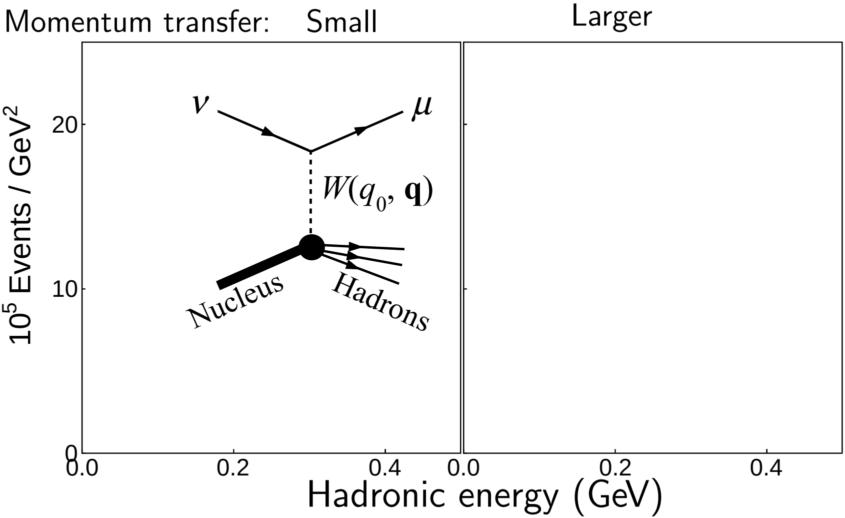
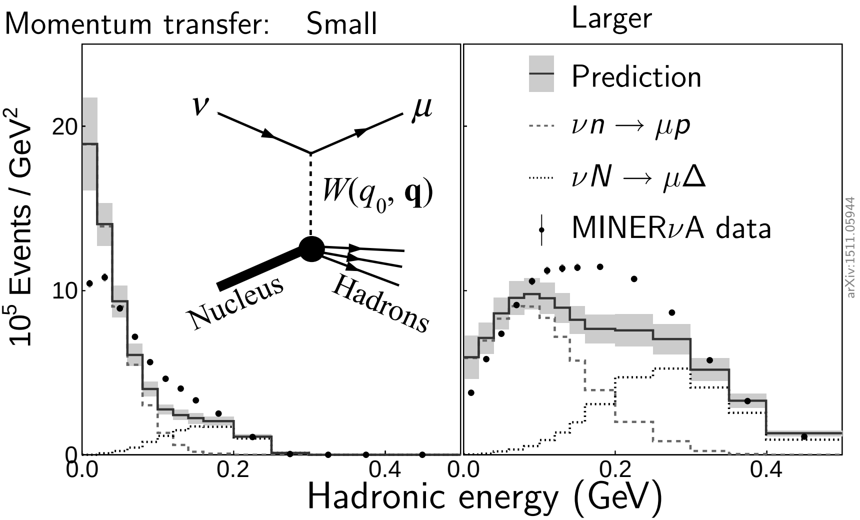
Identification of multinucleon effects in neutrino-carbon interactions at MINERνA

Philip Rodrigues, for the MINERνA collaboration

Fermilab Wine and Cheese seminar
Dec 11, 2015

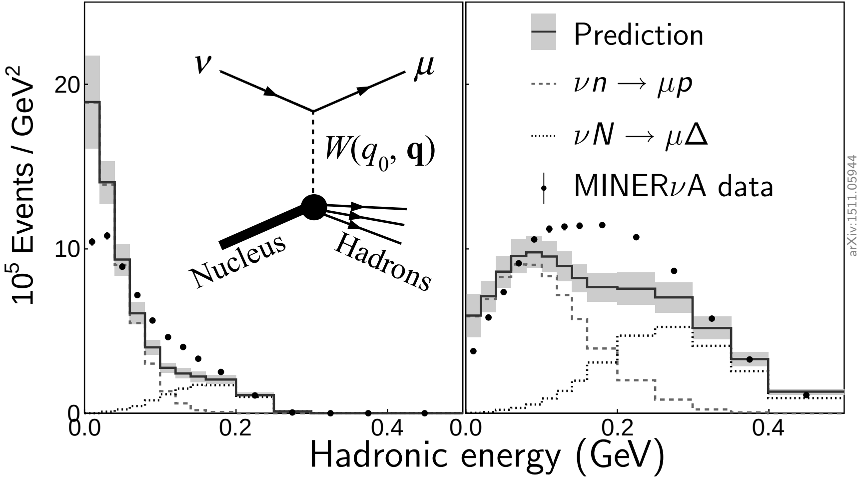


Momentum transfer: Small
Larger
10^5 Events / GeV^2
20
10
0
0.0
0.2
0.4
0.0
0.2
0.4
Hadronic energy (GeV)
ν
μ
W(q0, q)
Nucleus
Hadrons



Momentum transfer: Small
Larger
Prediction
$\nu n \to \mu p$
$\nu N \to \mu \Delta$
MINERνA data
ν
μ
$W(q_0, \mathbf{q})$
Nucleus
Hadrons
10^5 Events / GeV^2
20
10
0
0.0
0.2
0.4
0.0
0.2
0.4
Hadronic energy (GeV)
arXiv:1511.05944

Momentum transfer: Small Larger



We're going to measure neutrino oscillations precisely with *this*?!

Big questions in neutrino oscillations

- Do neutrinos violate CP?
- What does this imply for the baryon asymmetry of the universe?

$$P(\nu_\mu \longrightarrow \nu_e) \qquad\qquad P(\bar{\nu}_\mu \longrightarrow \bar{\nu}_e)$$

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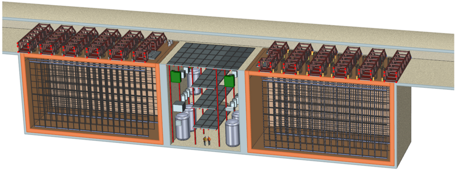

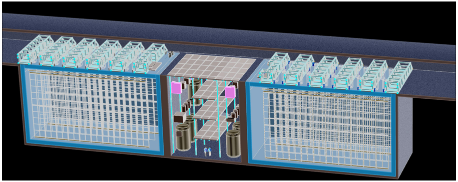

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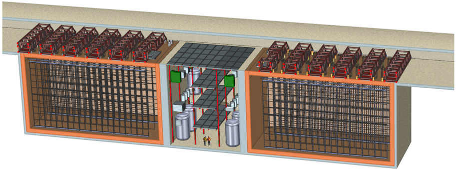
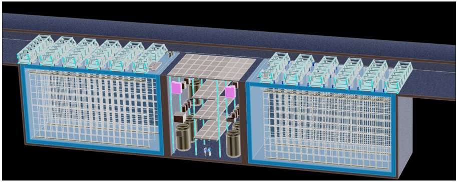
$P(\nu_\mu \to \nu_e)$



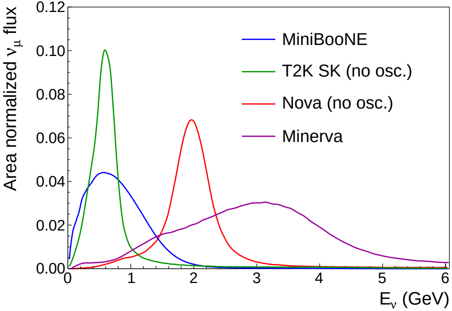
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$

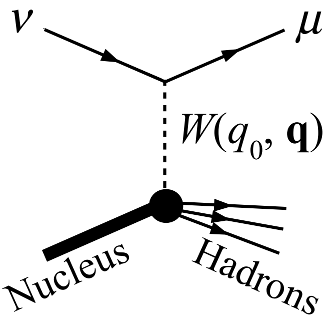


- But no anti-detectors! So we have to understand (anti-)neutrino interactions

Oscillation experiments need to reconstruct E_ν accurately

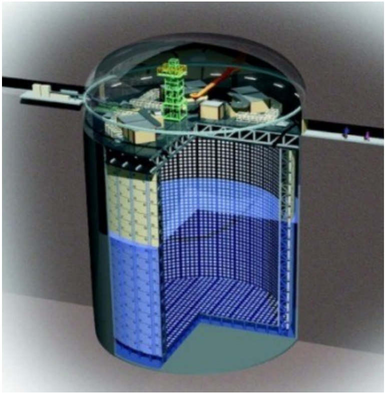
$$P(\nu_\alpha \to \nu_\beta) \approx 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{E_\nu} \right)$$

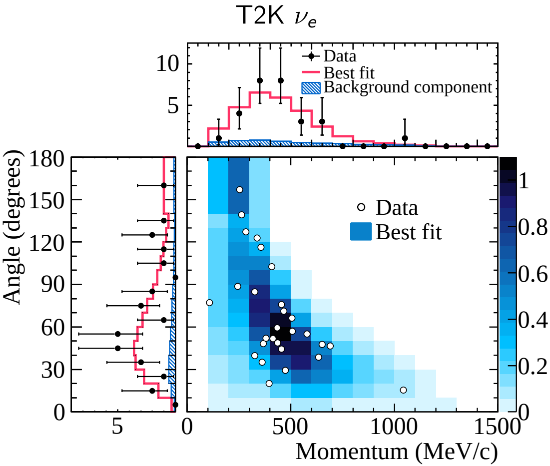




In Cerenkov detectors, need to model neutrino energy *vs* lepton kinematics

- Don't see hadrons: E_ν from lepton + two-body kinematic assumption

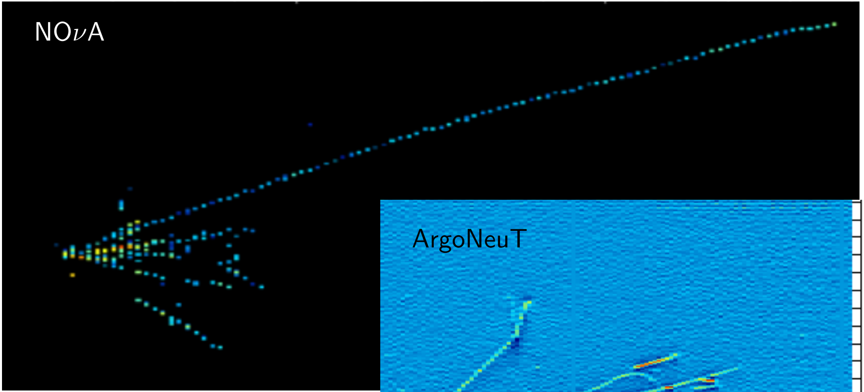


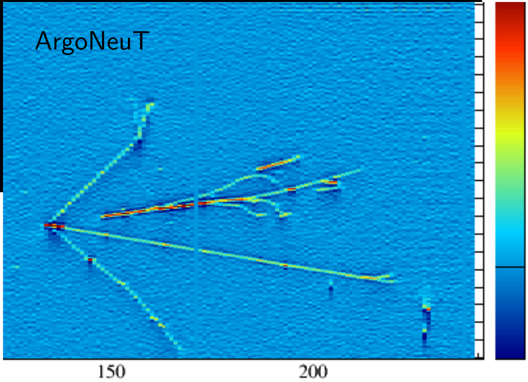


PRL 112, 061802 (2014)

In "fully-active" detectors, need to model hadron energy in detail

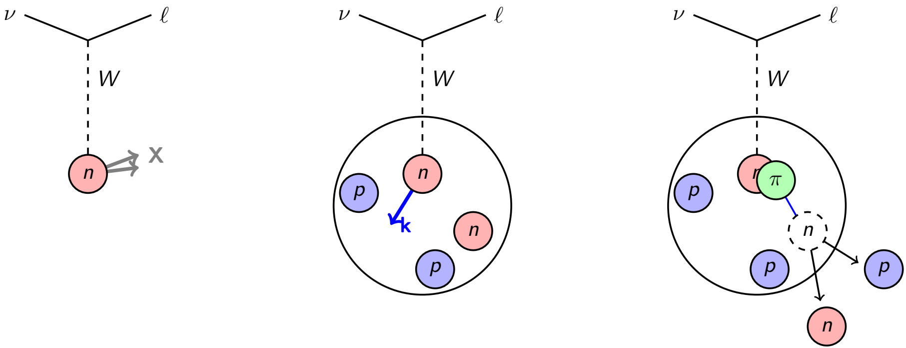
$$E_\nu = E_{\text{lepton}} + E_{\text{hadrons}}$$



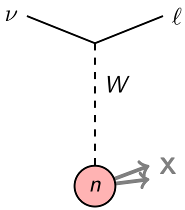


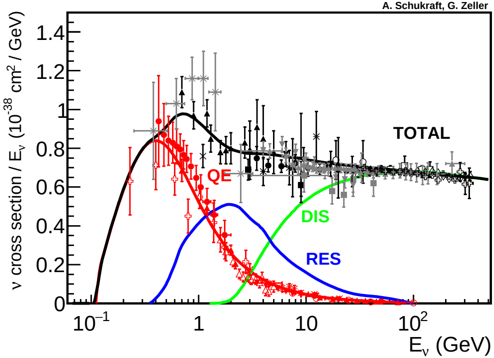
M. Sanchez, Fermilab neutrino seminar
http://t962.fnal.gov

Modeling neutrino-nucleus interactions proceeds in three steps

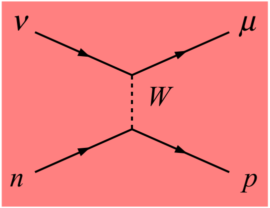


Even on free nucleons, several processes to model

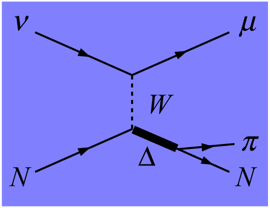




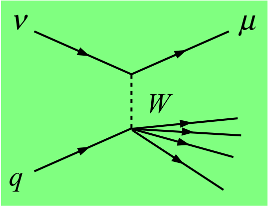
Quasielastic (QE)



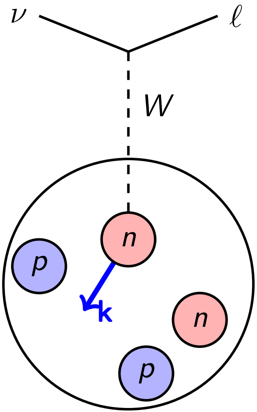
Resonance



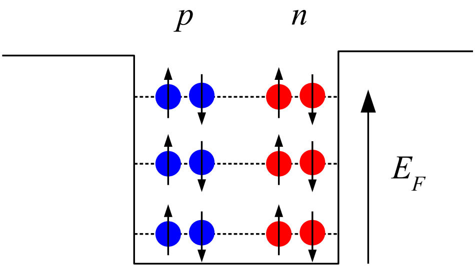
DIS



Nuclear effects modify cross sections and kinematics

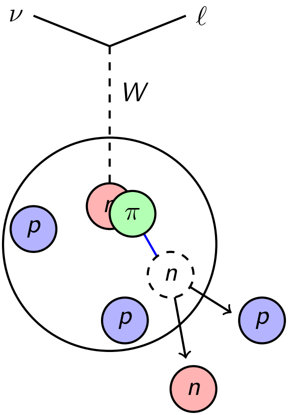


- Fermi gas (our "current model"):



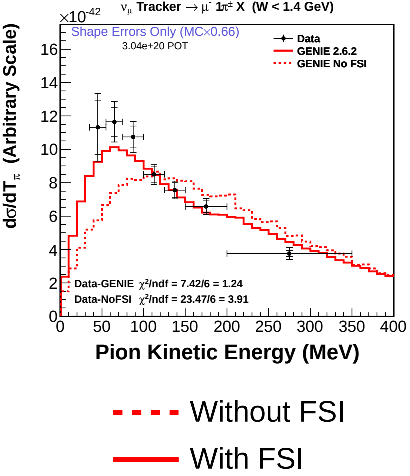
- Quasi-free nucleons in a mean field
- Fermi motion, binding energy, Pauli blocking

Final state interactions modify the observed hadrons



MINERνA CC $1\pi^{\pm}$

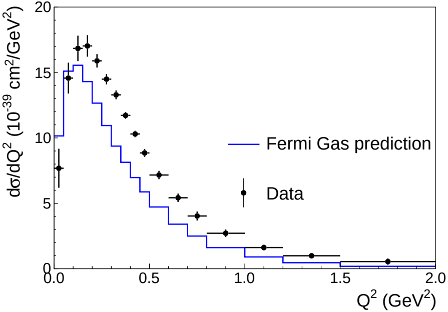
PRD 92, 092008 (2015)



Oscillation experiments have seen discrepancies with this model

Cerenkov: MiniBooNE 0 pion

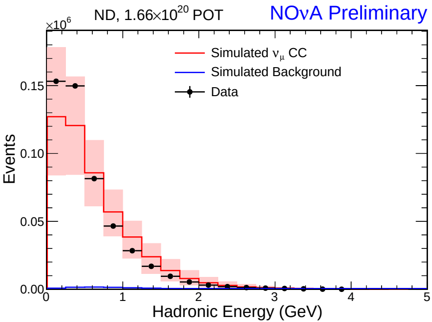
PRD 81, 092005 (2010)



(Four-momentum transfer)^2 $\rightarrow$

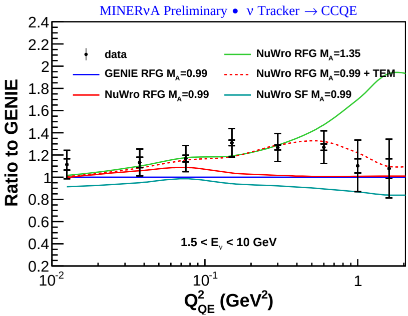
Fully active: NOνA ND ν_μ

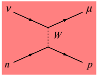
R. Patterson, FNAL JETP Aug 6, 2015



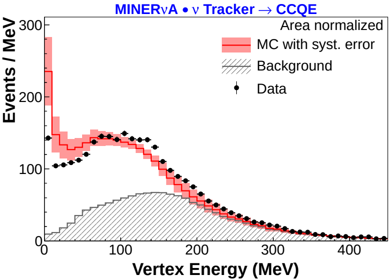
. . . so has MINERνA

Muon kinematics





Hadronic energy near interaction point

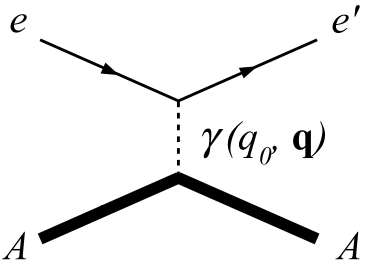


PRL 111, 022501 (2013); PRL 111, 022502 (2013) (updated flux)

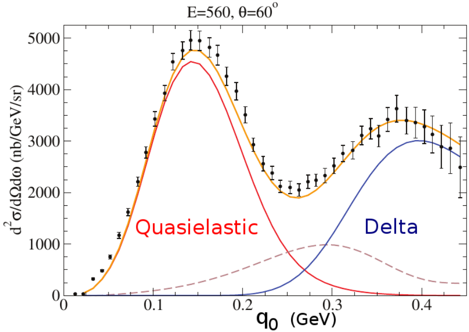
- So we know the model is wrong. Want to know exactly *what* is wrong

In electron scattering, reconstructing full event kinematics reveals details of nuclear structure

- Fixed electron energy, so just measure final state electron



Adapted from G. D. Megias, NuFact 2015



$$q_0 = E_e - E_{e'}$$

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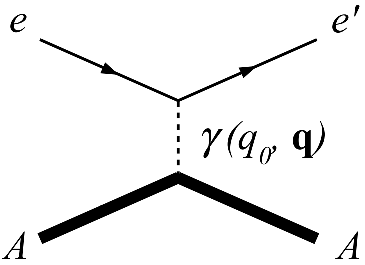

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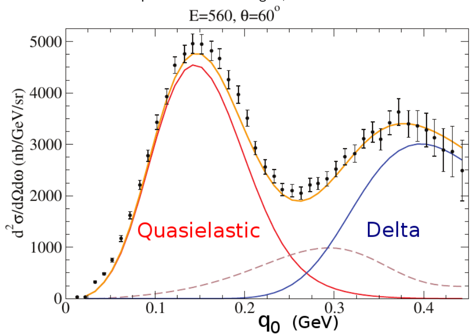
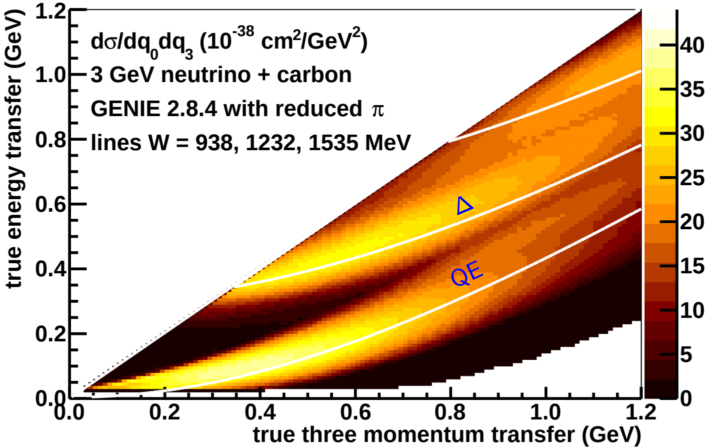


$$q_0 = E_e - E_{e'}$$

- What could we learn if we had similar variables in neutrino scattering?

Energy transfer and three-momentum transfer distinguish processes



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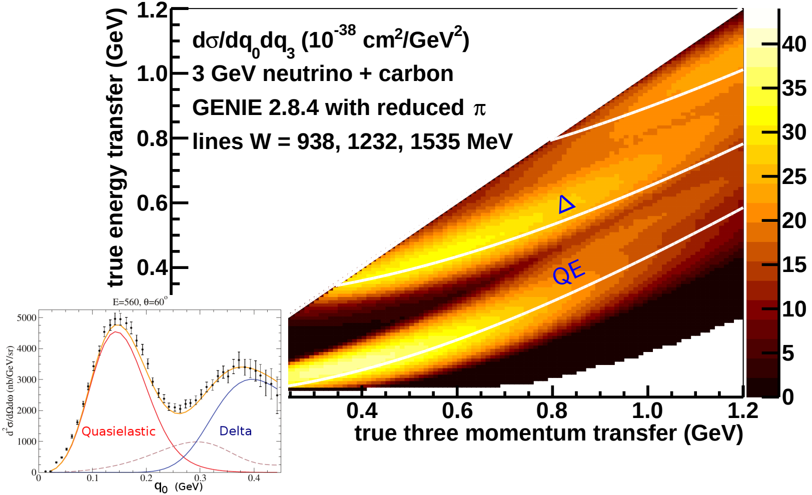
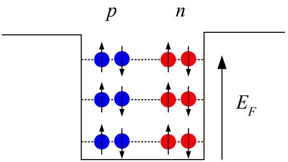
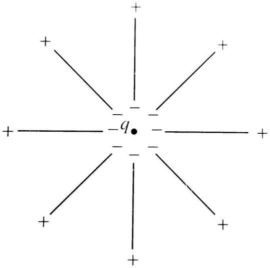


Evidence from nuclear physics suggests two effects missing in current event generators

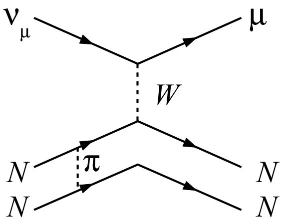


1. Screening from W polarization

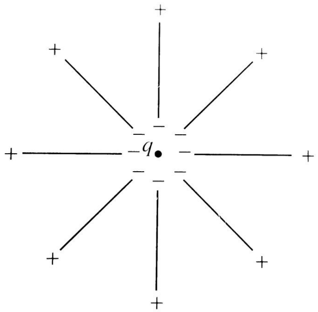


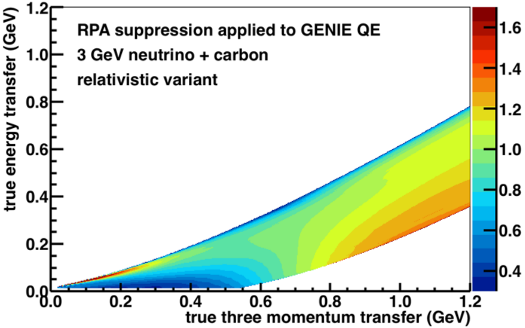
Griffiths, *Introduction to Electrodynamics*

2. Interactions involving multiple nucleons



Charge screening in nuclear medium: “RPA”

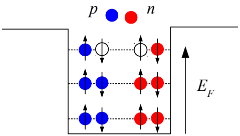


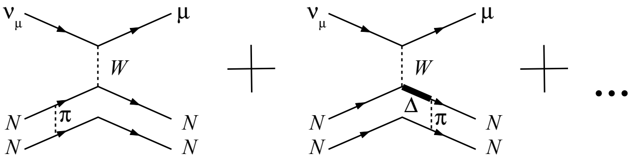


Griffiths, *Introduction to Electrodynamics*

- Analogous to screening of electric charge in a dielectric
- Calculated using Random Phase Approximation (RPA) PRC 70, 055503 (2004)
- Suppresses low energy, momentum transfer

Interactions involving multiple nucleons: “2p2h”





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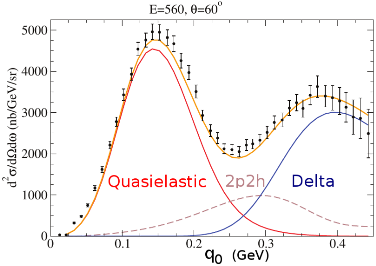

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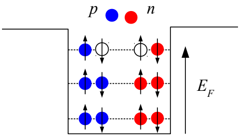

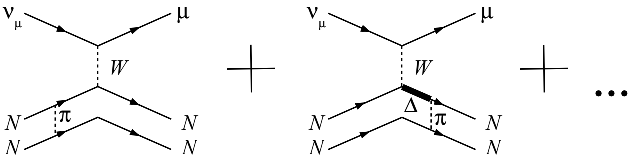

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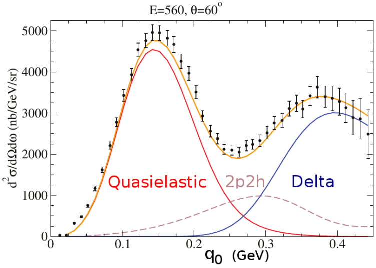
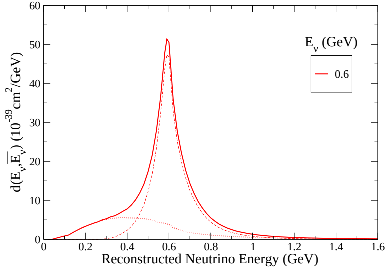


Breaks Čerenkov detector energy reconstruction!



These two effects turn up in different regions of our 2D space

- Put in both effects, take ratio to nominal:

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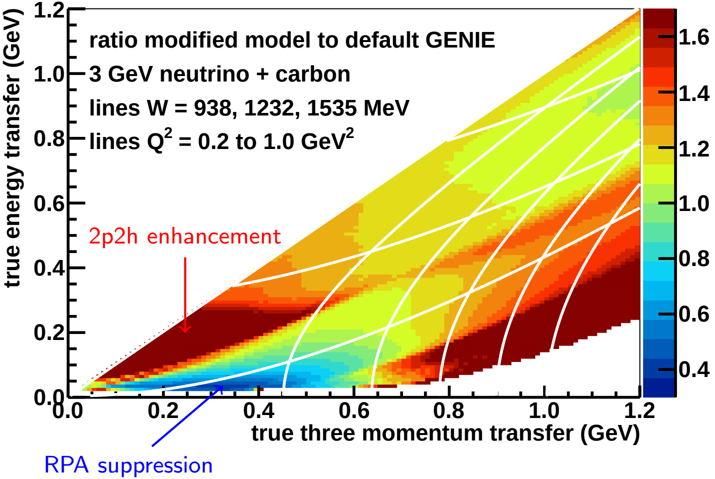
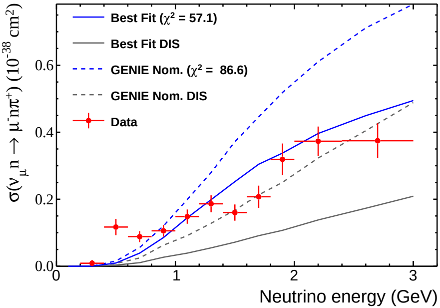


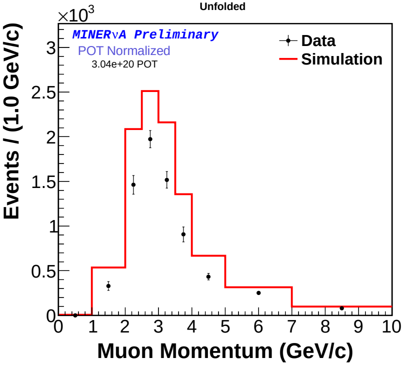
- Use illustrative Nieves *et al.* calculations PRC 70, 055503 (2004); PRC 83, 045501 (2011)
- Calculations only for 0π final states

Side story: We modify GENIE pion production to agree with deuterium and MINERνA data

BNL D_2 $\nu_\mu n \to \mu^- n \pi^+$

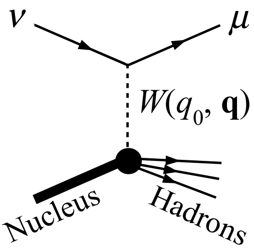


MINERνA $\pi^\pm$ production



- Scale down nonresonant pion production by 75% (1.5σ)
- Further scale down pion production with $W < 1.8$ GeV by 10%
- Applied throughout this talk

In neutrino scattering, we need to reconstruct the hadronic energy too



Energy transfer:

$$q_0 \equiv \nu = \text{Calorimetric hadronic energy}$$

Neutrino energy:

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

Four-momentum transfer squared:

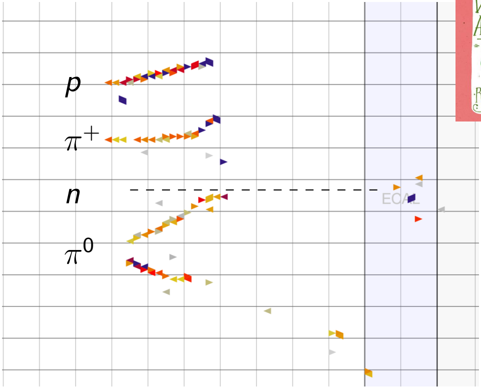
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$$

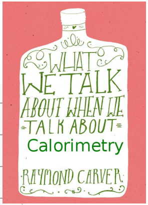
Three-momentum transfer:

$$q_3 \equiv |\mathbf{q}| = \sqrt{Q^2 + q_0^2}$$

- Produce inclusive CC ν_μ double-differential cross section in (q_0, q_3)

What does calorimetric energy really mean?





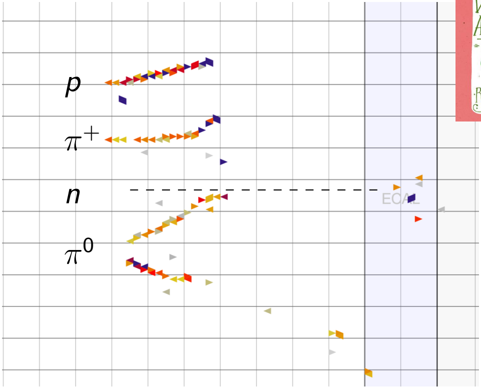
What does calorimetric energy really mean?

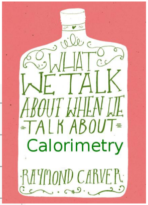
Kinetic energy

Kinetic energy

0

Total energy





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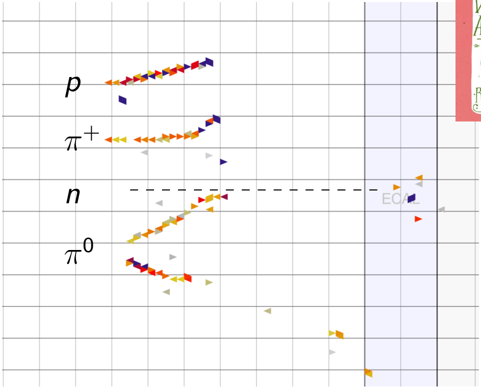
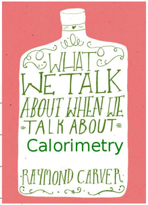




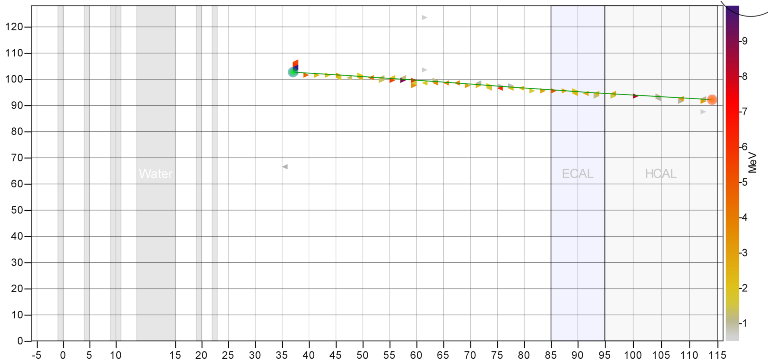
On average, we see *available* hadronic energy $E_{\text{avail}} \neq q_0$:

$$E_{\text{avail}} = \sum(\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total } E \text{ of other particles except neutrons})$$

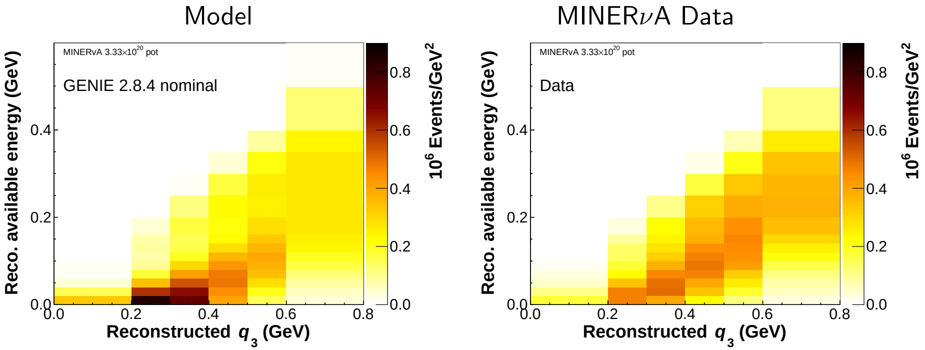
Start with an inclusive CC ν_μ selection

- All 3.33×10^{20} pot of NuMI LE neutrino-mode data. Thanks AD! Thanks SCD!
- Fiducial interaction (CH tracker)
- Negative muon matched to MINOS: Thanks MINOS!
- $2 < E_\nu < 6$ GeV

127,420 events, 97% purity

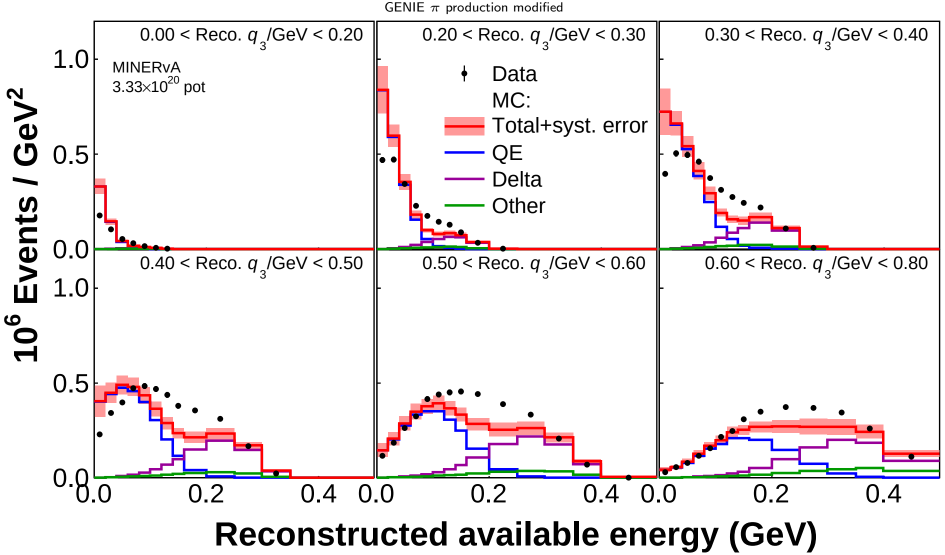


Data disagrees with model in reconstructed variables



- Easier to compare in slices of momentum transfer. . .

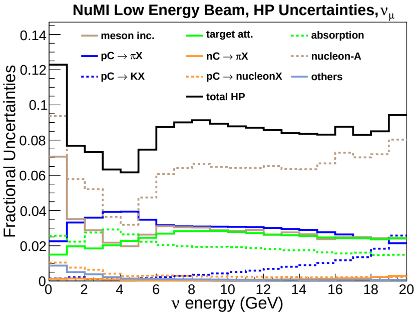
Data disagrees with model in reconstructed variables



- Interpret as problem with cross section model

Important systematics are well under control

- Flux
  - Tune to NA49 data
  - Remaining O(10%) uncertainties
  - Essentially an overall scale
  - L. Aliaga W&C, Dec. 18 at 1PM



+beam focusing

Important systematics are well under control

- Flux
  - Tune to NA49 data
  - Remaining O(10%) uncertainties
  - Essentially an overall scale
  - L. Aliaga W&C, Dec. 18 at 1PM
- Muon energy scale
  - Muon p scale known to 2–3%

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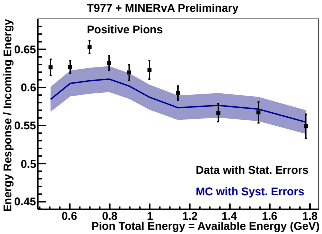
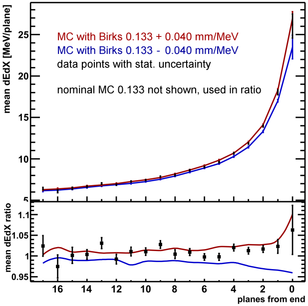
  - Testbeam measurements

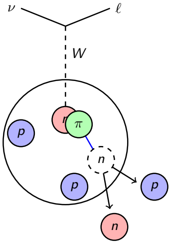




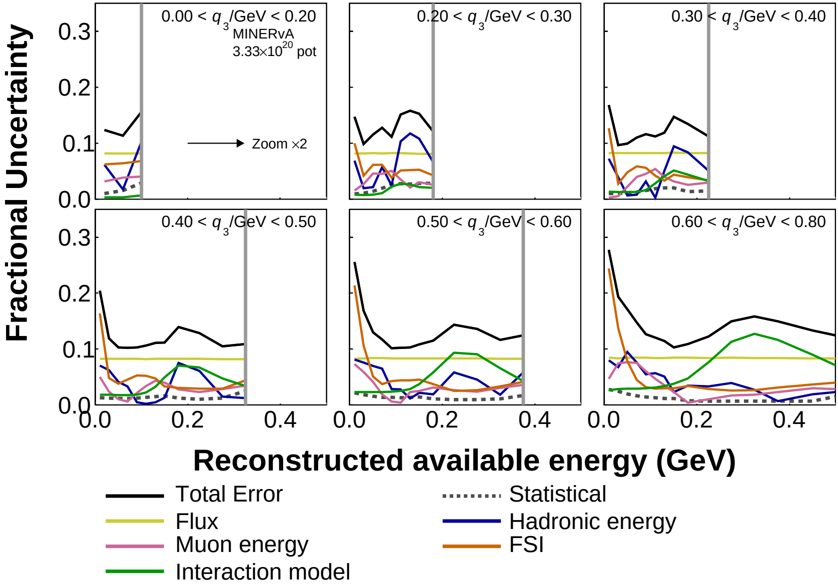
Important systematics are well under control

Model parameter	Uncertainty (%)
CC resonance prod.	20
Δ axial mass M_A^{res}	20
Non-resonant π prod.	50
FSI:	
π, N mean free path	20
π absorption	30

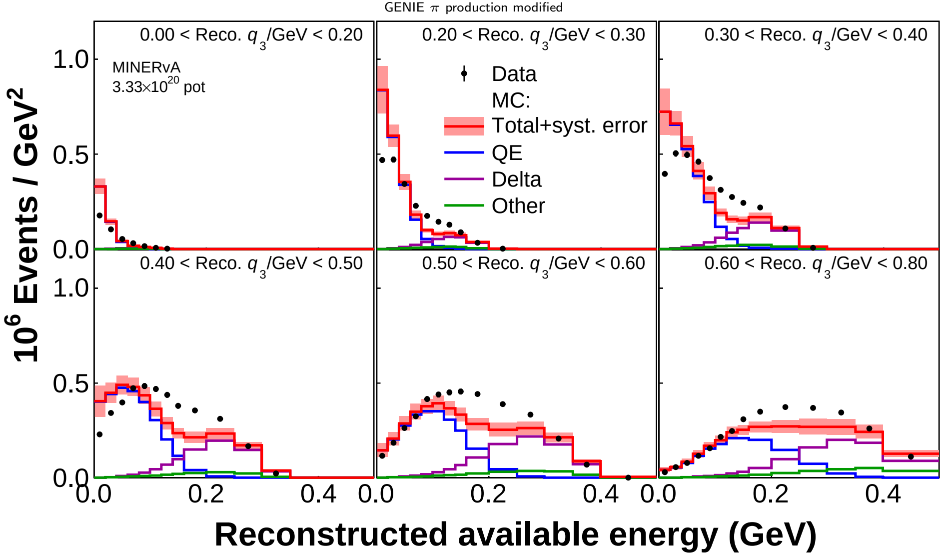
- Flux
  - Tune to NA49 data
  - Remaining O(10%) uncertainties
  - Essentially an overall scale
  - L. Aliaga W&C, Dec. 18 at 1PM
- Muon energy scale
  - Muon p scale known to 2–3%
- Recoil energy reconstruction
  - Testbeam measurements
- Interaction modelling
  - 10s of % uncertainties on primary interaction, FSI



10–20% systematic error on MC prediction > statistical error

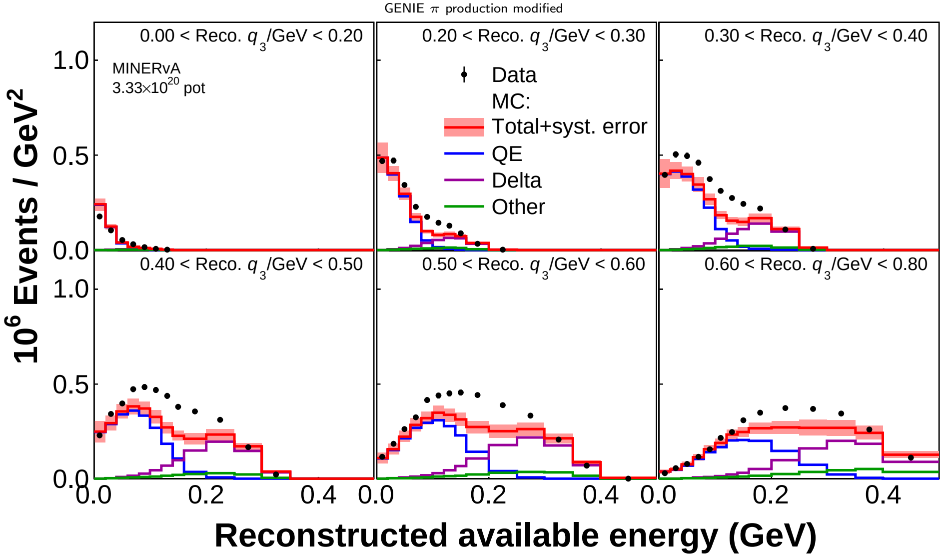


That default prediction again...



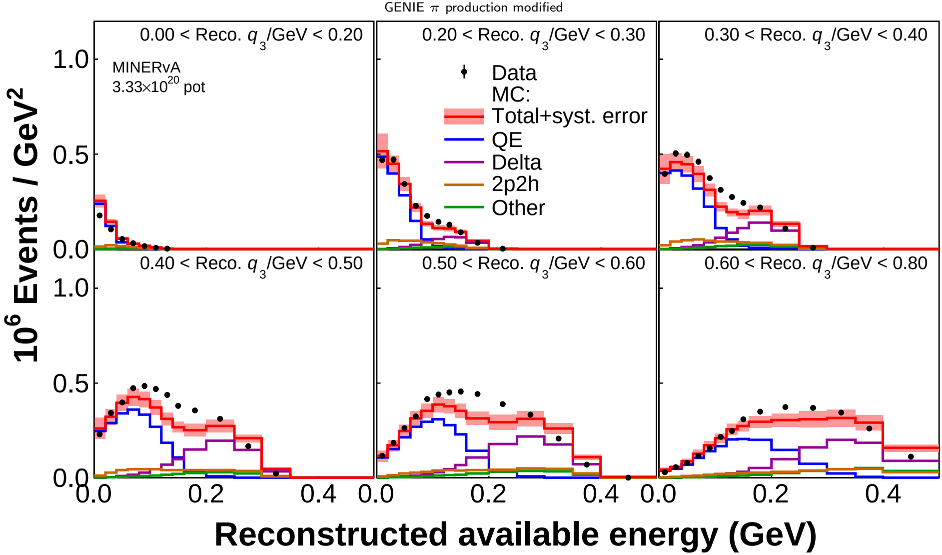
- $\chi^2 = 896$ (stat+syst, 62 dof)

RPA screening improves agreement at low q_3, E_{avail}



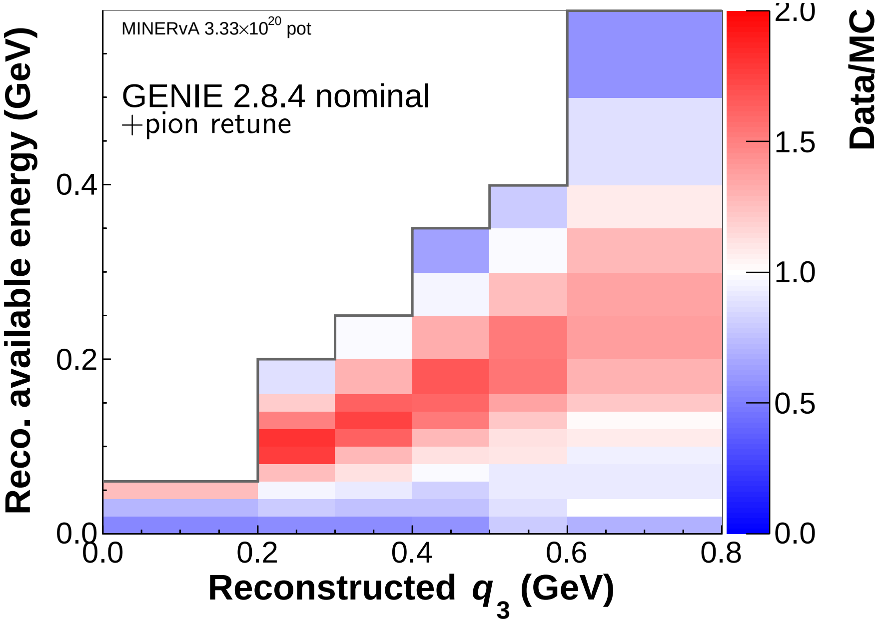
- $\chi^2 = 540$ (stat+syst, 62 dof)

Adding 2p2h events is a smaller improvement

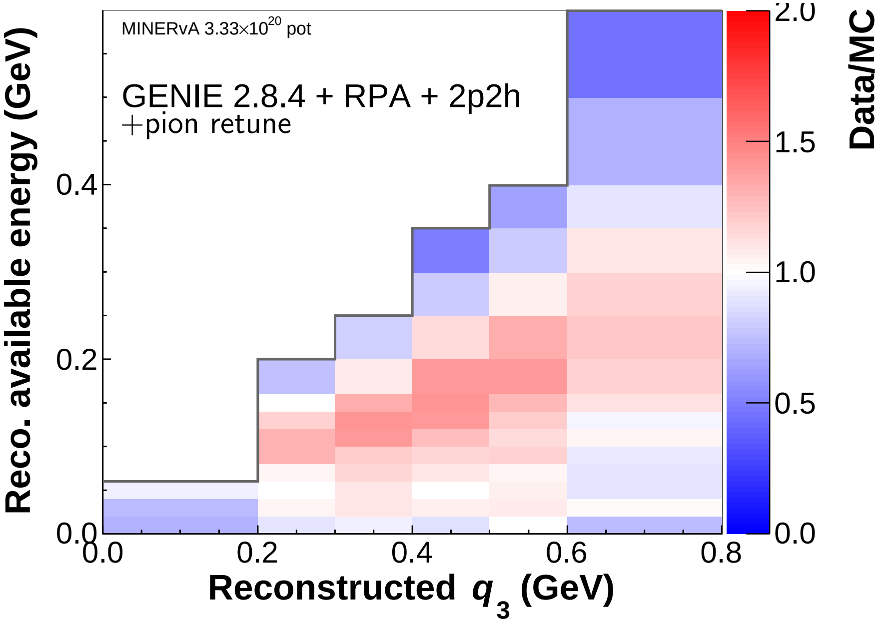


- $\chi^2 = 498$ (stat+syst, 62 dof)

Data/MC ratio shows discrepancies are in contiguous regions

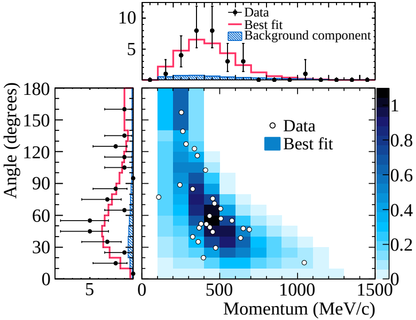


Discrepancy reduced with RPA+2p2h model

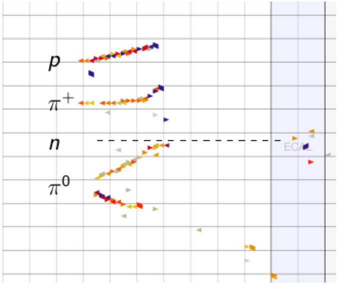


Step back: what have we learned?

- Got into details to demonstrate that our data shows where the current model falls down
- E_{avail} not well modeled. Possibilities:
  - q_0 not well modeled. Problem for Cerenkov detectors
  - Relationship $q_0 \rightarrow E_{avail}$ not well modeled. Problem for calorimetric detectors



PRL 112, 061802 (2014)



Step back: what have we learned?

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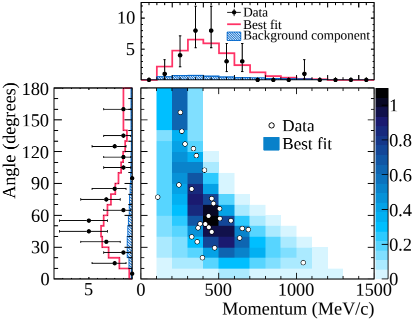
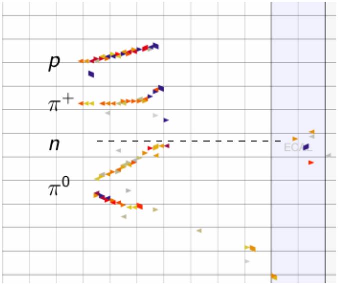


PRL 112, 061802 (2014)



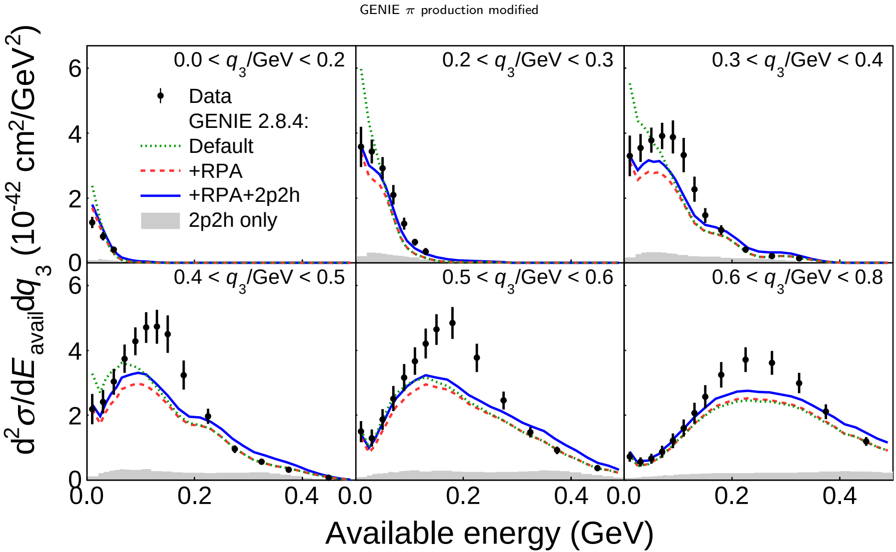
- To adapt to other detectors, need models. Models need cross-section data. . .

Making a cross section for comparison to models

$$\sigma_i = \frac{U_{ij}(N_j - B_j)}{\Phi_i T \varepsilon_i A_i}$$

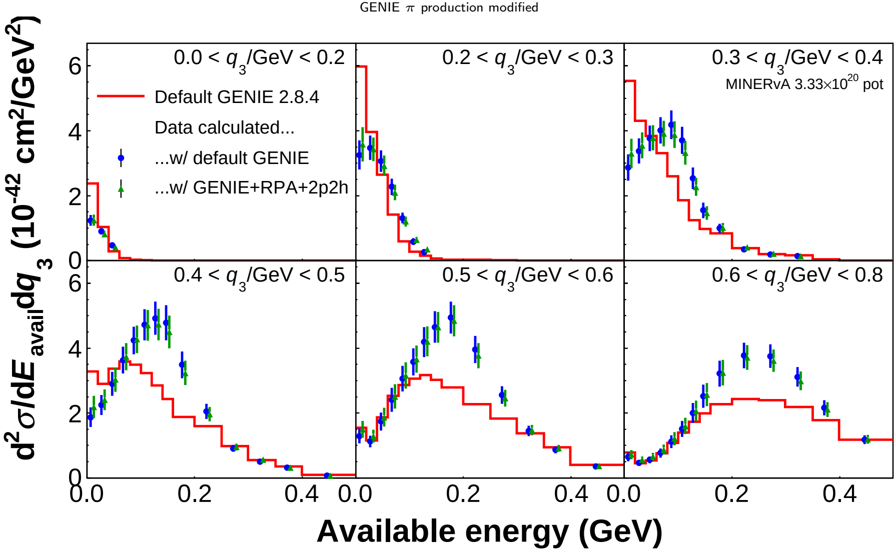
- Subtract small BG using MC (only 3%)
- Details:
  - Flux integrated over $2 < E_\nu < 6$ GeV
  - Don't extrapolate to undetected regions: require $p_\mu > 1.5$ GeV, $\theta_\mu < 20^\circ$

The inferred cross section will allow model comparisons



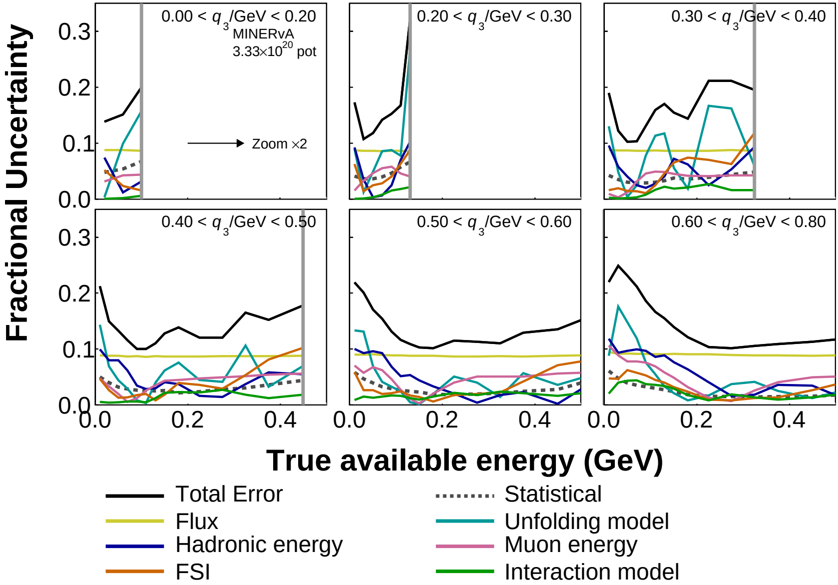
- Your model goes here!

Cross section calculation has small MC dependence

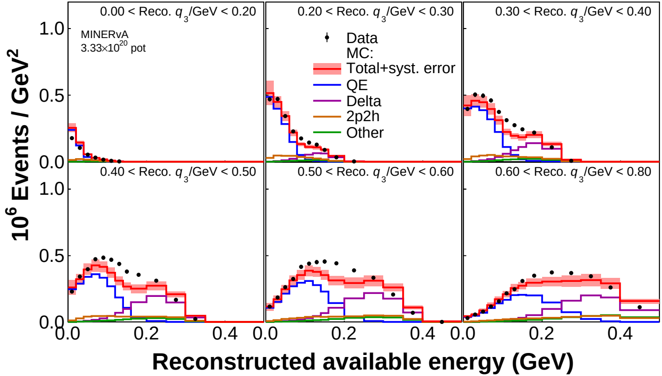


- 100% of difference is taken as "Unfolding model" systematic

10–20% systematic error on cross section > statistical error

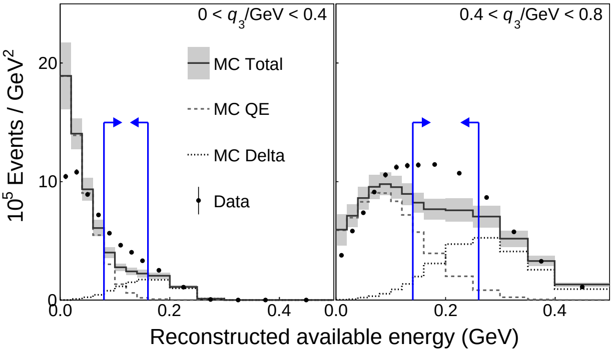


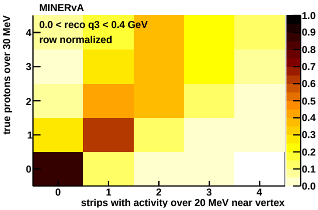
But what's with that excess?



- Look at particle content
- Possibilities for "excess":
  - Different 2p2h model, or modifications
  - Alter kinematics of Δ
  - RPA or 2p2h effects in Δ region? But no calculation...

Particle content of the excess: counting protons

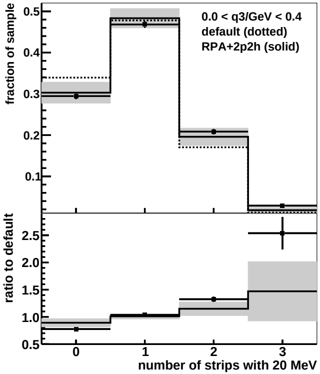




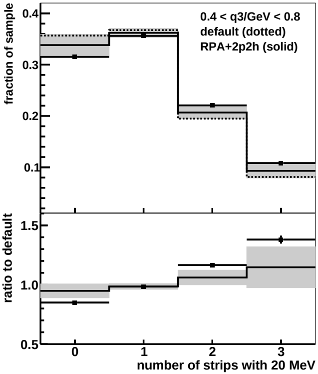
- Common prediction of 2p2h models is multiple protons in final state
- Proton Bragg peak produces one high-energy hit in MINERνA
- Count hits above 20 MeV near vertex ($\pm$225mm in z, $\pm$83mm transverse)

Counting multi-proton events: results

$0 < \text{Reco. } q_3 < 0.4$ GeV

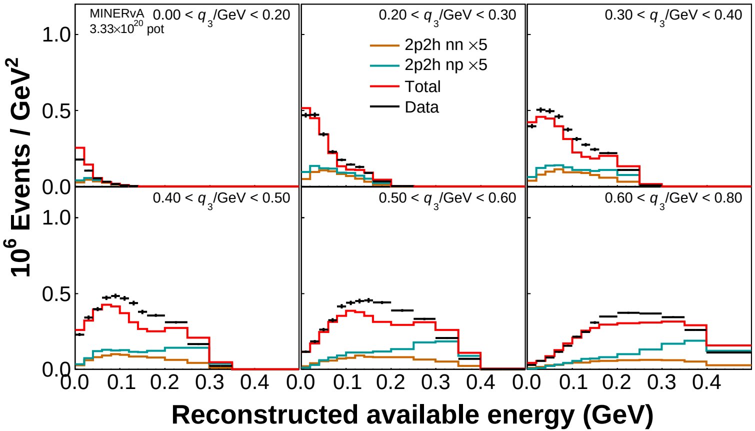


$0.4 < \text{Reco. } q_3 < 0.8$ GeV



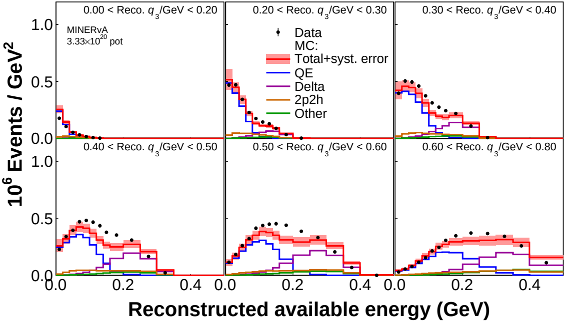
- Overall χ^2 reduced from 14.0 to 7.3 with RPA+2p2h (6 dof)

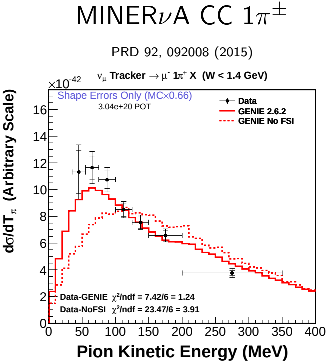
Does modifying initial state in 2p2h events help?



- Scaling *nn* : *np* ratio might help, probably not enough

Interpretation: modifying Δ kinematics shape

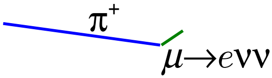




- MC Δ from Rein and Sehgal (1981 vintage)
- MINERνA $\pi^{\pm}$ data suggest no big changes to model for trackable pions

Where next?

- Lots of possibilities!
  - Pion ID by Michel tag: is the excess due to pions?



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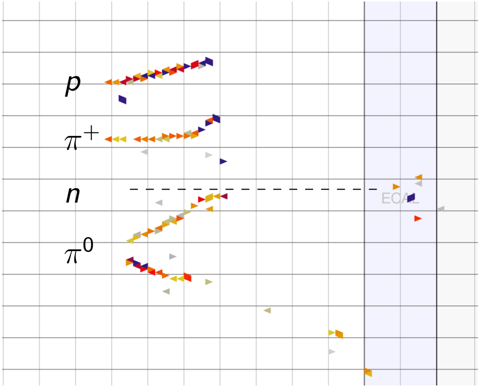

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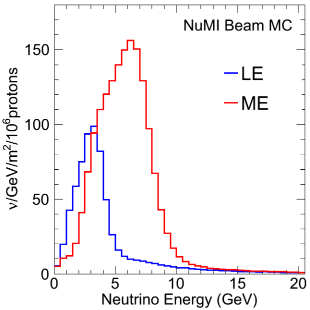


Where next?

- Lots of possibilities!
  - Pion ID by Michel tag: is the excess due to pions?
  - Antineutrino analysis: need neutron ID
  - Extend to higher neutrino energies with ME data
  - Use passive nuclear targets for measurement on Fe, Pb

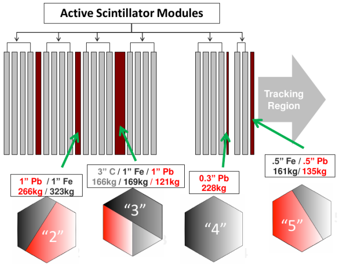
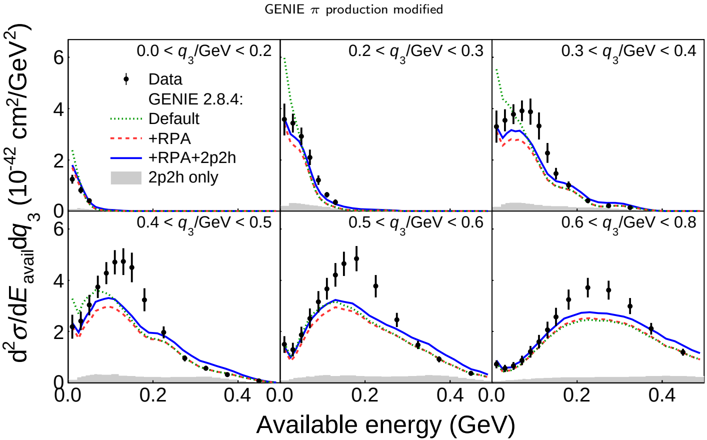


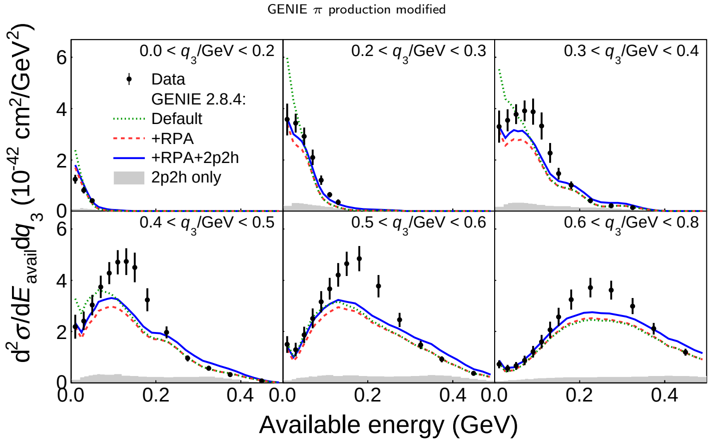
Figure: B. Tice

Recap



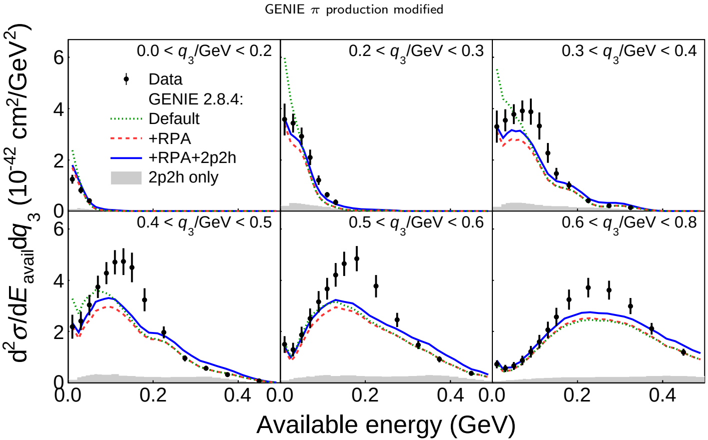
- Identified variables that allow an e-scattering-like analysis in neutrinos

Recap



- Identified variables that allow an *e*-scattering-like analysis in neutrinos
- A significant step forward in determining exactly *where* our interaction models can be improved

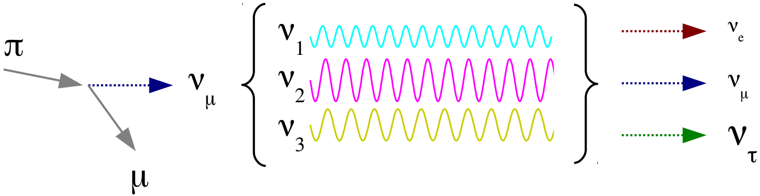
Recap



- Identified variables that allow an *e*-scattering-like analysis in neutrinos
- A significant step forward in determining exactly *where* our interaction models can be improved
- We're constraining exactly the model elements that oscillation experiments need

Backup slides

Neutrino oscillations offer a probe of beyond SM physics



- Oscillation probability:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E_\nu}\right)$$

(Nature, Experimental)

The future of neutrino oscillation physics is in measuring CP violation and the hierarchy

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \qquad\qquad \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The future of neutrino oscillation physics is in measuring CP violation and the hierarchy

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$
- Measured, Unmeasured

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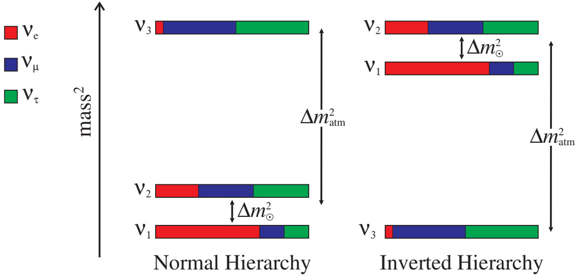
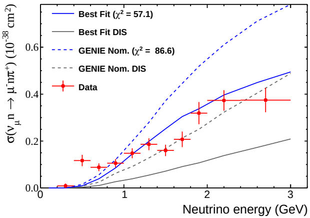
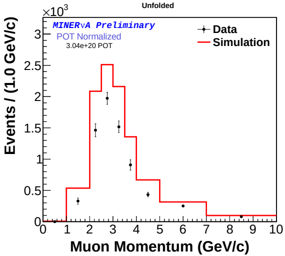


More on GENIE pion production modification

BNL D_2 $\nu_\mu n \rightarrow \mu^- n \pi^+$

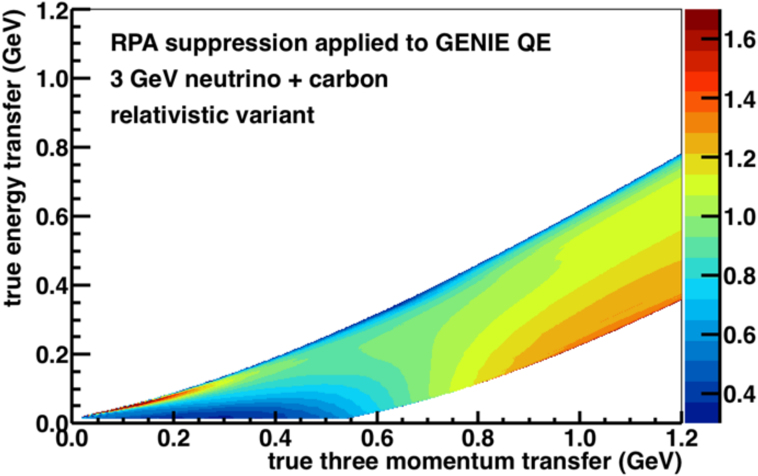


MINERνA $\pi^\pm$ production



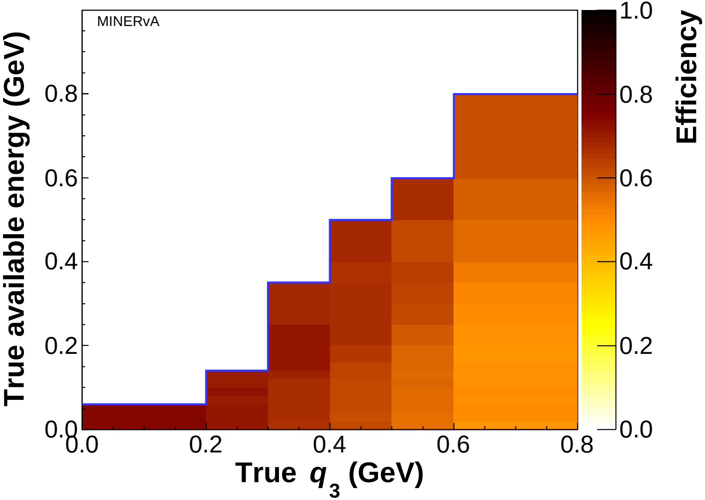
- Use reanalyzed ANL/BNL deuterium data *à la* Wilkinson *et al.* PRD 90, 112017
- Scale down nonresonant pion production by 75% (1.5σ): GENIE's `NonRESBGvnCC1pi`. Keep 50% fractional uncertainty
- See poster 70 from C. Wilkinson, PR and K. McFarland for an updated deuterium fit. Essential conclusions the same
- Further scale down pion production with $W < 1.8$ GeV by 10% based on comparison with MINERνA data
- From comparison with MINERνA CC coherent π^+, reduce coherent with $E_\pi < 450$ MeV by 50%

RPA reweight function



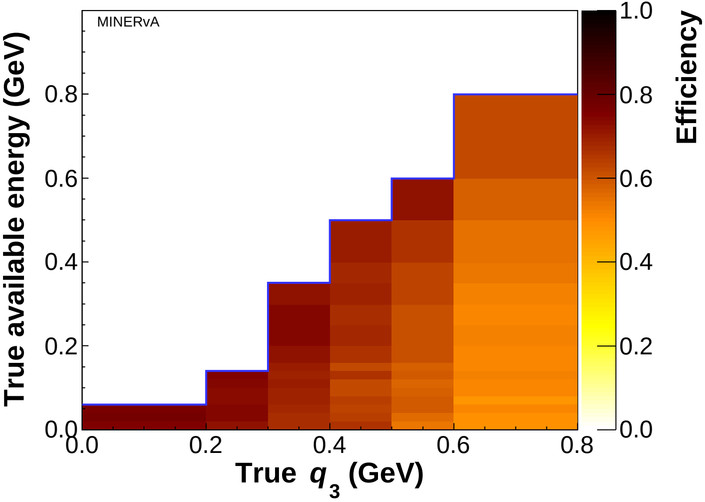
- Reweight applied to QE events as a function of (q_0, q_3)

Selection efficiency 1



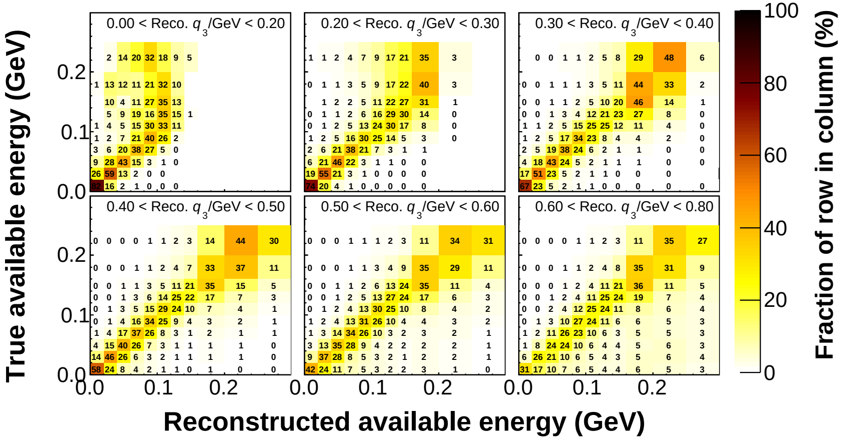
- GENIE nominal (with pion production reweighted)
- Selection efficiency is high everywhere
- Signal def'n: CC ν_μ with $2 < E_\nu < 5$ GeV, $p_\mu > 1.5$ GeV and $\theta_\mu < 20^\circ$

Selection efficiency 2



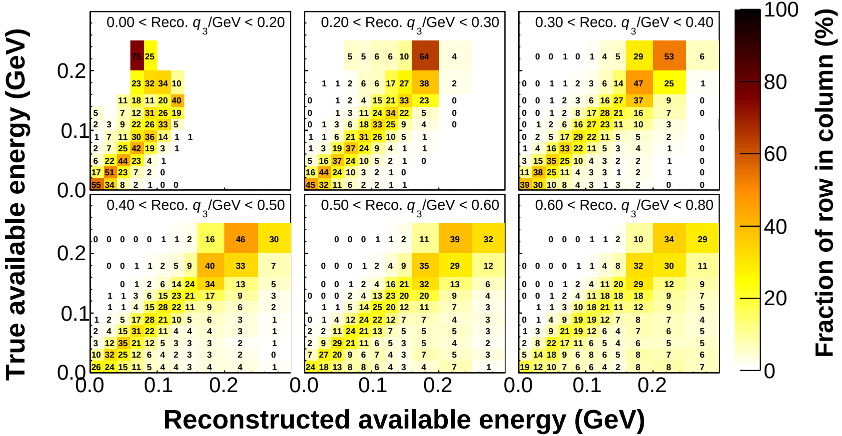
- Same as previous, but just for the GENIE 2p2h events

"Available energy" resolution: GENIE nominal



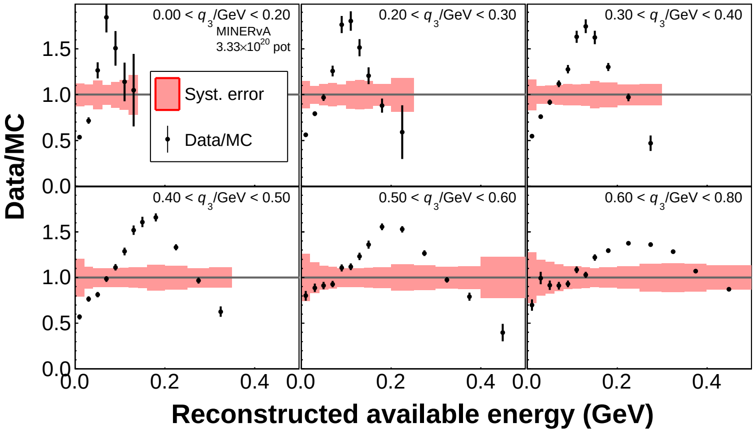
- This plot shows the resolution of E_{avail}, in the six q_3 regions we're quoting, for nominal GENIE (plus pion weights).
- It's not quite the same as the migration matrix used in the analysis, because events with the wrong q_3 are included here

“Available energy” resolution: GENIE 2p2h



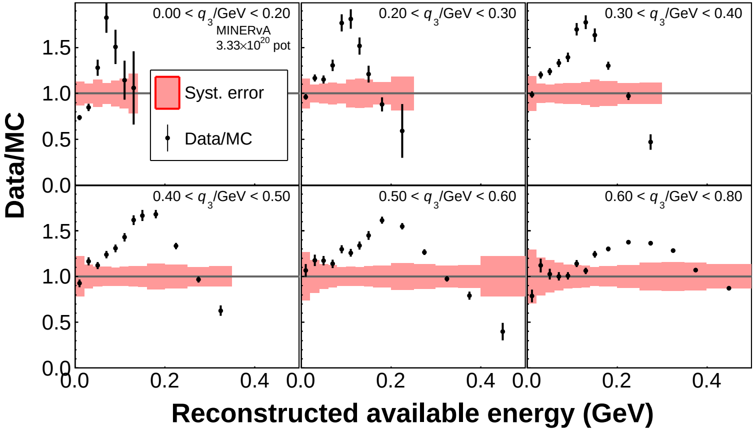
- Same as previous, but just for the GENIE 2p2h sample
- Resolution is a little worse than nominal

Selection: GENIE w/o RPA or MEC, data/MC ratio



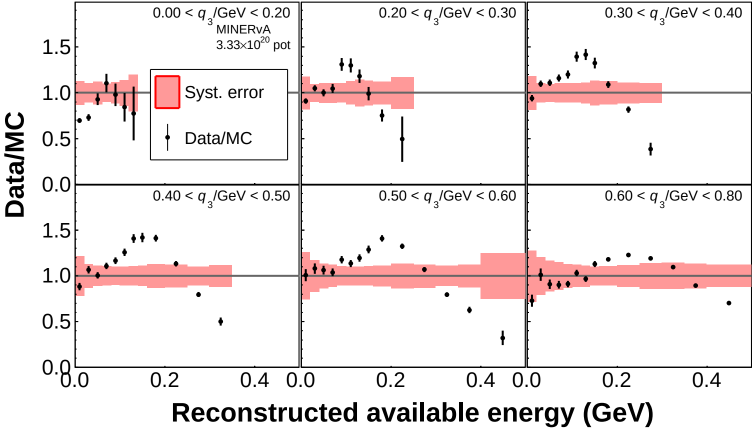
- Data/MC ratio is clearly larger than systematic uncertainties

Selection: GENIE plus RPA, data/MC ratio



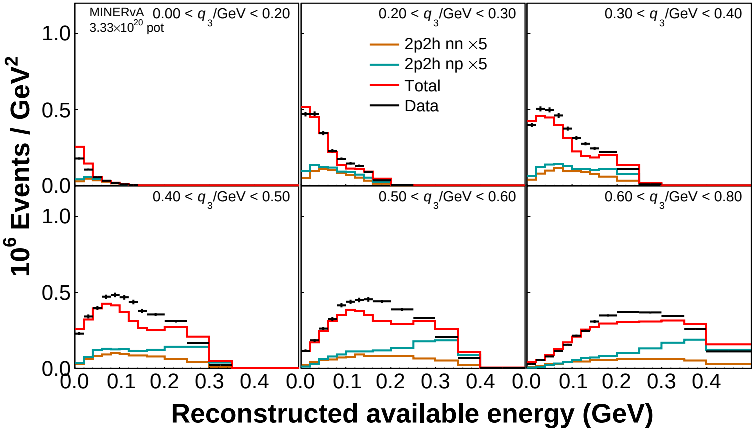
- This plot is the same as the previous, but the RPA effect has been applied to MC QE events as a reweight
- This improves low-energy region

Selection: GENIE plus RPA+2p2h, data/MC ratio



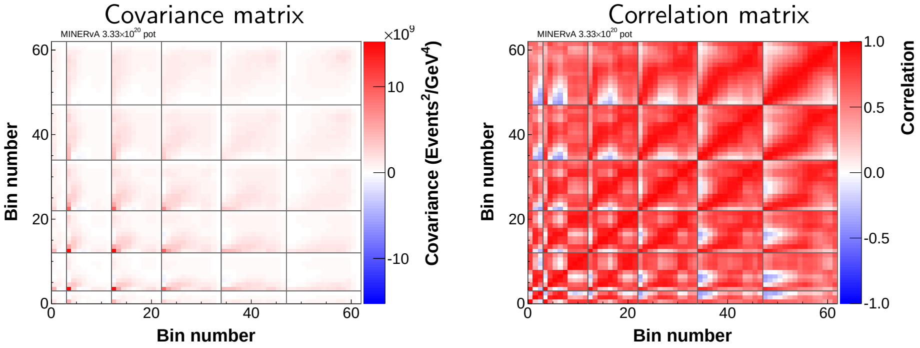
- This plot is the same as previous, with simulated 2p2h events added

2p2h prediction by initial state nucleon pair



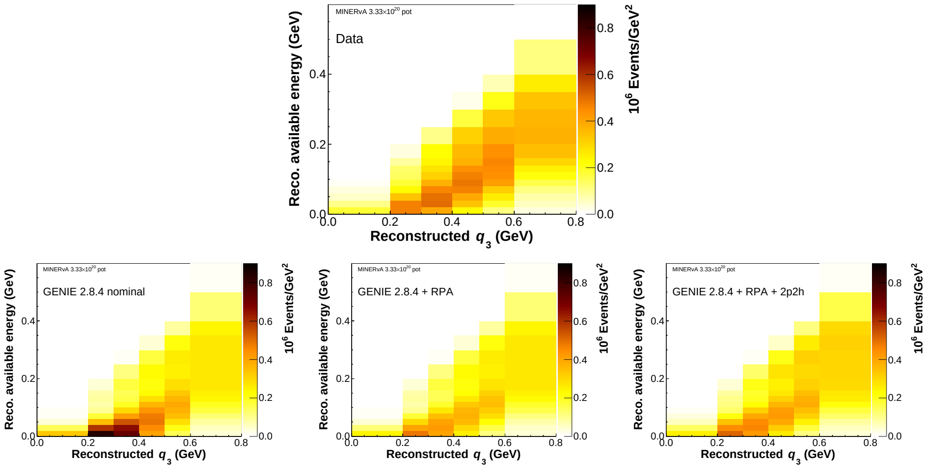
- This plot shows the reconstructed variables with the 2p2h component ($\times 5$) split up by whether the initial nucleon pair is *nn* or *np* (the *pp* prediction is ≈ 0).
- Both *nn* and *np* fill in the dip, and are similar up to higher q_3

Covariance matrix on reconstructed sample



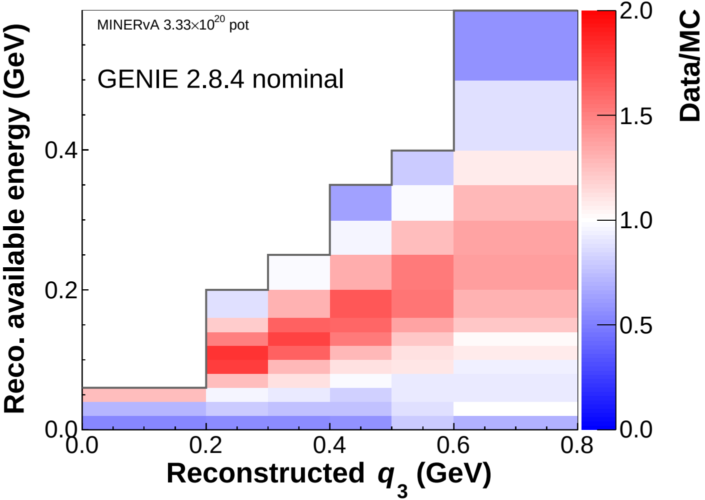
- Strong positive correlations between elements

2D reconstructed event distribution plots



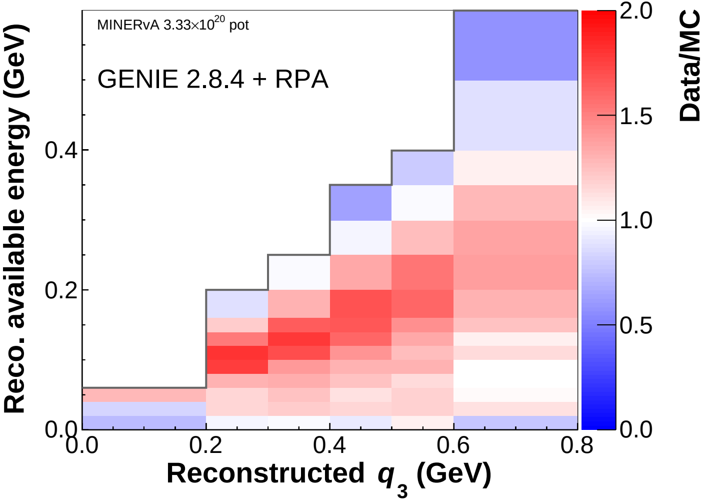
- These plots show the reconstructed selected event distribution in 2D. The top plot is data, and the bottom row is MC, with nominal (plus pion weights), RPA and RPA+2p2h

2D data/MC ratio in reco variables, GENIE w/o RPA or 2p2h



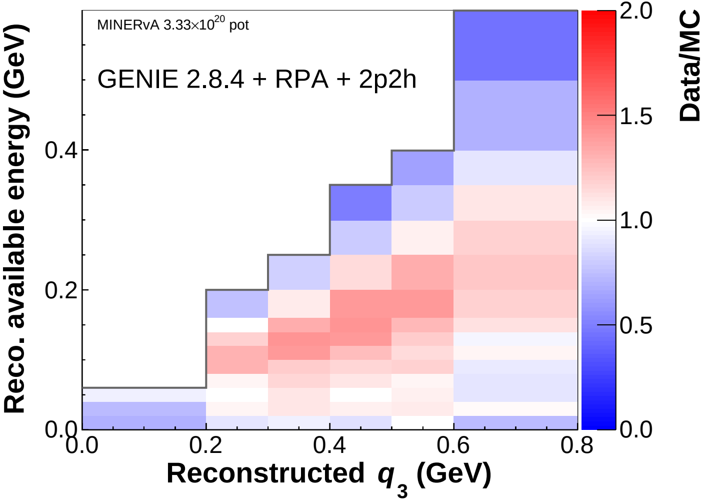
- This plot shows the ratio of data to MC in reconstructed variables

2D data/MC ratio in reco variables, GENIE plus RPA



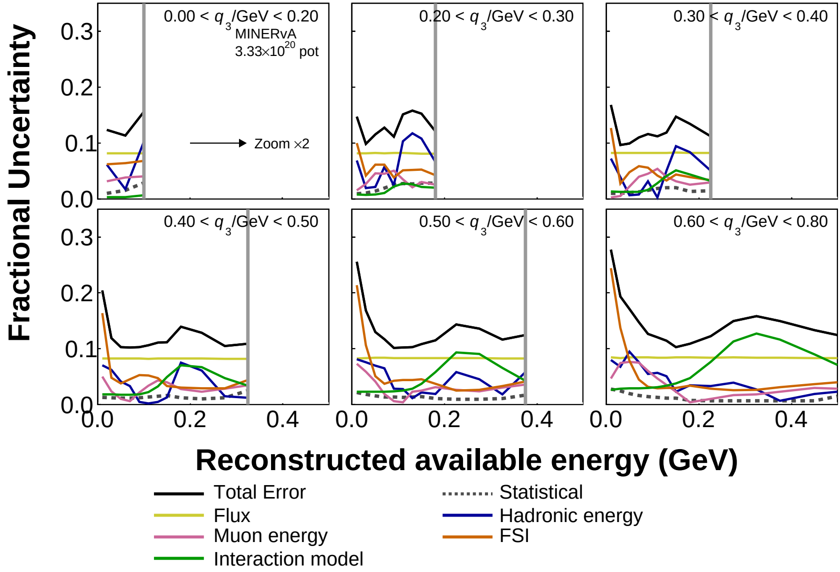
- Same as previous, but MC now has RPA applied

2D data/MC ratio in reco variables, GENIE plus RPA+2p2h

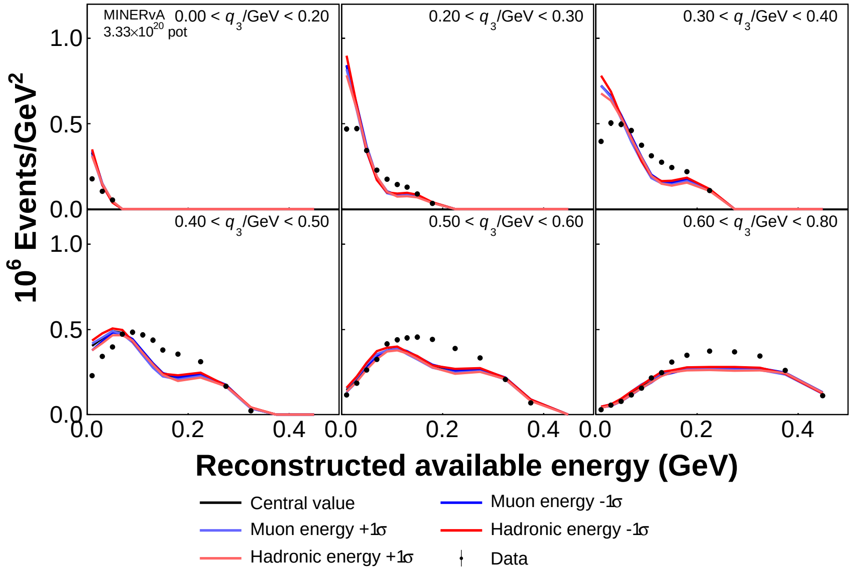


- Same as previous, but MC now has RPA applied and 2p2h included

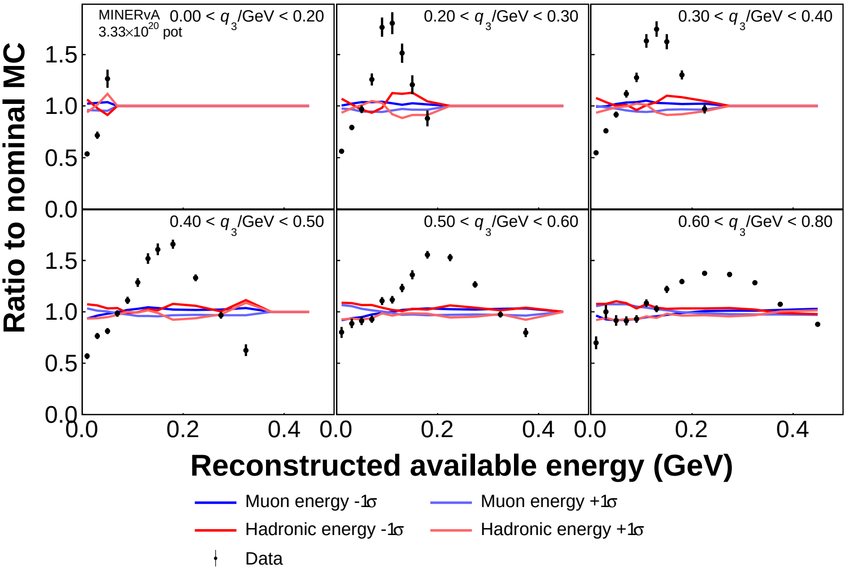
Uncertainties on MC prediction



Could the discrepancy just be an energy scale error?



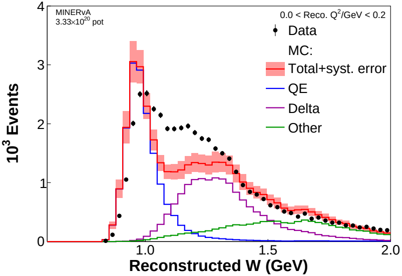
Could the discrepancy just be an energy scale error?



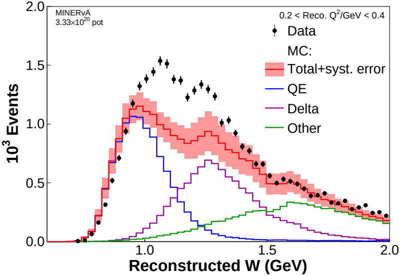
▶ This is the same as the previous, but now as a ratio to the central value MC

Reconstructed W in bins of Q^2, GENIE nominal

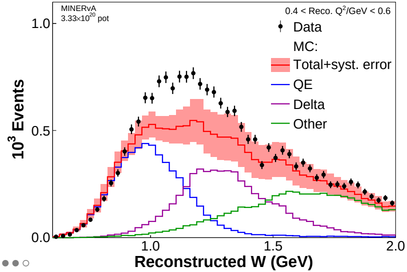
$0 < Q^2/\text{GeV} < 0.2$



$0.2 < Q^2/\text{GeV} < 0.4$



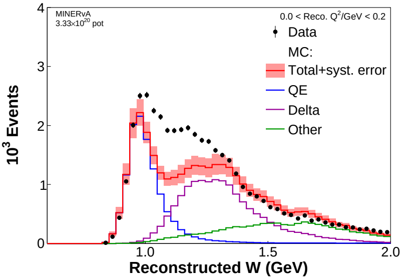
$0.4 < Q^2/\text{GeV} < 0.6$



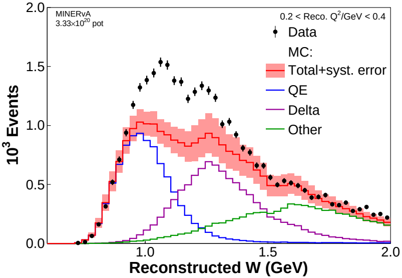
- Do the same in (Q^2, W)
- GENIE is nominal with pion weights
- $Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$
- $W = M_N^2 + 2M_N\nu - Q^2$
  $(M_N = (M_p + M_n)/2)$

Reconstructed W in bins of Q^2, GENIE plus RPA

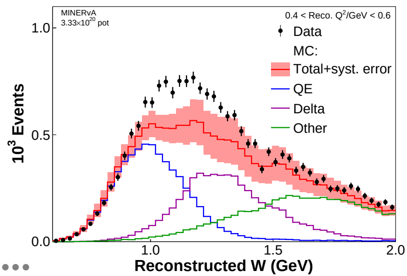
$0 < Q^2/\text{GeV} < 0.2$



$0.2 < Q^2/\text{GeV} < 0.4$



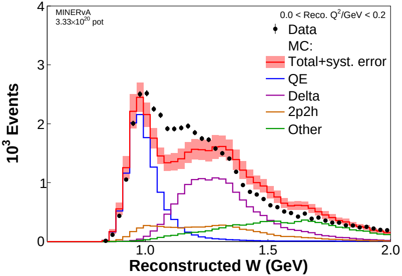
$0.4 < Q^2/\text{GeV} < 0.6$



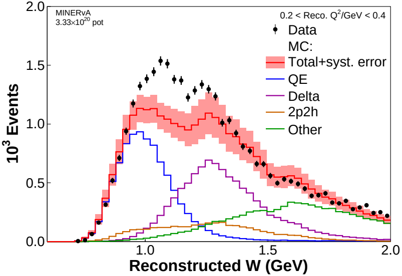
- Do the same in (Q^2, W)
- Each plot shows W in a slice of Q^2
- GENIE has pion weights and RPA

Reconstructed W in bins of Q^2, GENIE plus RPA+2p2h

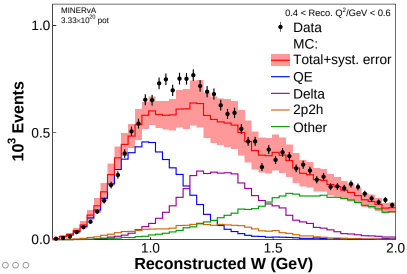
$0 < Q^2/\text{GeV} < 0.2$



$0.2 < Q^2/\text{GeV} < 0.4$

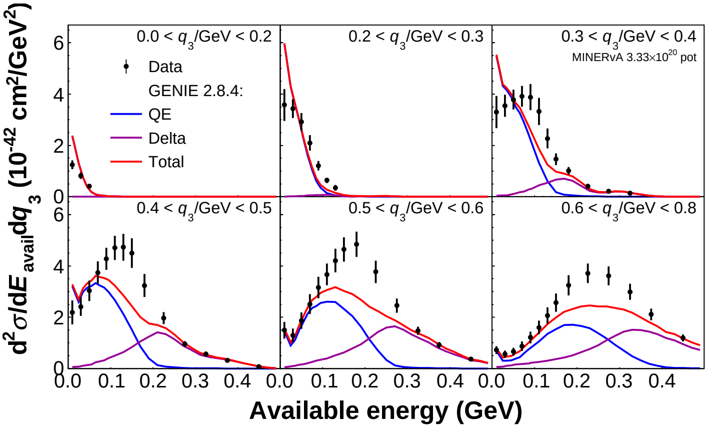


$0.4 < Q^2/\text{GeV} < 0.6$



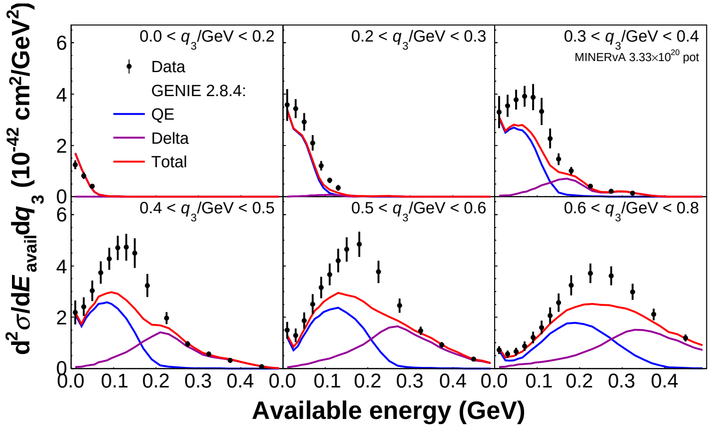
- Do the same in (Q^2, W)
- Each plot shows W in a slice of Q^2
- GENIE has pion weights and RPA+2p2h

Cross section



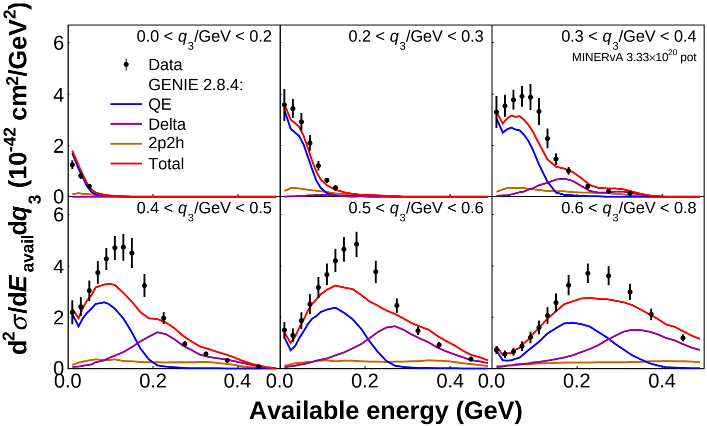
- MC with QE and Δ components

Cross section: MC with RPA



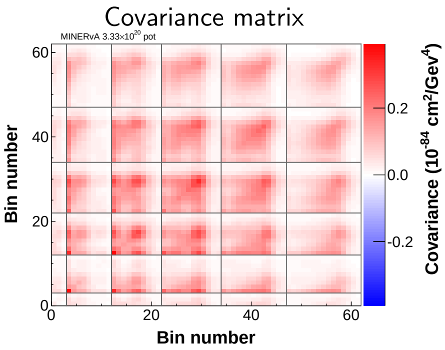
- This plot is the same as the previous one, but the prediction is now GENIE with pion weights and RPA applied to the QE component

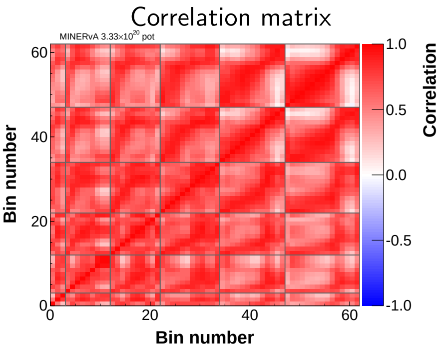
Cross section: MC with RPA+2p2h



- This plot is the same as the previous one, but the prediction is now GENIE with pion weights, RPA applied to the QE component, and 2p2h

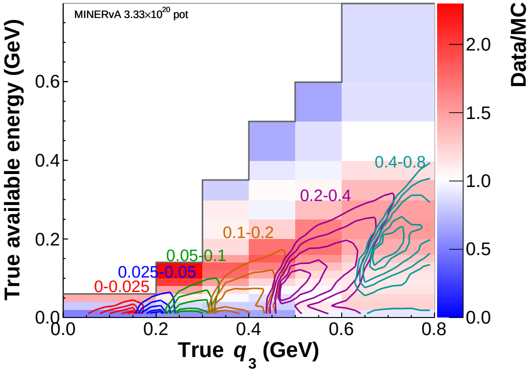
Covariance matrix on cross section

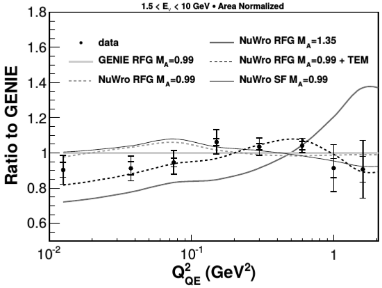




- Total covariance and correlation matrices on the cross section

How does this relate to the 2013 MINERνA CCQE result?





q2qe-bins-contours.pdf

- Select true CCQE events, split them up by the 2013 CCQE true Q^2_{QE} bin they come from, and find their true (q_3, E_{avail}). Draw each bin with contours
- Underneath is the data/MC cross section ratio
- Right is plot from CCQE 2013 neutrino paper