CC0pi/CC-inclusive Data Comparisons

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Introduction

- Learnt from the previous round of NIWG fits that there are tensions within our current models between the external data sets.

- Work since then has been trying to understand what causes some of these problems.

- **Aim:** Find a cross-section model that is capable of explaining a broad range of the published datasets and try to relieve the tensions.

Updated PGoF Fits

- Recap: MiniBooNE and MINERvA joint fits show a disagreement on best fit model parameters. NEUTs model cannot describe both simultaneously.

- MINERvA updated their flux which helped a little bit, but there are still issues!

MINERvA Flux Update
After and Before

Joint Fits PGoF

Type	$\chi^2/NDOF$	(TN192)	$\chi^2_{PG}/NDOF_{PG}$	(TN192)	PGoF (%)	(TN192)
RFG MEC	101/226	-	24.9/6	-	0	-
RFG Rel RPA MEC	105/226	97	14.2/6	18	2.8	0.66
RFG Non Rel RPA MEC	119/226	118	18.3/6	25	0.6	0.03
SF MEC	106/226	97	24.0/6	41	0.1	0.0

Parameter	M_A [GeV]	TN192	p_F [MeV]	TN192	MEC (%)	TN192
RFG MEC	1.34 ± 0.02	-	229 ± 7	-	0 (limit)	-
RFG Rel.RPA MEC	1.16 ± 0.03	1.15	219 ± 6	223	35 ± 11	27
RFG Non.Rel.RPA MEC	1.07 ± 0.02	1.07	223 ± 6	225	41 ± 11	34
SF MEC	1.35 ± 0.02	1.33	229 ± 8	234	0 (limit)	0

XSecFitter: Generic Fitting Framework

- Takes a long time to implement new models into generators, easier to take advantage of what is already setup in generators.

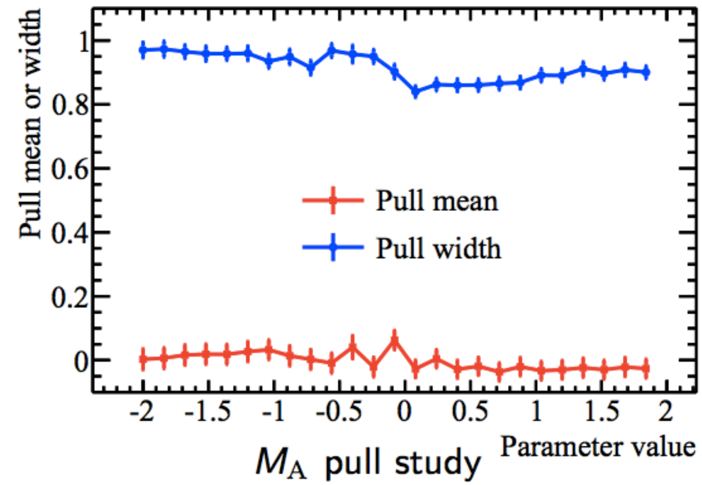
- Want to make comparisons/tunings of these different generators in a completely consistent and reliable way.

- Fitter Callum 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.

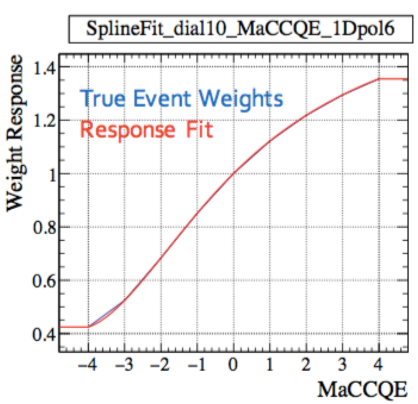
Name is a work in progress!
Suggestions welcome!

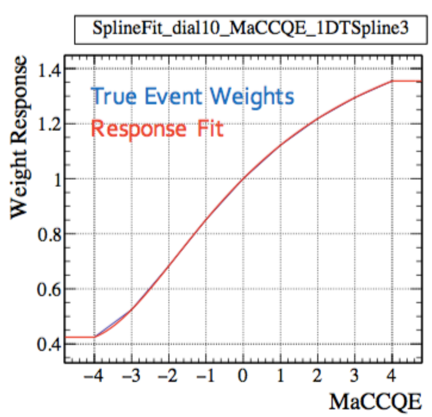
ReWeight Dial Tuning

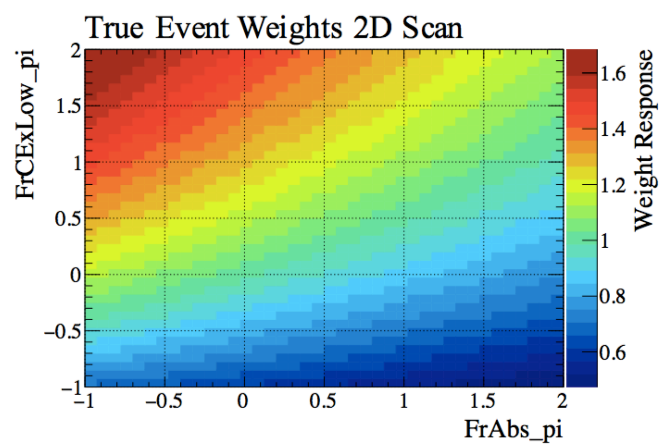
- **Multiple inputs:**
  - NEUT ✓
  - NuWro ✓
  - GENIE ✓
  - NUANCE ✗ – Coming Soon…
  - GiBUU ✗ – Coming Soon…
- Fake data study tools.



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

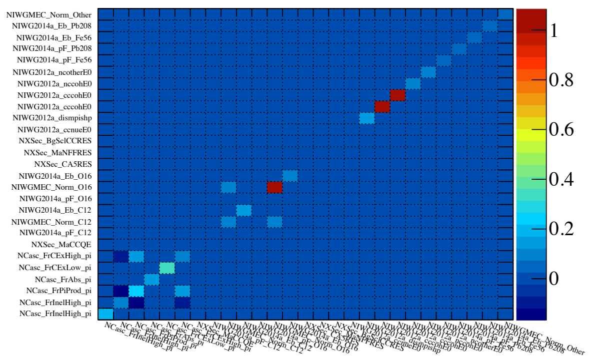


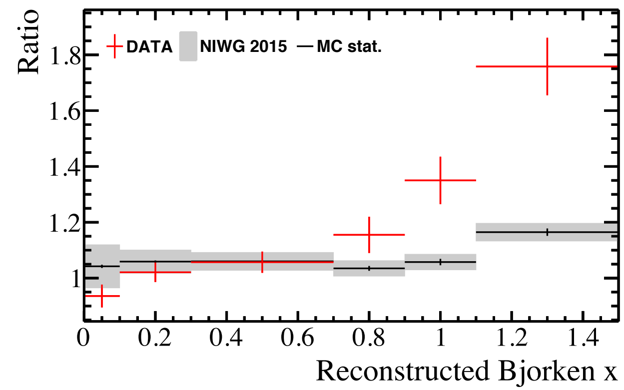


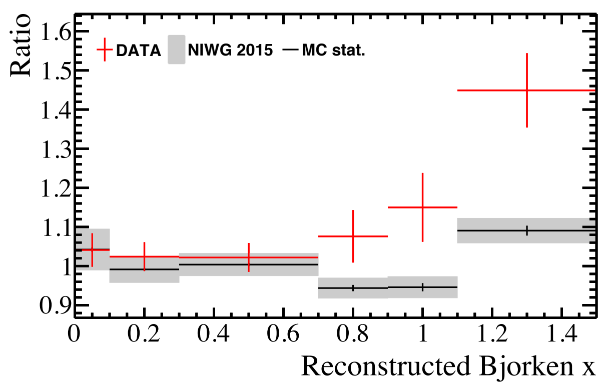


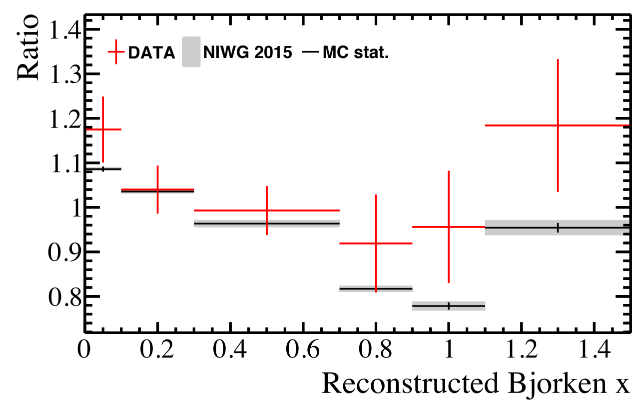
Systematic Analysis

- 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.

Experimental Collaboration

- Working to release this as **publicly available** software soon.

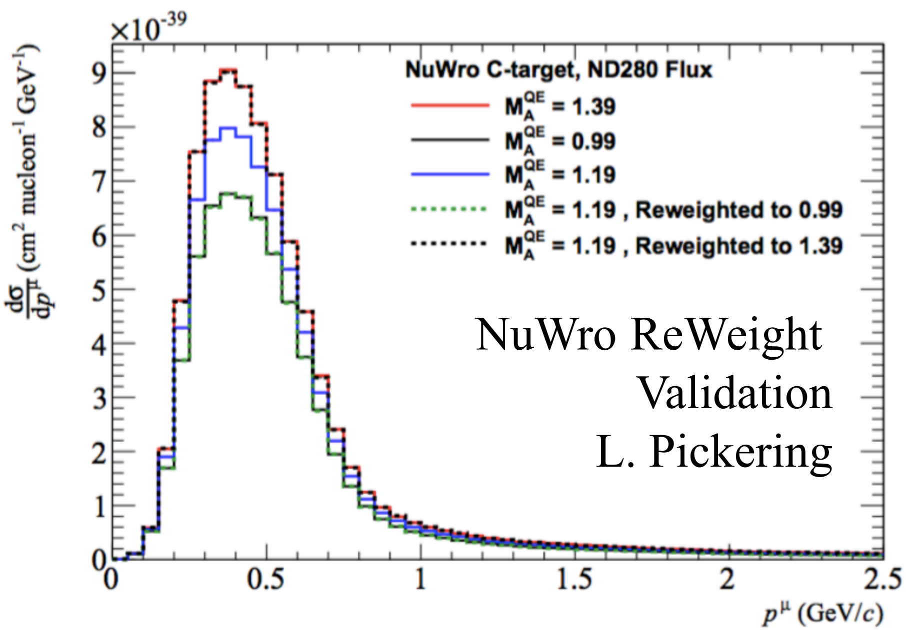
- Fitter tools will be freely available to use.
- Interested in more direct correspondence with experiments so we can properly test our cross-section models.

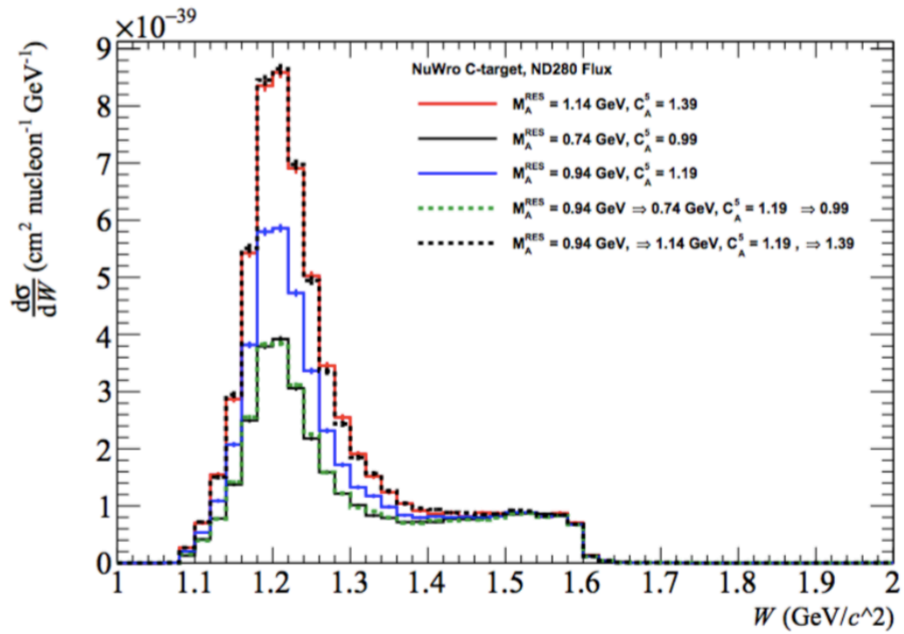
Using NuWro

- Included NuWro as a possible input. This opens up a range of extra models aswell 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!





NuWro LFG Fits

- Want to see whether the fitter inflating M_A and reducing MEC normalization is just a result of the stitched together RFG+Nieves model in NEUT.

Parameter	M_A [GeV]	TN192	p_F [MeV]	TN192	MEC (%)	TN192
RFG MEC	1.34 ± 0.02	-	229 ± 7	-	0 (limit)	-
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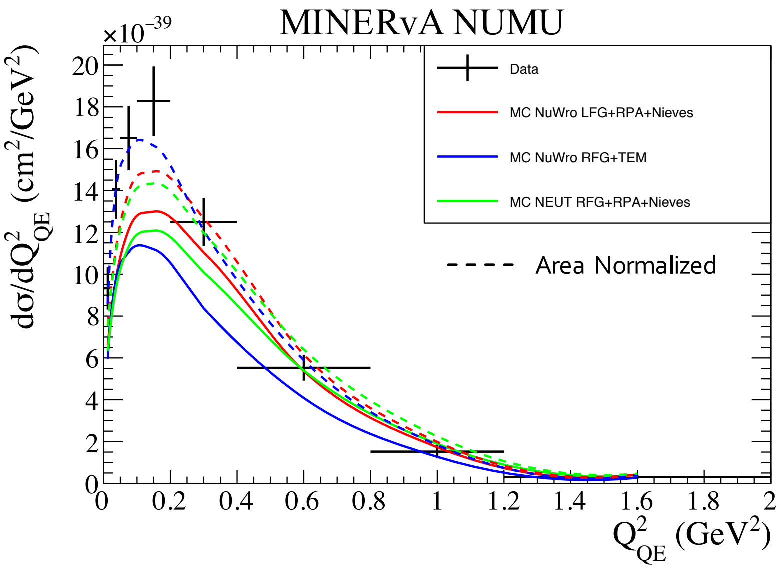
- Compare 3 models:
  - NEUT RFG + RPA + Nieves
  - NuWro LFG + RPA + Nieves
  - NuWro RFG + TEM

Found to be the best fit to MINERvA CCQE data in original data release.

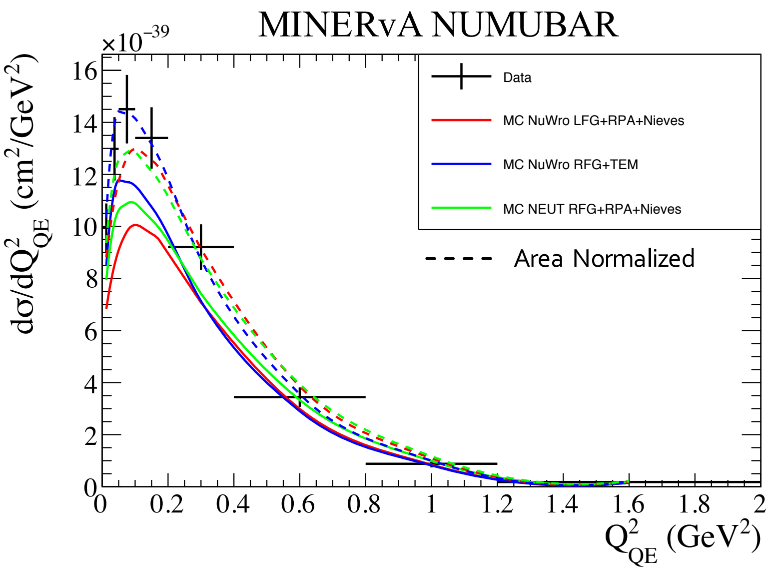
- In each model fit 2 free parameters:
  - Axial Mass
  - MEC Normalisation

Removed pF dial as NuWro RW doesn't have this yet.

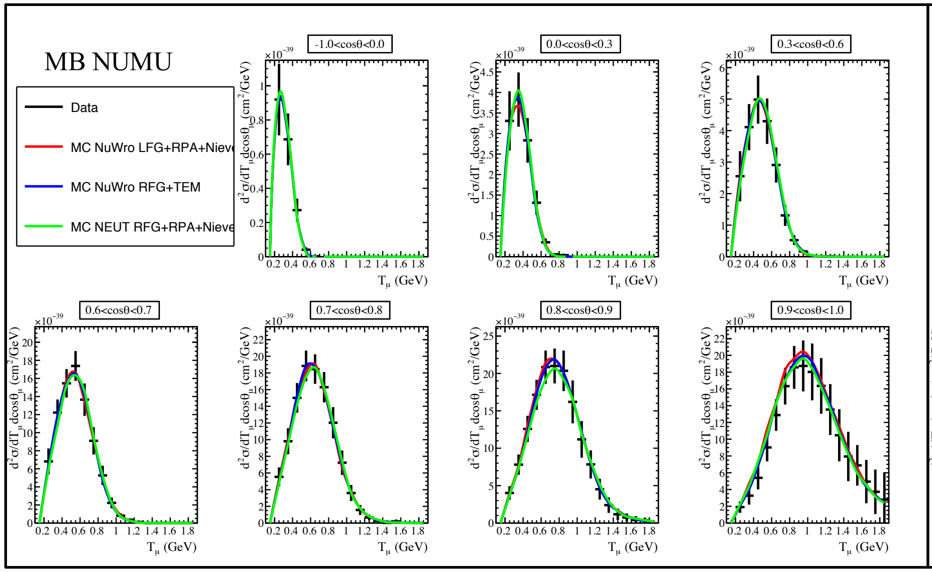
Fit Results



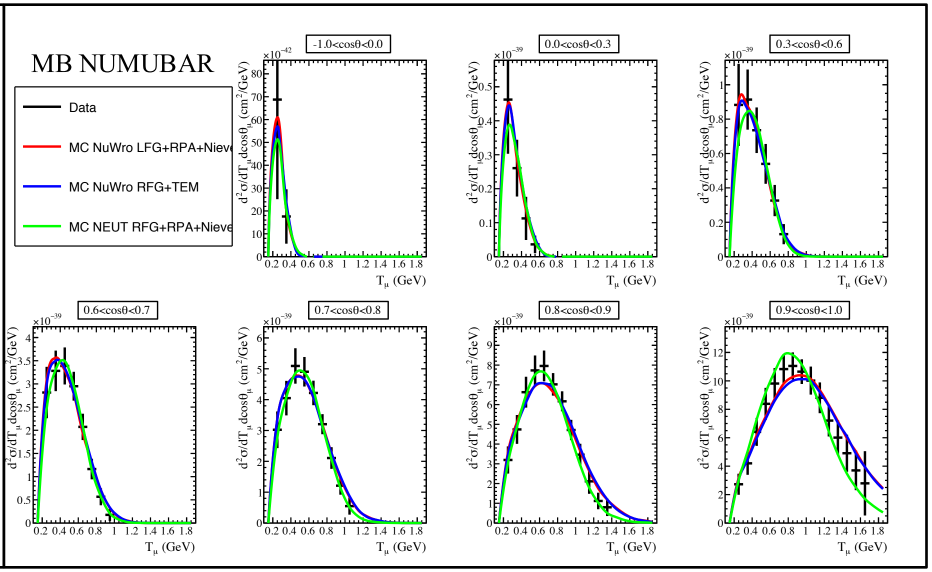
MINERvA NUMU
Data
MC NuWro LFG+RPA+Nieves
MC NuWro RFG+TEM
MC NEUT RFG+RPA+Nieves
Area Normalized



MINERvA NUMUBAR
Data
MC NuWro LFG+RPA+Nieves
MC NuWro RFG+TEM
MC NEUT RFG+RPA+Nieves
Area Normalized



MB NUMU
Data
MC NuWro LFG+RPA+Nieves
MC NuWro RFG+TEM
MC NEUT RFG+RPA+Nieves

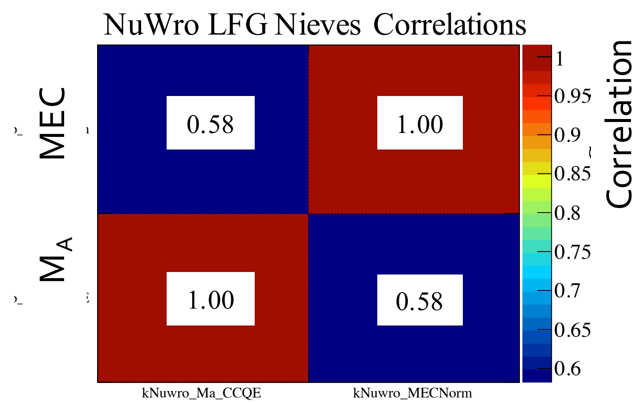


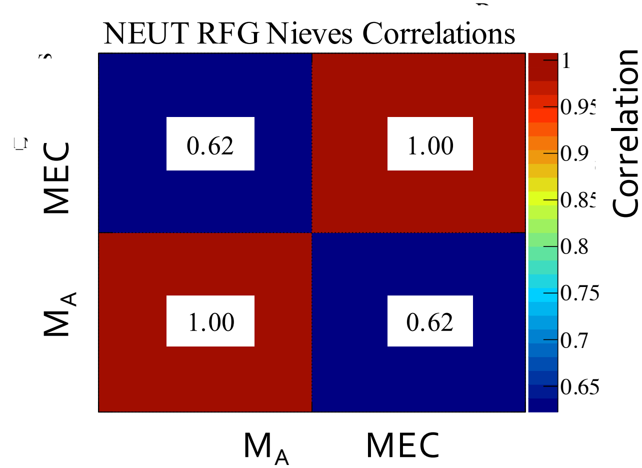
MB NUMUBAR
Data
MC NuWro LFG+RPA+Nieves
MC NuWro RFG+TEM
MC NEUT RFG+RPA+Nieves

NuWro LFG Fits

Model	M_A (GeV/c^2)	MEC Norm. (%)	λ^{ν}_{MB}	$\lambda^{\bar{\nu}}_{MB}$	χ^2/NDOF
Nuwro LFG + Nieves	1.16 ± 0.03	8.3 ± 11.9	0.80	0.91	100.74/229
Nuwro RFG + TEM	1.15 ± 0.02	21.3 ± 12.5	0.84	0.92	93.62/229
NEUT RFG + Nieves	1.14 ± 0.03	25.5 ± 12.4	0.78	0.77	106.25/229

- Fit results from NuWro with an LFG are quite similar to NEUT RFG model.
- Still have problem where M_A is being inflated and MEC normalization is being driven down.
- MEC and the Axial Mass are positively correlated at the best fit point.





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-expanstion 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

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

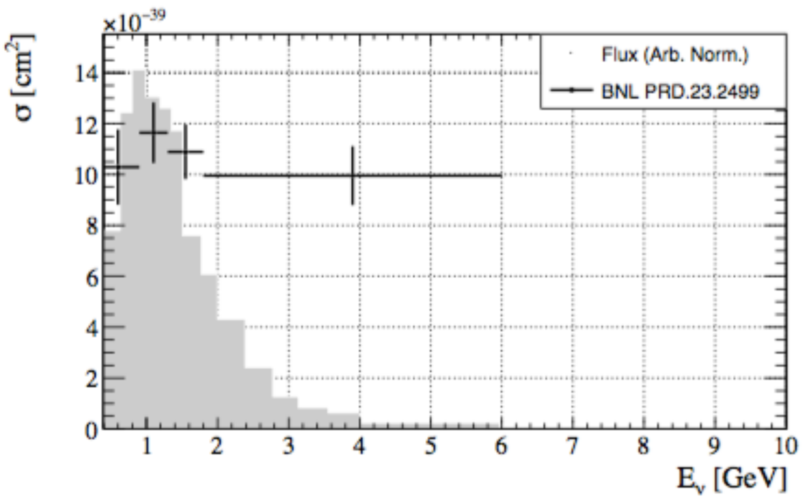
$$\chi^2_{\text{BNL}} = 2.0\sum_j^{49}[S_{\text{BNL}}M_j - D_j + D_j \times log(S_{\text{BNL}}M_j/D_j)]$$

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

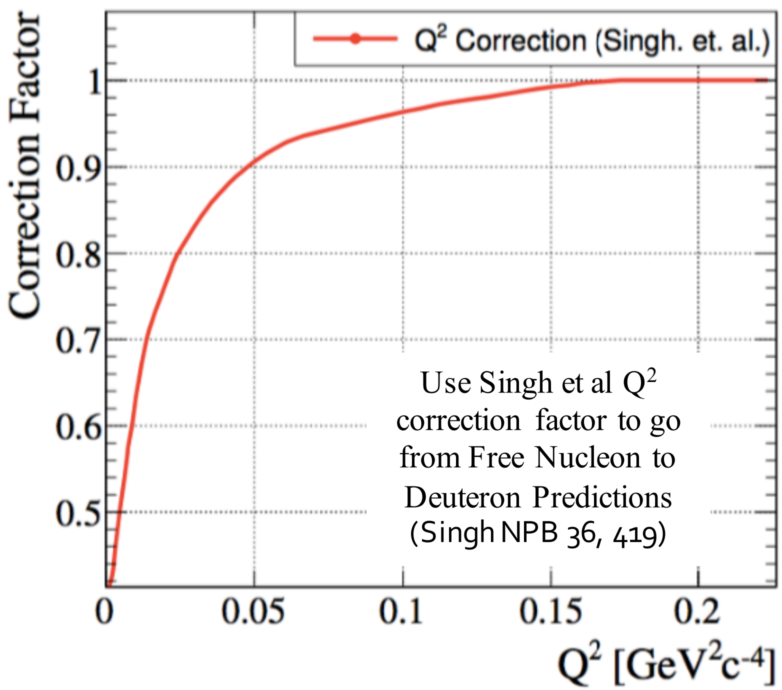
$$\chi^2_{\text{BEBC}} = \sum_l^{8}\left(\frac{M_l - D_l}{E_l}\right)^2$$

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.



Use Singh et al Q^2 correction factor to go from Free Nucleon to Deuteron Predictions (Singh NPB 36, 419)

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)*

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

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

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

p_j = Free Parameters

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

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

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

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

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

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

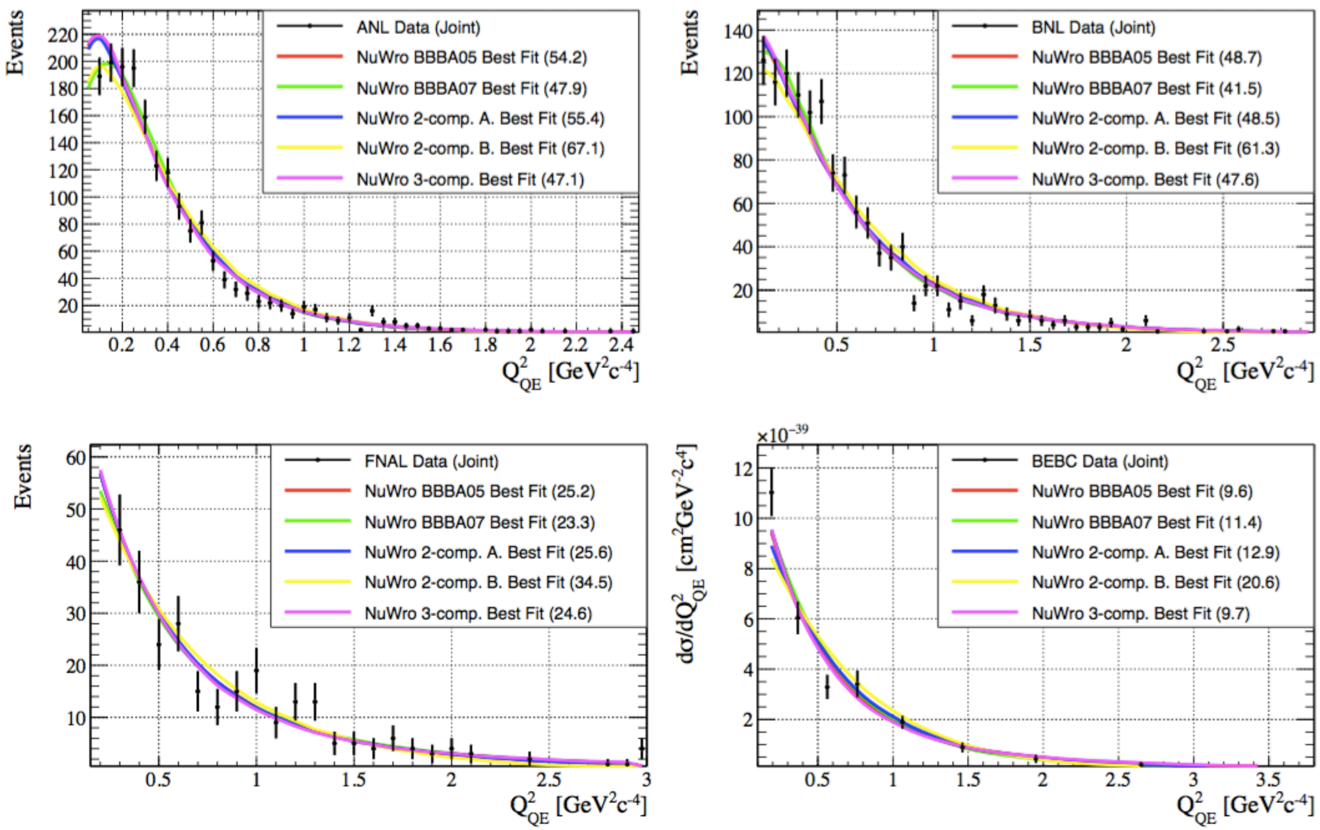
γ taken from previous EM form factor fits

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

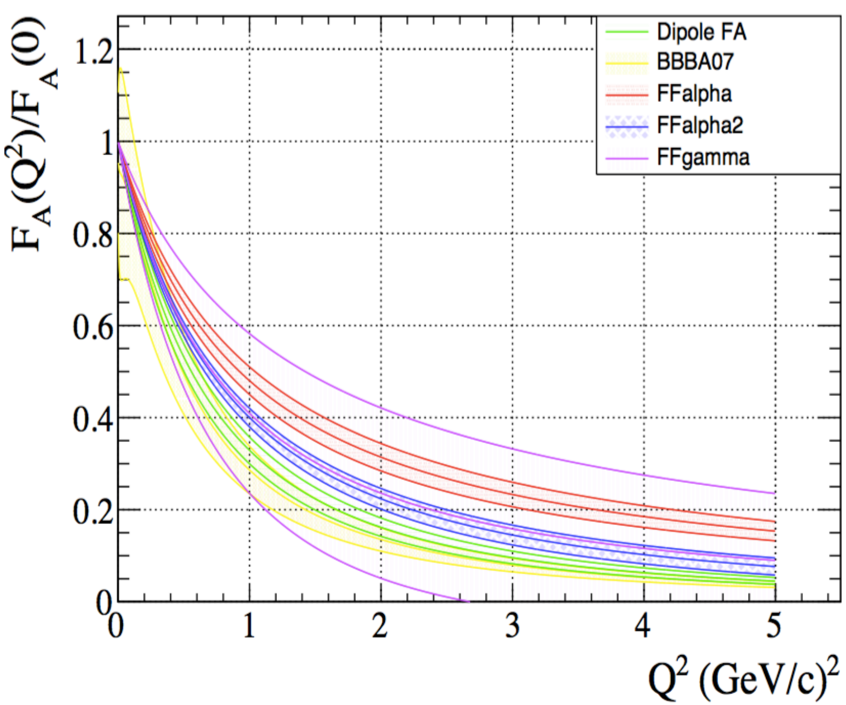


- For simple dipole (BBBA05) we get inflated M_A of 1.15 GeV due to performing a shape-only fit.
- Recent updates to this work use E_{nu} distributions to set the normalization results in lower values in agreement with previous fits ($M_A \sim 1.05$).

Alternative models

	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.

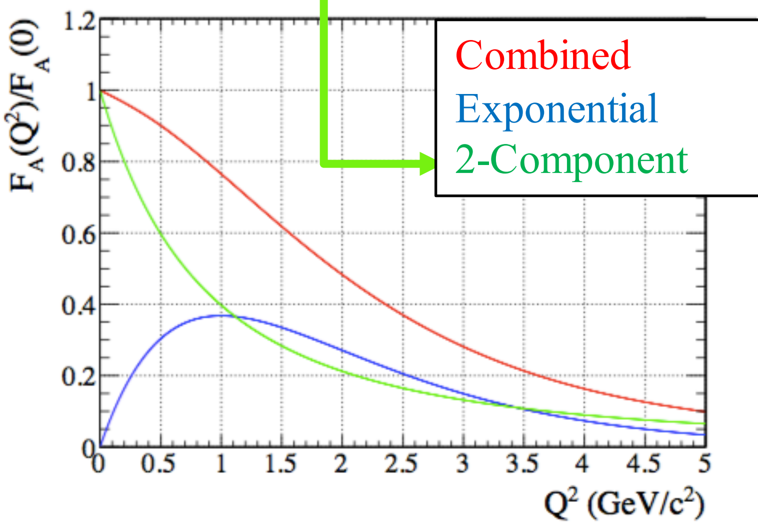


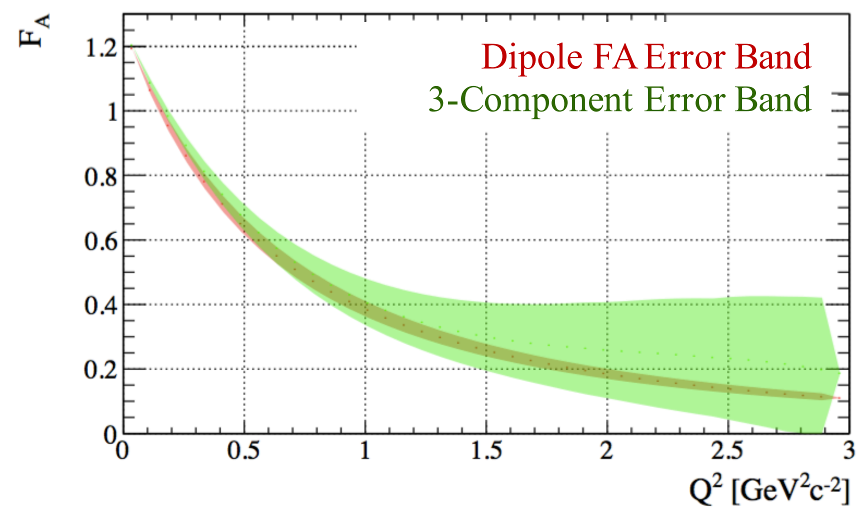
3 Component Model

- 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

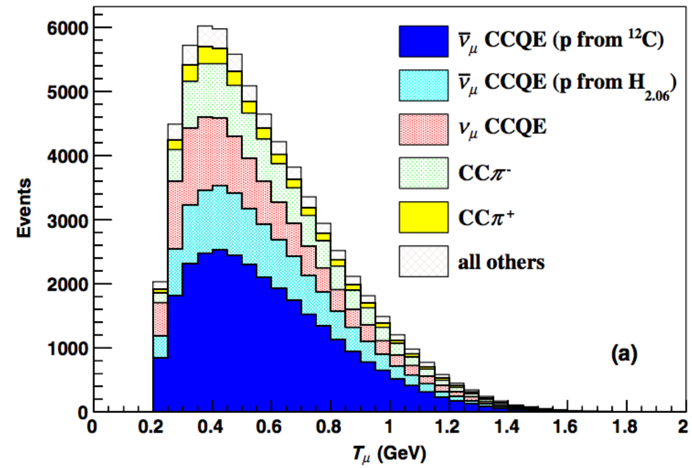
$$F_A(Q^2) = F_A(0)\left(\left[\frac{1}{1+\gamma Q^2}\left(1-\alpha+\alpha\frac{m_A^2}{(m_A^2+Q^2)}\right)\right] + \left[\theta Q^2 e^{\theta-\beta Q^2}\right]\right)$$

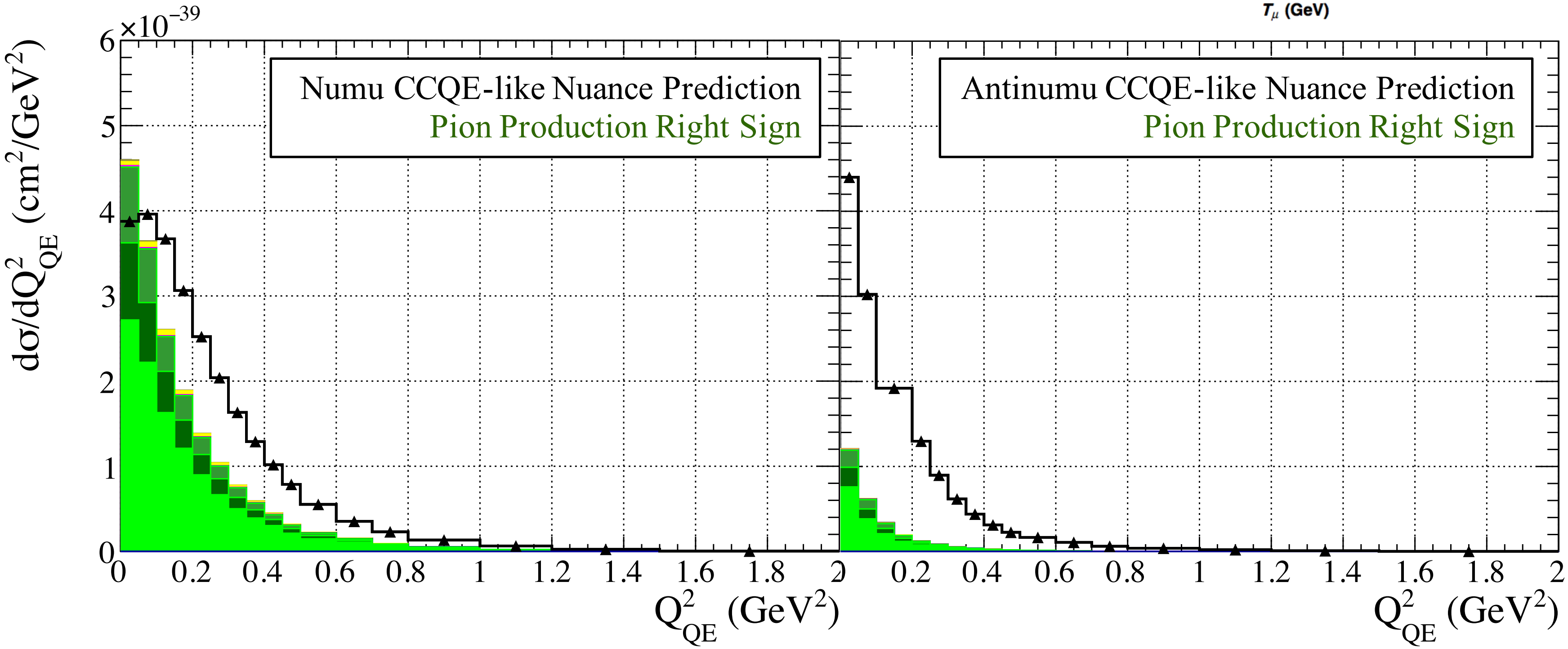




MiniBooNE CCQE-like

- 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.

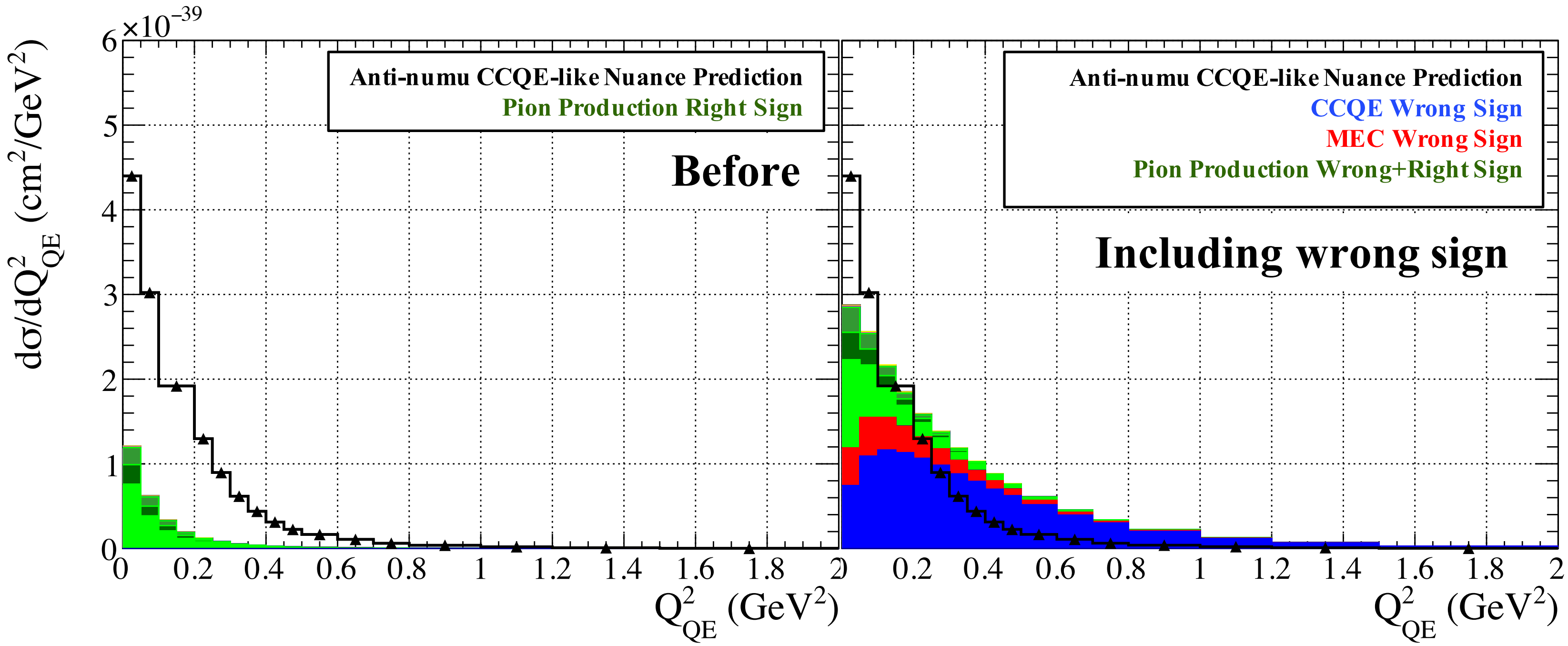




MiniBooNE CCQE-like Data

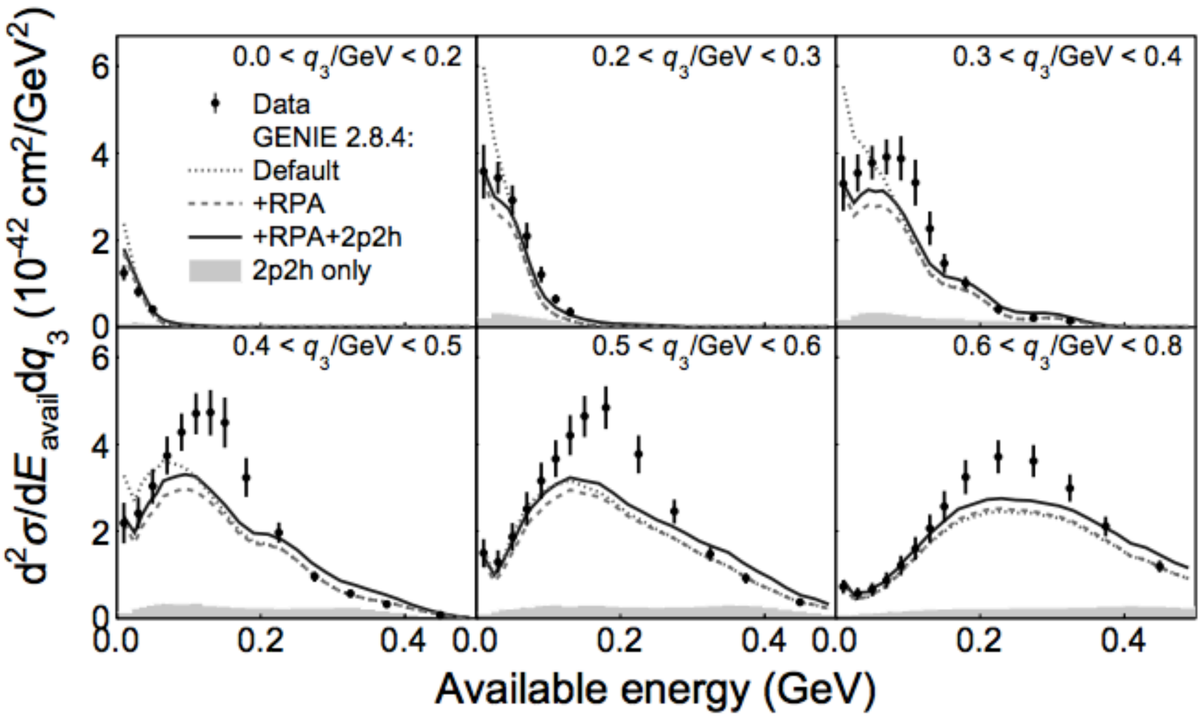
- Missing wrong sign was the reason for such a large discrepancy.
- Including this helps to at least match the normalization a bit better, but NEUT disagrees still.

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



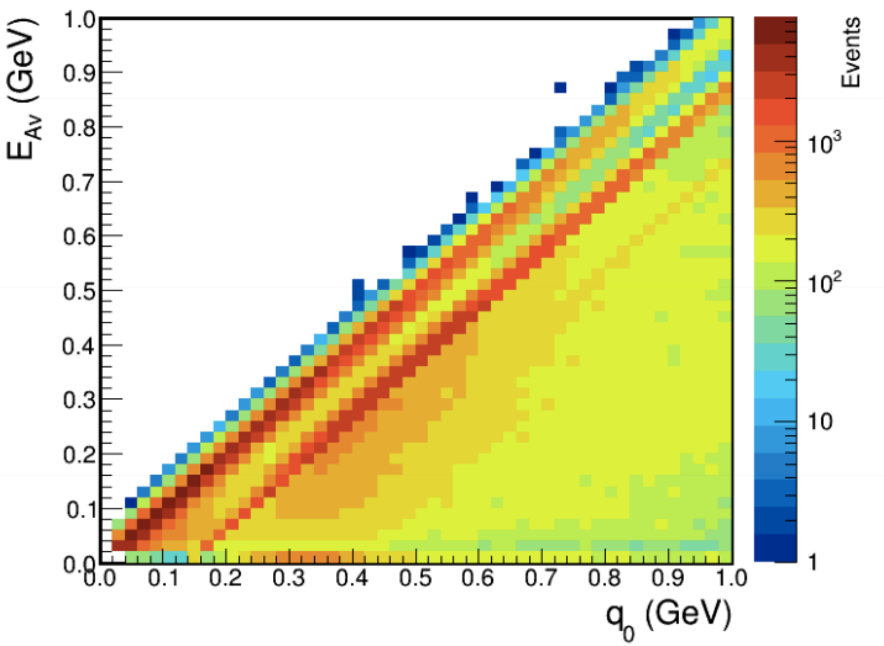
MINERvA Low Recoil Dataset

- MINERvA published a 2D CC-inclusive cross-section measurement at low three-momentum transfer *(Phys. Rev. Lett. 116, 071802 (2016))*
- Wanted to try and use this distribution to place a constraint on NEUT's modelling of nuclear effects (RPA and MEC models).



Energy Available

- Low Recoil Measurement uses the energy deposited in the detector to form a value "Energy Available" (E_{av}) which maps onto q_0.



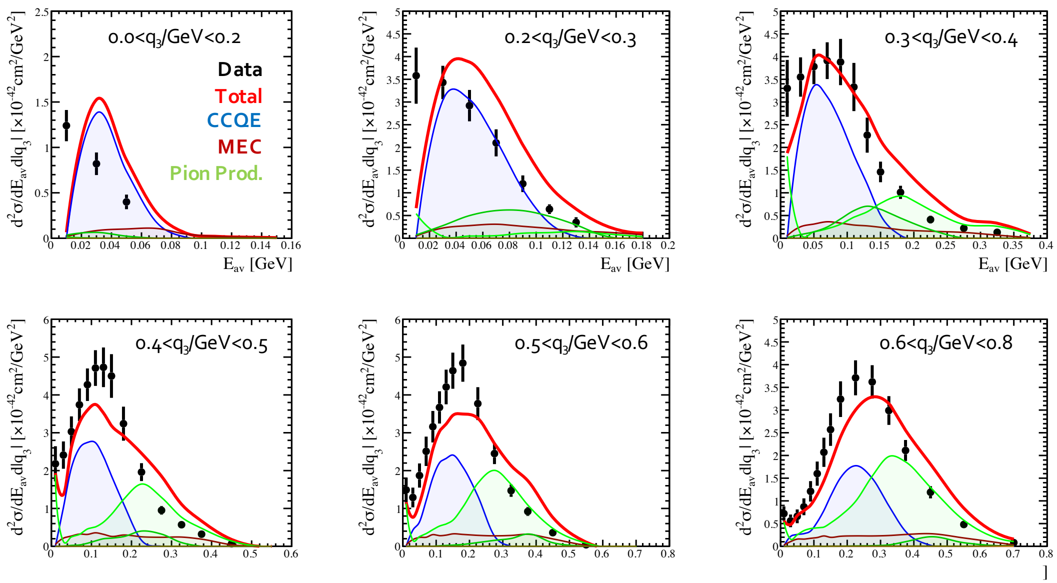
$$E_\nu = E_\mu + q_0$$

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

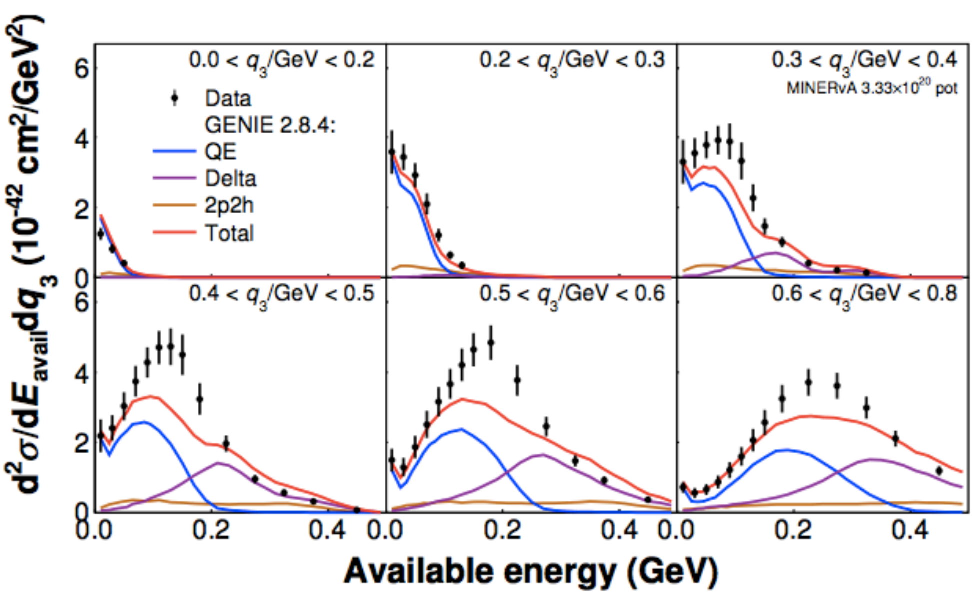
$$q_3 = \sqrt{q_0^2 + Q^2}$$

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

Comparison to MINERvA Data



- Rein-Sehgal Coherent Model in NEUT has quite larger prediction than Berger-Sehgal.
- NEUT distributions seem shifted to higher E_{av} bins.

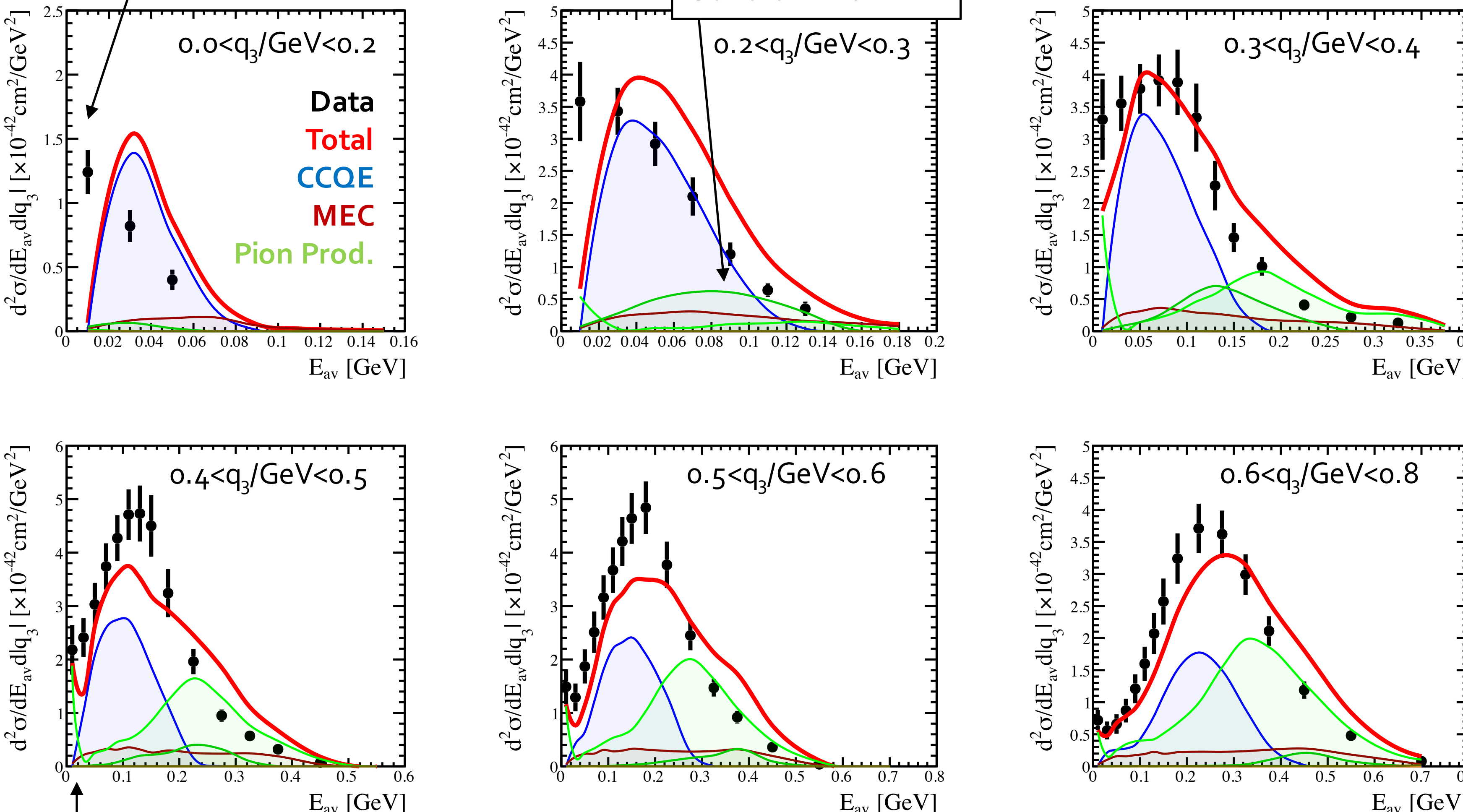


Original MINERvA result with GENIE comparisons

Low Recoil Features

Strong Pauli Blocking causes huge deficit.

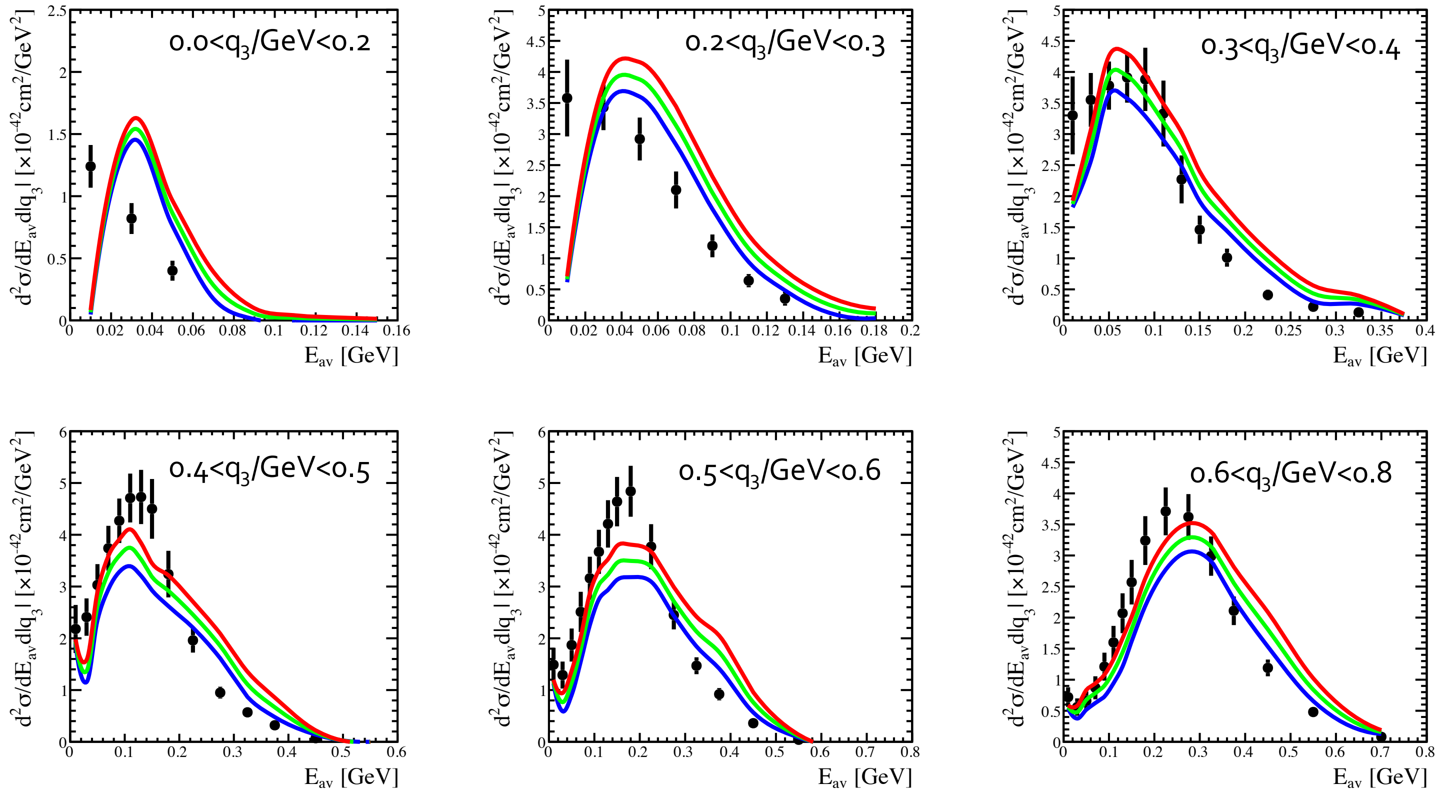
Large Rein-Seghal Coherent Pion



Lowest Eav dominated by events with only final state neutrons.

Variations MEC

- Can we fill in the dip region by varying MEC normalization alone?



- Increasing the MEC to very large values (~200%) would help push the cross-section up and slightly fill in the difference in the dip region, but would significantly modify the high E_{av} tail.

Inflate M_A?

- What do we like to do when faced with such a large data/MC disagreement?

Inflate M_A?

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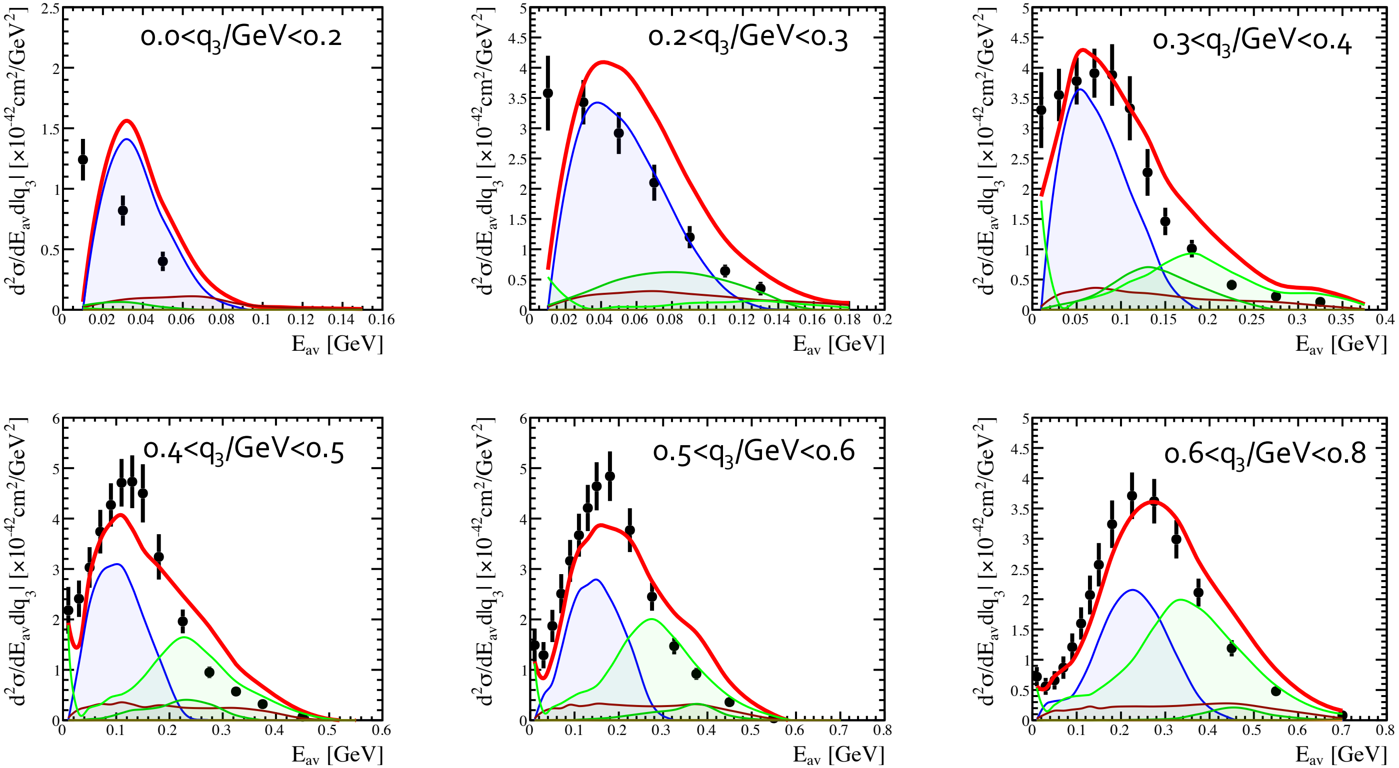
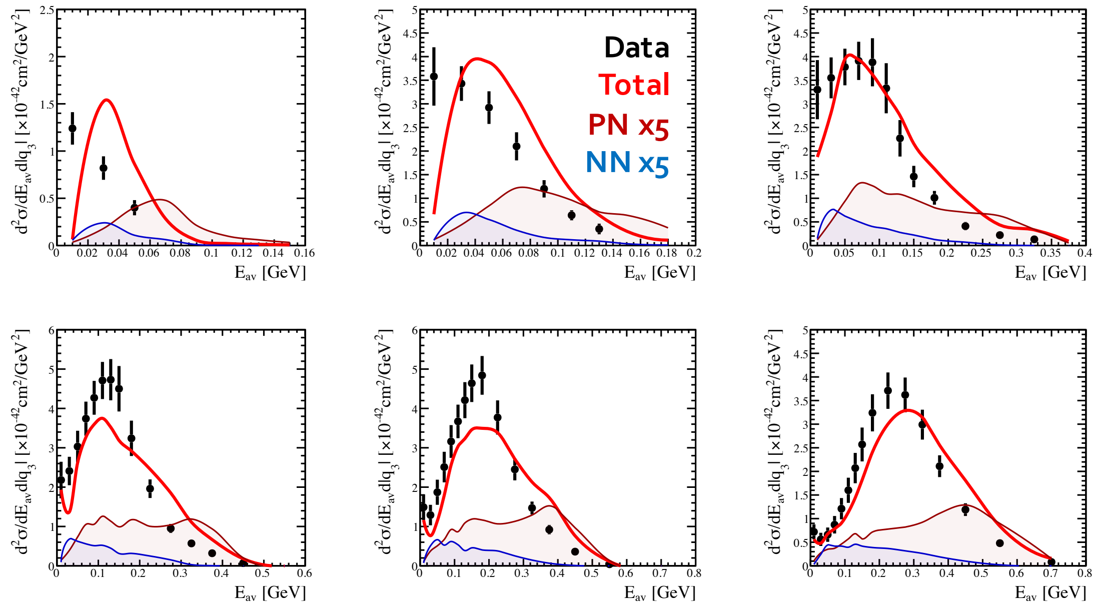
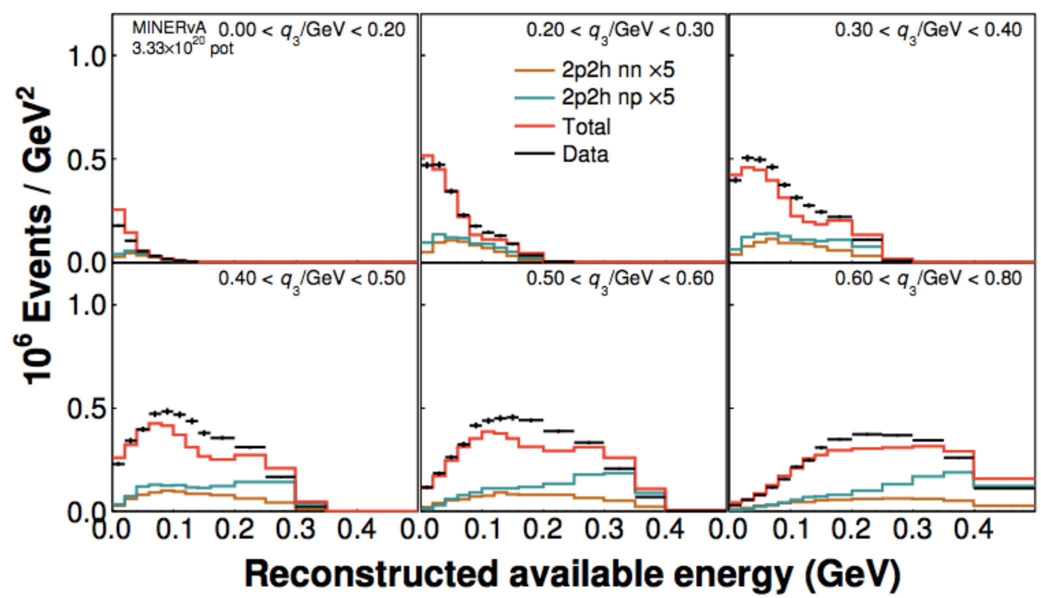


- Nominal NEUT with an axial mass of 1.21 GeV and Nieves RPA+MEC does do slightly better than with M_A = 1.00 GeV.
- Need to be careful with the fact that this is CC-inclusive…..

PN NN Contributions NEUT

- Low Recoil Dataset doesn't include neutrons in the definition of E_{av}.
- Separation in E_{av} of the PN and NN MEC contributions.
- MEC contribution for both PN and NN initial states has been scaled up by a factor of 5 here to make it visible.
- Some differences between NEUT and the GENIE model from original MINERvA study.





Low Recoil Future Steps

- Want to try and use this low recoil dataset to place a better constraint on nuclear effects.

- CC-inclusive measurement means this isn't simple and will only be powerful when combined with other exclusive measurements.

What we have learnt/Next Steps

- Difficult to find a model in NEUT/NuWro that is capable of describing MINERvA and MiniBooNE data well.
- More work is needed to implement new models and study how they perform in JOINT fits to multiple experiments.
  - Need to encourage people to stop showing how well it does by comparing just to MiniBooNE CCQE numu data!

- Lots of different paths we are taking that should eventually converge on an improved understanding of how to model the complete neutrino cross-section:

1. **Get full correlations for data** -> *Work in Progress for MB*
2. **Don't fit CCQE-corrected datasets** -> *Possible for MB but some technical subtleties.*
3. **Fit low recoil data** -> *CC-inclusive fits are difficult to keep well behaved. Working on building up a base model of priors to help, alongside improvements to the fitter framework.*