two-particle nuclear effects up to 10 GeV theory and experiment MEC and RPA and SRC

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Material based primarily around paper
R.G., J. Nieves, F. Sanchez, M.J. Vicente Vacas
Phys. Rev. D 88, 113007 (2013) arXiv:1307.8105
Page of citations and other references on a slide at end and in the paper

Motivation for MEC, RPA familiar to many of us

Many experiments, K2K, MiniBooNE, SciBooNE, MINOS found their Q^2 distributions not well described by QE models led to anomalously high "effective M_A" fit values

agreement with Deuterium at ~1sigma, driven by exp. uncerainty

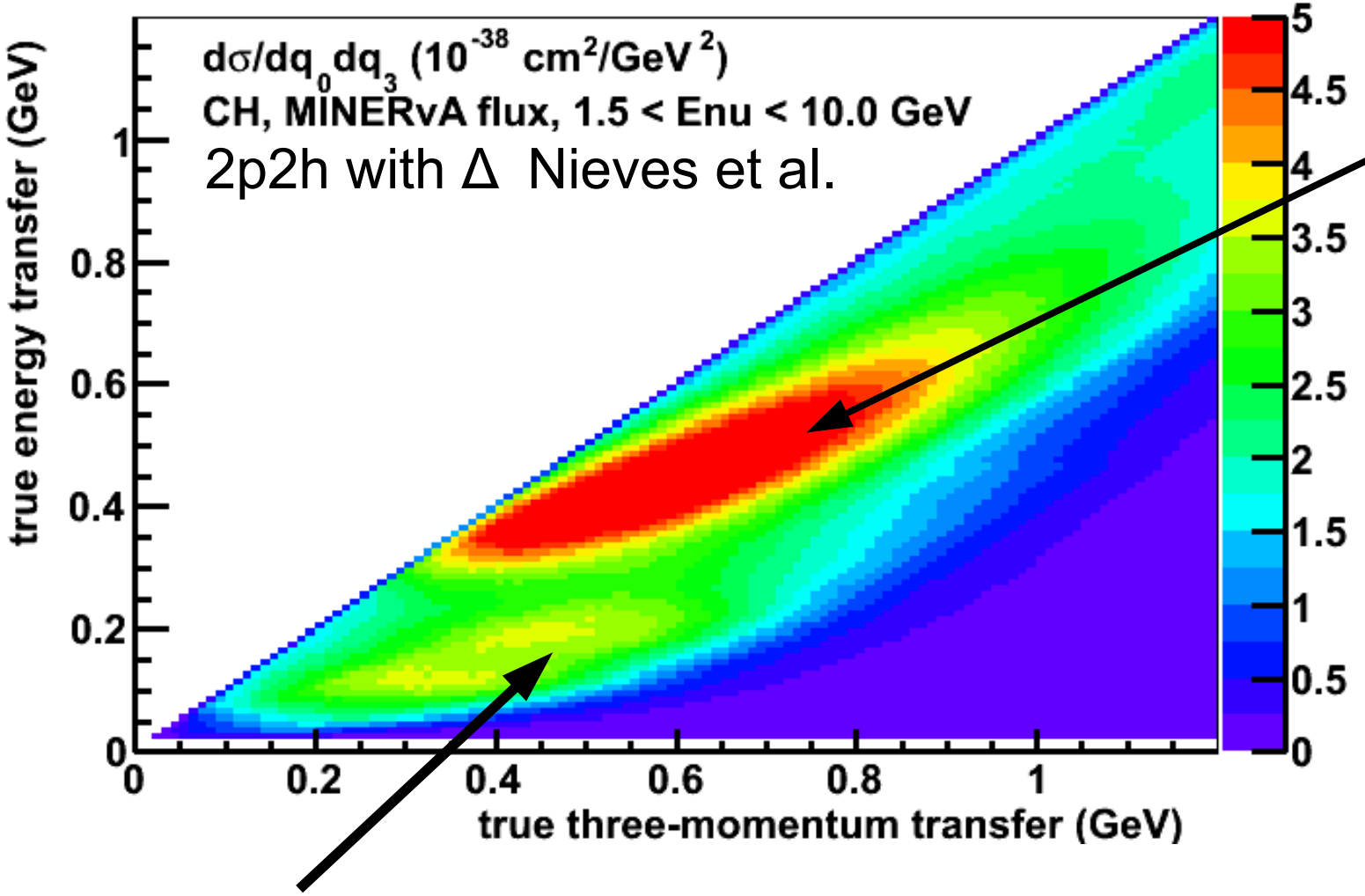
MiniBooNE led the new era with
double differential cross sections $d\sigma/dT_\mu d\theta_\mu$ and more

MINERvA has presented $d\sigma/dQ^2$
double, multi- differential work is in progress

NOMAD has flux and presents $\sigma(E)$
analysis outcome: M_A only a little higher

Electron scattering reveals both MEC and RPA components

2p2h (later QE+RPA) of Nieves, Ruiz Simo, Vicente Vacas with MINERvA flux and MINERvA-like muon acceptance

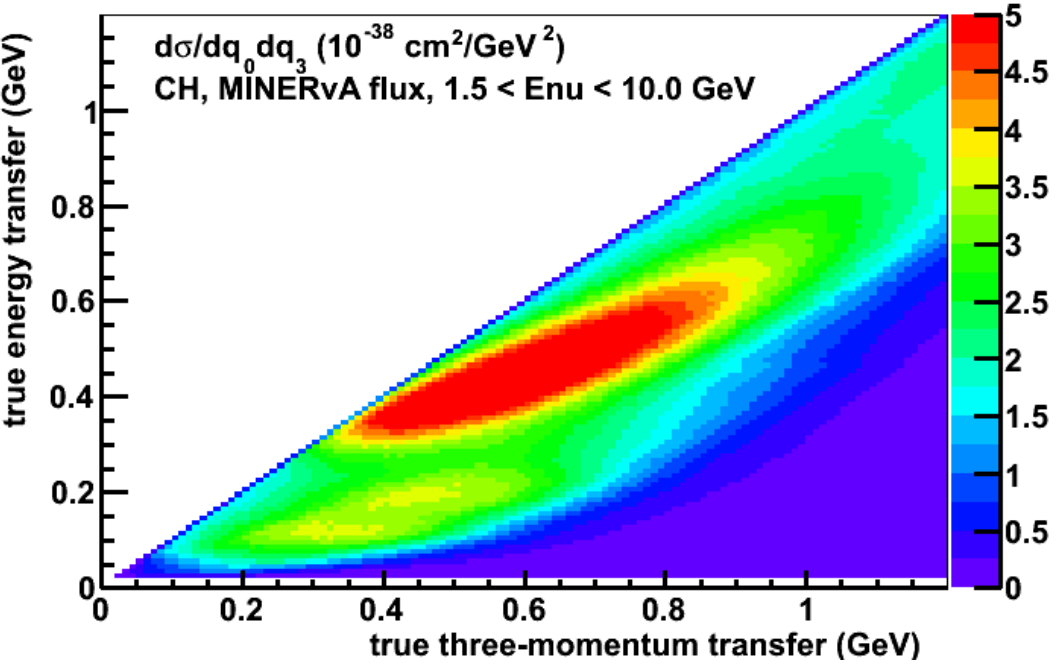


In-medium absorption $\Delta N \rightarrow NN$ before FSI

complete calculation includes interference terms, can then later subtract it

The “regular” 2p2h component peaks here, broad tails

Microscopic calculation features



Turns on ~1.5 GeV for neutrino
slower threshold for anti-nu, like QE
then cross section saturates

Stable lab-frame q_0 q_3 kinematics
can calculate p_μ and θ_μ or Q^2 W^2

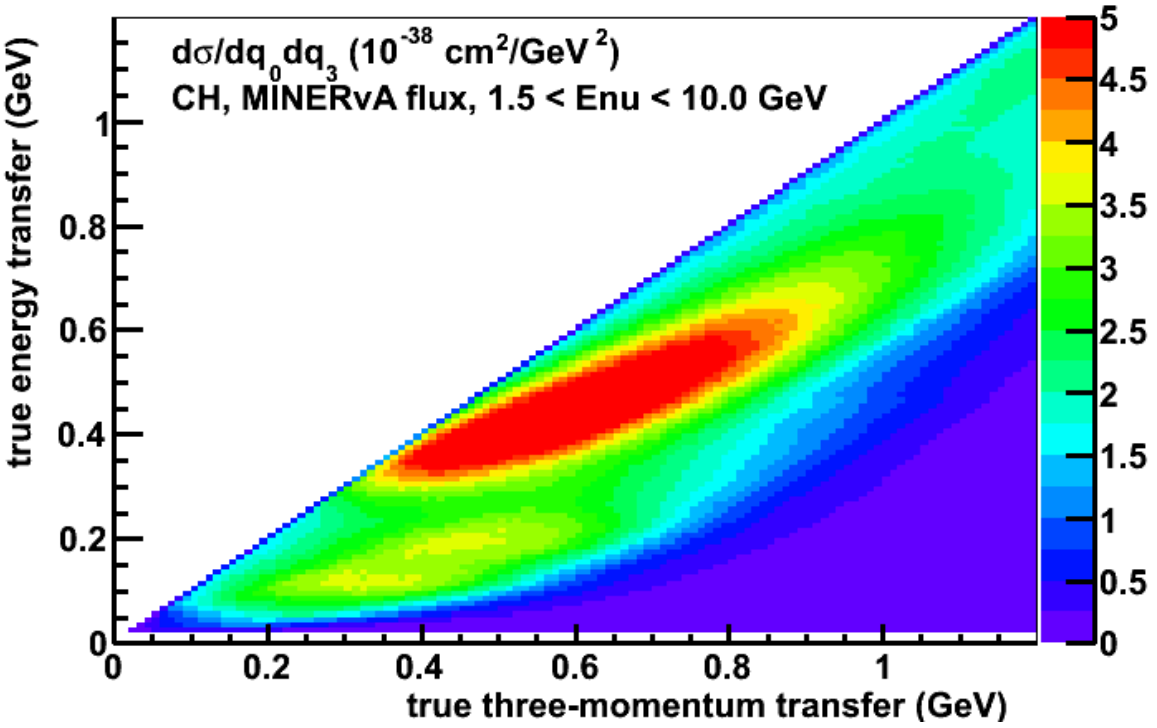
Fills in the "dip" between QE & Delta
at very-low Q^2

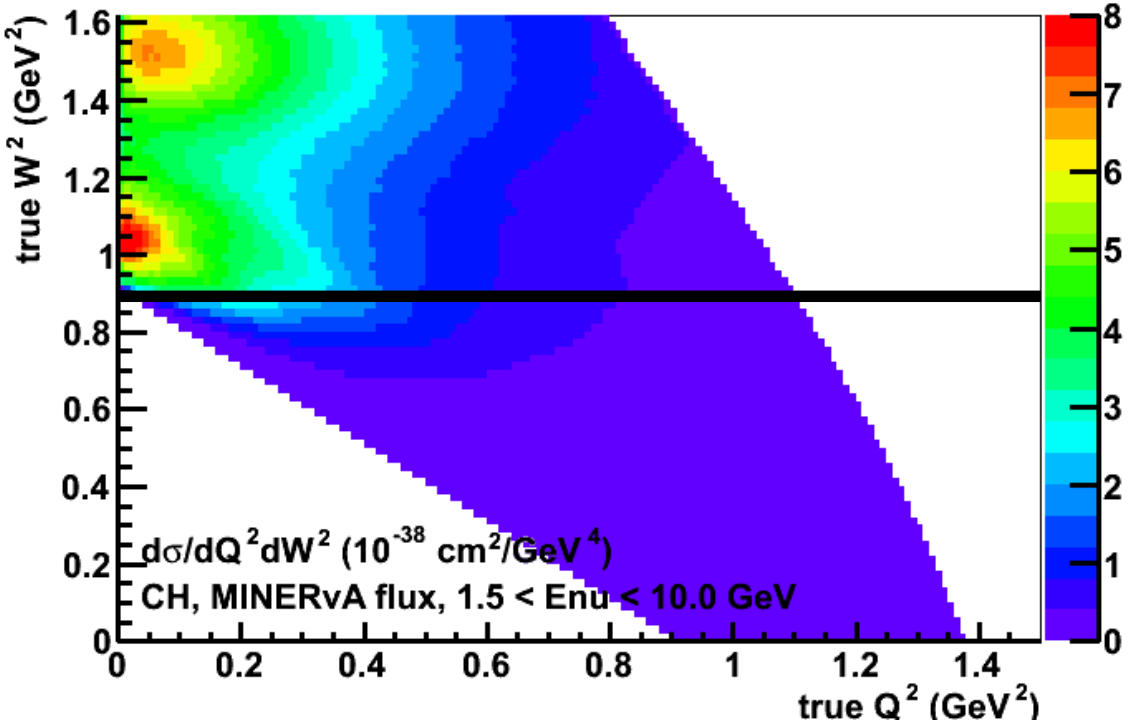
With QE+RPA
describes MiniBooNE data well
describes (e,e') data dip region

not shown, yes makes prediction
for nn, pn, and pp final state fractions
5/6 at Delta, 1/2 averaged elsewhere
but function of $q_0 q_3$

Caution:
Model's valid range
q_3 < 1.2 GeV

currently does not provide
kinematics of individual nucleons





2p2h in Q^2 and W^2

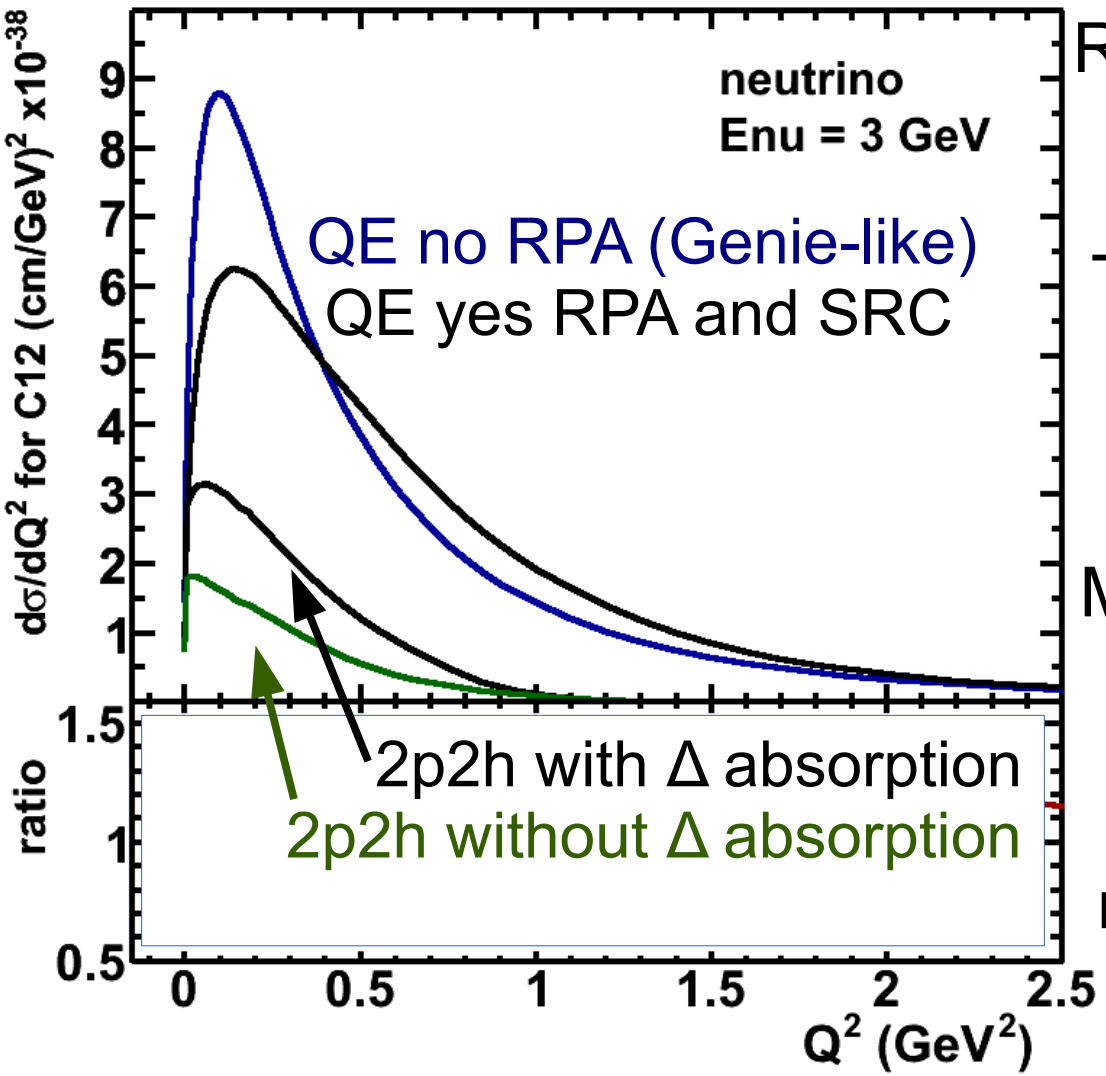
$W^2 = M^2 + 2Mq_0 - Q^2$

The "regular" 2p2h in this calculation is distinctly above QE "fills in the dip"

Does not fall along line of constant W^2 "crosses under QE"

Integrate out W^2 axis to get Q^2 spectrum

RPA and SRC effects up to 10 GeV



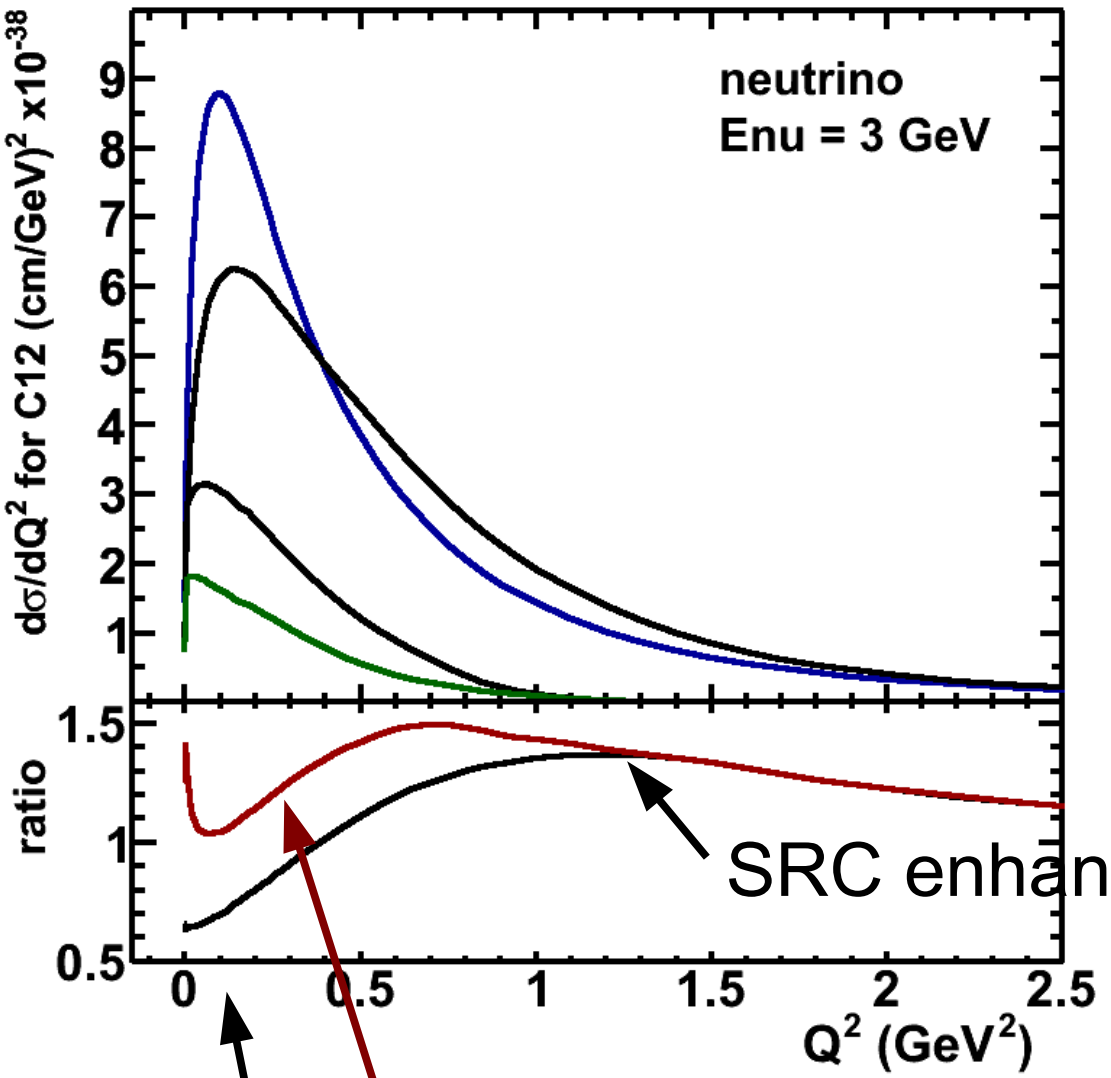
RPA suppression at low Q^2 tuned to describe muon capture data

Transition to SRC enhancement must happen around 0.5 GeV^2, must be some enhancement

Magnitude of SRC enhancement is not especially tuned to data uncertain above 1.2 GeV^2. Model has two variations non-relativistic from 2004 paper relativistic variant 2004 2013

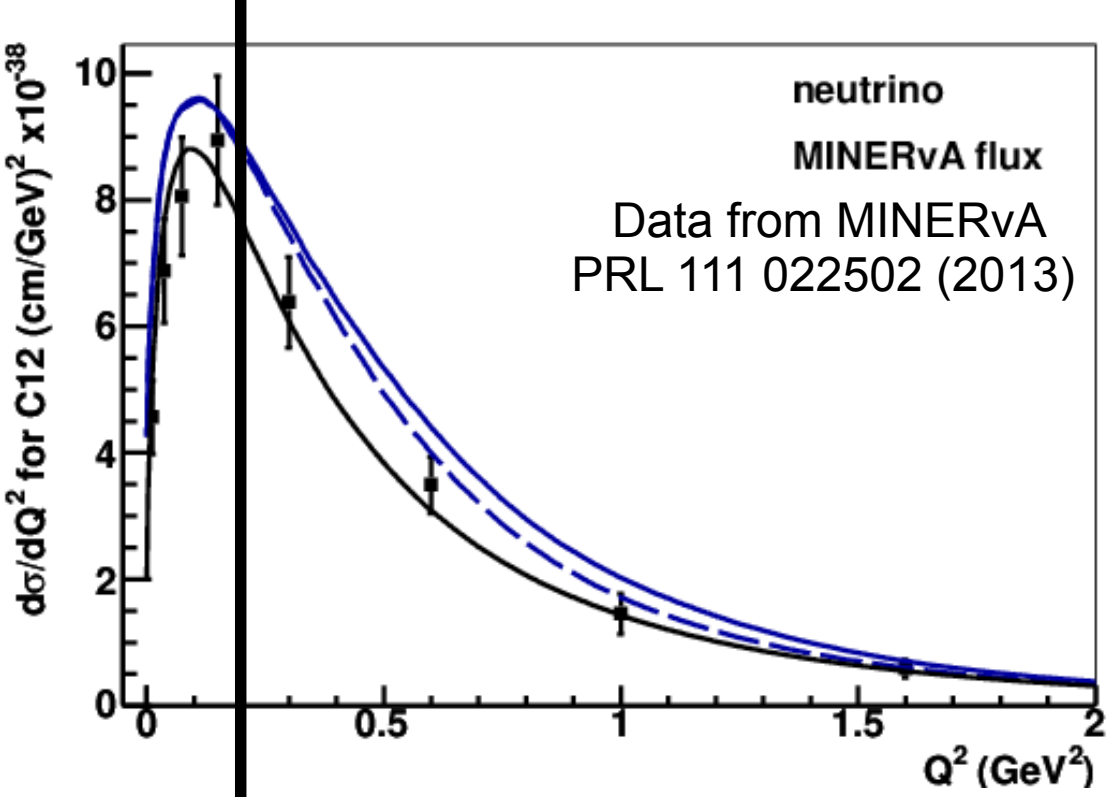
Good approximation to implement Q^2 reweight for neutrino picks up energy dependence vs. Q^2 for anti-neutrino some improvement if model 2D kinematics

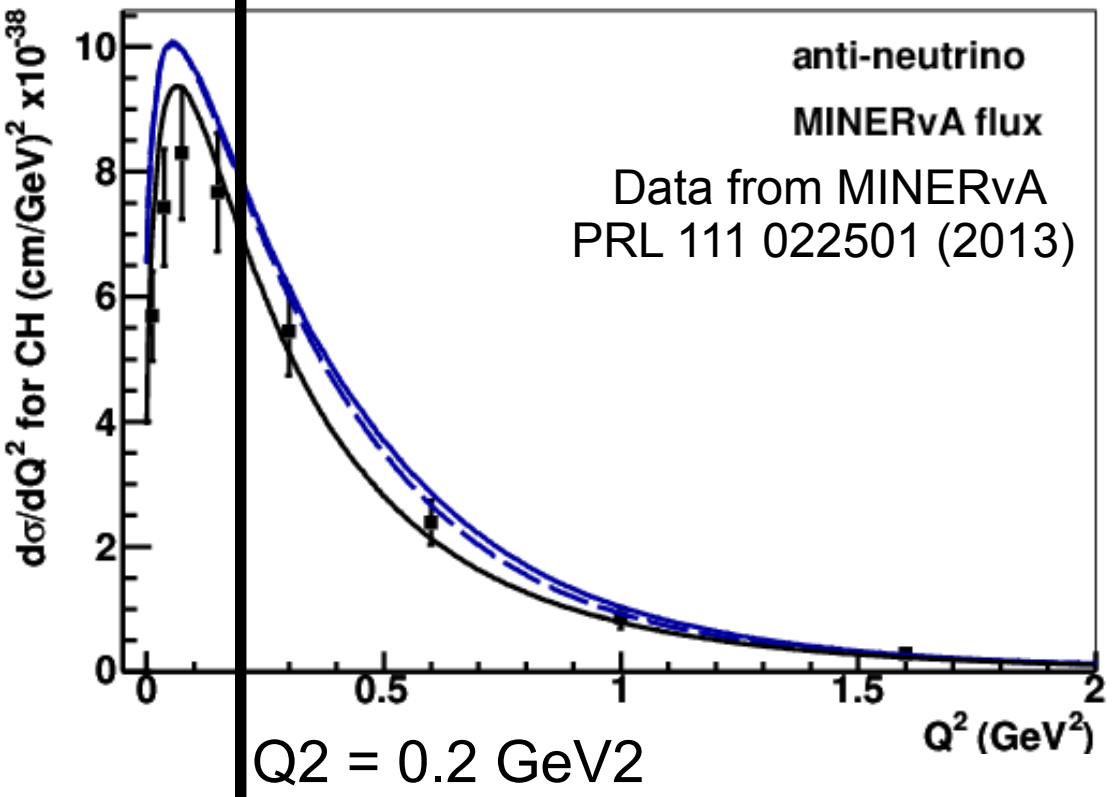
What 2p2h giveth, RPA taketh away



Prediction: two effects together shape for $0.2 < Q2 < 1.0$ GeV^2 rising, harder, flatter spectrum compared to simple model

If your only knob is M_A, expect data to want higher M_A





Q2 = 0.2 GeV2

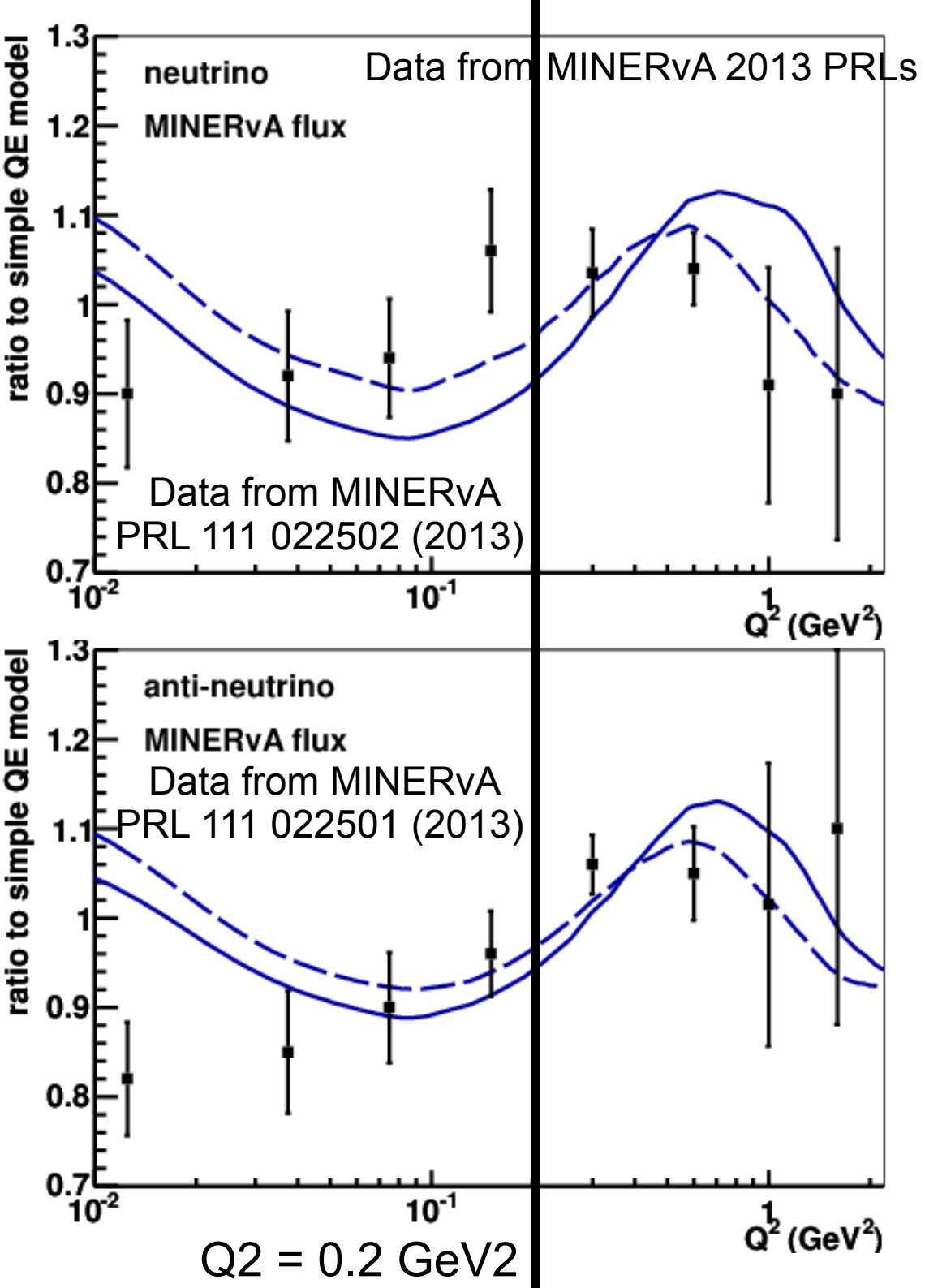
Comparison to MINERvA data

Black FGM
Blue 2p2h+QERPA

Absolute prediction high data uncertainties dominated by flux model is a little beyond 1σ

Dashed line shows the "relativistic" version of RPA+SRC

shape comparison on next slide



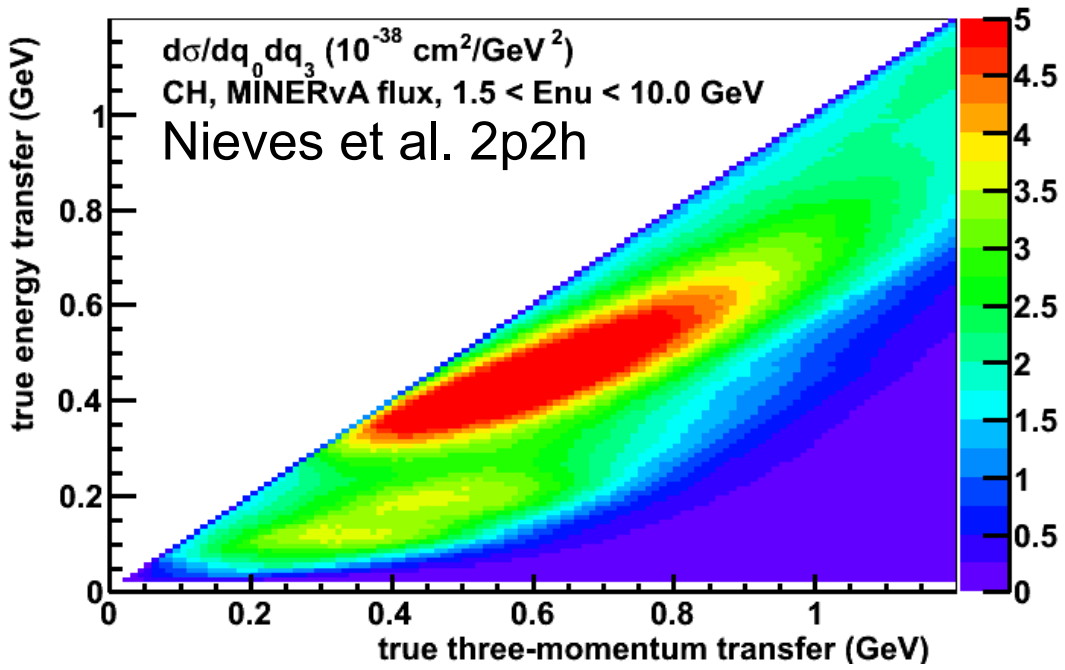
Comparison to shape MINERvA data

MINERvA data wants a rising shape relative to GENIE from 0.1 to ~1 GeV^2

The combination of MEC, RPA, and SRC effects predict same.

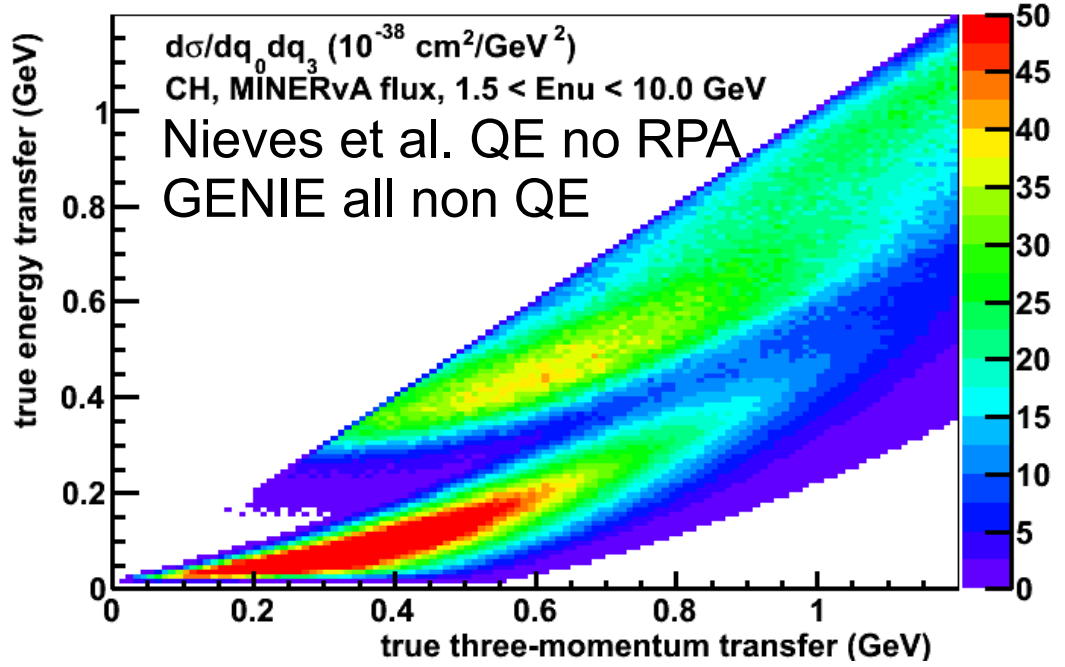
No quantitative comparison, distortion similar to previous "high M_A" fit results

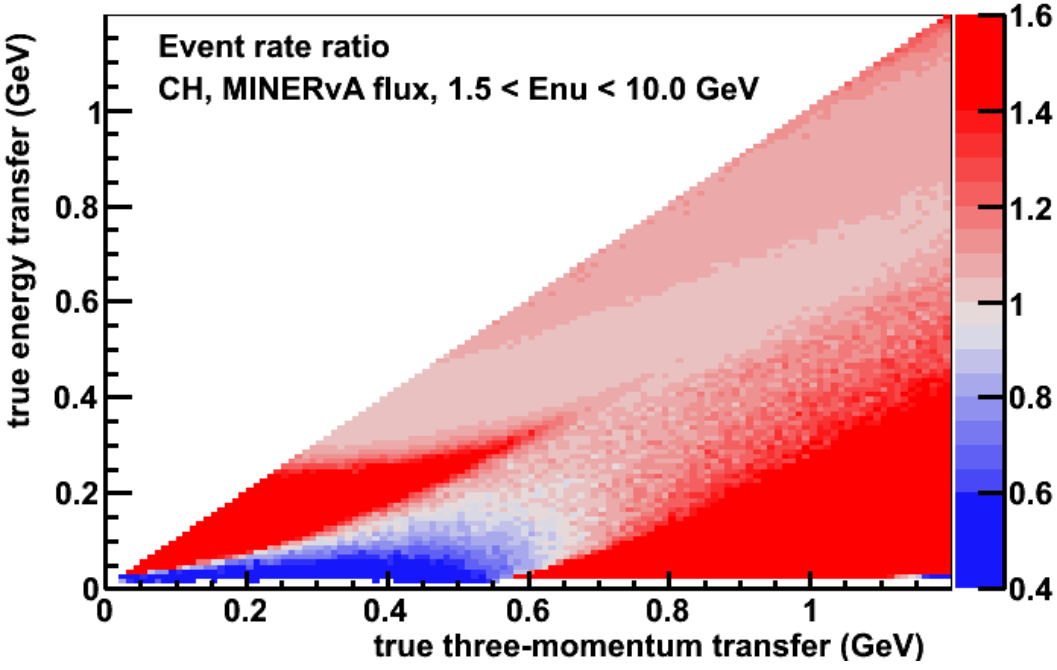
Beyond Q^2 distribution



The 2p2h effect ends up enhancing the same Q^2 as the RPA suppresses

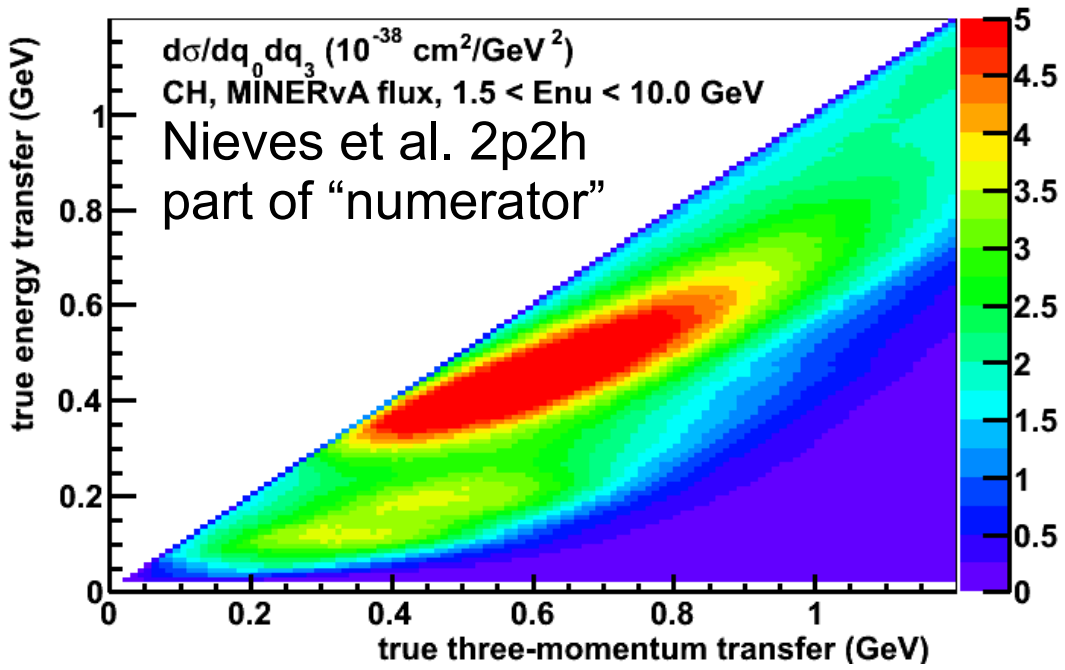
But these effects are separated in 2D

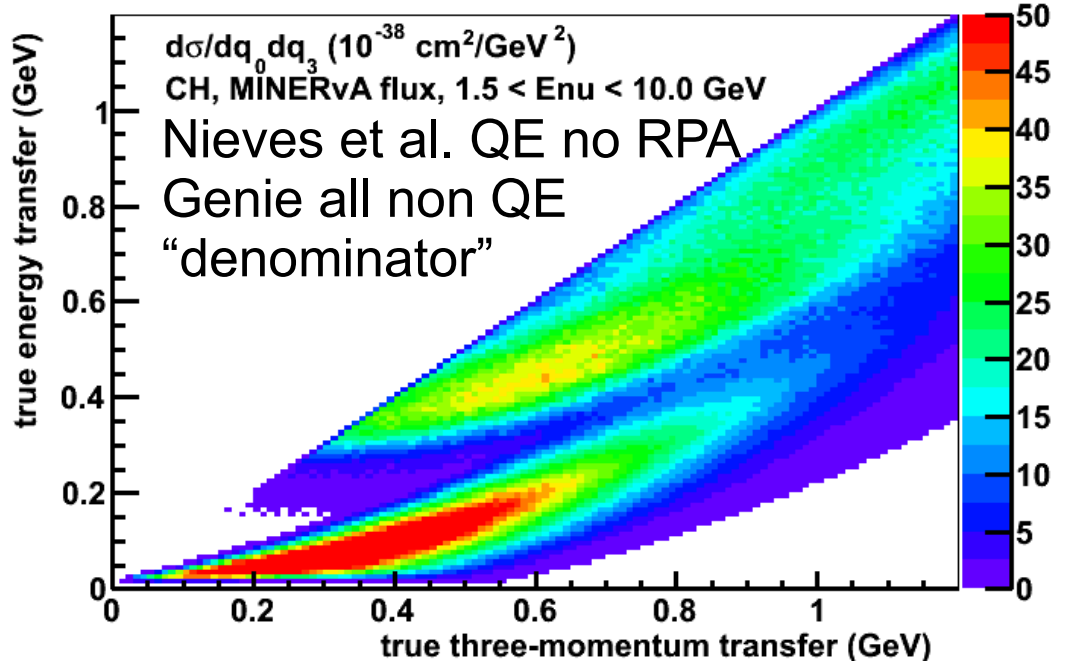


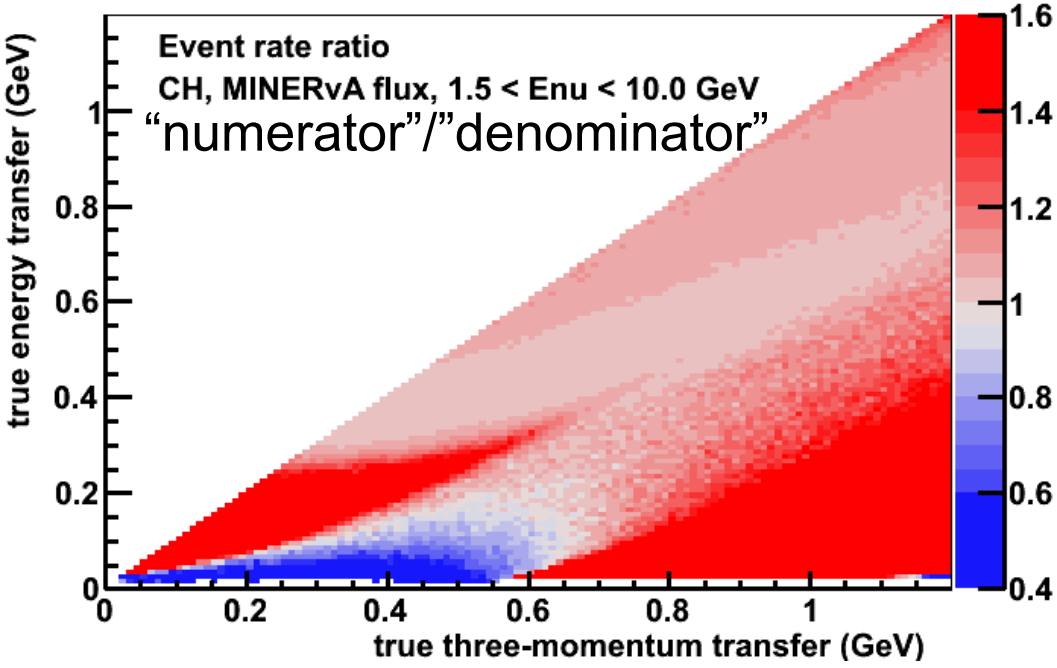


Beyond Q^2 distribution

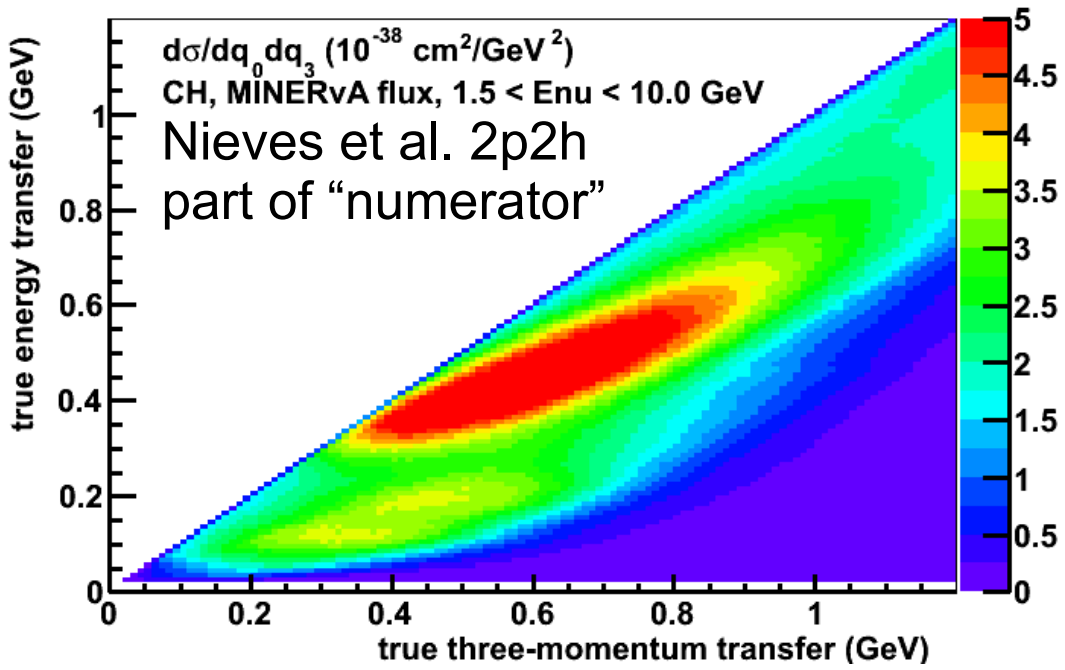
Like an event generator
mix and match models
INCLUSIVE (ν,μ') scattering
Genie for nonQE non2p2h
Nieves et al. 2p2h
and QE with & without RPA





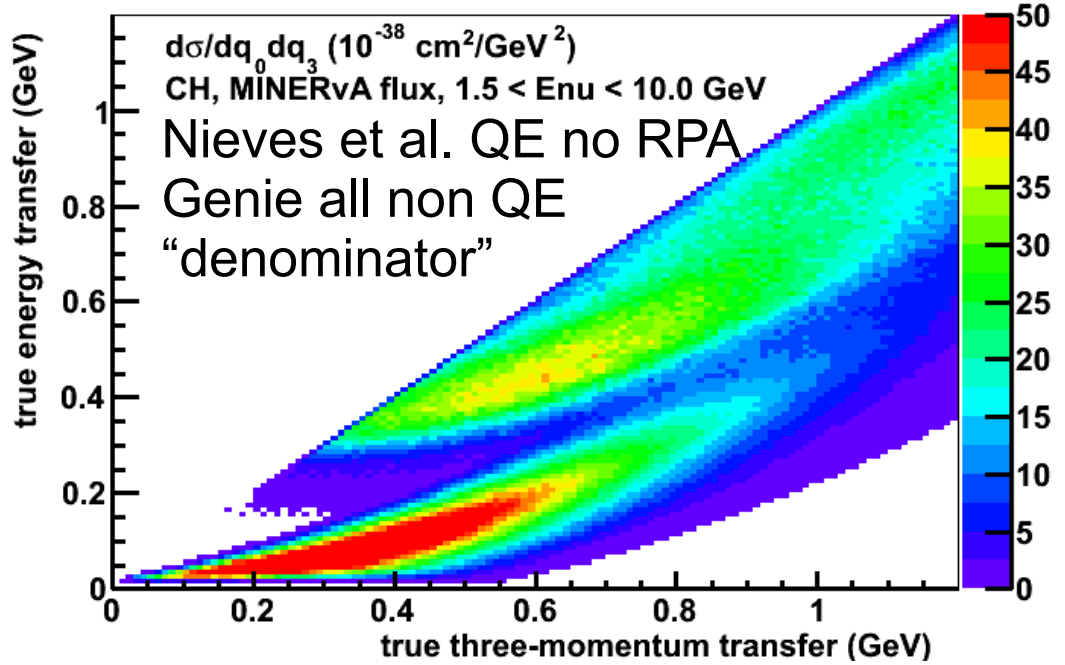


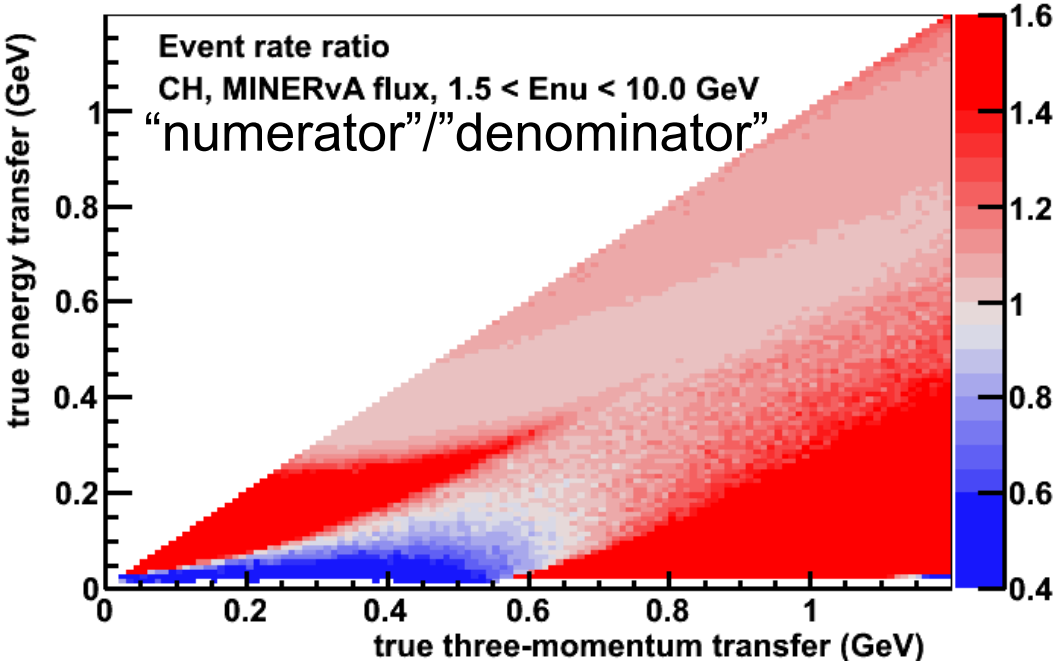
Beyond Q^2 distribution



ratio is

$$\frac{\text{2p2h+QE with RPA+Genie nonQE}}{\text{QE without RPA + Genie nonQE}}$$

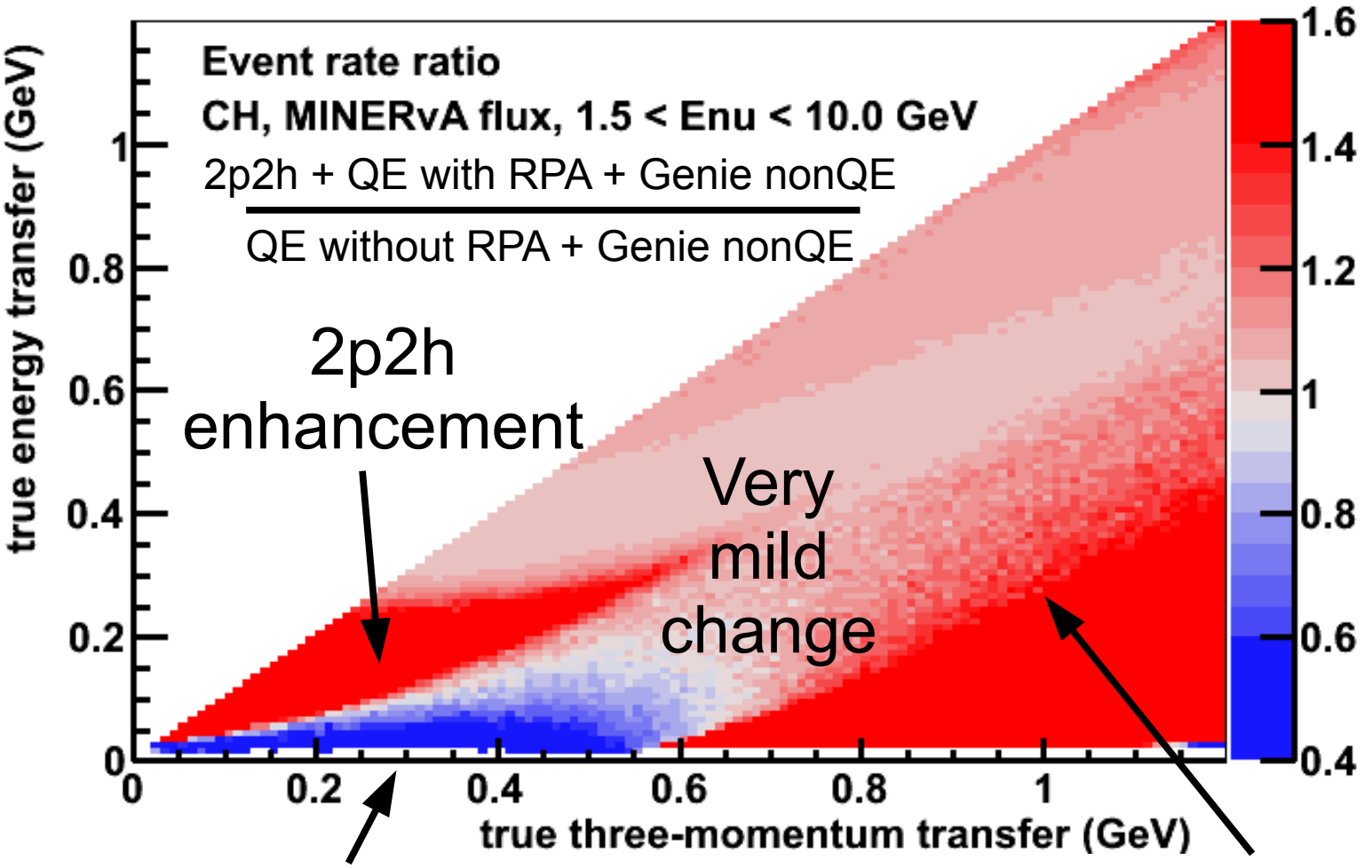




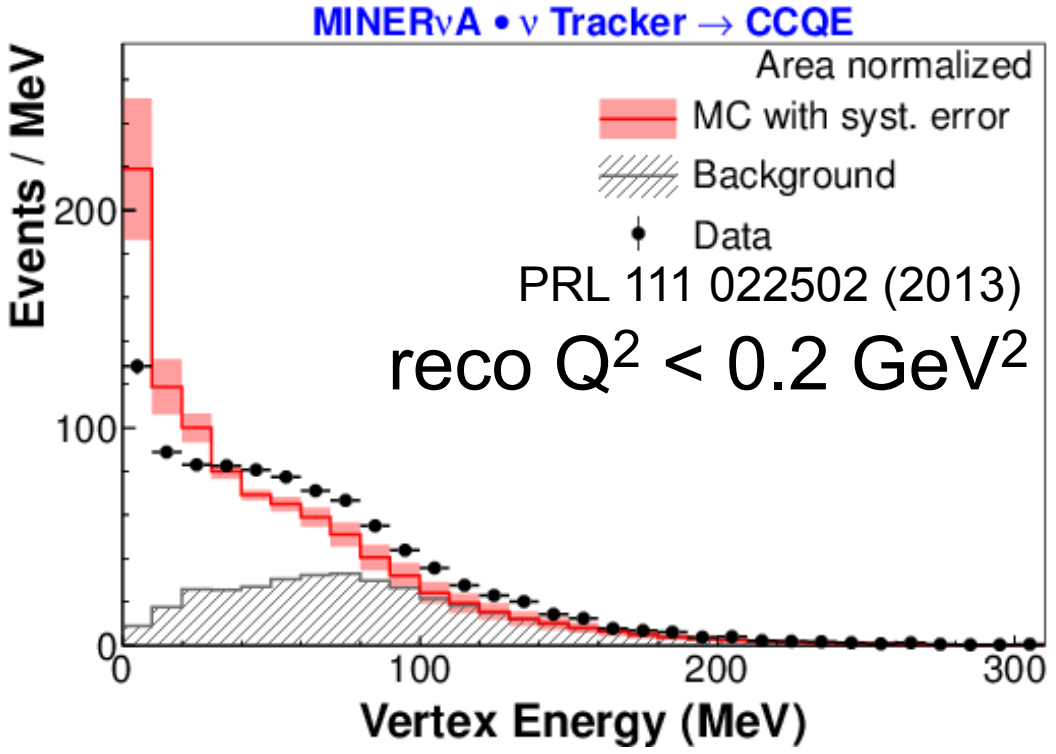
2p2h and RPA effects should separate in 2D

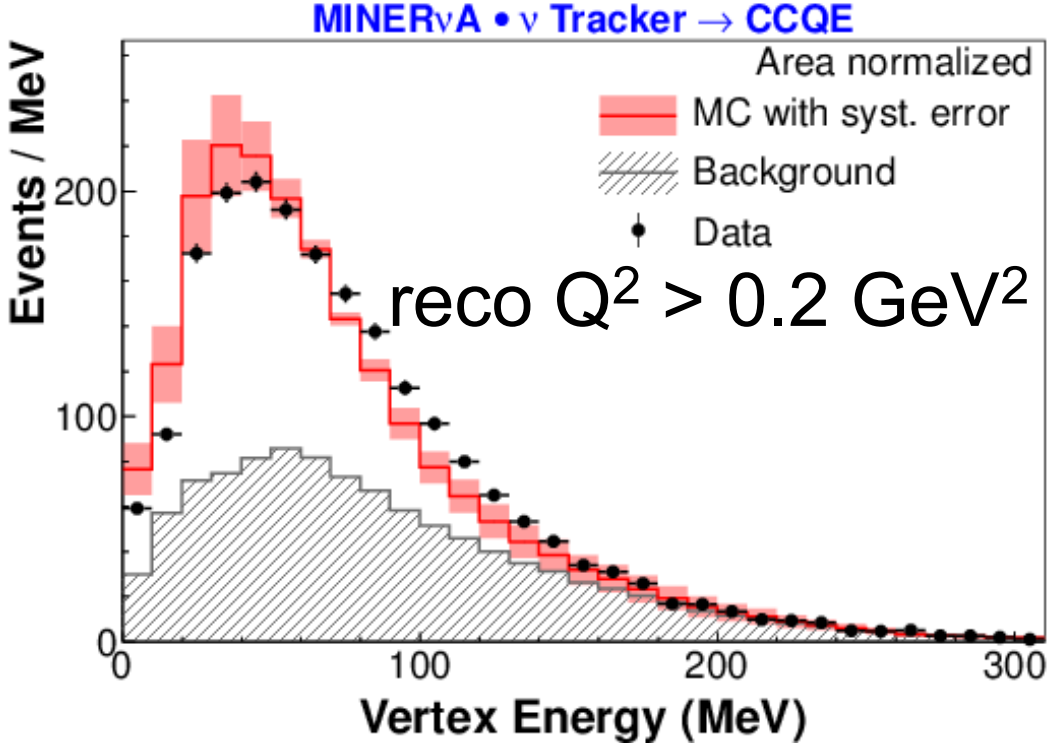
Can't do this using QE kinematics.

Need some Ehad estimator



Challenge with reconstructed kinematics
neutron FS content (missing energy) and resolution model
do large effects hold up against smearing?





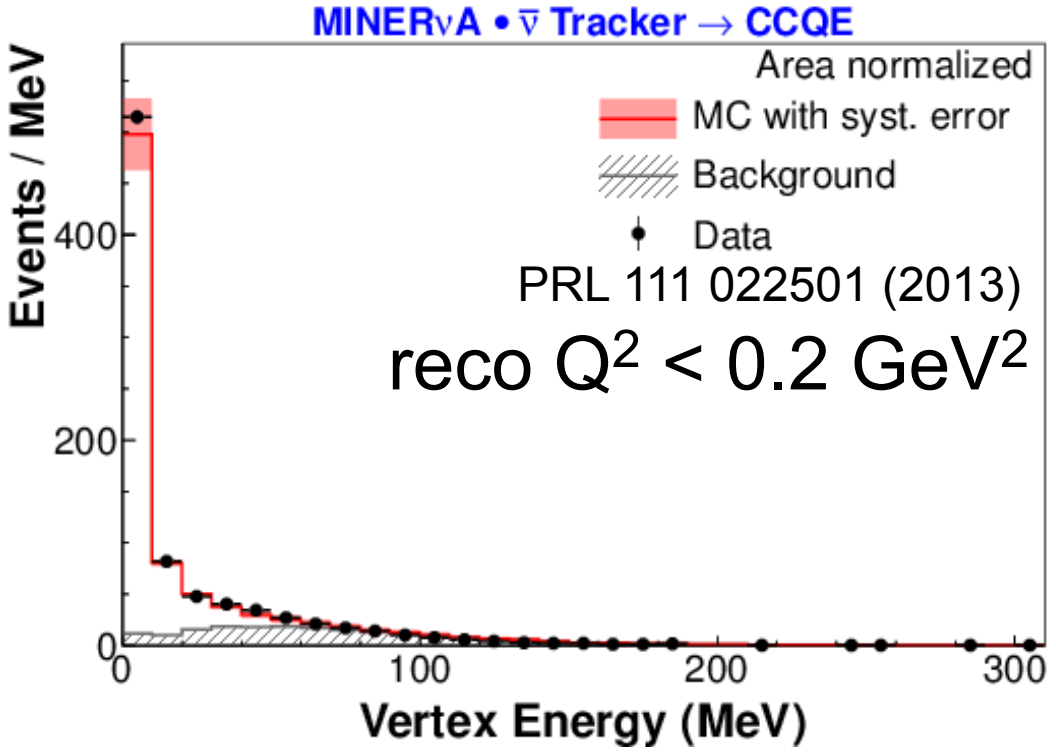
MINERvA hadrons from neutrino data

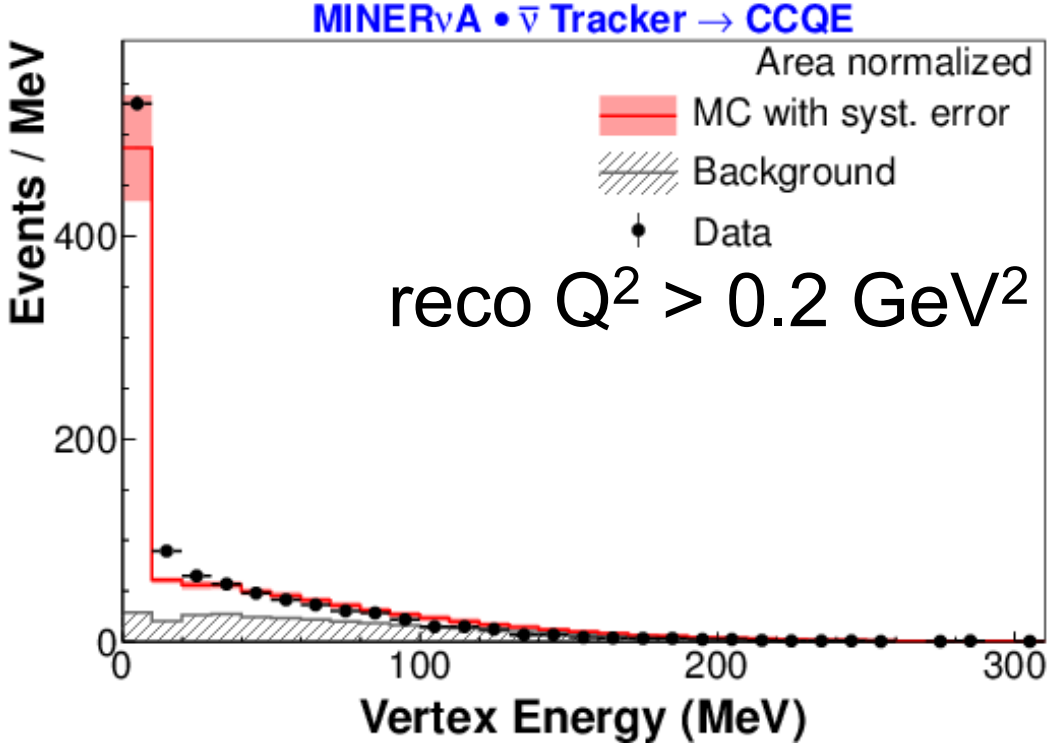
After QE selection
area normalized

Migration of MC to right
from -1σ FSI
captured by error band

Predict RPA takes away
dramatically from lowest bin
2p2h puts pn pp final states
into middle of distribution
strong effect $Q^2<0.2$ GeV^2

Little RPA effect
but some 2p2h
at $Q^2 > 0.2$ GeV^2





MINERvA hadrons from anti-nu data

After QE selection
area normalized

Agreement is already okay

Predict RPA takes
low energy transfer
events out of zero-bin

2p2h adds events with
moderate energy transfer
but lots of nn final states
back to the zero bin

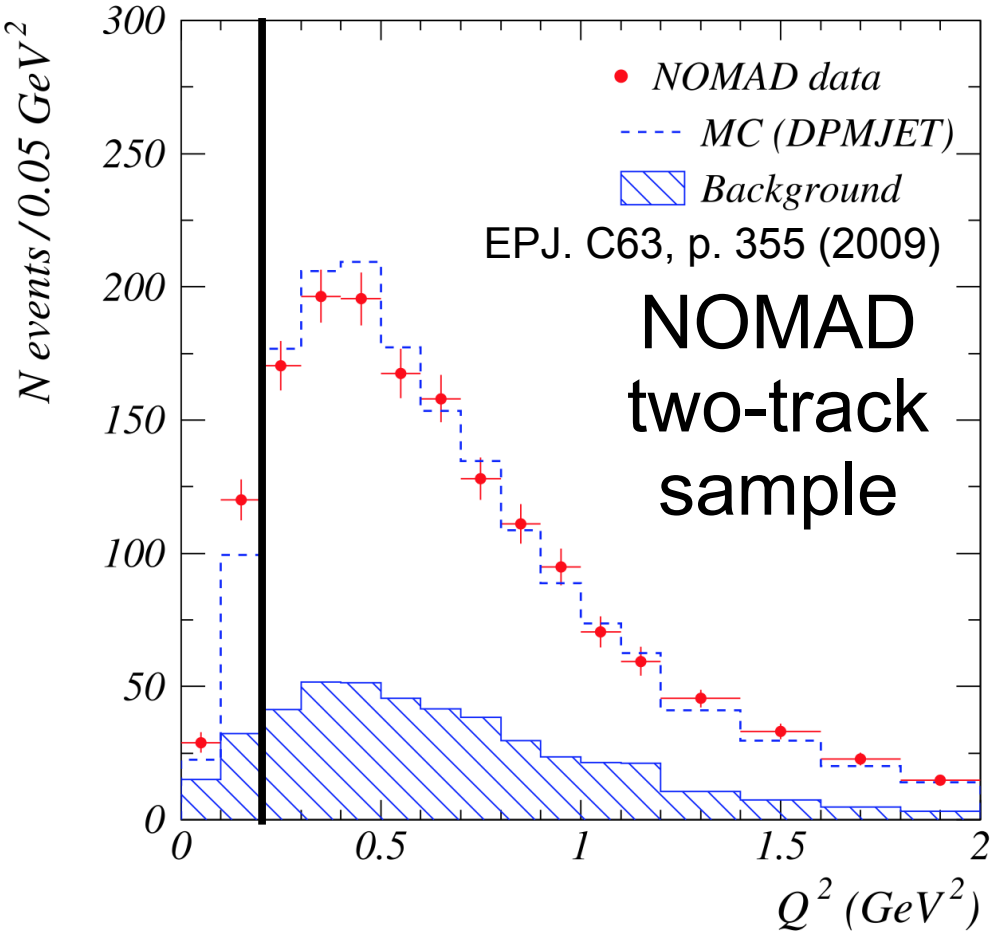
QE and QE-like event selection

Many experiments select sample with more QE purity
use both muon and proton kinematics to reject 2p2h and Delta
(also reject QE events with significant FSI)
NOMAD's 2-track sample is like this

Some reconstruct protons with high threshold
or separation of one-track an two-track samples
would put 2p2h (and FSI events) in the one-track sample
Most experiments have variation on this
2p2h signal and enhanced FSI might seem like same effect

Some experiments select QE-like = no pion
all models predict this is a combination of
true QE, Delta with FSI, Delta with DN->NN absorption, 2p2h

NOMAD



Low density straw-tube tracker
very low threshold for protons
ideal to look for pp final states

It would be very interesting
to see these data reanalyzed with
a 2p2h and RPA model in mind
and see more of what their
1-track kinematics look like

Two track sample selected
with constraint on p kinematics
I see an excess in the data
at very low Q^2, combined with
a flatter distribution.

Paper mentions difficulty with,
did tune FSI model to 1trk/2trk
before σ(E) based on event rate
MEC convoluted with FSI?

Conclusions

Feature-rich microscopic calculations,
like Nieves, Ruiz Simo, Vicente Vacas, et al.

Describes (e,e') data and MiniBooNE data

Quantitatively MINERvA data at 1.5 < Ev < 10 GeV

Would account for high effective axial mass

Predicts a rich structure in 2D+Ehad kinematics
qualitatively describes MINERvA vertex energy discrepancy

Suggests a challenging but interesting road-less-traveled
for future analysis

Confirming the right physics would lead to model tuning

citations and other references

2p2h model, QE+RPA model, both models [reorder and add color coding]

This talk based primarily around material in this paper
R. Gran, J. Nieves, F. Sanchez, M. Vicente Vacas, Phys. Rev. D88, 113007 (2013) arXiv:1307.8105

J. Nieves, I. Ruiz Simo, M. Vicente Vacas, Phys. Rev. C83, 045501 (2011) arXiv:1102.2777

J. Nieves, I. Ruiz Simo, M. Vicente Vacas Phys. Lett. B707, p.72 (2012) arXiv:1106.5374

J. Nieves, I. Ruiz Simo, M. Vicente Vacas Phys. Lett. B721, p. 90 (2013) arXiv:1302.0703

R. Gran, J. Nieves, F. Sanchez, M. Vicente Vacas, Phys. Rev. D88, 113007 (2013) arXiv:1307.8105

J. Nieves, F. Sanchez, I. Ruiz Simo, M. Vicente Vacas Phys. Rev. D85, 113008 (2012) arXiv:1204.5404

J. Nieves, J. E. Amaro, M. Valverde, Phys. Rev. C70, 055503 (2004) arXiv:nucl-th/0408005

J. Nieves, M. Valverde, M. Vicente Vacas, Phys. Rev. C73, 025504 (2006) arXiv:hep-ph/0511204

S. K. Singh, N. C. Mukhopadhyay, E. Oset Phys. Rev. C57, 2687 (1998)

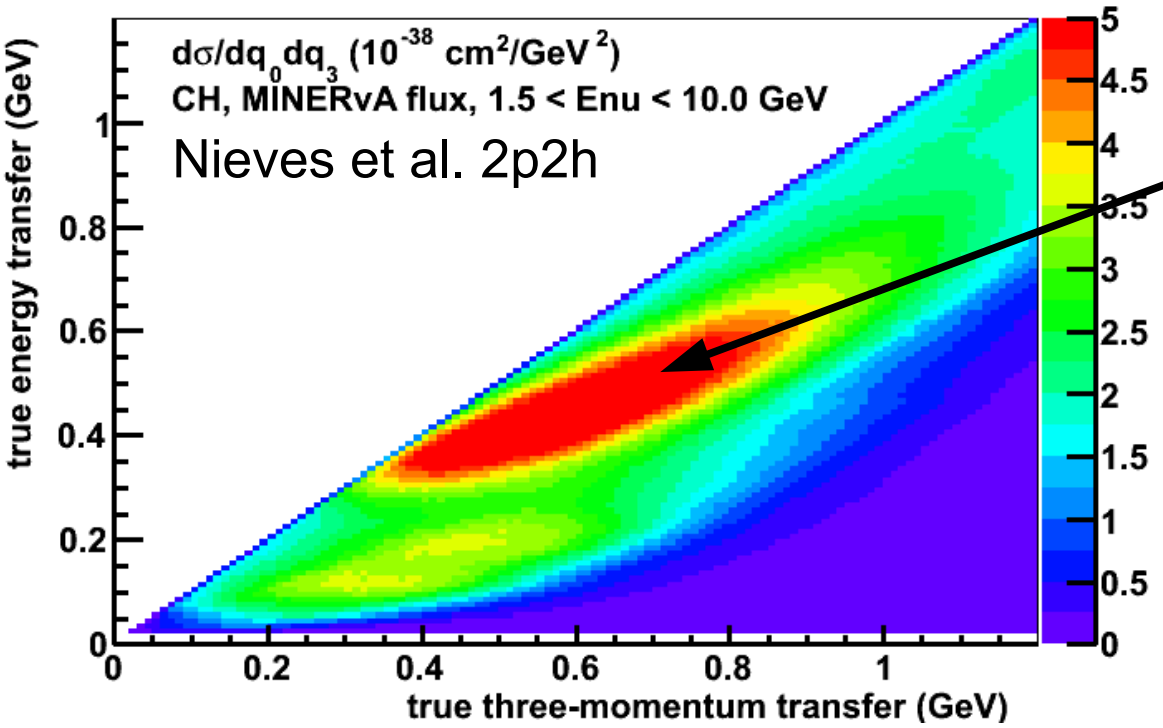
Measurements

V. Lyubushkin et al. [NOMAD], Eur. Phys. J. C63, p. 355 (2009) arXiv:0812.4543
(there is a plot in the journal that is not in the arXiv version)

L. Fields, J. Chvoka, et al. [MINERvA], Phys. Rev. Lett 111, 022501 arXiv:1305.2234

G. Fiorentini, D. Schmitz. P. Rodrigues, et al. [MINERvA], Phys. Rev. Lett. 111, 022502 (2013) arXiv:1305.2243

Backup slides



zero pion from Δ

how do generators treat it?

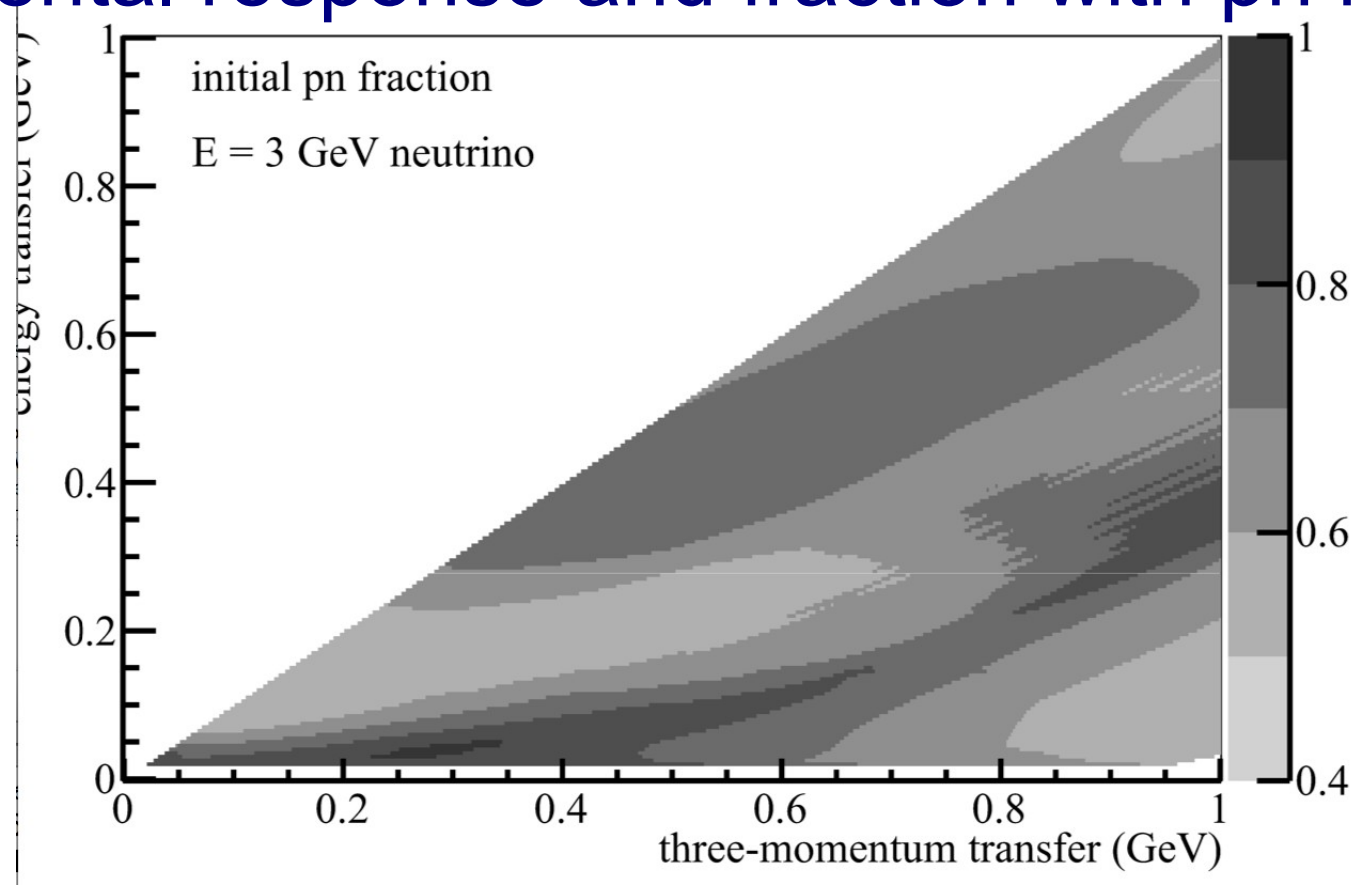
add uncertainty beyond our current FSI errors? measurement opportunity?

Δ blob is important because of interference terms, but

1. it is also an intrinsic no-pion component $\Delta N \rightarrow NN$
   One supposes further rescattering of the NN final state
2. We also expect $\Delta N \rightarrow \pi NN \rightarrow NNNx$ through FSI

Among many challenges surrounding pion production
Some kinds of trouble modeling the QE-like background could be underestimate or missing estimate of process 1 and overestimate of fraction that is $\Delta N \rightarrow \pi NN$

Experimental response and fraction with pn initial state

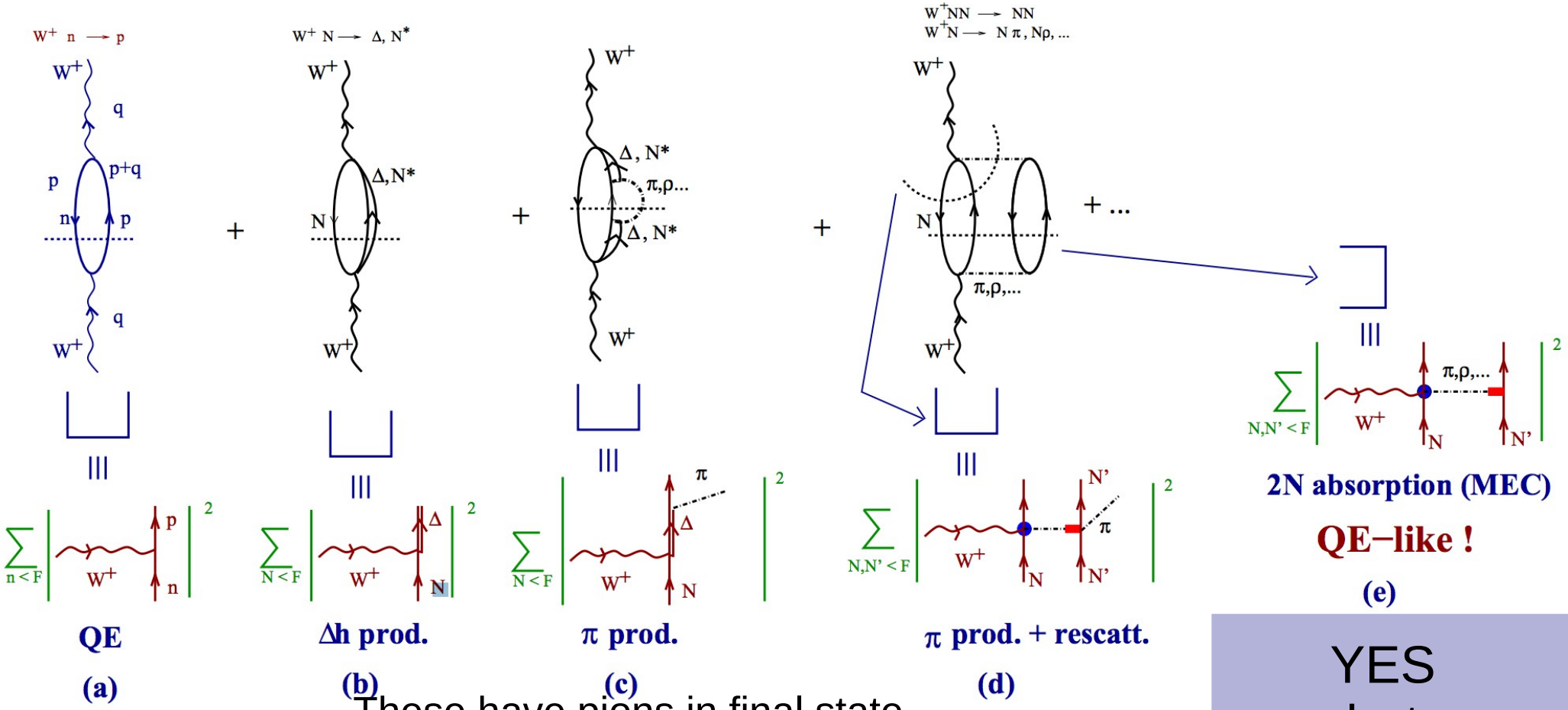


Structure in the 2p2h events from pn initial to pp final state
intrinsically high 5/6 at the Δ peak
elsewhere averages to about 50/50
before FSI produces excess QE-like events with two protons
SRC results in e scattering suggest very high pn initial state

dependence on A for isoscalar nuclei

	nonΔ linear	Δ >linear
16O / 12C	1.33	1.5
40Ca / 12C	3.33	4.0

Microscopic calculation of these diagrams



These have pions in final state

YES	No	No	No	YES but two types w&wo Δ

In the work I'm presenting today?

with and without RPA

Diagrams from Nieves et al. NuInt12 talk and proceedings