Detector Systematics

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2x2 Workshop
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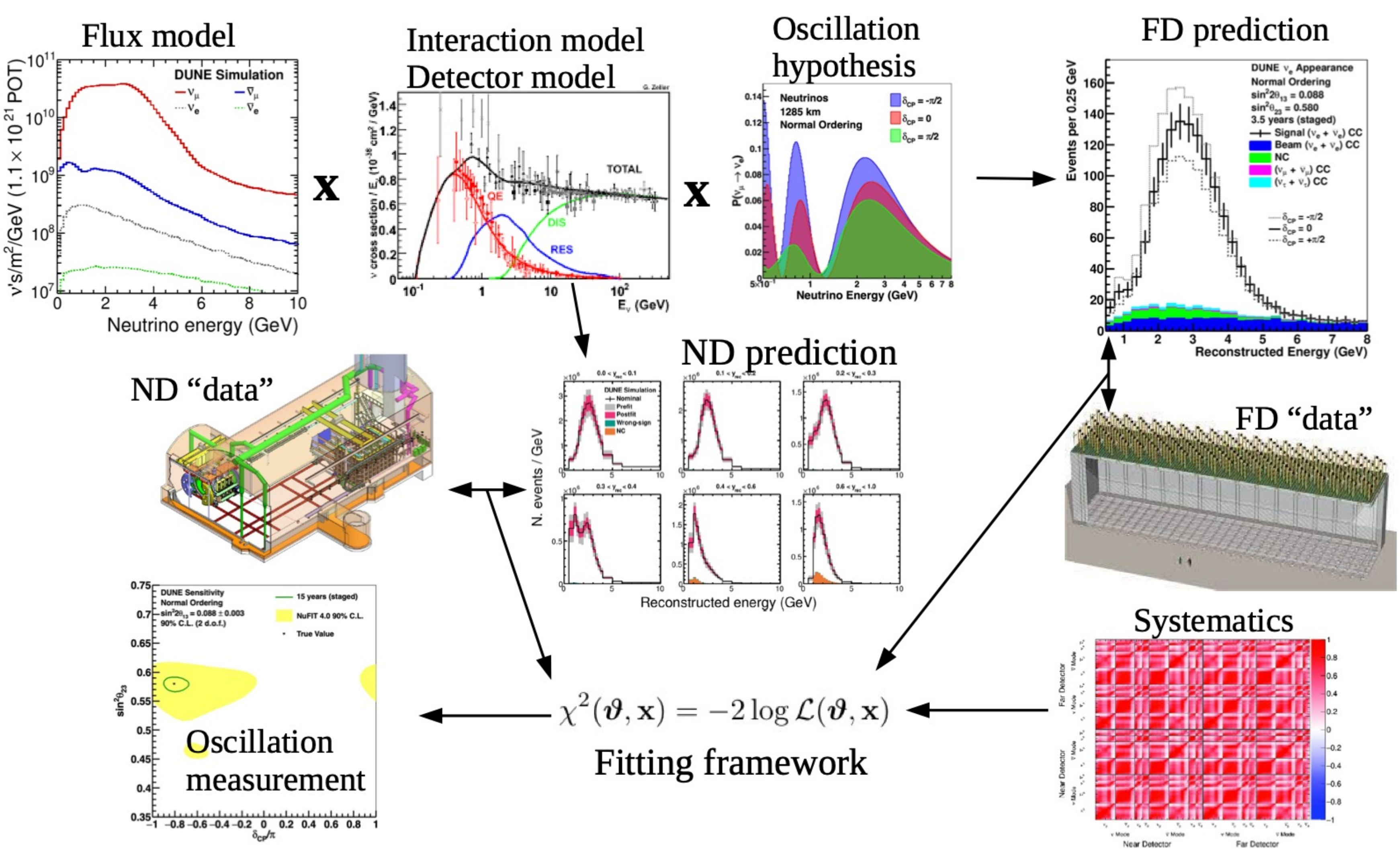
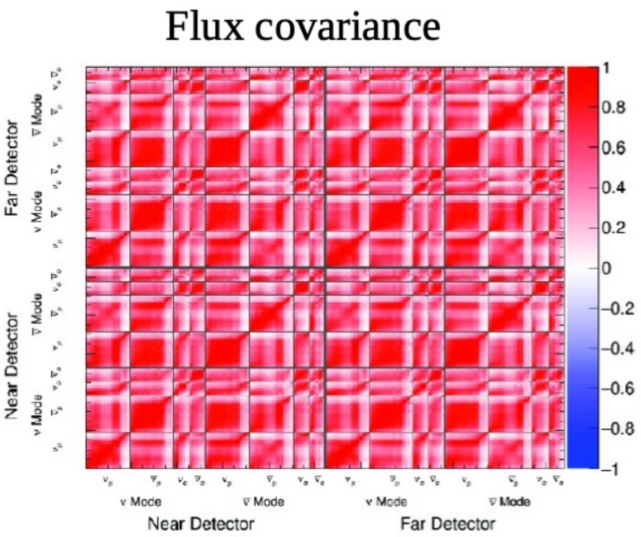
Wichita State University

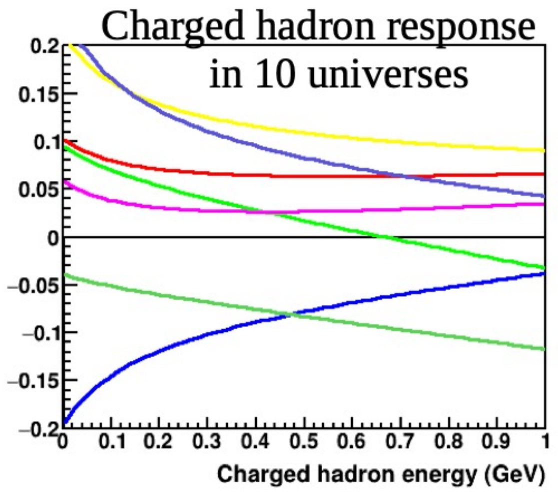
Standard LBL Analysis



From Chris Marshall

Systematic Sources





- Flux: big covariance matrix includes hadron production & focussing shifts; we do a PCA and implement 30 distinct shifts that correspond to eigenvectors
- XS: dozens of distinct shifts to XS model, implemented via reweighting
- Detector: vary overall energy response, and separately for each particle species
- Results in 110 nuisance parameters, which are each essentially distinct shifts to the distributions

From Chris Marshall

What we did in 2019 for detector systematics

$$E'_{rec} = E_{rec} \times (p_0 + p_1\sqrt{E_{rec}} + \frac{p_2}{\sqrt{E_{rec}}})$$

Particle type	Allowed variation		
	p_0	p_1	p_2
all (except muons)	2%	1%	2%
μ (range)	2%	2%	2%
μ (curvature)	1%	1%	1%
p, $\pi^{\pm}$	5%	5%	5%
e, γ, π^0	2.5%	2.5%	2.5%
n	20%	30%	30%

- Goal was to allow sufficient freedom for the fit → use several parameters rather than just one energy scale
- For each particle species, we allowed the reconstructed energy to vary according to a 3-parameter function
- Effectively 15 free parameters
- Think of it as a proxy for varying actual detector parameters

From Chris Marshall

2019 → 2024 detector systematics

- For 2019 analysis, detector systematics were essentially smearing high-level reconstructed quantities (e.g. reconstructed energy)
  - Part of this is due to the simplicity of the parameterized reconstruction
- Actual detector uncertainties modify low-level quantities, which propagate to high-level quantities in a complicated way
- Biggest need for 2024: capture this messiness → implement shifts on sufficiently low-level quantities

First steps

- Identify a list of effects that are potentially important
  - Things that will affect visible energy reco in ND-LAr, or the efficiency to find neutrino events
  - Things that will effect muon momentum in TMS, or the efficiency for matching
- Present this list to LBL → it is likely that there will be many iterations between LBL and detector experts
- There are ideas for how to implement detector systematics by parameterizing alternate samples that are feasible but not tested or demonstrated

Looking to 2x2 to blaze path to implementation

- What are some initial detector systematics that can provide examples that will allow us to begin developing framework for handling and who can take this on?
- What are the inputs that a “framework” needs to handle?
  - Alternate Simulation Samples
  - Data Control samples
  - Parameterized response function(s)
  - Covariances in measurement space
  - Weights for reweighting scheme?
- What about Inter-detector Systematics?
- This is something 2x2 and all ND group will take advantage of. (Coordination here will be needed.)

Framing the problem

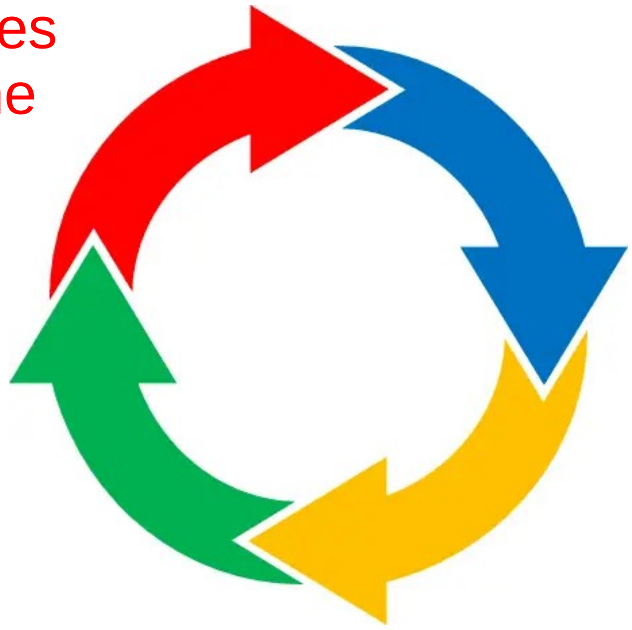
- What can go wrong? -- very analysis dependent question
- What detector information is being utilized:
  - Variables of interest
  - Implicit or explicit cut variables
  - Reconstruction efficiency
- Some effects can also be predicted from first principles, and may affect a number of variables used by an analysis

Tightly linked to calibration and data quality

Analysis complexity evolves over time...

Data quality: does the data look reasonable? E.g., no gross issues we can't fix in offline software

Detector systematics: Does it agree with my expectation? How can I assess the difference with my expectation



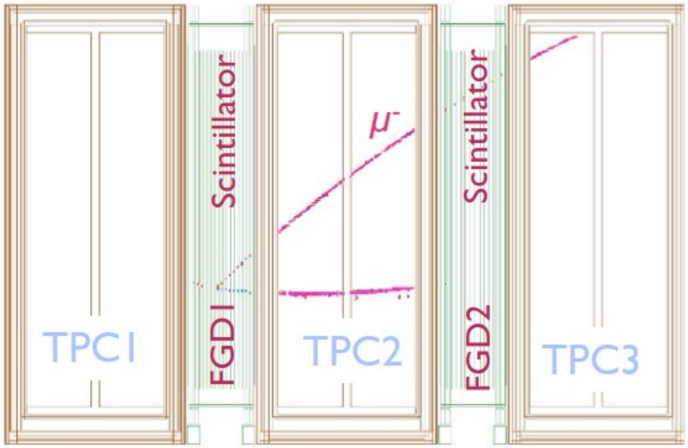
Profit $$$

Calibration: how can I refine my expectation for next time?

Tools for determining detector systematics?

- First principles/ calculations
- Beam tests
- Control samples → e.g., cosmic muons, $K^0 \rightarrow e^+e^-$ pairs, well understood subsamples which do not depend on the physics you are trying to extract directly
- Variations between repeated detector components for any sample
- Hybrid samples → take a control sample and inject additional MC particles
- Guesswork

A complete(ish) example from T2K



Simple analysis: FHC CC-inclusive, using highest momentum track as μ^- candidate

Vertex in FGD1, track measured sampled in TPC2 (maybe also TPC3)

Systematic Error	Data Sample	Error (%)
TPC momentum distortion	Special MC	0.3 – 7
TPC momentum scale	External data	0.1 – 2.4
TPC momentum resolution	Beam data/MC	0.2 – 2.3
TPC-FGD matching efficiency	Sand muon + cosmics	0.2 – 1
TPC track efficiency	Beam data/MC	0.05 – 0.8
Hit efficiency	Beam data/MC	< 0.002
Charge mis-ID	Beam data/MC	0.2 – 1.1
TPC particle ID (PID)	Beam data/MC	0.02 – 0.6
External background	Several samples	0.4 – 9
Sand muon background	Special MC	0.1 – 1.1
ND280 pileup background	Beam data/MC	0.2
Cosmic ray background	Special MC	Negligible

Example from arXiv:1302.4908

Each systematic has ~40 page internal note to support it

A complete(ish) example from T2K

Muon control samples:

- Rock (sand) muons
- Cosmic muons
- Upstream muons (cross all 3 TPCs)

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High momentum muons travel in straight lines… did the reco find/match things that it should have?

Do different TPCs get the same answer? Do they differ more in data than MC?

Do PID variables agree in data/MC? Add smearing to PID variable if not the case

(Some of these were also validated with proton control samples)

A complete(ish) example from T2K

Dedicated B-field measurements used to understand field uniformity

Permanent probes used to monitor stability

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Varied magnetic field according to measured uncertainties, evaluate effect in analysis bins

Run MC with&w/o the field correction, take difference (in analysis bins) as systematic

This is where the bodies are buried, but effect much smaller than stat. error so deemed appropriate

Example control sample: rock/cosmic muons

- If they're through-going:
  - TPC-TPC segment matching
  - TPC-MINERvA matching
  - dQ/dx (and/or dE/dx) uniformity
  - E-field uniformity
- If they stop:
  - dQ/dx (and/or dE/dx) studies
  - Michel electron efficiency

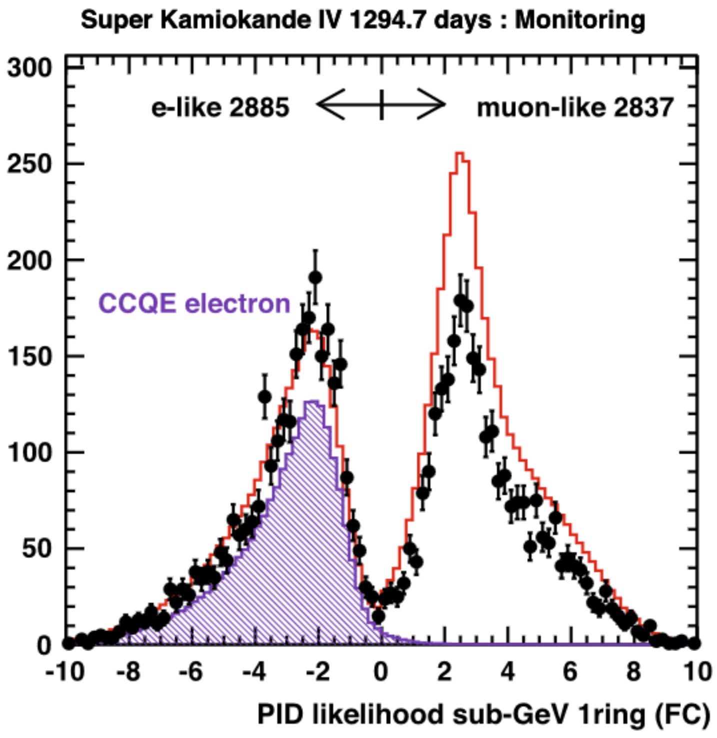
Example #1: weight-like matching systematic

- In a segmented detector, reconstruction can break tracks across detector boundaries, for many reasons
- Control sample, or other approach, may show data-MC difference, and you want to see how it modifies the analysis...
- Artificially break tracks which cross boundaries in MC, with probability determined by the above.
- May need to re-run PID algorithms at analysis time if the broken tracks would still enter the selection
- Pull out a bit of the reco algorithm and encapsulate in a function called at analysis time. Or, do standalone study, and parametrize results in terms of higher-level variables

Example #2: variation-like PID systematic

- Say you're cutting on a PID variable, which separates two components

- Use control samples to check data-MC agreement and see difference.



- Apply shift and smear to PID variables that artificially mimics the effect

- See how that migrates events over your cut boundary

Parting thoughts

- We need to start thinking about systematics → realistically, they are >70% of any physics analysis
- Approach to each is dependent on the nature of the effect, the information we have and the analysis in question
- **This requires focused effor**t. We also need to develop hooks for including them in analyses, preferably at CAF-level
- Potential for useful papers for DUNE and 2x2 program on systs/control samples as a stepping stone to an analysis

  → uBooNE did this effectively, e.g. look at π^0's (a useful control sample) before trying to measure π^0 production…

- Control samples, control samples, control samples…

Systematics

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