Neutrino Cross-section Fits: What a NUISANCE

NuFACT, WG2 2018-08-17, Virginia Tech

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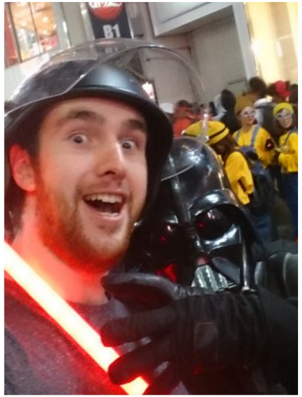


This Talk

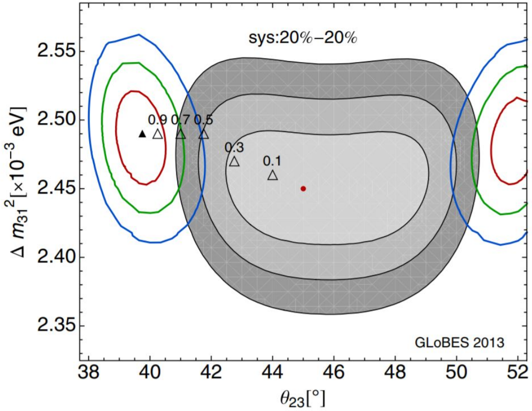
- Why you should care about ‘tuning’ neutrino interaction models
- Common problems found in global cross-section fits
- What is NUISANCE
- What do fitters really want? #3 will shock you!

Why do we need good interaction Models?

- The aim is to perform measurements of neutrino oscillations.
  - Oscillation occurs as a function of true neutrino energy, which is **not observable**.
- We use models to estimate: $\mathbf{D}\left(\mathbf{x}_{\mathrm{obs}}|\mathbf{x}_{\mathrm{true}}\right)$: *If we see* $\mathbf{x}_{\mathrm{obs}}$, *what was the true neutrino energy?* We need to understand:
  - Selected backgrounds
  - Selection efficiency
  - Exclusive channel interaction rates and kinematics
- Wrong model → wrong inferred $P_{osc}\left(E_{\nu}\right)$.

$$N_{\mathrm{near}}\left(\mathbf{x}_{\mathrm{obs}}\right) = \int d\mathbf{x}_{\mathrm{true}} \underbrace{\mathbf{D}_{\mathrm{near}}\left(\mathbf{x}_{\mathrm{obs}}|\mathbf{x}_{\mathrm{true}}\right)}_{\text{Smearing, Eff., Pur.}} \underbrace{N_{\mathrm{targ}}\sigma\left(\mathbf{x}_{\mathrm{true}}\right)\Phi\left(E_{\nu}\right)}_{N_{\mathrm{Int}}\left(\mathbf{x}_{\mathrm{true}}\right)}$$

$$N_{\mathrm{far}}\left(\mathbf{x}_{\mathrm{obs}}\right) = \int d\mathbf{x}_{\mathrm{true}} \underbrace{\mathbf{D}_{\mathrm{far}}\left(\mathbf{x}_{\mathrm{obs}}|\mathbf{x}_{\mathrm{true}}\right)}_{\text{Smearing, Eff., Pur.}} \underbrace{N_{\mathrm{targ}}\sigma\left(\mathbf{x}_{\mathrm{true}}\right)\Phi\left(E_{\nu}\right)P_{osc}\left(E_{\nu}\right)}_{N_{\mathrm{Int}}\left(\mathbf{x}_{\mathrm{true}}\right)}$$



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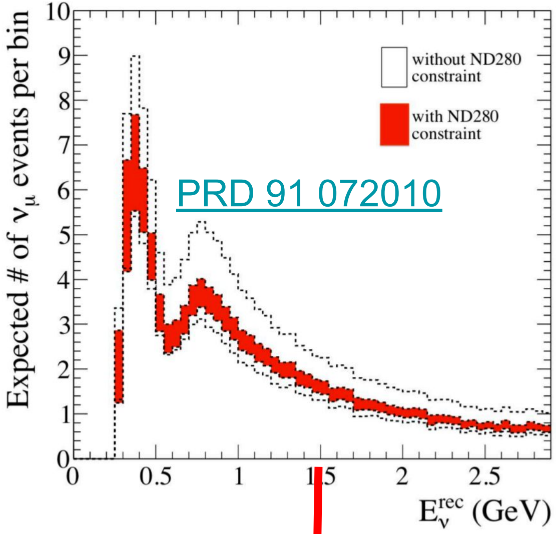
What about uncertainties?

- Need plausible variations of models that can 'cover' the extant data.
- For experimentalists, well-motivated prior uncertainties are *the* reason to compare models to historic data.
  - Hope/assume that the model and associated errors are then predictive for interpreting new data...
- **Without the ability to propagate theoretical uncertainties, an interaction model is hard to fully incorporate into an oscillation analysis.**



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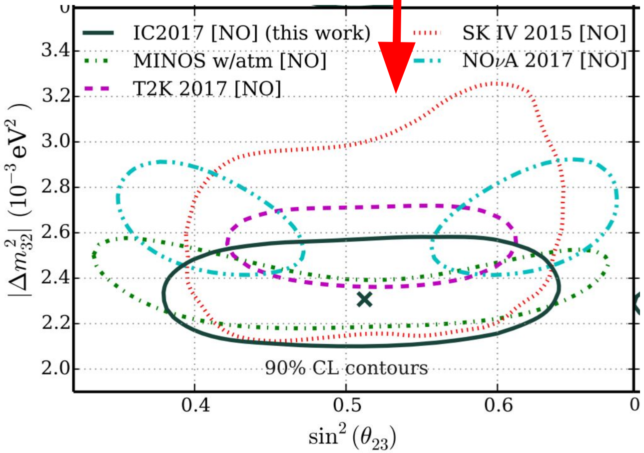

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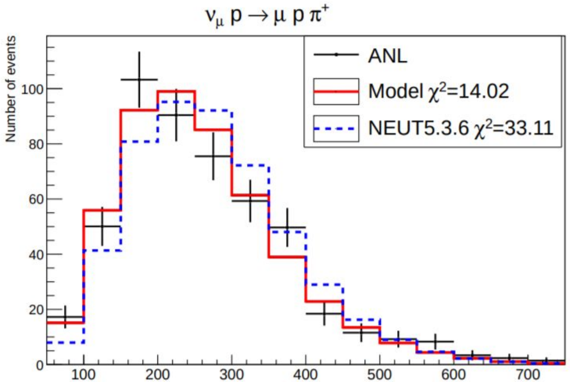
How are we getting there?

- More complete models, *e.g.*:
  - Multi-nucleon effects (Martini, Nieves, ...)
  - Improved pion-production predictions (DCC, **MK**, MAID, ...)
- High statistics, model independent neutrino-scattering data with associated experimental errors.
  - (Semi-)exclusive samples: CC0π, CC1π±, ...
  - Novel kinematic projections. *e.g.*:
    - **Available hadronic energy** (~energy transfer).
    - Transverse momentum imbalance
- Analyses to constrain understand uncertainties.



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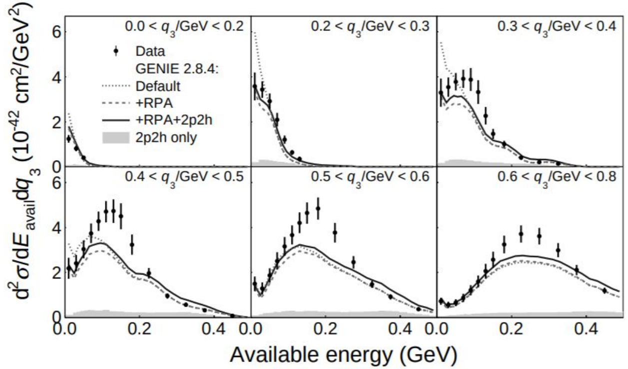

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Anatomy of a Cross-section Fit

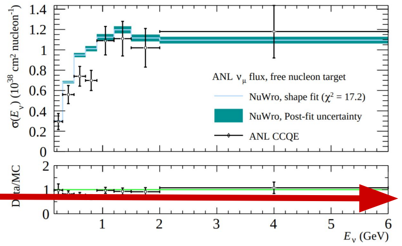
Choose model parameters

Interaction model

ANL CCQE

Data + Errors

Th. Prediction

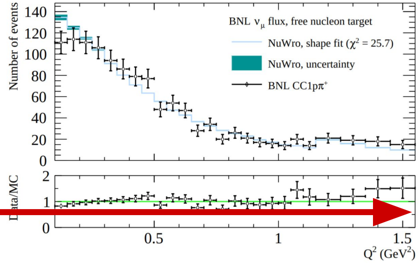


χ^2

BNL CC1pi+

Data + Errors

Th. Prediction



+

χ^2

⋮

+ …

+ Model parameter prior penalties

= Global χ2

Minimize χ2 by varying model parameters

Simple, Right?

- Global Fit Recipe:
  - Add all the data you can find
  - Stir free parameters until mixture is golden brown
  - Serve for updated interaction model and correlated uncertainties!

- But... have to take care:
  - Model parameterizations can be hard to uniquely constrain.
  - Hard to consistently evaluate test statistics.
  - Incomplete data coverage:
    - *e.g.* Many measurements focus on just charged lepton kinematics.
    - Need to be predictive in hadron kinematics...
  - Signal definitions not always clear/sensible.

- **This is a problem we are all working on together**, we know things now that we didn't before, but it is still worth highlighting specifics in historic data to be aware of.

The Proof is in the Parameterization

- Need to take care to not absorb differences into the wrong model components
  - *e.g.* Fitting MiniBooNE CCQE leads to high nucleon axial mass unless you include 2p2h.
- Need projections that can break degeneracies:
  - *e.g.* Missing transverse momentum in CC0pi at ND280 shows preference for 2p2h.
- Many other examples...

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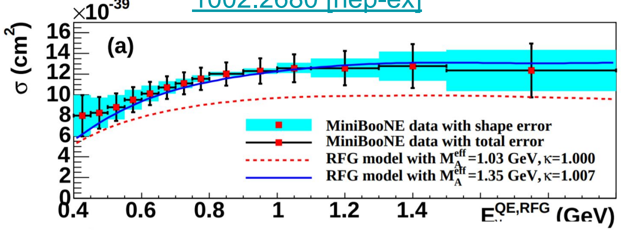

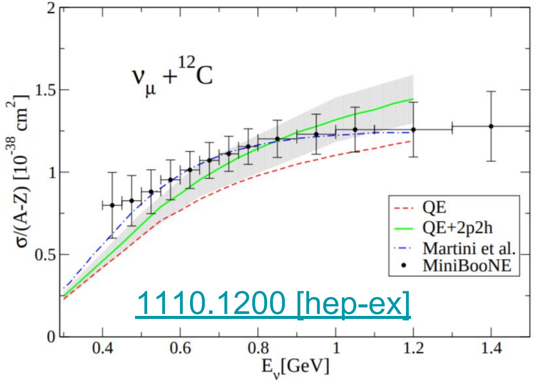

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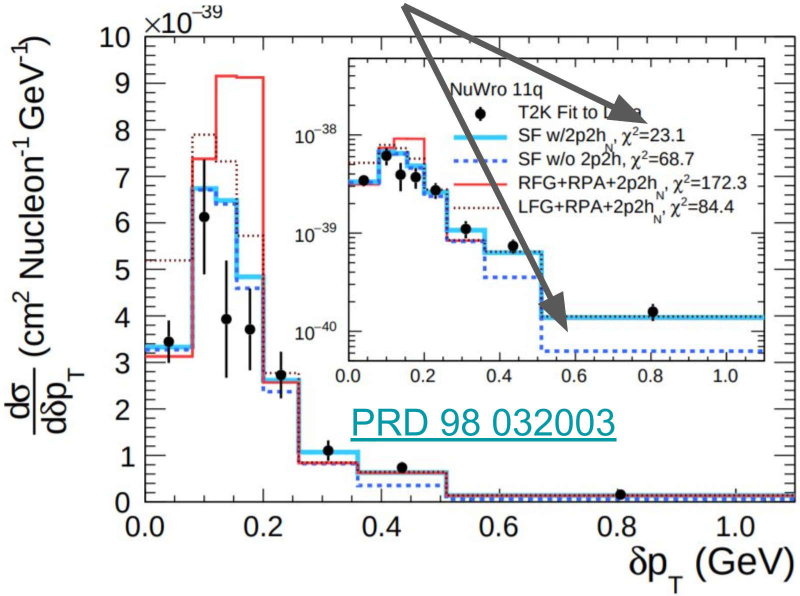

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Hard/Impossible to Evaluate GOF

- Data sets without published correlated errors are difficult to use in a global fit.
- MiniBooNE CCQE(like):
  - Many bins, no published error matrix.
  - What should the contribution to the global GOF be?
    - **Fully uncorrelated**: $\sim \sum_{i\in \mathrm{bins}} (\mathrm{Data}-\mathrm{MC})_i^2$
    - **Fully correlated**: $\sim \sum_{i\in \mathrm{bins}} (\mathrm{Data}-\mathrm{MC})_i^2 / \mathrm{NBins}$
  - If used naively, will incorrectly drive a fit **and more data won't help...**
- But, we need to use the information that this data holds, so cannot just throw it away.

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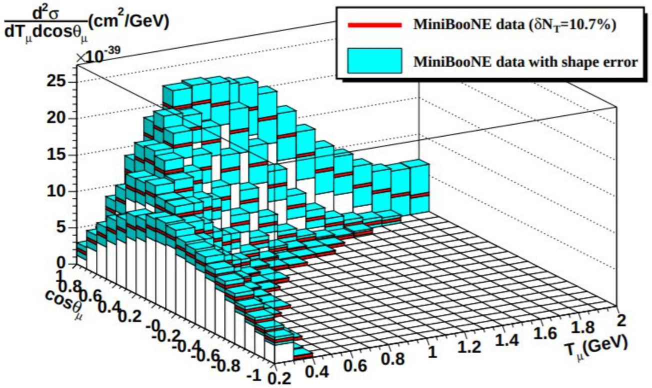

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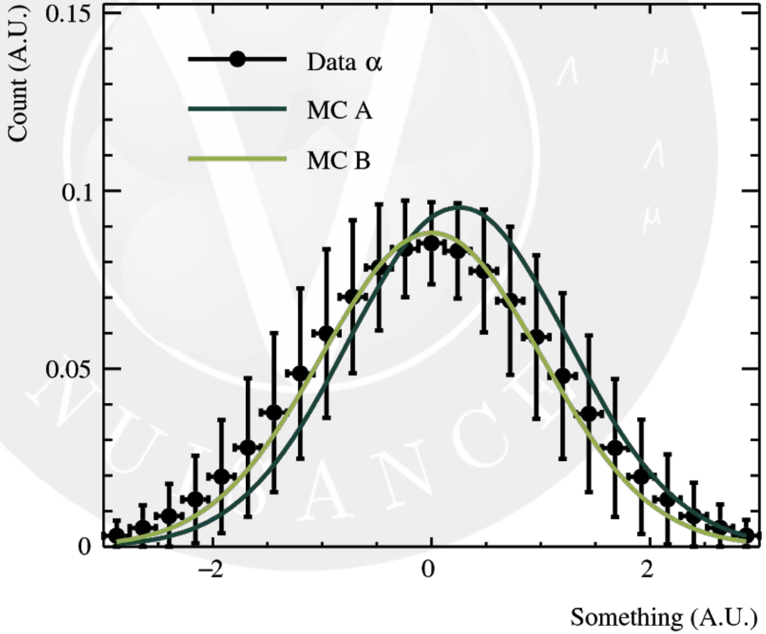
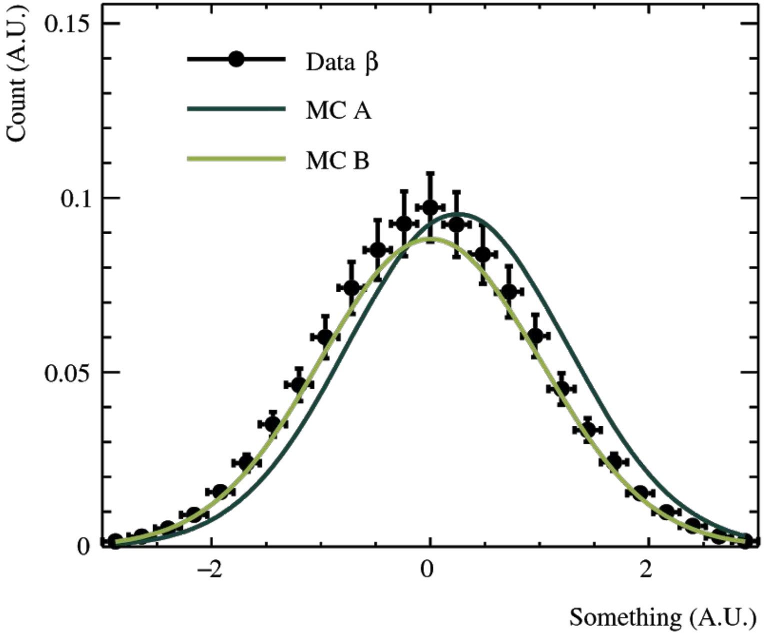
	$\chi^2_{\mathrm{min}}/N_{\mathrm{DOF}}$
All	117.9/228
MINERνA	30.3/13
MiniBooNE	65.7/212
ν	69.1/142
$\bar{\nu}$	46.1/83
MνA vs MB	117.9/228
ν vs $\bar{\nu}$	117.9/228

Let’s Play… Eyeball that $\chi2$!

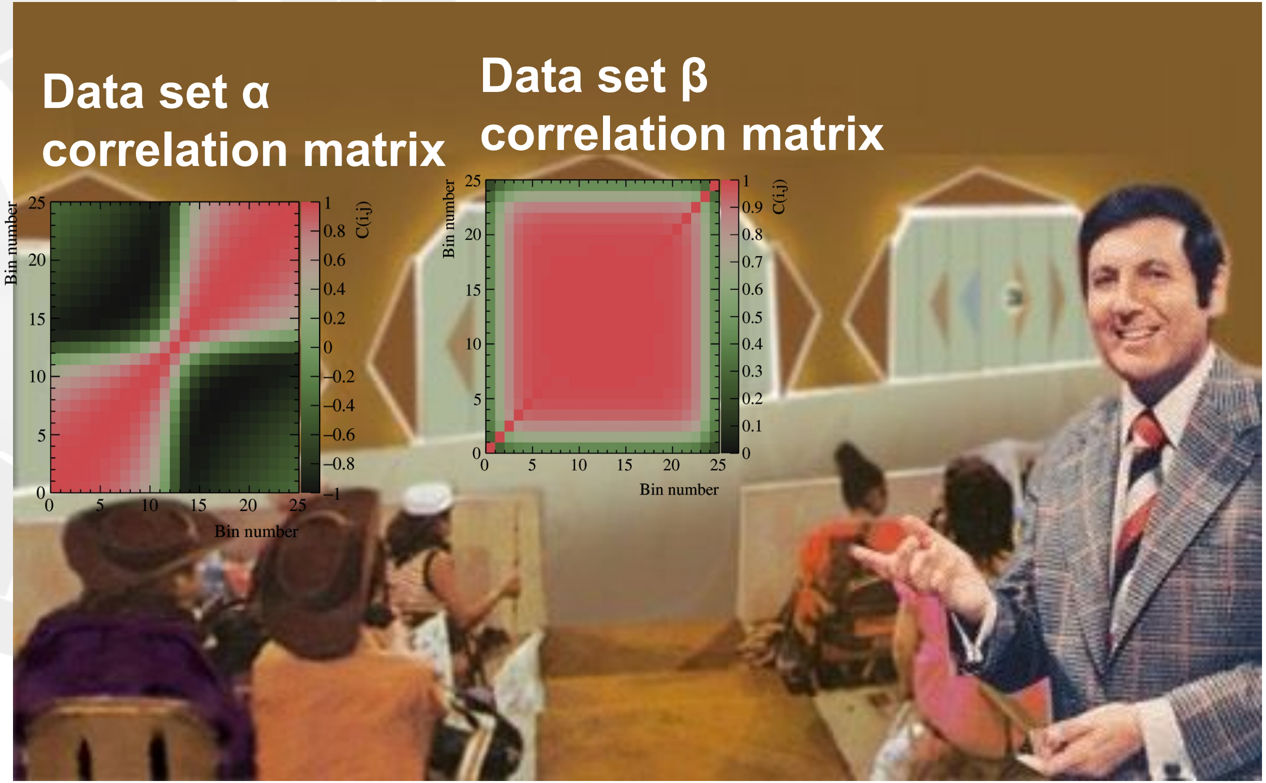
Let's Play... Eyeball that χ2!

- For each 'data set', guess which MC prediction fits the data better.

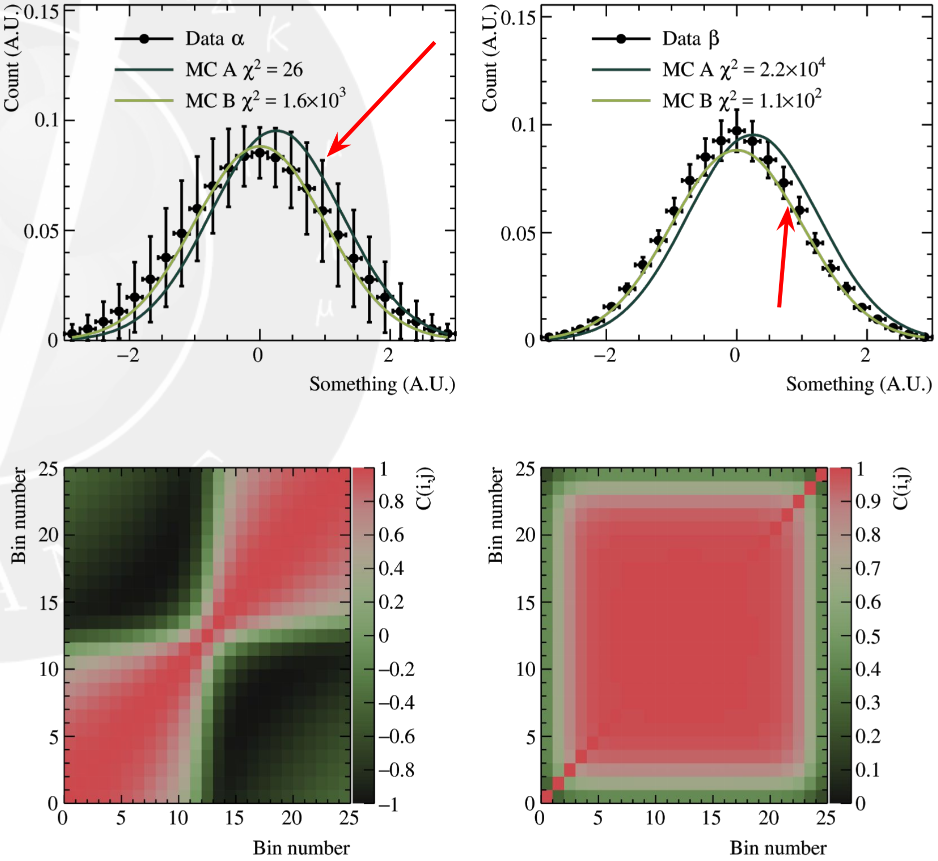




How About Now?



What you expected?



Systematic parameter allows shift in Something. *e.g.* separation energy

Systematic parameter allows normalization change. *e.g.* flux uncertainty.

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The data is the data is the data

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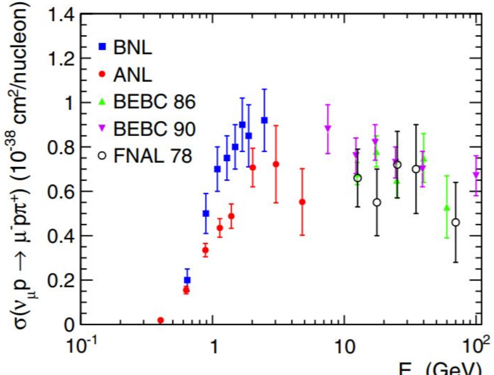
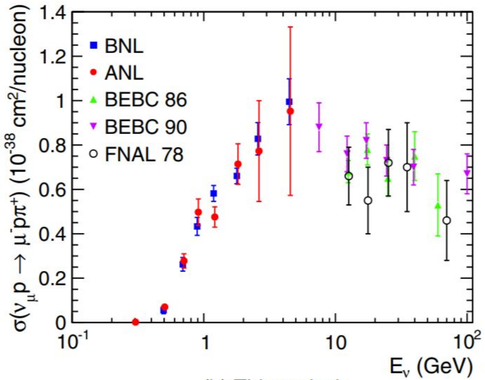
- Sometimes the data is not the data is not the data.
- ANL/BNL CC1pi+1proton discrepancy:
    - Data biased by problems in the neutrino flux models
    - ~ Reconciled by re-analysis.
    - **But, no correction for Q2 distribution!**
- Need to be familiar with included data sets and tensions between them.
    - May need to assign *confidence* weights to samples in the global GOF.



(a) Published



(b) Thisanalysis

Hidden Model Biases 1

- Un-smearing and efficiency corrections introduce bias.
- From a fitters point of view, it is better to cut out regions of very poor efficiency:
  - Don't want to compare to *model-of-the-day* contaminated 'data'.
- Very helpful that such plots are in the publication!
- *N.B.* These problems are tricky and ubiquitous, not specifically calling out this publication.

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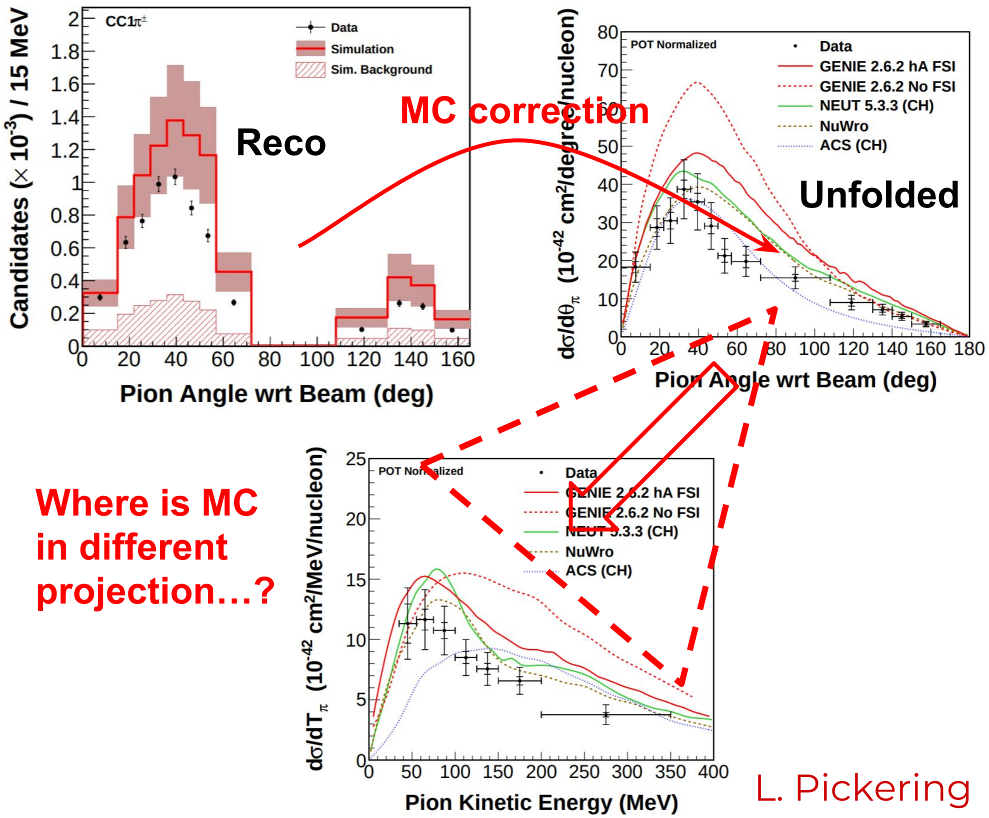
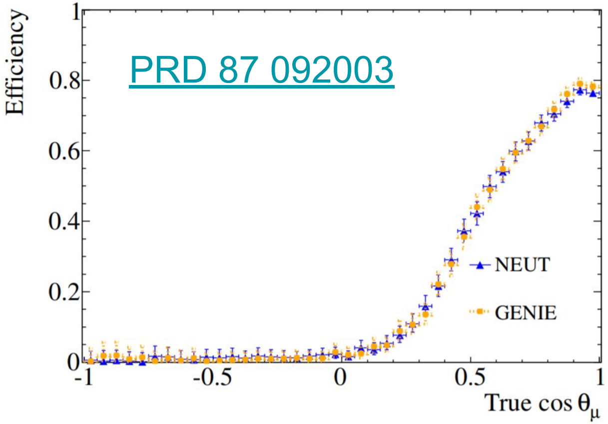
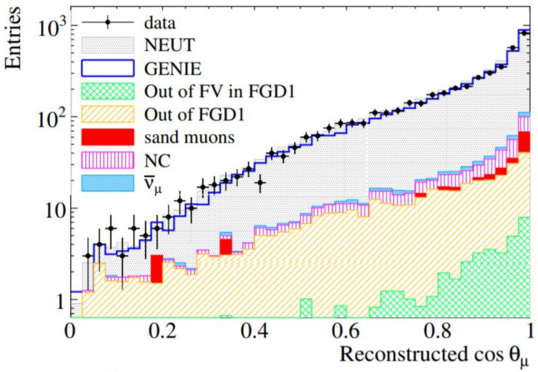
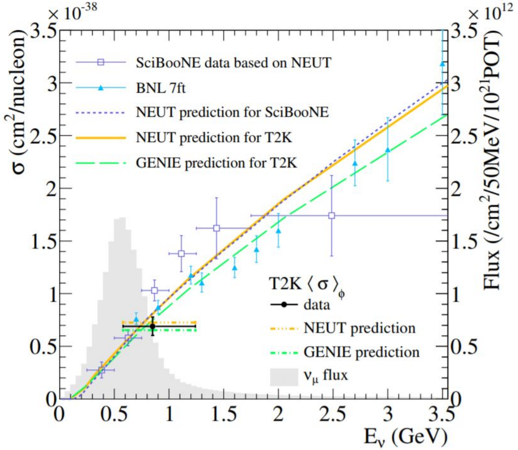


Hidden Model Biases 2: Stealth mode





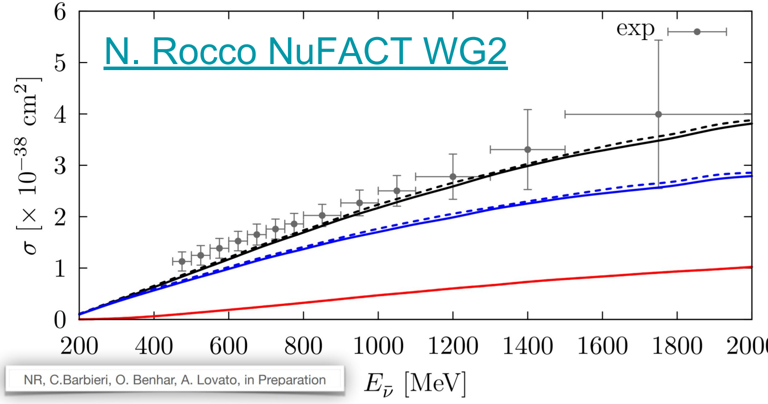


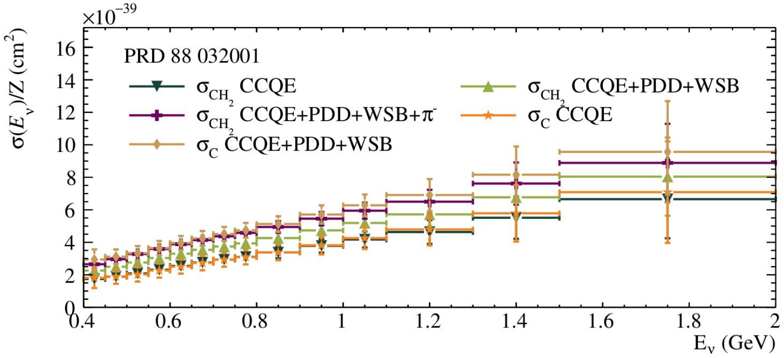
- It isn't always so clear: *e.g.* ND280 CCIncl
  - Practically cannot measure cos(θμ) < 0.
  - But, publish total cross-section.
- Similar out-of-acceptance corrections in many recent measurements: *Fiducial* cross-sections are much preferred!

Experimental Signal Definitions

- Not always fully clear from the publication:
  - Getting this correct is essential for interpreting the data.
- *e.g.* MiniBooNE CCQE C12 data, subtracts:
  - Wrong-sign background CH2.08 component
  - H2.08 component
  - non-QE component (PDD)
  - Mis-ID'd π-
- All predicted by `NUANCE`...
- But, the background subtractions are provided:
  - Might be better to produce H and ν-C12 predictions and compare to the less-corrected data.

$\bar{\nu}_\mu + {}^{12}\mathrm{C} \rightarrow \mu^+ + \mathrm{X}$





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What Can We Do?

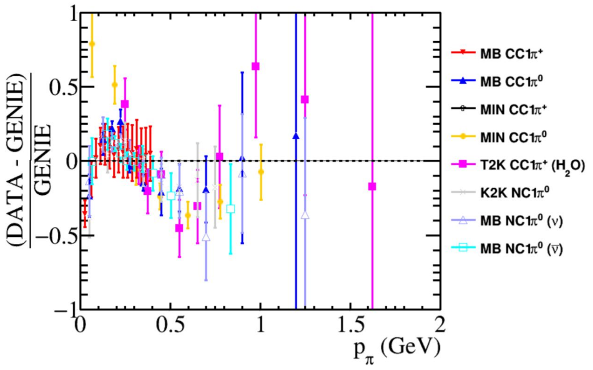
- Build more *hierarchical* analyses:
    a. Fit nucleon-parameters to bubble chamber data (~ free of nuclear effects, but low statistics)
    b. Use BC priors to investigate 0π, 1π, nπ, ... nuclear-target data separately.
    c. Combine to a joint fit
    d. ...
    e. Profit!
- Nuclear effects mean that interaction channels (*e.g.* QE) do not map onto single FS topologies (*e.g.* 0π): cannot study each in isolation.
- **On-going problem:** How best to architecture ‘global’ cross-section fits?
    a. Work being done by NUISANCE, GENIE+Professor, many others -- currently hovering around **b.**

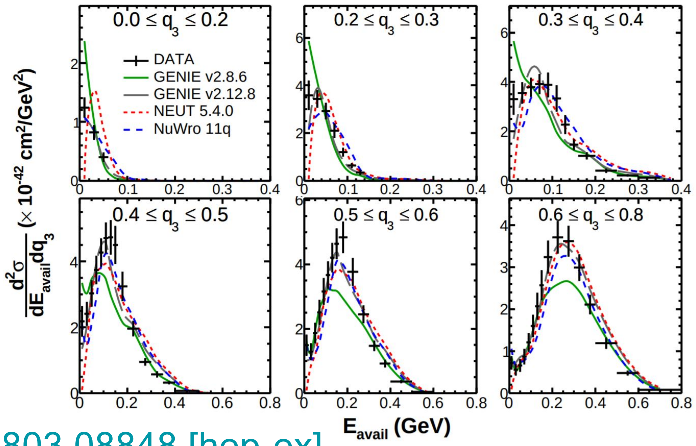
What a NUISANCE

- Global neutrino scattering data comparator and model fitter:
  - Contains hundreds of published data sets with associated errors and signal definitions.
  - **The most valuable part of NUISANCE is the person-hours that have been spent checking that these are implemented correctly as possible!**
- Applies experimental signal definitions to MC events from: GENIE, NEUT, NuWro, GiBUU, HepMC, ...
- Links to MC event generator interaction systematic uncertainty tools for model parameter fitting.
- Code is open source so analyses can be reproduced and extended: https://nuisance.hepforge.org/

Why NUISANCE might be right for you

- Consistently comparing your model predictions to many data-sets.
- Producing comparisons to your new data set with a variety of MCs --- without having to be an expert.
- Ensuring that comparisons to your data are done correctly.
- Tools make cross-section parameter fitting mechanically simple:
  - **But, garbage in → garbage out.**
  - Choice of data, choice of parameters, structure of fit is the tough bit.





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Current work

- **T2K** (and MicroBooNE):
  - Down select from available models.
  - Better-motivate prior interaction uncertainties
- **MINERvA**:
  - Benchmarking CC0π tune (`MnvTunev1`)
  - Producing a public π-production tune (Paper in prep.).
- **Connection to theory**:
  - G. King, K. Mahn, F. Nunes comparing to *ab initio* nuclear response models from Lovato, Gandolfi *et. al.*
  - S. Dolan, U. Mosel, comparing GiBUU multi-nucleon predictions to ND280 data.
  - K. McFarland, MINERvA students, benchmarking Z-expansion AxFFQE fits to MINERvA data.

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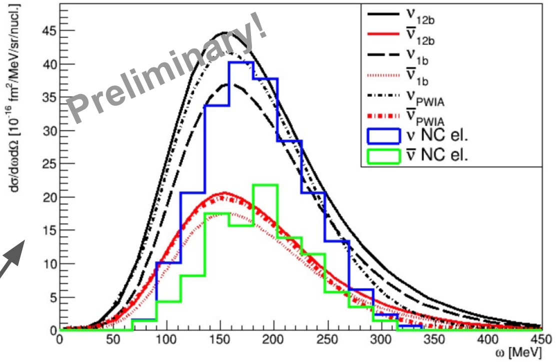

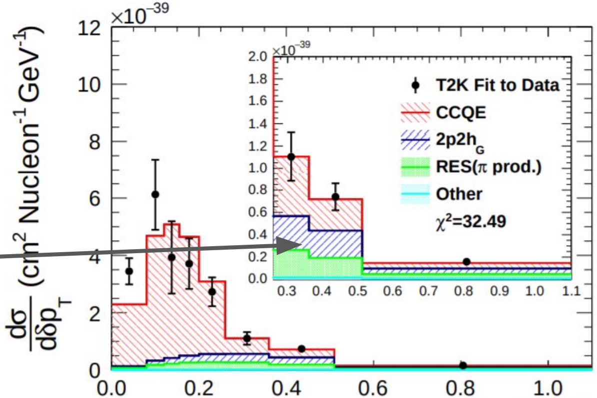

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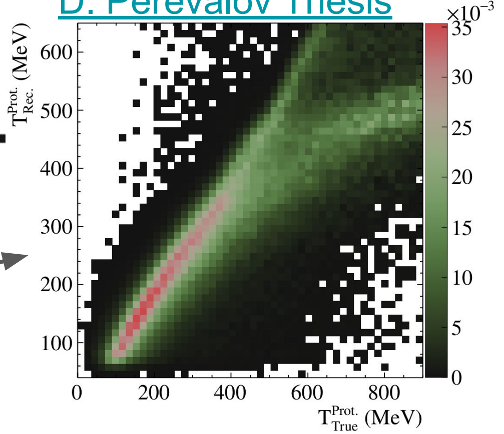
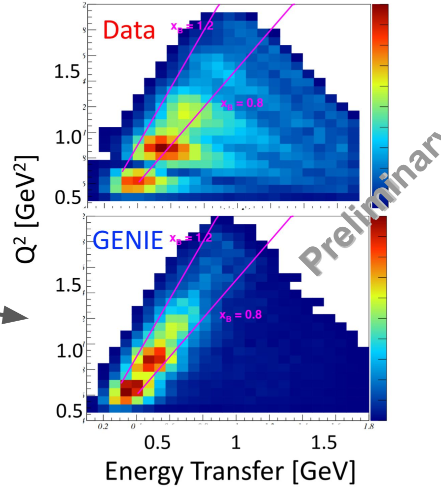
Future work

- Studies of ‘forward folding’ publication strategy:
  - Publish reco + smearing + efficiency + systematic propagation in formation.
  - May be better for data longevity.
- Also want more connection to non-ν-A data
  - Electron-scattering
    - Known beam energy
    - Different interaction kinematics
    - Benchmark common components in simulations that can run e-A and ν-A.
  - pi-A, N-A data sets:
    - ‘Standard’ technique for validating/tuning hadronic cascade/transport models.

D. Perevalov Thesis



L. Weinstein NuFACT WG2



What Fitters Really Want from Experiments

1. Clear, unambiguous signal definitions, chosen in the context of the detector:
   - If you cannot measure final state muons with $\theta_\mu > 30^\circ$, don't ask the MC to correct for it!

2. Covariance matrices describing the correlated errors between:
   - **NEED**: Bins in a projection
   - **Very useful**: Projections of the same sample
   - *Would be nice*: Different samples from the same experiment

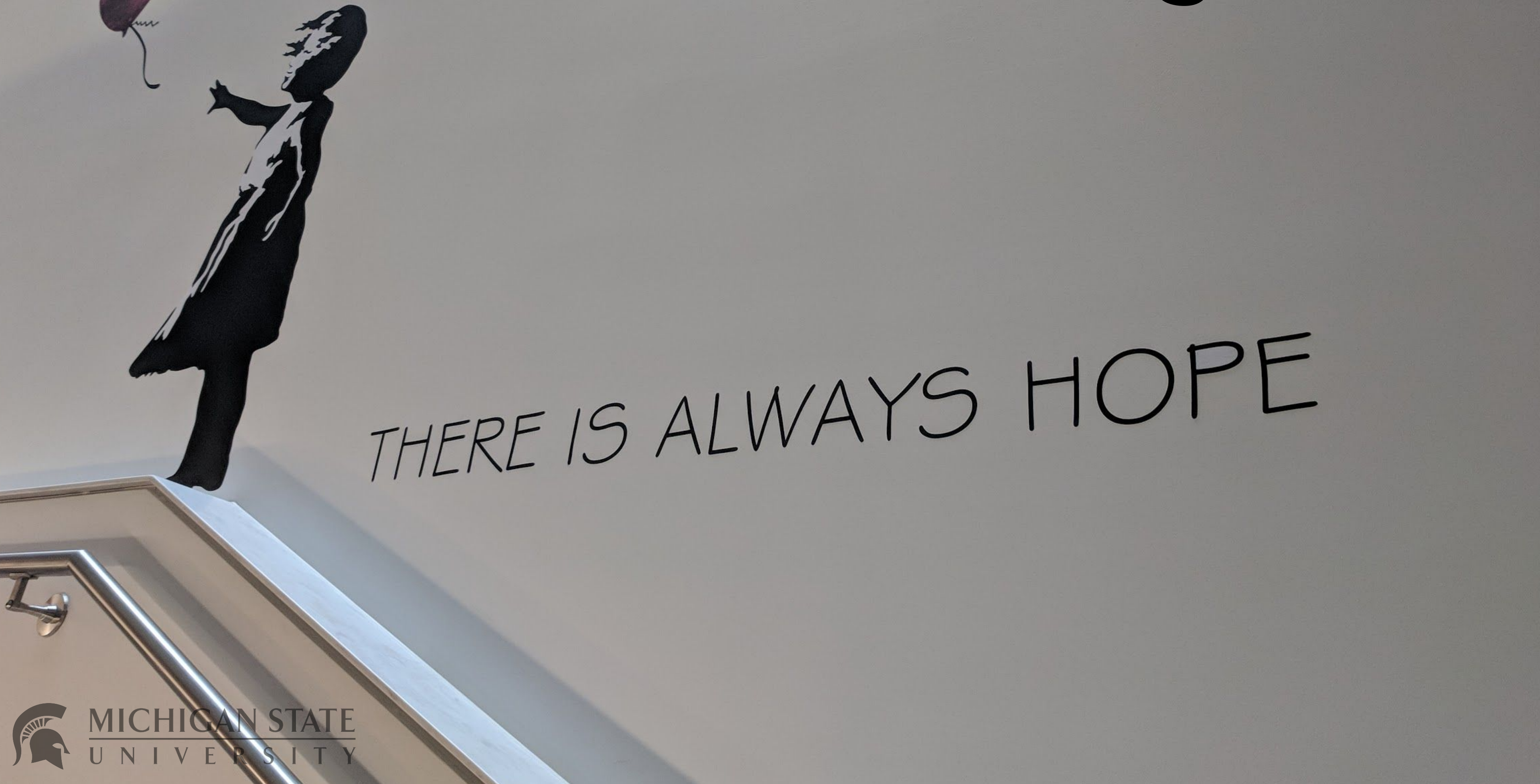
3. Interesting projections of both lepton and hadronic (and composite...) variables!

What Fitters Really Want from Theory

1. Interaction models to be implemented in event generators:
    - New models will not **really** be compared to experimental data unless they are available in generators.
    - A task for generator experts, experimentalists, and theoreticians.
2. Predictions for the hadronic system!
3. Parameterized uncertainties that allow meaningful variations in predictions:
    - If the freedom to match the data isn't available in the model, experimentalists will make something (rubbish) up...

Thanks for listening

L. Pickering



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