Using GENIE to compare multi-nucleon effects to MINERvA data

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Saint Surrounded by Three Pi Mesons

Salvador Dali
Figueres, Spain, 1957

GENIE implementation
tech note arXiv:1601.02038
(some updates coming soon
scheduled for GENIE 2.12)

Based on
Valencia QE-like 2p2h model
PRD 88 113007 (2013)
PRC 83 045501 (2011)

And MINERvA result
PRL 116 071802 (2016)

Valencia QE-like 2p2h model in GENIE

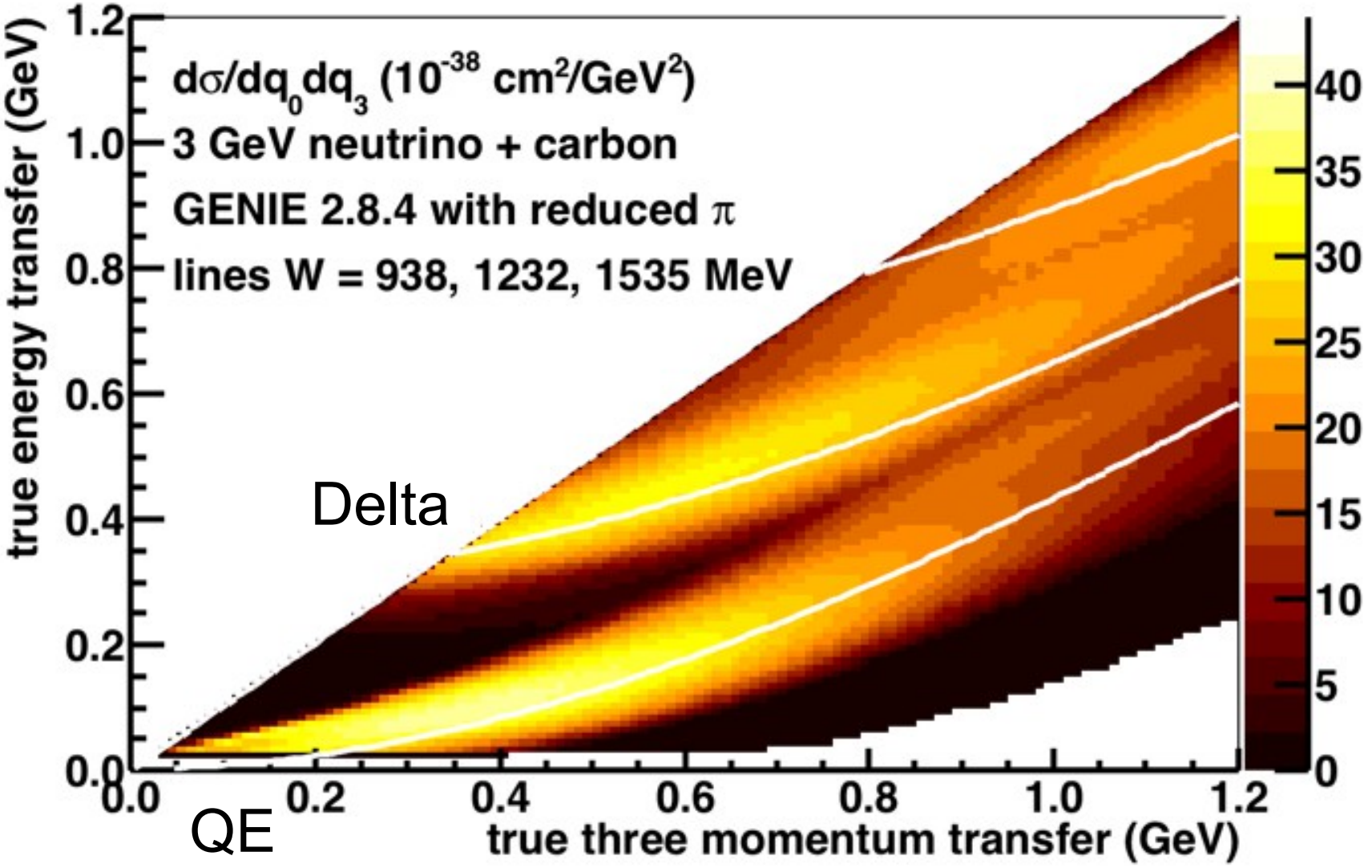
The FORTRAN calculation gives the event rate in pμ θμ
but the core of the calculation is the Hadronic Tensor in q0 q3
limited to isoscalar nuclei, integrates over all hadronic final states

For GENIE do two basic things:

Reproduce authors' original double-differential xsec, q3 < 1.2 GeV
Precompute two hadronic tensors (pn, all) from original FORTRAN
Recode (~100 lines) the contraction with leptonic tensor

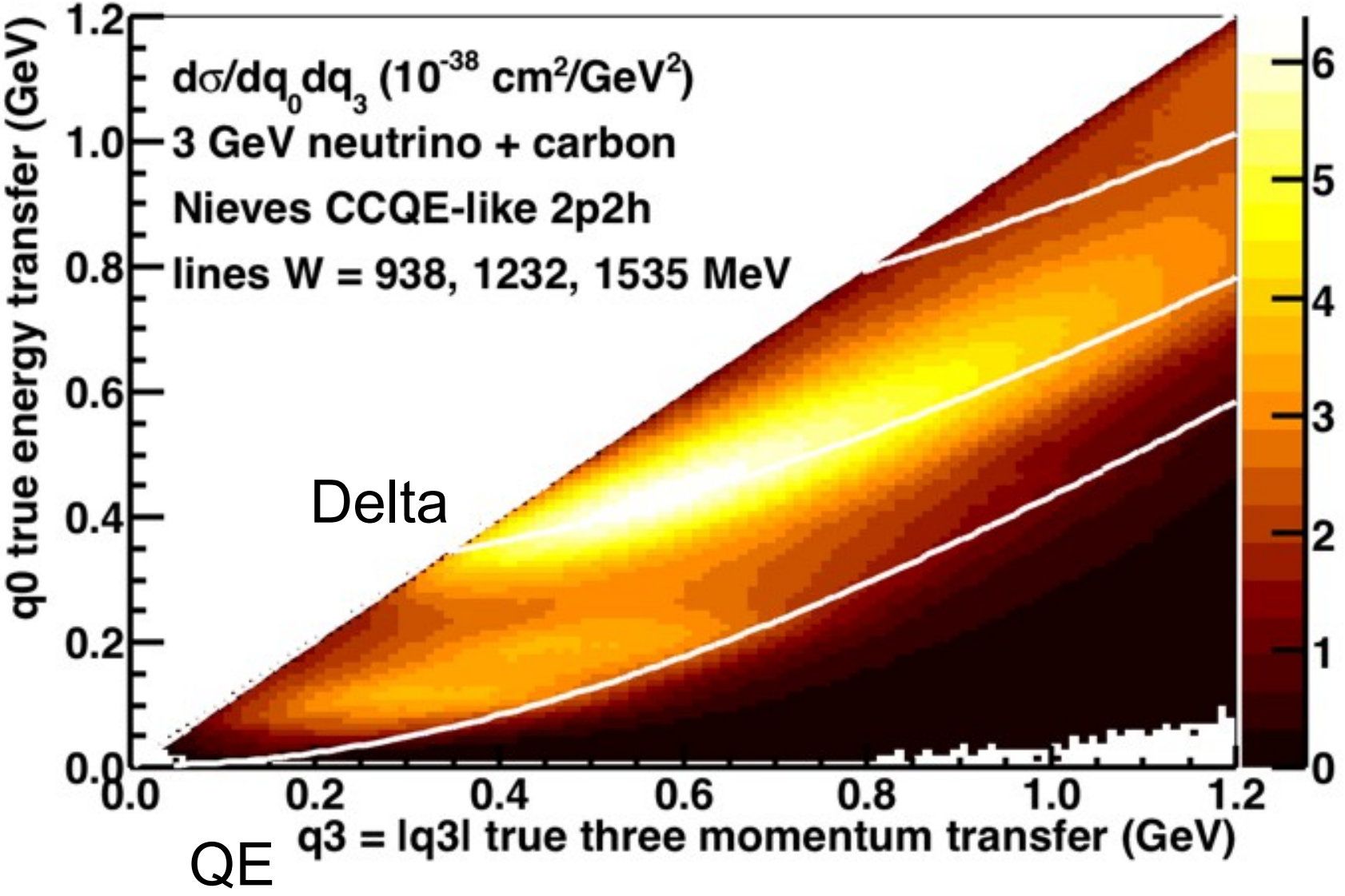
Approximate the hadron final state system
Choose two nucleons randomly from the GENIE nuclear model
Assign them energy and momentum transfer, less removal energy.
“Decay” the two nucleons isotropically and back to back in nucleus
Implemented by Steve Dytman in GENIE, similar to Sobczyk PRC 86 015504 (2012)
Let intranuclear rescattering model propagate nucleons out.

GENIE three-momentum and energy transfer vs. W



Can't get this with muon kinematics alone in broad band beam
use MINERvA's abilities as hadron calorimeter

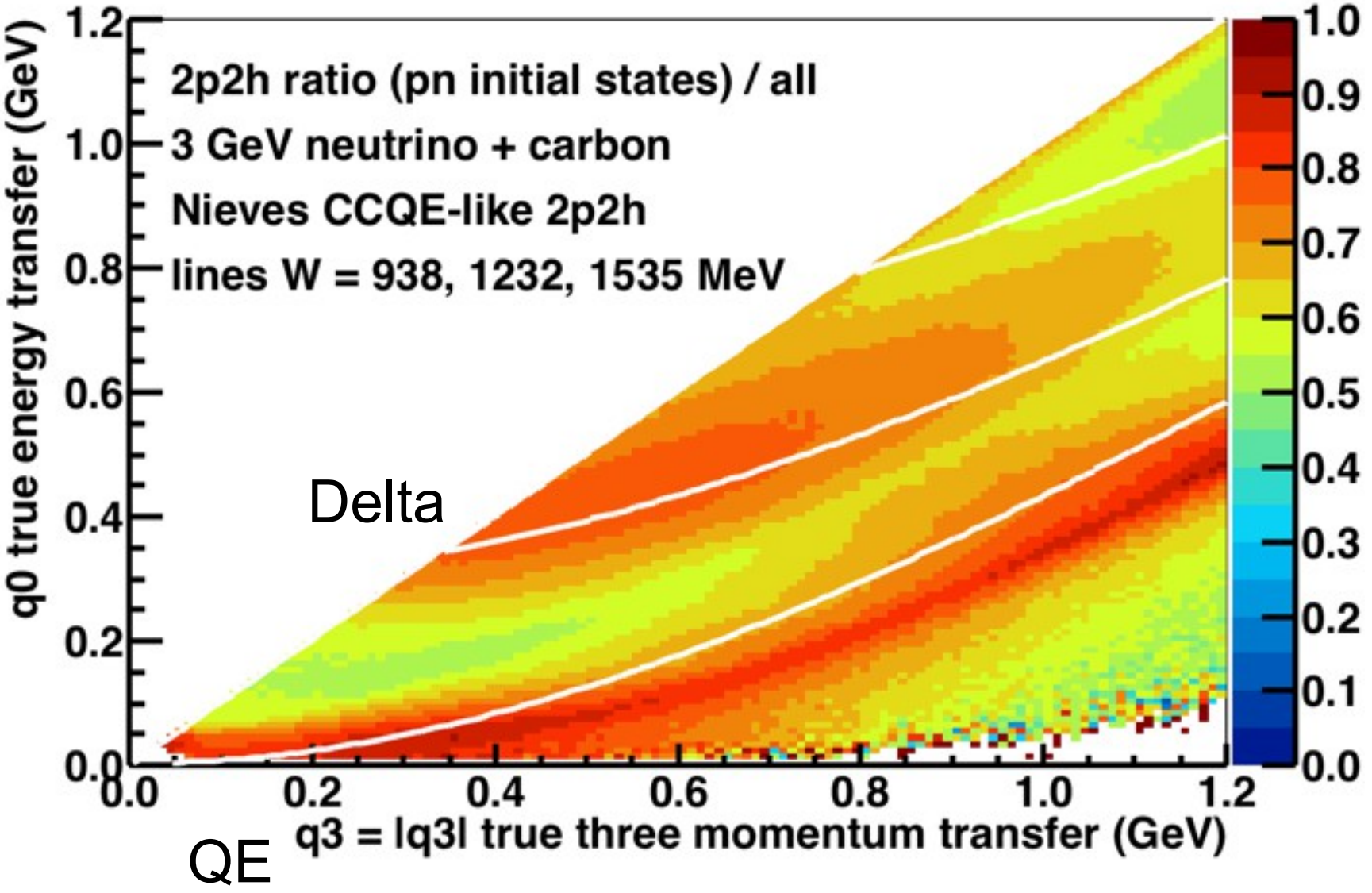
Valencia QE-like (no pion) 2p2h prediction



significant sorta-QE component but at W ~ 1.0

Large $W_{1p1h} = M^2 + 2\,M\,q_0 - Q^2 = 1.232$ GeV Δ component

Valencia QE-like (no pion) pn initial state fraction



GENIE implementation uses this prediction directly
it is not uniform, follows the interferences?

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Approximate QE-like 2p2h model for non-isoscalar A

Original calculation is for isoscalar, but want Fe56, Pb208, and Ar40

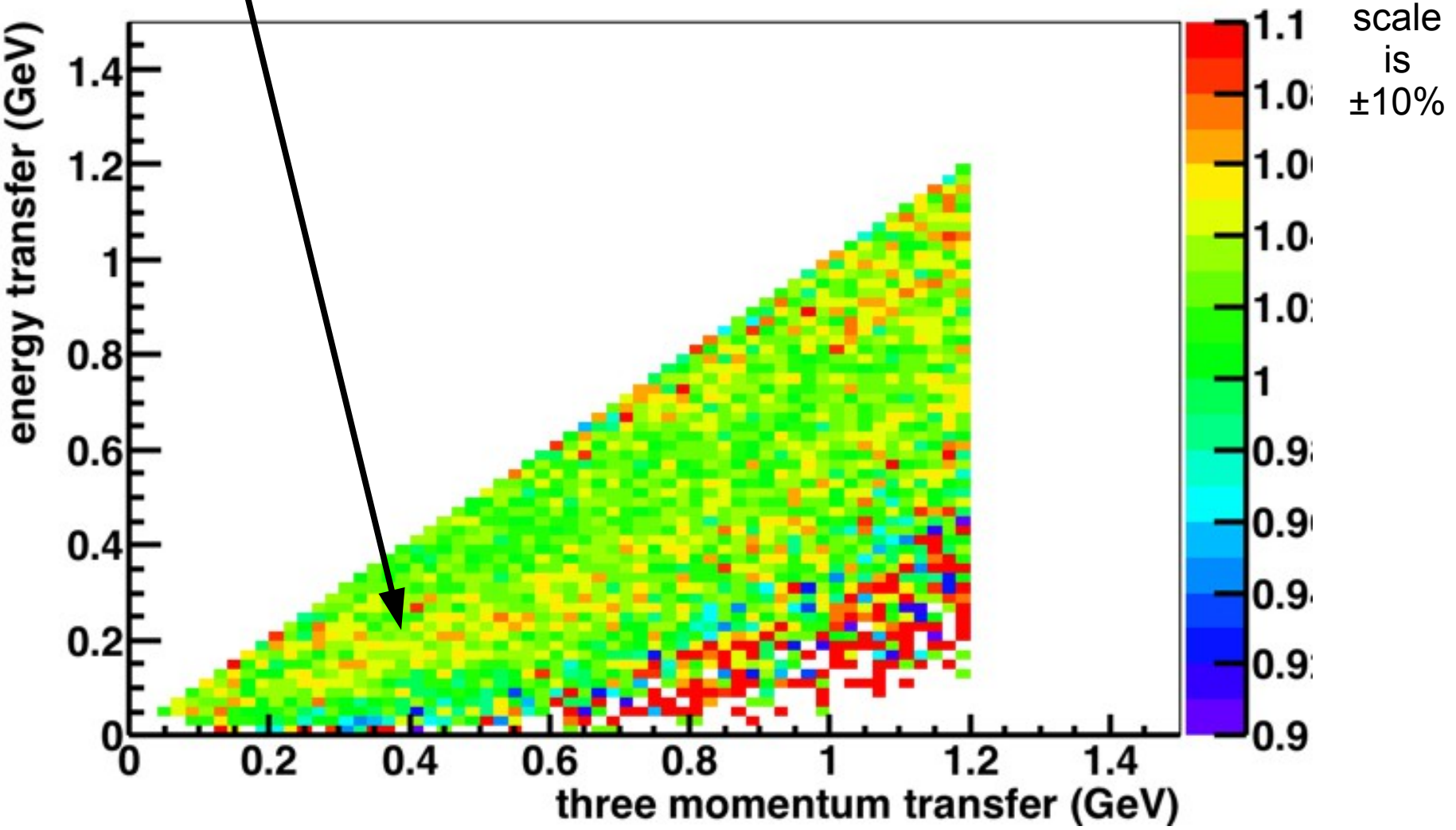
The Valencia model scales with A very closely
so the leading effect is the different probability
to find pn initial state pairs relative to nn (nu) or pp (nubar).

Generate isoscalar nuclei with similar or identical A
use Ca40 to make Ar40, use Ni56 to make Fe56

Actually three effects come into play
different Q-value enforcing energy conservation
and the pn, pp, nn scalings.
(different nuclear density parameters computing HadTensor)

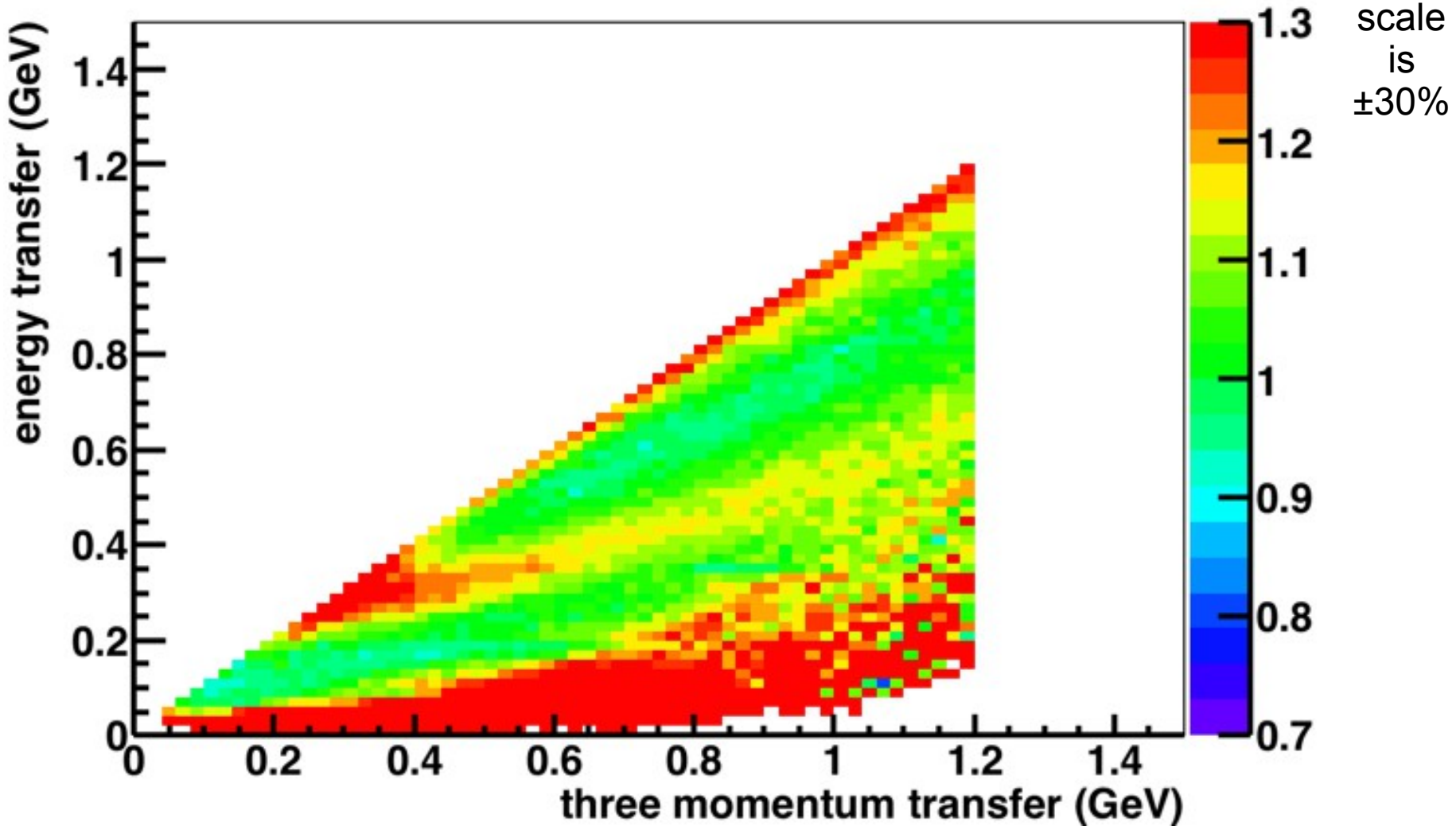
Must choose densities for HadTensor, so Ca40 is used for Ar40
But Pb208 is used for isoscalar Rf208 “pseudo208”
Result: can generate all nuclei A >= 10 from just 8 sets of tensors.
C12, O16, Si28, Ca40, pFe56, pCd112, pPb208

Ratio Ar40* / Ca40 (* gave Ar40 same Qvalue as Ca40)
Enhancement (yellow) follows high nn fraction.



Integrated σ = 4.928e-38 cm2 (Ar40*) and 4.797e-38 cm2 (Ca40)
base A scaling and specific pn scaling are factorized
not going very far from isoscalar, so not big effect

Ratio Ar40 / Ar40* (* gave Ar40 same Qvalue as Ca40)
Much lower Qvalue 1 Mev compared to 14 MeV for Ca40
Shifts whole distribution down, increases kinematic space



Dramatic effect in ratio is because the cross section is highly peaked and these two Q-values are about as different as you can get

Integrated s = 5.354e-38 cm2 (Ar40) and 4.928e-38 cm2 (Ar*40) (~9%)

Compare to MINERvA data PRL 116 071802 (2016)

Kevin McFarland's talk yesterday

Used flux published with the paper.
GENIE generated 89.5% C12, 7.5% H, 3% O16 by mass.
Default in this talk Reweights GENIE QE with Nieves RPA
Modify GENIE pion events as in the paper.
Use the Valencia 2p2h component in the default

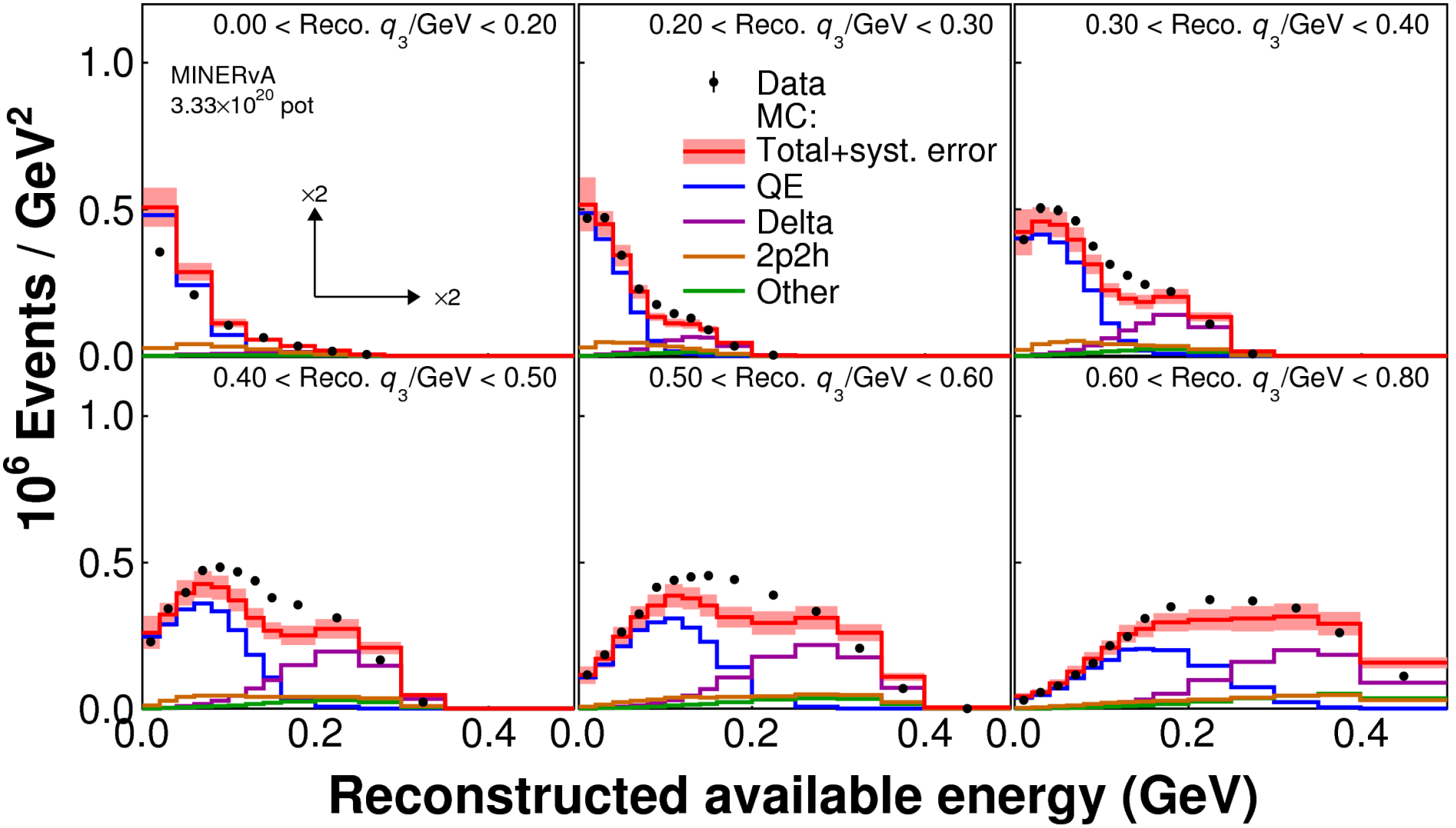
Explore non-default options, especially to the QE process

1. Turn up pion absorption, turn down other 1pi to compensate
2. Valencia 2p2h, but enhance the non-Delta 2p2h component
3. Boost QE-MA by 9% (c.f. arXiv:1603.03048, A. Meyer et al.)
4. Hack Nieves Local Fermi Gas as GENIE QE reweight

(bkup: Effective Spectral Function from GENIE for QE events only)

The inputs to the earlier 2D plot, before unfolding

Model is GENIE with RPA suppression and 2p2h events



Kevin showed this yesterday.

Examples of 2D unfolding

original

blurred

unfolded

Adorable Kitten from G. Cowan Statistical Data Analysis

requires you know smearing function

Important note!!!

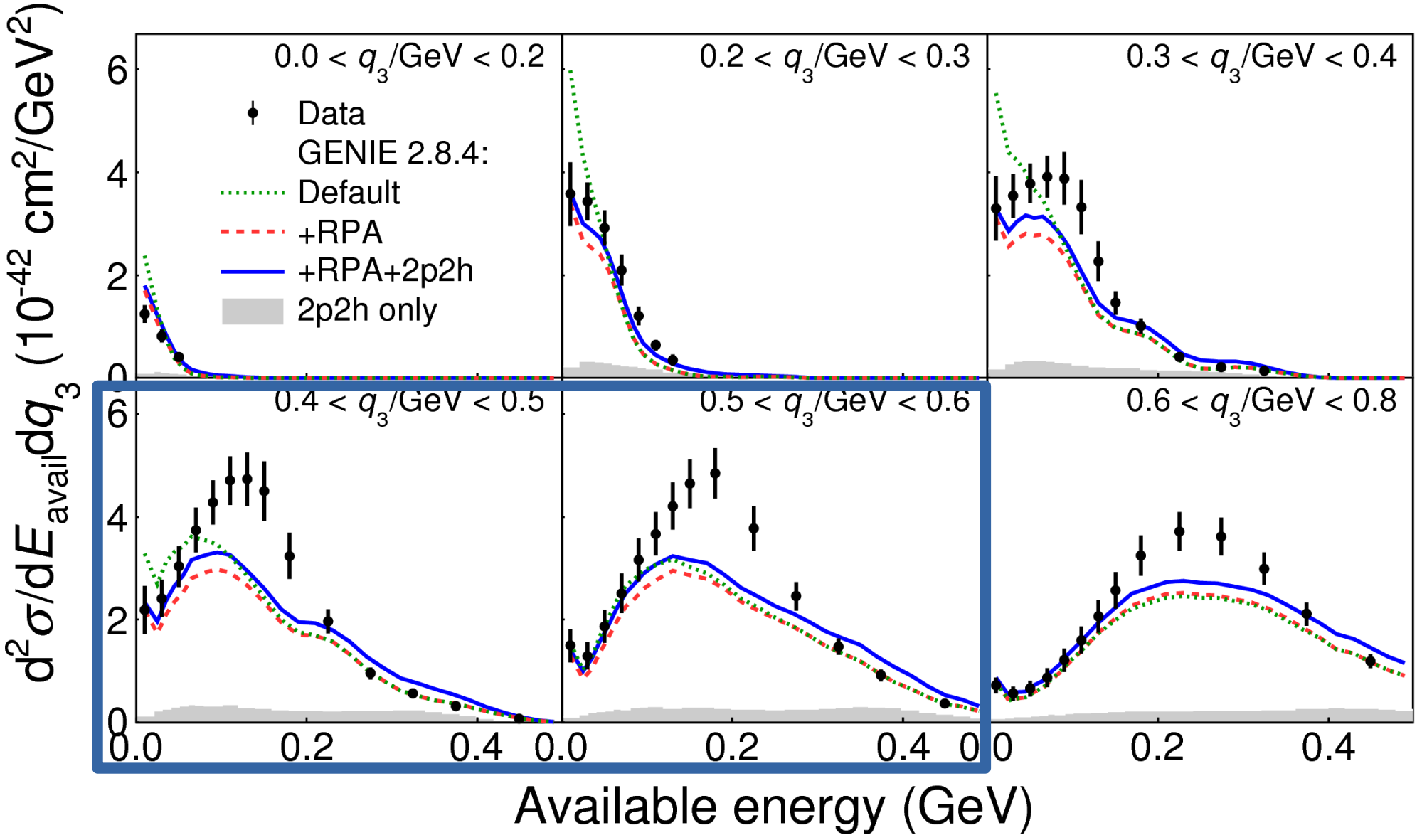
We can't unfold to true energy transfer

its too model dependent
but worse
places in q0,q3 where GENIE predicts zero events
pathological for unfolding!

Unfolding to available energy
(KE of p, pi) and (E of EM, pi0)
not neutrons, not removal energy

depends primarily on detector response model

Unfolded, double differential cross section



Choose an interesting model and compare to the data
Here, GENIE 2.8.4, next slides GENIE 2.10 + extras

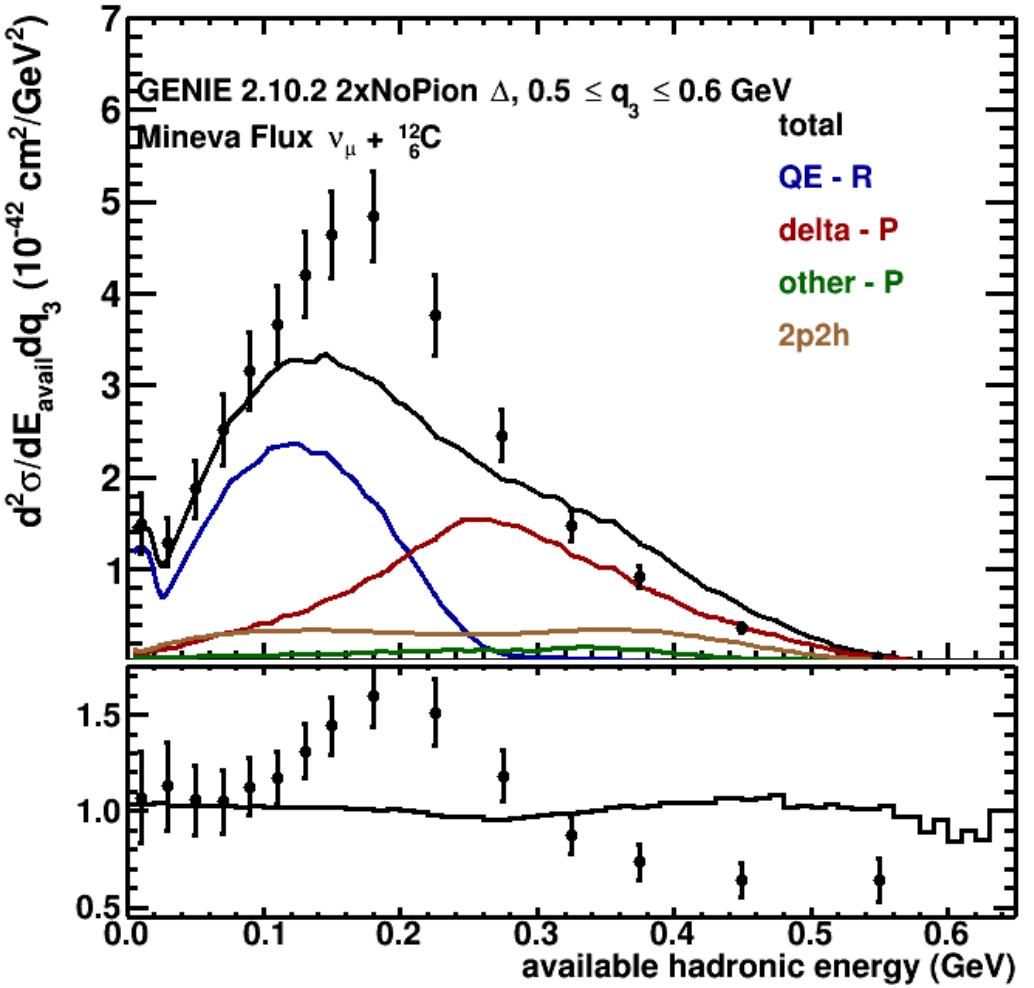
Structure of one model/default comparison

Each plot is one of the six “slices” in three-momentum transfer
I'll show 0.4-0.5 and 0.5-0.6

Model shown on top is the modified one and its subcomponents

Both model and data ratio with default in lower plot.

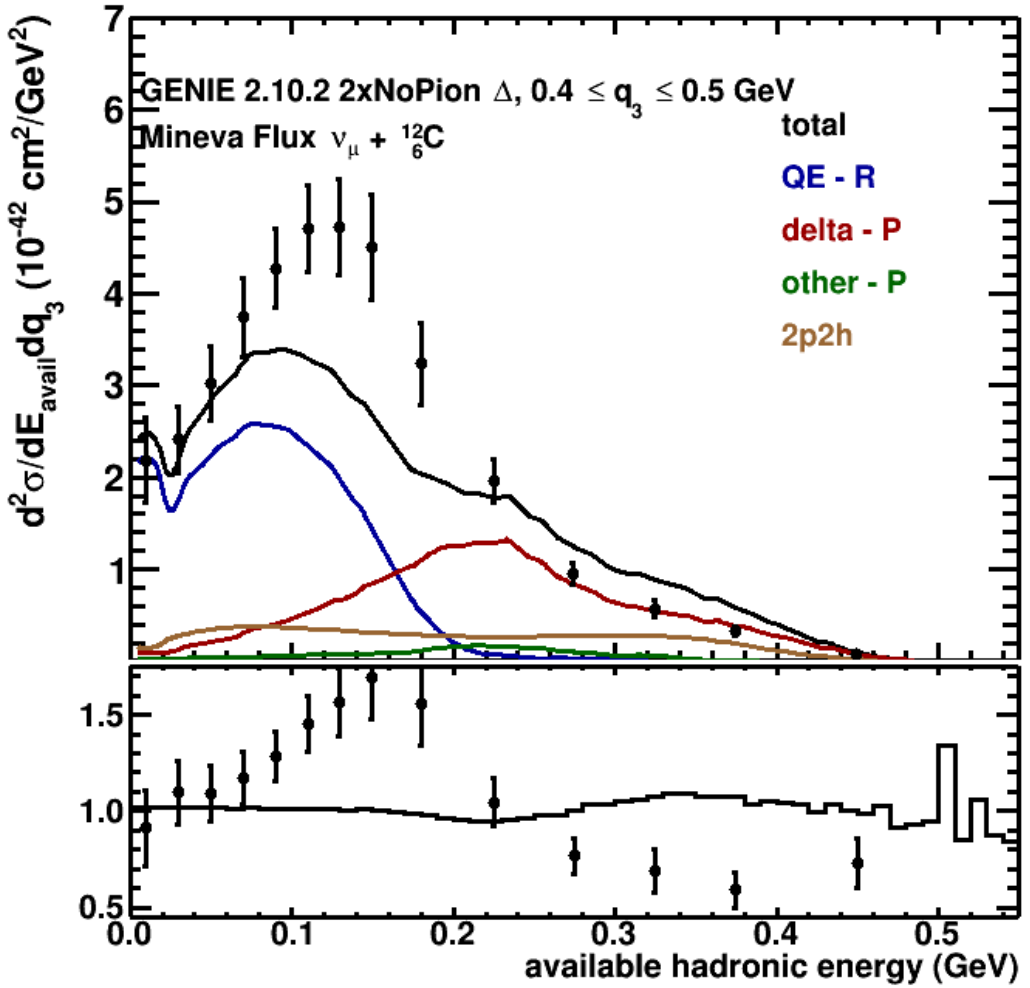
Looking for modified model distortions that mimic the data in ratio

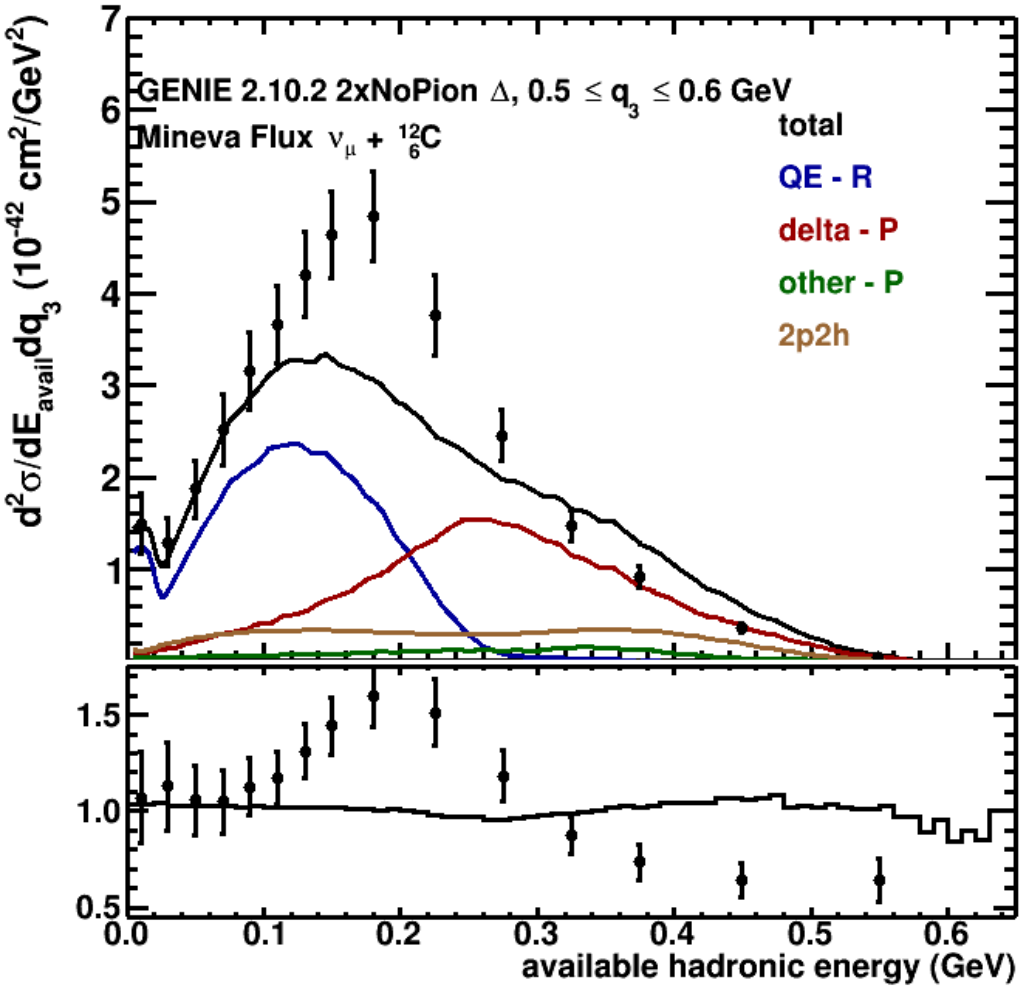


n.b. all models, including default have Valencia RPA, tuned pion!

2x boost to events that lose their pion to rescattering

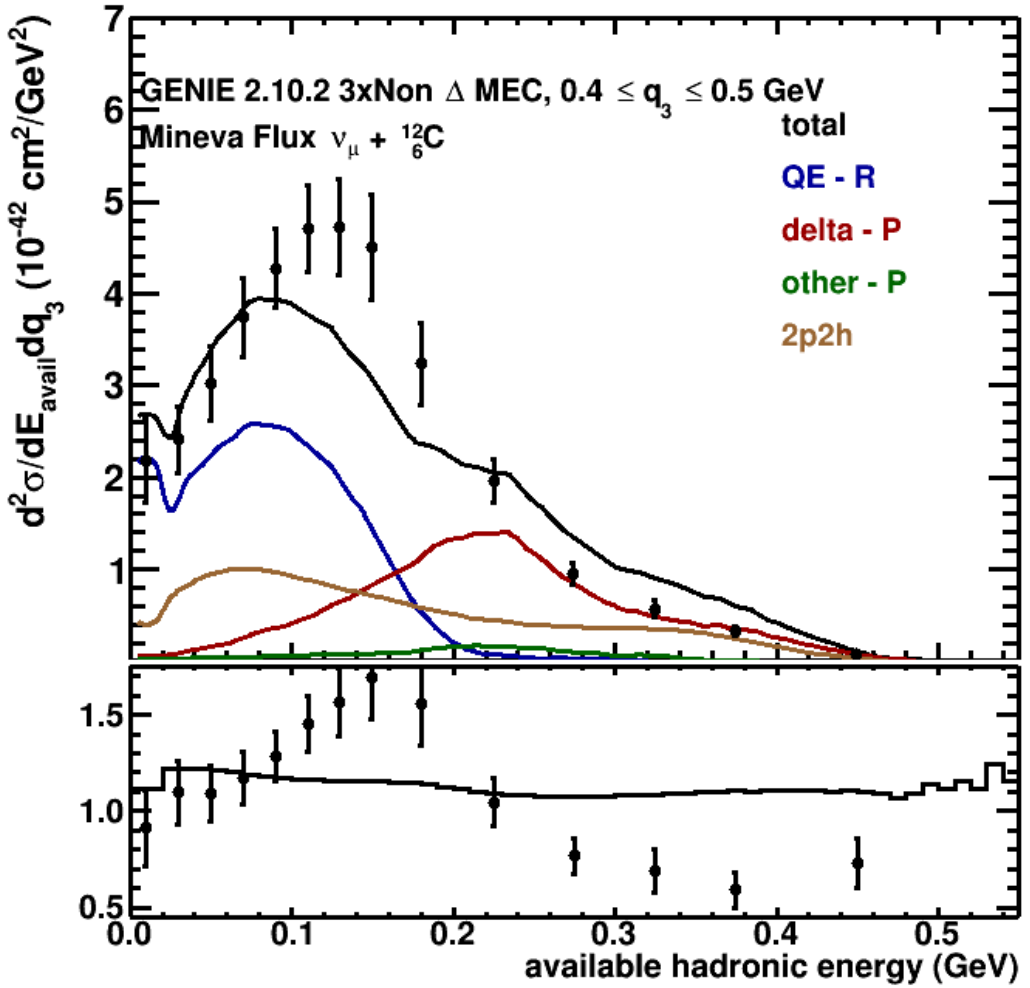
~20% to 40%, and reduce other pion production to keep same σ.

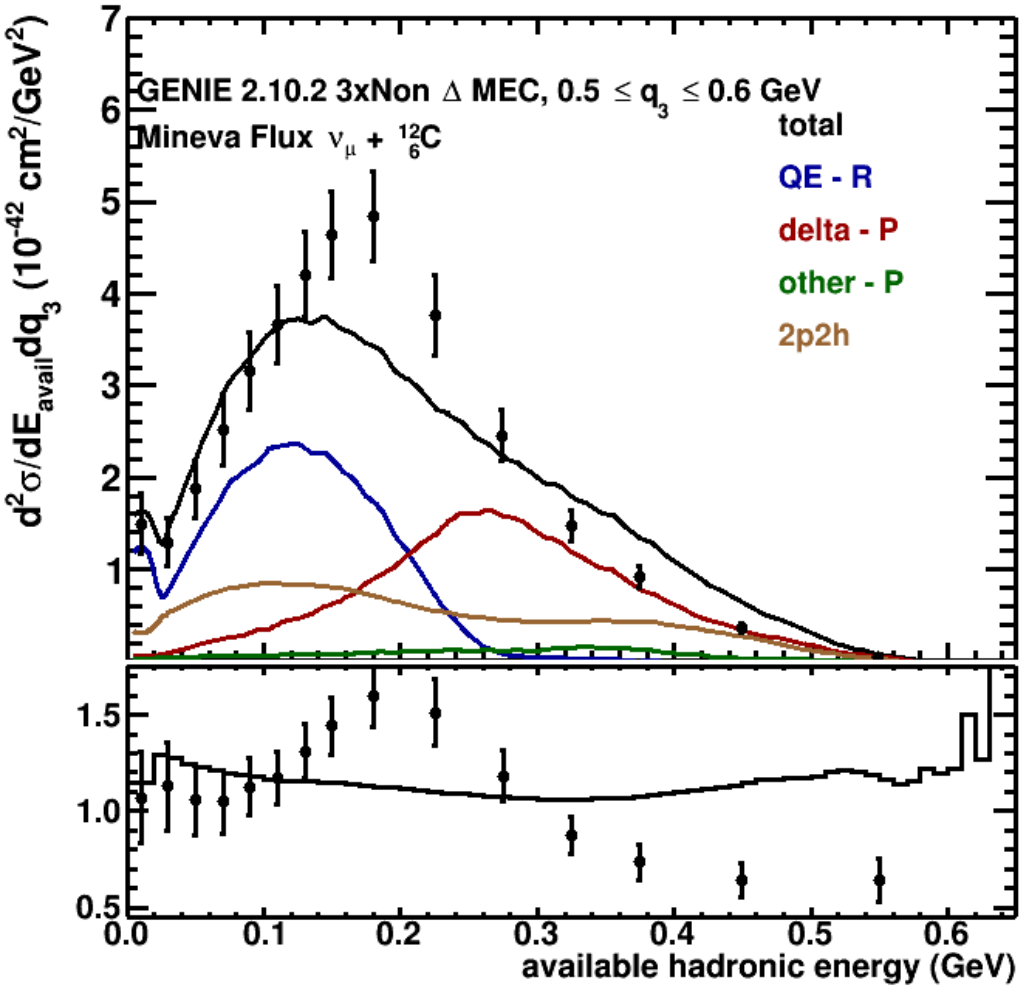




Moves events out of the Delta peak, enhances either side.
But predicts a very small and diffuse effect.

3x boost the non-Delta component of QE-like 2p2h

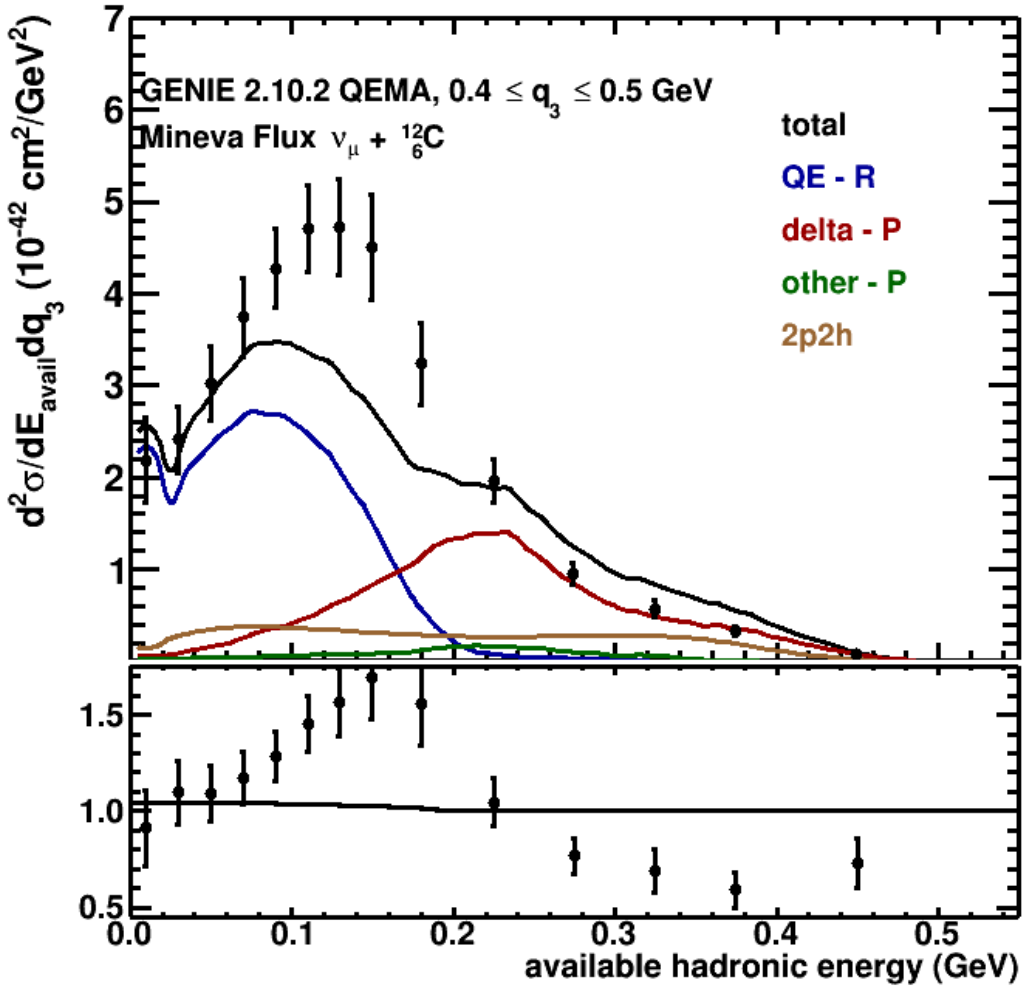


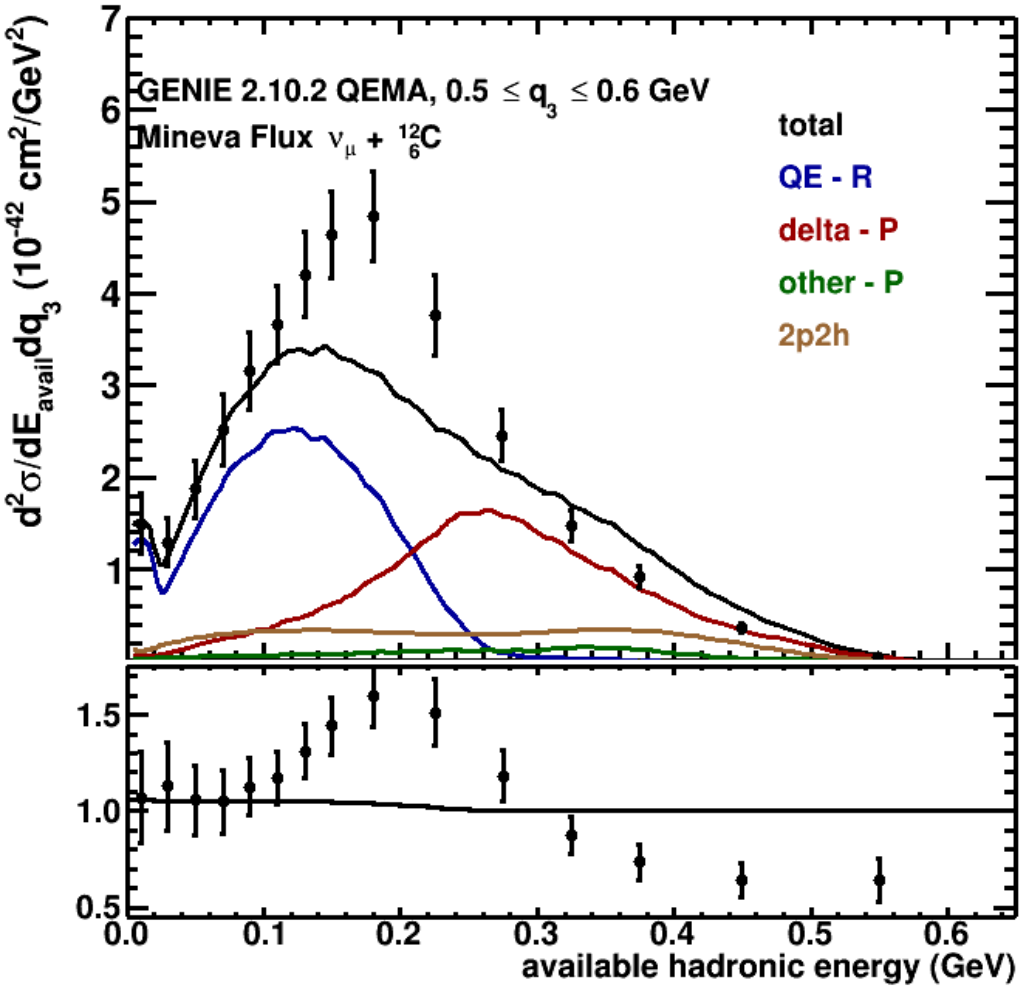


Delicate to explain how this was done. Yes, the data more like this.
But the pn final states push the contribution below QE
more pp, or neutron that got the CC to proton gets more momentum

Boost QE-MA by 9%

(Other axial form factor modifications available in GENIE soon)



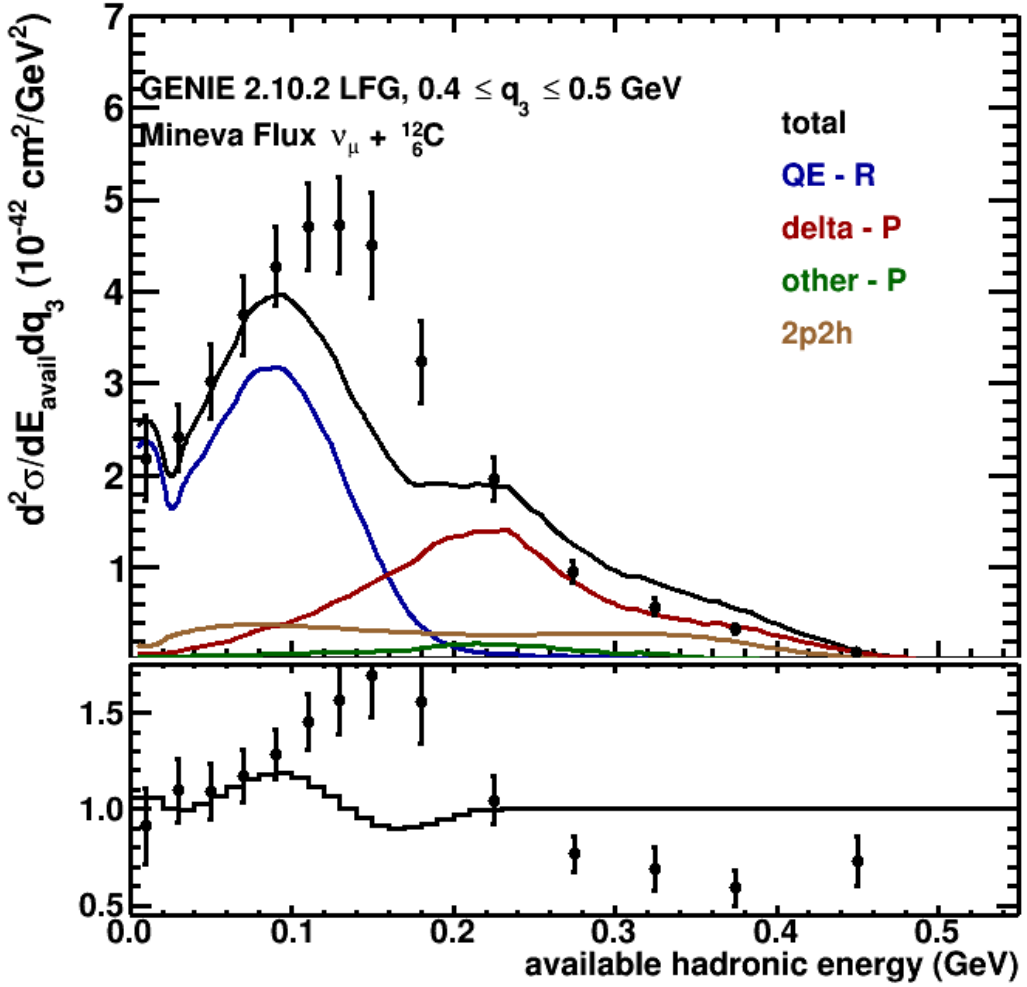


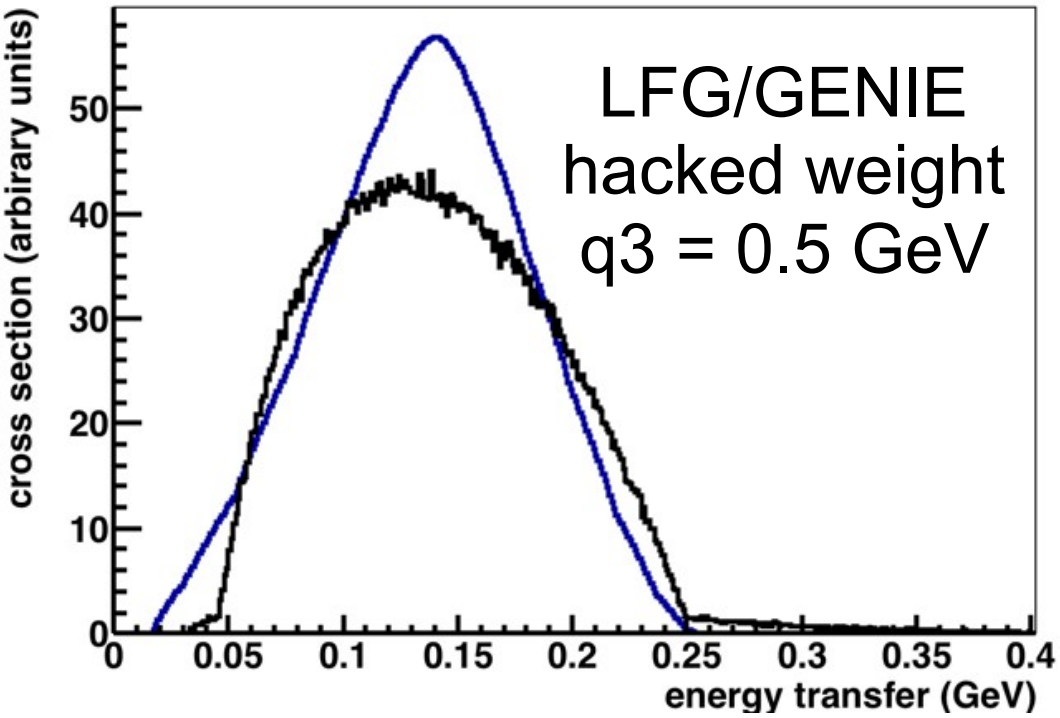
The analysis of deuterium data in Meyer et al. arXiv:1603.03048 axial form factor should be assigned a larger uncertainty.

Barely relevant here, gets diluted to a 6% effect, has wrong shape.

Hack GENIE QE to be like Nieves Local Fermi Gas

Constructed in q0 q3 2D space

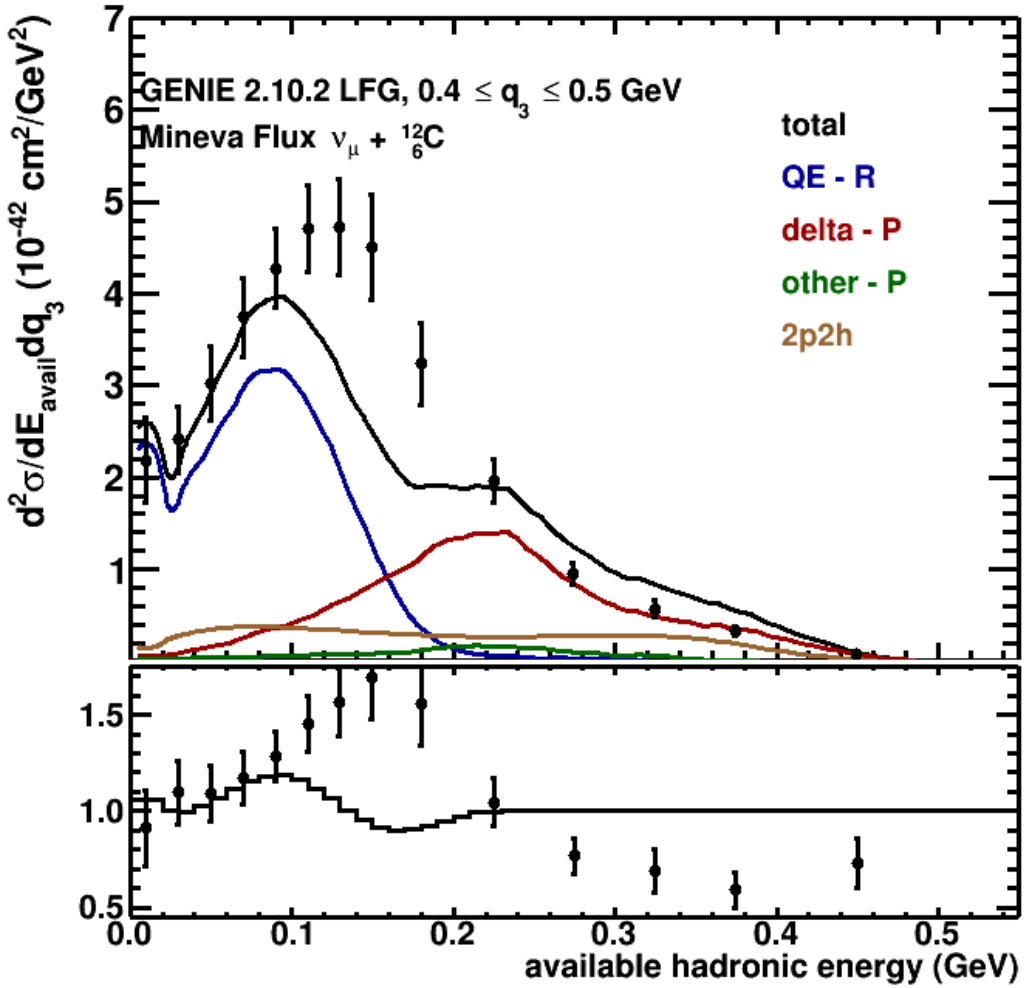


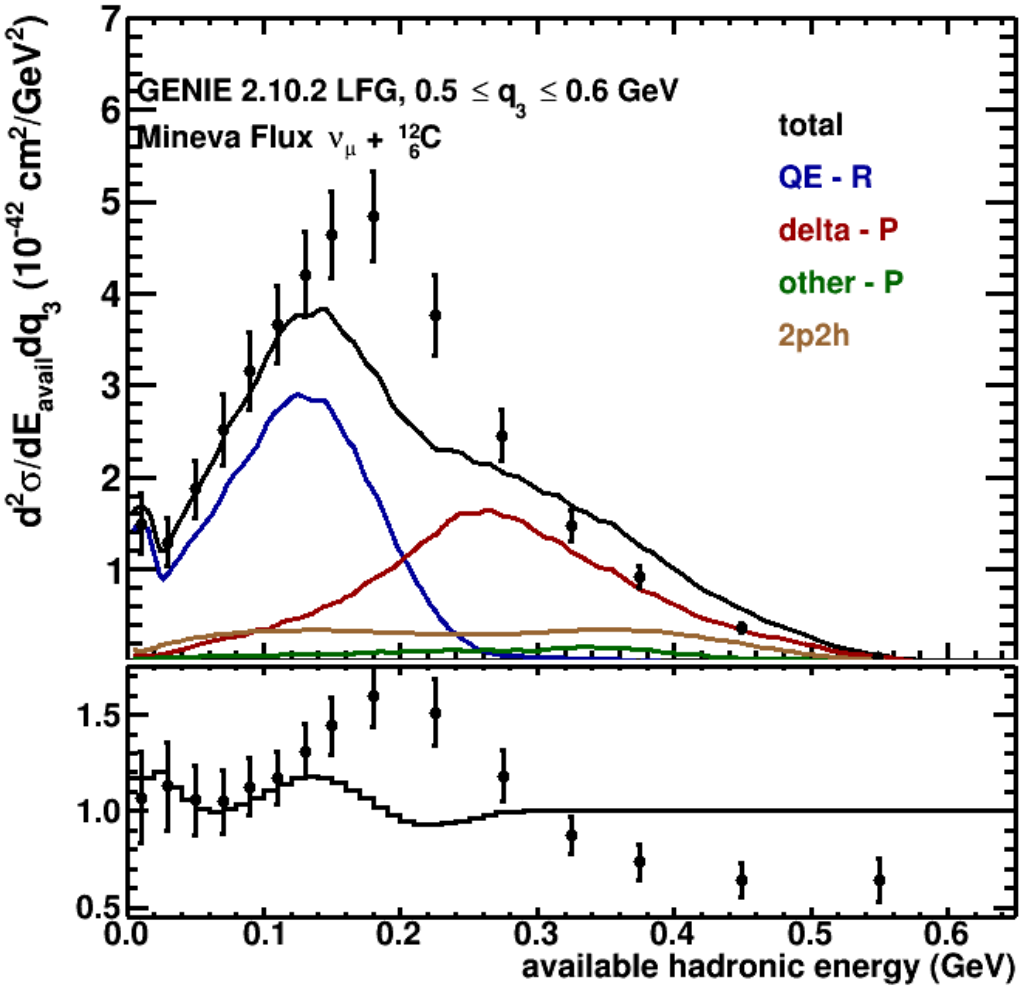


Blue Nieves LFG
more peaked, low-side tail
Black GENIE
broad, Bodek-Ritchie tail.

LFG is more peaked, yet also has more in low-side tail.
Benhar spectral function has more high-side tail
Bodek et al. effective spectral function yet more tail

Hack GENIE QE to be like Nieves Local Fermi Gas





Has a significant and localized effect that makes me wonder, what if the LFG peak was at just a little higher energy.

Necessary ingredients to compare to these data

INCLUSIVE model up to q3 = 0.8 GeV
for Carbon and Hydrogen at least
including QE+RPA, Delta, and your favorite 2p2h model
with pn initial state fraction
bonus: explicit nucleon exit kinematics
intranuclear rescattering of those hadrons

Make relatively simple selections on Eμ, θμ
that don't much matter, but mimic MINERvA acceptance
(they matter more at higher Q2, higher q3)

Available energy observable is not energy transfer
(proton and charged pion KE) + (pi0, e, g, K total E)
no neutron energy, no removal energy

Conclusions

MINERvA data want more QE-like 2p2h
certainly in the region around W_{1p1h} = 1.0 to 1.1 GeV
speculate, more pp final states there could also help
or give more energy to “struck” nucleon, less to “spectator”

It is clear from this workshop that such enhancements
are possible from models and model-updates being considered

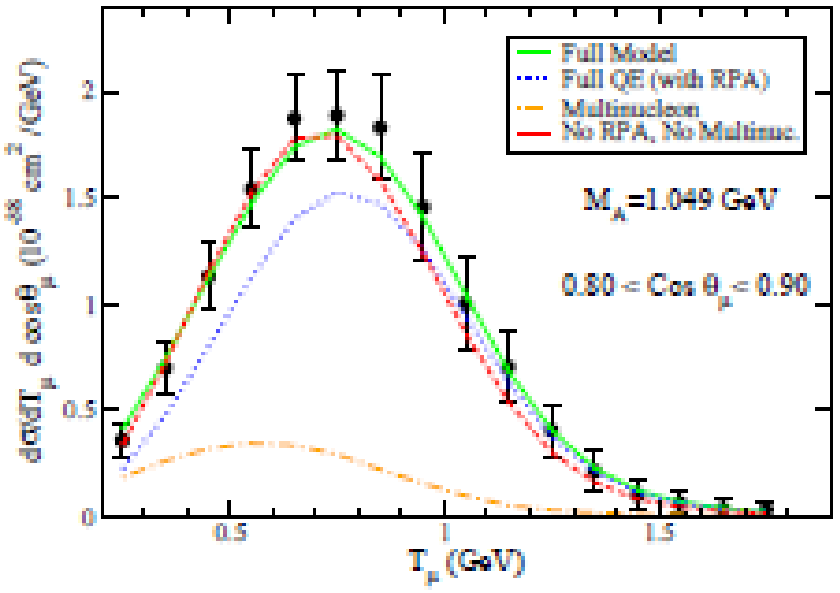
Modifications to the QE model may also play a role
in a better description of the data
but investigation of known shortcomings in MA, FG
reveal only modest effects.

Comments from Steve Dytman and GENIE

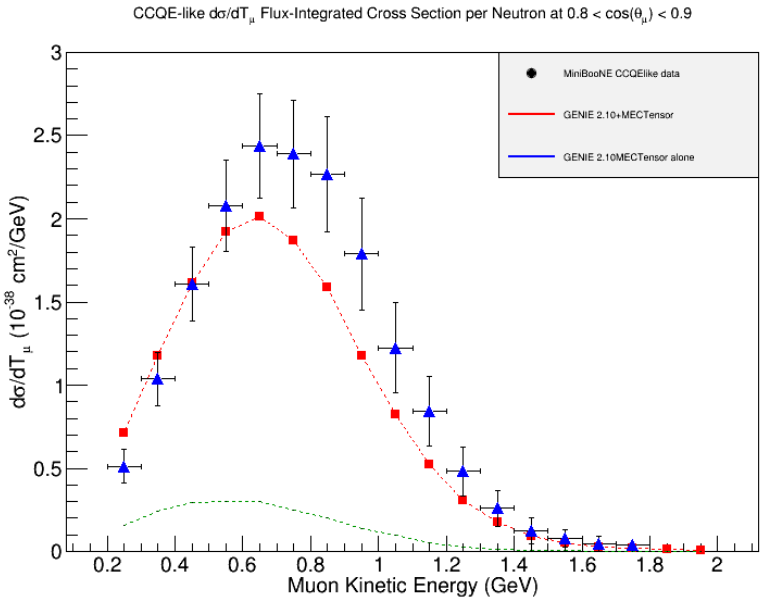
- Take broad view, want range of models
  - Let users sample, use what they prefer
- Empirical model (SD, CA) based on (e,e') alternate model for last 3 years. Used in NOvA.
- Valencia model (Jackie Schwehr, JN, MVV, RG, FS)
  - Tuned to (e,e'), extended to (ν,μ)
  - Spearheaded by Jackie and Rik, will be in next GENIE release
- Martini model (Marco, Magda Ericson, Marteaux, Chanfray)
  - Under development by Sara Bolognesi, Federico Sanchez, Marco
  - Cool, uses same tensor formalism as Valencia, easier addition
- We welcome theorists who will work with us

- Comparisons with MiniBooNE data (from Steve Dytman)

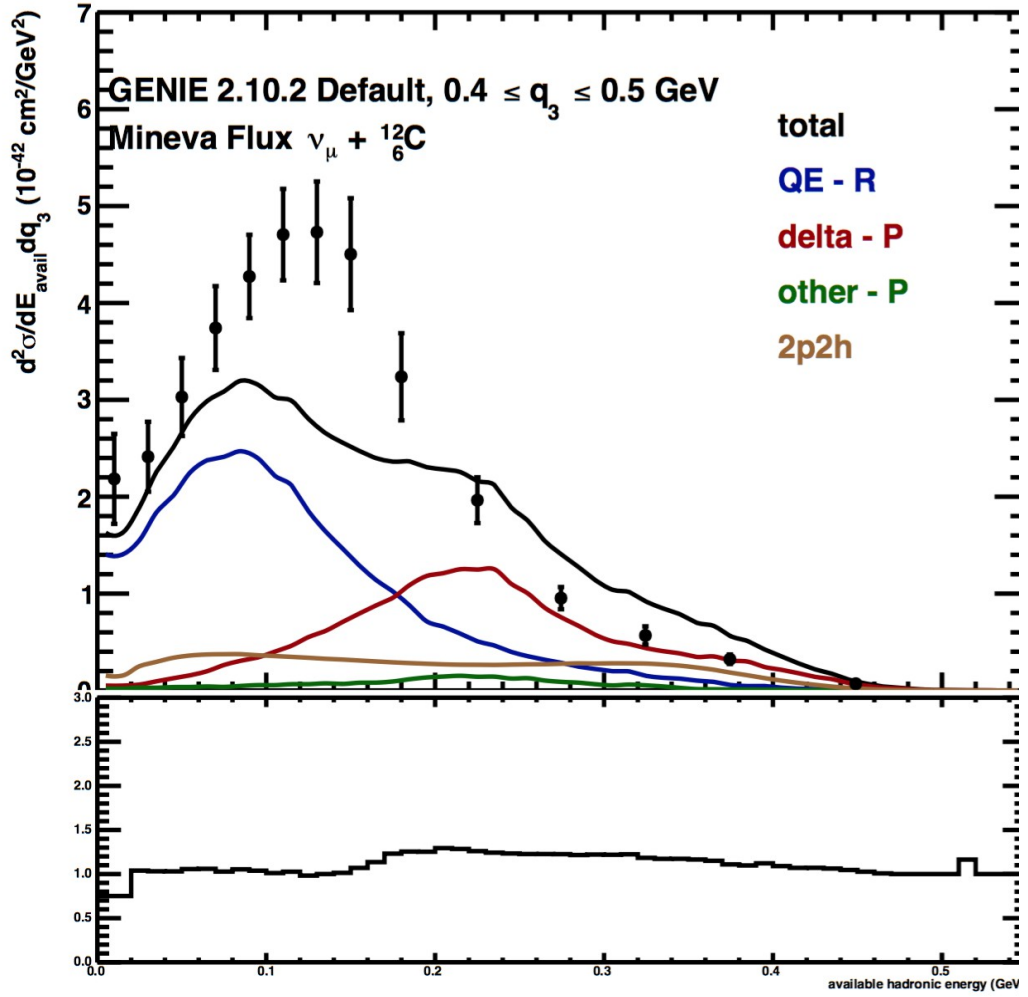
Valencia plot (Phys Lett)

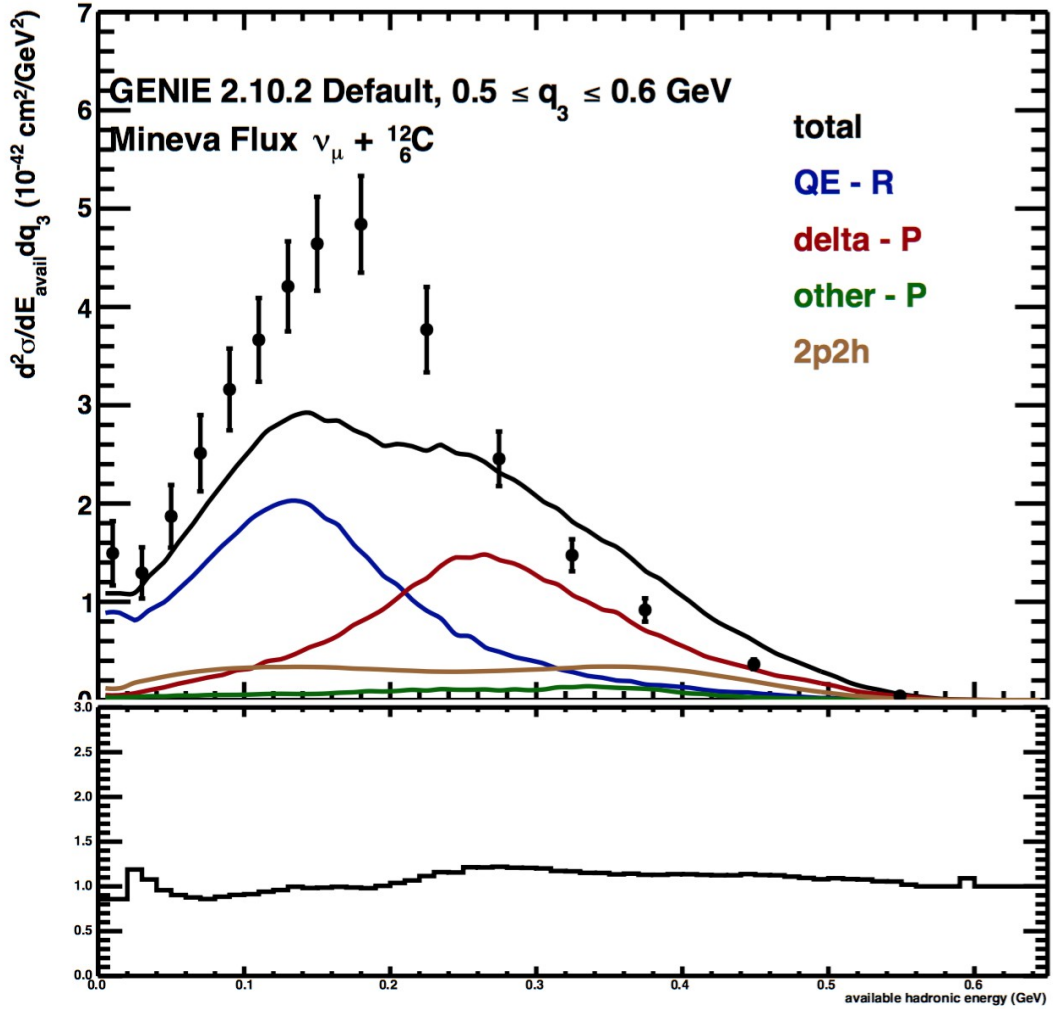


GENIE v2.10.0+MECTensor validation plot



Use GENIE's "effective" spectral function (Bodek, Coopersmith) but for QE only





Pushes a lot of QE events into the dip and Delta region
Unlike all the other plots, no RPA is applied to ESF model
Pulls it out of the low energy transfer (RPA-like effect)

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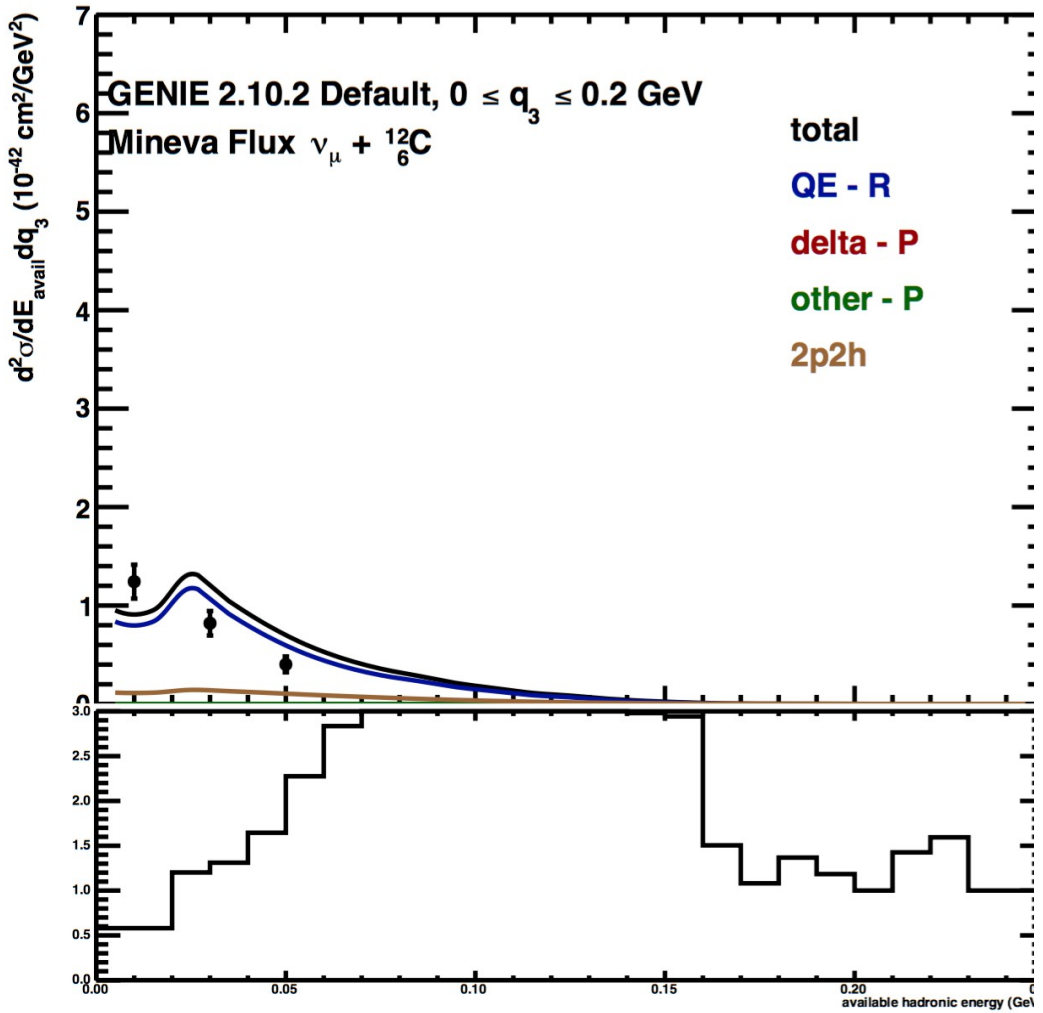
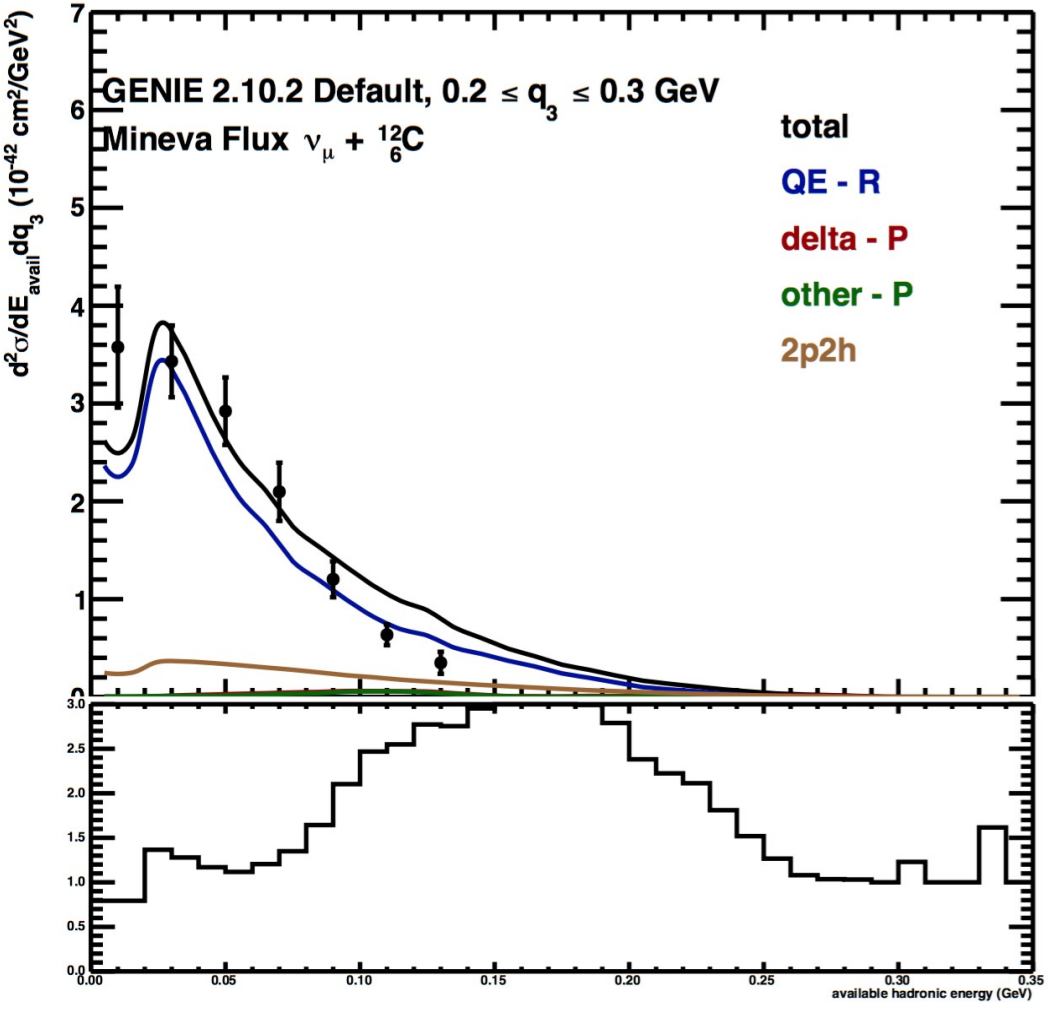
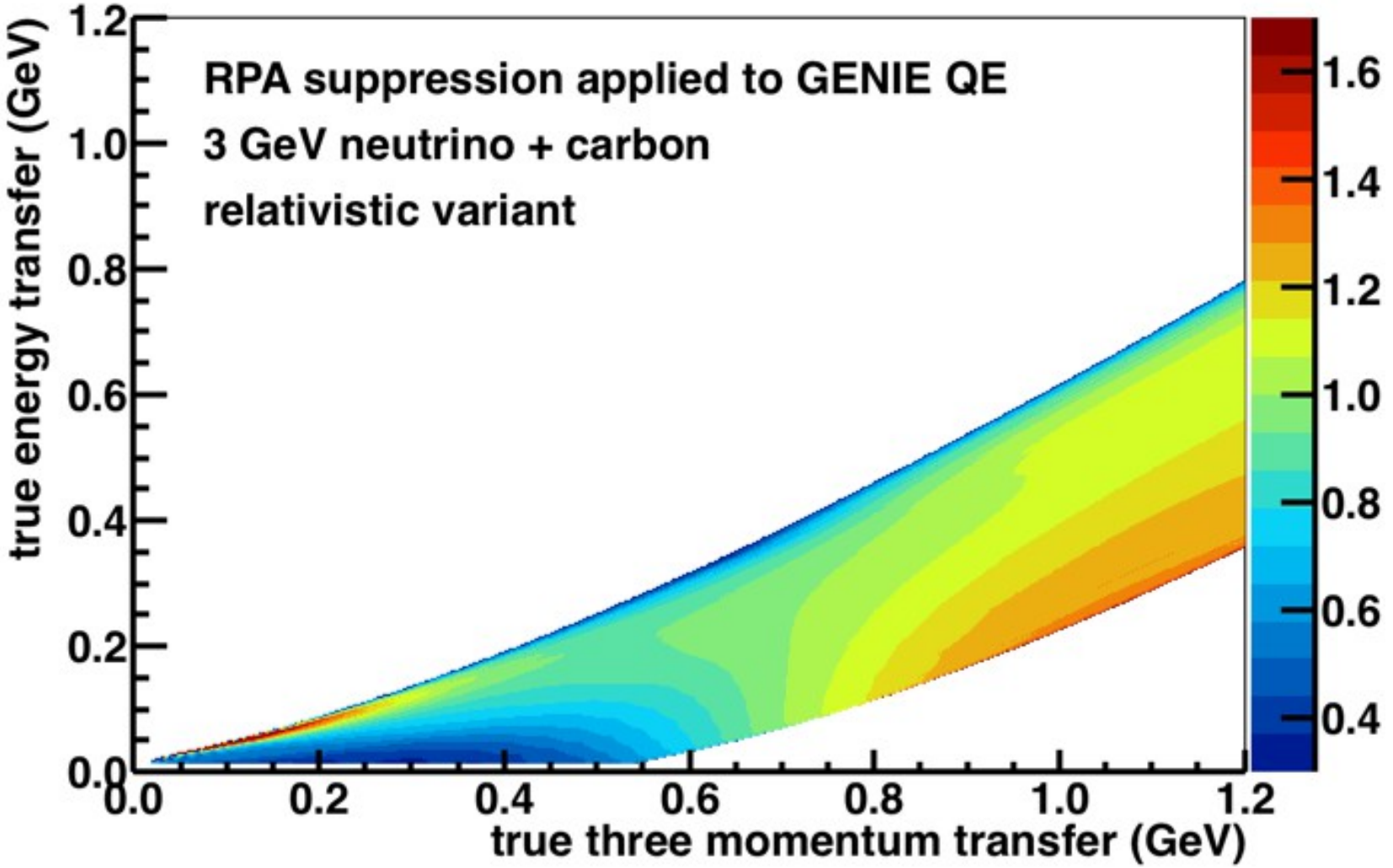




Pushes a lot of QE events into the dip and Delta region
Pulls it out of the low energy transfer (RPA-like effect)
at lowest Q3 (mostly QE), effect is dramatic, maybe too much?

Valencia RPA effect as a QE reweight



Formed by taking ratio ValenciaQE with RPA / without RPA