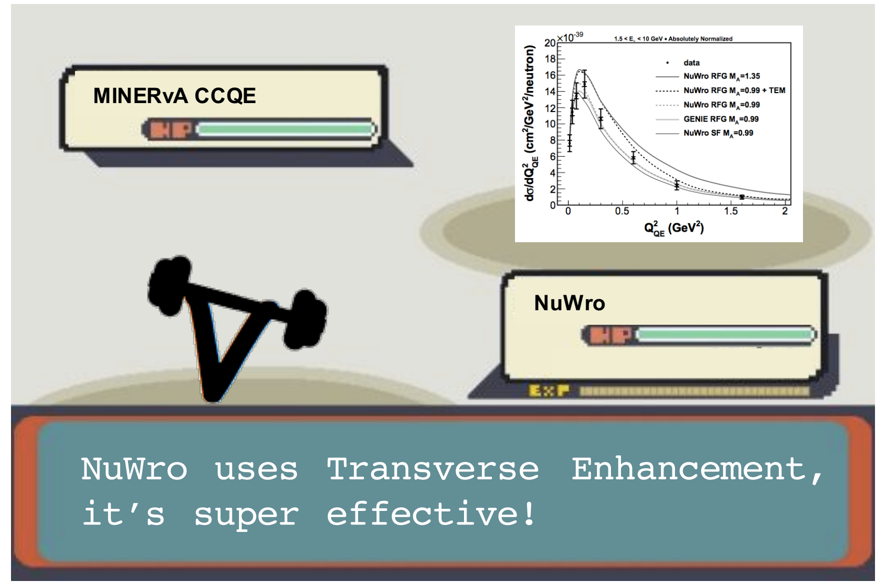
Monte-Carlo Event Generators vs Neutrino Cross-section Data



NuFact 2016

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Imperial College London

Introduction: Cross-section Modelling

Theoretical Model

XSec Data

Generator Model

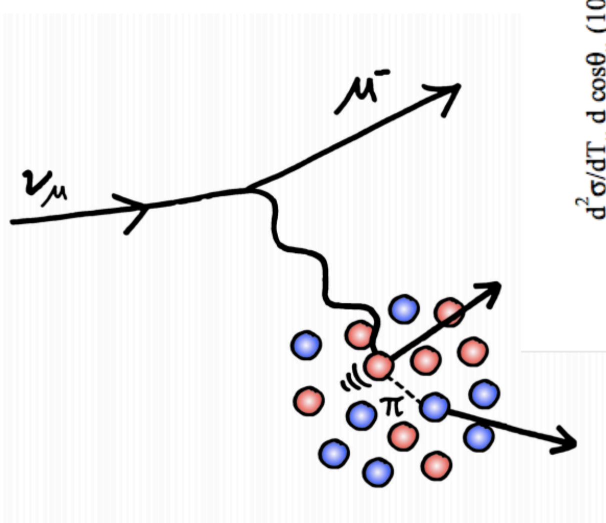
Future Predictions

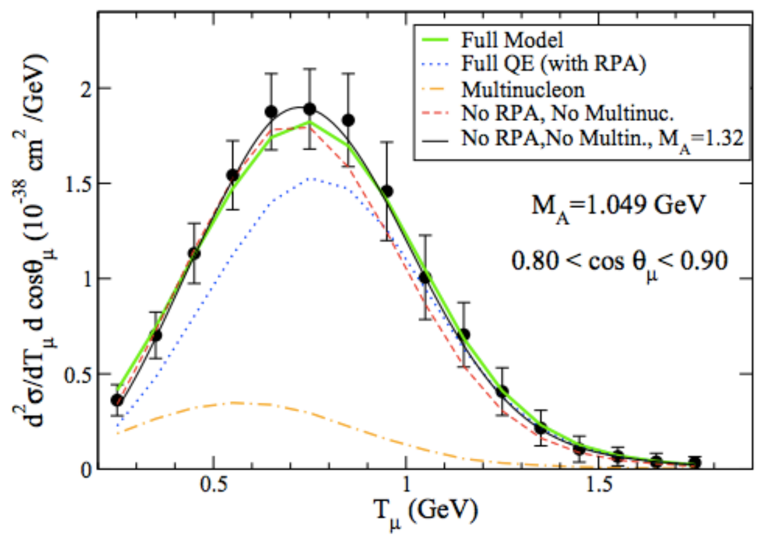
2p2h Model Implemented into Generator

Theorist comes up with a new model for additional nuclear effects

e.g. Nieves model for two-particle-two-hole (2p2h) interactions

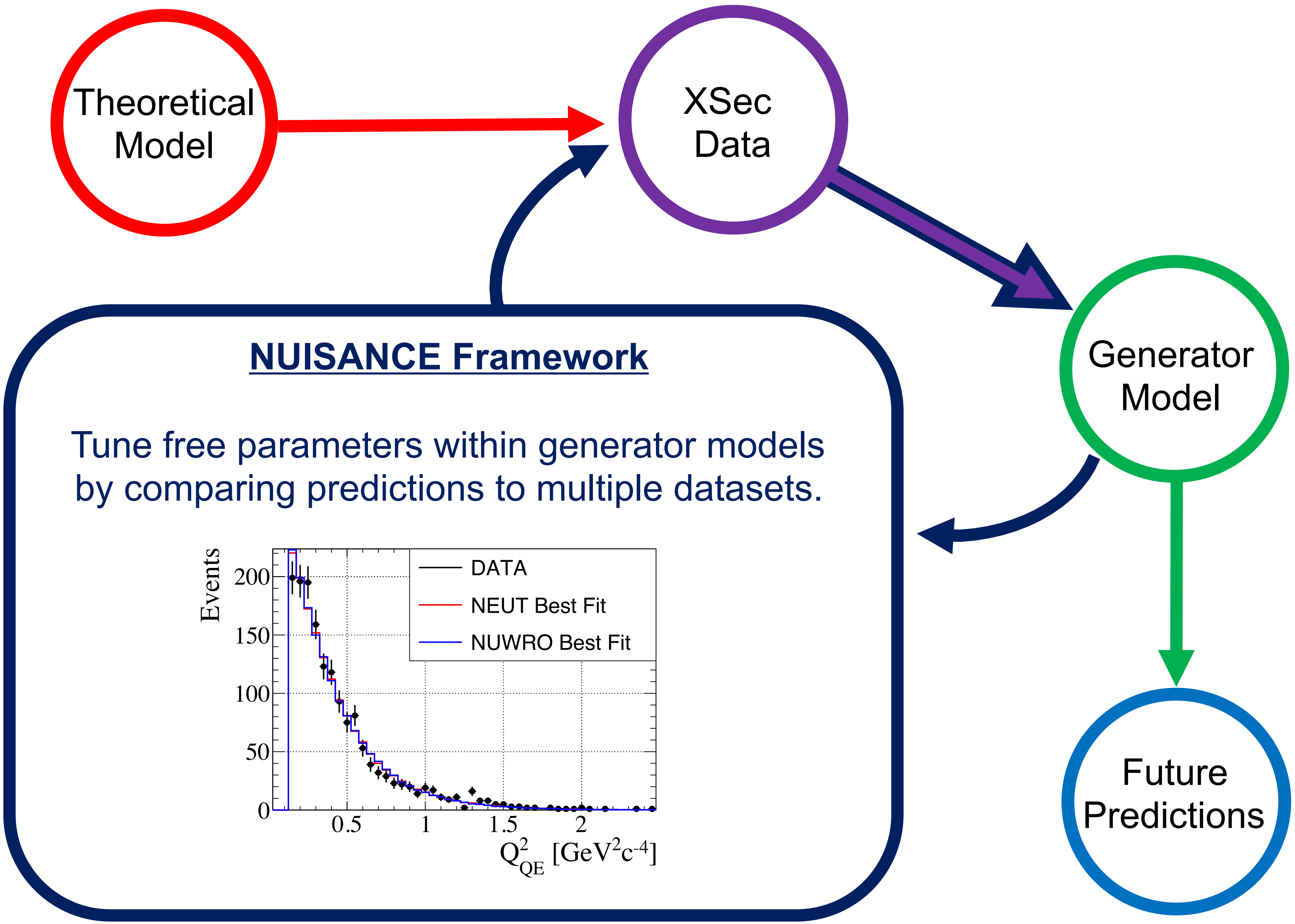
Does it agree well with existing data?





Need good understanding of cross-section systematics in generators.

Introduction: NUISANCE



NUISANCE Framework

- Analysis tool for studying systematic uncertainties on generator models.
  - Automated reweight dial tuning to existing cross-section data.
  - Easy to implement dataset comparisons.
  - Support for multiple generators and reweight engines:

    GENIE, NEUT, NuWro, NUANCE, GiBUU

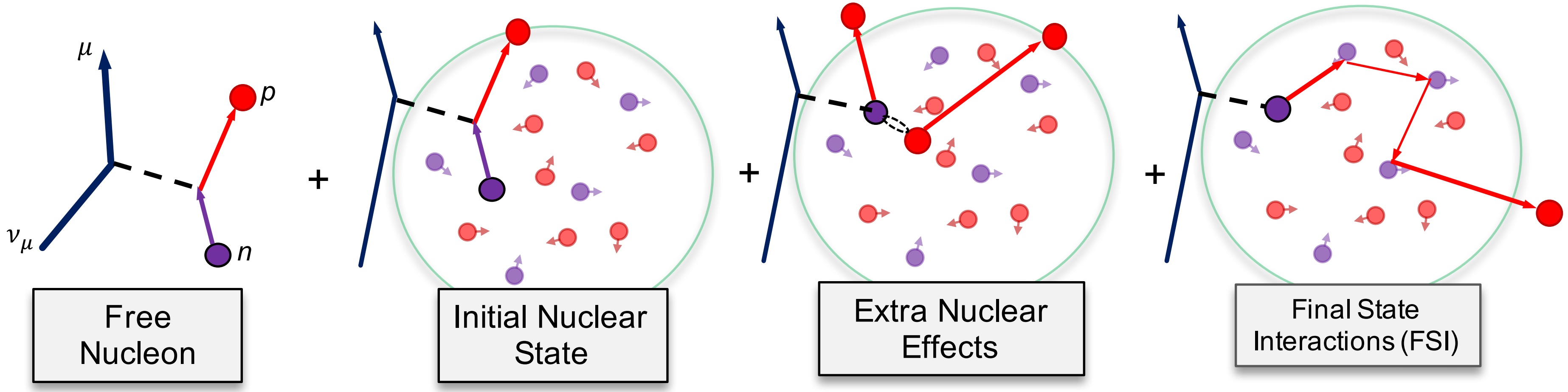
NUISANCE σ

https://nuisance.hepforge.org/

Source code used for all studies shown in this talk can be found inside the NUISANCE repo.

Building a set of model tunings

- Some generators build up models in discrete components



- Building up global model fits with the generators in a similar way.
- Group available data as:
    1. Quasi-Elastic (QE) scattering on D_2
    2. Resonant pion production (RES) on D_2
    3. QE scattering data on C

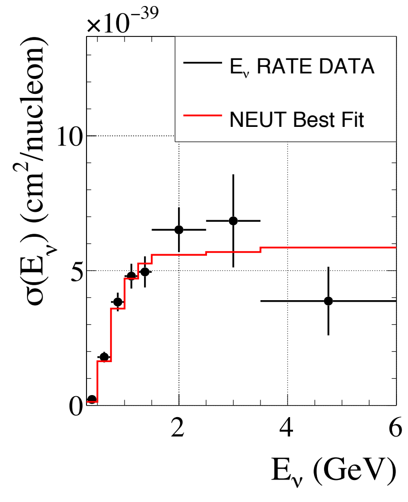
    } Performed free reweight dial tunings.

    4. Inclusive scattering on C } Currently showing comparison studies

NUISANCE WORK IN PROGRESS

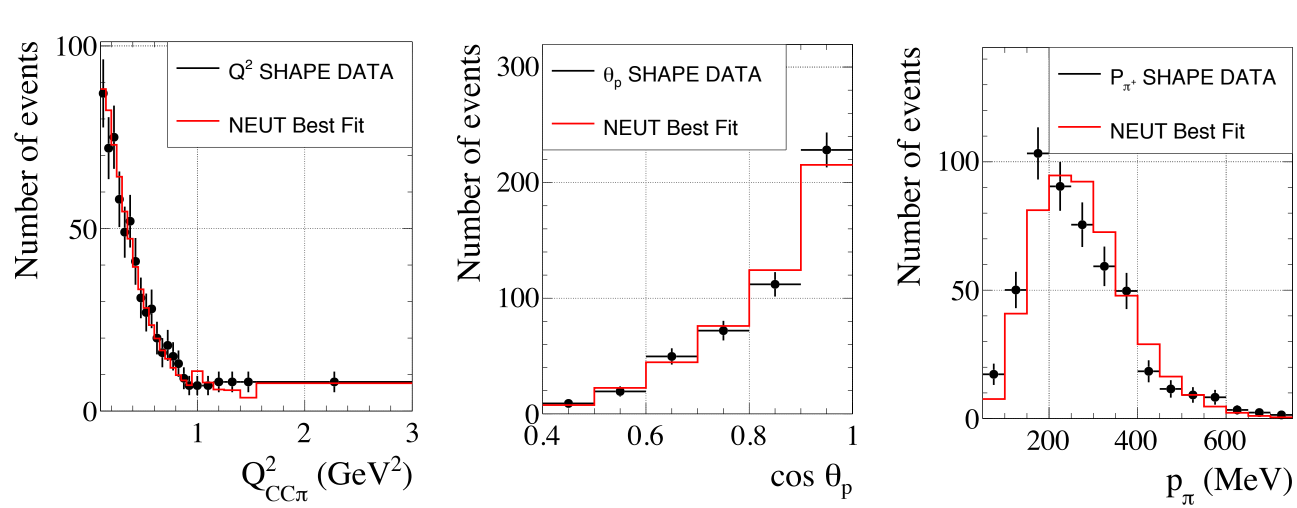
Fitting bubble chamber data

- Can use ν-D_2 data to place a constraint on the free nucleon cross-section.
- **Free Nucleon Models:**
  - **NEUT**: *Llewellyn-Smith QE, Rein-Seghal (Multiple Nuclear Resonances) RES*
  - **NUWRO**: *Llewellyn-Smith QE, Rein-Seghal (Only Delta Resonance) RES*



ANL CC1p1π Total Norm.

+



ANL CC1p1π Extra Shape Distributions

- Multiple distributions from single measurement are included in likelihood.
  - Neglect unknown correlations.

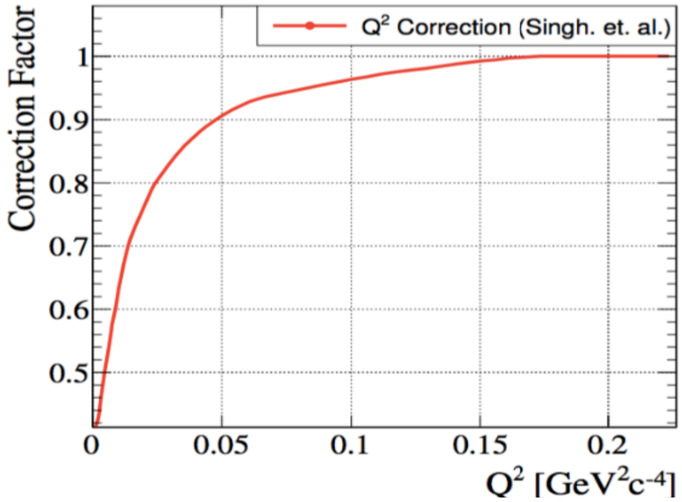
Bubble chamber CCQE fits

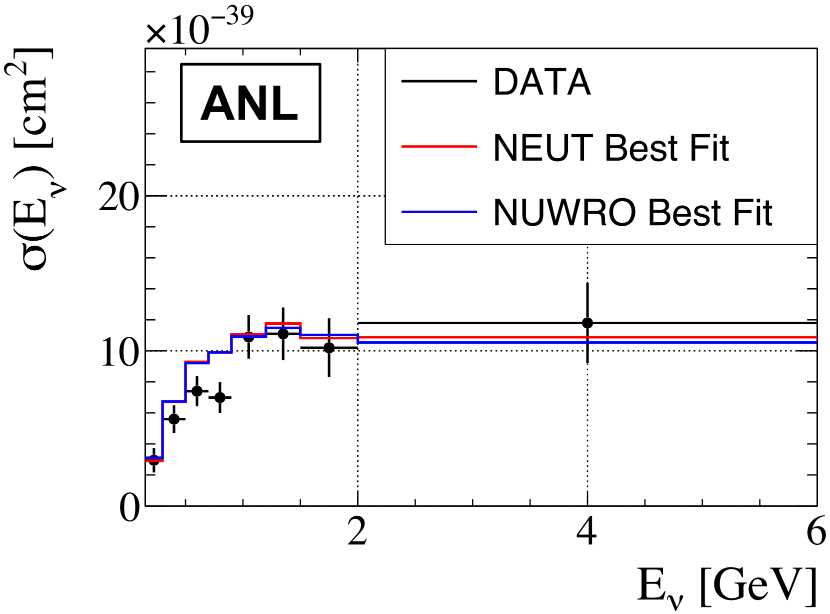
- Use charged-current quasi-elastic (CCQE) data from ANL/BNL/FNAL/BEBC to constrain on the dipole axial form factor.

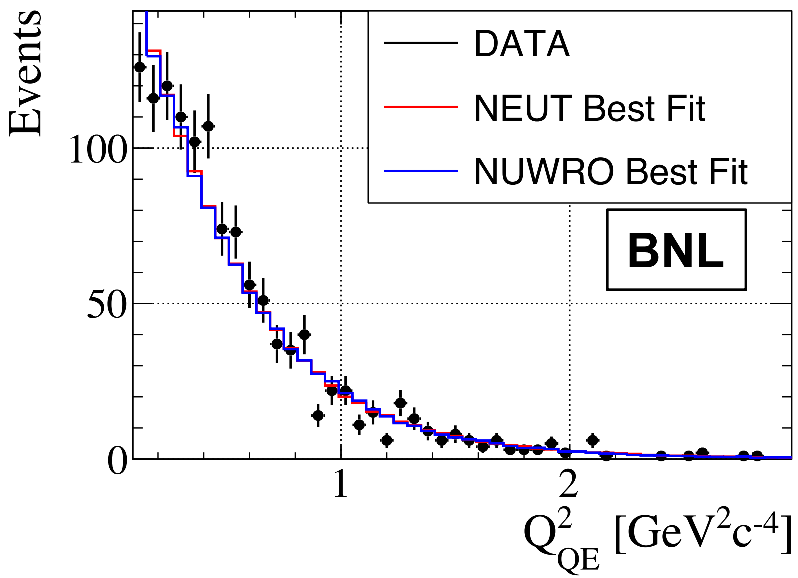
- Q^2 Correction used to make the transition

  Free Neutron → D_2

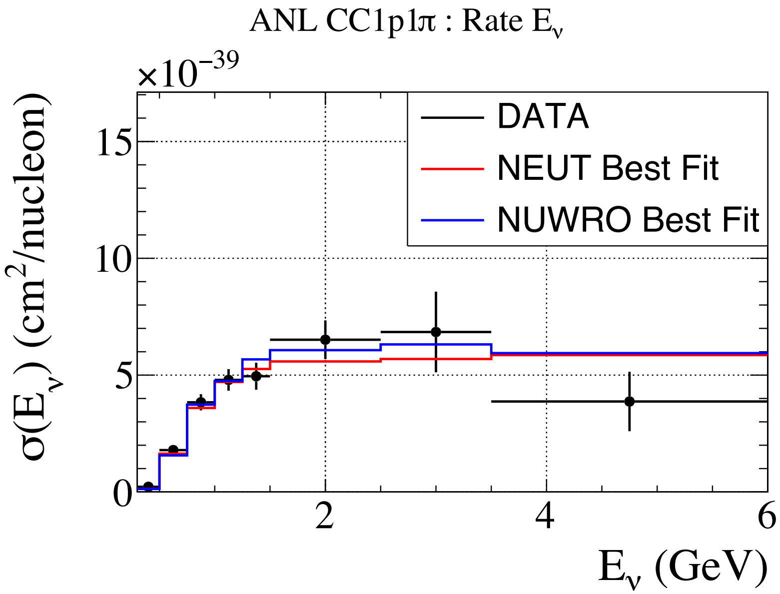
- Vary the axial mass M_A to find best fit to data.

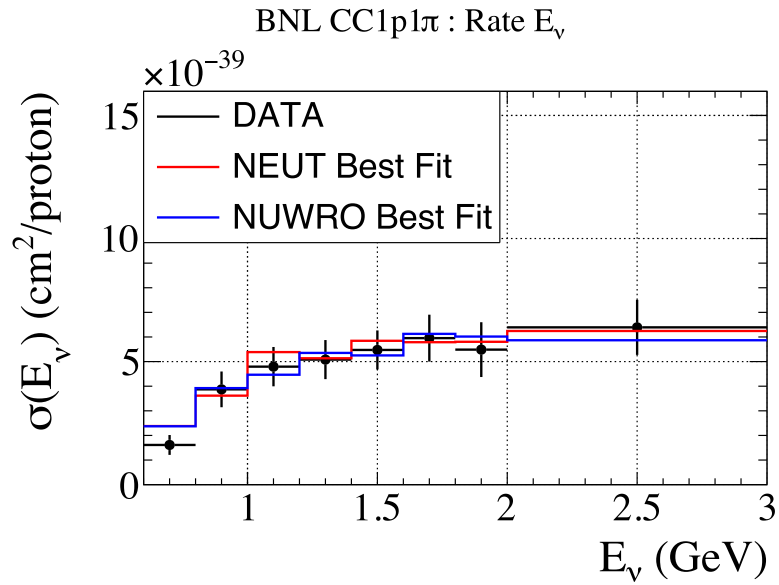




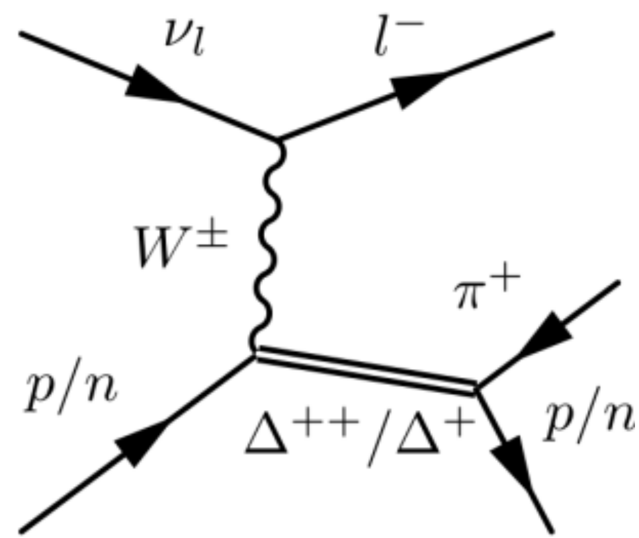


Bubble chamber RES fits



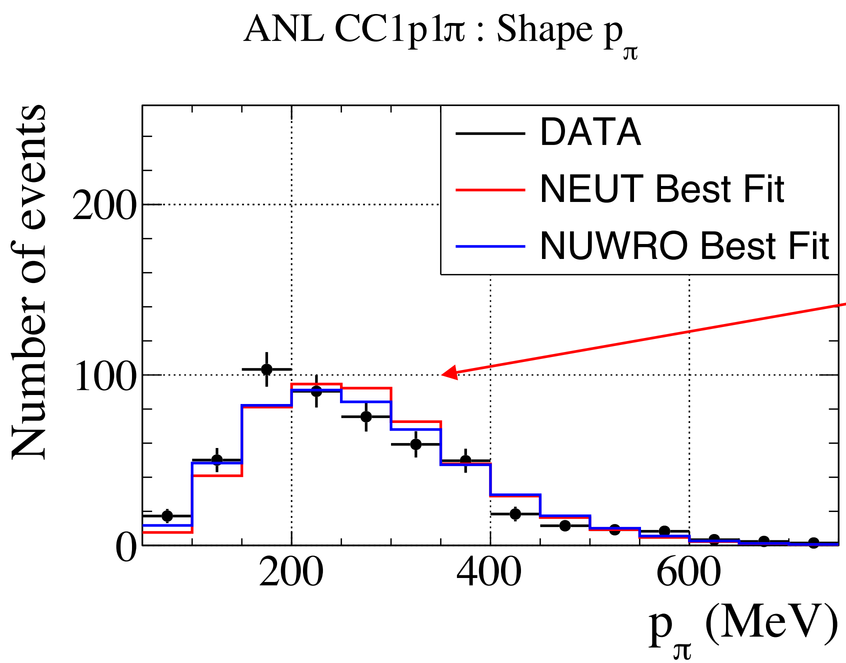


- Treat M_A^{RES} and C_A^5 as free parameters in the pion production model.
- Fit model to re-analyzed ANL/BNL CC1p1π channel data
- NEUT and NuWro should agree as both use similar Graczyk-Sobczyk Form Factors.

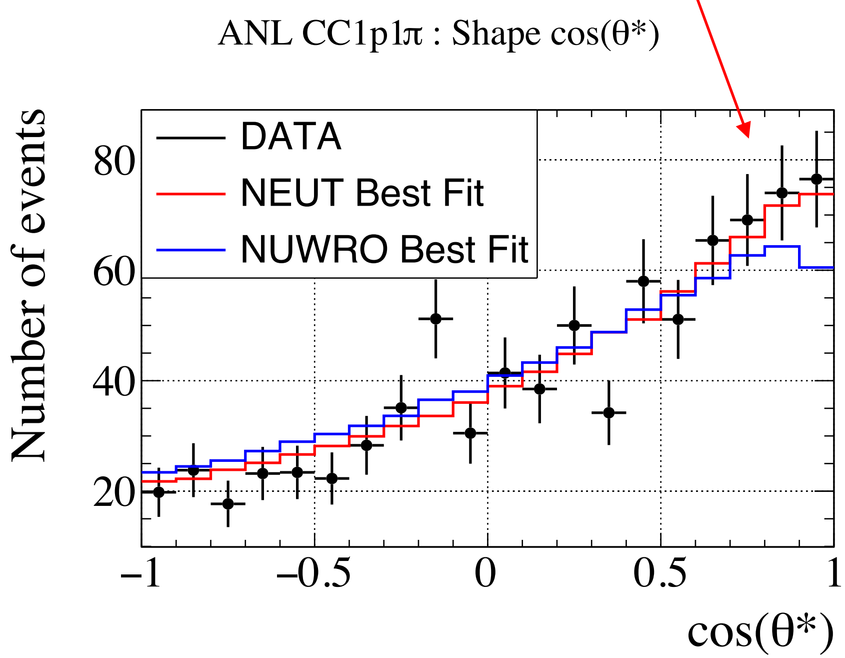


Bubble chamber RES fits

- Multiple CC1p1π datasets added to the fit for additional shape constraints.



Slight differences between NEUT and NuWro



Other shape distributions included can be found in the backups

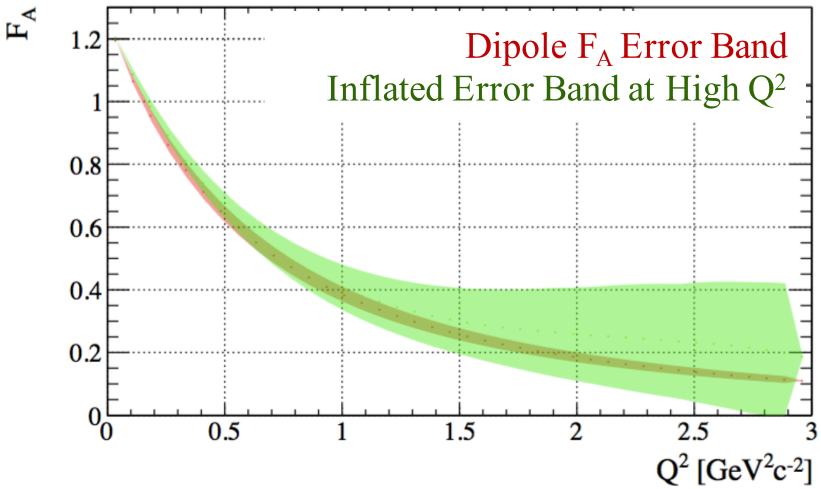
Bubble chamber results

	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

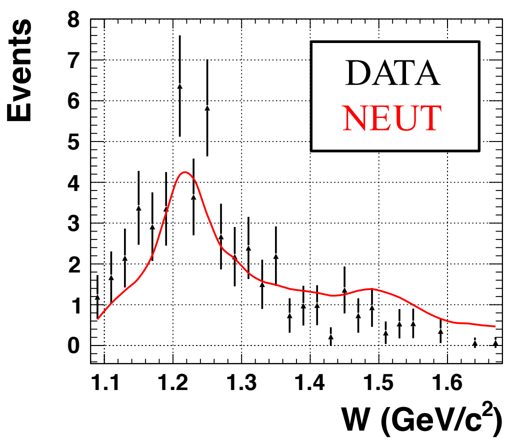
- Quasi-elastic fit results are as expected and NEUT and NuWro are in agreement for both likelihood fits.

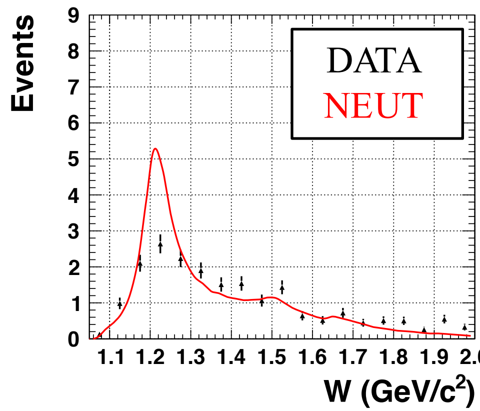
- Future/Ongoing Work:

Alternative Axial Form Factor Shapes



Additional RES Channels





Simulating QE on carbon

- QE fits are continuation of NEUT studies in *Phys. Rev. D 93, 072010 (2016)*

Fit Results (NEUT v5.3.3)	M_A [GeV/c^2]	**2p2h Norm**	p_F [MeV/c]	χ^2/NDOF
RFG+Rel. RPA + 2p2h	1.15 ± 0.03	**27 ± 12**	223 ± 5	97.8 / 228
RFG + Non-rel.RPA + 2p2h	1.07 ± 0.03	**34 ± 12**	225 ± 5	117.9 / 228
SF + 2p2h	1.33 ± 0.02	**0 (at limit)**	234 ± 5	97.5 / 228

Phys. Rev. D 93, 072010 (2016)

- **Choose 3 different nuclear models for study.**
  1. NEUT RFG+Nieves (NEUT v5.3.6)
     Relativistic Fermi Gas (RFG) + Nieves 2p2h + RPA
  2. NuWro LFG+Nieves (NuWro v12)
     Local Fermi Gas + Nieves 2p2h + RPA
  3. NuWro RFG+TEM (NuWro v12)
     RFG + Transverse Enhancement (TEM)

NuWro reweight engine developed to allow us access to these alternate models in joint fits.

Model variations

- **Consider 2 free reweight parameters for all models:**
  1. Axial Mass

     Allow an ad-hoc variation of M_A away from the QE bubble chamber prediction of ~ 1GeV if the nuclear data requires it.

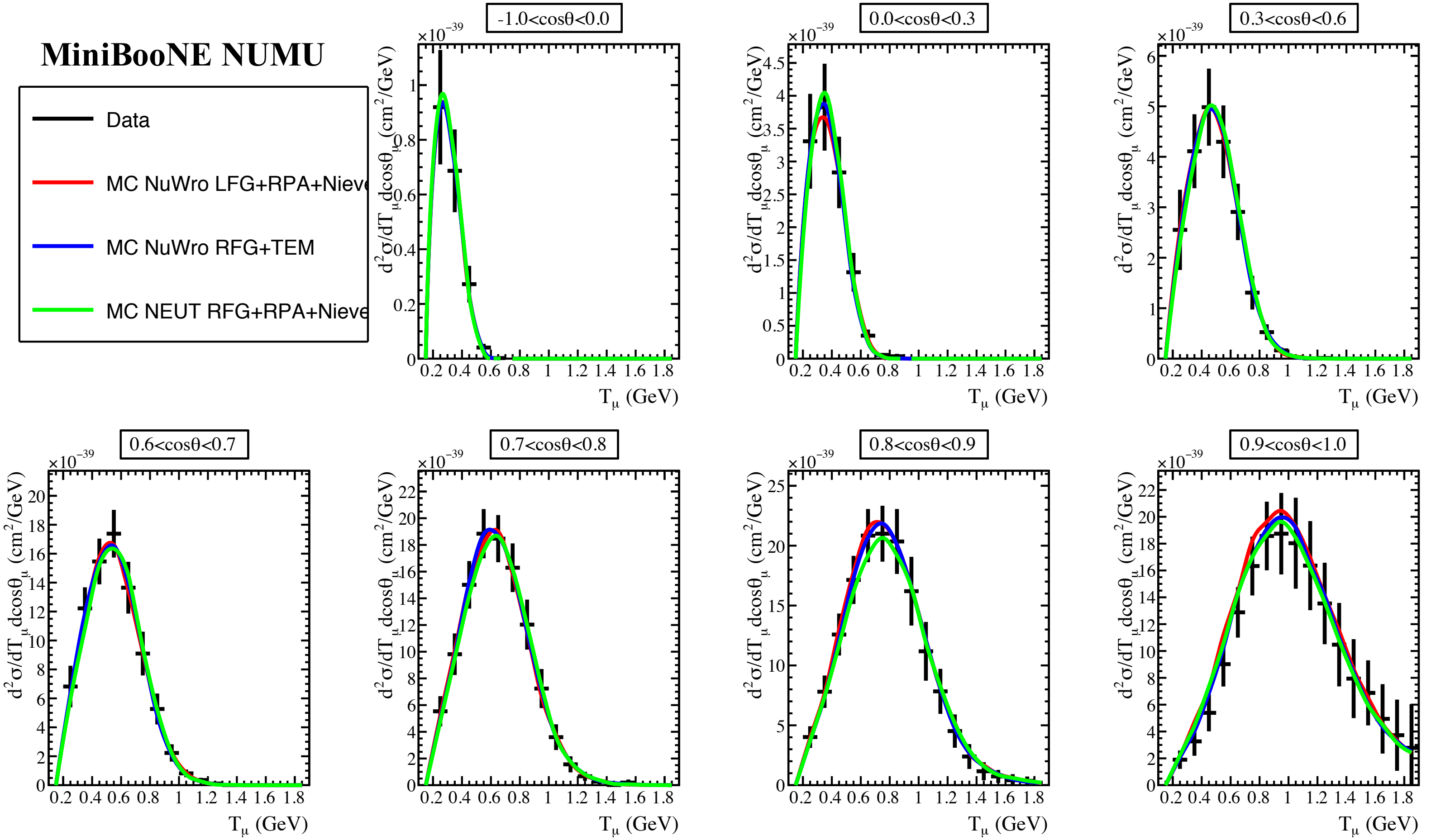
     Such a pull is a sign we need to rethink the treatment of nuclear effects in these models.

  2. 2p2h Norm.

     Scaling factor that applies an additional weight to all true 2p2h events.

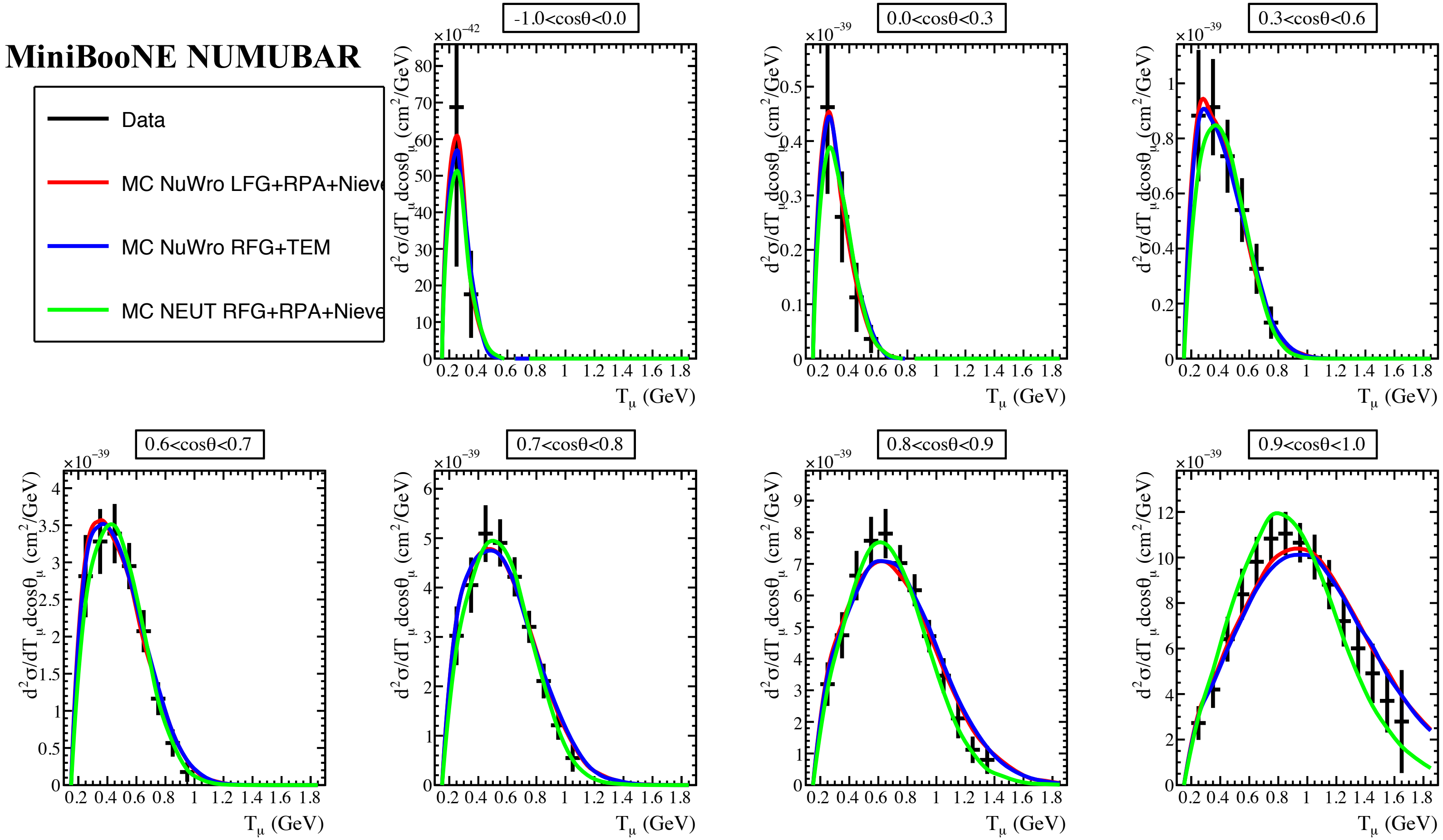
     Note no shape modification to 2p2h is applied only an overall scaling.

Joint fits to QE data (MiniBooNE)



- Perform a joint likelihood fit to MINERvA and MiniBooNE CCQE data.

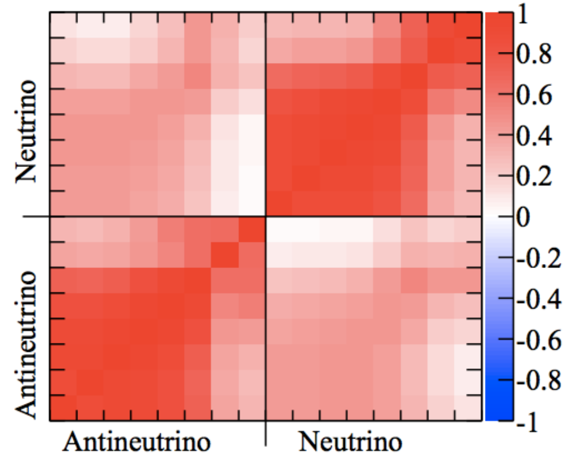
Joint fits to QE data (MiniBooNE)



- For each dataset MC predictions are produced by selecting only true Charged Current QE or 2p2h events within the required E_ν range.
  - Events with restricted phase-space θ_μ< 20° used in MINERvA datasets.

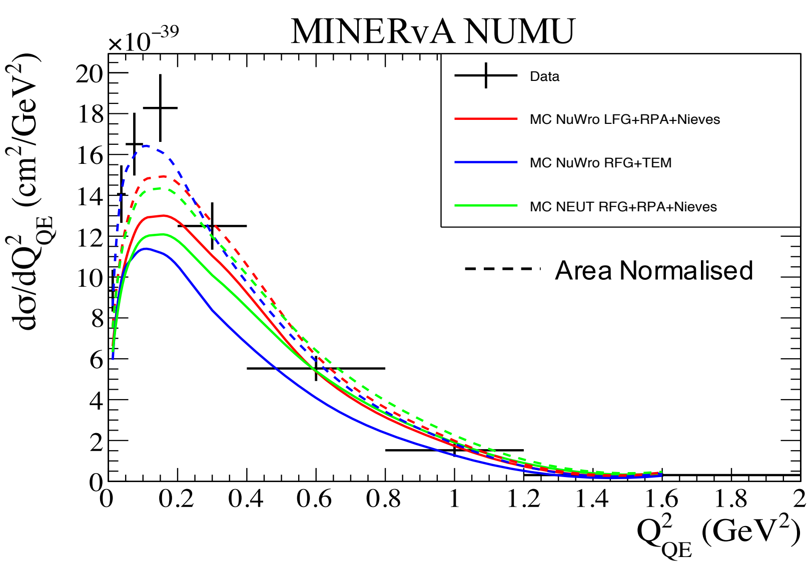
Joint fits to QE data (MINERvA)

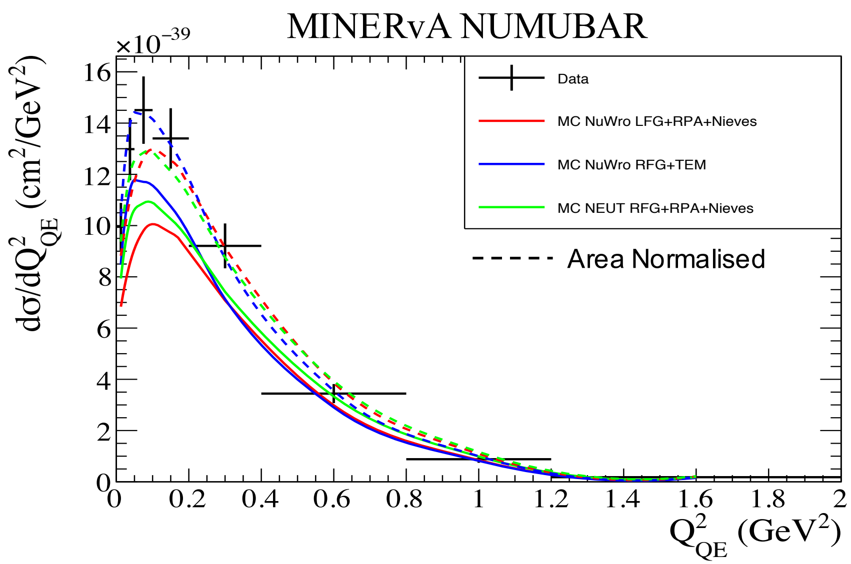
- **Likelihood defined from:**
  - MiniBooNE shape-only errors
  - MiniBooNE total normalisation error
  - MINERvA full cross-correlations
- Assume no correlations between the MINERvA and MiniBooNE datasets.



Correlation matrix

- Strongest model constraint comes from data/MC shape differences.





RFG/LFG fit results

Model	M_A [GeV/c2]	2p2h Norm (%)	χ^2/NDOF
NuWro LFG + Nieves	1.16 ± 0.03	8.3 ± 11.9	100.74 / 229
NuWro RFG + TEM	1.15 ± 0.03	21.3 ± 12.5	93.62 / 229
NEUT RFG + Nieves	1.14 ± 0.03	25.5 ± 12.4	106.25 / 229

MiniBooNE dataset has no covariance matrix so χ^2/DOF is very low!

- Very similar results between all models.
- 2p2h Norm and M_A correlation a feature of the strong shape constraint from data.
- **Large tensions in fitted 2p2h normalisation:**
  - MiniBooNE Neutrino ~100% 2p2h Norm.
  - MiniBooNE Antineutrino ~25% 2p2h Norm.
  - MINERvA ~5% 2p2h Norm.

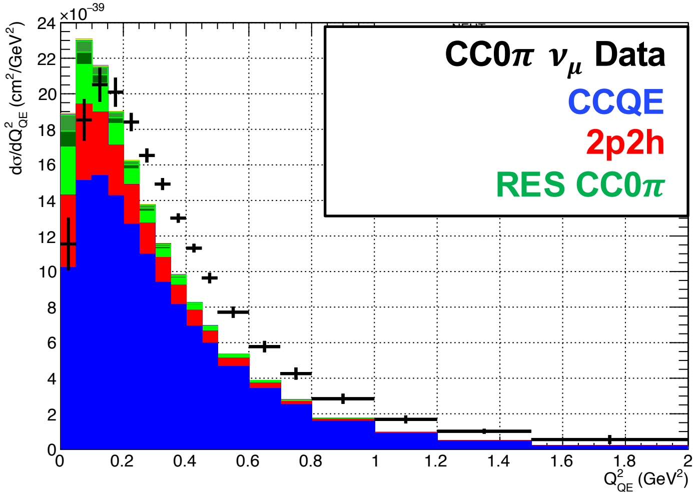
Correlations M_A/2p2h	
NuWro LFG + Nieves	0.58
NuWro RFG + TEM	0.48
NEUT RFG + Nieves	0.62

Background Subtraction

- Possible cause of data/MC tensions is model dependent background subtractions.

MiniBooNE : True CCQE-corrected

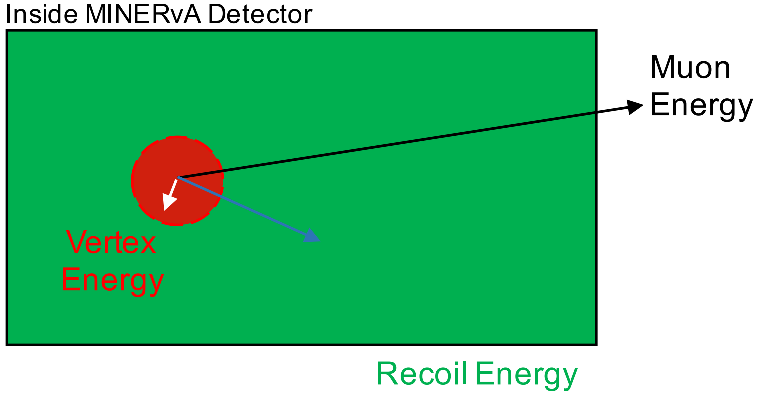
Subtract some unknown fraction of pionless delta decay.



MiniBooNE provided CC0PI data

MINERvA : True CCQE-corrected

Place a cut on the recoil energy (E_{recoil}) away from the vertex.



No E_{recoil} proxy for raw generator events.

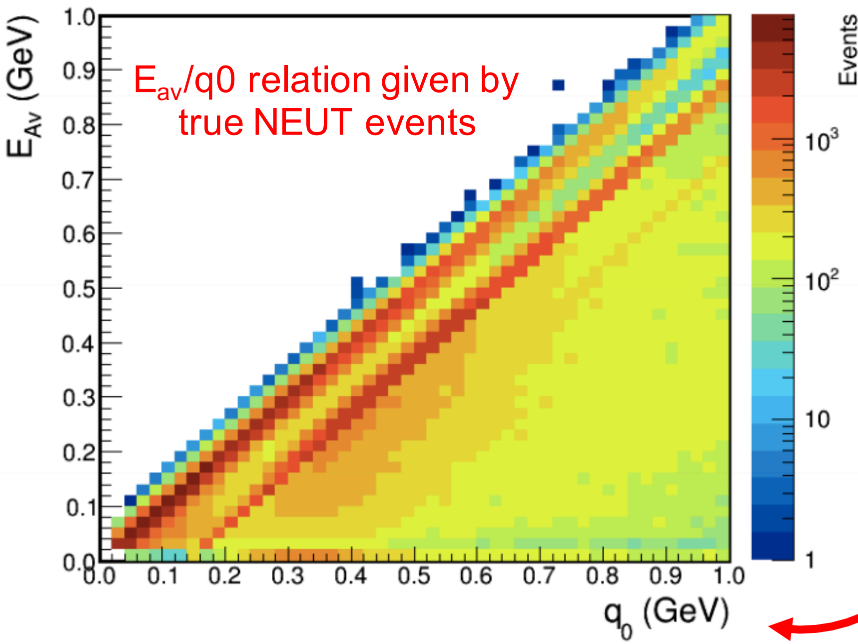
Unclear how cut sculpts the 2p2h models.

- Need to fit more inclusive data (CC0PI, CC-inclusive) but this has extra difficulties.

Low recoil MINERvA data

- Study of nuclear effects by looking at hadronic energy deposited in the detector (*Phys. Rev. Lett. 116, 071802 (2016)*).

- CC-inclusive 2D differential cross-section in three-momentum transfer (q_3) and energy available (E_{av}). NOVA looking at similar measurements.



$$E_\nu = E_\mu + q_0$$

$$Q^2 = 2E_\nu (E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$$

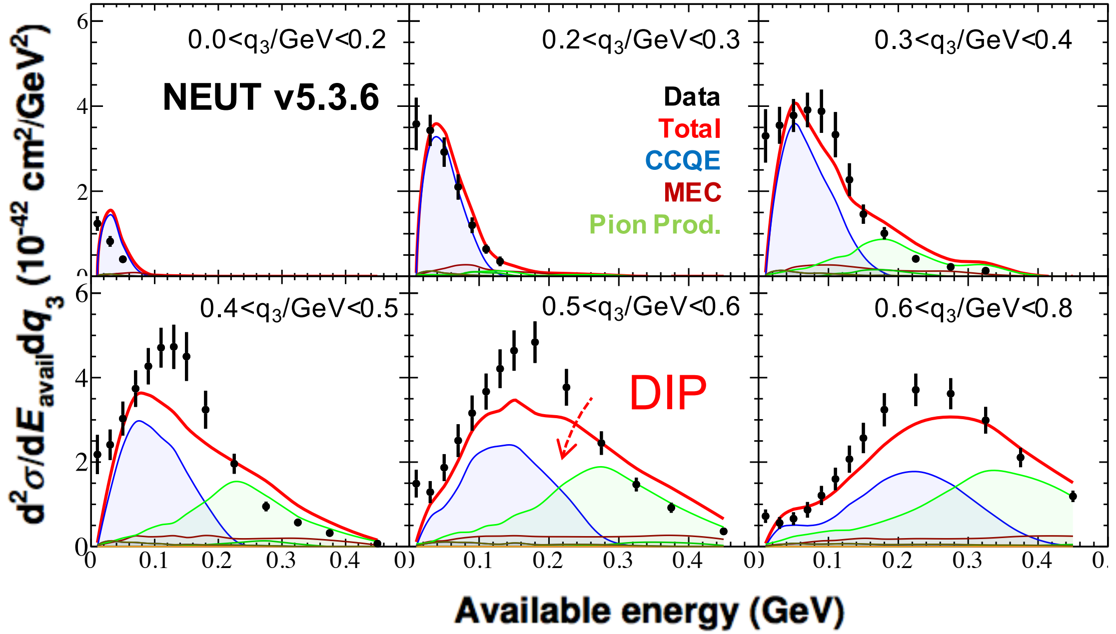
$$q_3 = \sqrt{q_0^2 + Q^2}$$

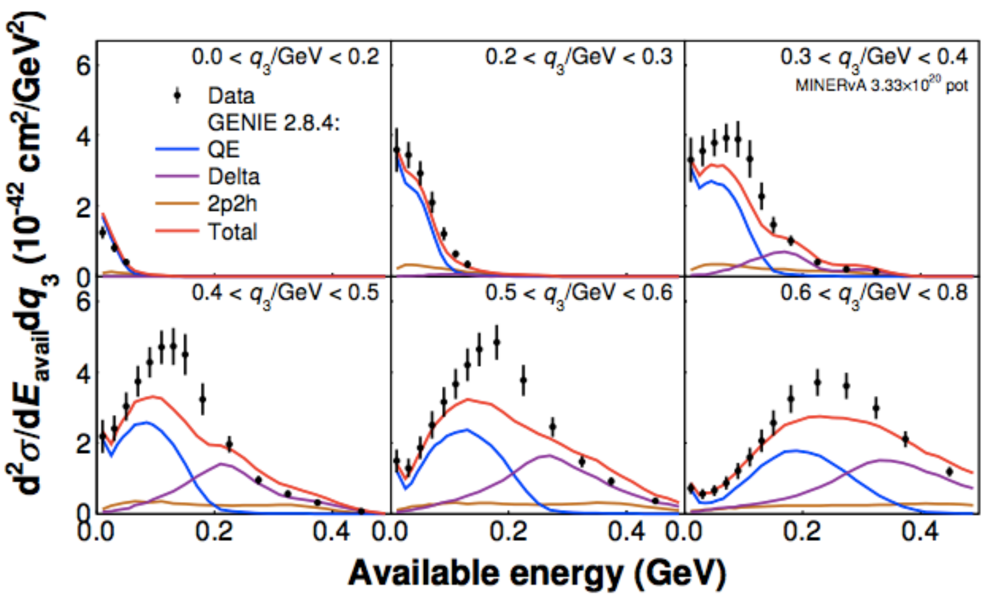
$$E_{av} = \sum_{i=p,\pi^\pm} T_i^K + \sum_{i=\pi^0,e,\gamma} E_i$$

Energy available tries to get at true energy transfer q_0 in neutrino interactions.

NEUT comparisons

- Model tuned to Free Nucleon best fit result. Rest of the model parameters left at generator nominal.



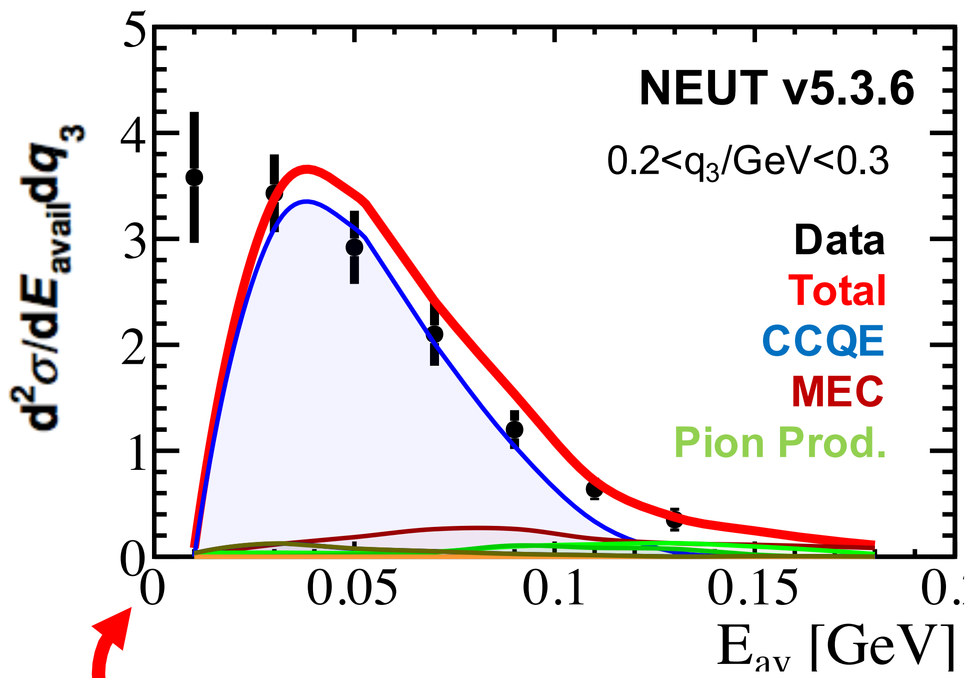


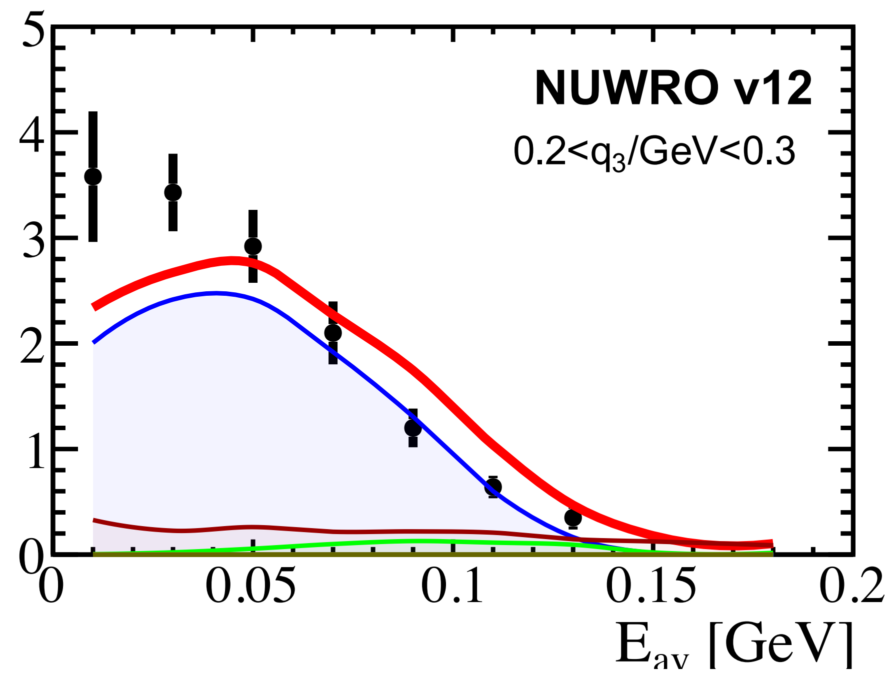
- NEUT/NuWro/GENIE show difference in the “DIP Region” between the CCQE and Pion production peaks.

Original GENIE prediction from *Phys. Rev. Lett. 116, 071802 (2016)*

Low E_{av}

- Strong Pauli blocking in Relativistic Fermi Gas (RFG) creates large deficit at low E_{av} in MC prediction.



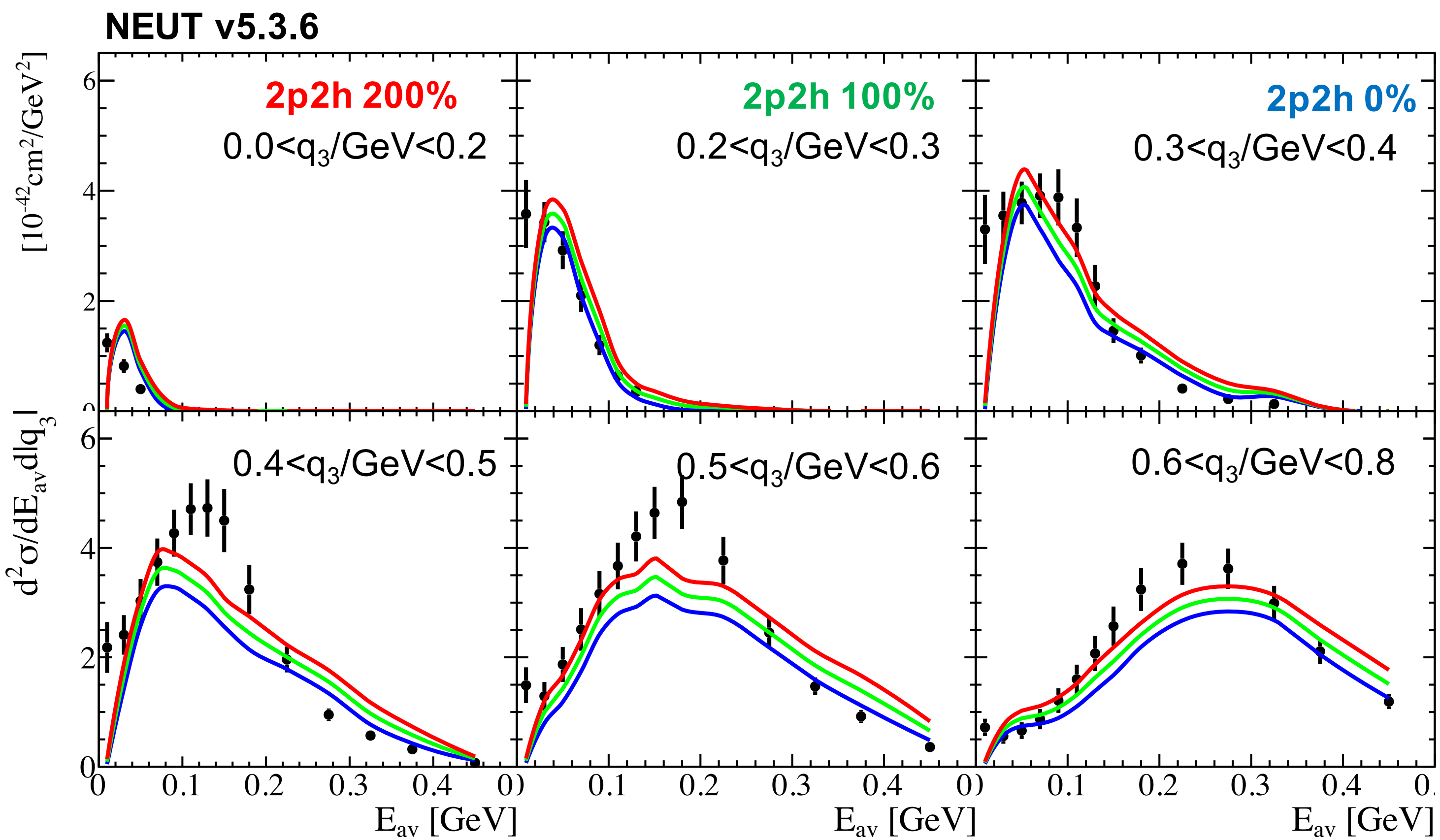


Lowest E_{av} Bin width ~ NEUT RFG Binding energy.

Local Fermi Gas in NuWro

2p2h normalisation

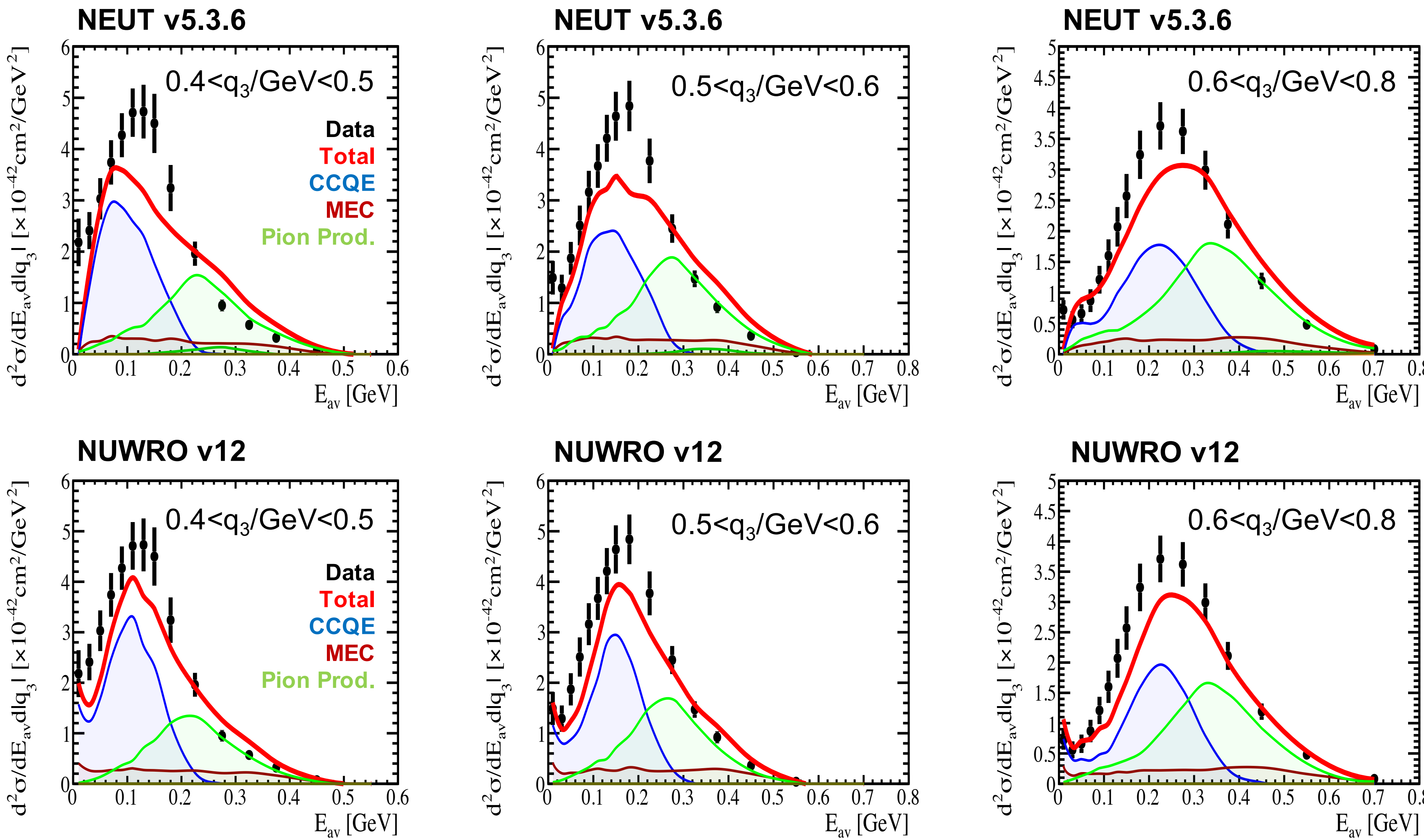
- Can variations in the Nieves 2p2h normalisation fill in the dip region alone?



- Flat shape of the Nieves 2p2h contribution in q_3-E_{av}
- Inflating 2p2h normalisation creates a larger data/MC disagreement.

NEUT/NuWro comparison

- Smaller “DIP disagreement” for NuWro comes from differences in the 1p1h model.



Software

- **NUISANCE**
  - Public software to make data/generator comparisons easier.
  - Multiple generator support and automated dial tuning.

https://nuisance.hepforge.org/

- **NuWro reweight**
  - Developed a set of reweighting tools for NuWro.
  - Already many dials to choose from for model tuning.
  - Merging into main NuWro branch soon!

Summary

- Tunings of NEUT and NuWro free nucleon models to bubble chamber data agree with one another.
- Joint fits to MINERvA and MiniBooNE CCQE data result in a best fit MEC normalisation ~30% and a slightly inflated axial mass.
- Tuning to more inclusive data (CC0π, $\mathrm{CC} - \mathrm{inc}$) is required, but much more data is needed to handle exclusive channel degeneracies.
- Disagreements between NEUT/NuWro/GENIE and the MINERvA Low Recoil dataset still need to be understood through combined fits alongside other datasets.

Data wish list

- Lots of new datasets being released at the moment
  - Exciting time for neutrino cross-sections!

- What we would like from future data:

  - Full covariance matrices (Cross-correlations, indiv. contributions)

  - Reco. data + smearing matrices (N-tuples?)

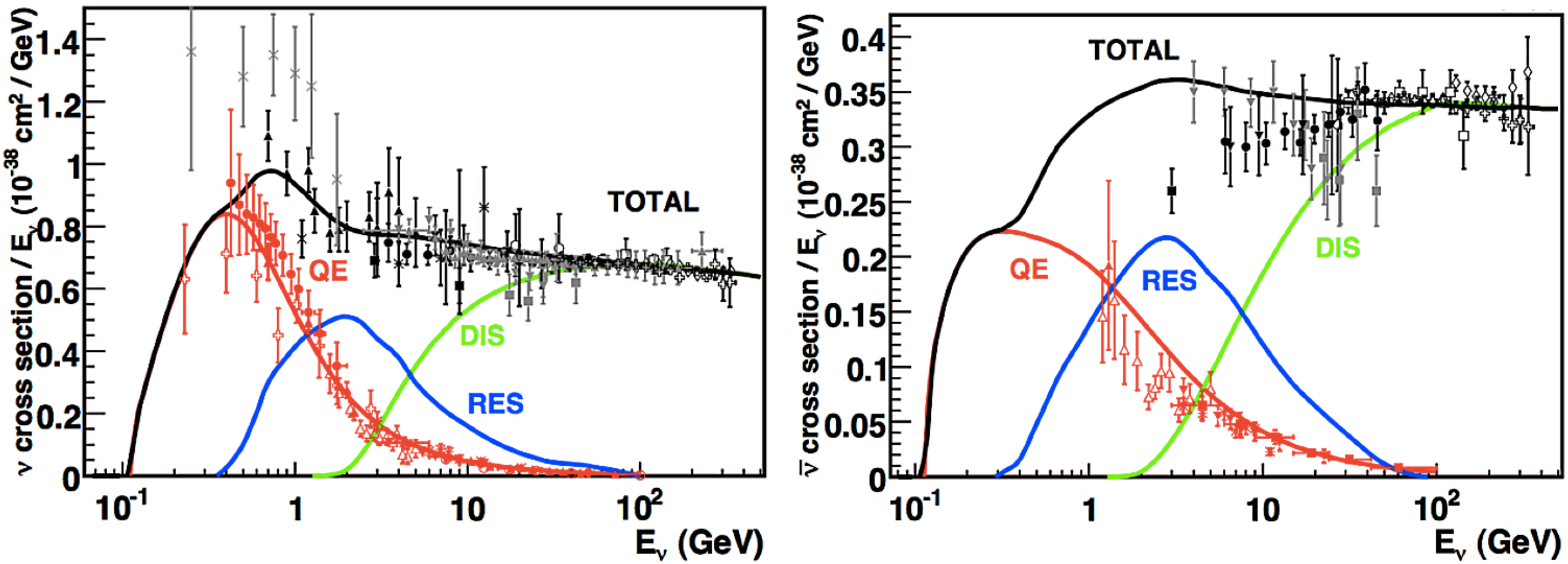
    "If they unfolded, they screwed you." – Bob Cousins, PhyStatNu

  - Inclusive datasets with clear final state signal definitions.

  - Data which isn't unfolded into phase space you can't measure.

BACKUP SLIDES

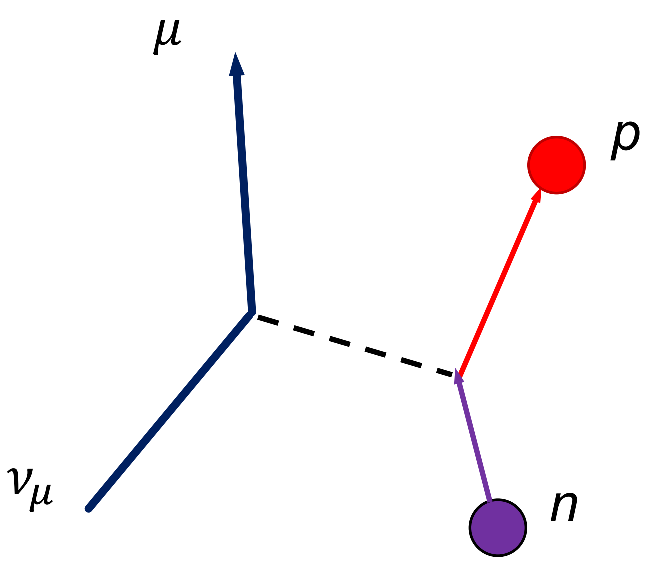
Neutrino Cross-sections



- Combination of multiple different interaction channels make up CC-inclusive cross-section over broad energy range.

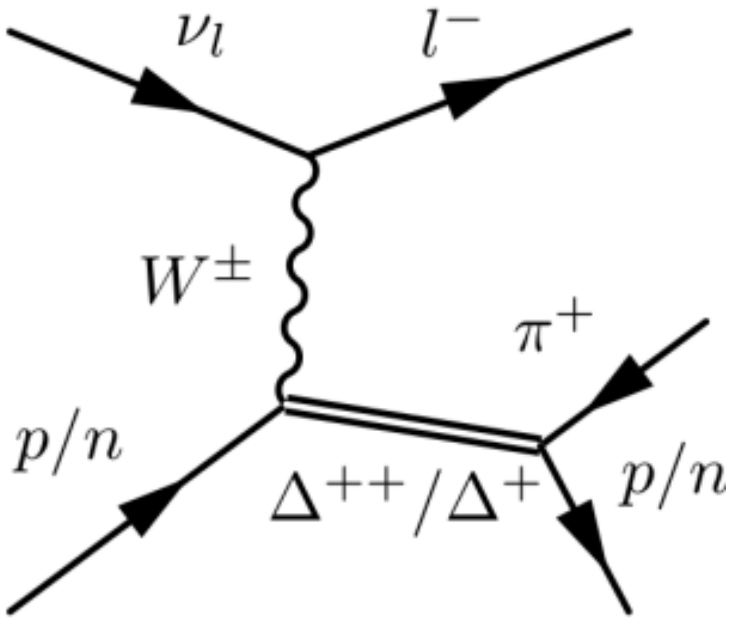
Quasi-elastic Scattering

- Scattering between a neutrino and nucleon.
- One of the simplest interactions.
- Main signal for many experiments.
- Reasonably well modelled on free nucleons…



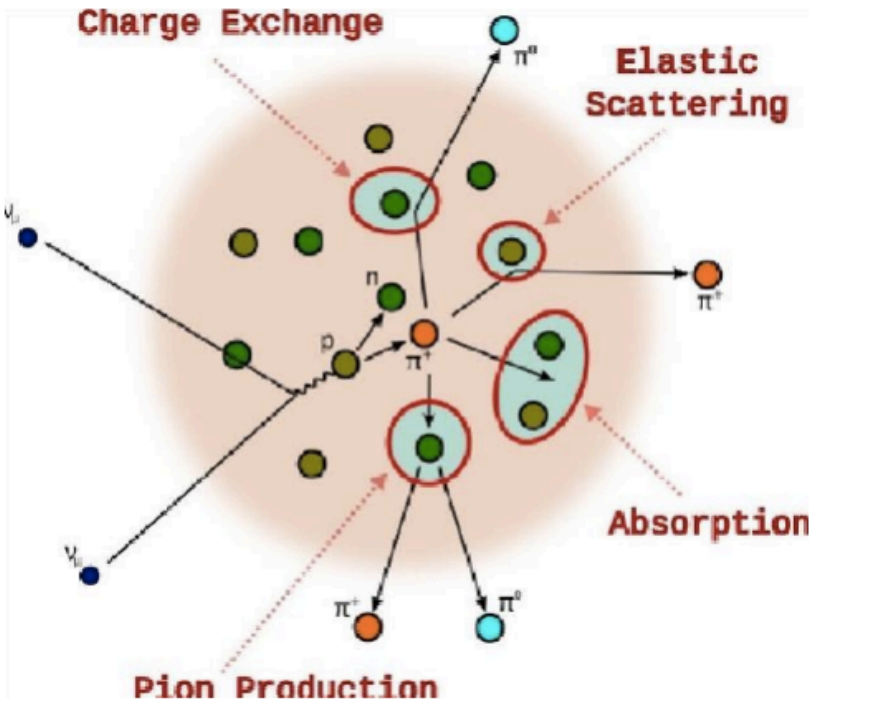
Resonant Pion Production

- Nuclear resonance produced which decays into nucleon + pion state.
- Multiple resonances can contribute to the total cross-section.
- Different possible final states.



Final State Interactions

- Scattering of particles produced at the interaction vertex as they are propagated out of the nuclear medium.



T. Golan

Pions are very likely to undergo re-interactions before leaving nucleus.

Different models for FSI in each generator.

NEUT/NUWRO uses Oset Cascade algorithm.

Llewellyn-Smith

- Formalism for QE neutrino scattering of a free nucleon

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 M^2 |V_{ud}|^2}{8\pi E_\nu^2}\left[A \pm \frac{(s-u)}{M^2}B + \frac{(s-u)^2}{M^4}C\right]$$

+neutrino
-antineutrino

$$A = \frac{(m^2+Q^2)}{M^2}\left[(1+\eta)F_A^2 - (1-\eta)F_1^2 + \eta(1-\eta)F_2^2 + 4\eta F_1 F_2 - \frac{m^2}{4M^2}\left((F_1+F_2)^2 + (F_A+2F_P)^2 - \left(\frac{Q^2}{M^2}+4\right)F_P^2\right)\right]$$

F1, F2 Vector Form Factors for proton/neutron

Pseudo-scalar Form Factor

$$B = \frac{Q^2}{M^2}F_A(F_1+F_2)$$

$$C = \frac{1}{4}\left(F_A^2 + F_1^2 + \eta F_2^2\right)$$

Axial Form Factor

$$(s-u) = 4ME_\nu - Q^2 - m^2$$

Joint Likelihoods Bubble Chamber

- For each experiment we include cross-section and measured event rates data.

$$\chi^2_{RATE} = \sum_{i}^{N} \left(\frac{\nu_i^{MC}(\vec{\vartheta}) - \nu_i^{Data}}{\sigma_i^2} \right)^2$$

Possion likelihood used for event rate plots.

$$\chi^2_{SHAPE} = 2 \sum_{i}^{N} \nu_i^{MC}(\lambda.\vec{\vartheta}) - \nu_i^{Data} + \nu_i^{Data} \log \left(\frac{\nu_i^{Data}}{\nu_i^{MC}(\lambda.\vec{\vartheta})} \right)$$

λ = shape scaling parameter

$$\chi^2_{Total} = \sum_{\substack{i=ANL,BNL,\\ FNAL,BEBC}}^{N} \chi^2_{RATE,i} + \sum_{\substack{i=ANL,BNL,\\ FNAL,BEBC}}^{N} \sum_{\substack{j=Other\\ Dists.}}^{M} \chi^2_{SHAPE,i,j}$$

Deuteron Corrections

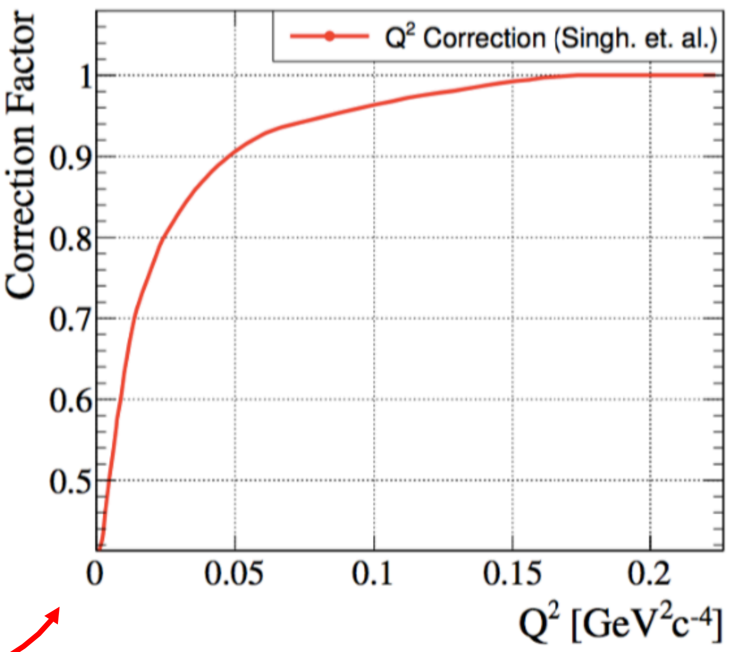
- For Charged Current Quasi-elastic fits events are converted

Free Neutron -> Deuteron

- Take events generated on a free neutron and calculate true Q^2.

- Apply an event weight as a function of Q^2 to fold in correction to final MC prediction.

$$w(Q^2) = R(Q^2) \times w_{xsec}(Q^2)$$



- Has only a small effect in ~4 bins across all CCQE datasets studied

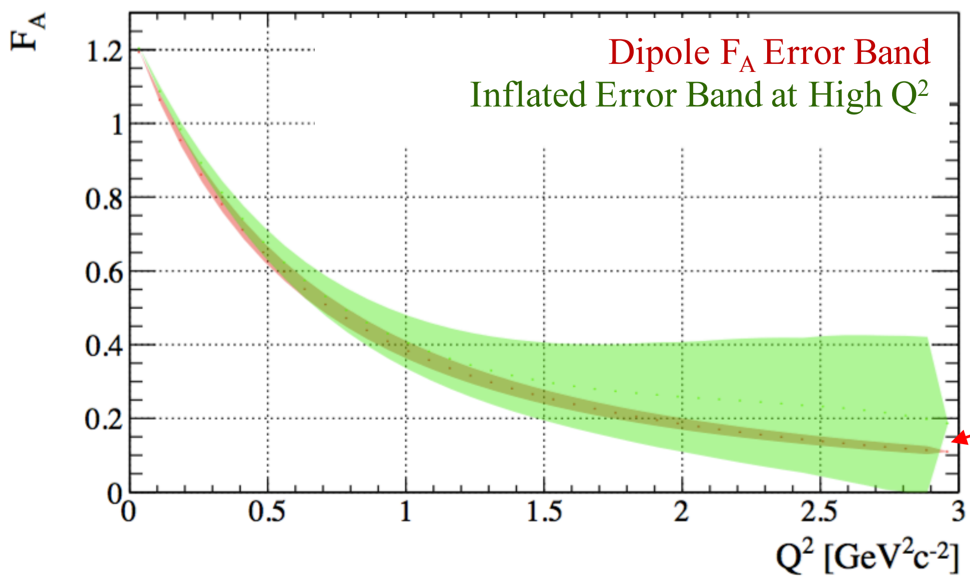
Axial QE Form Factors

- Common approach is to assume a dipole form for QE Axial FF.

$$F_A(Q^2) = \frac{F_A(0)}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

$F_A(0)$ is the axial coupling constant ~1.267

M_A is a free parameter.

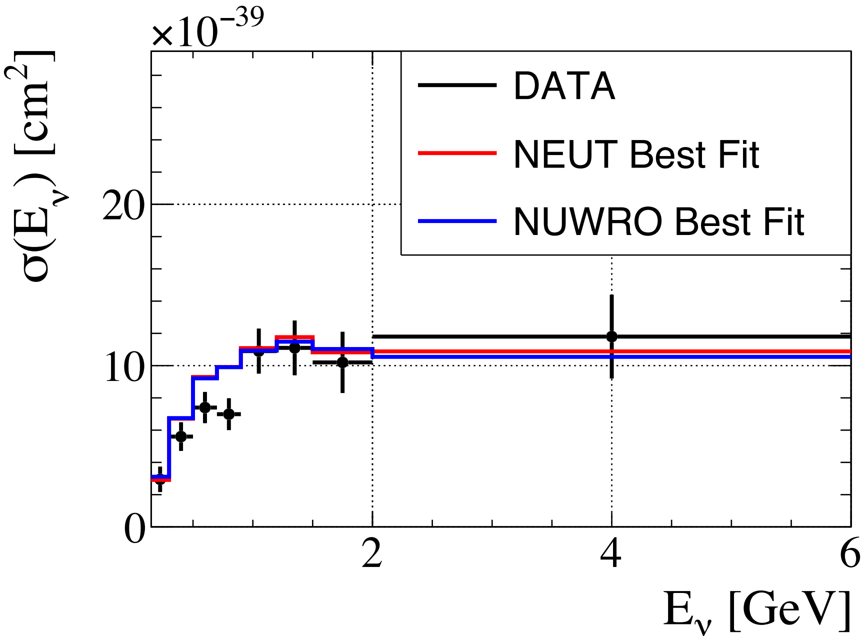


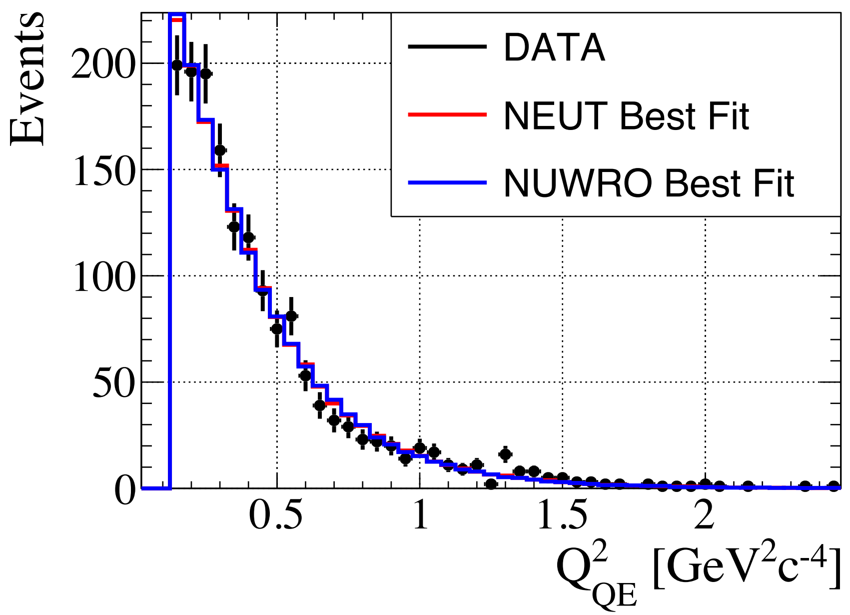
Dipole Form

F_A is then included in the Llewellyn-Smith model for neutrino nucleon scattering

QE Bubble Chamber Data (ANL)

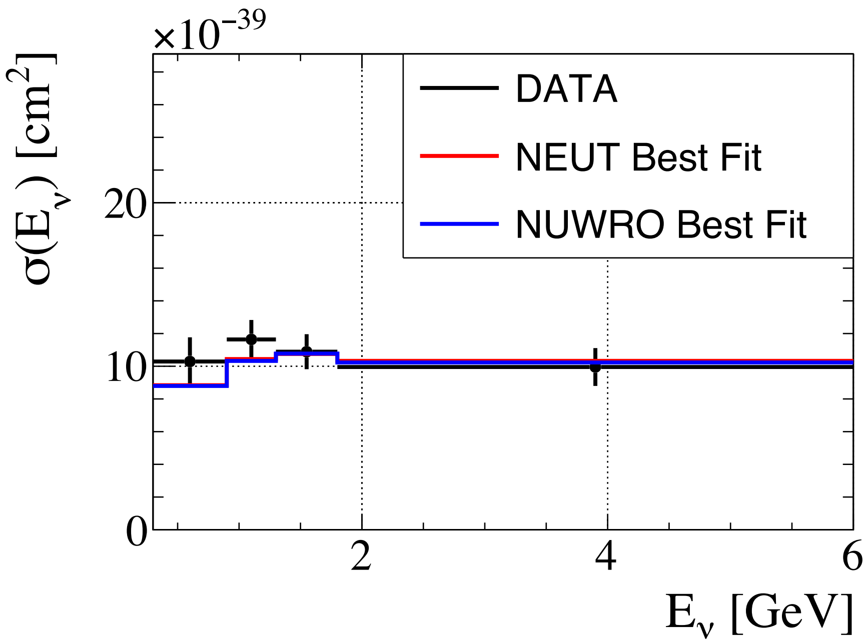
- Consider 6 datasets in total likelihood.
- ANL E_{nu} (RATE) + ANL Q^2 (SHAPE)

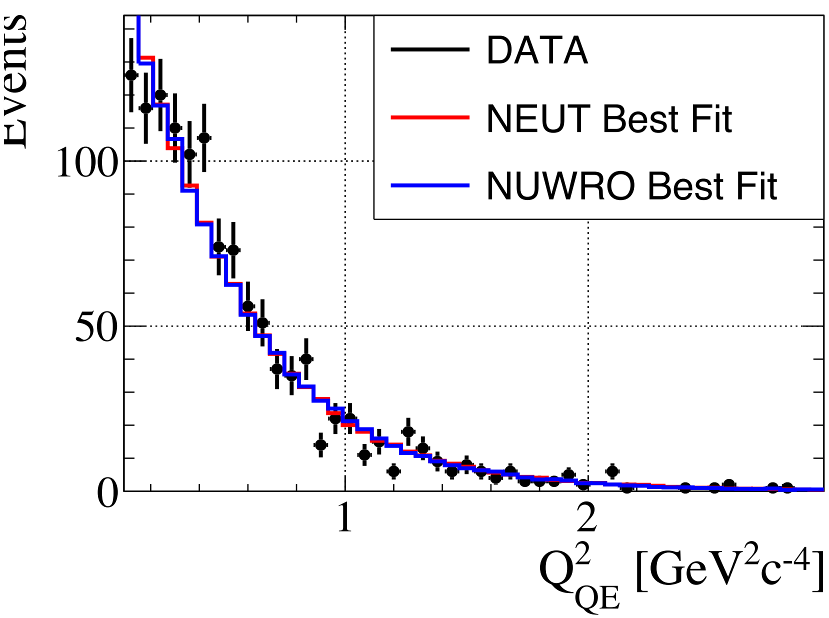




QE Bubble Chamber Data (BNL)

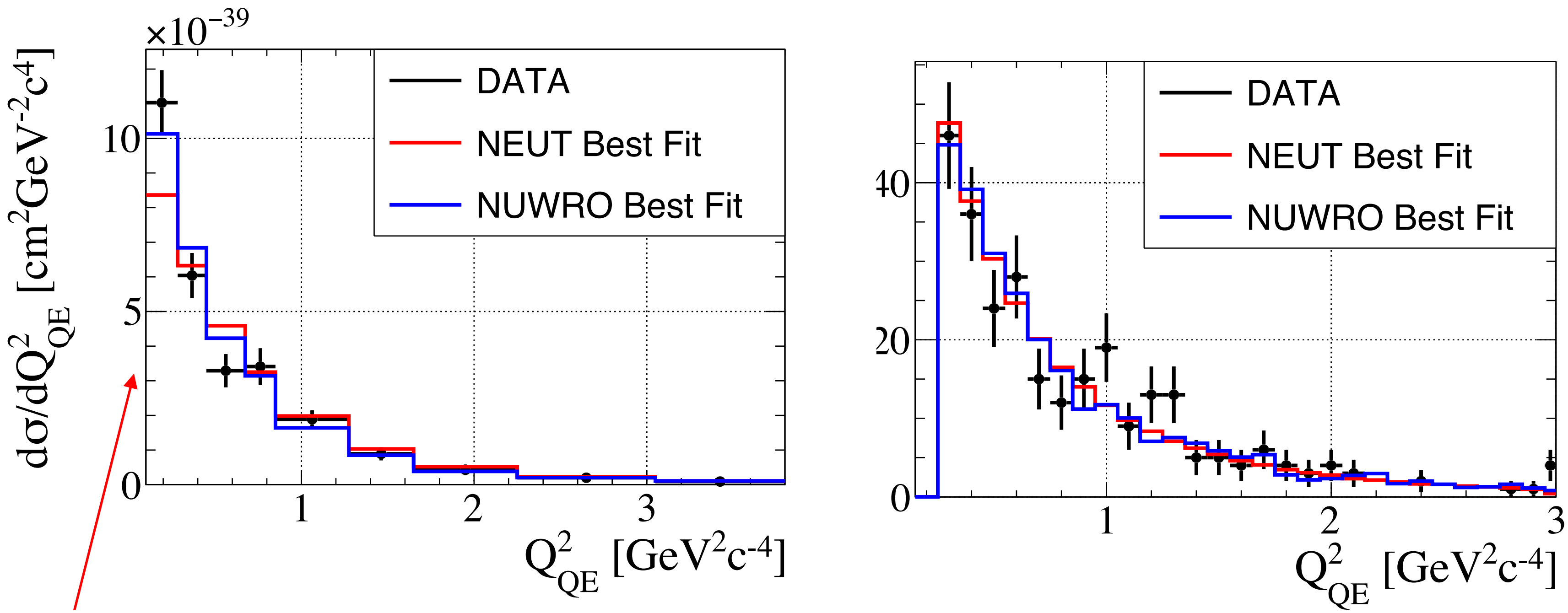
- Consider 6 datasets in total.
- BNL E_{nu} (RATE) + BNL Q^2 (SHAPE)





QE Bubble Chamber Data (BEBC/FNAL)

- Consider 6 datasets in total.
- BEBC Q^2 (RATE) + FNAL Q^2 (SHAPE)

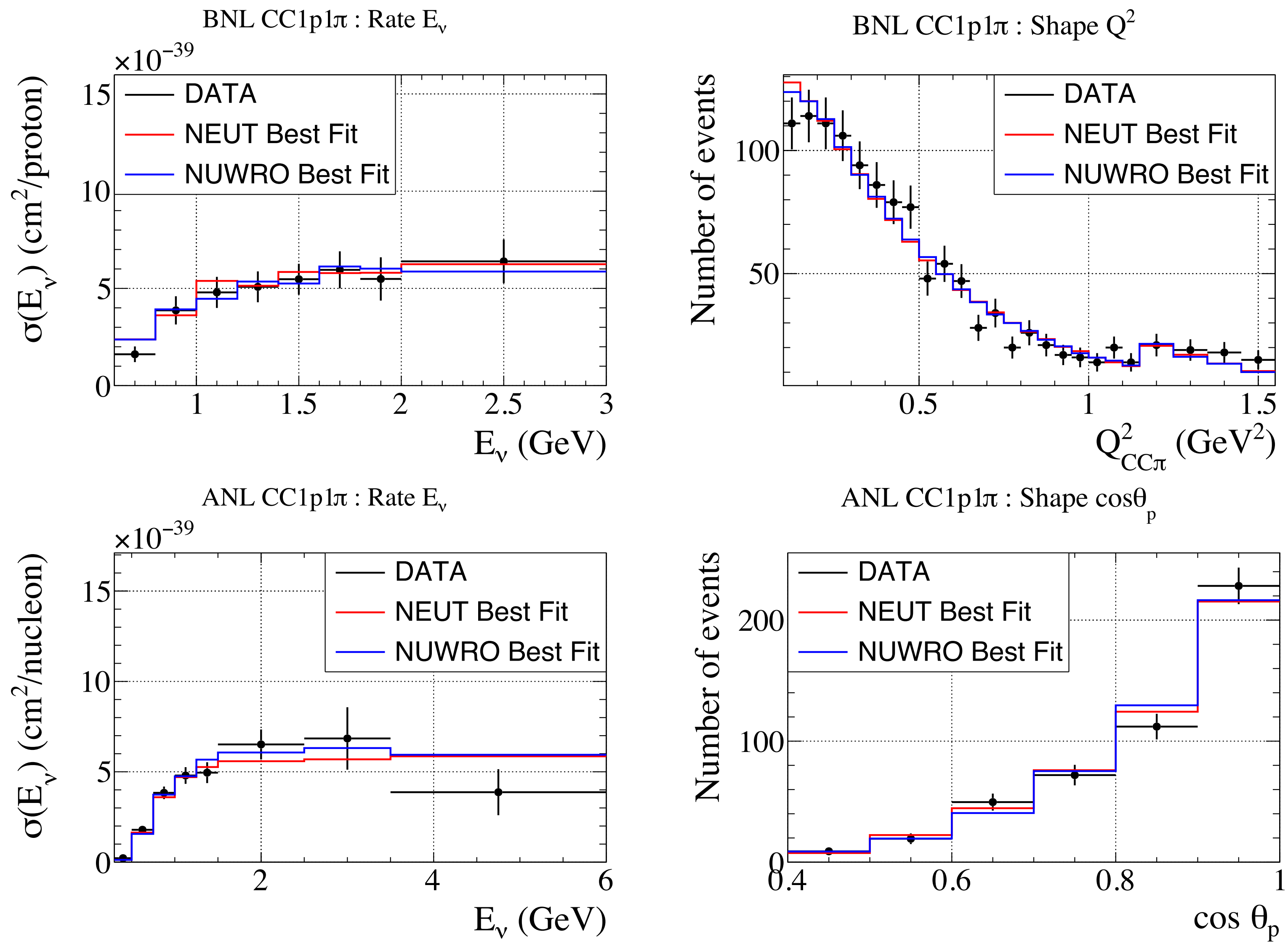


Difference comes from statistical fluctuations in BEBC data

BEBC is at much higher energy, so smaller proportion of 2.5E6 events generated are CCQE than the other event samples.

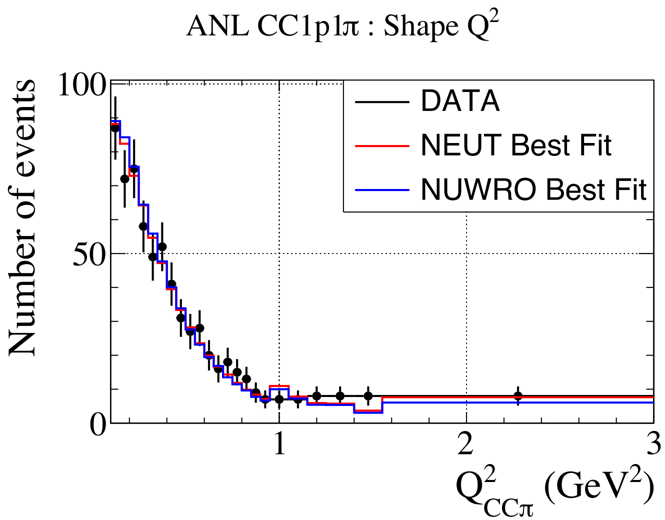
QES Bubble Chamber Data

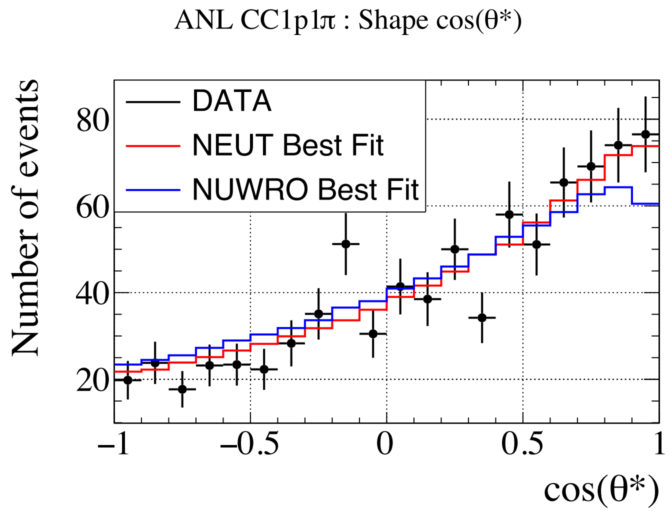
- 7 ANL/BNL datasets included in a joint likelihood.

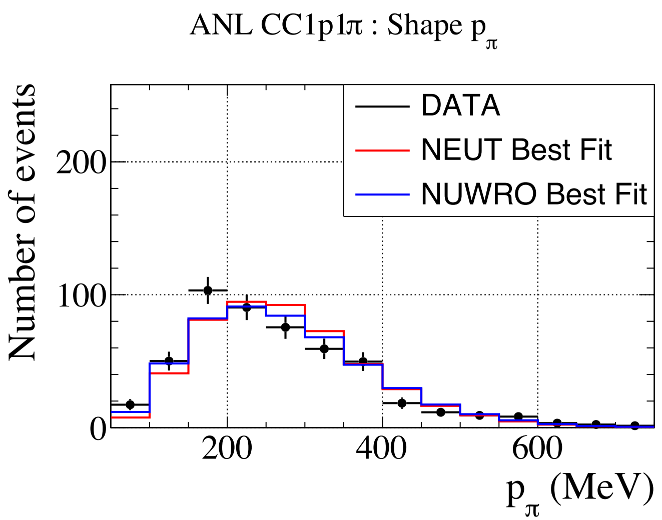


QES Bubble Chamber Data 2

- 7 ANL/BNL datasets included in a joint likelihood.



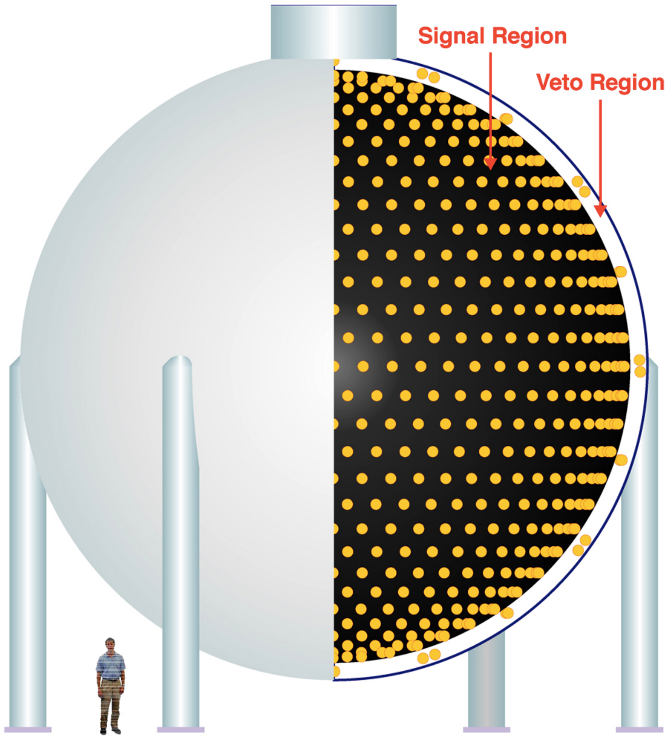


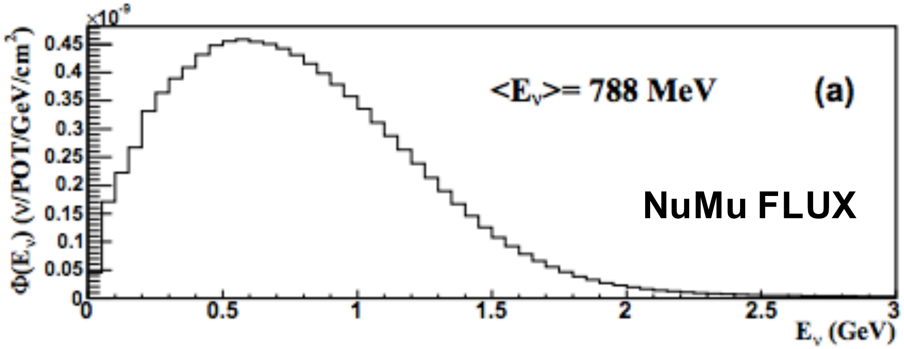


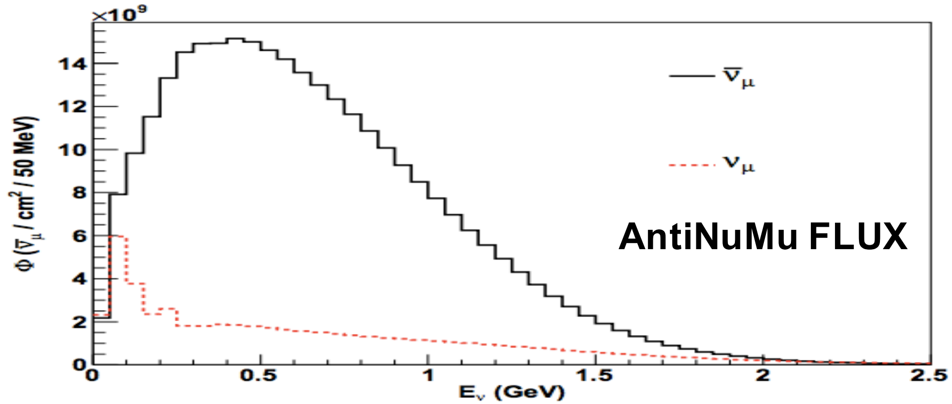
MiniBooNE Experiment

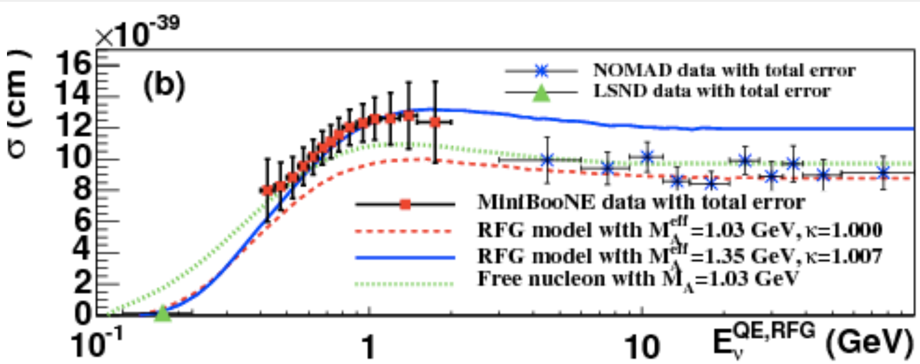
- Treat as a CH2 Target
- Full angular acceptance

MiniBooNE Detector





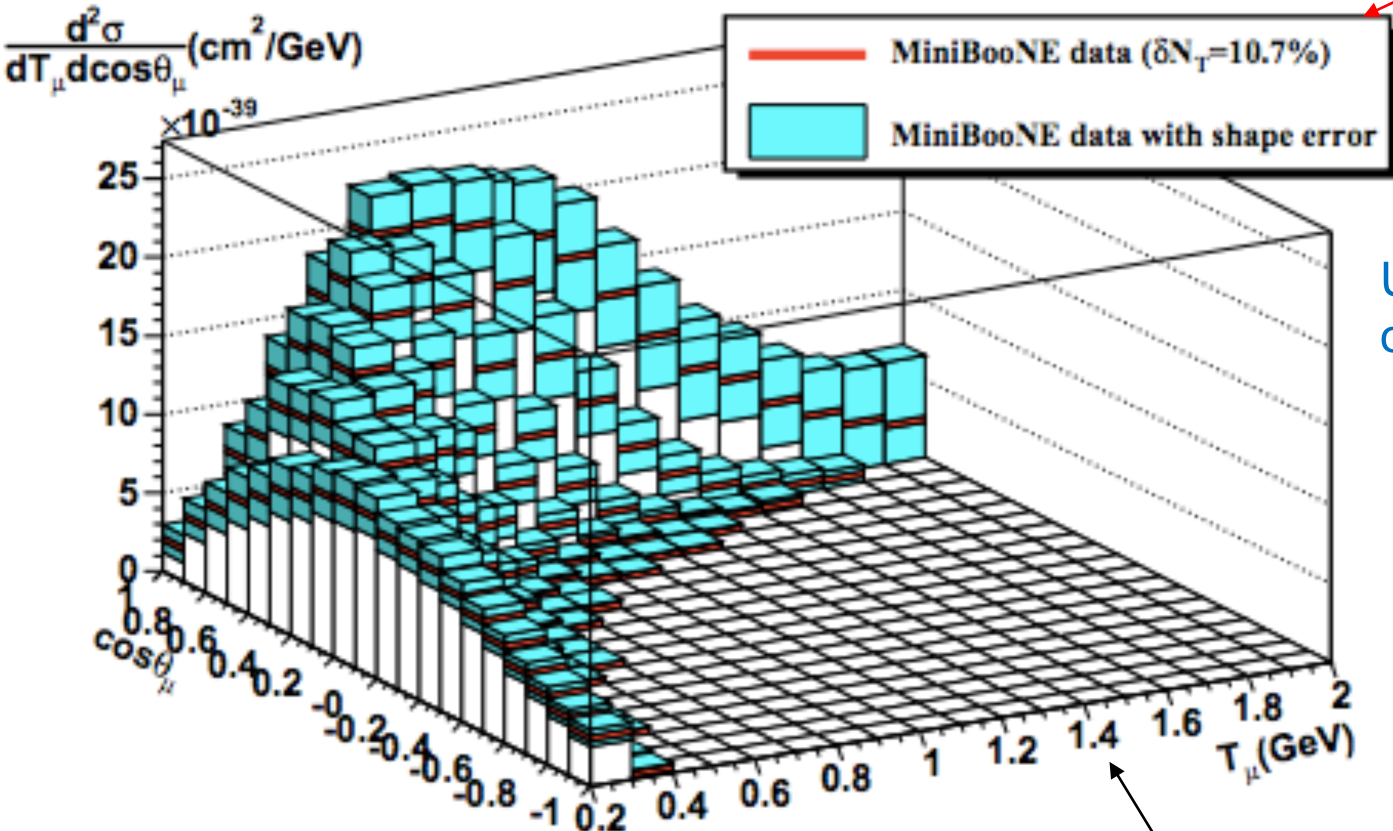




MiniBooNE QE Data Neutrino

- **Phys. Rev. D81, 092005 (2010)**

Total Normalisation Error

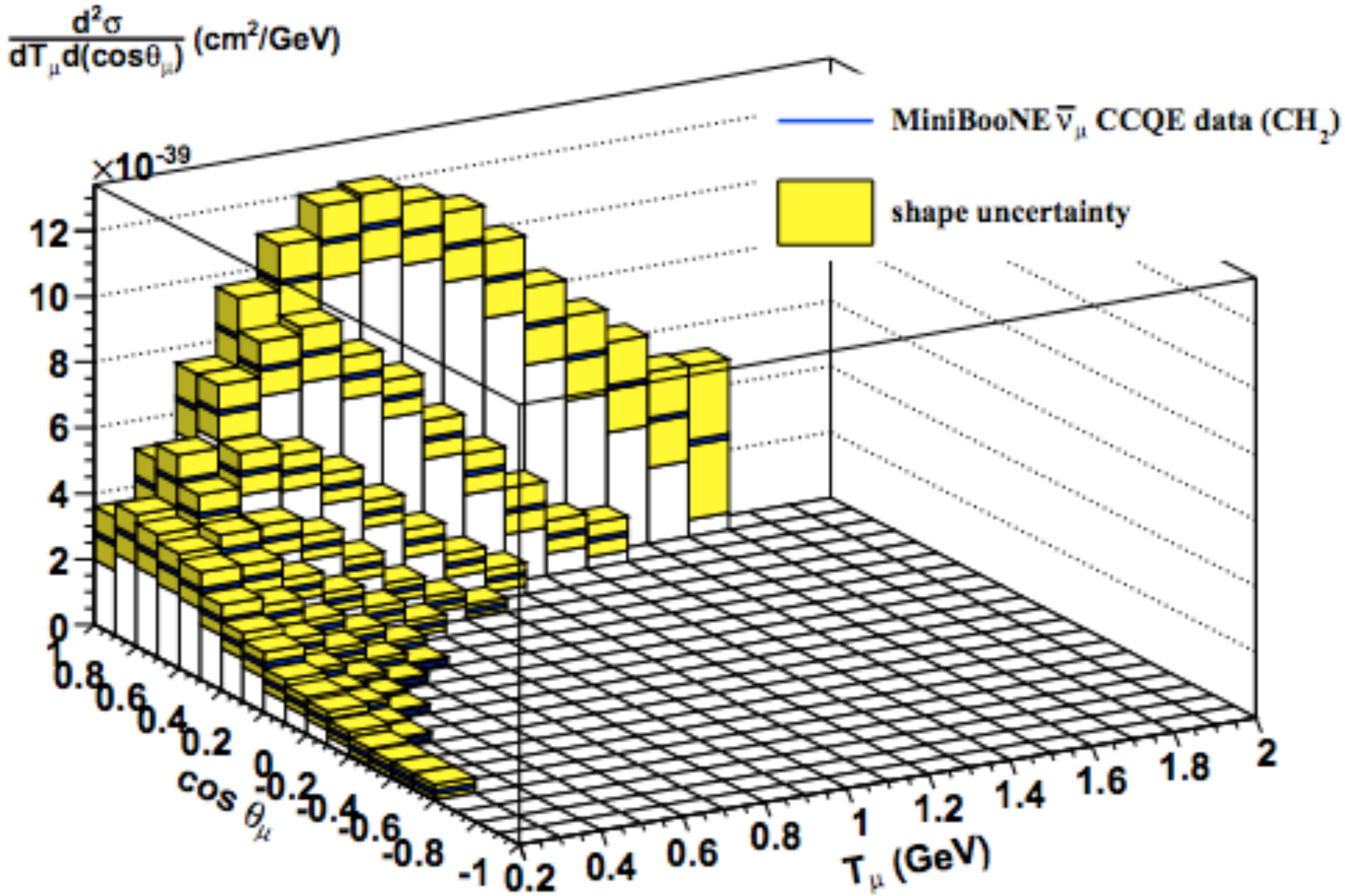


Uncorrelated errors on each bin

No information on empty bins

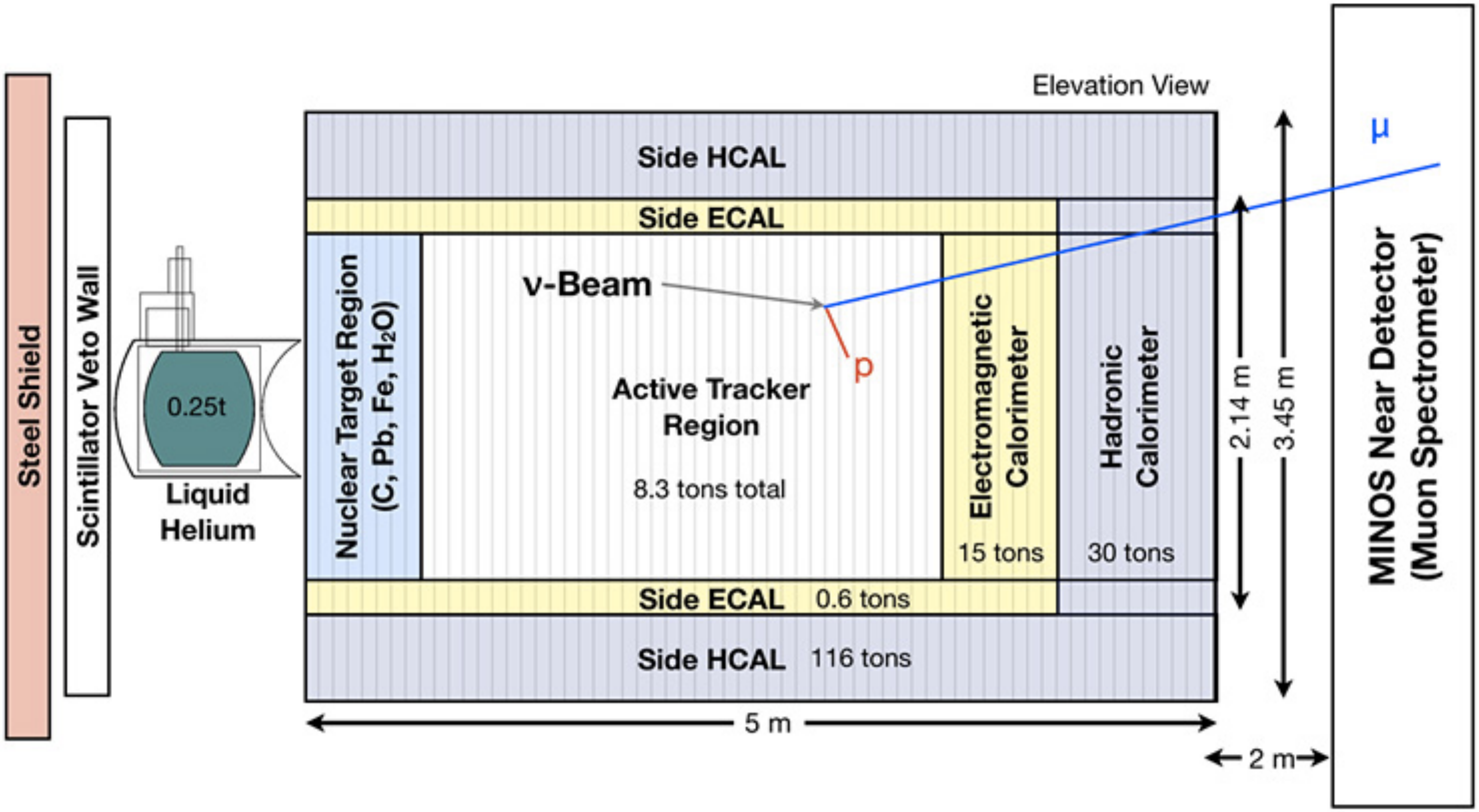
MiniBooNE QE Data Antineutrino

- **Phys. Rev. D 88, 032001 (2013)**
- Much larger wrong-sign background is subtracted using MC



MINERvA Experiment

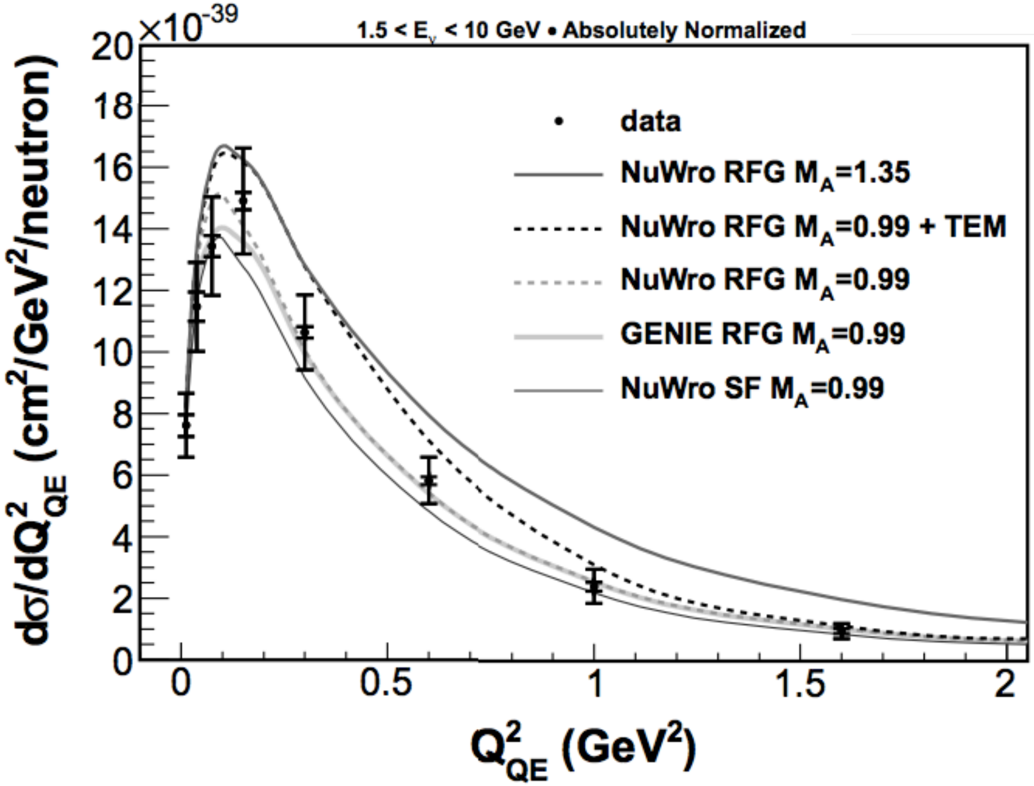
- Treat as a CH Target
- Must use MINOS to tag muons (restricted angle $\theta_\mu < 20°$).



MINERvA QE Data Neutrino

- **Phys. Rev. Lett. 111, 022502 (2013)**

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c^2)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8



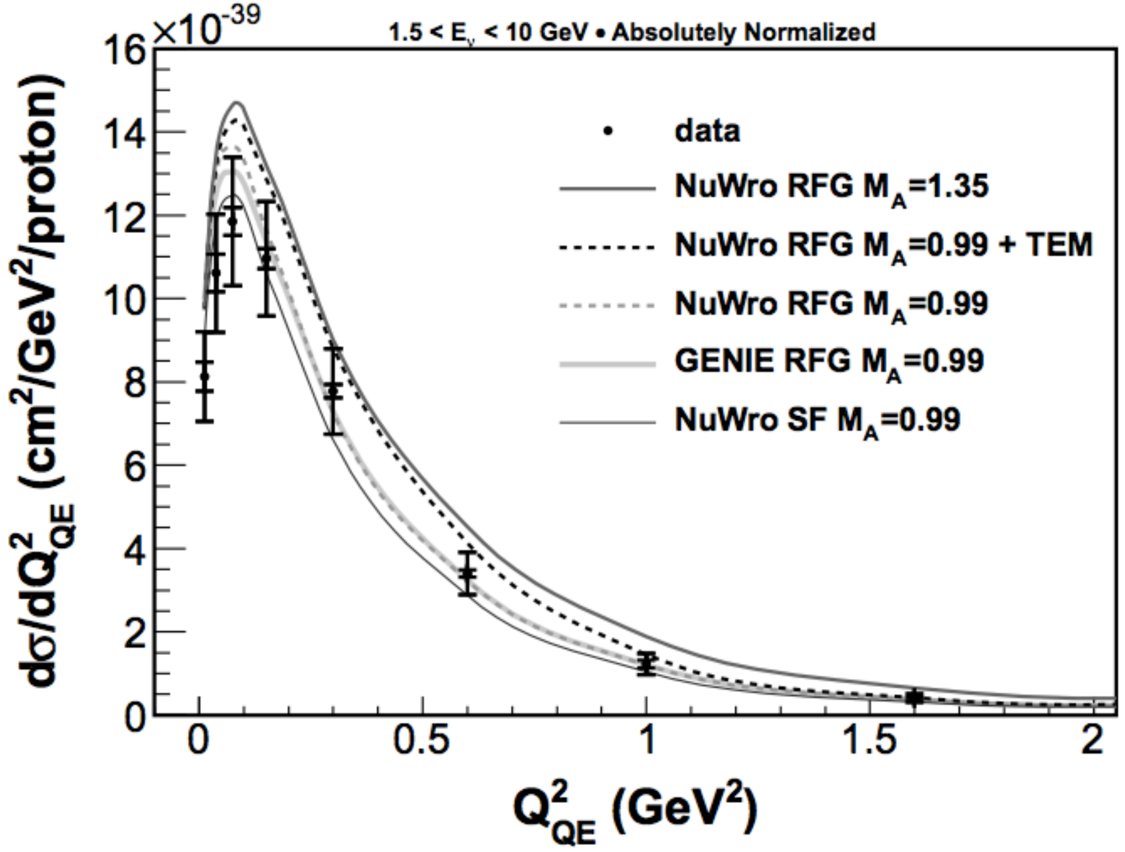
RFG+TEM in NuWro is best fit to data

MINERvA QE Data Antineutrino

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	2.64	1.06	2.90	2.14
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99

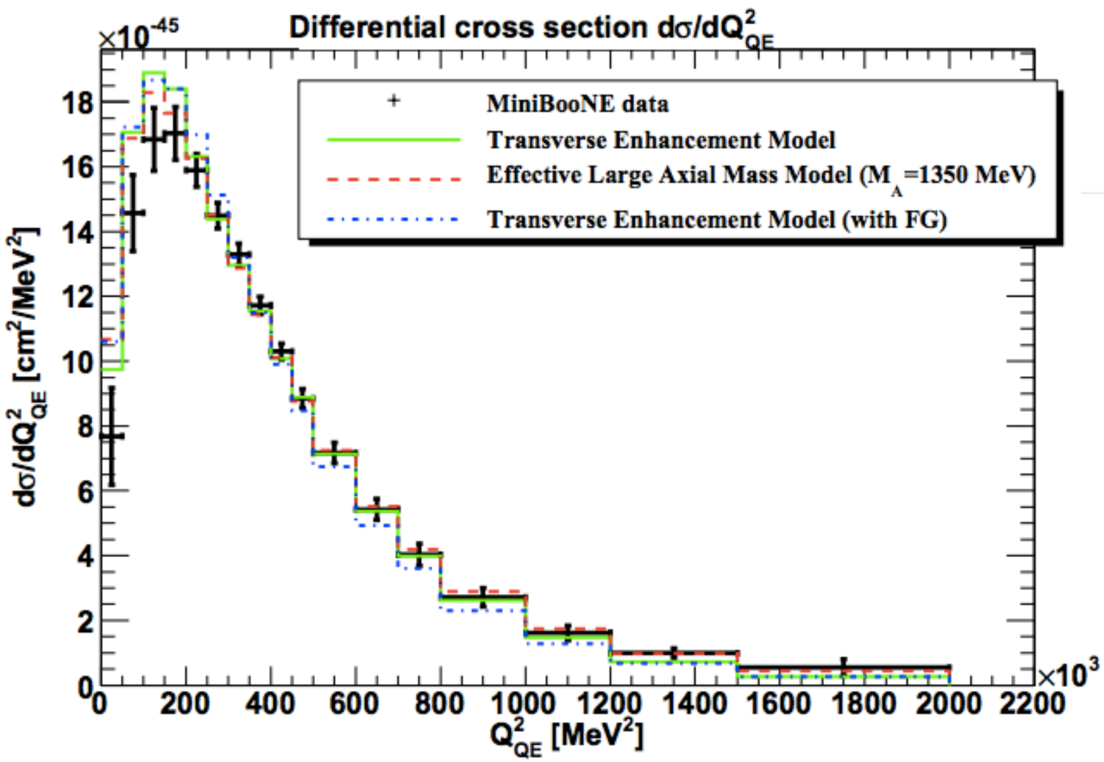
Phys. Rev. Lett. 111, 022501 (2013)

RFG + TEM in NuWro is best fit to data.



Transverse Enhancement Model

- ***arXiv:1109.1081***
- Proposed function to explain nuclear effects through an enhancement of the Transverse Quasi-elastic response function.
- Scaling applied to the proton/neutron magnetic form factors.
- Treated as a "true" 2p2h model in NuWro.

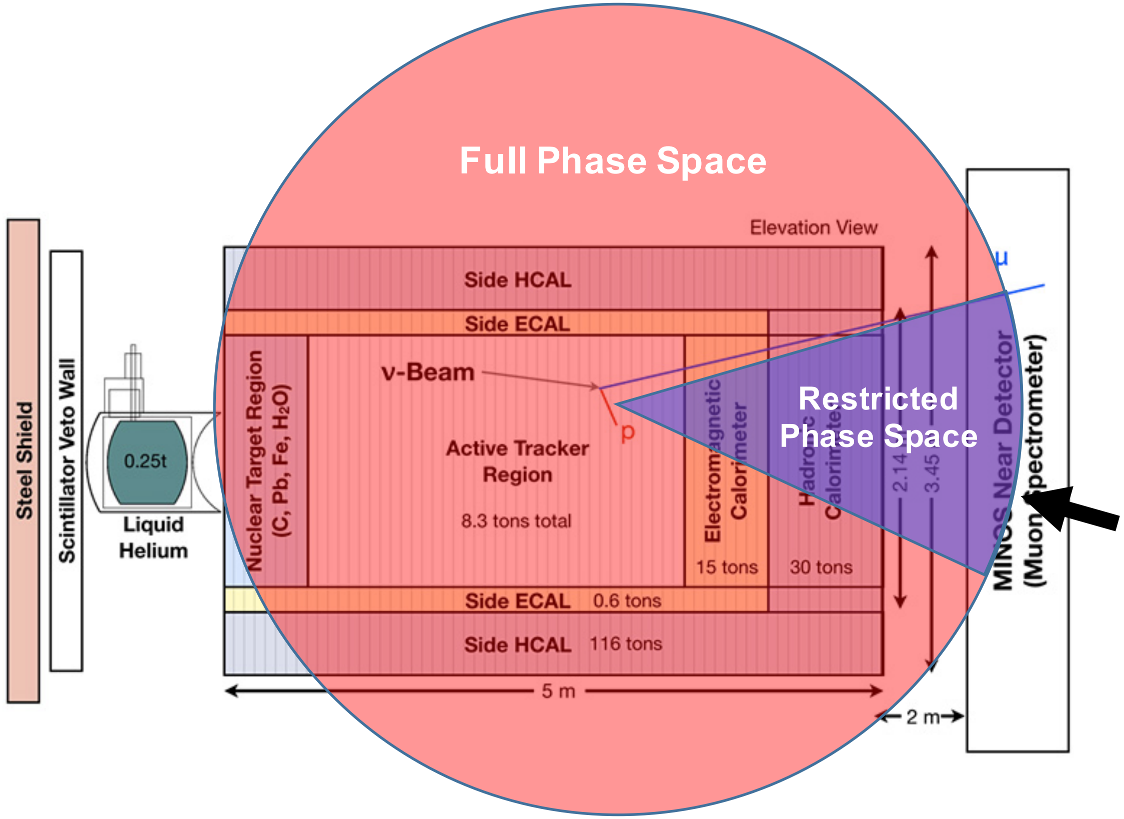


$$G_M^{p,n}(Q^2) \rightarrow \sqrt{1 + AQ^2 \exp(-\frac{Q^2}{B})} G_M^{p,n}(Q^2)$$

$$A = 6\ \mathrm{GeV}^{-2} \text{ and } B = 0.34\ GeV^2.$$

Restricted Phase Space

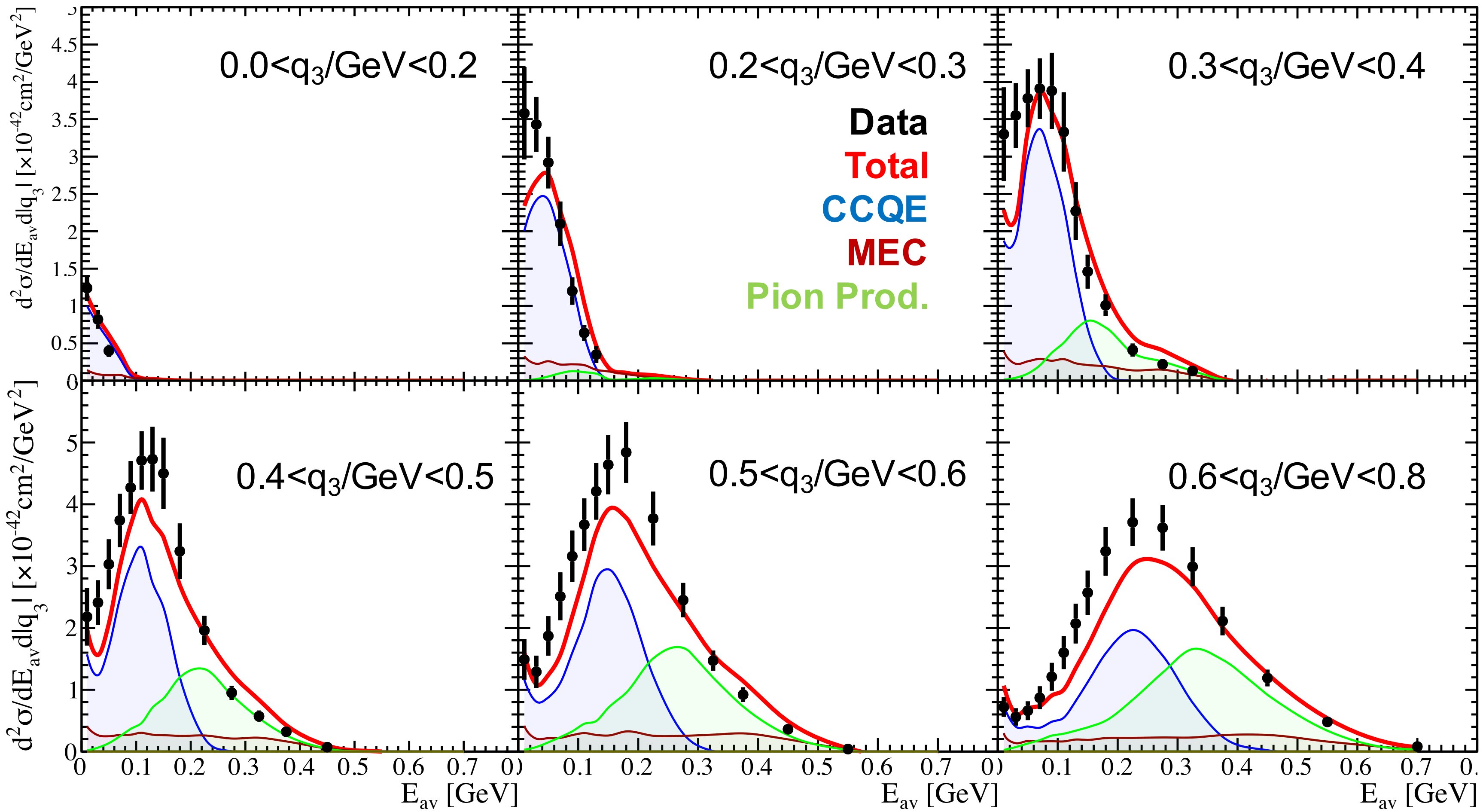
- MINERvA tag muons that make it into the MINOS detector.
- Acceptance of muons is ~20 degrees.
- Results are unfolded to cover all angles using GENIE.
- Introduces model dependence.



This is the TRUE phase space that can be measured.

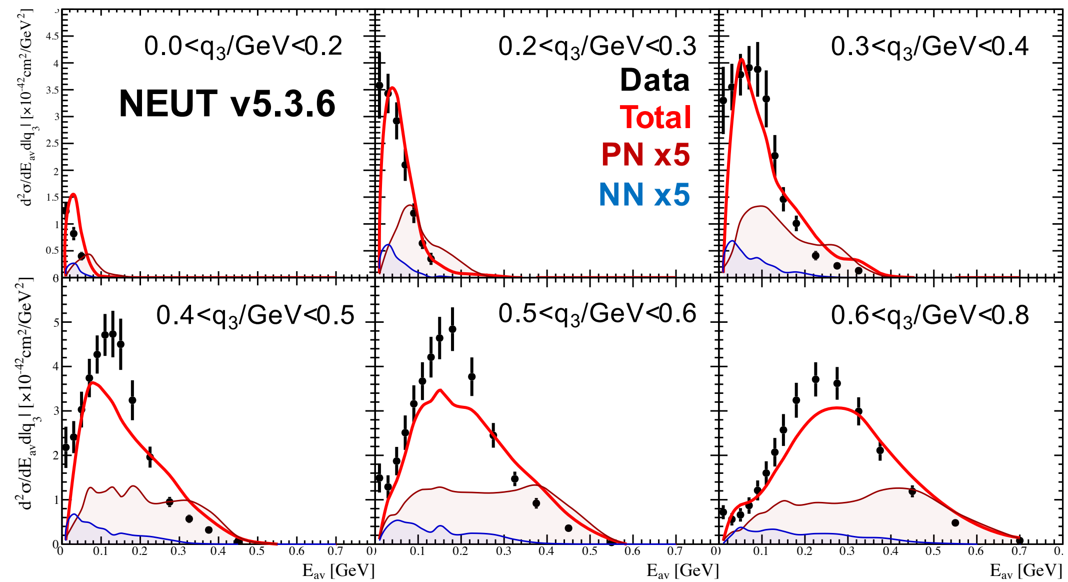
NUWRO

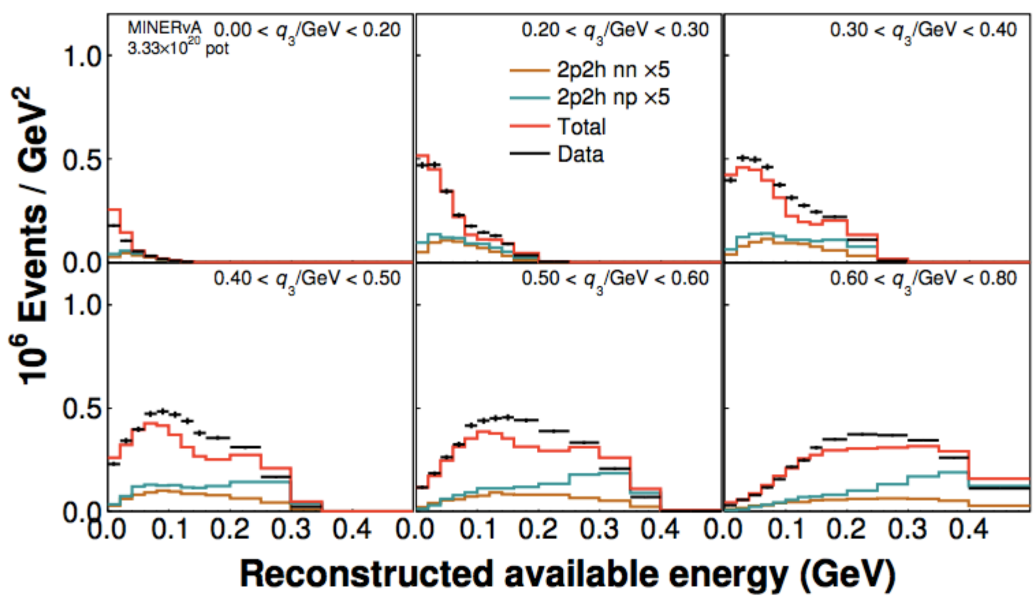
Low Recoil Dataset: NuWro v12



pn/nn 2p2h Contributions

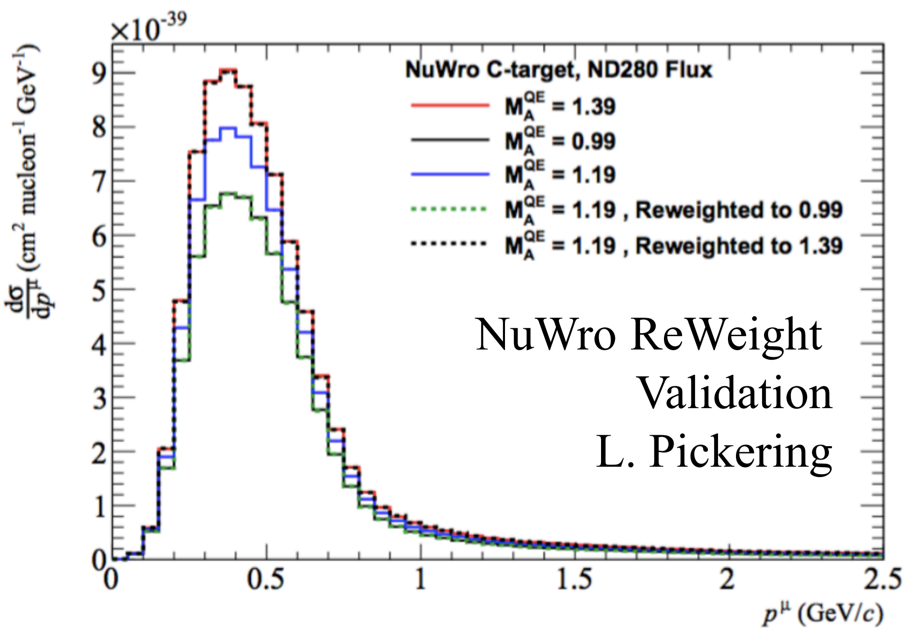
- Low Recoil Dataset doesn't include neutrons in the definition of E_{av}.
- Distribution is sensitive to final state particle multiplicities.
- MEC contribution for both pn and nn initial states has been scaled up by a factor of 5 here to make it visible.
- Variations in assumed pn/nn ratio can alter the observed shape of 2p2h in E_{av} distributions.

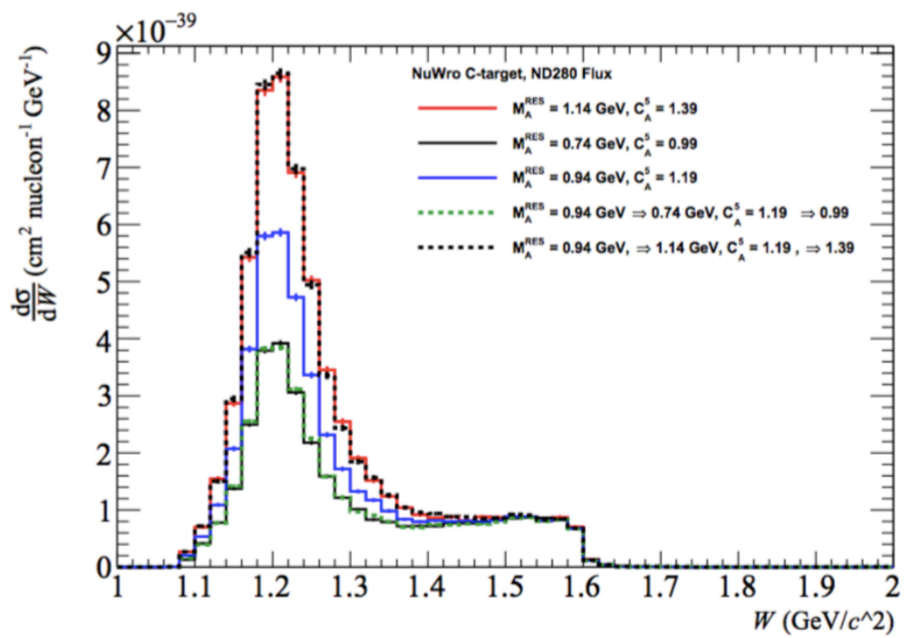




Using NuWro

- Included NuWro as a possible input. This opens up a range of extra models as well as providing a nicer C++ interface to prototype model changes.
  - LFG Model
  - Marteau MEC
  - NC TEM MEC
  - Alternative Form Factors
  - Alternative FSI Model tunings
- NuWro reweight module developed to allow systematic studies to be performed.
  - Myself, Luke Pickering, and Jan Sobczyk, working to get this released soon!





Is our High Q^2 Error Appropriate?

- Deuterium bubble chamber data can be used to place a constraint on the free nucleon cross-section. Data is statistically limited at high Q^2.
- If the model has a limited shape, like the simple dipole, the uncertainty on the bare CCQE cross-section can be underestimated in this region.

- Evaluating the free nucleon cross-section uncertainties also very recently done in: **Phys. Rev. D 93, 113015 (2016)**
  - They use Z-expansion formalism for F_A.

Fits to Bubble Chamber Data

- Fit multiple bubble chamber datasets at once.
- Datasets included in a shape-only fit:
  1. ANL 1DQ2 Event Rates
  2. BNL 1DQ2 Event Rates
  3. FNAL 1DQ2 Event Rates
  4. BEBC 1DQ2 Cross-section

$$\chi^2_{\text{ANL}} = 2.0 \sum_{i}^{49} [S_{\text{ANL}} M_i - D_i + D_i \times log(S_{\text{ANL}} M_i / D_i)]$$

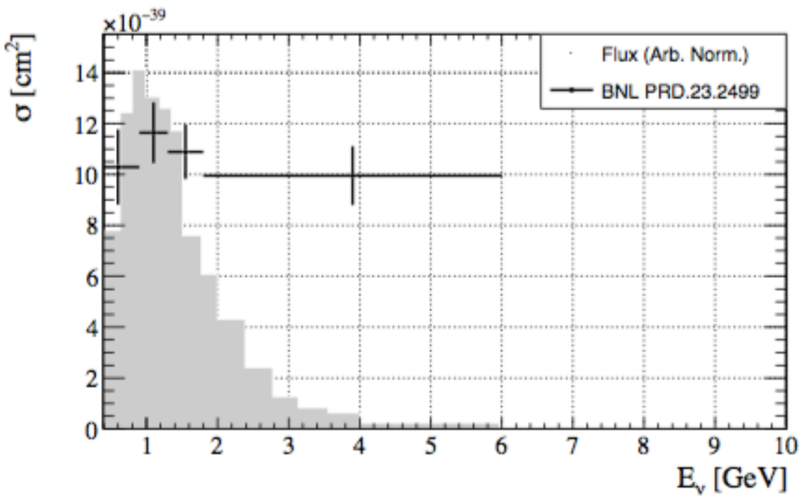
$$\chi^2_{\text{BNL}} = 2.0 \sum_{j}^{49} [S_{\text{BNL}} M_j - D_j + D_j \times log(S_{\text{BNL}} M_j / D_j)]$$

$$\chi^2_{\text{FNAL}} = 2.0 \sum_{k}^{29} [S_{\text{FNAL}} M_k - D_k + D_k \times log(S_{\text{FNAL}} M_k / D_k)]$$

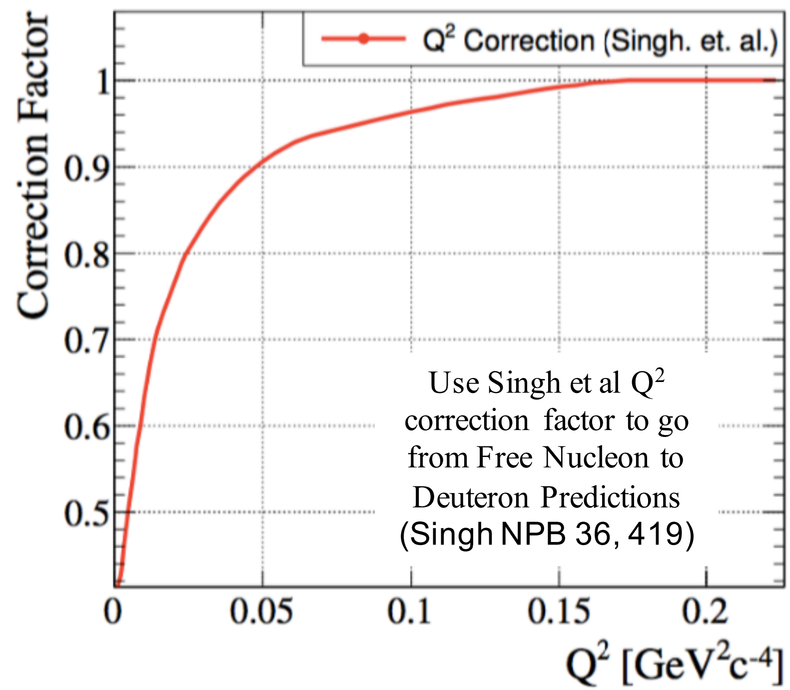
$$\chi^2_{\text{BEBC}} = \sum_{l}^{8} \left(\frac{M_l - D_l}{E_l} \right)^2$$

M=MC
D=Data
E=Error

$$\chi^2_{\textbf{Total}} = \chi^2_{\text{ANL}} + \chi^2_{\text{BNL}} + \chi^2_{\text{FNAL}} + \chi^2_{\text{BEBC}}$$



Generate NEUT/NuWro events with original published flux distributions.



Alternate F_A

- Consider alternate forms for F_A : Non-dipole form factors.
- Keep vector form factors at BBBA05 parametrizations.

- BBBA07 Model *(Eur.Phys.J.C53:349-354,2008)*

$$F_A'^{(Q^2)} = A_{Ax}(\zeta)\, F_A(Q^2) = A_{Ax}(\zeta) \frac{F_A(0)}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

$$A_N(\xi) = \sum_{j=1}^{n} P_j(\xi)$$

$$P_j(\xi) = p_j \prod_{k=1,k\neq j}^{n} \frac{\xi - \xi_k}{\xi_j - \xi_k}.$$

$$\zeta = \frac{2}{1 + \sqrt{1 + 1/\tau}}$$

p_j = Free Parameters

Original paper places several extra constraints on p_i. We do not!

- 2-component Model (*Phys.Rev.C 78, 035201 (2008))*

III. TWO-COMPONENT MODEL

In the two-component model [12,13], the axial nucleon form factor is described as

$$G_A(Q^2) = G_A(0) g(Q^2) \left[1 - \alpha + \alpha \frac{m_A^2}{m_A^2 + Q^2}\right], \quad (2)$$

$$g(Q^2) = (1 + \gamma Q^2)^{-2},$$

g denotes coupling to the intrinsic structure of the nucleon (qqq)

Mass of the lowest axial meson a1(1260) ma=1230GeV

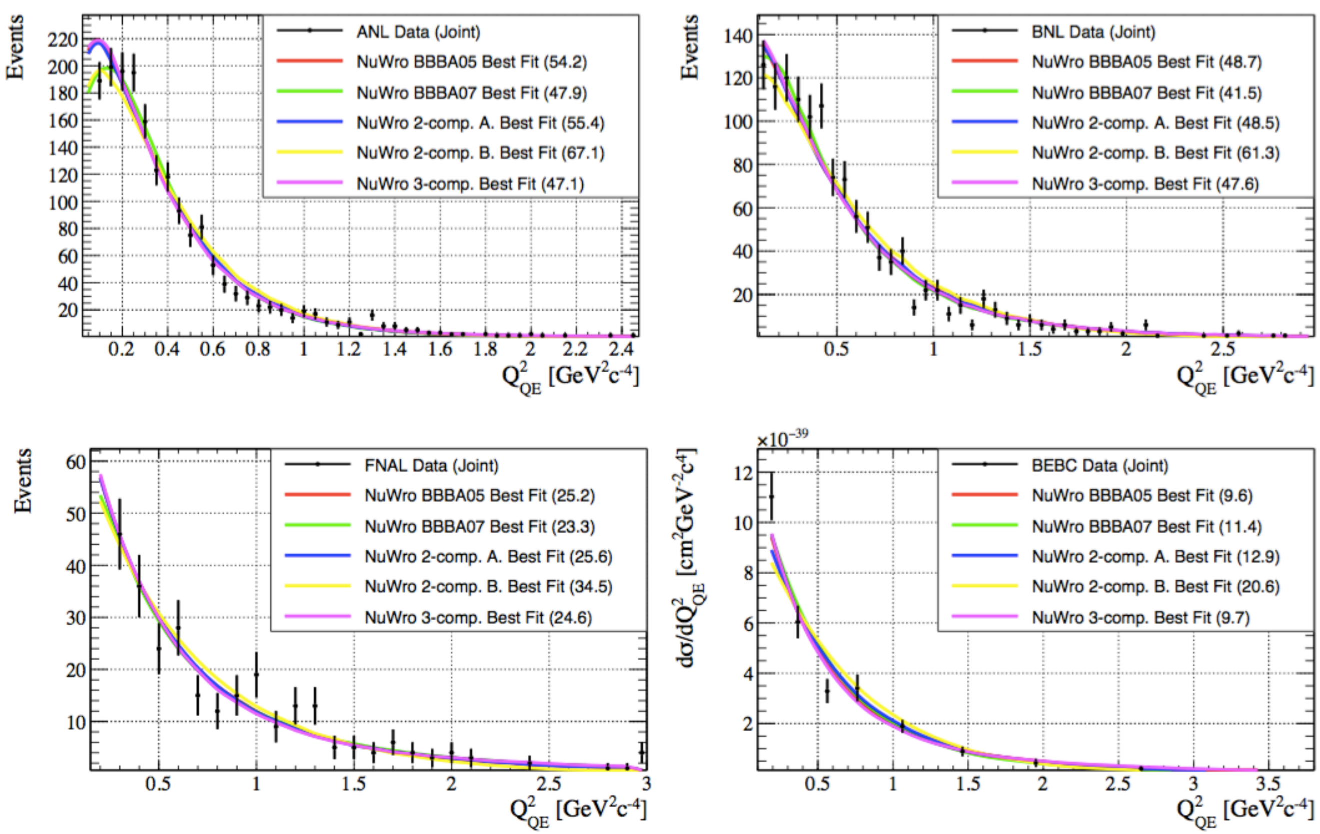
γ taken from previous EM form factor fits

α is a free parameter in the fit.

- Contribution from a qqq core and a q-qbar cloud.

- 3 possible models to fit.
- A. Alpha free, Gamma = 0.515
- B. Alpha free, Gamma = 0.25
- **C.** Alpha free, Gamma free

Fit Results

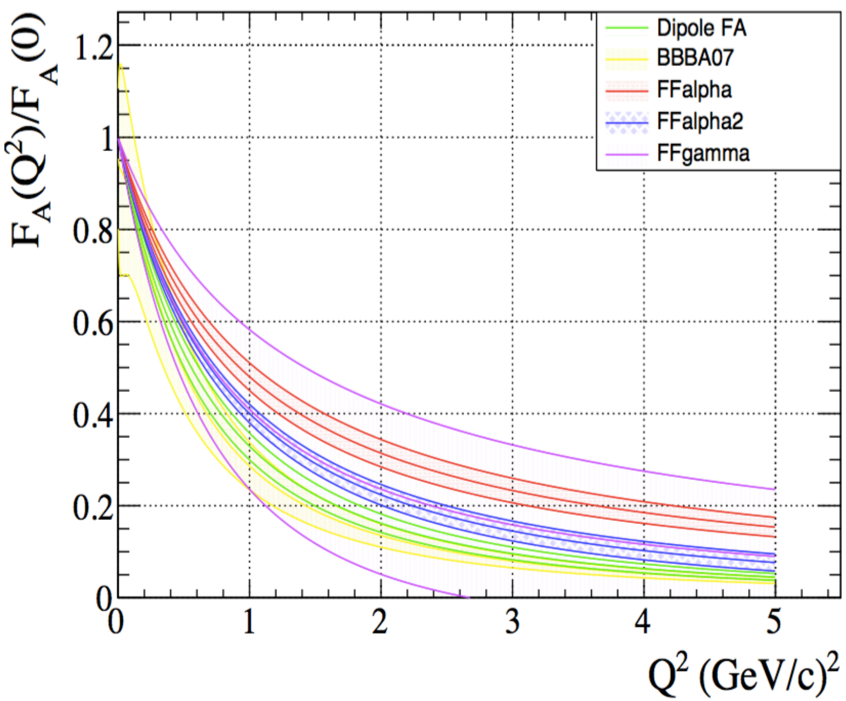


- For simple dipole (BBBA05) we get inflated M_A of 1.15 GeV due to performing a shape-only fit.
- Recent updates to this work use E_{nu} distributions to set the normalisation results in lower values in agreement with previous fits (M_A ~ 1.05).

Alternative FA models (Shape Fit)

	Dipole (BBBA05)	BBBA07	2-comp A.	2-comp B.	2-comp C.
χ^2	137.74	124.09	142.55	183.49	141.97
NDOF	134	130	134	134	133
χ^2/NDOF	1.03	0.95	1.06	1.37	1.07

- Considered alternative forms for F_A.
- Used NuWro to quickly generate predictions and reweighting dials for each model.
- Each one individually tuned to bubble chamber data.
- Agreement with data is remarkably similar even though high Q^2 behavior is quite different.

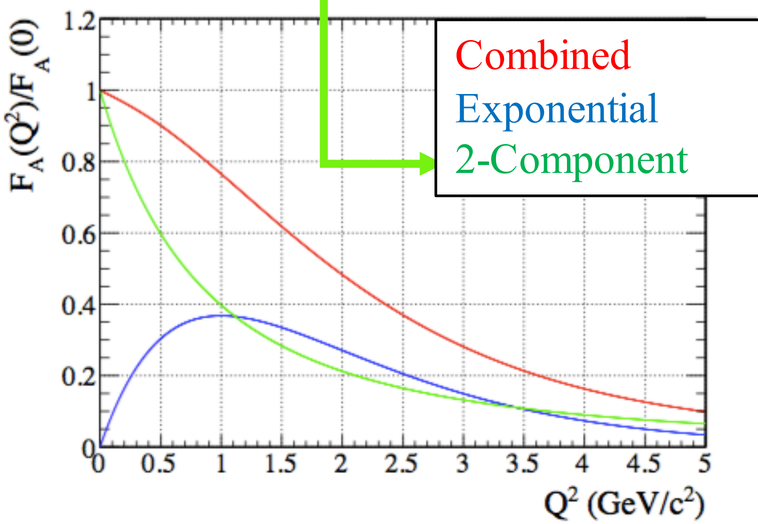


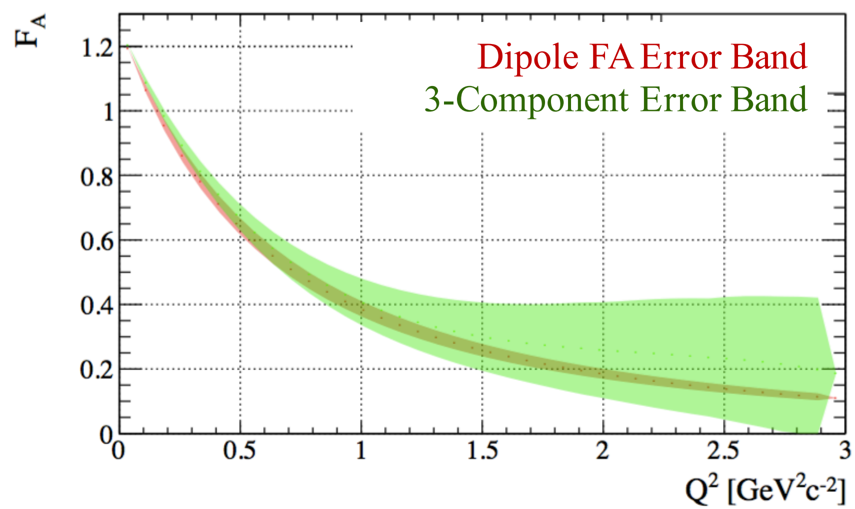
3 Component Model

- Create an effective model that is capable of describing each of the other models.
- Fit this to the data again to determine a new error band on the form factor.
- Best fit result matches the dipole form factor well (χ^2=131.19/131) but provides much larger error band at high Q^2.

Added exponential term to 2-component F_A model

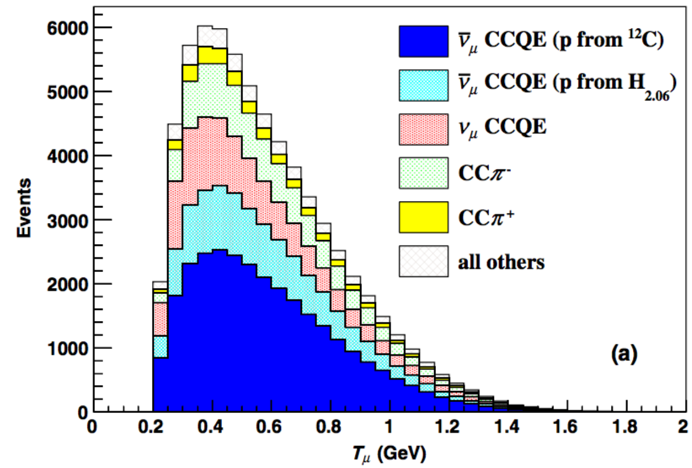
$$F_A(Q^2) = F_A(0)\left(\left[\frac{1}{1+\gamma Q^2}\left(1-\alpha+\alpha\frac{m_A^2}{(m_A^2+Q^2)}\right)\right] + \left[\theta Q^2 e^{\theta-\beta Q^2}\right]\right)$$

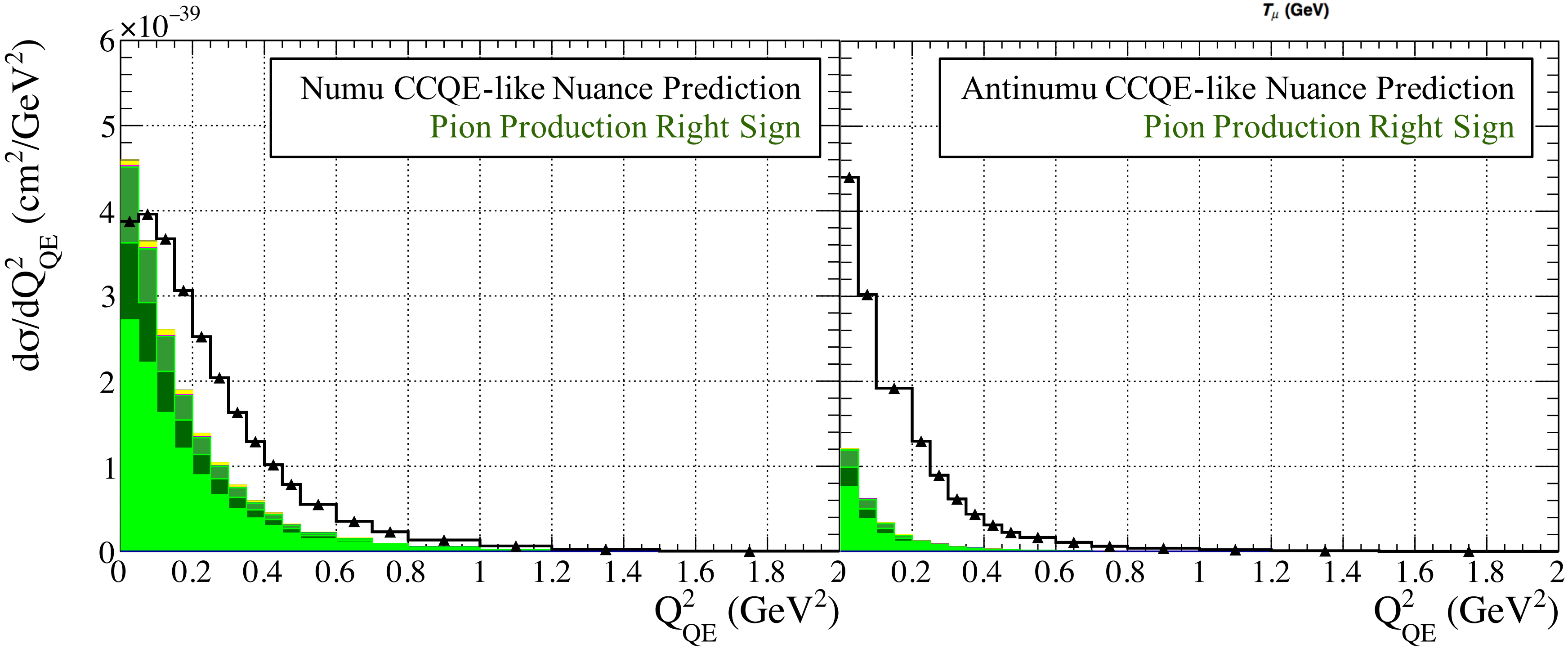




MiniBooNE CCQE-like

- Better to fit uncorrected final state topologies instead of background corrected samples.
- CC0PI > CCQE.
- Found a huge difference between the NUANCE prediction for antinu CCQE-like background.

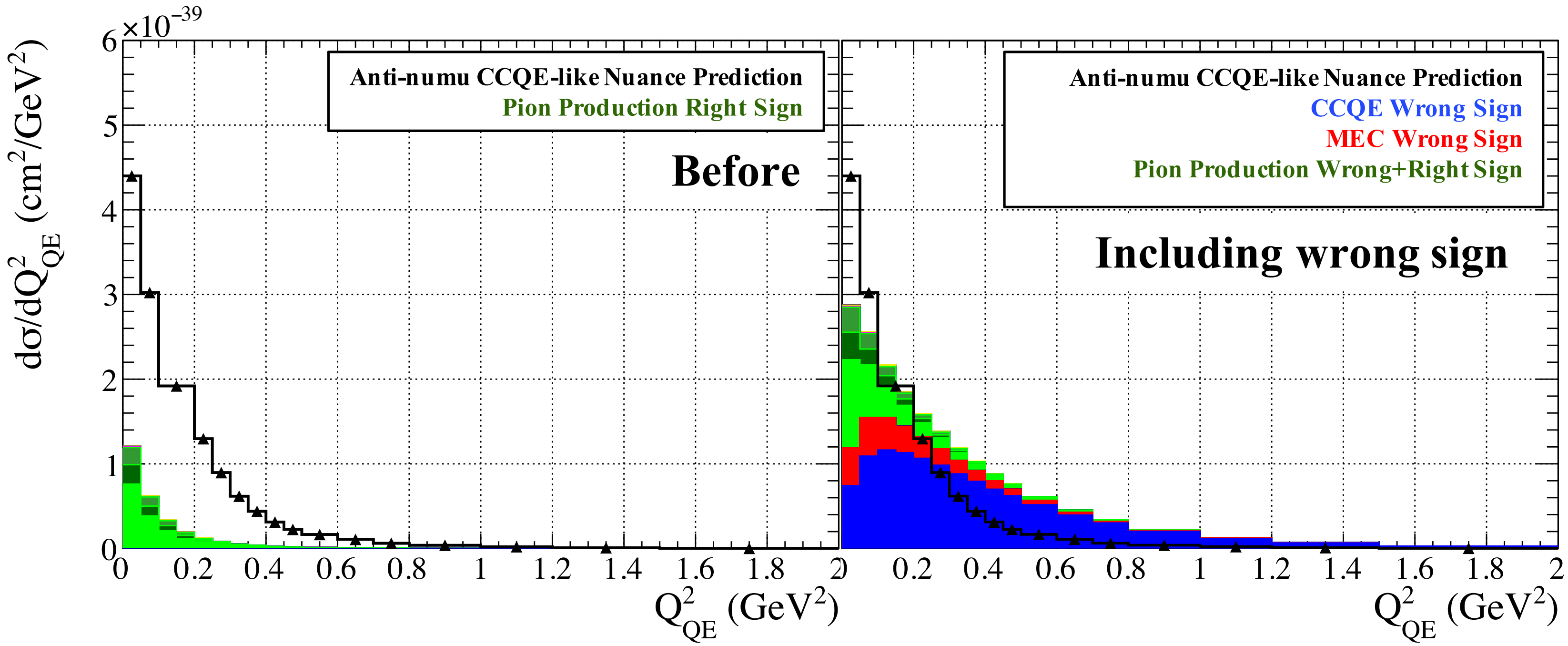




MiniBooNE CCQE-like Data

- Missing wrong sign was the reason for such a large discrepancy.
- Including this helps to at least match the normalisation a bit better, but NEUT disagrees still.

- Need to try and use final state topology measurements.
- MiniBooNE provided CCQE-like background prediction, but separated modes would be a huge improvement.



NUISANCE SLIDES

- The following slides give tips on running NUISANCE framework

NUISANCE: Generic Fitting Framework

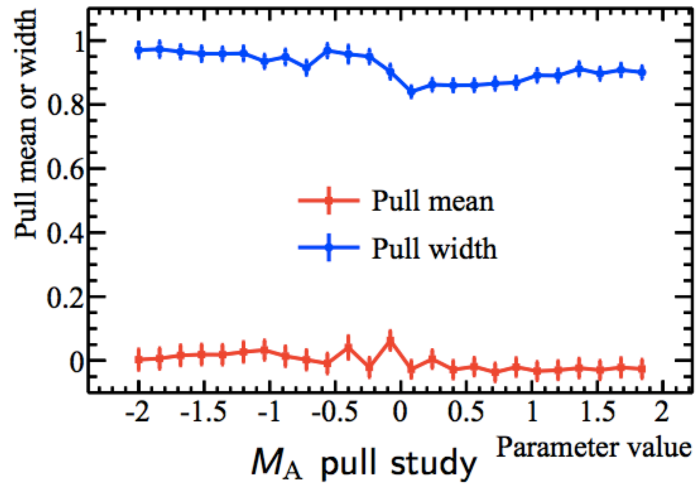
- Takes a long time to implement new models into generators, easier to take advantage of what is already setup in generators.
- Want to make comparisons/tunings of these different generators in a completely consistent and reliable way.

- Fitter initially developed for NIWG NEUT fits provides a framework to allow new dataset comparisons and tunings to be added very quickly.
- Restructured the code to turn it into a generic generator fitting package.
- Contains a broad range of implemented data/MC comparisons.

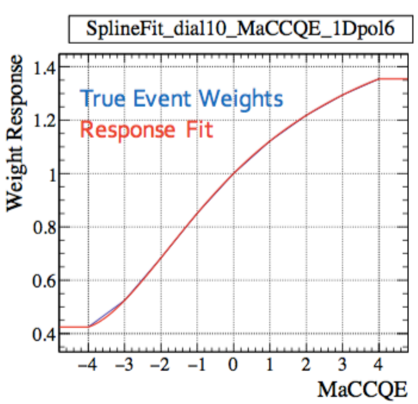
ReWeight Dial Tuning

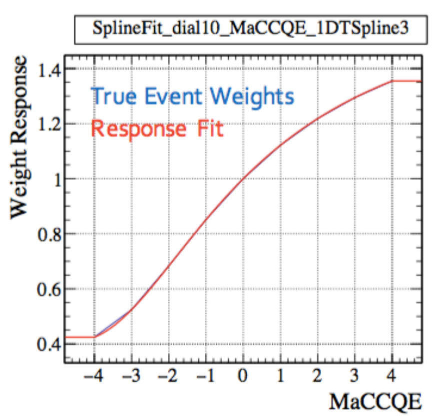
- **Multiple inputs:**
  - NEUT ✓
  - NuWro ✓
  - GENIE ✓
  - NUANCE ✓
  - GiBUU ✓

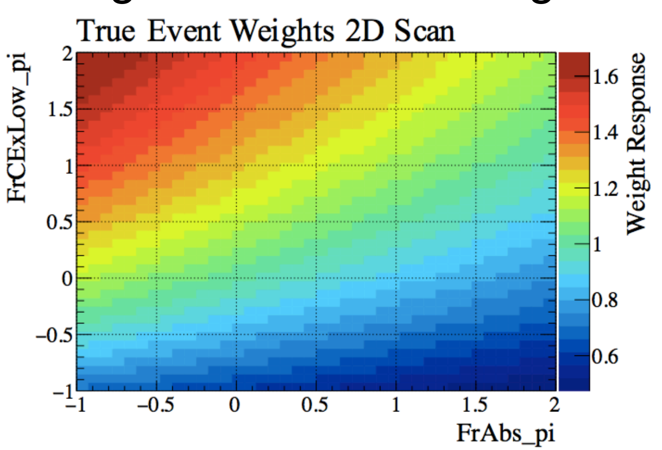
- Fake data study tools.



- Interface with generator reweight utilities to do tuning.
- Moving to spline reweighting soon to allow for more rigorous model testing.

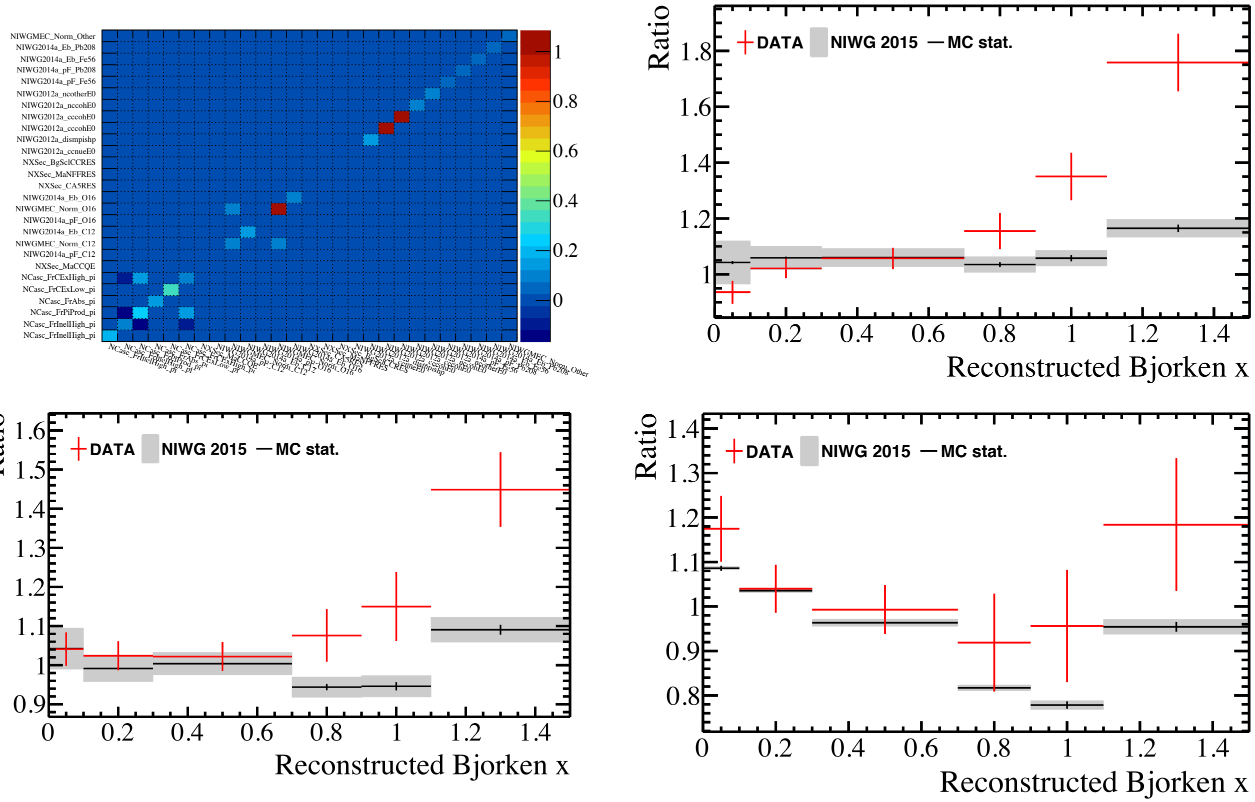






Systematic Analysis

- Lots of fitter development ongoing, added options to generate systematic throws from an arbitrary covariance.



- Should be shown as a standard for any model tuning so users can judge whether the fit parameters are actually appropriate for their analysis.

Writing a cardfile

- Comparing predictions requires you to write a cardfile that lists event files you want to look at.
- Simple example:

Can specify any applicable RW dial and set it to a chosen value.

```
# RW DIALS
# --------------- NOMINAL
neut_parameter    -1.0

# Other RW dial supported
# niwg_parameter
# nuwro_parameter
# genie_parameter


# SAMPLES
# ----- SAMPLE_NAME ----------------------------- TYPE --- INPUT ----------------- NORM
sample  MINERvA_CCQE_XSec_1DQ2_nu_20deg_newflux   FIX      NEUT:neut_events.root   1.00
```

Type gives the sample additional options at runtime.
e.g. how to handle the likelihoods.

Inverse normalisation Term 1/λ
e.g. For MiniBooNE ~0.8 will scale the MC to 125% of normal values.

“src/FCN/SampleList.cxx” gives all the possible samples that you can specify in the card files.

Input file. Must specify what type it is with following options
NEUT:
GENIE:
NUANCE:
NUWRO:
GIBUU:
JOINT:

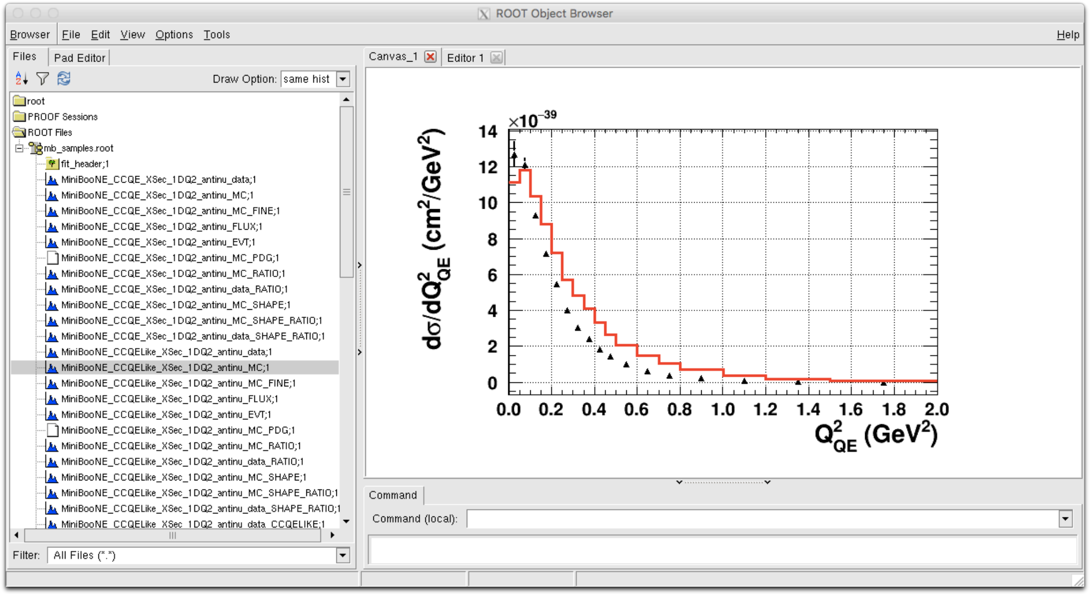
Best to read constructor src code of each sample you use to check how it handles input files.

Running Nuisance

- Once you’ve written a cardfile you just run ExtFit_comparison:

```
$ ExtFit_comparison -c mycardfile.card -o myoutputfile.root
```

- Processes all events and produces output file full of histograms.



Common Event Format

- What do we really need to compare to a published dataset?
  - True interaction channels (for BG corrected unfolded results)
  - Incoming particle info. (Neutrino and struck Nucleon)
  - Final state particle information (Leptonic and hadronic side).

- Converting input and statistical comparisons are all performed under the hood.
- Bare minimum required for differential cross-section:
  - Initial Histogram Setup: Constructor
  - Variable Definition: FillEventVariables
  - Signal Definition: isSignal

Initial Setup

- Taking MINERvA CCQE 1D Q^2_{QE} as an example

```
//********************************************************************
MINERvA_CCQE_XSec_1DQ2_nu::MINERvA_CCQE_XSec_1DQ2_nu(std::string name,
                                                     std::string inputfile,
                                                     FitWeight *rw,
                                                     std::string  type,
                                                     std::string fakeDataFile){
//********************************************************************

  // Measurement Defaults
  measurementName = name;
  plotTitles = "; Q^{2}_{QE} (GeV^{2}); d#sigma/dQ_{QE}^{2} (cm^{2}/GeV^{2})";
  EnuMin = 1.5;
  EnuMax = 10.;
  normError = 0.101;

  allowed_types = "FIX,FREE,SHAPE/DIAG,FULL/NORM";
  default_types = "FIX/FULL";

  isFluxFix      = name.find("_newflux") != std::string::npos;
  fullphasespace = name.find("_20deg")   == std::string::npos;
  Measurement1D::SetupMeasurement(inputfile, type, rw, fakeDataFile);

  // Setup the Data Plots
  std::string basedir = FitPar::GetDataBase()+"/MINERvA/CCQE/";
  std::string datafilename  = "20deg_Q2QE_numu_data_fluxfix.txt";
  std::string covarfilename = "20deg_Q2QE_numu_covar_fluxfix.txt";
  this->SetDataValues( basedir + datafilename );
  this->SetCovarMatrixFromText( basedir + covarfilename, 8 );

  // Setup Default MC Histograms to match Data
  this->SetupDefaultHist();

  // Set Scale Factor for this differential sampe
  // Measurement is in sigma/per neutron
  // scaleFactor = (EventNormalisation) * NNucl / NNeutrons / FluxIntegral
  scaleFactor = ( (this->eventHist->Integral("width")*1E-38/nevents)
                  *13.0/6.0
                  /this->TotalIntegratedFlux() );

};
```

Look here for possible fit type strings that can be used with a specific sample.

Input convertor setup is all handled in this function.

All distributions are normalised to the predicted event rate distribution for a given flux before transforming into a cross-section.

Normalisation factor to produce final cross-section needed is standardized for all generators.

isSignal?

```
//********************************************************************
bool MINERvA_CCQE_XSec_1DQ2_nu::isSignal(FitEvent *event){
//********************************************************************
  return SignalDef::isCCQEnumu_MINERvA(event, EnuMin, EnuMax, fullphasespace);
}
```

```
//*********************************************************************
bool SignalDef::isCCQEnumu_MINERvA(FitEvent* event, double EnuMin,
                                   double EnuMax, bool fullphasespace){
//*********************************************************************

  // For now, define as the true mode being CCQE or npnh
  if (event->Mode != 1 and event->Mode != 2) return false;

  // Only look at numu events
  if ((event->PartInfo(0))->fPID != 14) return false;

  // Get Theta Variables
  double ThetaMu = 999.9;
  double Enu_rec = -1.0;

  for (UInt_t i = 2; i < event->Npart(); i++){
    if (event->PartInfo(i)->fPID == 13){

      ThetaMu = (event->PartInfo(0)->fP.Vect().Angle(event->PartInfo(i)->fP.Vect()));
      Enu_rec = FitUtils::EnuQErec((event->PartInfo(i))->fP, cos(ThetaMu), 34.,true);
      break;
    }
  }

  // If Restricted phase space
  if (!fullphasespace &&  ThetaMu > 0.34906585) return false;

  // restrict energy range
  if (event->Enu()/1000.0 < EnuMin || event->Enu()/1000.0 > EnuMax) return false;
  if (Enu_rec < EnuMin || Enu_rec > EnuMax) return false;

  return true;
};
```

Look in "src/Utils/SignalDef.cxx" for implemented signal definitions.

Mode gives the true interaction channel. List of all channels given in: **src/FitBase/GeneratorUtils.cxx**

FillEventVariables

- Just used to define the X, Y, Z variables that events should be binned in.

```
//********************************************************************
void MINERvA_CCQE_XSec_1DQ2_nu::FillEventVariables(FitEvent *event){
//********************************************************************

  double q2qe = -1.0;
  double ThetaMu = -1.0;

  // Get the relevant signal information
  for (UInt_t j = 0; j < event->Npart(); ++j){

    if ((event->PartInfo(j))->fPID != 13) continue;

    ThetaMu     = (event->PartInfo(0))->fP.Vect().Angle((event->PartInfo(j))->fP.Vect());
    q2qe        = FitUtils::Q2QErec((event->PartInfo(j))->fP, cos(ThetaMu), 34.,true);

    break;

  }

  // Set binning variable
  this->X_VAR = q2qe;
  return;
}
```

Must tell the fitter what variable is X, Y for each event.

- Unless told otherwise the fitter assumes it is a differential cross-section distribution. Support for other types of distributions are available. See src code for examples.

GenericFlux_Tester

- Also included a generic flux tester class to make it easier to save new variables and signal definitions for this workshop.

- Add new variables into “src/MCStudies/GenericFlux_Tester.cxx”

```
// Setup the TTree to save everything
eventVariables = new TTree( (this->measurementName+"_VARS").c_str(), (this->measurementName+"_VARS").c_str() );
eventVariables->Branch("Mode",      &Mode,      "Mode/I");
eventVariables->Branch("Enu_true",  &Enu_true, "Enu_true/D");
eventVariables->Branch("Enu_QE",    &Enu_QE,    "Enu_QE/D"  );
eventVariables->Branch("PDGnu",     &PDGnu,     "PDGnu/D"   );

eventVariables->Branch("Q2_true",  &Q2_true,  "Q2_true/D" );
eventVariables->Branch("Q2_QE",    &Q2_QE,    "Q2_QE/D"   );
eventVariables->Branch("q0_true",  &q0_true,  "q0_true/D"   );
eventVariables->Branch("q3_true",  &q3_true,  "q3_true/D"   );

eventVariables->Branch("MLep",      &MLep,      "MLep/D"  );
eventVariables->Branch("ELep",      &ELep,      "ELep/D"  );
eventVariables->Branch("TLep",      &TLep,      "TLep/D"  );
eventVariables->Branch("CosLep",    &CosLep,    "CosLep/D");
eventVariables->Branch("PPr",       &PPr,       "PPr/D"   );
eventVariables->Branch("CosPr",     &CosPr,     "CosPr/D" );

eventVariables->Branch("FluxWeight", &FluxWeight, "FluxWeight/D");
eventVariables->Branch("Weight"    , &Weight,     "Weight/D"    );
```

Building Nuisance

- Moved to a CMAKE build which automatically detects environment variables. If you can run the generator you should be able to build NUISANCE against it.

```
# Make Build DIR
mkdir build
cd build

# Build against selected generators
cmake -DUSE_NuWro=1 -DUSE_NEUT=1 -DUSE_GENIE=0 -DUSE_GiBUU=1 -DUSE_NUANCE=1 ../
make -j4
make docs
make install
```

Build commands.

```
CMake Error at cmake/NEUTSetup.cmake:2 (if):
  if given arguments:

    "NOT" "DEFINED" "ENV{NEUT_ROOT}" "OR" "STREQUAL" ""

  Unknown arguments specified
```

BAD

```
-- [INFO]: Module targets:  Minimizer;FCN;expANL;expBEBC;expBNL;expFNAL;expGGM
;expK2K;expMINERvA;expMiniBooNE;expT2K;MCStudies;FitBase;Utils
-- Configuring done
-- Generating done
-- Build files have been written to: /home/stowell/t2krep/NIWG/nufix/build
```

GOOD

Example 1

- Code requires each generator you want to make a comparison with be built before you build the fitter.
- Best examples are to just try and make a comparison against generator of your choosing.

1. Compare a raw generator prediction to MiniBooNE numu CCQE 1DQ2 data.
   - Sample name is “MiniBooNE_CCQE_XSec_1DQ2_nu”
   - NEUT Example:

```
sample    MiniBooNE_CCQE_XSec_1DQ2_nu     FIX     NEUT:/path/to/neut/file.root     1.00
```

```
sample    MiniBooNE_CCQE_XSec_1DQ2_nu    FIX     NUWRO:/path/to/nuwro/file.root     1.00
```

Will need a separate card file for each one.

Example 2

2. Compare two different generator predictions in multiple variables.

- GenericFlux_Tester class should be used here.
- Can give multiple identifiers to separate results.

Extra config flag needed when using GenericFlux classes

```
config  EventManager  0

sample   GenericFlux_NEUT            FIX   NEUT:/path/to/neut/file.root       1.00
sample   GenericFlux_NUWRO_MODEL_1   FIX   NUWRO:/path/to/nuwro/file1.root    1.00
sample   GenericFlux_NUWRO_MODEL_2   FIX   NUWRO:/path/to/nuwro/file2.root    1.00
```

Identifier can be used to create multiple trees from different input files in a single file.

Event Access Tips

- Event->Enu()   True Neutrino Energy
- Event->Mode   True Interaction Channel

- Event->Npart()   Total Number of Particles
- Event->PartInfo(i)   Access ith Particle
- Event->PartInfo(i) -> fPID   ith Particle ID PDG code
- Event->PartInfo(i) -> fP   ith Particle 4-mom
- Event->PartInfo(i) -> fIsAlive   ith Particle is Final State Particle
- Event->PartInfo(i) -> fStatus   ith Particle State
  0 Final State, 1 Initial State,
  2 Intermediate State (Cascade)