Systematic uncertainties on SIS and DIS

Huma Haider, Anne Norrick, Rik Gran, Tristan Suojanen April 2025
Tristan made most of the plots, but with code start from Bode Applegate

Systematic uncertainties on SIS and DIS

Huma Haider, Anne Norrick, Rik Gran, Tristan Suojanen April 2025
Tristan made most of the plots, but with code start from Bode Applegate

This is a milestone status update but not final version
its not in nusystematics yet, some flaws will be apparent

Most of this is extracted from the AMU calculations
and provided by Huma Haider

It is done as a series of ratios feature-on / feature-off
so technically systematic can be applied to any base model

I'll talk about the default GENIE Bodek Yang model too.

Concept #1, the DIS model is structure functions

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\ dy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left(\left[y^2 x + \frac{m_l^2 y}{2E_\nu M}\right] F_{1N}(x,Q^2) + \left[(1-\frac{m_l^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})y\right] F_{2N}(x,Q^2) \pm \left[xy(1-\frac{y}{2}) - \frac{m_l^2 y}{4E_\nu M}\right] F_{3N}(x,Q^2)\right)$$

Isoscalar F1 F2 F3 do not depend on v/vbar or Enu, only (x, Q2)
AMU model delivers those for each variation
Weight code implements the rest and takes ratios

n.b. another popular form is expansion in v/Enu for low-nu method
n.b. ml2 / Enu M terms (also F4, F5) only relevant for tau neutrinos

Concept #2, the structure functions have ingredients

A leading order ansatz
parton distribution functions from someone
next to leading order corrections (NLO)
target (a nucleon) mass corrections (TMC)
higher twist effects (HT)
Callan Gross (spin ½ quarks) violating FL effects in F1
isoscalar = (p+n)/2 or p and n separately
nuclear corrections for C12 or Ar40 (Ca40)
uncertain axial component
include F4 and F5 ?

Idea: get ratio (ingredient on)/(ingredient off) use as a systematic

Baseline

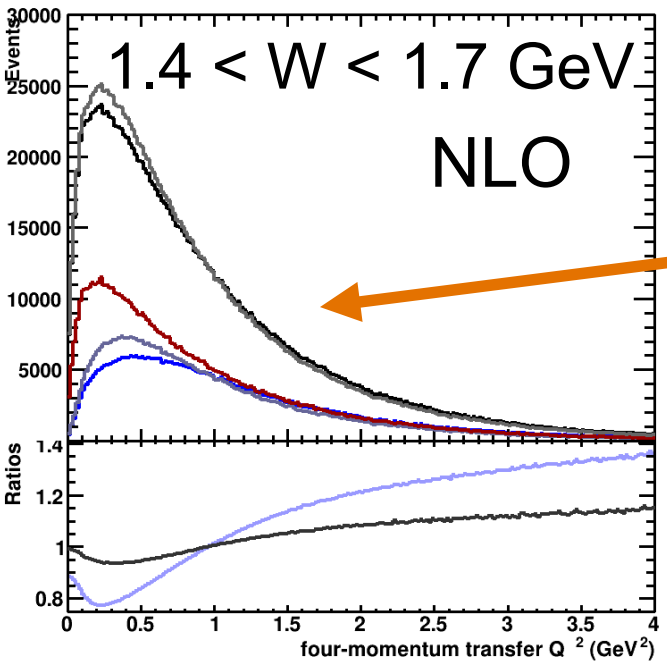
DUNE on-axis flux nu and anti-nu a few months of NDLAr data

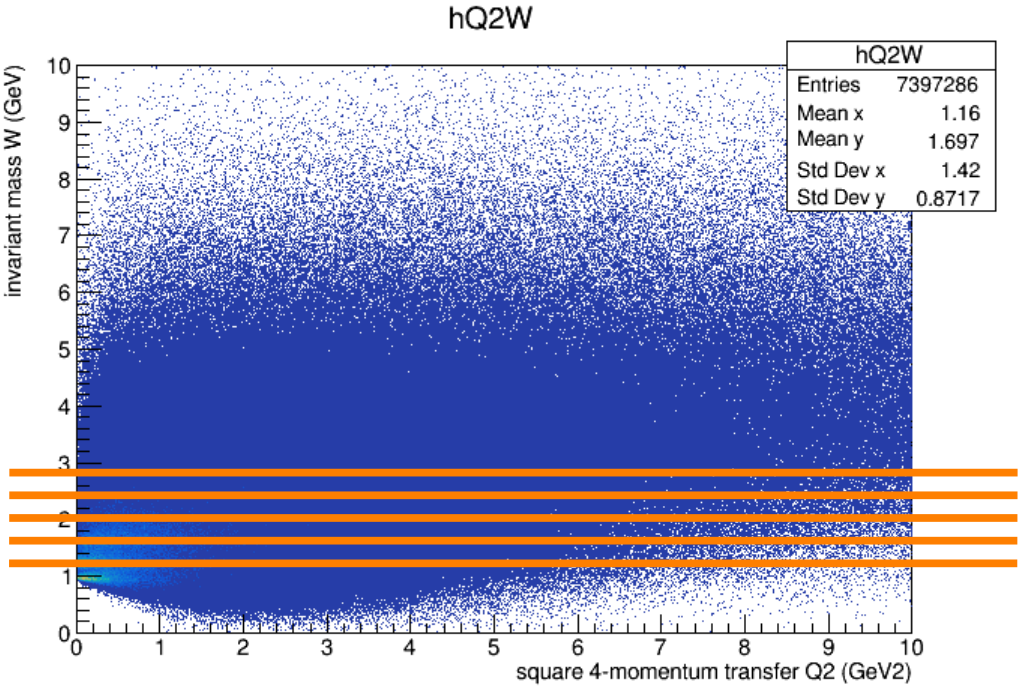
Get isoscalar ratios (p+n)/2 and apply to all DIS events
PDFs are from CT14 arXiv:1506.07443 PRD 93 (2016) 033006
NLO + TMC + HT are the baseline best model for free nucleon

F1 F2 F3 are tabulated in two dimensions
xbj from 0.05 to 0.95 in steps of 0.05
Q2 steps are 1, 2, 5, 10, 20 GeV2
standard 2D bilinear interpolation
For values outside the range, hold the last reasonable value
xbj < 0.04 or > 0.96 and Q2 < 0.6 and > 25 GeV

AMU “NLO feature” weights applied to GENIE3 AR23

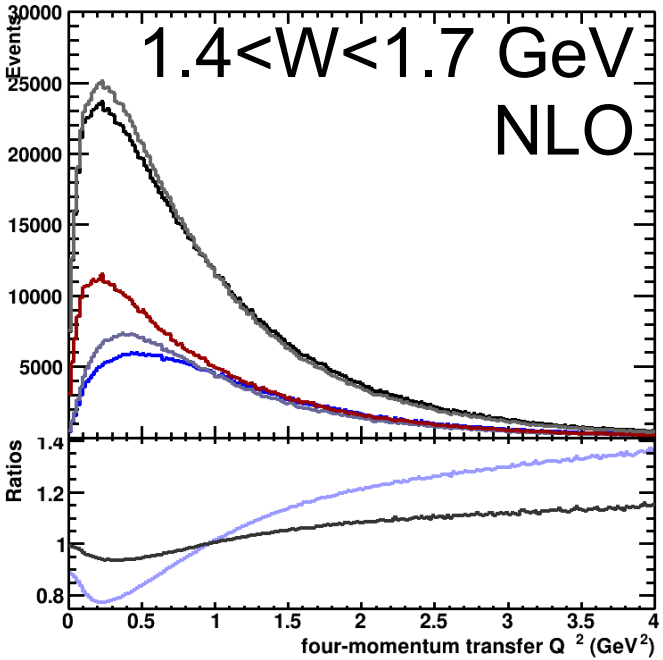
Q2+W histogram DUNE AR23
First select res > Δ region,
but half from GENIE DIS model



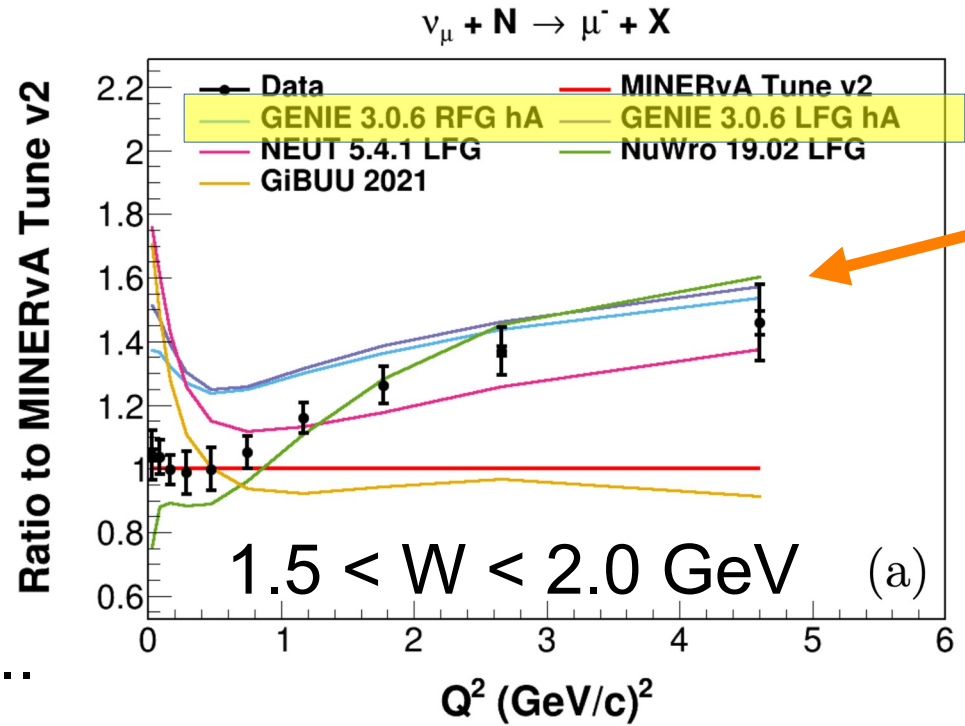


Upper plot is Default and new
Red = W>Δ resonances
Blue in ratio is the weighted DIS
Black in ratio is new total after weights

GENIE3 AR23 base (left) compared to MINERvA data



This particular panel is kinematic match to Lozano et al. [MINERvA] arXiv:2503.20043
Obviously DUNE ND can do this too

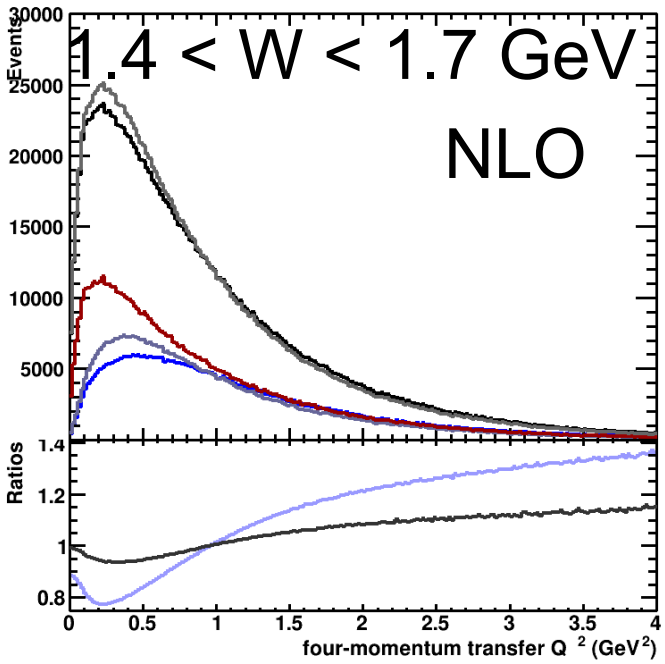


AR23 is

like the top two lines BY DIS plus the tune

Seems like improvement but thats upside-down this is NLO=on, next slide ...

The difference shown is total, but uncertainty is smaller



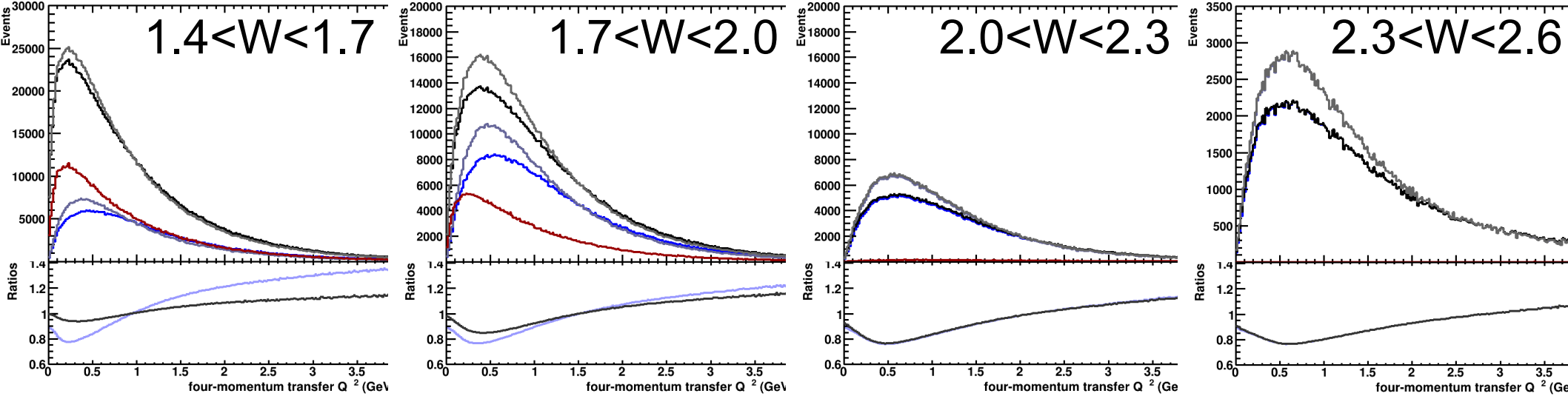
This is the NLO / LO weight from AMU
! Obvious NLO is better physics
The uncertainty is a fraction of the weight
Maybe symmetric 20% or something.

Repeat what I am doing here
Taking NLO / LO free nucleon as systematic
(not taking 20% of it yet, will do later)
applying it to DUNE GENIE AR23
which uses Bodek Yang 1999-2000

Afaik: GENIE v2, v3
DIS same except tune

The result is NOT the AMU model
Its a warp of the GENIE BY model

NLO feature in three regions of W (applied to GENIE)



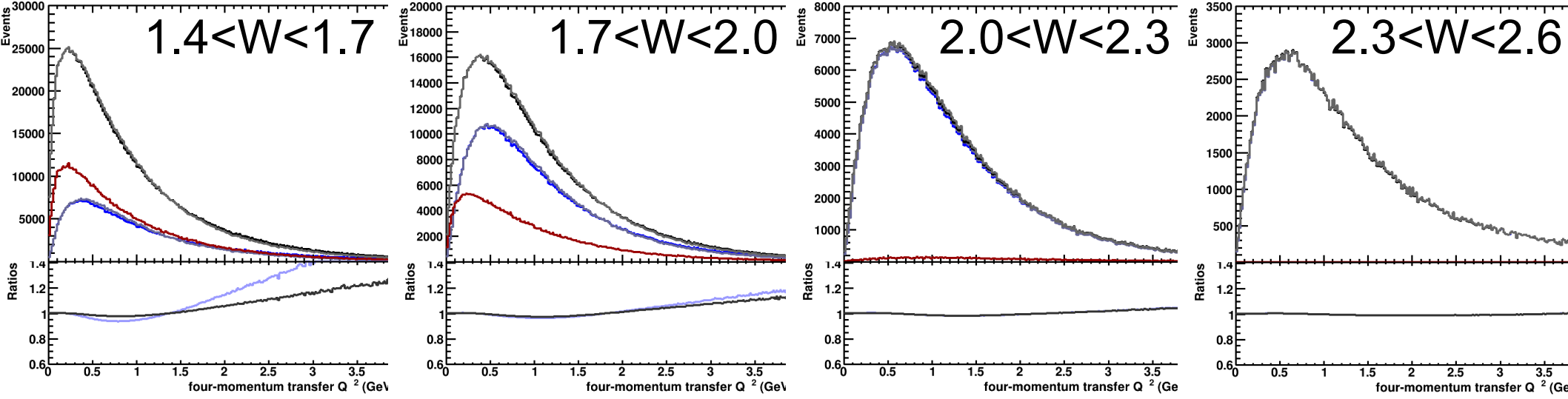
Vertical scale is changing order of magnitude left to right, ratio is not

In AR23 (with tune) resonances disappear middle of second panel

Again, this full effect is probably larger than a reasonable error band

Because NLO is better, we want 20% or 10% or something.

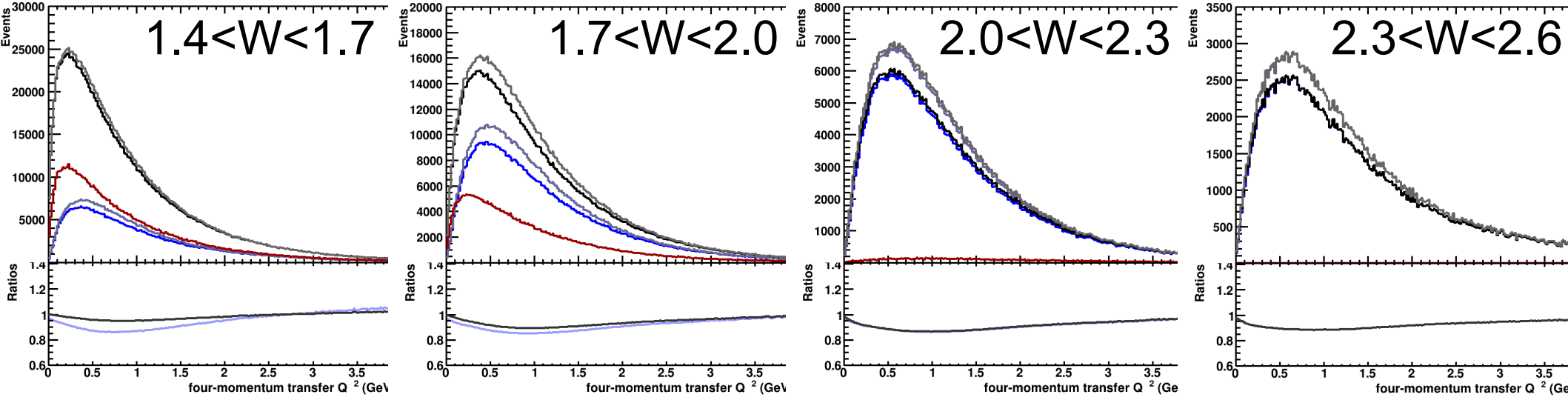
Target (nucleon) mass corrections (TMC) feature



Vertical scale is changing order of magnitude left to right, ratio is not

The target mass corrections are stronger in left panel
Which is higher x for given Q2 (e.g. because its closer to QE)
TMC is also pretty solid physics, so error band also smaller?

Higher twist (HT) feature



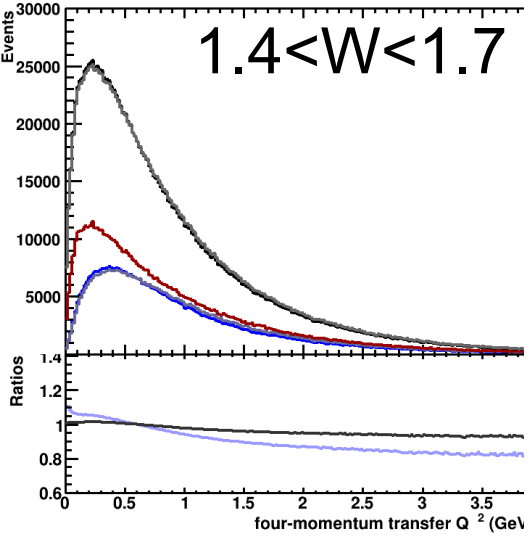
Vertical scale is changing order of magnitude left to right, ratio is not

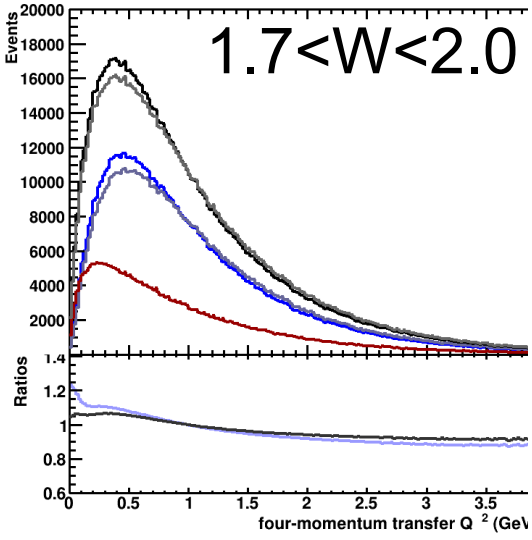
Some people state higher twists and NNLO are similar

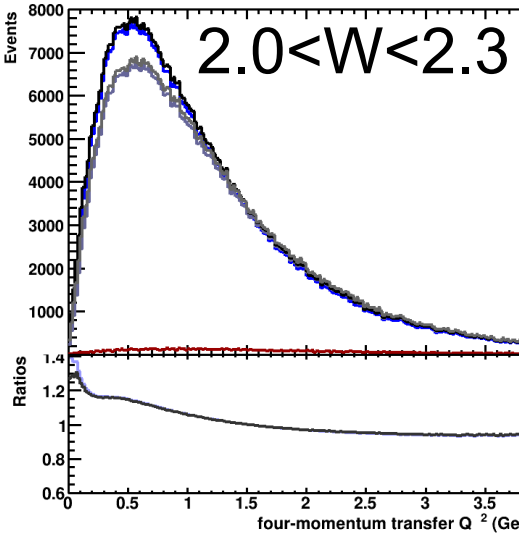
Up to 10% effect in the heart of the distribution Q2 ~ 1 GeV2

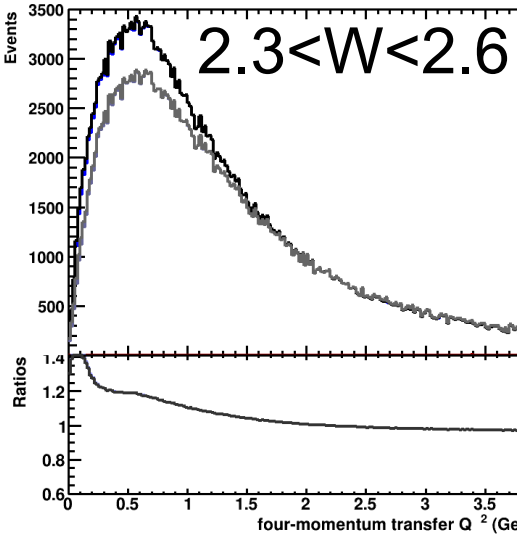
The full effect might be a reasonable error band here

Defeat FL feature





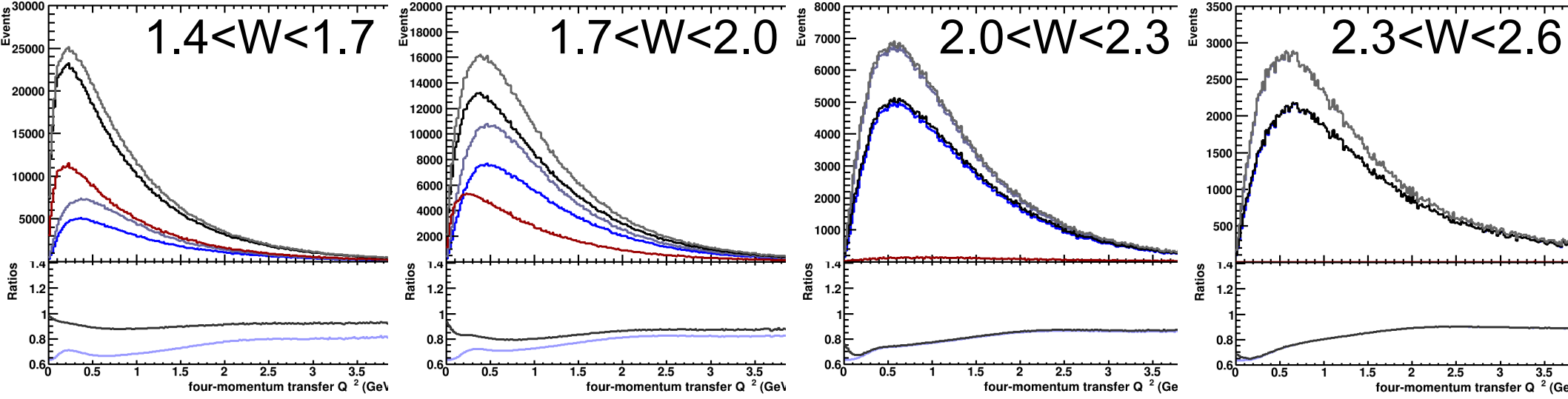




Vertical scale is changing order of magnitude left to right, ratio is not

This one turns OFF a feature: replace the FL piece of F1
With simple Callan Gross F1 = F2/2x
A subtle thing about how to apply it that needs to be checked

C12 nuclear effects feature in four regions of W



Vertical scale is changing order of magnitude left to right, ratio is not

This is applied to the best free nucleon model with NLO, TMC, HT

It also appears to be relatively constant at 20%

more on this later. Isoscalar Ca40 is on the todo list.

On the GENIE3 Bodek Yang Model

Reminder of the scheme
Take a model and tabulate its isoscalar F1 F2 F3 variations
Extract a ratio feature on / feature off = feature weight

Apply it to a DUNE sample from GENIE's Bodek Yang model
used for our (Tristan's) "production" Monte Carlo
call it an uncertainty band or a warp

Why stop with just the AMU variations,
what other F1 F2 F3 variations can we get ?

Hmm. How about GENIE's Bodek Yang model?

On the GENIE3 Bodek Yang Model

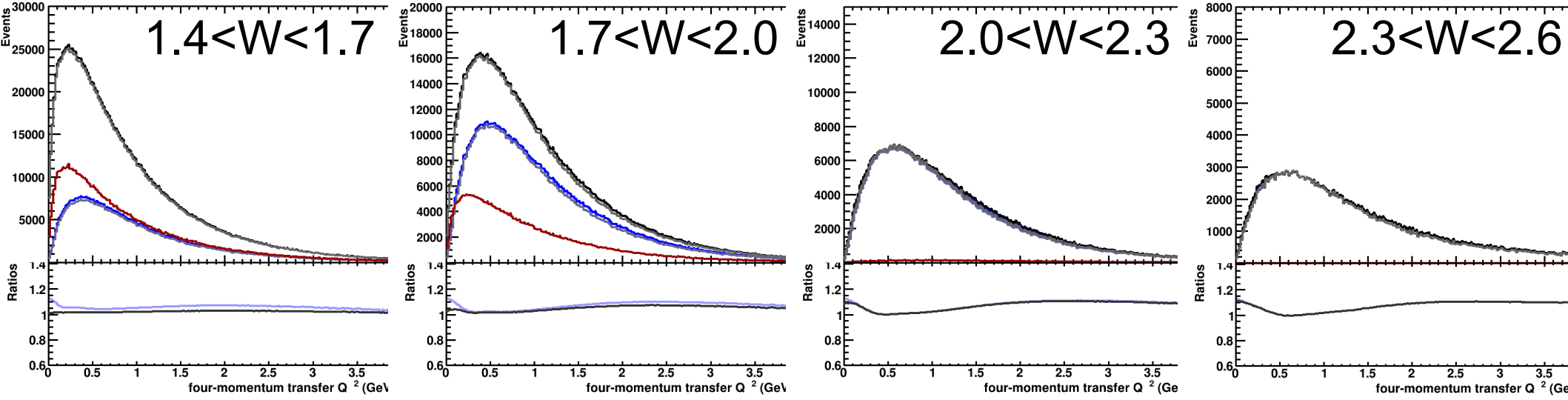
Its the same as GENIE2 based on BY 1999 and 2000 papers
PRL 82 (1999) 2467 and Eur.Phys.J. C13 (2000) 241
Not updated to arXiv:2108.09240 (2021)

It empirically modifies the scaling variable (x to ξ and beyond)
to account for NLO, TMC, and HT effects in F1 F2 F3
And a Callan-Gross violating r (or FL) effect relating F1 to F2
And a f(x) nuclear effect (data-driven iron?) for F1 F2 F3 all A

A bugfix in the code since 2016 GENIE v2 is still turned off

Get F1 F2 F3 by intervention in GENIE itself

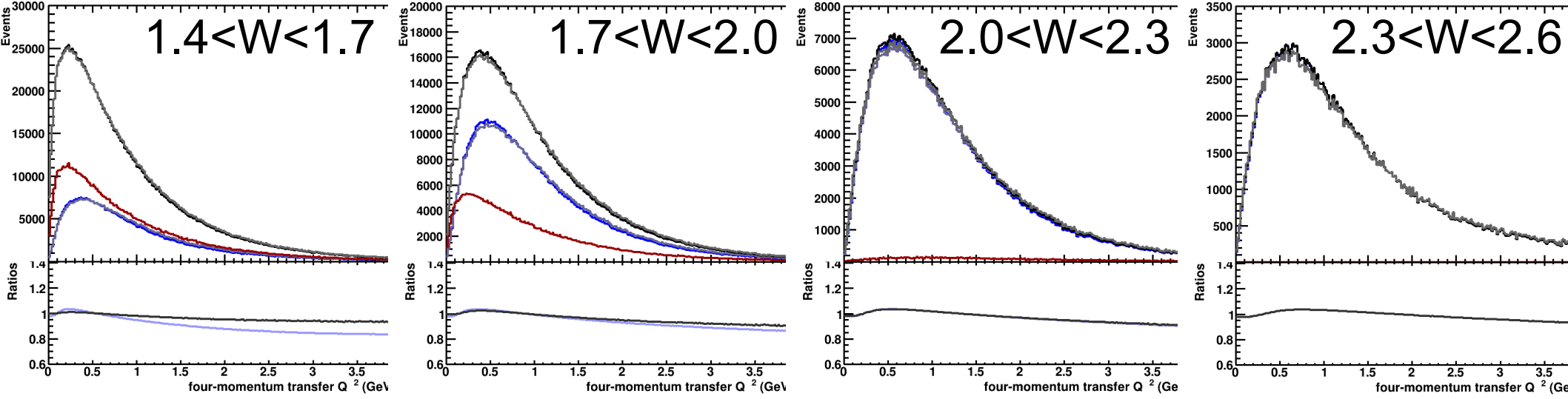
AMU / GENIE Bodek Yang both free nucleon



Vertical scale is changing order of magnitude left to right, ratio is not

Both models advertise being consistent with NLO + TMC + HT
so its probably not a shock that they are in close agreement
But I think they take very different paths to get there
This applied to GENIE samples does give AMU model

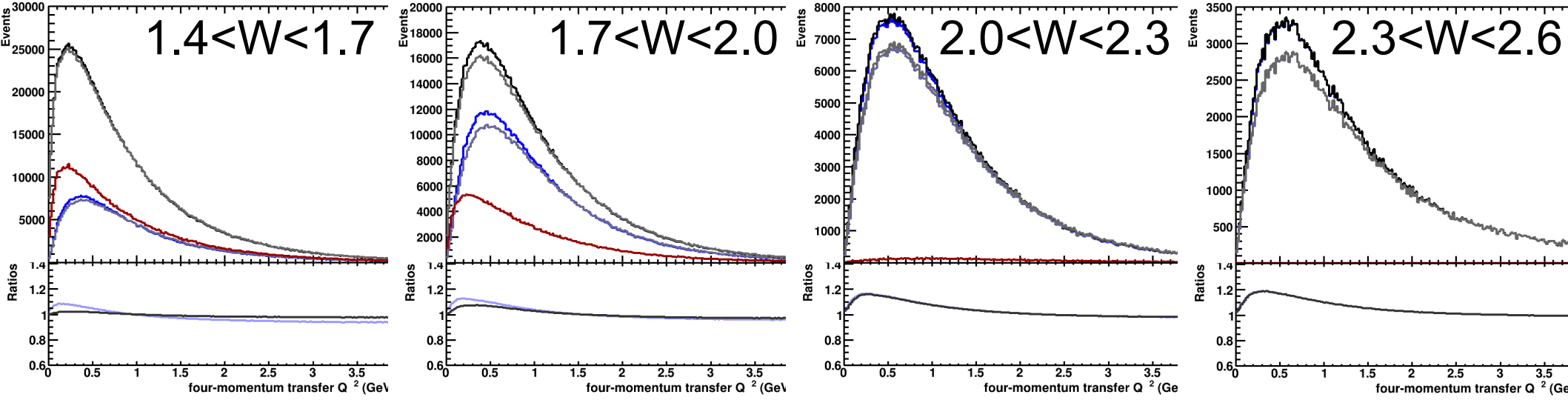
GENIE nuclear effect feature vs GENIE free nucleon



Vertical scale is changing order of magnitude left to right, ratio is not

This has much smaller magnitude than the AMU effect.
its literally a constant function of x only, not Q2
And scales all the structure functions so also the total d2σ/dxdy

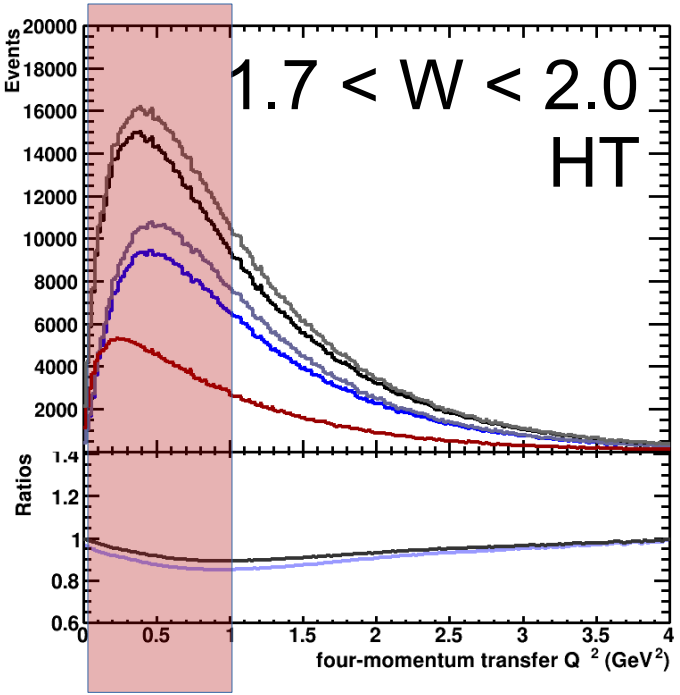
GENIE bugfix free nucleon / GENIE free nucleon



Vertical scale is changing order of magnitude left to right, ratio is not

The default GENIE in AR23 and back through GENIE2 has a bug
The BY scaling variable with empirical parameters is used in one section outside of the structure functions, but should not be so.
The fix is in the code since 2016 but turned off by default. 10%?

Q2 < 1 is an especially strange place to operate



Lot of low Q2 events

Word on street is that the 1 < Q2 < 4 GeV2 region is in good shape with NLO+TMC+HT

Unlucky: Q2 < 1 (all W)
Should be 2, 3-quark processes
So PDFs do not apply and model is wrong

Duality ansatz seems ok in EM scattering
So thats a rescue at low Q2, W, keep pdfs
Evidence is unclear in Weak scattering

Enhance uncertainty ad hoc? How much?

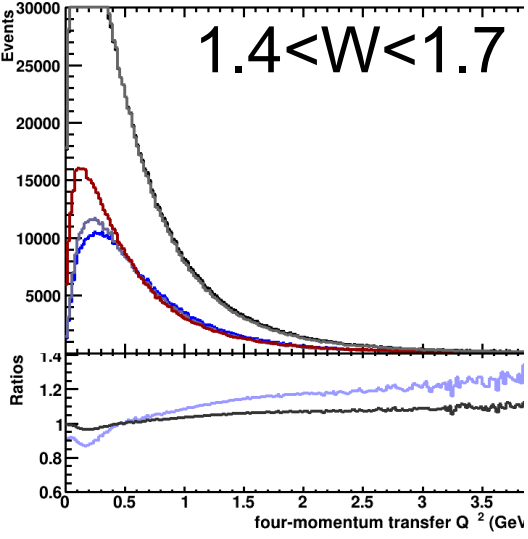
Switch to anti-neutrino

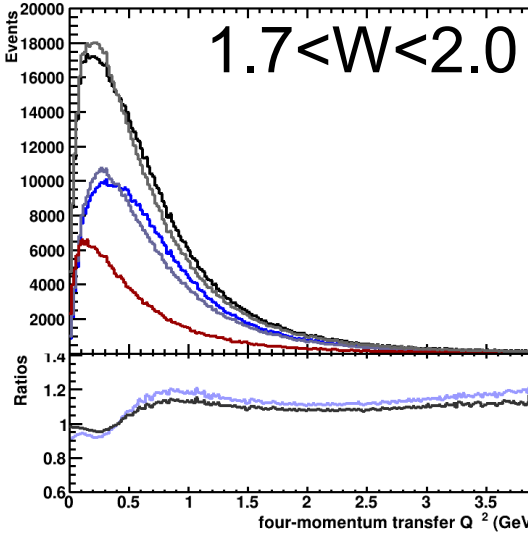
Reminder of the scheme
Take a model and tabulate its isoscalar F1 F2 F3 variations
Extract a ratio feature on / feature off = feature weight

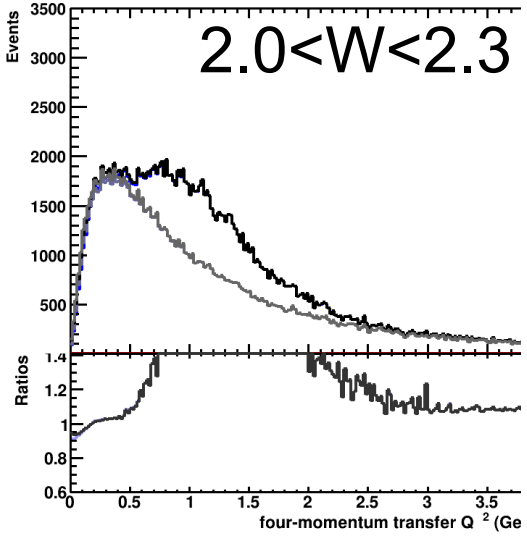
Apply it to a DUNE sample from GENIE's Bodek Yang model
used for our (Tristan's) "production" Monte Carlo
call it an uncertainty band

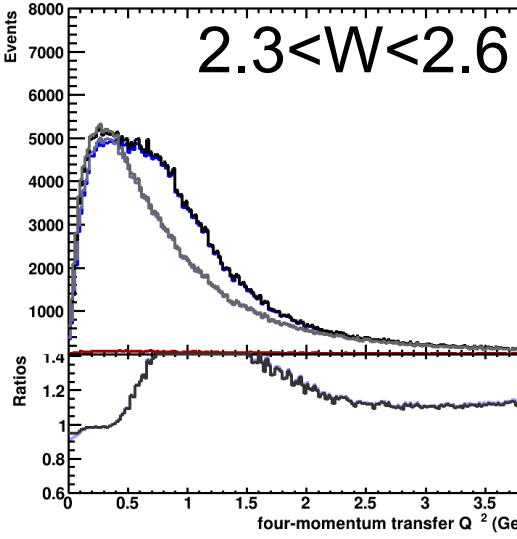
Isoscalar structure functions are same for nu and anti-nu
but the overall sign of the F3 term changes to negative
Produces a challenge, $d2\sigma/dxdy$ is sometimes nearly zero
especially a problem in the denominator of the weight

NLO something isn't right here, lets move on









Vertical scale is changing order of magnitude left to right, ratio is not

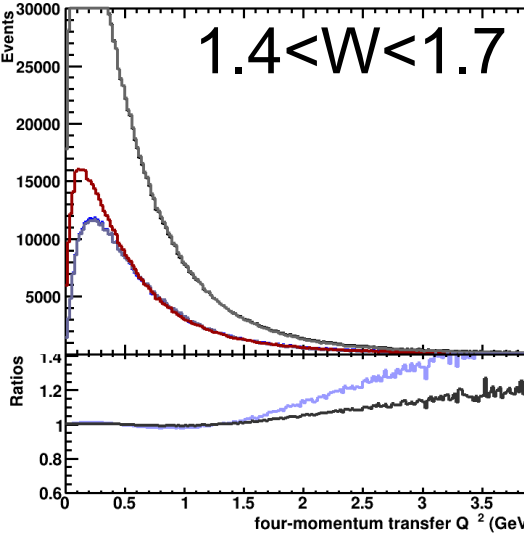
NLO off gave negative cross sections which I truncated near zero

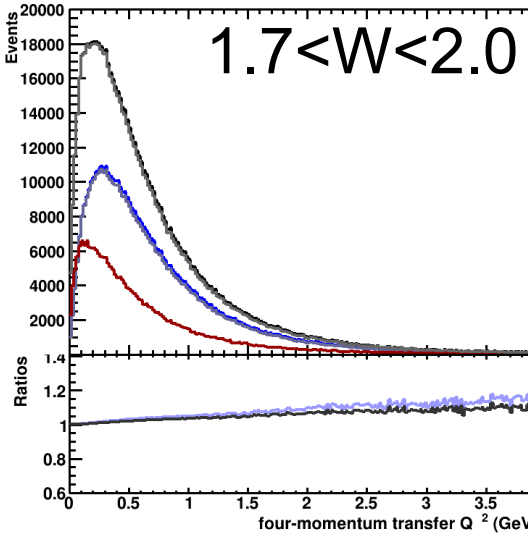
NLO off = LO is in the denominator, so high weights, also truncated

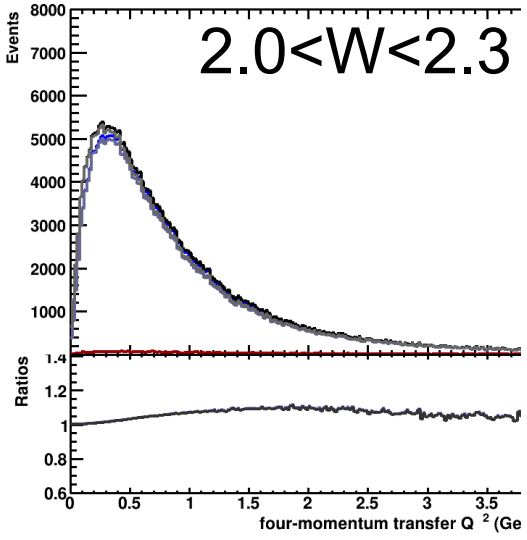
But these band-aids don't solve the underlying problem

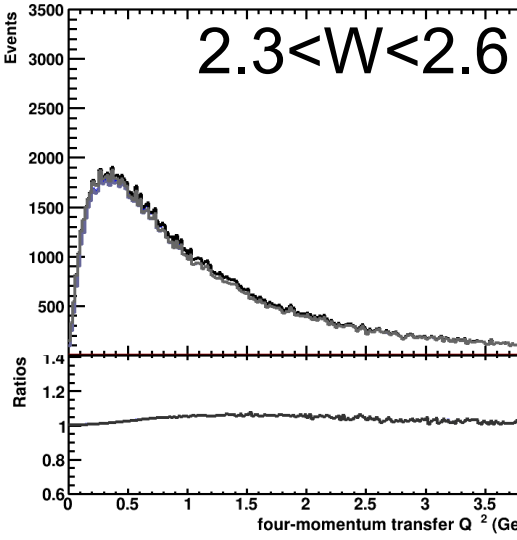
LO model goes to zero in regions different than NLO = bad weights

TMC anti-neutrino





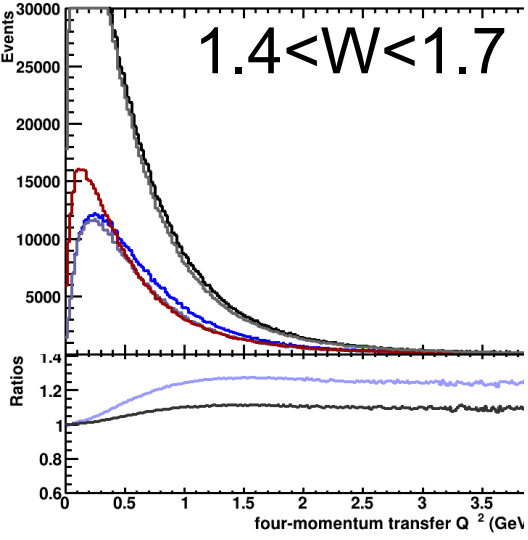


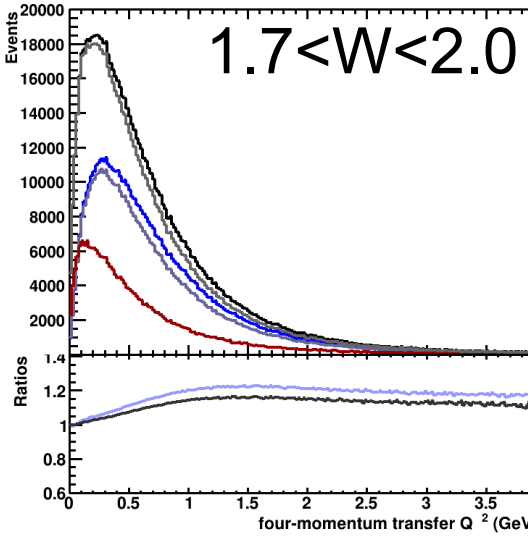


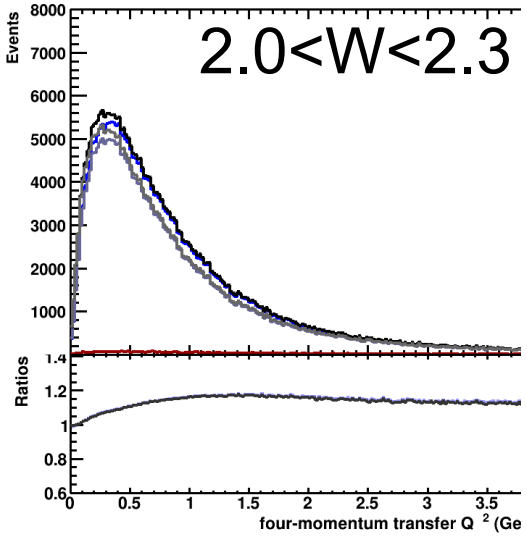
Vertical scale is changing order of magnitude left to right, ratio is not

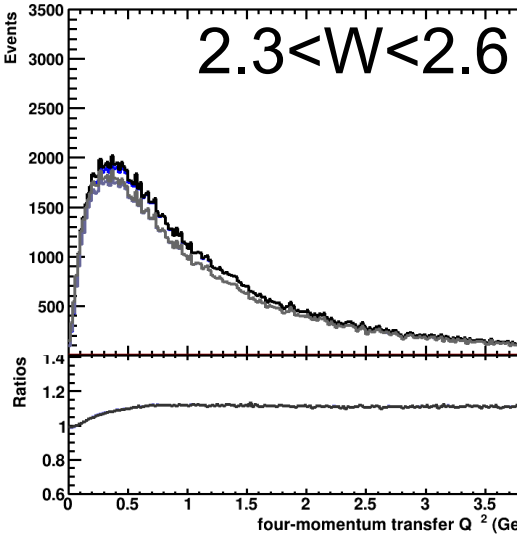
Similar to the neutrino case. Most or all the same sign effect
Not sure what to expect.

HT anti-neutrino





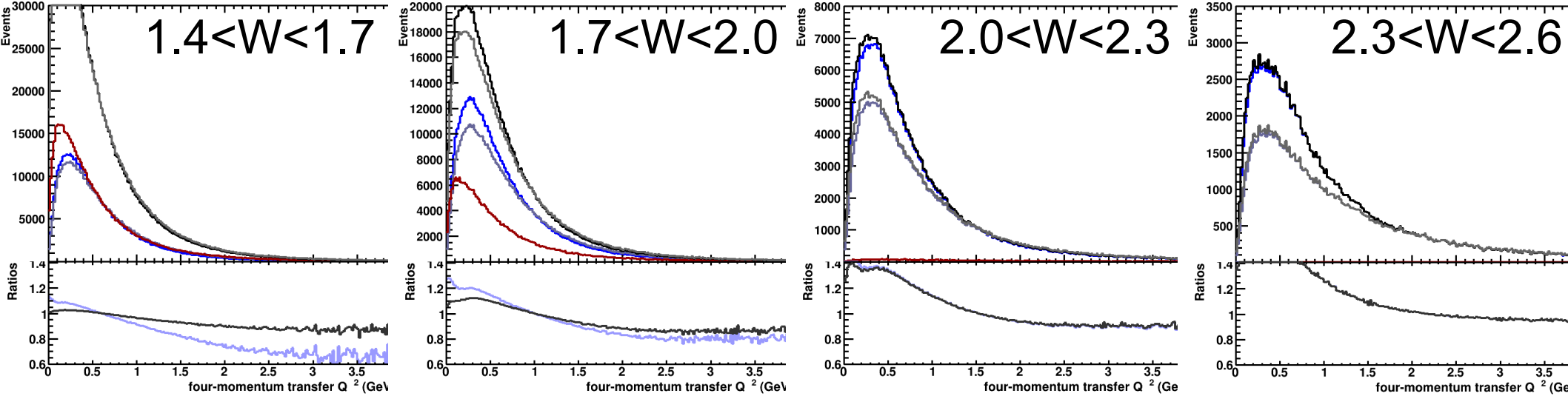




Vertical scale is changing order of magnitude left to right, ratio is not

This changes sign compared to the neutrino case
Suggesting its almost all in F3

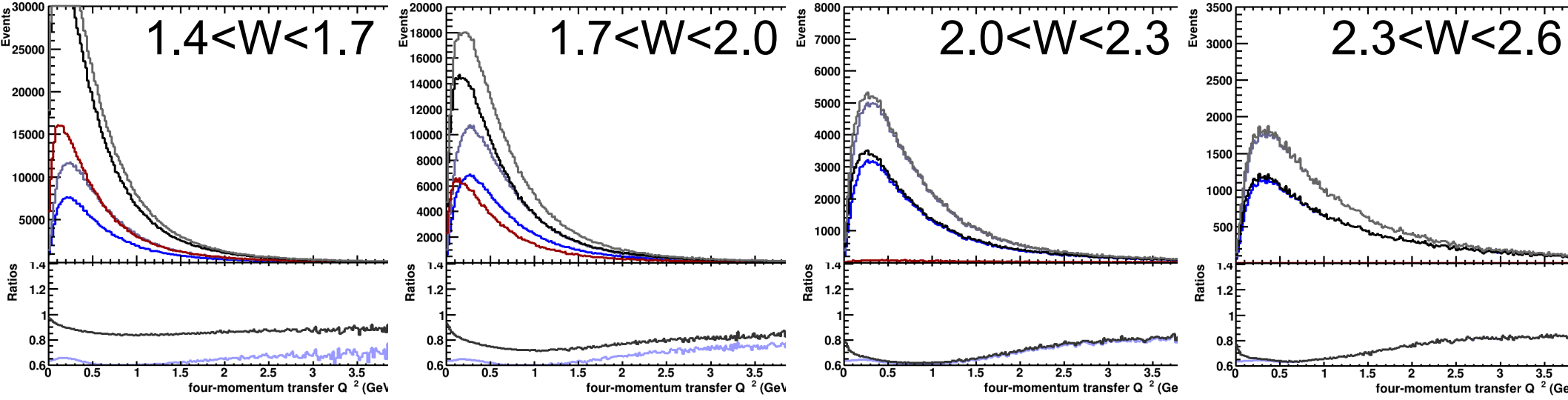
Callan Gross not full FL in F1 anti-neutrino



Vertical scale is changing order of magnitude left to right, ratio is not

This one does not change sign because its all in F1

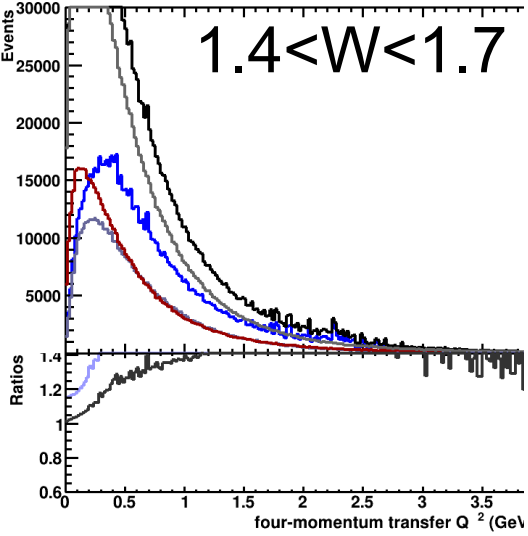
Carbon12 antineutrino

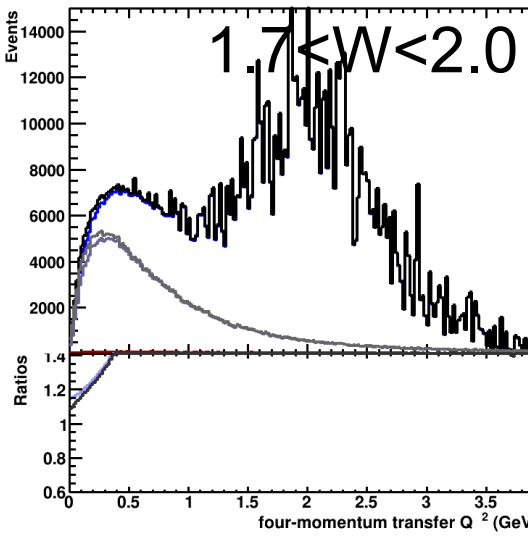


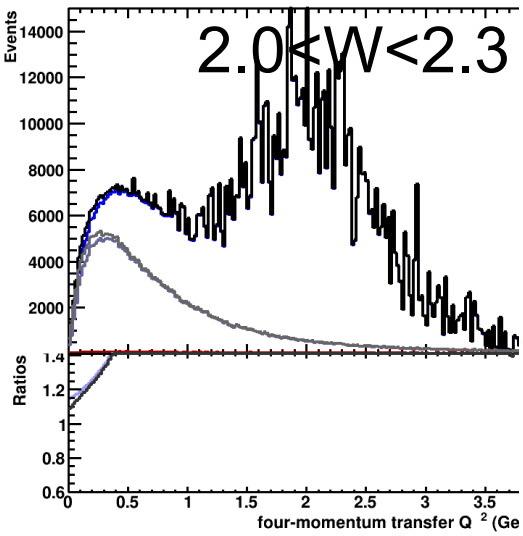
Vertical scale is changing order of magnitude left to right, ratio is not

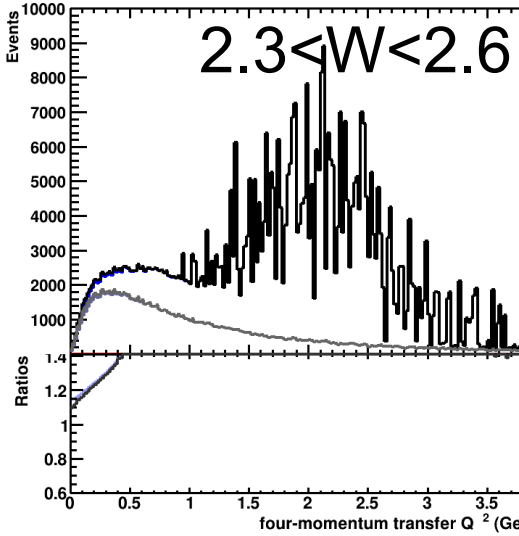
Same direction similar magnitude to neutrino case,
huge effect like the neutrino case, even bigger effect.
I hope we have an Ar based Near Detector

AMU / GENIE Bodek Yang free nucleon antineutrino





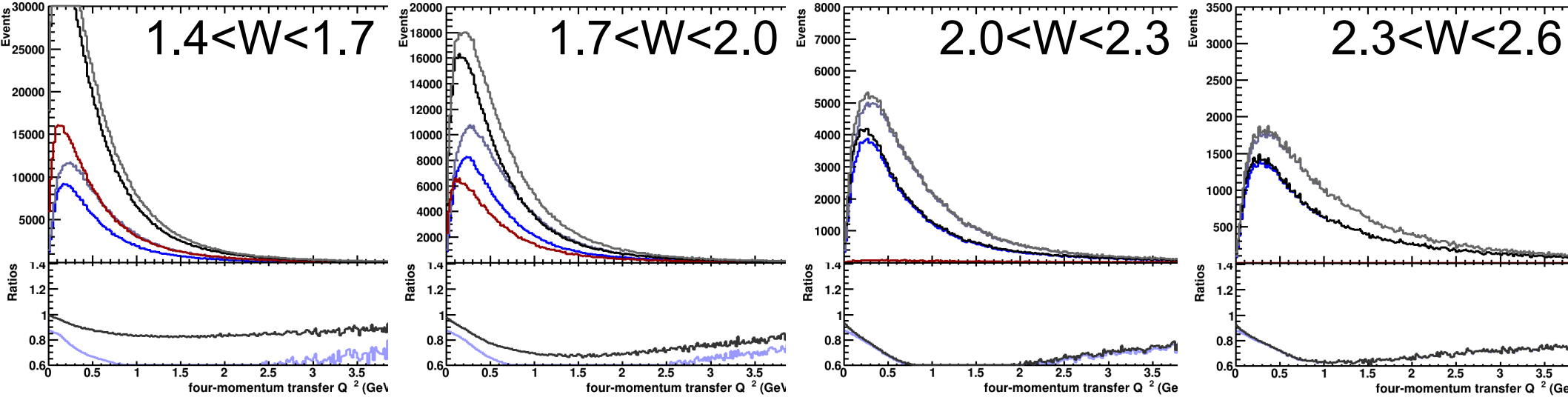




Vertical scale is changing order of magnitude left to right, ratio is not

Problem here too. Spiky because weights are not truncated.
Denominator approaches zero not followed exactly by numerator.
Is this a robust feature of GENIE Bodek Yang or my mistake?
n.b. only Anti-nu can go near zero. Need look into it.

GENIE Bodek Yang / AMU free nucleon antineutrino



Vertical scale is changing order of magnitude left to right, ratio is not

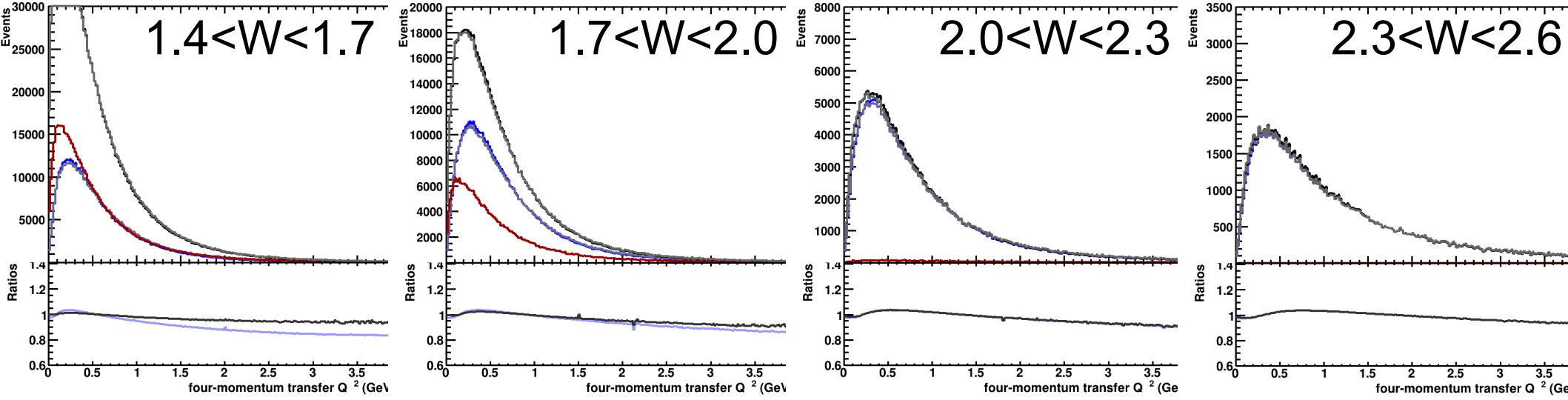
This is the inverse weight to the previous one as a diagnostic

It is smooth, because the numerator is the one that goes to zero

But not symmetric with the inverse weight previous slide

Have some additional cross-checks in mind.

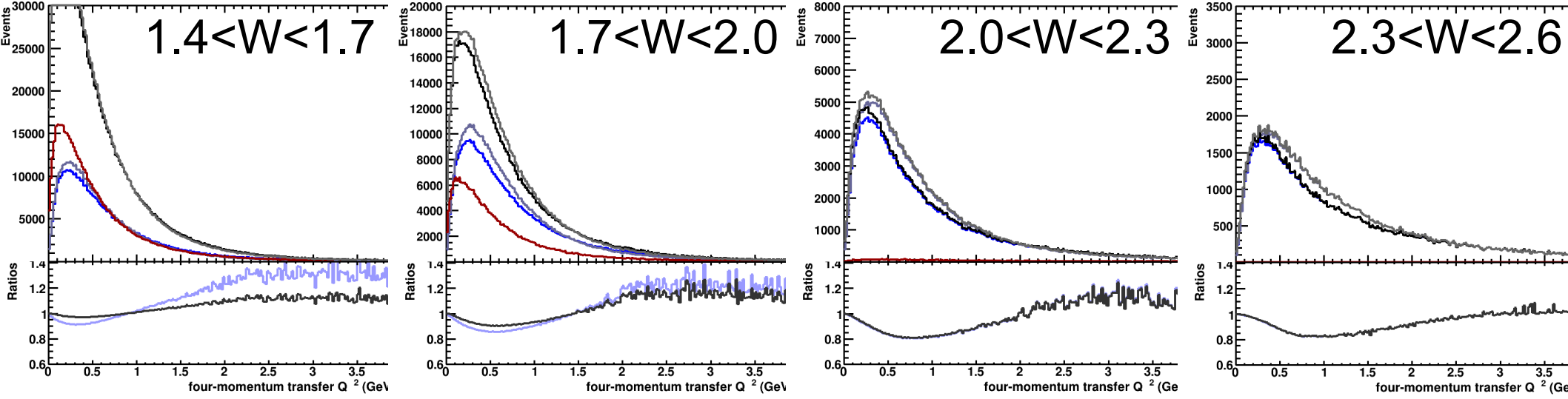
GENIE nuclear effects antineutrino



Vertical scale is changing order of magnitude left to right, ratio is not

The nuclear effects in Bodek Yang are the same for anti-neutrino
Same function of x not Q2 multiplying all structure functions
(or at least thats what GENIE told me)

GENIE bugfix over GENIE base free nucleon antinu



Vertical scale is changing order of magnitude left to right, ratio is not

This one also gave negative cross sections

But doesn't exhibit the crazy behavior of the NLO and previous two

Probably (hopefully) because the numerator similarly goes to zero

Look at pairs that make for an interesting comparison

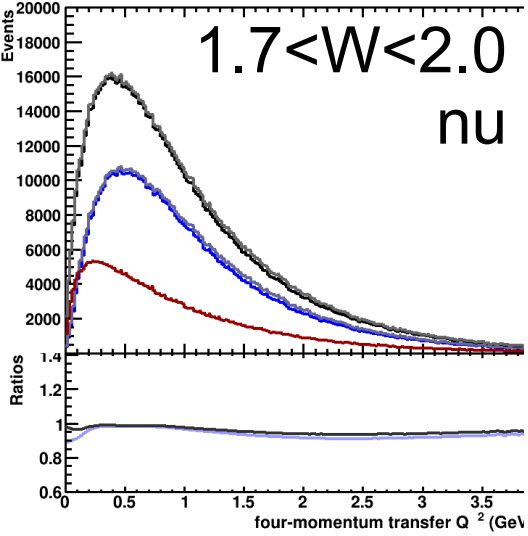
see them side by side

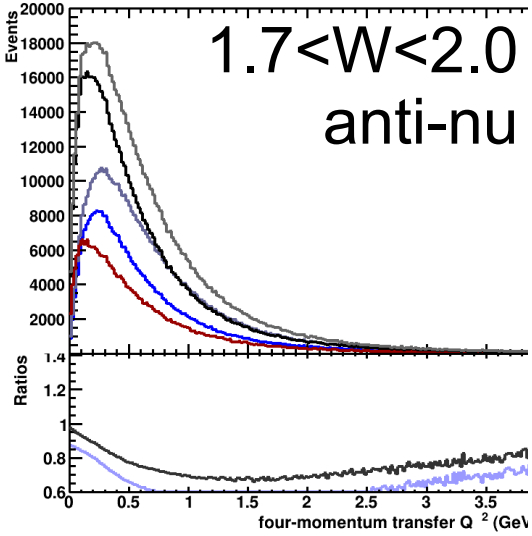
The AMU/GENIE weight, but really the smooth inverse weight
two ranges of W, neutrino and anti-neutrino

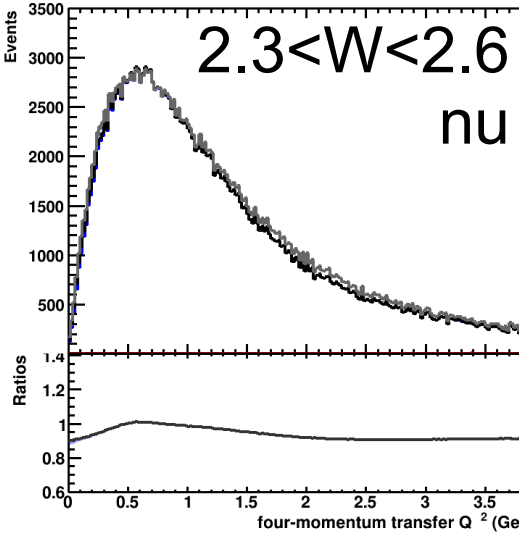
And

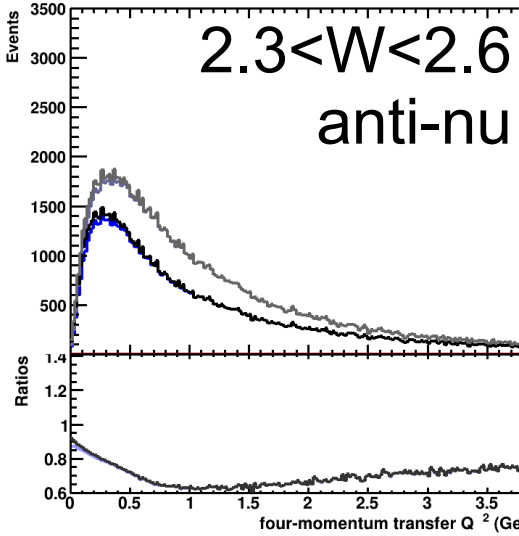
the nuclear effect weight
AMU and GENIE, both neutrino and anti-neutrino

GENIE / AMU free nucleon neutrino vs anti-neutrino



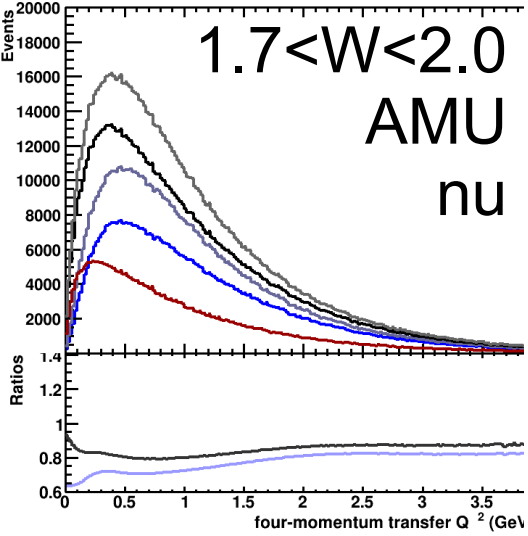


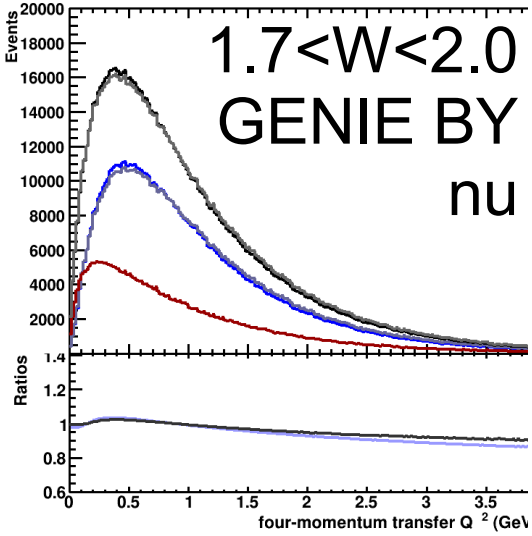


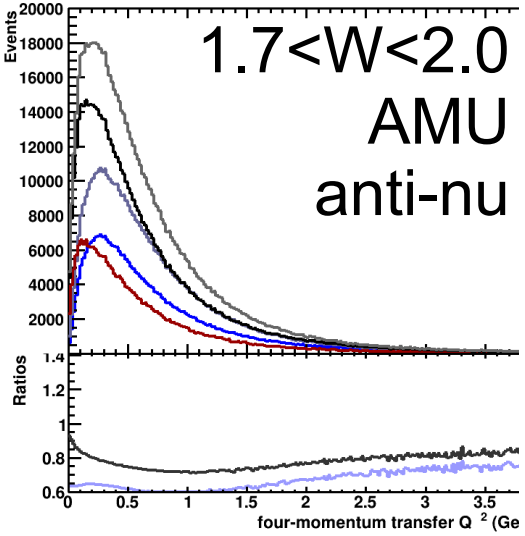


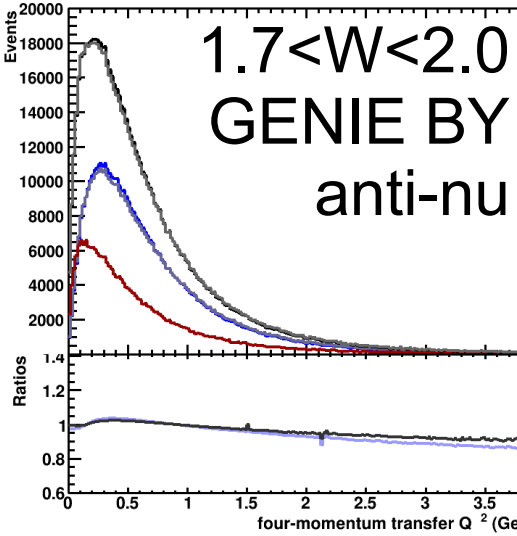
This one is the upside down weight GENIE/AMU applied to GENIE
Still presuming that zero (right or wrong) is the main cause here
Still possible I messed up extracting BY from GENIE?

GENIE / AMU nuclear effect









Higher magnitude of nuclear effects for Carbon in AMU
And opposite direction at low Q2 ?

Conclusions

A milestone demonstration of weights for SIS and DIS

Some behavior to explain, even for the ones that look “right”

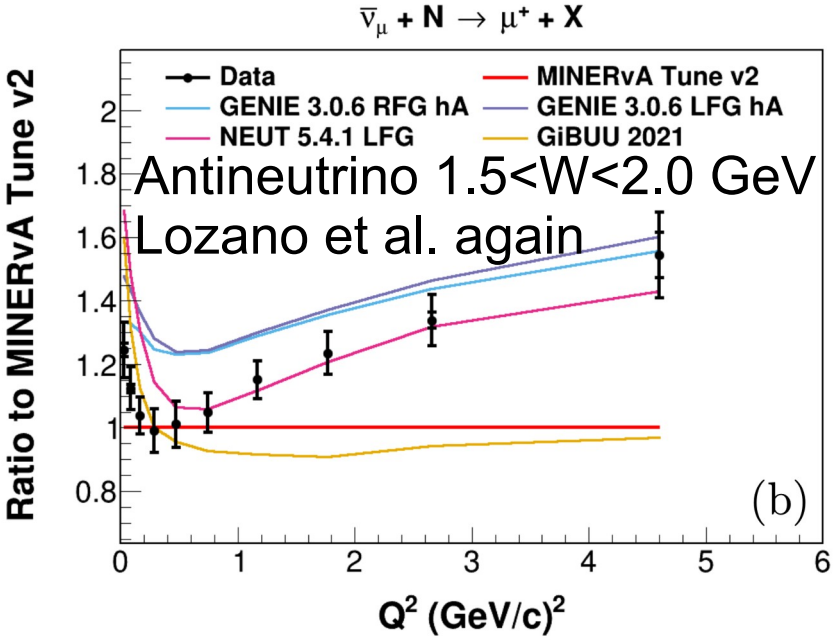
Mainline options, especially GENIE Bodek Yang
Produce near zero anti-nu cross section at some kinematics
not obviously a bug on its own, but may be one.

We are starting an iteration on these and other points
plus need to justify scaling from effect to uncertainty

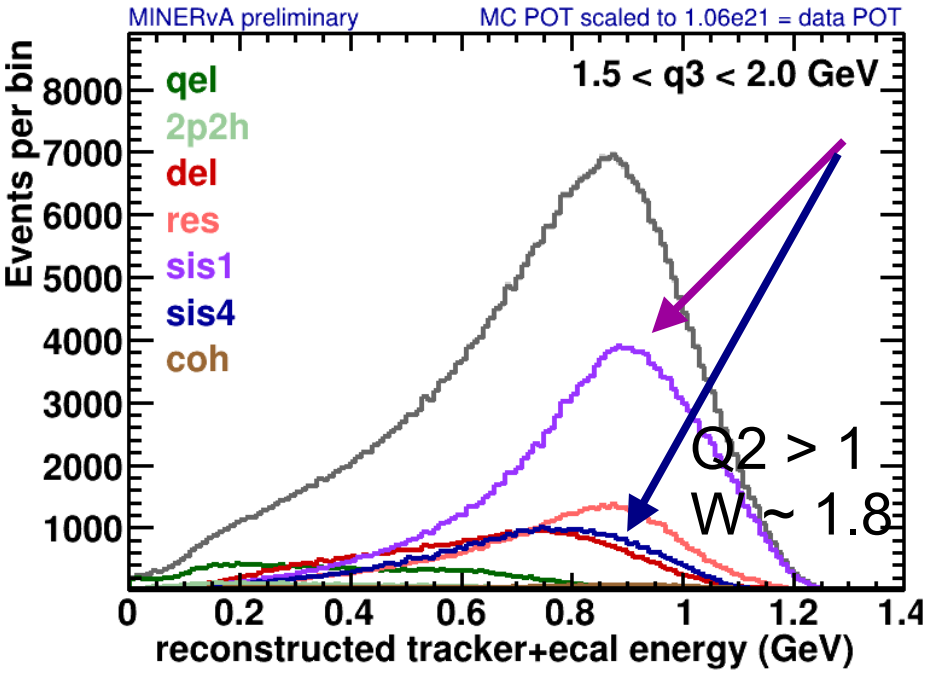
Add more features, more precision, other models?

Parting thoughts

This implementation is also being tested on MINERvA data
it will be a while before approved results



Active 2D followup by Daniel Correia



Technical features

What should go in a backup slie

Future work

Tweak the inputs for more reliable precision
Add more features ? Competing PDFs or PDF error bands

On the GENIE3 Bodek Yang Model

Its the same as GENIE2 based on BY 1999 and 2000 papers
PRL 82 (1999) 2467 and Eur.Phys.J. C13 (2000) 241
Not updated to arXiv:2108.09240 (2021)

It empirically modifies the scaling variable (x to ξ and beyond)
to account for NLO, TMC, and HT effects in F1 F2 F3
and implements a Whitlow r (or FL) effect relating F1 to F2
And a f(x) nuclear effect (data-driven iron?) for F1 F2 F3 all A

A bugfix in the code since 2016 GENIE v2 is still turned off

On the GENIE3 Tunes

AR23 is using a global tune made up of simple ingredients
Scalings of RES, DIS rate, and the 1pi and 2pi fractions
Tena Vidal et al. [GENIE] in PRD 104 (2021) 072009

The DIS is scaled up by X%
One side effect is the global sigma/E is overpredicted
By 5% (two sigma) when this tune is used
(and anti-nu by)

Similar things could happen with these weights
Not clear how this constraint should be applied or ignored