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3-flavour results with NOvA

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The NOvA collaboration has presented the 3-flavour oscillation results using a frequentist approach before [1]. In this contribution, we present the results obtained with a bayesian approach. The conclusions with respect to the frequentist approach are unchanged, that is, the upper octant of θ_{23} is preferred, $\delta_{\text{CP}} = \frac{3\pi}{2}$ is not preferred at the 2σ level with normal ordering and $\delta_{\text{CP}} = \frac{\pi}{2}$ excluded at 3σ with inverted ordering. As a novelty of the bayesian analysis, the results obtained when θ_{13} is left as a free parameter in the fit are also.

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1. Introduction

NOvA is a long baseline neutrino accelerator experiment [3, 4]. Neutrinos come from the Fermilab NuMI beam and go through a Near Detector 1 km away from the source reaching the Far Detector 810 km away in Minnesota. The Far Detector is a 40 kton detector, with alternating vertical and horizontal PVC cells filled with liquid scintillator. The Near Detector is a similar detector but smaller in size. The structure of the detectors allows to perform a 3D reconstruction, see Figure 1. After hit clustering and reconstruction, a neural network is used to classify invididual neutrino candidate events into ν_e CC, ν_μ CC, NC or cosmogenic backgrounds.

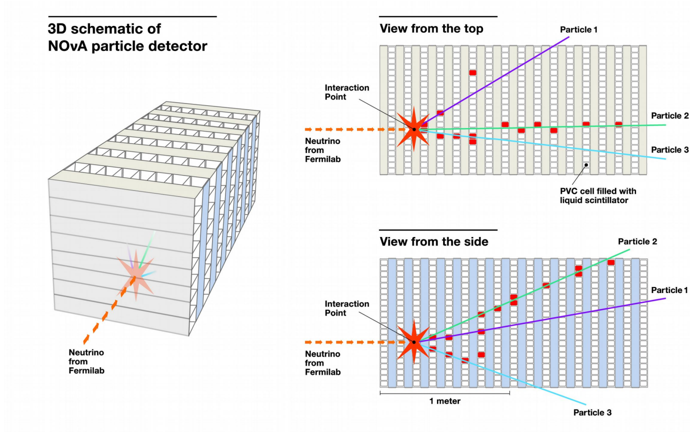

Figure 1: Schematic diagram of the NOvA detectors (left) and how the neutrino interactions are seen in the detectors (right).

The 3-flavour results in NOvA are based on a frequestist approach [1]. In this contribution the results obtained with a bayesian approach are presented. This results were presented in Neutrino 2022 [2] for the first time and a paper with all the details is in preparation.

2. Bayesian methods

Bayesian methods are based on Bayes' rule, see Figure 2. Bayes' rule gives us a way of estimating the posterior probability density of a set of parameters $\vec{\theta}$ given a set of observations $\vec{x}$, as long as we can predict the likelihood of the observations given the parameters. The results depend on the prior, which is an assumption about the plausibility of the parameters $\vec{\theta}$.

For approximating the posterior probability densitiy, a Markov Chain Monte Carlo (MCMC) method is used. In this iterative method, samples are taken proportionally to their probability density. The posterior can then be approximated to any desired precision by collecting a sufficient number of steps. Two different methods were used for obtaining the bayesian results: Metropolis-Hastings and Hamiltonian MCMC. In Metropolis-Hastings [5, 6], at each step there is a proposal which can be accepted or rejected, see Figure 2. In Hamiltonian MCMC (see [7] for an introduction) momentum is added to the minimization process. The two methos were developed independently and were used to cross check the results, that are very similar.

Likelihood → Prior

$$\underbrace{P(\vec{\theta}|\vec{x})}_{\text{Posterior}} = \frac{P(\vec{x}|\vec{\theta}) \cdot P(\vec{\theta})}{\underbrace{P(\vec{x})}_{\text{Evidence}}}$$

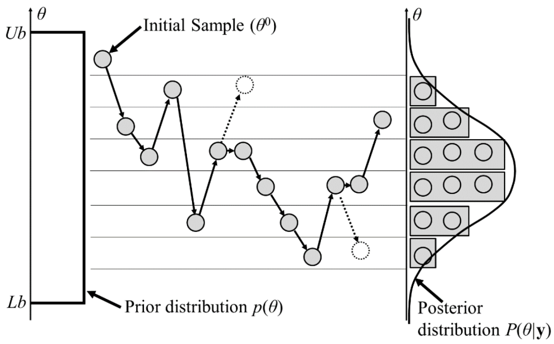

Figure 2: Left: Bayes' rule. Right: Diagram for the Metropolis-HastingsMarkov Chain Monte Carlo (MCMC).

3. Results

The results obtained using the value of θ_{13} that appears in the PDG can be found in Figure 3. The conclusions are not changed with respect to the 2020 analysis: $\delta_{\mathrm{CP}} = \frac{3\pi}{2}$ is not preferred at the 2σ level with normal ordering, $\delta_{\mathrm{CP}} = \frac{\pi}{2}$ is excluded at 3σ with inverted ordering and the upper octant of θ_{23} is preferred. In the bayesian results we use σ as a way of denoting the probability covered by the posterior (2σ for 95% and so on) that is different from the usual σ notation in the frequentist case.

Results obtained for $\sin^2 2\theta_{13}$ are also presented for the first time for NOvA in Figure 4. Unlike the frequentist case and in the previous results, θ_{13} is not constrained anymore. From the inclined ellipse shape in Figure 4, we can deduce that larger θ_{13} favour the lower octant and small θ_{13} favour lower octant. Results agree with reactor experiments and the value of $\sin^2 2\theta_{13}$ where the posterior probability density is maximized is $\sin^2 2\theta_{13} = 0.085^{+0.020}_{-0.016}$.

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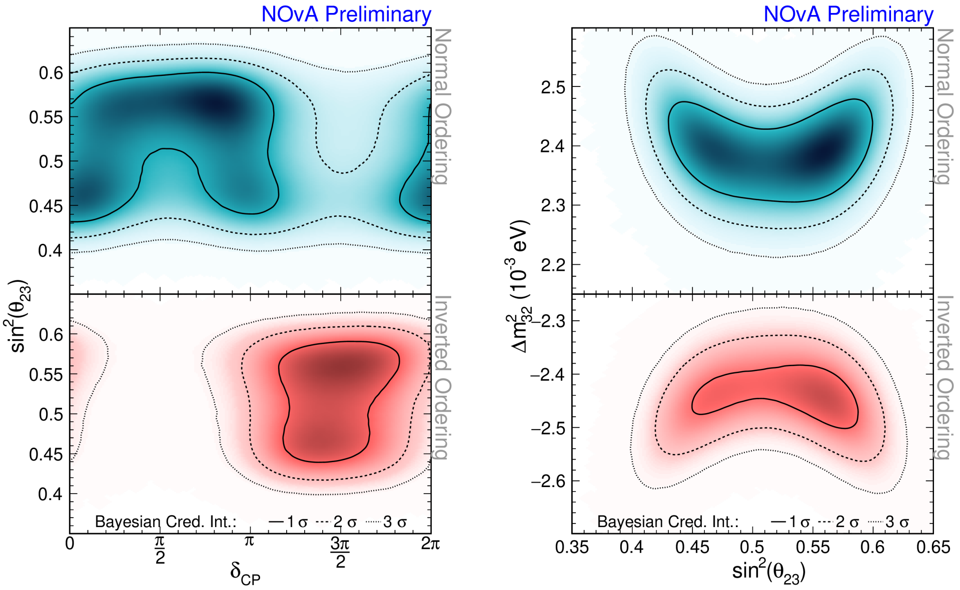

Figure 3: Left: $\sin^2\theta_{23}$ as a function of δ_{CP} for the normal (top) and inverted (bottom) ordering. Right: Δm^2_{32} as a function of $\sin^2\theta_{23}$ for the normal (top) and inverted (bottom) ordering.

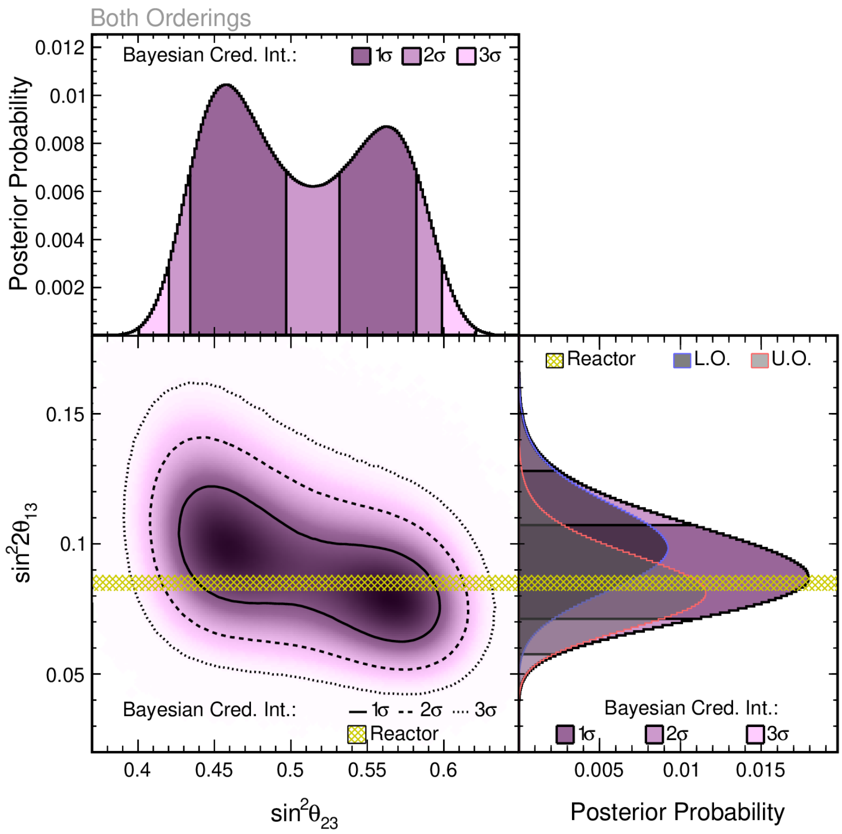

Figure 4: Posterior probability density when θ_{13} is a free parameter in the fit.