no-pion 2p2h implementations in GENIE

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comment:
I am not officially
a GENIE collaborator
but I play one on TV.
My opinions are my own
but may not be representative
of GENIE collaborators.
But they should be!

Saint Surrounded by Three Pi Mesons
Salvador Dali 1956

There are three models with a few options

Empirical MEC is the out-of-box model in GENIE
puts a blob of events at a W corresponding to the dip region.
Includes a NC version. Both are 0.45 of QE cross section
Options to tune pn initial state fraction from default 80% pn
NOvA and MicroBooNE using this default recently.

Valencia model implements generic hadronic tensor contraction
more details at https://arxiv.org/abs/1601.02038
Implementation same time as in Neut, NuWro
and produces extremely similar results (previous talks).
MINERvA based on this and NOvA, NUISANCE have used it.

Now a third model being ported from G. Megias / SuSA group
using the same GENIE/NEUT interface developed for Valencia

Valencia “NSV” model in GENIE overview

Five-component hadronic tensors pretabulated (four of them) separately for all and pn only initial states, all and Delta only

Final state nucleons get energy, momentum transfer, then isotropic “decay” in their rest frame, then boost to lab frame (very nearly the Sobczyk prescription PRC 86 015504)

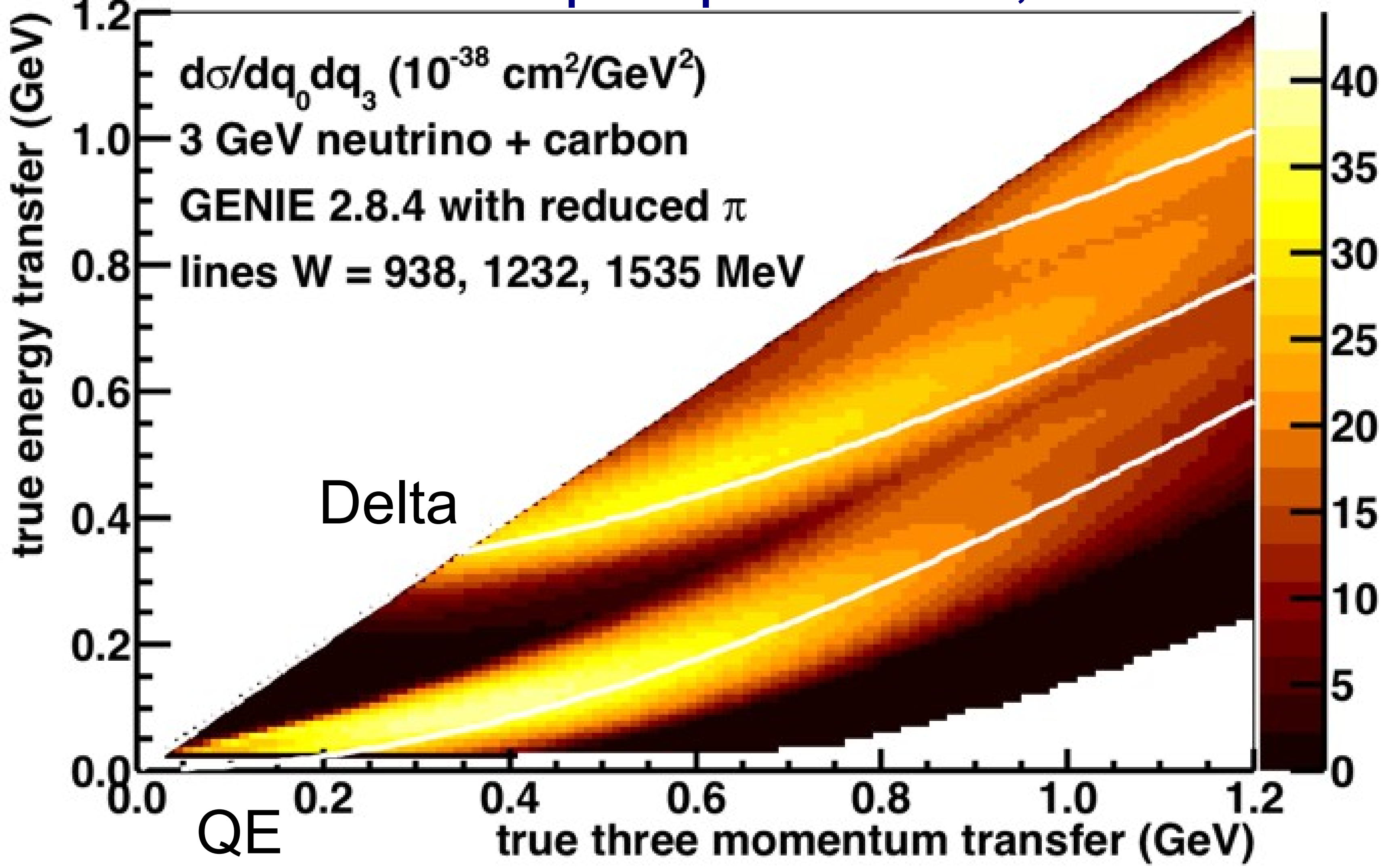
Explicit Delta component “tagged” and reweightable.

Versions after 2.12.6 run for nuclei other than C12,O16,Ca40. Generate tensors for nearby isoscalar nuclei, then approximate use isospin combinatorics to scale the pn, !pn initial state.

Limited to q<1.2 GeV, does not include 1p1h “SRC” diagrams missing some diagrams/interferences, has non-relativistic bits.

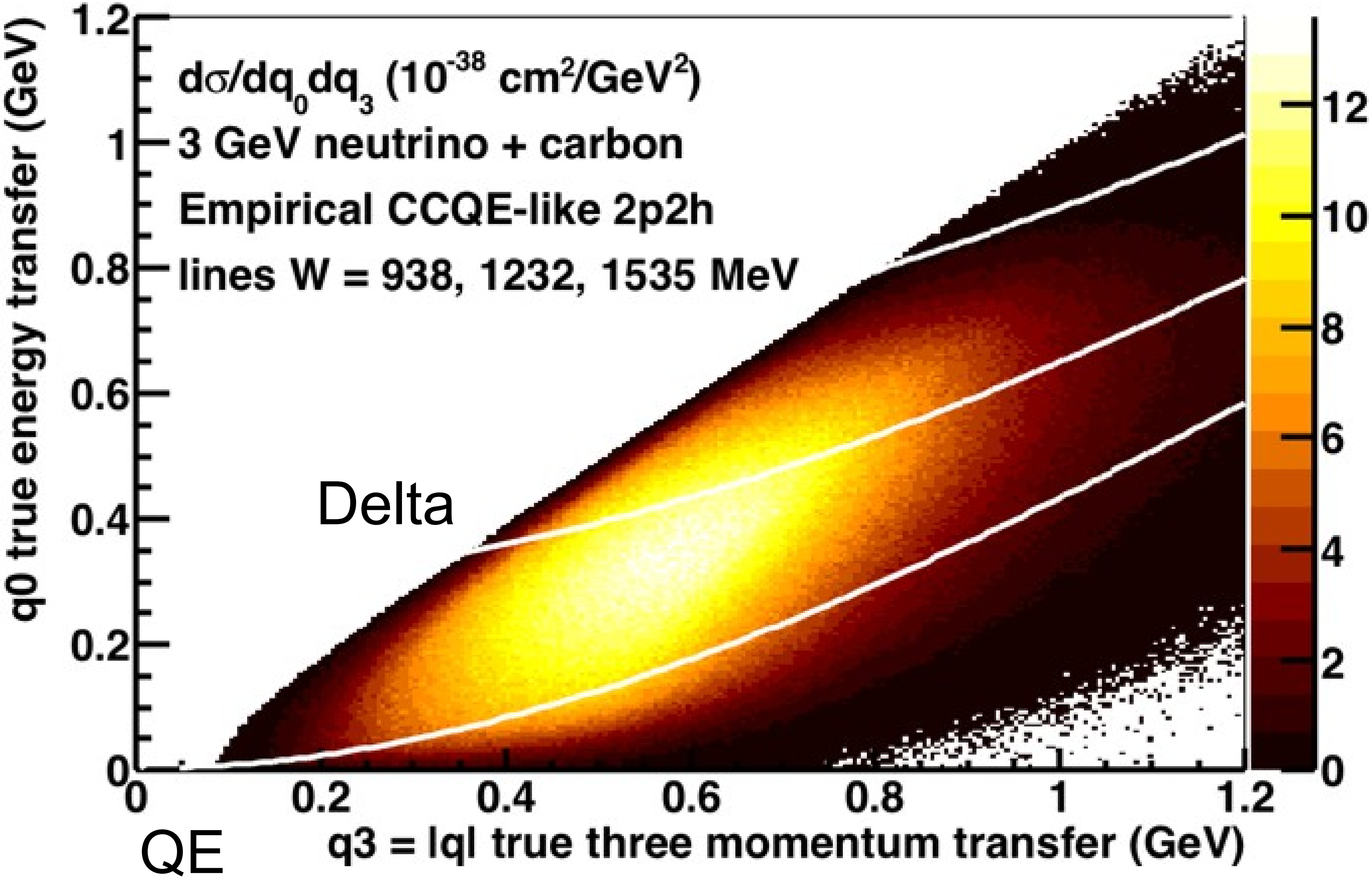
MINERvA tune was to this model using these features

GENIE three-momentum and energy transfer vs. W baseline for NON 2p2h processes, for reference



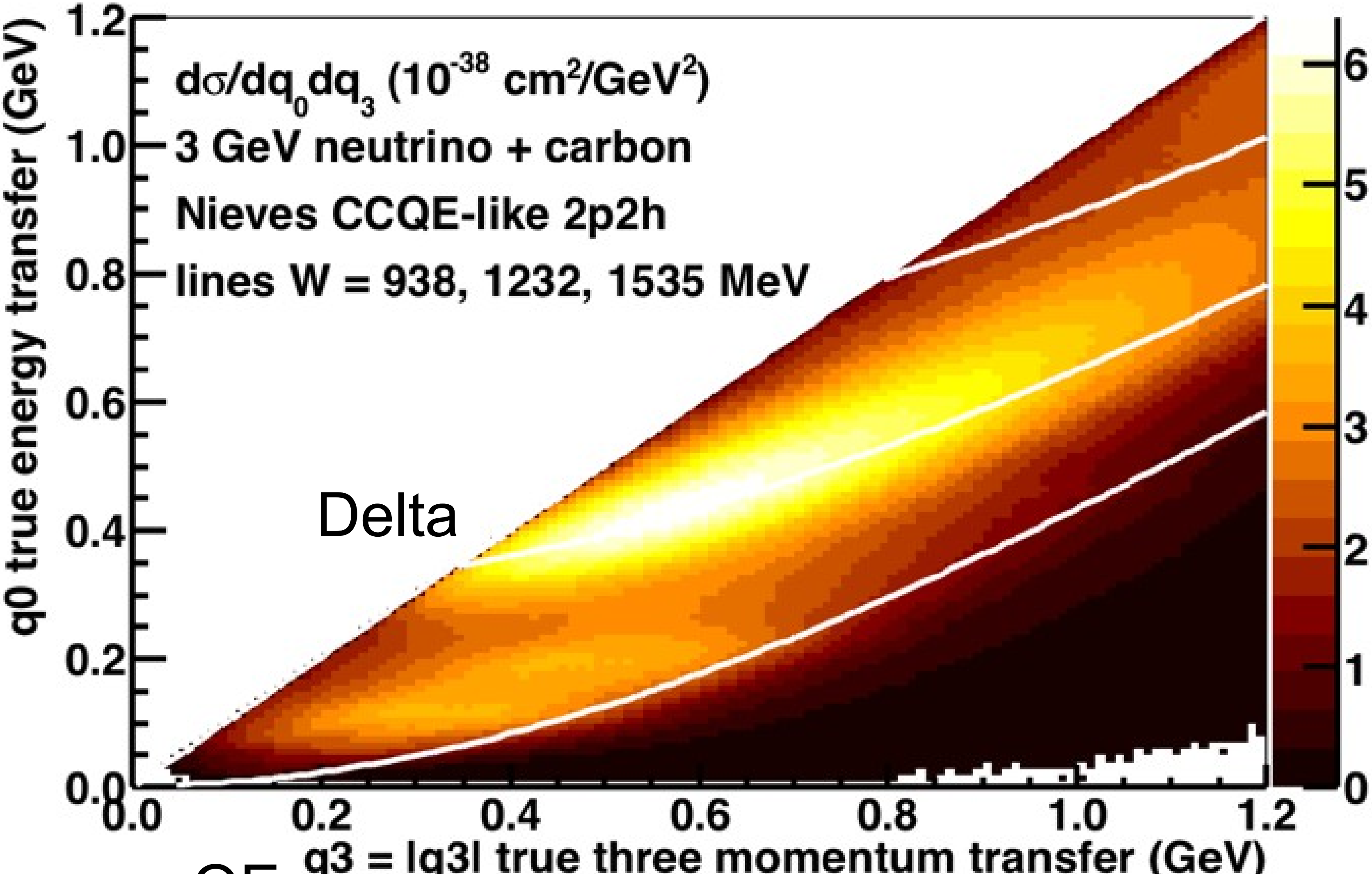
Can't get this with muon kinematics alone in broad band beam
personally use MINERvA's abilities as hadron calorimeter

GENIE "empirical" QE-like (no pion) 2p2h prediction



Empirical (e,e') dip region strategy Lightbody, OConnell 1988
45% of QE strength, in dip region, 80% pn initial states

Valencia QE-like (no pion) 2p2h prediction



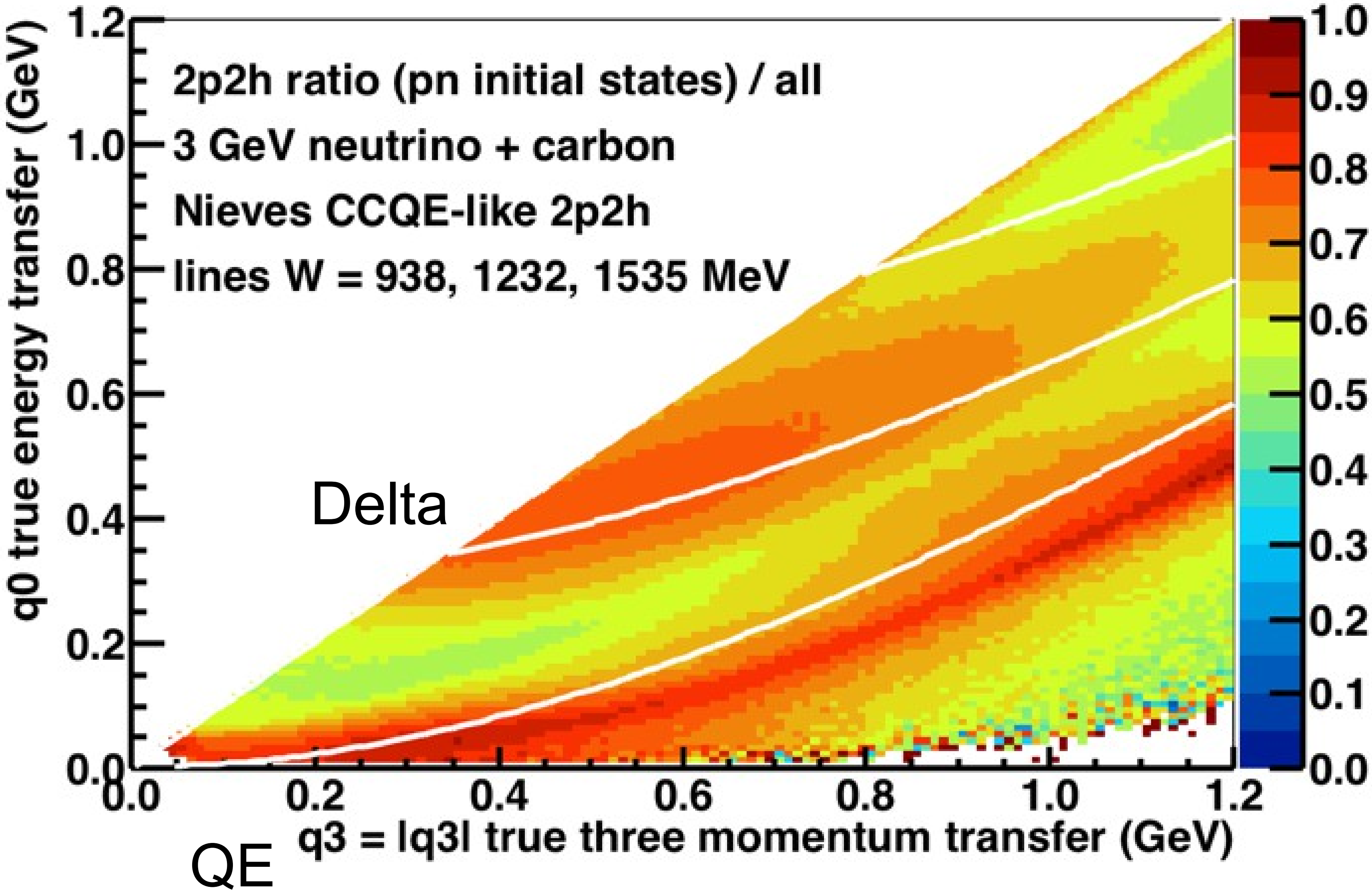
QE

significant sorta-QE component but at W ~ 1.0

Explicit "W"$_{(1p1h)}$ = $M^2 + 2\,M\,q_0 - Q^2$ = 1.232 GeV Δ bit

Strength is ~1/4 QE in total, but missing some 2p2h diagrams

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



GENIE implementation uses this prediction directly by making two separate hadron tensors, one pn, one !pn scale to other Z,A. Is not uniform, follows the interferences.

Another layer of detail, shared with NEUT, NuWro

Original partnership Nieves, Vicente Vacas, Sanchez, R.G.
and several students (Jackie Schwehr for GENIE).

Innovation: authors deliver 5-component hadron tensors
generator does lepton tensor contraction, accounts for Q-value,
lepton mass according to mu/e, also nu/anti-nu, A.

Model authors have integrated over all hadronic kinematics.

(no simplification) Generator picks from d2σ/dqdω

Useful documentation of model, implementation, limitations
Nieves, Ruiz Simo, Vicente Vacas PRC 83 (2011) 045501
R.G., Nieves, Sanchez, Vicente Vacas PRD 88 (2013) 113007
Sobczyk, PRC 86 (2012) 015504
Schwehr, R.G., Cherdack arXiv.org:1601.02038

Another layer of detail, shared with NEUT, NuWro

Authors have integrated over all hadronic kinematics.

(no simplification) Generator picks from d2σ/dqdω

(practical factorization of physics, approximation)
Generator picks two nucleons from nuclear model
probably a Fermi gas for GENIE.

Energy and momentum transfer are given to these

(practical factorization of physics, approximation)
The resulting nucleons “decay” their total energy
back to back in CM frame, then boosted to lab frame.

Cost to remove nucleon (25 MeV in Genie) is subtracted.

Comments to other model authors

about the factorization and approximation

If your dσ/dqdω is an improvement over a Fermi gas
it is an improvement even if we used these factorizations, right?

Second use of this interface shown in G. Megias talk

There are two? ways to better deal with the hadronic system.

Unpack the some or all the hadron integrations explicitly.
(Has been done for Nieves 1p1h QE model in NEUT, GENIE)

Reuse the hadron tensor because its fast, but then
better approximate the hadronic system via tables/parameterization
of final states for ranges of q,ω from your model

MINERvA added 2p2h using Valencia as a base

(NOvA recently did same using Empirical as a base)

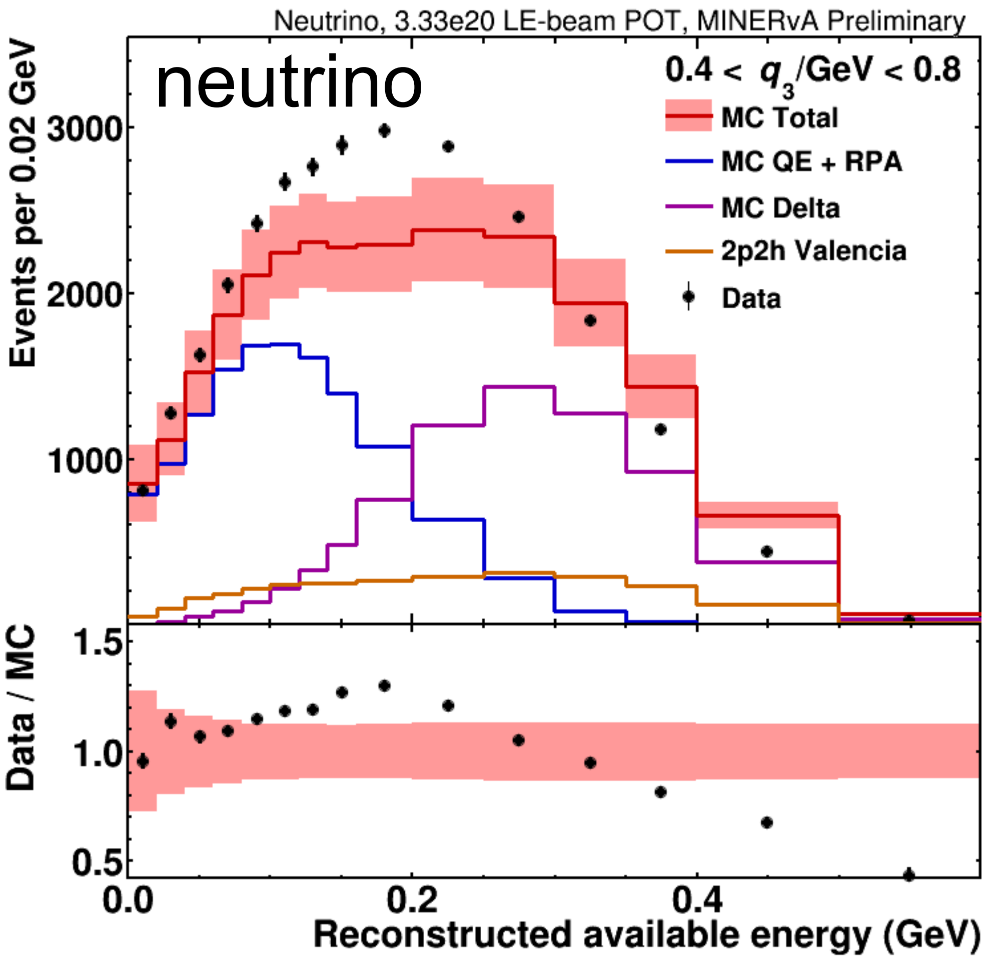
Model kinematics are q0, q3 via hadron tensor.
Data is reco q0, q3 with very good correlation to true.
Energy dependence > 3 GeV is mild and easy to work with.
That allows a (mostly) straightforward empirical tuning,
relative to this model and everything else in GENIE.

The main procedural questions: scope of tune and
weight up the pn initial states or the nn initial states or both
(or weight up 1p1h QE events instead?)
MINERvA first to try this, so tried them all.

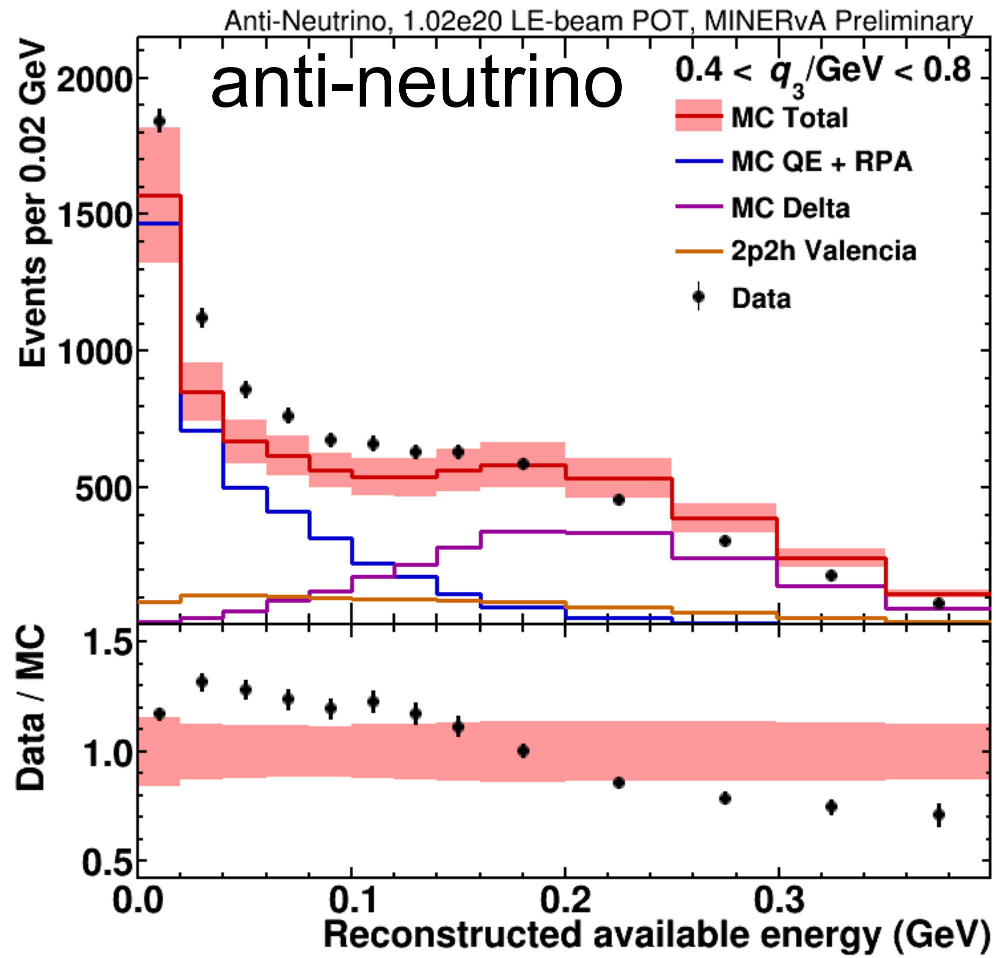
Is NOT a GENIE 2p2h product, it is a MINERvA product
that uses GENIE as the reference, if you use Valencia model.
Built for GENIE 2.8.6, works for versions of 2.12.6
NOvA, NUISANCE folks for sure have reproduced this.

GENIE + RPA + Valencia 2p2h before additional 2p2h

PRL 116 (2016) 071802



PRL 120 (2018) 221805



Uses RPA + Valencia 2p2h model without empirical enhancement

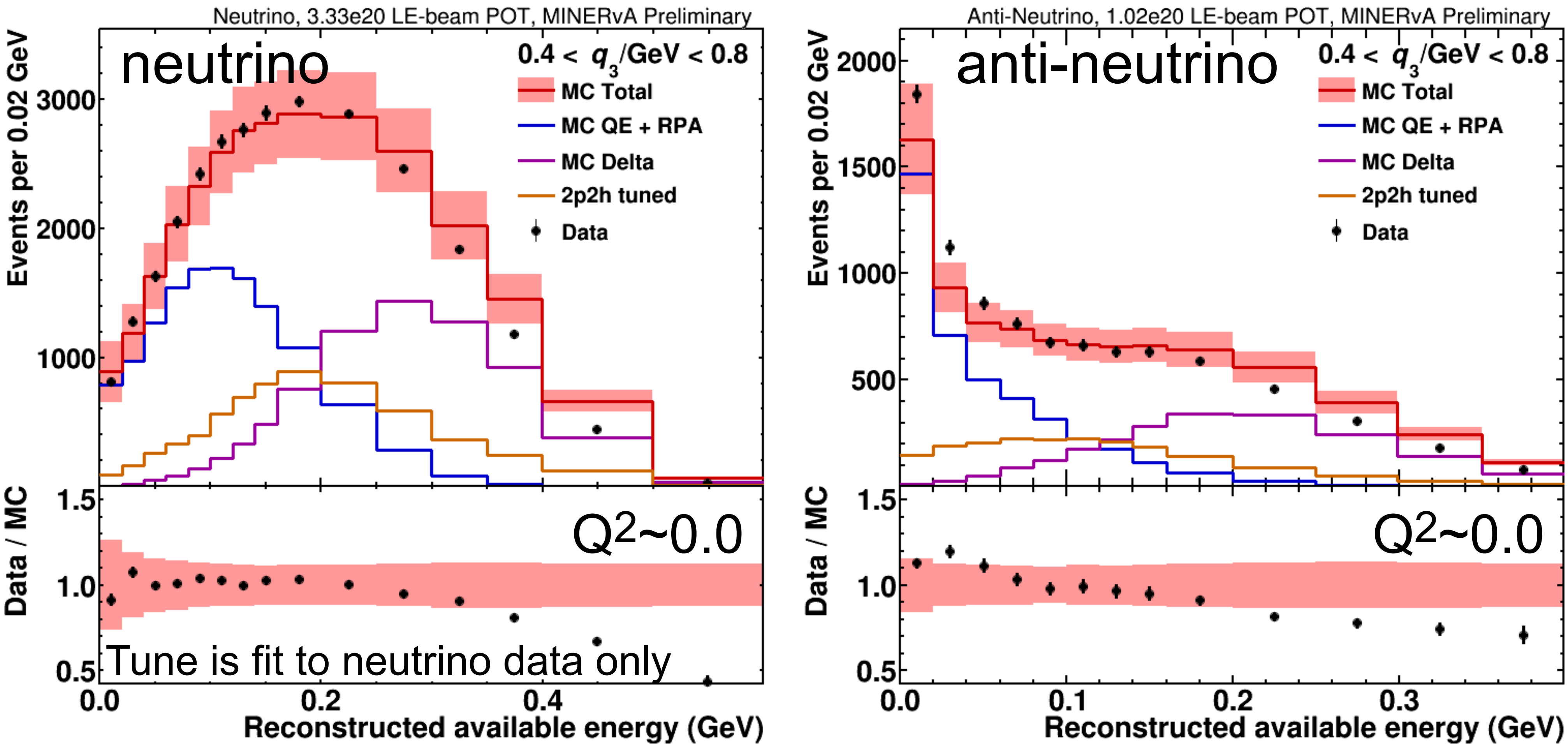
Nieves, Ruiz Simo, Vicente Vacas PRC 83 (2011) 045501

Nieves, R.G. Sanchez, Vicente Vacas PRD 88 (2013) 113007

Code as in Genie 2.12.6 Schwehr, R.G., Cherdack, arXiv:1705.02932

GENIE, RPA, 2017 Tuned 2p2h "MINERvA tune v1"

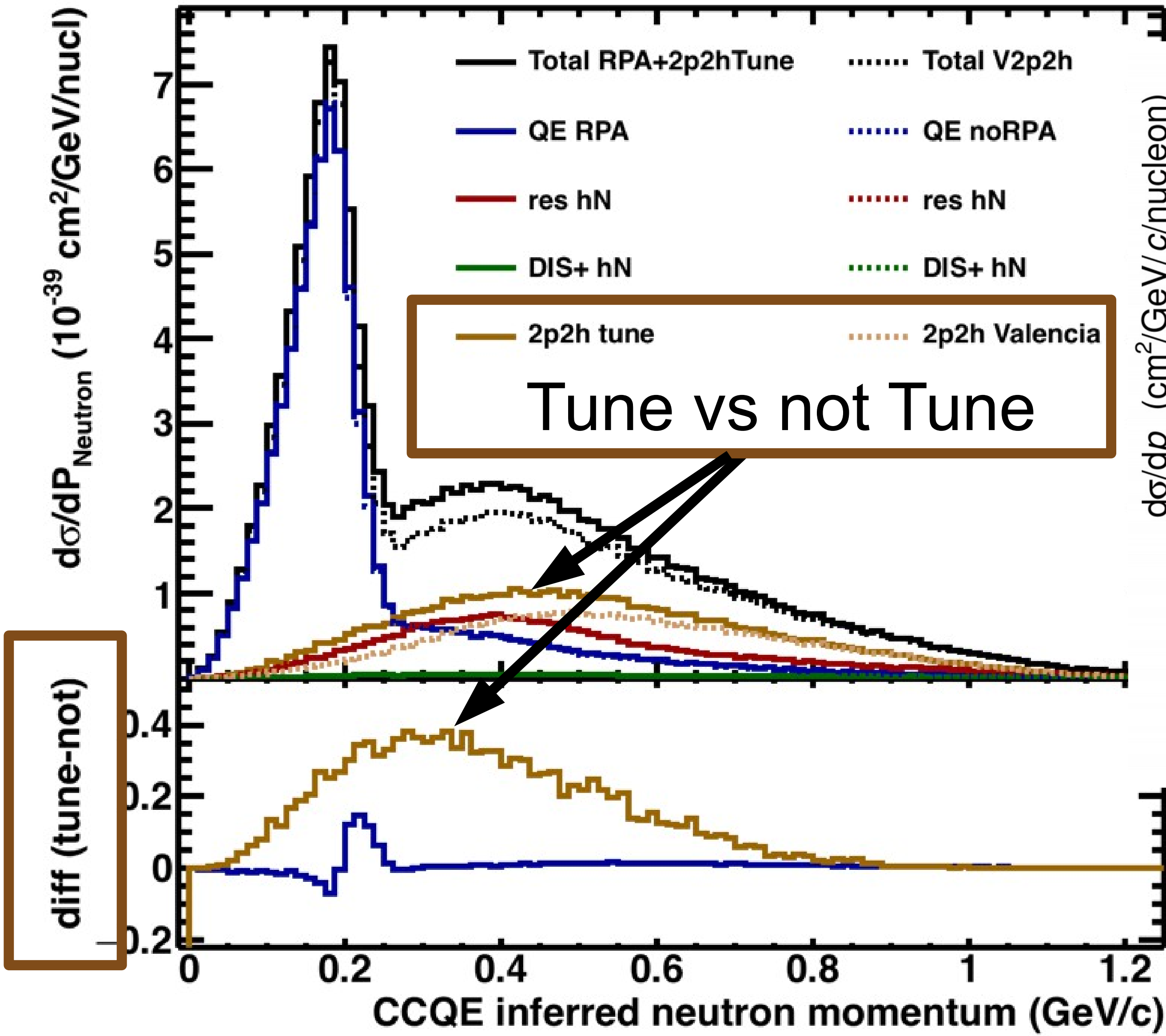
An empirical fit is not so interesting, what does it enable?

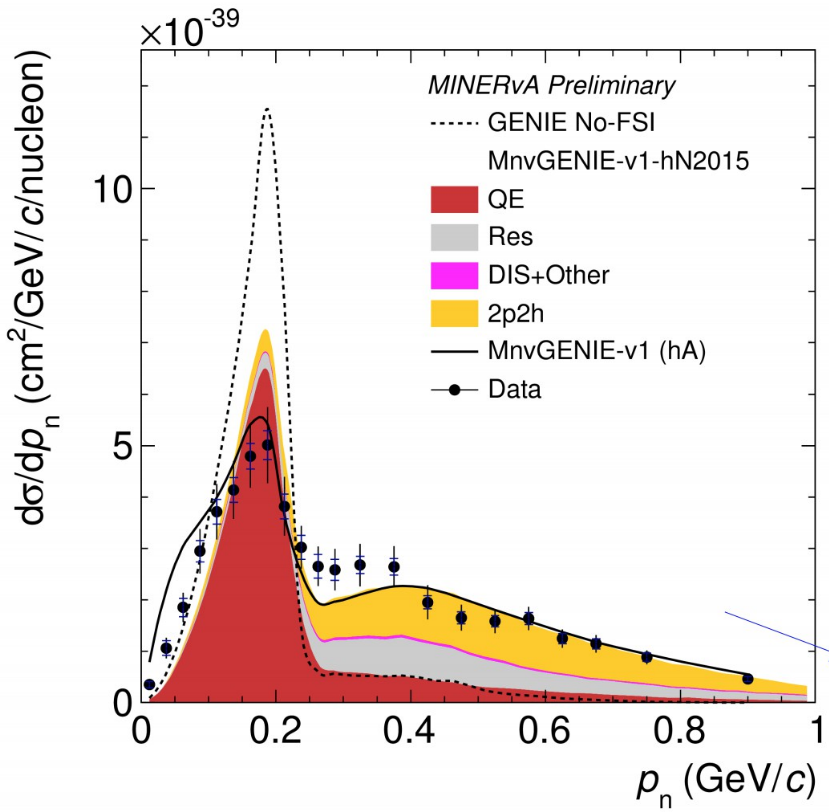


weighting up the 2p2h events with a 2D Gaussian weight
this base tune designed to empirically "Fill in" the dip region
not whole kinematic range. Adds ~50% overall, but x2 in dip region
Improves left plot by construction, those parameters are applied
to the anti-neutrino plot, which is also greatly improved!

MINERvA tuned 2p2h proton+muon observables

Tune becomes internal prediction for other observables





Xianguo Lu, MINERvA
FNAL W&C 2 March 2018
and arXiv:1805.05486
PRL in press

Tune adds x2 in traditional dip region, 50% overall to Nieves

Adds 20% to the predicted **total** rate for pn ~ 0.3 GeV/c

Pause to generate an idea

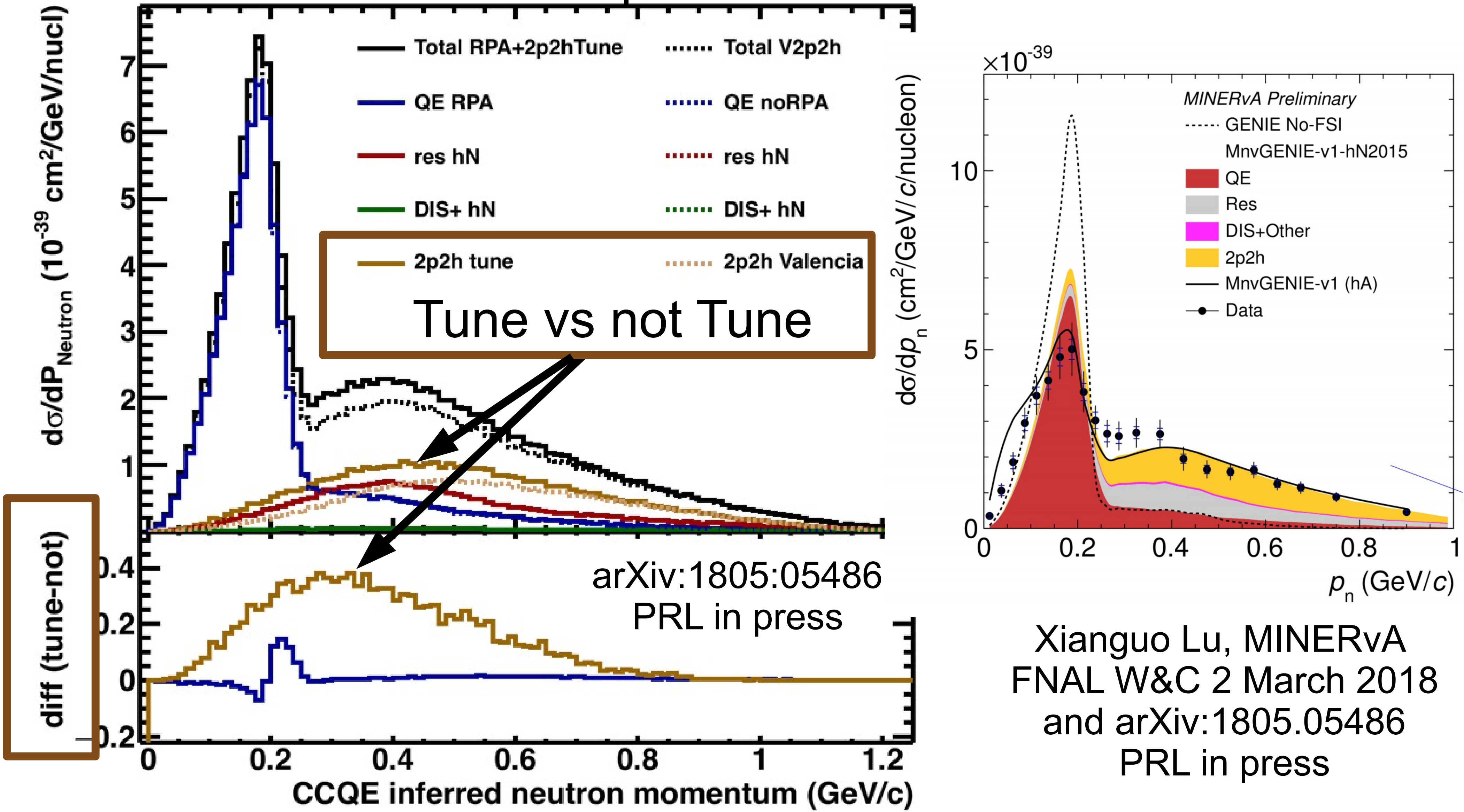
The additional two-nucleon knockout strength
is accounting for deficiencies in
this set of GENIE models and comprimises,
compared to your better models.

Without saying them out loud,
think of your favorite one.

Everybody will have a different one, right?

MINERvA tuned 2p2h proton+muon correlation

Turn tune into internal prediction for other observables



Xianguo Lu, MINERvA
FNAL W&C 2 March 2018
and arXiv:1805.05486
PRL in press

Empirical tune is adding strength to the 2p2h component

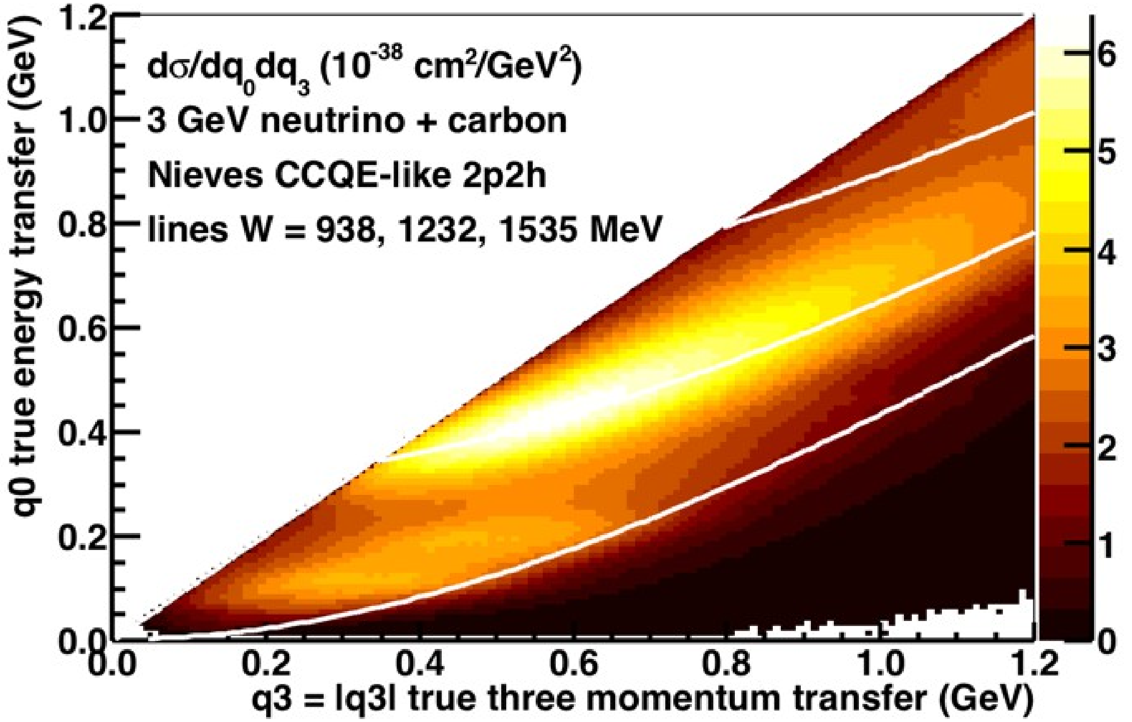
in a region where three different effects may be deficient

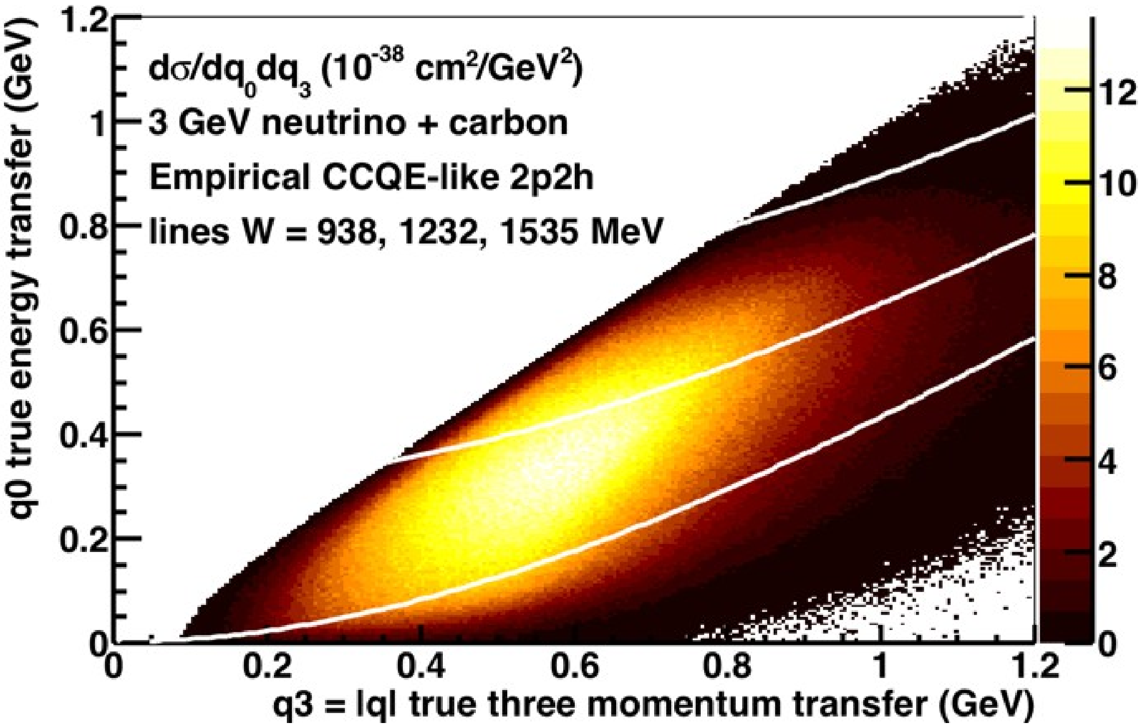
Potential development options

Because it uses the hadron tensor,
some code/physics development could
expose the q0,q3 portions of the components
W1 W2 W3 W4 W5
or in GiBUU style W1 and W3 only
and better explore the energy dependence.

This information is sitting not very deep in GENIE.
Structure functions give access to energy dependence.

OR! user can insert other special case hadron tensors
revised? (from Nieves, Jo. Sobczyk, in progress)
“competing”? (Megias/SuSA, today)
subcomponents? (tried by Sanchez, Cudd, other framework)





Don't fear Frankenmodels!

Think: tools to make progress
Experiments generate libraries of millions of these will full detector simulations. They take weeks, months, last for ~year of analysis

You: generate this distribution externally with pn, !pn

Partner to reweight to these and compare to reco data even in situations where that is all that is available.

Hadron system in this approx is function of q,ω

1p1h extra nucleon ejection

There should be 1p1h reactions on nucleons which have momenta in the spectral function tail. “SRC”

Nieves 2p2h does not include this process.
Some (GiBUU, GENIE Effective Spectral Function) maybe do.
Empirical MEC doesn't, uh, whatever.

Several ways to choose that in GENIE
Bodek Ritchie in the legacy Fermi Gas
to one or more kinds of spectral functions

GENIE has a facility to pair the chosen struck nucleon
and eject a correlated spectator nucleon
producing a two-nucleon final state.
Have not used it, but don't have to code it, so maybe I will.

Conclusions

Two codes live in GENIE for our 2p2h needs

The Empirical one has simple structure

The Valencia one implements a hadron tensor
that can be (has been) exploited or repurposed
or updated if new calculations are available.

MINERvA has data in the same kinematic bases
and has “tuned” = explored the consequences
of an enhanced 2p2h event rate on other observables

It is more successful than we expected
across a wide range of QE-like rich samples
with different hadronic final state observables.

Update of Valencia model code to approximate all nuclei A > 9 and He4

The code still does C12, O16, Ca40 equivalently to
what it did in June 2015 when it passed validations
The O16 and C12 code was used in a MINERvA publication.

New code gives most nuclei
which was a feature request from GENIE
and matched my personal motivation to get Ar40 for DUNE.

These plots are challenging to read
because some effects that show up large in color
are not the ones that are ultimately interesting ...

Pick apart the effects of nuclear size, non-isoscaler.
Three things in the calculation play a role.

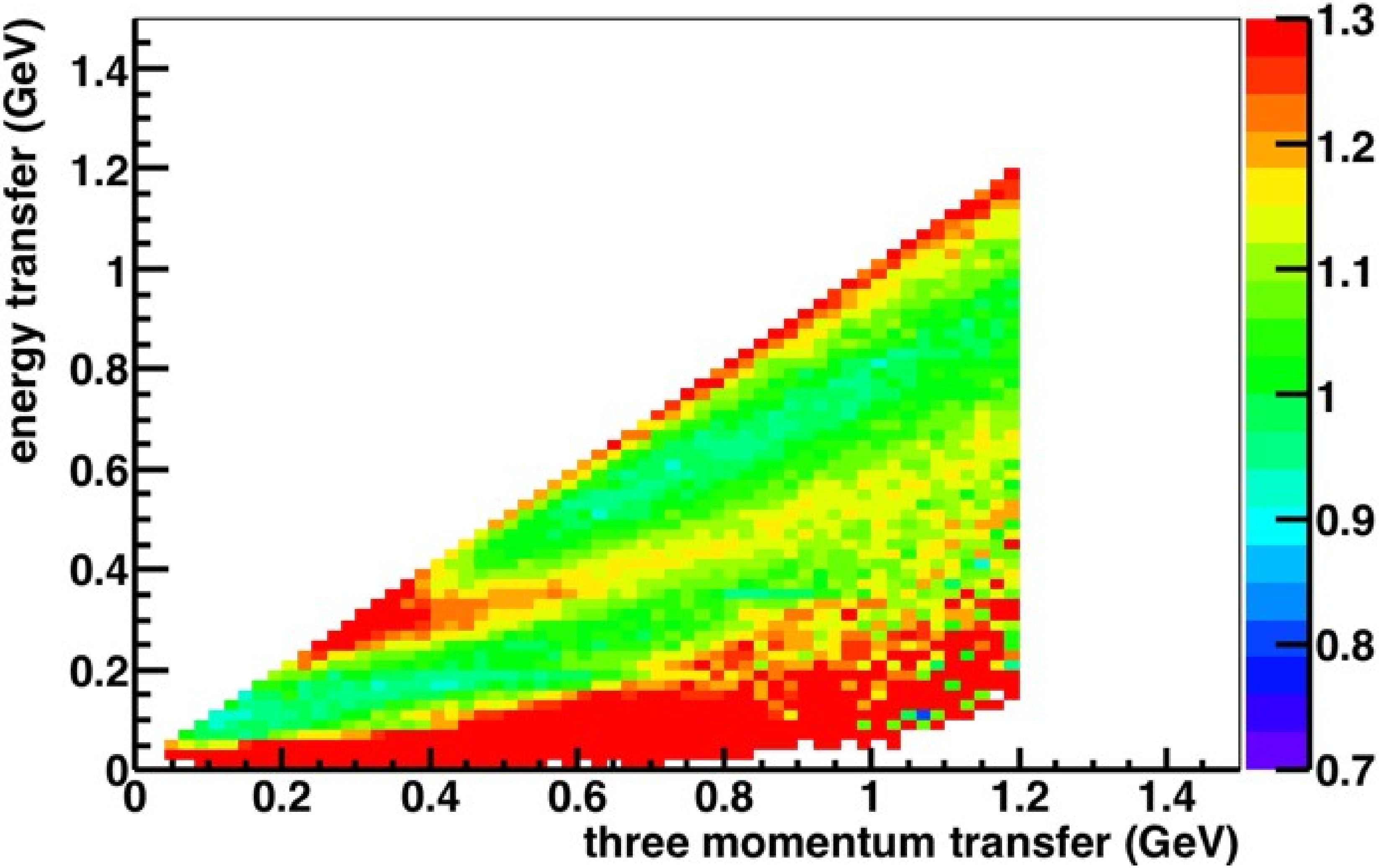
Q-value = specific to each isotope
example: Ar40 = 1 meV , Ca40 = 14 MeV

Non-isoscalar
enhances pn, nn, and pp initial states separately

Nuclear density = changes with nucleus
two-parameter Fermi function in original code

Showing the ratio Ar40/C12 $d\sigma/dq0dq3$ changes all three
so do this in stages, change one thing at a time
* means use wrong Qvalue
Ratio Ar40 / Ar40* show the effect of Qvalue only
Ratio Ar40* / Ca40 keeping same Qvalue, density.
Ratio Ca40* / C12 keeping same Qvalue, both isoscalar.

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

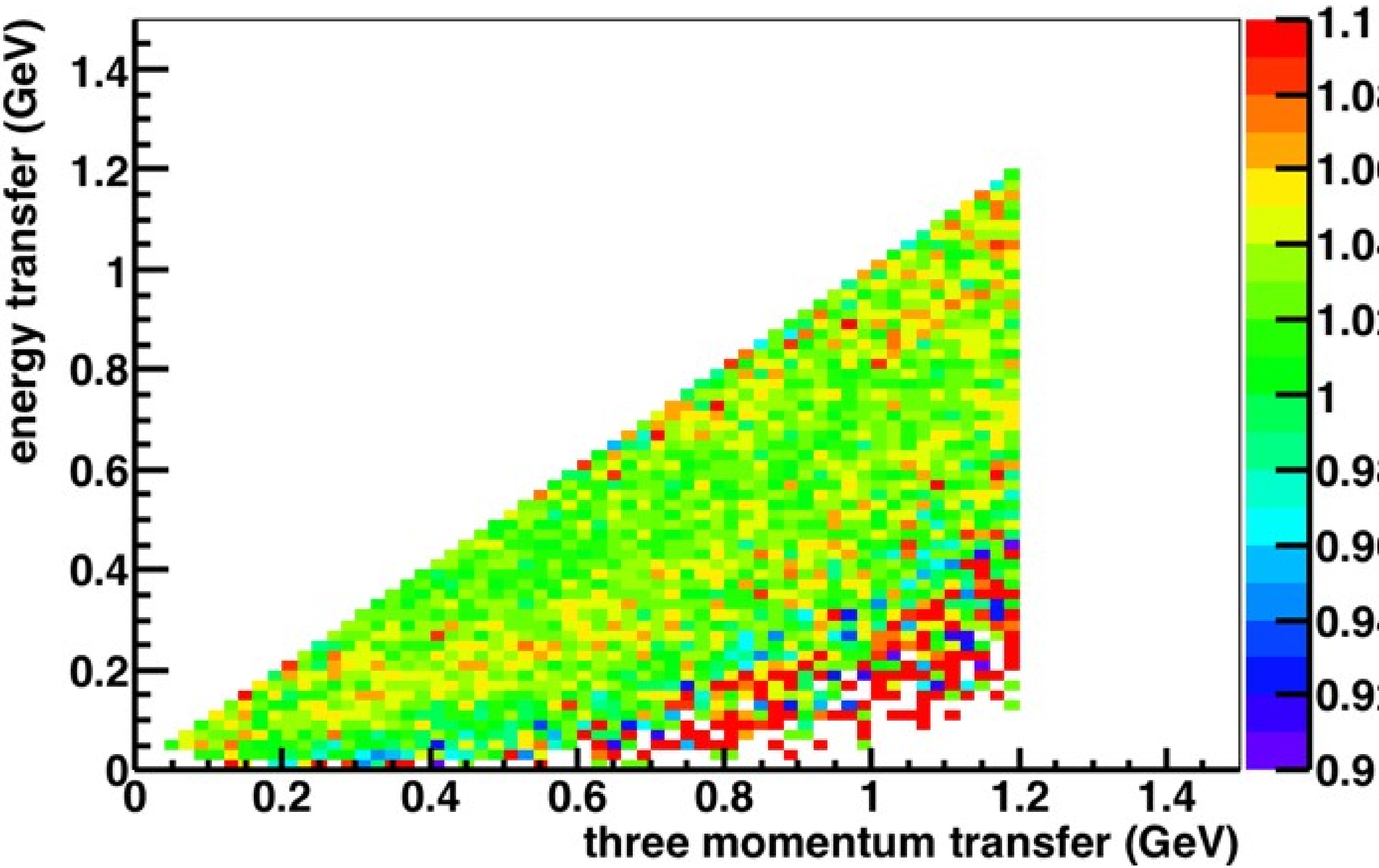


scale is ±30%

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

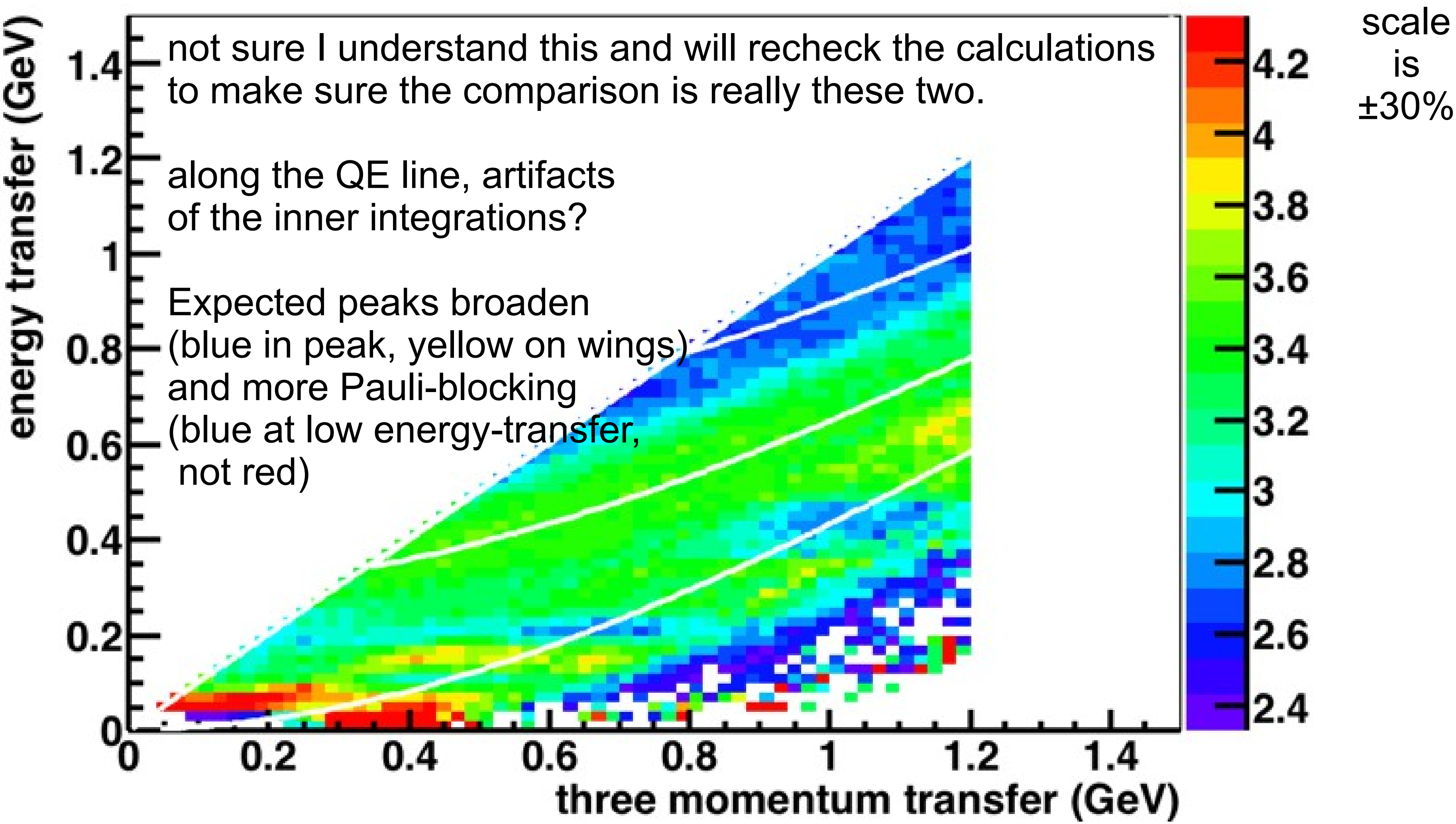
Ratio Ar40* / Ca40 (* gave Ar40 same Qvalue as Ca40)
Enhancement (yellow) follows high nn fraction.



scale is ±10%

Integrated s = 4.928e-38 cm2 (Ar40*) and 4.797e-38 cm2 (Ca40)

Ratio Ca40* / C12 (* gave Ca40 same Qvalue as C12)
Only change is the nuclear density function parameters



Integrated s = 4.797e-38 cm2 (Ca40*) and 1.464e-38 cm2 (C12)

The pn initial state fraction is scaled by
Sqrt[PN/pn]
Where P and N are for the new nucleus,
p and n for the isoscalar tensor
For most nuclei of interest, this scales with A.

The nn initial state fraction is scaled by
Sqrt[N(N-1)/n(n-1)]

For most nuclei of interest with a neutron excess
this increases the cross section in total and for nn initial states.

The pp initial state fraction is scaled similarly
Sqrt[P(P-1)/p(p-1)]

Someone using this code could “reweight” this scaling
to match some other preferred A-dependent prediction
as their central prediction or to generate an uncertainty.

The tensors are generated using parameters
to describe the nuclear density distribution.

The original code uses two-parameter Fermi functions.

(Could be augmented in the future to use
modified harmonic oscillator function for light nuclei.)

But here is the thing.
Isoscalar Nickel 56, nobody wants that.
We put in the parameters for Iron 56.

Similar for Cd112 and Pb208 (“Ba112”, “Rf208”)

Kept Si28 as Si28, even though just as likely
someone wants it for Al27.

Code adopts language calling these pseudo-nuclei