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Global status of the three-neutrino mixing

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The neutrino evolution is a long-standing problem in particle physics since many decades ago. In the 3-neutrino mixing framework, the description of the evolution depends on two different wavelengths Δm^2_{21} and Δm^2_{31}, three mixing angles θ_{12}, θ_{13}, θ_{23} and a complex phase δ_{cp} that quantifies the CP-violation in the leptonic sector. The goal of a global fit is to determine those six parameters by combining the last data set. After a brief discussion about the description of the neutrino evolution, I am going to present the main problems in the neutrino oscillation experiments and their impact on the results of the global fit. In the conclusions, I am going to present the determination of the oscillation parameters with the data up to January 2018. The results are based on NuFit 3.2 [1]

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1. Introduction

Among all the different measurements of the neutrino evolution, there are just a few examples that cannot be explained within the 3-neutrino mixing framework. In this scenario, the neutrino evolution is described by

$$i\frac{d\vec{\nu}}{dt} = \frac{1}{2E}\left[U^{\dagger}Diag(0,\Delta m^2_{21},\Delta m^2_{31})U + V_{mat}\right]\vec{\nu} \tag{1.1}$$

where $\vec{\nu} = (\nu_e, \nu_\mu, \nu_\tau)^T$, the lepton mixing matrix depens on $U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{cp})$ and $V_{mat} = \sqrt{2}G_F N_e Diag(1,0,0)$ describe the coherent interaction of neutrinos when they propagate through matter. For anti-neutrinos the evolution equation is the same up to a minus sign in the matter potential.

To have a global description of the neutrino evolution we need to measure the three mixing angles, the two mass parameters and the complex phase. Since all the experiments are not sensitive to all the parameters, we need to perform a global analysis, including all the available data sets that covers the different oscillation regimes. In the next section I will describe the main ingredients that form the global fit.

2. Reactor parameters

In nuclear reactors, $\bar{\nu}_e$ with energies around $E_\nu \sim 4$ MeV are created in fission processes. At baselines of ~ 1 km, neutrino detectors are sensitive to Δm^2_{ee} [2] and θ_{13} by measuring the number of disappeared $\bar{\nu}_e$. The configuration of the latest experiments includes also a near detector. By a rate-only analysis, those experiments have been able to establish with high precision the value of θ_{13}. The measurement of Δm^2_{ee} is done by a shape-only analysis. The non-observation of an oscillation in the near detector imposes an upper bound over θ_{13} and Δm^2_{ee}, whereas the oscillation measured in the far detector impose an lower-bound over those parameters. Recently, two anomalies have been observed in the anti-neutrino reactor flux in all the experiments. A theoretical re-evaluation of the $\bar{\nu}_e$ flux indicates a deficit in the number of events measured. In addition, there has been observed an enhancement of the predicted over the measured flux around 5 MeV. The impact of both anomalies on the determination of the mixing parameters is very small due to the near-far detector configuration.

3. Solar parameters

In the Sun are created ν_e with energies up to 20 MeV. There are several mechanisms that contribute to the solar neutrino flux, in some of them the neutrinos have a characteristic energy, that is the case of ^7Be and *pep*, in other processes, like *hep* and ^8B, ν_e can have a broader energy spectrum.

The measurement of P_{ee} using the solar neutrino flux provides the best constraints over θ_{12}. The experiments that present a better precision on that parameter are SuperK [1] and SNO [1]. In addition, the dependence of P_{ee} with the effective mixing angle in the matter (θ^m_{12}) carries also a sensitivity to Δm^2_{12}.

The best determination of the solar mass splitting is given by KamLAND [1] a reactor experiment with a baseline of ~ 180 km. The comparison on the determination of Δm^2_{12} between solar experiments and KamLAND indicates a 2σ tension [1], where KamLAND prefers higher values of the mass parameter. There are two issues that contribute to this discrepancy. The predicted turn up of P_{ee} by the LMA-MSW solution and the Δm^2_{21} measured by KamLAND it is not observed in the measurement of ^8B. The second contribution comes from the day-night asymmetry, before arriving at the detector solar neutrinos must travel through the Earth at night. The matter effects induce an asymmetry between the flux measured during the day and during the night. The differences in the flux observed by SuperK are stronger than the predicted by KamLAND.

4. Atmospheric parameters

In the atmosphere, the initial flux is composed of two flavors, muon and electron neutrinos, that are created by the collision of cosmic rays with the nucleus in the atmosphere. The flux expands from more than six orders of magnitude, from tens of MeV up to hundreds of TeV.

Atmospheric experiments have a poor energy resolution for energies lower than $E_\nu < 0.5$ GeV. For higher energies, the solar mass parameter has a subleading effect on the neutrino evolution, therefore those experiments are sensitive to the remaining four parameters (θ_{13}, θ_{23}, δ_{cp} and Δm^2_{31}). In addition, the different contribution to the total number of events of neutrinos and anti-neutrinos carry some sensitivity to the mass ordering by measuring the 1-3 mixing resonance in the mantle.

The atmospheric parameters are also determined with high precision by Long-baseline accelerator facilities. In those experiments, the energy of the neutrino fluxes ranges from ~ 0.6 GeV to ~ 7 GeV, and the baselines are of the order of hundreds of km. By measuring the number of disappeared muons ($P_{\mu\mu}$), the LBL experiments are sensitive to $\Delta m^2_{\mu\mu}$ [2] and $\sin 2\theta_{23}$, so they can distinguish between maximal mixing or not. In the appearance channel ($P_{\mu e}$), the oscillation probability depends on $\sin^2\theta_{13}$, $\sin^2\theta_{23}$, which provides sensitivity over the octant, and $\sin\delta_{cp}$.

About the determination of the atmospheric mass splitting and θ_{23}, all the experiments show a good agreement. Both octants are still allowed at 90% CL, being T2K [5] the experiment with a higher precision. About the mass ordering, SuperK [6] and T2K, shows a preference for normal ordering with a significance of 2σ each one. About the CP-violation phase, T2K, SuperK (for both mass orderings) and NOνA [7] (only for invert ordering) show a preference for maximal CP violation ($\delta \sim 270$). For normal ordering, NOνA has a preference for δ_{cp} close to CP-conserving.

5. Conclusions

A combination of the relevant data sets provides a global picture of the neutrino evolution. In this talk, I have presented the main ingredients that constitute a global analysis. In the Fig. 1, I show the bounds on the parameters that determine the neutrino evolution, obtained by a projection of the global analysis NuFIT 3.2 [1], which includes the latest data until January 2018. The precision over some parameters reach the percent level, like θ_{13} and $|\Delta m^2_{31}|$. The least known oscillation parameters are the CP-violation phase, the octant of θ_{23} and the mass ordering. Comparing this results with the other global analysis [**?**, 4], they show a very good agreement.

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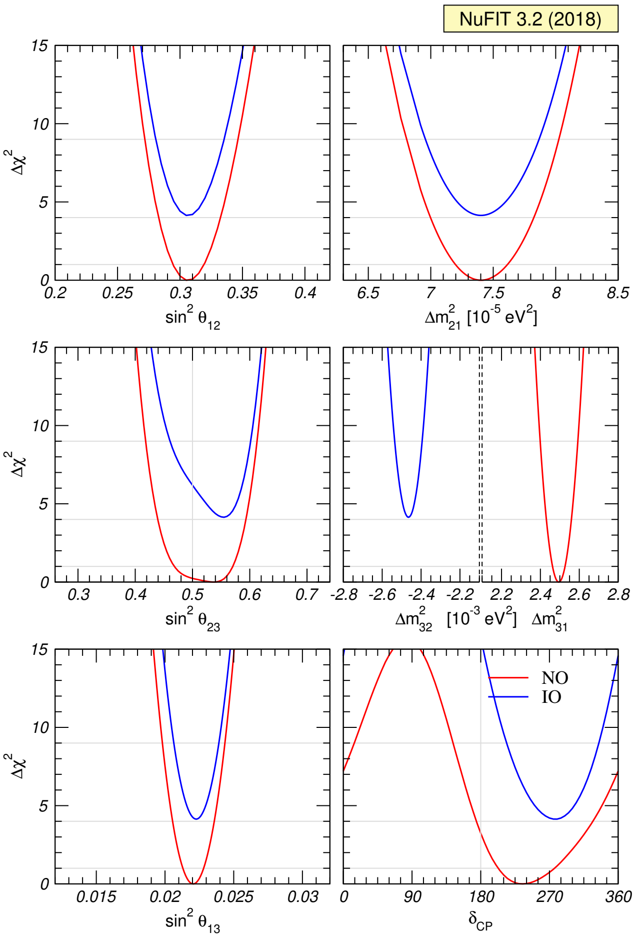

Figure 1: Global analysis including the of the oscillation data until January 2018 [1]

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