

Status of three-neutrino mixing

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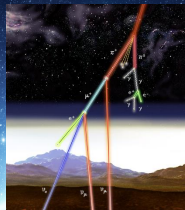
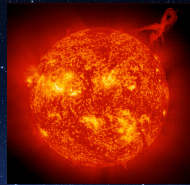
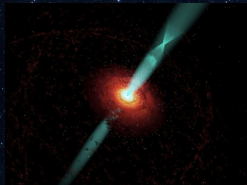
Neutrino Oscillation Workshop (NOW 2018)

September 10th, 2018



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Neutrino evolution

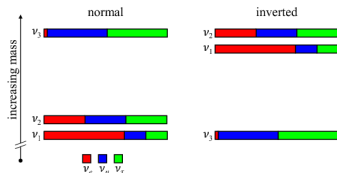
In the 3ν scenario, neutrino evolution is described by the Schrödinger equation

$$i \frac{d\vec{\nu}}{dt} = \frac{1}{2E} \left[U^\dagger \text{Diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U \pm V_{mat} \right] \vec{\nu}$$

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

$$\vec{\nu} = (\nu_e \nu_\mu \nu_\tau)^T \quad V_{mat} = \sqrt{2}G_F N_e \text{Diag}(1, 0, 0)$$

Two possible mass ordering



The global fit goal is the determination of the six parameters describing the evolution.

Neutrino evolution

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Experiment	Dominant	Important
Solar	θ_{12}	$\Delta m_{21}^2, \theta_{13}$
Reactor LBL	Δm_{21}^2	θ_{12}, θ_{13}
Ractor MBL	θ_{13}	$ \Delta m_{3l}^2 $
Atmospheric	θ_{23}	$ \Delta m_{3l}^2 , \theta_{13}, \delta_{CP}$
Accelerator LBL ν_μ Disapp	$ \Delta m_{3l}^2 , \theta_{23}$	
Accelerator LBL ν_e App	δ_{CP}	$\theta_{13}, \theta_{23}, \text{sign}(\Delta m_{3l}^2)$

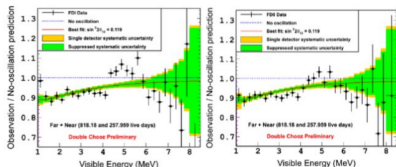
Reactor neutrinos: determination of θ_{13}

- ▶ $\bar{\nu}_e$ emitted from fission reactions.
- ▶ The energy spectrum rise from 1.8 MeV to 4 MeV, and falls to very low rate at 8 MeV.
- ▶ At distances of ~ 1 km

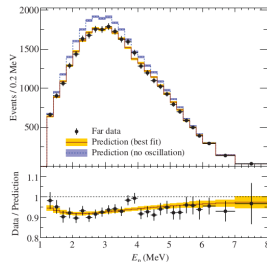
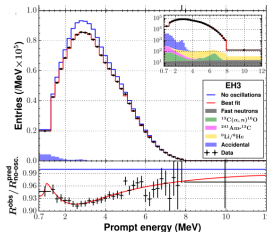
$$P_{ee} = 1 - c_{13}^4 \sin^2 2\theta_{21} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$$

$$\Delta m_{ee}^2 \approx \cos^2 \theta_{12} |\Delta m_{31}^2| + \sin^2 \theta_{12} |\Delta m_{32}^2|$$

- ▶ Reactor neutrinos are sensitive to θ_{13} and Δm_{31}^2 .
- ▶ Double-Chooz, RENO and Daya Bay established that $\theta_{13} \neq 0$
 - ▶ A rate-only analysis determines (Daya Bay Neutrino 2018) $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$



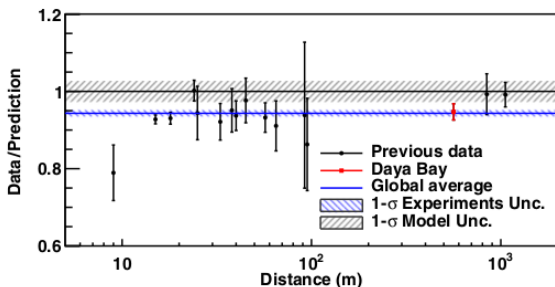
F.P. An et al. (Daya Bay), Phys. Rev. D95, 072006 (2017)



S.H. Seo et al. (RENO), Phys. Rev. D98, 012002 (2018)

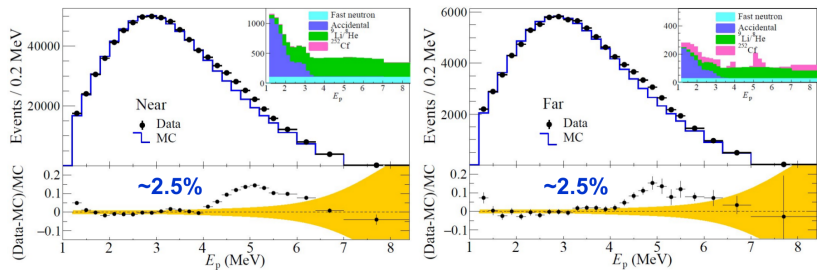
Reactor anomaly

- ▶ The reevaluation of the $\bar{\nu}_e$ flux determined a deficit in the experimental data.
 - ▶ Data/Prediction = $0.952 \pm 0.014 \pm 0.023$ (Daya Bay, NEUTRINO 2018), 0.918 ± 0.018 (RENO, NEUTRINO 2018)
- ▶ A large initial flux prefers larger values of θ_{13} .
- ▶ Small impact over θ_{13} since it is dominated by experiment with near detector.



Flux excess at 5 MeV

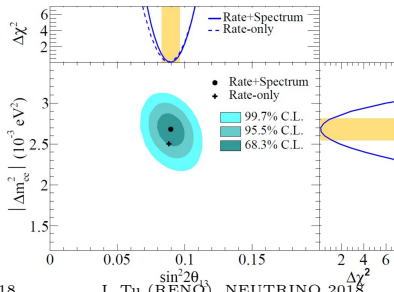
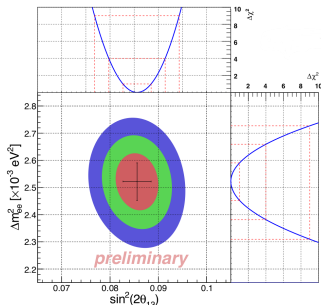
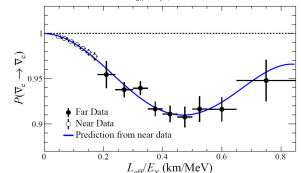
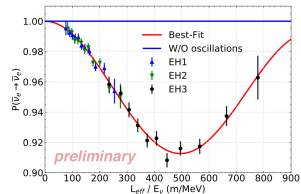
- ▶ The ratio of measured over the predicted flux shows an excess at 5 MeV.
- ▶ The excess is present in all experiments.
- ▶ The “bump” is time independent and it is correlated with the reactor power.
- ▶ The near/far detector arrangement $\rightarrow \theta_{13}$ depends on the relative uncertainties.



I. Tu (RENO), NEUTRINO 2018

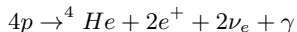
Reactor neutrinos: determination of Δm_{31}^2

- ▶ A spectrum analysis determines Δm_{31}^2
- ▶ Near detector impose an upper bound over Δm_{31}^2 .
- ▶ The oscillations measured at the far detector impose lower bound on θ_{13} and Δm_{31}^2



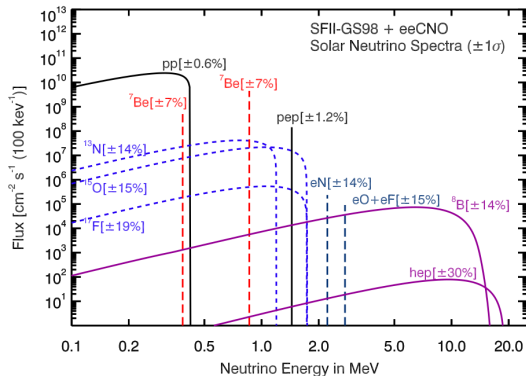
Solar neutrinos

- ▶ Solar neutrinos are produced by two different nuclear fusion reactions: pp chains and CNO cycles.



- ▶ The flux is composed by ν_e with a characteristic energy (${}^7\text{Be}$, pep) or spectrum (pp, CNO, ${}^8\text{B}$, hep).

M. Tanabashi et al. (PDG), Phys. Rev. D 98, 030001 (2018)



Observations indicates:

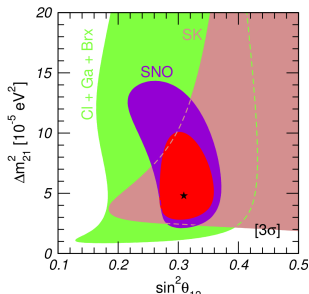
- ▶ $P_{ee} \sim 30\%$ at high energy (${}^8\text{B}$, hep).
- ▶ $P_{ee} \sim 60\%$ at low energy (pp, ${}^7\text{Be}$, CNO and low ${}^8\text{B}$).

Determination of the solar parameters ($\Delta m_{21}^2, \theta_{21}$)

▶ $\Delta m_{31}^2 \gg E/L$

$$P_{ee}^{3\nu} \approx \cos^2 \theta_{13} \cos^2 \theta_{13}^m P_{eff}^{2\nu}(\Delta m_{21}^2, \theta_{12}, \theta_{13}) + \sin^2 \theta_{13}^m \sin^2 \theta_{13}$$

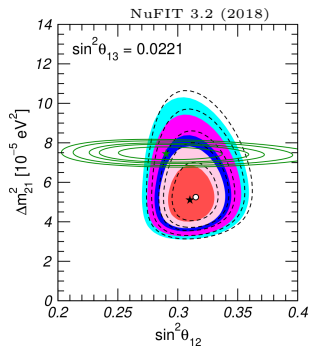
- ▶ Solar neutrino experiment are mainly sensitive to θ_{12} .
 - ▶ There is a small dependence on Δm_{21}^2 .
 - ▶ θ_{13}^m carries a slight dependence with Δm_{31}^2 .
- ▶ The constraints over θ_{12} are mainly driven by SK+SNO .
 - ▶ SNO present a better precision than SK.
- ▶ The results are independent of Solar model used.



M. Maltoni, A.Yu Smirnov,
Eur.Phys.J. A52 (2016) no.4, 87

Determination of the solar parameters ($\Delta m_{21}^2, \theta_{21}$)

- ▶ Δm_{21}^2 is determined by KamLAND.
- ▶ Long-baseline reactor experiment.
 - ▶ $\bar{\nu}_e$ with $E_\nu \sim \text{few MeV}$.
 - ▶ Baseline $\sim 180 \text{ km}$.
- ▶ $P_{ee}^{3\nu} \simeq c_{13}^4 P_{eff}^{2\nu} + s_{13}^4$
 - ▶ No sensitivity to Δm_{31}^2 .



$$i \frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m_{21}^2}{4E} \begin{pmatrix} -\cos 2\theta_{12} & \sin \theta_{12} \\ \sin \theta_{12} & \cos 2\theta_{12} \end{pmatrix} \pm \sqrt{2} G_F N_e \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} \right] \vec{\nu}, \quad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix}$$

KamLAND determination of Δm_{21}^2 shows a $(1.4 - 2)\sigma$ [1-3] tension with solar experiments.

[1] NuFIT 3.2 (2018), www.nu-fit.org

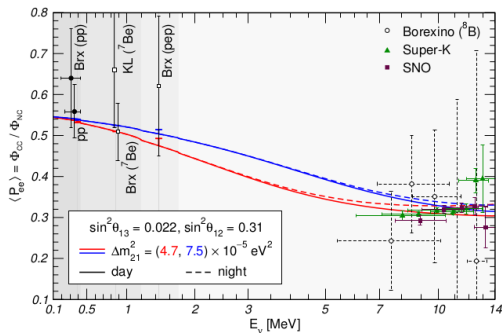
[2] F. Capozzi, et al., Prog.Part.Nucl.Phys. 102 (2018) 48-72

[3] P.F. de Salas, et al., Phys.Lett. B782 (2018) 633-640

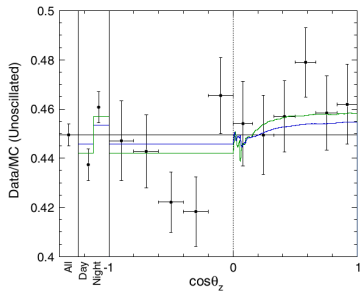
Tension in Δm_{21}^2

The tension in the mass parameter comes from:

- ▶ Non observation of low-energy turn up 8B neutrino spectrum measured by SNO, SK and Borexino.
- ▶ Observation of a larger day/night asymmetry than predicted by KamLAND



M. Maltoni, A.Yu Smirnov,
Eur.Phys.J. A52 (2016) no.4, 87



K. Abe et al. (Super-Kamiokande),
Phys. Rev. D94, 052010 (2016)

Atmospheric neutrinos

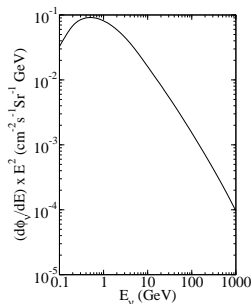
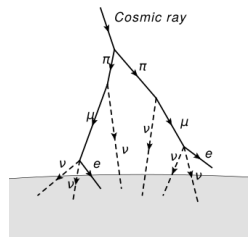
- ▶ Created in the collisions of cosmic rays with the atmosphere.

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu)$$

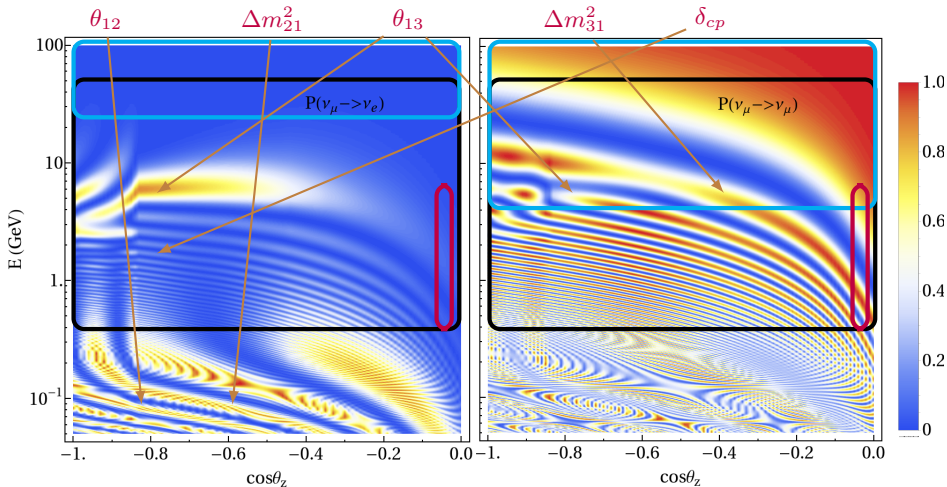
- ▶ Atmospheric flux covers a wide range of energies ($\phi_\nu \sim E_\nu^{-2.7}$).
- ▶ The main uncertainties are parametrized by:
 - ▶ The normalization.
 - ▶ A energy dependence ($\phi_\nu \sim \phi_0(E/E_0)^\gamma$)
 - ▶ The relative contribution of π and K ($R_{\pi/K}$)
 - ▶ The ratio between the neutrino and the antineutrino flux ($\phi_\nu/\phi_{\bar{\nu}}$)



M. Honda et al., Phys. Rev. D92, 023004 (2015)

Atmospheric neutrinos: contribution to the global fit

- ▶ For $E_\nu \geq 0.5$ GeV and the earth baselines ($10^2 - 10^4$) km $\Delta m_{21}^2 L/E_\nu$ has a subleading effect.
- ▶ Atmospheric neutrinos are sensitive to Δm_{31}^2 , θ_{23} , θ_{13} and δ_{CP} .



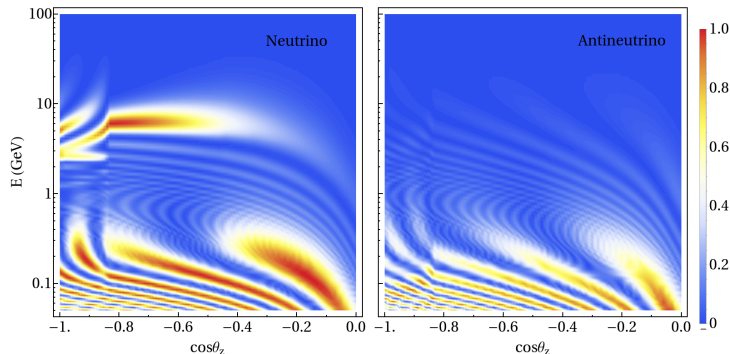
SK

IceCube/DeepCore

LBL accelerator

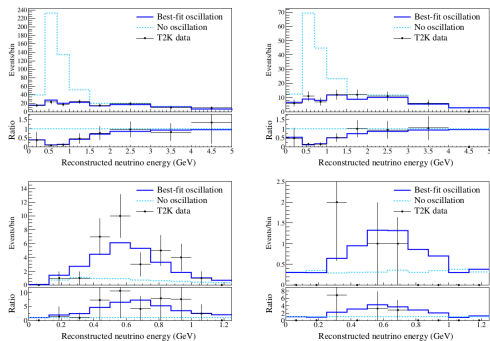
Atmospheric neutrinos: mass ordering determination

- ▶ 1-3 resonance for ν crossing the Earth with energies $E_\nu \in [2 - 10]$ GeV.
- ▶ For NO (IO) there is a resonance in the ν -channels ($\bar{\nu}$ -channels).
- ▶ Atmospheric experiment cannot distinguish ν from $\bar{\nu}$
 - ▶ Cherenkov radiation.
- ▶ The number of events contains a contribution of $\nu + \bar{\nu}$.
 - ▶ The neutrino contribution is four times bigger
- ▶ Statistical determination of the mass ordering.



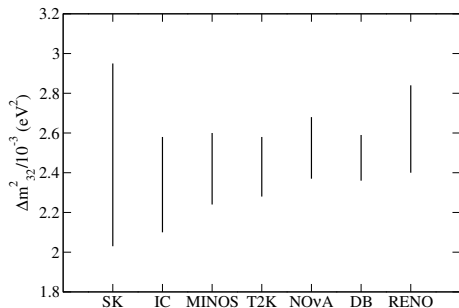
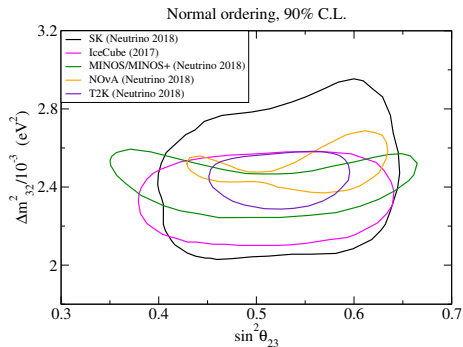
Long-baseline accelerators

- ▶ $\nu_e/\bar{\nu}_e$ and $\nu_\mu/\bar{\nu}_\mu$ with $E_\nu \in [0.6 - 7]$ GeV
(T2K: ~ 0.6 GeV, NO ν A: ~ 2 GeV, MINOS: ~ 3 GeV, MINOS+: ~ 7 GeV)
- ▶ The baseline is ~ 100 km
(T2K: ~ 295 km, NO ν A: ~ 810 km, MINOS/MINOS+: ~ 735 km)
- ▶ $\nu_\mu \rightarrow \nu_\mu$ is sensitive to Δm_{31}^2 and θ_{23} (maximal mixing or not)
- ▶ $\nu_\mu \rightarrow \nu_e$ is sensitive to the θ_{23} octant, δ_{CP} and θ_{13}



Determination of θ_{23} and Δm_{31}^2

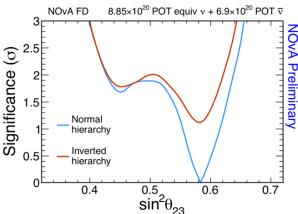
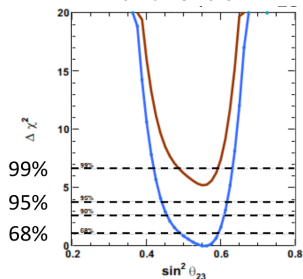
- ▶ Good agreement between LBL accelerator and atm. neutrinos in θ_{23} and Δm_{31}^2 .
- ▶ T2K shows the highest precision over the atmospheric parameters.
- ▶ Δm_{31}^2 is determined by reactor experiment with similar precision.



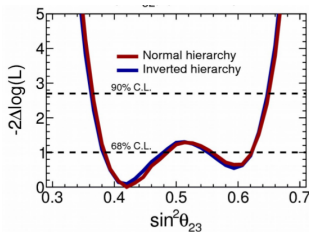
Determination of mass ordering

- ▶ SK (SK + T2K) (bounds θ_{13} from reactors): favor NH $\sim 2.1\sigma$ ($\sim 2.3\sigma$)
- ▶ T2K (adding θ_{13} from reactors): NH favored $\sim 2.2\sigma$
- ▶ NO ν A: NH favored $\sim 1.3\sigma$
- ▶ MINOS + MINOS+: very weak preference for NH $\sim 0.6\sigma$.

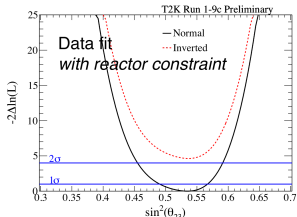
Y. Hayato
(Super-Kamiokande),
NEUTRINO 2018



M. Sanchez (NO ν A),
NEUTRINO 2018



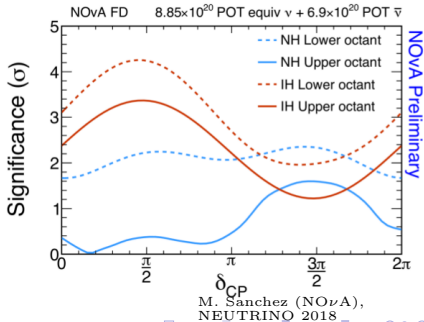
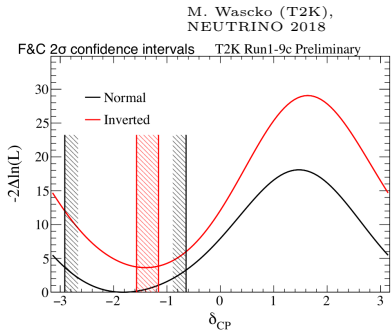
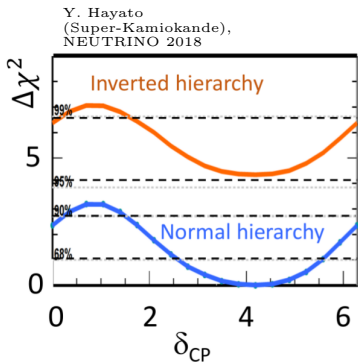
A. Aurisano (MINOS and
MINOS+), NEUTRINO 2018



M. Wascko (T2K),
NEUTRINO 2018

Determination of CP-violation phase

- ▶ Indication of T2K and SK and $\text{NO}\nu\text{A}$ (IO) of maximal CP violation ($\delta_{CP} \sim 90^\circ$)
- ▶ $\text{NO}\nu\text{A}$ (NO) prefer $\delta_{CP} \sim 30^\circ$



Conclusions

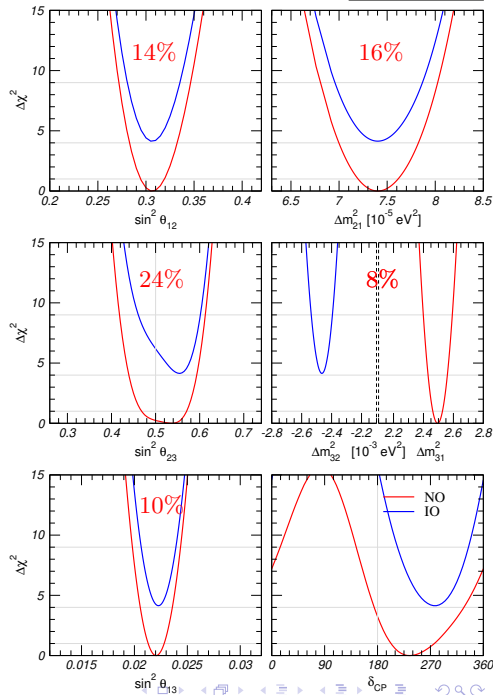
Most of the neutrino oscillation data can be explained in the framework of 3 neutrino mixing.

The least known oscillation parameters:

- ▶ δ_{CP}
- ▶ The octant of θ_{23}
- ▶ The mass ordering. Recent results show a preference for NO [1,2] at more than 3σ .

[1] F. Capozzi, et al.,
Prog.Part.Nucl.Phys. 102 (2018) 48-72

[2] P.F. de Salas, et al., Phys.Lett.
B782 (2018) 633-640



Conclusions

Comparison between different global fits

	Nufit[1]	Capozzi et al.,[2]	Salas et al.,[3]
$\sin^2 \theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.304^{+0.014}_{-0.013}$	$0.320^{+0.20}_{-0.16}$
$\sin^2 \theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.551^{+0.019}_{-0.070}$	$0.547^{+0.20}_{-0.30}$
$\sin^2 \theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.0214^{+0.0009}_{-0.0007}$	$0.0216^{+0.00083}_{-0.00069}$
δ_{CP}	234^{+43}_{-31}	234^{+41}_{-32}	218^{+38}_{-27}
$\frac{\Delta m_{21}^2}{10^{-5} \text{eV}^2}$	$7.4^{+0.21}_{-0.20}$	$7.34^{+0.17}_{-0.14}$	$7.55^{+0.20}_{-0.16}$
$\frac{\Delta m_{31}^2}{10^{-3} \text{eV}^2}$	$2.494^{+0.033}_{-0.031}$	$2.455^{+0.035}_{-0.032}$	$2.50^{+0.03}_{-0.03}$

[1] NuFIT 3.2 (2018), www.nu-fit.org

[2] F. Capozzi, E. Lisi, A. Marrone, and A. Palazzo, Prog.Part.Nucl.Phys. 102 (2018) 48-72

[3] P.F. de Salas, D.V. Forero, C.A. Ternes, M. Tortola, J.W.F. Valle, Phys.Lett. B782 (2018) 633-640

Thank you!

KamLAND and the 5 MeV excess

- ▶ There is no near detector in KamLAND.
- ▶ the flux can be affected by the excess around $E_\nu \sim 5$ MeV.
- ▶ There is a small impact on the determination of Δm_{21}^2

