Neutrino cross section measurements from E_ν ~ 100s MeV to few GeV

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CIPANP 2018
31 May, 2018
Based on Mahn, CM, Wilkinson
arxiv:1803.08848

Outline

- Motivation: near detectors are crucial, but not magical
- Neutrino-nucleus scattering: life would be easier if we could build our detectors out of hydrogen
- The (re-)discovery of two-particle two-hole interactions
- Recent measurements from MiniBooNE, MINERvA, and T2K
- Argon: you thought carbon was hard?
- Caveat: I am a member of DUNE, and a former member of MINERvA

Motivation: neutrino oscillation measurements

$$P(\nu_\mu \to \nu_e) = \frac{\Phi_{\nu_e}(E_{true}, L)}{\Phi_{\nu_\mu}(E_{true}, 0)}$$

Oscillation probability is the ratio of neutrino fluxes...

Motivation: neutrino oscillation measurements

...but what you measure is the product of flux, cross section, detector acceptance, and detector smearing...

$$N^{far}(E_{reco}) = \int dE_{true}\Phi_{\nu_e}(E_{true}, L) \times \sigma_{\nu_e}(E_{true}) \times \epsilon^{far} \times D^{far}_{\nu_e}(E_{true}, E_{reco})$$

observed distribution

flux

cross section

acceptance

detector reconstruction matrix

Measure neutrino energy calorimetrically:

$$E_\nu = E_{lep} + E_{had}$$

or by “QE hypothesis”:

$$E_\nu^{\mathrm{QE}} = \frac{M_f^2 - (M_i - E_{\mathrm{b}})^2 - m_l^2 + 2(M_i - E_{\mathrm{b}})E_l}{2(M_i - E_{\mathrm{b}} - E_l + p_l \cos\theta_l)}$$

Near detectors help, but do not cancel out everything

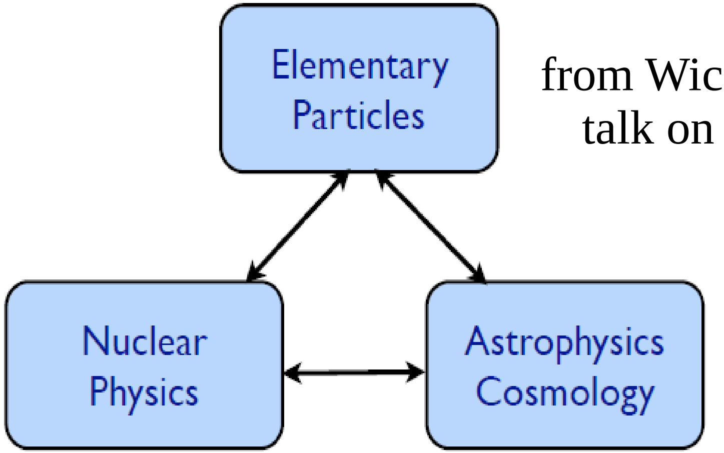
$$\frac{\int dE_{true}\Phi_{\nu_e}(E_{true},L) \times \sigma_{\nu_e}(E_{true}) \times \epsilon^{far} \times D^{far}_{\nu_e}(E_{true},E_{reco})}{\int dE_{true}\Phi_{\nu_\mu}(E_{true},0) \times \sigma_{\nu_\mu}(E_{true}) \times \epsilon^{near} \times D^{near}_{\nu_\mu}(E_{true},E_{reco})}$$

- Fluxes are different at near and far detectors due to
  - Neutrino oscillations!
  - Solid angle effects
- Cross sections are different: ν_μ vs. ν_e
- Unless near and far detectors are identical:
  - Detector acceptance is different (ND typically smaller)
  - Energy reconstruction may be different

Non-cancellation requires use of neutrino interaction model

- Models of flux, cross sections, detector are required to correct for far/near differences
- Event Generators = collection of cross section predictions
- GENIE (used by DUNE, NOvA, MINOS)
- NEUT (used by T2K, Super-K, Hyper-K)
- Predicts both ν-nucleon, and ν-nucleus
- Must be validated with data

CIPANP model also works for neutrino cross sections

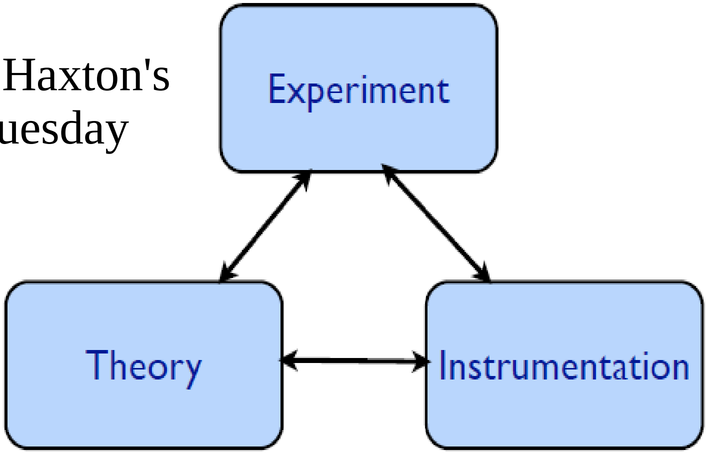


Elementary Particles

Nuclear Physics

Astrophysics Cosmology

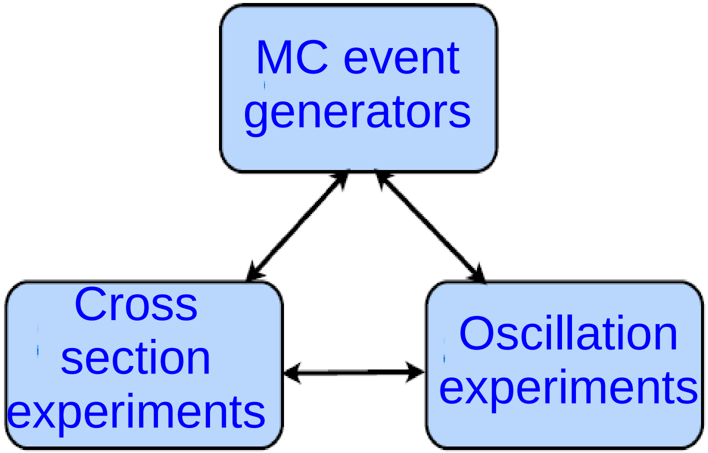
from Wick Haxton's
talk on Tuesday



Experiment

Theory

Instrumentation

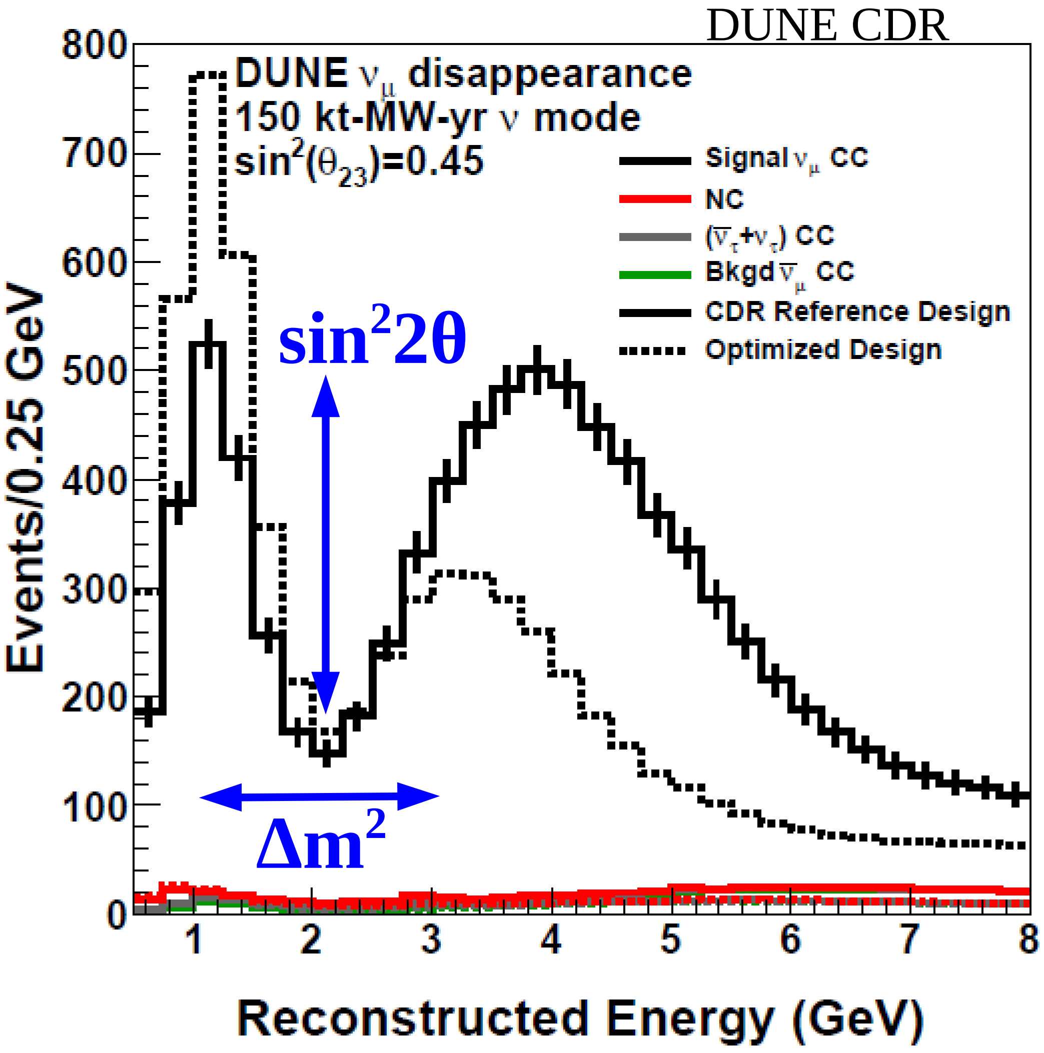


MC event generators

Cross section experiments

Oscillation experiments

Using the wrong cross section model can bias oscillation parameters

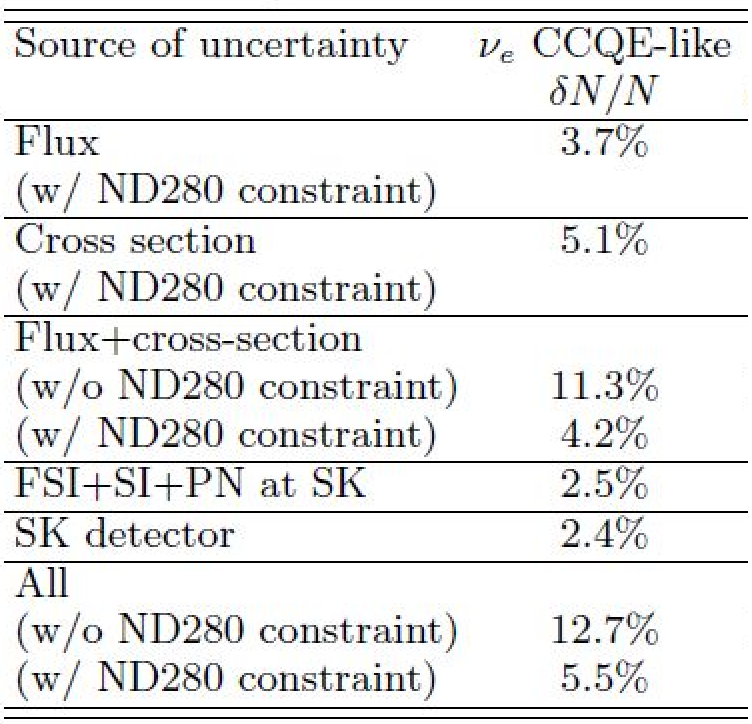


- Location and depth of "dip" in oscillated ν_μ spectrum sensitive to mixing parameters
- But it is also sensitive to energy reconstruction
- For example, if more energy goes to neutrons, the dip moves down

Cross section systematics in T2K: ND gets you from 12.7%→5.5%

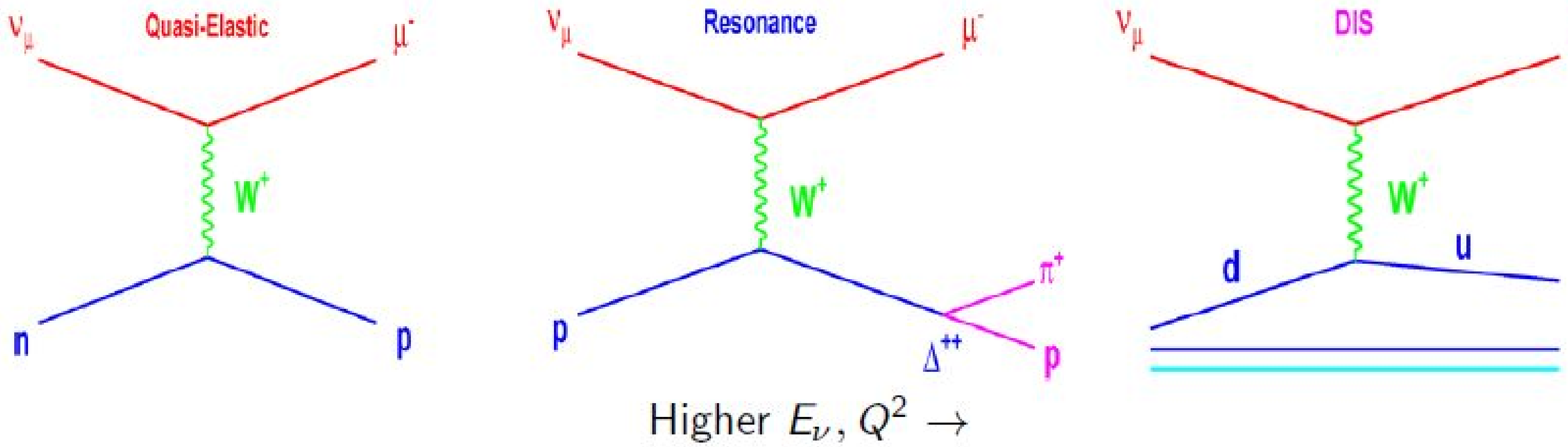
- Even with near detector constraint, cross sections are dominant systematic in T2K
- ND constrains flux & cross section in a correlated way
- 5.1% uncertainty on ν_e CCQE at far detector
- DUNE goal is 2-3%

Phys. Rev. D 96, 092006 (2017)



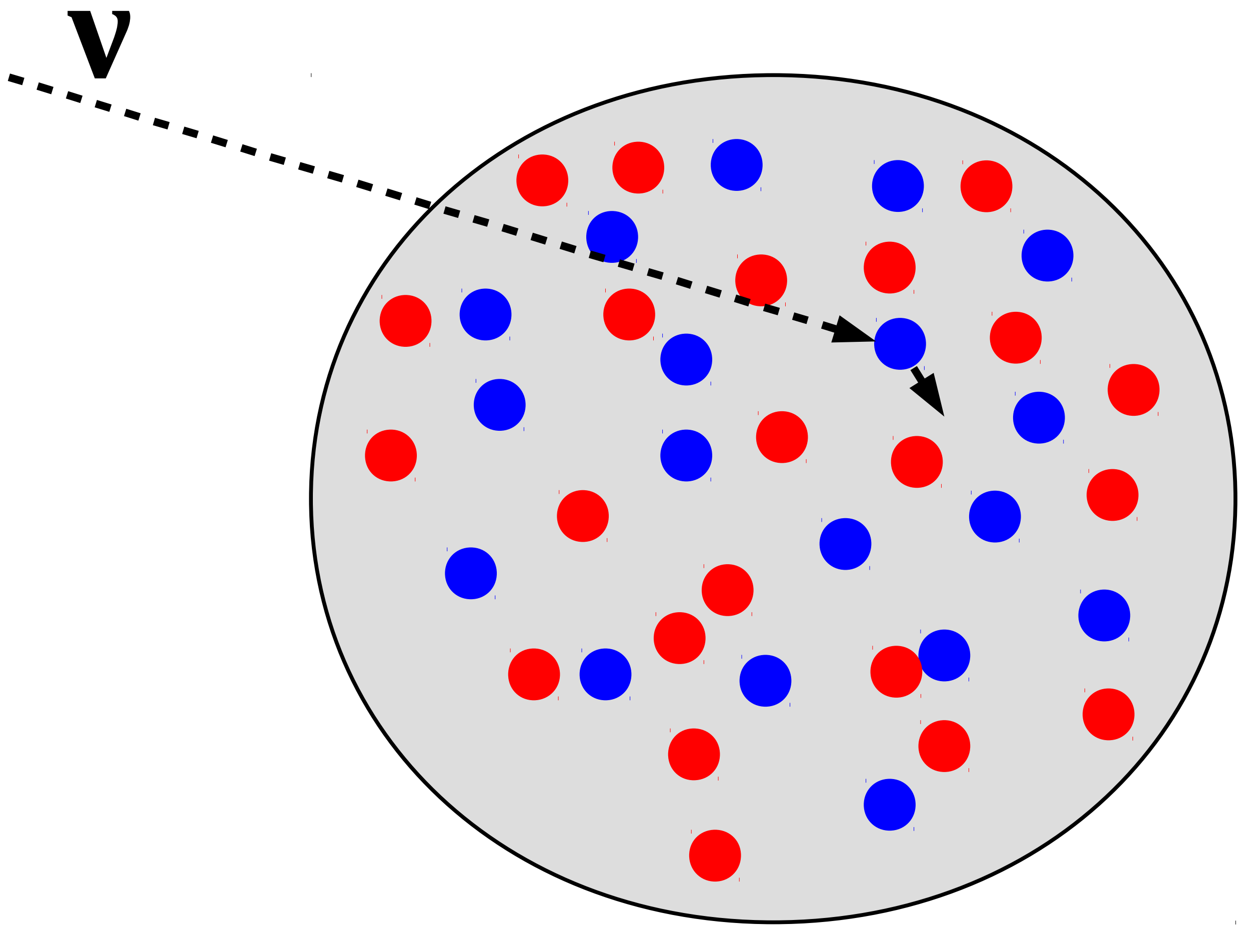
Source of uncertainty	ν_e CCQE-like $\delta N/N$
Flux (w/ ND280 constraint)	3.7%
Cross section (w/ ND280 constraint)	5.1%
Flux+cross-section	
(w/o ND280 constraint)	11.3%
(w/ ND280 constraint)	4.2%
FSI+SI+PN at SK	2.5%
SK detector	2.4%
All	
(w/o ND280 constraint)	12.7%
(w/ ND280 constraint)	5.5%

Neutrino-nucleon interaction types: quasi-elastic, resonance, DIS



- Quasi-elastic (CCQE): single nucleon final state
- Resonance (RES) pion production: pion + nucleon
- Deep inelastic scattering (DIS): neutrino scatters off constituent quark, hadronization produces mesons

Moving to a nucleus: Relativistic Fermi Gas model

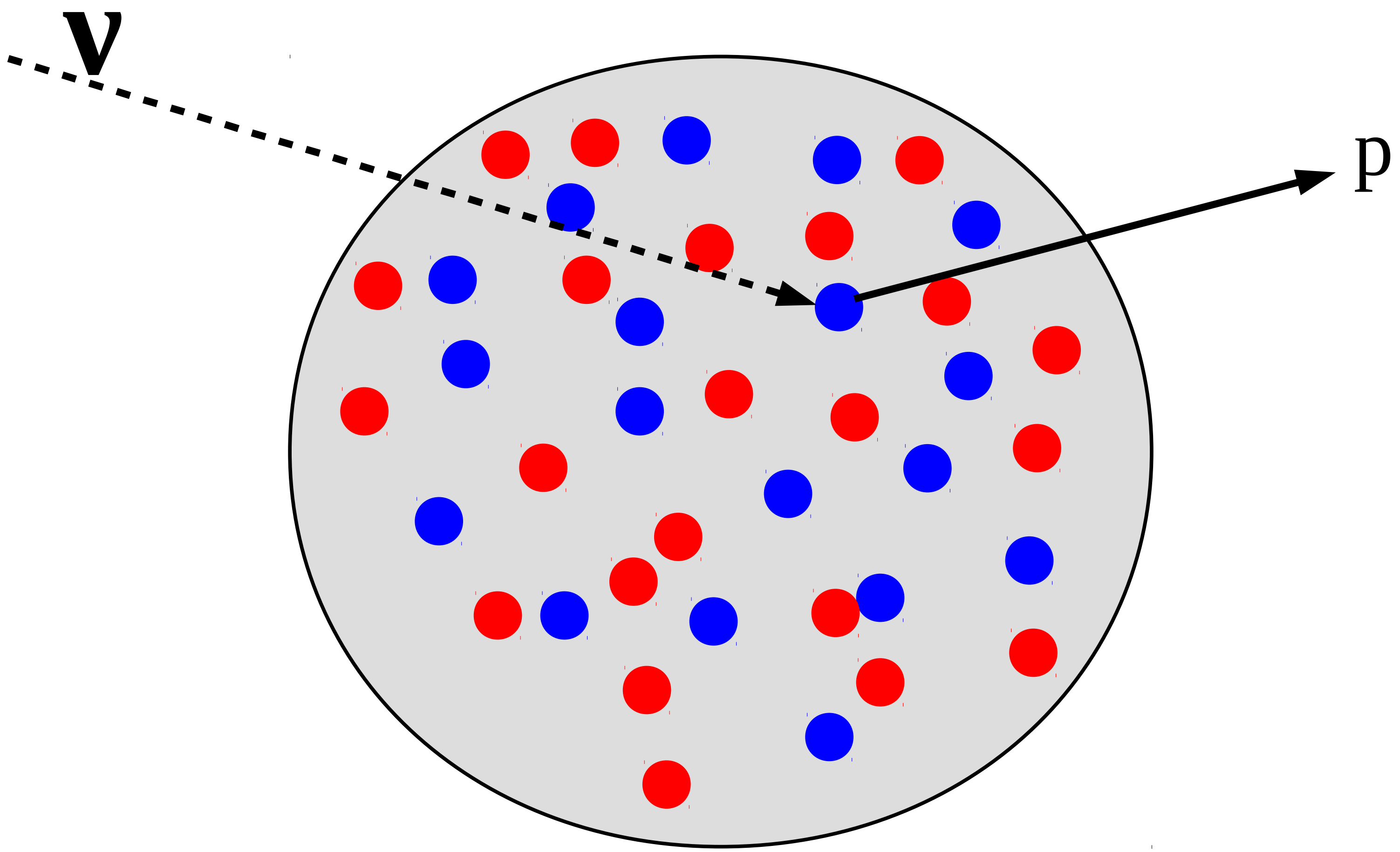


Very simple nuclear model used by neutrino experiments for many years

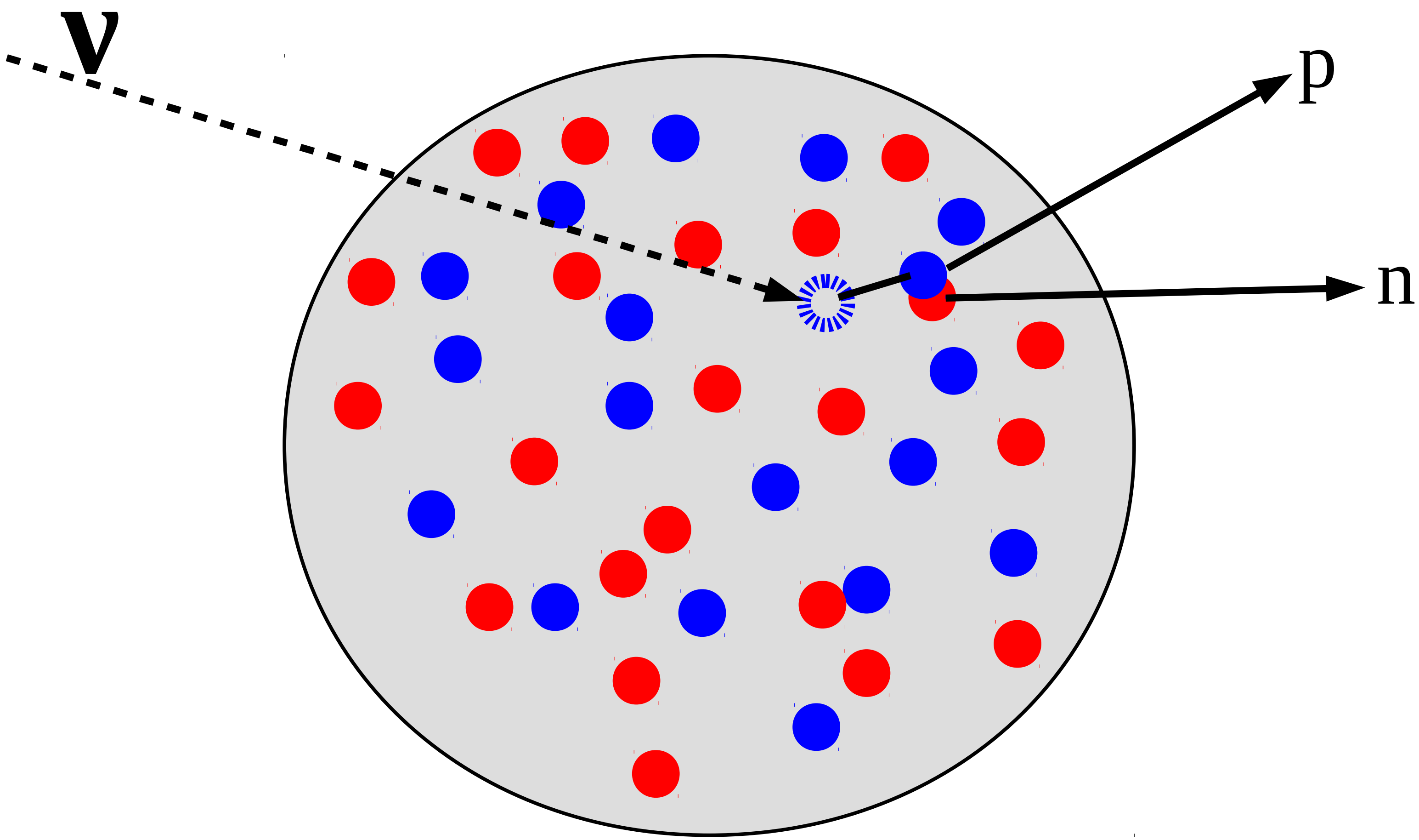
Nucleons are quasi-free in mean field

Fermi momentum, Pauli suppression, Final-state interactions

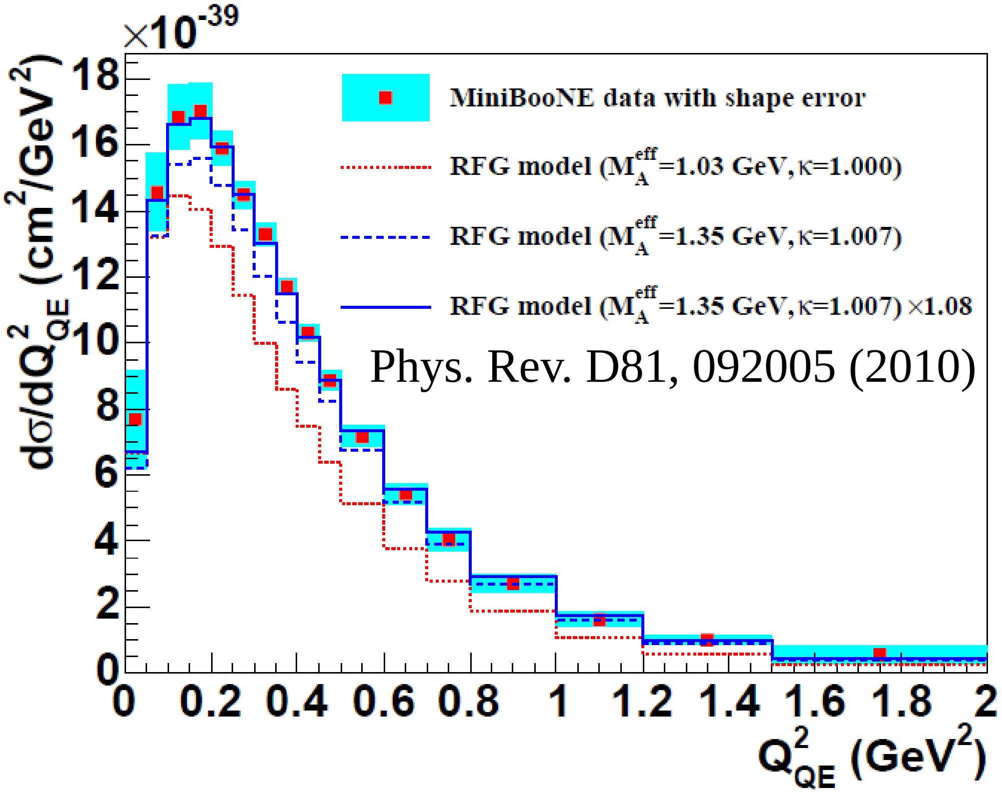
CCQE in RFG



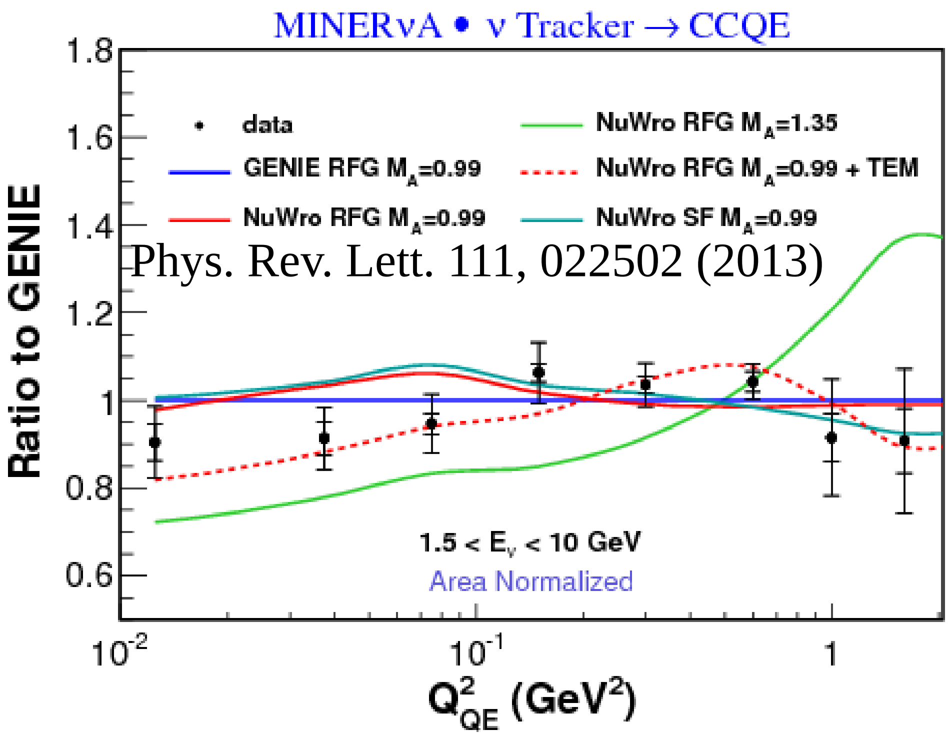
Final-state interaction (FSI)



CCQE on hydrocarbon MiniBooNE and MINERvA



Phys. Rev. D81, 092005 (2010)

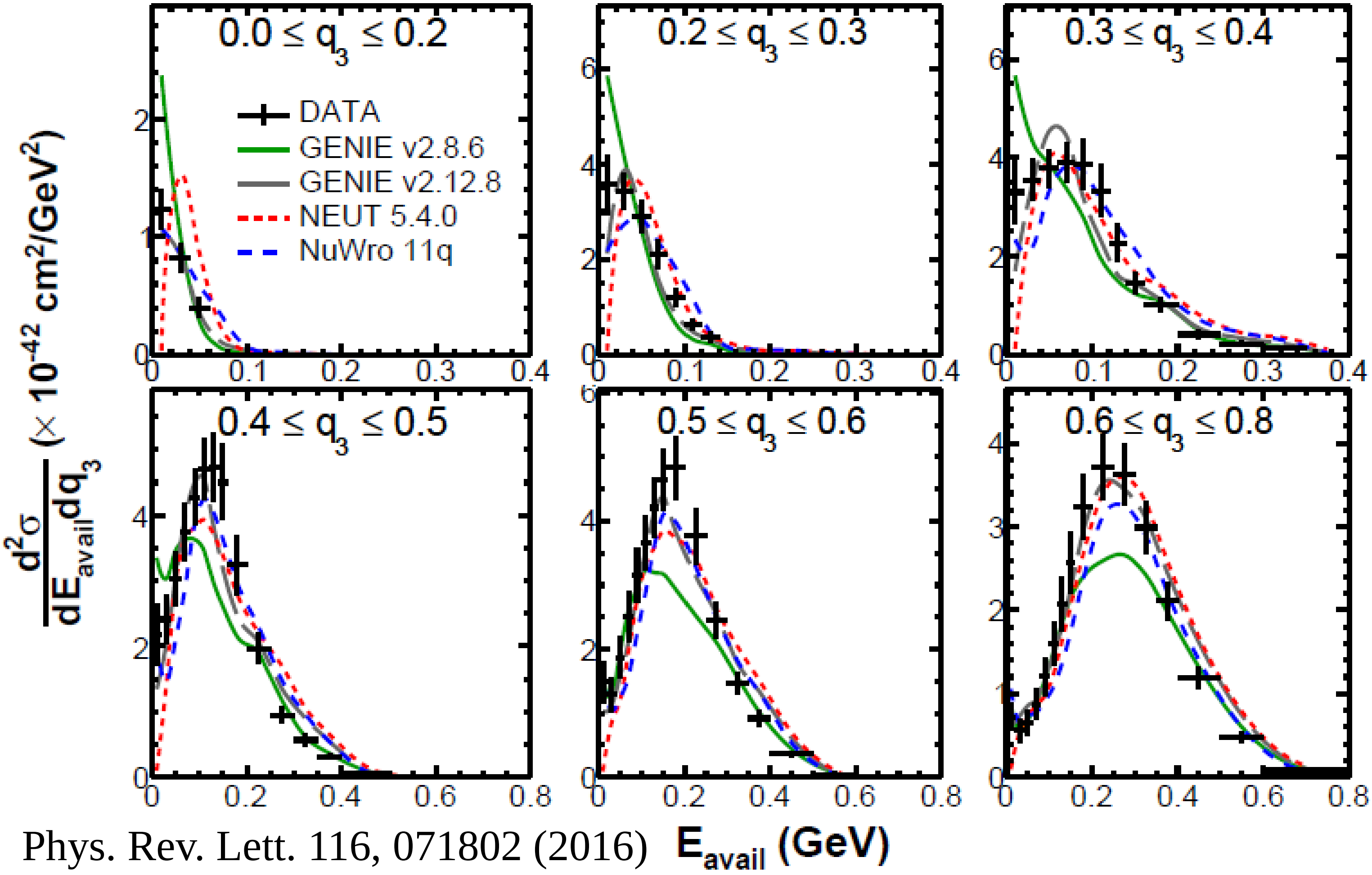


Phys. Rev. Lett. 111, 022502 (2013)

- Simple RFG not compatible with data
- Suggests more complicated nuclear effects

$$Q^2_{\mathrm{QE}} = 2E_\nu^{\mathrm{QE}}(E_l - p_l \cos\theta_l) - m_l$$

MINERvA CC inclusive at low momentum transfer

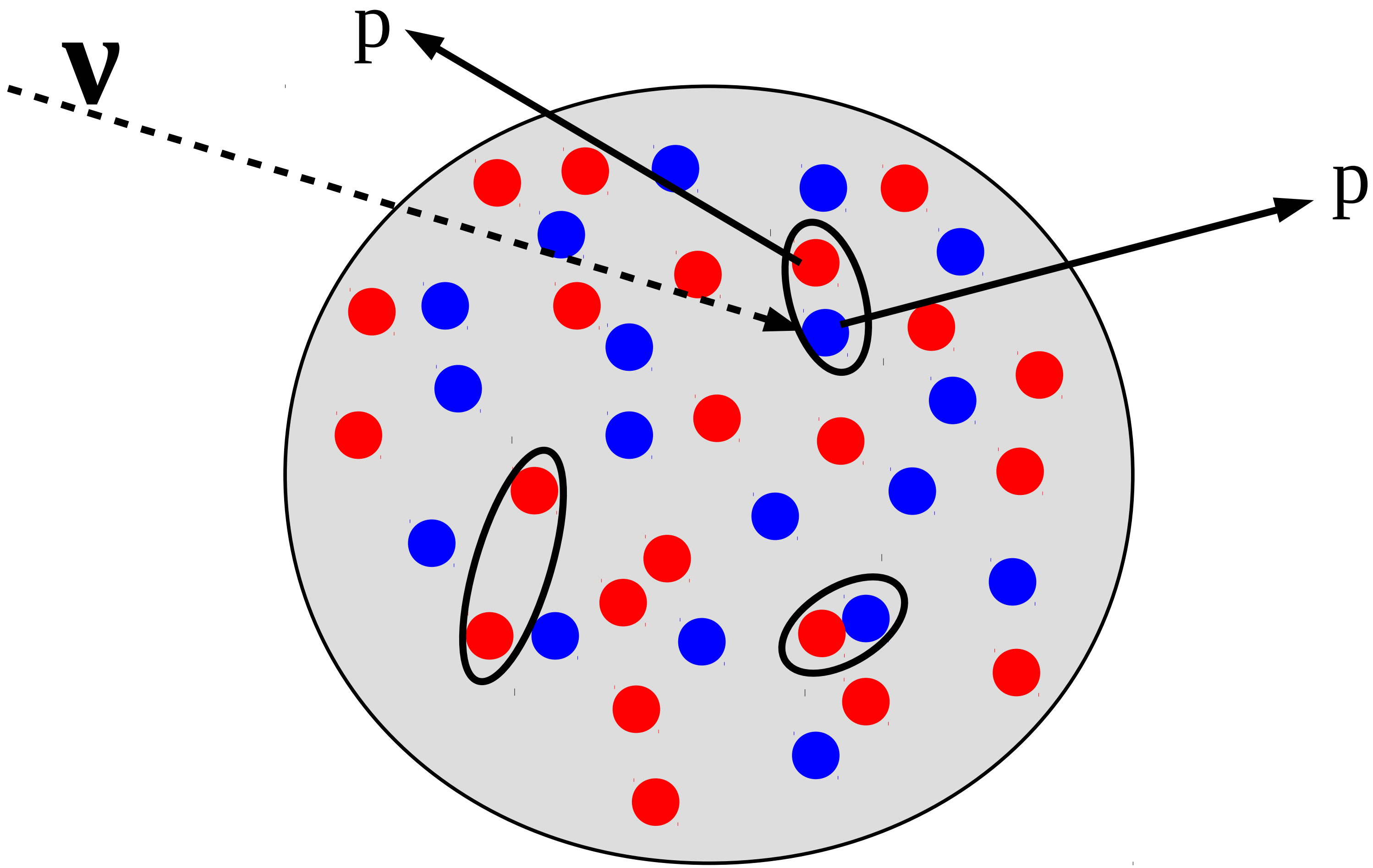


Phys. Rev. Lett. 116, 071802 (2016)

- $E = T_p + T_{\pi\pm} + E_{\pi 0} + E_\gamma$
- Neutrons are not included as they are generally not detected

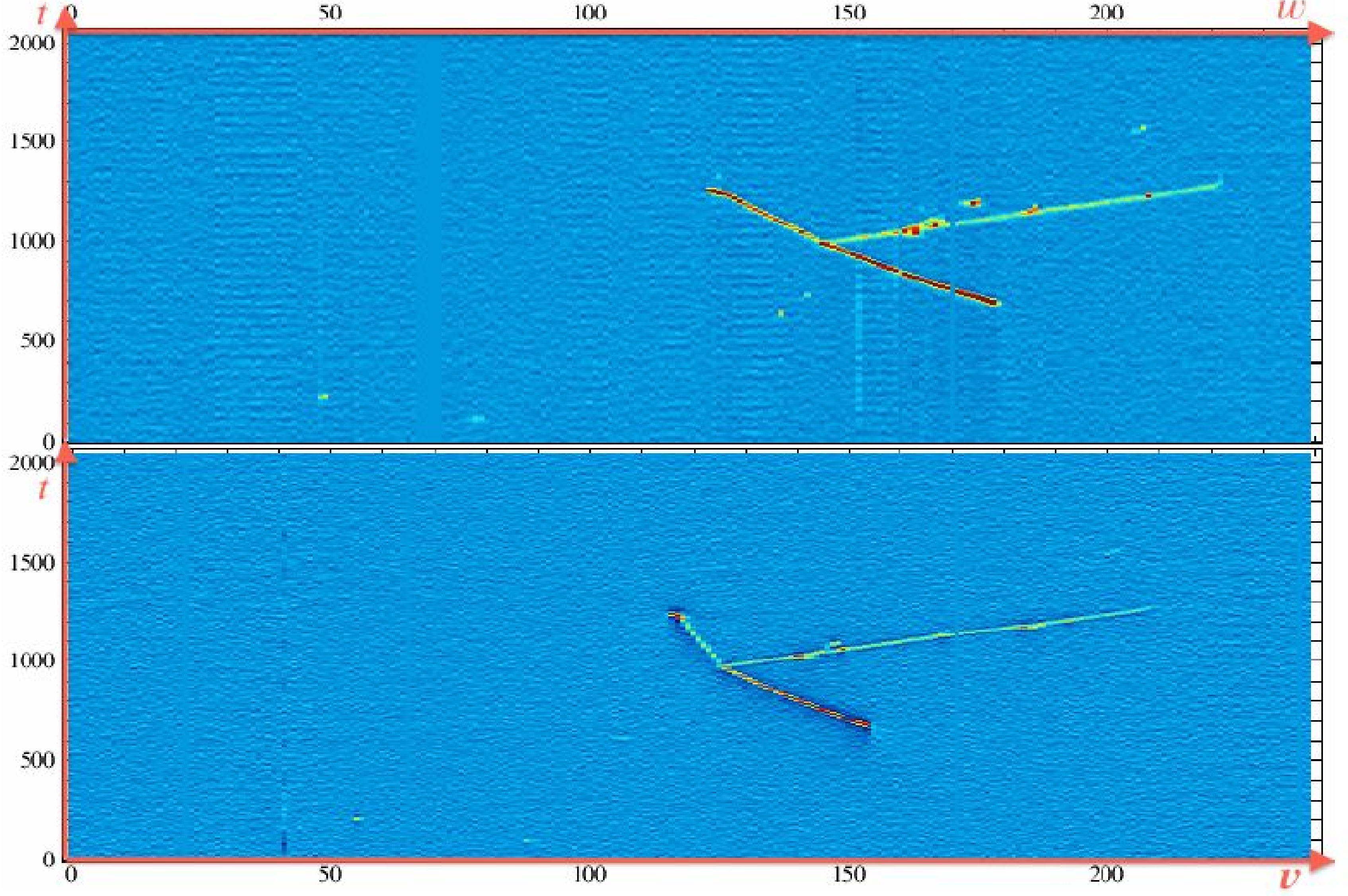
GENIE v2.8.6 is old school RFG, v2.12.8 includes 2p2h, RPA suppression at low energy transfer

Two-particle two-hole interaction (2p2h)

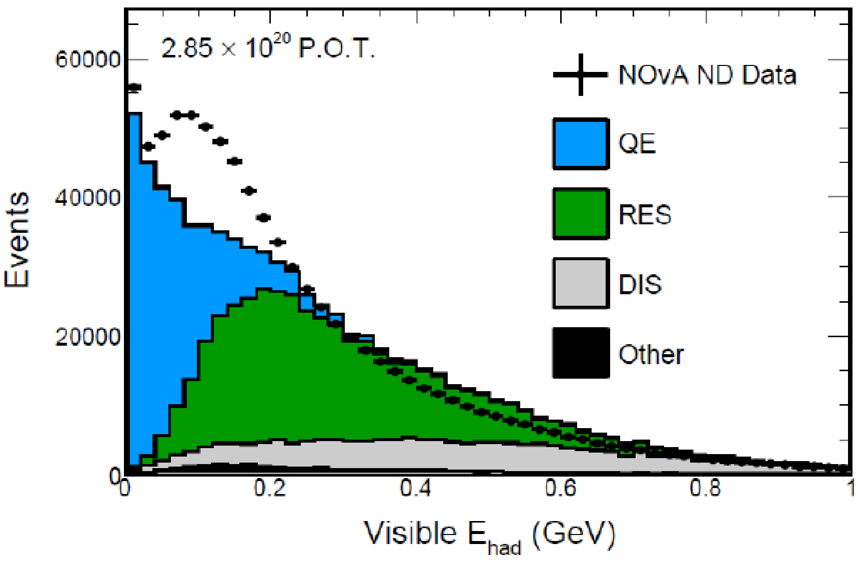


ν_μ Ar → μpp in ArgoNeuT

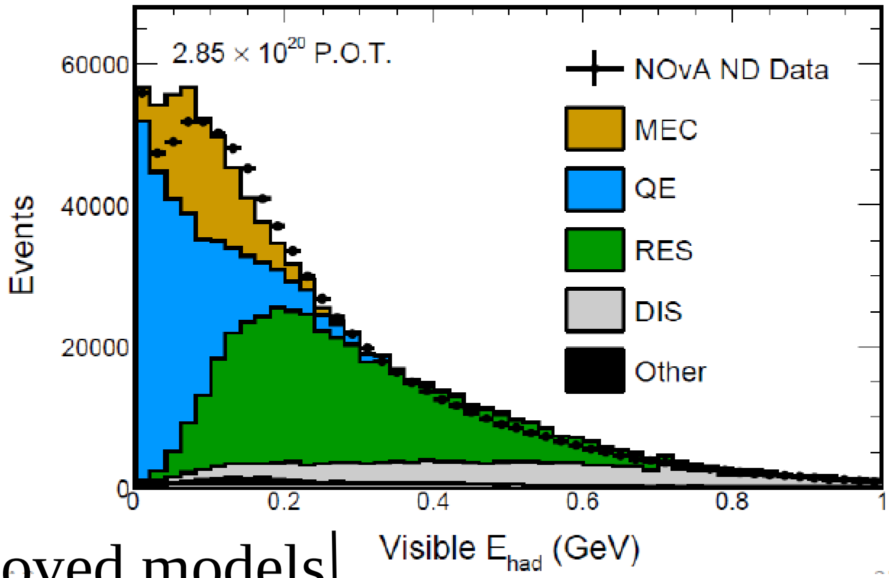
Phys. Rev. D 90, 012008 (2014)



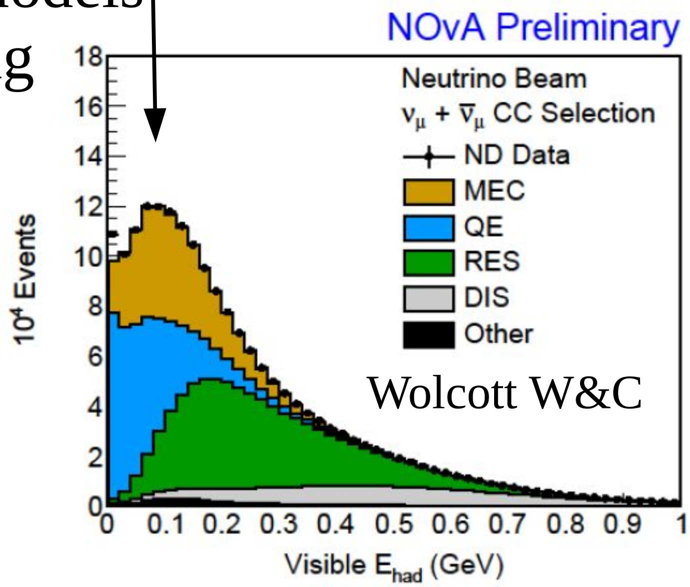
Moving on from RFG
NOvA ND hadronic energy



Adding 2p2h



Improved models & tuning



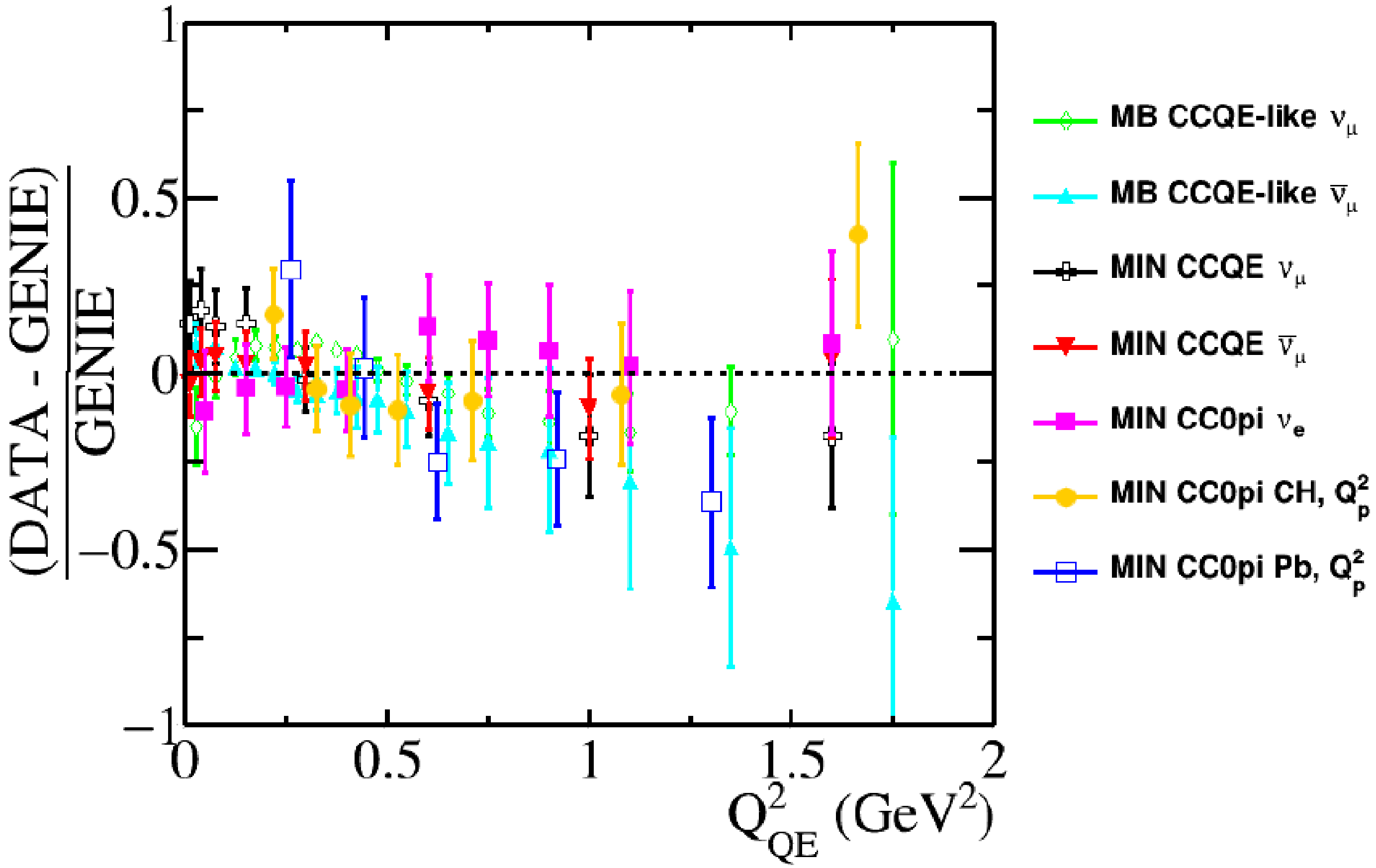
Wolcott W&C

- XS and oscillation experiments are now using improved 2p2h+RPA models in GENIE
- PRC 79 (2004) 055503, PRC 83 (2011) 045501, PRD 88, 113007 (2013)

Comparison of recent CC0π measurements

- Challenging to compare measurements directly, for some good reasons:
  - Flux-integrated differential cross sections using different fluxes
  - Different nuclear targets
  - Signal definitions in terms of final-state particles, not nucleon-level interaction modes, and motivated by detector sensitivity
  - Phase space restricted to detector acceptance
- Instead, look at ratios to a common reference model

Comparison of CC0π dσ/dQ² data to GENIE 2.12.8 reference model



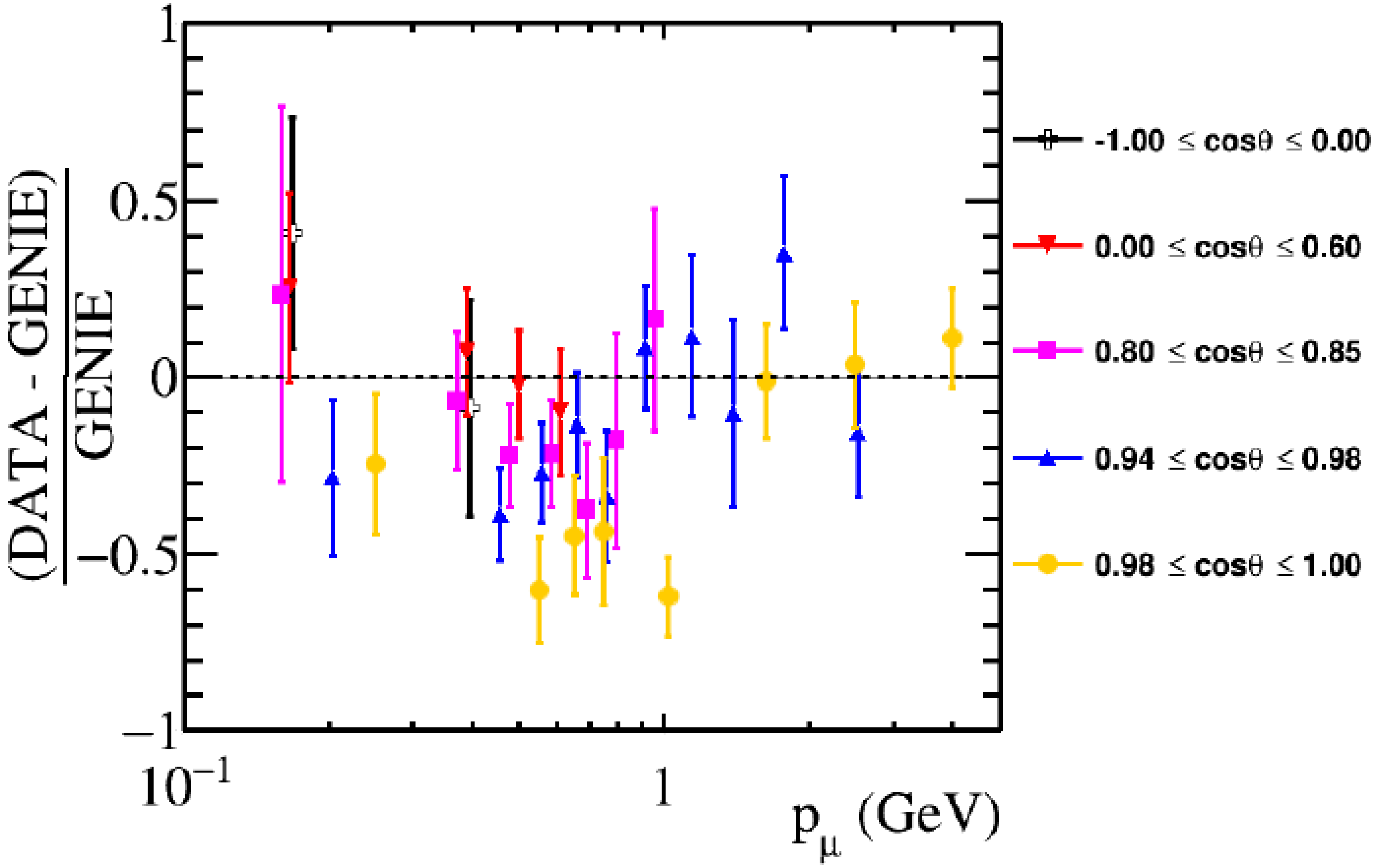
From Mahn, CM, Wilkinson arxiv:1803.08848

Using NUISANCE comparison tool: JINST 12, P01016 (2017),

- GENIE 2.12.8, ValenciaQEBergerSehgalCOHRES

$$Q^2_{\mathrm{QE}} = 2E_\nu^{\mathrm{QE}}(E_l - p_l \cos\theta_l) - m_l$$

T2K double differential in muon kinematics



backward muons

~50-90 degrees

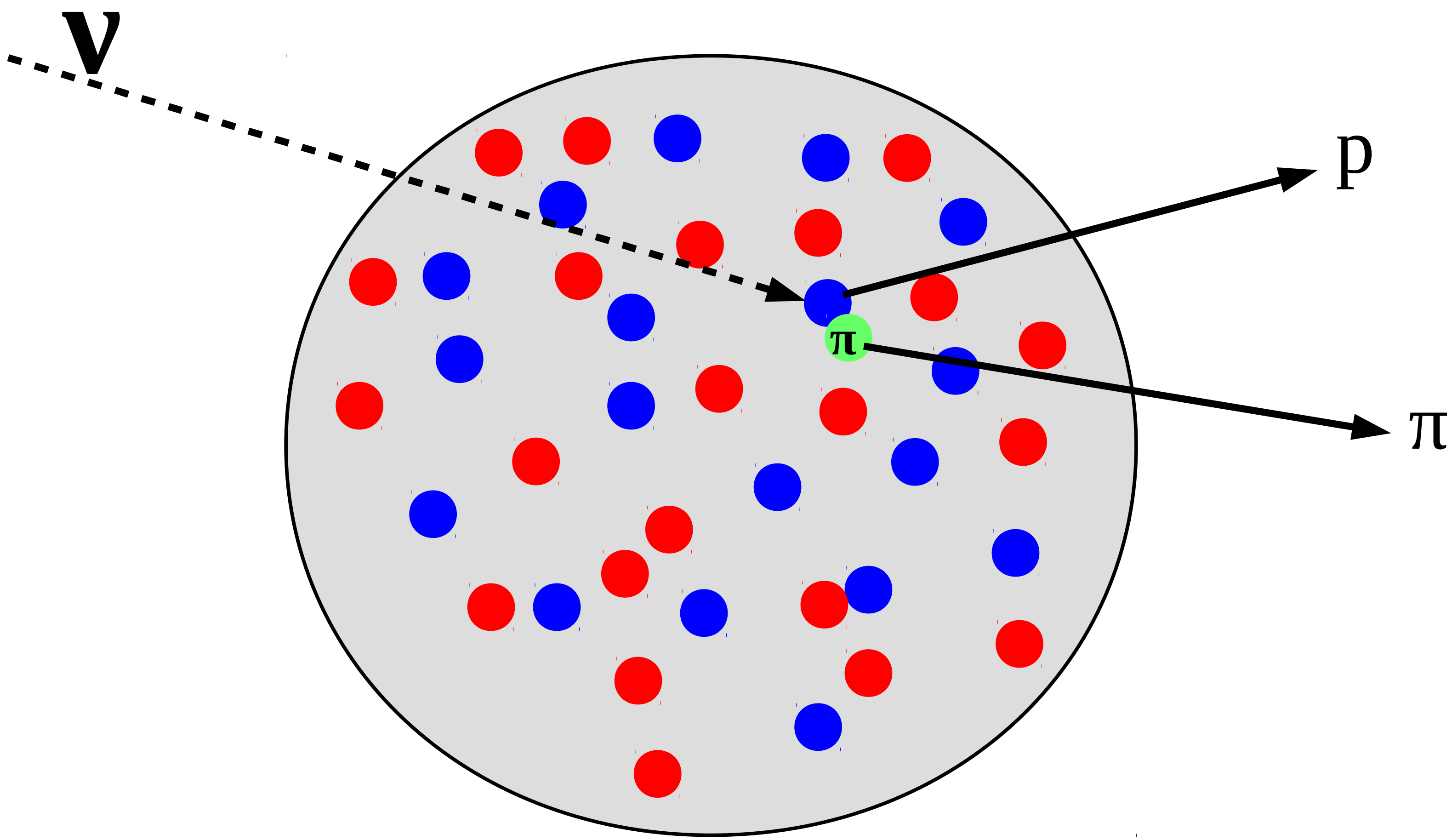
~35 degrees

~15 degrees

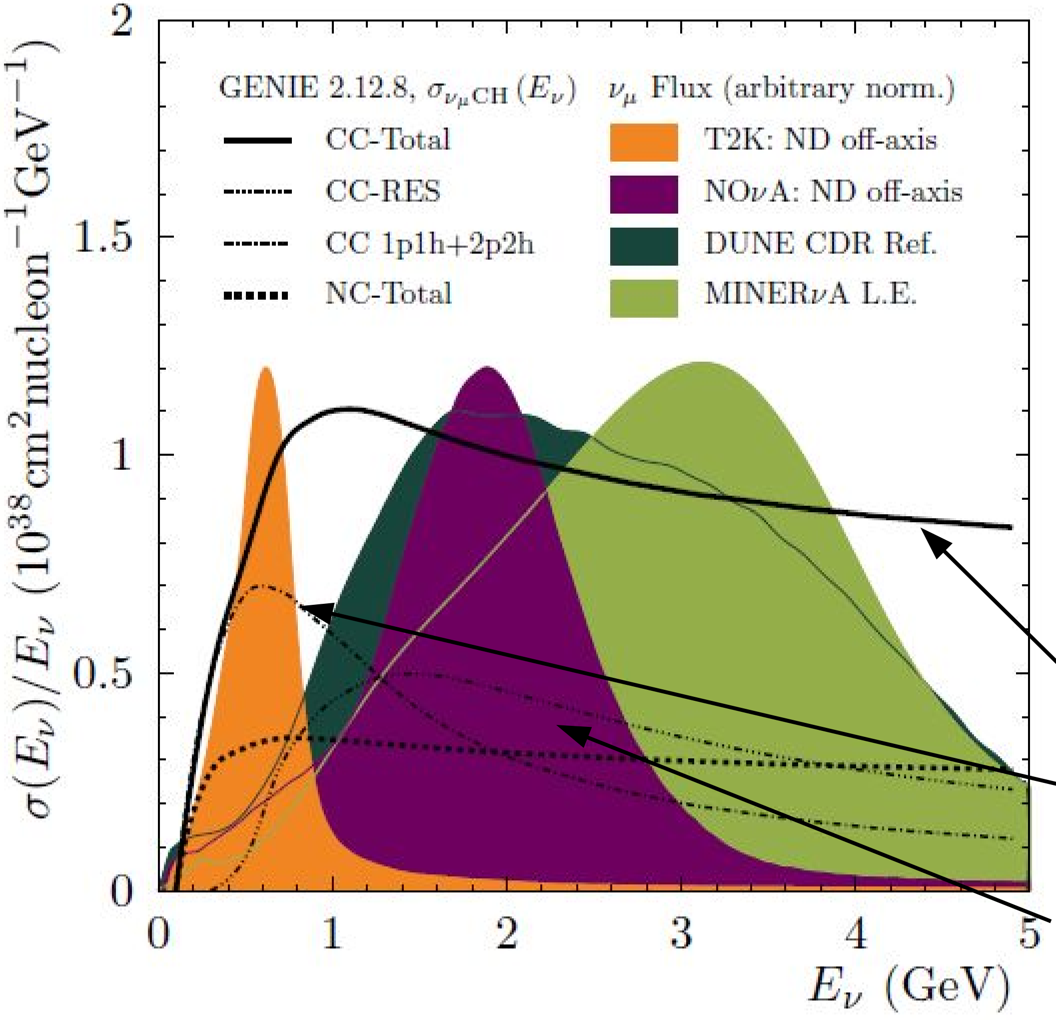
<10 degrees

- Significant discrepancy for most forward muons

Pion production



Fluxes and cross sections vs. neutrino energy



Oscillation experiments, especially DUNE, sit in a region where quasi-elastic (0π), resonant (1π), and deep inelastic are all significant

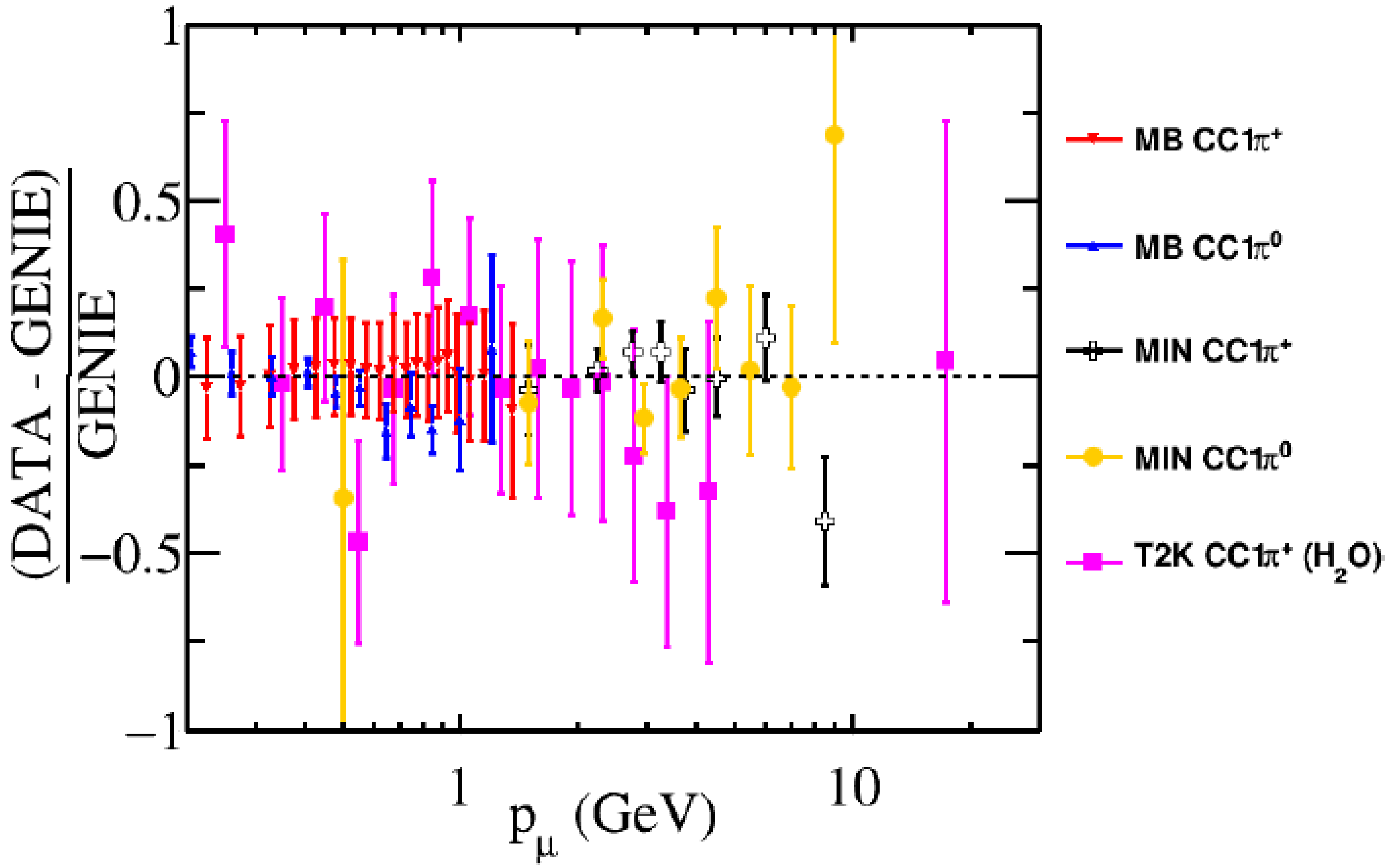
In DUNE, most events have pions in the final state

Total CC

CC0π

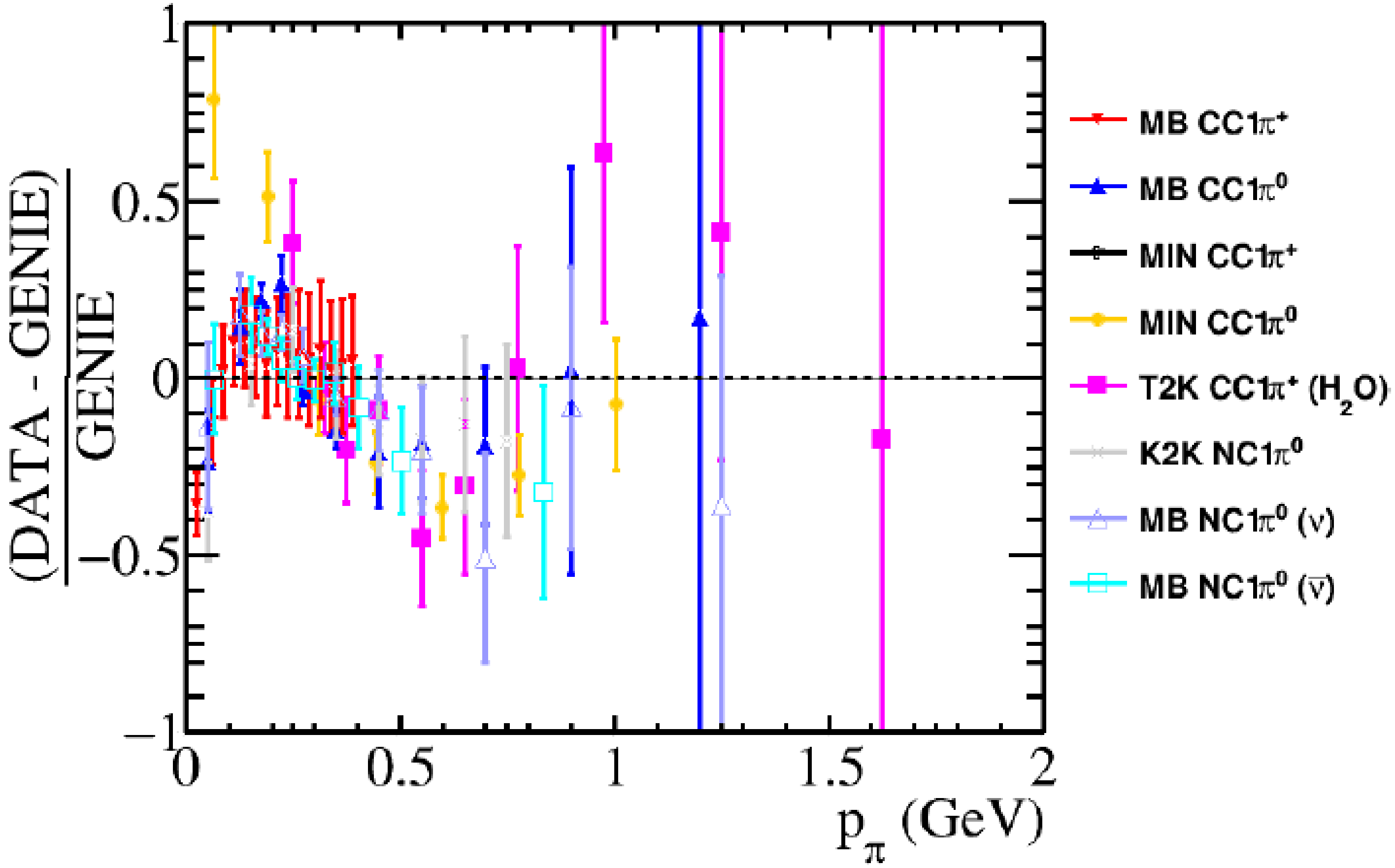
CC RES 1π

CC1π – muon momentum



- Muon kinematics in broad agreement with GENIE for MiniBooNE, MINERvA, and T2K

CC1π – pion momentum

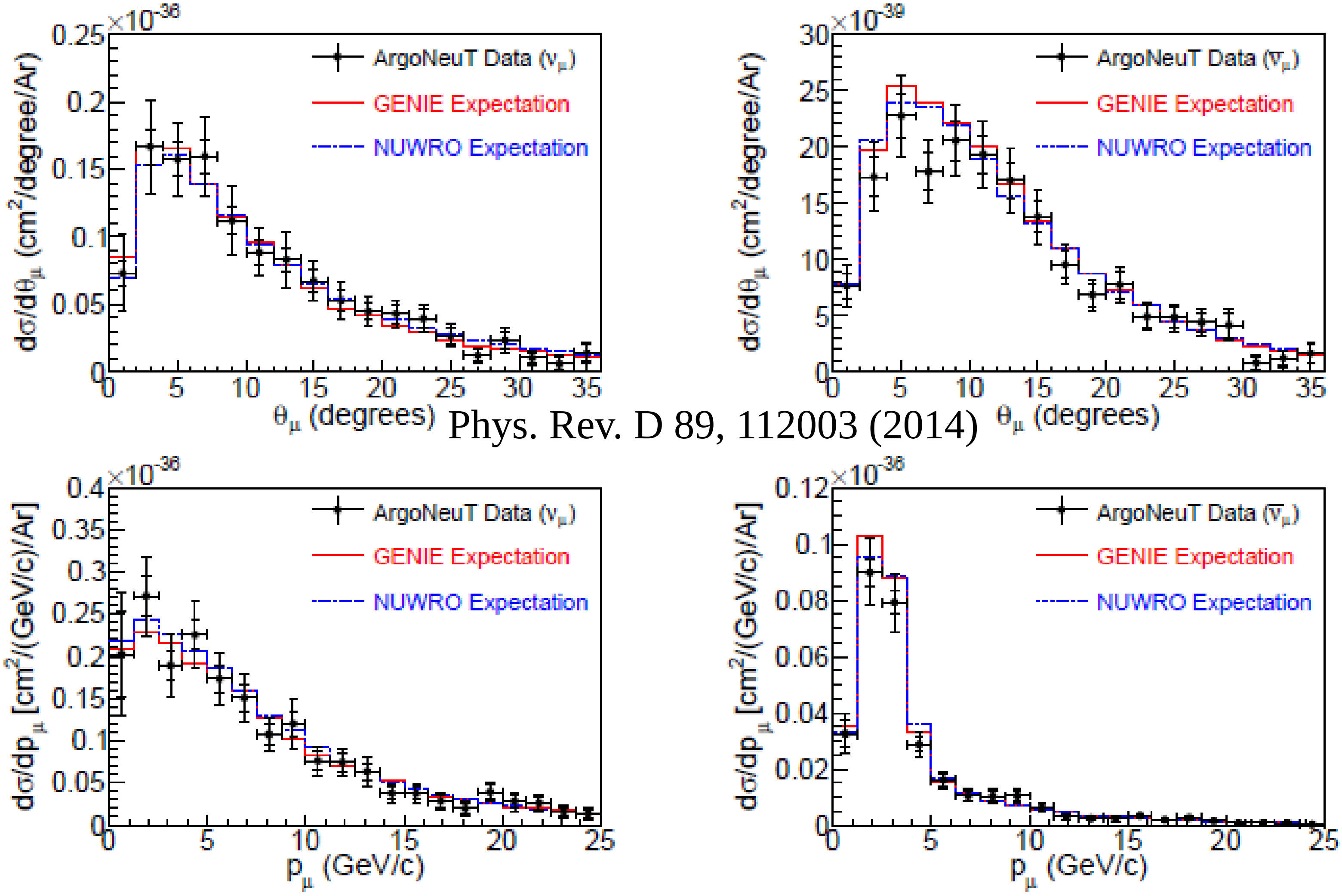


- Common thread seen in many experiments: deficit at low pion momentum, excess in few 100s MeV/c

What does ν-C scattering data tell us about ν-Ar?

- DUNE will be made of Argon
- We have some nice data now, mostly on carbon
- It is not clear what this tells us about ν-Ar
- We really need Argon data

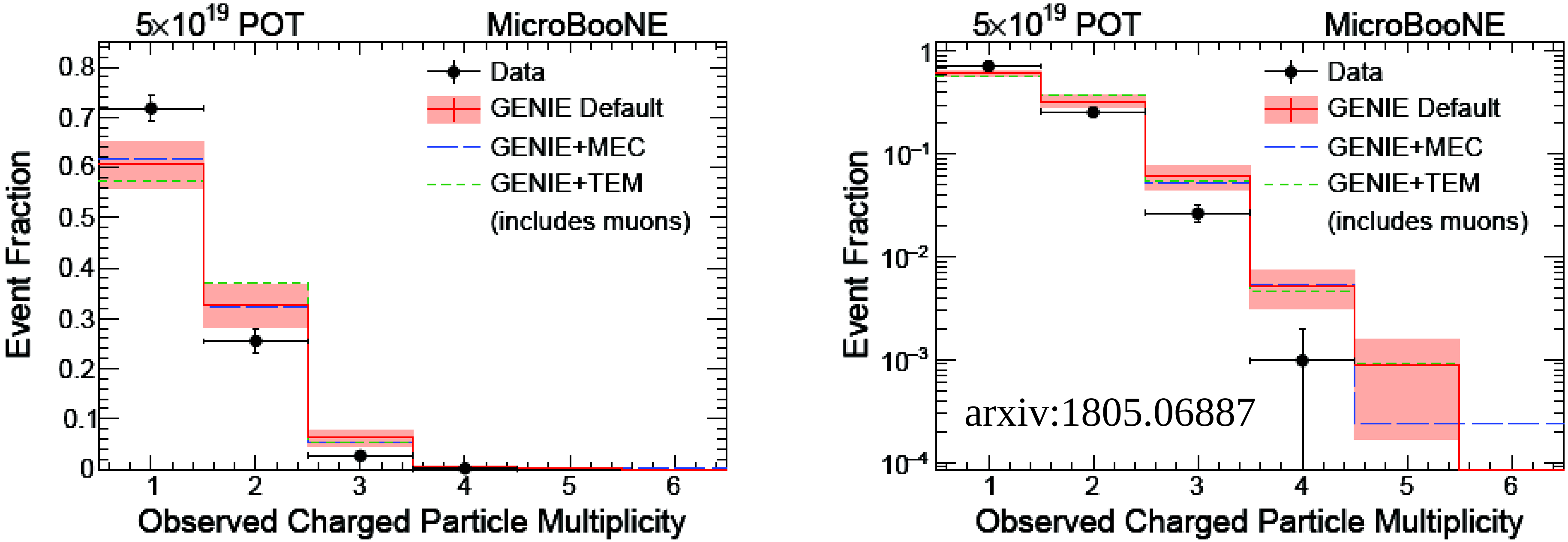
ArgoNeuT CC inclusive



Phys. Rev. D 89, 112003 (2014)

Real ν-Ar scattering measurements! But statistics are limited, and exclusive, differential measurements probably not useful

MicroBooNE & SBND



- First MicroBooNE result: multiplicities of charged particles compared to several model predictions
- Looking forward to more results
- In a few years: SBND will have even more statistics

Summary

- Recent data from MiniBooNE, MINERvA, T2K is sensitive to initial-state and final-state nuclear effects
- Significant improvements to cross section models have been incorporated in GENIE and NEUT generators
- We see hints of additional unmodeled effects, especially in pion production
- We have a lot more work to do

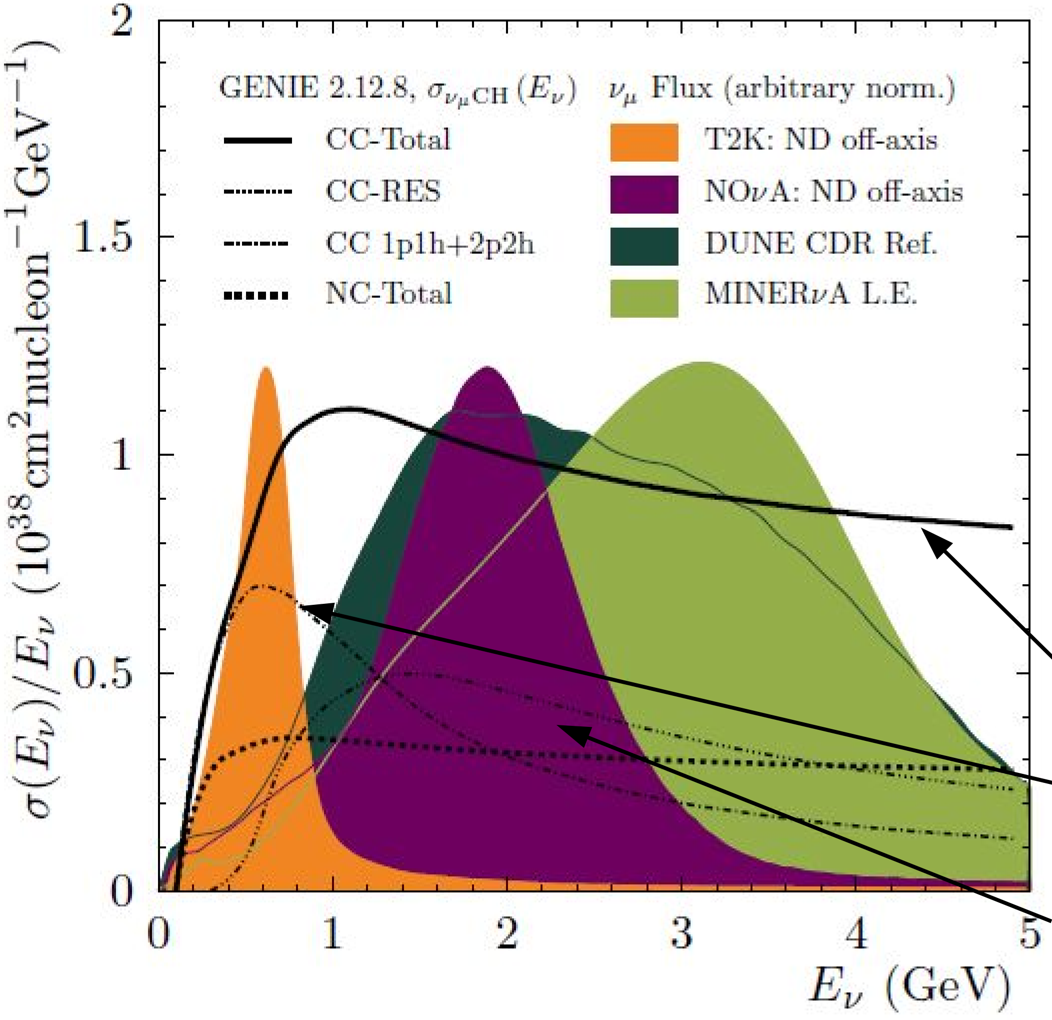
Thank you

Backups

Neutrino-nucleus cross section measurements

- MiniBooNE (CH_2)
- T2K ND280 (CH, also H_2O)
- MINERvA (CH, also C, Fe, Pb)
- NOMAD (CH)
- ArgoNeut (Ar)
- MicroBooNE (Ar)

Fluxes and cross sections vs. neutrino energy



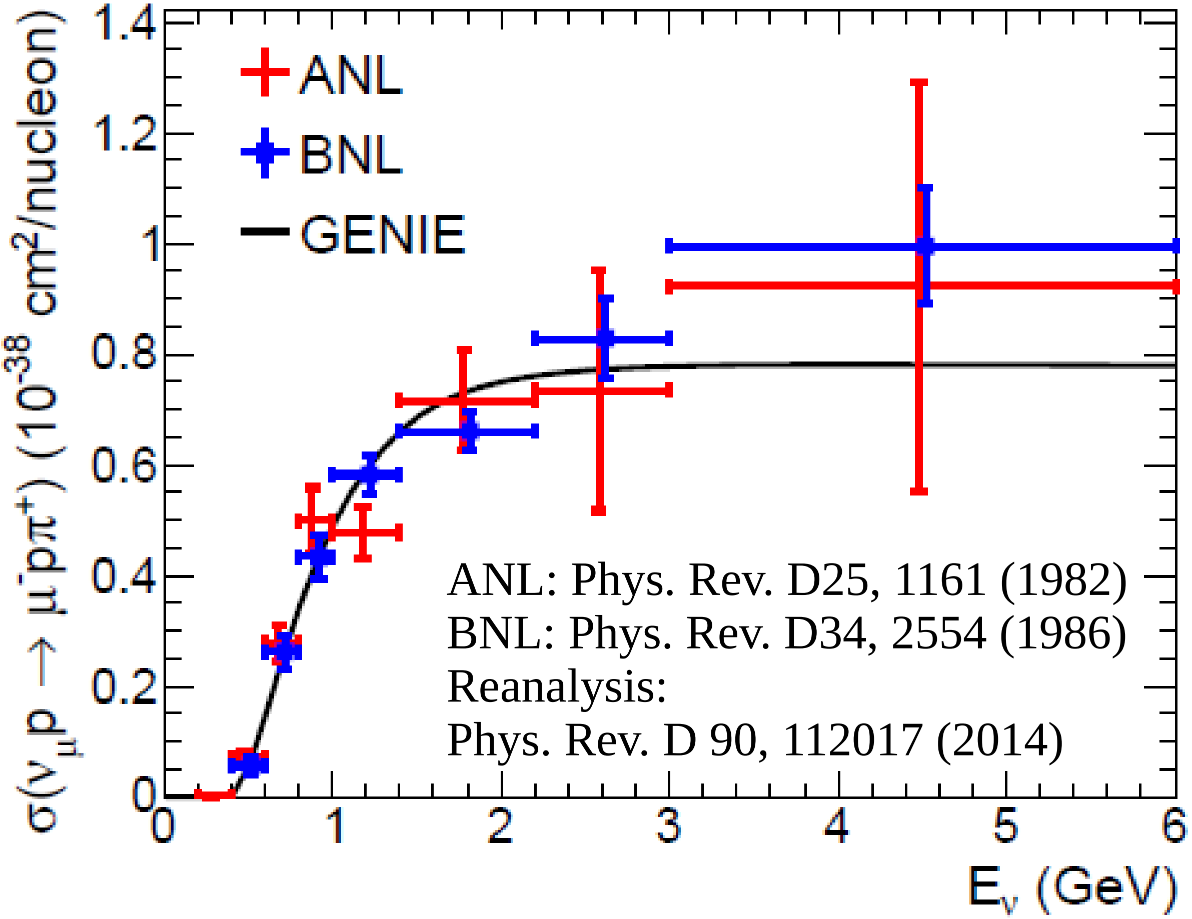
Oscillation experiments, especially DUNE, sit in a region where quasi-elastic (0π), resonant (1π), and deep inelastic are all significant

Total CC

CC0π

CC RES 1π

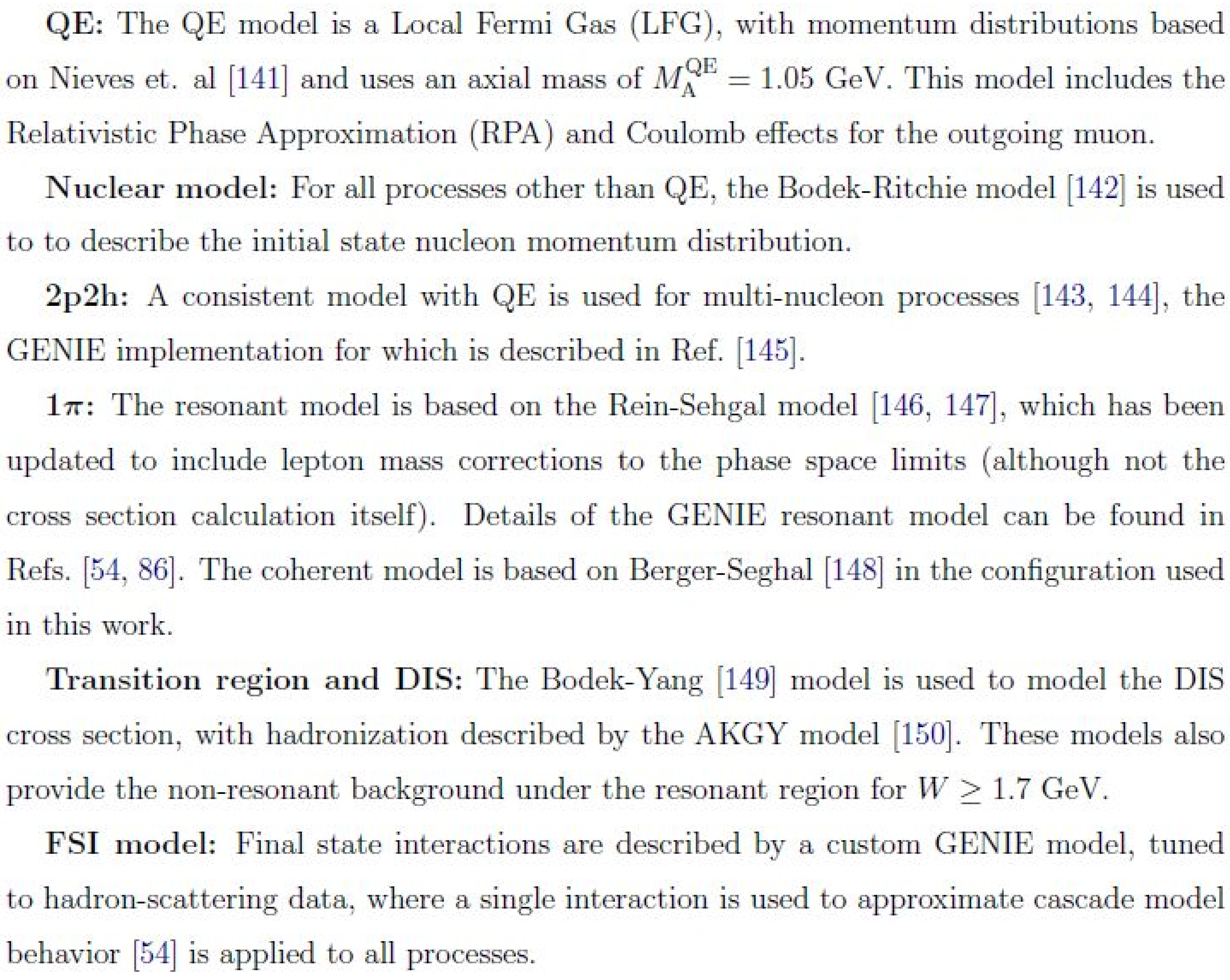
Deuterium bubble chamber data still critical for tuning



ANL: Phys. Rev. D25, 1161 (1982)
BNL: Phys. Rev. D34, 2554 (1986)
Reanalysis:
Phys. Rev. D 90, 112017 (2014)

- Free nucleon CCQE can be calculated
- Deuterium bubble chamber CC1π^+ data from ANL and BNL
- Recent re-analysis appears to resolve longstanding normalization issue

Reference GENIE model



QE: The QE model is a Local Fermi Gas (LFG), with momentum distributions based on Nieves et. al [141] and uses an axial mass of $M_{\mathrm{A}}^{\mathrm{QE}} = 1.05$ GeV. This model includes the Relativistic Phase Approximation (RPA) and Coulomb effects for the outgoing muon.

Nuclear model: For all processes other than QE, the Bodek-Ritchie model [142] is used to to describe the initial state nucleon momentum distribution.

2p2h: A consistent model with QE is used for multi-nucleon processes [143, 144], the GENIE implementation for which is described in Ref. [145].

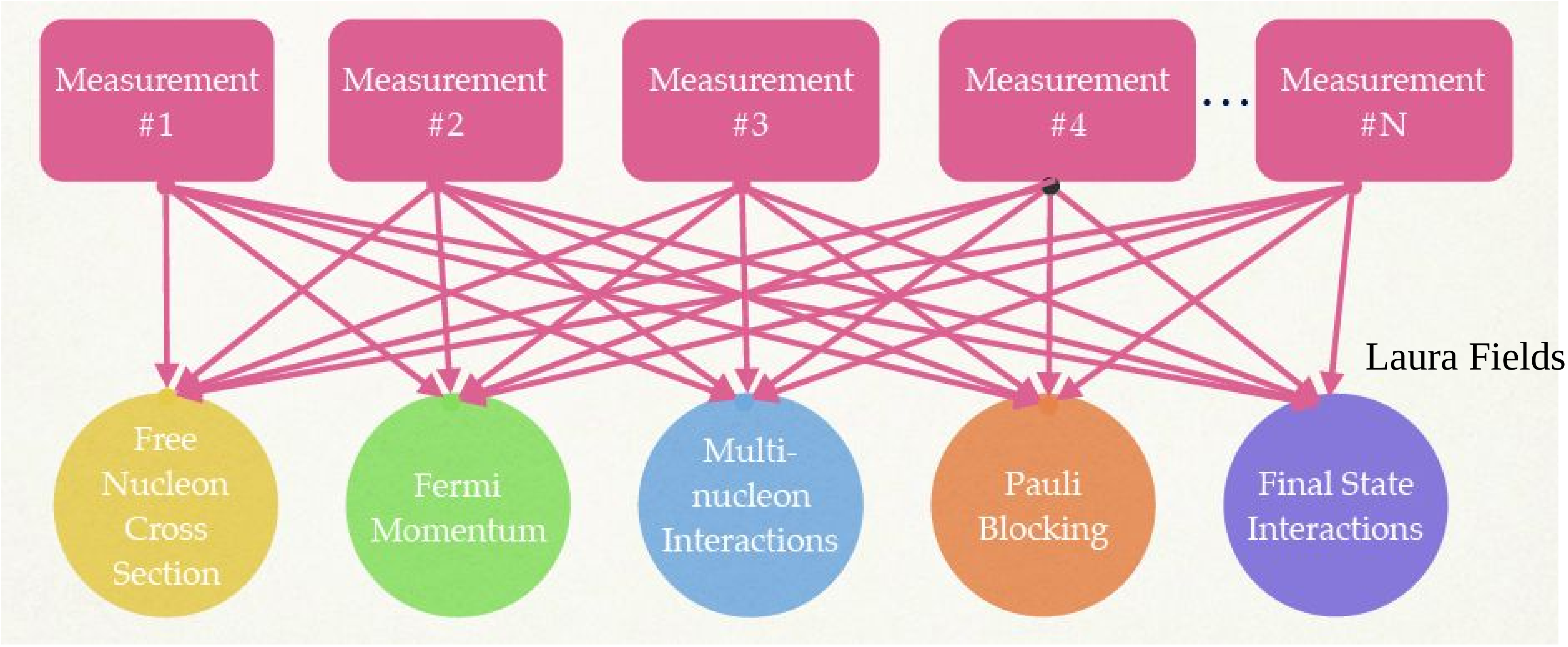
1π: The resonant model is based on the Rein-Sehgal model [146, 147], which has been updated to include lepton mass corrections to the phase space limits (although not the cross section calculation itself). Details of the GENIE resonant model can be found in Refs. [54, 86]. The coherent model is based on Berger-Seghal [148] in the configuration used in this work.

Transition region and DIS: The Bodek-Yang [149] model is used to model the DIS cross section, with hadronization described by the AKGY model [150]. These models also provide the non-resonant background under the resonant region for $W \geq 1.7$ GeV.

FSI model: Final state interactions are described by a custom GENIE model, tuned to hadron-scattering data, where a single interaction is used to approximate cascade model behavior [54] is applied to all processes.

Strategy fro constraining cross section models

- Many model parameters affect cross section measurements
- Make many measurements, with different sensitivities



Laura Fields

Llewellyn Smith CCQE and RFG

- Relativistic Fermi Gas (RFG): free nucleons in mean field
- Free nucleon cross-section formula: Llewellyn Smith

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 cos^2\theta_C}{8\pi E_\nu^2} \times [A(Q^2) \mp \frac{(s-u)B(Q^2)}{M^2} + \frac{C(Q^2)(s-u)^2}{M^2}]$$

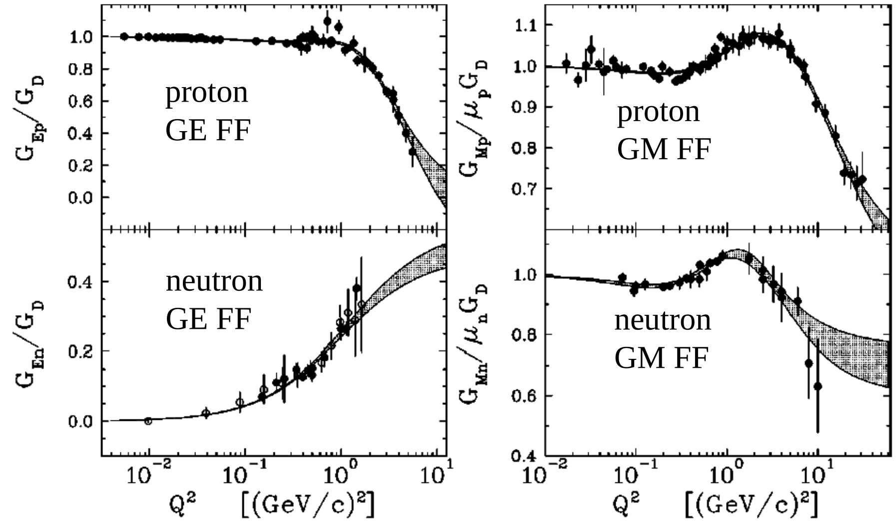
$$\boxed{\begin{aligned} A(Q^2) = \frac{m_l^2+Q^2}{M^2}&[(1+\tau)|F_A|^2 - (1-\tau)|F_1^V|^2 + \tau(1-\tau)|F_2^V|^2 + 4\tau F_1^V F_2^V] \\ &- \frac{m_l^2+Q^2}{M^2}\frac{m_l^2}{M^2}[|F_1^V + F_2^V|^2 + |F_A + 2F_P|^2 - 4(1+\tau)F_P^2] \\ B(Q^2) = 4\tau F_A(F1^V + F_2^V) \qquad & C(Q^2) = \frac{1}{4}(|F_A|^2 + |F_1^V|^2 + \tau|F_2^V|^2) \end{aligned}}$$

Llewellyn Smith, C.H., 1972, Phys. Rep. C3, 261.

Relativistic Fermi Gas (RFG) model

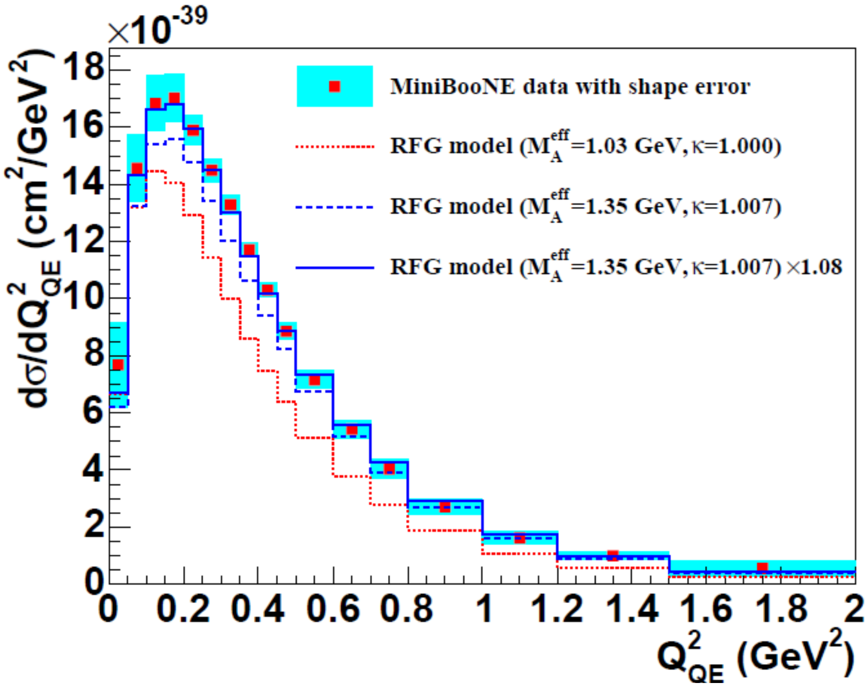
- Relativistic Fermi Gas (RFG): free nucleons in mean field
- Free nucleon cross-section formula: Llewellyn Smith
- F_V from electron scattering
- Assume dipole form of F_A

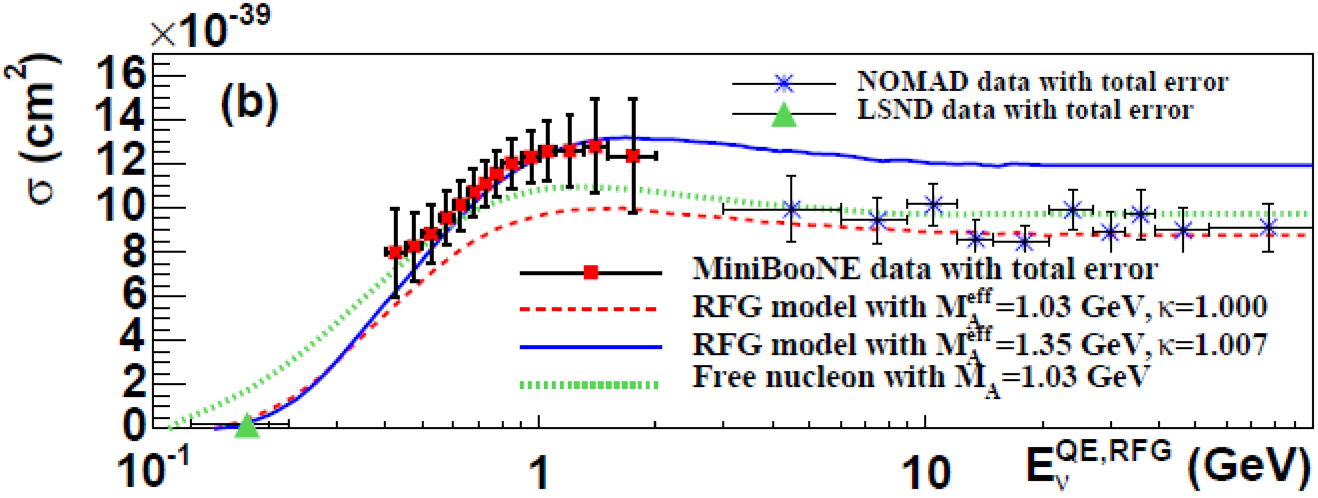
$$F_A(Q^2) = \frac{F_A(0)}{(1 + \frac{Q^2}{M_A^2})^2}$$


Kelly, Phys. Rev. **C70**, 068202 (2004)

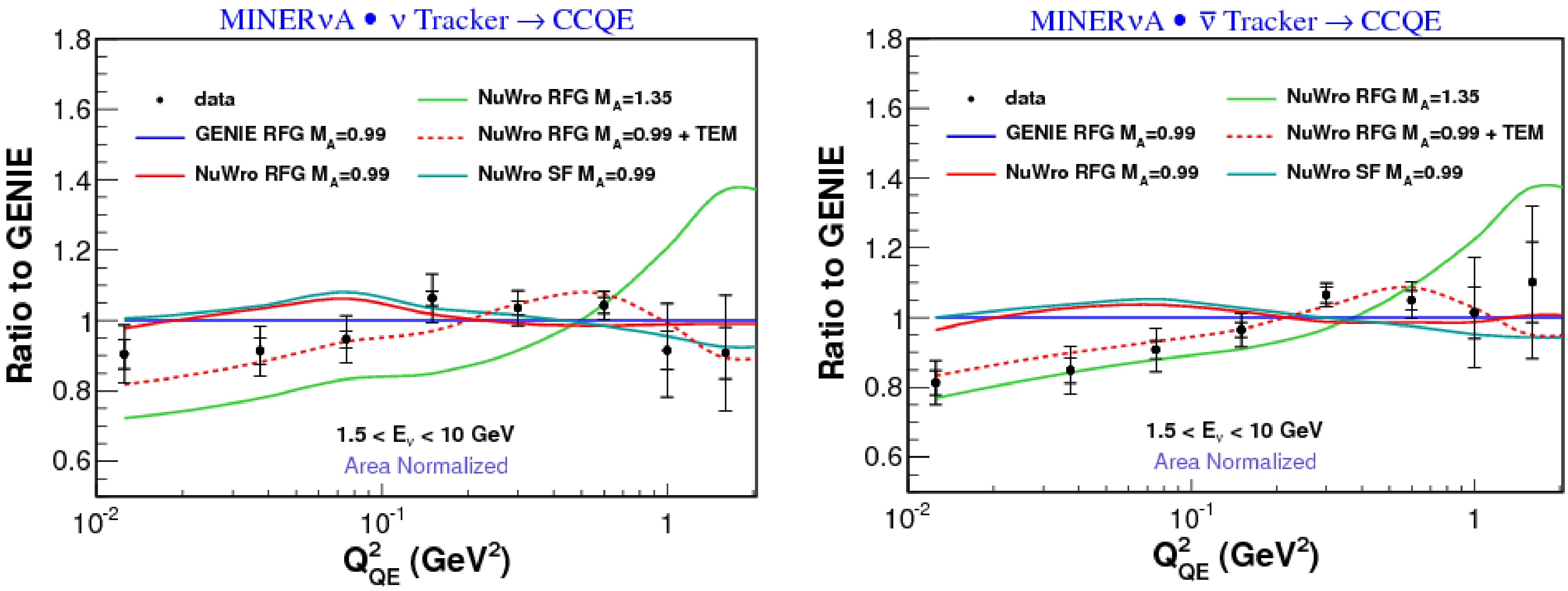
MiniBooNE CCQE

- MiniBooNE data show enhanced cross section compared to expectation based on deuterium
- Can accommodate RFG with increased axial mass
- NOMAD at higher energy do not see this enhancement



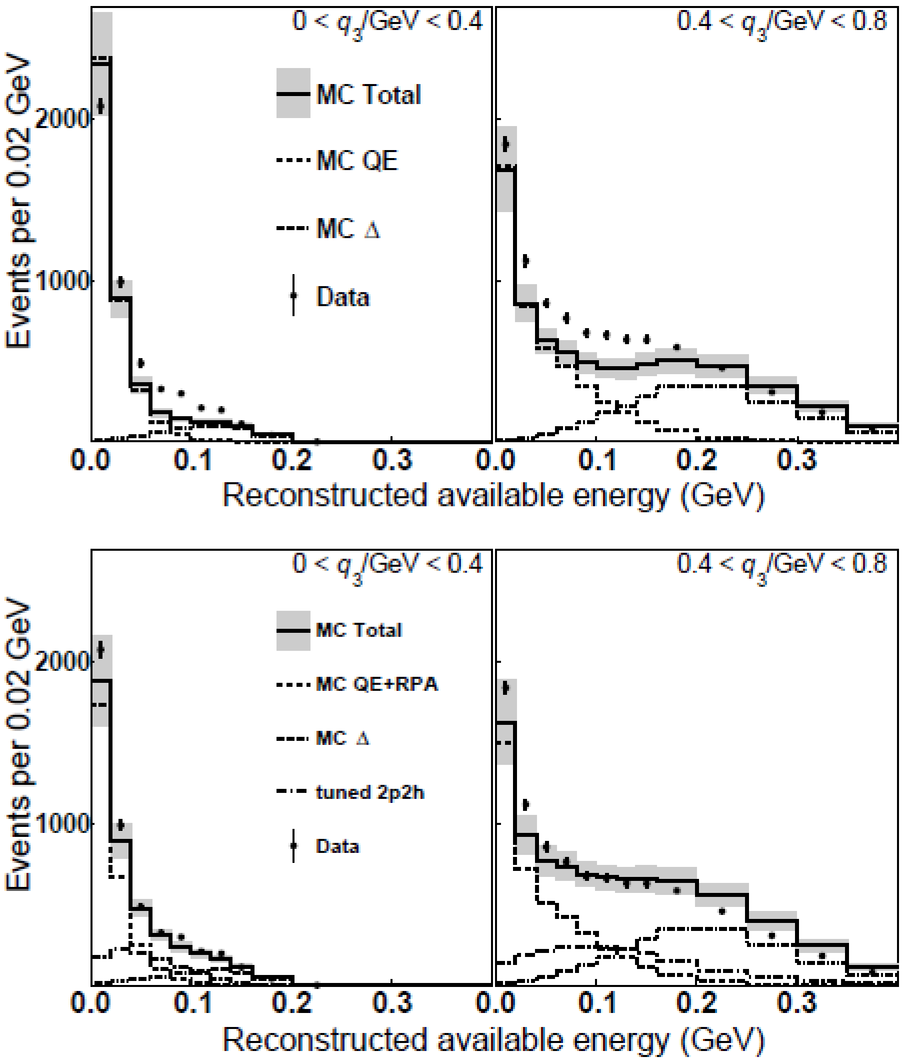


MINERvA CCQE



M_A = 1.35 —— Phys.Rev.Lett. 100, 032301 (2008)
TEM - - - - Eur. Phys. J. C 71, 1726 (2011)
GENIE —— Nucl.Instrum.Meth. A 614:87-104 (2010)
SF —— Nucl.Phys. A579, 493 (1994)

MINERvA q0q3 antineutrino

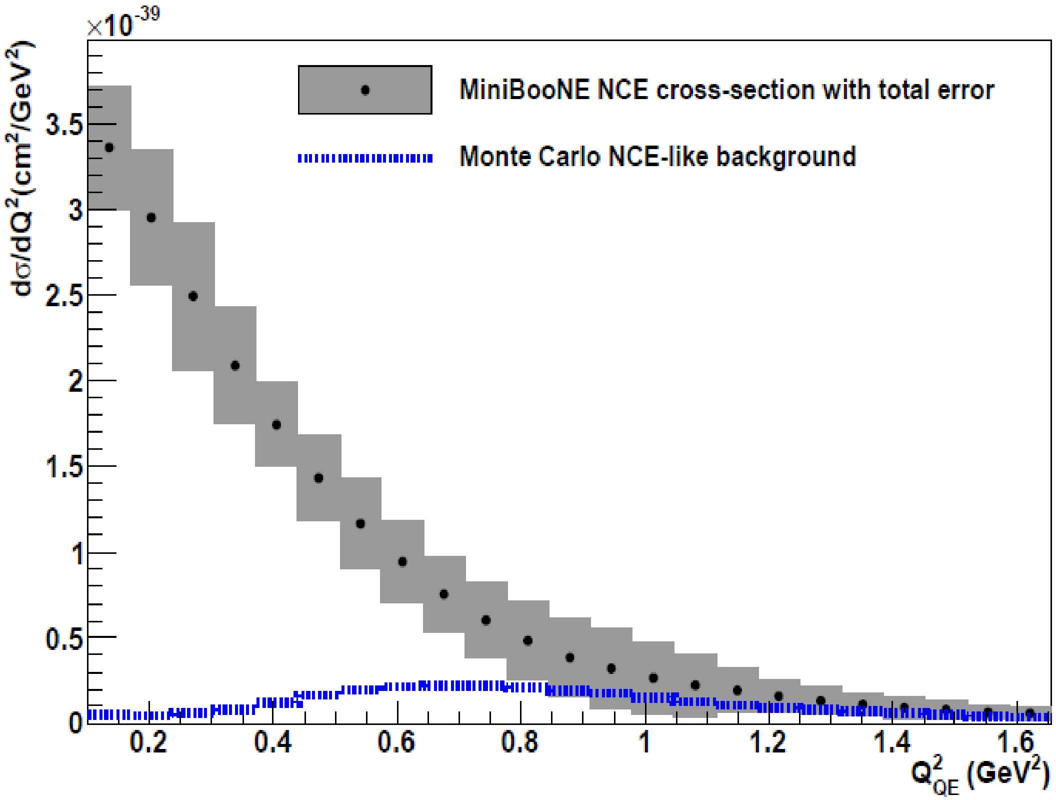


- Inclusive CC selection
- Bottom panels include QE RPA, tuned 2p2h
- Much better agreement in 2p2h region but Δ region still disagrees

Neutral current scattering

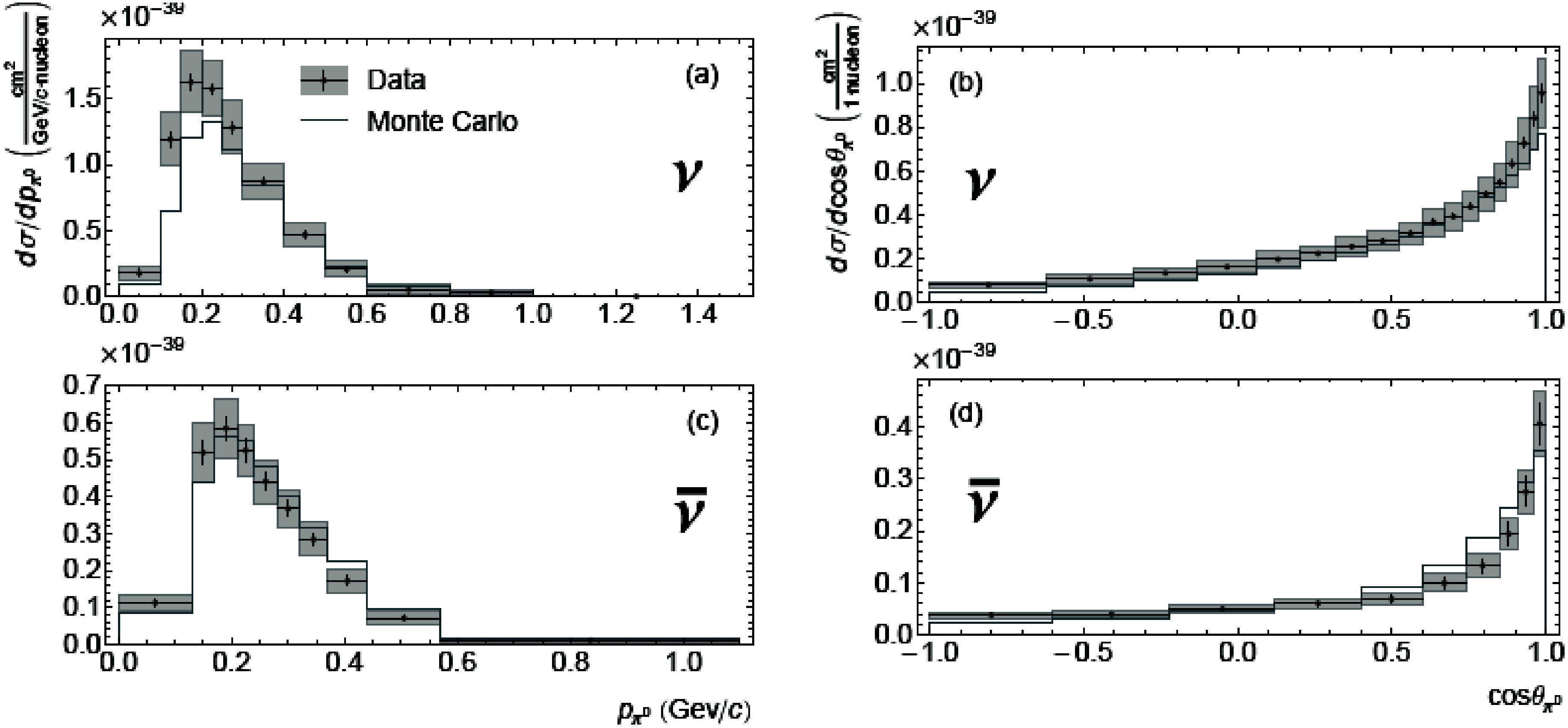
- NC processes are typically backgrounds in long-baseline oscillation searches
  - Single π^0 final state mimics ν_e CC
  - Single $\pi^\pm$ final state mimics ν_μ CC
- Also signal in active-sterile oscillation searches
- Very little high-statistics data available

MiniBooNE NC elastic



- ν C → ν p
- Differential measurement in momentum transfer, as measured from proton kinematics
- Very challenging backgrounds from rock neutrons

MiniBooNE NC π^0



- Measured in both neutrino and antineutrino modes
- Some disagreement with NUANCE in energy and angle