



# Impact of new neutrino scattering data on GENIE

S. Dytman , S. Boyd

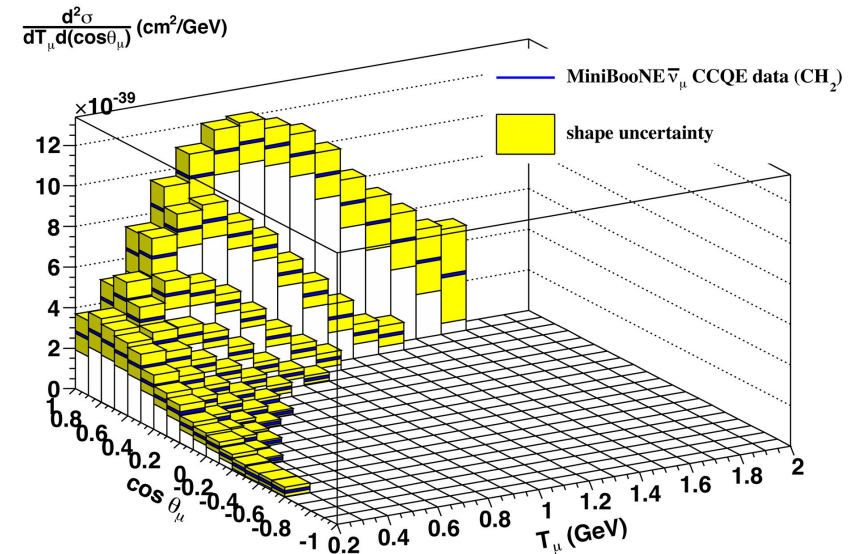
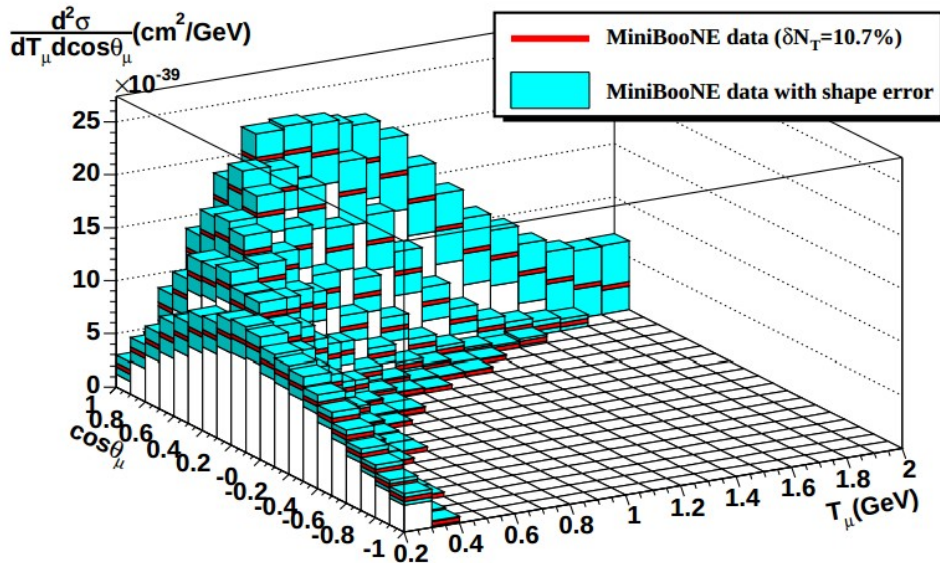
NuFact 14, 28/8/2014

# Introduction



- ▶ All modern target/detectors are 'heavy' nuclei- C, O, Ar
- ▶ Current generators use a combination of old light target data from the 70's, ad hoc and/or easy-to-implement models
- ▶ More precise data now being delivered offers a challenge to model makers and to implementation in generators

# MiniBooNE



MiniBooNE published the first , high statistics, doubly differential cross-section data @ 1-2 GeV

This data has been hugely valuable in trying to understand neutrino interaction models.

# Experimental programme



Argoneut



MINERvA

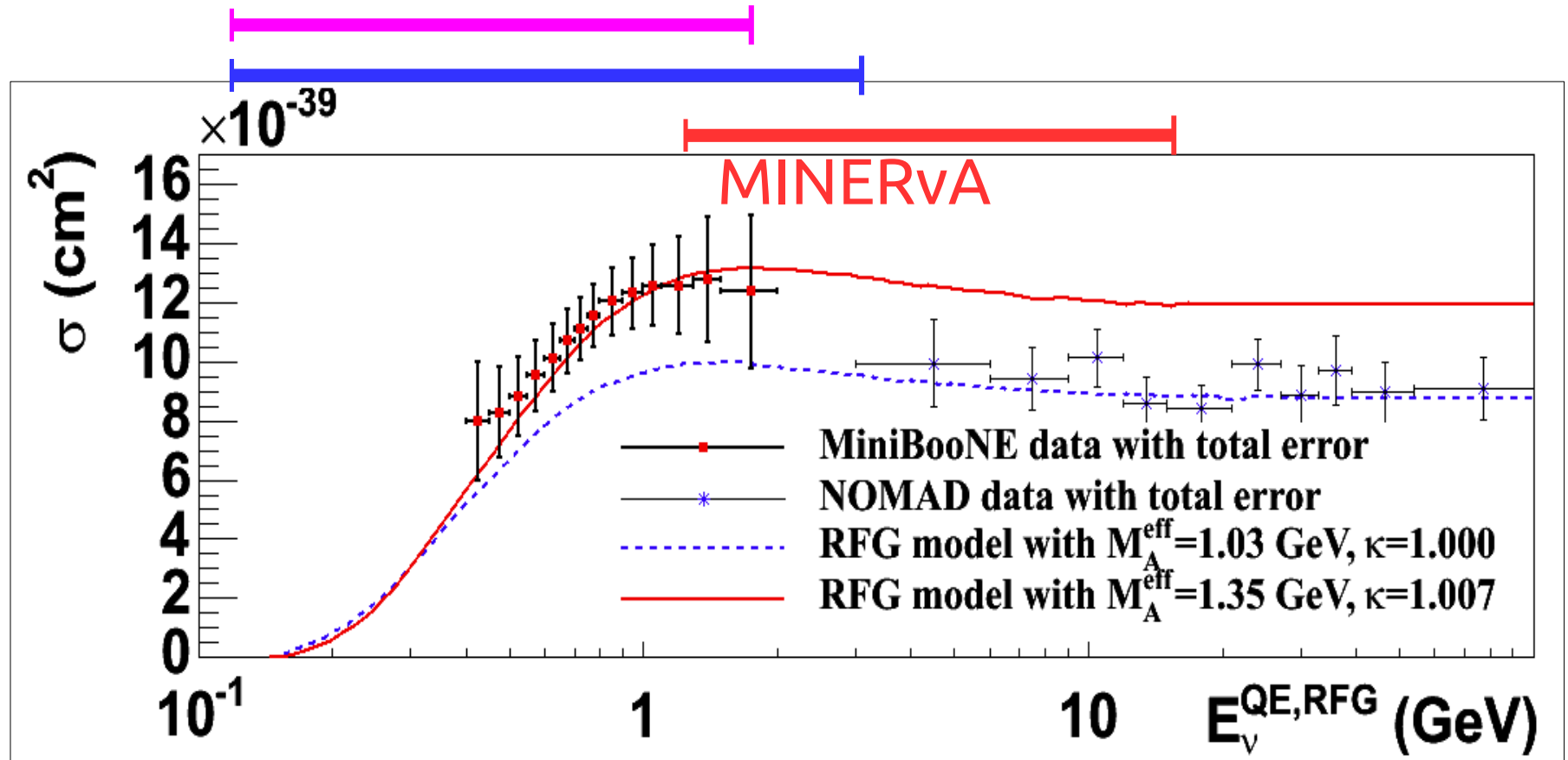


# Quasielastic questions

# Motivation

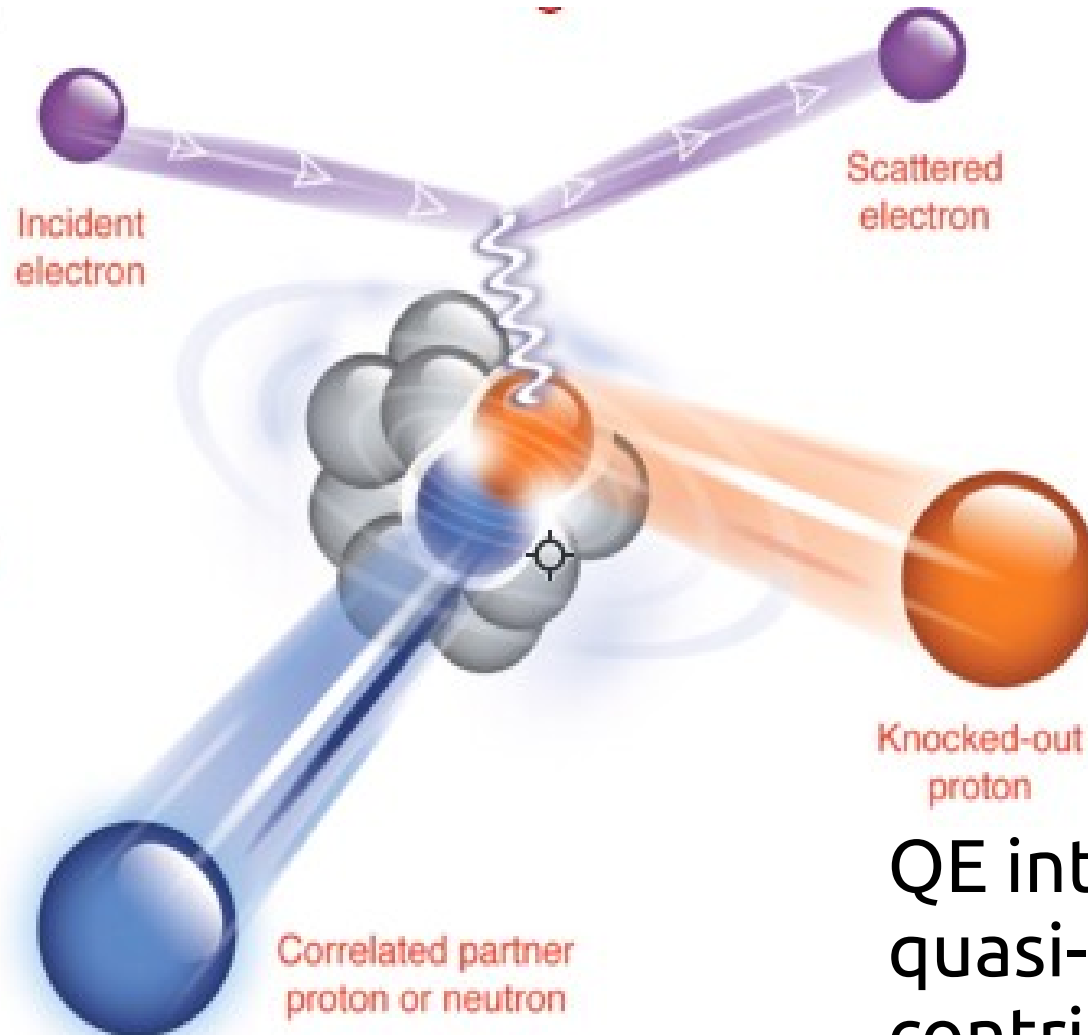


T2K on (off) -axis



- ▶ Definition of “signal”?
- ▶ Inclusion of extra nuclear processes

# Experimental Focus : NN-correlations

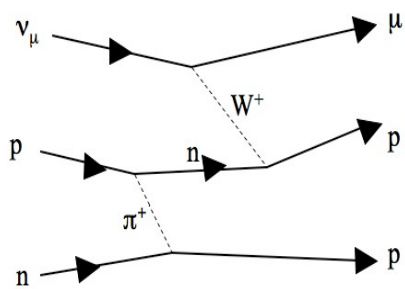


QE interactions off  
quasi-deuterons can  
contribute to the  
observed QE signal

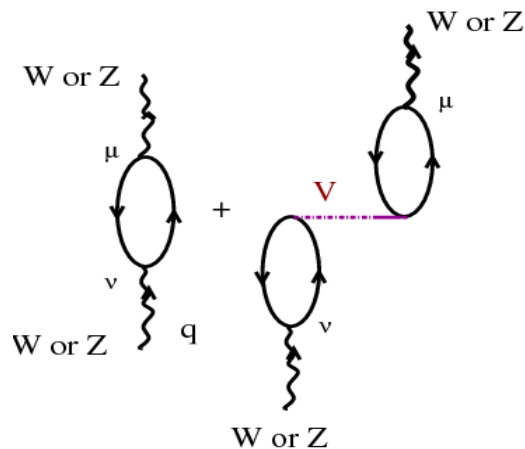
# GENIE model : In development (2.10)



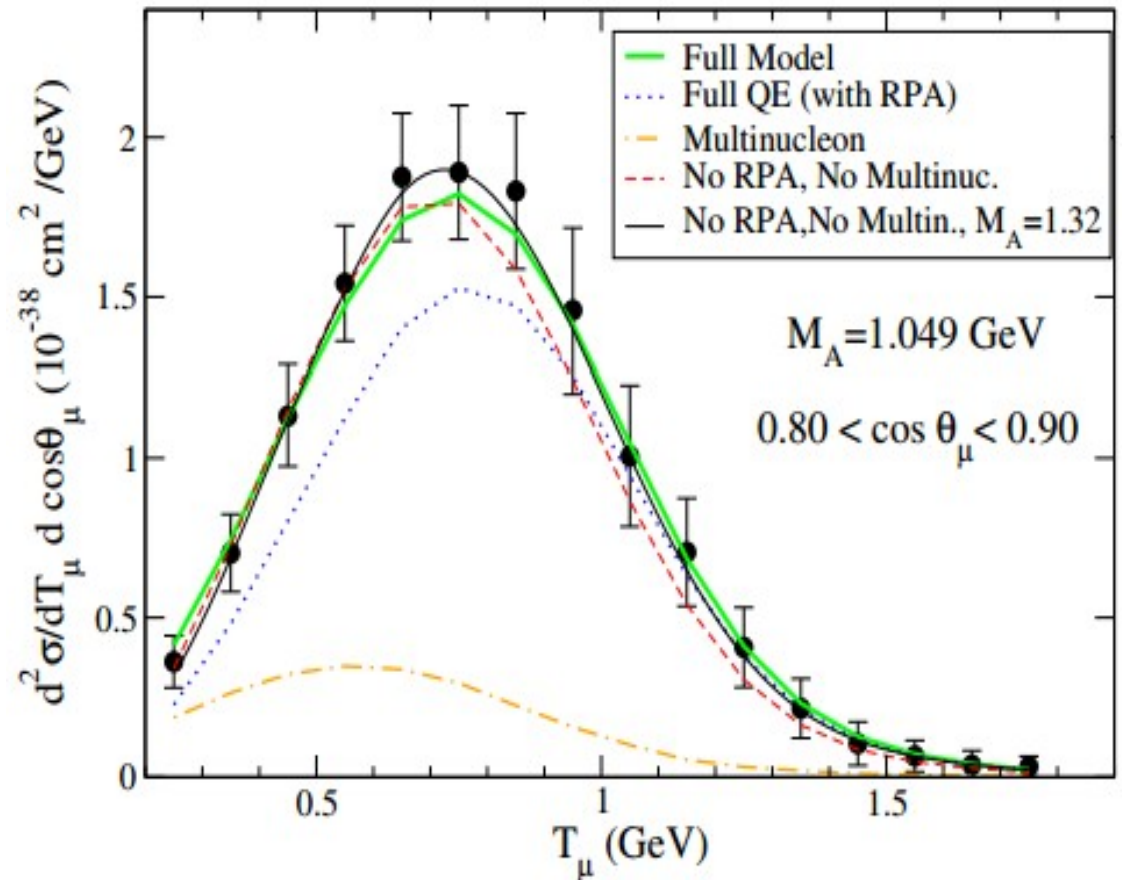
- ▶ Valencia model : Local Fermi gas + RPA + MEC + Delta
- ▶ Nuclear model with full correlations validated against electron and neutrino data



*MEC*



*RPA*



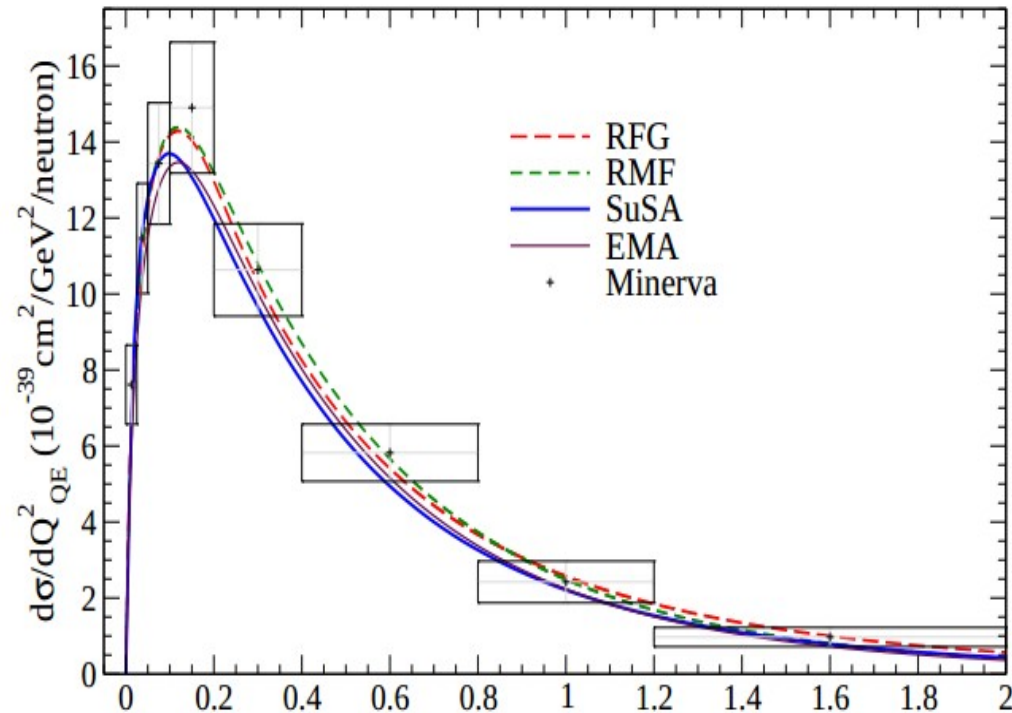
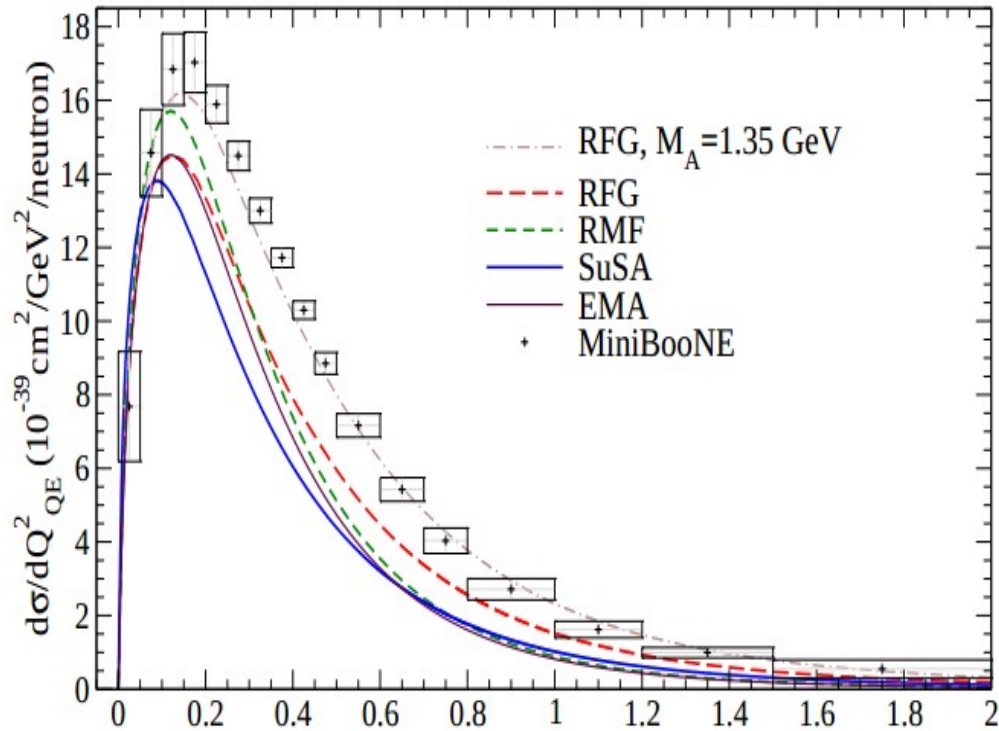


# Other options are available



miniBooNE

MINERvA



Superscaling model + 10-15% MEC : matches wide range of (e,e') data  
Relativistic Mean Field calculation : microscopic model with no MEC

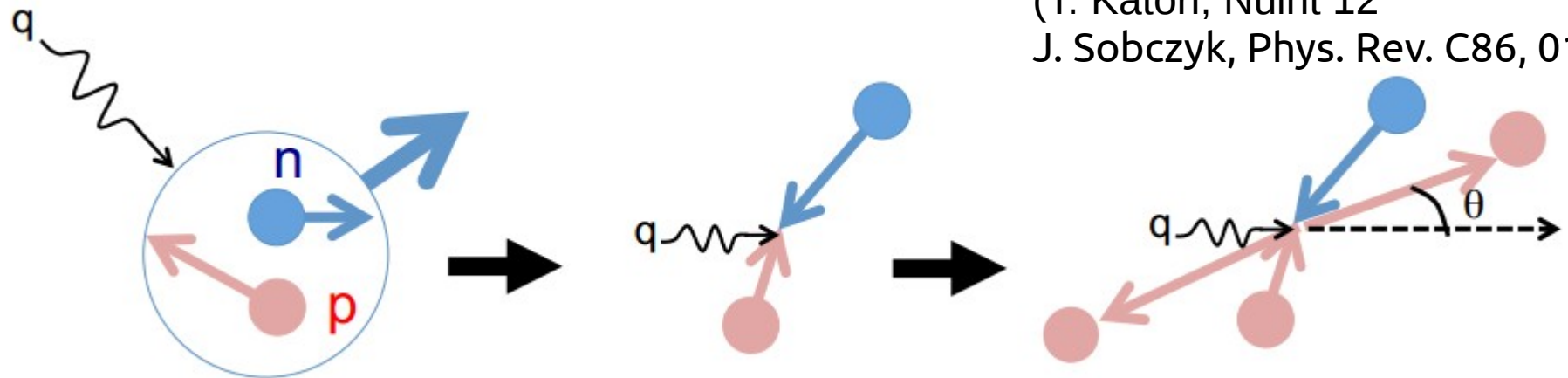
Amaro et al, Phys. Rev. C 71 015501

Megias et al., nucl-th 1402.161

# Hadron kinematics



- ▶ Event generators also need to have a model of the hadronic side of the interaction.
- ▶ For MEC GENIE (and others) implement a nucleon cluster model

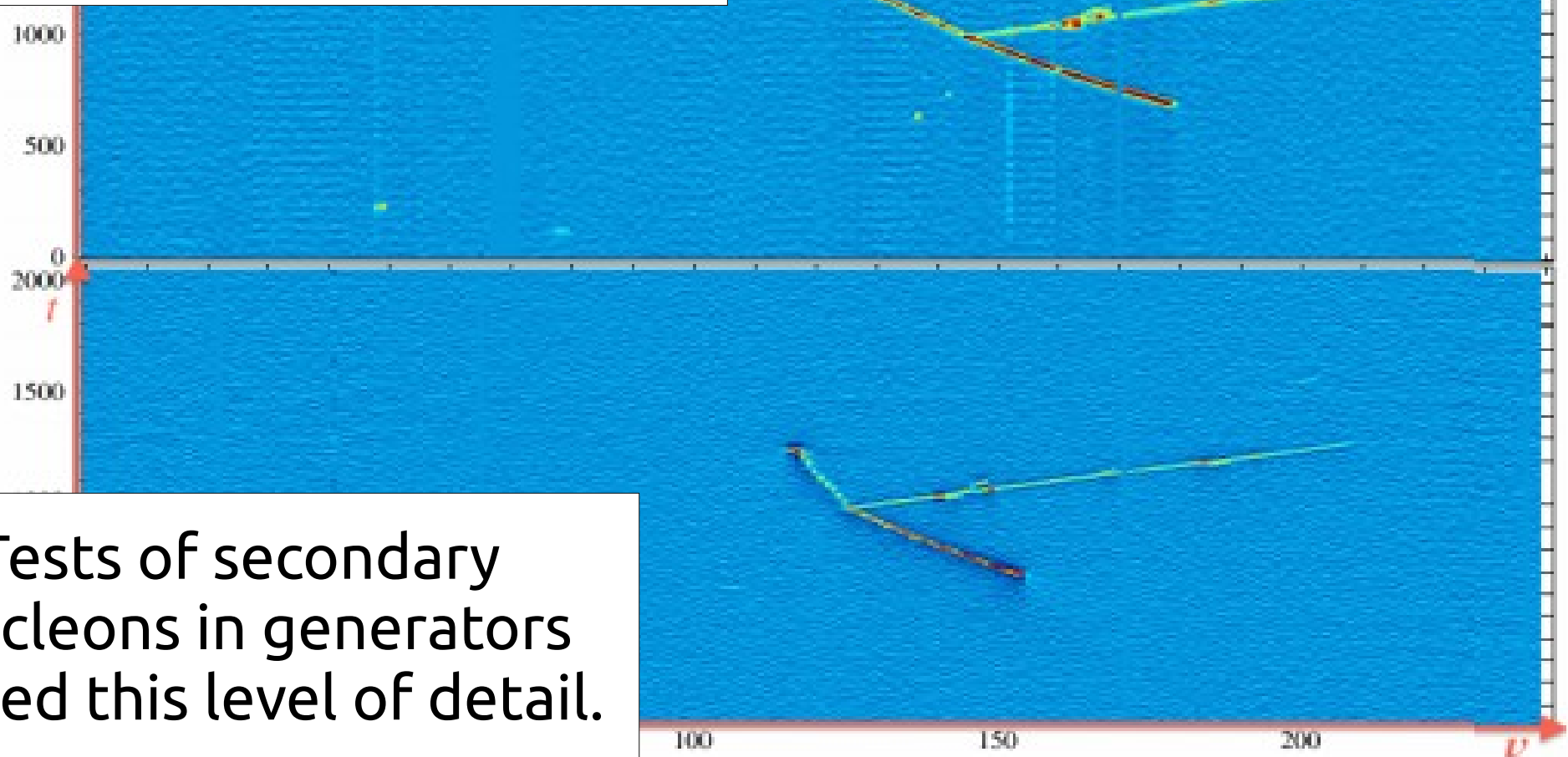


- ▶ Prediction about kinematics of secondary nucleon
- ▶ Is this right? Need some data on the hadronic final state.
- ▶ Will help disentangle 1p1h from 2p2h effects

# Argoneut

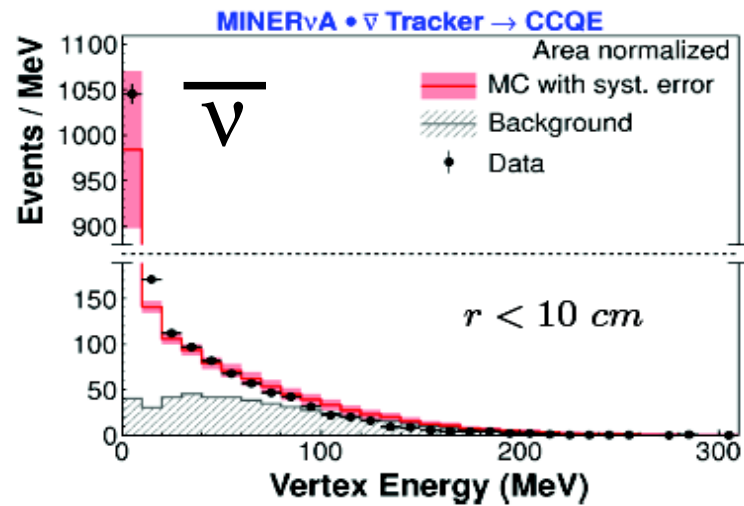
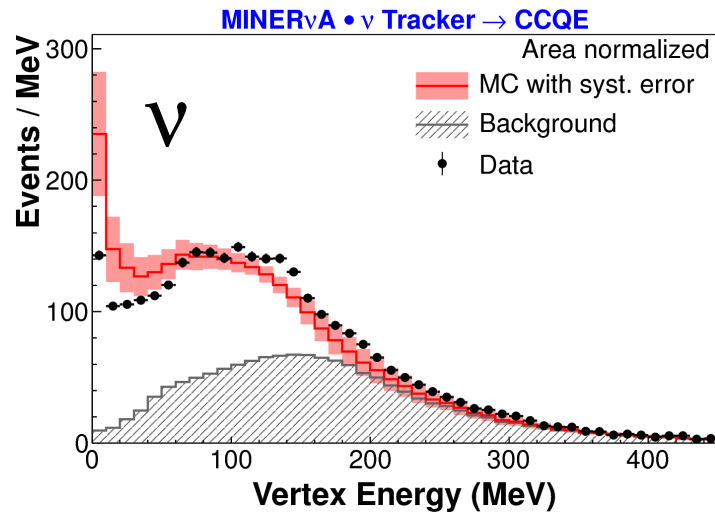
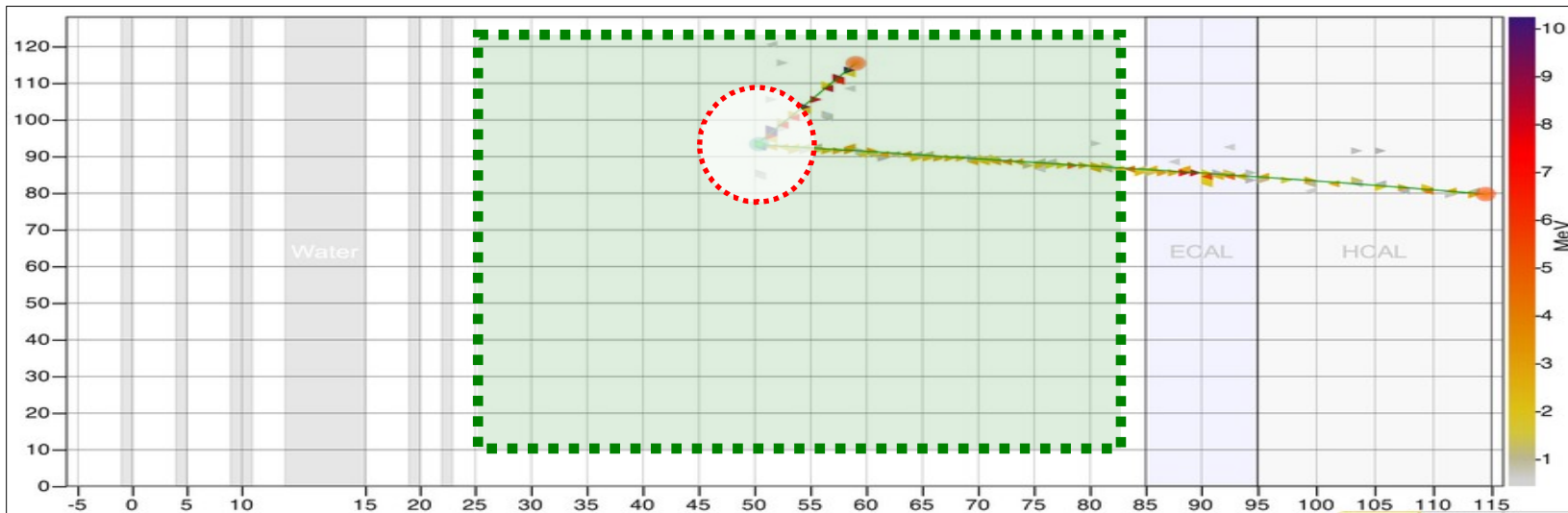


- ▶ one of 4 “hammer” events in  $\mu + 2p$  topology

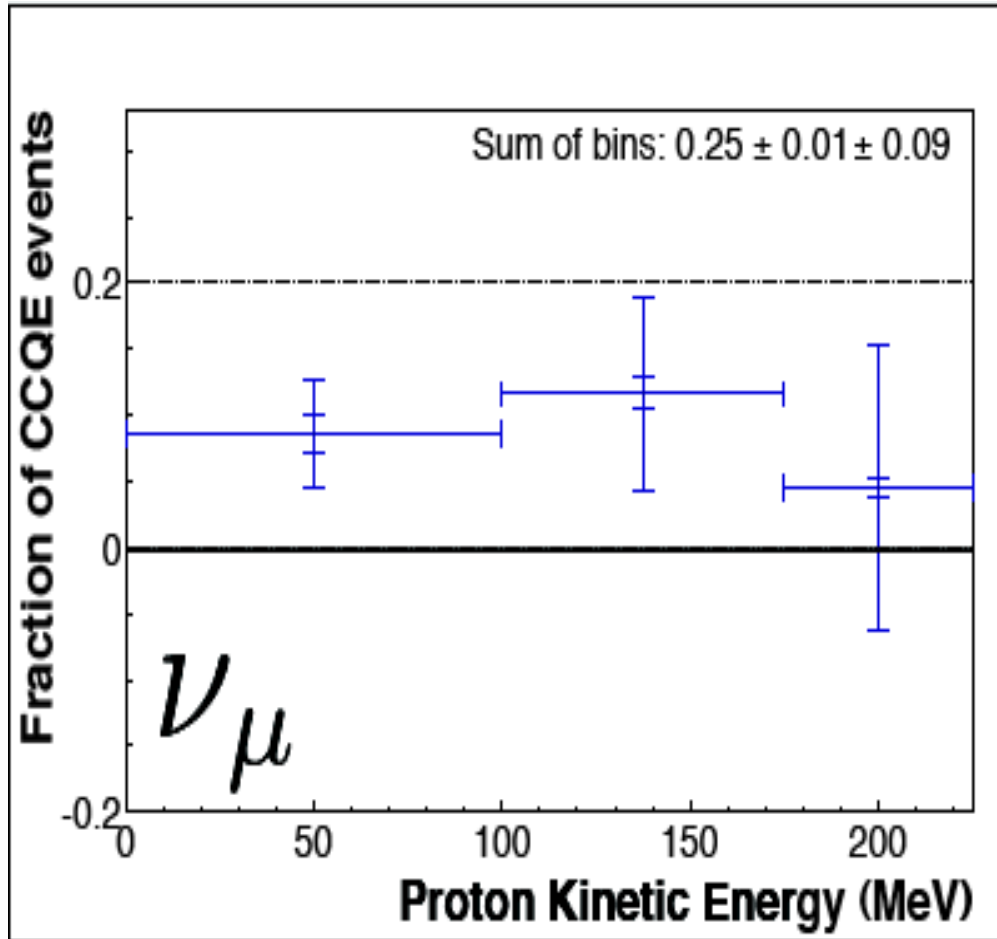


- ▶ Tests of secondary nucleons in generators need this level of detail.

# Minerva



# 2p2h interpretation

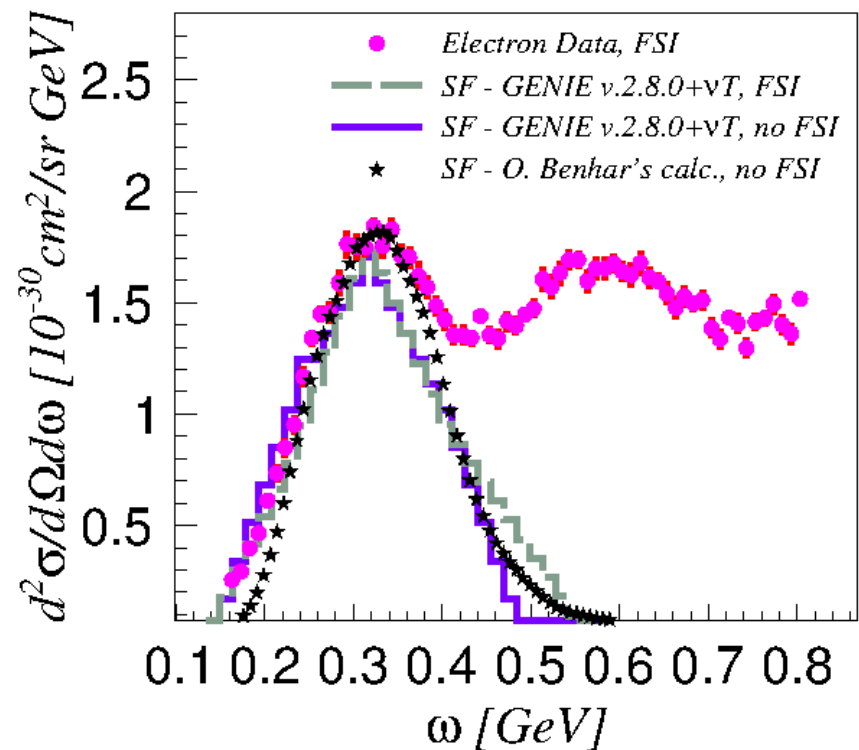


- ▶ Extra vertex activity only seen for  $\nu$
- ▶ Consistent with a proton knockout from  $np$  correlated pair
- ▶ Adding an additional proton with kinetic energy  $< 225$  MeV to  $(25 \pm 9)$  % of QE events improves data/MC agreement

# GENIE model : Spectral Functions



- ▶ O. Benhar's spectral function model
- ▶ O. Benhar, Nucl. Phys. A, 505 (1989) 267–299
- ▶ Provides 1p1h response for C, O, Ca and Fe
- ▶ Includes NN correlations but only one emitted nucleon



C.M.Jen et al, arxiv:1402.6651 (Virginia Tech)  
Work done by Mindy Chen (VT) and Andy Furmanski (Warwick)

# Summary I



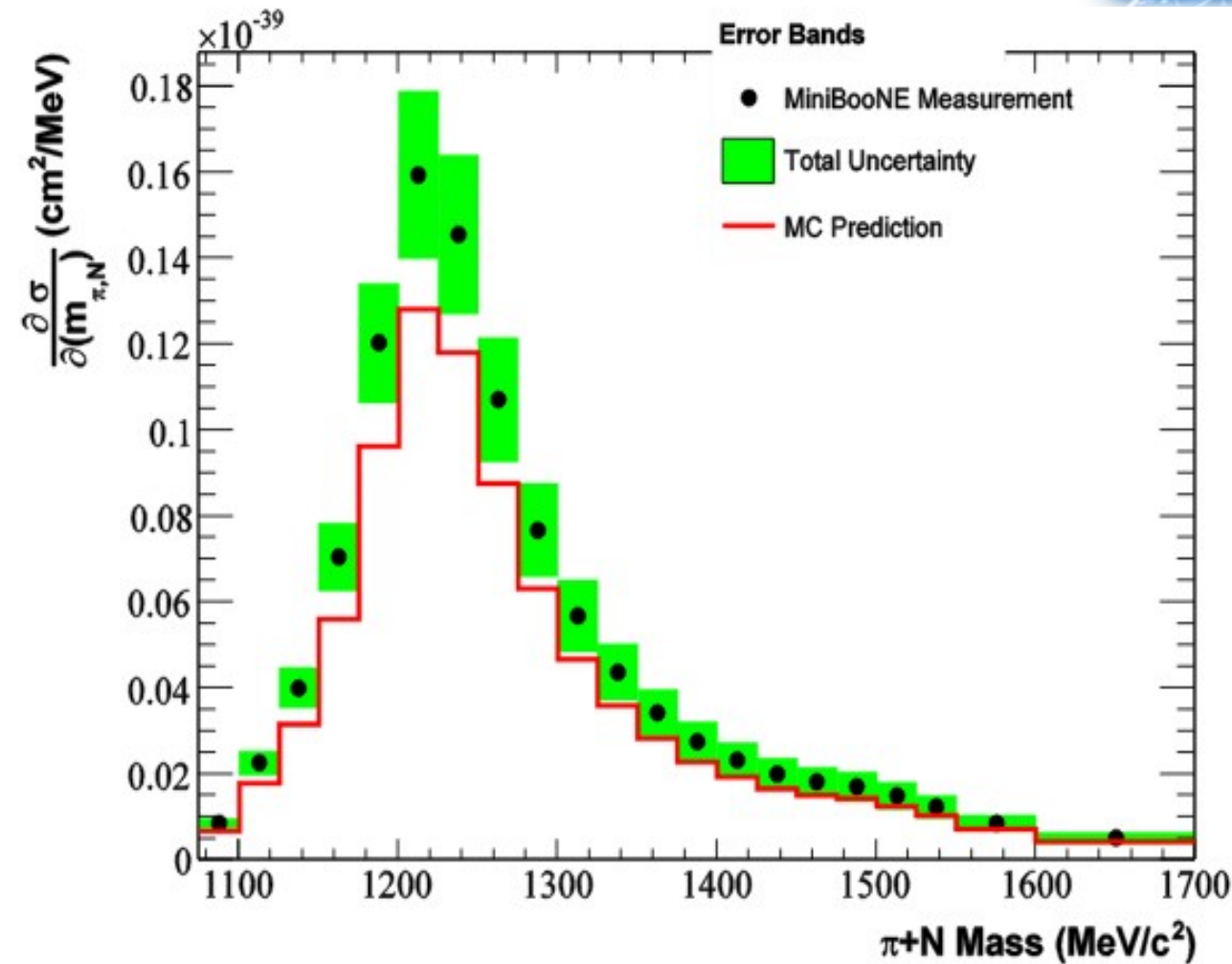
- ▶ Discrepancy between miniBooNE (@ 1 GeV) and NOMAD (@ 10 GeV) has led to an exploration of additional processes taking part in the CCQE-like cross section measurements
- ▶ NN processes are the experimental focus
- ▶ Other processes / models could also contribute
- ▶ Information about the vertex local environment can be obtained with Argoneut and MINERvA (& T2K)
- ▶ pressurised gas / liquid TPC data would be very valuable input to generator tuning



# Pion Puzzles



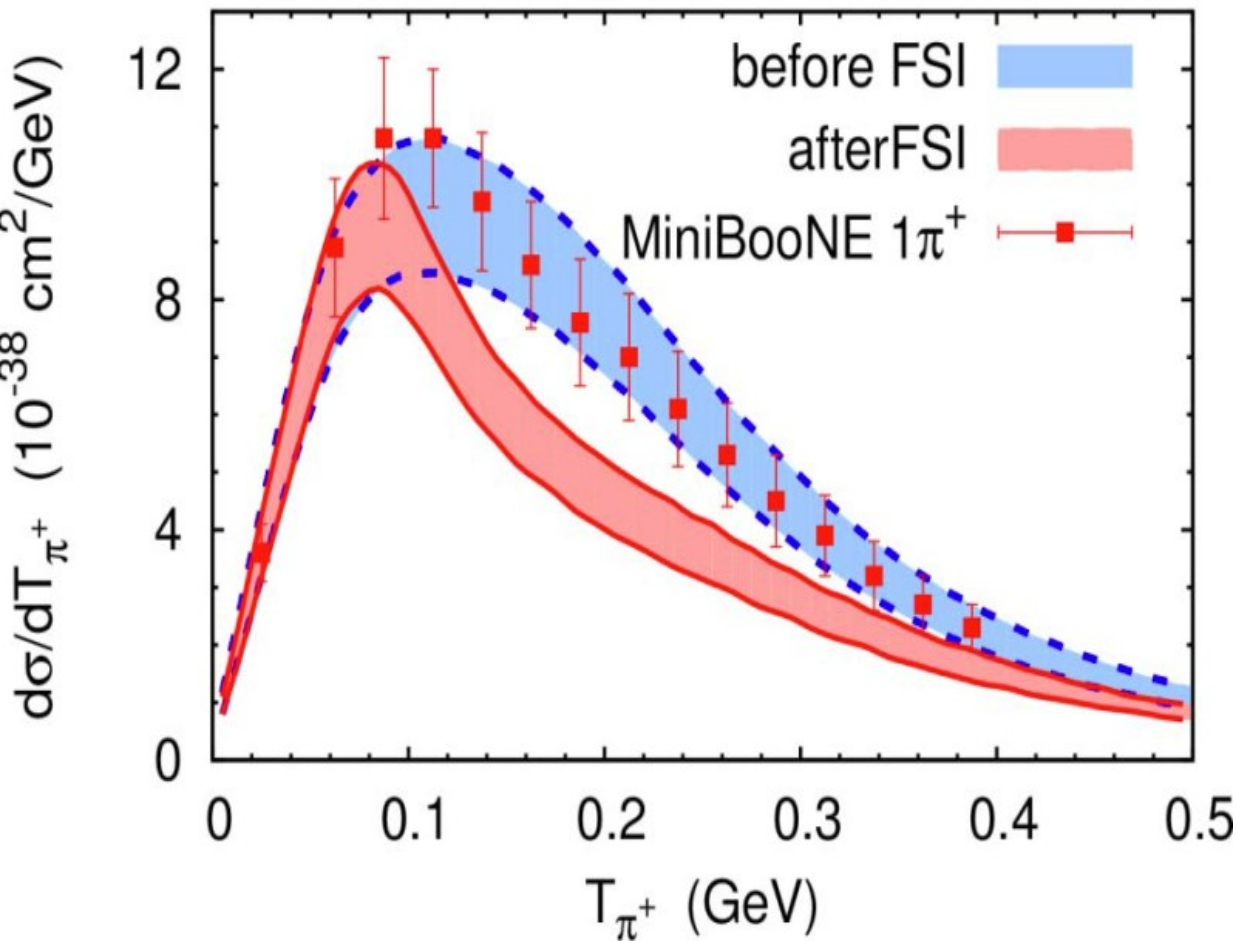
# miniBooNE



- ▶ First detailed differential cross-section for resonant pion production
- ▶ 1  $\pi$ , 1  $\mu$  and no other visible mesons
- ▶ Background prediction from NUANCE generator

A. A. Aguilar-Arevalo et al, Phys Rev D 83, 052007 (2011)

# FSI puzzle

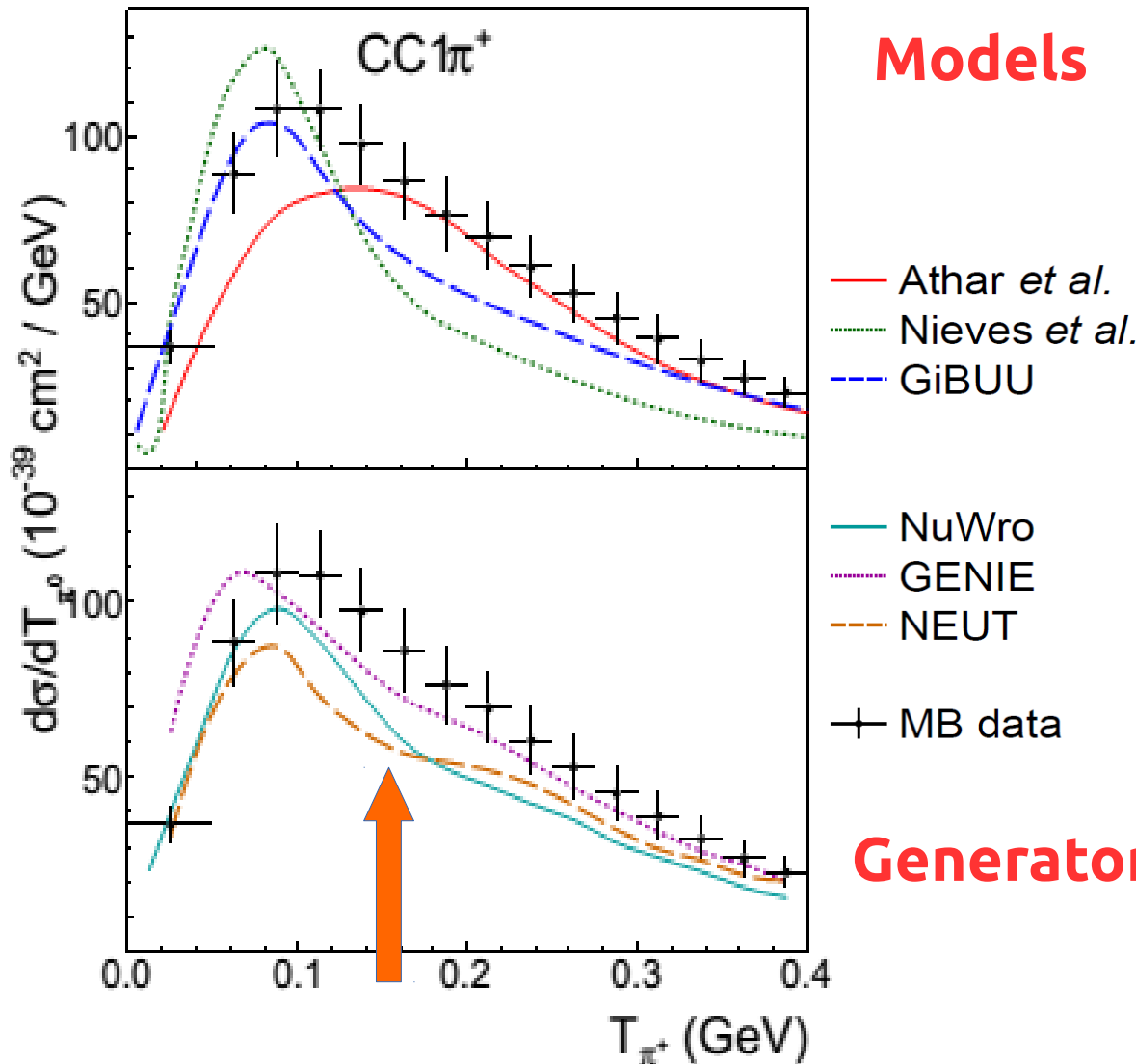


- ▶ Comparison with GIBUU generator with and without FSI
- ▶ Model with FSI disfavoured!
- ▶ Problem with underlying single nucleon interaction model, or FSI models?

GiBUU: O. Lalakulich and U. Mosel, PRC 87, 014602 (2013)  
Nieves: E. Hernandez, J. Nieves, M. Vicente Vacas, Phys Rev D87, 113009 (2013)

# Model Comparisons

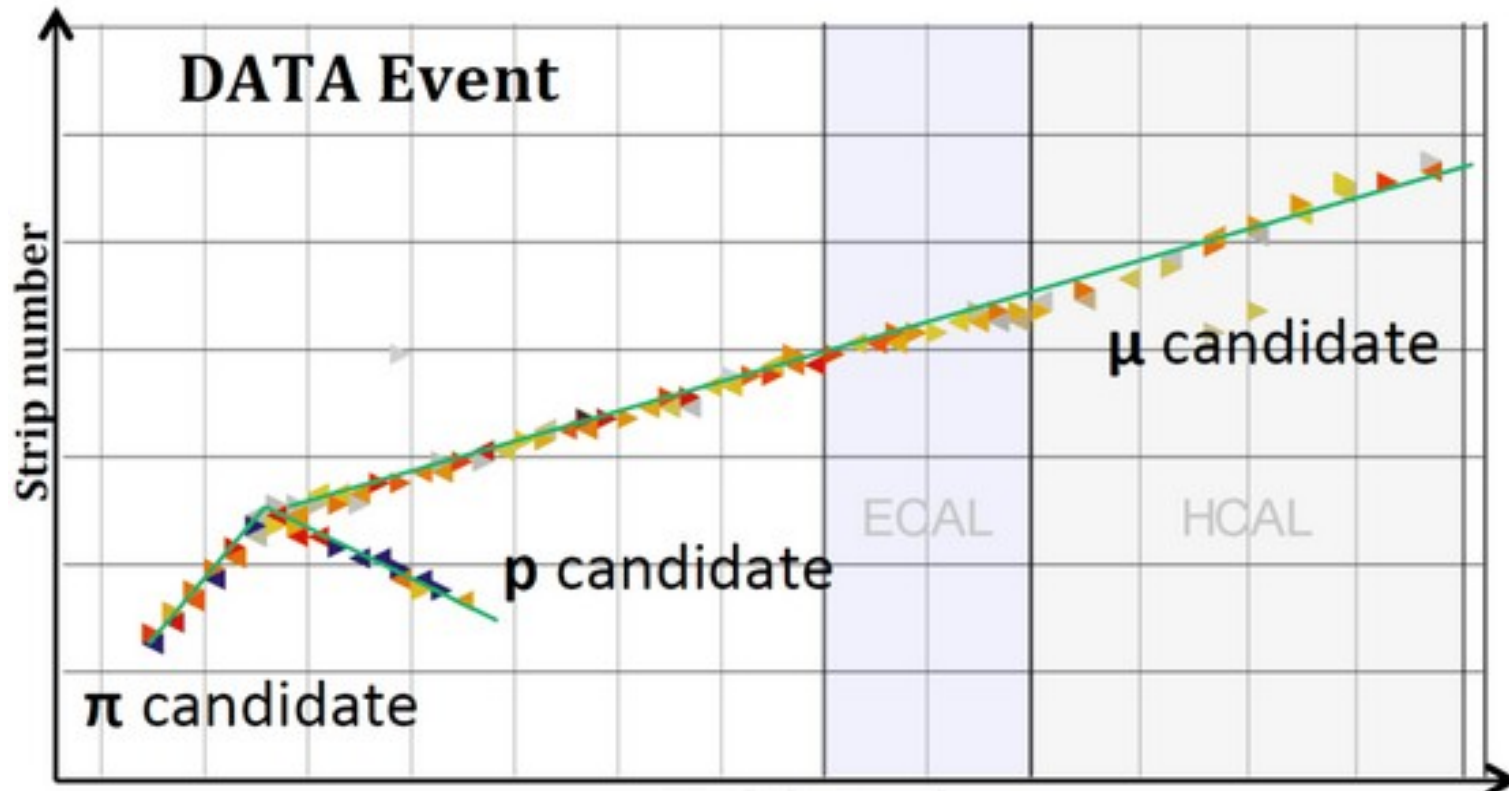
P. Rodrigues [hep-ex] arXiv:1402.4709



$\pi$  absorption in medium

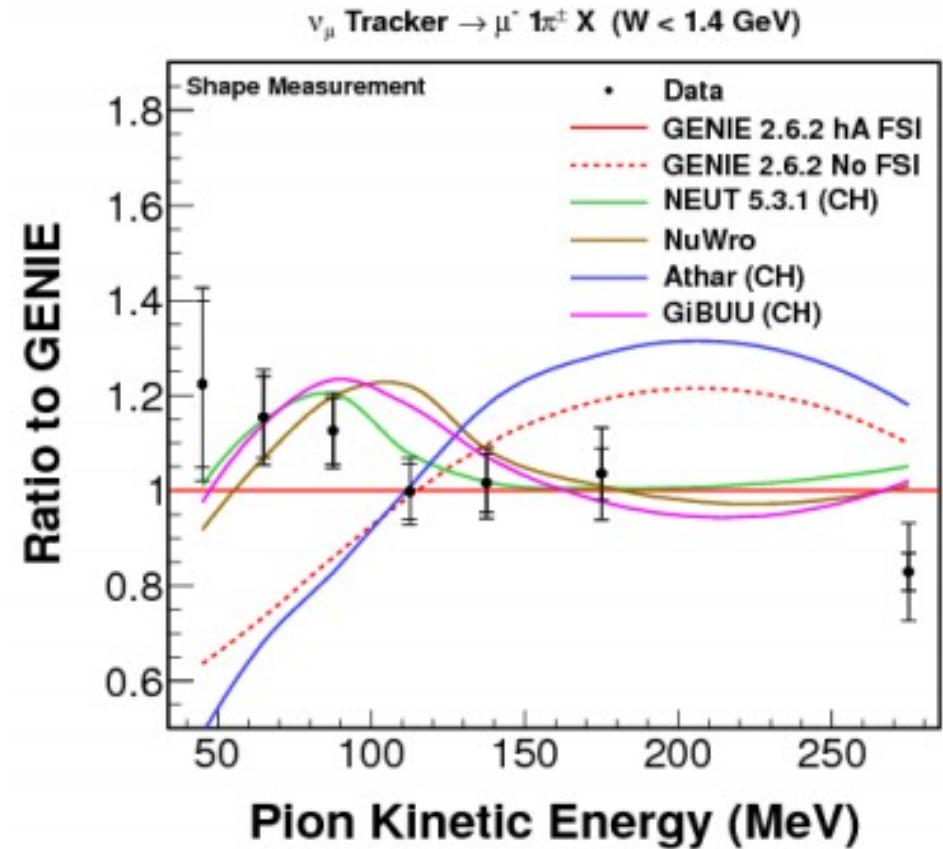
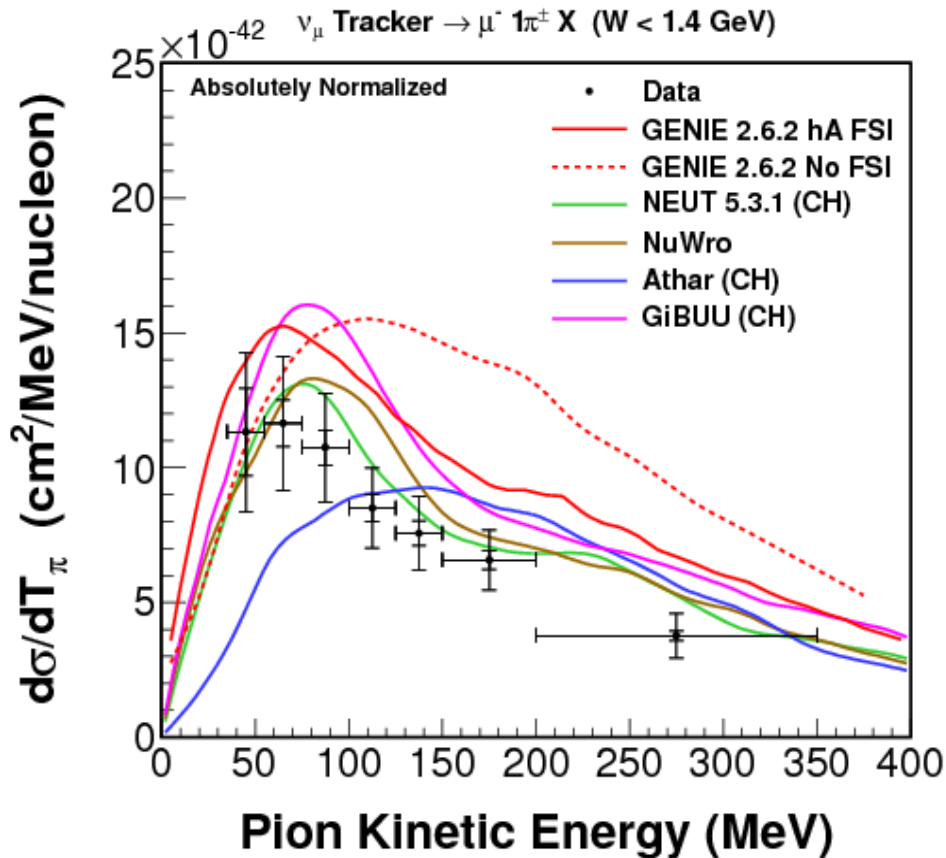
- ▶ Models disagree in
  - ▶ Shape
  - ▶ Normalisation for  $T_{\pi} > 0.1$  GeV
- ▶ Slightly better agreement in shape for generators
- ▶ Most models/gens exhibit a dip around 0.2 GeV indicative of  $\pi$  absorption
- ▶ MB data does not seem to exhibit this

# MINER $\nu$ A



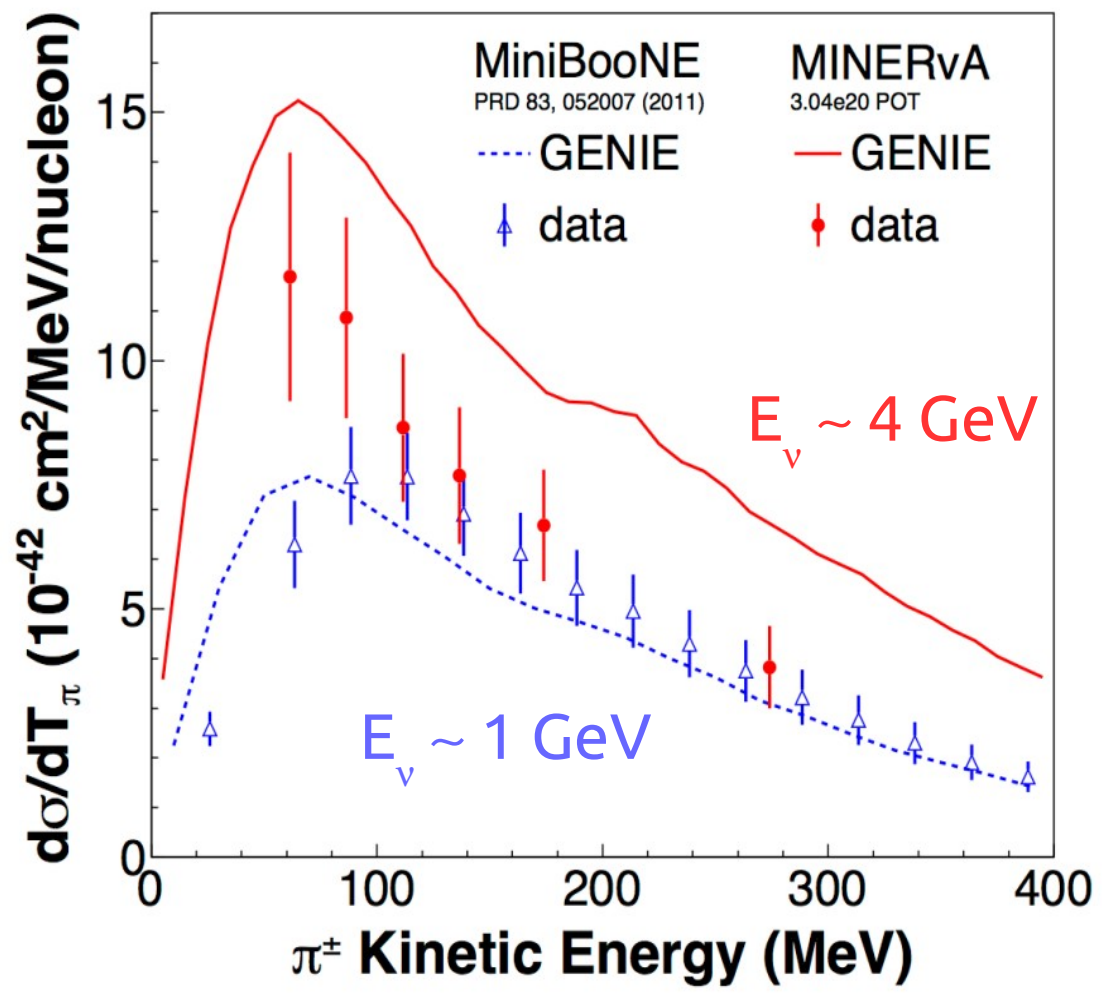
- ▶ Average neutrino energy of 4 GeV, but  $Q^2$  range comparable to miniBooNE ( $< 2 \text{ (GeV/c)}^2$ )
- ▶ 1  $\mu$ , 1  $\pi$ , no other charged pions, but  $\pi^0$  are allowed
- ▶ Background estimate from data-driven template fit

# MINERvA



- ▶ Data disfavors no-FSI GENIE model
- ▶ Agrees in shape with most models/generators (except no-FSI)
- ▶ NEUT & NuWro agree best in normalisation

# MINERvA vs miniBooNE

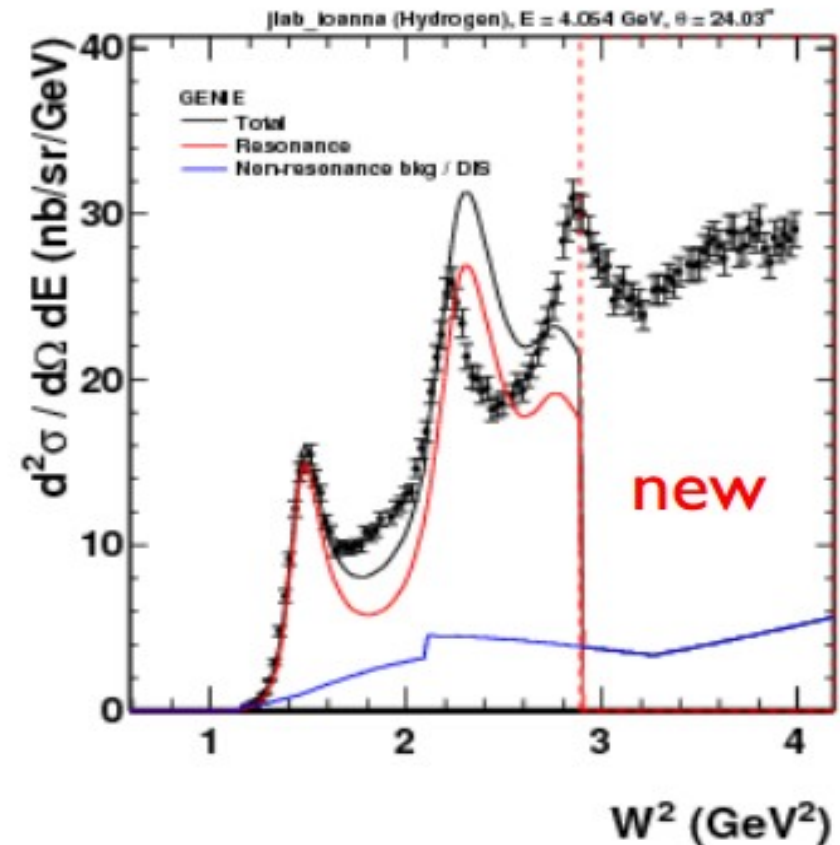
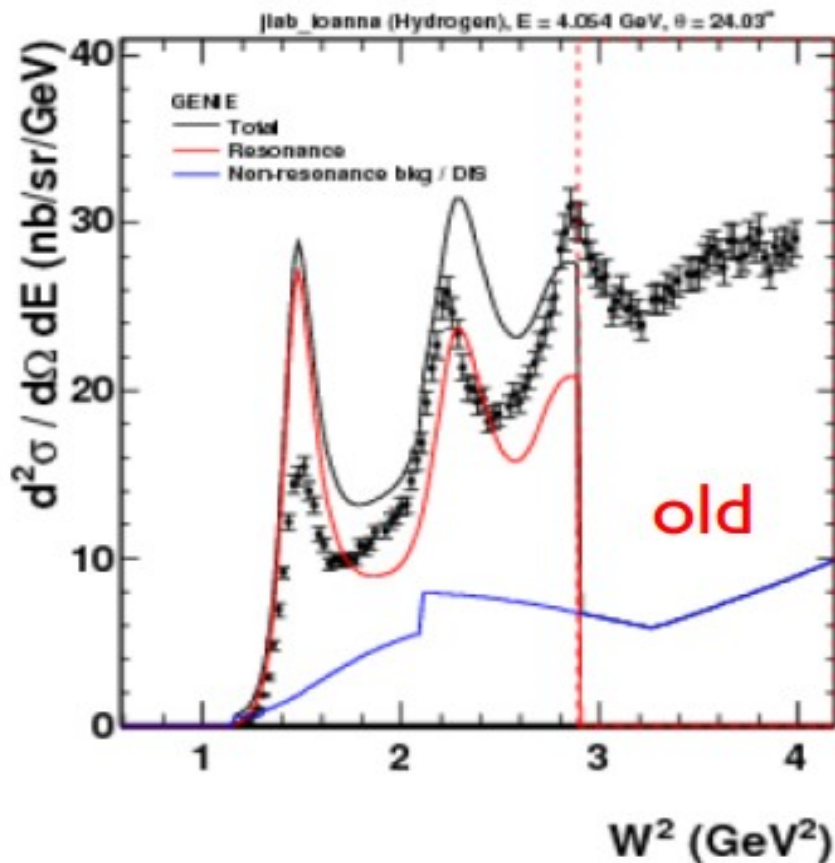


- ▶ GENIE 2.6.2 predicts
- ▶ the shape but not normalisation of MINERvA data
- ▶ the rate but not the shape of the MB data
- ▶ No significant dip in either dataset
- ▶ No calculation describes all the data well. Is it possible to get agreement?

# GENIE $\geq 2.8$ Improvements



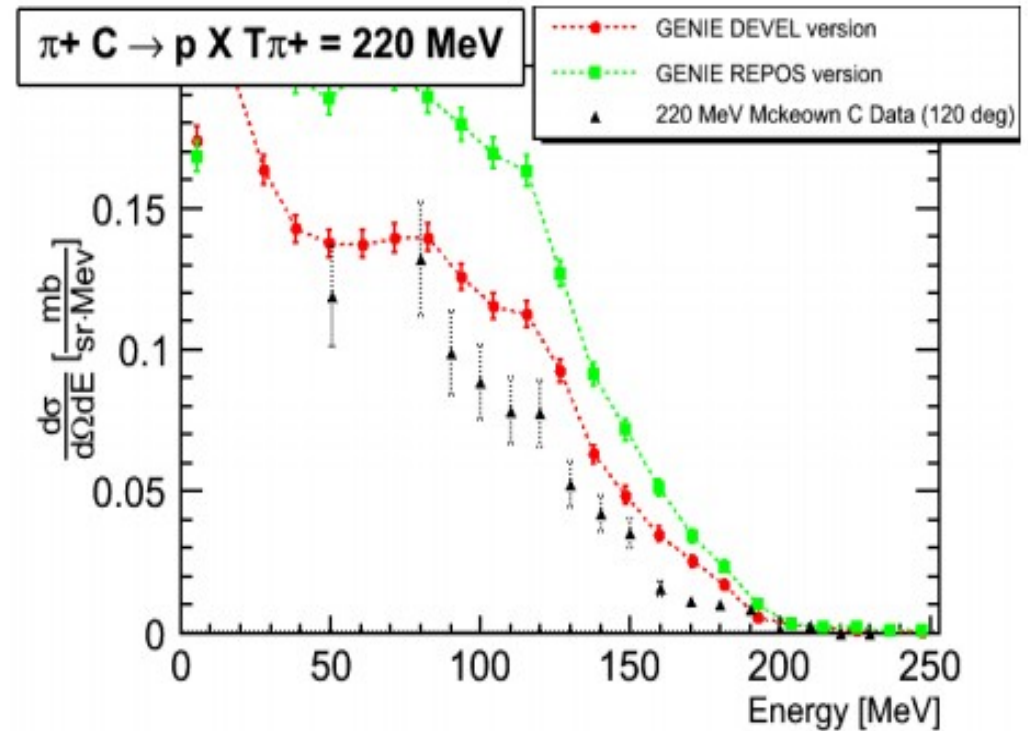
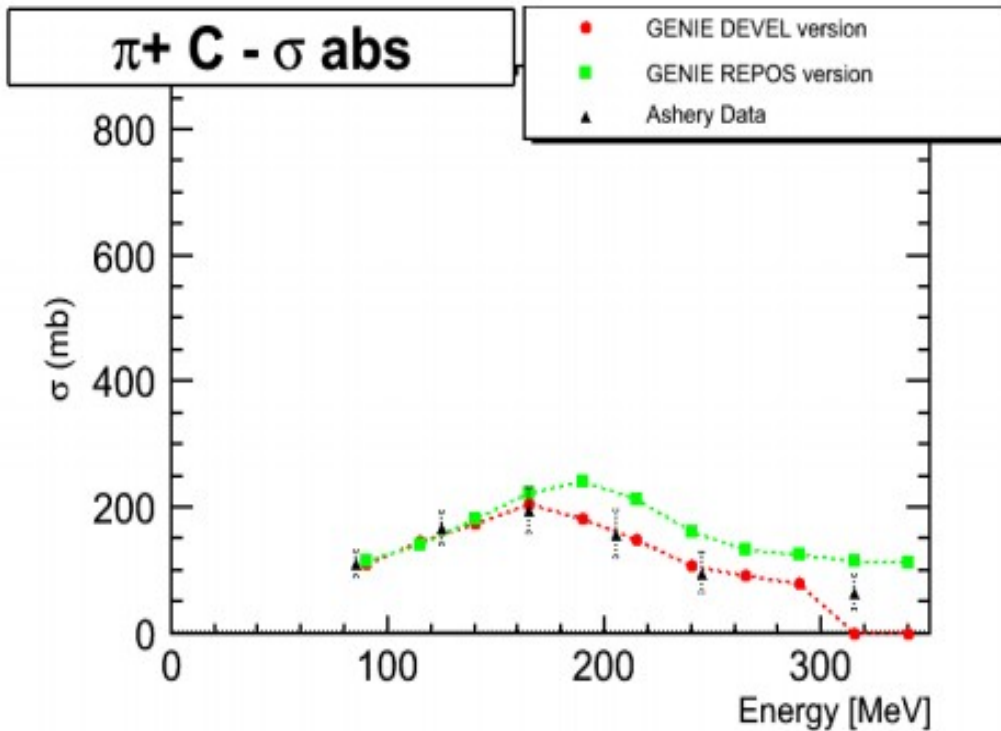
- ▶ Use MAID model to give better constrained resonance model.
- ▶ Correctly account for lepton mass thresholds



# FSI



- ▶ Pion FSI in GENIE v 2.8 tuned for Fe (MINOS) not CH
- ▶ GENIE 2.10 will use FSI tuned for appropriate A





# Summary II



- ▶ Situation is complicated (!).
- ▶ Better modelling of FSI effects underway.
- ▶ More data to cross-check current datasets is needed. T2K is in the same energy range as miniBooNE.
- ▶ Models use light target ANL and BNL data. Is this data reliable?
- ▶ Need more light target data (!!!).



# CC Coherent Conundrum

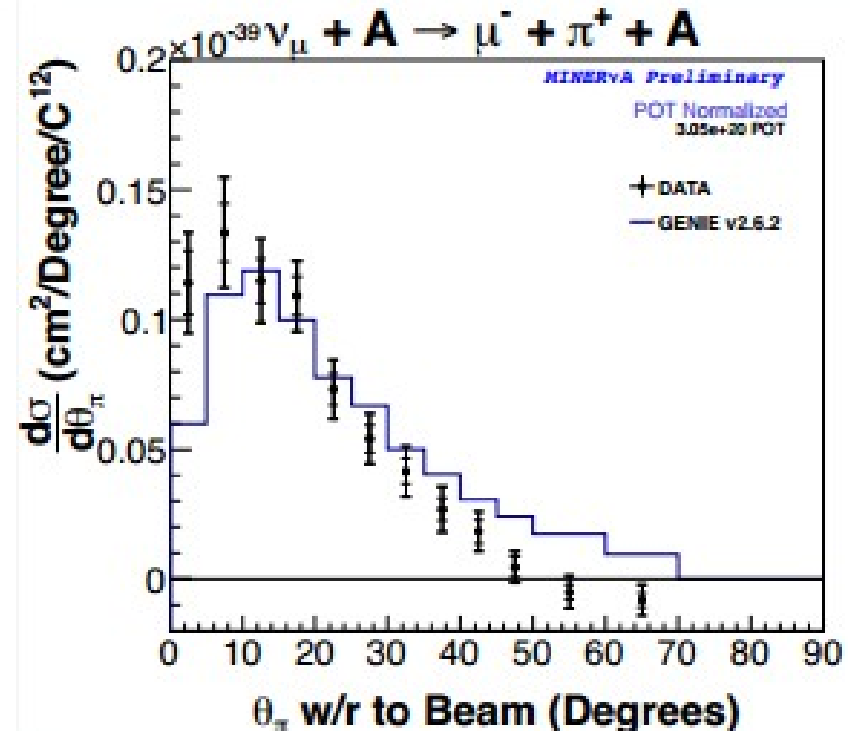
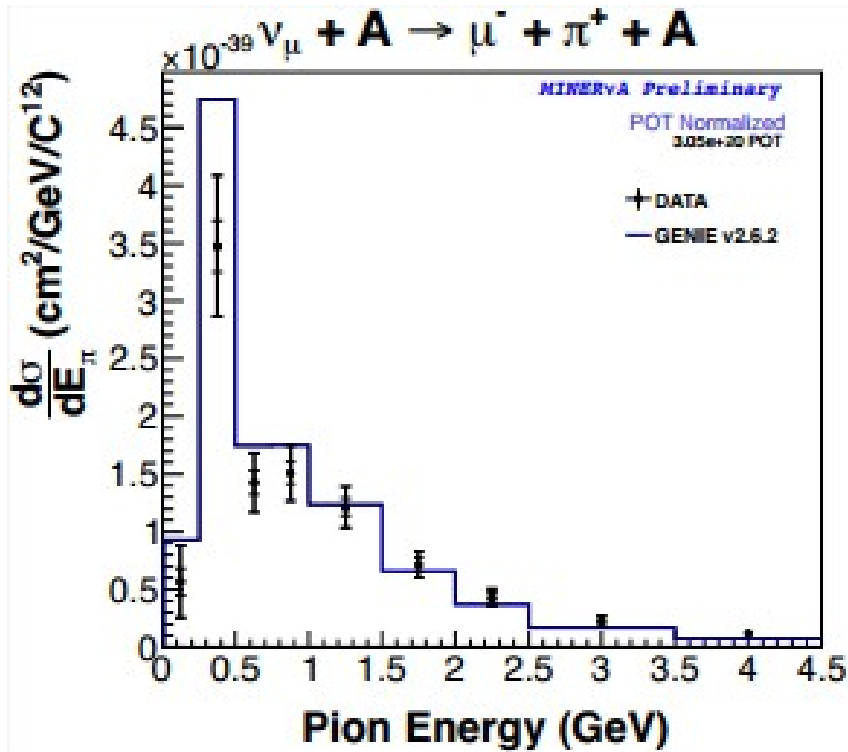
# CC Coherent Production



Experiment	$\langle E_\nu \rangle$ (GeV)	$\langle \sigma \rangle (\nu) \times 10^{-39}$ cm <sup>2</sup> /nucleus	$\langle \sigma \rangle (\bar{\nu}) \times 10^{-39}$ cm <sup>2</sup> /nucleus
T2K Off-axis (C)	0.6	In progress	
T2K On-axis (C)	1.5	$1.0 \pm 0.74$	
MINERvA (C)	5.0	Differential	Differential
Argoneut (Ar)	9.6	$27.0 \pm 13.0$	$6.8 \pm 2.7$

- ▶ Measurements on this channel are starting to appear
- ▶ Energy range the experiments cover also covers PCAC/microscopic model validity ranges

# MINERvA

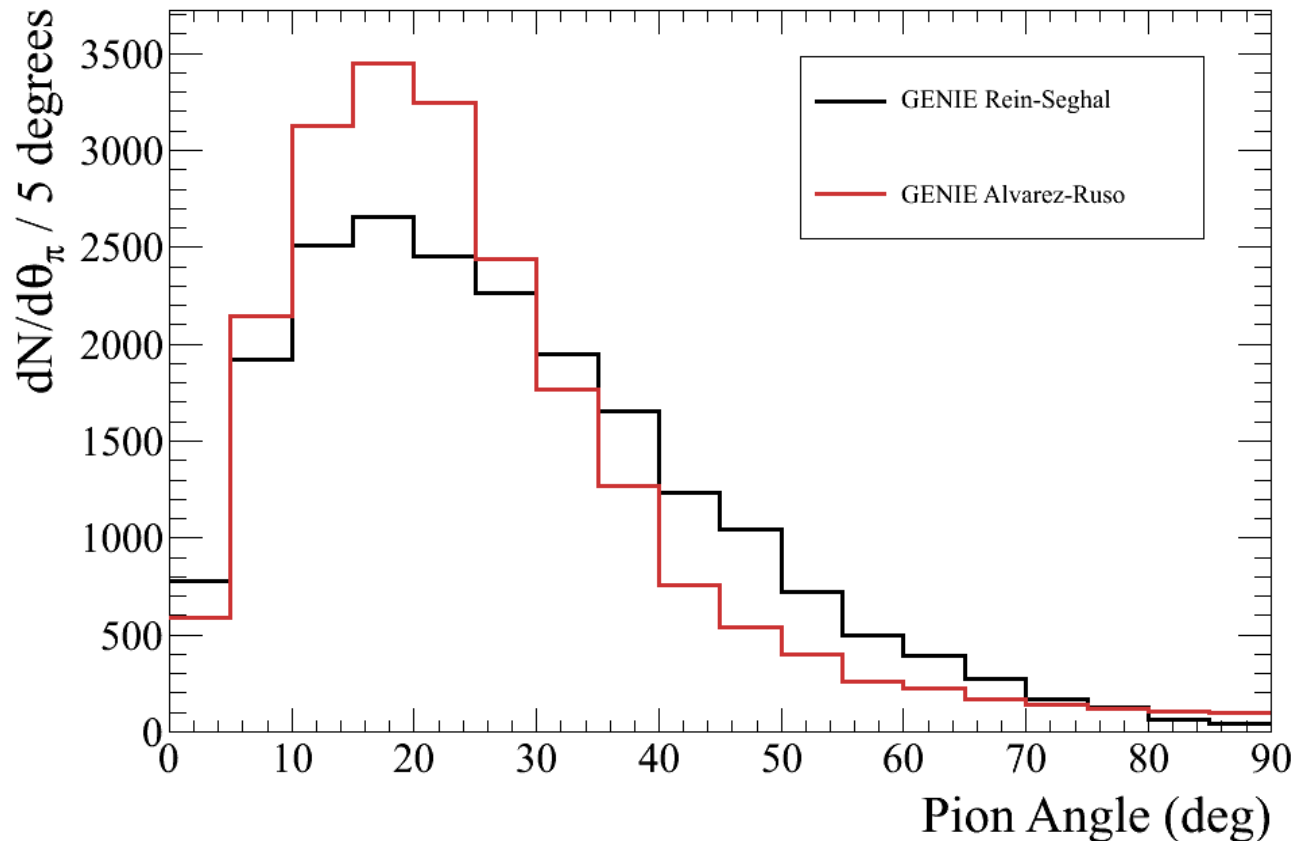


- ▶ Pion kinematic distributions from MINERvA  $\nu_{\mu}$  CC Coh
- ▶ Data indicates harder, more forward pion spectra than predicted in GENIE 2.6.2
- ▶ See other MINERvA talks by J. Wolcott, J. Morfin and J. Nelson

# GENIE $\geq 2.8$ Improvements



- ▶ Implementation of the Berger-Seghal model
- ▶ Implementation of Alvarez-Ruso microscopic model



Comparison of  
GENIE Rein-Seghal  
with Alvarez-Ruso  
using T2K flux

# Summary III



- ▶ CC coherent measurements are now being made at low energy.
- ▶ MINERvA, in particular, has the power to make statements about models based on kinematics.
- ▶ A number of sophisticated microscopic models exist (Alvarez-Ruso, Sato, Nakamura, Hernandez)
- ▶ Neutrino measurements are still using Rein-Seghal ; mostly through lack of any other implemented option
- ▶ More work on implementing coherent models is needed.

# GENIE Development



- ▶ To keep up with all this new data, and prepare for upcoming experiments GENIE organisation is evolving
  - ▶ Core development team
  - ▶ Working group structure
  - ▶ Significant resourcing in Europe and US
- ▶ Forums and workshops ( GENIE developers workshop, NUSTEC GENIE workshop for users)
- ▶ Planned release schedule with medium-term development plan

# Release Plans



- ▶ GENIE 2.8.0 is production version
- ▶ GENIE 2.8.2 soon
  - ▶ Bug fixes
  - ▶ Validation system
- ▶ GENIE 2.9.0 in Autumn, 2014
  - ▶ Some new packages
  - ▶ Updated Rein-Seghal, Berger-Seghal
  - ▶ Spectral functions and improved FSI
- ▶ 2.10.0 in Summer 2015
  - ▶ Valencia QE (QE+RPA+MEC)



# Conclusion

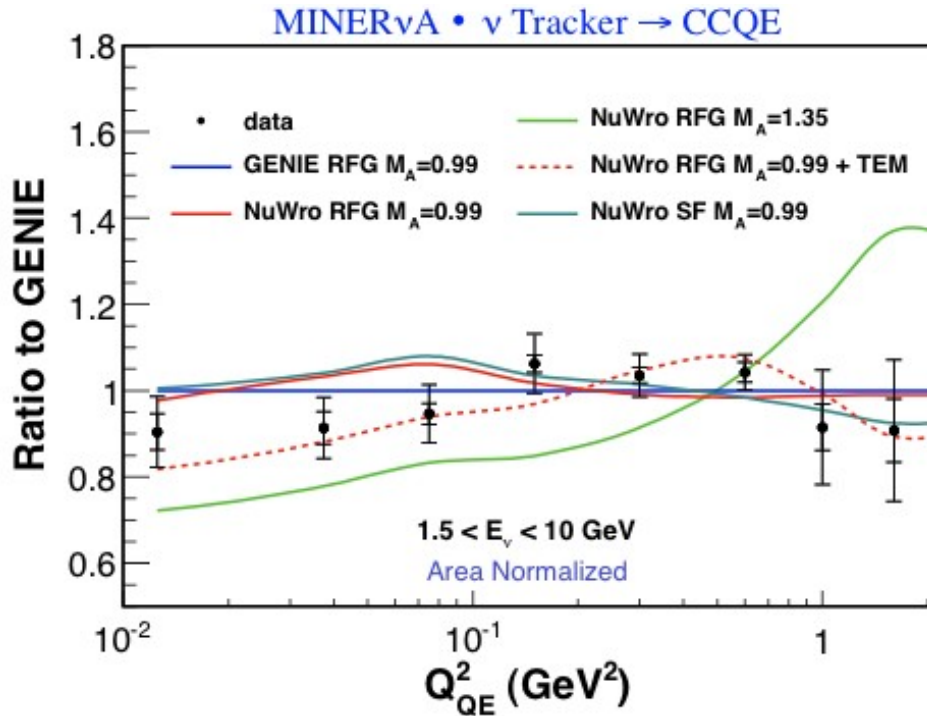


- ▶ New, detailed data from experiments such as MiniBooNE , MINERvA and T2K are posing a challenge to the model and generator builders.
- ▶ This is a good thing!
- ▶ There is a lot of effort going into implementation of new ideas in GENIE. We have benefited from close co-operation between the experiments and theorists.
- ▶ Lot's more to do, not many to do it
- ▶ Please join!



# Backups / Excess

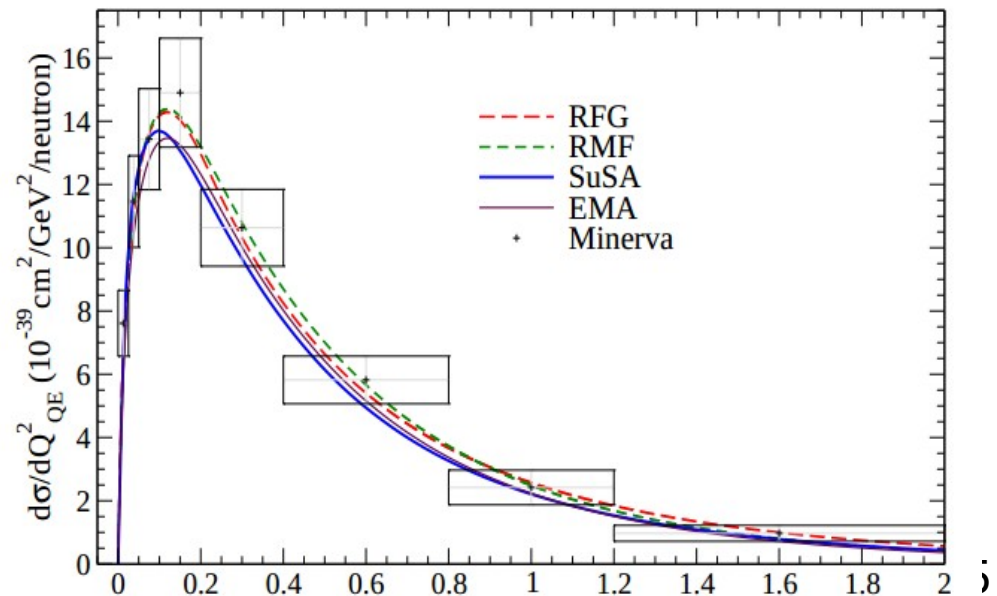
# Can data help distinguish?



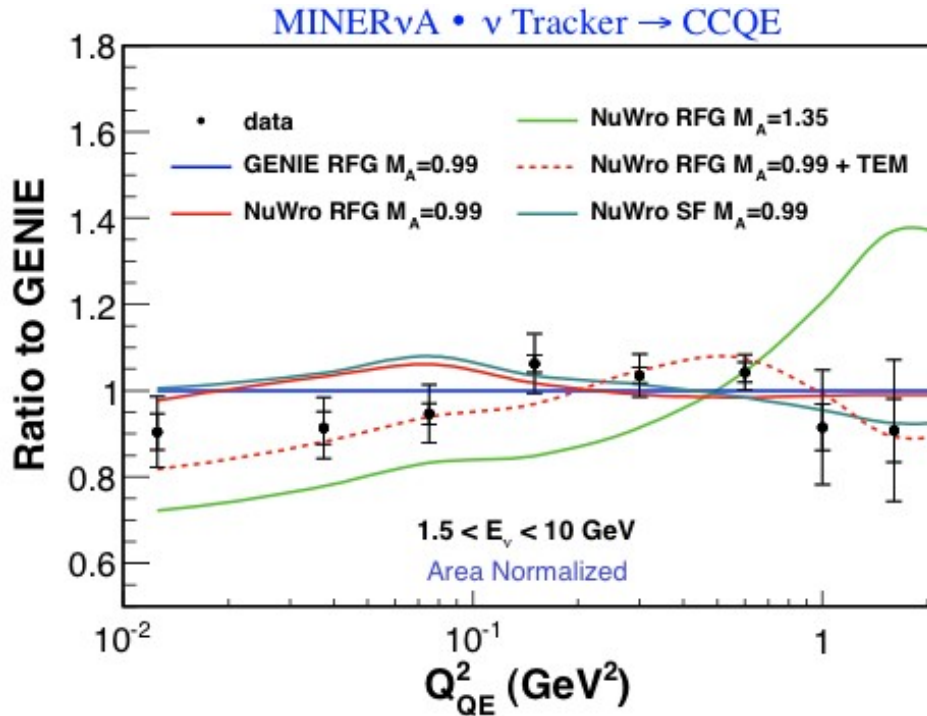
RFG with  $m_A = 1.35 \text{ GeV}/c^2$   
disfavoured

Multi-nucleon model (TEM)  
is best fit

although SUSA (without  
MEC) and RMF also agree  
with MINERvA



# Can data help distinguish?

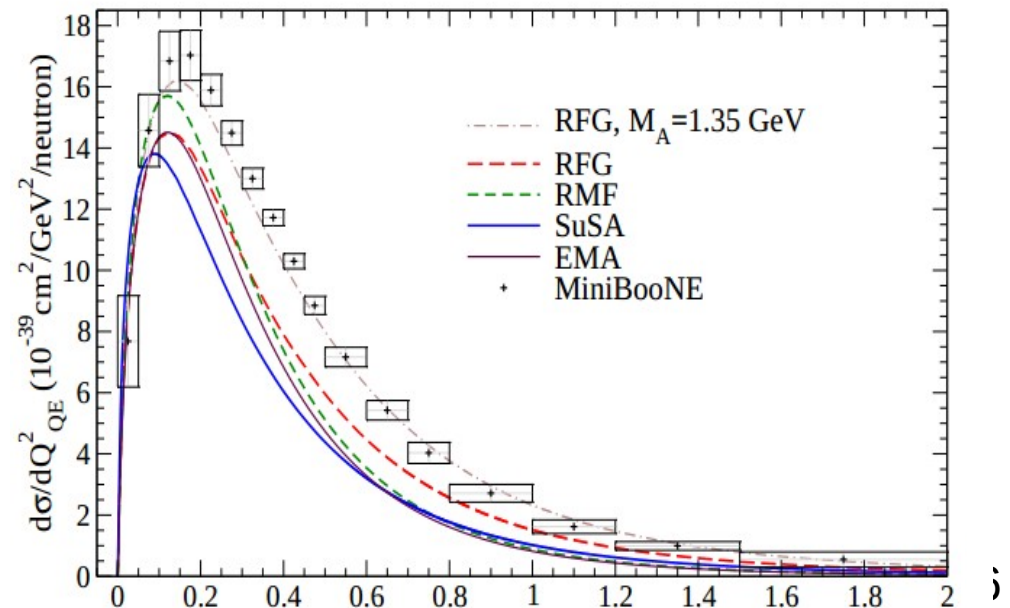


Bodek, Budd, Christy, Eur. Phys. J. C71, 1726 (2011)

RFG with  $m_A = 1.35 \text{ GeV}/c^2$   
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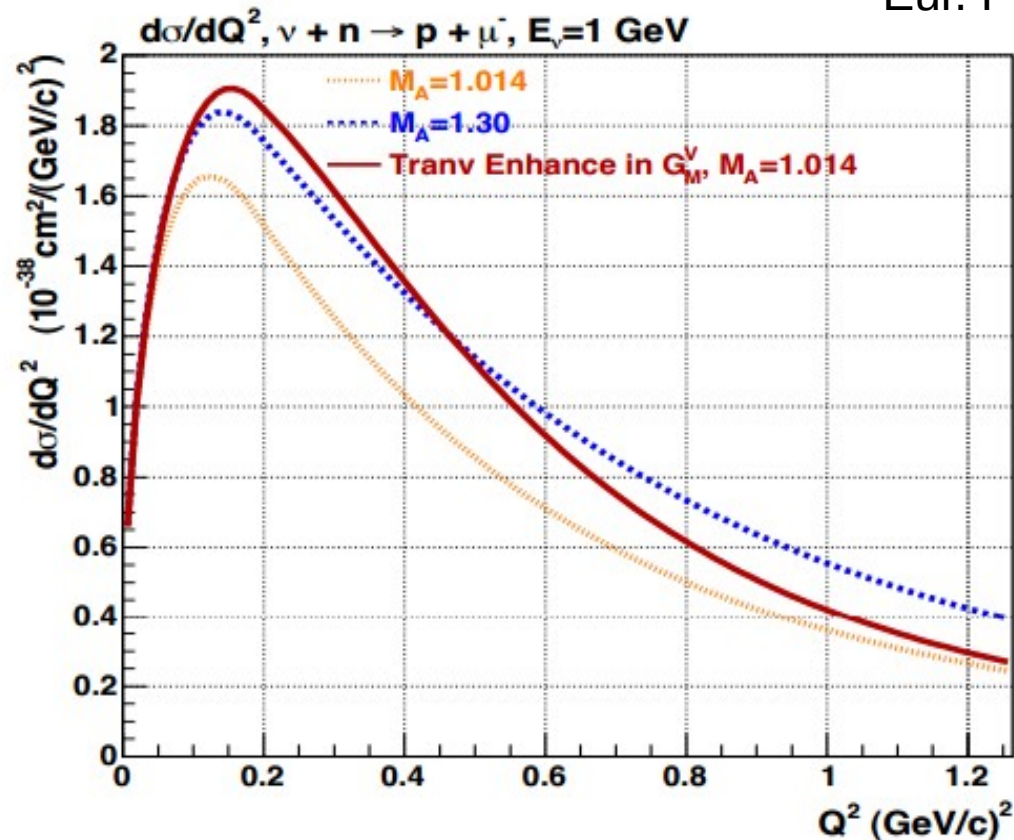
but not with MiniBooNE



# Model : Transverse Enhancement



Bodek, Budd, Christy  
Eur. Phys. J. C 71 (2011) 1726



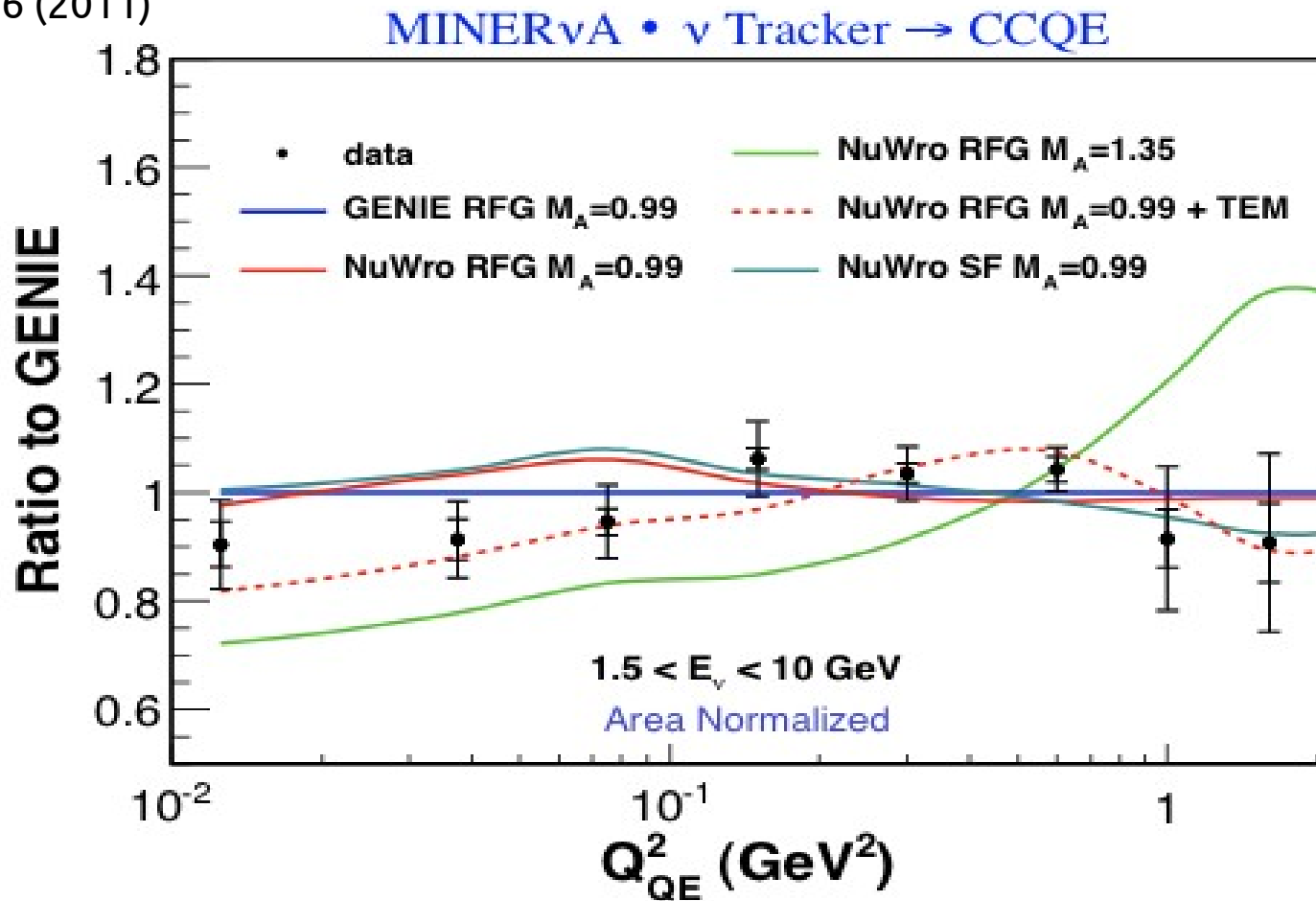
$$G_{Mp}(Q^2)(nuclear) = G_{Mp}(Q^2) \sqrt{1 + A Q^2 e^{-Q^2/B}}$$

$$G_{Mn}(Q^2)(nuclear) = G_{Mn}(Q^2) \sqrt{1 + A Q^2 e^{-Q^2/B}}$$

# Test of MEC in MINERvA



Bodek, Budd, Christy,  
Eur. Phys. J. C71, 1726 (2011)

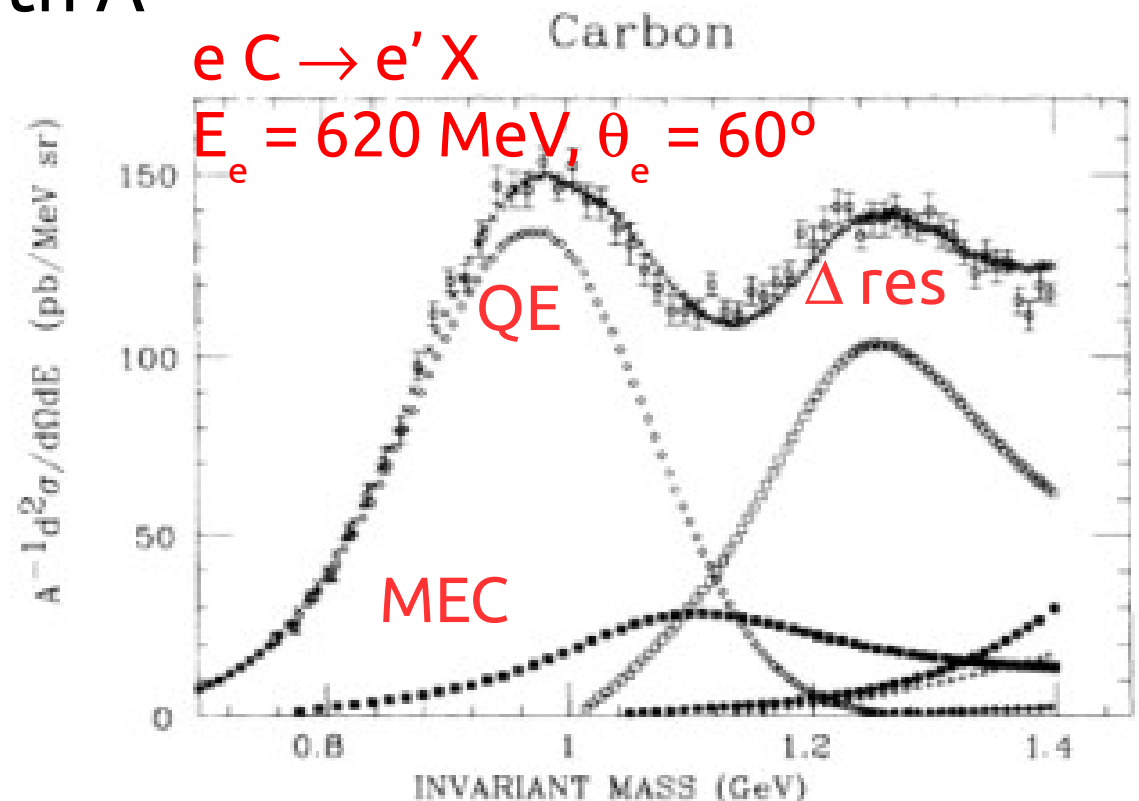


RFG with  $m_A = 1.35 \text{ GeV}/c^2$  disfavoured

# GENIE Model : Dip region



- ▶ Based on O'Connell and Lightbody (1988)
- ▶ MEC contribution added to cross section as a Gaussian in the hadronic invariant mass ( $M = 1.9 \text{ GeV}$ ,  $\Gamma = 300 \text{ MeV}$ )
- ▶ Tune normalisation with MiniBooNE data
- ▶ Cross section scales with  $A$

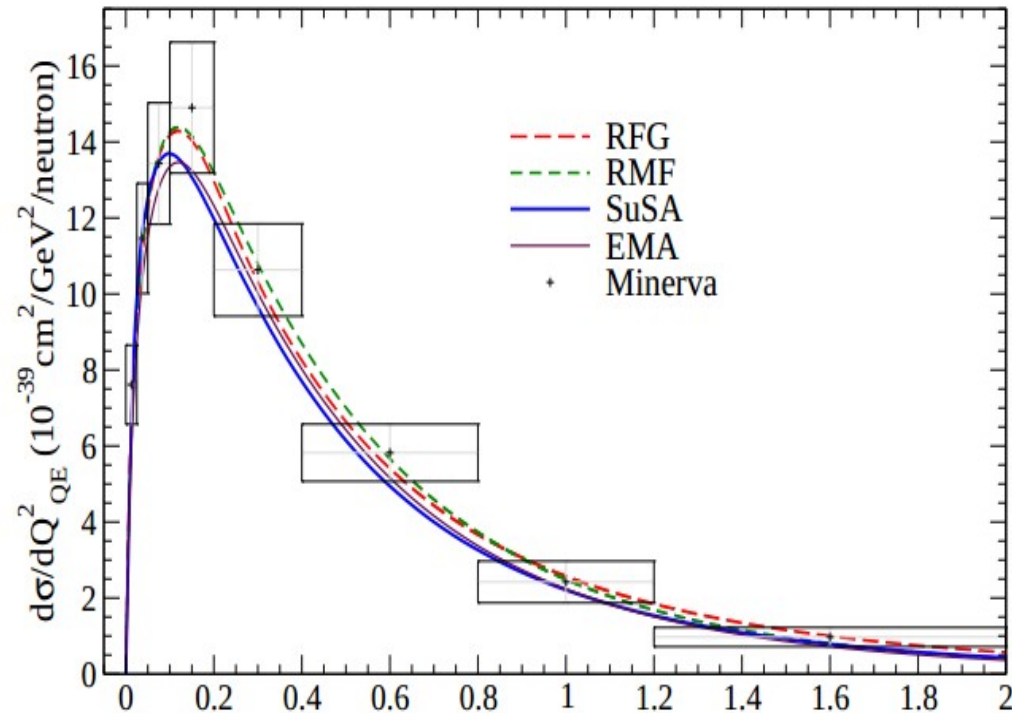
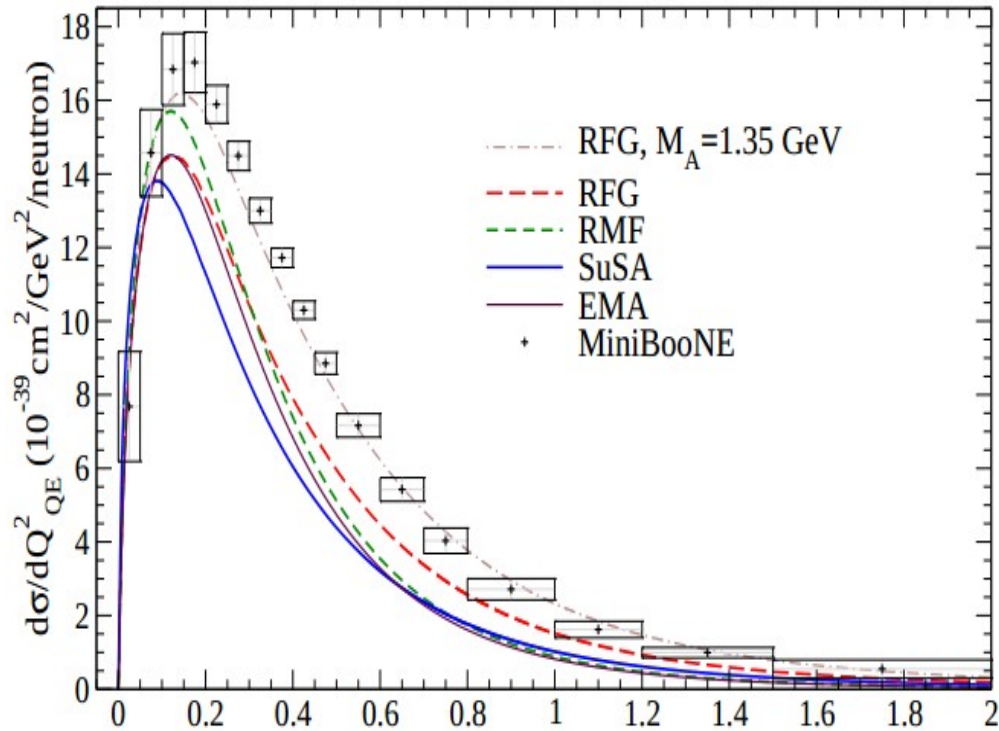


# Other options are available



miniBooNE

MINERvA



miniBooNE data needs  
20-30% additional MEC to  
agree

MINERvA is consistent  
with SUSAs & RMF



# Observation of extra nucleons



- ▶ 2p2h processes can eject an extra nucleon
- ▶ could help untangle contributions from Impulse Approximation (1p1h) based models (SUSA, RMF) from 2p2h models
- ▶ and would aid generation of the event 4-vectors in generators
- ▶ Sensitivity to the local environment around the primary vertex would be useful
  - ▶ ArgoNeut (& microBooNE) can image the vertex
  - ▶ MINERvA (& T2K) can measure vertex activity

# ANL/BNL

