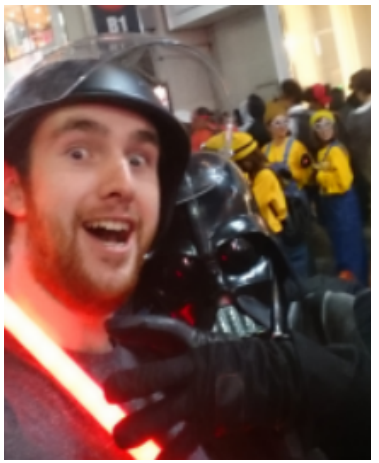
NUISANCE

NeUtrino Interaction Systematics ANalyser by Comparing Experiments
NeUtrino Interaction Synthesiser Aggregating Constraints from Experiments
NeUtrino Interaction Systematics from A-Neutrino sCattering Experiments
...

https://nuisance.hepforge.org/
P. Stowell et al 2017 JINST 12 P01016

Imperial College London

The University Of Sheffield.

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UNIVERSITÄT BERN

NuInt 2017
28 June, Fields Institute, Toronto

Clarence Wret, Patrick Stowell, Luke Pickering, Callum Wilkinson
Help from S. Dytman, U. Mosel, Hayato-san, J. Sobczyk, C. Juszczak, K. Mahn, K. McFarland, G. Perdue, S. Dolan, P. Lasorak, J. Calcutt, C, L. O'Sullivan, and more...

Disclaimer #1

Plots shown are snapshots of the generators in their current states

Disclaimer #2

I'm informing of a new tool, not here to present lovely new physics (sorry)

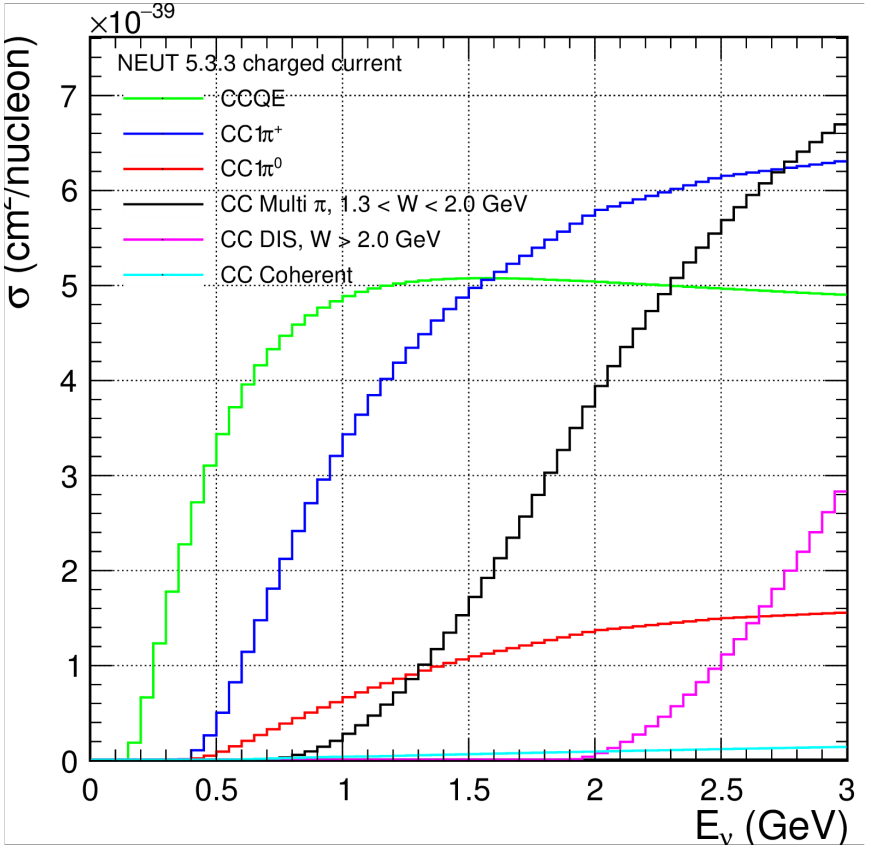
NUISANCE does not guarantee your physics makes sense!

Introduction

- Precision neutrino oscillation measurements require well modelled neutrino interaction: $E_\nu^{rec} \rightarrow E_\nu^{true}$ mapping

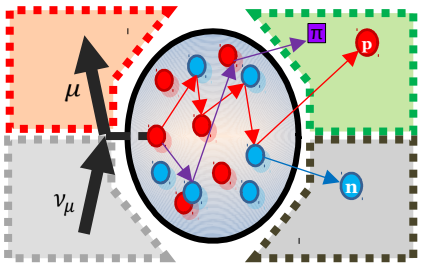
$$N_{SK} \sim \Phi_{SK}(E_\nu)\,\sigma(E_\nu)\,\epsilon_{SK} P(\nu_\alpha \rightarrow \nu_\beta)$$

- Well modelled cross-section at near detector with $E_\nu \sim 1$ GeV? But what about
  - Far detector with oscillated E_ν
  - Different acceptance at far detector
  - Possibly different target materials
- Calorimetric reconstruction requires accounting for neutral particles
  - Effect partially informed from cross-section simulations

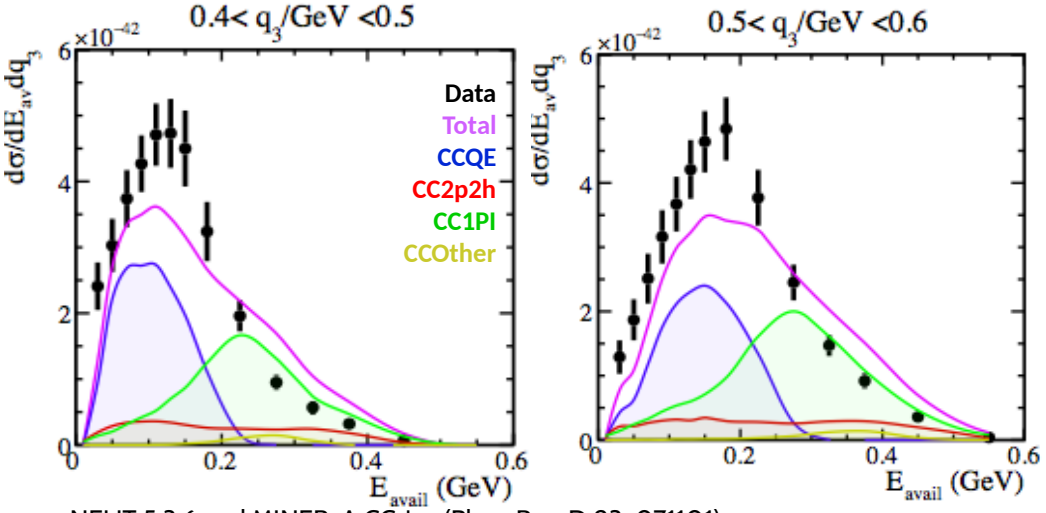


Introduction

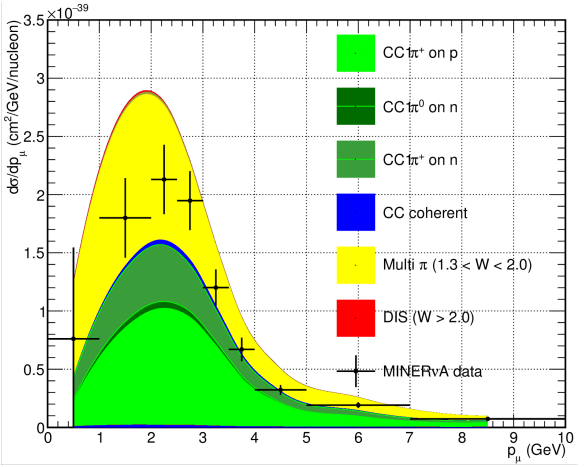
- In an experiment, event selection is done by topology
  - e.g. CC0π selection has contributions from 2p2h, SPP, FSI
- The experiment requires a "full theory" in the generators
  - e.g. how does sophisticated FSI model "play" with simple Rein-Sehgal SPP



- Difficult to assign Data/MC disagreement to a particular interaction model from only one data-set, especially if doing so "by-eye"



NEUT 5.3.6 and MINERvA CC-inc (Phys. Rev. D 93, 071101)

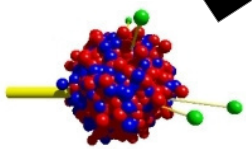


NEUT 5.3.6 and MINERvA CCNπ (Phys. Rev. Lett. 116)

- Identified a need for large custom Data/MC comparisons
  - Started with NEUT, grew to support GENIE, NuWro and GiBUU

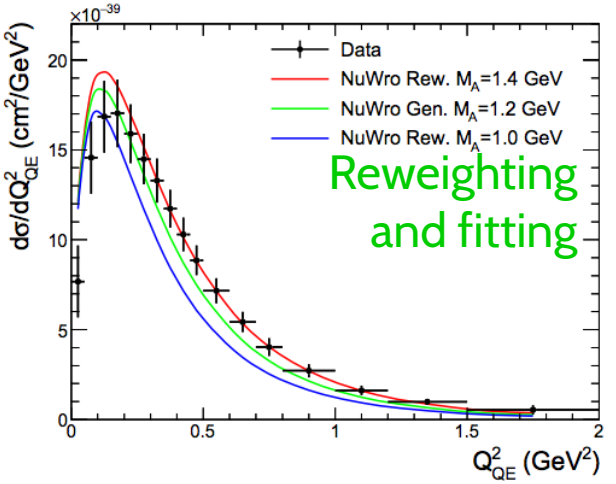
How NUISANCE works

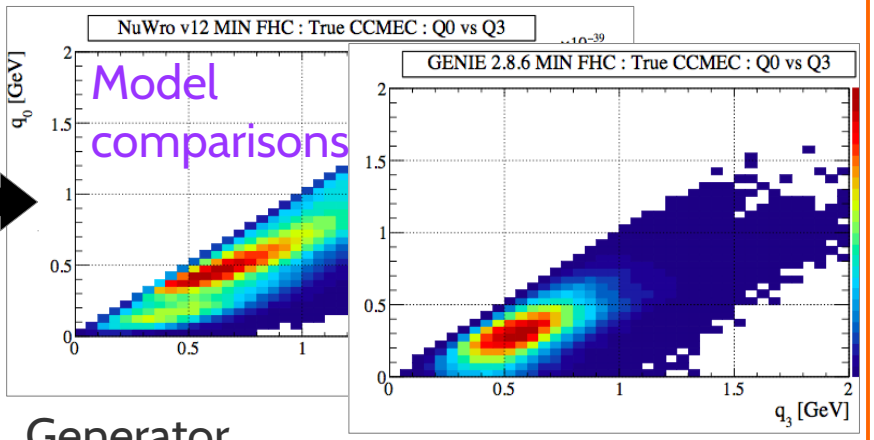
Generators provide particle vectors



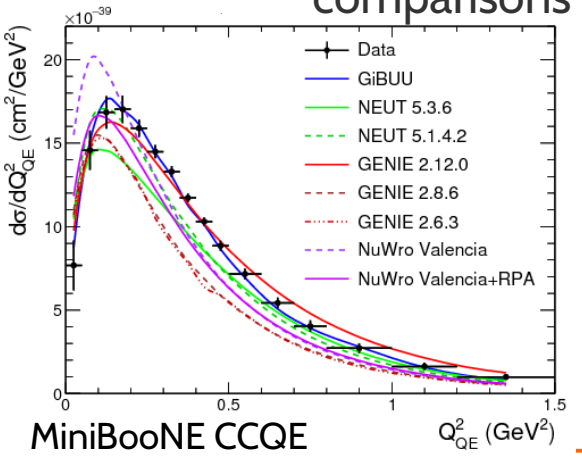
Convert into common event format

Event selection, cross-section scaling, reweight

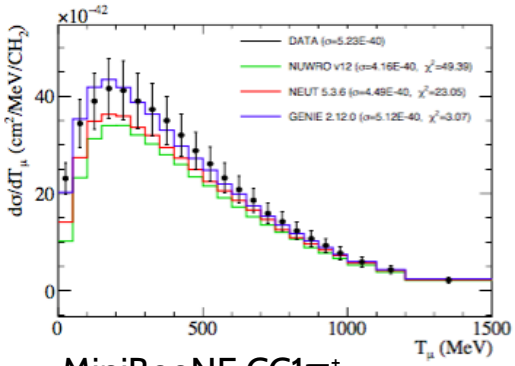




Generator comparisons



MiniBooNE CCQE



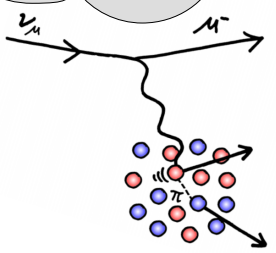
MiniBooNE CC1π^+

Using NUISANCE

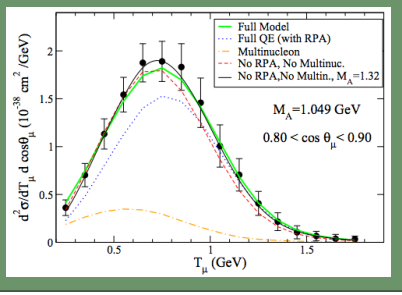
- >200 neutrino dataset for multi-generator comparisons, tunings and systematics studies
- Learn more and talk to us: hepforge, trac wiki, Slack channel, Github, mailing list
- MSc+early PhD student friendly
  - Model interpretation is the tricky bit, making the plots is easy!
- The data distributions are stand-alone from NUISANCE
  - Working with Durham IPPP (HEPdata) on extending their database
- Unsure on a signal definition for an experiment? We've got them
- Can't find the flux for an experiment? Read this long monologue
- Seen examples in Minoo, Marcela and Steve's talks, thanks!

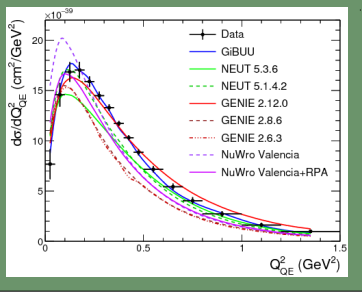
For theory/generator development

Theory model



Confront with cross-section data





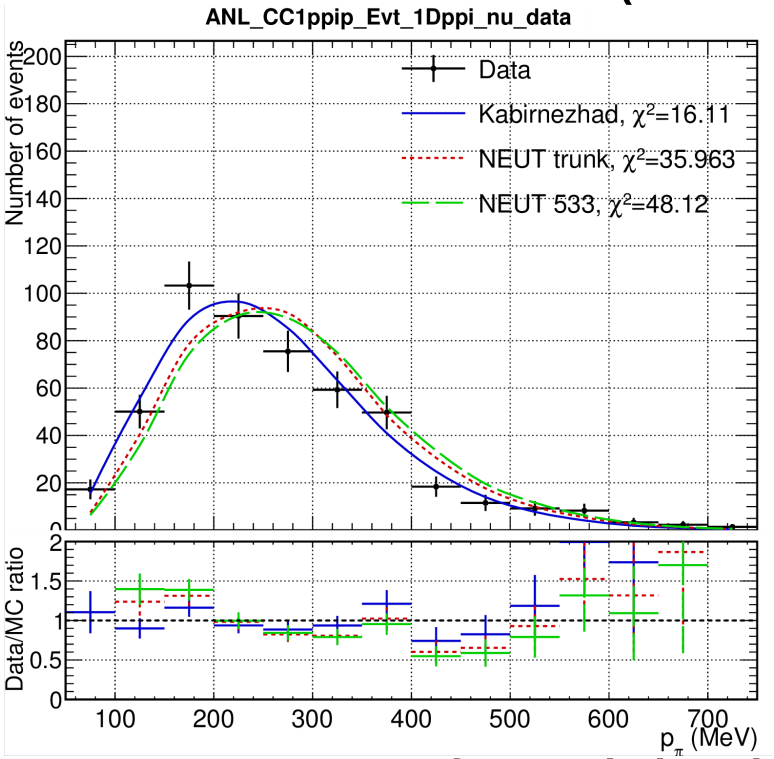
Implement in generators

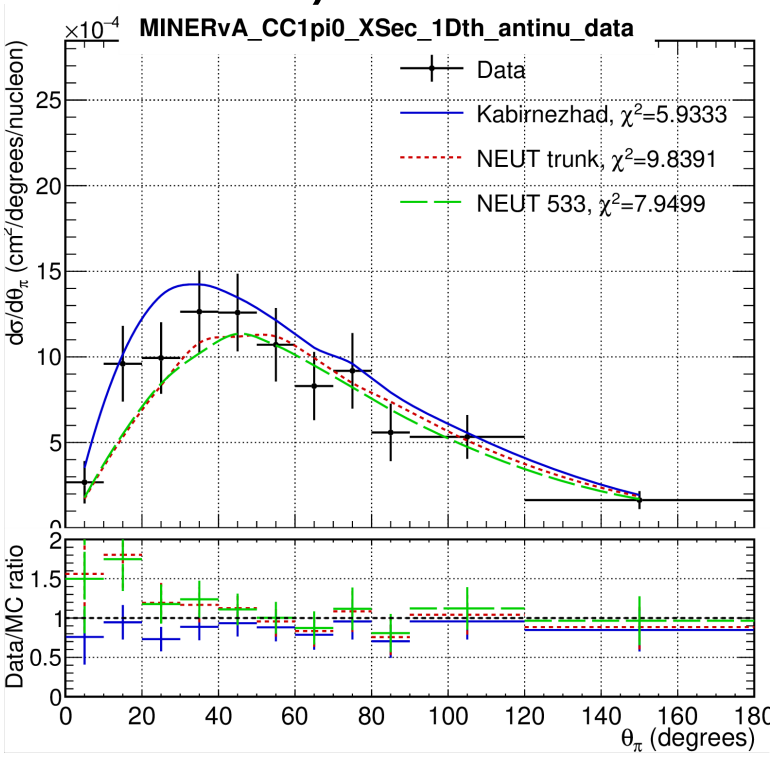
Improve future cross-section and oscillation measurements

- Once theory is implemented in generators, it **should** be easy to update predictions
- Confront the generator model(s) with as much data as possible
- Highlight when generator A might be getting it right → Implement alternative in generator B
- Parameter tuning also supported

Theory uses at T2K

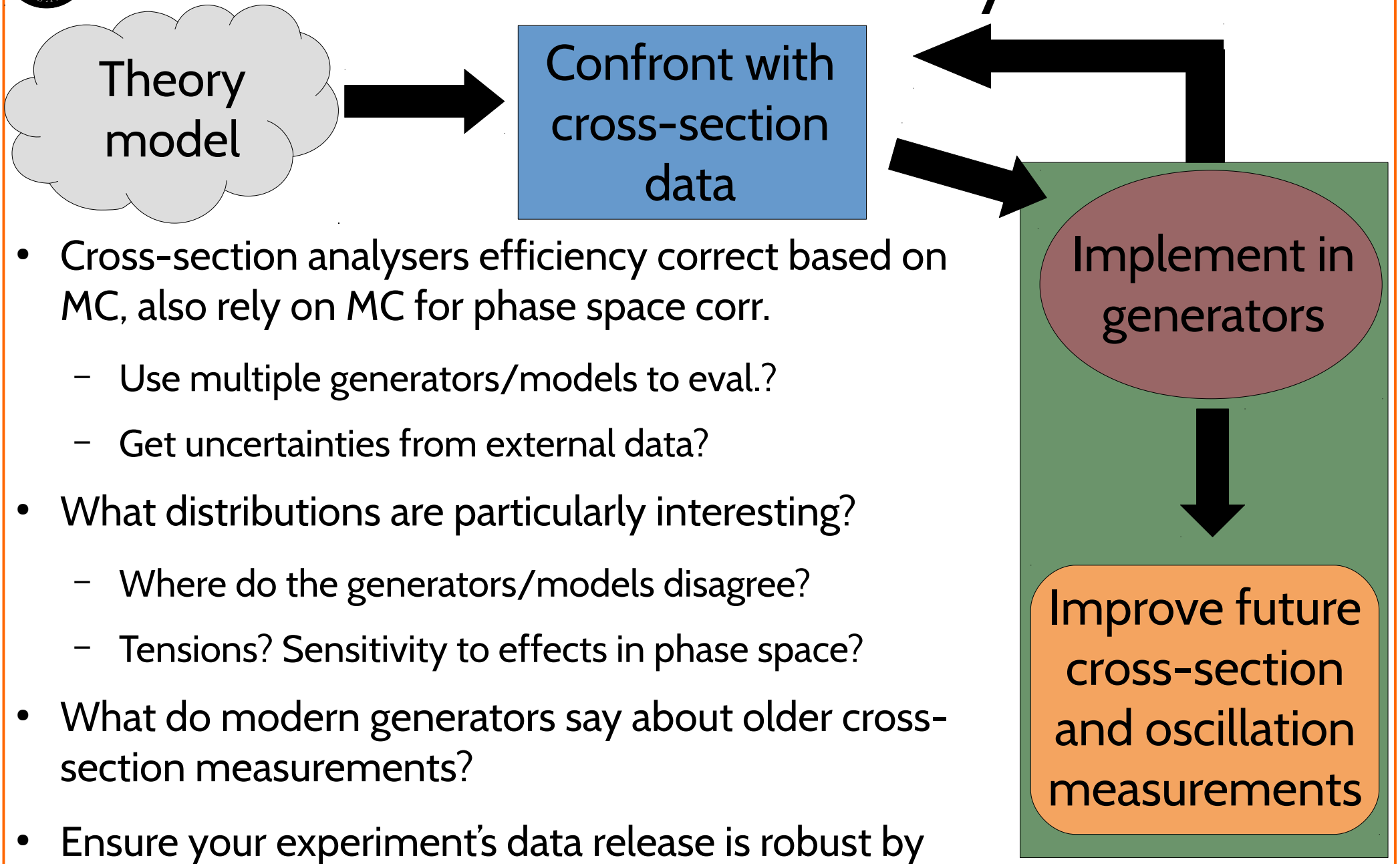
- Minoo Kabirnezhad and I have been evaluating her SPP model implementation in NEUT (see more in her talk)





- Evaluating impact of model selection on external and T2K data, looking at its impact on oscillation analyses
- Parameter tuning to nucleon data (e.g. M_A^{RES}, M_A^{bckg}, $C^A_5(0)$)
- How does the SPP play with NEUT's initial state and FSI models

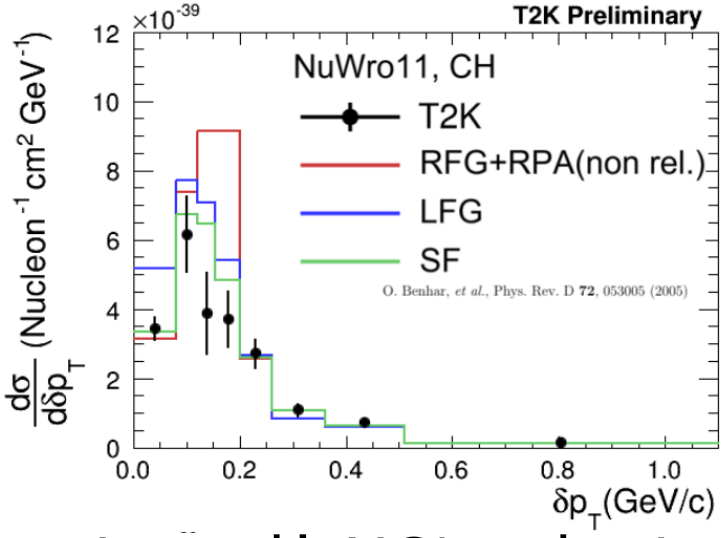
For cross-section analysers

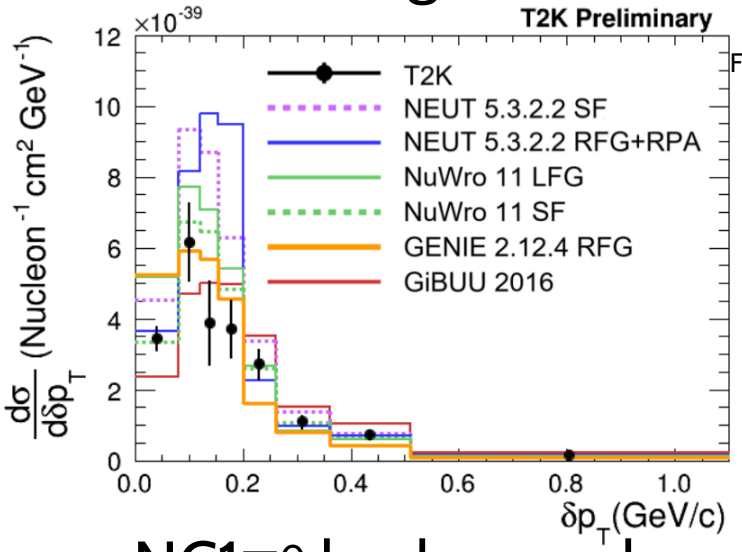


- Cross-section analysers efficiency correct based on MC, also rely on MC for phase space corr.
  - Use multiple generators/models to eval.?
  - Get uncertainties from external data?
- What distributions are particularly interesting?
  - Where do the generators/models disagree?
  - Tensions? Sensitivity to effects in phase space?
- What do modern generators say about older cross-section measurements?
- Ensure your experiment's data release is robust by implementing it into NUISANCE

Cross-section uses at T2K

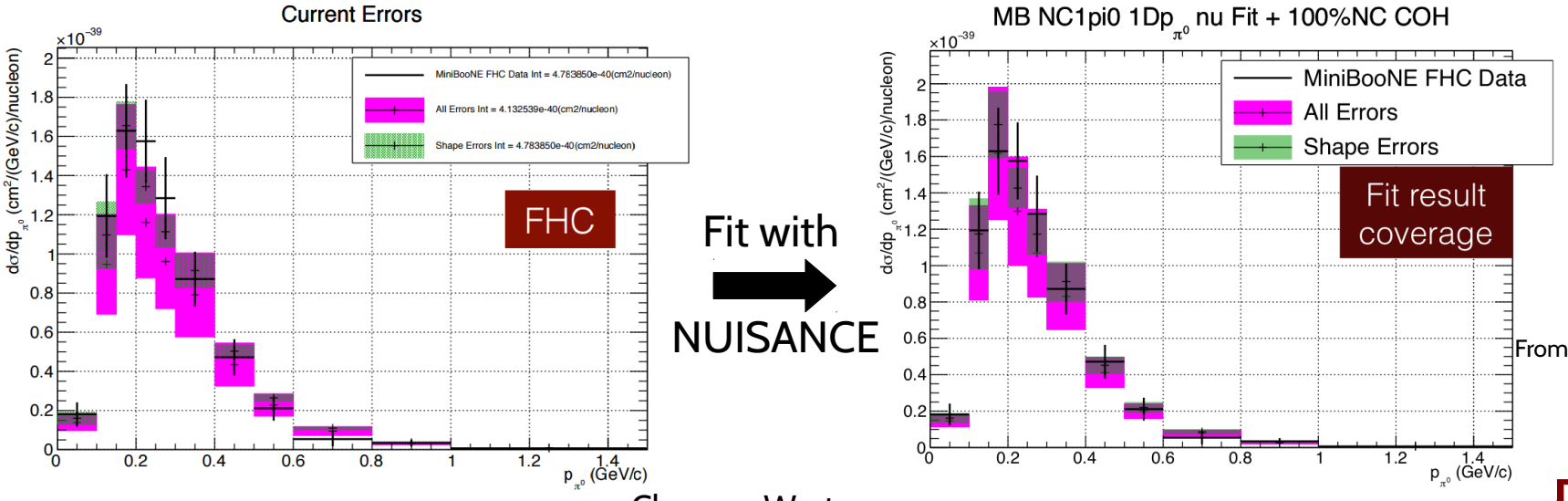
- Stephen Dolan CC0πNp (transverse variables) measurement looked at effect of various initial state models in NuWro and generators





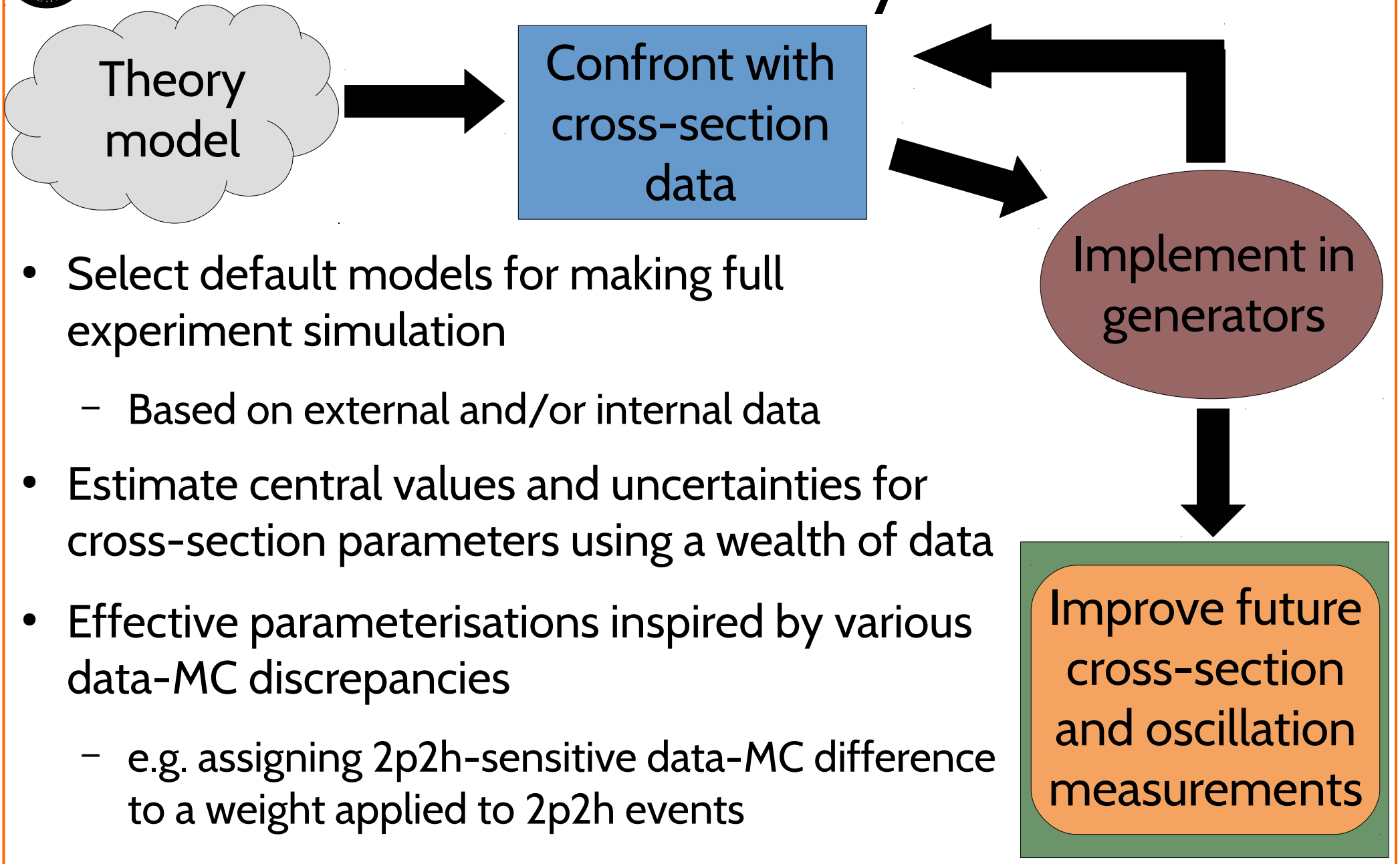
From S. Dolan

- Pierre Lasorak's NC1γ selection has large NC1π⁰ background: used MiniBooNE NC1π⁰ data to survey the coverage of the NEUT model



From P. Lasorak

Oscillation analysers

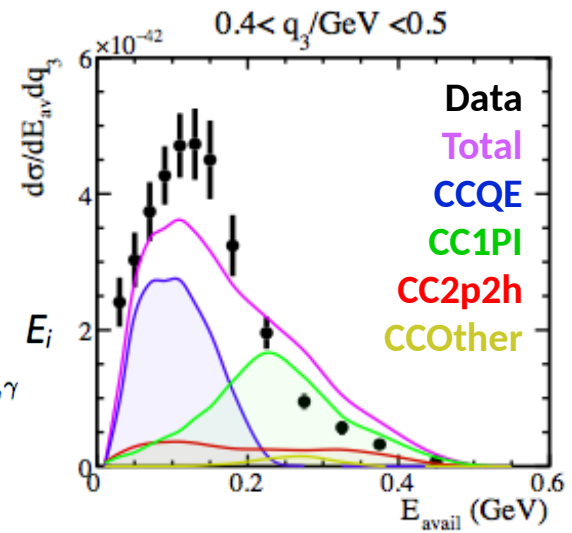


- Select default models for making full experiment simulation
  - Based on external and/or internal data
- Estimate central values and uncertainties for cross-section parameters using a wealth of data
- Effective parameterisations inspired by various data-MC discrepancies
  - e.g. assigning 2p2h-sensitive data-MC difference to a weight applied to 2p2h events

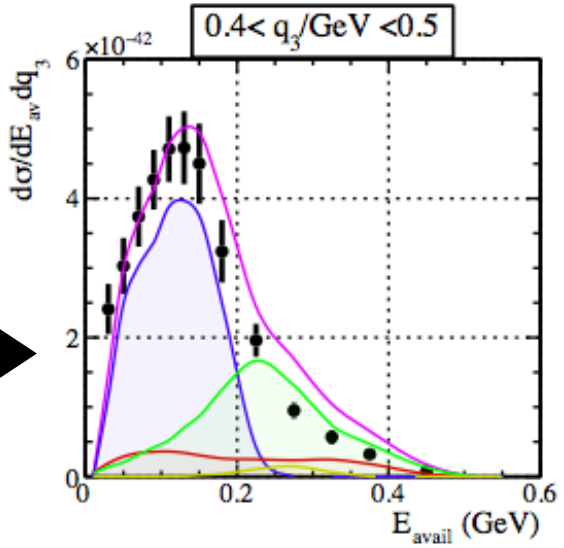
NUISANCE uses at T2K

- Can use to construct fake-data studies
- MINERvA CC-inclusive data indicates the NEUT prediction is missing ingredients in mid-E_{avail} (see Rik Gran's talk)
- Is the difference from CCQE? From 2p2h? ...from CC1π?

$$E_{av} = \sum_{i=p,\pi^{\pm}} T_i^K + \sum_{i=\pi^0,e,\gamma} E_i$$



Assign fully to CCQE



- Assign the difference in data and MC to various interaction modes
  - External data-driven MC correction to interaction model
- Investigate the effect of such corrections on oscillation parameters and how it may bias E_ν reconstruction

Tuning NEUT single pion model

- Short example of how tuning NEUT 5.3.3 works in NUSIANCE
  - Showing for demonstrative purposes only
- Chose ANL and BNL data without W cut, corrected[1] $\sigma(E_\nu)$ and fitting $N(Q^2)$ shape only, leading to the test statistic

$$\chi^2 = \sum^{N(\vec{x})} \left\{ 2 \sum_{i=1}^{N_{\text{bins}}} \left(\text{NEUT}_i - \text{Data}_i + \text{Data}_i \ln \left(\frac{\text{Data}_i}{\text{NEUT}_i} \right) \right) \right\} + \sum^{\sigma(E_\nu)} \left\{ \sum_{i=1}^{N_{\text{bins}}} \frac{(\text{Data}_i - \text{NEUT}_i)^2}{\delta_i^2} \right\}$$

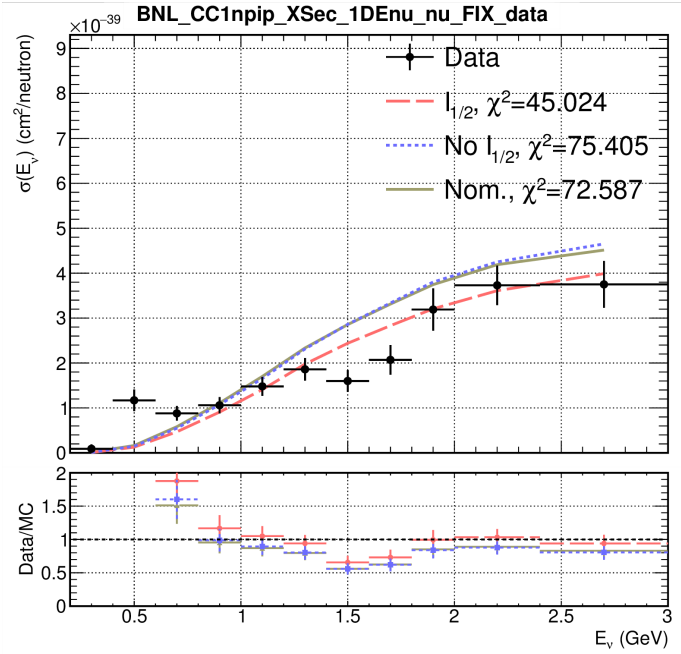
- NEUT single pion model is currently Rein-Sehgal with lepton mass effects (Kuzmin et al[2], Berger Sehgal[3]) and form factors from Graczyk & Sobczyk[4]
  - Identified three parameters: **M_A^{RES}**, **$C^A_5(0)$** and the scaling factor for the Rein-Sehgal I½ non-resonant background, **I½ bkg**
- NUISANCE set-up in backups

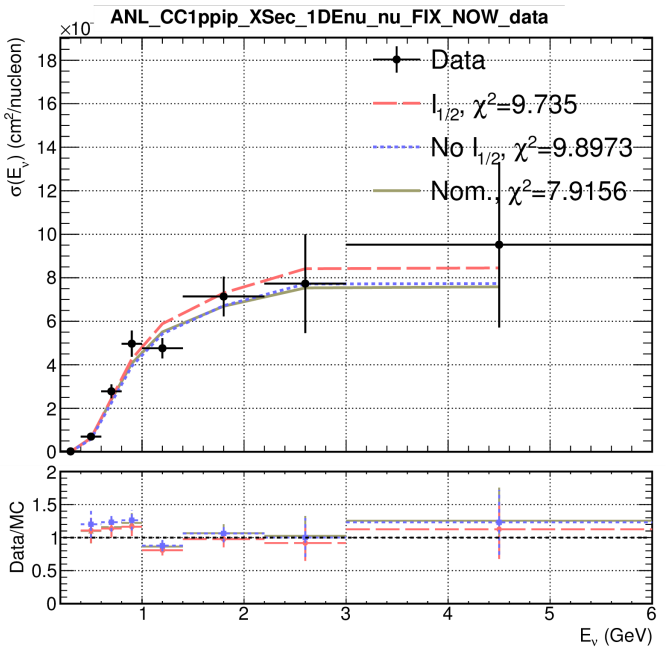
[1]Phys. Dev. D90 (2014)
[2]Nucl. Phys. B Proc Supp. 139 (2005)
[3]Phys. Rev. D76 (2007)
[4]Phys. Rev. D77 (2008)

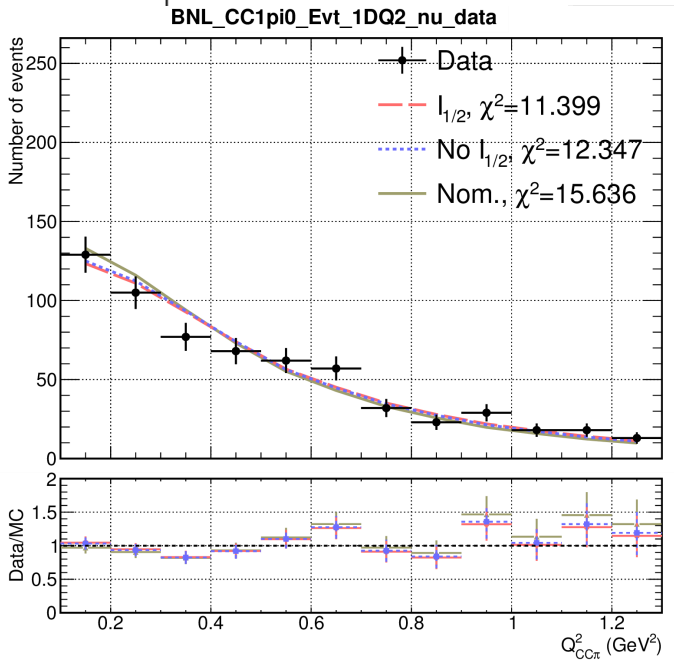
Tuning NEUT single pion model

- Non-resonant I½ background helps in many distributions, shifts $C^A_5(0)$

Data	M_A^{RES} (GeV)	$C_5^A(0)$	$I_{1/2}$ scale	χ^2/ndof
ANL, BNL $W < 2.0$ with $I_{1/2}$	1.07 ± 0.05	0.95 ± 0.05	0.97 ± 0.07	$235.0/137 = 1.71$
ANL, BNL $W < 2.0$ without $I_{1/2}$	1.06 ± 0.04	0.89 ± 0.06	N/A	$265.7/138 = 1.93$



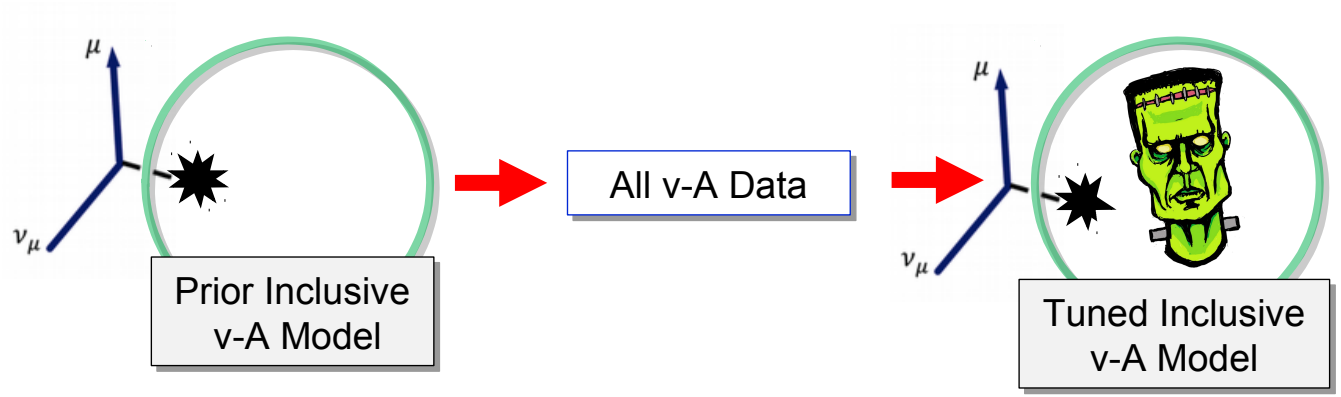




- Do further analysis of parameters: other bubble chamber distributions
  - Use parameters to predict e.g. MiniBooNE CC1π⁺, CC-inclusive...

Long-term fit goal

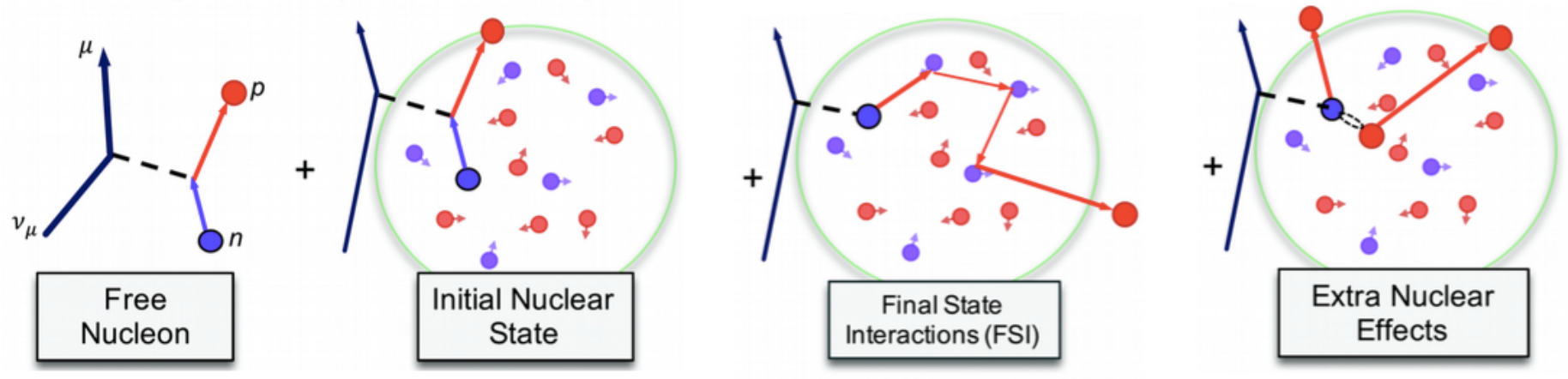
- Large ensemble of data available in NUISANCE
- Blindly fitting all parameters tells us little about physics
  - Very likely to end up with a unphysical Frankenmodel, e.g. unnaturally high M_A^{QE}, $C_A^5(0)$ far from ~1.2...
  - Not necessarily statistically correct because of missing covariances, leading to a poor test-statistic, pulls from certain experiments



- Instead develop a step-by-step tune using priors from earlier NUISANCE fits with generator experts

Long-term fit goal

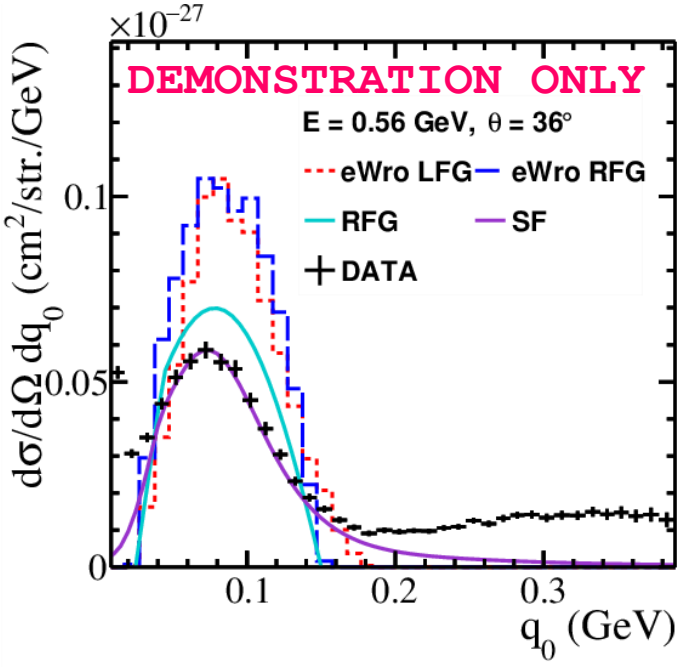
- First fit to exclusive bubble chamber data
  - Constrain the fundamental interaction without nuclear effects
- Include exclusive data from nuclear target (e.g. CC0π, CC1π^+)
  - Use priors from BC fit, include the relevant nuclear parameters
- Include inclusive data from nuclear targets (e.g. E_{avail})
  - Use priors from earlier fit(s)

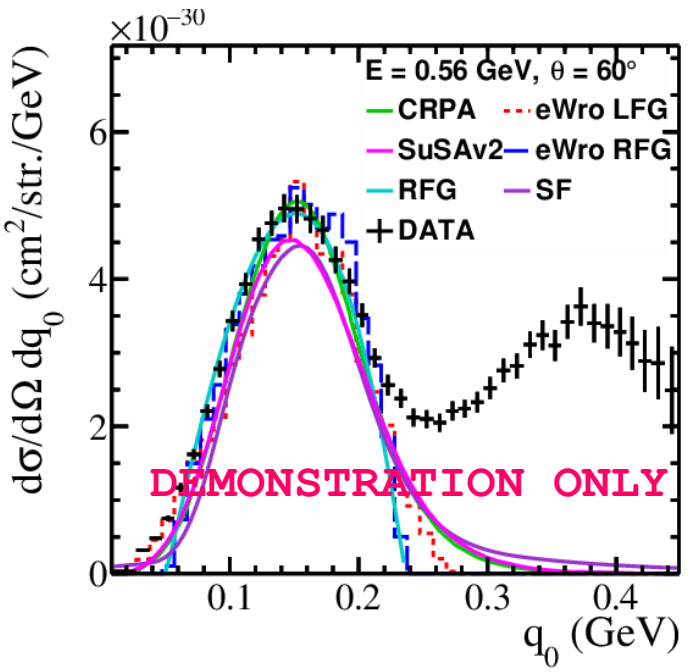


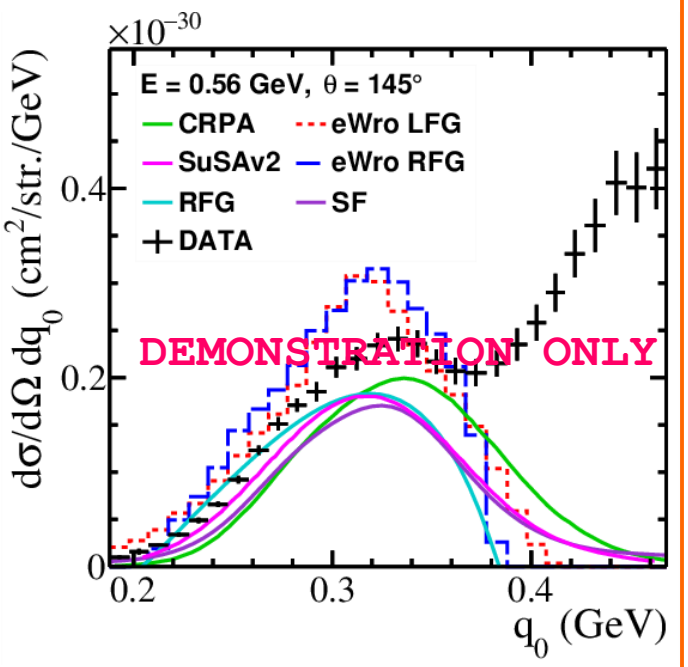
- All whilst checking for dataset compatibilities and possible tensions

Electron scattering

- **Vishvas Pandey** has joined us with expertise on electron scattering
- **VERY** preliminary, but framework is running
  - Need to validate eWro calculations
  - GENIE and GiBUU interface being built and tested
- Don't read into these, showing for future plans







- Special thanks to eWro group for providing beta version for testing

Future projects

- Attempt combined generator fits and comparisons
  - Requires the knowledge of generator experts
  - Starting with bubble chamber tunes this summer
- Patrick is working with MINERvA to develop a MINERvA tune
- Extending interface to pion and photon scattering
- Easily accessible website
  - Publish nominal predictions of generator A, B, C with models X, Y, Z
- Agree on "HepMC"-like format to include theory predictions
  - Produce outgoing particles by accept-reject
  - Make these stacks into a common format

Summary

- NUISANCE is a large open source neutrino cross-section comparison framework
- Supports simple Data/MC comparisons, systematics evaluations parameter fitting
- NEUT, GENIE, NuWro and GiBUU support
  - Additionally links to reweighting libraries
- Can inform the users of model "goodness" vs data and other generators, previous measurements, error coverage
- We encourage any collaboration; from theory and experiment

- Stay tuned for NuSTEC 2017 tutorial!

Thank you

https://nuisance.hepforge.org/

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NUISANCE card file for 1pi tune

Parameter name in ReWeight

Specify the parameter type

Parameter start point, limits, step size, type

```
# The NEUT parameters we're fitting
neut_parameter MaNFFRES 0.0 -5.0 5.0 1.0 FREE
neut_parameter CA5RES   0.0 -5.0 5.0 1.0 FREE
neut_parameter BgSclRES 0.0 -5.0 5.0 1.0 FREE

# Add the no W cut ANL and BNL samples
sample ANL_CC1ppip_XSec_1DEnu_nu  NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root SHAPE/NOW
sample ANL_CC1ppip_Evt_1DQ2_nu    NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root NOW

sample ANL_CC1npip_XSec_1DEnu_nu  NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root SHAPE/NOW
sample ANL_CC1npip_Evt_1DQ2_nu    NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root NOW

sample ANL_CC1pi0_XSec_1DEnu_nu   NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root SHAPE/NOW
sample ANL_CC1pi0_Evt_1DQ2_nu     NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root NOW

sample BNL_CC1ppip_XSec_1DEnu_nu  NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root SHAPE
sample BNL_CC1ppip_Evt_1DQ2_nu    NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root

sample BNL_CC1npip_XSec_1DEnu_nu  NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root SHAPE
sample BNL_CC1npip_Evt_1DQ2_nu    NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root

sample BNL_CC1pi0_XSec_1DEnu_nu   NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root SHAPE
sample BNL_CC1pi0_Evt_1DQ2_nu     NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root
```

Sample type

Specify the data sets

Specify the generator

File location

```
./nuiscomp -c a.card -o o.root
```

Want to do it with GENIE instead?
Give `genie_parameter` and `GENIE:GENIE_FILE_LOCATION`

Implementing a new sample

- To implement a new sample we need
  - The data distribution (e.g. $d\sigma/dp_\mu$)
  - Method to construct a test-statistic (e.g. covariance matrix)
  - Neutrino flux distribution to generate events
  - Well-defined dependent variable (e.g. p_μ)
  - Well-defined signal definition (e.g. one $\mu^\pm$, no mesons, any nucleons)
- Measurements inherit from a `MeasurementBase` base class
- Measurements are entirely separated from the generators
  - Implement measurement once, then can use all the generators
  - All functionality enabled: compare, fit, make error bands
  - Does not require generator experts to create, modify or use measurements

Lessons from handling neutrino data

- Have handled a lot of neutrino data with varying degrees of success

- Publish and test your final **covariance matrices**
  - Statisticians consider **data without covariances to be incomplete**
  - Bob Cousins, Louis Lyons (CMS), Pumplin, Stump (CTEQ/CT10) **recommended simply excluding these "useless measurements"**
  - If you want maximum juice from your measurement, consider **distribution-to-distribution correlations**

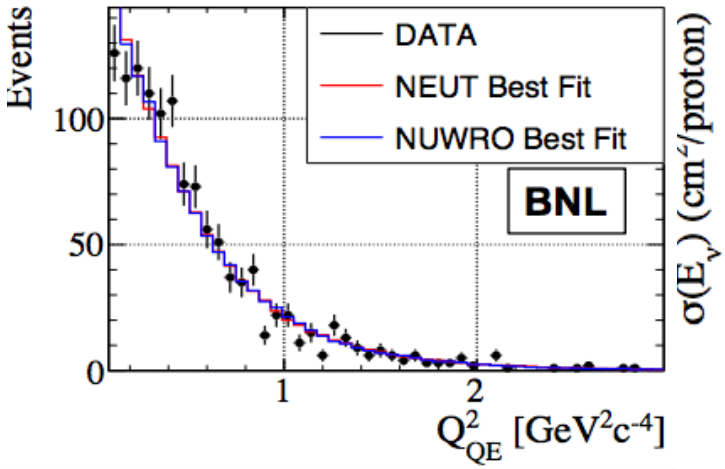
- Signal definition needs to be reproducible in raw MC (truth)
- Don't correct for blind detector regions. **Data is pure, data is sacred**

Fitting with NuWro ReWeight

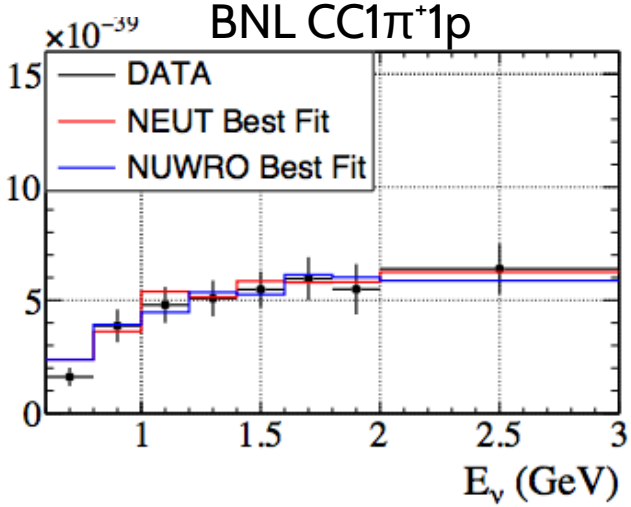
- Luke and Patrick developed NuWro ReWeight for CCQE and SPP interactions; **here for demonstrative purposes**
- Similar models to NEUT for free nucleon CCQE and SPP in the W < 1.4 GeV regime: expect similar results for the two generators

	QE		RES		
Fit Results	M_A [GeV/c^2]	χ^2/NDOF	M_A^{RES} [GeV/c^2]	C_A^5	χ^2/NDOF
NEUT (v5.3.6)	1.04 ± 0.03	159.8 / 146	0.89 ± 0.04	1.02 ± 0.05	102.8 / 102
NuWro (v12)	1.03 ± 0.03	154.4 / 146	0.92 ± 0.03	1.04 ± 0.05	111.9 / 102

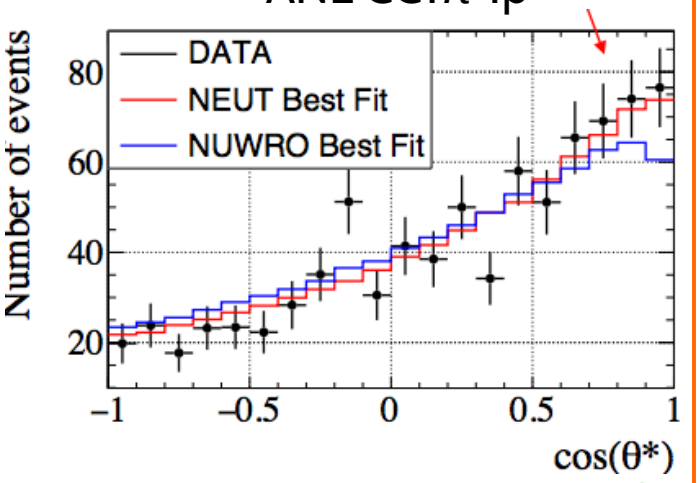
BNL CCQE



BNL CC1π⁺1p



ANL CC1π⁺1p



NEUT 5.3.6 results

- NEUT 5.3.3 result disagrees with NuWro tune
- Expected because NEUT 5.3.3 → 5.3.6 slightly different 1pi treatment
- Fitting NEUT 5.3.6 is very similar results to NuWro W < 1.4

ANL, BNL $W < 2.0$ with $I_{1/2}$	0.96 ± 0.03	1.05 ± 0.05	0.99 ± 0.07	$233.1/137 = 1.70$
NEUT 5.3.3	1.07 ± 0.05	0.95 ± 0.05	0.97 ± 0.07	$235.0/137 = 1.71$
ANL, BNL $W < 2.0$ without $I_{1/2}$	0.94 ± 0.03	1.00 ± 0.04	N/A	$256.0/138 = 1.86$
NEUT 5.3.3	1.06 ± 0.04	0.89 ± 0.06	N/A	$265.7/138 = 1.93$