# NIUWG and other thoughts on (pion) multiplicity

Doing a couple things with this talk for NDLAr

Belated introduction to NIUWG product “nusystematics” and the base mode coming through production now

Summary of ideas on charged particle multiplicity

Some current work on single pion production

1 December 2023

# NIUWG is creating a product “nusystematics”

Your (future) CAFs (will) contain the GENIE event record
This product provides frameworky things
Uniform interface to 1-sigma, 2-sigma, some 3-sigma dials
for analyzers looking for specific ND or oscillation effects
for fitters to roll through all possible effects
lightweight distribution, no LArSoft dependence
is fast to implement and deploy development of new dials

It provides physicsy things
All the knobs available in GENIE
rationalization of the central value and priors
knobs not in GENIE used by T2K and MINERvA
new and detailed knobs created by NIUWG and partners

# NIUWG already has a list, summarized here

Delta form factors and energy dependence

Removal energy and nuclear effects e.g. Bodek & Cai

SIS delta vs higher resonance vs non-res background
including the Kabirnezhad effort and precursors
plus the AGKY and Tena Vidal efforts

Extend multiplicity knobs for KNO and Pythia

Examine pion angle distribution effects

Final state reinteractions including strength and angle

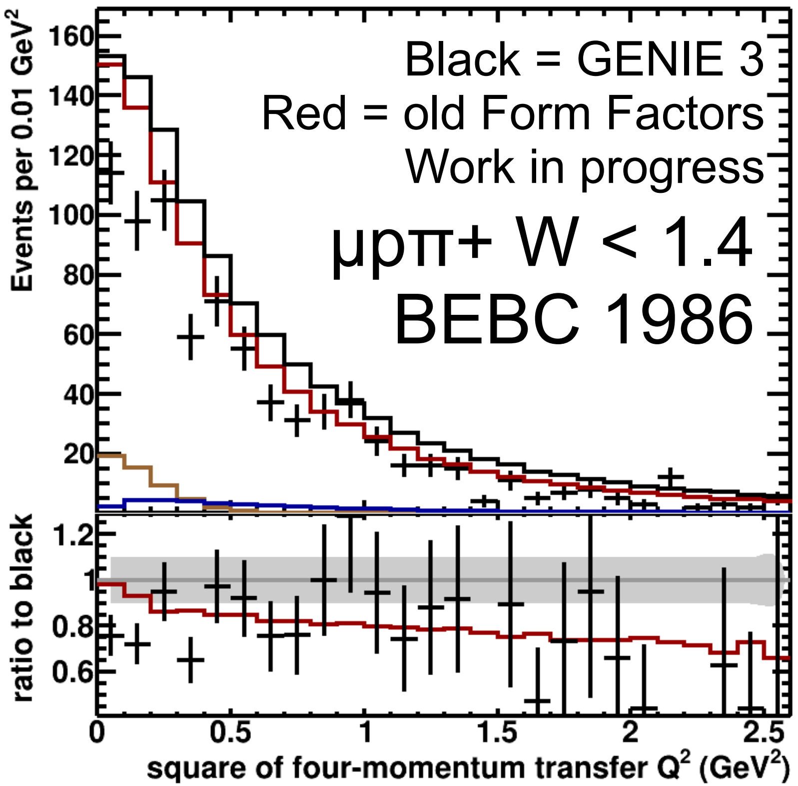
# Physics-wise GENIE factorizes π production into steps

What interaction type happens (RES, DIS, Coherent)
in kinematic quantities like Q2 and W2
or energy & momentum transfer or xbj and y
A lot of theoretical input and (e,e') input at this step

Given a hadron state at those kinematics
what nucleon and meson(s) come out of the Feynman diagram
A lot of empirical input at this step. Many uncertainties.

On their way out of the nucleus
does some FSI rescattering occur?
Largely based on πA or NA scattering data

# Delta form factors (0 or 1 pi) and energy dependence



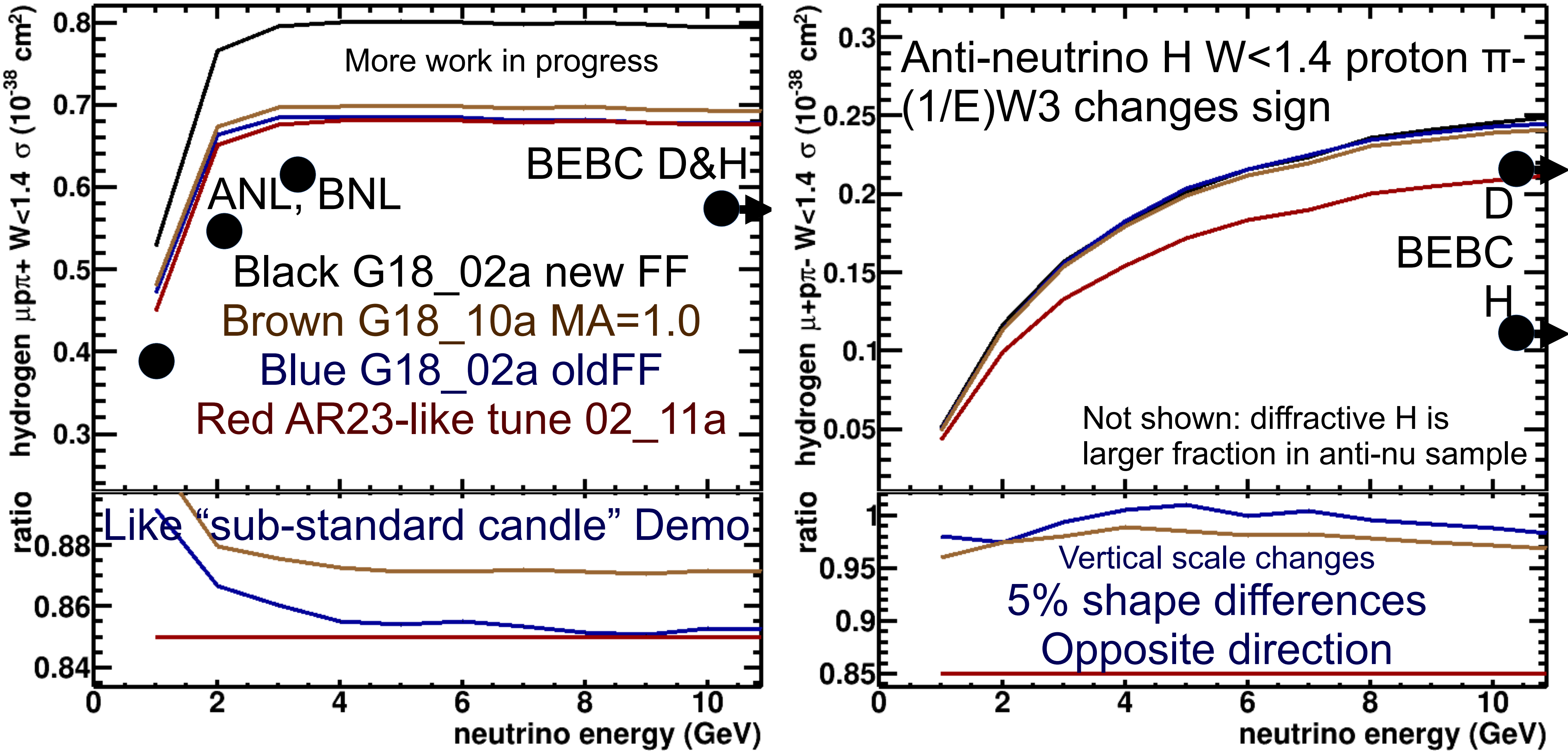

Without a tune, GENIE 3 is much higher than data

Data on hydrogen ~20 GeV
Model is Res W2 structure function
(W3 and W5 are negligible)

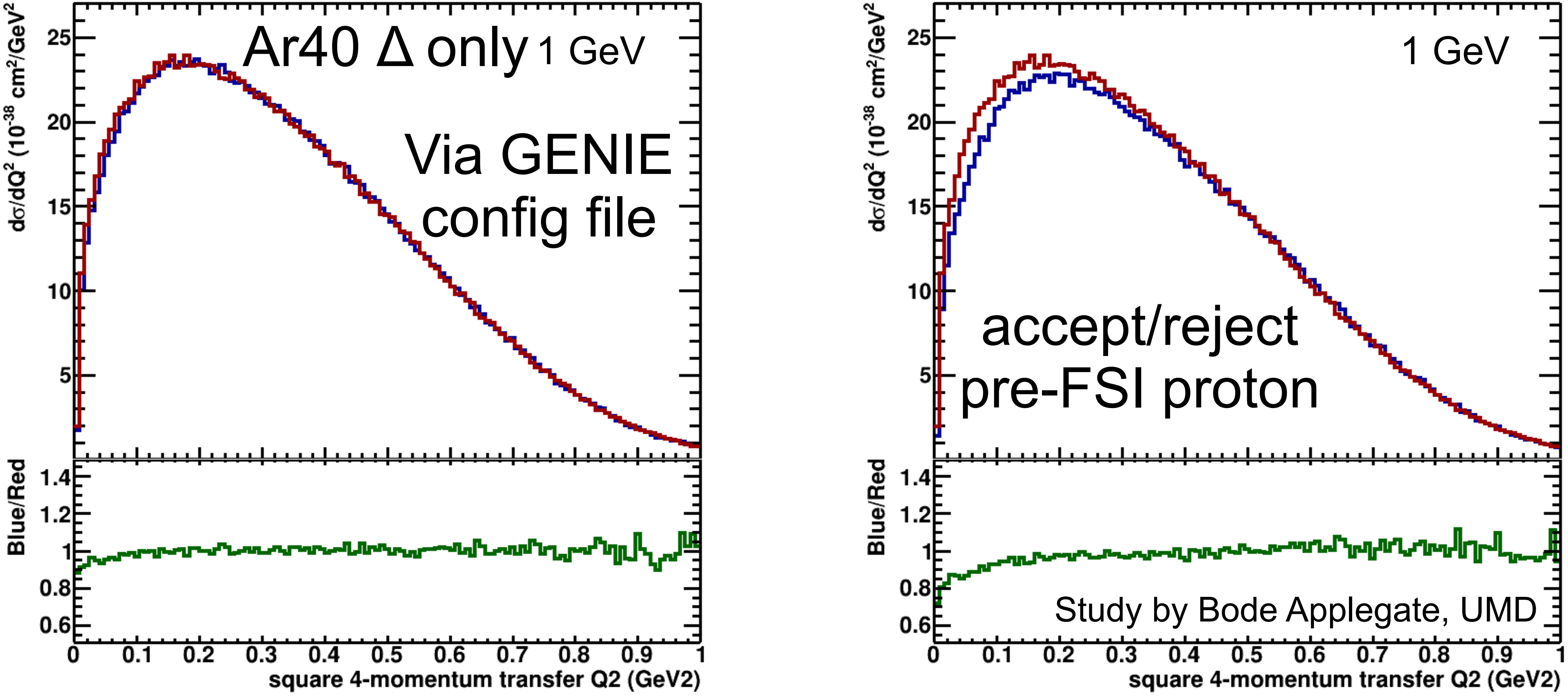
But also (brown) "diffractive" PCAC sorta from Rein 1986 & these data
And (blue) non-res from DIS model

Campaign going beyond MA by the Duluth group for a few years
Directly affects single pion production relative to QE, 2p2h, DIS

# Nu and Anti-nu similar 5% shape, opposite direction

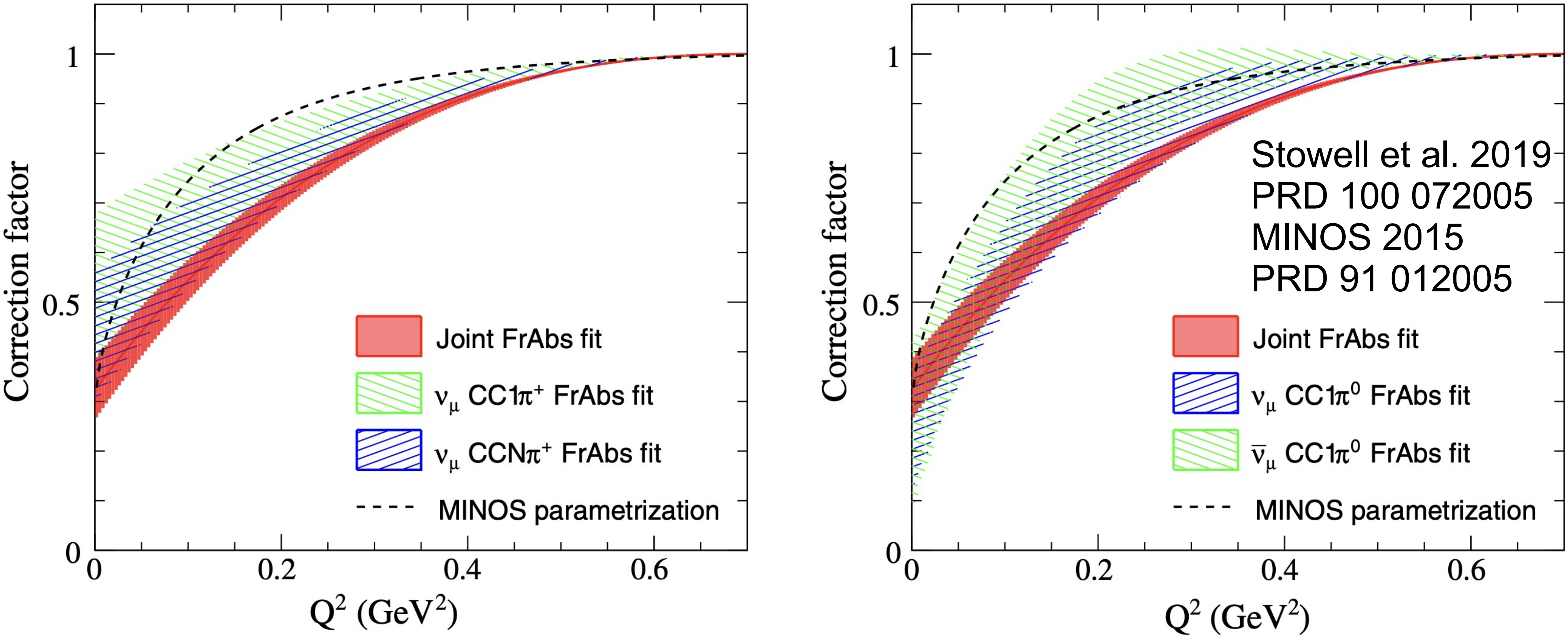


# Pauli Blocking, low Q2, other medium effects?



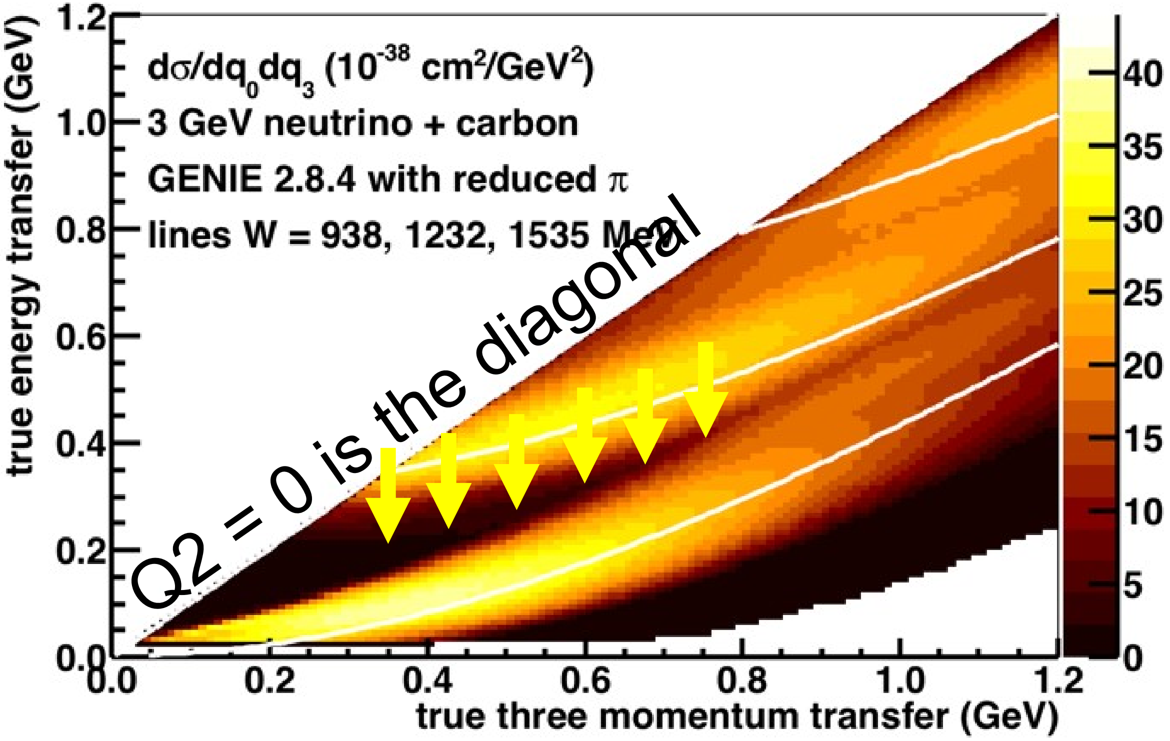

Many medium effects distort the low Q2 part of the spectrum.

# Low Q2 suppression fit to MINOS (Fe) , MINERvA (C)




Much stronger than Pauli Blocking. Affects pion KE spectrum
This is already in, but not as strong with new form factors.

# Removal energy and kinematic shifts




Size of arrows is exaggerated by x10

Combines work from
Ascencio et al. 2022
PRD 106 032001

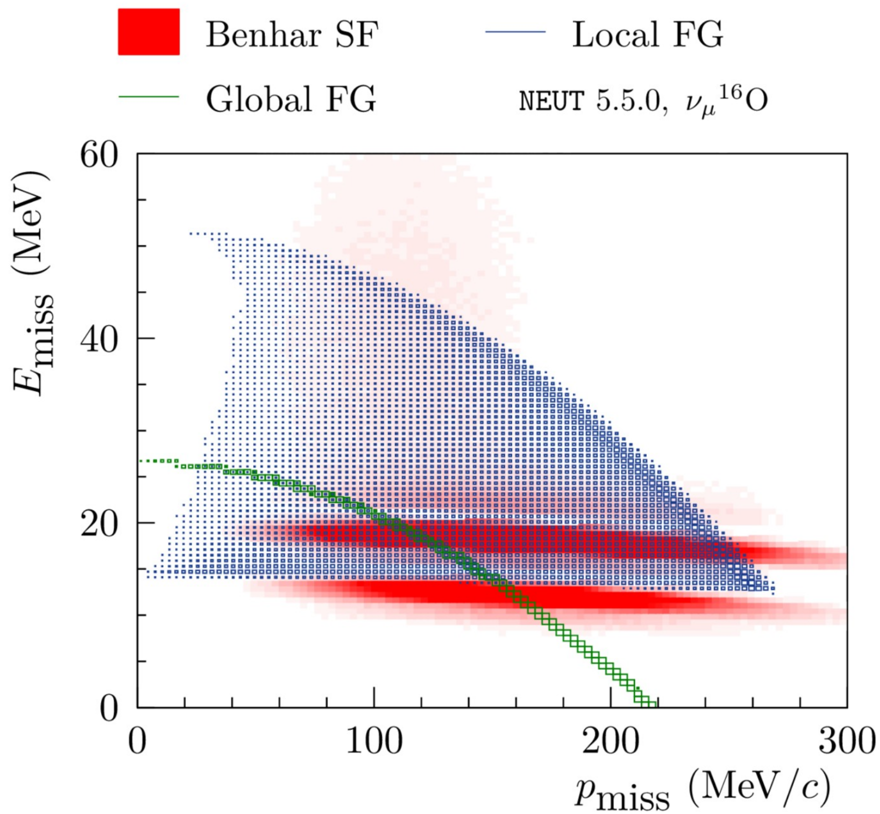
And from
Bodek and Cai 2020
Eur.Phys.J 80 p655

Gives low Q2 effect
Without a suppression
Affects muon kinematics
Pion and nucleon energy

QE implementation first, maybe Tom Holvey

# Nuclear initial state freedoms

Eur.Phys.J.ST 230 (2021) 24, 4469-4481




This is a T2K graphic

Our version (similar to blue) might be how we implement the Bodek and Cai inspired resonance shift and other ad hoc

At a minimum, ~10 MeV effects make new Q2 and pion KE distortions for resonances that we've never played with before

2D distribution = lots of freedoms.

# Delta decay parameters

No one in NIUWG assigned yet

There is an existing knob for the non-isotropic angle distribution
Parameter but no knob for fraction of $\Delta^{\circ} \rightarrow n\,\gamma$ and $\Delta^{+} \rightarrow p\,\gamma$
Likely MicroBooNE coded an uncertainty for this ?
The decay in medium could be different (probably longer-lived)
affecting the invariant mass width and maybe location

The FSI only acts on the Delta decay products
And the strength of FSI could be different for a resonance
Imagine some kind of transparency parameter
That makes these FSI not the same as the default.

# Higher Resonance Decay Parameters

Minoo has some ongoing work on theory side
And a student Callum (at RHUL with Asher) for NIUWG
Resonance strength and width are the most obvious things.

Higher resonances have decay chains specified by PDG
Many of them lead to two outgoing pions before FSI

Presumably those decay chains represent decay in free space
but a study could modify them in ad hoc ways
and separately for different resonances
and see how easy it is to obtain observable effects.

# FSI parameters

Richie Diurba and Yinrui Liu
Going beyond the out-of-box GENIE hA uncertainties

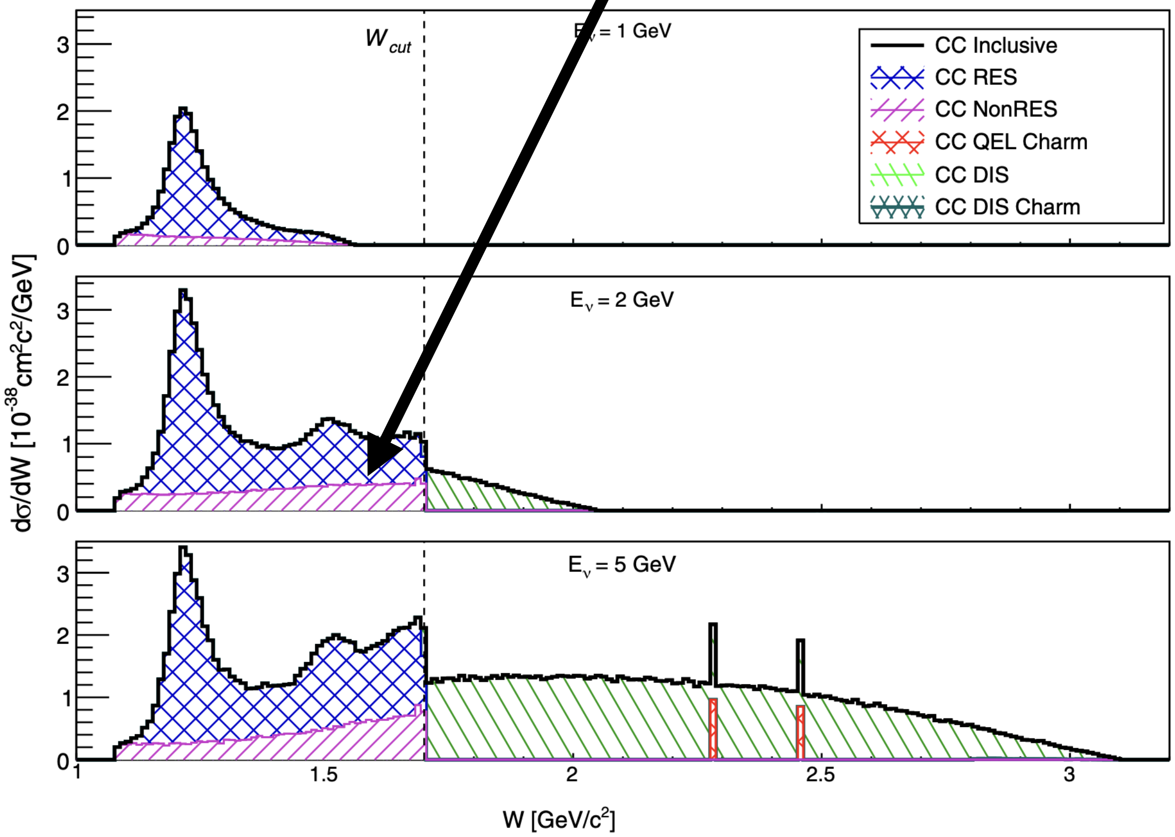
Especially the pion absorption component
in hA does not lead to single nucleon knockout without pion
Requires a quasi-deuteron -- absorption would require in free space

Likewise, no nucleon knockout process (?) on quasi-deuterons
So there is pi N and pi N N but not pi N N N

And of course, the strength of the processes already
depends on KE and A, but the error band is simplistic

# The non-resonance component in SIS region

Lots of freedoms here




Folks who calculate the non-res component from diagrams presumably get different kinematics and rates vs. Q2 at a given W

Opportunity for a Theory + experiment Collaboration?

Julia Tena Vidal + GENIE et al. 2021 PRD 104 072009

# Tuning to multiplicity distributions a la KNO & AGKY

The DIS model uses multiplicity data, a paper by KNO
And a tune one-pion and two-pion outcomes of the DIS model

avg
π±

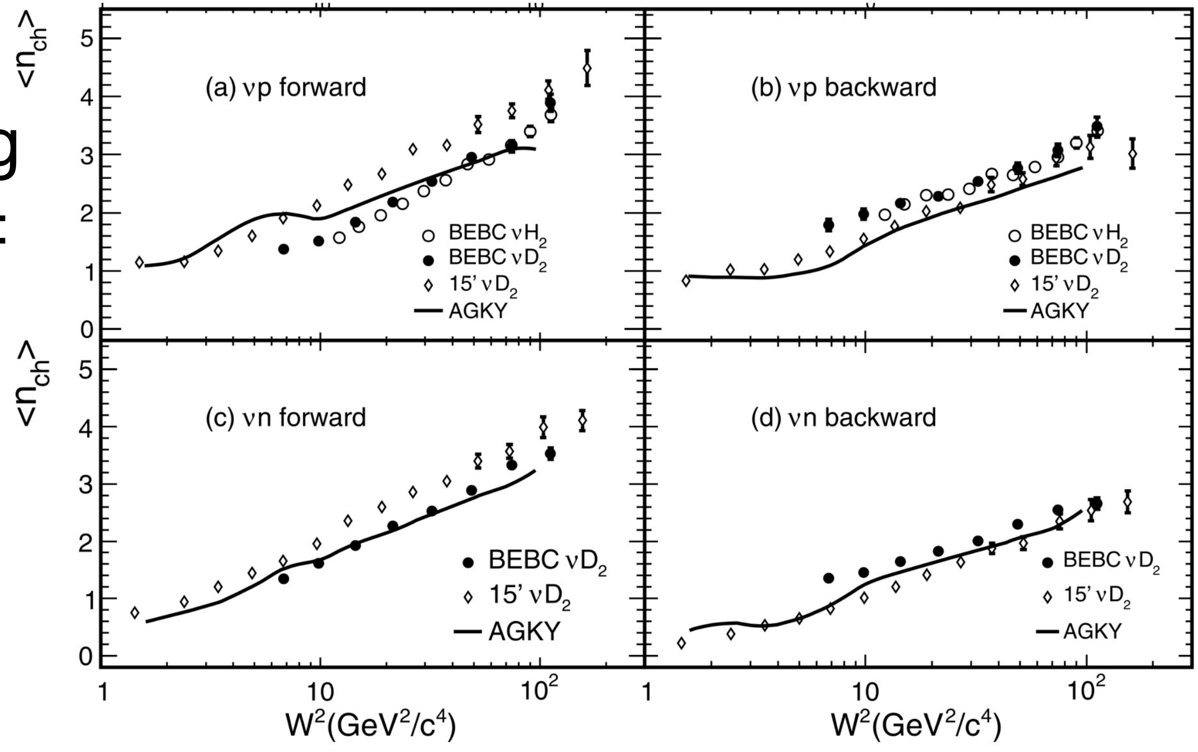



**Fig. 7** Average charged-hadron multiplicity in the forward and backward hemispheres as functions of $W^2$: (**a**) $\nu p$, forward, (**b**) $\nu p$, backward, (**c**) $\nu n$, forward, (**d**) $\nu n$, backward. Data points are taken from [7, 25, 26]

AGKY 2009
Eur.J.Phys.C
v. 63 p.1-10

Charged hadrons
vs. W not Q2
(but also dispersion)

Also Neon data
and forthcoming
MINERvA data

# Tuning to multiplicity distributions a la J. Tena Vidal

TABLE VII. Best-fit parameter values and parameter ranges obtained by requiring that $\Delta\chi^2_{\text{profiled}} < \Delta\chi^2_{\text{critical}} = 1$. Results are shown for all alternative CMCs considered in this analysis. The best-fit values obtained for the G18_02a(/b) CMC can be used for the G18_10a(/b) as the same bare-nucleon underlying models are used.

| Parameter | G18_01a(/b) | G18_02a(/b) |
| --- | --- | --- |
| $W_{\text{cut}}$ | 1.94 | 1.81 |
| $M_A^{\text{QE}}$ | $1.00 \pm 0.01$ | $1.00 \pm 0.013$ |
| $M_A^{\text{RES}}$ | $1.09 \pm 0.02$ | $1.09 \pm 0.014$ |
| $R_{\nu p}^{\text{CC}1\pi}$ | $0.06 \pm 0.03$ | 0.008 |
| $R_{\nu p}^{\text{CC}2\pi}$ | $1.1 \pm 0.2$ | $0.94 \pm 0.075$ |
| $R_{\nu n}^{\text{CC}1\pi}$ | $0.14 \pm 0.03$ | $0.03 \pm 0.010$ |
| $R_{\nu n}^{\text{CC}2\pi}$ | $2.8 \pm 0.4$ | $2.3 \pm 0.12$ |
| $S_{\text{RES}}$ | $0.89 \pm 0.04$ | $0.84 \pm 0.028$ |
| $S_{\text{DIS}}$ | $1.03 \pm 0.02$ | $1.06 \pm 0.01$ |
| $\chi^2/157$ DoF | 1.84 | 1.64 |

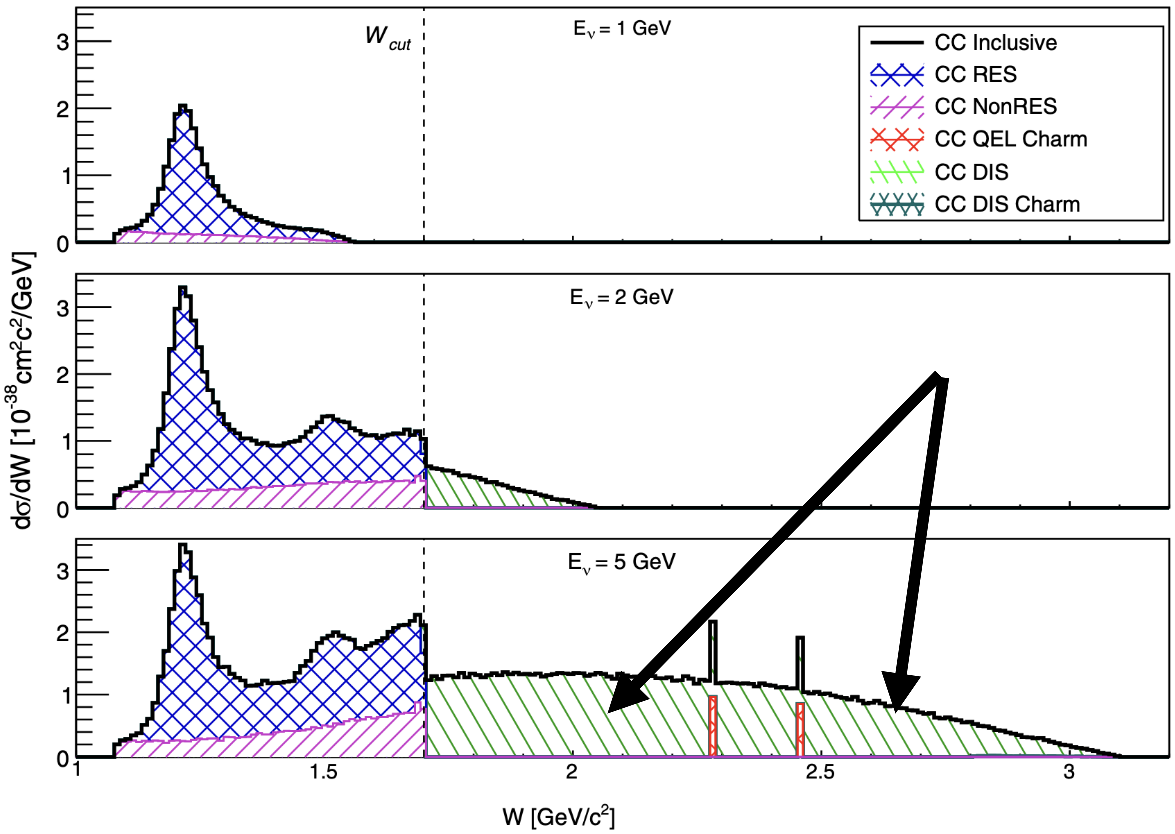
A study with GENIE3 02a, 10a
Fit to lots of bubble chamber data
Rik's take home message
(not exactly same as the author's)

This is our AR23 default
1π pulled very low (def val 0.1, 0.3)
2π pulled high (def val 1.0)
But MAQE and MARES have
unusually strong prior

(almost) all are existing GENIE knobs, can dial to original settings
Directly changes multiplicity. No one assigned.

# Higher DIS final states from Pythia

Lots of freedoms here



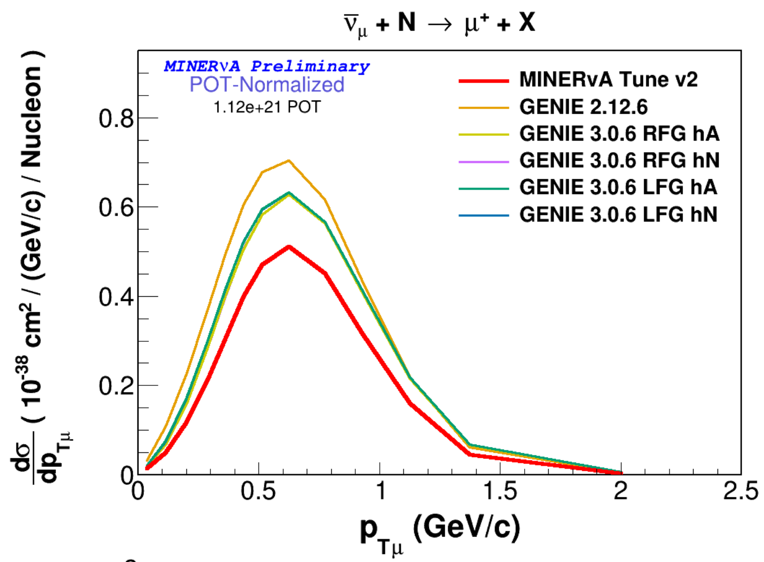

Julia Tena Vidal + GENIE et al. 2021 PRD 104 072009

… in a regime where Pythia's string fragmentation might not be accurate AGKY and JTV fighting it

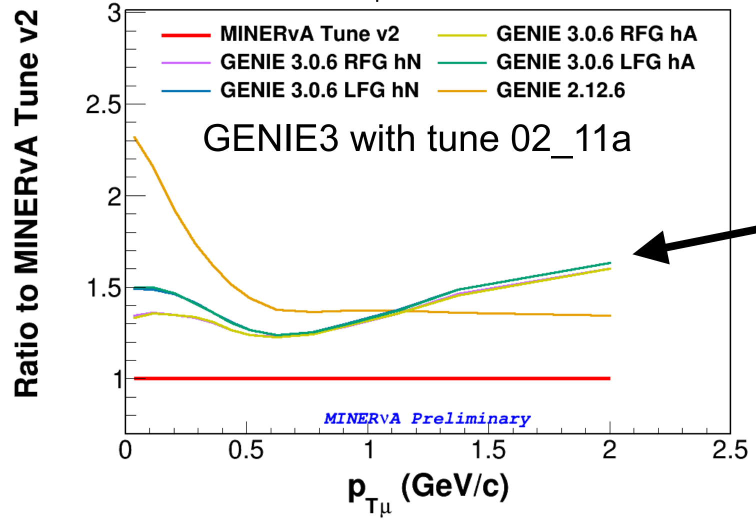
Might be a good idea to make cross-section preserving but ad hoc weights to multiplicity fates With dependences beyond The existing 1pi 2pi weights

No one assigned yet

# Inclusive SIS model predictions




This example, Anti-neutrino mode
Can plot more than invariant mass W
SIS here means 1.5 < W < 2.0
MINERvA appropriate selection
(but MINERvA data not included yet)




Breakdown not shown
Resonances at low pT
DIS at high pT

Not sure what difference GENIE3 vs 2 gives such a strong effect.
Immediate MINERvA overlap project?

# DIS Structure Functions

Work within DUNE by Anne Norrick
with input from the AMU group (Huma Haider)

DIS structure functions vs W and Q2 (or xbj and y)
Adjustments to these play a major role in how
the models at high pT on previous slide diverge

Numerous 1D knobs already available via GENIE
but we have additional freedoms in mind to develop

This is an inclusive rate, with Pythia hadronization attached
your efforts might be focused more on what Pythia does
but the rate itself could dial around the DIS vs Resonance

# Can do some random stuff

Motivated by continued inability to describe data
Make things that were not tunable into knobs

No Q2 dependence to multiplicity tested before,
only W dependence

Drop out a resonance and its decay products completely?
(NuWro only simulates the Delta resonance)

We want to hire someone to break stuff

# Conceptual question

What is the easiest way to go beyond simple multiplicity
and describe measurements of the angle distribution
For multi pion events ?

Several pion angle distribution knobs mentioned
historically few have been tunable

Maybe separate multiplicity as an observable

And angle for single pion events
(and TKI of course)

# Takeaway messages

Pion (and also proton) multiplicity
Touches a wide variety of physics

Some prominent knobs in GENIE
are already being extended by the NIUWG
largely using lessons from QE + 2p2h

Invitation that someone reconstructing samples
plan a role implementing a new knob
and being early testing others
pseudo-experts available to guide the effort