The VALOR Neutrino Oscillation Analysis

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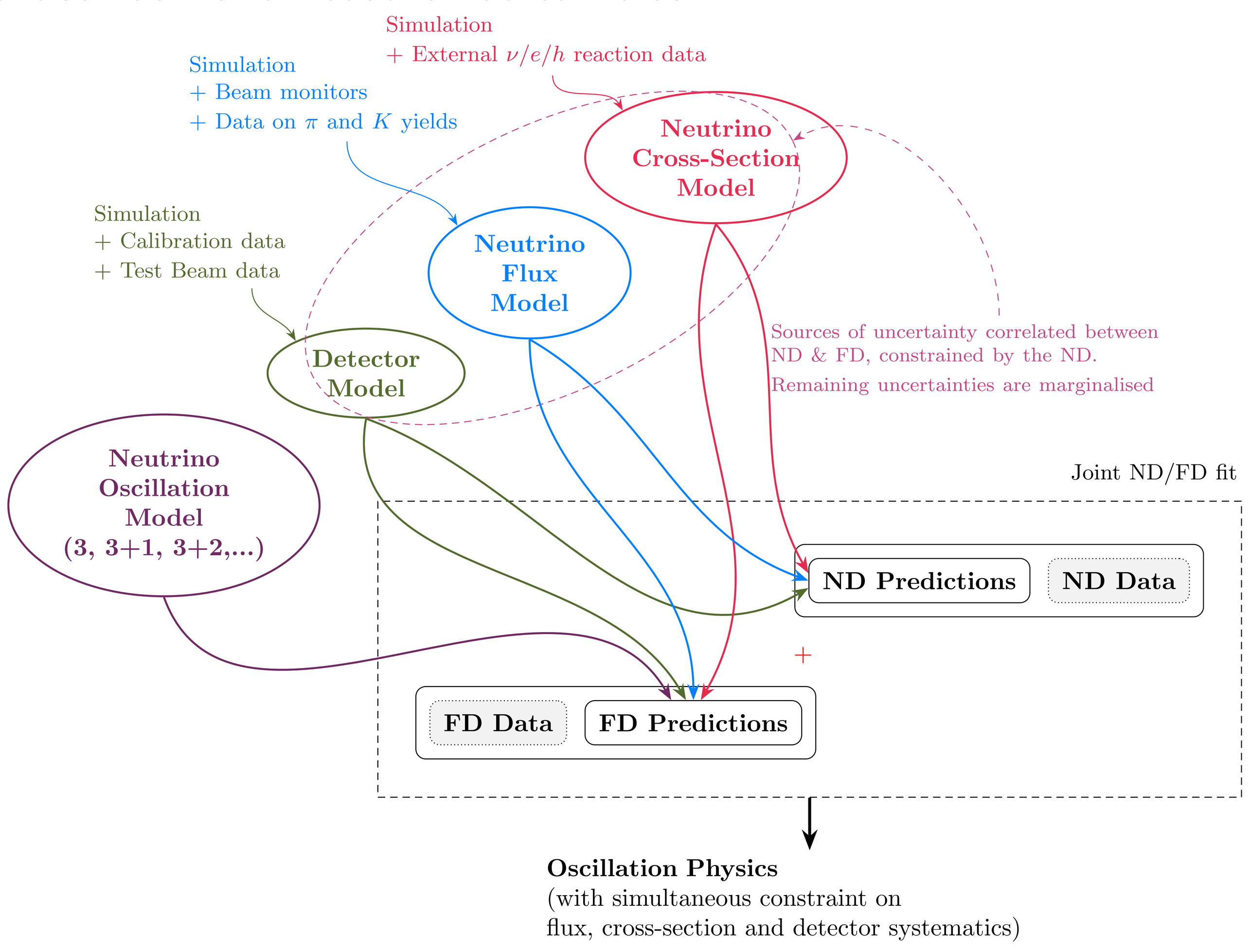
on behalf of the VALOR group

Introduction

The VALOR analysis describes both a flexible software package and as a well-motivated set of anaylsis choices for current and next-generation experiments.
The VALOR software is a likelihood fitter, originally designed for the T2K experiment which has been enhanced and updated to allow it to be capable of the requirements of future experiments such as DUNE, Hyper-K and the SBN program. A flexible set of true and reconstructed kinematics as well as interaction types allow the analysis to be easily tailored to the needs of a specific experiment.
Precision neutrino experiments typically use a near detector to constrain far detector spectral predictions and their uncertainties. There may also be variations in horn configuration to vary beam profile. VALOR has been designed to allow either simultaneous fitting of all detectors/beams to produce contours in only the oscillation parameters, or fitting of an individual detector followed by a matrix-based propagation of uncertainties to a far detector.
This tool has been used for many critical T2K publications, as is being used internally to the experiments under construction at FNAL (SBND, DUNE).

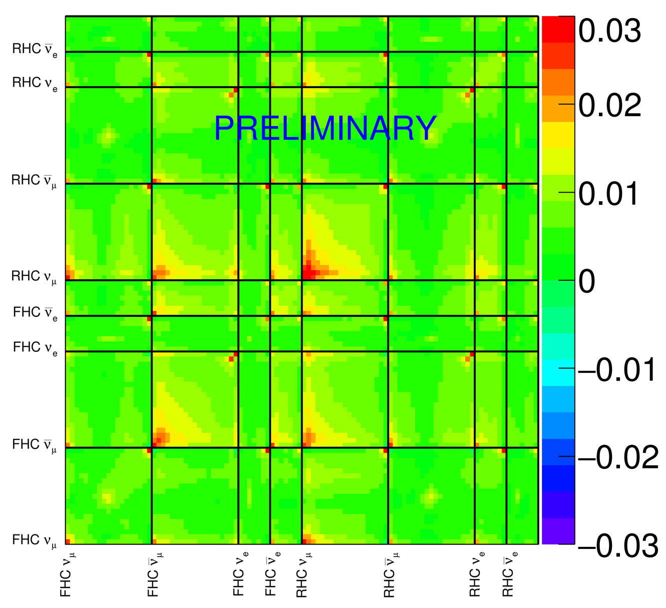
Simultaneous Fitting to Multiple Detectors

In order to maximise the power provided by the data, we allow the data from all available detectors and beam configurations to be fitted simultaneously. In a capable near detector, we typically recommend fitting in a number of exclusive samples defined by their final state toplogies. We provide several pre-constructed lists of topologies which have been defined to produce samples which constrain specific sources of uncertainty in the systematic parameter space. By fitting many such samples simultaneously, this technique allows us to break the degeneracies between variations in flux, detector and interaction uncertainties. A simultaneous fit prevents statistical mistakes from using the same events to constrain multiple inputs to the final oscillation analysis, and provides a full set of correlations between the fitted uncertainties.

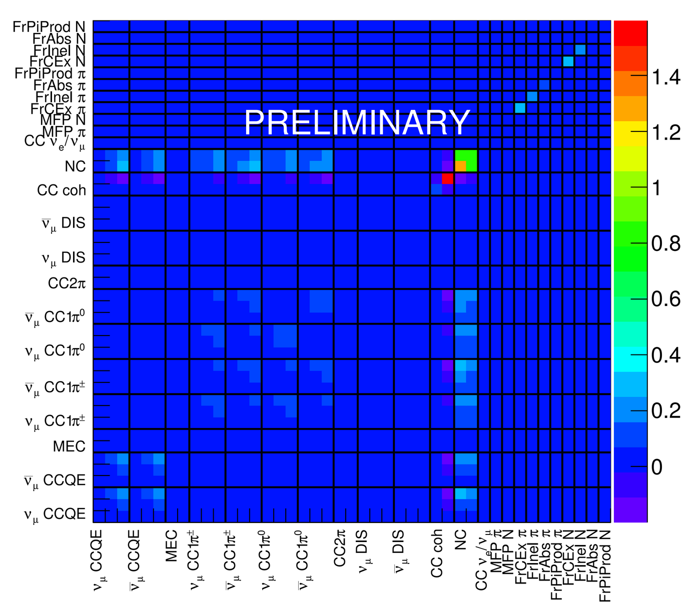


Default Systematic Uncertainty Parameterisation

We implement our flux uncertainties as the normalisations on event rate for a given true neutrino flavour in bins of true neutrino energy, for each beam mode. These are fed in as a large matrix encapsulating the prior uncertainties and, critically, their correlations.
For interaction systematics with a single primary nuclear target, like argon, we use an effective model in which the effects of varying GENIE model parameters is used to evaluate the total effect on number of events produced by a given interaction process or primary vertex topology. In processes with higher event rates, we bin in another kinematic variable to allow shape variations (Q^2 for lower energy processes, $E_{\nu;true}$ for DIS). For all processes we use separate parameters for neutrinos and antineutrinos. In addition to these effective normalisations, we also use the GENIE parameters for Final State Interactions, which have a non-linear effect.



Example of a prior flux covariance matrix.



Example of a prior interaction covariance matrix.

Additional uncertainties such as detector effects can be included in a number of ways, including simple binned normalisations, 1D or 2D response functions, bin migration from energy scaling and reweighting.
When creating a final contour in the oscillation parameters of interest, each uncertainties can be marginalised or profiled out, with a flexible system for including prior shape in one or multiple dimensions.

Construction of Likelihood

We construct our likelihood using a Monte Carlo production to evaluate a predicted number of events for a given physics model and set of uncertainty parameters, which can then be compared to data.

Using MC templates, the predicted number of events $n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f})$ in a N_r-dimensional reconstructed kinematical bin r, for a specific sample s, seen in a detector d exposed in a beam configuration b, and for a particular set of M physics parameters $\vec{\theta} = (\theta_0, \theta_1, ..., \theta_{M-1})$ and N nuisance (systematic) parameters $\vec{f} = (f_0, f_1, ..., f_{N-1})$, is computed as:

$$n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f}) = \sum_m \sum_t P_{d;b;m}(t;\vec{\theta}) \cdot R_{d;b;s;m}(r,t;\vec{f}) \cdot T_{d;b;s;m}(r,t)$$

where $P_{d;b;m}(t;\vec{\theta})$ encapsulates the effect of a physics hypothesis (e.g. neutrino oscillations in a 3-flavour framework), and $R_{d;b;s;m}(r,t;\vec{f})$ parameterizes the response of a template bin to systematic variations.

Given the experimental observation $n^{obs}_{d;b;s}$ we calculate a likelihood ratio:

$$\ln \lambda_{d;b;s}(\vec{\theta};\vec{f}) = -\sum_r \left\{ \left(n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f}) - n^{obs}_{d;b;s}(r) \right) + n^{obs}_{d;b;s}(r) \cdot ln \frac{n^{obs}_{d;b;s}(r)}{n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f})} \right\}$$

Summing this statistic over all of our datasets and optionally including a penalty term derived from our prior knowledge, we can provide accurate estimates of parameter values and their errors.

Physics Hypotheses

The software has been designed and validated to be able to fit many physics hypotheses including:

- Standard 3-flavour oscillations.
- 2 active flavour approximation for any reasonable mass splitting.
- Full 3+1 and 3+2 sterile oscillation calculations.
- Nonstandard matter interaction effects (NSI).
- Decoherence and decay.

Exclusive event samples

For a water Cerenkov detector like Super-K, there is limited potential to fit many exclusive toplogies. However, in the liquid argon era, it will become possible to count particles exiting the vertex and use these to distentangle flux/detector uncertainties and identify specific sources of tension in interaction models.

- **ν_μ CC**
  1. 1-track 0π (μ^- only)
  2. 2-track 0π (μ^- + nucleon)
  3. N-track 0π ($\mu^- + (>1)$ nucleons)
  4. 3-track Δ-enhanced ($\mu^- + \pi^+ +$ p, with $W_{reco} \approx 1.2$ GeV)
  5. $1\pi^\pm$ ($\mu^- + 1\pi^\pm + X$)
  6. $1\pi^0$ ($\mu^- + 1\pi^0 + X$)
  7. $1\pi^\pm + 1\pi^0$ ($\mu^- + 1\pi^\pm + 1\pi^0 + X$)
  8. Other
- **Wrong-sign ν_μ CC**
  9. 0π ($\mu^+ + X$)
  10. $1\pi^\pm$ ($\mu^+ + \pi^\pm + X$)
  11. $1\pi^0$ ($\mu^+ + \pi^0 + X$)
  12. Other
- **ν_e CC**
  13. 0π ($e^- + X$)
  14. $1\pi^\pm$ ($e^- + \pi^\pm + X$)
  15. $1\pi^0$ ($e^- + \pi^0 + X$)
  16. Other
- **NC**
  17. 0π ($+X$)
  18. $1\pi^\pm$ ($\pi^\pm + X$)
  19. $1\pi^0$ ($\pi^0 + X$)
  20. Other
- **ν_e Other**
  21. $\nu_e + e^-$ elastic
  22. Inverse muon decay $\bar{\nu}_e + e^- \to \mu^- + \bar{\nu}_\mu$ (including the annihilation channel $\nu_\mu + e^- \to \mu^- + \nu_e$).

The VALOR Group

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