Identification of nuclear effects at low momentum transfer in MINERνA

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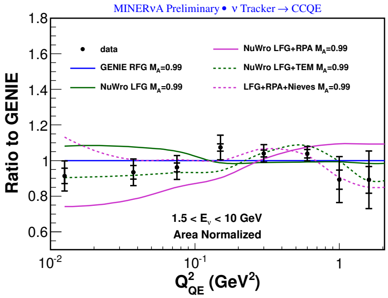
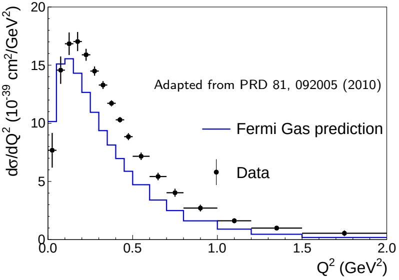
NuInt 2015

Evidence for nuclear effects beyond RFG in νA scattering is compelling

MINERνA CCQE (2013)

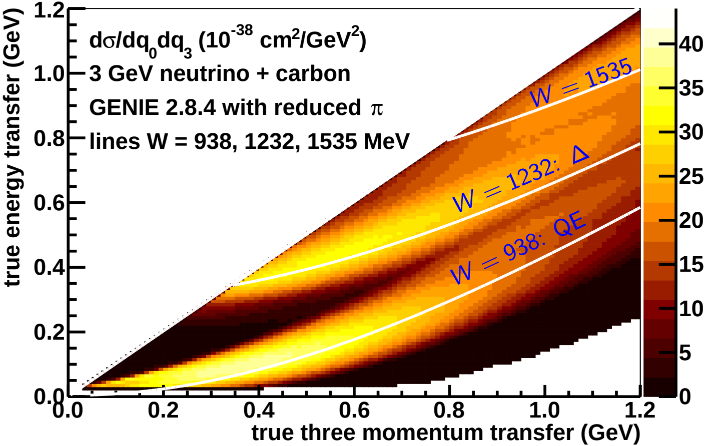


MiniBooNE CCQE



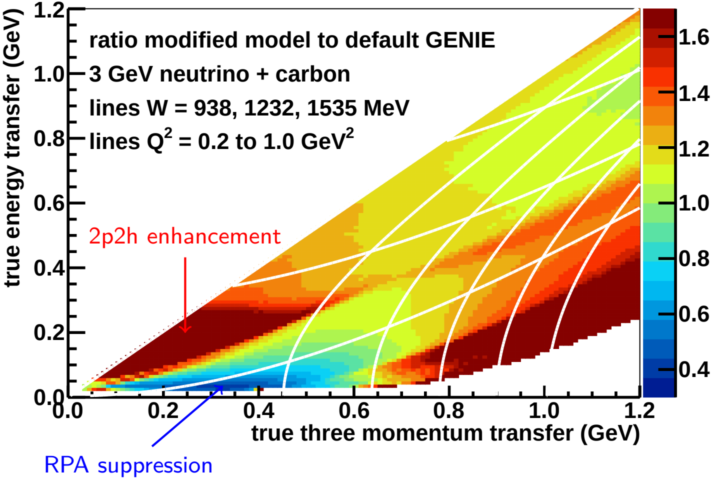
- Task now is to distinguish between available models

Energy transfer q_0 & three-momentum transfer q_3 distinguish processes



- Produce inclusive CC ν_μ double-differential cross section in this space

Energy transfer q_0 & three-momentum transfer q_3 distinguish processes

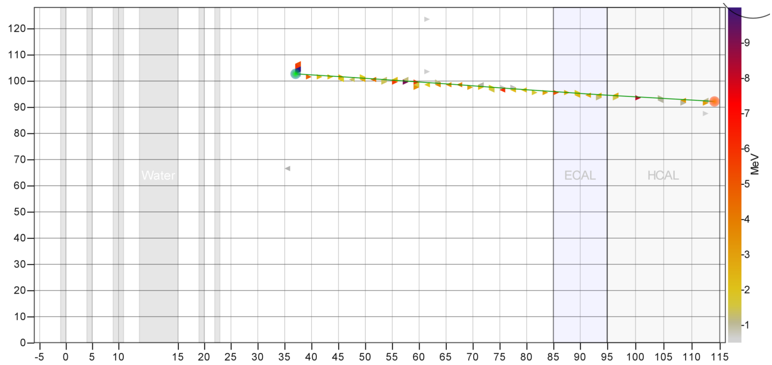


- RPA-like long range effects and 2p2h events live in distinct regions
- Use illustrative Nieves *et al.* calculations PRC 70, 055503 (2004); PRC 83, 045501 (2011)
- GENIE implementation by J. Schwehr (CSU), R. Gran (UMD)

To reconstruct (q_0, q_3), we start with an inclusive CC ν_μ selection

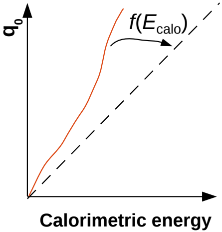
- Fiducial interaction (CH tracker)
- Negative muon matched to MINOS
- $2 < E_\nu < 6$ GeV, $p_\mu > 1.5$ GeV, $\theta_\mu < 20^\circ$

127,420 events, 97% purity



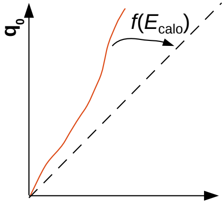
To reconstruct (q_0, q_3), we use both lepton and hadron kinematics

$$
\begin{aligned}
q_0 \equiv \nu &= f(E_{\text{calo}}) \\
E_\nu &= E_\mu + q_0 \\
Q^2 &= 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2 \\
q_3 &= \sqrt{Q^2 + q_0^2}
\end{aligned}
$$



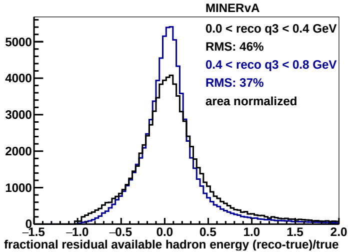
To reconstruct (q_0, q_3), we use both lepton and hadron kinematics

$$\begin{aligned} q_0 \equiv \nu &= f(E_{\text{calo}}) \\ E_\nu &= E_\mu + q_0 \\ Q^2 &= 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2 \\ q_3 &= \sqrt{Q^2 + q_0^2} \end{aligned}$$



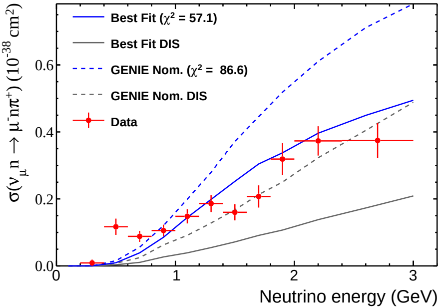
- Reduce cross-section model dependence with hadronic "available energy":

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

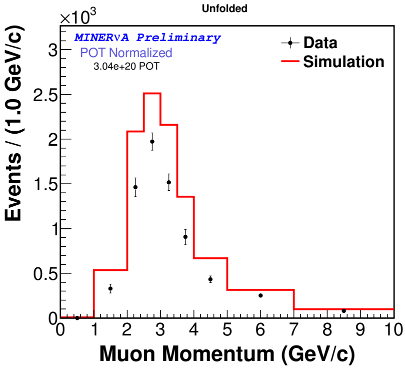


We modify GENIE pion production to agree with deuterium and MINERνA data

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

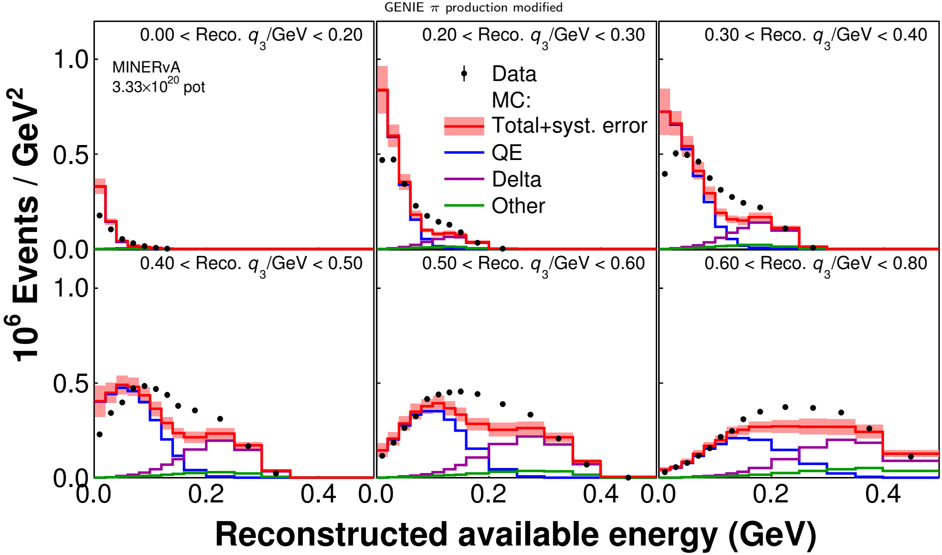


MINERνA $\pi^\pm$ production



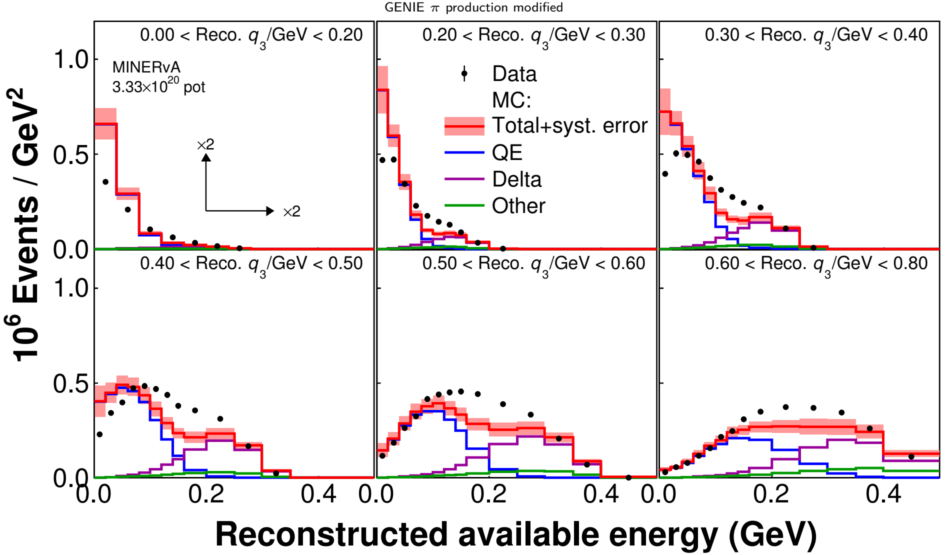
- Scale down nonresonant pion production by 75% (1.5σ)
- Further scale down pion production with $W < 1.8$ GeV by 10%
- Applied throughout this talk

Data disagrees with GENIE in reconstructed variables



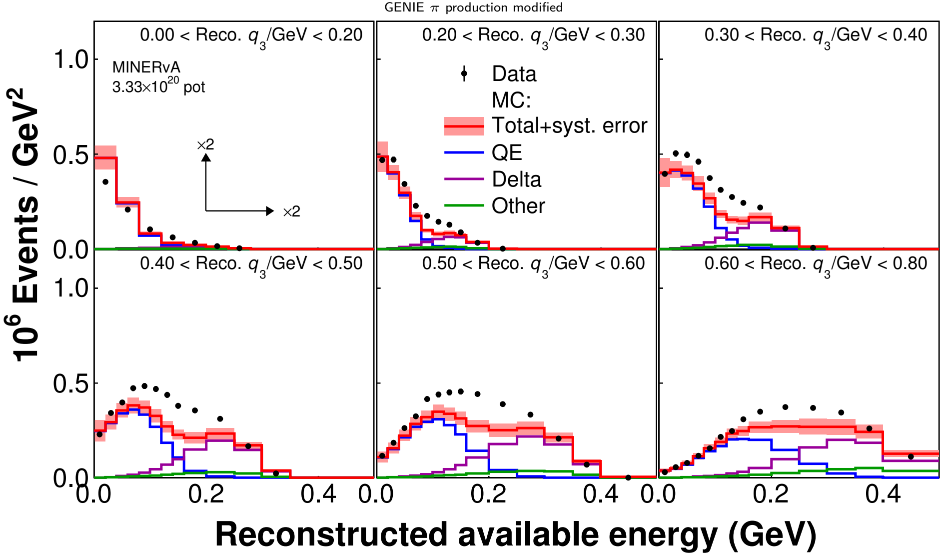
- $\chi^2 = 896$ (stat+syst, 62 dof)

Data disagrees with GENIE in reconstructed variables



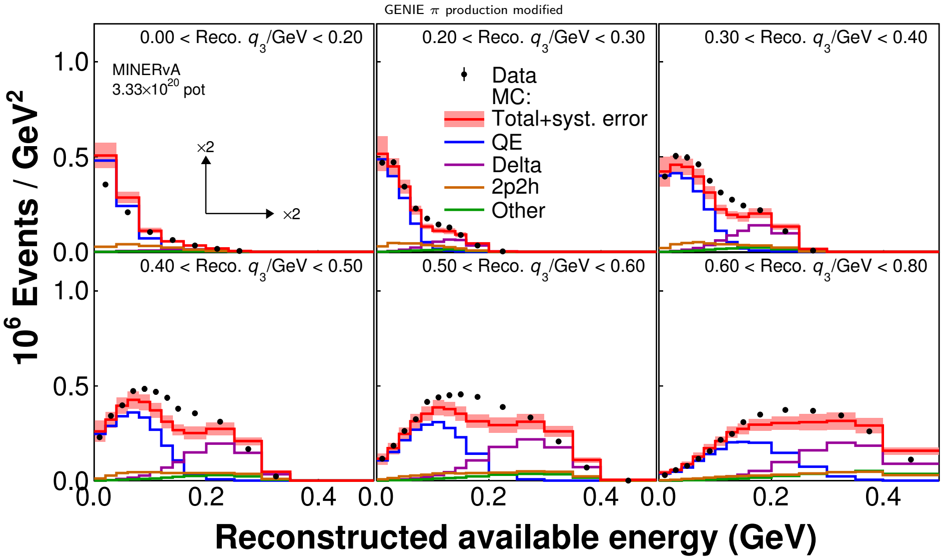
- $\chi^2 = 896$ (stat+syst, 62 dof)

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



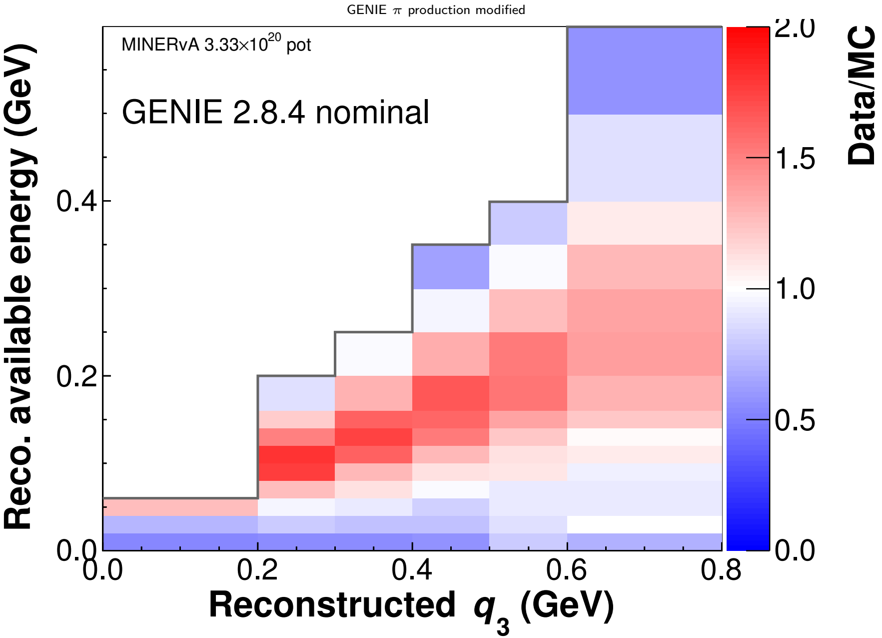
- $\chi^2 = 540$ (stat+syst, 62 dof)

Data has more strength in dip region than provided by 2p2h model

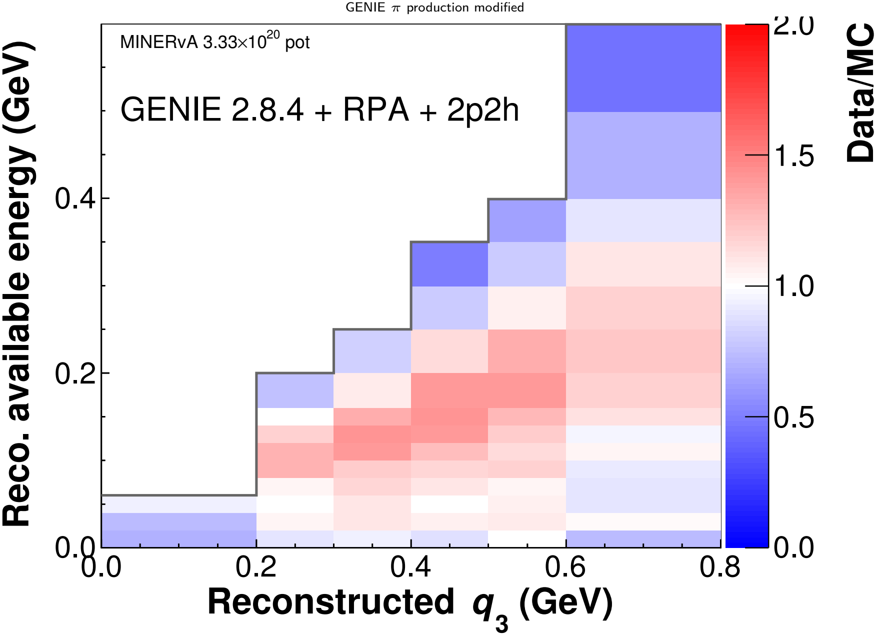


- $\chi^2 = 498$ (stat+syst, 62 dof)

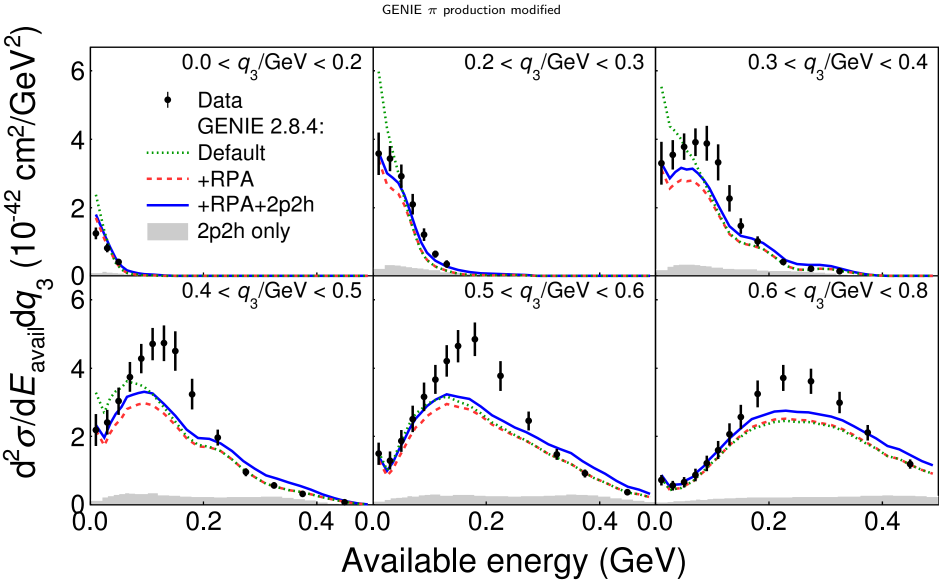
Data/MC ratio shows discrepancies are in contiguous regions



Discrepancy reduced with RPA+2p2h model

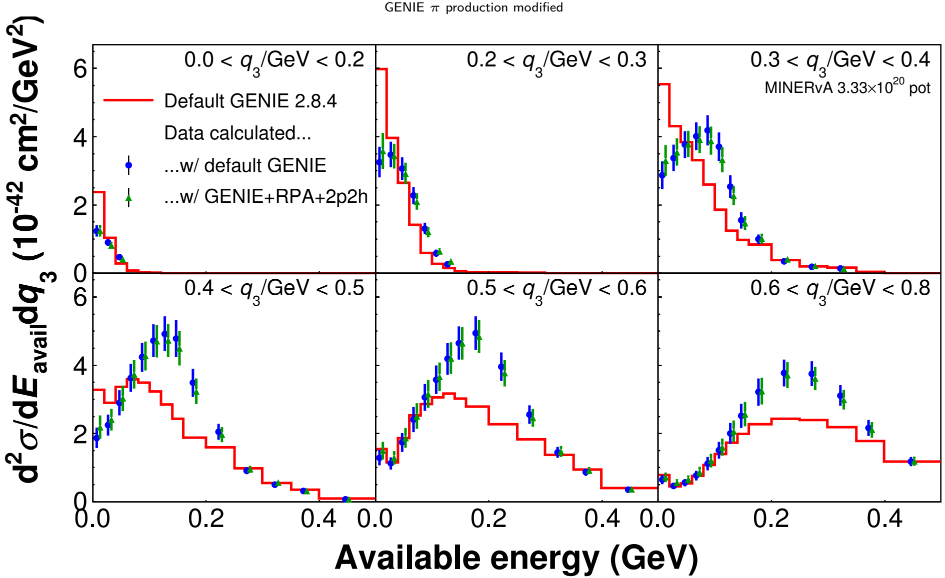


The inferred cross section shows similar features



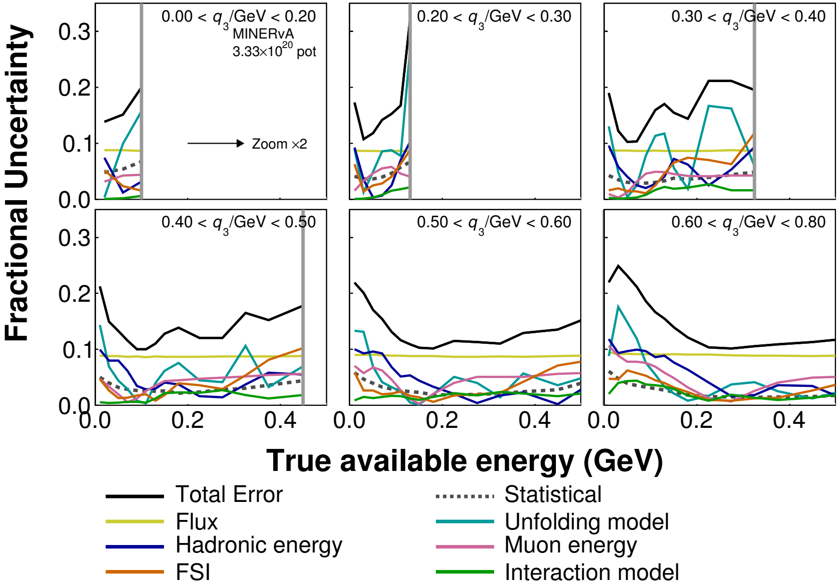
- Your model goes here!

Cross section calculation has small MC dependence

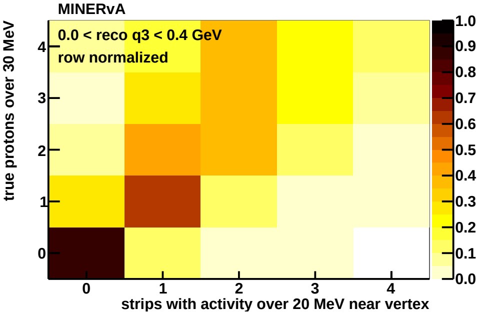


- 100% of difference is taken as "Unfolding model" systematic

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

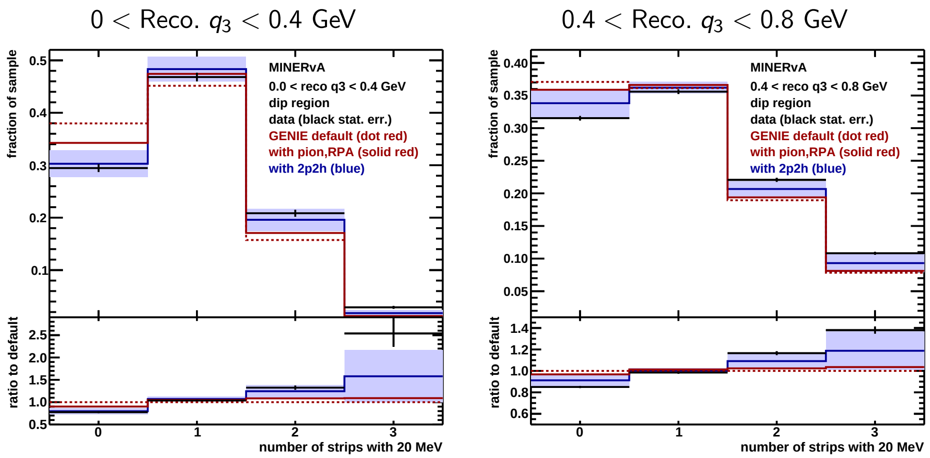


Counting multi-proton events



- Proton Bragg peak produces one high-ph hit in MINERνA
- Count hits above 20 MeV near vertex ($\pm$225mm in z, $\pm$83mm transverse)

Counting multi-proton events: results

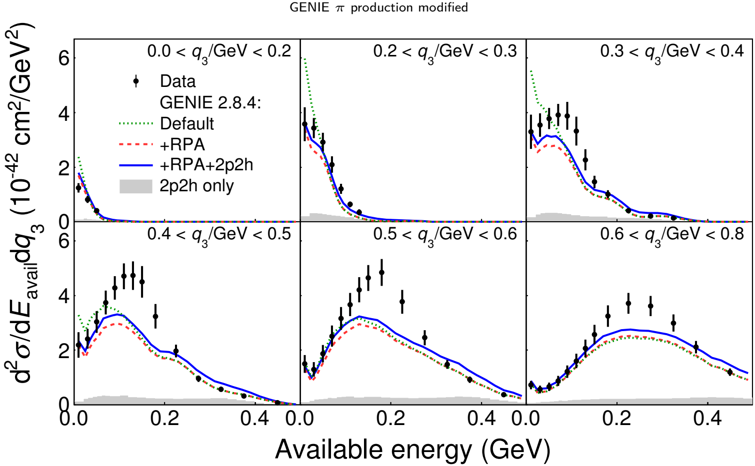


Dip region 0.08–0.16 GeV

Dip region 0.14–0.26 GeV

- Overall χ^2 reduced from 14.0 to 7.3 with RPA+2p2h (6 dof)
- (Systematic error shown on blue curve only)

Recap

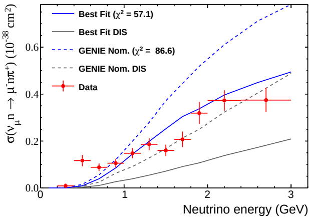


- CC inclusive cross section in (q_3, E_{avail}) helps distinguish nuclear effects
- Strong evidence for RPA-like suppression at low energy transfer
- Excess in dip region above prediction of RPA+2p2h model
- High-energy hits near vertex provide evidence for multi-nucleon knockout

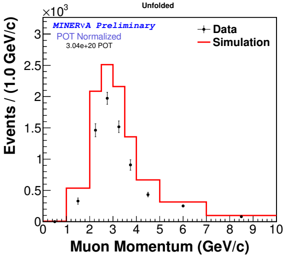
Backup slides

More on GENIE pion production modification

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

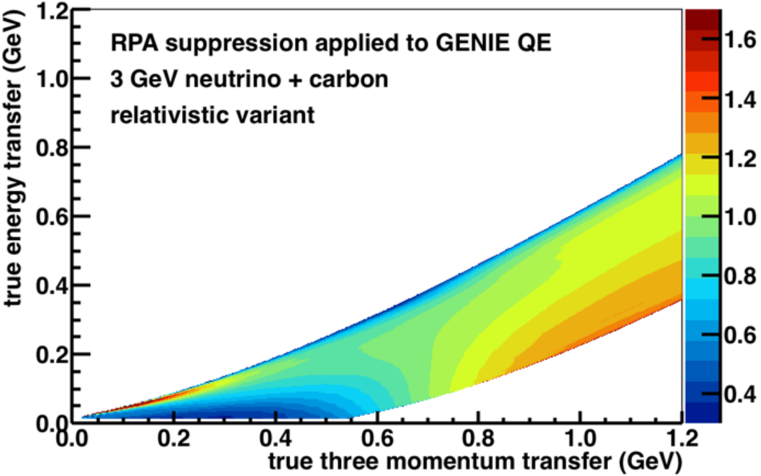


MINERνA $\pi^\pm$ production



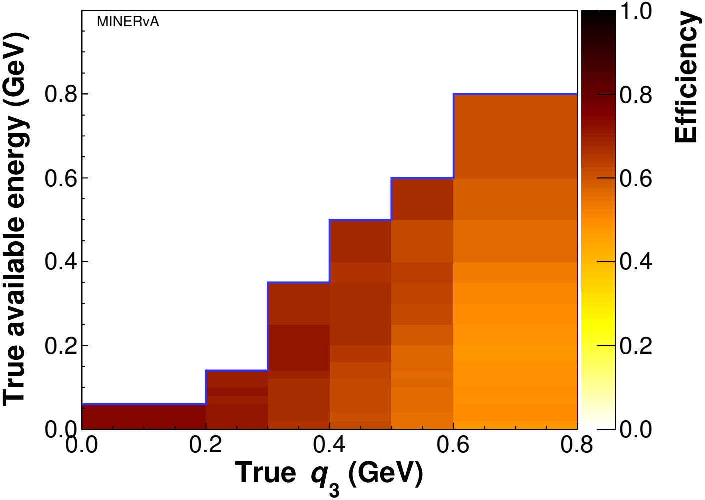
- Use reanalyzed ANL/BNL deuterium data *à la* Wilkinson *et al.* PRD 90, 112017
- Scale down nonresonant pion production by 75% (1.5σ): GENIE's `NonRESBGvnCC1pi`. Keep 50% fractional uncertainty
- See poster 70 from C. Wilkinson, PR and K. McFarland for an updated deuterium fit. Essential conclusions 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



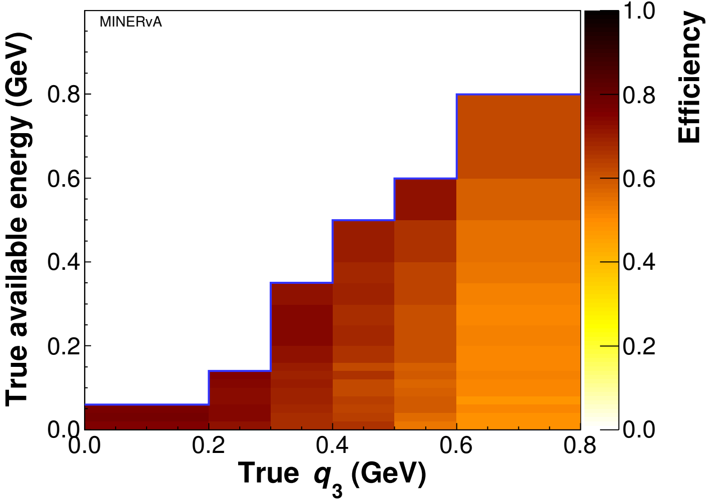
- Reweight applied to QE events as a function of (q_0, q_3)

Selection efficiency 1



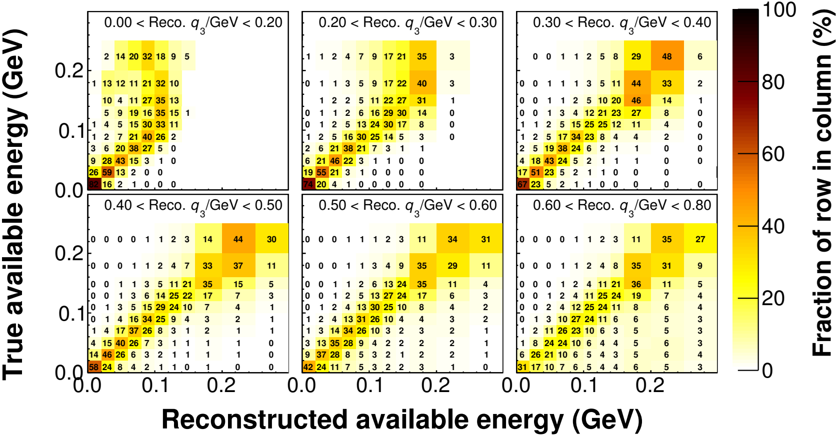
- GENIE nominal (with pion production reweighted)
- Selection efficiency is high everywhere
- Signal def'n: CC ν_μ with $2 < E_\nu < 5$ GeV, $p_\mu > 1.5$ GeV and $\theta_\mu < 20^\circ$

Selection efficiency 2



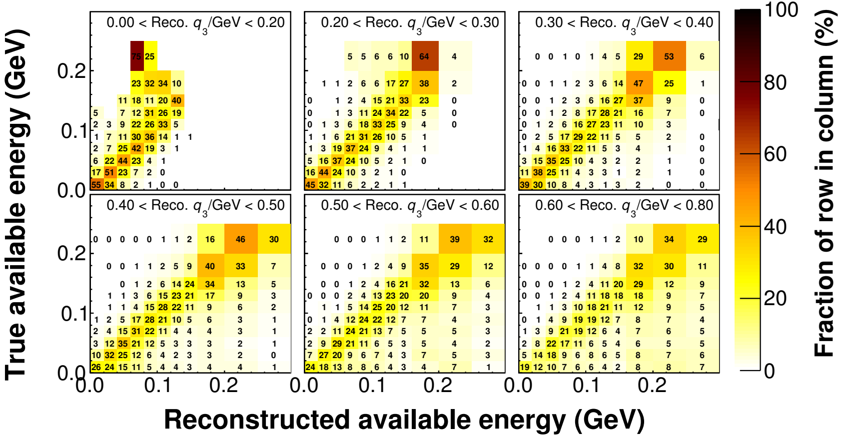
- Same as previous, but just for the GENIE 2p2h events

“Available energy” resolution: GENIE nominal



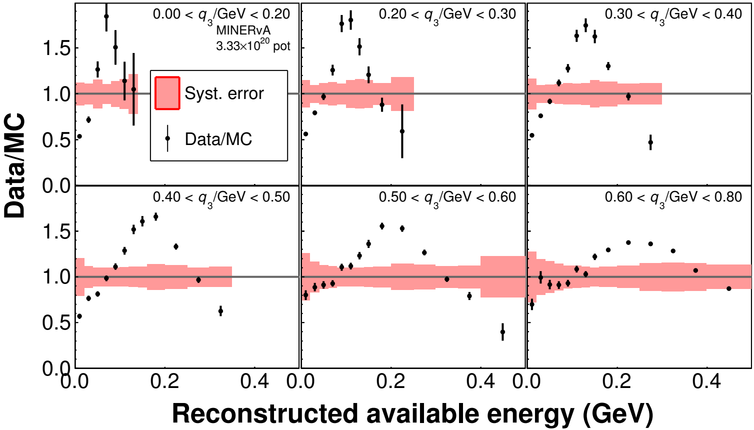
- This plot shows the resolution of E_{avail}, in the six q_3 regions we’re quoting, for nominal GENIE (plus pion weights).
- It’s not quite the same as the migration matrix used in the analysis, because events with the wrong q_3 are included here

"Available energy" resolution: GENIE 2p2h



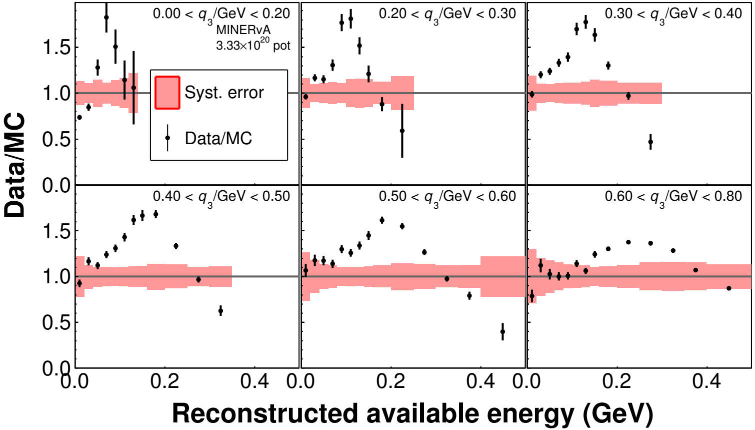
- Same as previous, but just for the GENIE 2p2h sample
- Resolution is a little worse than nominal

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



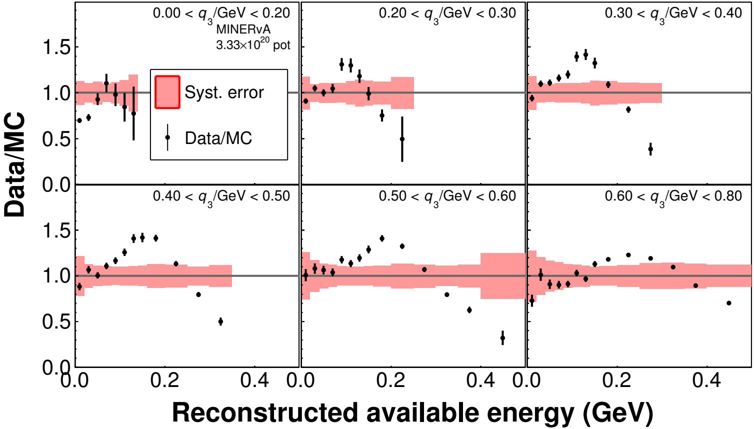
- Data/MC ratio is clearly larger than systematic uncertainties

Selection: GENIE plus RPA, data/MC ratio



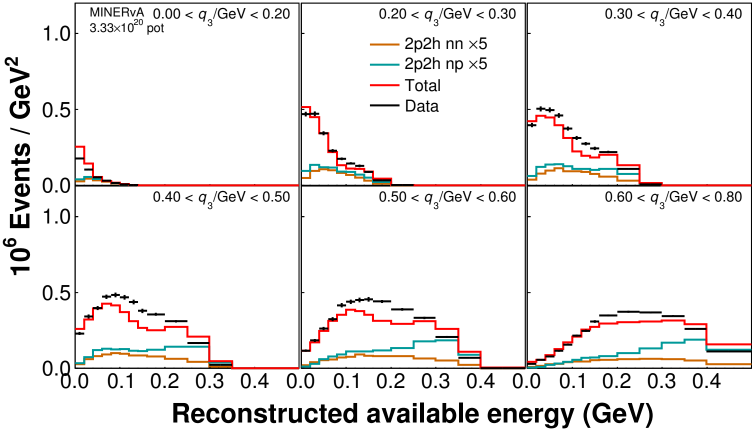
- This plot is the same as the previous, but the RPA effect has been applied to MC QE events as a reweight
- This improves low-energy region

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



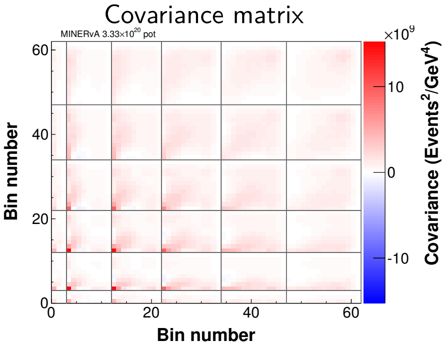
- This plot is the same as previous, with simulated 2p2h events added

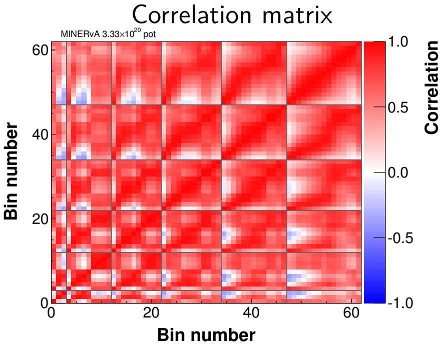
2p2h prediction by initial state nucleon pair



- 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

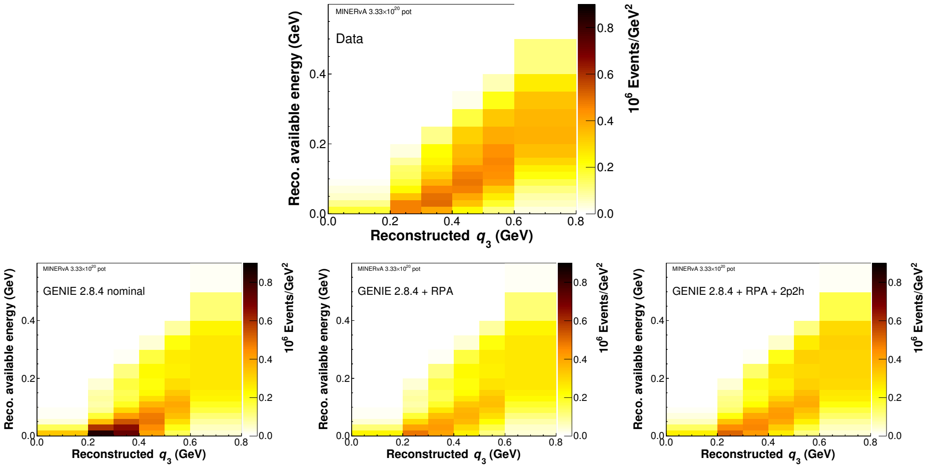
Covariance matrix on reconstructed sample





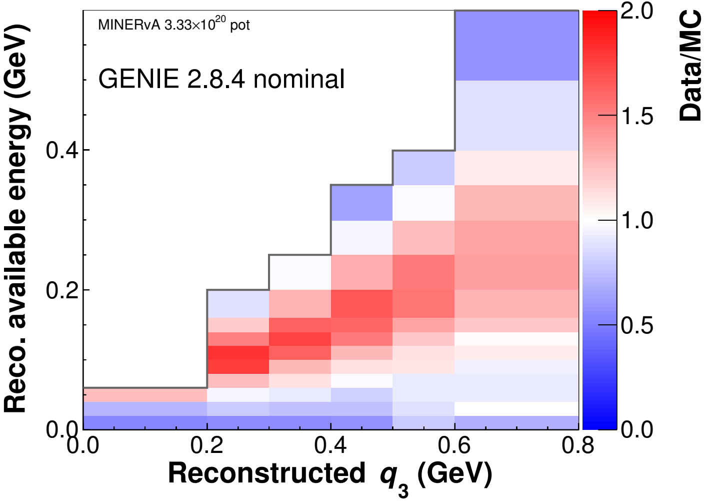
- Strong positive correlations between elements

2D reconstructed event distribution plots



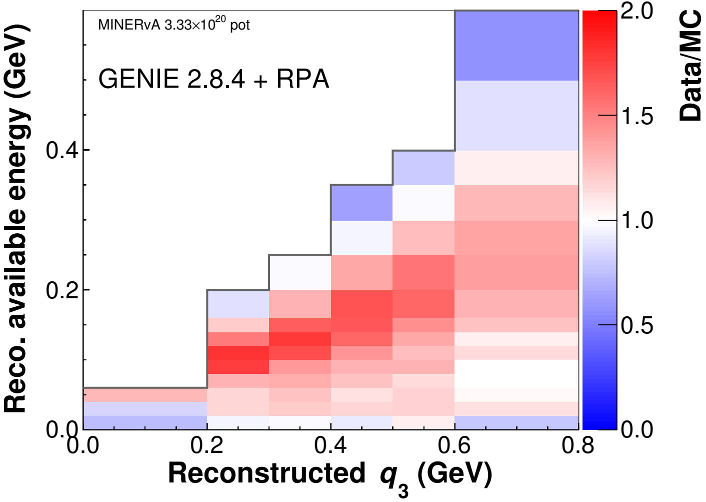
- These plots show the reconstructed selected event distribution in 2D. The top plot is data, and the bottom row is MC, with nominal (plus pion weights), RPA and RPA+2p2h

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



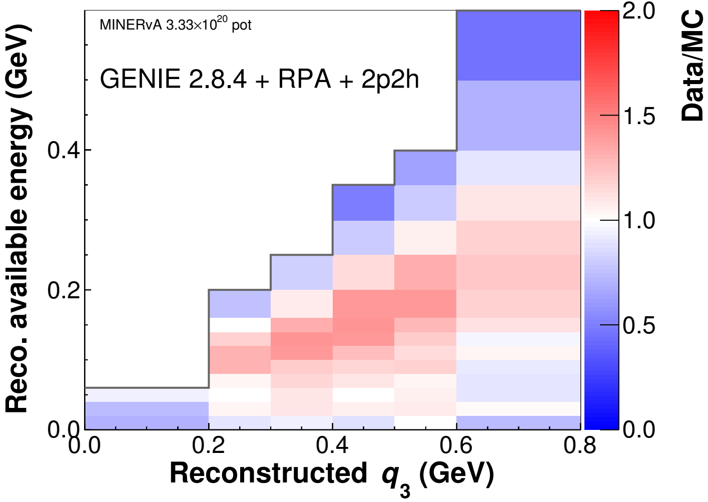
- This plot shows the ratio of data to MC in reconstructed variables

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



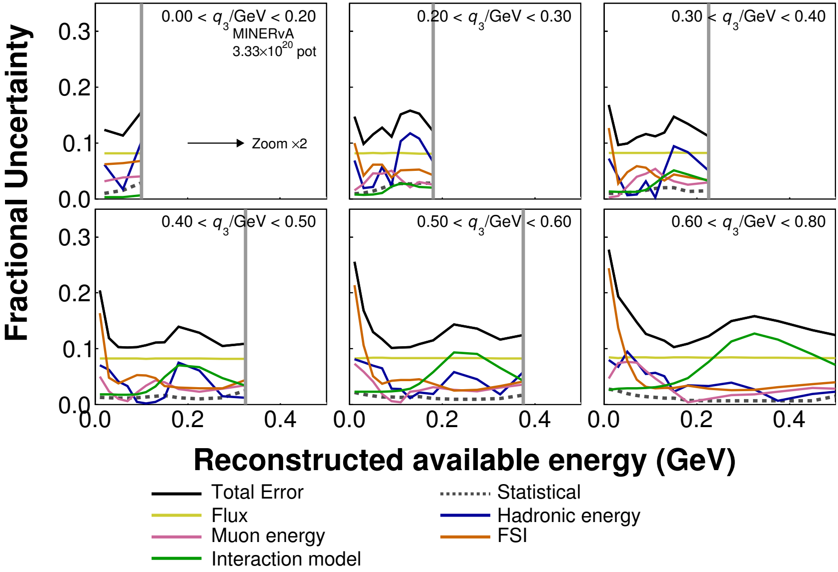
- Same as previous, but MC now has RPA applied

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

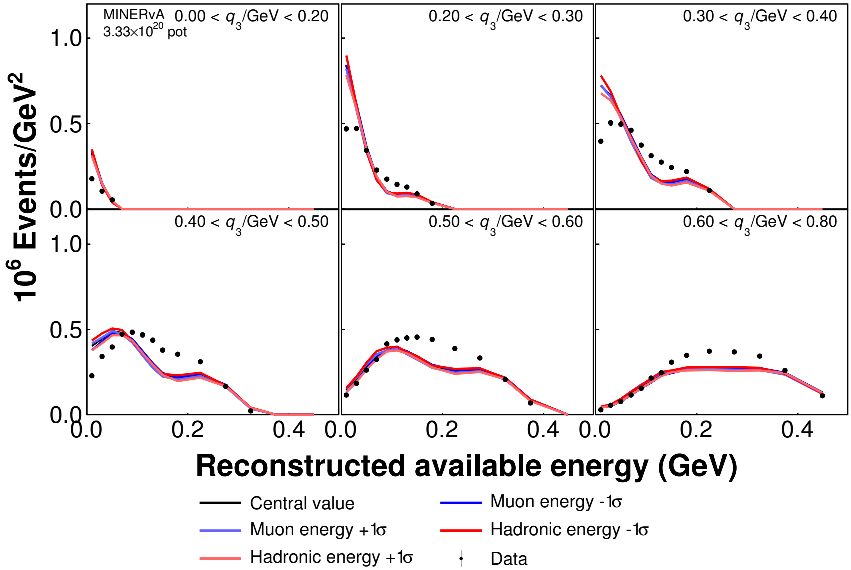


- Same as previous, but MC now has RPA applied and 2p2h included

Uncertainties on MC prediction

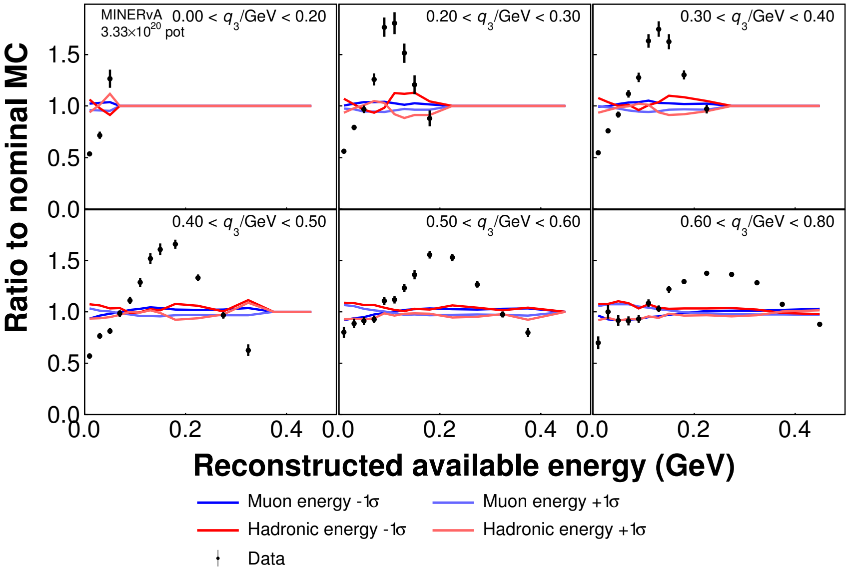


Could the discrepancy just be an energy scale error?



- No

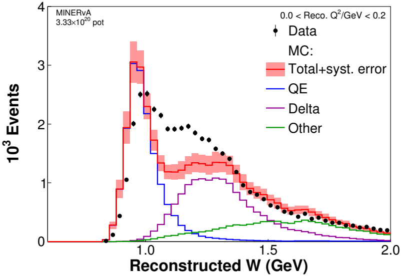
Could the discrepancy just be an energy scale error?



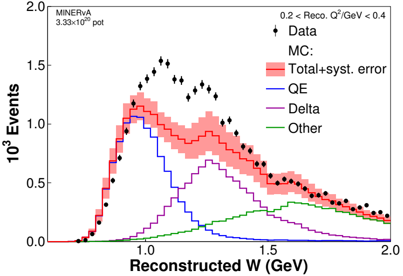
- This is the same as the previous, but now as a ratio to the central value MC

Reconstructed W in bins of Q^2, GENIE nominal

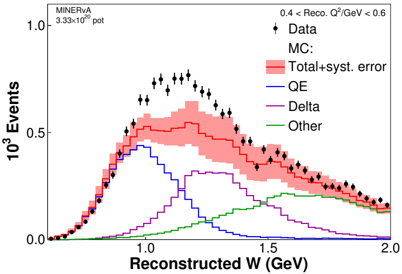
$0 < Q^2/\text{GeV} < 0.2$



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



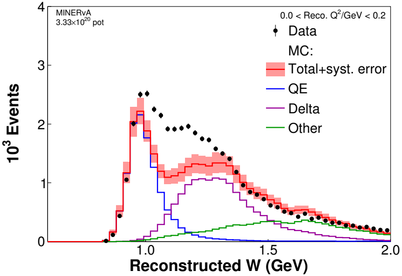
$0.4 < Q^2/\text{GeV} < 0.6$



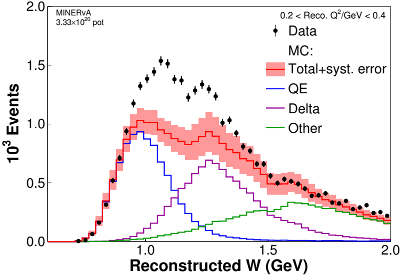
- Do the same in (Q^2, W)
- GENIE is nominal with pion weights
- $Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$
- $W = M_N^2 + 2M_N\nu - Q^2$
  $(M_N = (M_p + M_n)/2)$

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

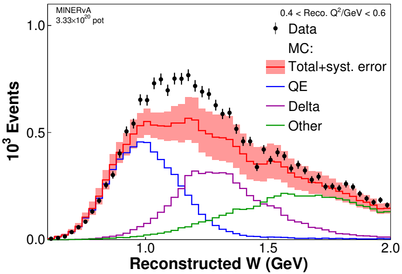
$0 < Q^2/\mathrm{GeV} < 0.2$



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



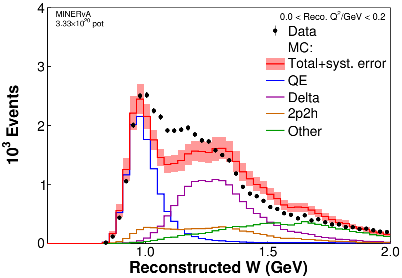
$0.4 < Q^2/\mathrm{GeV} < 0.6$



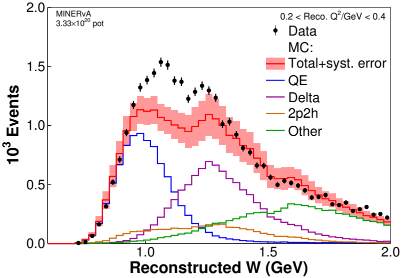
- Do the same in (Q^2, W)
- Each plot shows W in a slice of Q^2
- GENIE has pion weights and RPA

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

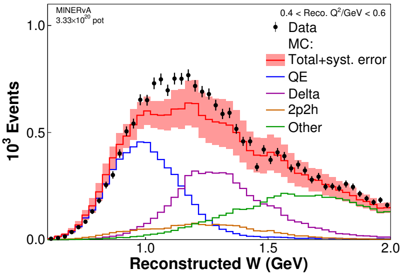
$0 < Q^2/\text{GeV} < 0.2$



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

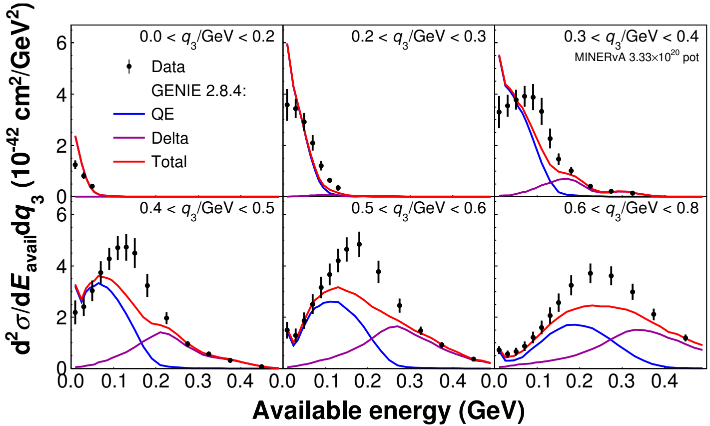


$0.4 < Q^2/\text{GeV} < 0.6$



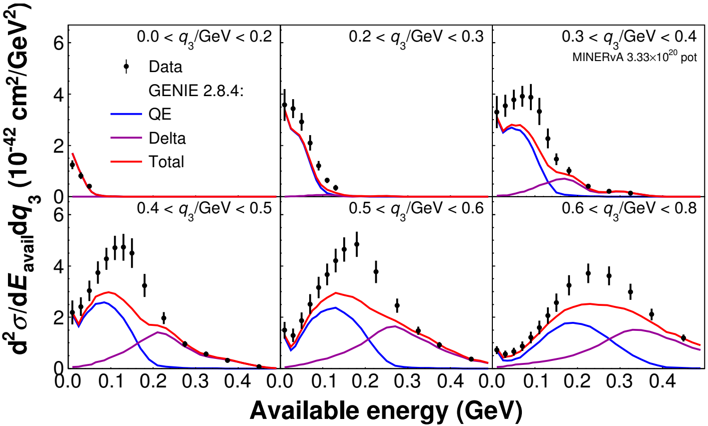
- Do the same in (Q^2, W)
- Each plot shows W in a slice of Q^2
- GENIE has pion weights and RPA+2p2h

Cross section



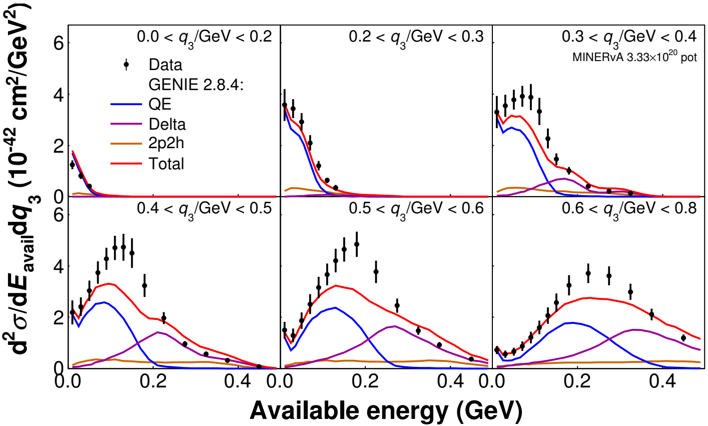
- MC with QE and Δ components

Cross section: MC with RPA



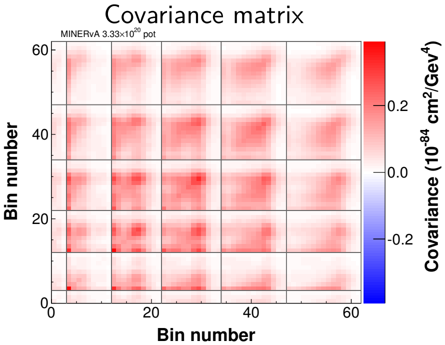
- This plot is the same as the previous one, but the prediction is now GENIE with pion weights and RPA applied to the QE component

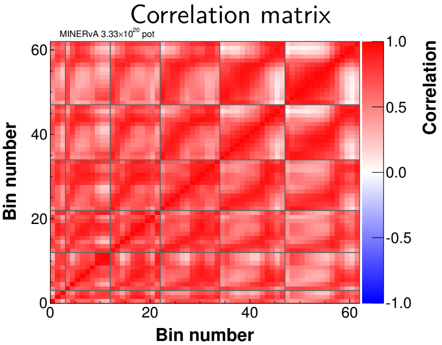
Cross section: MC with RPA+2p2h



- 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

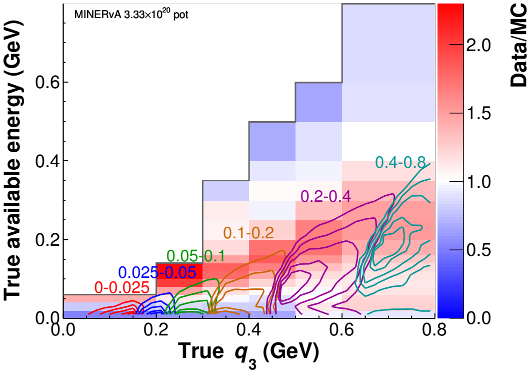
Covariance matrix on cross section

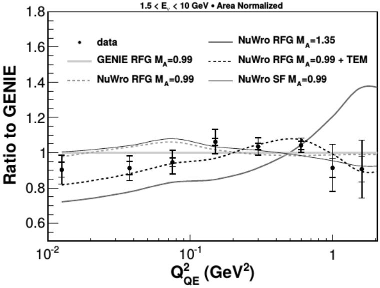




- Total covariance and correlation matrices on the cross section

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 $(q_3, E_{\mathrm{avail}})$. Draw each bin with contours
- Underneath is the data/MC cross section ratio
- Right is plot from CCQE 2013 neutrino paper