VALOR joint oscillation analysis using multiple LAr-TPCs in the Booster Neutrino Beam at Fermilab

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Abstract. Anomalies observed by different experiments, the most significant ones being the $\sim 3.8$ sigma $\nu_e$ appearance in a $\sim 50$ MeV $\nu_\mu$ beam from muon decay at rest observed by the LSND experiment and the $\sim 3.8$ sigma $\nu_e$ and $\bar{\nu}_e$ appearance in a $\sim 1$ GeV neutrino beam from pion decay in flight observed by MiniBooNE, suggest the existence of sterile neutrinos. The Short Baseline Neutrino (SBN) program at Fermilab aims to perform a sensitive search for sterile neutrinos by performing analyses of $\nu_e$ appearance and $\nu_\mu$ disappearance employing three Liquid Argon Time Projection Chambers (LAr-TPCs) at different baselines.

The VALOR neutrino fitting group was established within the T2K experiment and has led numerous flagship T2K oscillation analyses, and provided sensitivity and detector optimisation studies for DUNE and Hyper-K. The neutrino oscillation framework developed by this group is able to perform fits of several samples and systematic parameters within different neutrino models and experiments. Thus, VALOR is an ideal environment for the neutrino oscillation fits using multiple LAr-TPC detectors with proper treatment of correlated systematic uncertainties necessary for the SBN analyses.

1. Introduction

The Short Baseline Neutrino (SBN) program at Fermilab is a novel experimental effort aiming to resolve the anomalies observed in the past years and to perform the most sensitive search for sterile neutrinos to date. It will employ multiple LAr-TPCs with different designs, placed along the Booster Neutrino Beam (BNB), also receiving exposure from the off-axis NuMI (Neutrinos at the Main Injector) beam, situated at different baselines to be able to measure the unoscillated flux and to reduce flux and neutrino interaction uncertainties. The current proposal \cite{1} consists of three LAr-TPCs: SBND (with 112-tons active mass, which will be situated at 110 m from the BNB target), MicroBooNE (with 89-tons active mass, situated at 470 m from the BNB target and taking data since October 2015) and the refurbished ICARUS/T600 (with 476-tons active mass, which will be situated at 600 m from the BNB target).

For the search of sterile neutrinos, VALOR \cite{2} will perform a joint fit of neutrino mixing parameters, studying more than 3 neutrinos in 3+1, 3+2 and 1+3+1 models, and of neutrino flux, interaction and detector model systematics, to the observable kinematical distributions of several semi-inclusive or exclusive samples of the three LAr-TPCs detectors.
2. VALOR Joint Oscillation Analysis of Multiple LAr-TPC Detectors

The VALOR joint oscillation analysis of multiple LAr-TPC detectors will include in a single fit:

- **Multiple selections**: distributions in the observable kinematic space of multiple semi-inclusive or exclusive topologies (e.g. $\nu_\mu$ CC interactions separated by the number of pions in the final state), which will be driven by the selection of systematic parameters.

- **Multiple detectors**: selections will be defined and included for each LAr-TPC detector.

- **Systematic parameters**: including their correlations, to account for i) detector model efficiencies, ii) neutrino flux model uncertainties and iii) neutrino interaction model uncertainties, for which the VALOR group has developed an in-house calculation described in next section.

- **Neutrino oscillation parameters** in 3+1, 3+2 and 1+3+1 models.

An overview of the different components of the VALOR joint oscillation analysis of multiple (generalized to N) LAr-TPC detectors is presented in the diagram in Fig. 1.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Schematic of the VALOR joint oscillation analysis of multiple LAr-TPC detectors.

A binned log-likelihood ratio function will be calculated comparing predicted ($n_{\text{pred}}^{d;bs}$) and observed ($n_{\text{obs}}^{d;bs}$) number of event for each selection ($s$) recorded in a detector ($d$) and exposed to a beam configuration ($b$) such as e.g. neutrino(or anti-neutrino)-enhanced beam. The predicted number of events is evaluated when applying the effect of a physical hypothesis ($\vec{f}$) and a variation of the systematic parameters ($\vec{\theta}$) to Monte Carlo templates of each selection as a function of several reconstructed ($r$) and true quantities.

$$\ln \lambda_{d;bs}(\vec{\theta}; \vec{f}) = -\sum_r \left\{ n_{\text{pred}}^{d;bs}(r; \vec{\theta}; \vec{f}) - n_{\text{obs}}^{d;bs}(r) \right\} + n_{\text{obs}}^{d;bs}(r) \cdot \ln \frac{n_{\text{obs}}^{d;bs}(r)}{n_{\text{pred}}^{d;bs}(r; \vec{\theta}; \vec{f})}$$

(1)

The statistic in Eq. 1 is then summed over all the datasets, and a penalty term can be included to account for prior uncertainties on systematics and/or oscillation parameters. Best-fit values of the neutrino mixing parameters and flux, interaction and detector model systematics are then calculated by minimizing $-2(\ln \lambda_{d;bs}(\vec{\theta}; \vec{f}))$ (which follows approximately a $\chi^2$ distribution).
3. VALOR Studies for Neutrino Interaction Uncertainties

The VALOR group has developed a method to evaluate neutrino interaction uncertainties using GENIE [3] re-weighting tools with the aim to be model-independent, simplifying the treatment of multiple model choices, the addition of uncertainties from independent studies and the migration to different GENIE releases; and to ensure that the constraints on the systematic uncertainties are driven by the data and not the priors.

For this VALOR/GENIE error assignment process, we have defined a set of model-independent neutrino interaction systematic parameters which account for normalizations of different interaction channels at certain kinematical ranges. The set of parameters currently used in the DUNE near detector optimization studies [4] consists of parameters for CCQE, CC $1\pi^{\pm}$, CC $1\pi^{0}$, DIS (different parameters for $\nu_\mu$ and $\bar{\nu}_\mu$ in three true kinematical bins) and for CC MEC, CC $2\pi$, CC coherent, NC (one parameter, different for $\nu_\mu$ and $\bar{\nu}_\mu$), and one parameter for the $\nu_e/\nu_\mu$ cross-section ratio. These are linear parameters describing the uncertainty in absence of final state re-interaction (FSI) effects. In addition, non-linear systematic parameters parametrising FSI effects are considered, and response functions are pre-computed in a range of values of each systematic parameter for each detector, sample and kinematic bin.

Using a large ensemble of events generated with GENIE, we translate the effect of the internal neutrino interaction parameters to the appropriately chosen set of linear model-independent ones listed above. A covariance matrix containing the neutrino interaction uncertainties (input to the oscillation analysis) is computed in a two-step process. Firstly, the effect of the $1\sigma$ variation of each GENIE parameter is calculated varying them independently to avoid potential cancellations (Fig. 2, left). Then we vary all the internal parameters at the same time to compute correlations among them. A graphical representation of the correlations obtained is presented in Fig. 2 (right). The combination of the results of both steps allows us to compute the final covariance matrix. Several comparisons with external data were performed in collaboration with the GENIE group, in support of the systematic error assignments calculated with this method.

Figure 2. VALOR/GENIE neutrino interaction uncertainties (left) and correlations (right).

References
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