Status of Three Neutrino Mass and Mixig Parameters

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Abstract

We present current constraints on neutrino mass and mixing parameters in the context of the three-neutrino framework. We use data from both oscillation and non-oscillation experiments.

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1. INTRODUCTION

Almost all data from neutrino oscillation experiments can be accomodated in a three-neutrino framework [1], where the flavor eigenstates ν_α ($\alpha = e, \mu, \tau$) are a superposition of the mass eigenstates m_i ($i = 1, 2, 3$) through the three mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$ and a CP phase δ. Neutrino oscillation are driven by two mass differences: $\delta m^2 = m_2^2 - m_1^2 > 0$ and $\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. If $\Delta m^2 > 0$ we have normal mass ordering (NO), whereas we have inverted ordering (IO) when $\Delta m^2 < 0$. Assuming neutrinos are Majorana particles, the mixing matrix contains also two additional Majorana phases $\phi_{1,2}$. Finally, the absolute neutrino mass scale can be parametrised as the sum of the mass eigenstates $\Sigma = m_1 + m_2 + m_3$, accessible through cosmological observations, or as the effective Majorana mass $m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$, accessible through neutrinoless double beta decay ($0\nu\beta\beta$) searches, or as the effective mass $m_\beta = \sum_i |U_{ei}|^2 m_i^2$ measured in β decays.

The mixing angles and the mass differences are known with a precision better than 5%. The value of δ and the nature of the mass ordering are partially unknown, even though very recent data begins to constrain them at 3σ level. The Majorana phases are completely unknown, since there is no experimental evidence in support of the Majorana nature of neutrinos. Concerning the absolute mass scale, there are only upper limits at O(0.1) eV. In such a context, global analyses are a powerful tool to test the consistency of all available data, to get the most stringent bounds on the known parameters and to obtain information on those that are not well constrained by single experiments.

In this contribution we present the results of a recent global analysis of oscillation and non-oscillation data (as of summer 2019). In particular, with respect to our previous analysis [2], we add the latest result from T2K [3], NOνA [4], and SBL reactor experiments (Daya Bay and RENO) [5, 6]. We also provide an update of non-oscillation results, focusing on the most stringent constraints from cosmology. A remark is in order: all results will be presented in terms of standard deviations $N\sigma$ from a local or global χ^2 minimum, $N\sigma = \sqrt{\Delta\chi^2}$.

2. GLOBAL ANALYSIS OF OSCILLATION DATA

Figure 1 shows the constraints on all oscillation parameters for both NO and IO, obtained by combining all the available oscillation data. The χ^2 is minimized with respect to the global minimum in NO: $\Delta\chi^2 = \chi^2 - \chi^2_{\min}(\text{NO})$. This is the reason why the minimum χ^2 in NO lies exactly at $N\sigma = 0$, whereas in IO it corresponds to $\sim 3\sigma$. This represents the first evidence in favour of normal mass ordering. Concerning δ, the CP-conserving value $\delta = 0$ (or 2π) is disfavored at 2.6σ; the value $\delta = \pi$ is disfavored at 1.8σ. If we define the uncertainty on each parameter as 1/6 of the allowed 3σ region we obtain a 15% error on δ. Finally, we find an overall preference for the second octant of θ_{23} (i.e. $\theta_{23} > \pi/4$), although both octants are allowed at 2σ.

In order to fully understand the synergy of different class of experiments, it is helpful to look at parameters correlations for increasingly rich data sets. We start by combining solar, KamLAND and long baseline accelerator (LBL Acc.) data, which provides a good measurement of mixing angles and mass square differences, and also a hints in favor of $\sin\delta = 0$ and of normal ordering. We then strongly constrain θ_{13} using short baseline (SBL) reactor data, which enhances the hints obtained in the previous data set. Finally, we combine atmospheric neutrino data, sensitive to all parameters.

Figure 2 shows the allowed regions in the plane charted by $(\sin^2\theta_{23}, \sin^2\theta_{13})$, for both NO (upper row) and IO (lower row). From left to right each panel refers to an increasingly rich data set, as explained in the previous paragraph. The oscillation amplitude for the $\nu_\mu \to \nu_e$ channel in LBL experiments is proportional to $\sin^2\theta_{23}\sin^2\theta_{13}$, which induces an anticorrelation between these two parameters, visible in the left panels. Subleading effects sensitive to sign(Δm^2) generate a difference in the allowed θ_{13} ranges for NO and IO, where the latter ones are higher. The middle panels show that current accelerator and SBL reactor constraints on θ_{13}

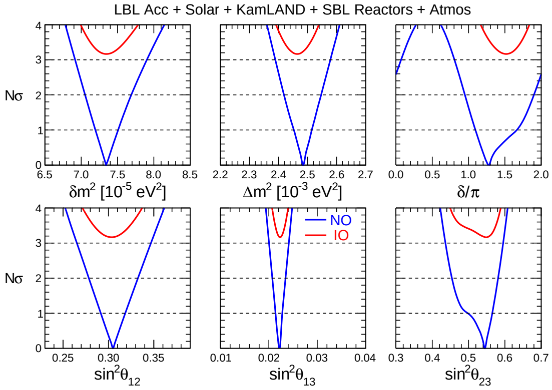

FIGURE 1: Bounds on the δm^2, $|\Delta m^2|$, $\sin^2\theta_{ij}$, and δ, for NO (blue) and IO (red), in terms of $N\sigma = \sqrt{\Delta\chi^2}$ from the best fit.

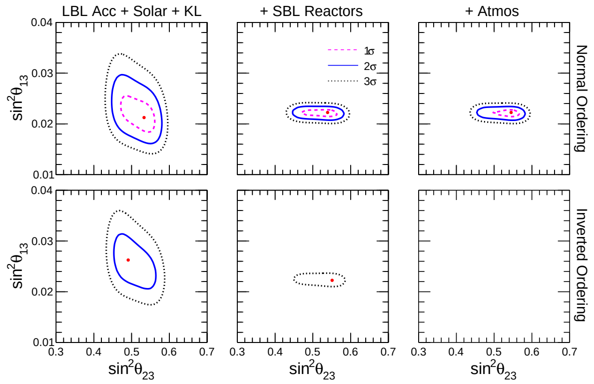

FIGURE 2: Covariance plot for the $(\sin^2\theta_{13}, \sin^2\theta_{23})$ parameters and for increasingly rich data sets.

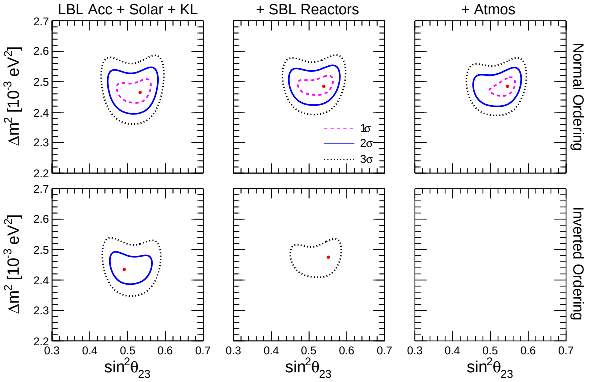

FIGURE 3: Covariance of the $(\sin^2\theta_{23}, \Delta m^2)$ parameters.

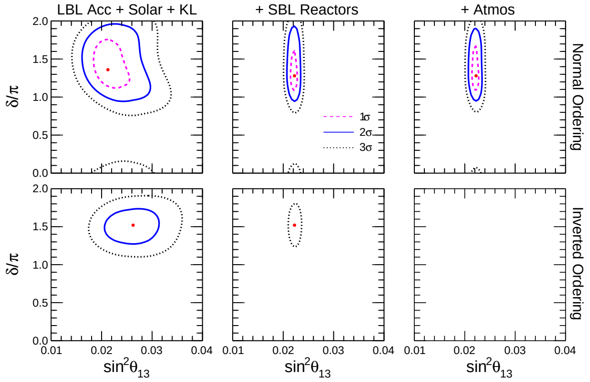

FIGURE 4: Covariance of the $(\sin^2\theta_{13}, \delta)$ parameters.

are more consistent in NO than in IO. This fact provides the increment of the $\Delta\chi^2$ between NO and IO. Atmospheric neutrino data is intrinsically sensitive to the mass ordering and provide an independent increment in $\Delta\chi^2$. Thus, the overall 3σ hint in favor of NO emerges consistently for increasingly rich data sets and thus deserves attention. Taken at face value, a 3σ rejection of IO would imply that the only relevant scenario is NO. However, caution should be exercised at this stage, since the value $\Delta\chi^2 \sim 9$ derives from two main contributions of comparable size but with rather different origin. Regarding θ_{23}, the constraints on θ_{13} from short baseline reactors induce a preference for the second octant in both orderings. Nevertheless, the octant ambiguity remains unresolved at 2σ level in both NO and IO.

The covariance of $(\sin^2\theta_{23}, \Delta m^2)$ is displayed in Fig. 3. It is remarkable that in NO all data sets give basically the same best fit value of Δm^2. On the other hand, in IO the constraints from SBL reactors are compatible with the allowed regions in the left panels only at 2σ. Therefore, the increase in $\Delta\chi^2$ between NO and IO is not only due to a different best fit of $\sin^2\theta_{13}$, but also of Δm^2. Note that, in general, at $\theta_{23} = \pi/4$ one gets the lowest allowed values of Δm^2, while for either octants the preferred values tend to increase.

The covariance in the plane $(\sin^2\theta_{13}, \delta)$ is shown in Fig. 4. A strong correlation between these two parameters is observed for NO in the left panels, which stems from the subleading terms in the $\nu_\mu \to \nu_e$ oscillation probability of LBL accelerator data. The same correlation induce a slight improvement in the precision of δ when introducing the strong constraints on θ_{13} from short baseline reactor data. A further reduction of the uncertainty is obtained with atmospheric data, which have an intrinsic sensitivity to δ, especially in the sub-GeV energy range. In NO there is also a slight decrease of δ from left to middle panels, correlated to the increase of θ_{13}. However, the best fit of δ remains almost unchanged when considering increasingly rich data sets.

3. CONSTRAINTS FROM NON-OSCILLATION DATA

We follow the same 3ν (frequentist) methodology as in [7], based on the construction of χ^2 functions for m_β, $m_{\beta\beta}$ and Σ, to be added to the χ^2 function coming from the previous oscillation data analysis, marginalized over all the known and unknown mass-mixing parameters and phases.

Fig. 5 shows the results of a combined 3ν analysis of oscillation and non-oscillation data in the plane charted by $(\Sigma, m_{\beta\beta})$. The left, central and right panel correspond to the "aggressive","default" and "conservative" cosmological data sets, labelled as #6, #3 and #9 in [7], respectively. Allowed regions are always present in IO, since non-oscillation data do not yet discriminate IO from NO at $> 2\sigma$ in any of the cases that we have considered. Of course, the IO regions would disappear by adding also the indications in

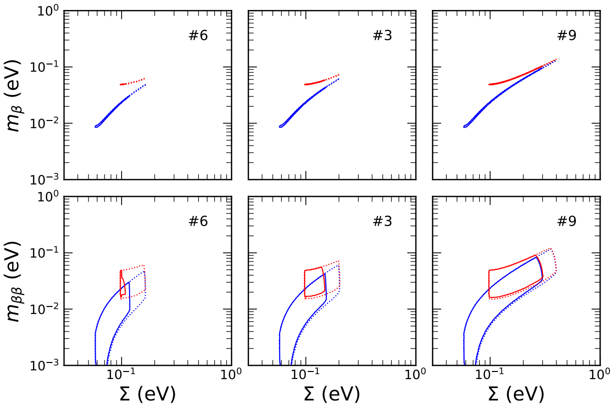

FIGURE 5: Combined 3ν analysis of oscillation and non-oscillation data, in the planes charted by $(\Sigma, m_{\beta\beta})$. The allowed bands correspond to $N\sigma = 2$ (solid) and $N\sigma = 3$ (dotted), for both NO (blue) and IO (red), taken as separate cases. If the $\Delta\chi^2$ between IO and NO were included, the IO bands would disappear. The pairs of panels on the left, in the middle and on the right correspond to the “aggressive”, “default” and “conservative” cosmological data sets considered in [7], respectively.

favor of NO derived from oscillation data. The final 2σ upper limits on Σ are the following:

$$\begin{aligned} \Sigma &< 0.15 \quad (\text{default})\,, \\ \Sigma &< 0.12 - 0.69 \quad (\text{range}), \end{aligned}$$

where we have singled out our default case #3, and reported the whole range spanned by the different cosmological data sets considered in [7].

4. CONCLUSIONS

We have presented a global analysis of data coming from neutrino oscillation and non oscillation data, within the standard framework including three massive and mixed neutrinos. The main results of this work from the analysis of oscillation searches are summarized graphically in Fig. 1. A preference for NO emerges at 3σ level as a combination of hints from different class of experiments. The Dirac CP phase δ is constrained within $\sim 15\%$ ($\sim 9\%$) uncertainty in NO (IO) around nearly-maximal CP-violating values. The octant of θ_{23} is still undetermined. Merging oscillation and non-oscillation data enhance the indications in favor of NO. The overall indication in favor of NO can be summarized as follows in terms of standard deviation units:

$$N\sigma\,(\text{IO} - \text{NO}) = 3.5 \quad (\text{default})\,, \tag{1}$$

$$N\sigma\,(\text{IO} - \text{NO}) = 3.2 - 3.7 \quad (\text{range})\,. \tag{2}$$

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