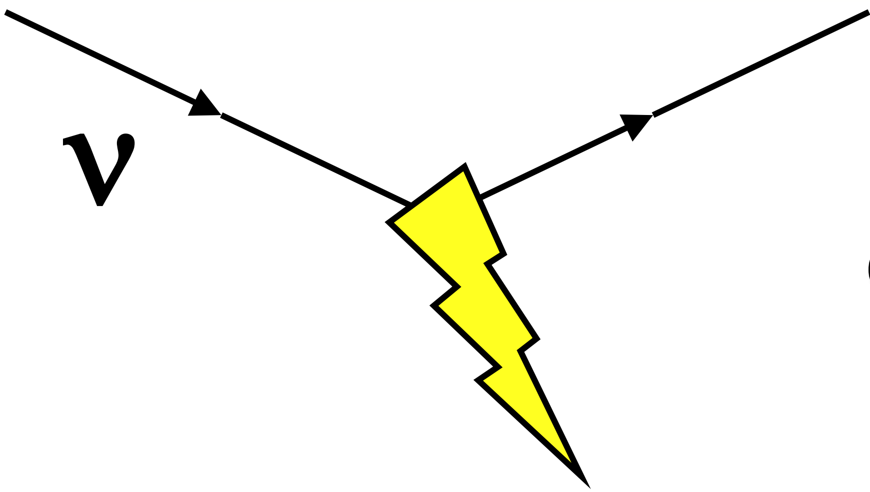
Identification of Nuclear Effects in Carbon in MINERvA



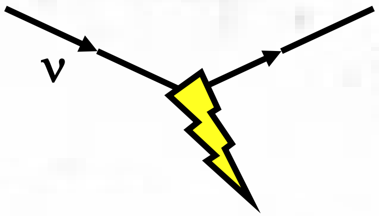
Kevin McFarland
University of Rochester
on behalf of the MINERvA collaboration

Two Body Current Workshop
CEA-Saclay
18 April 2016

Outline

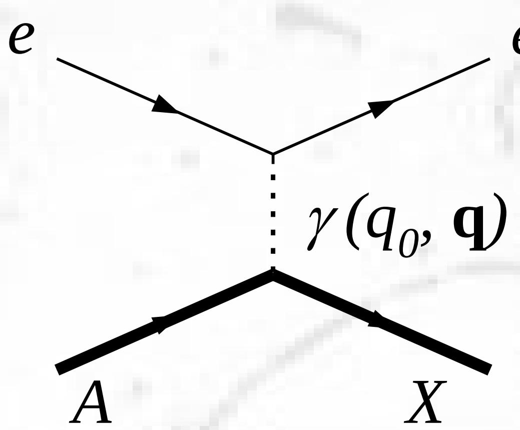
- Goals and realities of the measurement
- Future work with the method
- Interpretation for Oscillation and Cross-section Measurements

Based on work published as Phys.Rev.Lett. 116 (2016) 071802

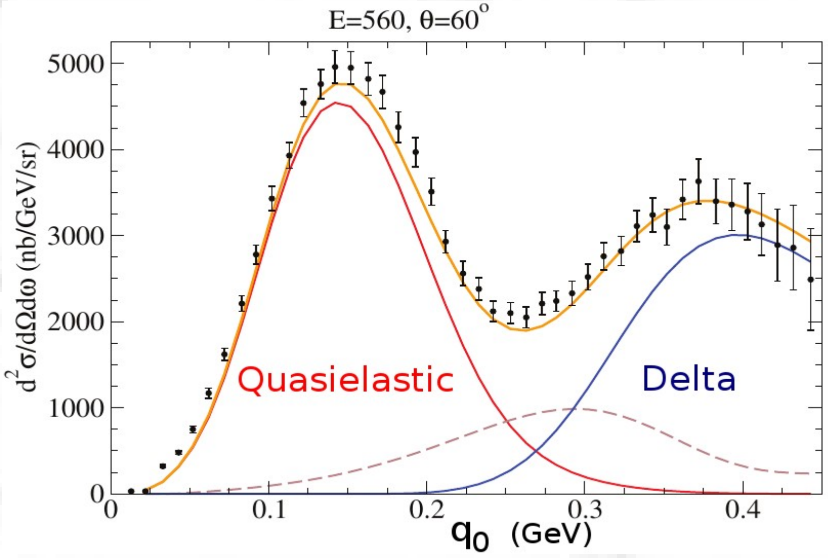


What we dream of doing

- If we had a tunable, high rate source of monochromatic neutrinos, we would repeat single arm electron scattering experiments

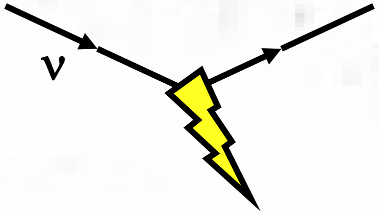


Adapted from G. D. Megias, NuFact 2015

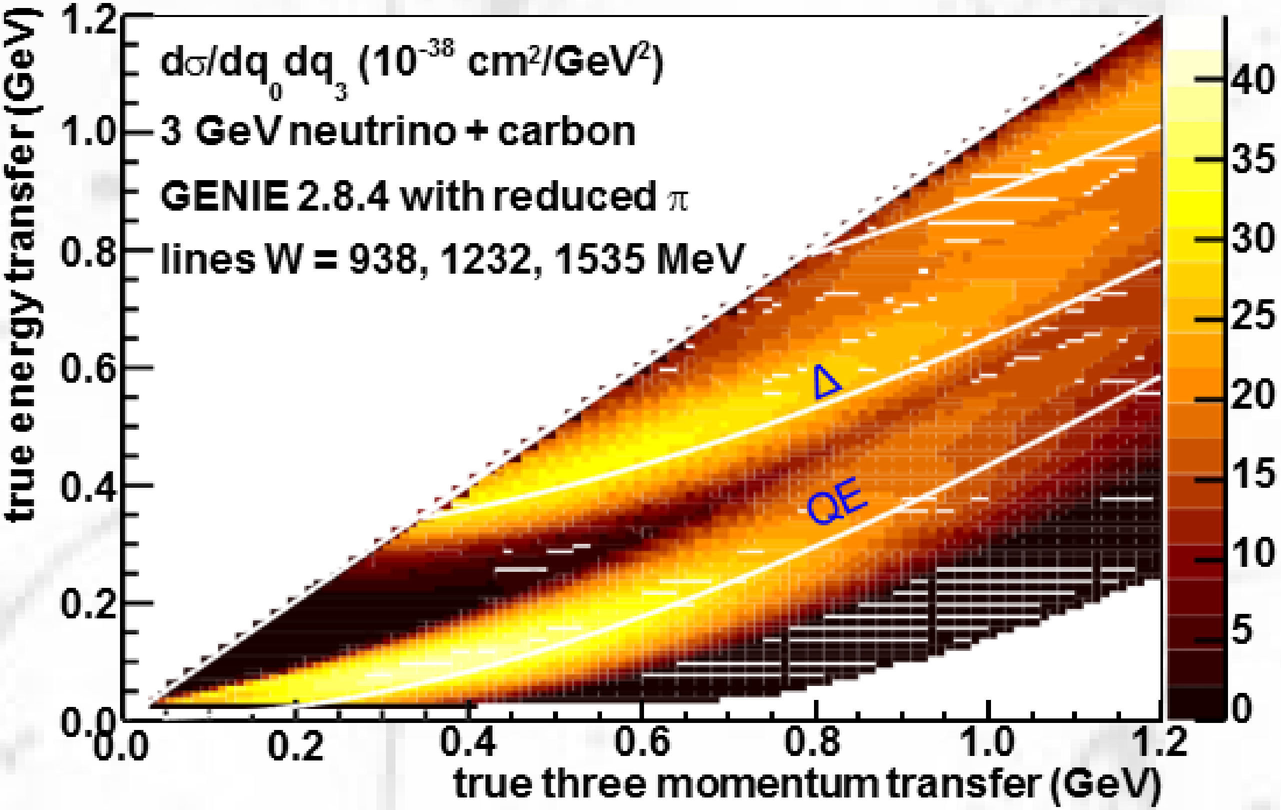


$$q_0 = E_e - E_{e'}$$

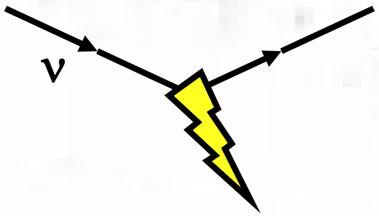
Specifics of our dream



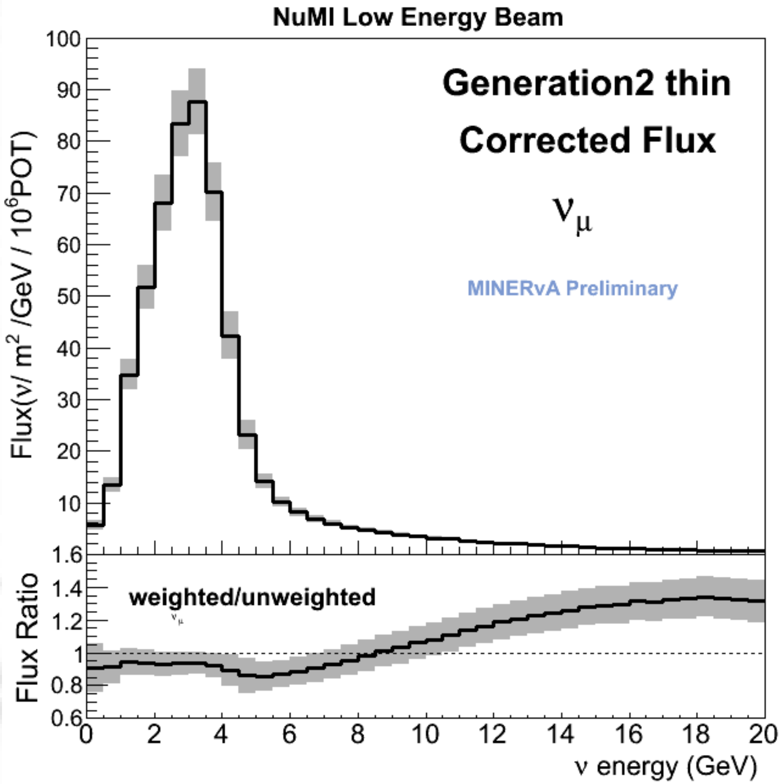
- More precisely, since single arm experiments would be wasteful, we would form these distributions



What defers our dream?

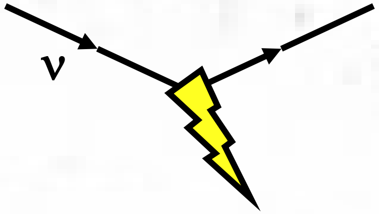


- The compromises to make a neutrino beam lead to two sources of evil
  - The neutrinos come to us with all different energies with no tagging possible
  - We don't cannot even predict those energies well
- On the latter point, after several physicist-decades of work and a combination of *in situ* and *ex situ* data, σ_Φ/Φ~8%



The best known high rate accelerator beam flux on earth: at NuMI

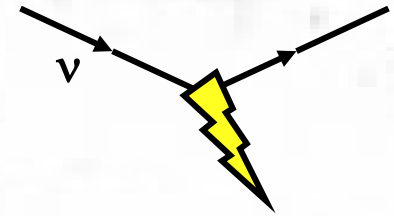
What can we do? And what may go wrong if we do?

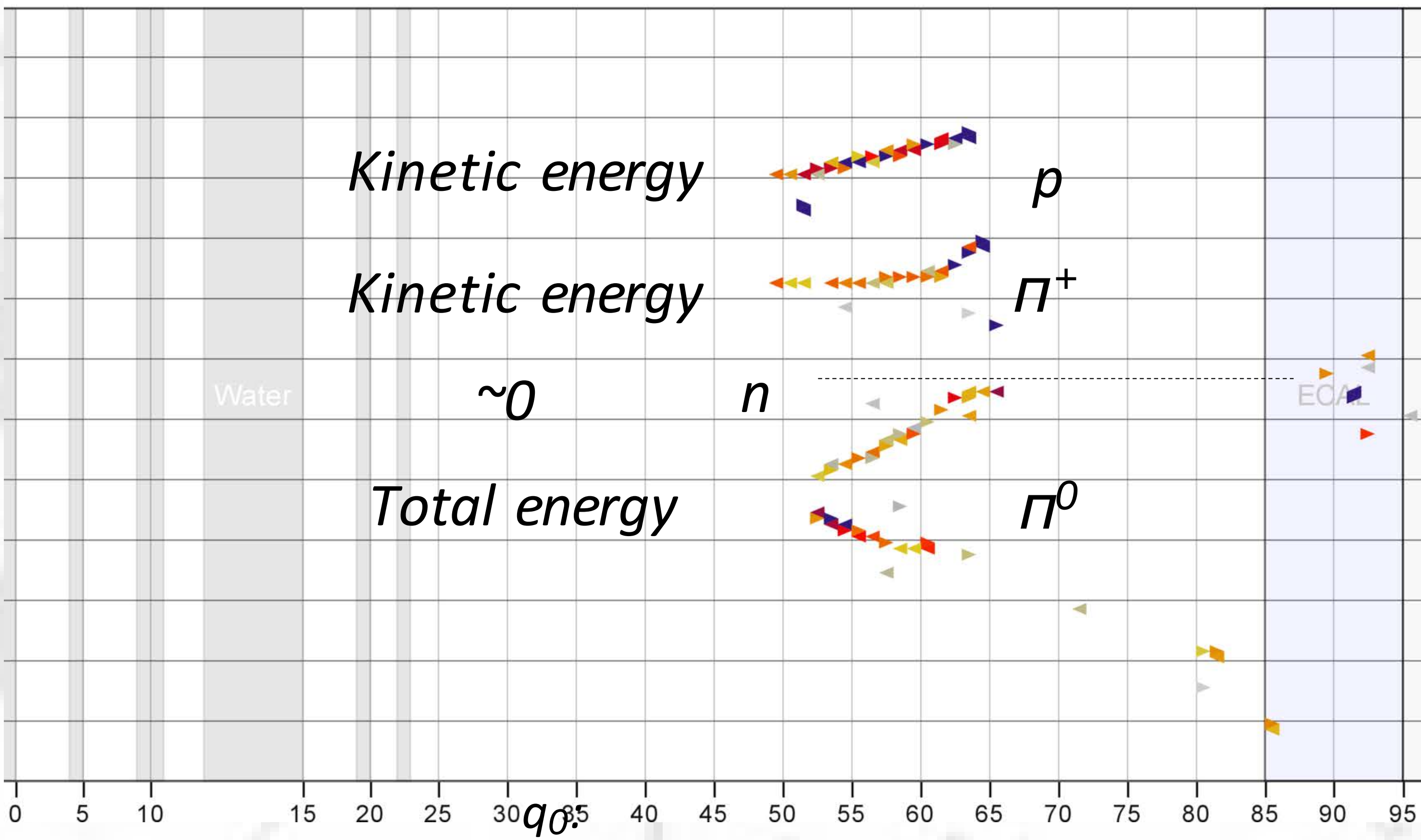


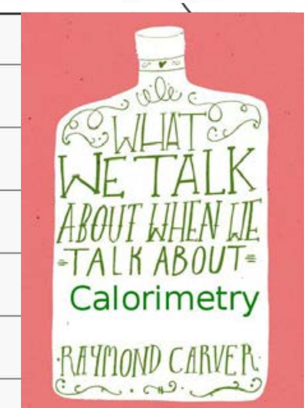
- The only recourse we have is to determine incoming neutrino energy from the final state energy.
- If that is known,
  - Neutrino direction fixed
  - Outgoing lepton is well measured.
- Done

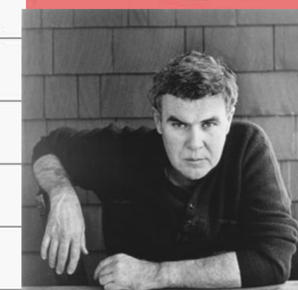
- *MINERvA's approach is to use calorimetry for all but the final state lepton*
- *This couples details of the final state to our measurement*
- *Will complicate attempts to correlate lepton and hadron kinematics*

What does calorimetric energy really mean?







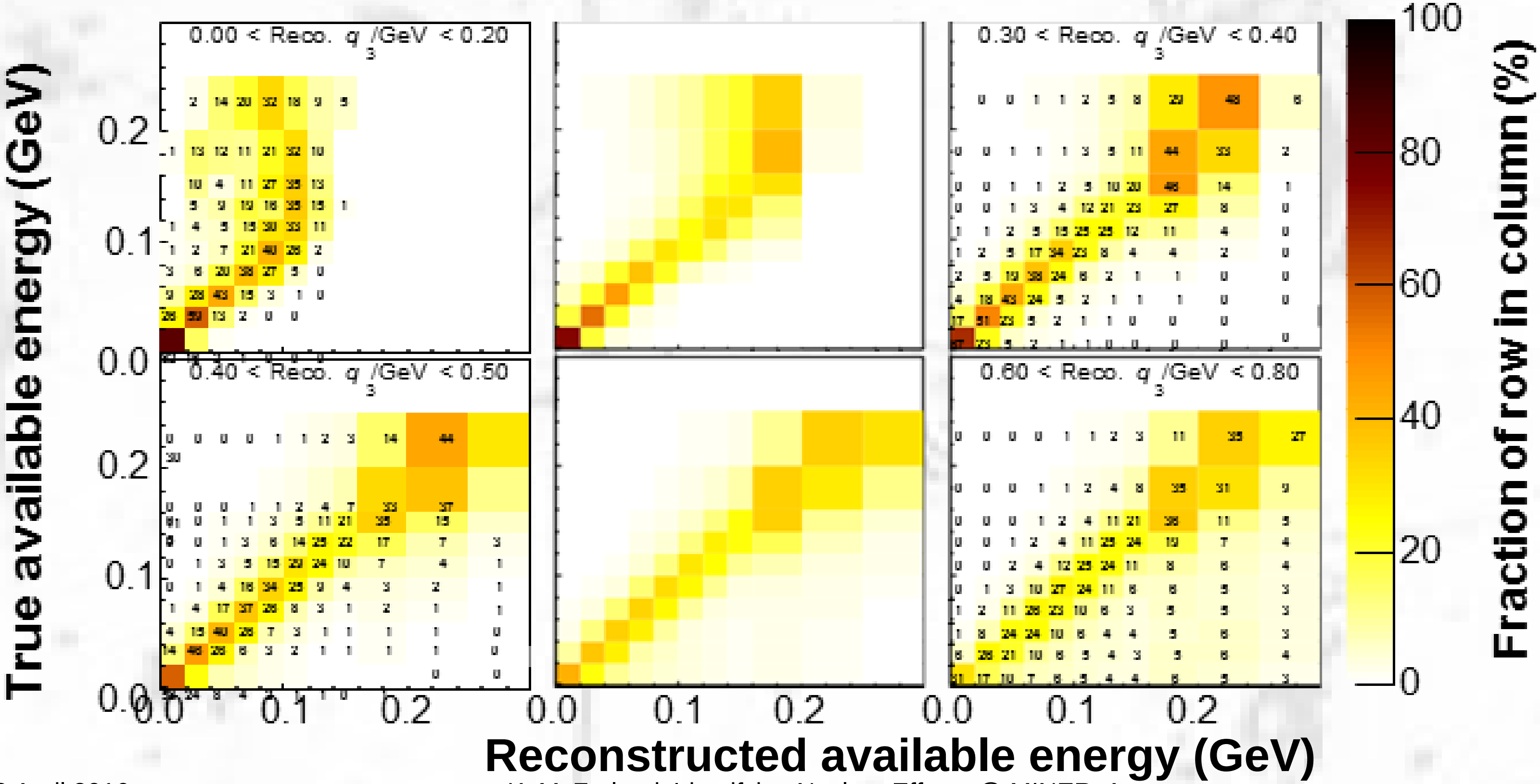


Phil Rodrigues was brilliant to channel Carver here!

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

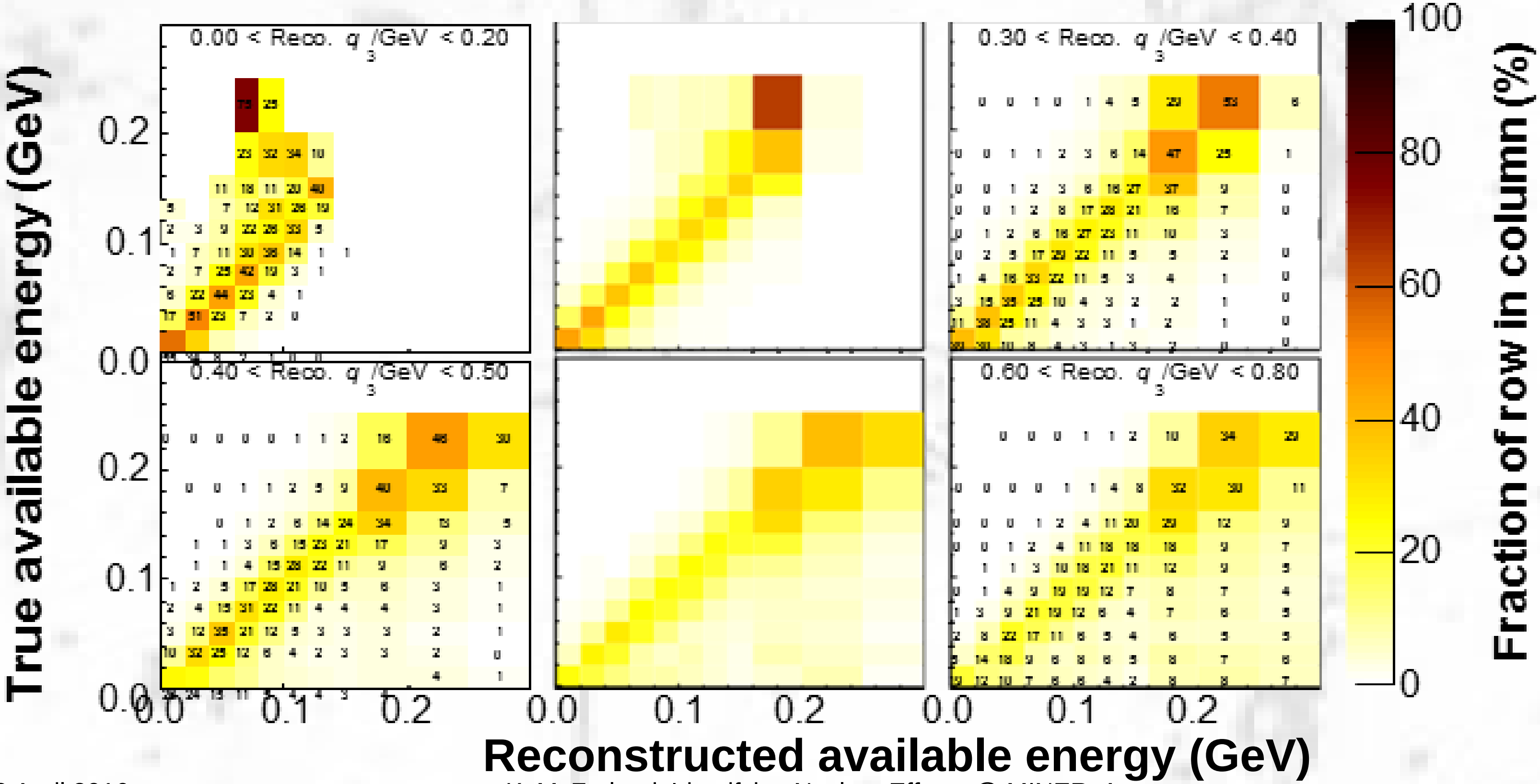
How well does it work?

- Do we reconstruct E_{avail} correctly? Yes.



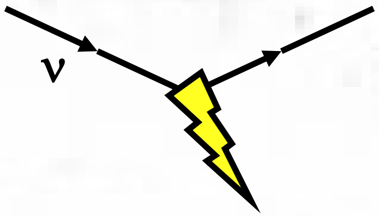
How well does it work?

- Here is the same plot for a 2p2h model
- Very slightly different. E_{avail} is a sound choice.



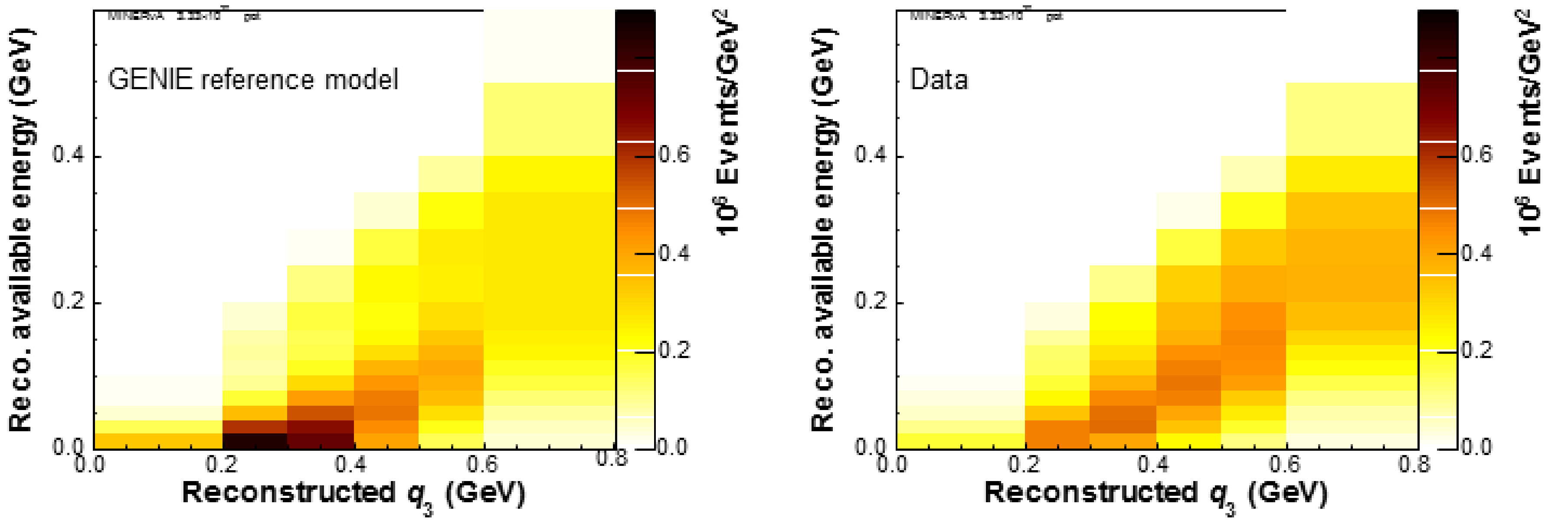
Results

Agreement with reference model (GENIE)?*



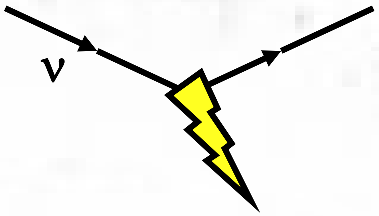
- No, but we in this room don't expect it to

Model MINERνA

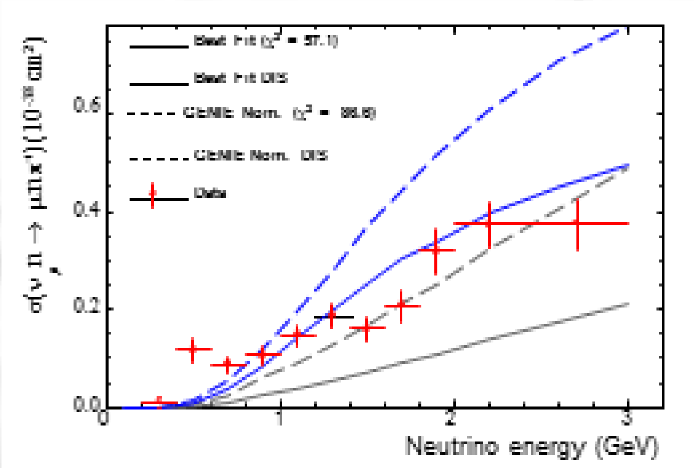


** GENIE 2.8.4 with no RPA or Valencia 2p2h model and MINERvA's pion tuning applied to Rein-Sehgal model*

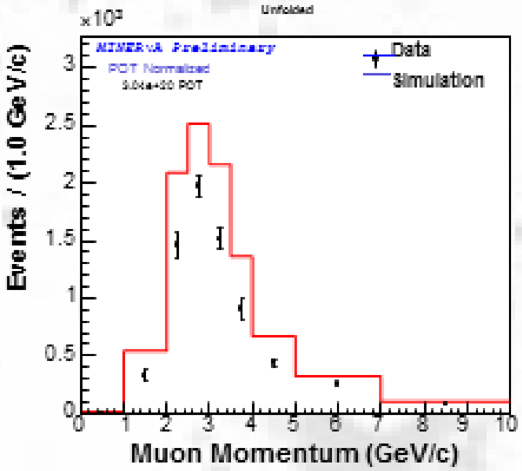
What is that pion modification?



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

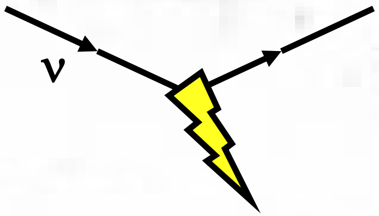


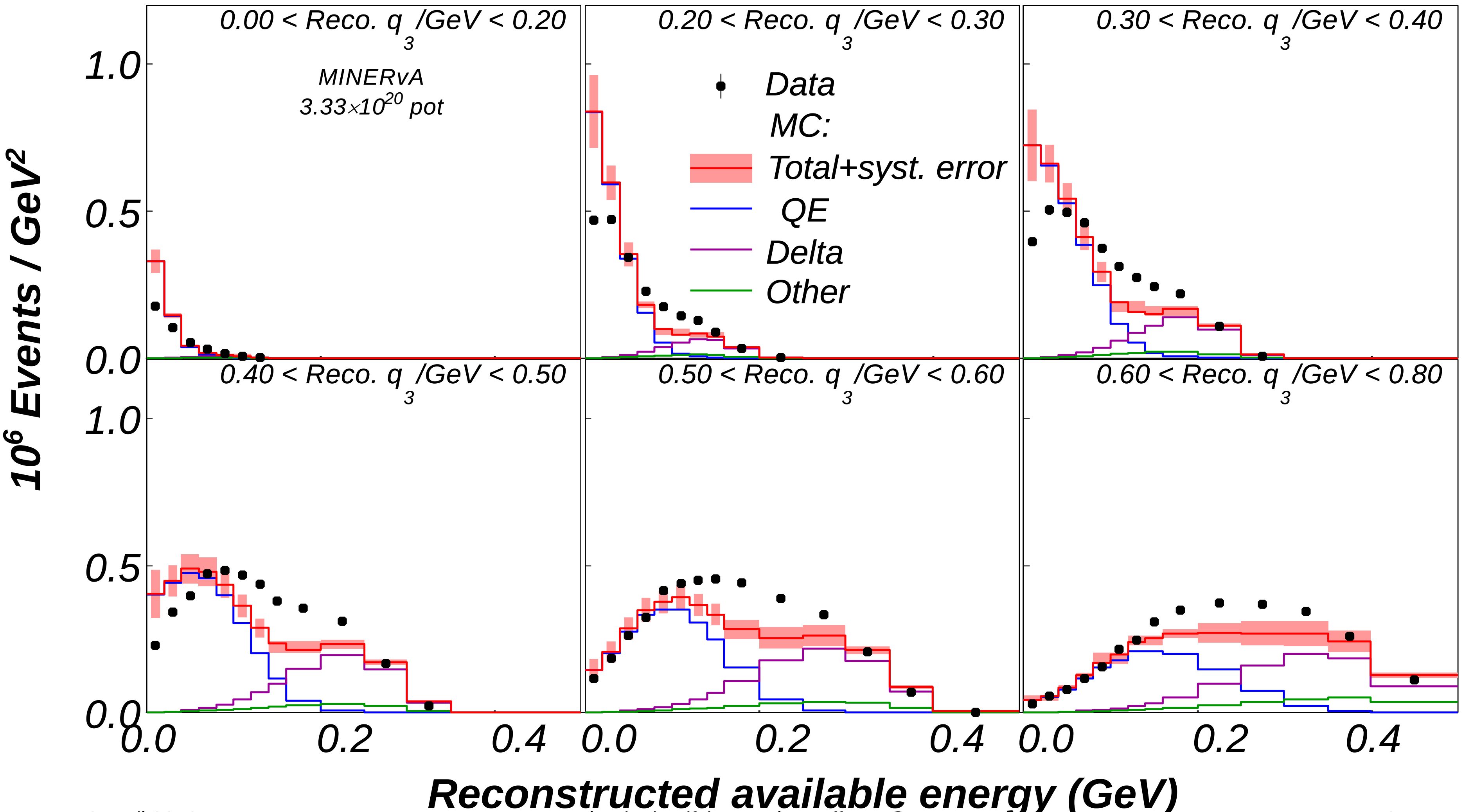
MINERvA $\pi^\pm$ production



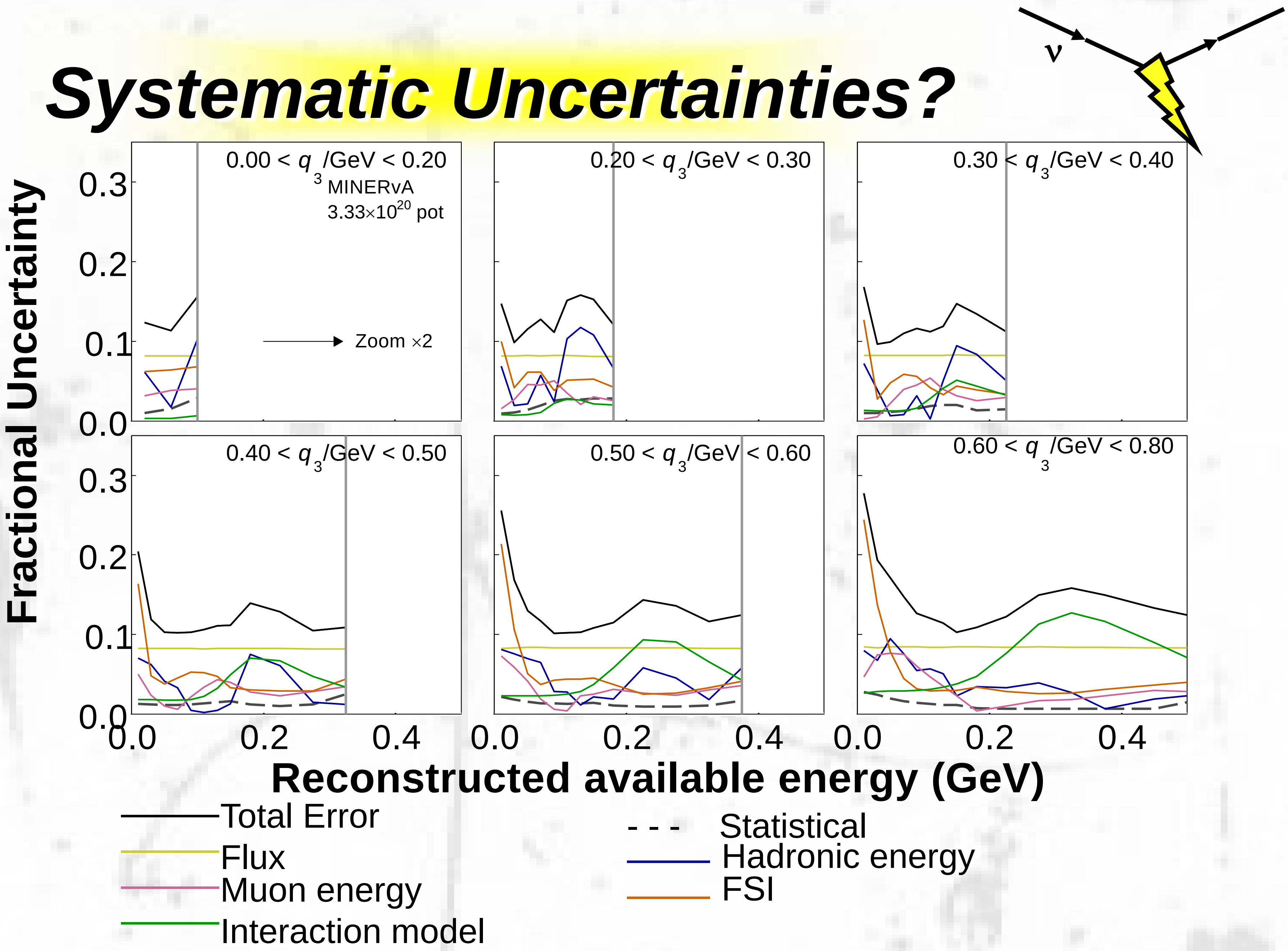
- Use reanalyzed ANL/BNL deuterium data (Wilkinson et al. PRD 90, 112017)
  - Scale down nonresonant production (): GENIE's NonRESBGvnCC1π) by 75% (1.5σi w/ 50% fractional uncertainty (Wilkinson et al. arXiV:1601.01888)
- Further scale down pion production with W < 1.8 GeV by 10% based on comparison with MINERvA data
- From comparison with MINERvA CC coherent π^+, reduce coherent with E_π < 450 MeV by 50%

Agreement with reference model (GENIE*)?

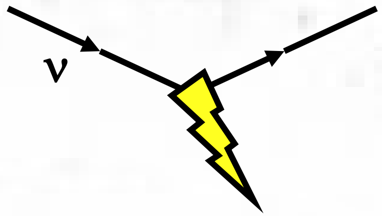


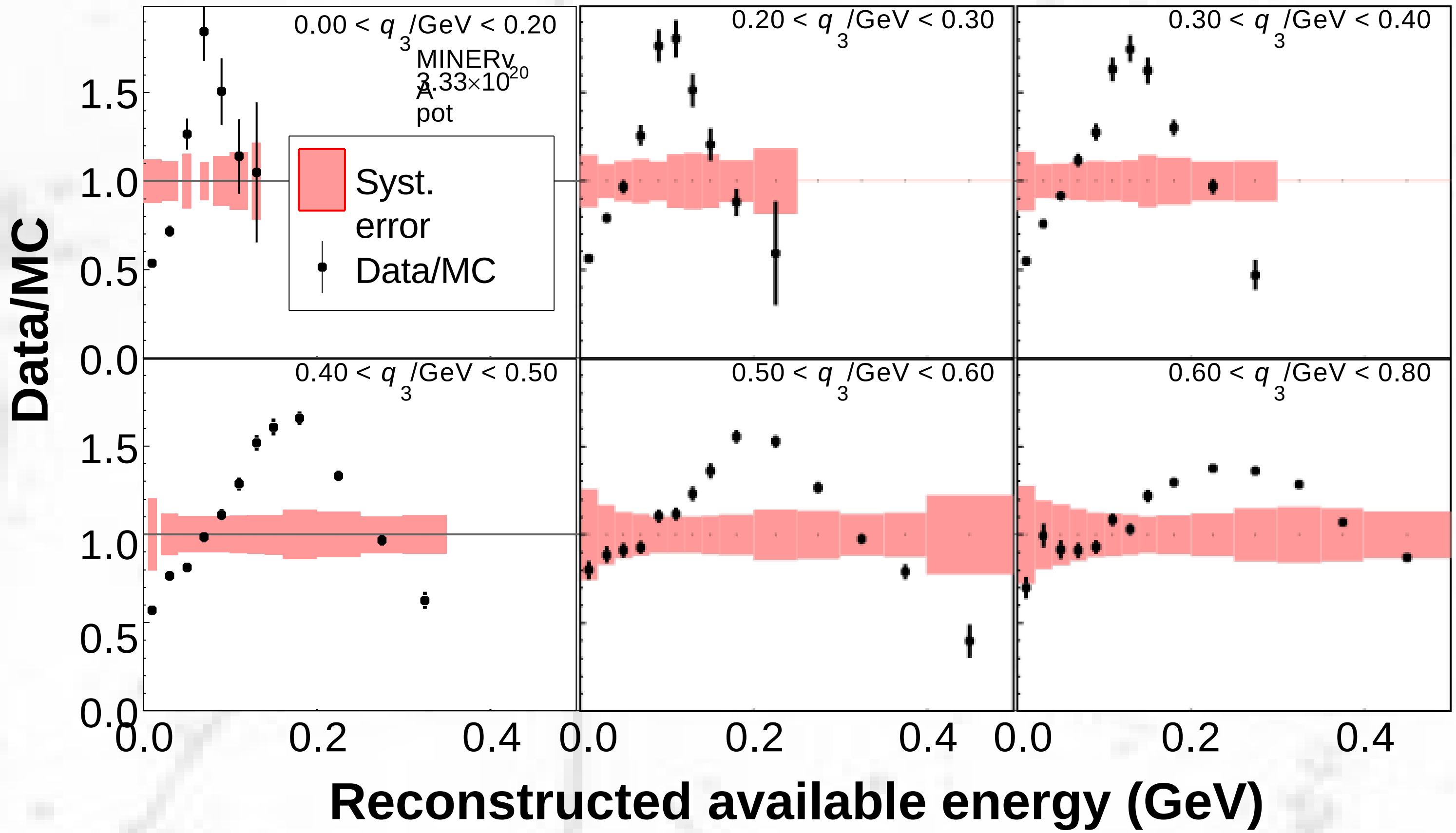


Systematic Uncertainties?

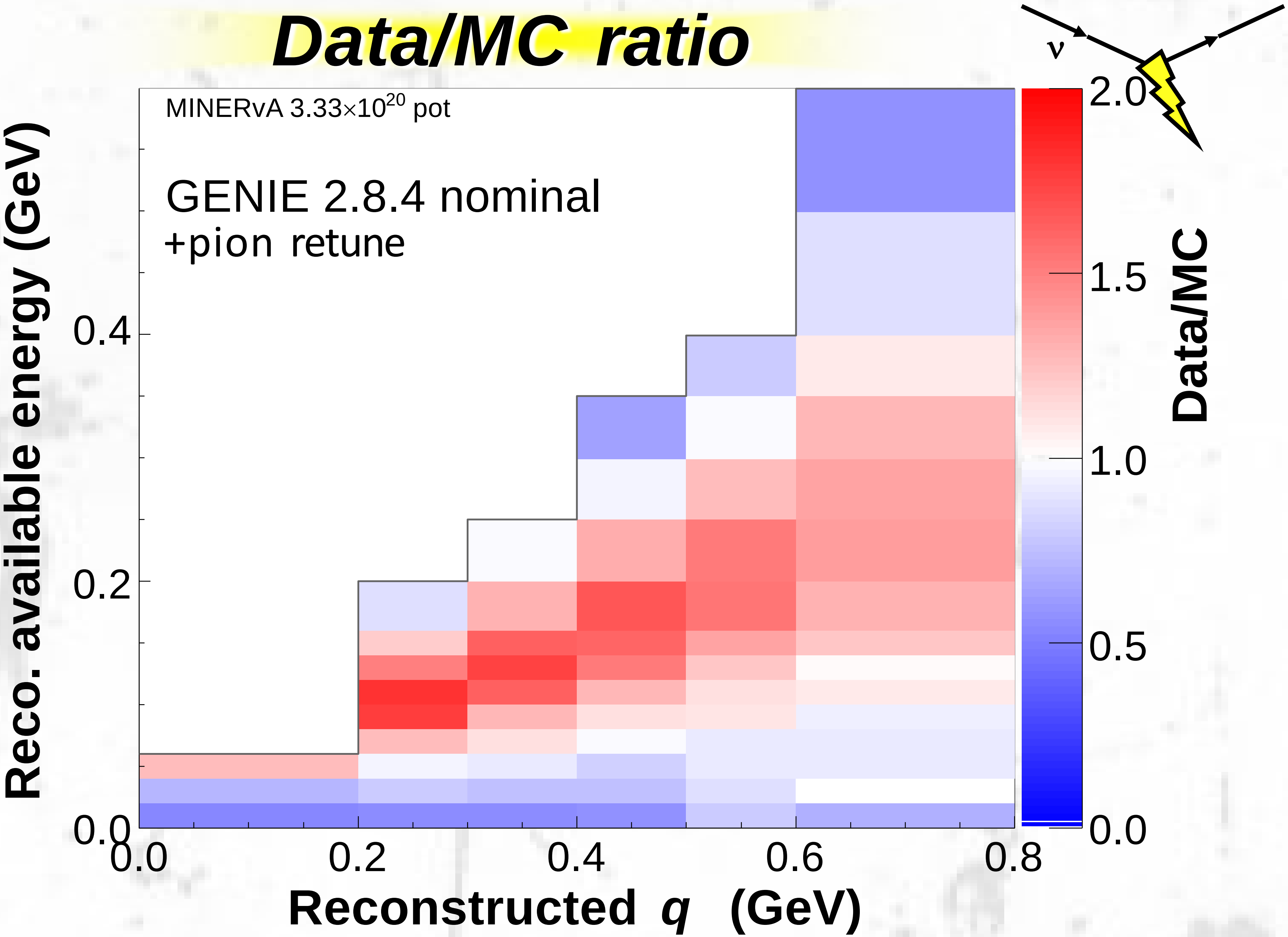


But they are small compared to disagreement

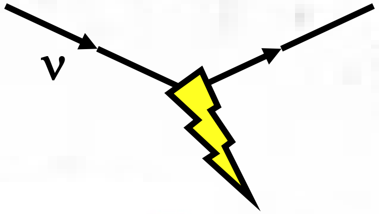


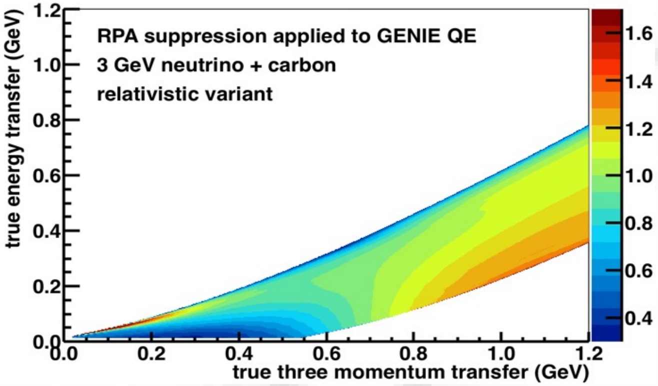


Data/MC ratio



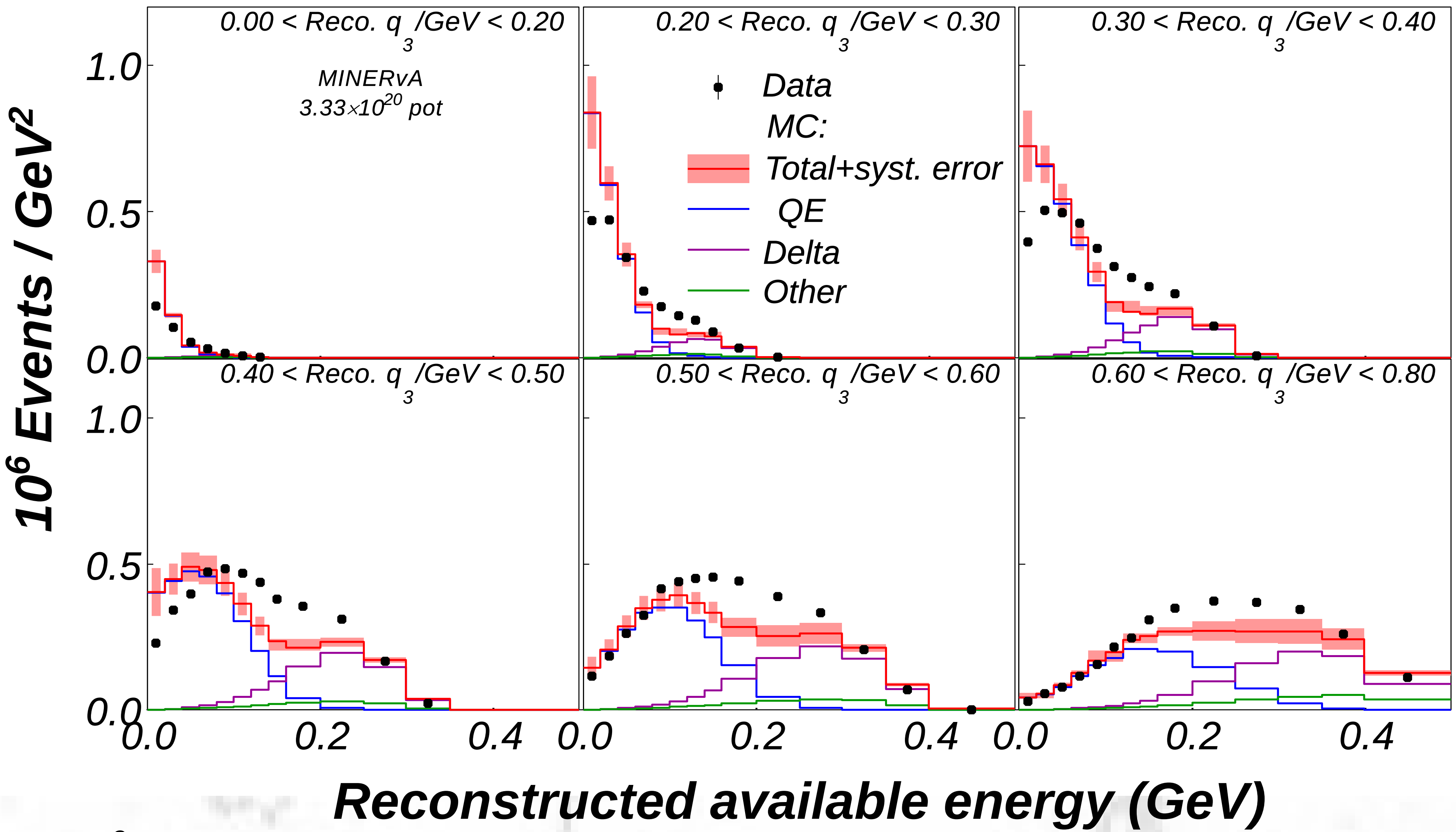
Beyond the reference model





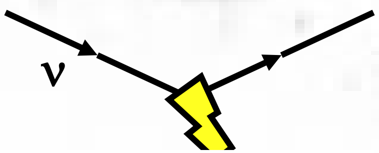
- Can add RPA correction
  - Valencia model RPA/no RPA prediction
    (Nieves, Ruiz Simo, Vicente Vacas, Phys.Rev. C83 (2011) 045501)
- Also added Valencia model 2p2h
  - High q_3 dealt with by cutoff
    (Gran, Sanchez, Nieves, Vicente Vacas, Phys.Rev. D88 (2013) 113007)
- Both of these extensions will be in future (2.12) GENIE releases implemented more or less as we have done

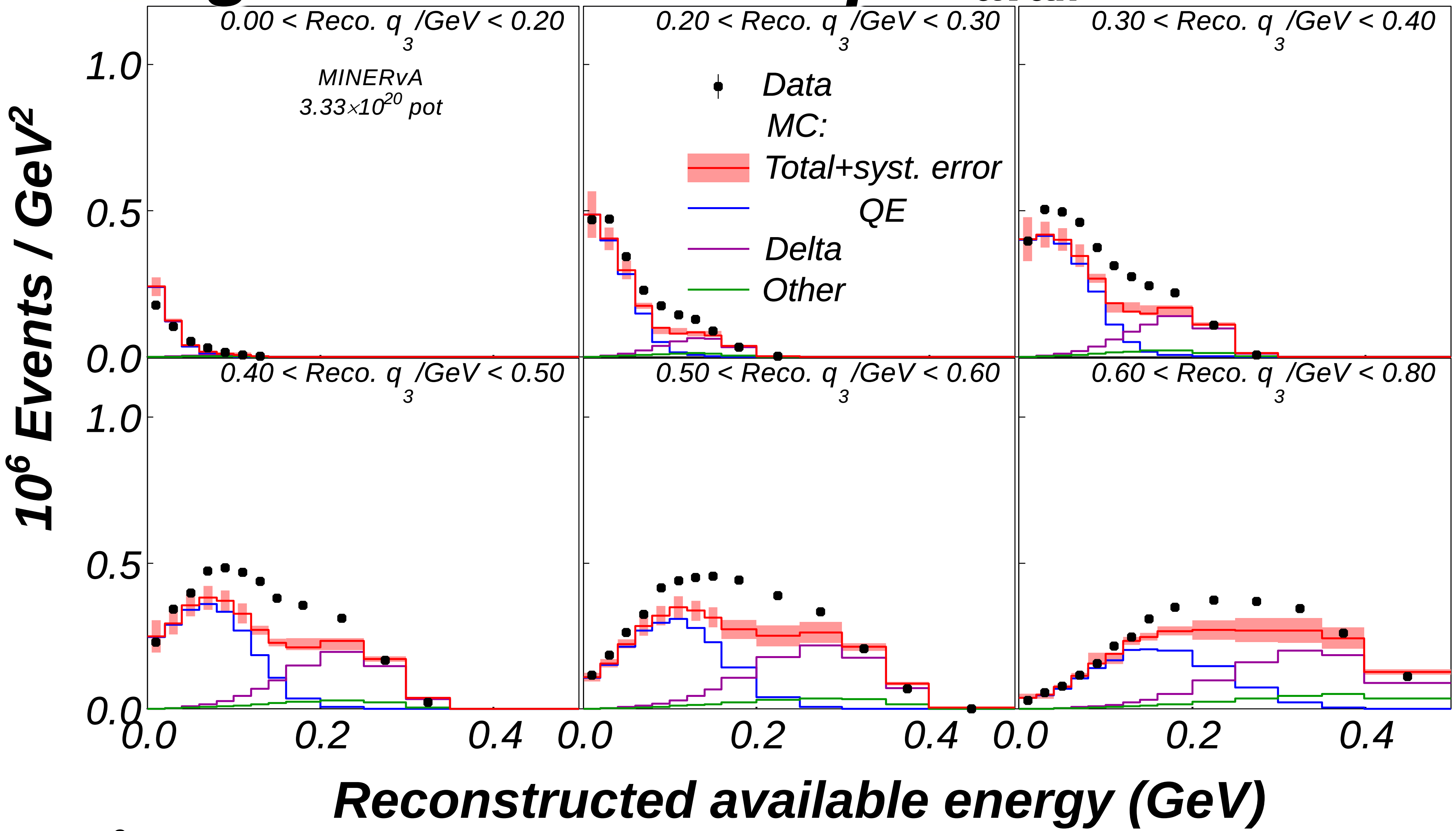
That default prediction again



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

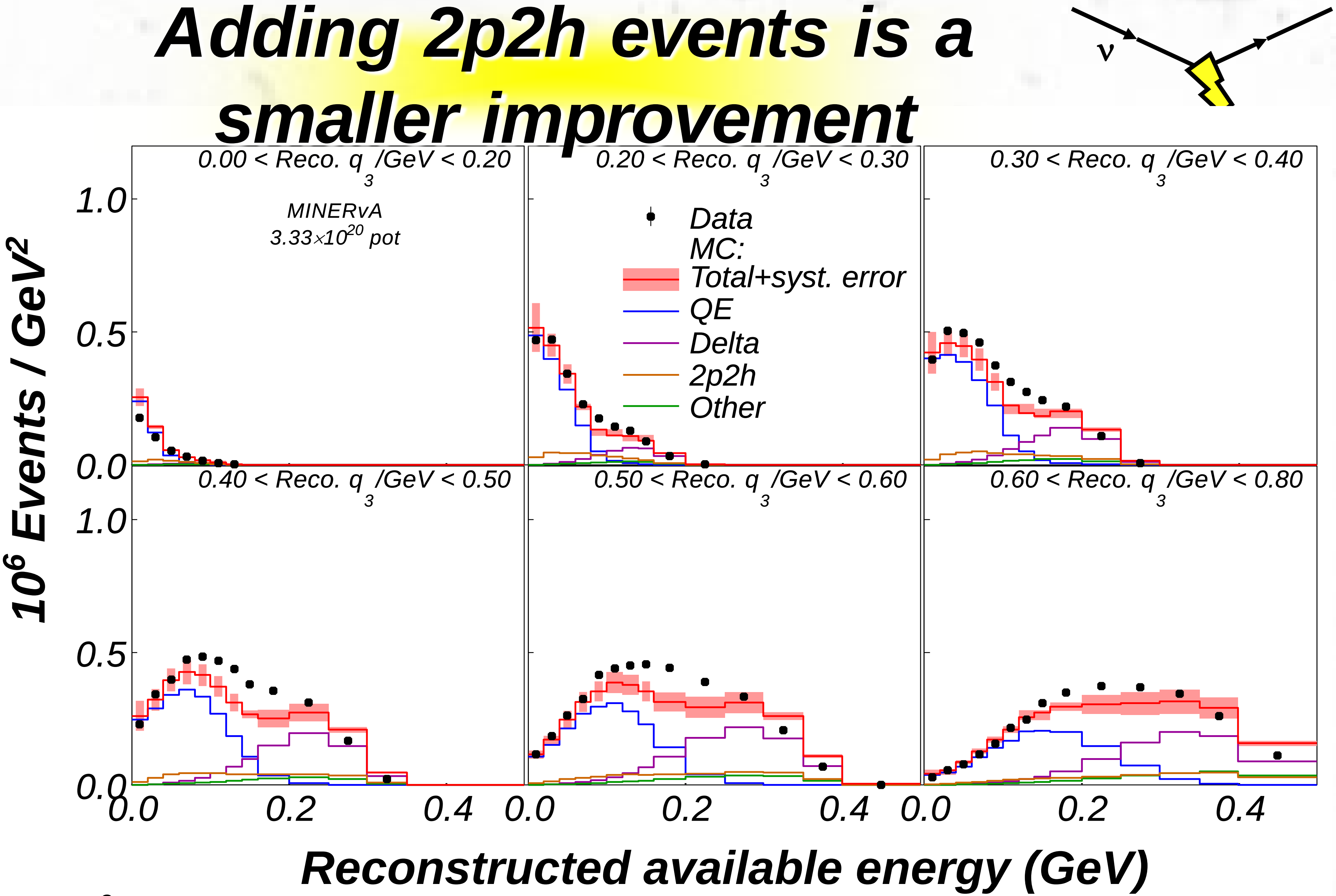
RPA screening improves agreement at low q_3, E_{avail}





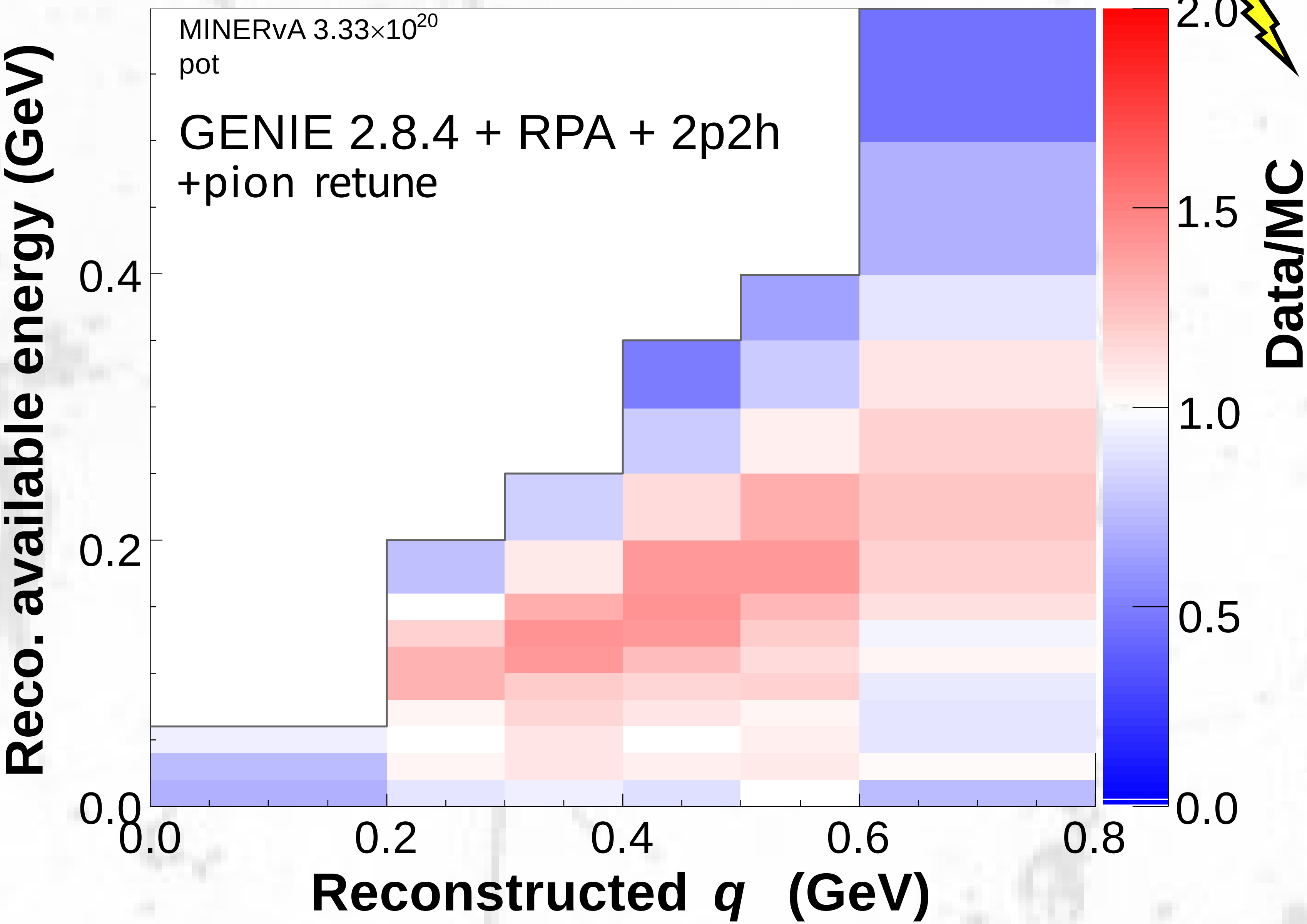
$\chi^2 = 540$ (stat+syst, 62 dof)

Adding 2p2h events is a smaller improvement

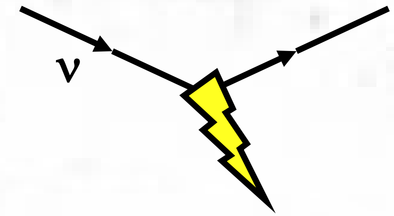


$\chi^2 = 498$ (stat+syst, 62 dof)

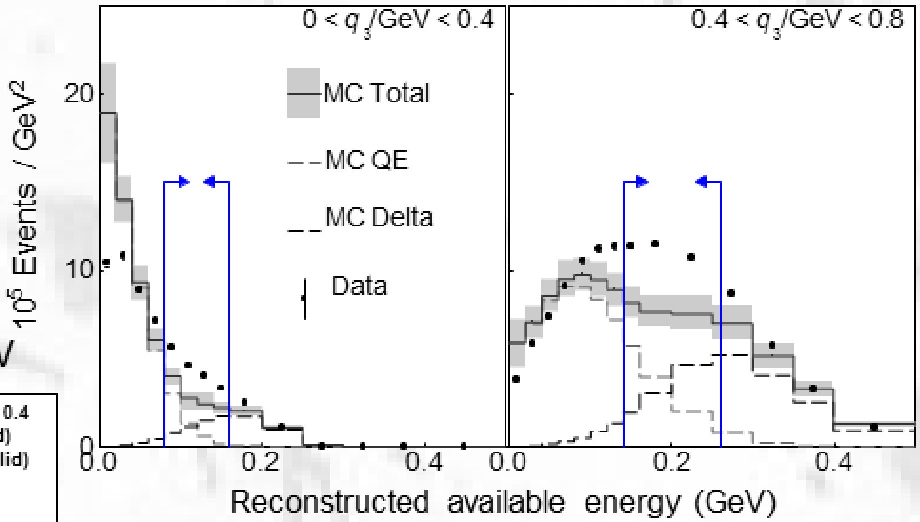
Data/MC ratio w/ RPA, 2p2h

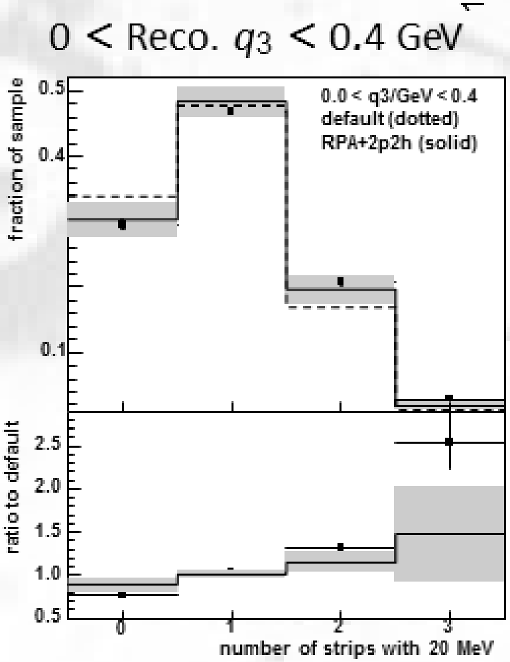


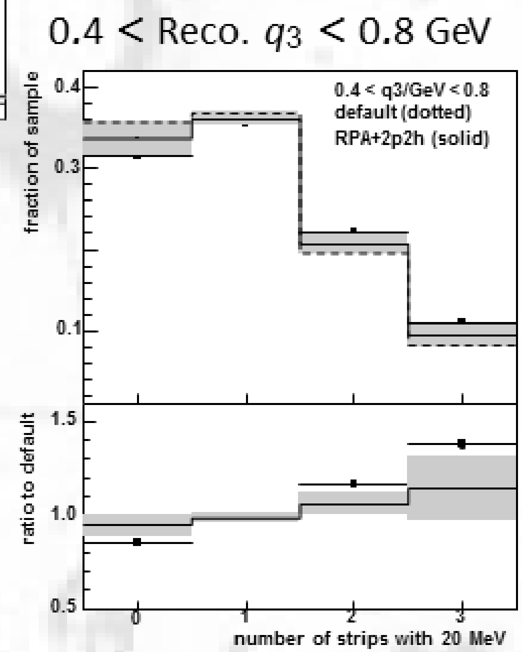
Proton content in region of excess?



- MINERvA tags final state protons by Bragg peak



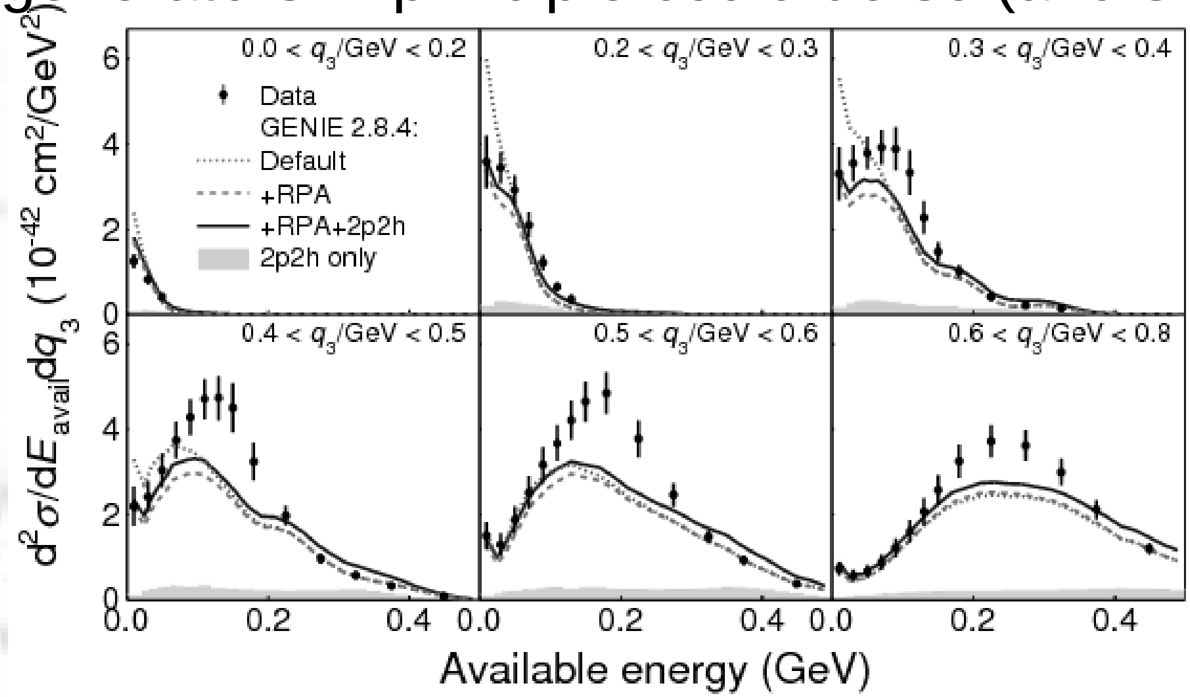




- Adding Valencia 2p2h improves agreement, but not "enough"

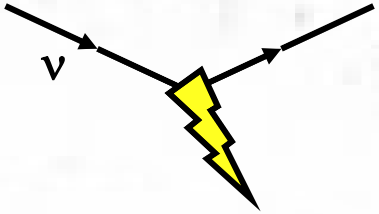
Result has been "unfolded" to be compared with theory

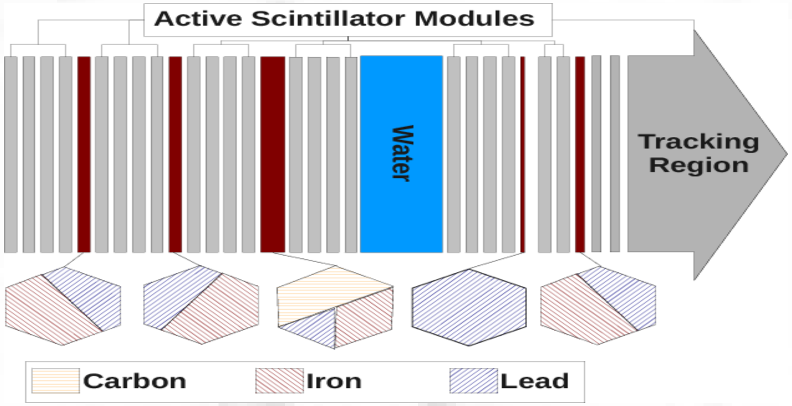
- Corrected to true E_{avail} and q_3 by unfolding
- A model that can predict the final state (by whatever means), can try to reproduce this
  - All generators in principle could do so (and should)



Extensions

How is MINERvA extending this measurement?



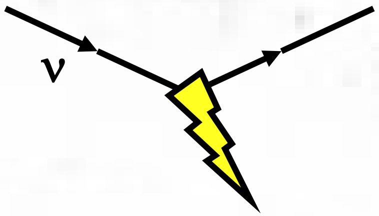


- MINERvA has Fe and Pb passive targets
  - Likely that resolution in available energy will suffer, particularly if from low momentum protons
- MINERvA can tag π^+ with understood efficiency with Michel electrons from $\pi^+ \rightarrow \mu^+ \nu \rightarrow e^+ \nu\nu$
- MINERvA can tag neutrons from recoiling protons from np or nC collisions in the scintillator
  - Could use this as part of the recoil energy estimator

Interpretations

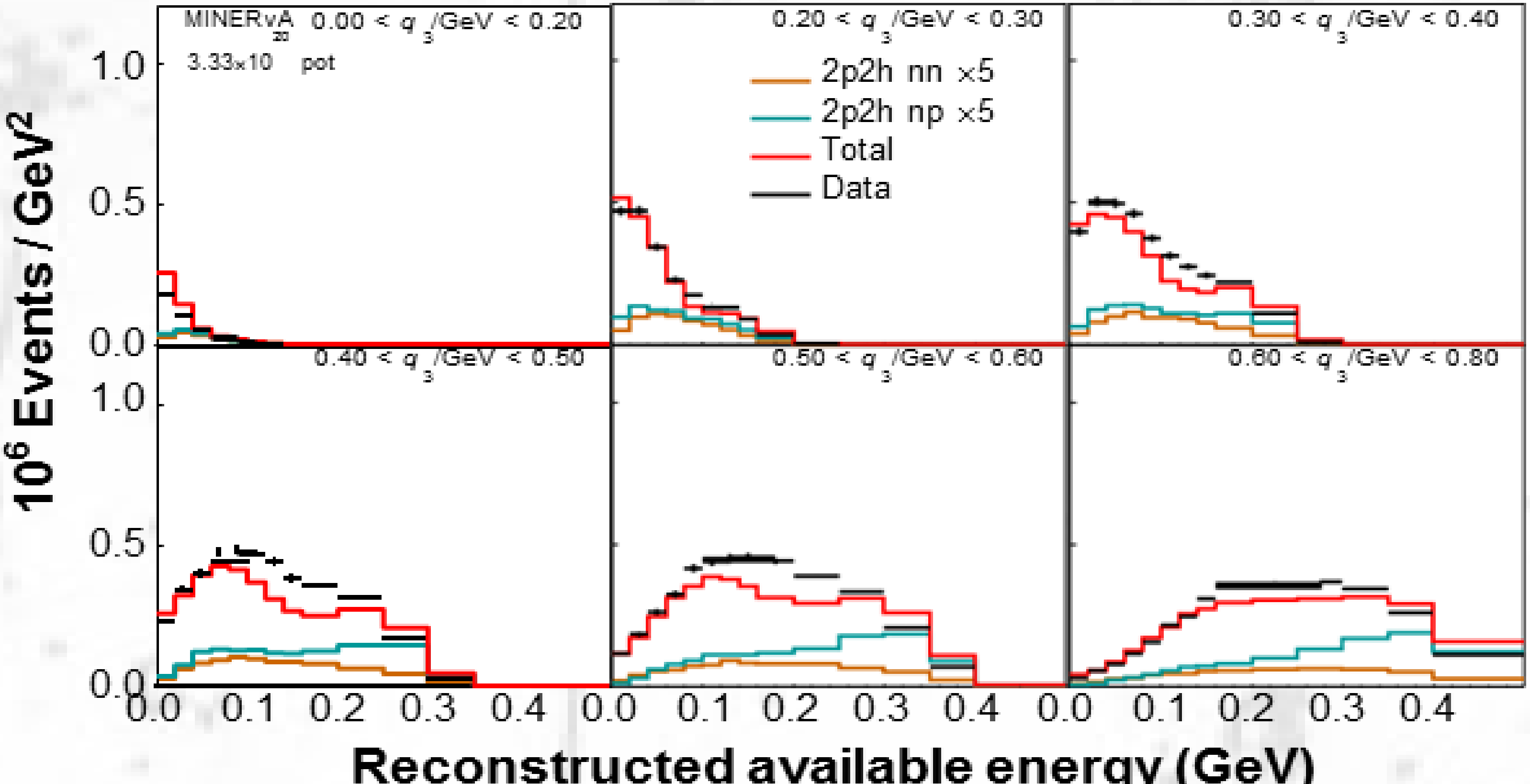
Stating the obvious…

- The agreement with the reference model is very poor. Adding RPA screening and 2p2h Valencia prediction helps, but there are still deficits at higher E_{avail} at high q_3
- For an oscillation experiment, this should be very worrying. E.g., T2K assumes the correspondence between muon momentum and neutrino energy
- As we all know, those worried experimentalists will start grasping at any “dial” to try to “fix” this, however poorly motivated. So here we go.

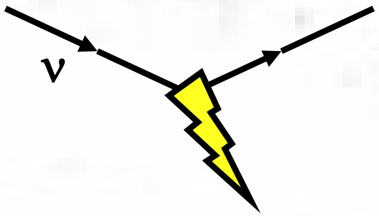


Initial state nucleons?

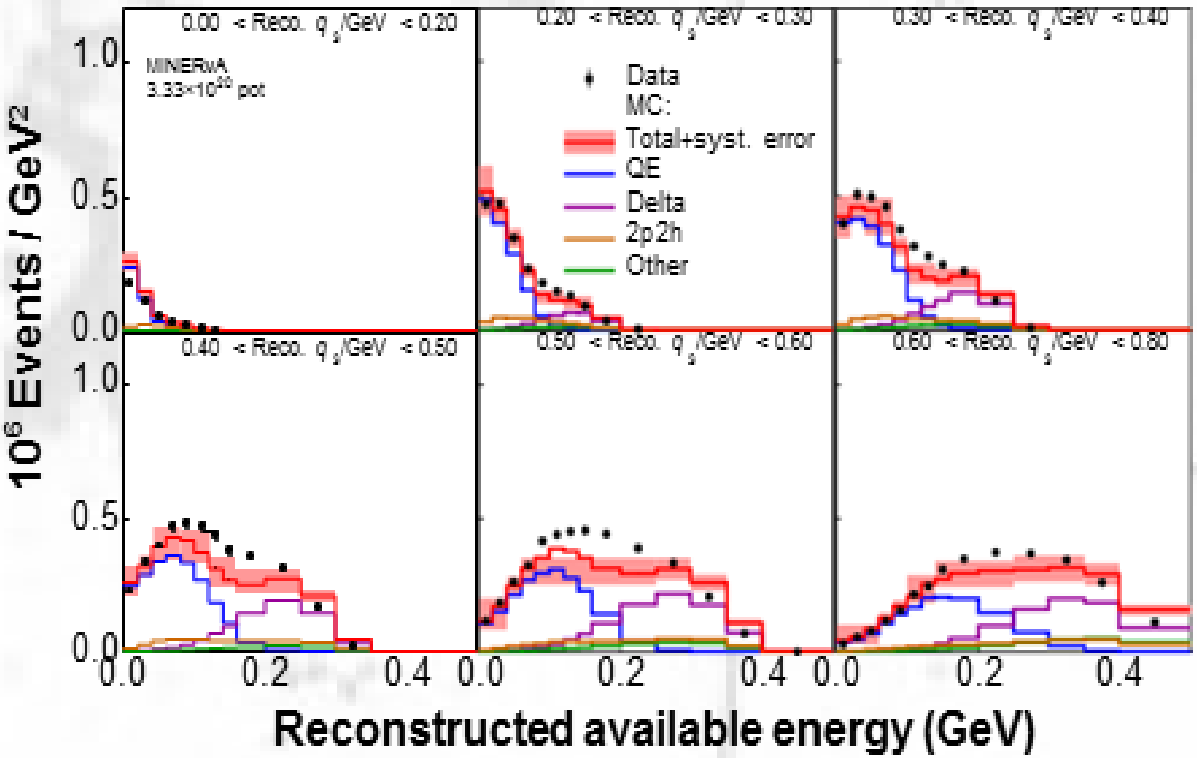
- Can look at nn and np initial state separately
  - Extreme changes to prediction in Valencia model could help, but not enough to “fix” it

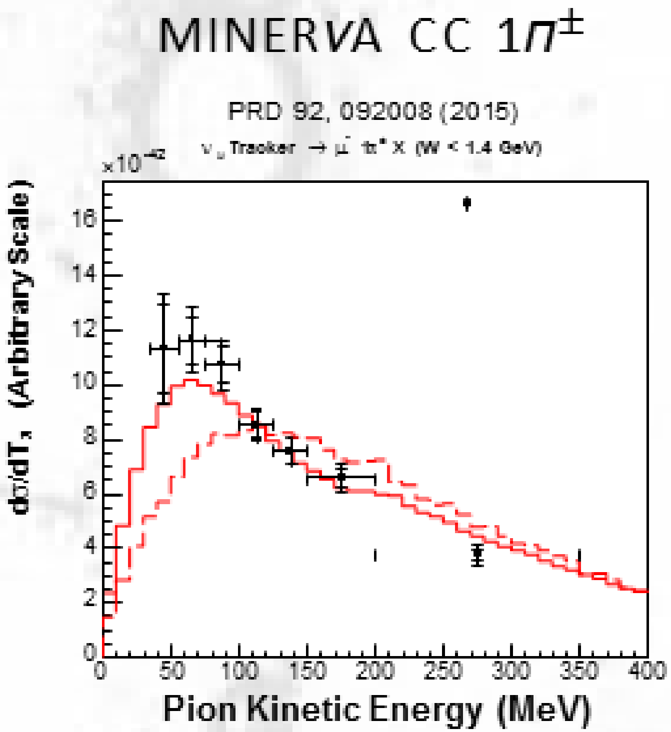


Pion Production



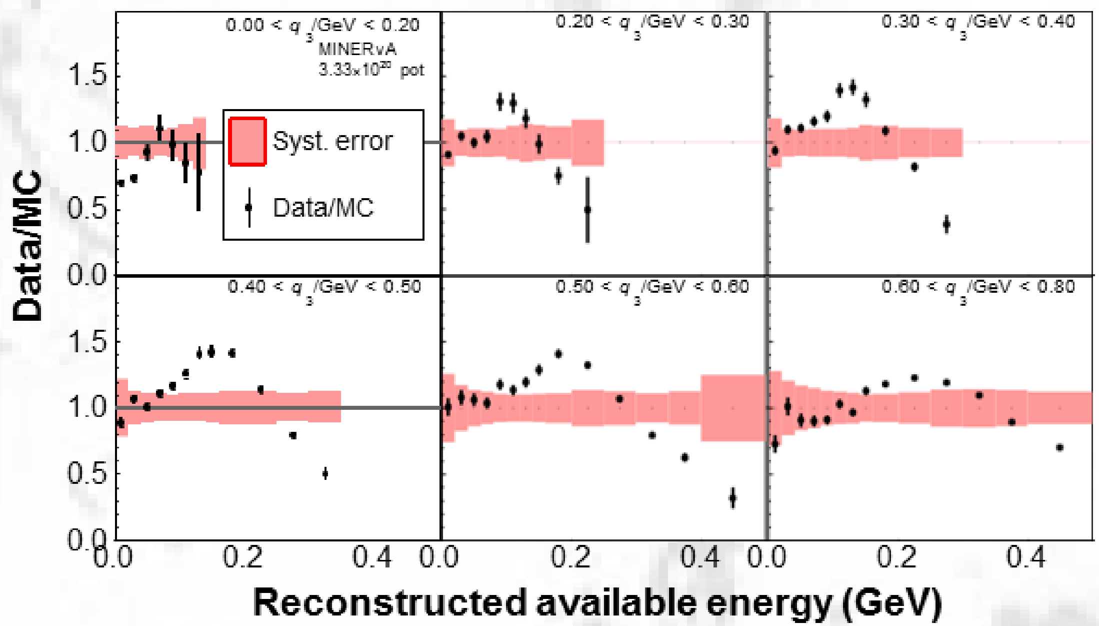
- Change the pion (Δ region) model significantly?
  - Maybe at high E_{avail}, but constrained by data to fairly small changes





What MINERvA does now

- For systematic studies, we construct a ratio of 2p2h prediction as a function of E_{avail} and q_3 and use that to modify Valencia 2p2h
- It's a large weighting at high E_{avail} and q_3
- Anyone have a better idea for MINERvA and T2K and NoVA?



Conclusions

What have we learned?

- At a minimum, there is significant disagreement between the E_{avail}–q_3 distributions predicted by GENIE+Valencia 2p2h
  - GENIE as tuned by MINERvA, Valencia 2p2h with the Gran-Sanchez-Nieves-Vicente-Vacas q_3 cutoff
- Probably it's more than that
  - It seems difficult to make enough change to the final state to make q_0 agree and E_{avail} be this wrong

What should happen next?

- More measurements of a similar spirit
  - MINERvA extensions, but also T2K, NOvA
- Better hadron side modeling of 2p2h
- Work on quantifying the FSI uncertainties in this beyond GENIE cascade model uncertainties

- My challenge to the theorists here is to get that unified prediction form the theory side before the experimentalists get a unified picture of data