Multi-channel analyses for future neutrino oscillation experiments

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Outline

- Neutrino physics is entering a new precision era.
- Liquid argon TPCs give us a wealth of information about our neutrino interactions.
- Short baseline detectors will have colossal statistics available.
- So do we really want to just fit CC-inclusive samples for oscillation results?
- Today I'm going to talk about two alternative approaches that use more of our available information:
  - In short-baseline detectors (eg SBND, DUNE ND), we can fit *many* exclusive final states, based on counts of outgoing particles.
  - While in detectors at long baselines, events can be divided into high and low neutrino energy resolution samples.

Caveats

- I'm going to show a couple of example sensitivities comparing inclusive and exclusive event fits for a couple of FNAL programs:
  - SBN
  - DUNE
- These are done using GENIE events fed into a realisticly powerful but entirely cheated reconstruction and selection.
- They are not official inputs nor are they rated for publishable physics.
- These figures are provided to compare between single and multi-channel analysis methods only, not to imply a given absolute sensitivity for either experiment.
- If you use them for this, particularly the SBN ones, you will mislead yourself and others.

Near Detector Sample List

VALOR is a **multi-channel analysis** - Currently defining **46 samples/detector**.
The current VALOR analysis supports the following 23 samples for each neutrino beam configuration:

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

Different samples provide access to different parts of the physics parameter space.

A simultaneous oscillation and systematics constraint fit

Different samples "*speak*" to different physics.

A simultaneous fit of all 46 (currently) event samples per SBN detector **maximizes physics sensitivity** by

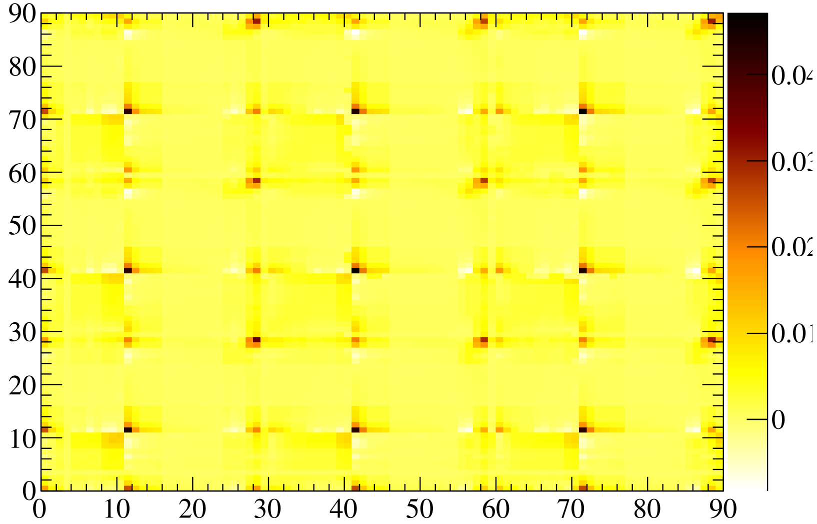
- breaking flux, cross-section and efficiency degeneracies, and
- providing in-situ constraint on systematic uncertainties

The method is statistically robust and provides **correlations between physics parameters**.

It exploits the **complementarity and redundancy of information** that is brought about by the novel LArTPC technology.

Flux systematics

We use a near detector to constrain *flux* and *interaction* systematics. Here I've included an example of the SBN covariance matrix, including 9 ν_e and 11 ν_μ flux uncertainties (binning in true neutrino energy) for each of the three detectors (SBN, MicroBooNE, ICARUS)



Each parameter is a normalization factor for a particular

- detector (ND, FD),
- beam configuration (FHC, RHC),
- neutrino flavour (ν_μ, ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$), and
- true neutrino energy bin.

(taken from SBN proposal - `arXiv:1503.01520`

Neutrino interaction systematics in the VALOR fit

To evaluate our ability to constrain interaction systematics, we consider **44 neutrino interaction systematics**.

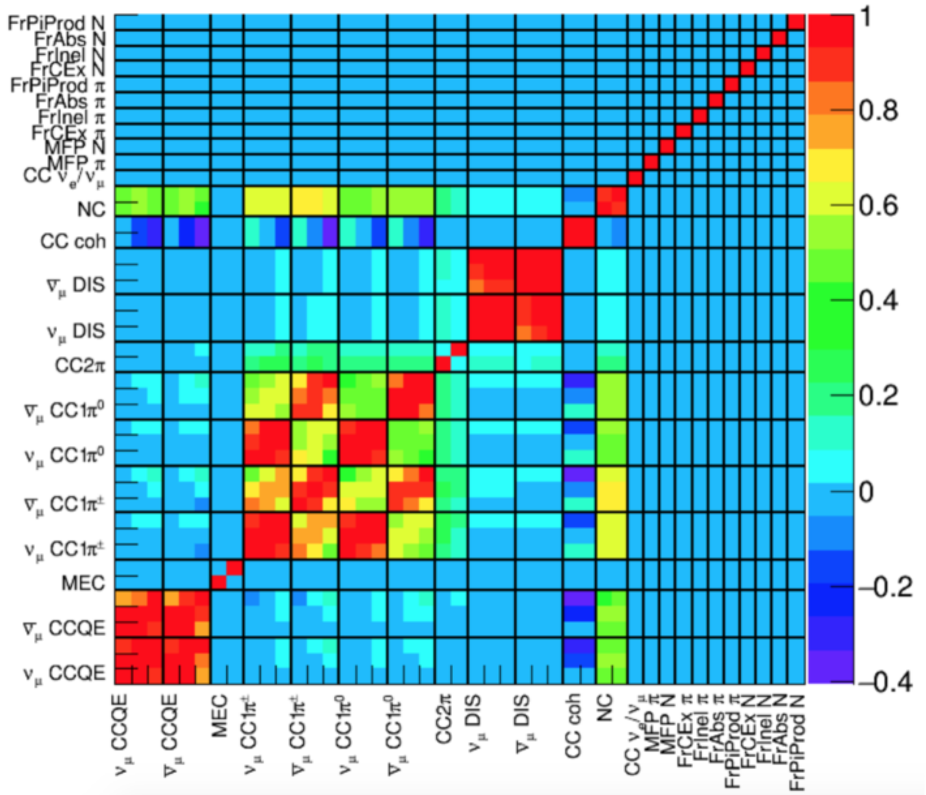
- 34 cross-section linear systematics
  - CCQE normalization in 3 Q^2 bins, separately for ν and $\bar{\nu}$ (6)
  - CCMEC normalization in 2 Q^2 bins, separately for ν and $\bar{\nu}$ (4)
  - CC1$\pi^{\pm}$ normalization in 3 Q^2 bins, separately for ν and $\bar{\nu}$ (6)
  - CC1π^0 normalization in 3 Q^2 bins, separately for ν and $\bar{\nu}$ (6)
  - CC2π normalization, separately for ν and $\bar{\nu}$ (2)
  - CCDIS normalization in 3 E_ν bins, separately for ν and $\bar{\nu}$ (6)
  - CC coherent normalization, separately for ν and $\bar{\nu}$ (2)
  - NC normalization, separately for ν and $\bar{\nu}$ (2)
  - ν_e/ν_μ normalization, separately for ν and $\bar{\nu}$ (2)
- 10 FSI non-linear systematics (require pre-computed response functions)
  - π and nucleon mean free paths (2)
  - probabilities for an interacting π or nucleon to participate in charge exchange, inelastic, absorption or π-production interaction (8)

Parameterization extension for NC modes under development for use in sterile fitting.

Neutrino interaction systematics

This is a parameterization that was developed primarily by C. Andreopoulos (Liverpool/RAL) and L. Escudero (Cambridge).

- Covers all relevant uncertainties for a 3-flavour oscillation fit.
- And mostly sufficient for a sterile fit.
- Using predominantly **linear** and **model-independent** parameters.

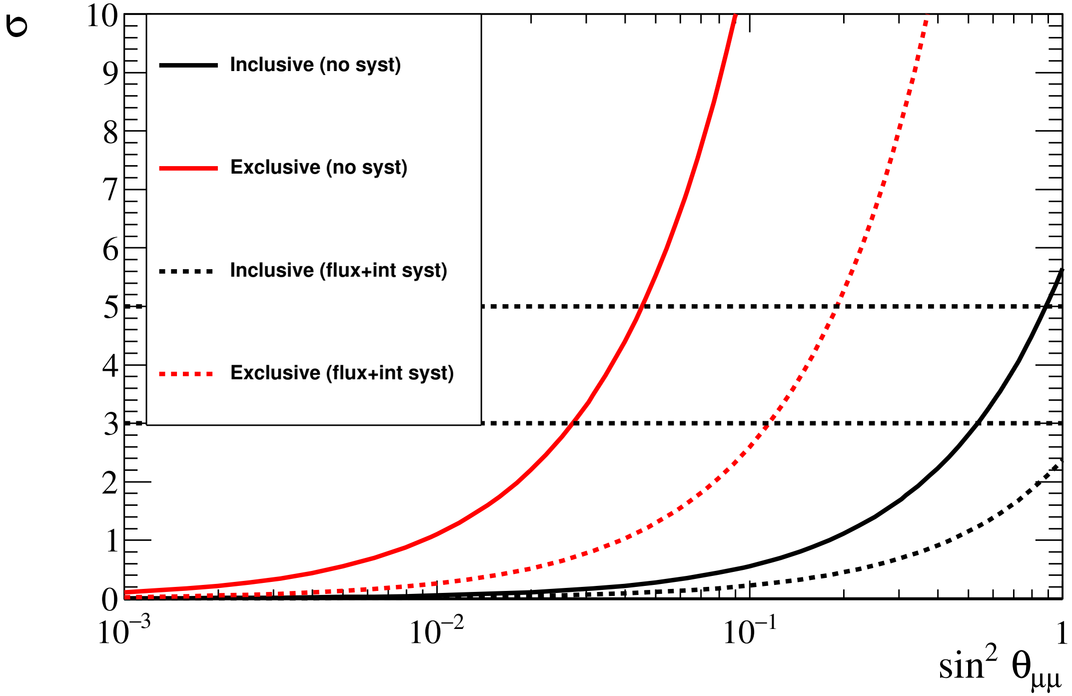


A prior (pre-fit) correlation matrix for our neutrino interaction systematic parameters (see on the left) was computed by tweaking the parameters of the default GENIE model.

Model-independent parameterization:

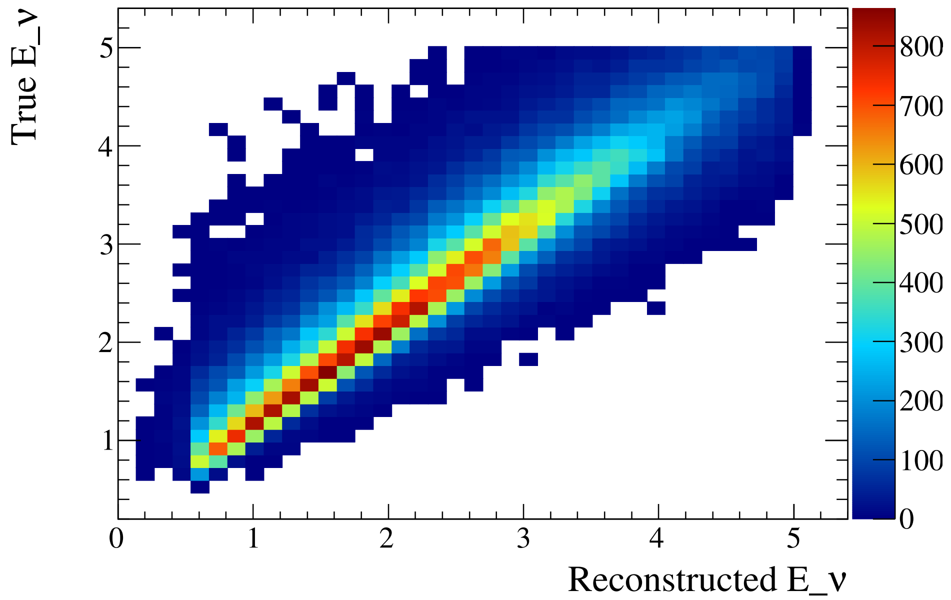
- Any set of model-dependent GENIE parameters can be mapped onto it..
- Parameterization used in the fit remains stable.
- Flexibility to move to new GENIE tunes / model configurations, or to use several of them concurrently (for example, to investigate effect on the fit) with identical fitting code.

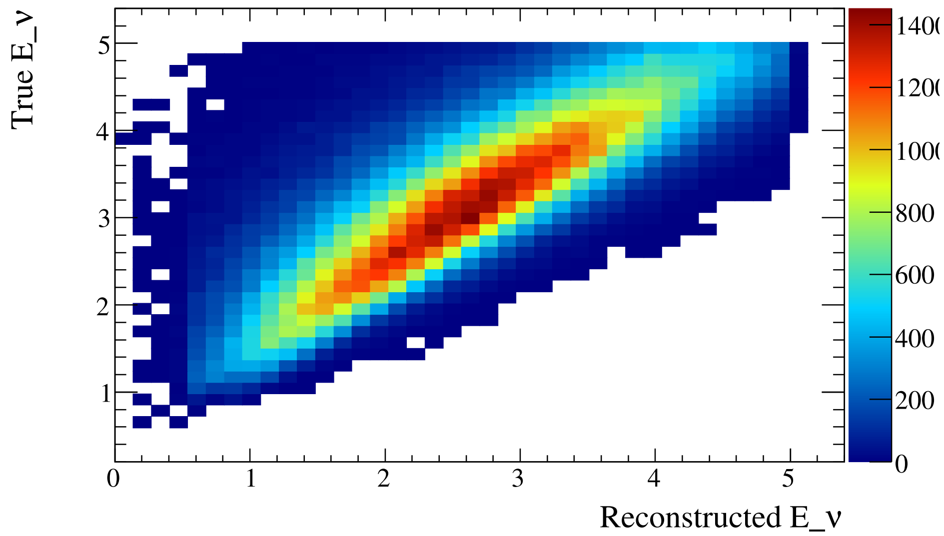
Example of disappearance discovery for a 1 eV^2 sterile



- Very preliminary! SBND + MicroBooNE, disappearance only.
- There is zero true neutrino appearance in this figure.
- Incredibly noticeable effect of breaking correlations.

Far Detector Energy Resolution Samples





High Resolution (QE-like)

Low resolution (non-QE-like)

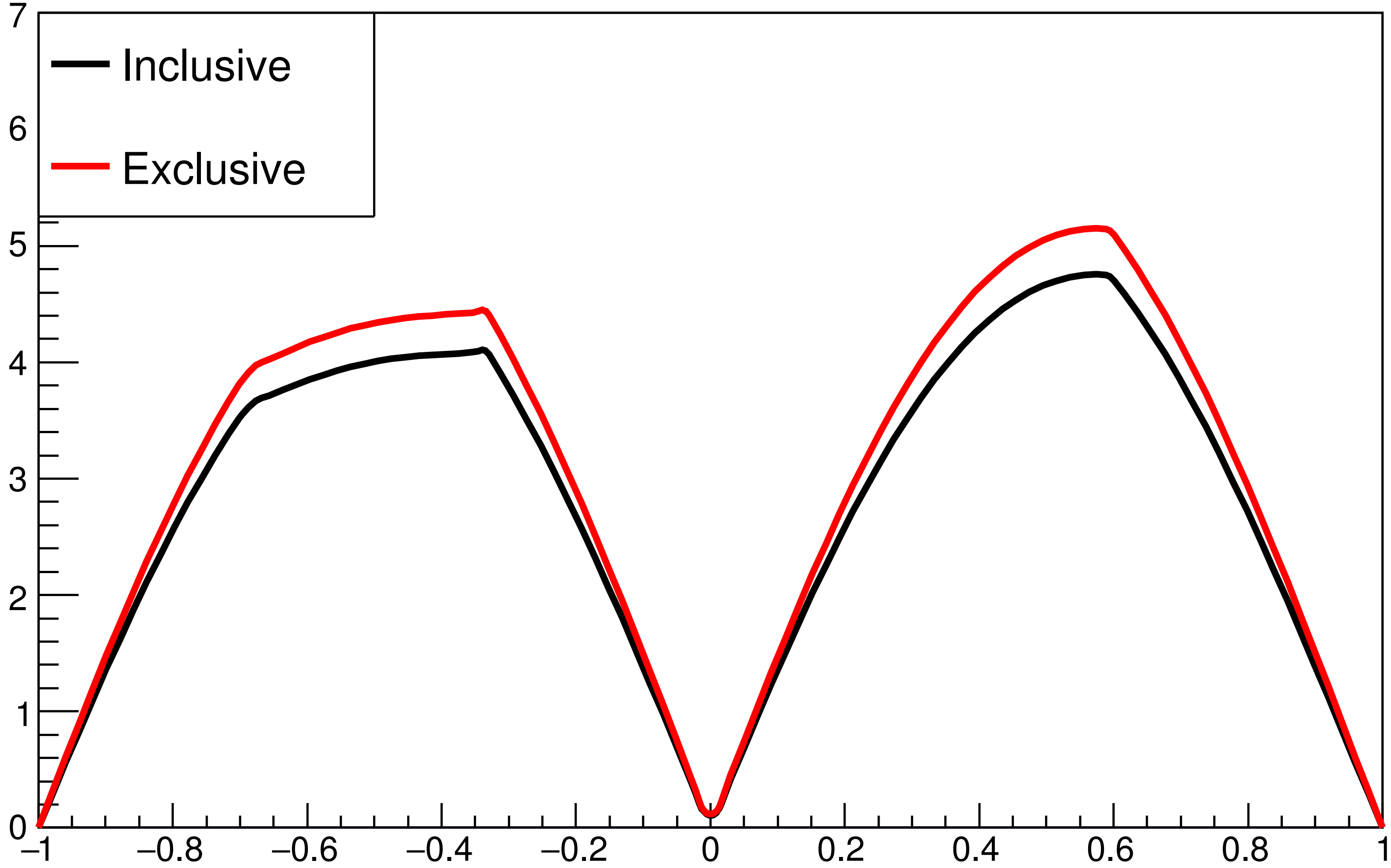
Advantages of the high-resolution sample

- Better energy reconstruction - the energy is less smeared.
- Truth neutrino energy can be calculated using the kinematics of a CCQE interaction rather than calorimetry etc.
- The deposited energy in detector from high-resolution events comes primarily from leptons.
    - We have better uncertainties on leptonic energy than hadronic energy.
- Upshot: our reconstructed neutrino energy is closer to the true neutrino energy, and far better understood.

Trial set up for DUNE

- Perform CP violation sensitivity using the split fit.
- Use uncertainty model for event rate from the DUNE CDR proposal (uncertainty of 2% ν_e rate and 5% on ν_μ rate).
- Add uncertainties on muon (3%), electron (3%) and hadronic (20%) energy.

Effect of splitting the two samples at DUNE



Unofficial! And preliminary!

Conclusions

- It's clear that we can eke out more sensitivity for both our sterile neutrino and our CP-violation fits using the extra information that liquid argon affords us.
- As analyses on the SBN experiments begin to mature, I expect fits of ever greater complexity will become necessary to make the most of our detector.
- And we can eke out extra sensitivity to delta CP by ensuring we maintain the maximum information on our knowledge of the neutrino energy, rather than binning events known well with events known badly and washing out that precision.

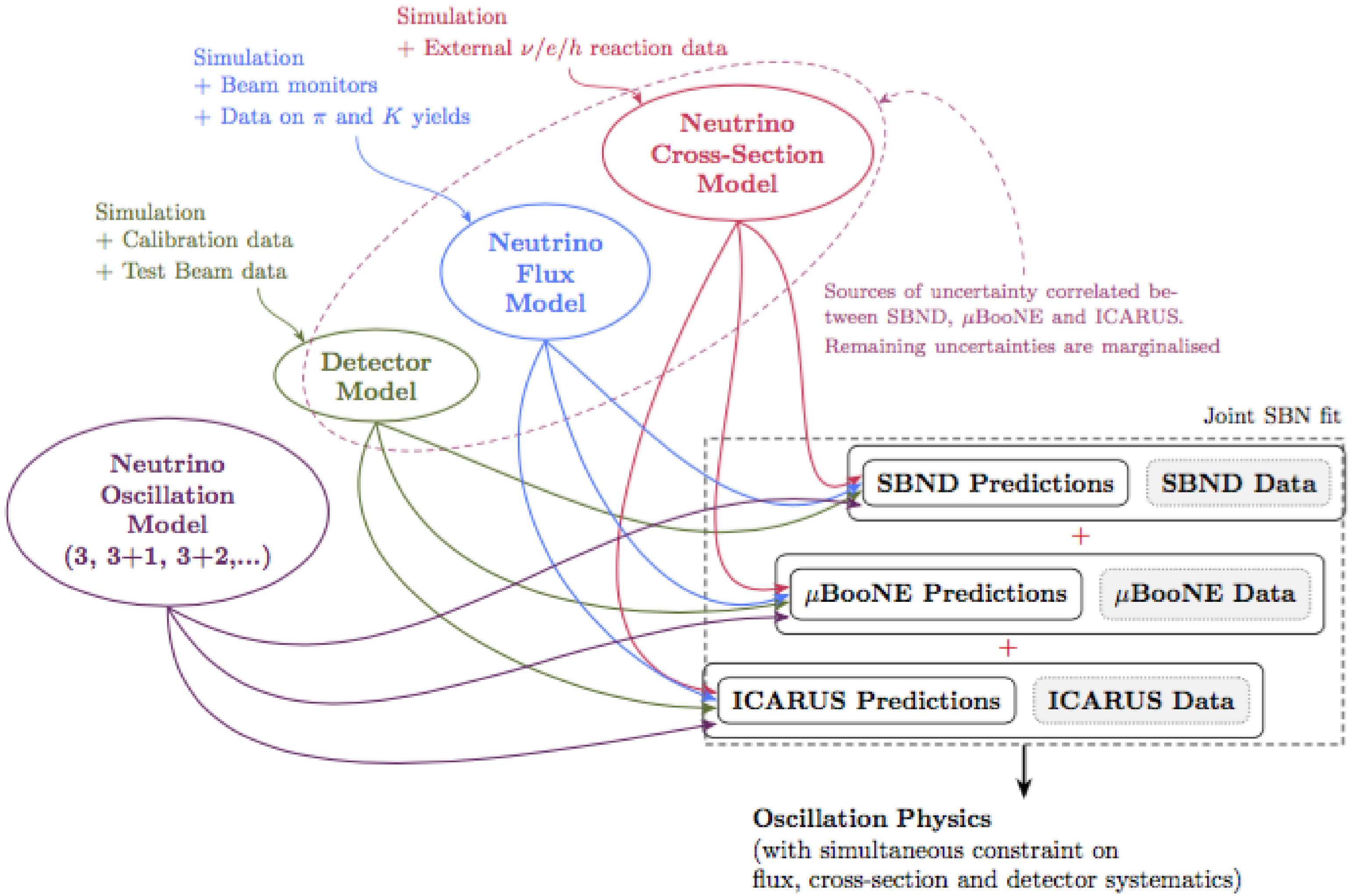
Section 1

Backup

SBN Oscillation analysis strategy implemented in VALOR

VALOR analysis being implemented for **SBN**: A joint oscillation and systematics constraint fit using multiple event samples from all 3 LArTPCs.

And now MiniBooNE!



VALOR fit: Construction of likelihood

A joint VALOR fit considers simultaneously:

- A flexibly-defined **set of detectors d**. *E.g.* $d \in \{SBND, \mu BooNE, ICARUS\}$.
- A flexibly-defined **set of beam configurations b** (for each d). *E.g.* $b \in \{FHC, RHC, ...\}$
- A flexibly-defined **set of event selections s** (for each d and b). *E.g. see page 11.*

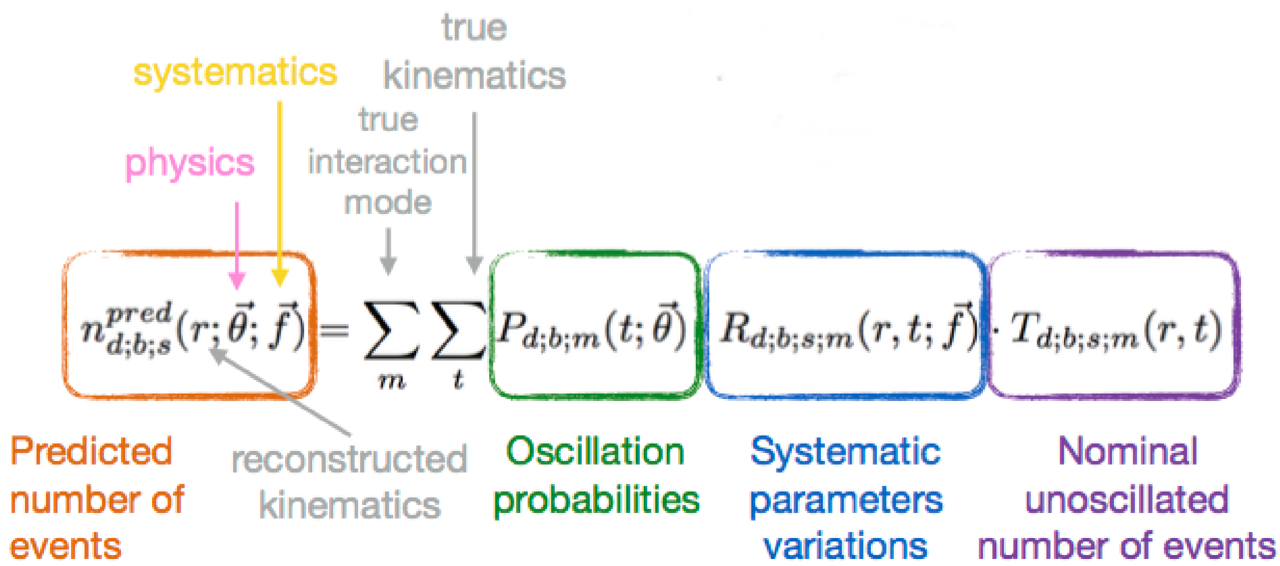
For each (d,b,s):

- Experimental information is recorded in a number of **multi-dim. reco. kinematical bins r** *E.g.* $r \equiv \{ E_{\nu;reco} \}, \{E_{\nu;reco}, y_{reco} \}, \{ p_{\ell;reco}, \theta_{\ell;reco} \}, \{ E_{vis;reco} \}, ...$

Our predictions for

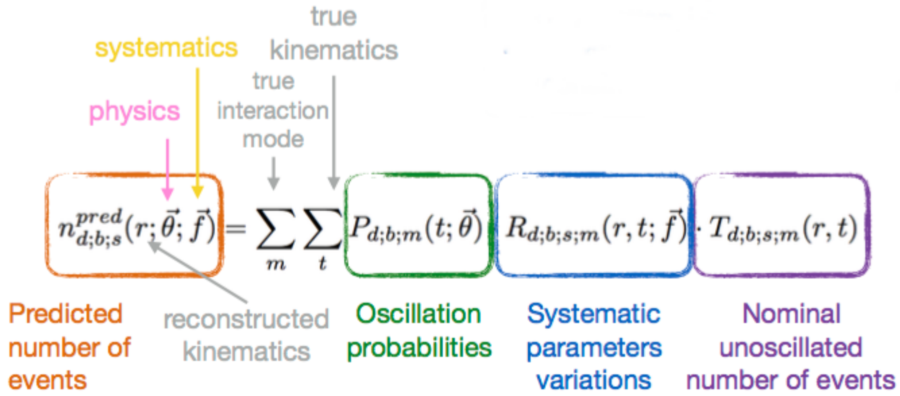
- a set of **interesting physics params** $\vec{\theta}$ (*e.g.* $\{\theta_{23}, \delta_{CP}, \Delta m^2_{31}\}$ *or* $\{\theta_{\mu e}, \theta_{\mu\mu}, \Delta m^2_{41}\}$), and
- a set of O(10^2)-O(10^3) **systematic (nuisance) params** $\vec{f}$

are constructed as follows:



VALOR fit: Construction of likelihood

Predictions are built using **MC templates** $T_{d;b;s;m}(r,t)$ constructed by applying event selection code to the output of a full event simulation and reconstruction chain.



For each (d,b,s), MC templates are constructed for a set of **true reaction modes m**.

- Currently, templates are constructed for the 52 true reaction modes shown on the right.

The templates store the mapping between reconstructed and truth information (as derived from full simulation and reconstruction).

- E.g. $\{\ E_{\nu;true},\ Q^2_{true},\ W_{true}\} \leftrightarrow \{\ p_{\ell;reco},\ \theta_{\ell;reco}\ \}$

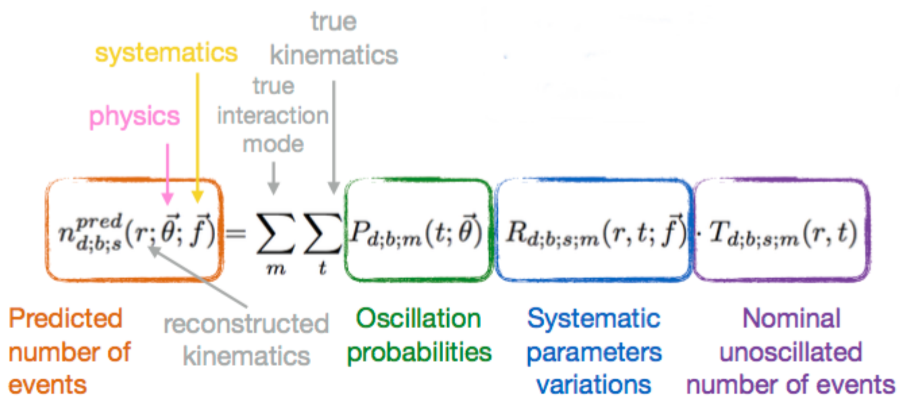
The choice of true kinematical space { t } and true reaction modes m is **highly configurable** for each (d,b,s) independently.

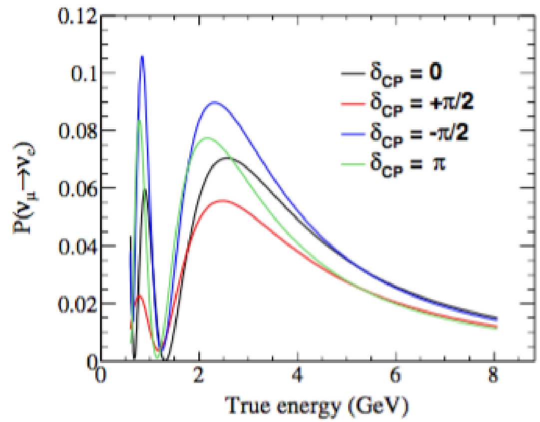
- Main consideration: **Sufficient granularity to apply desired physics and systematic effects** (function of truth quantities).

- ν_μ CC QE
- ν_μ CC MEC
- ν_μ CC $1\pi^\pm$
- ν_μ CC $1\pi^0$
- ν_μ CC $2\pi^\pm$
- ν_μ CC $2\pi^0$
- ν_μ CC $1\pi^\pm + 1\pi^0$
- ν_μ CC coherent
- ν_μ CC other
- ν_μ NC $1\pi^\pm$
- ν_μ NC $1\pi^0$
- ν_μ NC coherent
- ν_μ NC other
- **similarly for** $\bar{\nu}_\mu$
- **similarly for** ν_e
- **similarly for** $\bar{\nu}_e$

VALOR fit: Construction of likelihood

Finally, the effect of **neutrino oscillations** is included in $\boldsymbol{P_{d;b;m}(t;\vec{\theta})}$.



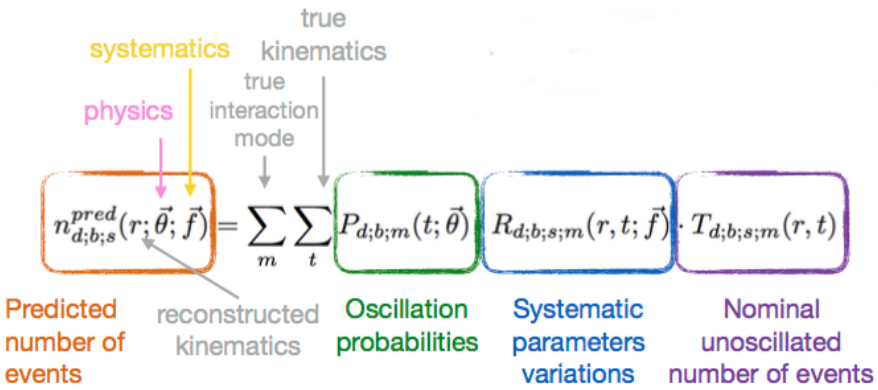


- Using bespoke library for calculation of osc. probabilities.
- **Very fast!**
- **Extensively validated** against GloBES and Prob3++.
- Supports 3-flavour calculations (incl. standard matter / NSI effects) and, also, calculations in 3+1, 3+2, 1+3+1 schemes.
- **Flexibility** provided by bespoke library is immensely useful (tuning performance, moving between different parameter conventions, trying out different oscillation frameworks).

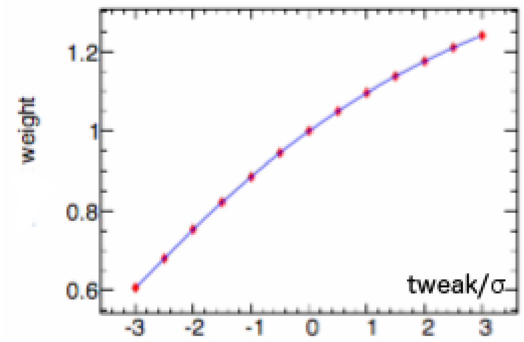
- $\sin^2(\theta_{12}) = 0.3$
- $\sin^2(\theta_{13}) = 0.025$
- $\sin^2(\theta_{23}) = 0.5$
- $\Delta m^2_{21} = 7.5\times10^{-5}$ eV^2/c^4
- $\Delta m^2_{32} = 2.5\times10^{-3}$ eV^2/c^4
- Normal ordering
- Earth matter density = 2.7 g/cm^3
- Baseline = 1300 km

VALOR fit: Construction of likelihood

Systematic variations are applied using the **response functions** $\boldsymbol{R_{d;b;s;m}(r,t;\vec{f})}$.



Example of a non-linear response function.



Typically, but not always, the response $R_{d;b;s;m}(r,t;\vec{f})$ factorises and it can be written as

$$R_{d;b;s;m}(r,t;\vec{f}) = \prod_{i=0}^{N-1} R^i_{d;b;s;m}(r,t;f_i)$$

For several systematics the response is linear and, therefore,

$$R^i_{d;b;s;m}(r,t;f_i) \propto f_i$$

For non linear systematics, the response function $R^i_{d;b;s;m}(r,t;f_i)$ is pre-computed (for every detector, beam, sample, mode, true kinematical bin and reconstructed kinematical bin) using event reweighting libraries in the [-5σ, +5σ] range of the parameter f_i and it is represented internally using an Akima spline.

VALOR fit: Construction of likelihood

Once we have estimates of $n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f})$, VALOR computes a **likelihood ratio**:

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

$$\lambda_{SBN}(\vec{\theta};\vec{f}) = \prod_d \prod_b \prod_s \lambda_{d;b;s}(\vec{\theta};\vec{f})$$

Most parameters in the fit come with prior constraints from external data. Where needed, the following Gaussian penalty term is computed:

$$ln\ \lambda_{prior}(\vec{\theta};\vec{f}) = -\frac{1}{2}\left\{ (\vec{\theta}-\vec{\theta}_0)^T C_\theta^{-1}(\vec{\theta}-\vec{\theta}_0) + (\vec{f}-\vec{f}_0)^T C_f^{-1}(\vec{f}-\vec{f}_0) \right\}$$

and combined likelihood ratio is given by:

$$\lambda(\vec{\theta};\vec{f}) = \lambda_{SBN}(\vec{\theta};\vec{f}) \cdot \lambda_{prior}(\vec{\theta};\vec{f})$$

In the large-sample limit, the quantity $-2\lambda(\vec{\theta};\vec{f})$ has a χ^2 distribution and it can therefore be used as a goodness-of-fit test.