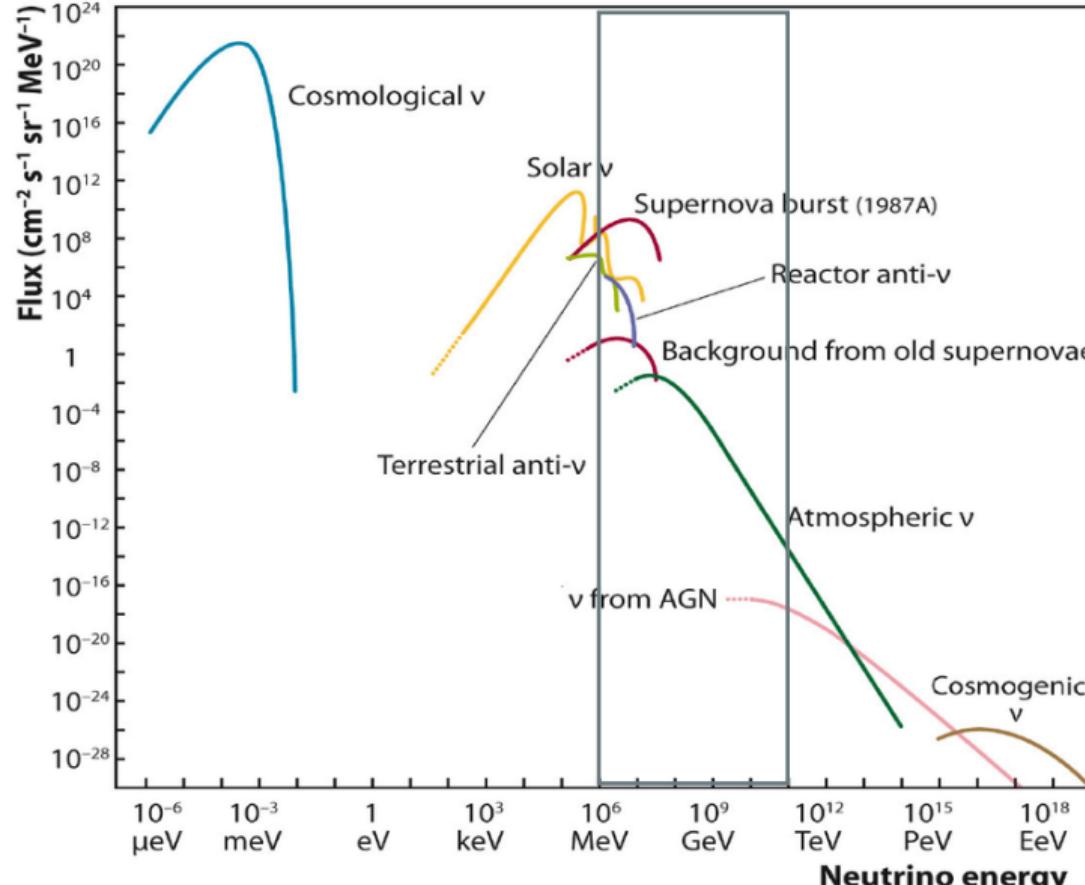
- It is a fundamental particle, a fermion.
- Has no electric charge.
- Interacts only through the weak interaction.
- Comes in three flavors, associated to each charged lepton ( $e$ ,  $\mu$  &  $\tau$ ). There are only 3-active neutrinos (Exp. fact).
- It changes flavor during propagation, which is explained by **neutrino oscillations**.
- Has a tiny mass but different from zero.
- It is the massive particle more abundant in the Universe.

Three and only three active neutrinos:  
 $N_\nu = 2.984 \pm 0.008$

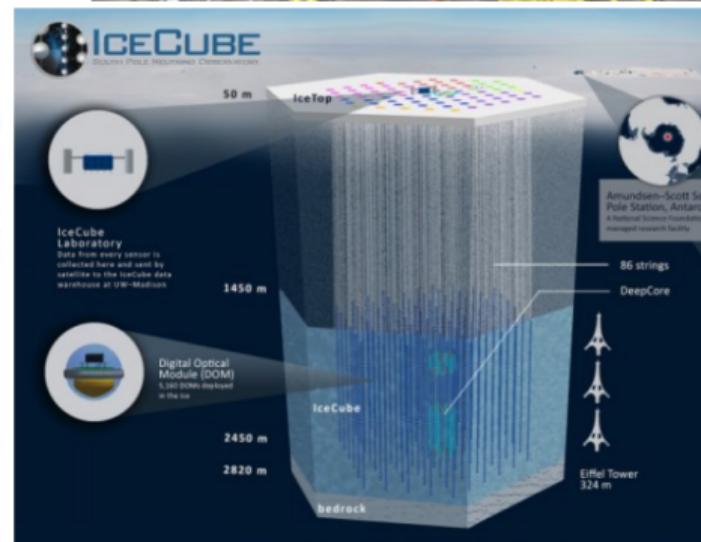
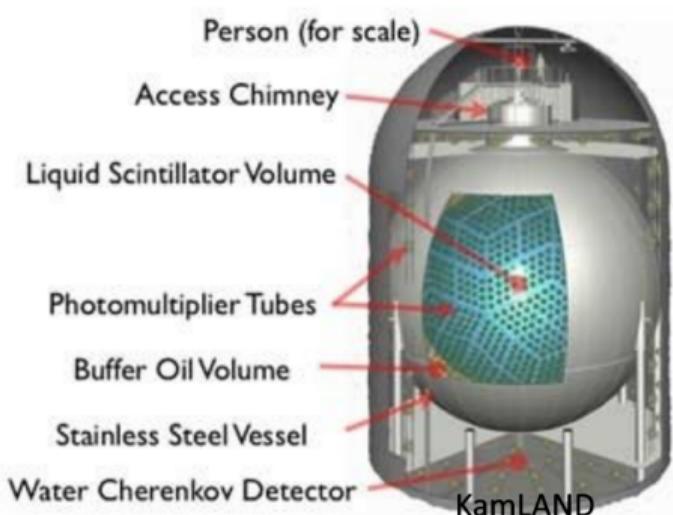
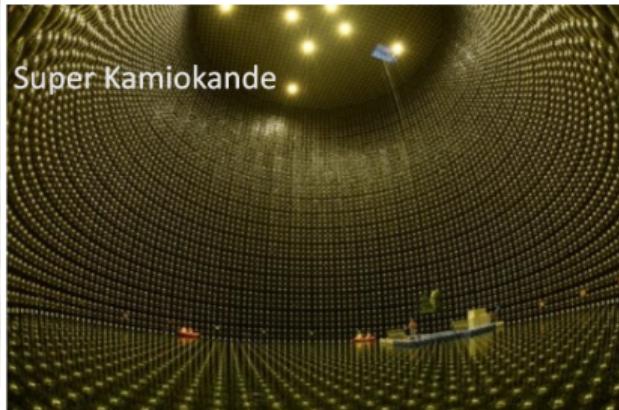
Phys.Rept. 427 (2006) 257-454 arxiv:hep-ex/0509008



# Neutrino sources



# Double Chooz Neutrino detectors



# Neutrino Oscillations ‘in a nutshell’

What conditions should be met?



$$P_{\alpha\beta}^{2\nu} = \sin^2(2\theta) \sin^2(\phi_{\text{osc}})$$

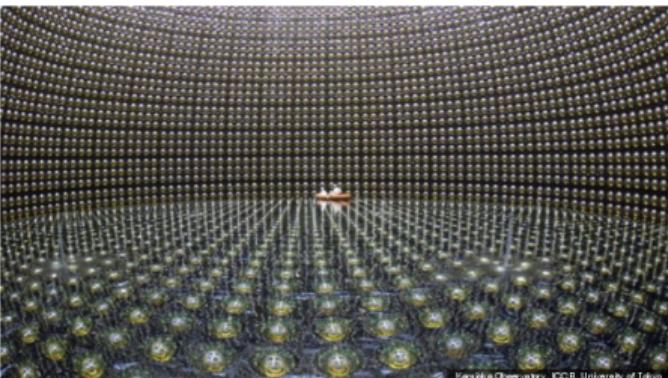
with  $\phi_{\text{osc}} \equiv \frac{\Delta m^2 L}{4E} = 1.27 \frac{\Delta m^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]}$  &  $\theta \equiv$  Mixing angle;  $\theta^{\text{max.}} = \pi/4$ .

- $\Delta m_{jk}^2 \equiv m_j^2 - m_k^2$  sensitivity range depends on  $L/E$  ( $E \equiv$  Neutrino energy).
- Mass squared differences found in Nature:  $\Delta m_{\text{sol.}}^2$  (KamLAND) &  $\Delta m_{\text{atm.}}^2$  (SK).
- **Non-zero neutrino masses!**, a discovery recognized with a Nobel Prize.

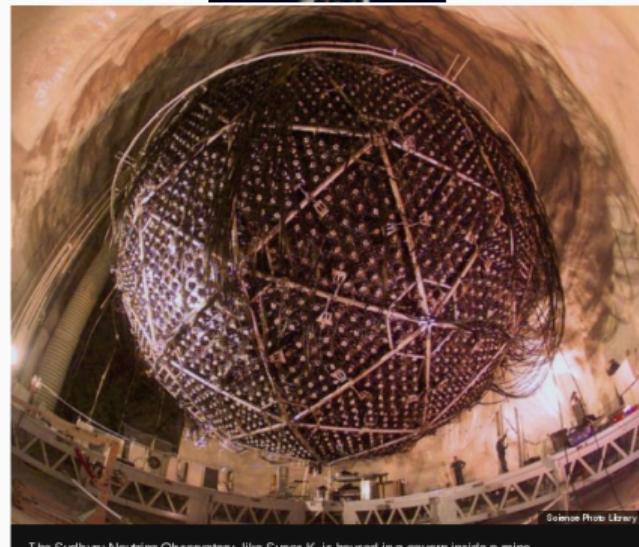
# Neutrino 'flip' wins physics Nobel Prize

By Jonathan Webb  
Science reporter, BBC News

© 6 October 2015 | Science & Environment



Crucial measurements were made at the Super-Kamiokande neutrino detector in Japan



The Sudbury Neutrino Observatory, like Super-K, is housed in a cavern inside a mine

# Neutrino oscillations

$\Delta m^2$ -sensitivity

Experiments (some still running) that ‘have seen’  $\nu$ -oscillations driven by both  $\Delta m^2$ s:

| Channel   | Baseline         | Energy           | Experiment                    |
|---|------------------|------------------|-------------------------------|
| $\nu_e \rightarrow \nu_x$                                   | $\sim 10^8$ km   | $\sim$ MeV       | Solar: SK, SNO, et. al.       |
| $\bar{\nu}_e \rightarrow \bar{\nu}_e$                       | $\sim 200$ km    | $\sim$ MeV       | Reactor: KamLAND              |
| $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$     | $20 - 10^4$ km   | $0.5 - 10^2$ GeV | Atmospheric: SK, IceCube (DC) |
| $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$     | 295(735, 810) km | $\sim$ GeV       | LBL: T2K(MINOS, NOvA)         |
| $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_\mu(\bar{\nu}_\mu)$ |                  |                  |                               |
| $\bar{\nu}_e \rightarrow \bar{\nu}_e$                       | $\sim 1$ km      | $\sim$ MeV       | Reactors: DC, RENO, Daya Bay  |

Vacuum  $\nu$ -oscillations probabilities, driven by  $\Delta m_{\text{atm}}^2$ , will be shown in a moment

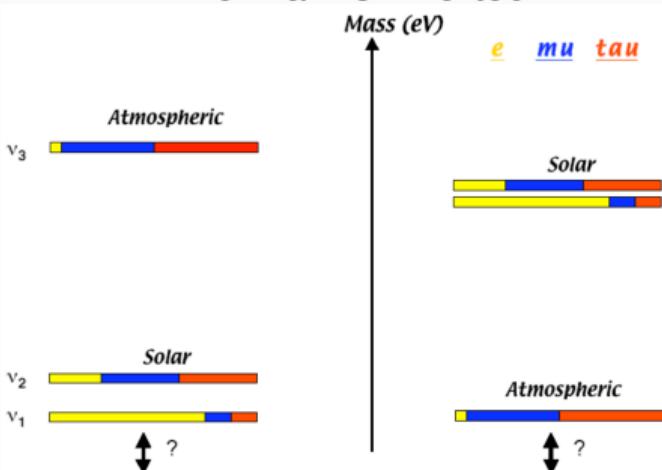
# Three active $\nu$ -framework

$$|\nu_\alpha\rangle = \sum_{k=1}^3 U_{\alpha k}^* |\nu_k\rangle$$

Where  $U$  can be parametrized in the form:

Two possible mass orderings:

Normal Vs Inverted



$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{Atm. -- Solar Interference}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}}$$

Atmospheric

Reactor

- Six oscillation parameters:  $\vec{\lambda} = (\theta_{ij}, \delta, \Delta m_{21}^2, \Delta m_{31}^2)$ .
- Three unknowns:
  - ▶ Is there a violation of the CP-symmetry  $J_{CP} \propto \sin \delta \neq 0$ ?
  - ▶ What is the correct neutrino mass ordering, NO or IO?
  - ▶ Is the atm mixing angle maximal, if not, what is its octant?  $\sin^2 \theta_{23} (<, >, =) 0.5$ ?

Note: Neutrino oscillations are not sensitive to neither the absolute neutrino mass nor the Majorana phases (if only if Majorana  $\nu$ s).

# Oscillation channels (Vacuum)

Appearance Vs Disappearance

$\nu_e$  Appearance from a  $\nu_\mu$ -beam

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &\approx |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2 \\ &= P_{\text{atm}} + \underbrace{2\sqrt{P_{\text{atm}}}\sqrt{P_{\text{sol}}}\cos(\Delta_{32} + \delta)}_{P_{\sin \delta} + P_{\cos \delta}} + P_{\text{sol}} \end{aligned}$$

$\bar{\nu}_e$ -Disappearance

$$\begin{aligned} P(\bar{\nu}_e \rightarrow \bar{\nu}_e) &\approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) \\ &\quad + \text{solar term} \end{aligned}$$

$$\sqrt{P_{\text{atm}}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31},$$

$$\sqrt{P_{\text{sol}}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$$

$\nu_\mu$ -Disappearance

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_\mu) &\approx 1 - \sin^2(2\theta_{23}) \sin^2 \Delta_{32} \\ &\quad - \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} \end{aligned}$$

with  $a \equiv V_{CC}/2$  and  $\Delta_{ij} \equiv (\Delta m_{ij}^2 L)/(4E)$

# Oscillation channels

## Parameter dependency

Two mass squared differences have been found in Nature:  $\Delta m_{21}^2 = \Delta m_{\text{sol.}}^2$  and  $\Delta m_{31}^2 = \Delta m_{\text{atm.}}^2$ .

| Channel   | Experiment                    | Main                           | Other                          |
|---|-------------------------------|--------------------------------|--------------------------------|
| $\nu_e \rightarrow \nu_x$                                     | Solar: SK, SNO, et. al        | $\theta_{12}$                  | $\Delta m_{21}^2, \theta_{13}$ |
| $\bar{\nu}_e \rightarrow \bar{\nu}_e$                         | Reactor: KamLAND              | $\Delta m_{21}^2$              | $\theta_{12}, \theta_{13}$     |
| $\nu_\mu (\bar{\nu}_\mu) \rightarrow \nu_e (\bar{\nu}_e)$     | Atmospheric: SK, IceCube (DC) | $\theta_{23}, \Delta m_{31}^2$ | $\theta_{13}, \delta$          |
| $\nu_\mu (\bar{\nu}_\mu) \rightarrow \nu_e (\bar{\nu}_e)$     | LBL: T2K(MINOS, NOvA)         | $\theta_{13}, \delta$          | $\theta_{23}$                  |
| $\nu_\mu (\bar{\nu}_\mu) \rightarrow \nu_\mu (\bar{\nu}_\mu)$ | LBL: T2K(MINOS, NOvA)         | $\Delta m_{31}^2, \theta_{23}$ |                                |
| $\bar{\nu}_e \rightarrow \bar{\nu}_e$                         | Reactors: DC, RENO, Daya Bay  | $\theta_{13}, \Delta m_{31}^2$ | $\theta_{12}$                  |

No single neutrino experiment is sensitive to all parameters, so we need global fits:

- To account for correlations between parameters.
- Combination of experiments give precise measurement of common parameters.

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# 'New' data sets considered in (this update)

de Salas et. al. arxiv:2006.11237

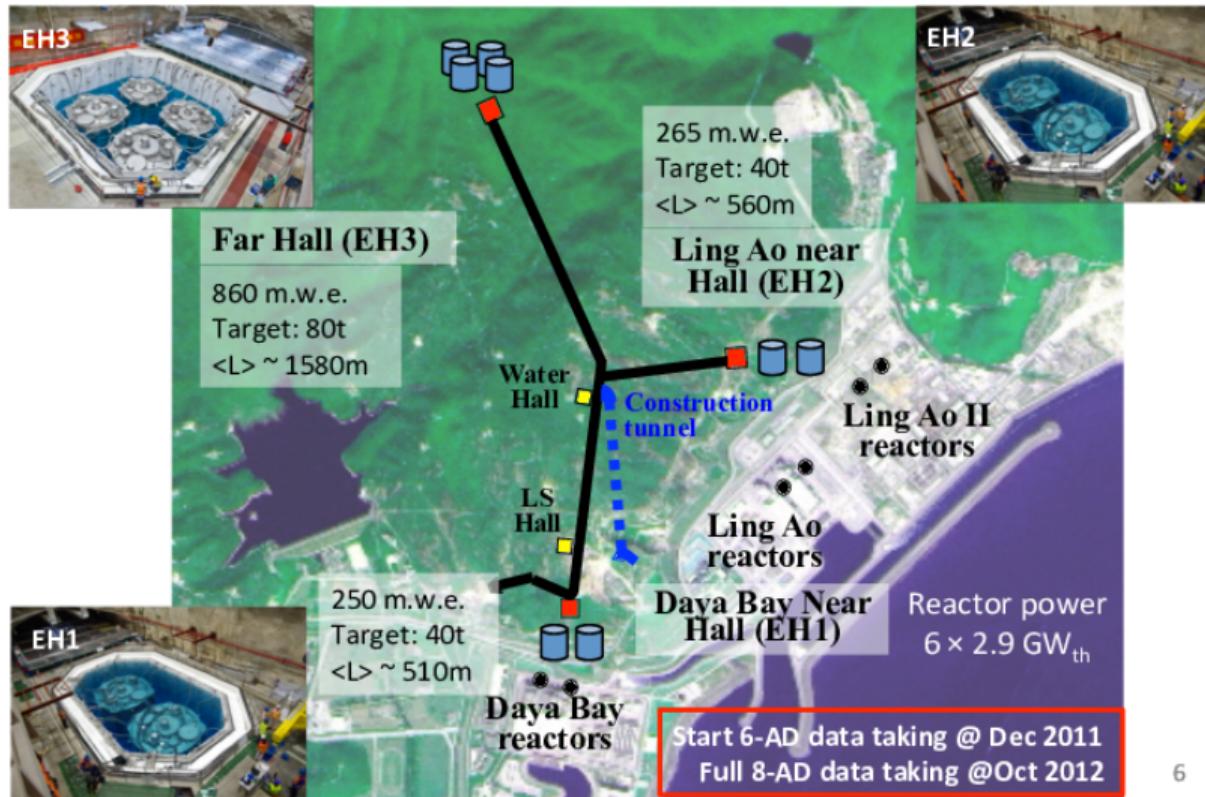
## 2020 global reassessment of the neutrino oscillation picture

P.F. de Salas,<sup>a</sup> D.V. Forero,<sup>b</sup> S. Gariazzo,<sup>c,d</sup> P. Martínez-Miravé,<sup>c,e</sup> O. Mena,<sup>c</sup>  
C.A. Ternes,<sup>c,d</sup> M. Tórtola<sup>c,e</sup> and J.W.F. Valle<sup>c</sup>

- Updated solar  $\nu$ -data sample: Last results from SNO, combined data from the three phases.
- Atmospheric  $\nu$ -data sample:
  - ▶ IceCube Deep Core: 3-years data. Addition to track-like, shower-like events included increasing the number of events from  $\sim 6000$  to  $\sim 20000$ .
- Reactor  $\nu$ -data sample:
  - ▶ Daya Bay: 1958 days, energy spectra from the three EH's.
  - ▶ RENO: 2900 days, FD energy spectra.
- LBL  $\nu$ -data sample:
  - ▶ T2K:  $19.7 \times 10^{20}$  POT ( $16.3 \times 10^{20}$  POT) of exposure in  $\nu$ -mode ( $\bar{\nu}$ -mode), 318  $\nu_\mu$  disapp. events and 94  $\nu_e$  app. events (137  $\bar{\nu}_\mu$  disapp. events and 16  $\bar{\nu}_e$  app. events).
  - ▶ NOvA:  $13.6 \times 10^{20}$  POT ( $12.5 \times 10^{20}$  POT) of exposure in  $\nu$ -mode ( $\bar{\nu}$ -mode), 211  $\nu_\mu$  disapp. events and 82  $\nu_e$  app. events (105  $\nu_\mu$  disapp. events and 33  $\nu_e$  app. events).

In this talk, the role of **reactor** and **L<sub>B</sub>L** exps. will be highlighted.

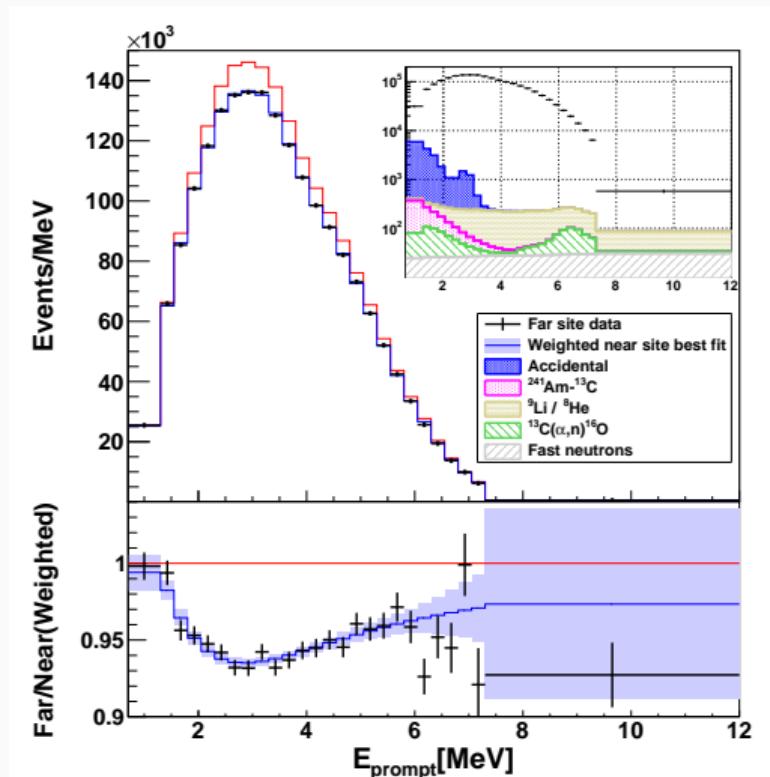
# Daya Bay Experimental Setup



# Antineutrino events

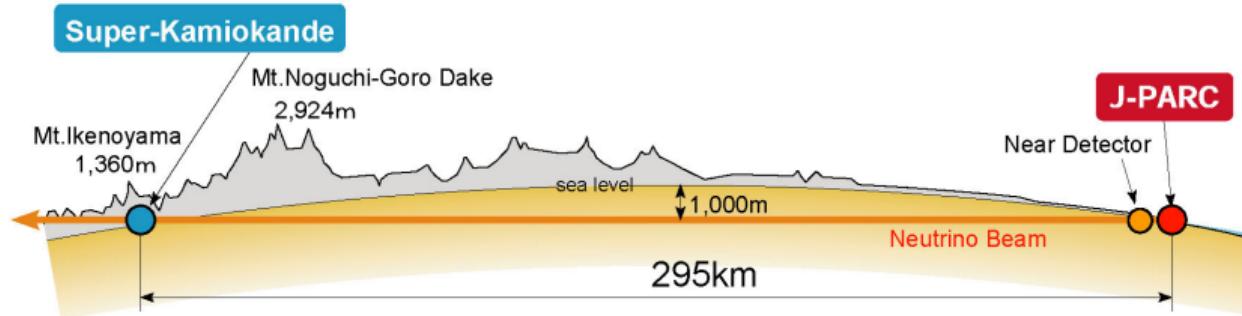
1958 days of operation at Daya Bay

Phys.Rev.Lett. 121 (2018) 24 arxiv:1809.02261



# T2K Experiment

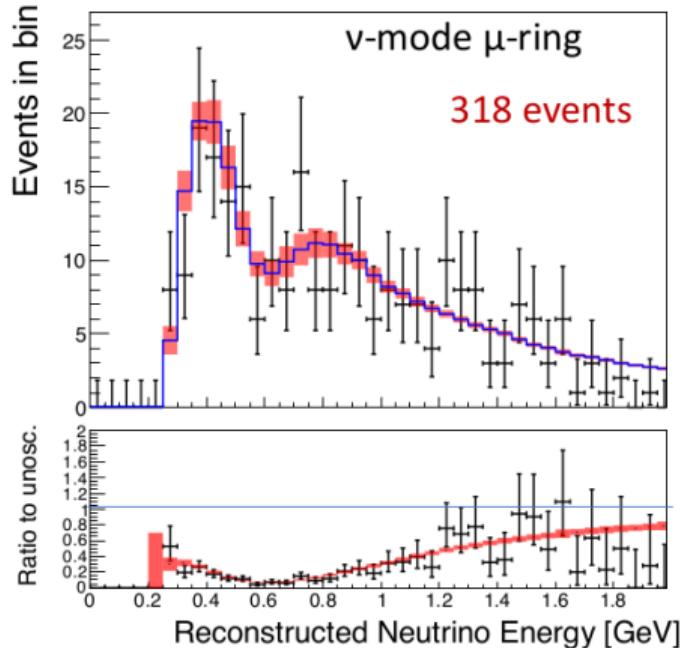
K. Iwamoto @ ICHEP 2016



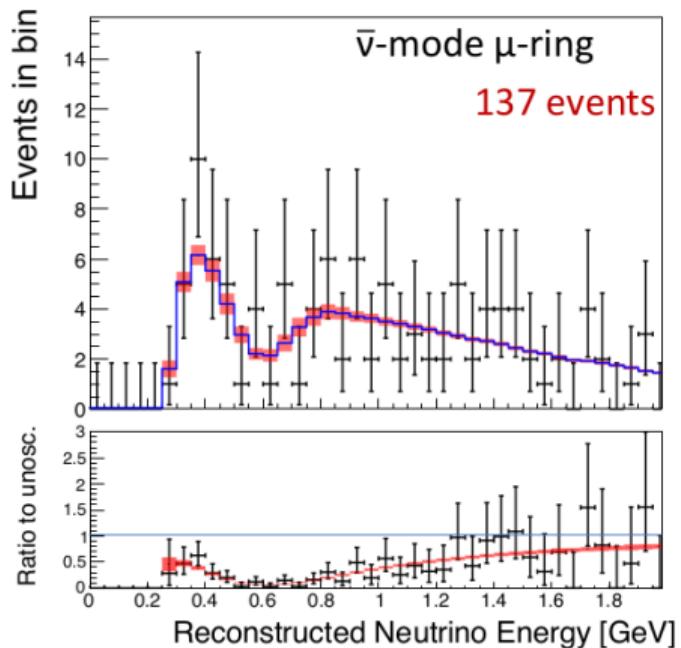
# T2K $\nu_\mu(\bar{\nu}_\mu)$ FD events

The T2K collaboration @neutrino2020

T2K Run 1-10 Preliminary



T2K Run 1-10 Preliminary

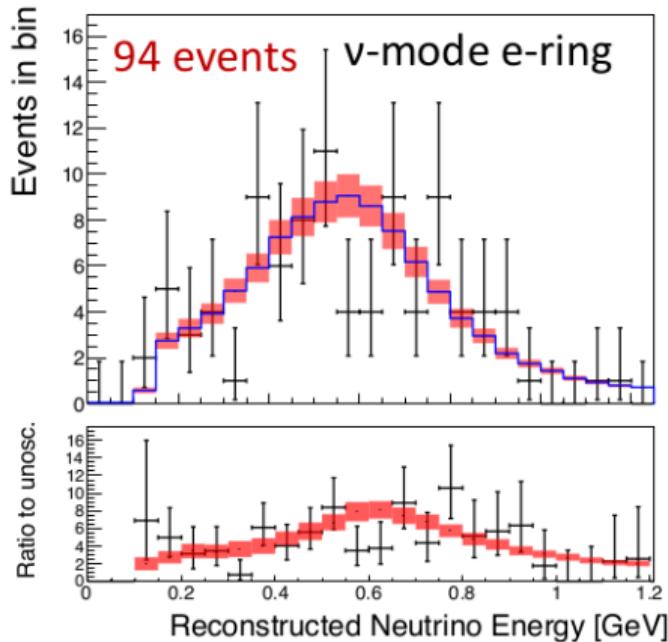


Muon neutrino (left) and muon antineutrino (right) disappearance.

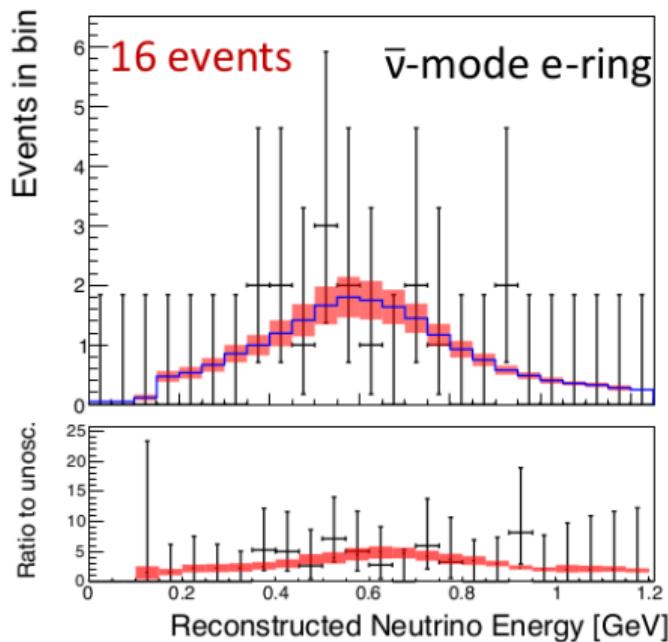
# T2K $\nu_e$ ( $\bar{\nu}_e$ ) FD events

The T2K collaboration @neutrino2020

T2K Run 1-10 Preliminary



T2K Run 1-10 Preliminary



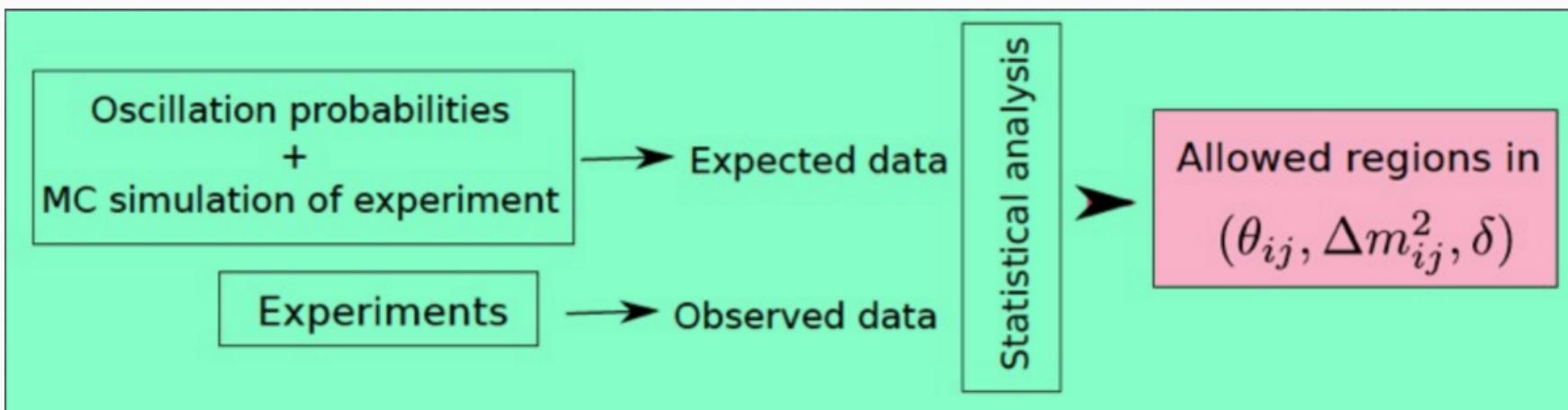
Electron neutrino (left) and electron antineutrino (right) appearance.



- Long-baseline, off-axis neutrino oscillation experiment
- Study neutrinos from NuMI beam at Fermilab
- At 14 mrad off-axis, energy peaked at 2 GeV
- Functionally identical detectors
  - ND on site at Fermilab
  - FD 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD

See Mario's talk (later today!)

# Analysis scheme



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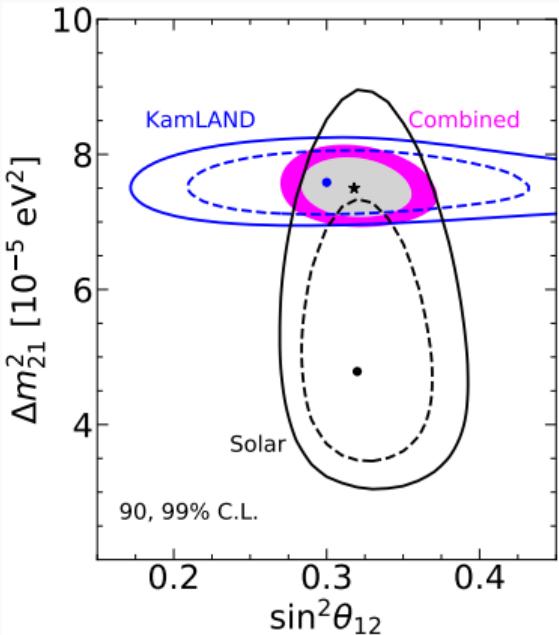
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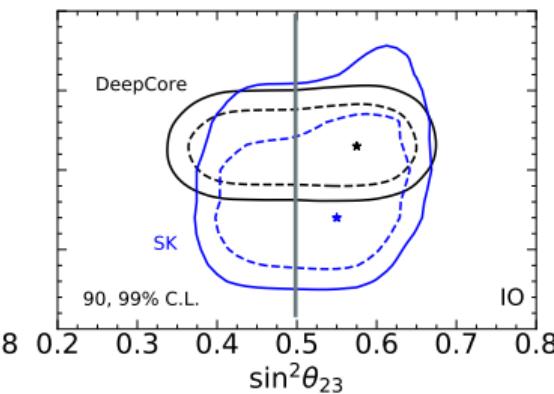
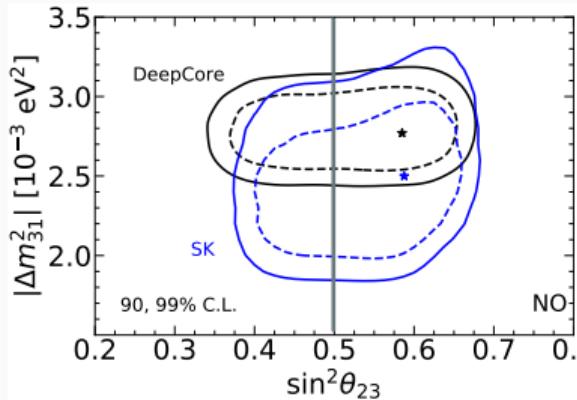
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# Solar and atmospheric sectors



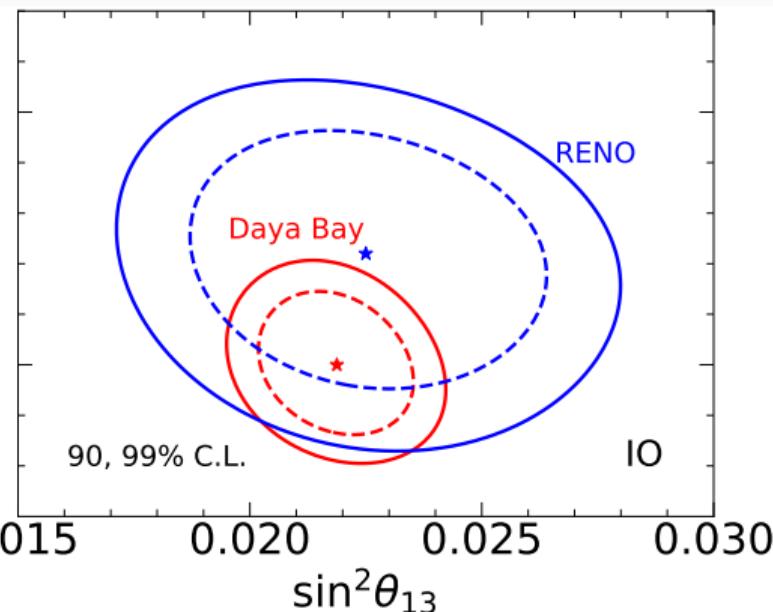
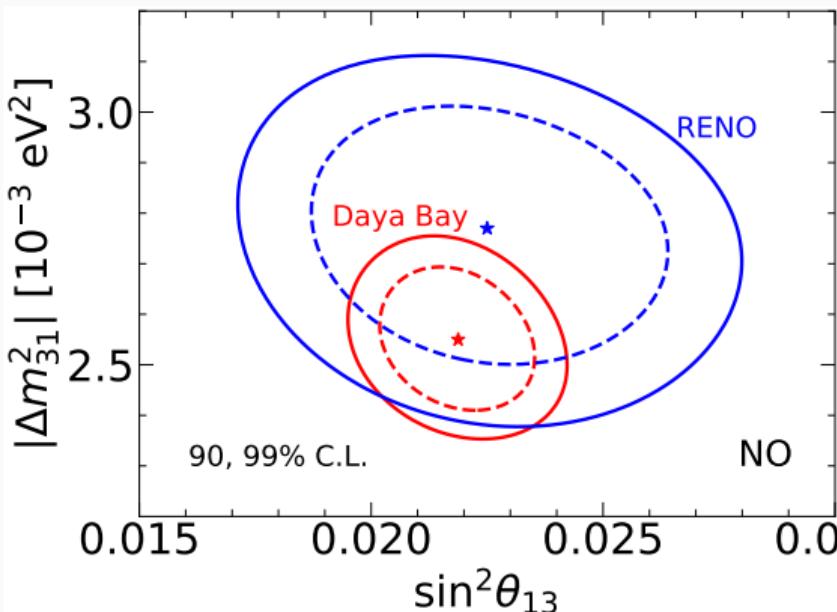
- Directional information was crucial to solve the atm. neutrino problem.



- Neutrino-matter interactions at the interior of the Sun are very relevant (MSW).
- NC measurements at SNO was crucial to solve the solar neutrino problem.

# Reactor experiments

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

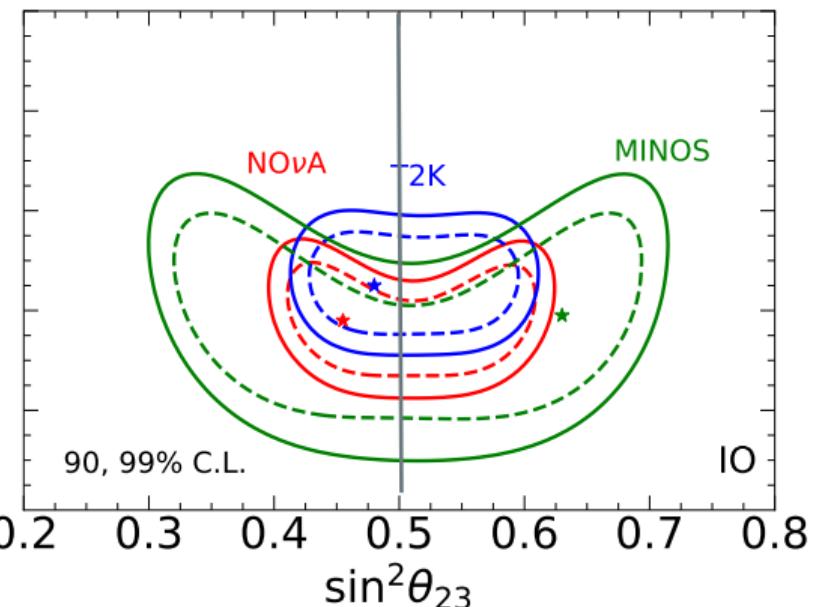
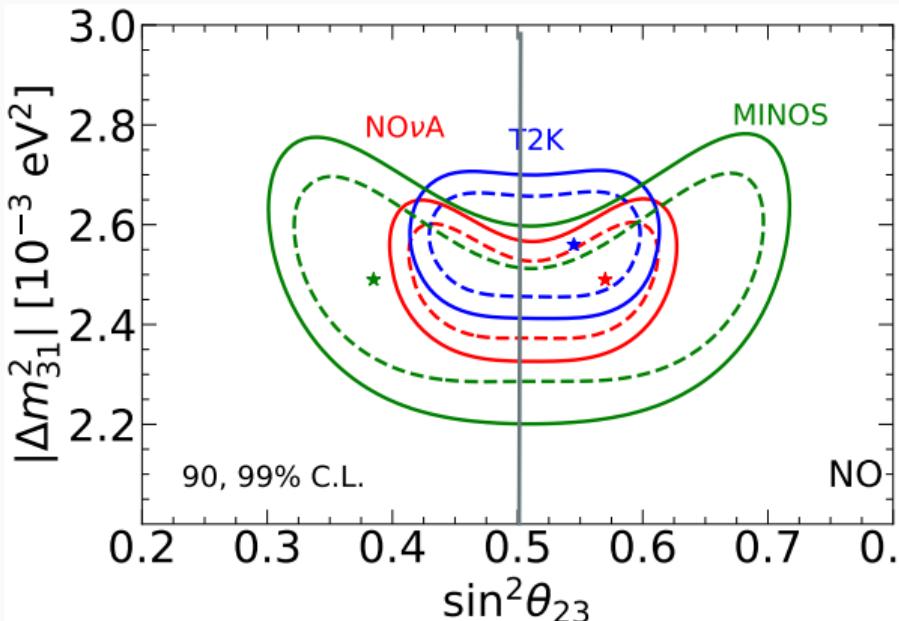


Reactor experiments provide a  $\Delta m_{31}^2$  determination that is compatible with LBL results!

# LBL experiments

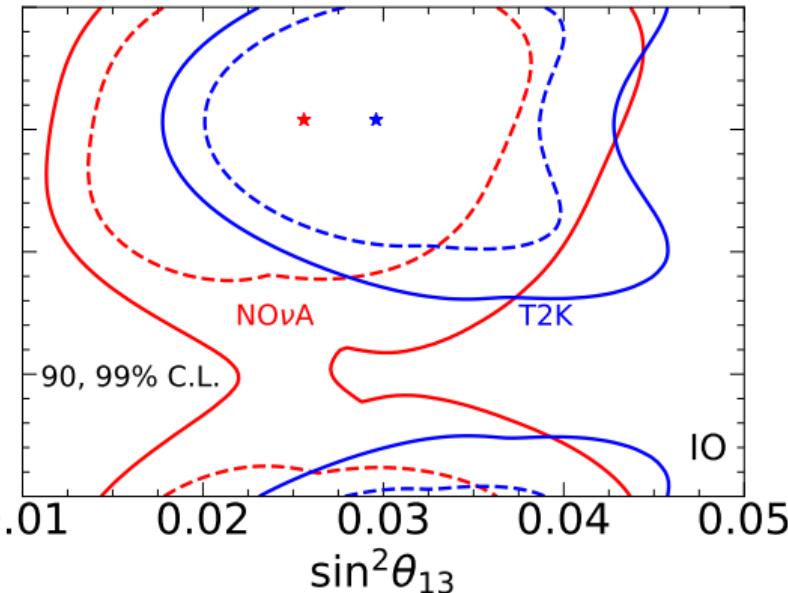
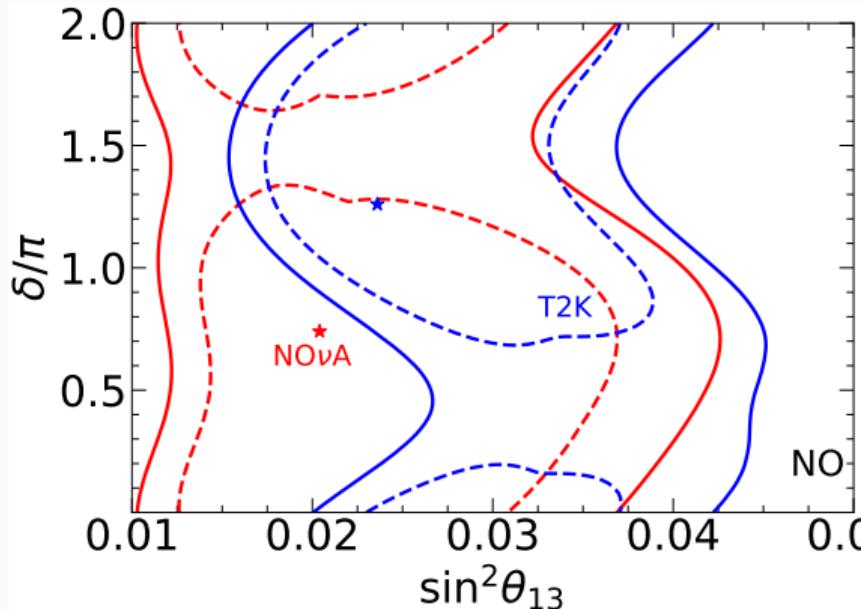
Octant degeneracy

$$\text{Disapp.: } P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \Delta_{32} - \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31}$$



# LBL experiments

T2K & NOvA tension (NO)



- LBL experiments allow large  $\theta_{13}$ .
- What happens after combining with reactor neutrino experiments?

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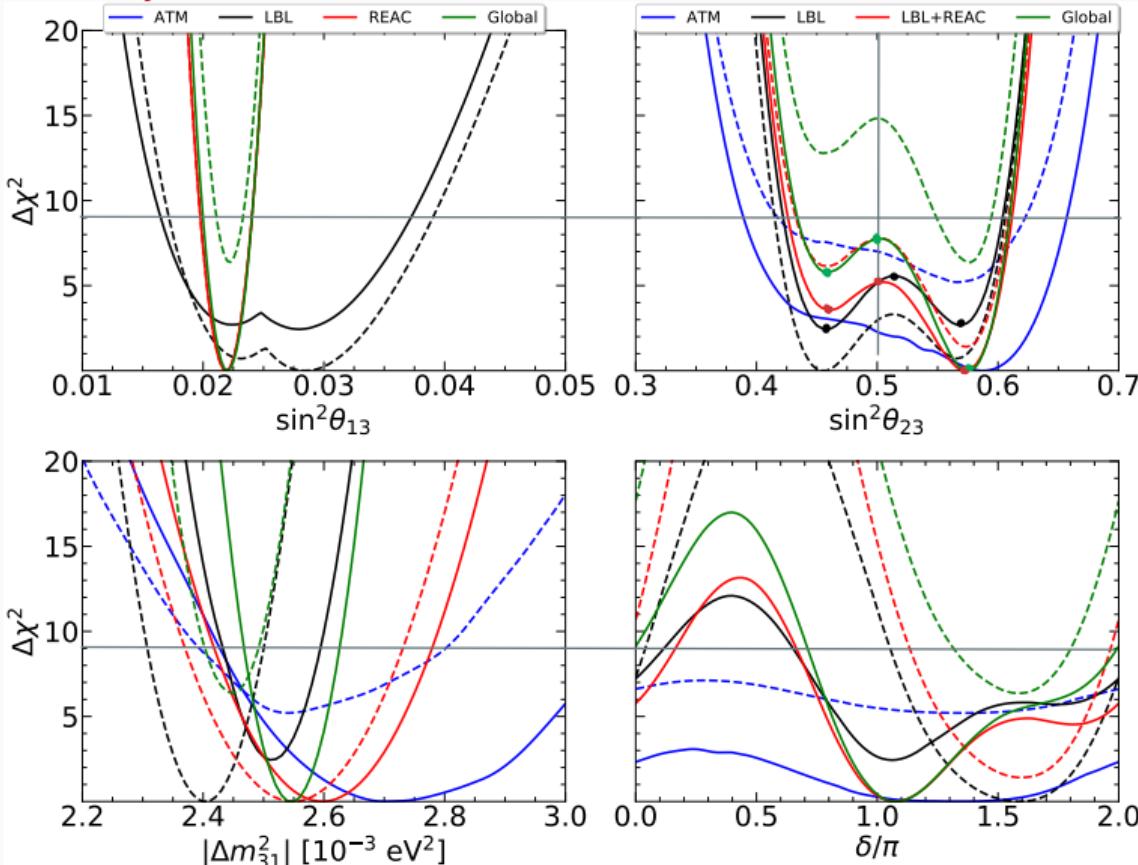
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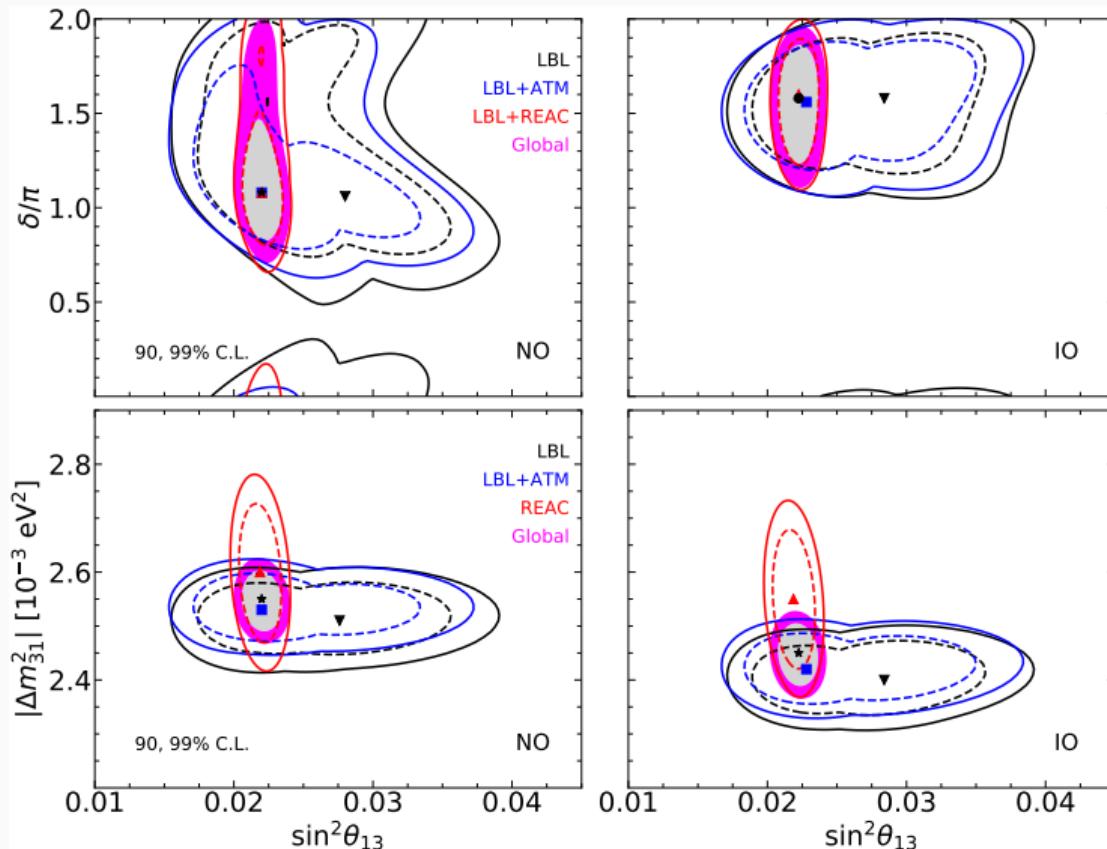
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# Global fit results, contributions from different data-sets



# Global fit results, correlations I



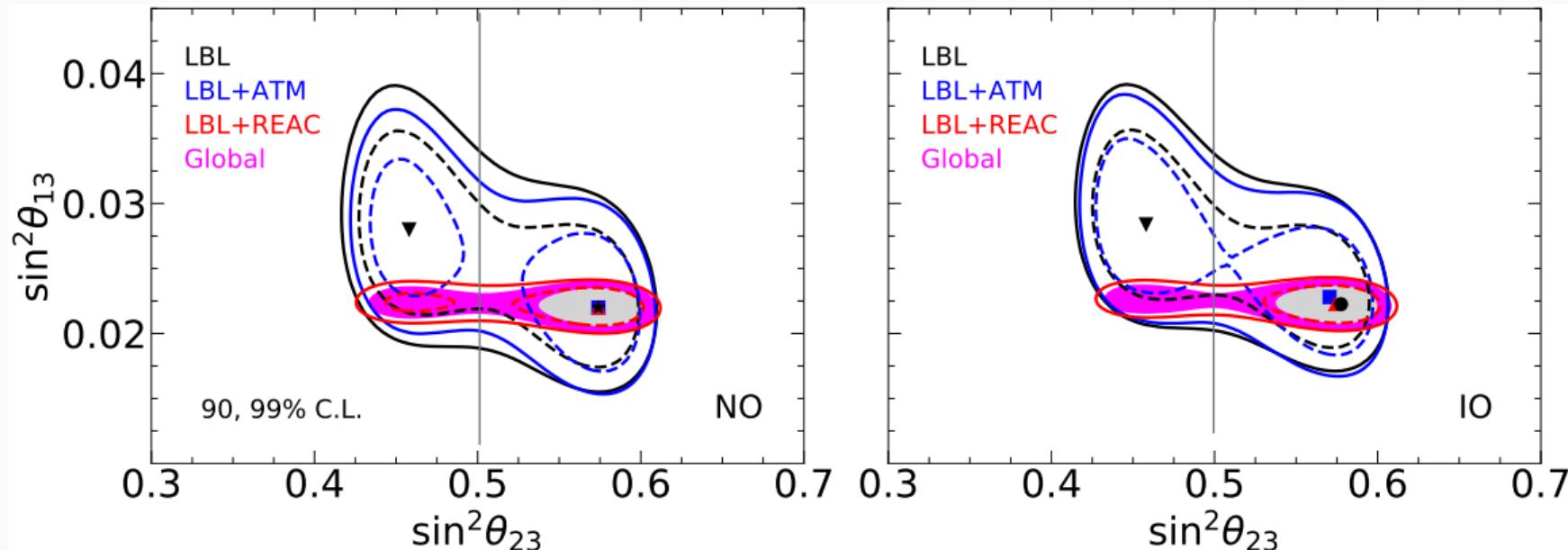
Global: Colored regions.

- Global min.: 'Star'

Partial: Lines.

- 'Squared' and 'Triangles'.

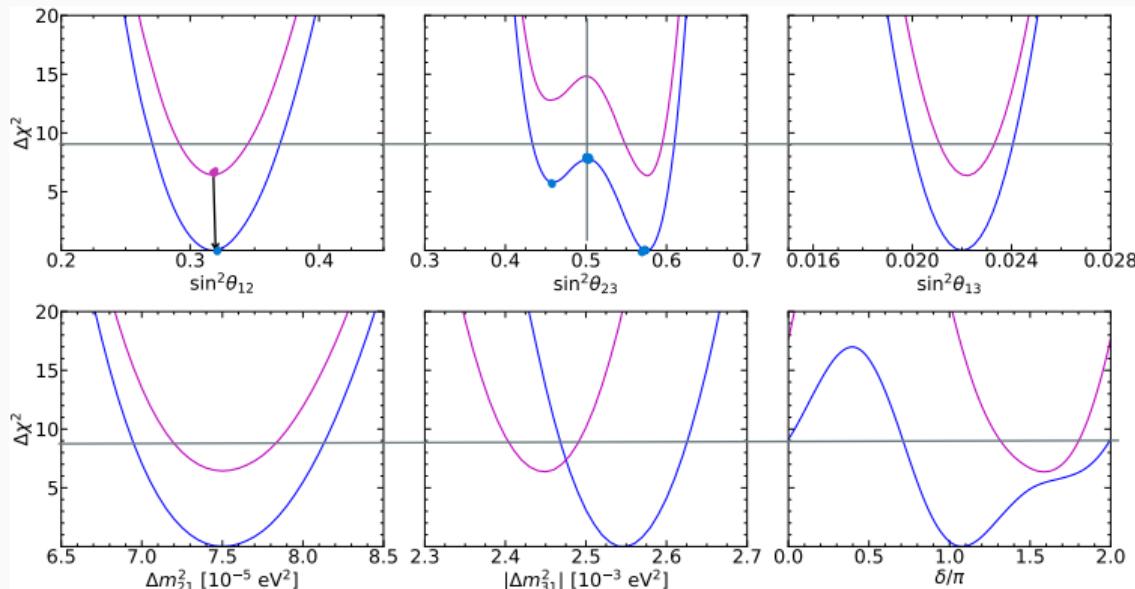
## Global fit results, correlations II



- Global: Colored regions. Global min.: ‘Star’.
- Reactor data help to partially break the  $\theta_{23} - \theta_{13}$  degeneracy.

# Global Fit Results

The precision reached so far



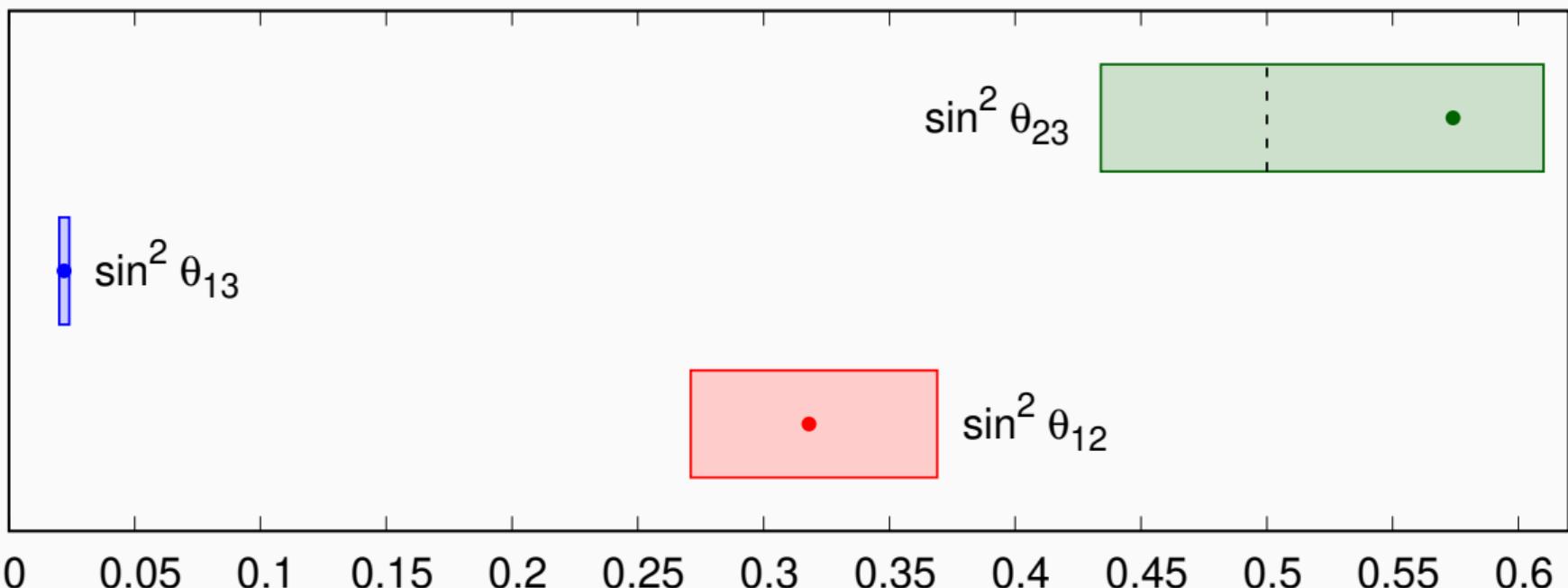
| parameter                                 | $bf \pm 1\sigma$                |            |
|---|---------------------------------|------------|
| $\Delta m_{21}^2 [10^{-5} \text{eV}^2]$   | $7.50^{+0.22}_{-0.20}$          | $\sim 3\%$ |
|   | $2.55^{+0.02}_{-0.03}$          | $\sim 1\%$ |
|   | IO<br>$2.45^{+0.02}_{-0.03}$    |            |
| $ \Delta m_{31}^2  [10^{-3} \text{eV}^2]$ | $2.55^{+0.02}_{-0.03}$          | $\sim 1\%$ |
|   | IO<br>$2.45^{+0.02}_{-0.03}$    |            |
|   |                                 |            |
| $\sin^2 \theta_{12}/10^{-1}$              | $3.18 \pm 0.16$                 | $\sim 5\%$ |
| $\sin^2 \theta_{13}/10^{-2}$              | $2.200^{+0.069}_{-0.062}$       | $\sim 3\%$ |
|   | IO<br>$2.225^{+0.064}_{-0.070}$ |            |
|   |                                 |            |
| $\sin^2 \theta_{23}/10^{-1}$              | $5.74 \pm 0.14$                 | $\sim 6\%$ |
|   | IO<br>$5.78^{+0.10}_{-0.17}$    |            |
|   |                                 |            |
| $\delta/\pi$                              | $1.08^{+0.13}_{-0.12}$          |            |
|   | IO<br>$1.58^{+0.15}_{-0.16}$    |            |

- NO is preferred over IO with  $2.5\sigma$  statistical significance.

# Global Fit Results

Lepton mixing pattern

Mixing angles BFPs and  $3\sigma$  ranges for NO



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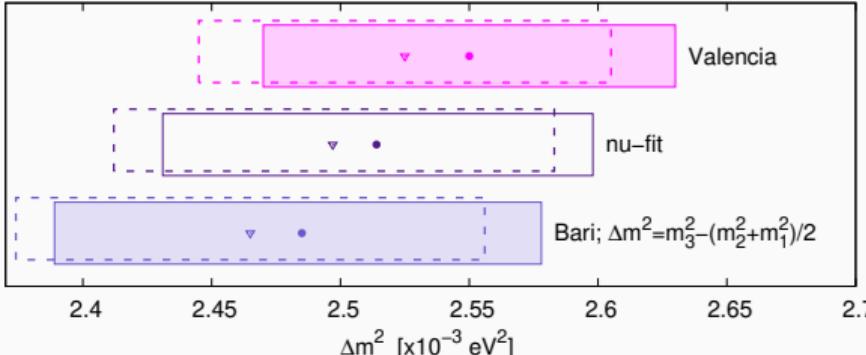
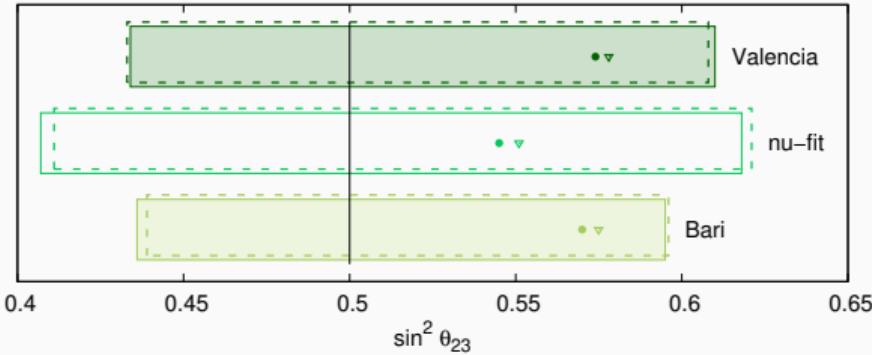
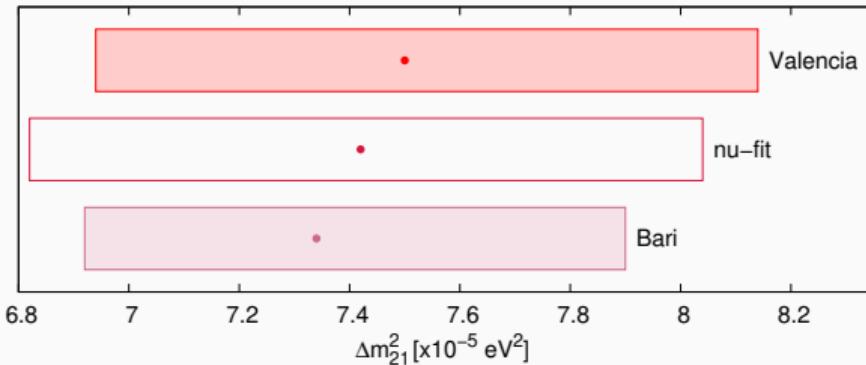
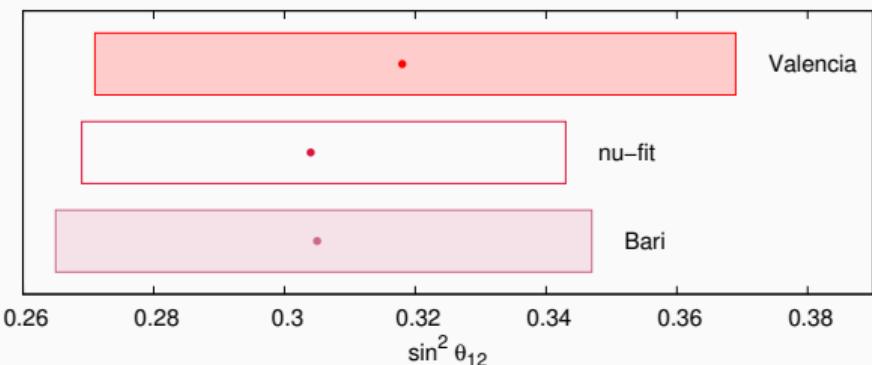
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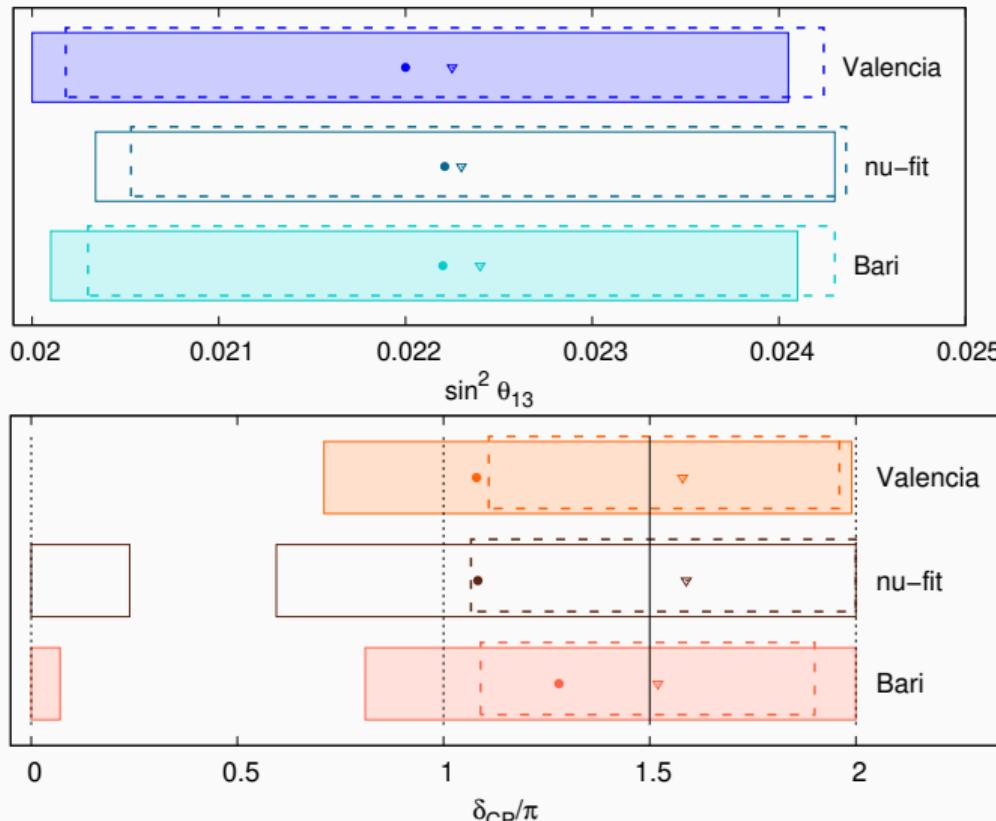
# Comparison with other global-fits: BFPs and $3\sigma$ ranges

de Salas et al. (JHEP 02 (2021)) arxiv:2006.11237 (VLC) Esteban et al. (JHEP 09 (2020)) arxiv:2007.14792 (nu-fit) Capozzi et al. (PRD 101 (2020)) arxiv:2003.08511 (Bari)



# Comparison with other global-fits: BFPs and $3\sigma$ ranges

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## Summary & Conclusions

- Precision of the measured neutrino oscillation parameters ranges from 1% to 6%.
- T2K & NOvA tension in the determination of  $\delta$  for NO has impacted not only the  $\delta$  sensitivity, but also the mass ordering significance.
- Atmospheric mixing angle in the second octant for both orderings. Lower octant disfavored  $\Delta\chi^2 \geq 5.8(6.4)$  for NO (IO).

Measurement of the  $3\nu$  oscillation unknowns and improvement in precision, expected from funded experiments.

- DUNE/T2HK: Expected to measure  $\delta$ .
- JUNO: Precise determination of the solar parameters.
- DUNE/JUNO: Different strategies to determine the correct neutrino mass ordering.
- DUNE: Improve the  $\theta_{23}$  determination.

This is not the full story: Massive neutrinos imply BSM Physics

- Several BSM physics scenarios can be probed at neutrino oscillation experiments:
  - ▶ NSI, new neutrino flavor states, LED, non-unitarity, ... DM scenarios ...

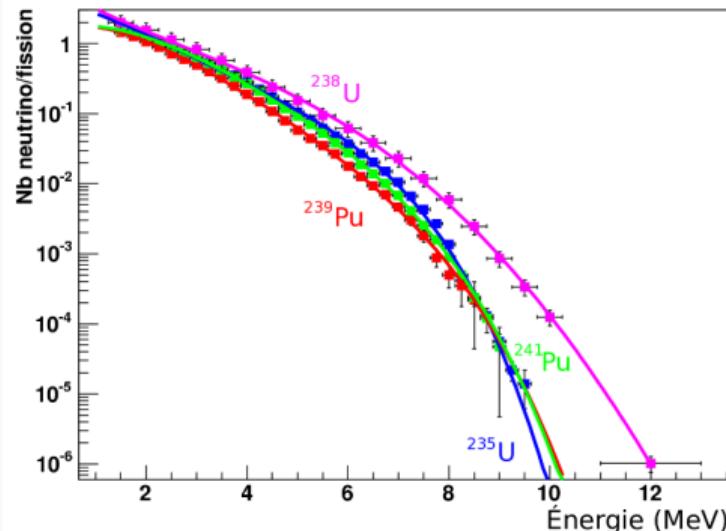
THANK YOU FOR YOUR ATTENTION!

Back up

# $\bar{\nu}_e$ -production and detection at reactors

Production:  $\beta$  decay of  $^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$  and

$^{238}\text{U}$

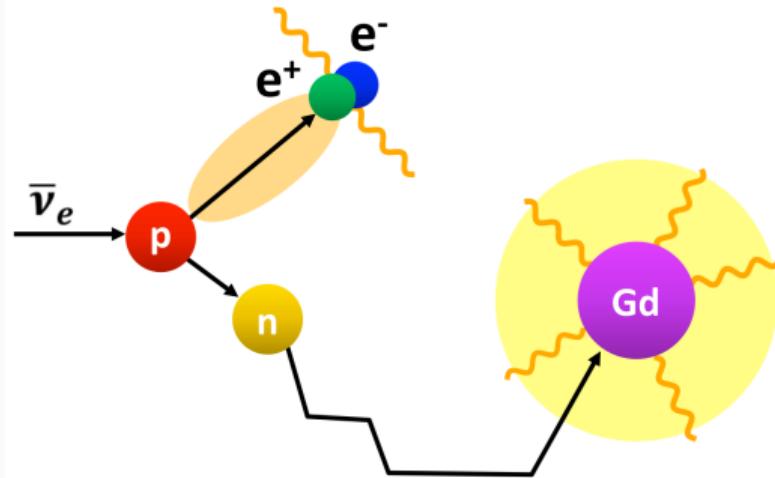


Flux parametrizations:

P. Huber (PRC 84 (2011))

T. Mueller *et al.* (PRC 83 (2011))

Detection: Inverse  $\beta$  decay,  $\bar{\nu}_e + p \rightarrow n + e^+$



Coincidence signals: Prompt  $e^+$ -annihilation and delayed  $n$ -capture.

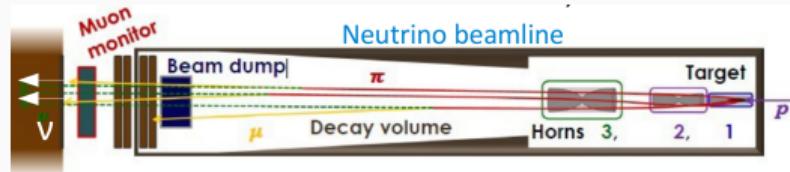
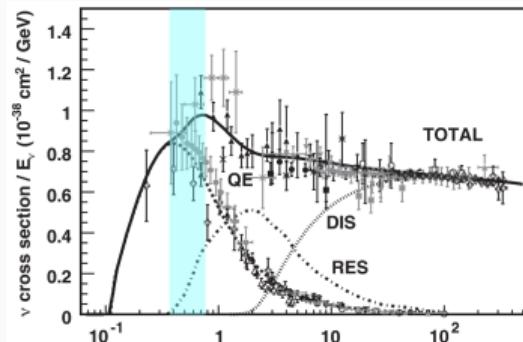
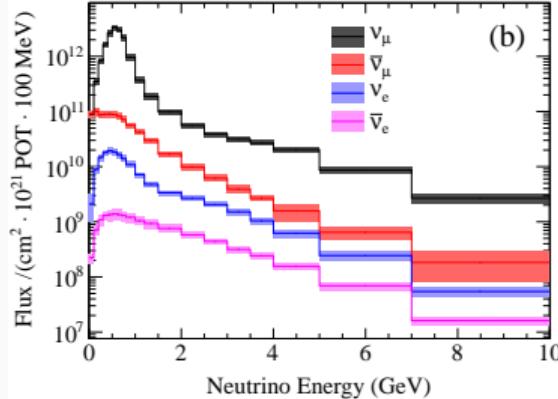
For  $\sim 1\text{ km}$  baseline,  $\bar{\nu}_e$ s propagate to FD practically in Vacuum!

# Neutrino production and detection at accelerators

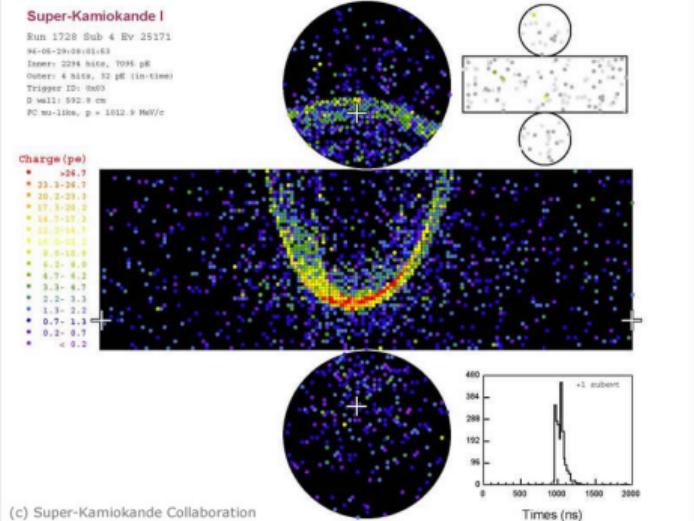
The case of T2K

Measured flux @ ND:  $\Phi_k(E)$

K. Abe et al. (PRD 88 (2013)) arxiv:1304.0841



Cherenkov  $\mu$  ring @ SK



(c) Super-Kamiokande Collaboration