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Oscillation Parameters, Present: Session Summary

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We provide a brief summary of the parallel session I, "Oscillation Parameters: Present" at the Neutrino Oscillation Workshop 2022. The topics discussed in this session are the current status of neutrino mass-mixing parameters in the three neutrino framework, both from the experimental and the model building point of view, as well as the recent constraints on the existence of a light sterile neutrino. Special importance has been given to the role of systematics and of new tools adopted in data analysis, such as machine learning.

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1. Introduction

In the context of a three-neutrino framework there are seven oscillation parameters: three mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and one phase δ_{CP}, which are the building blocks of the PMNS mixing matrix, two squared mass differences $\Delta m^2_{21} = m^2_2 - m^2_1$ and $\Delta m^2_{31} = m^2_3 - m^2_1$, and the mass ordering (MO), which is normal (inverted) if Δm^2_{31} is positive (negative). The mixing angles provide the amplitude of the oscillation probability, whereas the mass differences give the energy dependence for a fixed propagation distance. Neutrino oscillations have been studied by a plethora of experiments using both natural and artificial sources. We have now entered in the precision era since all parameters, apart from δ_{CP} and the MO, are known with a precision better than 5%. However, with increasing precision a more careful scrutiny is required. Indeed, systematics uncertainties and, more generally, how statistical analyses are performed have now a crucial role. In this context, we included in this session an update of the experimental results, a first glimpse of the ongoing joint analysis of T2K and Super-Kamiokande and a review on the role of machine learning techniques. Considering the still standing anomalies in very short baseline experiments, the latest results on the search for a light sterile neutrino were also reviewed. From a theoretical point of view, the most compelling topics are: a combined phenomenological analysis of all oscillation data, the connection between the solar neutrino and abundance problem, the origin of the observed structure of the mixing matrix and neutrino masses and the modelling of neutrino interactions with nuclei.

2. Experimental results

We started the session with an overview on Daya Bay history and achievements [1], reporting results obtained with the full data set (3158 days). Thanks to energy calibration and background reduction improvements, the best fit values of oscillation parameters are: $\sin^2 2\theta_{13}$=0.0853 ± 0.0024 and $\Delta m^2_{23} = +(2.454 \pm 0.057) \times 10^{-3}$ eV^2 assuming Normal Ordering. The first evidence (6.2σ) of reactor antineutrinos with energy above 10 MeV was also reported, representing another benchmark for a comparison with theory expectations. The joint analysis with PROSPECT shows an agreement for the prompt energy spectrum and a joint Daya Bay/MINOS+ sterile neutrino search was reported. Despite the detector being decommissioned, there is still work in progress, including an analysis using inverse β decay events from neutron capture on Hydrogen.

We heard news from atmospheric neutrino oscillation studies of IceCube/DeepCore (IC/DC) [2], mostly sensitive to Δm^2_{31} and θ_{23}. After an overview of the analysis technique, results obtained using a 3 year samples were presented, as well as the expected sensitivity with an 8 year sample. Current results are in good agreement with measurements at long-baseline experiments, while IC/DC reports the best measurement of the ν_τ flux normalisation. The Beyond Standard Model (BSM) physics program of IC/DC was also mentioned, including the search for Non Standard Interaction (NSI) and for unstable sterile neutrinos. The talk concludes advertising incoming analysis results with the 8 year sample.

Atmospheric neutrinos have been discussed in the context of a joint T2K/Super-Kamiokande (SK) analysis [3]. T2K is particularly sensitive to δ_{CP}, while atmospheric neutrinos in SK, experiencing large matter effects, are sensitive to the mass Ordering. Combining their data, the experiments aim at improving their sensitivity to both δ_{CP} and MO, by breaking intrinsic degeneracies. Details were given about the treatment of flux, neutrino interaction and detector systematics that will be used in the joint analysis. Considering the present statistics, sensitivity plots show an improved sensitivity to MO (about 2σ) for both orderings, as well as an improved sensitivity to exclude CP conservation also for δ_{CP} for values in the [0,π] range. In particular, CP conservation can be excluded at $\sim 3\sigma$ if $\delta_{CP} = -\pi/2$ and at $\sim 2\sigma$ if $\delta_{CP} = +\pi/2$. Results from this joint analysis are expected in 2023.

MO and δ_{CP} were also discussed by NOvA [4] that presented results obtained with an alternative analysis with respect to the previously used frequentist approach. They use the same data set as for the 2020 analysis, that is 13.6×10^{20} POT in ν mode and 12.5×10^{20} POT in $\overline{\nu}$ mode, and exactly the same procedure for the extrapolation from the near to the far detector. Results obtained with the Bayesian approach are in clear agreement with those obtained in the frequentist analysis: $\delta_{CP} = \pi/2$ is rejected at 3σ for inverted ordering and the upper octant for θ_{23} as well as normal ordering are preferred (Bayes factor ~ 2). NOvA also presented its first measurement of $\sin^2 2\theta_{13} = 0.85^{+0.02}_{-0.016}$, well compatible with reactor results. Finally, the collaboration announced that a joint T2K/NOvA analysis will soon be public.

The uncertainties on neutrino cross sections are the dominant source of systematics for both T2K and NOvA experiments and need to be reduced in view of future Hyper-Kamiokande (HK) and DUNE. S. Dolan gave an overview of the current status of neutrino generators and data/model (dis-) agreement [5], underlying the necessity to properly model the cross section energy dependence, the smearing of the reconstructed neutrino energy and the difference between ν_μ and ν_e cross sections. As an exemple, concerning the energy dependence, models differ by 5-10% in the region of interest for DUNE and HK but this can be mitigated by measuring neutrino cross section at different energies, for instance at different off-axis angles. To carefully prepare the HK and DUNE era, a continued collaboration between experimentalists, theorists and generator builders is crucial.

Concerning solar neutrinos, Borexino presented its latest results [6]. Thanks to the extreme radiopurity of the scintillator and to accurate calibration campaigns, Borexino was able to provide not only the first direct measurement of ^{7}Be neutrinos, but also the first direct measurements of pep and pp neutrinos. Another milestone was the first detection of CNO neutrinos, first reported in 2020, that was possible through a thermal insulation of the detector that allowed to constrain the background coming from ^{210}Bi. The detector was dismantled at the end of 2021 and the most updated Borexino results, using the full "Phase III" data set (2017-2021), were presented. With respect to the 2020 results, the precision on the CNO flux has improved of almost a factor two, bringing to the value $\Phi_{\text{CNO}} = 6.6^{+2.0}_{-0.9} \times 10^8$ cm^{-2}s^{-1} with a corresponding significance of 7σ. As explained in Sec. 3, measuring CNO neutrinos is a way to discriminate between the "high" (HZ) and "low" (LZ) solar metallicity models. Recent results from Borexino disfavour the LZ models at $\sim 3\sigma$ level. To conclude, the first demonstration of solar neutrinos directionality in a liquid scintillator detector was presented, as well as an independent measurement of the Earth orbit eccentricity made with ^{7}Be neutrinos.

Despite oscillation data strongly favors a three-neutrino scenario, there are several unsolved anomalies. These are the ν_e appearance excess seen by LSND [7] and MiniBooNE [8], known as Low Energy Excess (LEE), the ν_e deficit in gallium detector calibrations [9], known as Gallium anomaly (GA), and the Reactor Antineutrino Anomaly (RAA) [10], where a deficit of reactor $\overline{\nu}_e$ is seen with respect to model predictions. In this session there were talks by current experiments investigating these tensions. One of these is MicroBooNE [11], which has run for 15 years (2007-2022) with the main goal of testing the MiniBooNE anomaly [8]. MicroBooNE exploits the same neutrino beam as MiniBooNE at a very similar baseline, but with a different technology, and it is able to better distinguish electron like tracks from photons. MicroBooNE has checked two possible origins of the LEE: from single photon background ($\Delta \to N\gamma$) and from single electron background (enhancement of the intrinsic ν_e background in the beam). Both possibilities are ruled out. LEE search results have also been reinterpreted under a sterile neutrino oscillation hypothesis, combining ν_μ disappearance with both ν_e appearance and disappearance, showing no evidence for sterile neutrino oscillations.

The DANSS collaboration has presented its latest results [13] with the aim of studying the RAA by detecting $\bar{\nu}_e$. With a plastic scintillator based detector that, placed below a reactor, can move vertically in three different positions, DANSS can scan the possible short baseline oscillations induced by a light sterile. The experiment benefits from a new energy calibration campaign. The positron spectrum is compared with expectations based on the Huber-Mueller (H-M) model, and to spectra from other reactor experiments (RENO or Daya Bay), showing a dependence of the energy spectrum on the reactor fuel composition. The best fit point from the GA+RAA is ruled out at 5σ, although the existence of a sterile neutrino is still possible at $\sim 2\sigma$. The DANSS collaboration is now working at an upgrade with the aim of improving the energy resolution by a factor ~3.

The PROSPECT experiment [14] uses instead liquid scintillator contained in bars with a double PMT readout. Events are usually reconstructed via the so-called double end event reconstruction, that exploits the waveform reconstruction from both the PMTs of a bar. Due to leakage problems of some PMT housing, a new Single Ended Event Reconstruction has been developed in order to recover events from bars with a single working PMT. The new analysis will benefit from several improvements, including the increase of statistics ($\times 1.2$) and of the Signal/Background ratio. The framework is ready and includes the possibility for a multi-period spectrum analysis, as well as combined analysis with other experiments.

STEREO presented its final results [15]. The detector, made of 6 independent cells of liquid scintillator (Gd loaded), allows to test the RAA or GA using a research reactor. Data were collected from the end of 2017 until the end of 2020 and the analysis realized with the full data set was presented. Among the improvements of this new analysis we notice the use of an improved version of the FIFRELIN code [16] for the γ cascade model for the neutron capture on Gd. Oscillation results exlude most of the RAA allowed region at 95% (for $\Delta m^2_{41} < 4\,\mathrm{eV}^2$) and the RAA best fit point is excluded at $\sim 4\sigma$. STEREO does not exclude the existence of a sterile neutrino (p-value = 0.54). STEREO also provided the most precise measurement of ^{235}U $\overline{\nu}_e$ spectrum, confirming a 5% deficit with respect to the commonly used H-M predictions, while encouraging for a test of nuclear data thanks to reactor antineutrinos.

3. Theoretical results

In the context of the three neutrino framework, there are three phenomenological groups [17] performing independent analyses combining all available oscillation data. These are known as global analyses. Exploiting correlation among different oscillation parameters, they provide the most stringent constraints, as well as new information on those that are still unknown. A review

PoS(NOW2022)020

of the analysis performed by the Valencia group was given by C. Ternes [18]. The experimental results discussed in this conference were not included in the analysis, but their impact should be marginal. The main outcome is that all oscillation parameters are known with a precision better than 5%, apart from δ_{CP}. There is a preference for the second octant of θ_{23}, i.e. $\theta_{23} > \frac{\pi}{4}$, at 2σ, and for normal mass ordering at 2.5σ. The measured values of Δm^2_{21} from solar experiments and KamLAND are consistent at 1.1σ. The best fit values of δ_{CP} from NOνA and T2K have a 2σ tension in normal ordering. Finally, Ternes mentioned that DUNE, Hyper-Kamiokande, T2HK and ORCA will improve considerably current constraints on θ_{23} and δ_{CP}, as well as on the MO. On the other hand JUNO will reach sub-percent precision on $\Delta m^2_{21,31}$ and θ_{12}, whereas in combination with current data it can improve the preference of normal ordering to 5σ, assuming this is indeed the mass ordering realized in nature. More details on future sensitivities were given in Session II.

Entering the precision era of neutrino oscillations was possible also thanks to an impressive development of data analyses, which has been partially driven by the use of machine learning techniques. A review talk on the role of these techniques was given by F. Psihas [20]. Machine learning consists in algorithms whose performance for a given task improves with experience. Each algorithm is composed by a set of nodes, each equipped with an activation function and some weights, which, given some input, set an output value. The accuracy of the output is assessed through a loss function, which is minimized by changing the action of the nodes in order to reproduce what is called a training sample. The “trained" algorithm can then be applied to data. These algorithms are commonly used to improve signal to background ratio. This is the case in the analysis of NOνA, with an increase of detection efficiency of 10% with respect to old procedures. Another example is Borexino, where an algorithm exploits the scintillation time-decay differences from alpha and beta-like events to improve the tagging of ^{210}Po α-decay, which is essential to measure the CNO flux. Despite the adavantages, machine learning techniques have to face some issues. The choice of an appropriate training sample is crucial to avoid bias and model dependence. In this regard, using training samples that are relatively well understood (test beams, known sources, etc.) should be common practice. Furthermore, to minimize the chance of missing signatures of new physics one should use unsupervised learning to identify missing physics and unexpected learned features.

The results of a global analysis represent an important input for studies with the purpose of understanding the origin of the structure of the neutrino mixing matrix and masses. A review on the state of the art has been provided by A. Titov [21]. The standard approach consists in imposing a flavour symmetry at high energy, which is then broken to residual symmetries for the mass matrices of both charged lepton and neutrino sectors. A significant research activity has been devoted to non-abelian discrete symmetries, such as A_4, S_4, A_5, etc. Focusing on S_4, Titov showed that in its original form this model predicts a tri-bimaximal structure for the PMNS matrix ($\sin^2\theta_{13} = 0$, $\sin^2\theta_{12} = \frac{1}{3}$, $\sin^2\theta_{23} = \frac{1}{2}$). A vanishing value of θ_{13} is definitely excluded by current global analyses, but the use of S_4 can be reconciled with data by adopting some variants of the original model. Future measurements by ESSνSB, T2HK, DUNE, and JUNO have the potential to disproof a large number of these models. The second part of the talk was dedicated to the use of modular symmetry $\Gamma = SL(2,\mathbb{Z})$. This symmetry is common in superstring theory. For instance a torus obtained through compactification is described by the modulus τ, and the modular group transforms the modulus non-trivially. Moreover, the modular group includes finite subgroups such as the non-abelian discrete symmetries described before. Another strength of modular symmetry is that Yukawa couplings are functions of the modulus, so they transform non trivially under the symmetry. This means that this approach is able not only to explain the structure of the PMNS matrix, but also neutrino masses. Additionally, this method does not require the presence of numerous flavon fields to implement a symmetry breaking. However, we are still far from a complete theory of flavour symmetries. Despite the advantages of modular invariance, more effort is needed for a robust application to the flavour problem.

The talk of Francesco Villante [22] described the role of the measurement of the CNO neutrino flux from Borexino in solving long-standing solar abundance problem. This problem consists in the discrepancy between the prediction of solar models based on photospheric (low) metellacities derived from 3D models and the observations from helioseismology. Agreement is restored if higher metallicities derived from older 1D models are considered. Recently a new 3D determination of the photospheric composition has been performed [23], which prefers again a low metallicity and leads to a solar model in agreement with helioseismology. Although this might seem a clear indication of the robustness of high metallicity, Villante is rather cautious. Indeed, the degeneracy between opacity and composition is treated in a simplified way in modern solar models, so the current situation might change when a more precise approach is employed. A possible solution might come from a direct detection of solar neutrinos produced in the CNO chain. As Villante showed, one can find a linear combination of this flux and the (well measured) one from ^{8}B decays which depends only on the composition and not on the opacity. Borexino has now a 7σ evidence of the CNO flux and a 3σ hint in favor of low metallicity. Nevertheless, in the future the uncertainties on nuclear cross sections must be reduced in order to have a solution of the abundance problem from neutrinos.

References

[1] Y. B. Hsiung, *Reactor neutrino oscillations in Daya Bay*, talk given at NOW 2022.

[2] J. V. Maed, *Atmospheric neutrino oscillations in IceCUBE-Deepcore*, talk given at NOW 2022.

[3] J. Xia, *T2K-SK Joint Neutrino Oscillation Sensitivity*, talk given at NOW 2022.

[4] J. M. Canceller, *3-flavour results with NOvA*, talk given at NOW 2022.

[5] S. Dolan, *Uncertainties in modelling neutrino interactions for oscillation experiments*, talk given at NOW 2022. arXiv:2207.02086.

[6] N. Rossi, *Update of the results on solar neutrino physics exploiting the most recent Borexino data*, talk given at NOW 2022.

[7] LSND Collaboration, Phys. Rev. D 64, 112007 (2001).

[8] MiniBooNE Collaboration, Phys. Rev. Lett. 121, 221801 (2018).

[9] SAGE Collaboration, Phys. Rev. C 80, 015807 (2009).

[10] G. Mention *et al.*, Phys. Rev. D 83, 073006 (2011).

[11] G. Karagiorgi, *Overview of MicroBooNE results*, talk given at NOW 2022.

[12] R. Acciarri *et al.*, arXiv:1503.01520.

[13] I. Alekseev, *Recent results from DANSS*, talk given at NOW 2022.

[14] C. Roca Catala, *New analysis opportunities with PROSPECT*, talk given at NOW 2022.

[15] P. Del Amo Sanchez, *STEREO final results*, talk given at NOW 2022.

[16] H. Almaz *et al.*, arXiv:2207.10918.

[17] M. C. Gonzalez-Garcia *et al.* Universe **7** (2021) no.12, 459; P. F. de Salas *et al.* JHEP **02** (2021), 071; F. Capozzi *et al.* Phys. Rev. D **104** (2021) no.8, 083031

[18] C. A. Ternes, *Global analysis of neutrino oscillation experiments*, talk given at NOW 2022.

[19] Y. Koshio, Talk at Neutrino 2022, https://doi.org/10.5281/zenodo.6695966

[20] F. Psihas, *Role of machine learning in neutrino physics*, talk given at NOW 2022.

[21] A. Titov, *Theoretical models on the structure of nu mixing matrix*, talk given at NOW 2022.

[22] F. L. Villante, *New SSM vs helioseismic and solar neutrino data*, talk given at NOW 2022.

[23] E. Magg *et al.*, 2022, A&A, 661, A140.