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The Global Three-Neutrino Oscillation Picture

Iván Martínez Soler

Physics Opportunities in the Near DUNE Detector hall

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Neutrino evolution

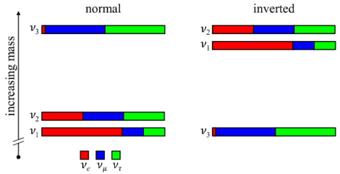
In the 3ν scenario, neutrino evolution is described by the Schrödinger equation

$$i\frac{d\vec{\nu}}{dt} = \frac{1}{2E}\left[U^\dagger Diag(0, \overbrace{\Delta m^2_{21}}^{\sim 7.5\times 10^{-5} eV^2}, \underbrace{\Delta m^2_{31}}_{\sim 2.5\times 10^{-3} eV^2})U \pm V_{mat}\right]\vec{\nu}$$

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

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

Two possible mass hierarchies



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

Neutrino evolution

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

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

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

Neutrino evolution

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

$\sim 7.8\%$

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

$\sim 16\%$

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

$\sim 27\%$ $\sim 8.9\%$ $\sim 100\%$ $\sim 14\%$

Reactor neutrinos: determination of θ_{13}

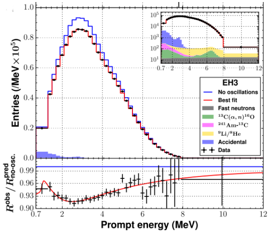
- $\overline{\nu}_e$ emitted from fission reactions.
- The energy spectrum rise from 1.8 MeV to 4 MeV, and falls to very low rate at 8 MeV.
- At distances of $\sim$ 1 km [1]

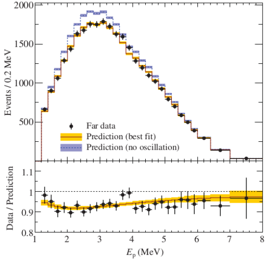
$$P_{ee} = 1 - c_{13}^4 \sin^2 2\theta_{21} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$$

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

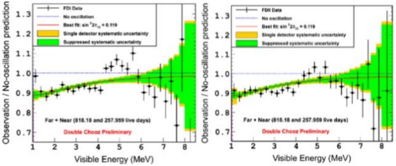
- Reactor neutrinos are sensitive to θ_{13} and Δm_{31}^2.
- Double-Chooz, RENO and Daya Bay established that $\theta_{13} \neq 0$
  - A rate-only analysis determines (Daya Bay Neutrino 2018) $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$

Phys. Rev. D95, 072006 (2017)





Phys. Rev. D98, 012002 (2018)

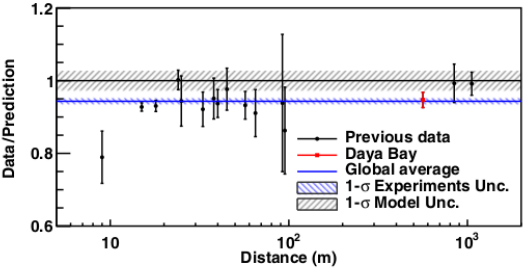


PoS (EPS - HEP2017)109

[1] Phys. Rev. D72 (2005) 013009

Reactor anomaly

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

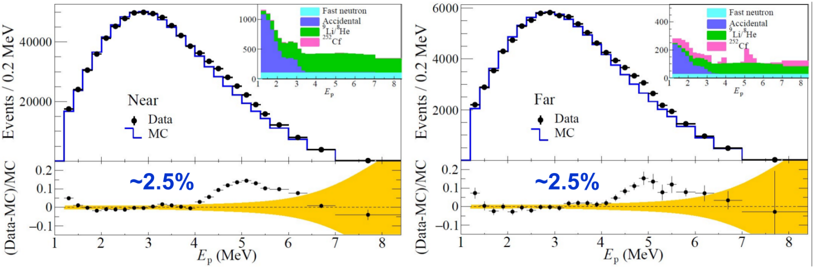


$$P_{ee} = 1 - c_{13}^4 \sin^2 2\theta_{21} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$$

PRL 116, 061801 (2016)

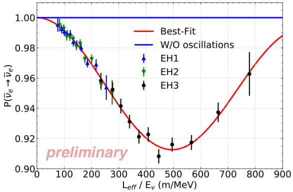
Flux excess at 5 MeV

- 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 → θ_{13} depends on the relative uncertainties.

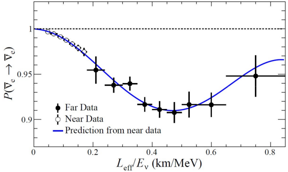


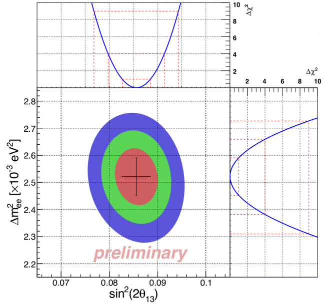
I. Tu (RENO), NEUTRINO 2018

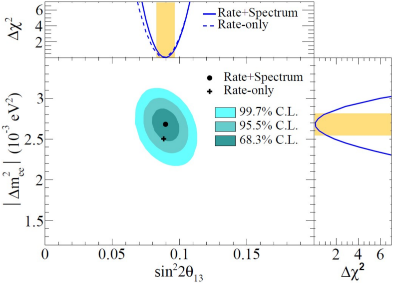
Reactor neutrinos: determination of Δm^2_{31}



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







J.P. Ochoa-Recoux (Daya Bay), NEUTRINO 2018 I. Tu (RENO), NEUTRINO 2018

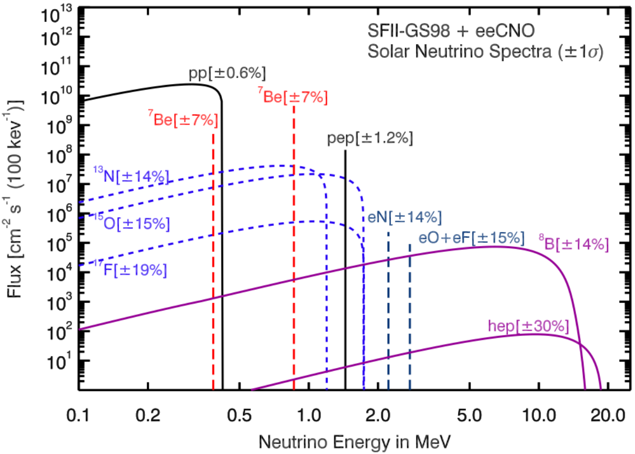
Solar neutrinos

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

$$4p \rightarrow^4 He + 2e^+ + 2\nu_e + \gamma$$

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

Phys. Rev. D 98, 030001 (2018)



Determination of the solar parameters (Δm^2_{21}, θ_{21})

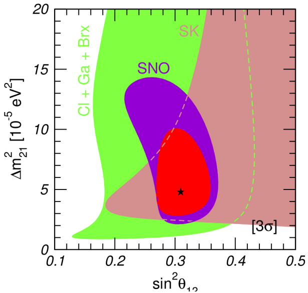
- $\Delta m^2_{31} >> E/L$

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

- For neutrinos created in high densities

$$P^{2\nu}_{eff}(\Delta m^2_{21}, \theta_{12}) = \frac{1}{2}(1 + \cos\theta^m_{12}\cos\theta_{12})$$

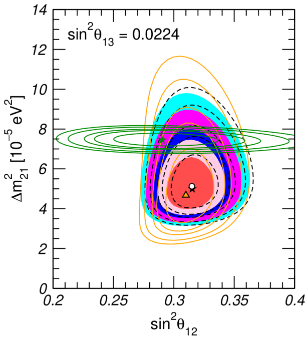
  - Solar neutrino experiment are mainly sensitive to θ_{12}.
  - There is a small dependence on Δm^2_{21}.
  - θ^m_{13} carries a slight dependence with Δm^2_{31}.
- The constraints over θ_{12} are mainly driven by SK+SNO .
  - SNO present a better precision than SK.
- The results are independent of Solar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



Eur.Phys.J. A52 (2016) no.4, 87

Determination of the solar parameters (Δm^2_{21}, θ_{21})

NuFIT 4.0 (2018)



- Δm^2_{21} is determined by KamLAND.
- Long-baseline reactor experiment.
  - $\overline{\nu}_e$ with $E_\nu \sim$ few MeV.
  - Baseline $\sim$ 180 km.

$$P^{3\nu}_{ee} \simeq c^4_{13} P^{2\nu}_{eff} + s^4_{13}$$

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

KamLAND determination of Δm^2_{21} shows a $\sim 2\sigma$ [1-3] tension with solar experiments.

[1] I. Esteban, et al., arXiv:1811.05487, NuFIT 4 (2018), www.nu-fit.org

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

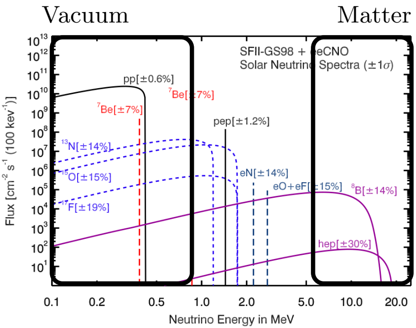
[3] P.F. de Salas, et al., Phys.Lett. B782 (2018) 633-640

Tension in Δm^2_{21}

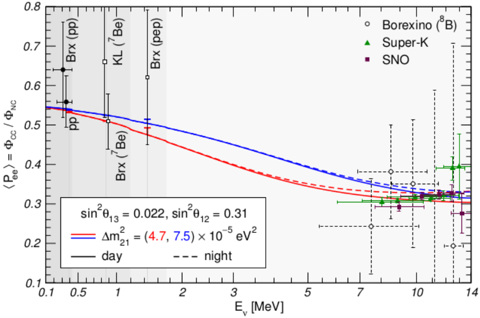
Non observation of low-energy turn up ^8B neutrino spectrum measured.

Observations indicates:

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



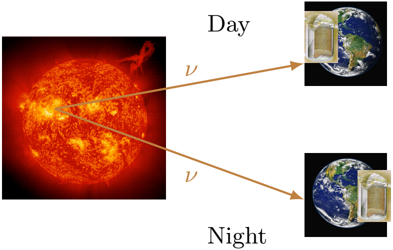
Phys. Rev. D 98, 030001 (2018)

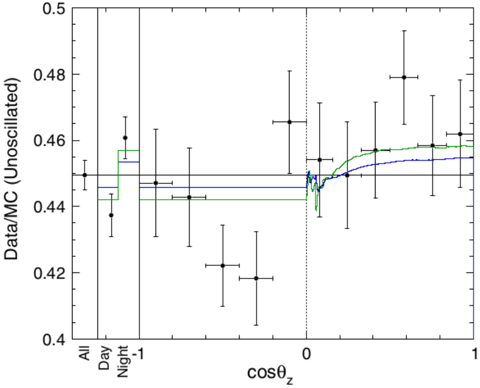


Eur.Phys.J. A52 (2016) no.4, 87

Tension in Δm^2_{21}

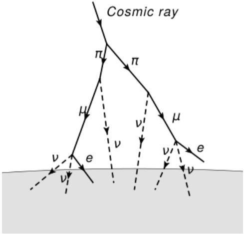
Observation of a larger day/night asymmetry than predicted by KamLAND.





Phys. Rev. D94, 052010 (2016)

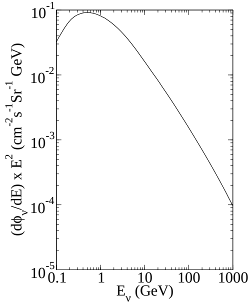
Atmospheric neutrinos



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

$$\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\overline{\nu_\mu})$$
$$K^{\pm} \to \mu^{\pm} + \nu_\mu(\overline{\nu_\mu})$$
$$\mu^{\pm} \to \qquad e^{\pm} + \nu_e(\overline{\nu_e}) + \nu_\mu(\overline{\nu_\mu})$$

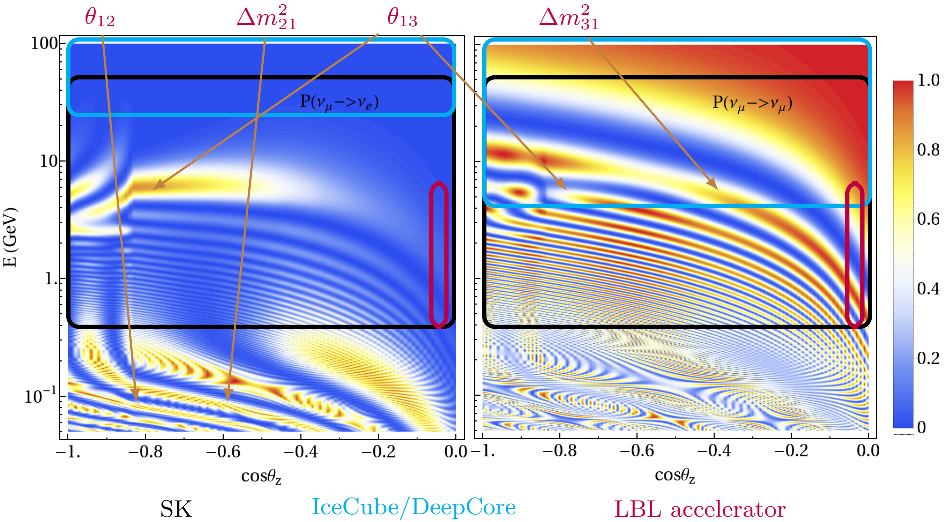
- Atmospheric flux covers a wide range of energies ($\phi_\nu \sim E_\nu^{-2.7}$).
- The main uncertainties are parametrized by:
  - The normalization.
  - A energy dependence ($\phi_\nu \sim \phi_0(E/E_0)^\gamma$)
  - The relative contribution of π and K ($R_{\pi/K}$)
  - The ratio between the neutrino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



Phys. Rev. D92, 023004 (2015)

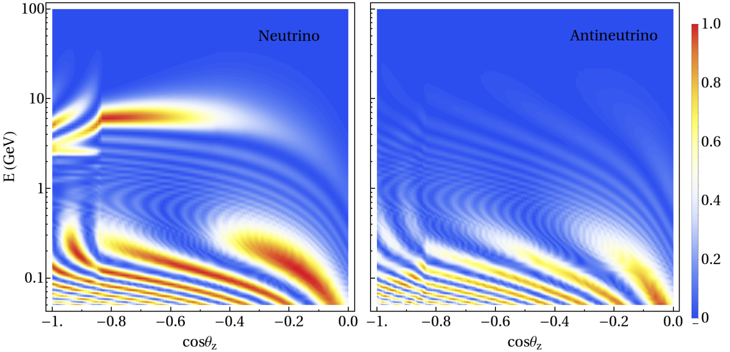
Atmospheric neutrinos: contribution to the global fit

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



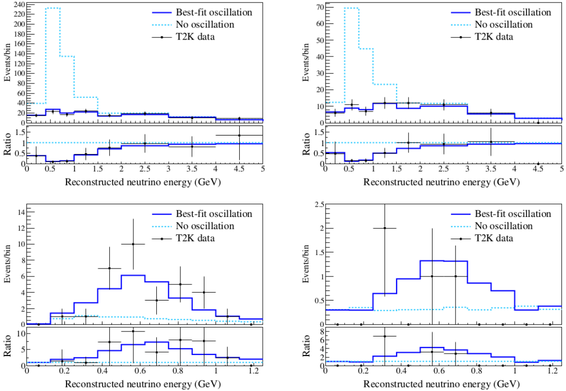
Atmospheric neutrinos: mass hierarchy determination

- 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 ($\overline{\nu}$-channels).
- Atmospheric experiment cannot distinguish ν from $\overline{\nu}$
  - Cherenkov radiation.
- The number of events contains a contribution of $\nu + \overline{\nu}$.
  - The neutrino contribution is four times bigger
- Statistical determination of the mass hierarchy.



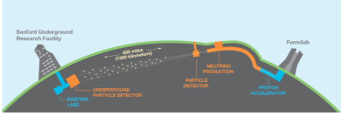
Long-baseline accelerators

- $\nu_e/\overline{\nu}_e$ and $\nu_\mu/\overline{\nu}_\mu$ with $E_\nu \in [0.6 - 7]$ GeV
  (T2K:$\sim$ 0.6 GeV, NOνA: $\sim$ 2 GeV, MINOS: $\sim$ 3 GeV, MINOS+: $\sim$ 7 GeV)
- The baseline is $\sim$ 100 km
  (T2K:$\sim$ 295 km, NOνA: $\sim$ 810 km, MINOS/MINOS+: $\sim$ 735 km)
- $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$

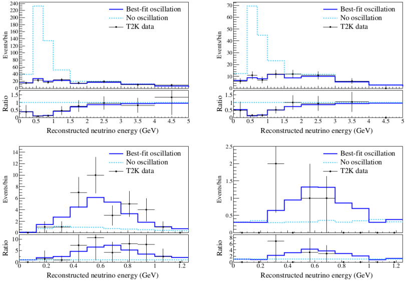


Phys. Rev. D96, 092006 (2017)

Long-baseline accelerators



- $\nu_e/\overline{\nu}_e$ and $\nu_\mu/\overline{\nu}_\mu$ with $E_\nu \in [0.6-7]$ GeV (T2K:$\sim$ 0.6 GeV, NOνA: $\sim$ 2 GeV, MINOS: $\sim$ 3 GeV, MINOS+: $\sim$ 7 GeV, **DUNE:$\sim$ 2.5 GeV**)
- The baseline is $\sim$ 100 km (T2K:$\sim$ 295 km, NOνA: $\sim$ 810 km, MINOS/MINOS+: $\sim$ 735 km, **DUNE:1300 km**)
- $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$



Phys. Rev. D96, 092006 (2017)

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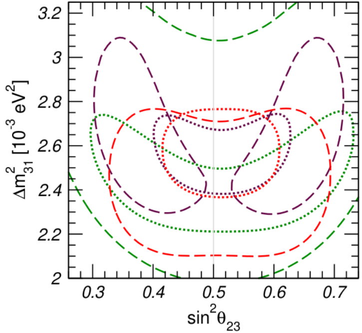


NuFIT 4.0 (2018)

$\nu_\mu \to \nu_\mu$ is senstive to $\Delta m^2_{\mu\mu}$ and $\theta_{\mu\mu}$ [1,2]

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E}$$

where

$$\sin^2\theta_{\mu\mu} = \cos^2\theta_{13} \sin^2\theta_{23}$$

$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \cos\delta_{cp} \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23}\Delta m^2_{21}$$

- $P_{\mu\mu}$ is symmetric around $\theta_{23} \sim 45$ (maximal mixing or not)
  - Discriminate between maximal mixing or not.
- $P_{\mu\mu}$ is sensitive to Δm^2_{31}

[1] Phys. Rev. D72 (2005) 013009

[2] Prog. Theor. Phys. 114 (2006) 1045-1056

Long-baseline accelerators

ν_e apperance channel

$$P_{\nu_\mu \to \nu_e} \approx 4 \sin^2 \theta_{13} \sin^2 \theta_{23} (1 + 2oA) - C \sin \delta_{cp} (1 + oA)$$
$$P_{\bar{\nu_\mu} \to \bar{\nu_e}} \approx 4 \sin^2 \theta_{13} \sin^2 \theta_{23} (1 - 2oA) + C \sin \delta_{cp} (1 - oA)$$

JHEP 09 (2015) 016

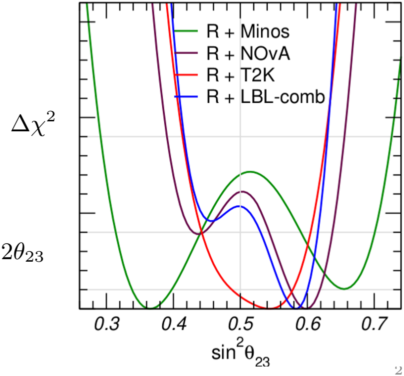
$\nu_\mu \to \nu_e$ is sensitive to

- the θ_{23} octant;
- mass hierarchy;
- δ_{cp};
- θ_{13}.

where

$$C = \Delta m^2_{21} L/4E \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$
$$o = sign(\Delta m^2_{31})$$
$$A = |2EV/\Delta m^2_{31}|$$

NuFIT 4.0 (2018)



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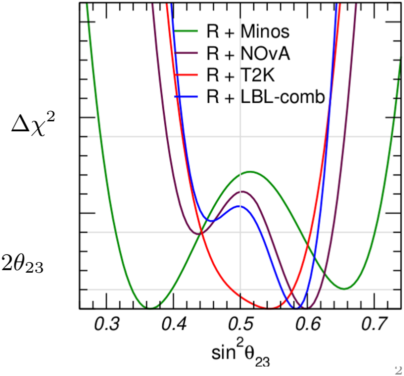

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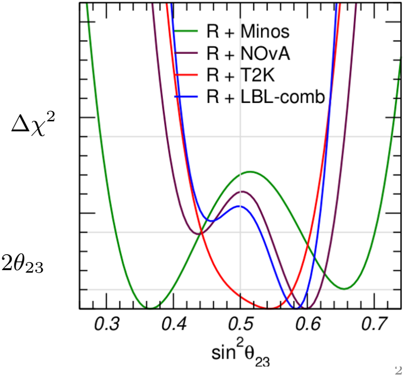

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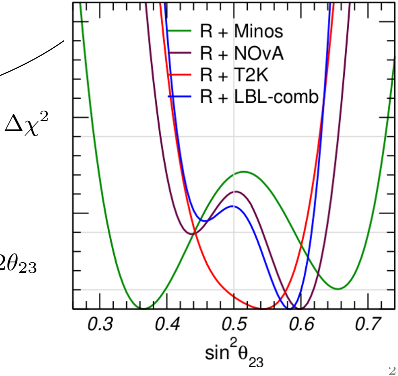

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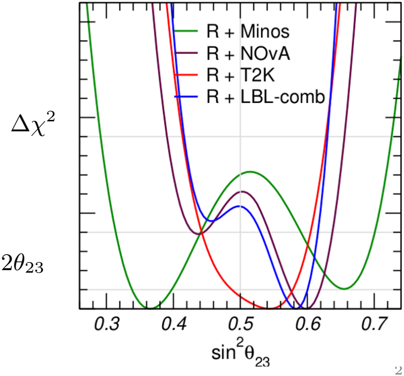
- the θ_{23} octant;
- mass hierarchy;
- δ_{cp};
- θ_{13}.

NuFIT 4.0 (2018)

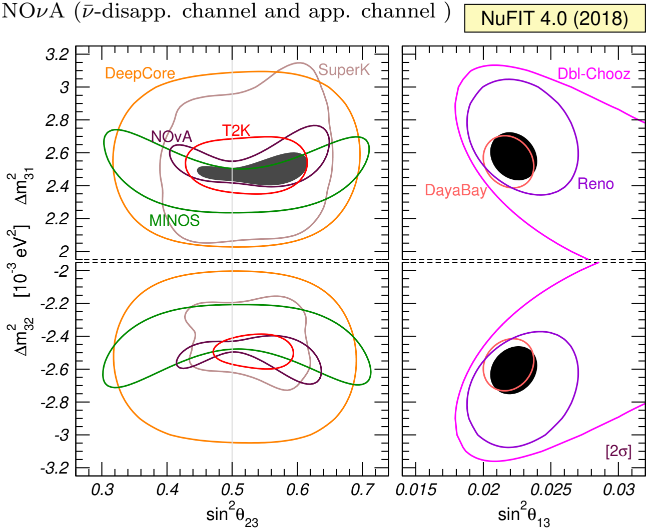


where

$$C = \Delta m^2_{21} L / 4E \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$
$$o = sign(\Delta m^2_{31})$$
$$A = |2EV / \Delta m^2_{31}|$$

Determination of θ_{23} and Δm^2_{31}

- Preference for the second octant of θ_{23}
- Maximal mixing is disvafor by:
  - T2K (app. channel)
  - NOνA ($\bar{\nu}$-disapp. channel and app. channel)

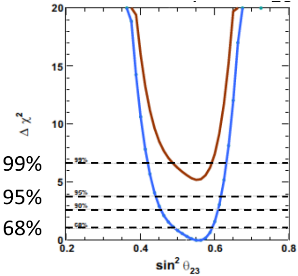


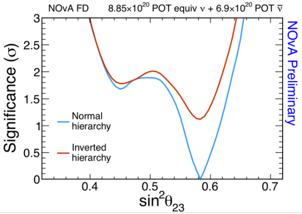
Determination of mass hierarchy

Preference for NH $\sim 3\sigma$.

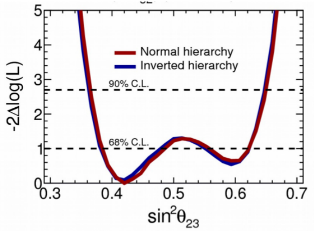
- SK (SK + T2K) (bounds θ_{13} from reactors): favor NH $\sim 2.1\sigma (\sim 2.3\sigma)$
- T2K (adding θ_{13} from reactors): NH favored $\sim 2\sigma$
- NOνA: NH favored $\sim 1.3\sigma$
- MINOS + MINOS+: very weak preference for NH $\sim 0.6\sigma$.

Y. Hayato (Super-Kamiokande), NEUTRINO 2018

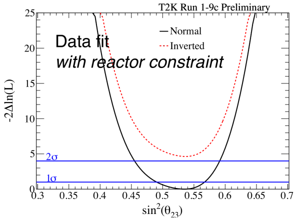




M. Sanchez (NOνA), NEUTRINO 2018



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

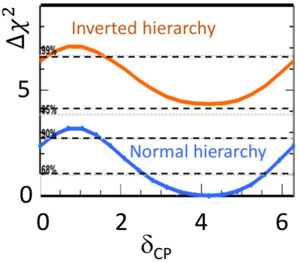


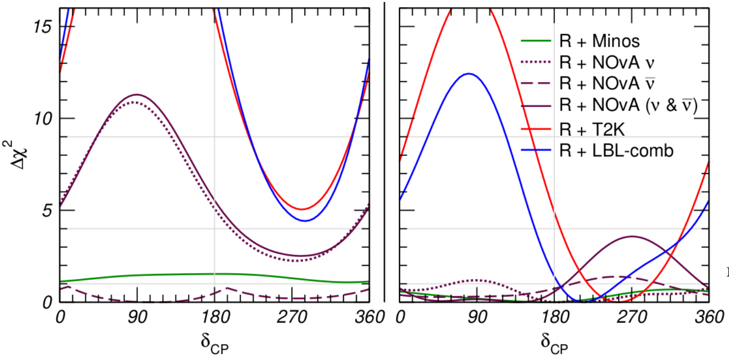
M. Wascko (T2K), NEUTRINO 2018

Y. Hayato
(Super-Kamiokande),
NEUTRINO 2018

Determination of CP-violation phase

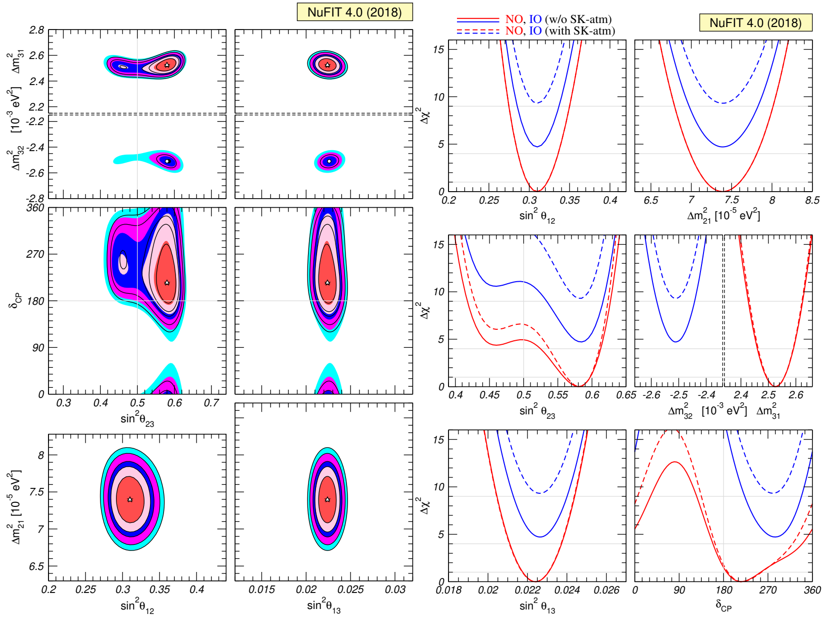
- The best-fit of LBL shows $\delta_{cp} = 215°$
  - T2K and NOνA (IO) prefer maximal CP violation ($\delta_{CP} \sim 270°$)
  - NOνA (NO) prefer $\delta_{CP} \sim 30°$
- SK favor $\delta_{cp} = 270°$





NuFIT 4.0 (2018)

Conclusions

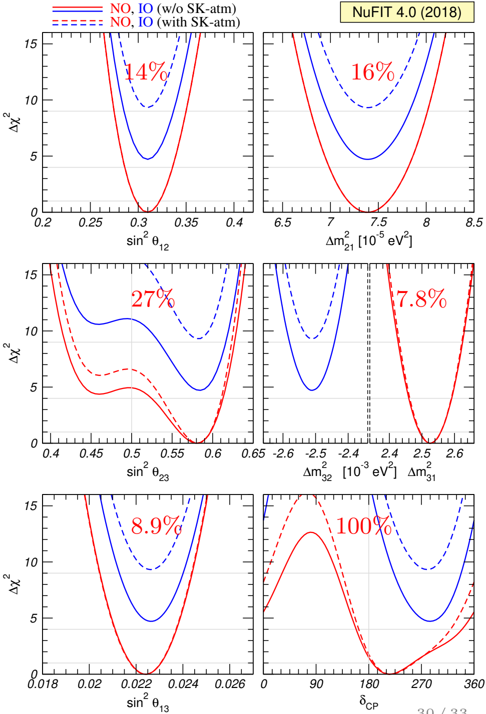


Conclusions

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

The least known oscillation parameters [1,2,3]:

- δ_{CP} (Recent result push to non-maximal violation)
- The octant of θ_{23} (preference for the second octant)
- The mass hierarchy (preference for NO at more than 3σ)



[1]I. Esteban, et al., arXiv:1811.05487, NuFIT 4 (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

Conclusions

Comparison between different global fits

	Esteban et al., [1]	Capozzi et al.,[2]	Salas et al.,[3]
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.304^{+0.014}_{-0.013}$	$0.320^{+0.20}_{-0.16}$
$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.551^{+0.019}_{-0.070}$	$0.547^{+0.20}_{-0.30}$
$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.0214^{+0.0009}_{-0.0007}$	$0.0216^{+0.00083}_{-0.00069}$
δ_{CP}	215^{+40}_{-29}	234^{+41}_{-32}	218^{+38}_{-27}
$\frac{\Delta m^2_{21}}{10^{-5}\mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$7.34^{+0.17}_{-0.14}$	$7.55^{+0.20}_{-0.16}$
$\frac{\Delta m^2_{31}}{10^{-3}\mathrm{eV}^2}$	$2.525^{+0.033}_{-0.031}$	$2.455^{+0.035}_{-0.032}$	$2.50^{+0.03}_{-0.03}$

[1] I. Esteban, et al., arXiv:1811.05487, NuFIT 4 (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 a 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^2_{21}