Interaction Models in Oscillation Fitters

Liban Warsame
Imperial College London
ljw20@ic.ac.uk

Era of low statistics is over…

Stephen Dolan

- Current long baseline experiments are **mostly statistics limited**
  - Issues with our systematic models could **hide behind the stats uncertainty**

	T2K	NOvA
Baseline	295 km	800 km
N_μ^{rec} (ν-mode)	318	211
N_μ^{rec} ($\bar{\nu}$-mode)	137	105
N_e^{rec} (ν-mode)	94	82
N_e^{rec} ($\bar{\nu}$-mode)	16	33

Reconstructed events in samples at the experiment's far detectors

Era of low statistics is over…

Stephen Dolan

- Current long baseline experiments are **mostly statistics limited**
  - Issues with our systematic models could **hide behind the stats uncertainty**
- Next generation experiments are going to see **10-100x more FD events**
- Near detectors will have **very little stats uncertainty** —> no longer anything to hide behind

	Hyper-K (arXiv:1805.04163)	DUNE (arXiv:2002.03005)
Baseline	295 km	1300 km
N_{μ}^{rec} (ν-mode)	~10000	~7000
N_{μ}^{rec} ($\bar{\nu}$-mode)	~14000	~3500
N_{e}^{rec} (ν-mode)	~2000	~1500
N_{e}^{rec} ($\bar{\nu}$-mode)	~2000	~500

Approximate late-stage projections for reconstructed events in samples at the experiment's far detectors

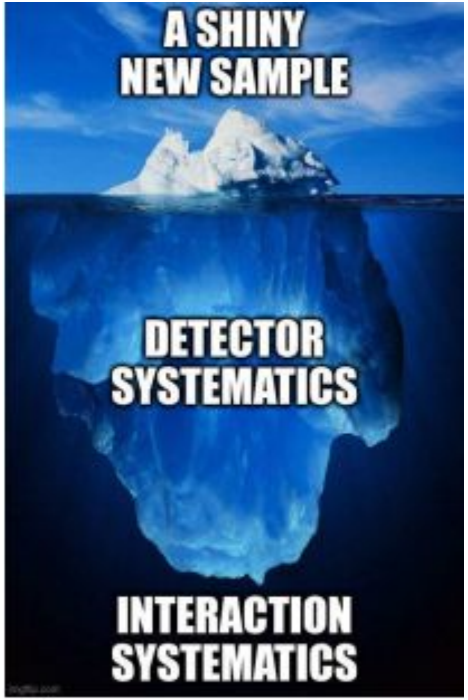
Long Baseline Analyses

$$N(\text{Observables}) = \int \text{Flux}(E_\nu, \text{time}) \times \text{Interaction prob}(E_\nu, \text{final state}) \times \text{Detector Efficiency}(\text{final state}) \times \text{Osc}(E_\nu)$$

- Measure an event rate —> convolution of **oscillations** and **systematics models**
- Near Detector has **no oscillations** —> **constrain the systematics**
- Far detector has far fewer events and oscillations —> **apply systematic constraints**

What problems are we facing currently?

- We need to **perform sensitivity studies to show we can achieve our physics goals**
  - Prove that we need our complex high stats ND
- New samples for constraining the model
- **Current systematic models aren't sophisticated enough to handle the high statistics**
- No real data yet —> **we input our own systematics**
- Analysers have to choose between:
  - Pinning down our systematic uncertainty to 0
  - Artificially inflating our uncertainty until it looks reasonable
- Reality is somewhere in the middle!



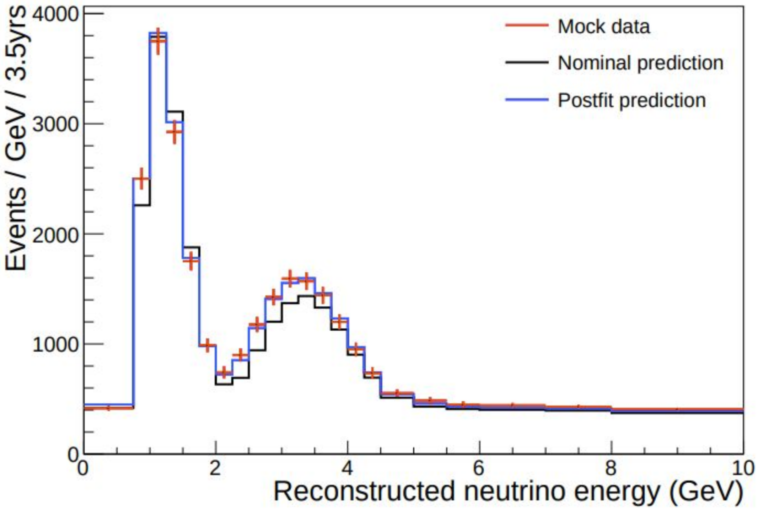
Fake Data Studies

- Asimov studies **are a good start**
  - **Predict our sensitivity based on our nominal predictions**

- The data we take won't fit perfectly with our model
  - Explicitly designed to include something not in your base model
  - **Check how bad the damage is**

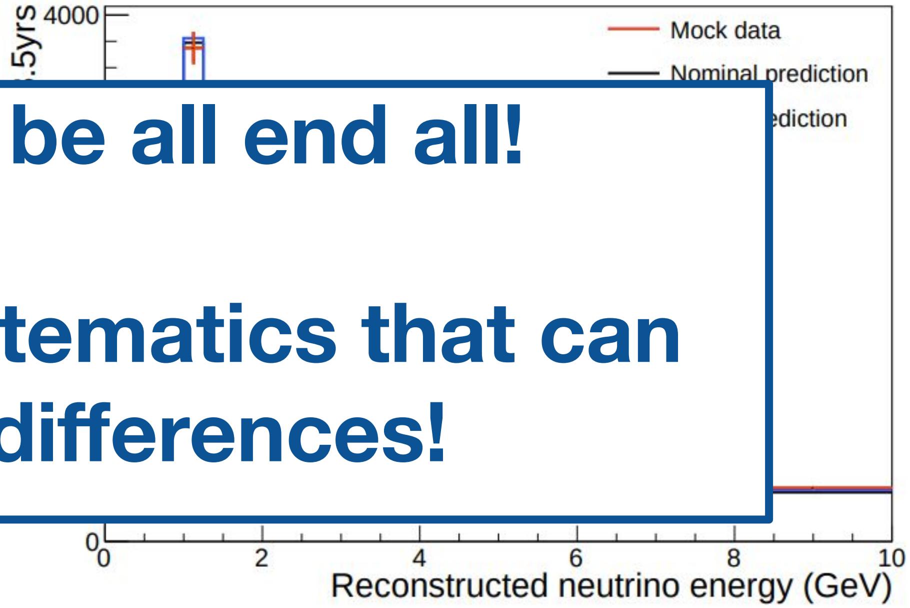
- Produce fake data based on scenarios we think could actually happen
  - Motivated by concerns from both theorists/experimentalists
  - **Identify the hidden systematics**

- Our current way forward to producing accurate sensitivities



Fake Data Studies

- Asimov studies **are a good start**
  - **Predict our sensitivity based on our nominal predictions**
- T
- F
  c
  - **Identify the hidden systematics**
- Our current way forward to producing accurate sensitivities

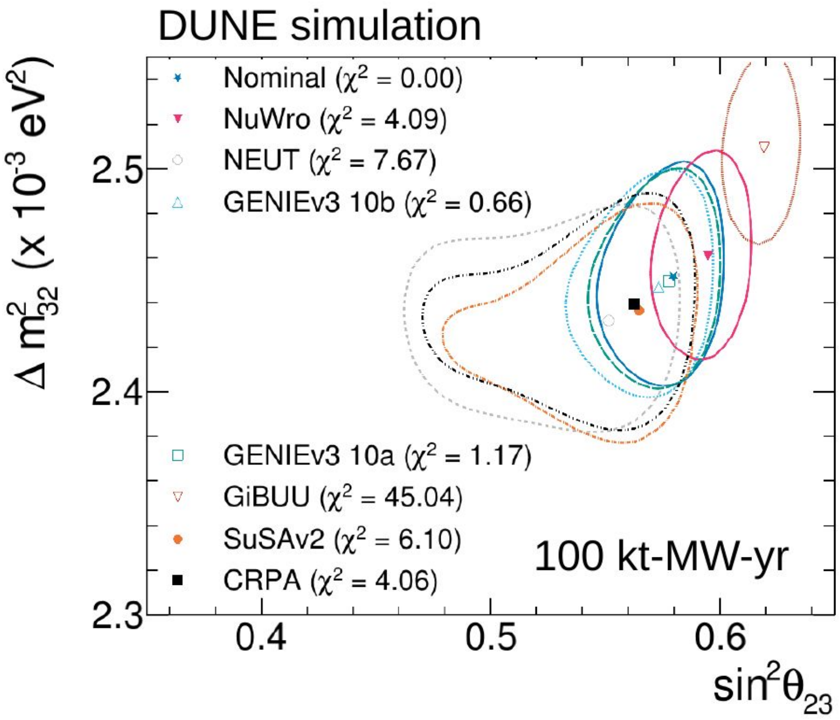


They aren't the be all end all!

Ideally we have systematics that can cover model differences!

Example: DUNE Alternative Generator Study

- Check to see **the effect of using different generators** on DUNE sensitivities
- Model differences aren't always reweightable
  - Passing multiple models full sim+reco chain is unfeasible
- High-dimensional BDT (Instruments 5 (2021) 4, 31) used to reweight between generators
- **Clear bias** depending on which base model we use in the analysis
- **Failure of our systematic model…**
  - How do we solve this in a realistic way?



What will help going forward (from a fitter perspective…)

- Three key points that I think are important going forwards…
  - This is definitely not an exhaustive list

1.) More comprehensive systematic models

2.) A better understanding of current fitting techniques

3.) Universal MC format (generic machinery for implementing models?)

What will help going forward (from a fitter perspective…)

- Three key points that I think are important going forwards…
    - This is definitely not an exhaustive list

1.) More comprehensive systematic models

2.) A better understanding of current fitting techniques

3.) Universal MC format (generic machinery for implementing models?)

ND Over-constraint

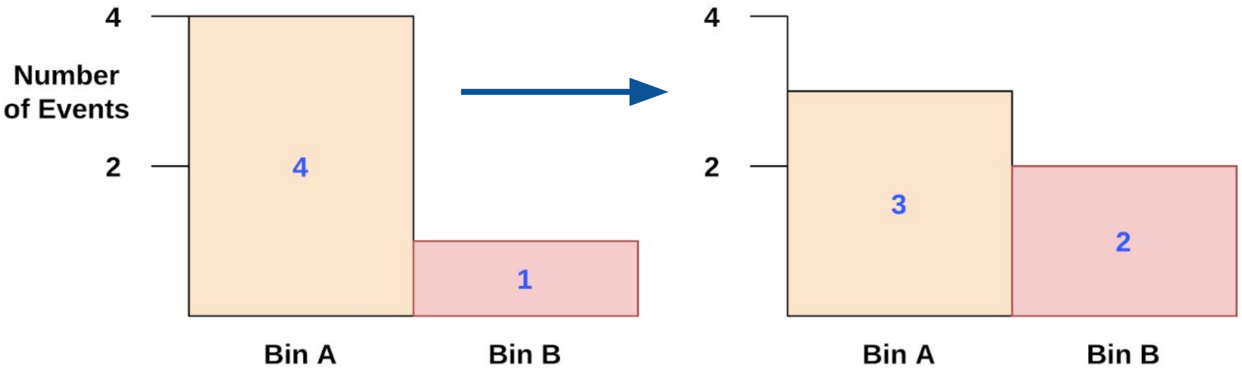
- Currently we have parameters that affect normalisation + some shape effects
  - **Fitting with O(10 million) events**
  - **This probably isn't enough anymore**

- Lack of statistical uncertainty —> **ND pins down systematic parameters**
  - Issue encountered by **DUNE TDR analysis** (parameterized reconstruction also played a factor)
  - Solution was to prevent ND detector systematics from being constrained

- To prevent the over-fitting we need parameters that have:
  - **Same effect in the observables**
  - **Different effects in other projections e.g. Enu**

Toy Example: Muon Energy Scale & FSI Effect

- Both muon energy scale and FSI parameters **will shift the erec distributions in similar ways**
- **Limit the effect of ND constraining power on these systematics**
- MC events which are affected by muon energy scale and FSI parameters have **different erec —> etrue mapping**
  - Degeneracy between parameters **changes oscillation constraint**



HK vs DUNE differences

- DUNE and HK use **different methods of reconstructing neutrino energies**
  - DUNE uses **'calorimetric method'**: lepton energy + all hadronic energy
  - HK uses **'kinematic method'**: outgoing lepton kinematic

- Different methods have different priorities in terms of interaction modelling

- DUNE priorities:
  - **Fraction of neutrino energy to neutrons - invisible energy**
  - **Charged pion multiplicity - missed rest mass**

- HK priorities:
  - **Nucleon ground state - motion and binding energy affect lepton kinematics**
  - **2p2h and pion absorption FSI**

Novel Samples, Novel Systematics

- High statistics at ND allow us to take advantage of novel samples/techniques
  - **More exclusive sample options**
  - Use **known cross-sections** to extract extra constraints

- Lots of options currently being thought about:
  - **$\nu + e \rightarrow \nu + e$ elastic scattering**
  - **Inverse muon decay: $\nu_\mu + e \rightarrow \mu + \nu_e$**

- PRISM also allows us to reduce the xsec uncertainty

- **But new samples/techniques might need new systematics!**
  - **Probing unusual parts of the phase space** which haven't had much dedication
  - **Very specific backgrounds**

What will help going forward (from a fitter perspective…)

- Three key points that I think are important going forwards…
  - This is definitely not an exhaustive list

1.) More comprehensive systematic models

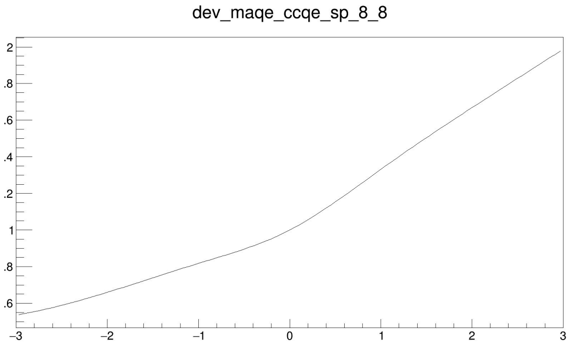
2.) A better understanding of our current fitting techniques

3.) Universal MC format (generic machinery for implementing models?)

MaCh3 - A Markov Chain Monte Carlo Fitter with a built-in Likelihood Calculator

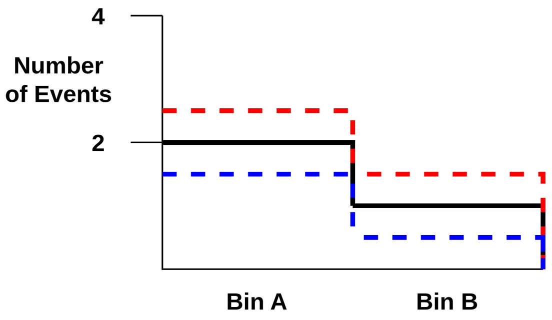
How do we build our likelihood space

Splines



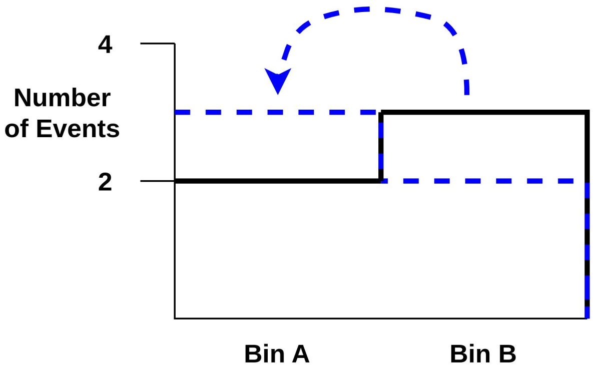
- Continuous response functions using piecewise cubic interpolation
- Binned or **event-by-event**
- Cross-section parameters

Normalisation



- Weights events up and down relative to parameter movement
- Apply to specific kinematic ranges and events
- Flux parameters

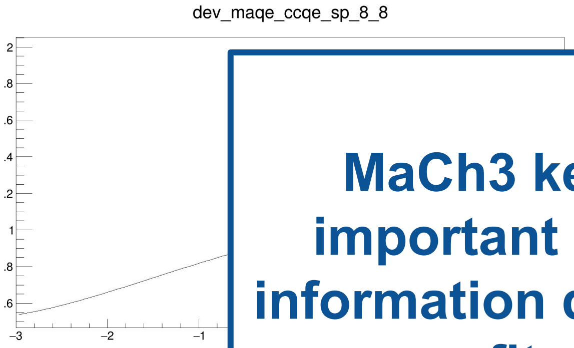
Shift-like



- Move events from one bin to another
- Systematics which **change reconstructed variables**

How do we build our likelihood space

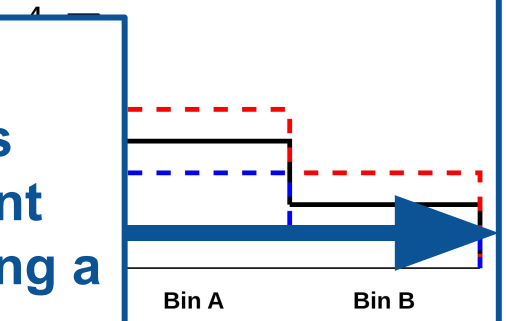
Splines



MaCh3 keeps important event information during a fit

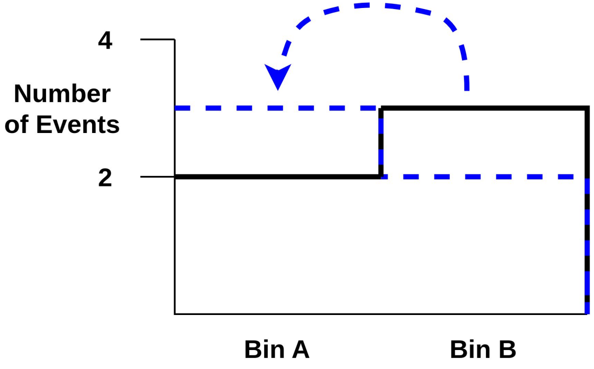
- Continuous r
piecewise cubic interpolation
- Binned or **event-by-event**
- Cross-section parameters

Normalisation



- events up and down
to parameter
movement
- Apply to specific kinematic ranges and events
- Flux parameters

Shift-like



- Move events from one bin to another
- Systematics which **change reconstructed variables**

Shift-like Systematics

- Most of our interaction systematics are dealt with using reweighting
  - **What if the phase space you want to weight up isn't filled in your original model?**
  - This issue came up with **binding energy systematic in T2K** (see P.Dunne talk)

- Shifting gives us another degree of freedom —> **discrete changes**

- Events that shift bins keep their original weights —> **recalculate total response for that bin**
  - With shift systematics response to multiple pars is not reducible to a reweight f(x) * f(y) = f(x,y)
  - Significant when varying in O(100) parameters

- We think this **could** be useful for implementing cross-section systematics too
  - FSI effects:
    - Shift reco. variables for final-state particles
    - Sample migration for events which change final-state

We can handle a lot of parameters…

- Parameter space in MaCh3 analyses has gotten pretty large!
  - T2K fits often have **700+ parameters**
  - Currently in DUNE we have **300+ and counting (work in progress)**
- MCMC fitting can handle large, discontinuous parameter spaces
- Often complex cross-section models are described with just a few parameters
  - **We can handle more granularity!**

What will help going forward (from a fitter perspective...)

- Three key points that I think are important going forwards…
  - This is definitely not an exhaustive list

1.) More comprehensive systematic models

2.) A better understanding of current fitting techniques

3.) Universal MC format (generic machinery for implementing models?)

A Technical Barrier…

- **The neutrino community doesn't have a common data structure for generated events**
  - Each generator group has their own unique format

- Difficult for experiments implementing several generators in one simulation workflow

- **Significant barrier to iteration of studies**

- The collider community has had this for years

NuHepMC

arXiv:2310.13211

NuHepMC: A standardized event record format for neutrino event generators

S. Gardiner[a], J. Isaacson[a], L. Pickering[b]

[a]*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA*
[b]*STFC, Rutherford Appleton Laboratory, Harwell Oxford, United Kingdom*

Abstract

Simulations of neutrino interactions are playing an increasingly important role in the pursuit of high-priority measurements for the field of particle physics. A significant technical barrier for efficient development of these simulations is the lack of a standard data format for representing individual neutrino scattering events. We propose and define such a universal format, named NuHepMC, as a common standard for the output of neutrino event generators. The NuHepMC format uses data structures and concepts from the HepMC3 event record library adopted by other subfields of high-energy physics. These are supplemented with an original set of conventions for generically representing neutrino interaction physics within the HepMC3 infrastructure.

Conclusion

- Sensitivity studies show that **our current systematics aren't sufficient to cover models differences**

- ND statistics pin down current interaction model parameters

- **A more comprehensive systematic model is vital for accurate sensitivity studies**
    - Novel methods for reducing uncertainty **might introduce new challenges to the model**

- Learning about fitter methods/techniques can help motivate model outputs

- Ability to rapidly test different models will be helpful
    - **Universal MC structure would be ideal**