VALOR Flux and Cross-Section Systematic Constraints *for DUNE Oscillation Sensitivity Simulation and Near Detector Design Optimisation.*

Costas Andreopoulos[1,2]

[1]University of Liverpool, [2]STFC Rutherford Appleton Laboratory

October 15, 2015

Outline

- VALOR history and contributions
- Oscillation analysis strategy implemented in VALOR
    - ND analysis strategy
    - Advantages of a simultaneous fit of several samples
- The VALOR (2015v1) DUNE ND analysis **(all preliminary)**
    - Samples for a systematics constraint fit
    - Fit distributions
    - Building-up the expected nominal spectra / MC templates
    - Example nominal spectra
    - Systematic variations
    - Choice of fit parameters and prior constraints
    - Examples of systematically varied spectra
    - Fitting method
    - Fit validation
    - Example toy-MC fits
    - Example flux and cross-section sensitivities
- Interfaces with Beam simulation WG, GENIE and Detector option WGs
- Summary and next steps

The VALOR group

VALOR is a well-established T2K fitting group (2010-present).
Code was adapted for DUNE and HyperK (for ND optimization studies).

Costas Andreopoulos[1,2], Chris Barry[1], George Christodoulou[1], Thomas Dealtry[3], Steve Dennis[2,4], Lorena Escudero[5], Nick Grant[4], Davide Sgalaberna[6], Raj Shah[2,7]

[1] University of Liverpool, [2] STFC Rutherford Appleton Lab, [3] University of Lancaster
[4] University of Warwick, [5] IFIC Valencia, [6] ETH Zurich, [7] University of Oxford

current students, postdocs (former students with VALOR T2K PhD theses), postdocs

T2K contributions:

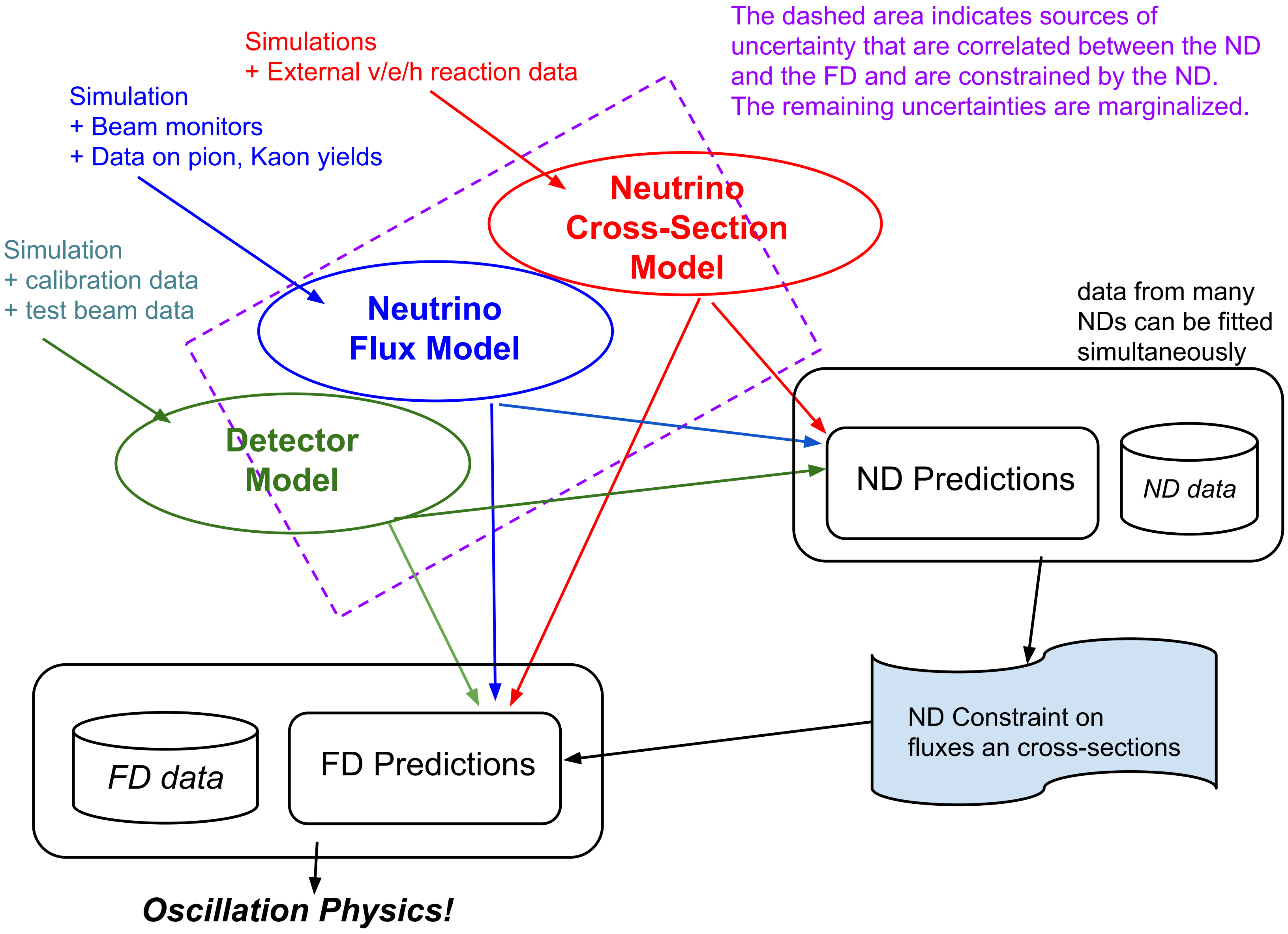
- 2-flavour ν_μ disappearance analysis with Run 1 data (2010)
- 2-flavour ν_μ disappearance analysis with Run 1-2 data (2010)
- 3-flavour ν_μ disappearance analysis with Run 1-2 data (2010)
- 3-flavour ν_μ disappearance analysis with Run 1-3 data (2012)
- 3-flavour joint ν_μ disappearance + ν_e appearance analysis with Run 1-3 data (2012)
- 3-flavour ν_μ disappearance analysis with Run 1-4 data (2013)
- 3-flavour joint ν_μ disappearance + ν_e appearance analysis with Run 1-4 data (2013)
- 3-flavour $\bar{\nu}_\mu$ disappearance analysis with Run 5-6 data (2015)
- 3-flavour $\bar{\nu}_e$ appearance analysis with Run 5-6 data (2015)
- *3-flavour joint $\nu_\mu/\bar{\nu}_\mu$ disappearance + $\nu_e/\bar{\nu}_e$ appearance analysis with Run 1-6 data* (now)

VALOR oscillation analysis in a nutshell

- **Joint measurement of**: $sin^2\theta_{13}$, $sin^2\theta_{23}$, δ_{CP} and Δm^2. (*)
- Implements an **indirect extrapolation** method with a (correlated) flux and cross-section systematic constraint from a high granularity ND.
- **Point / interval estimation by comparing the measured and predicted kinematical distributions** (typically 1-D reco. energy distributions, but multi-D kinematical distributions now also in use) of 1-ring μ-like and 1-ring e-like SK events + other (e.g. control) samples.
- Oscillation probabilities calculated in a **3-flavour framework**, including matter effects in constant-density matter (**3+1, 3+2 options** supported).
- **Minimization: Binned likelihood ratio method**, using MINUIT (many other options supported, eg Simulated annealing, Levemberg-Marquardt,...)
- Intervals: Feldman-Cousins or const-$\Delta\chi^2$ / Cousins-Highland.
- All systematics (O(100)) are allowed to float in the fit and are eliminated using the profile likelihood method. Marginalization used in later analyses.

(*) Fogli-Lisi conventions used by default. Many parameter options supported.

Oscillation analysis strategy implemented in VALOR



The dashed area indicates sources of uncertainty that are correlated between the ND and the FD and are constrained by the ND. The remaining uncertainties are marginalized.

Near detector analysis strategy

To first order: A **simultaneous fit** of important systematic (neutrino flux and neutrino interaction) parameters to **several ND samples**

- marginalizing over detector nuisance parameters
- also (depending on the intended use) marginalizing over some "interesting" physics parameters
  - e.g. parameters that do not help improve the event rate model in the far detector, but impact other parameters that do influence that model.
  - this will be relevant for interaction constraints coming from nuclei other than Argon

What we measure is **event rates** for **specific final-state topologies**

We also need an **ND event rate model**

The rate $N_{ev}^{(s)}(K_o)$ for a sample (s) and any set of observed kinematics K_o (e.g. (E_{reco}, Q^2_{reco})) is built from our flux Φ, interaction $\sigma_{\nu A}$ and detector models ϵ_D (acceptance), including reconstruction effects.

Near detector analysis strategy

Very schematicaly, brushing over details:

$$N_{ev}^{(s)}(K_o) = \int dE_{true} \, \frac{\Phi(E_{true})}{dE_{true}} \sum_t \int dW_{true} dQ^2_{true} \ldots \; \frac{d\sigma^t_{\nu A}(E_{true}; W_{true}, Q^2_{true}, \ldots)}{dW_{true} dQ^2_{true} d\ldots} \cdot$$

$$\cdot \int dK'_o \;\; P^{s;t}(E_{true}, W_{true}, Q^2_{true}, \ldots; K_o, K'_o) \;\; \epsilon_D^{s;t}(K_o, K'_o)$$

where

- the sum is over true topologies (t) that may contribute to sample s.
- $P^t(E_{true}, W_{true}, Q^2_{true}, \ldots; K_o, K'_o)$ is the probability (derived from full MC and reconstruction) that a particular event topology (e.g $\mu^- \ \pi^+ \ \pi^0 \ p \ n \ n$) with true parameters $(E_{true}, W_{true}, Q^2_{true}, \ldots)$ will end-up with observed kinematics K_o (the ones we are looking at / binning our events in) and K'_o (the ones we not looking at but depend upon, so integrating over).

Near detector analysis strategy

Flux Φ and interaction $\sigma_{\nu A}$ models have (parameterised) **uncertainties**.

$$\Phi_\nu(E_\nu) = \Phi_\nu(E_\nu; f^{\Phi_1}, f^{\Phi_2}, ..., f^{\Phi_N})$$

$$\sigma^t_{\nu A}(E_\nu, W, Q^2, ...) = \sigma^t_{\nu A}(E_\nu, W, Q^2, ...; f^{\sigma_1}, f^{\sigma_2}, ..., f^{\sigma_N})$$

All $f^{\Phi_2}, ..., f^{\Phi_N}$, $f^{\sigma_1}, f^{\sigma_2}, ..., f^{\sigma_N}$ have *prior* “preferred values” and uncertainties (from MC tunes based on external data).

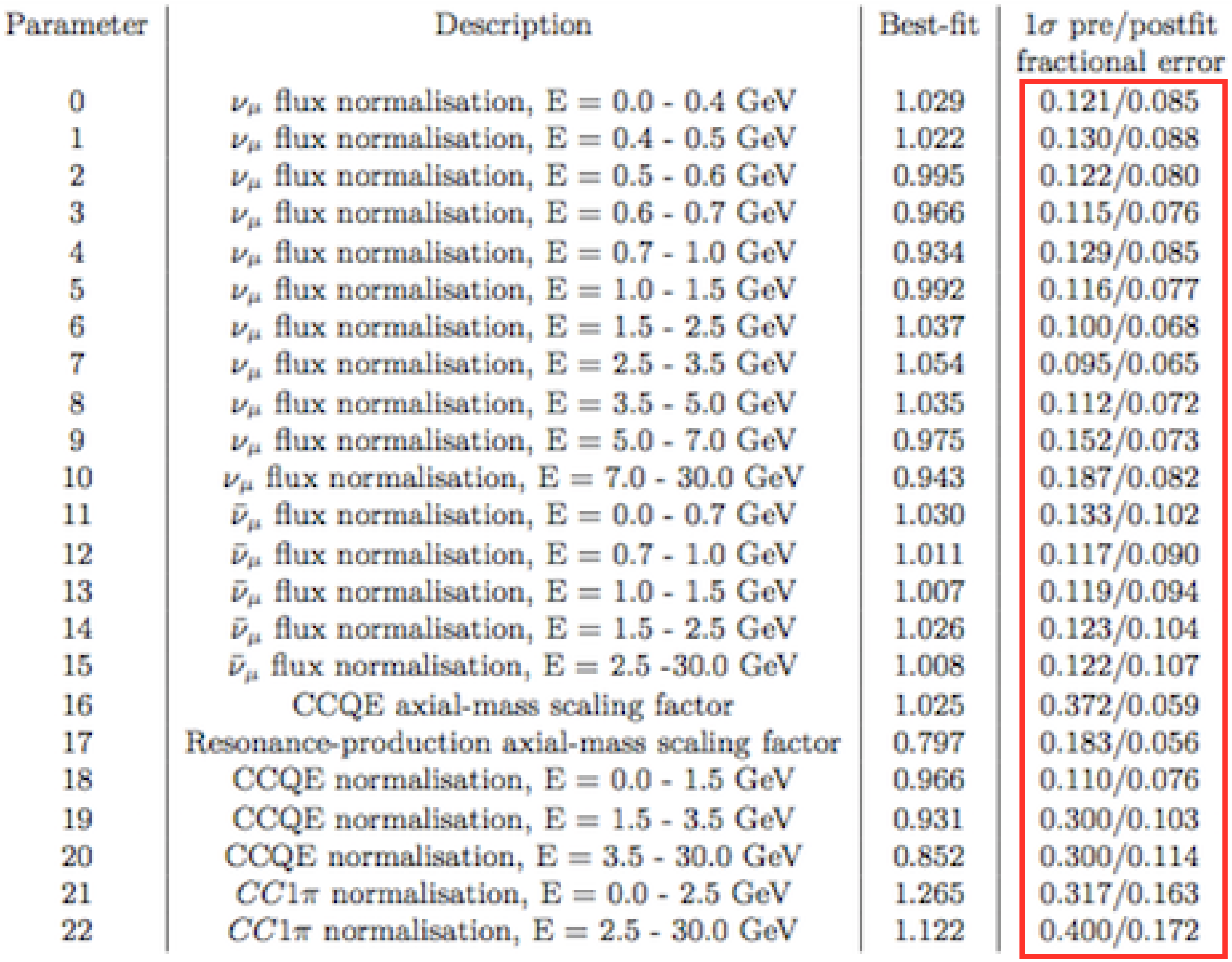
The **objective is to exploit the power of** (simulated, for now) **ND data** to reduce the errors on $f^{\Phi_2}, ..., f^{\Phi_N}$, $f^{\sigma_1}, f^{\sigma_2}, ..., f^{\sigma_N}$ and, therefore, **to reduce the spread of FD predictions**.

The detector models ϵ_D also has (parameterised) uncertainties.

- They degrade the constraints on flux and cross-sections
- This needs to be taken into account, and detector nuisance parameters are marginalised

T2K example: Errors after ND280 Constraint

Example from our earlier Run 1-4 T2K disappearance analysis (23 params in the ND fit).
ND fit included 17.5k $\nu_\mu CC0\pi$, 4k $\nu_\mu CC1\pi^+$ and 4k $\nu_\mu CCother$ events.



Parameter	Description	Best-fit	1σ pre/postfit fractional error
0	ν_μ flux normalisation, E = 0.0 - 0.4 GeV	1.029	0.121/0.085
1	ν_μ flux normalisation, E = 0.4 - 0.5 GeV	1.022	0.130/0.088
2	ν_μ flux normalisation, E = 0.5 - 0.6 GeV	0.995	0.122/0.080
3	ν_μ flux normalisation, E = 0.6 - 0.7 GeV	0.966	0.115/0.076
4	ν_μ flux normalisation, E = 0.7 - 1.0 GeV	0.934	0.129/0.085
5	ν_μ flux normalisation, E = 1.0 - 1.5 GeV	0.992	0.116/0.077
6	ν_μ flux normalisation, E = 1.5 - 2.5 GeV	1.037	0.100/0.068
7	ν_μ flux normalisation, E = 2.5 - 3.5 GeV	1.054	0.095/0.065
8	ν_μ flux normalisation, E = 3.5 - 5.0 GeV	1.035	0.112/0.072
9	ν_μ flux normalisation, E = 5.0 - 7.0 GeV	0.975	0.152/0.073
10	ν_μ flux normalisation, E = 7.0 - 30.0 GeV	0.943	0.187/0.082
11	$\bar{\nu}_\mu$ flux normalisation, E = 0.0 - 0.7 GeV	1.030	0.133/0.102
12	$\bar{\nu}_\mu$ flux normalisation, E = 0.7 - 1.0 GeV	1.011	0.117/0.090
13	$\bar{\nu}_\mu$ flux normalisation, E = 1.0 - 1.5 GeV	1.007	0.119/0.094
14	$\bar{\nu}_\mu$ flux normalisation, E = 1.5 - 2.5 GeV	1.026	0.123/0.104
15	$\bar{\nu}_\mu$ flux normalisation, E = 2.5 -30.0 GeV	1.008	0.122/0.107
16	CCQE axial-mass scaling factor	1.025	0.372/0.059
17	Resonance-production axial-mass scaling factor	0.797	0.183/0.056
18	CCQE normalisation, E = 0.0 - 1.5 GeV	0.966	0.110/0.076
19	CCQE normalisation, E = 1.5 - 3.5 GeV	0.931	0.300/0.103
20	CCQE normalisation, E = 3.5 - 30.0 GeV	0.852	0.300/0.114
21	$CC1\pi$ normalisation, E = 0.0 - 2.5 GeV	1.265	0.317/0.163
22	$CC1\pi$ normalisation, E = 2.5 - 30.0 GeV	1.122	0.400/0.172

Significant reduction wrt the a-priori error estimates.

Correlations between the parameters are also provided.

Method separates the effects of flux and cross-section systematics.

The power of the ND in reducing systematic uncertainties is always clear and explicit.

Advantages of a simultaneous fit of several samples

- Method is **very powerful**
- Combines several pieces of information is a single fit.
- It can break the degeneracies and separate the effects of flux, cross-section and detector model systematics.
- Method is **statistically robust**
    - and prevents you from using the same datasets again and again to constrain a sequence of parameters (*)
- Provides the **correlations between parameters**

Also, notice that the indirect extrapolation method implemented in VALOR

- Does not require similar ND and FD technologies.
- Can also work for a hybrid ND (multiple technologies).

Hence, it is particularly suited for ND design optimization!

(*) The bubble-chamber era example comes to mind: assume QE model → use assumed QE model to extract flux → use the measured flux to measure QE → go back at square 1 and retrieve your initial assumption.

Is it a “fudge”?

I know well that ND folks have a **distaste for the overly empirical methods** that oscillation analysis folks end up using.

Let me assert that we are **not fudging anything**! (studies to follow)

On the contrary!
By including several samples it becomes easier to break correlations / degeneracies and to disentangle various physics and detector effects.

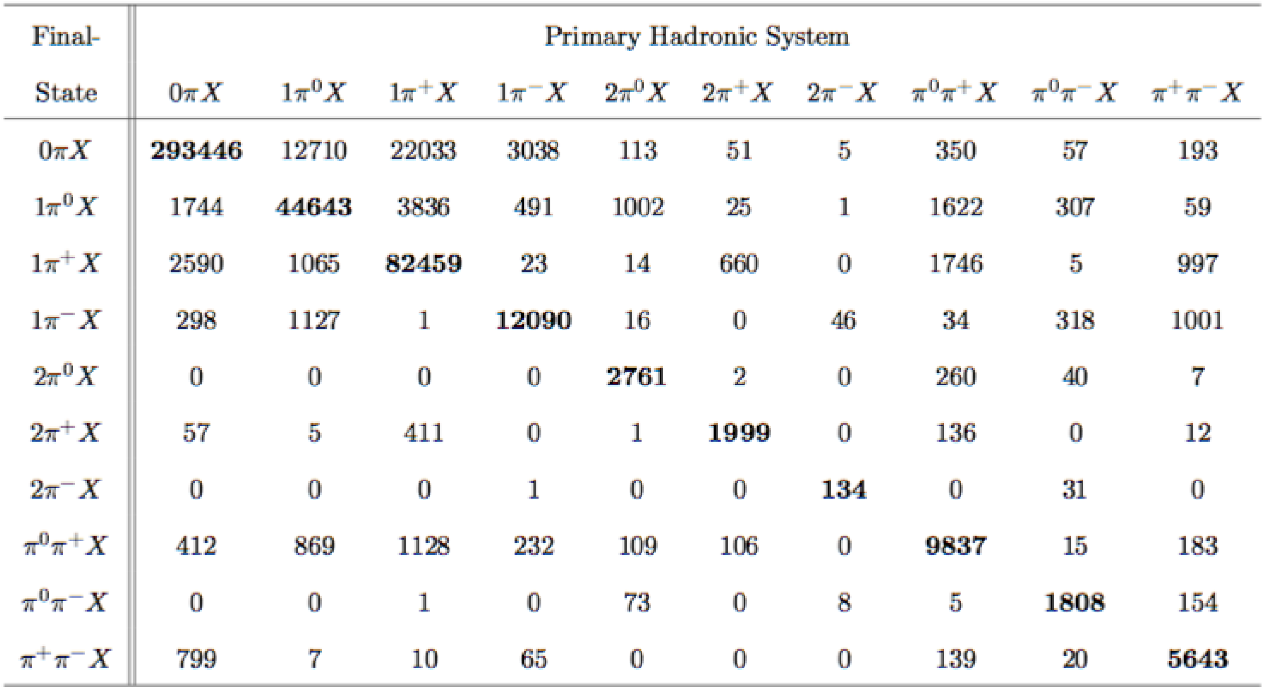
- For example, one can no longer force your FSI model to unphysical extremes to match your $1\pi^+$ data, if FSI is not the culprit!
  - The 0π, $\pi^+\pi^0$, $2\pi^+$ and other datasets which are connected to $1\pi^+$ via the *same FSI physics* will keep one “honest” (not misled).

The method fully exploits the advertised **complementarity / redundancy of information** that is brought about by the highly-capable NDs under consideration.

Simultaneous fit of several samples is a necessity

Really, rather than just *advantageous*, such an analysis is a necessity!

- It is dictated by the very same physics we want to study.



Final-State	Primary Hadronic System									
	$0\pi X$	$1\pi^0 X$	$1\pi^+ X$	$1\pi^- X$	$2\pi^0 X$	$2\pi^+ X$	$2\pi^- X$	$\pi^0\pi^+ X$	$\pi^0\pi^- X$	$\pi^+\pi^- X$
$0\pi X$	**293446**	12710	22033	3038	113	51	5	350	57	193
$1\pi^0 X$	1744	**44643**	3836	491	1002	25	1	1622	307	59
$1\pi^+ X$	2590	1065	**82459**	23	14	660	0	1746	5	997
$1\pi^- X$	298	1127	1	**12090**	16	0	46	34	318	1001
$2\pi^0 X$	0	0	0	0	**2761**	2	0	260	40	7
$2\pi^+ X$	57	5	411	0	1	**1999**	0	136	0	12
$2\pi^- X$	0	0	0	1	0	0	**134**	0	31	0
$\pi^0\pi^+ X$	412	869	1128	232	109	106	0	**9837**	15	183
$\pi^0\pi^- X$	0	0	1	0	73	0	8	5	**1808**	154
$\pi^+\pi^- X$	799	7	10	65	0	0	0	139	20	**5643**

Left: Migration from "primary" (before re-interactions) to final state / observed topologies ($\nu_\mu O^{16}$, 1 GeV)

The primary interaction processes that we want to study and constrain are **mingled** together due to the presence of the nucleus.

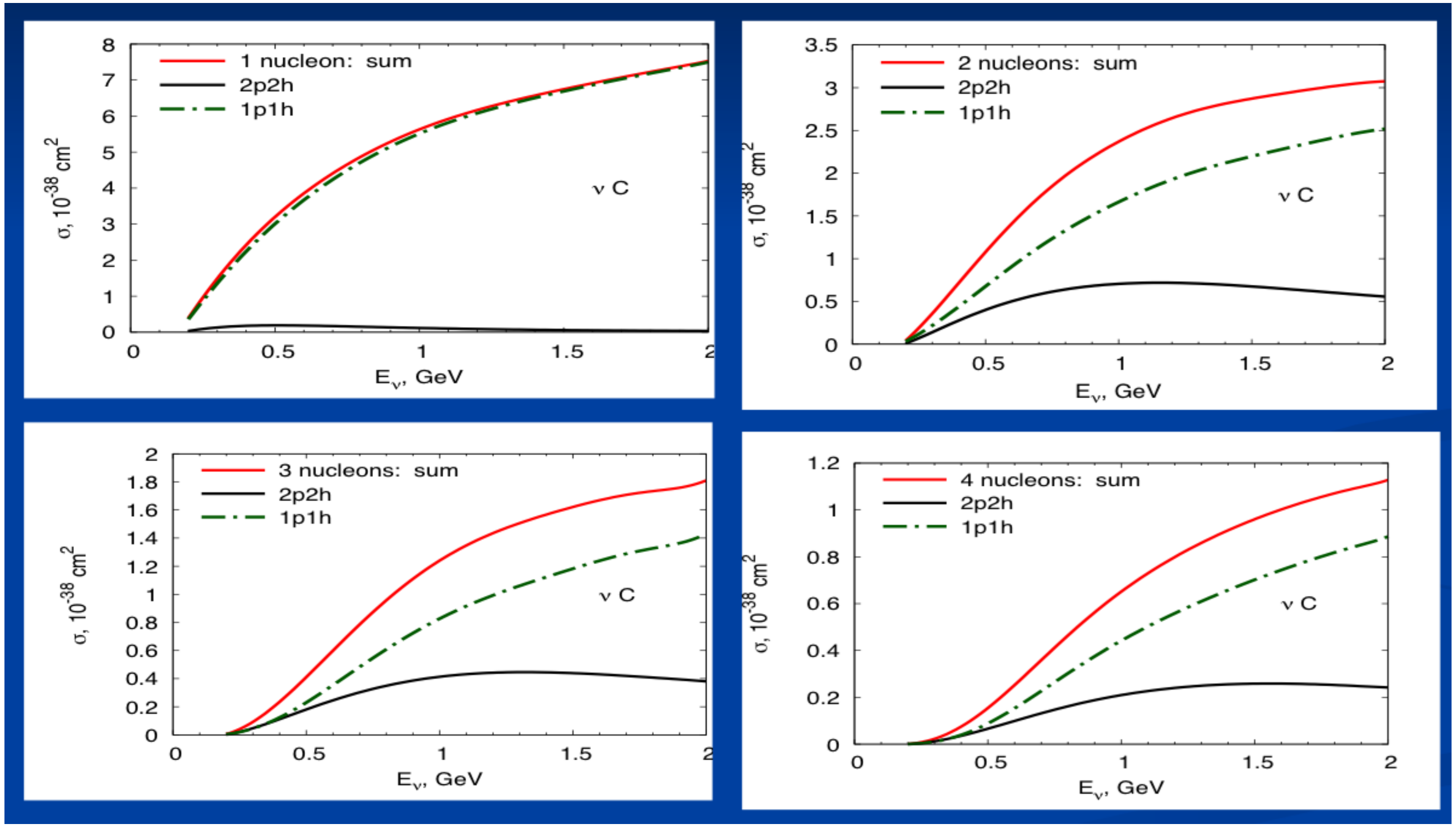
For example, in the FGT:

- The ν_μCC 1-trk QE-like sample is only ~75% true CCQE (~20% true CC1$\pi^\pm$)
- The ν_μCC1π^0 sample is only ~60% true CC1π^0 (~20% true CC1$\pi^\pm + 1\pi^0$).

Processes with no *smoking gun* signature

2p-2h is causing a concern for DUNE (primarily for the 2^{nd} osc. maximum) and, in particular, for other lower energy experiments. How to constrain it?

No smoking gun signature! **Avalanching shadows the initial reaction** [Mosel].



Need to look at several samples to disentangle its contribution.

VALOR DUNE-ND analysis

Specifics of our current ND analysis implementation for DUNE.

VALOR/DUNE-ND: Samples for systematics constraint fit

In our 2015v1 analysis, we include either **fully inclusive samples** or **exclusive / semi-inclusive samples of low track multiplicities.** Separate samples are used for FHC and RHC running.

- ν_μ CC inclusive
  - ν_μCC 1-track QE enhanced (FHC: μ^- only)
  - ν_μCC 2-track QE enhanced (FHC: μ^- + p)
  - ν_μCC $1\pi^\pm$ (FHC: $\mu^- + 1\pi^\pm +$ X)
  - ν_μCC $1\pi^0$ (FHC: $\mu^- + 1\pi^0 +$ X)
  - ν_μCC $1\pi^\pm + 1\pi^0$ (FHC: $\mu^- + 1\pi^\pm + 1\pi^0 +$ X)
  - ν_μCC other

    → in future, subdivide further (3-track Δ-enhanced, νe)
- Wrong-sign ν_μCC inclusive (FHC: $\mu^+ +$ X)

  → in future, subdivide further
- ν_eCC inclusive (FHC: $e^- +$ X)

  → in future, subdivide further
- NC inclusive

  → in future, subdivide further (NCEL, NC $1\pi^\pm$, NC $1\pi^0$)

Samples in red are included in the *current (2015v1) version* of the ND fit.

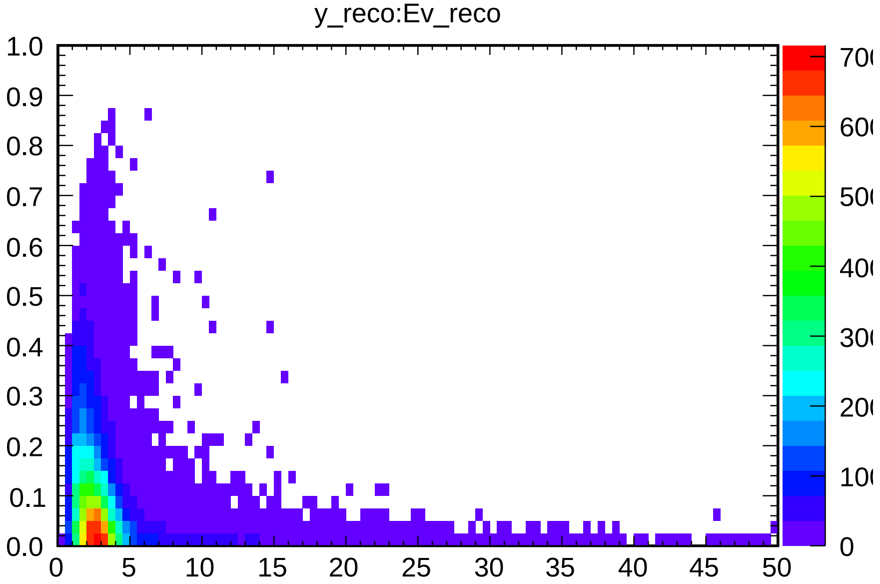
Samples already installed can be *“disabled”* individualy.

Inclusion of other samples, and their utility in constraining systematics will be tested in future iterations of this work.

VALOR/DUNE-ND: Fit distributions

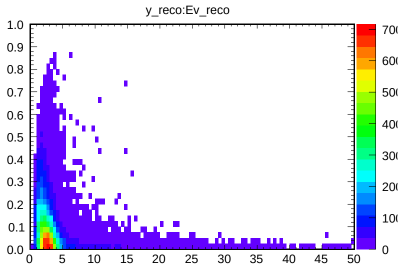
In the 2015v1 VALOR/DUNE-ND analysis we fit:

- **2-D (E_{reco}, y_{reco}) distributions** for CC-like samples,
- **1-D $E_{visible}$ distributions** for NC-like samples.

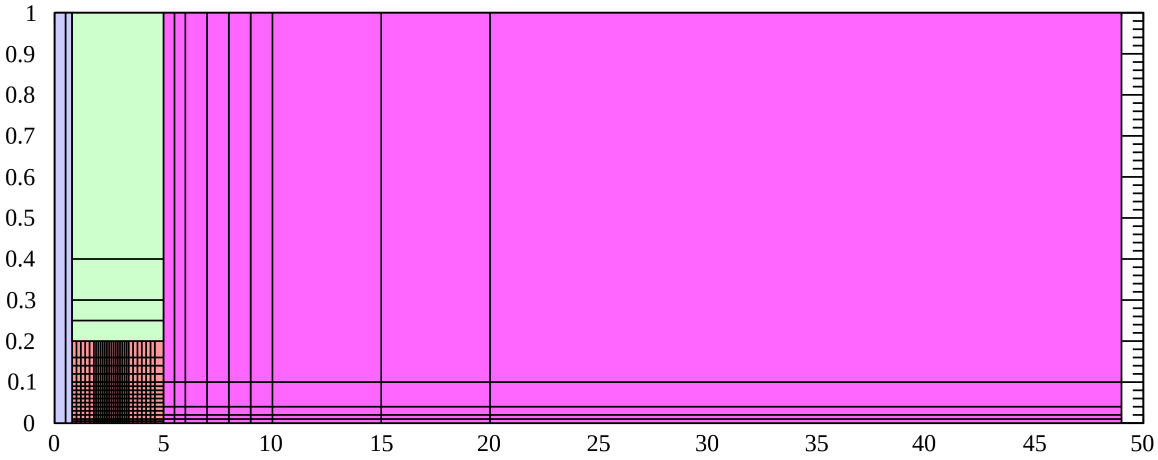


Example: E_{reco}, y_{reco} distribution for a ν_μ CCQE enhanced sample.

VALOR/DUNE-ND: Binning optimisation



Below is somewhat optimised (albeit too fine) binning scheme. Generally, a number of **zones** are defined and a different variable-size binning is used in each zone. Requiring a constant number of MC events / per bin.



- Different binning scheme allowed for each sample
- Binning not optimised just yet
- The binning that optimizes CPU-efficiency is useless for plots (e.g. for 1-D slices).
- A parallel set of distributions with a fine and regular binning are also constructed (e.g. post-fit) for visualisation purposes.

VALOR/DUNE-ND: Building-up the expected spectra

The **expected spectra** are constructed **from MC templates**.

Separate MC templates are constructed for:

- **Each beam configuration** included in the fit
    - e.g FHC
- **Each sample** included in the fit
    - e.g. ν_μCC 2-track QE enhanced
- **A number of “true reaction modes”** contributing to each sample.
    - e.g. ν_μCCQE

VALOR/DUNE-ND: True modes kept track of

In the 2015v1 analysis, we are keeping track of the **52 true reaction modes** shown on the right.

- for each (beam, sample), an MC template is constructed for each true reaction mode.

The **choice is independently configurable** for each (beam, sample).

The **granularity depends on the choice of systematics** (cross-section, FSI and efficiency systematics) that need to be applied.

- For example, to reweight the NC coherent component of FHC ν_μNC$1\pi^0$ sample, one must keep track of its contribution to each kinematic bin.

- 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/DUNE-ND: MC template binning

The **expected spectra** are constructed **from MC templates**. The MC templates are binned in the same kinematical variables we use for fitting (obviously) and a number of "extra" MC-truth variables, as needed to apply systematics.

Currently the MC templates are:

- **3-D (E_{true}, E_{reco}, y_{reco}) distributions** for CC-like samples,
- **2-D (E_{true}, $E_{visible}$) distributions** for NC-like samples.

So there currently is a single "extra" MC-truth variable: E_{true}

- as needed to apply E_{true}-dependent systematics (most)

Additional ones can be added (paying attention to CPU efficiency).

DUNE ND Event Selections

Selections (Christodoulou) based on DUNE/FGT FastMC - Used for all plots shown.

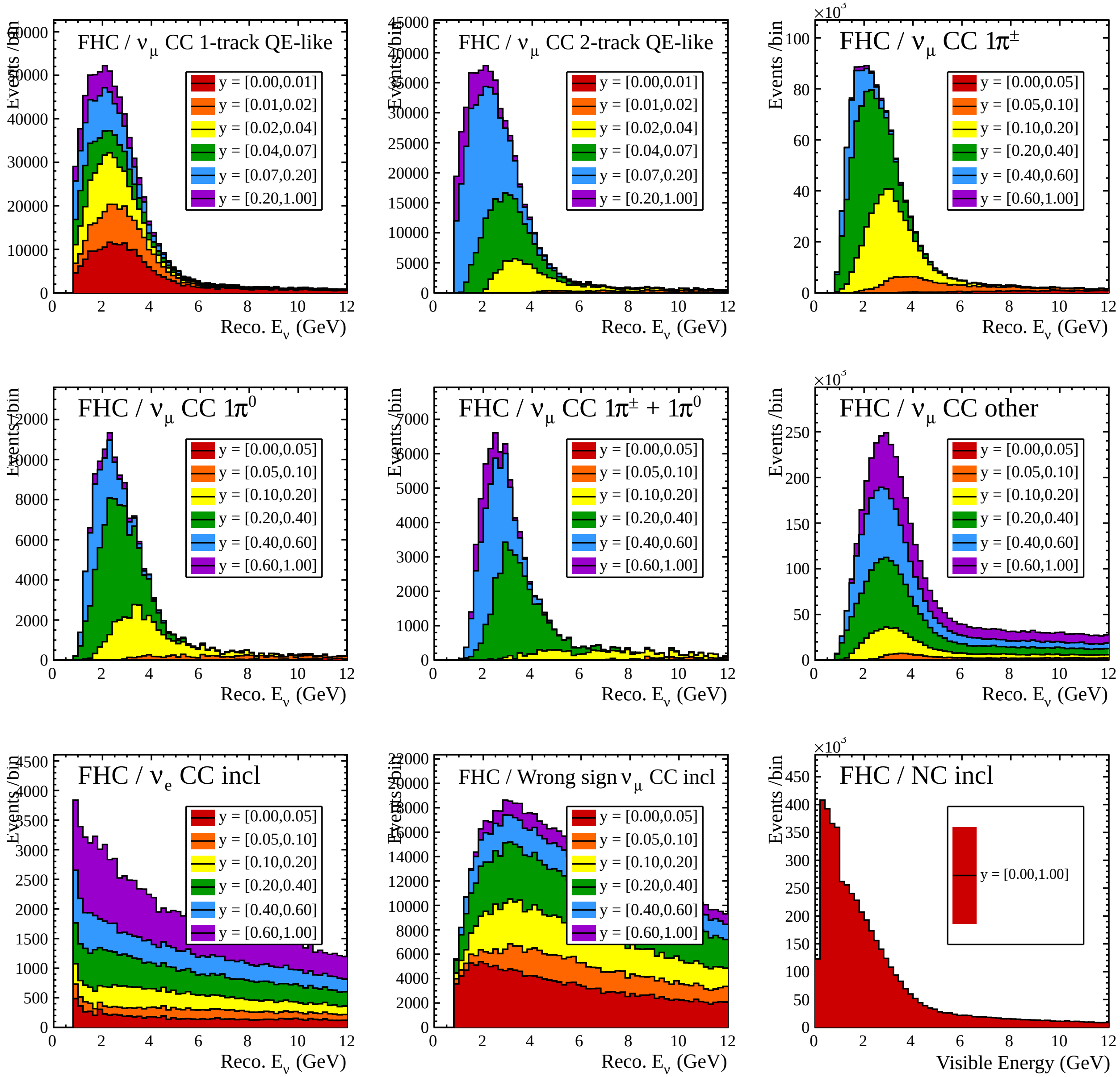
Thresholds (KE):

- μ: 50 MeV
- e: 50 MeV
- γ: 100 MeV
- π: 50 MeV
- p: 80 MeV
- n: 250 MeV

- For $\nu_\mu/\bar{\nu_\mu}$CC: μ track $>$ 2m
- Number of hit straw tubes (1cm diameter) $>$ 12 for each track
- Charge mis-ID: 0.2%-0.3% for $p_\mu \approx$ 1 GeV, increasing to 1%.
- μ/π/K/p PID using dE/dx from PANDA
- π^0 invariant mass cut, $|M_{reco}$ - 140 MeV$| <$ 40 MeV
- Everything not a $\nu_\mu/\bar{\nu}_\mu$CC, is either $\nu_e/\bar{\nu}_e$CC or NC
- Using transition radiation to separate $e^\pm$/hadrons (0.1% mis-ID)

FHC sample	$N_{ev}/10^{21}$POT/5t	Efficiency	Purity (and bkgs)
ν_μCC 1-track QE enhanced	860k	36%	73% CCQE (22% CC1$\pi^\pm$)
ν_μCC 2-track QE enhanced	455k	20%	78% CCQE (18% CC1$\pi^\pm$)
ν_μCC 1$\pi^\pm$	1,600k	41%	84% CC1$\pi^\pm$ (6% CC2$\pi^\pm$)
ν_μCC 1π^0	350k	22%	59% CC1π^0 (21% CC1$\pi^\pm$+1π^0)
ν_μCC 1$\pi^\pm$+1π^0	235k	17%	66% CC1$\pi^\pm$+1π^0 (25% CC$>$ 2π)
ν_μCC other	5,400k	73%	44% CCother
Wrong-sign ν_μCC inclusive	1,200k	93%	92% $\bar{\nu_\mu} CC$
ν_eCC inclusive	190k	80%	81% ν_eCC (15% NC)
NC inclusive	4,130k	66%	55% NC

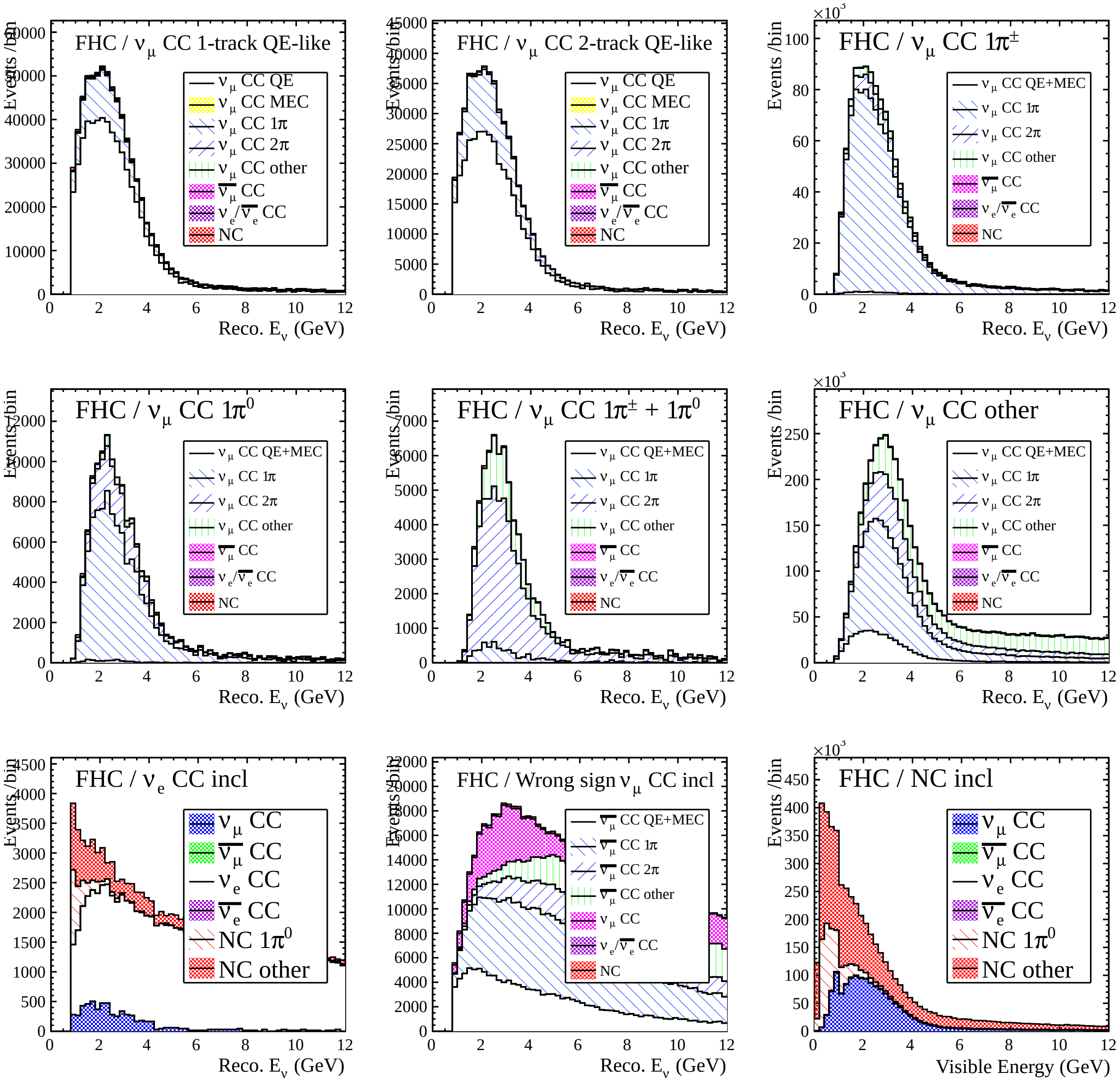
VALOR/DUNE-ND: Example nominal ND spectra



Nominal ND E_{reco} (or $E_{visible}$) spectra are shown for the 9 FHC samples included in the 2015v1 VALOR DUNE-ND fit.

The contributions from different y_{reco} ranges are shown.

VALOR/DUNE-ND: Example nominal ND spectra



Nominal ND E_{reco} (or $E_{visible}$) spectra are shown for the 9 FHC samples included in the 2015v1 DUNE LBNE-ND fit.

In the fit, 52 true reaction mode components are kept track of for each sample. Here these components have been bundled in just a **few broad categories** and their **contribution to each sample is shown**.

Systematics

The next logical step is to **implement systematics in the flux, cross-section and detector model**.

- This allows us to study changes to the event rate model for each sample included in the analysis.

Notice that this is still in the **prototyping phase**, so the list of systematics is **far from complete**. In particular:

- Many **more GENIE model parameters**, for which we have written corresponding reweighting functions, need **to be included**.
  - And, certain systematics we know we want to include have no GENIE reweighting function, so we neeed to develop these.
- The **detector systematics are virtually non-existest** (just a simple overall efficiency error for each sample).
- Need to employ VALOR facilities to **enable non-linear** systematics (i.e. systematics for which a **response function** (typically implemented as a cubic spline) is needed for every kinematical bin).

Systematics ib VALOR/DUNE-ND analysis

51 parameters are included in the 2015v1 VALOR/DUNE-ND analysis.

- f (FHC; $\Phi\nu_\mu$; 0-2.0 GeV)
- f (FHC; $\Phi\nu_\mu$; 2.0-2.5 GeV)
- f (FHC; $\Phi\nu_\mu$; 2.5-3.0 GeV)
- f (FHC; $\Phi\nu_\mu$; 3.0-3.5 GeV)
- f (FHC; $\Phi\nu_\mu$; 3.5-4.0 GeV)
- f (FHC; $\Phi\nu_\mu$; 4.0-5.0 GeV)
- f (FHC; $\Phi\nu_\mu$; 5.0-7.0 GeV)
- f (FHC; $\Phi\nu_\mu$; 7.0-10.0 GeV)
- f (FHC; $\Phi\nu_\mu$; 10.0-25.0 GeV)
- f (FHC; $\Phi\nu_\mu$; $>$ 25.0 GeV)
- f (FHC; $\Phi\bar{\nu}_\mu$; 0-3.0 GeV)
- f (FHC; $\Phi\bar{\nu}_\mu$; 3.0-5.0 GeV)
- f (FHC; $\Phi\bar{\nu}_\mu$; 5.0-7.0 GeV)
- f (FHC; $\Phi\bar{\nu}_\mu$; 7.0-10.0 GeV)
- f (FHC; $\Phi\bar{\nu}_\mu$; $>$ 10.0 GeV)
- f (FHC; $\Phi\nu_e/\bar{\nu}_e$; 0-5.0 GeV)
- f (FHC; $\Phi\nu_e/\bar{\nu}_e$; 5.0-10.0 GeV)
- f (FHC; $\Phi\nu_e/\bar{\nu}_e$; $>$ 10.0 GeV)

- f (RHC; $\Phi\nu_\mu$; 0-3.0 GeV)
- f (RHC; $\Phi\nu_\mu$; 3.0-4.0 GeV)
- f (RHC; $\Phi\nu_\mu$; 4.0-5.0 GeV)
- f (RHC; $\Phi\nu_\mu$; 5.0-7.0 GeV)
- f (RHC; $\Phi\nu_\mu$; 7.0-10.0 GeV)
- f (RHC; $\Phi\nu_\mu$; 10.0-25.0 GeV)
- f (RHC; $\Phi\nu_\mu$; $>$ 25.0 GeV)
- f (RHC; $\Phi\bar{\nu}_\mu$; 0-2.0 GeV)
- f (RHC; $\Phi\bar{\nu}_\mu$; 2.0-3.0 GeV)
- f (RHC; $\Phi\bar{\nu}_\mu$; 3.0-4.0 GeV)
- f (RHC; $\Phi\bar{\nu}_\mu$; 4.0-5.0 GeV)
- f (RHC; $\Phi\bar{\nu}_\mu$; 5.0-7.0 GeV)
- f (RHC; $\Phi\bar{\nu}_\mu$; 7.0-10.0 GeV)
- f (RHC; $\Phi\bar{\nu}_\mu$; 10.0-25.0 GeV)
- f (RHC; $\Phi\bar{\nu}_\mu$; $>$ 25.0 GeV)
- f (RHC; $\Phi\nu_e/\bar{\nu}_e$; 0-5.0 GeV)
- f (RHC; $\Phi\nu_e/\bar{\nu}_e$; 5.0-10.0 GeV)
- f (RHC; $\Phi\nu_e/\bar{\nu}_e$; $>$ 10.0 GeV)

- f (σ; CC QE)
- f (σ; CC $1\pi^{\pm}$)
- f (σ; CC $1\pi^{0}$)
- f (σ; CC other)
- f (σ; NC)
- f (σ; ν_e/ν_μ)

- f (ϵ; ν_μ CC; 1-trk QE-like)
- f (ϵ; ν_μ CC; 2-trk QE-like)
- f (ϵ; ν_μ CC; $1\pi^{\pm}$)
- f (ϵ; ν_μ CC; $1\pi^{0}$)
- f (ϵ; ν_μ CC; $1\pi^{\pm}$+$1\pi^{0}$)
- f (ϵ; ν_μ CC; other)
- f (ϵ; ν_e CC)
- f (ϵ; Wrong sign ν_μ CC)
- f (ϵ; NC)

Φ: flux
σ: cross-section
ϵ: efficiency

Prior systematic constraints

Again, just something to start with.

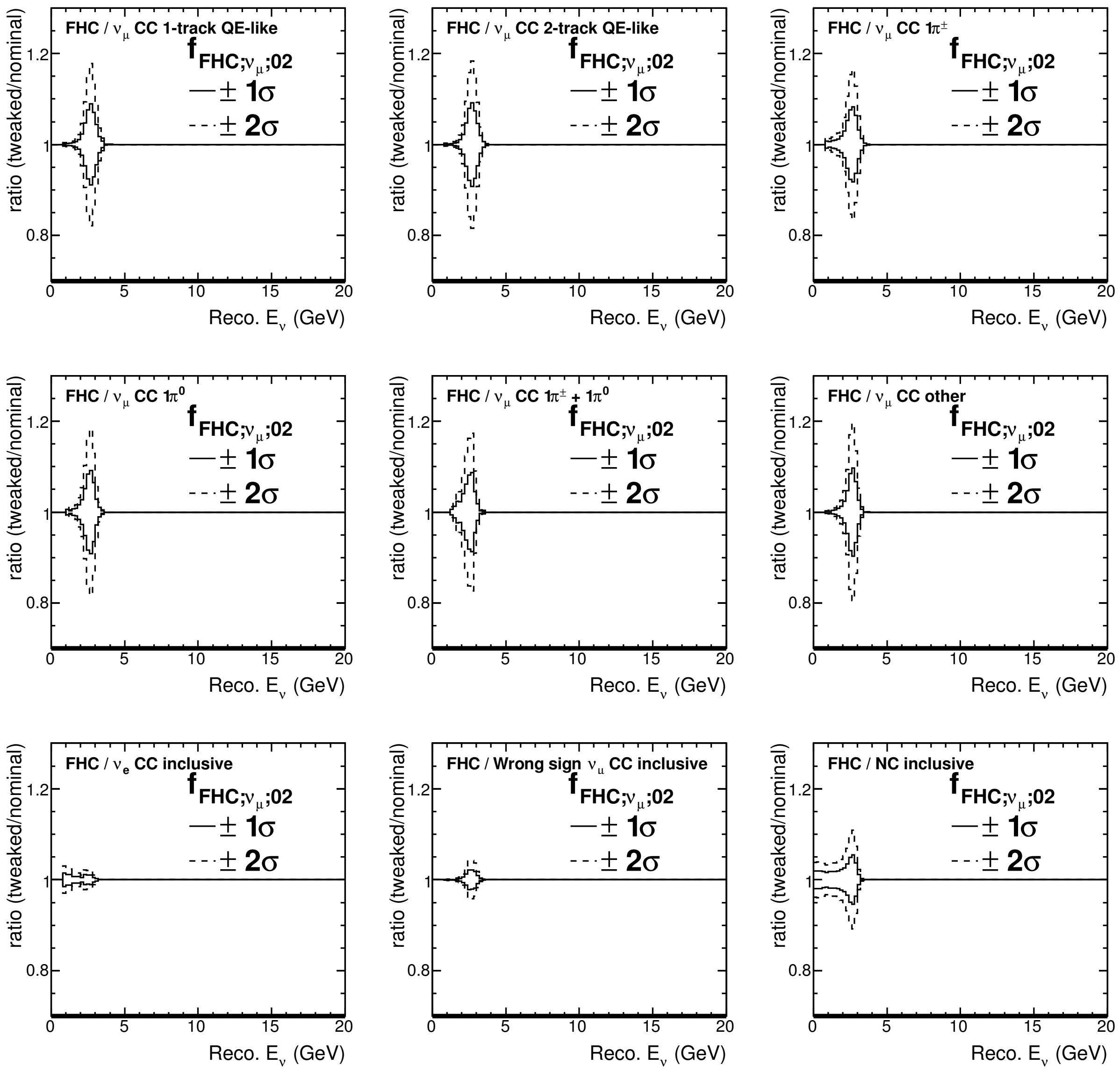
Prior constraints and their correlations will need to come from

- Flux simulation tunes (⇒ for the flux parameters).
- GENIE tunes (⇒ for the interaction model parameters).
- Guesstimates, previous experience and analyses of fully simulated / reconstructed DUNE-ND control samples (⇒ for the detector model parameters).

External to VALOR.

- f (FHC; $\Phi\nu_\mu$) → 15%
- f (FHC; $\Phi\bar{\nu}_\mu$) → 20%
- f (FHC; $\Phi\nu_e/\bar{\nu}_e$) → 20%
- f (FHC; $\Phi\nu_\mu$) → 20%
- f (FHC; $\Phi\bar{\nu}_\mu$) → 20%
- f (FHC; $\Phi\nu_e/\bar{\nu}_e$) → 20%
- f (σ; CC QE) → 15%
- f (σ; CC $1\pi^\pm$) → 25%
- f (σ; CC $1\pi^0$) → 25%
- f (σ; CC other) → 20%
- f (σ; NC) → 35%
- f (σ; ν_e/ν_μ) → 5%
- f (ϵ; ν_μ CC; 1-trk QE-like) → 5%
- f (ϵ; ν_μ CC; 2-trk QE-like) → 5%
- f (ϵ; ν_μ CC; $1\pi^\pm$) → 5%
- f (ϵ; ν_μ CC; $1\pi^0$) → 5%
- f (ϵ; ν_μ CC; $1\pi^\pm+1\pi^0$) → 5%
- f (ϵ; ν_μ CC; other) → 5%
- f (ϵ; ν_e CC) → 7%

VALOR/DUNE-ND: Example systematic variation

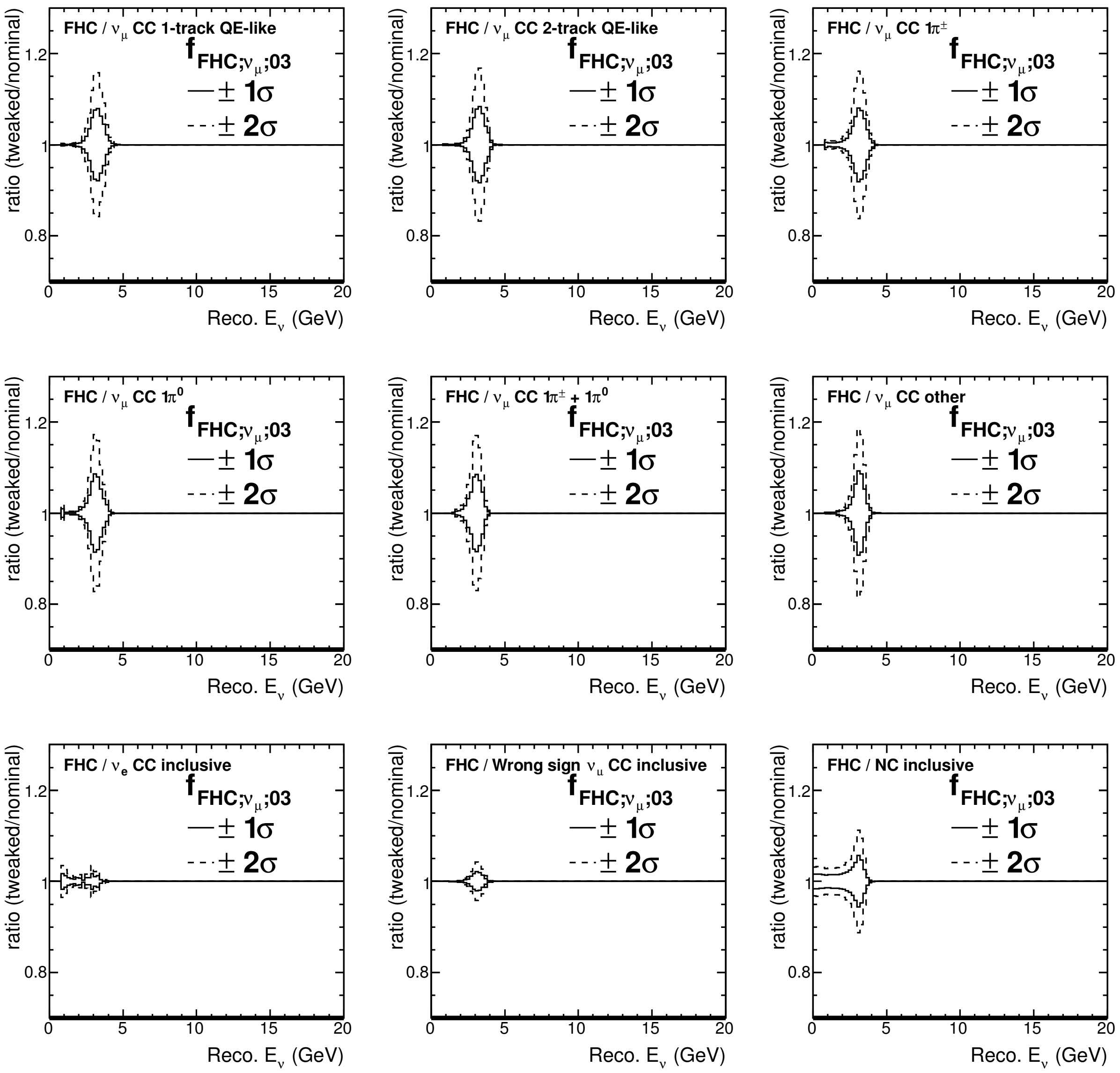


Effect of flux parameter
f(FHC; $\Phi\nu_\mu$; 2.5-3.0 GeV)

Shown for the 9 FHC samples (currently) included in the VALOR DUNE-ND fit.

Showing ratio of tweaked/nominal spectra for $\pm 1\sigma$ and $\pm 2\sigma$ variations of the given flux parameter.

VALOR/DUNE-ND: Example systematic variation

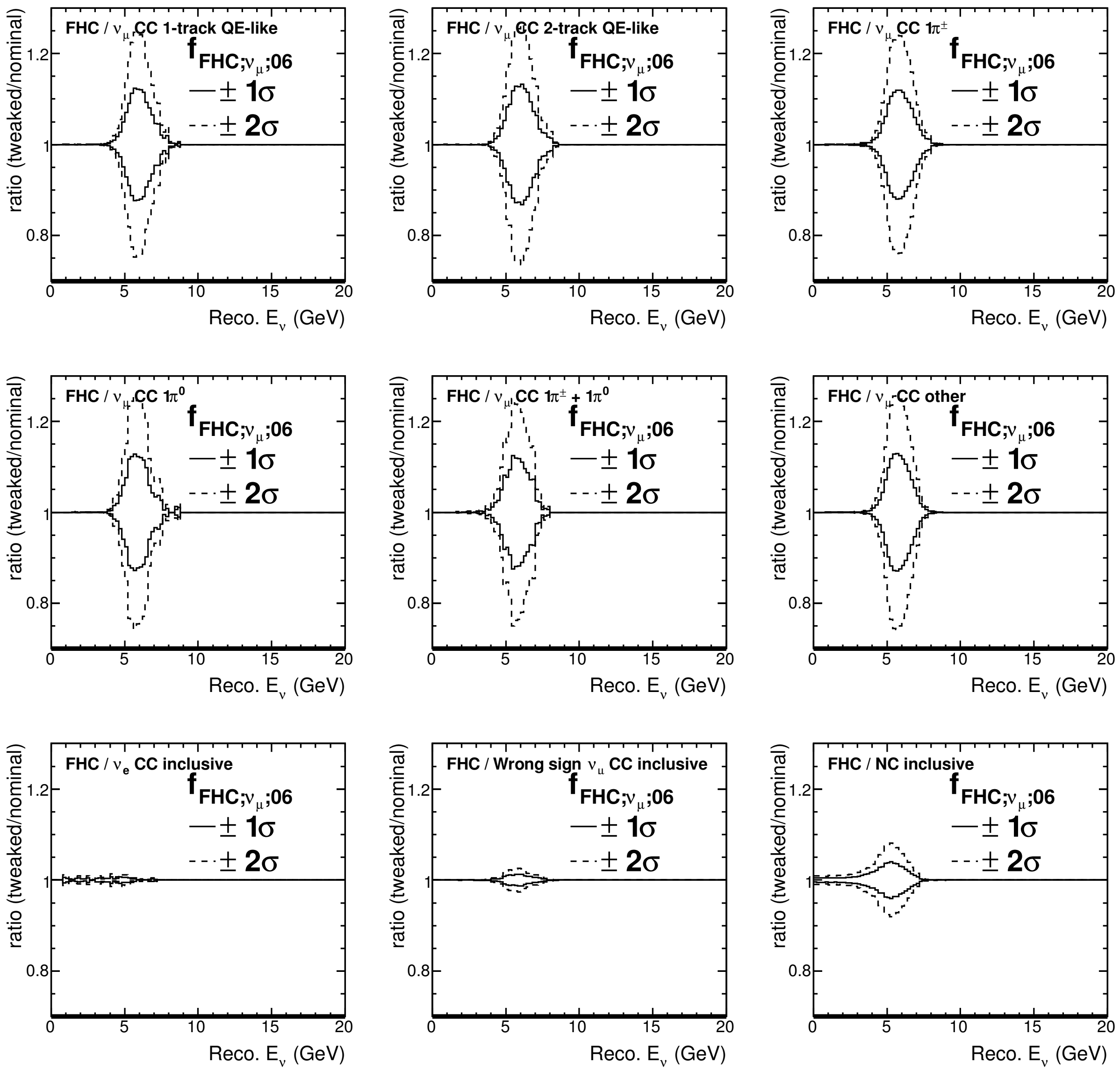


Effect of flux parameter
f(FHC; $\Phi\nu_\mu$; 3.0-3.5 GeV)

Shown for the 9 FHC samples (currently) included in the VALOR DUNE-ND fit.

Showing ratio of tweaked/nominal spectra for $\pm1\sigma$ and $\pm2\sigma$ variations of the given flux parameter.

VALOR/DUNE-ND: Example systematic variation

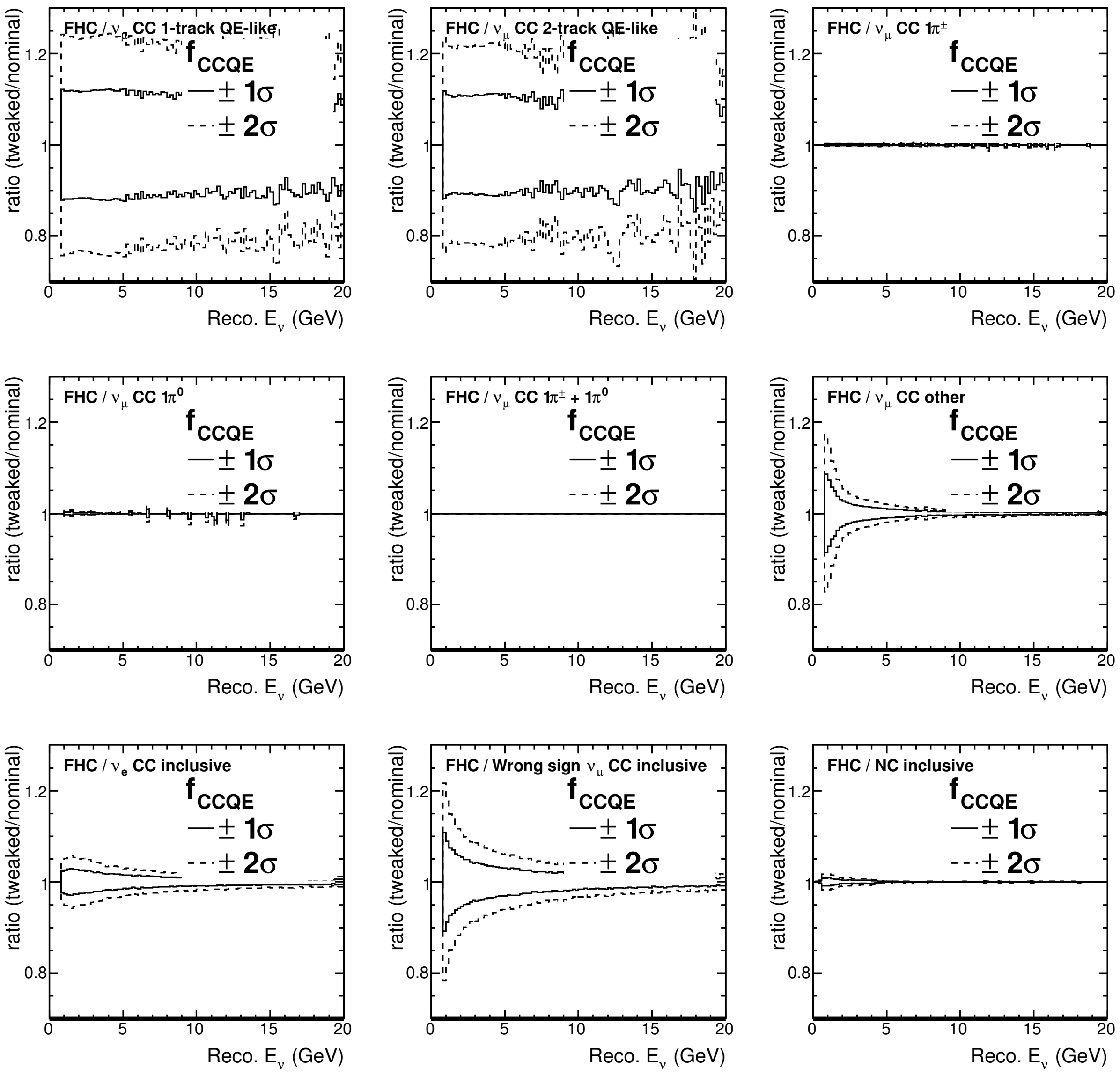


Effect of flux parameter **f(FHC; $\Phi\nu_\mu$; 5.0-7.0 GeV)**

Shown for the 9 FHC samples (currently) included in the VALOR DUNE-ND fit.

Showing ratio of tweaked/nominal spectra for $\pm 1\sigma$ and $\pm 2\sigma$ variations of the given flux parameter.

VALOR/DUNE-ND: Example systematic variation

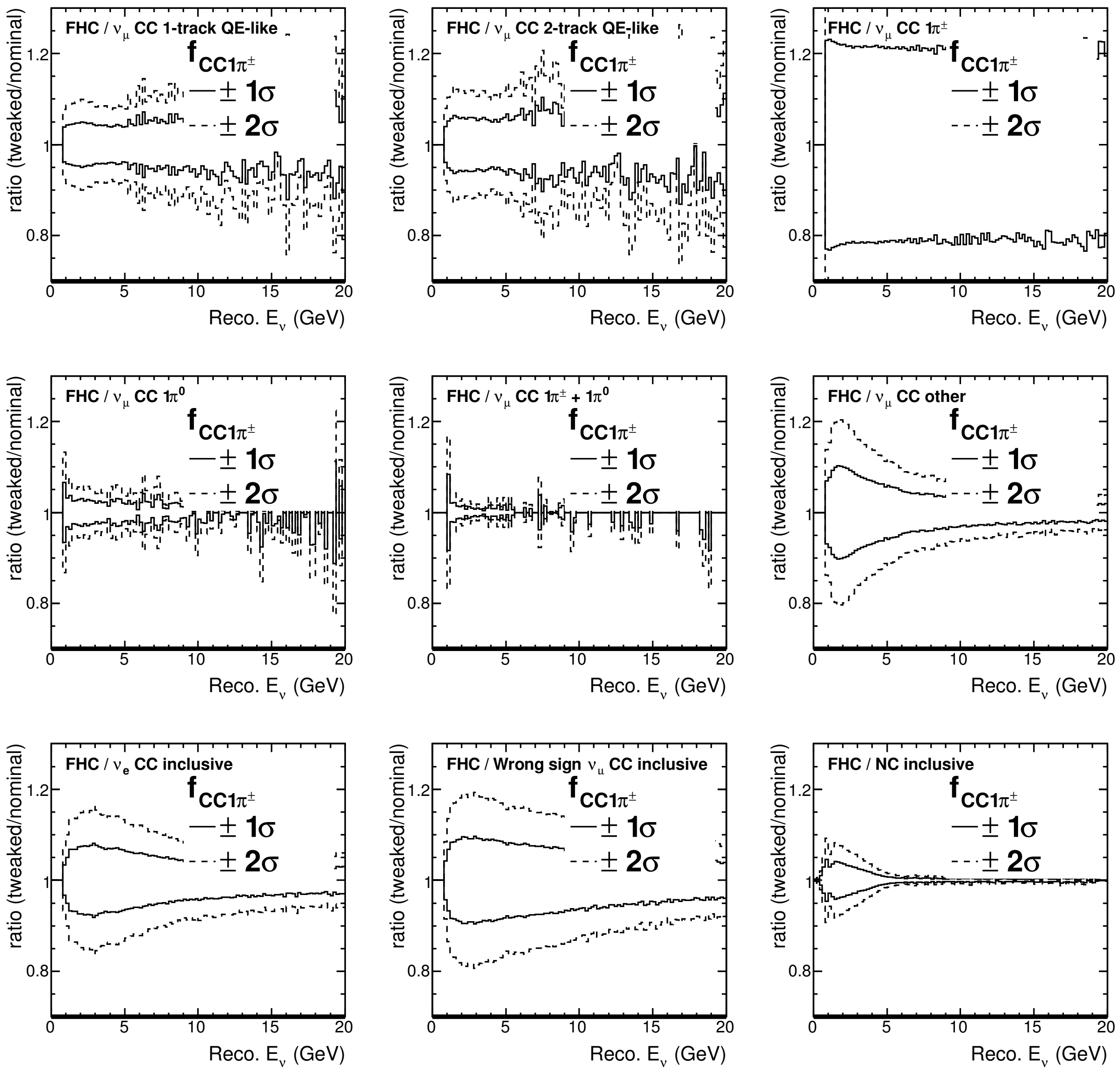


Effect of cross-section parameter $\mathbf{f(\sigma_{CCQE})}$

Shown for the 9 FHC samples (currently) included in the VALOR DUNE-ND fit.

Showing ratio of tweaked/nominal spectra for $\pm 1\sigma$ and $\pm 2\sigma$ variations of the given cross-section parameter.

VALOR/DUNE-ND: Example systematic variation

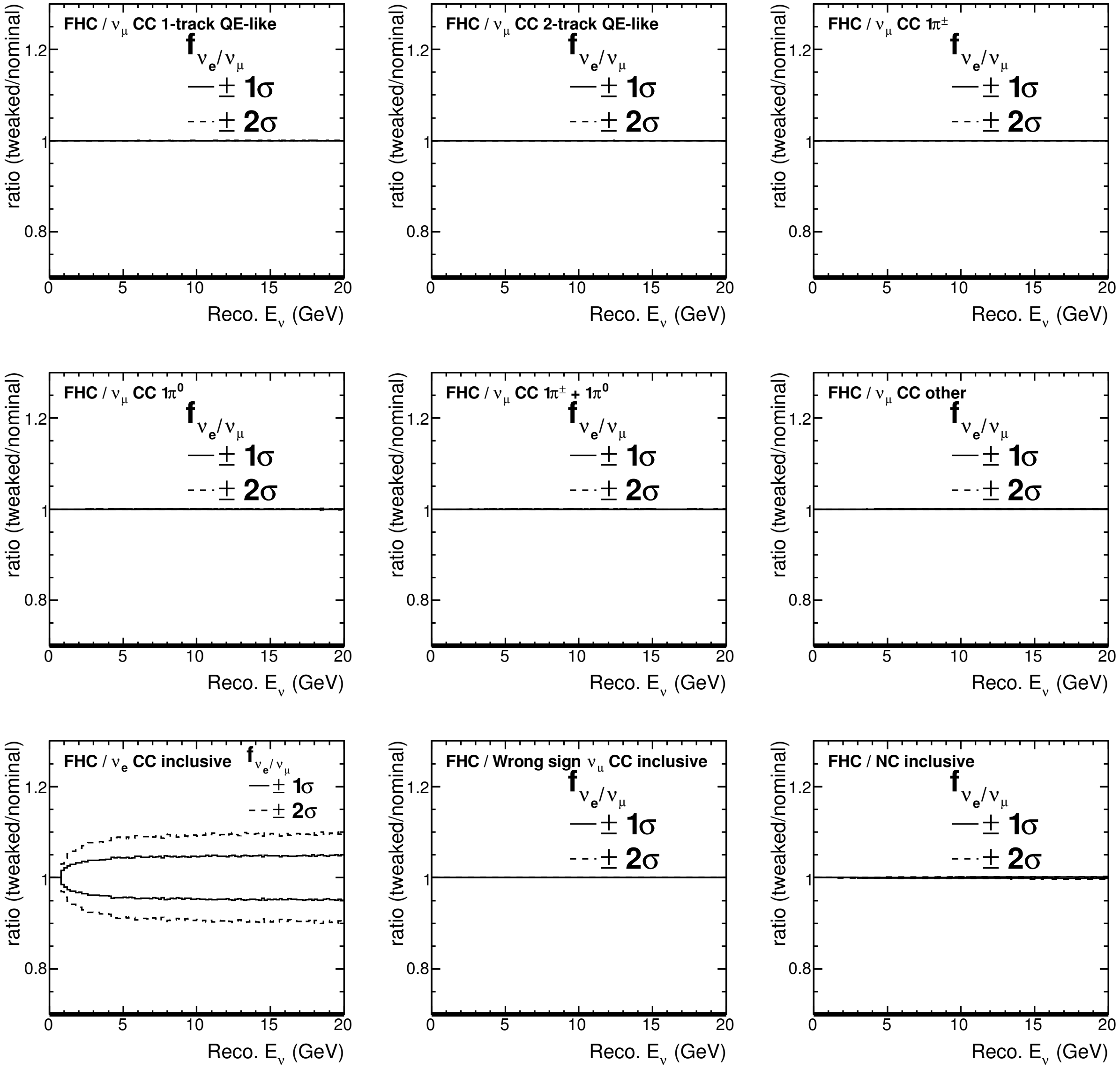


Effect of cross-section parameter **f**($\sigma_{CC1\pi^\pm}$)

Shown for the 9 FHC samples (currently) included in the VALOR DUNE-ND fit.

Showing ratio of tweaked/nominal spectra for $\pm 1\sigma$ and $\pm 2\sigma$ variations of the given cross-section parameter.

VALOR/DUNE-ND: Example systematic variation

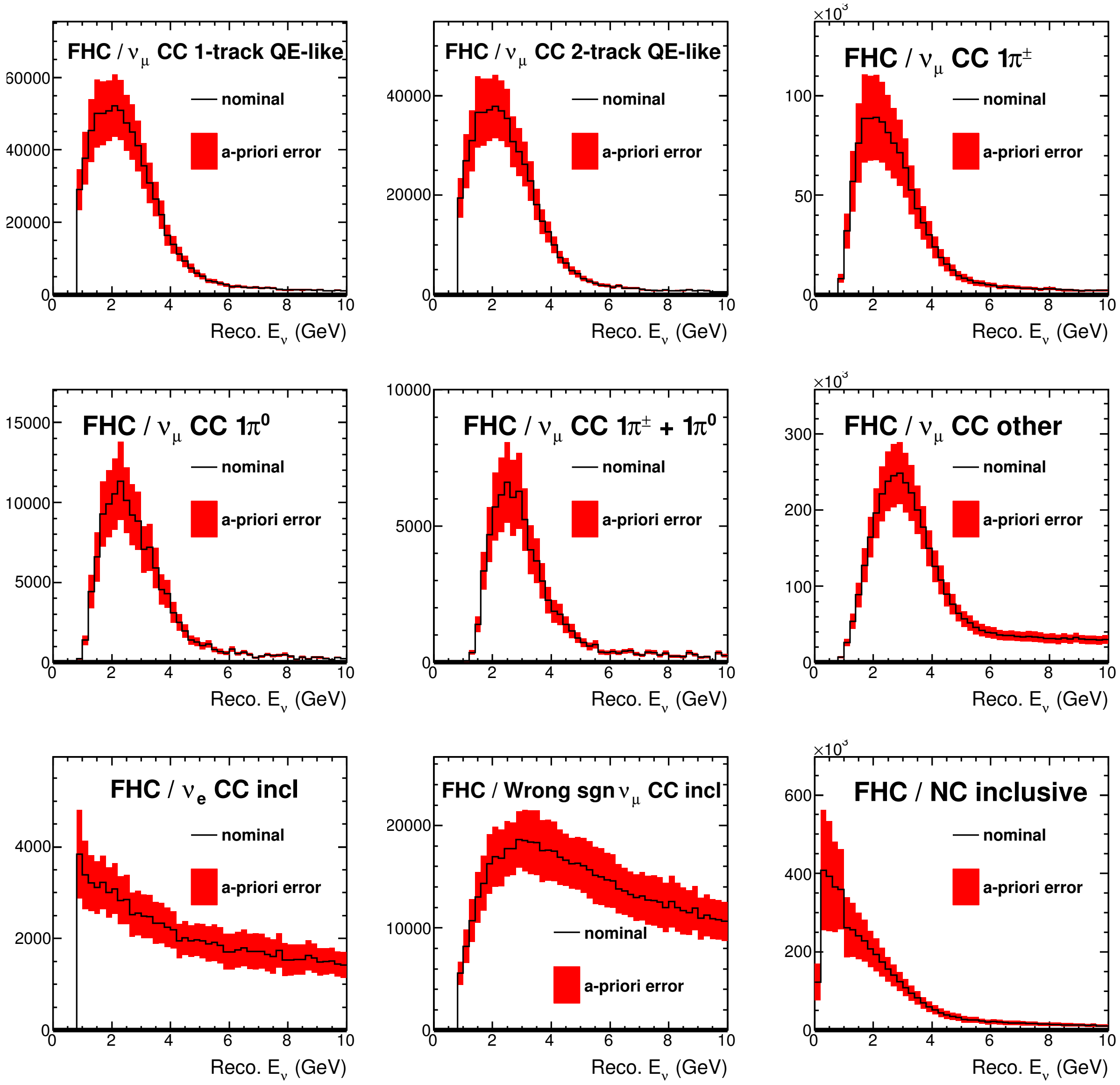


Effect of cross-section parameter **f**$(\sigma_{\nu_e CC}/\sigma_{\nu_\mu CC})$

Shown for the 9 FHC samples (currently) included in the VALOR DUNE-ND fit.

Showing ratio of tweaked/nominal spectra for $\pm 1\sigma$ and $\pm 2\sigma$ variations of the given cross-section parameter.

VALOR/DUNE-ND: A-priori (pre-fit) uncertainty



Generated N toy-MC experiments with flux, cross-section and efficiency systematic parameters thrown from their corresponding unconstrained (by DUNE) p.d.fs.

All flux and cross-section parameters were thrown simultaneously.

The red area indicates the size of the spread (1 standard deviation) around the default prediction for the 9 FHC samples (currently) included in the VALOR DUNE-ND fit.

Fitting method

We use a binned likelihood ratio method, implemented using MINUIT (*). The following quantity is minimized:

$$
\begin{aligned}
-2ln\lambda(\mathbf{f}_{\mathbf{\Phi}}, \mathbf{f}_{\sigma}; \mathbf{f}_{\epsilon}) = & 2 \cdot \sum_{samples} \sum_{i} \Big(n_i^{obs} \cdot ln(n_i^{obs}/n_i^{exp}) + (n_i^{exp} - n_i^{obs}) \Big) \\
& + (\mathbf{f}_{\mathbf{\Phi}} - \mathbf{f}_{\mathbf{\Phi};0})^T \cdot C_{\Phi}^{-1} \cdot (\mathbf{f}_{\mathbf{\Phi}} - \mathbf{f}_{\mathbf{\Phi};0}) \\
& + (\mathbf{f}_{\sigma} - \mathbf{f}_{\sigma;0})^T \cdot C_{\sigma}^{-1} \cdot (\mathbf{f}_{\sigma} - \mathbf{f}_{\sigma;0}) \\
& + (\mathbf{f}_{\epsilon} - \mathbf{f}_{\epsilon;0})^T \cdot C_{\epsilon}^{-1} \cdot (\mathbf{f}_{\epsilon} - \mathbf{f}_{\epsilon;0})
\end{aligned}
$$

where

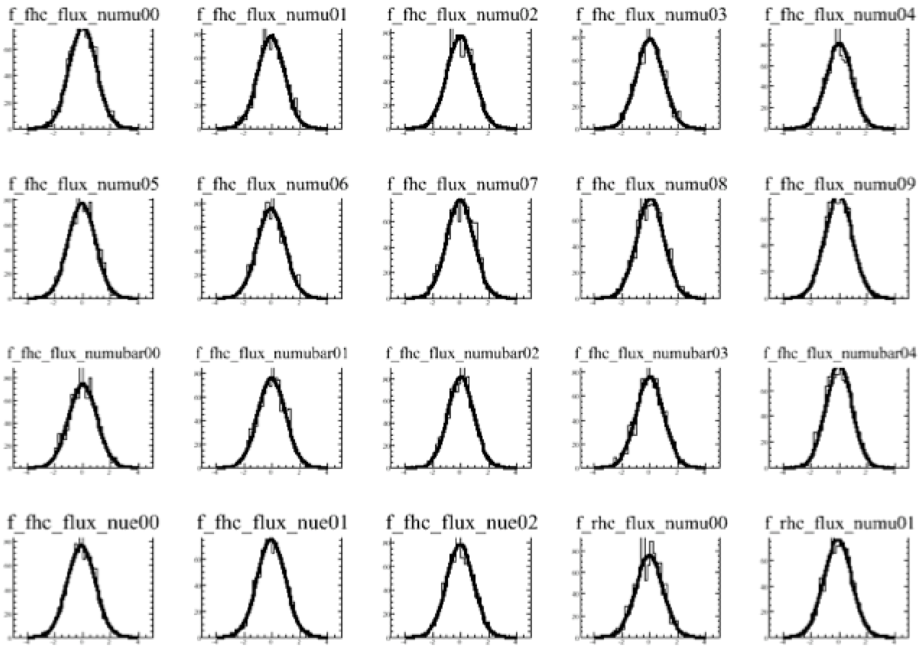
- f_{Φ} denotes flux systematics, f_{σ} interaction modelling systematics and f_{ϵ} detector systematics
- Index i loops over kinematic bins
- Prior constraints are included in the C_{Φ}, C_{σ} and C_{ϵ} covariance matrices.

Several other minimization methods available via VALOR/GSL interface: eg Simulated annealing, Levemberg-Marquardt,..

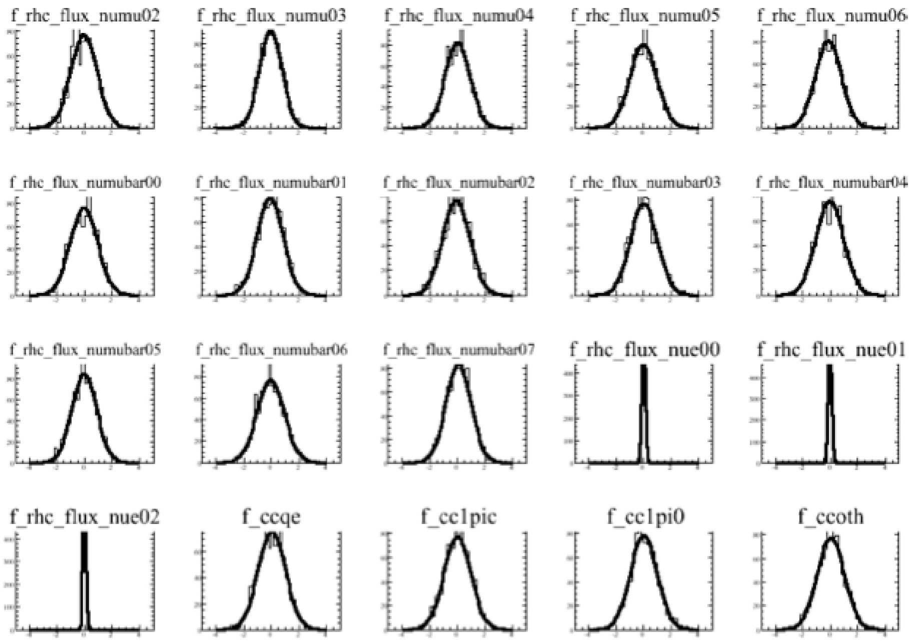
VALOR/DUNE-ND fit validation

Pulls from fits to 1k toy-MC experiments generated with randomized systematic parameters (according to priors) and statistical fluctuations. MIGRAD MINUIT errors were used.

parameters 1-20:



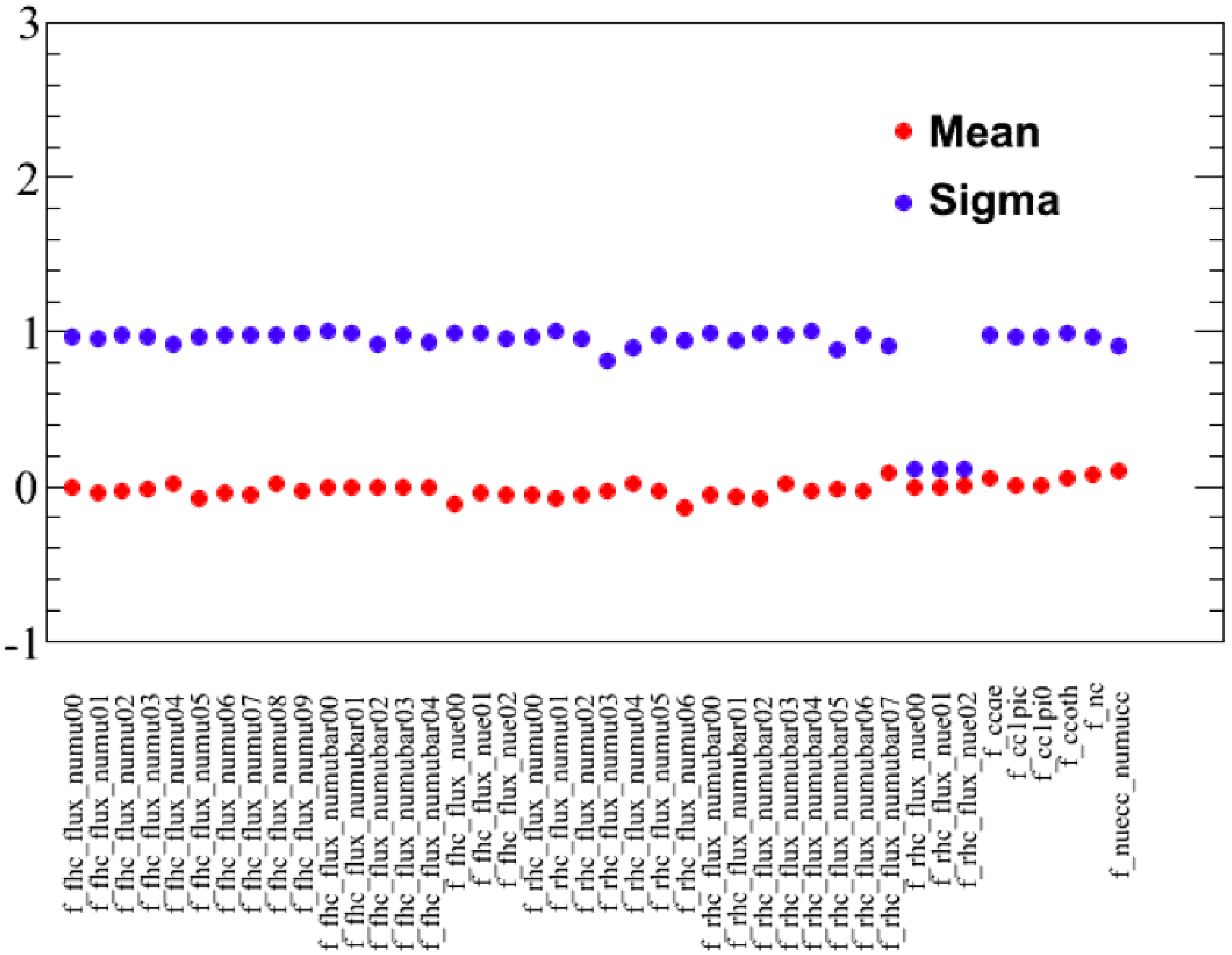
parameters 21-40:



The 3 odd ones are RHC ν_e flux systematics - we currently miss a RHC ν_e MC sample

VALOR/DUNE-ND fit validation

Pulls from fits to 1k toy-MC experiments generated with randomized systematic parameters (according to priors) and statistical fluctuations. MIGRAD MINUIT errors were used.



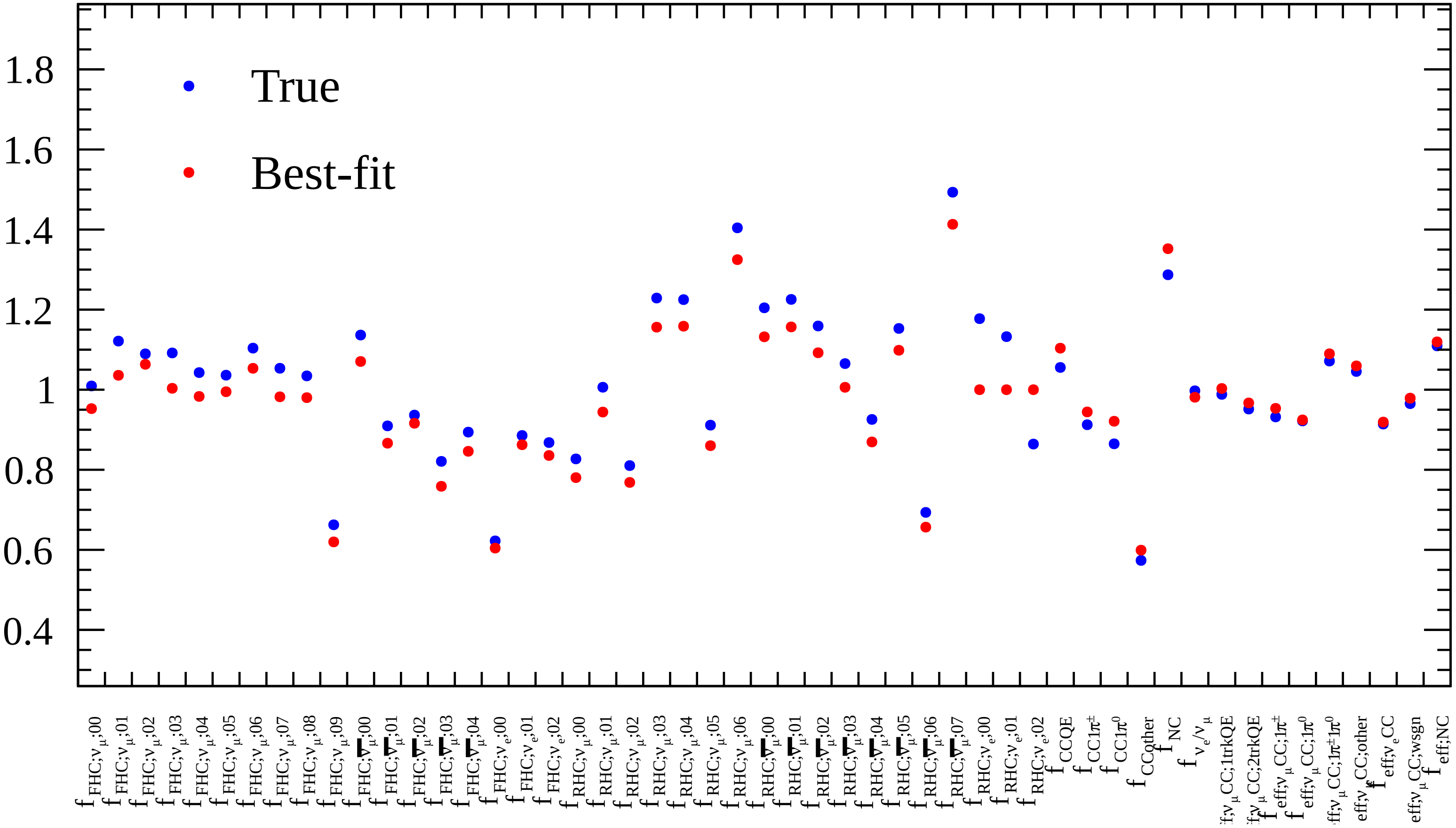
$$\text{pull} = (f_{bf} - f_0) \Big/ \sqrt{\sigma^2_{prior} - \sigma^2_{fit}}$$

where

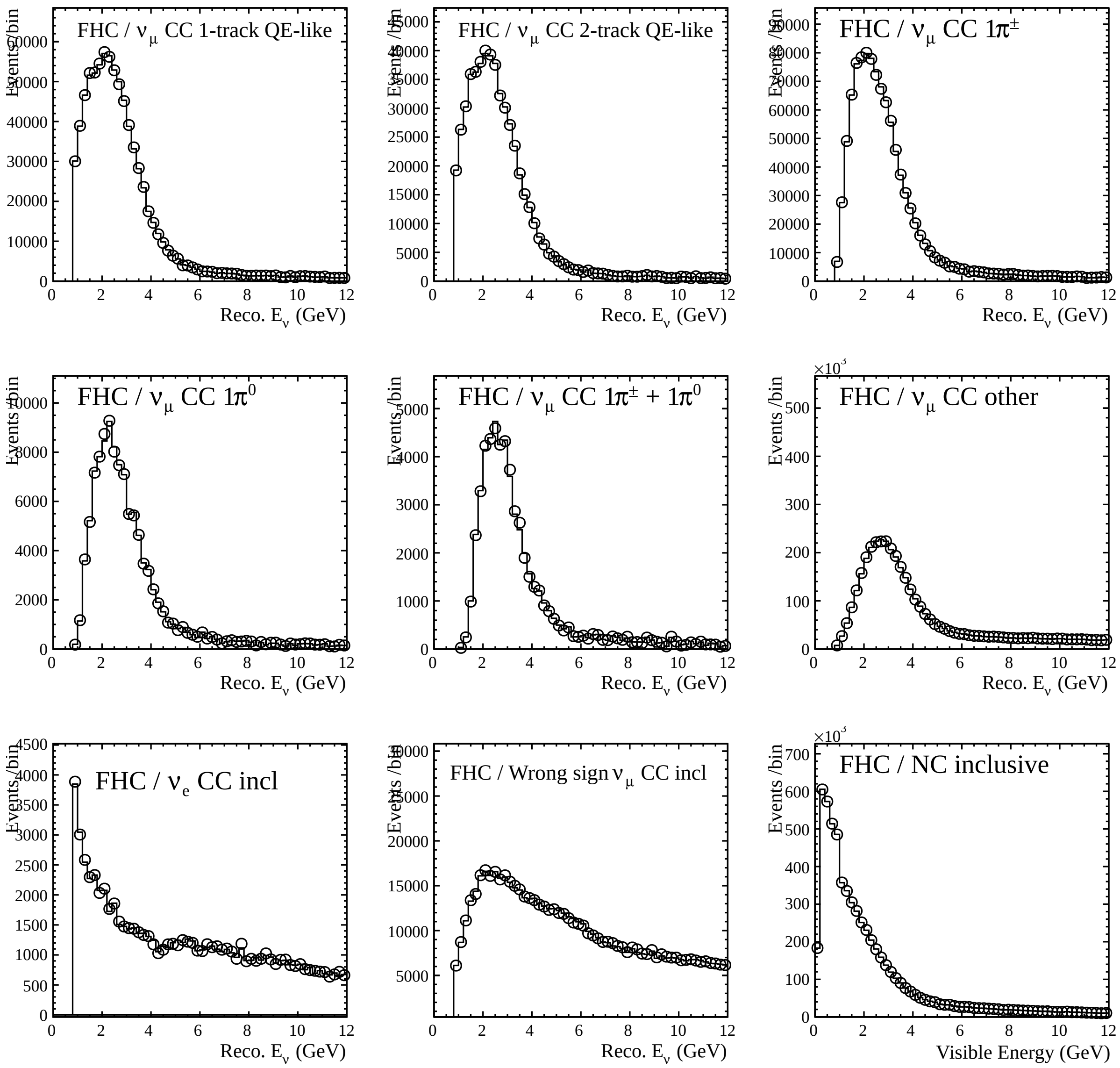
- f_{bf}: best-fit value of systematic parameter f
- f_0: nominal value
- σ_{prior}: prior error on f
- σ_{fit}: fit (MIGRAD) error on f

VALOR/DUNE-ND: Example toy-MC fit

Comparison of true and best-fit parameters for a toy-MC experiment:

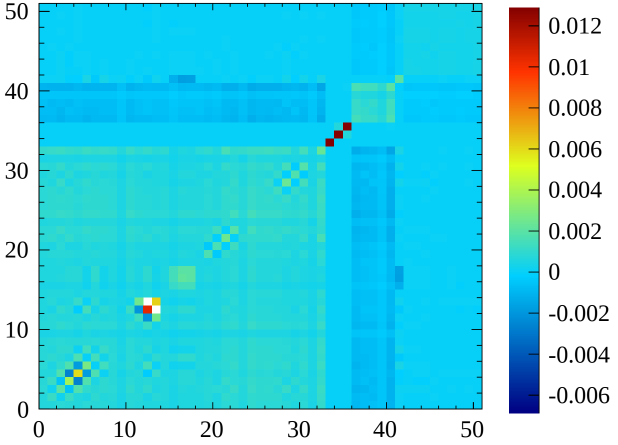


VALOR/DUNE-ND: Example toy-MC fit



Toy-MC and best-fit energy spectra shown for the 9 FHC samples (currently) included in the VALOR LBNE-ND fit

The covariance matrix of fit parameters is shown below:



Computing flux and cross-section parameter sensitivities

To generate the DUNE-ND sensitivity to a particular physics parameter P, at a particular value λ, the following procedure was used.

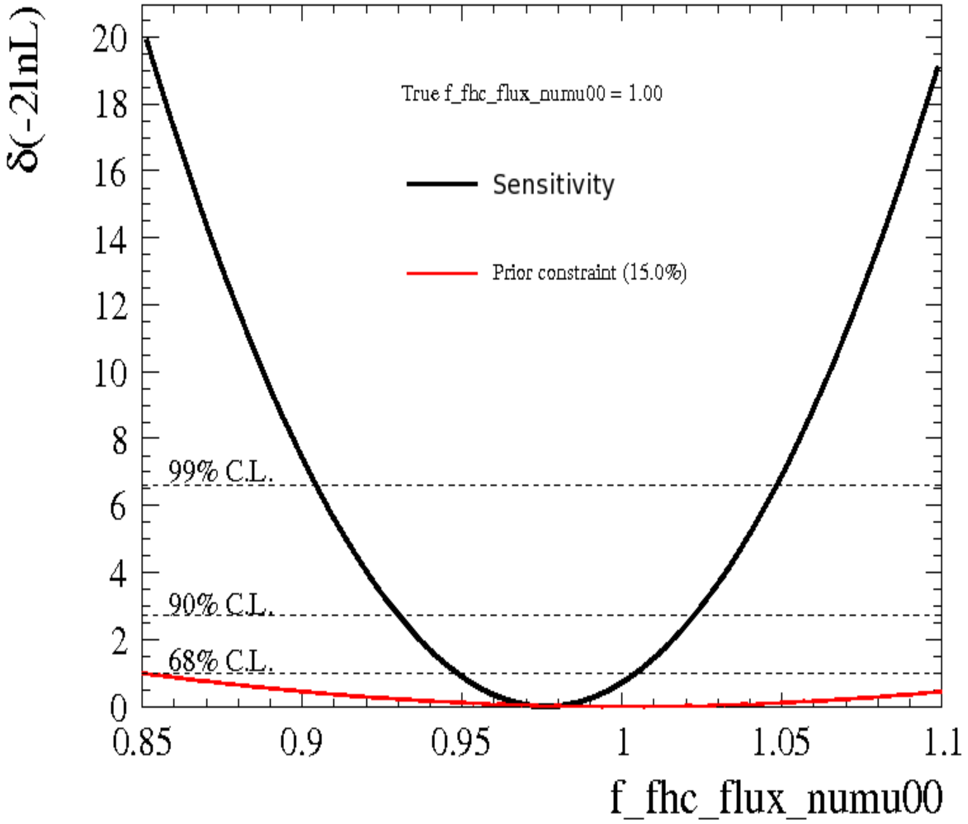
- Fix P to λ and randomize the other N-1 parameters according to priors
- Generate a toy-MC experiment (spectra for 9 FHC + 9 RHC distributions)
- Loop over M values of P in range $[\lambda_{min}, \lambda_{max}]$
- For each value in $[\lambda_{min}, \lambda_{max}]$, fix P to that value and fit the other N-1 parameters

The above gives us the best-fit statistic, as function of λ for 1 toy-MC experiment. The procedure is repeated for N_{toy} toy experiments and the best-fit statistic curves are averaged (Examples in next pages).

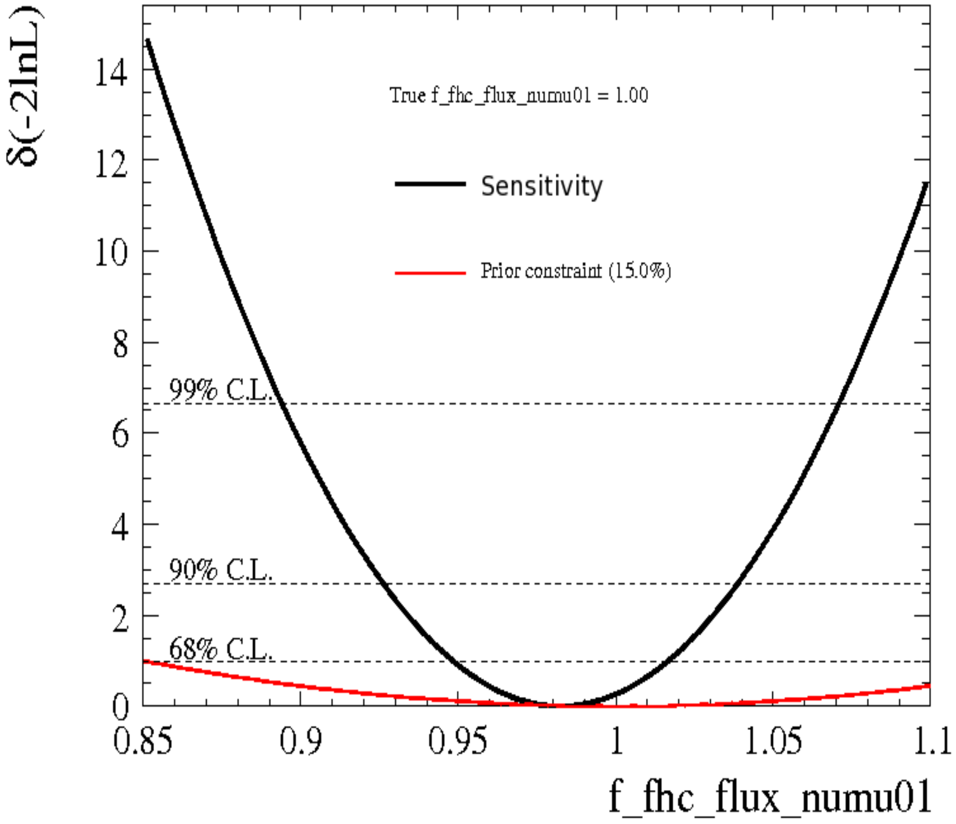
Note: The above is prohibitively expensive as the fit complexity increases. The fit time is likely to be measured in days, and we will soon start making use of approximate methods (Asimov datasets; arXiv:1110.5002).

VALOR/DUNE-ND: Preliminary sensitivities

FHC ν_μ flux in 0-2 GeV

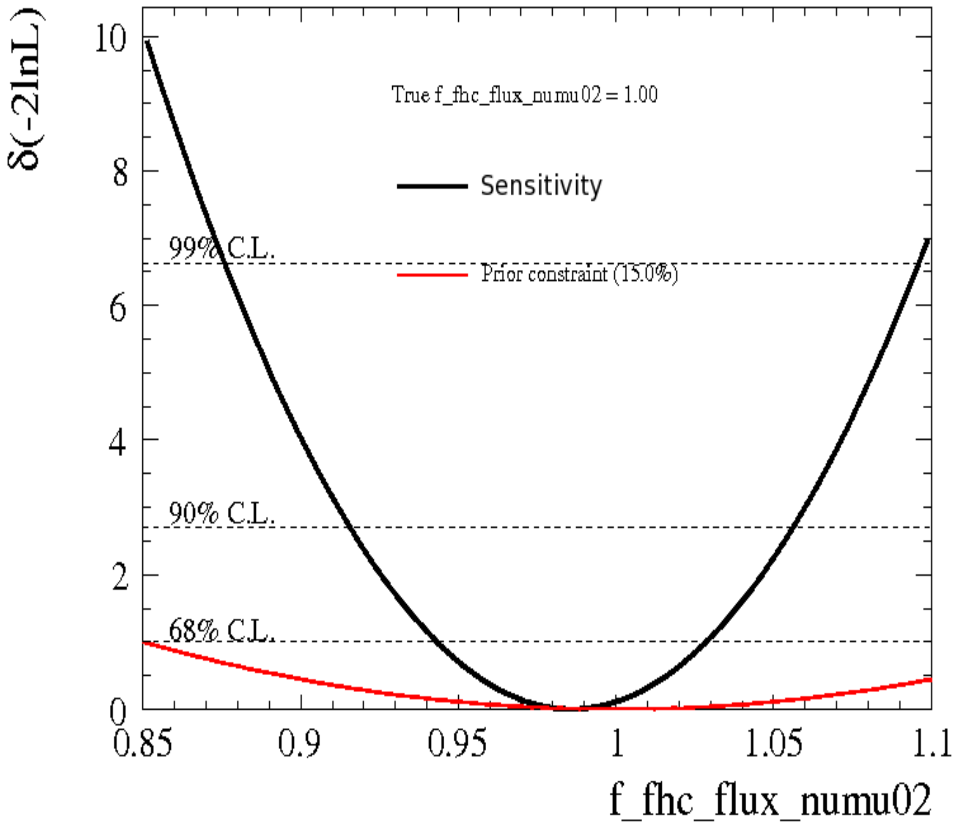


FHC ν_μ flux in 2-2.5 GeV

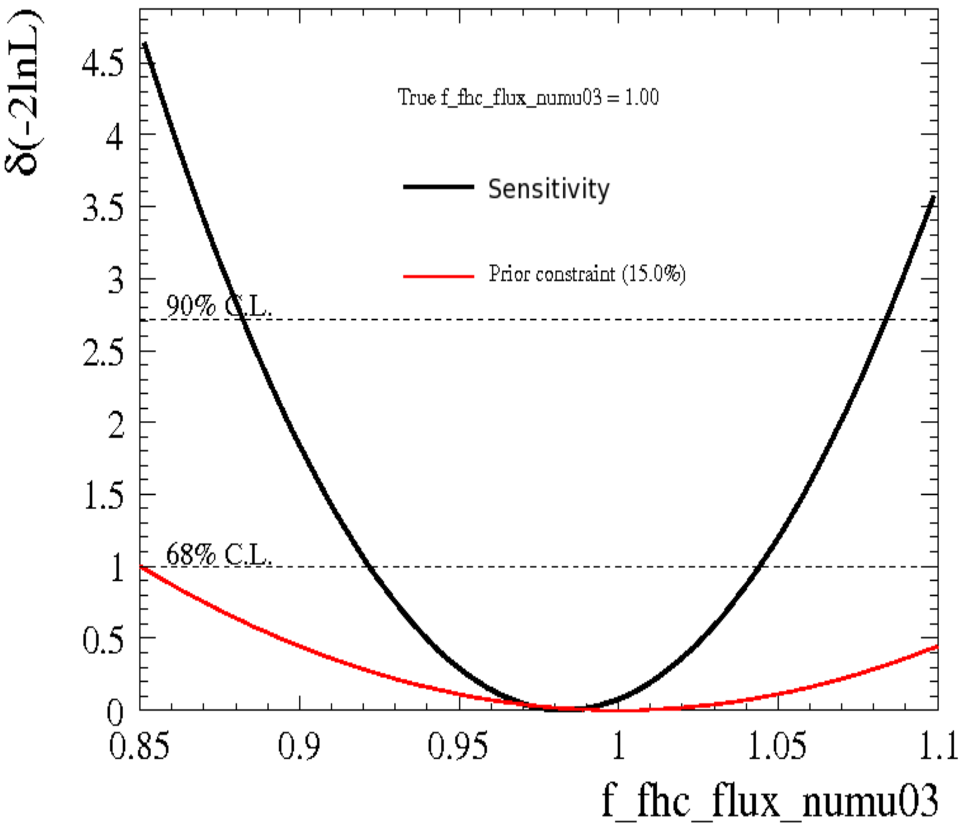


VALOR/DUNE-ND: Preliminary sensitivities

FHC ν_μ flux in 2.5-3 GeV

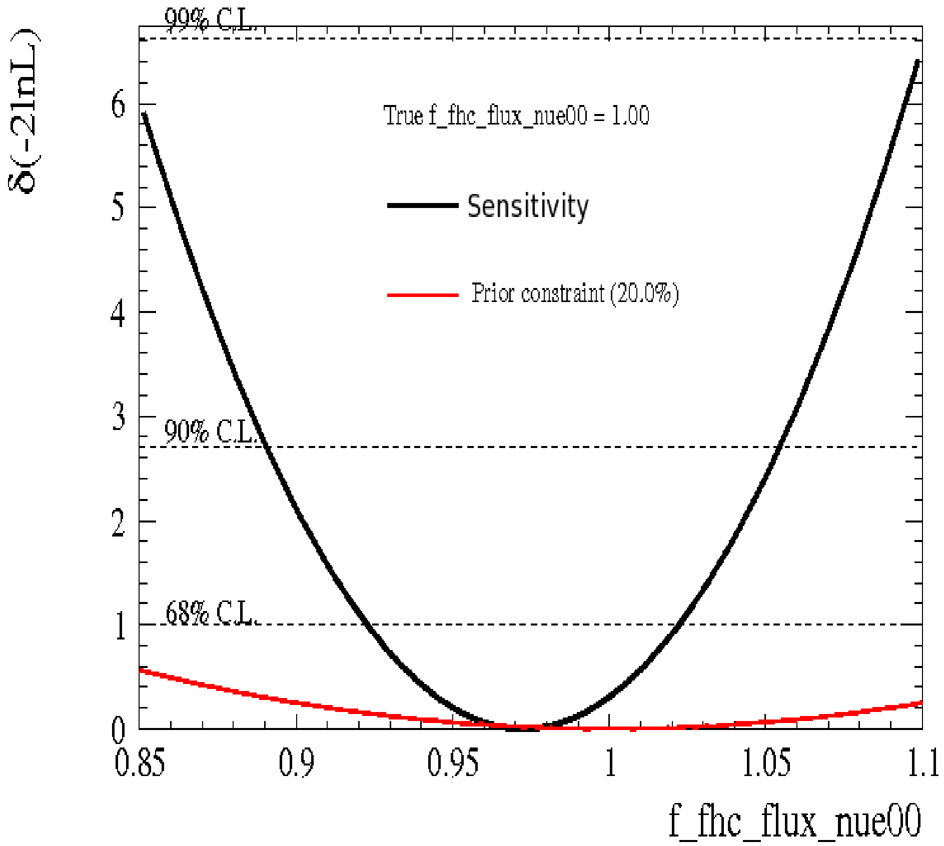


FHC ν_μ flux in 3-3.5 GeV

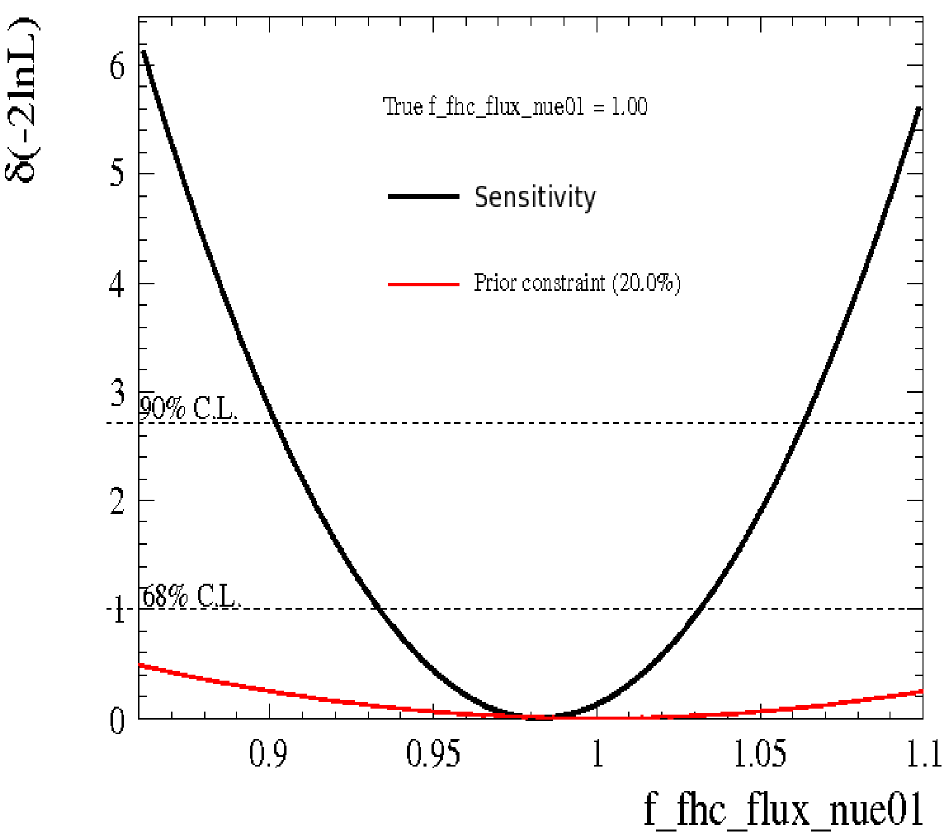


VALOR/DUNE-ND: Preliminary sensitivities

FHC ν_e flux in 0-5 GeV

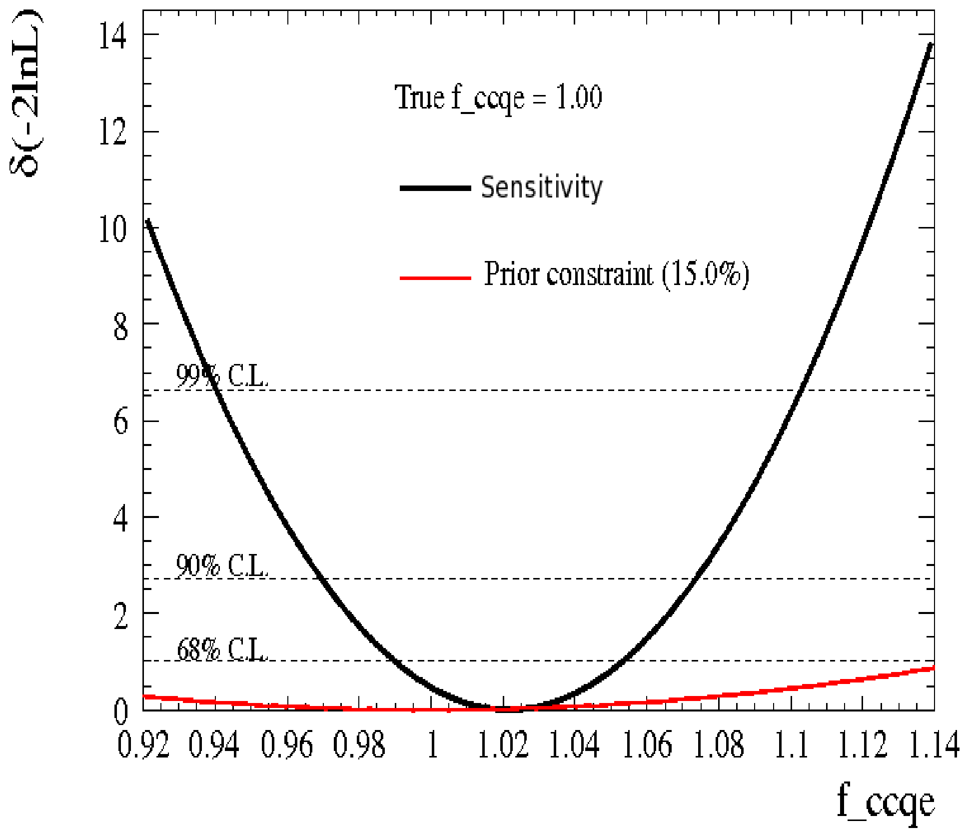


FHC ν_e flux in 5-10 GeV

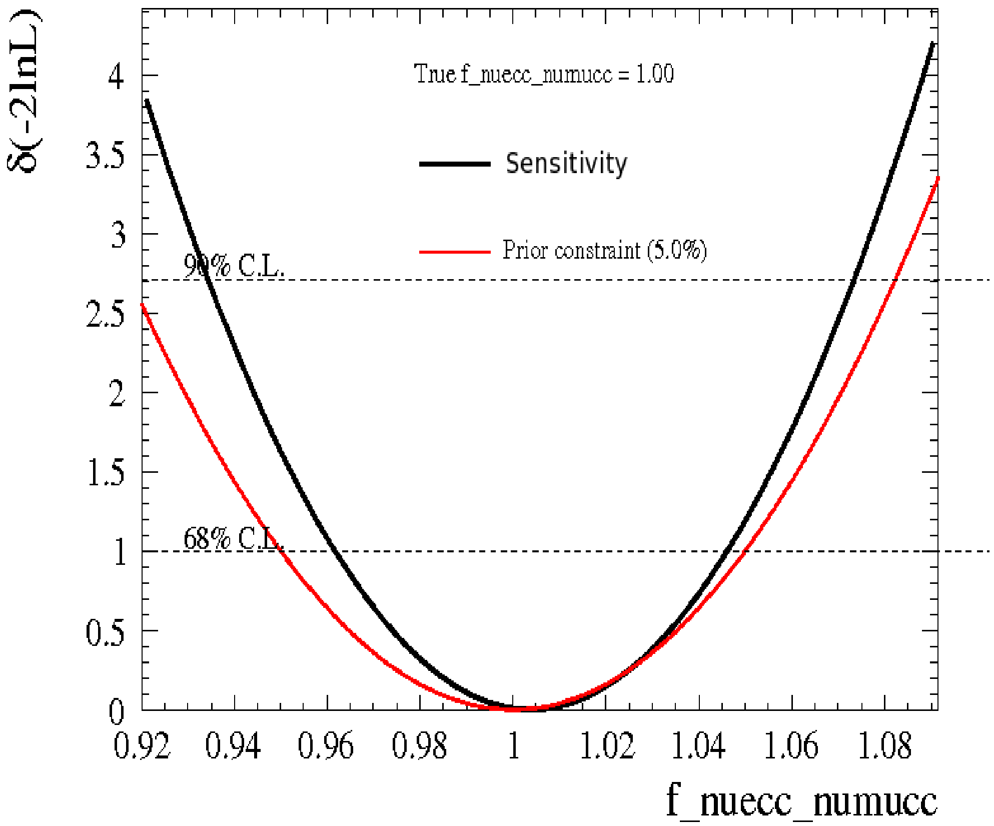


VALOR/DUNE-ND: Preliminary sensitivities

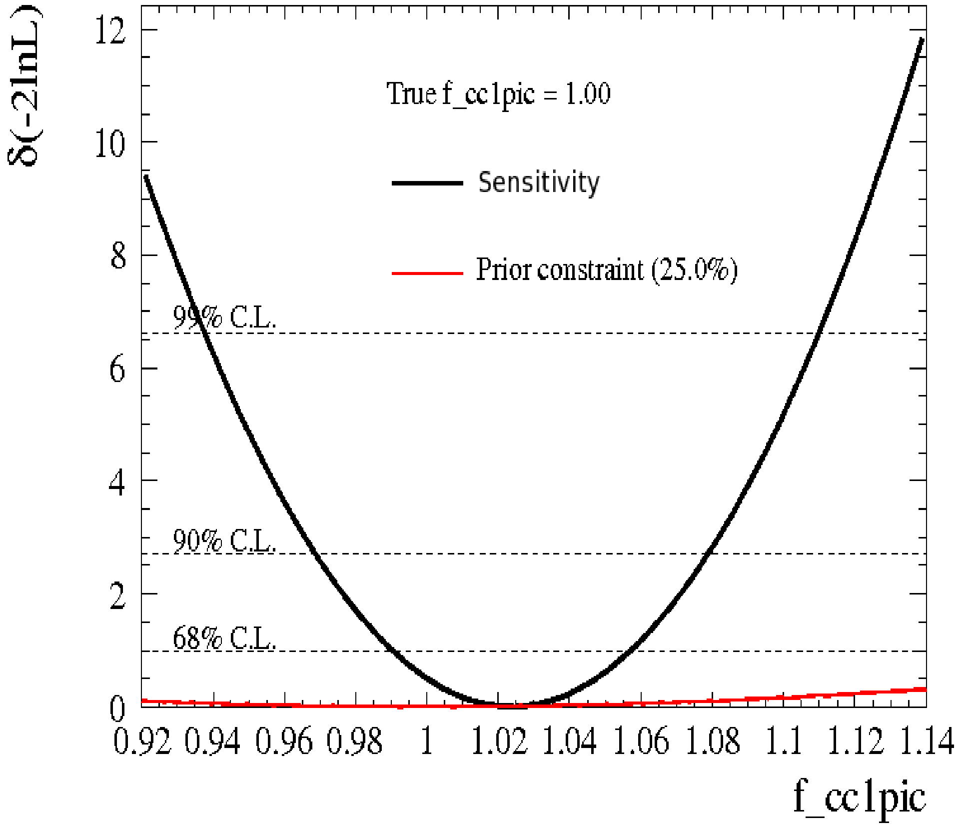
CCQE cross-section



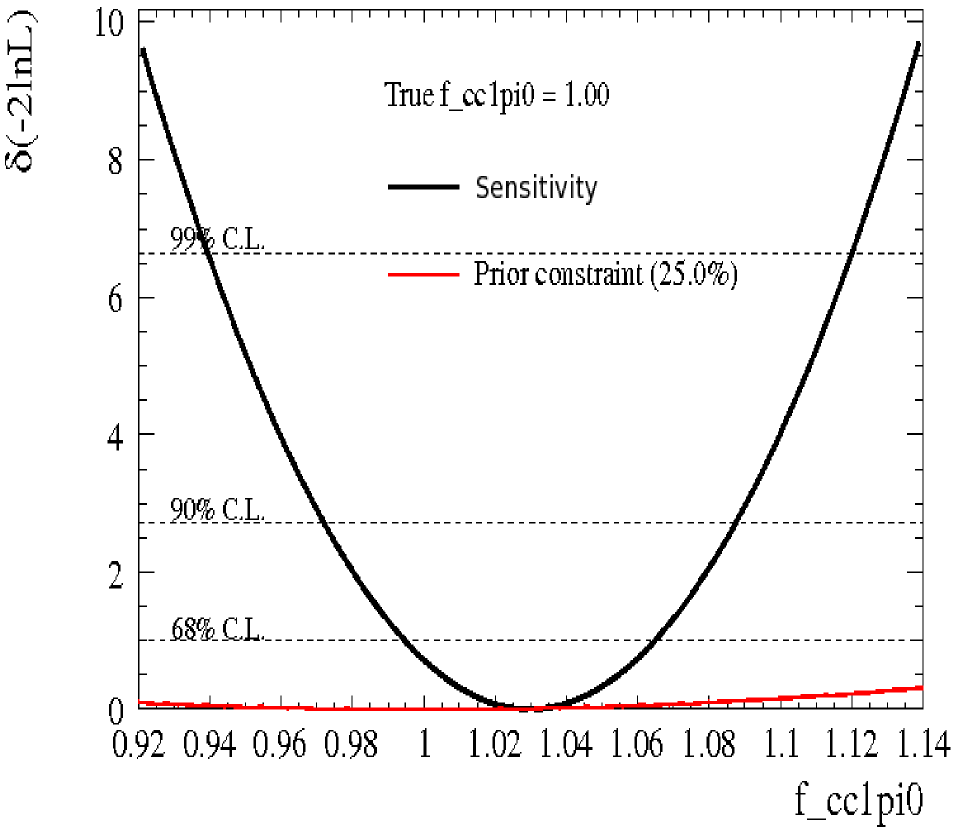
ν_eCC/ν_μCC cross-section ratio



VALOR/DUNE-ND: Preliminary sensitivities



$CC1\pi^{\pm}$ cross-section



$CC1\pi^{0}$ cross-section

VALOR: On-going work

- Revamping analysis shown at CETUP14
    - Bring in sync with VALOR framework used in more recent T2K analyses
    - Investigating some known bias issues
- Investigate marginalization (instead of profiling) for detector errors
    - Now default option in VALOR oscillation analysis
    - Potential for speed improvements for detector systematics that, in each bin, “commute” with flux and cross-section systematics
- Start interacting with other Beam and Detector option WGs
- Start designing end-to-end studies.

- New manpower (2 postdocs) available in immediate future.
- Expect this effort to accelerate substantially within the next 2-3 months.

VALOR and DUNE: Interfaces and inputs

What is needed, at a bare minimum, **to inject more realism** in the VALOR analysis:

From Beam Simulations WG:

- **Flux covariance matrix** (in true energy bins, at ND location, all species and beam configurations)

From GENIE:

- Missing **Reweighting functions** for important systematics (hadronization)

From Detector WGs:

- **Mini-DST** (following simulation and mock-up reconstruction) **including the required analysis samples**
  - including all GENIE MC truth info for event reweighting
- **Efficiency errors (and correlations)**.

Summary

- VALOR a well-established oscillation analysis
    - Expanded to ND fitting for DUNE and HyperK optimization studies
- VALOR DUNE-ND analysis particularly suitable for ND needs
- Revamping CETUP14 analysis
- Designing new studies
- Start interactions with Beam and Detector groups to inject more realism (improve inputs).