Global neutrino data analyses

Iván Martínez Soler

8th Workshop on Theory, Phenomenology and Experiments in Flavour Physics

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π+
π0
γ
μ+
e+
e-
νe
ν̄μ
νμ
C9745

Neutrino evolution

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

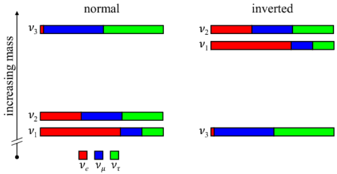
$$i\frac{d\vec{\nu}}{dt} = \frac{1}{2E}\left[U^{\dagger} Diag(0, \Delta m^2_{21}, \Delta m^2_{31}) U\right]\vec{\nu} \qquad \vec{\nu} = (\nu_e\, \nu_\mu\, \nu_\tau)^T$$

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

In the case of Majorana neutrinos, we will have two extra phases

$$P = \mathrm{diag}(1, e^{i\phi_1}, e^{i\phi_2})$$

Two possible mass orderings



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

Neutrino evolution

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

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}	$\theta_{13}, \theta_{23}, \text{sign}\left(\Delta m^2_{3l}\right)$

Reactor neutrinos

In reactor experiments, a flux of $\overline{\nu_e}$ with energies around $\sim$ MeV

- At distances of ~ 1 km

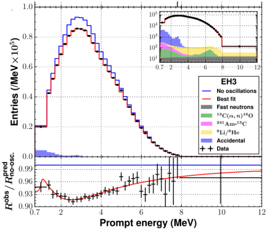
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$$

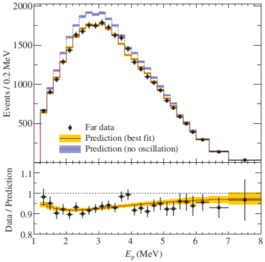
$$\Delta m^2_{ee} = \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$$

- Reactor neutrinos are sensitive to θ_{13} and Δm^2_{31}.
- Double-Chooz, RENO and Daya Bay established that $\theta_{13} \neq 0$

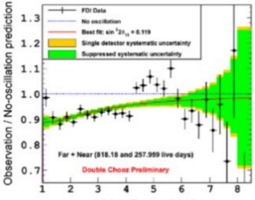
$\sin^2 2\theta_{13} = 0.0853 \pm 0.0024$ Daya Bay (Neutrino 2022)

Phys. Rev. D95, 072006 (2017)

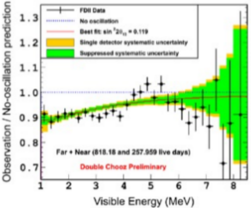




Phys. Rev. D98, 012002 (2018)



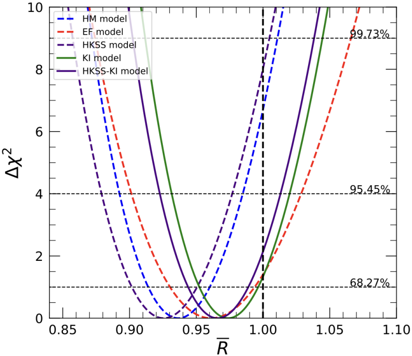
PoS (EPS - HEP2017)109



Phys. Rev. D72 (2005) 013009

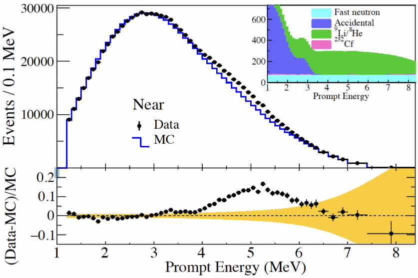
Reactor flux uncertainties

The reevaluation of the $\overline{\nu}_e$ flux determined a deficit in the experimental data.



C. Giunti, et al., Phys.Lett.B 829

The ratio of measured over the predicted flux shows an excess at 5 MeV.



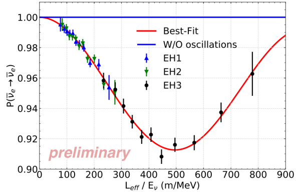
K. Kwang Joo (RENO), NEUTRINO 2022

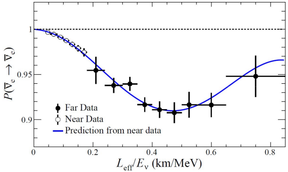
- New evaluations of the flux aliviate those tensions
- The uncertainties do not affect the results because they are based on a near/far comparison.

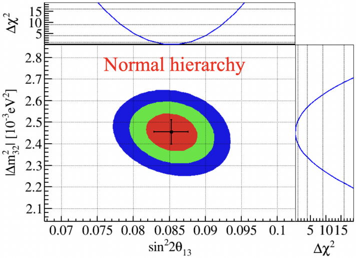
Reactor neutrinos: determination of Δm^2_{31}

The spectral information from reactor experiments make possible the determination of Δm^2_{31}

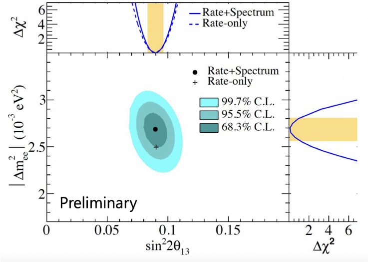
- Near detector imposes an upper bound over Δm^2_{31}.
- The oscillations measured at the far detector impose lower bound on θ_{13} and Δm^2_{31}







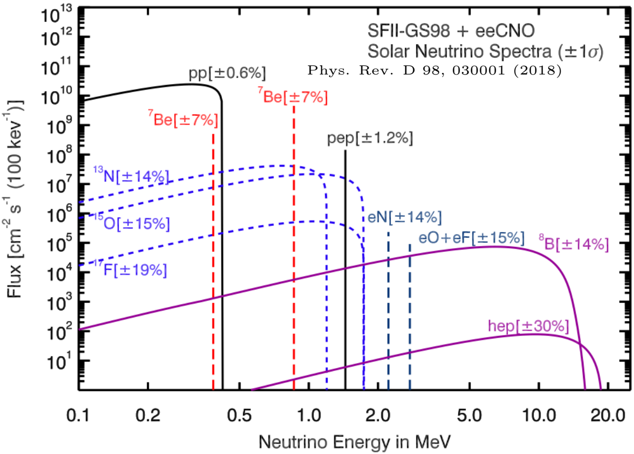
K. Luk (Daya Bay), NEUTRINO 2022



K. Kwang Joo (RENO), NEUTRINO 2022

Solar neutrinos

Solar neutrinos are produced by nuclear fusions reactions: pp chains and CNO cycles



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

- For solar neutrinos $\Delta m^2_{31} >> E/L$, the electron survival probability can be written as

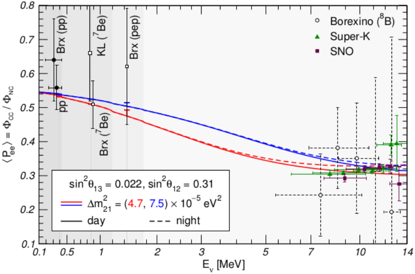
$$P^{3\nu}_{ee} \approx \cos^2\theta_{13}\cos^2\theta^m_{13}P^{2\nu}_{eff}(\Delta m^2_{21},\theta_{12})$$
$$+\sin^2\theta^m_{13}\sin^2\theta_{13}$$

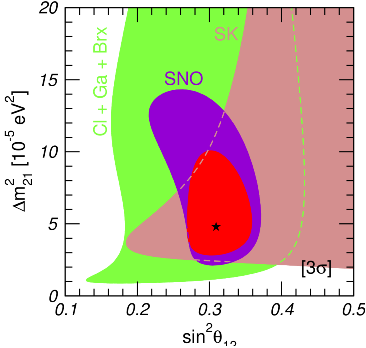
- For neutrinos created in high densities

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

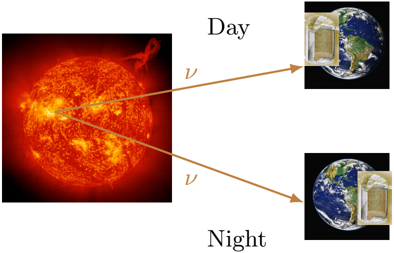
  - Solar neutrino experiment are mainly sensitive to θ_{12}.
  - There is a small dependence on Δm^2_{21}.
  - θ^m_{13} carries a slight dependence with Δm^2_{31}.
- The constraints over θ_{12} are mainly driven by SK+SNO .
- The results are independent of Solar model used.

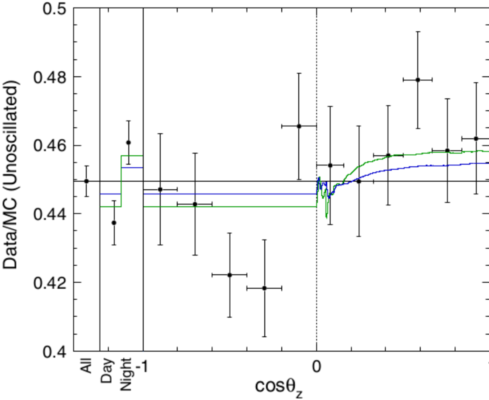
Eur.Phys.J. A52 (2016) no.4, 87





Day-night assymetry





Phys. Rev. D94, 052010 (2016)

$$A_{D/N} = \frac{\Phi_{\text{day}} - \Phi_{\text{night}}}{0.5 * \Phi_{\text{day}} - \Phi_{\text{night}}}$$

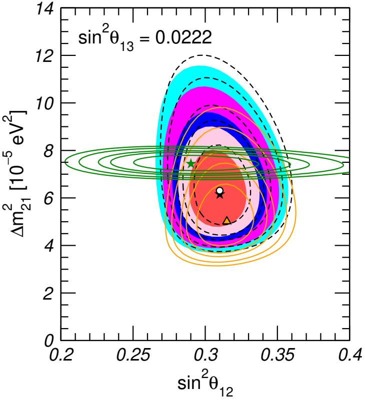
$$\begin{array}{lccc} & \text{SK4-2055} & & \text{SK4-2970} \\ A_{D/N} = & -3.1\% & \rightarrow & -2.1\% \end{array}$$

Long-baseline reactor: Determination of Δm^2_{21} and θ_{21}

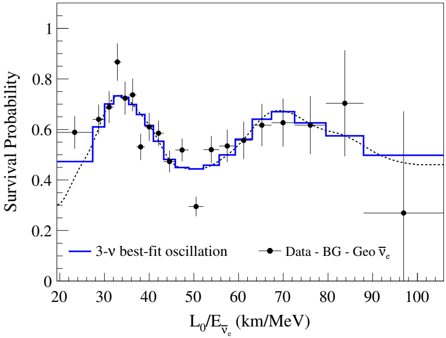
- Δm^2_{21} is determined by KamLAND.
- Long-baseline reactor experiment.
  - $\overline{\nu}_e$ with $E_\nu \sim$ few MeV.
  - Baseline $\sim$ 180 km.

$$P_{ee}^{3\nu} = c_{13}^4\left(1 - \frac{1}{2}\sin^2(2\theta_{12})\sin^2\frac{\Delta m^2_{21}L}{2E}\right) + s_{13}^4$$

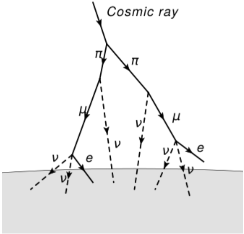
NuFIT 5.1 (2021)



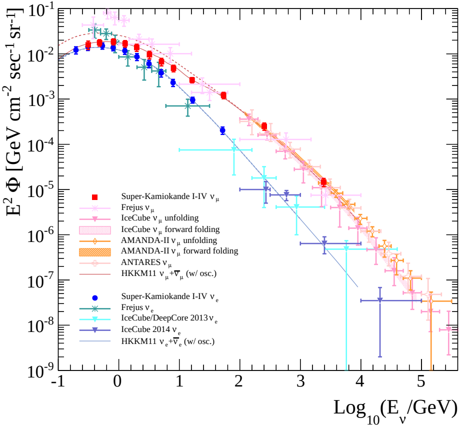
A.Gando et al. (KamLAND), PRD 88 (2013)



Atmospheric neutrinos



Created in the collisions of cosmic rays with the atmosphere.



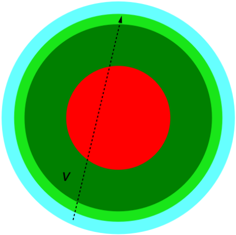
$$\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\overline{\nu_\mu})$$

$$K^{\pm} \to \mu^{\pm} + \nu_\mu(\overline{\nu_\mu})$$

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

E. Richard et al. (SK), Phys.Rev.D 94 (2016) 5, 052001

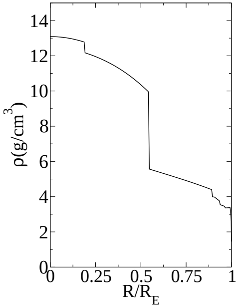
Atmospheric neutrinos

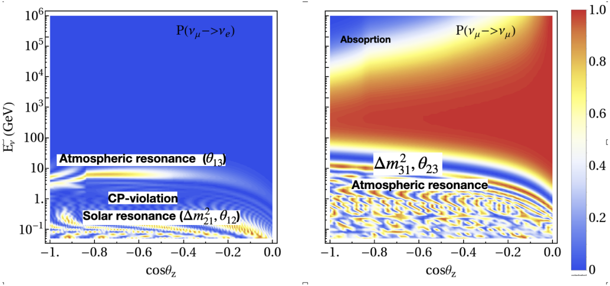


In matter, the evolution is affected by the matter potential

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

$$V_{mat} = \sqrt{2}G_F N_e \mathrm{Diag}(1,0,0)$$





Atmospheric neutrinos: sub-GeV

For $E < 1$ GeV, the CP-violation term is enhanced due to the development Δm_2^2.

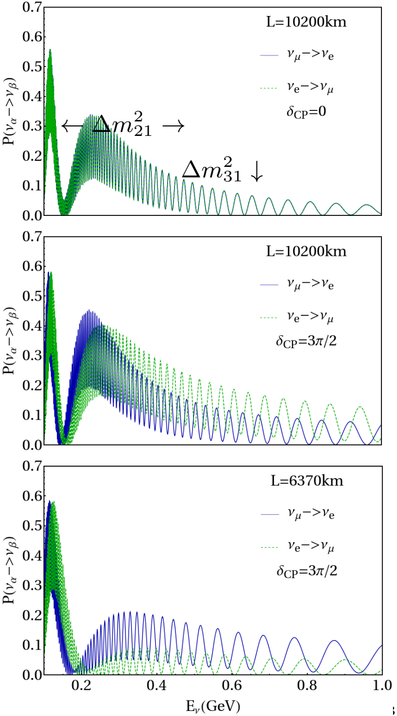
$$P_{CP} = -8 J_{CP}^{max} \sin\delta_{CP} \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32}$$

- For $E > 1$, $\sin(\Delta_{21}) << 1$
- For $E < 1$, $\sin(\Delta_{31})\sin(\Delta_{32}) \sim 1/2$

For $\delta \neq 0$, the CPT conservation implies

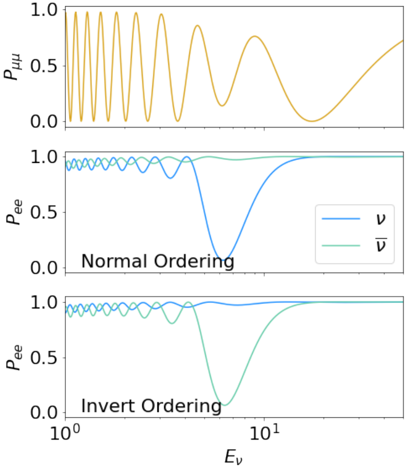
$$P(\nu_\mu \to \nu_e) \neq P(\nu_e \to \nu_\mu)$$

- The impact of δ_{cp} depends on the neutrino direction



Atmospheric neutrinos: multi-GeV

In the multi-GeV region, atmospheric neutrinos are sensitive to Δm^2_{31} and θ_{23}



At the GeV scale, there is resonant flavor conversion. Neutrinos are sensitive to the mass ordering:

- The matter effect enhances the oscillation of ν ($\overline{\nu}$) for NO (IO)
- There is an enhancement of θ_{13}

$$E_r \simeq 5.3\text{GeV}\left(\frac{\Delta m^2_{31}}{2.5\times 10^{-3}\text{eV}^2}\right)\left(\frac{cos2\theta}{0.95}\right)\left(\frac{\rho}{6\text{g/cc}}\right)$$

Long-baseline accelerators

Long-baseline experiments are sensitive to Δm^2_{31} and θ_{23} in the ν_μ-disappearance channel

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

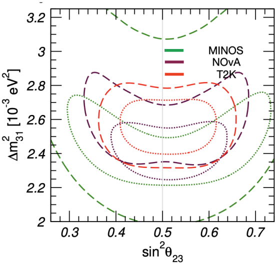
Experiment	Energy	Baseline
T2K	$\sim$ 0.6 GeV	$\sim$ 300 km
NOvA	$\sim$ 2 GeV	$\sim$ 800 km
MINOS	$\sim$ 3 GeV	$\sim$ 735 km
MINOS+	$\sim$ 7 GeV	$\sim$ 735 km

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 $\theta_{23} = 45$. It can discriminate whether θ_{23} is maximal mixing or not



Long-baseline accelerators

In the apperance channel ($\nu_\mu \to \nu_e$), LBL are sensitive to:

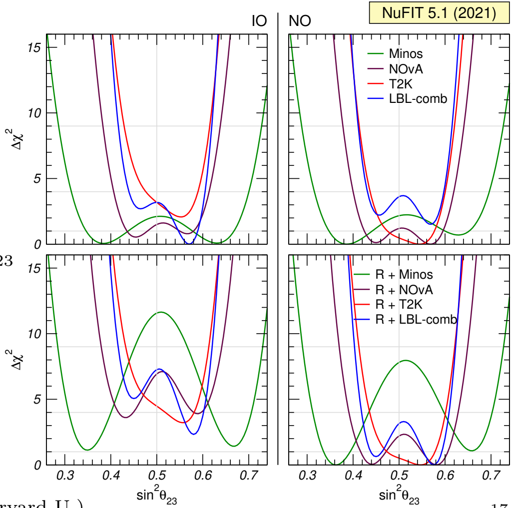
$$P_{\nu_\mu \to \nu_e} \approx 4 \sin^2 \theta_{13} \sin^2 \theta_{23} (1 + 2oA) - C \sin \delta_{cp} (1 + oA)$$

- mass ordering
- octant of θ_{23}
- the CP phase
- θ_{13}

$C = \frac{\Delta m^2_{21} L}{4E} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$

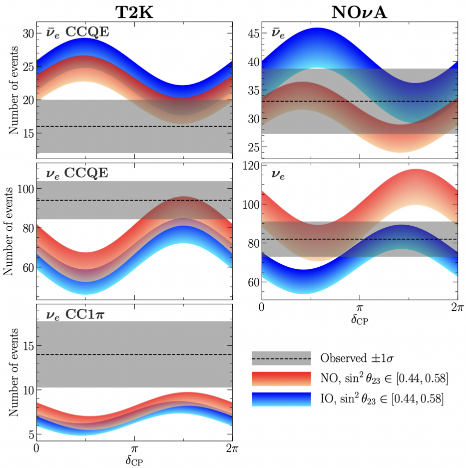
$o = sign(\Delta m^2_{31})$

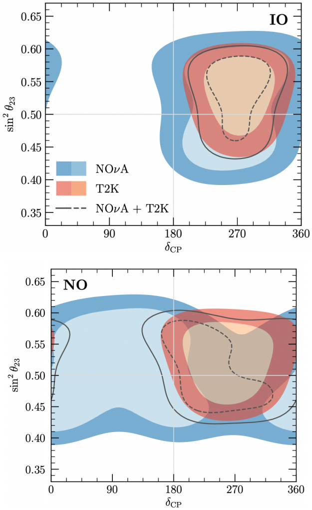
$A = |2EV/\Delta m^2_{31}|$



Tension between NOvA and T2K

The new data from NOvA and T2K show tension in the determination of δ_{cp} for NO

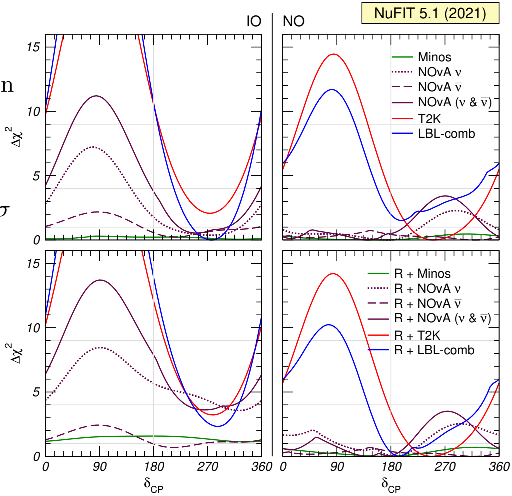


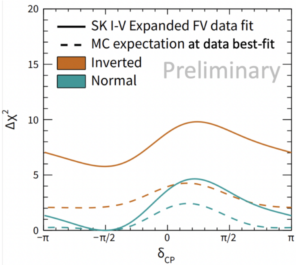


See also Kelly, Machado, Parke, Perez-Gonzalez and Funchal Phys.Rev.D. 103 (2021) 1

Status of δ_{cp}

- The combined analysis of LBL has a preference for $\delta_{cp} \sim 180$ in NO and close to maximal CP-violation for IO
- T2K has preference for NO and $\delta_{CP} = 270$
- NOvA event distribution can be explained by NO and $\delta_{cp} \sim 180$ or IO and $\delta_{cp} = 270$
- SK exclude $\delta_{cp} \sim 90$ with 2σ

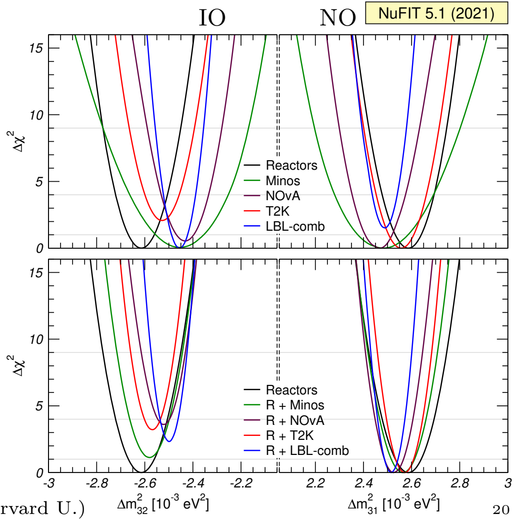




Δm^2_{31} and the mass ordering

The combination between LBL and reactors leads to a preference for NO lower than 2σ.

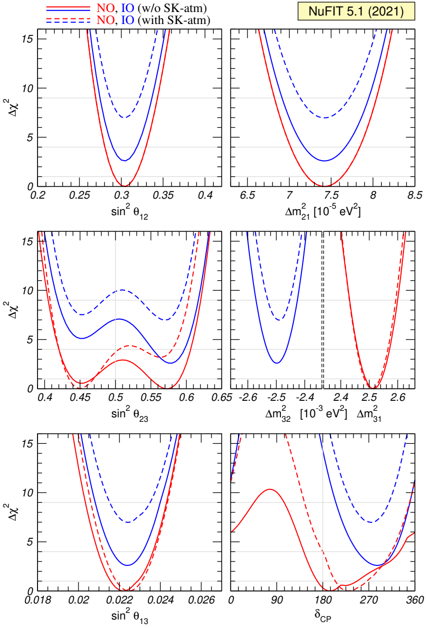
- Each LBL has a preference for NO
- The tension between T2K and NOvA leads a preference for IO
- Combining LBL ($\Delta m^2_{\mu\mu}$) and reactors (Δm^2_{ee}), we get a preference for NO of $\sim 2\sigma$
- Super-K increases the preference for NO upto $\sim 2.7\sigma$



Status of the 3ν mixing scenario

The best-fit values and the 1σ region for each parameter are:

Param.	Best-fit	Prec
θ_{12}	33.44	4%
θ_{13}	8.57	2.8%
θ_{23}	49.2	2.8%
δ_{cp}	197	
Δm^2_{21}	$7.4 \times 10^{-5}\text{eV}^2$	$\sim 3\%$
Δm^2_{31}	$2.5 \times 10^{-3}\text{eV}^2$	$\sim 1\%$



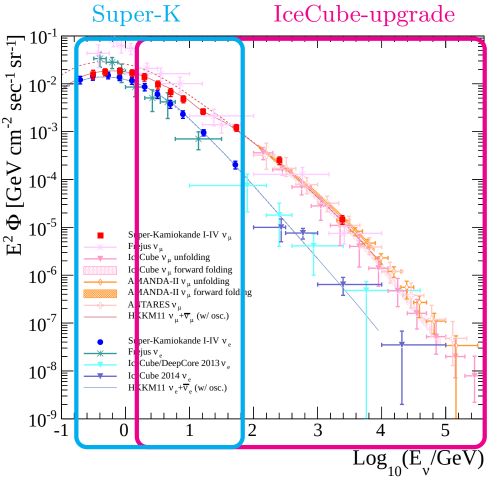
The less constrained parameters are:

- Mass ordering
- Octant of θ_{23}
- CP-phase

Future sensitivity with atmospheric neutrinos

Measuring the atmospheric neutrino flux

In the near future we are going to have a more precise measurement of the atmospheric neutrino flux



Super-K

- 22.5 kton water Cherenkov
- Event sample divided in: FC, PC and Up-μ
- **Low directionality** for sub-GeV ν
- Currently, SK is using Gd-tagging

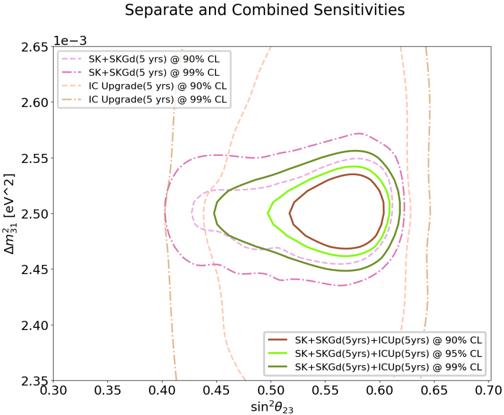
IceCube-upgrade

- $\sim 1\text{km}^3$ ice Cherenkov
- Events sample divided in: cascades and tracks
- The upgrade will lower the $E \geq 1$ GeV

Combined analysis: θ_{23} and Δm^2_{31}

Making a combined analysis of SK and IceCube-upgrade, we have estimated the sensitivity of δ_{cp}, θ_{23} and the **mass ordering**

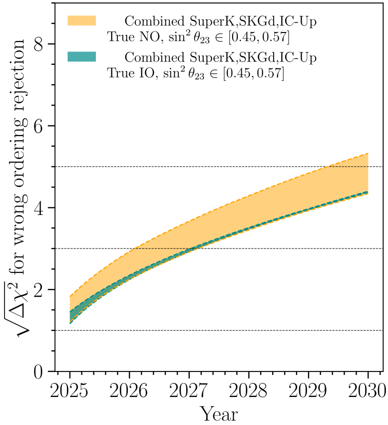
- Adding both experiments, we can resolve the **octant of** θ_{23} at 2σ
- The measurement of Δm^2_{31} is dominated by IC

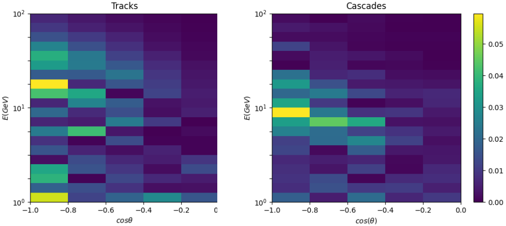


C. Argüelles, P. Fernandez, I. Martinez-Soler, M. Jin, in preparation

Combined analysis: mass ordering

- The sensitivity to the ordering is dominated by the tracks crossing the core in IC-upgrade
- We expect a sensitivity at 5σ by the end of the decade



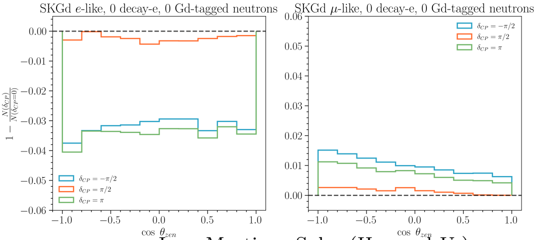


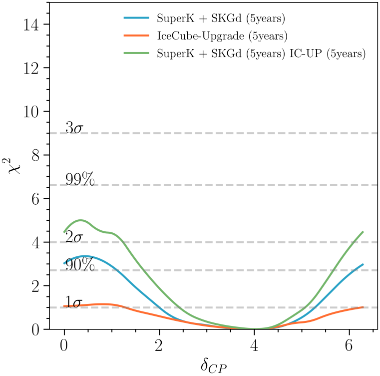
C. Argüelles, P. Fernandez, I. Martinez-Soler, M. Jin, in preparation

Combined analysis: δ_{cp}

The sensitivity to δ_{cp} is dominated by Super-kamiokande

- The samples that dominate the sensitvity are the e-like and μ-like with no neutron tagged
- By the end of the decade, we expect a sensitivity larger than 2σ just with atmospheric neutrinos





C. Argüelles, P. Fernandez, I. Martinez-Soler, M. Jin, in preparation

Conclusions

- The 3ν mixing scenario explains with a good accuracy most of the data measured in reactors, accelerators, solar and atmospheric neutrinos.
  - LBL and reactors shows a preference for NO lower than 2σ. If SK is included, the significance increases to $\sim 2.7\sigma$
  - Both octants for θ_{23} are still possible.
  - For NO, $\delta_{CP} \sim 195$. In the case of IO, the CP phase remains close to the maximal violation.
- In the future, atmospheric neutrinos can provide valuable information about the less constraints parameters:
  - The ordering can be resolved to $\sim 5\sigma$.
  - The octant of θ_{23} can be exlcuded 2σ.
  - Some values of θ_{cp} can be explored at more than 2σ.

Thank you!

Backup: Comparison between global analysis

Comparison between different global fits

	Esteban et al., [1]	Capozzi et al.,[2]	Salas et al.,[3]
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.303^{+0.01}_{-0.013}$	$0.318^{+0.16}_{-0.16}$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.455^{+0.018}_{-0.015}$	$0.574^{+0.14}_{-0.14}$
$\sin^2\theta_{13}$	$0.0222^{+0.00068}_{-0.00062}$	$0.0223^{+0.0007}_{-0.0006}$	$0.022^{+0.00069}_{-0.00069}$
δ_{CP}	194^{+52}_{-25}	234^{+41}_{-32}	218^{+38}_{-27}
$\frac{\Delta m^2_{21}}{10^{-5}\mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$7.36^{+0.16}_{-0.15}$	$7.50^{+0.22}_{-0.20}$
$\frac{\Delta m^2_{31}}{10^{-3}\mathrm{eV}^2}$	$2.515^{+0.033}_{-0.031}$	$2.458^{+0.023}_{-0.029}$	$2.55^{+0.02}_{-0.03}$

[1] I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou, JHEP 09 (2020) 178, www.nu-fit.org

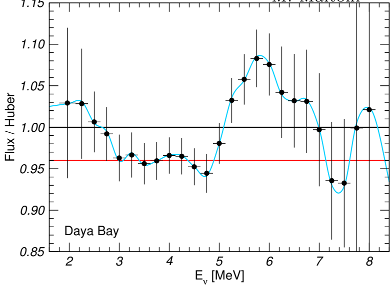
[2] F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri, and A. Palazzo, Phys.Rev.D 104 (2021) 8

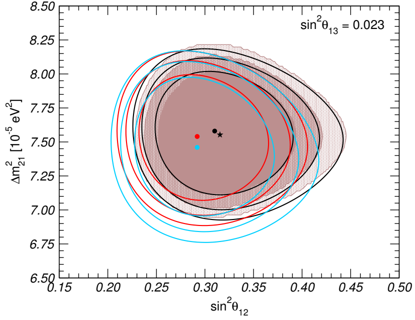
[3] P.F. de Salas, D.V. Forero, S. Gariazzo, P. Martinez-Mirave, O. Mena C.A. Ternes, M. Tortola, J.W.F. Valle, JHEP 02 (2021) 071

KamLAND and the 5 MeV excess

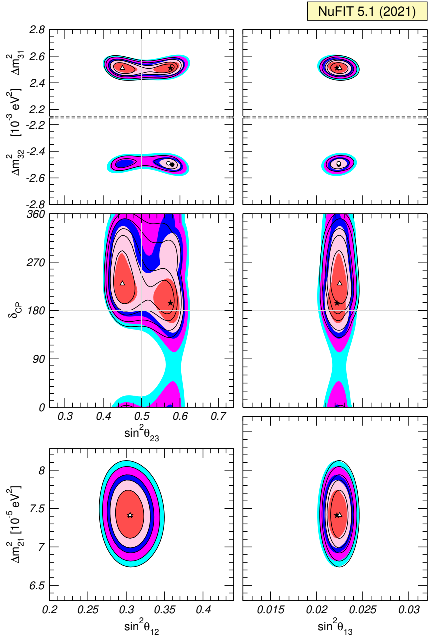
- There is no a near detector in KamLAND.
- the flux can be affected by the excess around $E_\nu \sim 5$ MeV.
- There is a small impact on the determination of Δm^2_{21}

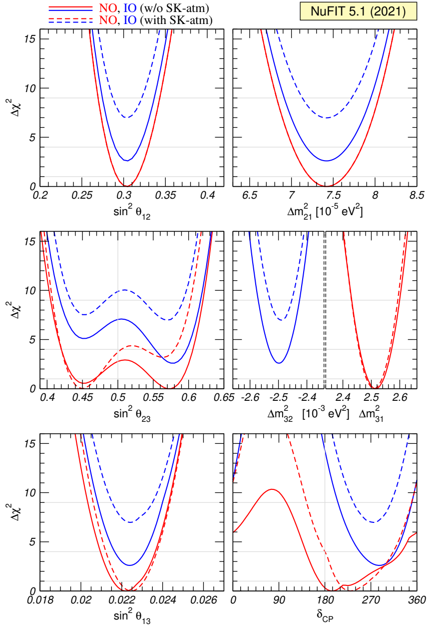
M. Maltoni





Backup: Status of the mixing parameters



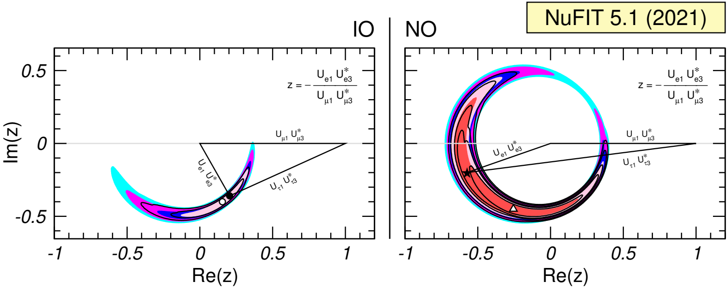


Backup: Unitarity triangle

NuFIT 5.1 (2021)

$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.232 \to 0.507 & 0.459 \to 0.694 & 0.629 \to 0.779 \\ 0.260 \to 0.526 & 0.470 \to 0.702 & 0.609 \to 0.763 \end{pmatrix}$$

$$|U|_{3\sigma}^{\text{with SK-atm}} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.144 \to 0.156 \\ 0.244 \to 0.499 & 0.505 \to 0.693 & 0.631 \to 0.768 \\ 0.272 \to 0.518 & 0.471 \to 0.669 & 0.623 \to 0.761 \end{pmatrix}$$



$$J_{CP} = \text{Im}\left[U_{\alpha i} U_{\alpha j}^* U_{\beta i} U_{\beta j}^*\right]$$