Hydrogen single pion data, May the 4th be with you

UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

vs.

Episode IX Rise of SIS & DIS

Update for NDGAr May 2024

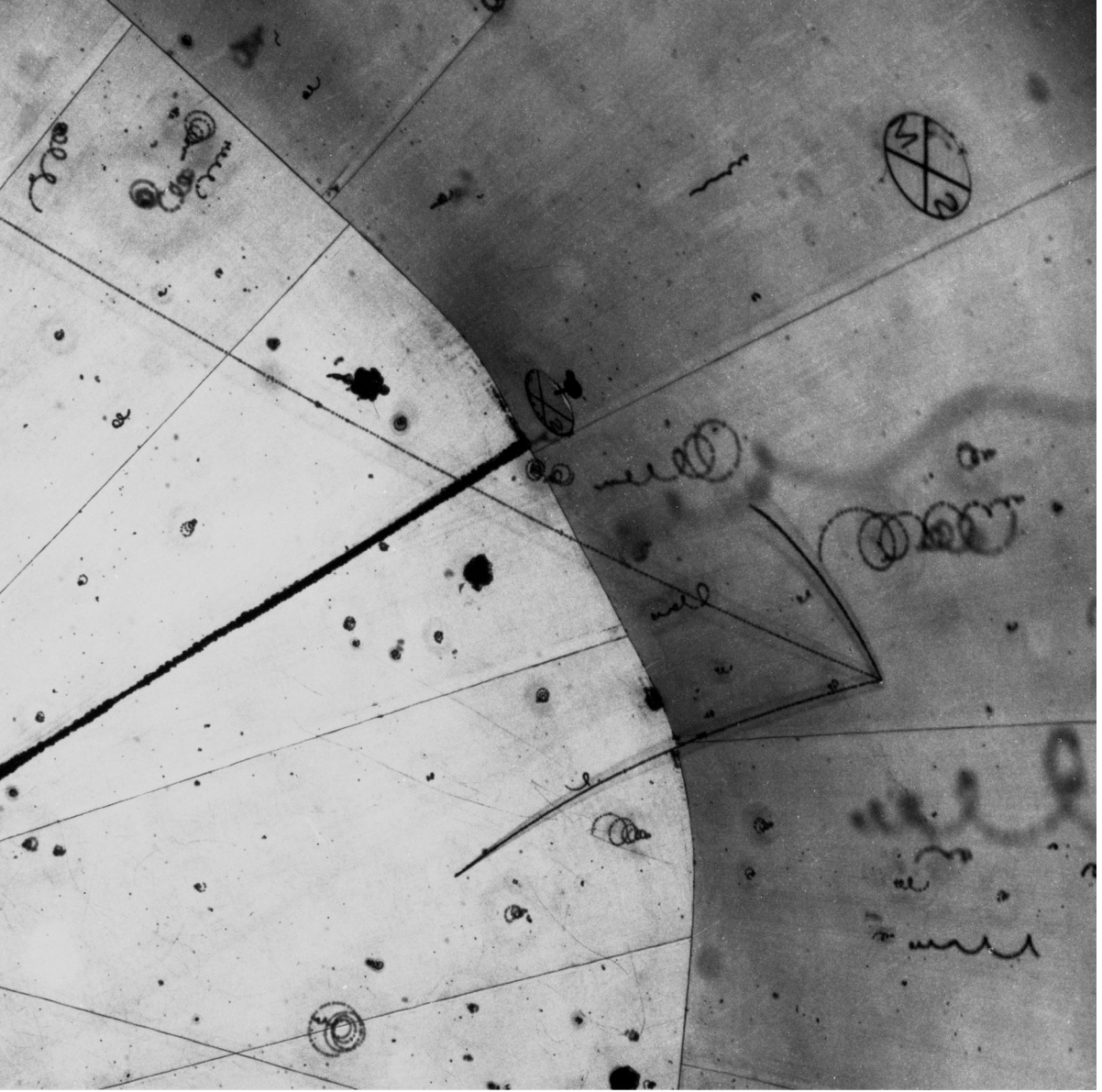
A long time ago, in a galaxy far away

Models were created for Pion production
then changed, then simulated, then forgotten

The BEBC Q2 data on hydrogen at 10 < Ev < 200 GeV
with a single pi+ and a proton in the final state
is a powerful dataset with ~7% systematic uncertainty

Until recent experiment(s) pulling H out of hydrocarbons
We have these 1000+ BEBC events + 138 from FNAL 15’

They published data for 1.4 < W < 2.0 and W > 2.0 GeV
then hid them from the dark side of the weak interaction



Three prong event on H

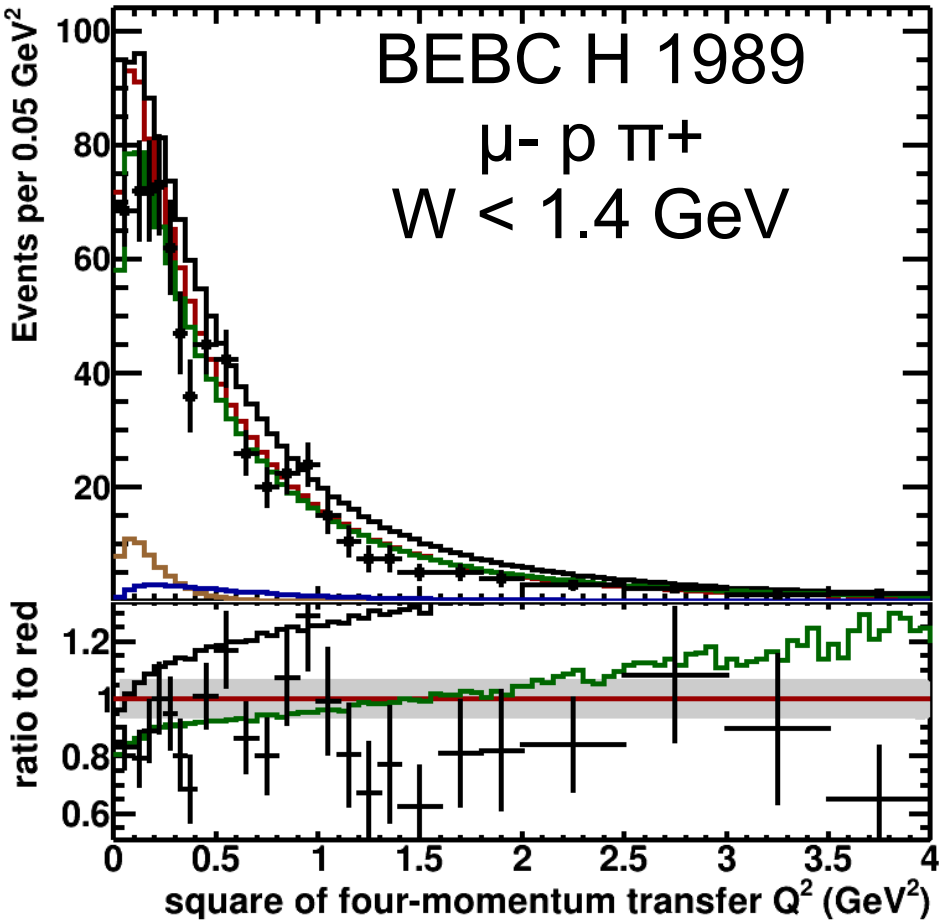
This one from ANL 1970
Featured in Physics Today
Todays analysis BEBC 1980s

$\nu_\mu + p \rightarrow \mu^- p \pi^+$
has ++ hadron state

$\text{anti-}\nu_\mu + p \rightarrow \mu^+ p \pi^-$
has neutral hadron state

No missing E, no n or π0
No FSI, no backgrounds
95% scanning efficiency

The Delta++ data from my previous talk.

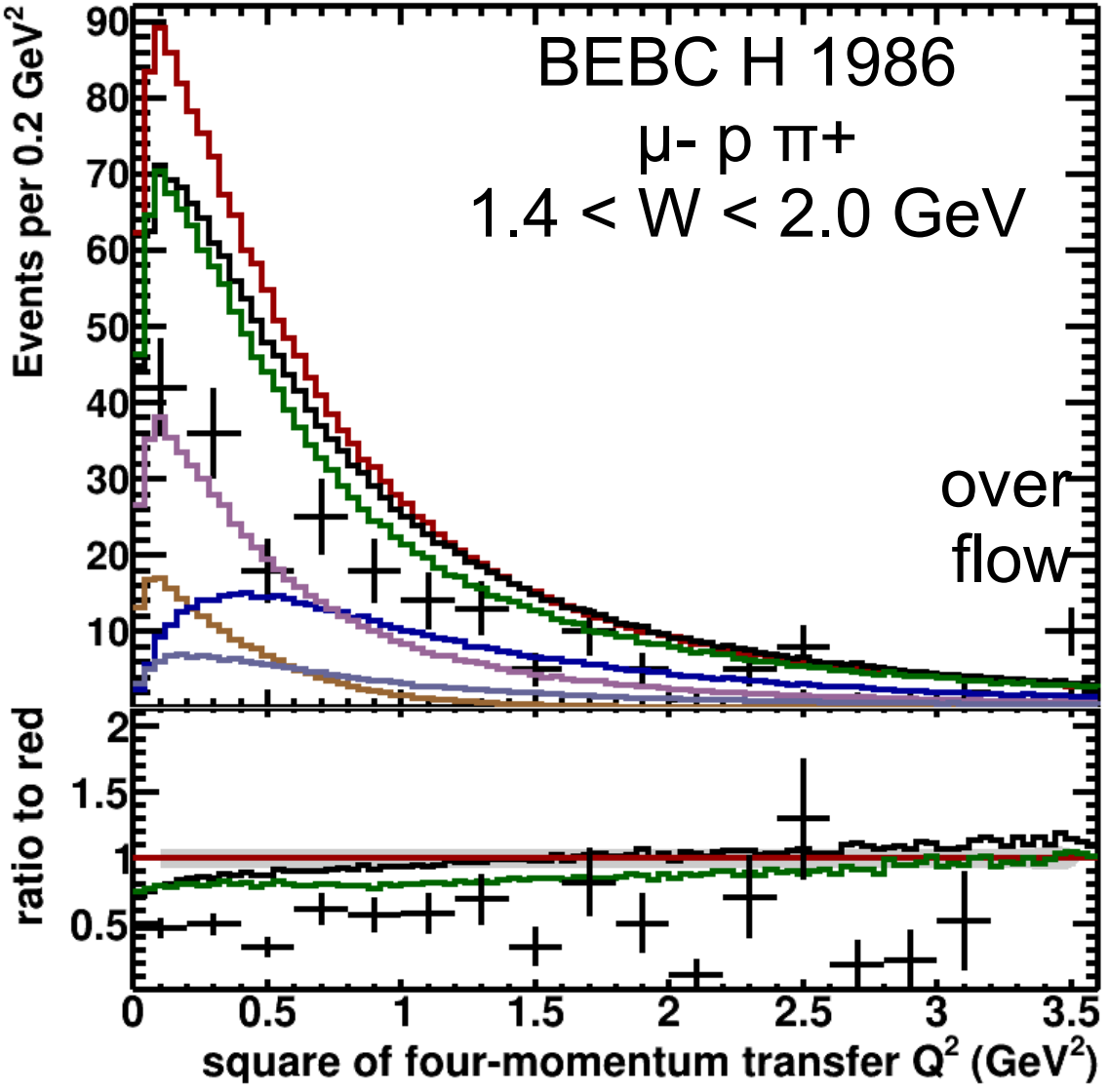


Note: lowQ2 rolloff feature

Black line is G18 out of the box
New form factors no tuning MA
Its way off, above all but one bin

Red is old form factors ~ GENIE v2
MA was tuned to BEBC, ANL, BNL

Green is Tena Vidal 02_11b tune as in AR23_20i. Start from Black...
Scale down resonances 0.84
Small change in MARES, MAQE
Almost eliminate DIS 1π for W<2
No modification of diffractive



Q2 distribution in SIS 1.4 < W < 2.0 one π+

Data bins combined 2x

Components include
Top to bottom
Purple = Delta
Blue = DIS
Brown = diffractive
gray/blue = higher res

Normalization is close
But worried ~20%

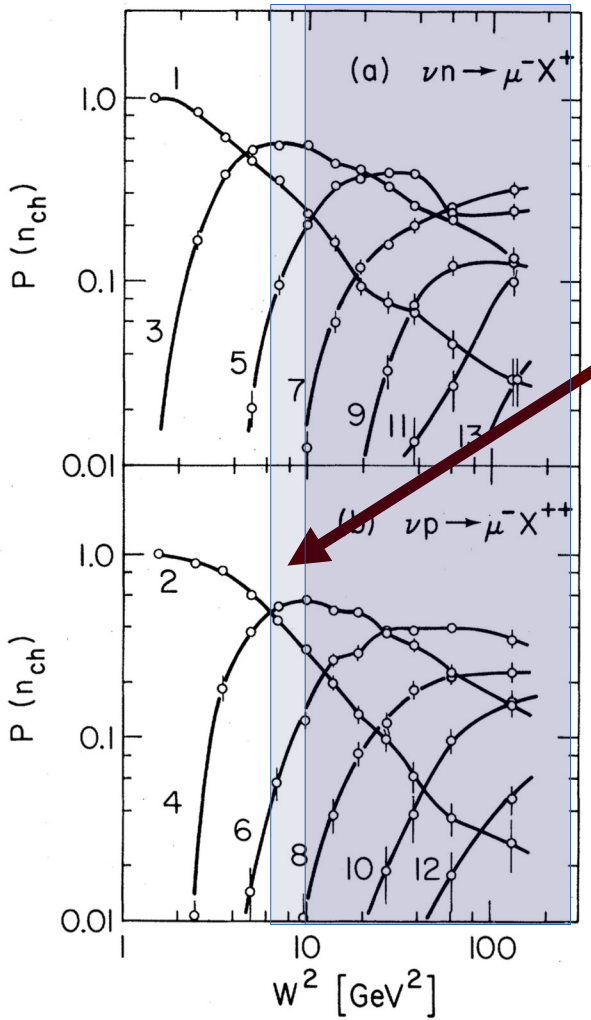


FIG. 3. Normalized topological cross sections versus W^2 for charged-hadron multiplicities. (a) $\nu n \to \mu^- + (n_{ch})^+$. (b) $\nu p \to \mu^- + (n_{ch})^{++}$. The lines are drawn between experimental points to guide the eye.

Single pi+ channel drops to half fractionally around W ~ 2 GeV

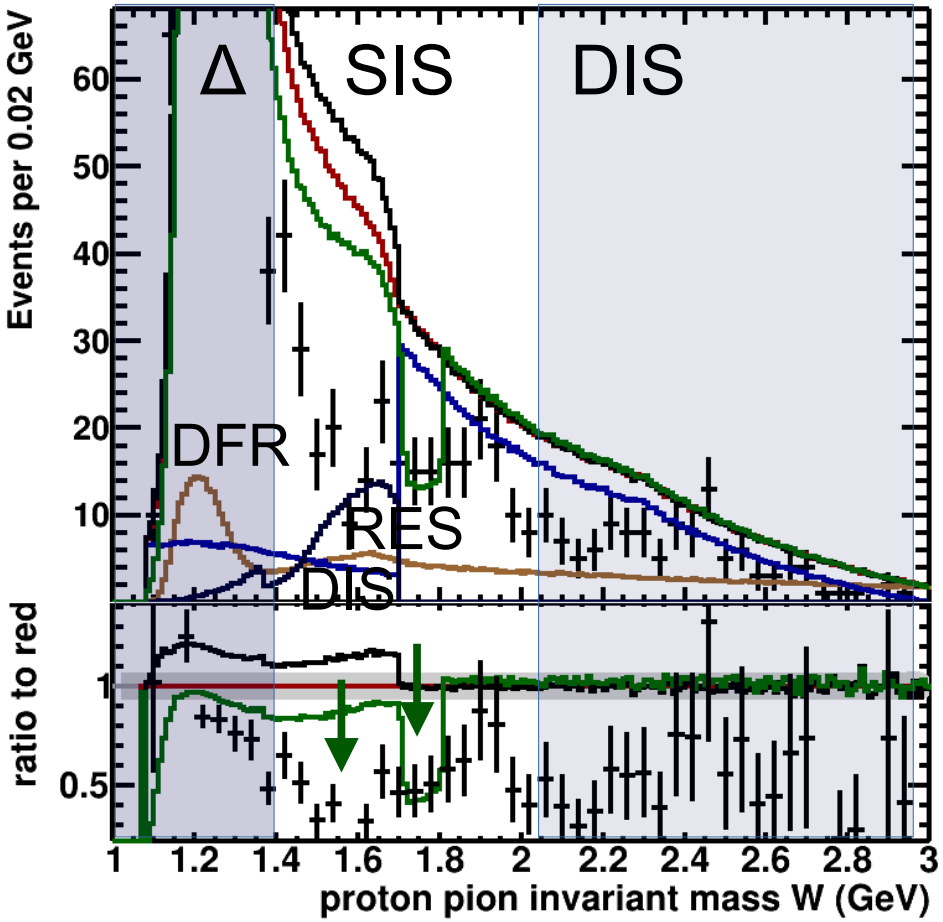
So that SIS+BEBC plot on previous slide is already showing MOST of the event rate. Have not, but could ask if GENIE agrees.

The data on the left is from FNAL 15' deuterium fill so it has n (upper) and p (lower) So 2 = p π+ (& π0) and 4 = p π+ π+ π- … I think BEBC and others also have data.

DUNE flux approx range is W < 3 GeV

D. Zieminska et al. FNAL 15' PRD 27 (1983) p. 47

SIS and more but still single π+ BEBC sample



from BEBC Jones:1989
But rebinned 2x and zoom y axis

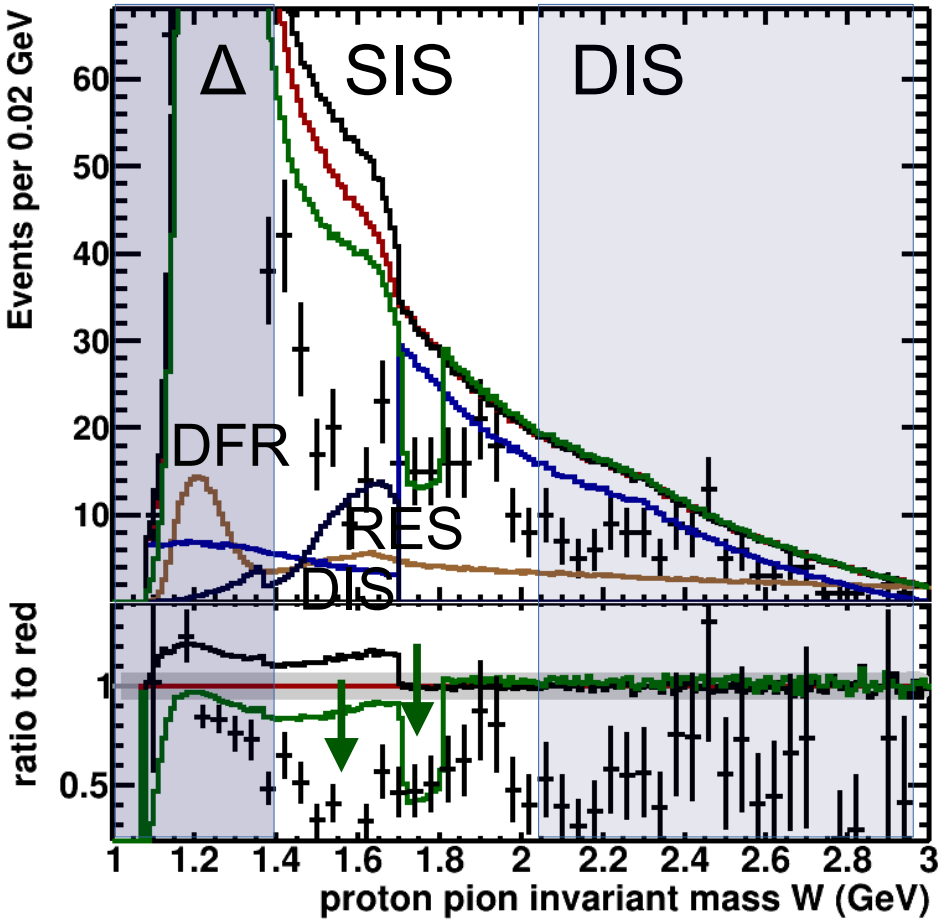
Can see components are messy

Delta not shown
Brown = diffractive H scattering
Black = higher resonances
Blue = DIS

All three models overpredict badly
Several features to see …

Adequate. By design! ™

Delta width and tail is wrong 1.3 < W < 1.5 GeV



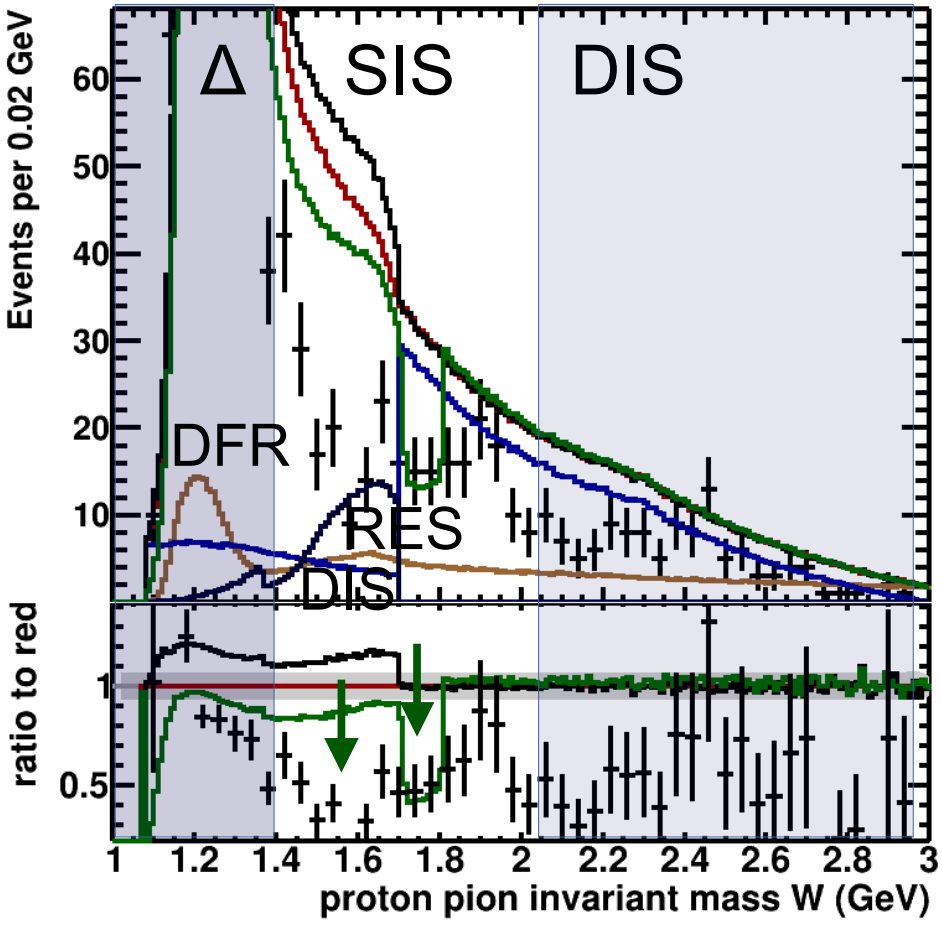
In the ν + H channel
there is a resonance desert.

So this is obviously a mistake to fix

Tail is too high, goes on too far.

Adequate. By design! ™

The Green JTVb tune makes even more W artifacts



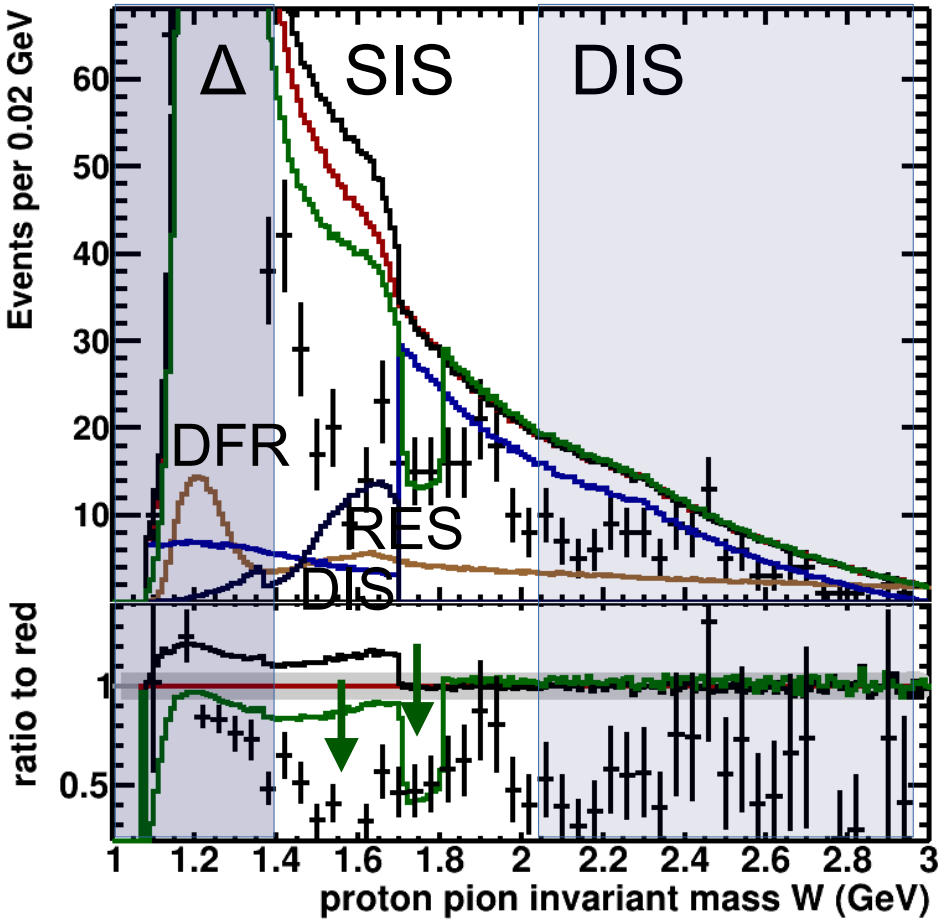
The red curve (old FF) looks smooth
Maybe by construction
was (sorta) the original GENIE2 tune
Smooth might have been by design

Subsequent tunes didn't try to
maintain smoothness here
or other physically realistic things

In reco space, not sure what artifact
will affect fits & measurements
especially in SAND & ND-GAr

Adequate. By design! ™

Diffractive component (brown) is significant throughout



Adequate. By design! ™

Model follows the coherent model Rein:1986 and sorta these data

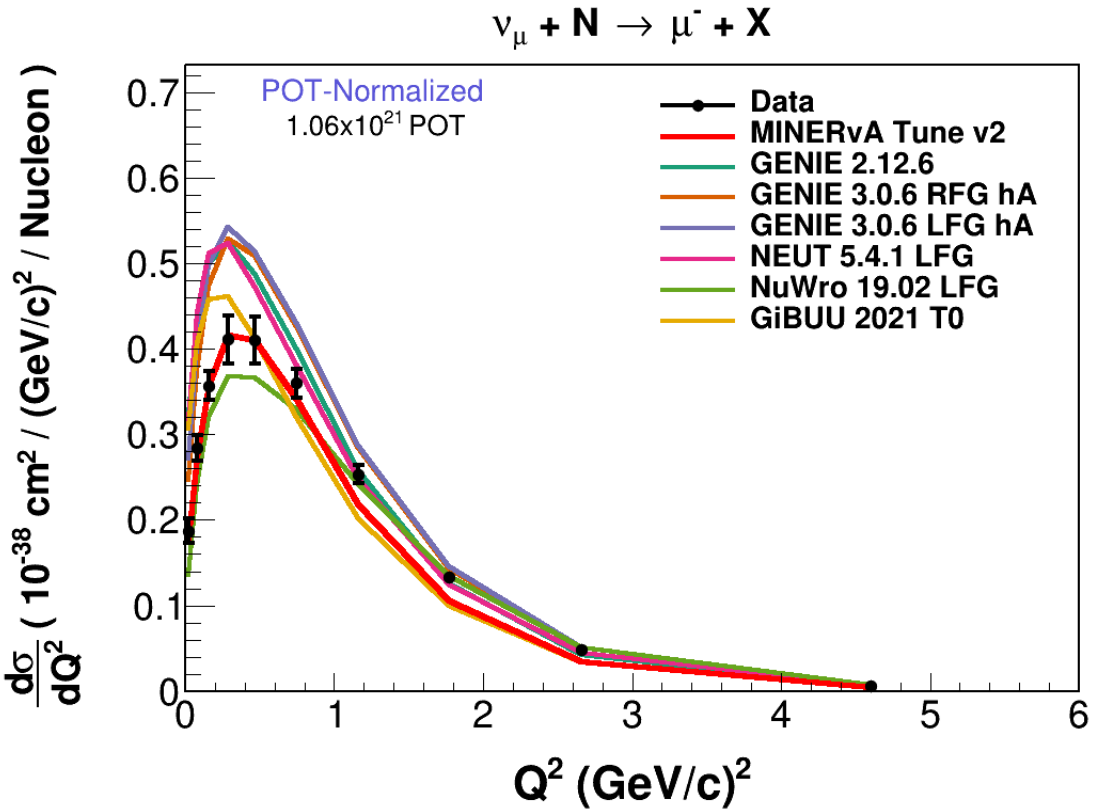
The shape and the Δ peak is from how the model uses the πp cross section

GENIE implements Rein mostly (its 10%ish lower than Rein)

Only H data as of Feb 2024 Diffractive + GENIE DIS makes too much single π+

Switch to SIS in MINERvA data in CH scintillator

SIS sensitivity in a MINERvA inclusive sample



Several features to see

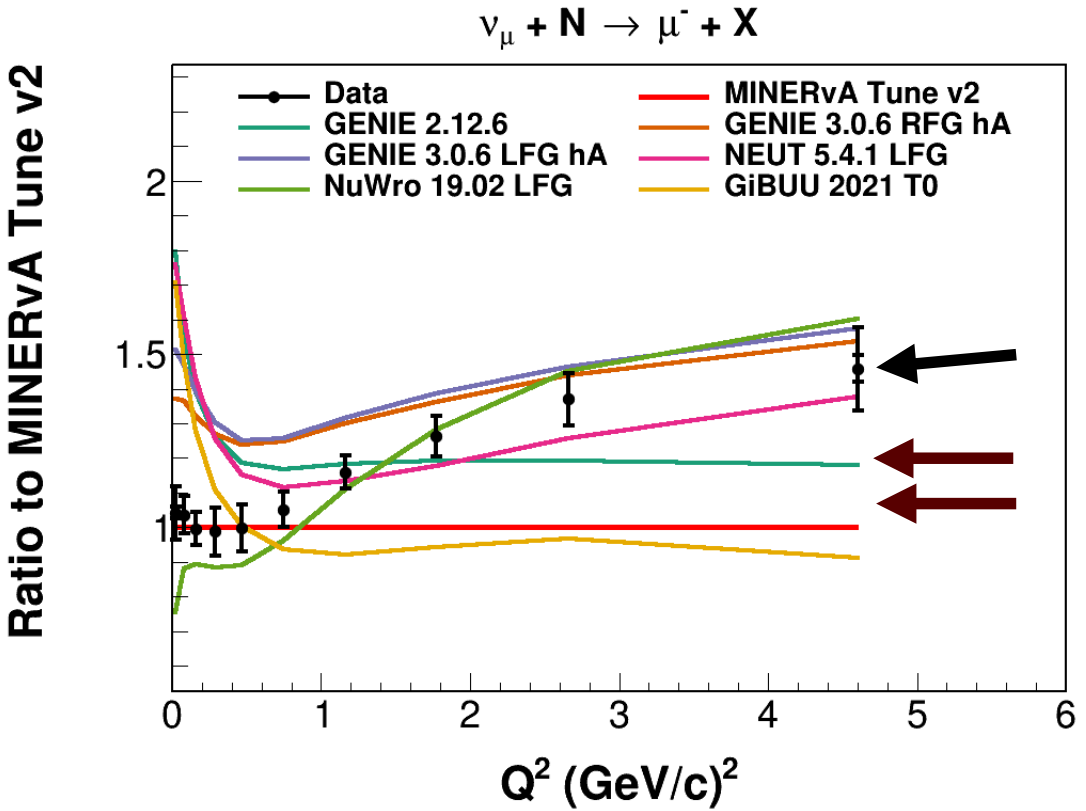
1.5 < W < 2.0 GeV

Several generators of interest

Peaks at Q2 ~ 0.5
Lets look at the ratio

Adrian Lozano Sanchez, MINERvA thesis paper internal review

SIS sensitivity in a MINERvA inclusive sample



Several features to see

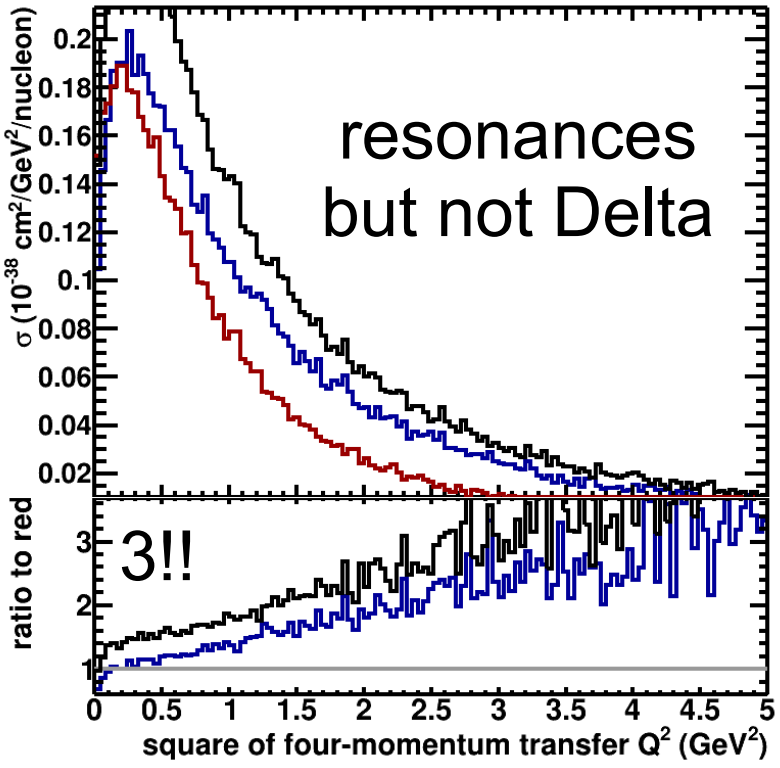
1.5 < W < 2.0 GeV

GENIE3 and NuWro rise
At high pT high Q2
Compared to GENIE2

Reason is the resonances

Adrian Lozano Sanchez, MINERvA thesis paper internal review

Higher resonance only (not Delta not shown) rises x3

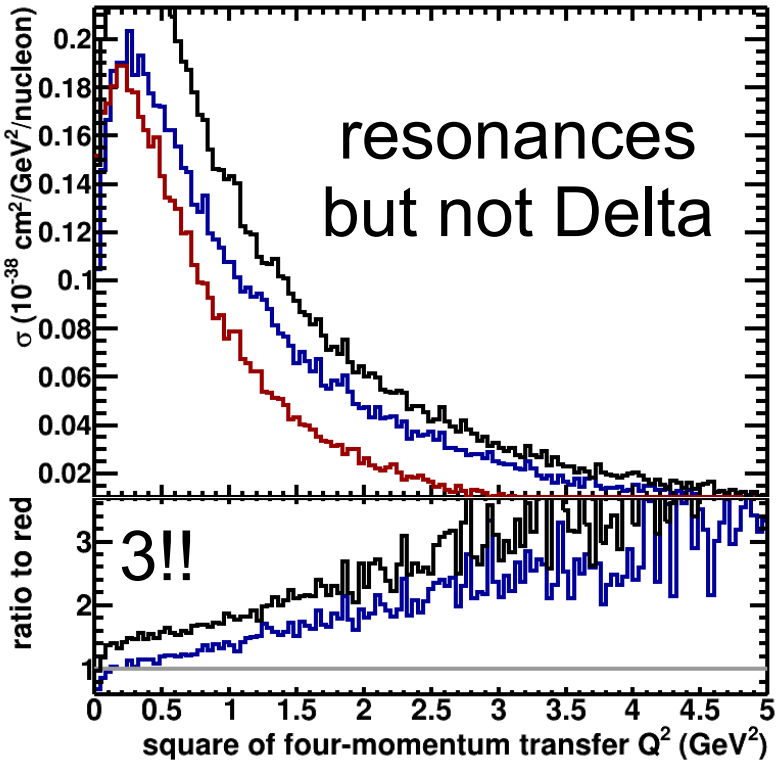


Old FF (red) is GENIE2-like
Blue is JTVa tune, black is untuned
(maybe I have them mixed up)

New FF are huge change at high Q2
This is the cause of the slope in pT, Q2
Seems like the data like this feature.

Little surprised. Not this strong for Δ
Did MINOS notice something like this?
one or the other behavior unrealistic?

MINOS would have preferred more high Q2 events



Adamson et al. [MINOS Collaboration]
Phys.Rev.D 91 (2015) 012005
NEUGEN3 nu + Fe interactions

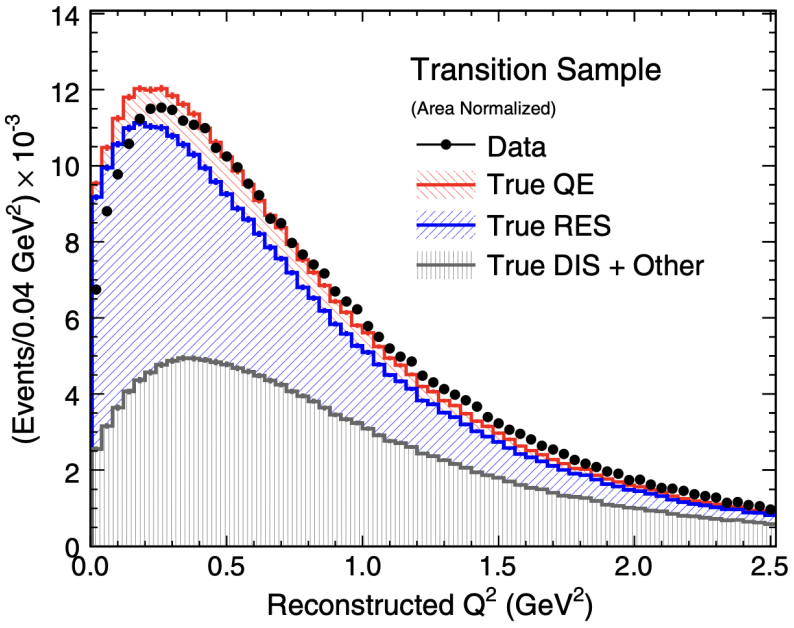
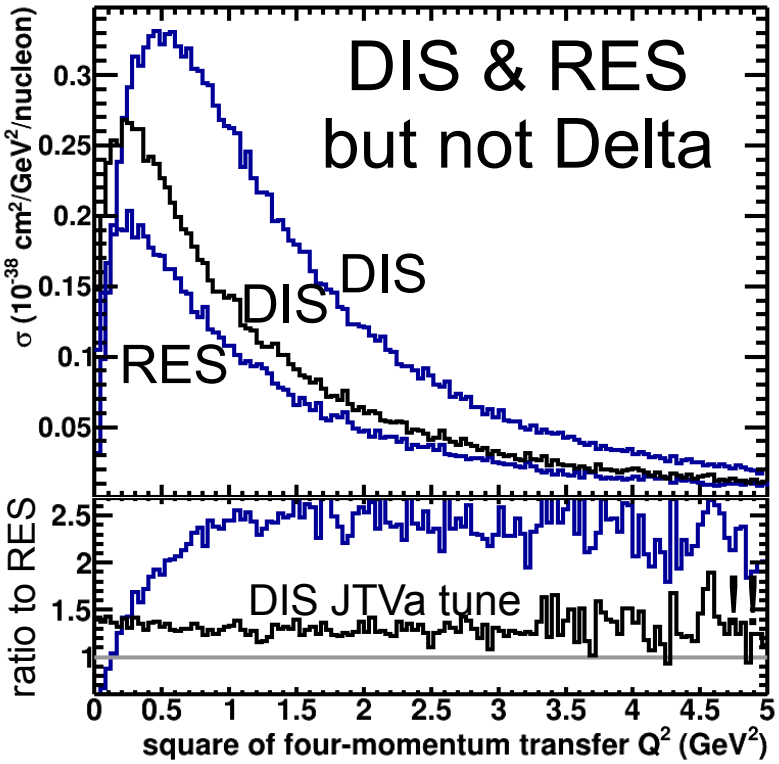


FIG. 7 (color online). Distribution of reconstructed Q^2 for events of the RES-to-DIS transition sample ($1.3 < W < 2.0$ GeV). The MC prediction (stacked histograms) is normalized to the number of data events. The MC spectrum lies above the data over the low-Q^2 region dominated by CC baryon resonance channels.

New RES shape is same as DIS shape



Blue res line is same as previous plot

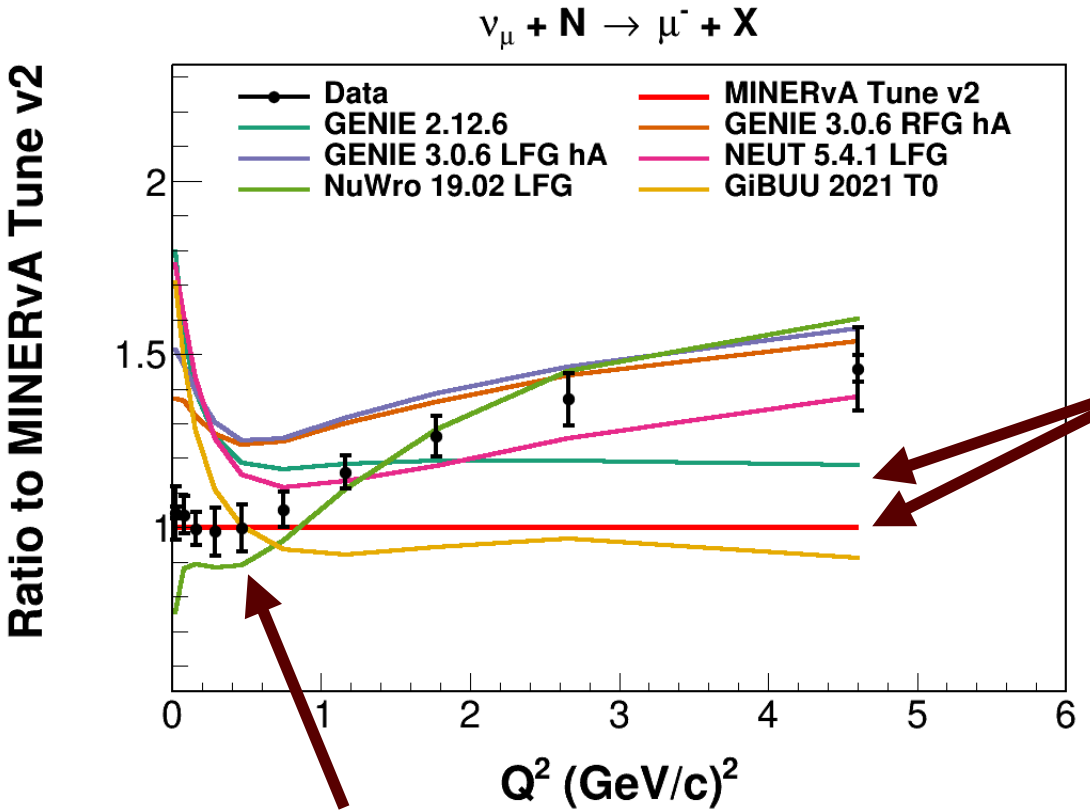
Did we know something was unrealistic?

Folks who like to argue Duality is a strong if not perfect principle at these W they would like the new model too.

At high Q2 has same shape as DIS because the ratios are nearly flat

Explains why GENIE3 has same shape as NuWro which is all Bodek-Yang DIS at the SIS W

What goes into the MINERvA Tune v2 at SIS



Low Q2 suppression
tuned to Minerva Data
Stowell et al. mostly Δ

Rodrigues & Wilkinson fit
To ANL and BNL data
reduces DIS at all W < 2.0
(GENIE knobs to implement)
But tuned at Q2<1, W<1.4
so is extrapolated far beyond
Yes, shabby (is a real word?)

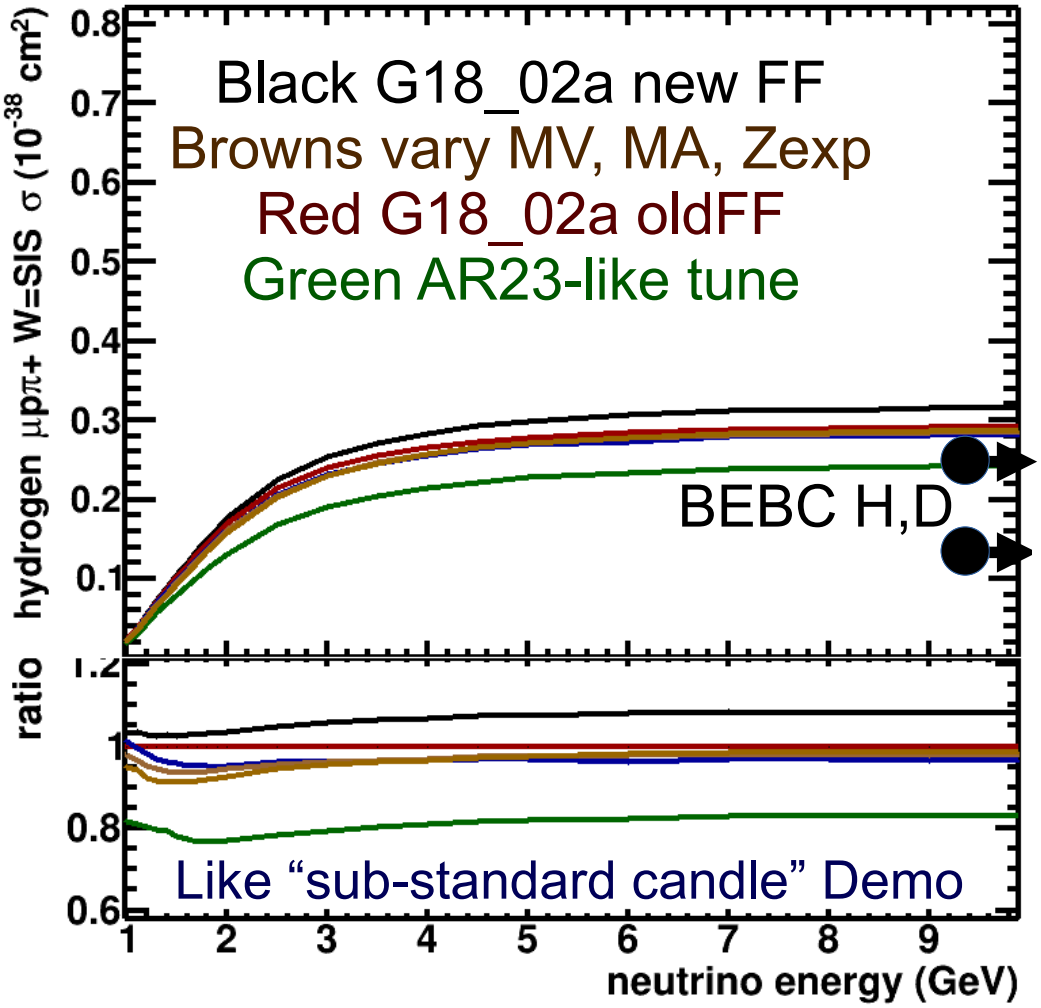
Not too shabby
Tuned to Delta and 2p2h samples

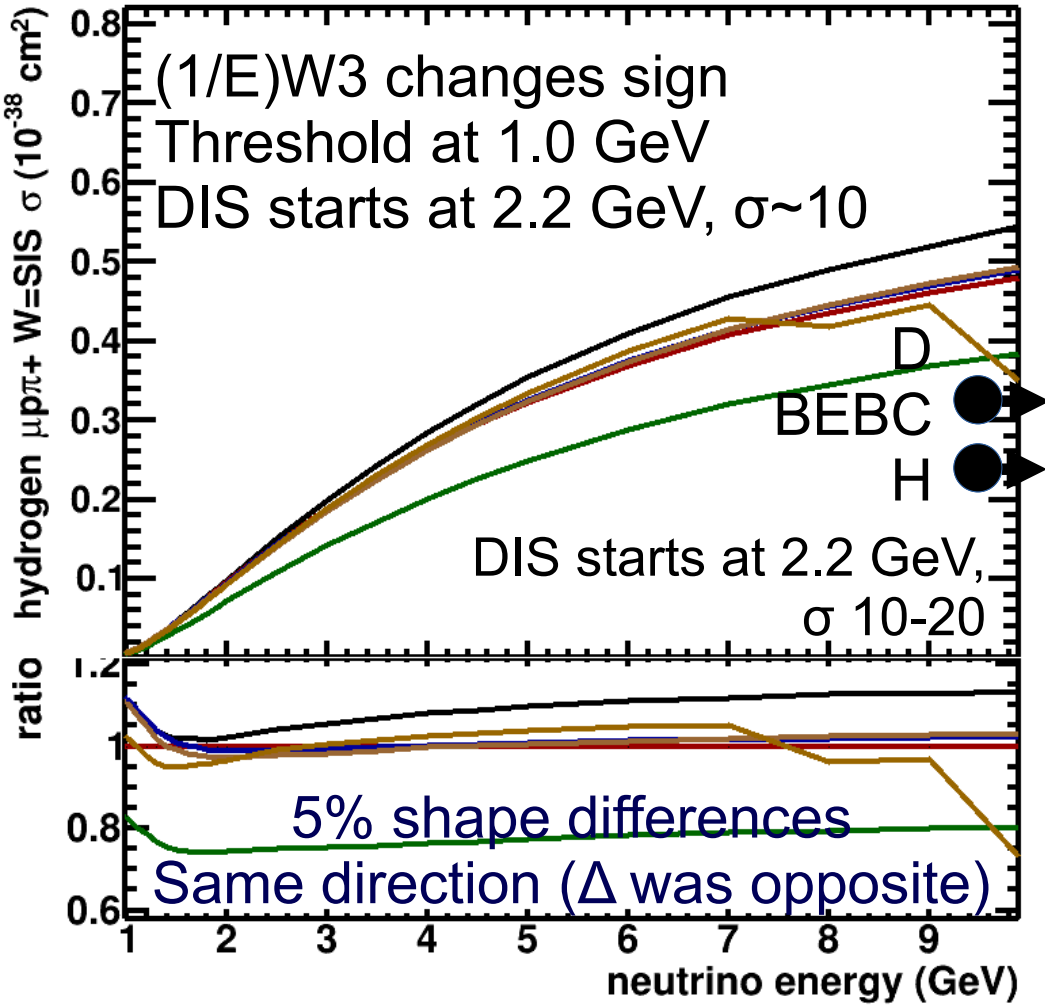
Pause. This is inclusive. NDGAr measures final state

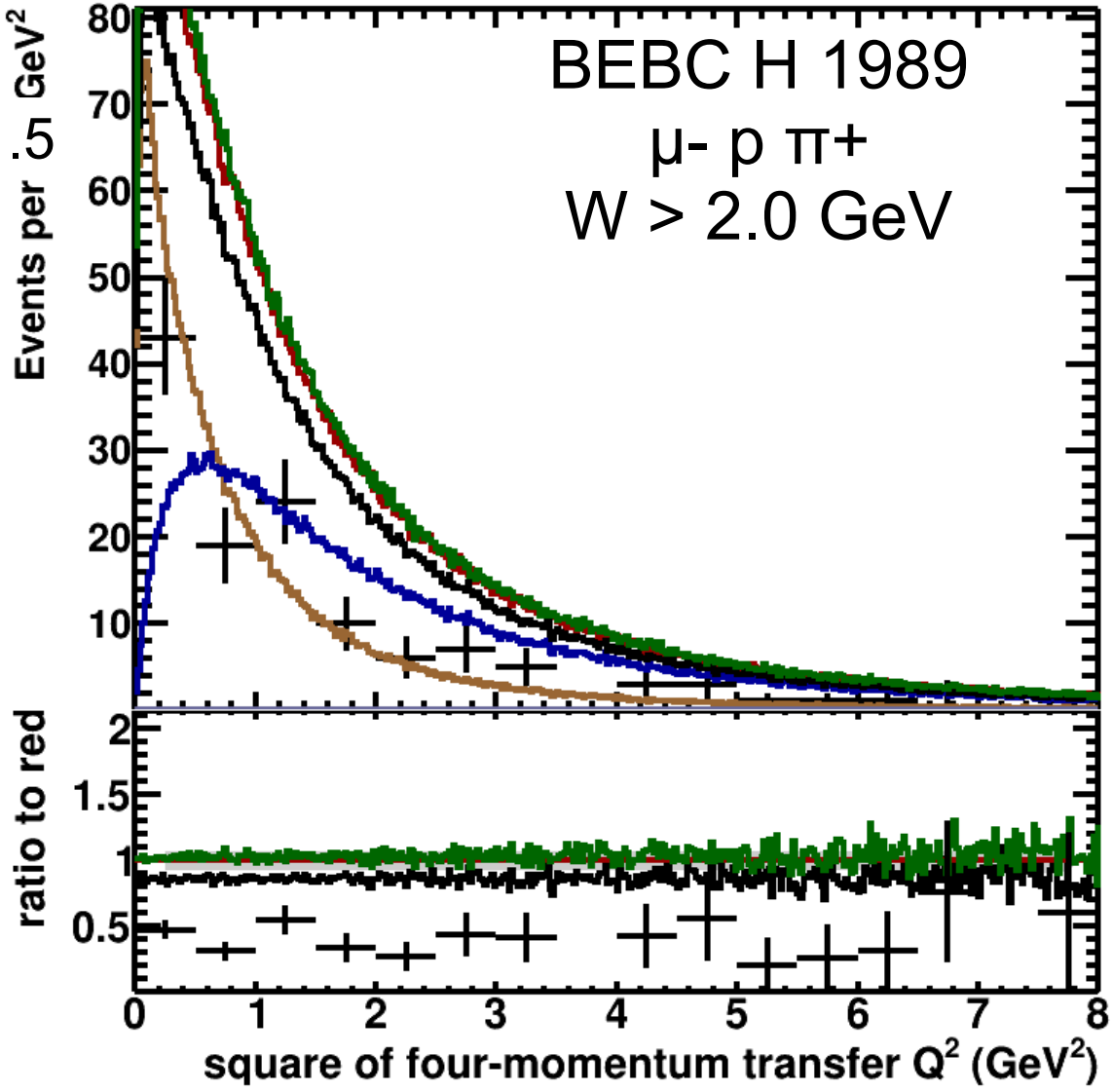
There is a sensitivity to explore here
Between MINERvA CH and Bubble Chamber H, D

These slides are the prescription to what model elements matter

1.4 < W < 2.0 SIS 1π+ region energy dependence







Q2 distribution in DIS
W > 2.0 one π+ (no Nπ)

Only GENIE components
Brown = diffractive
Blue = DIS

Need to check norm
Cant see ~10% norm error

DFR+DIS = too high

These data are the one the Rein diffractive paper a kind of PCAC test

What do we know about the Rein diffractive model?

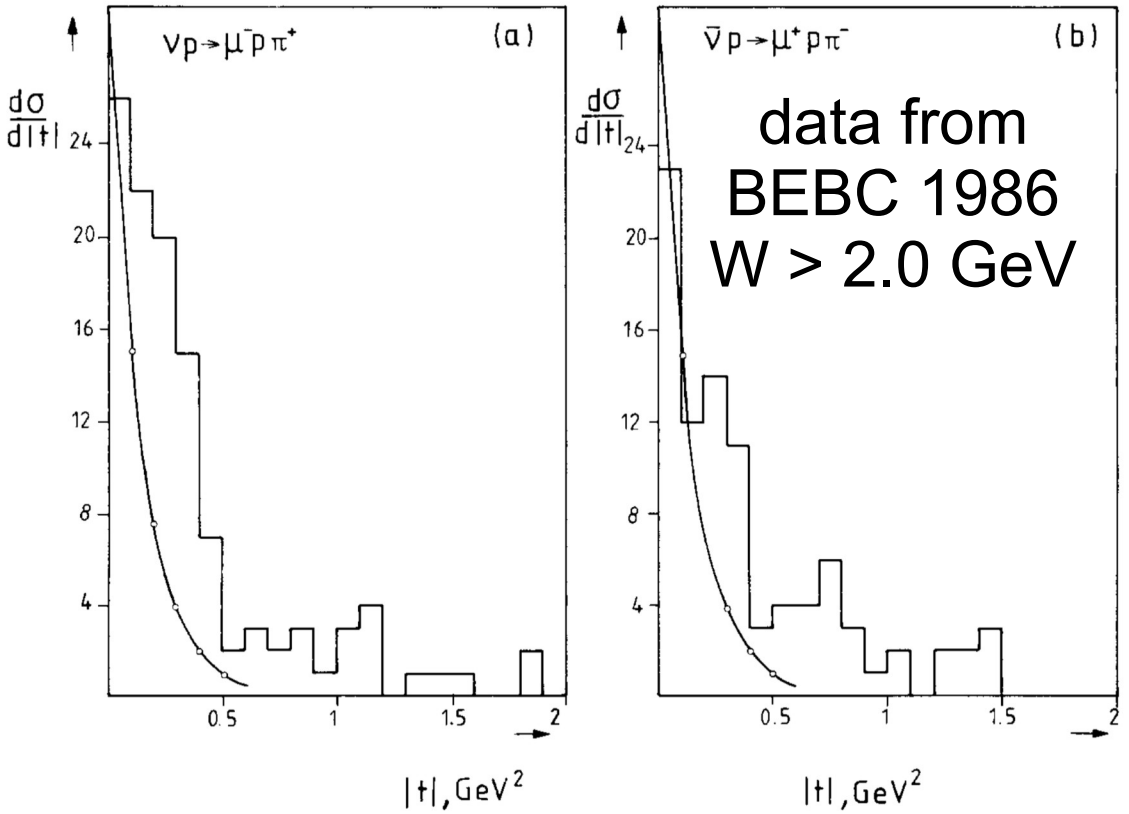


Fig. 7. t-distributions compared with data (from ref. [8]) (a) for neutrino reaction (b) for antineutrino reaction; $W > 2$ GeV, $b = 7$ GeV^{-2}, $m_A = 1.1$ GeV/c^2.

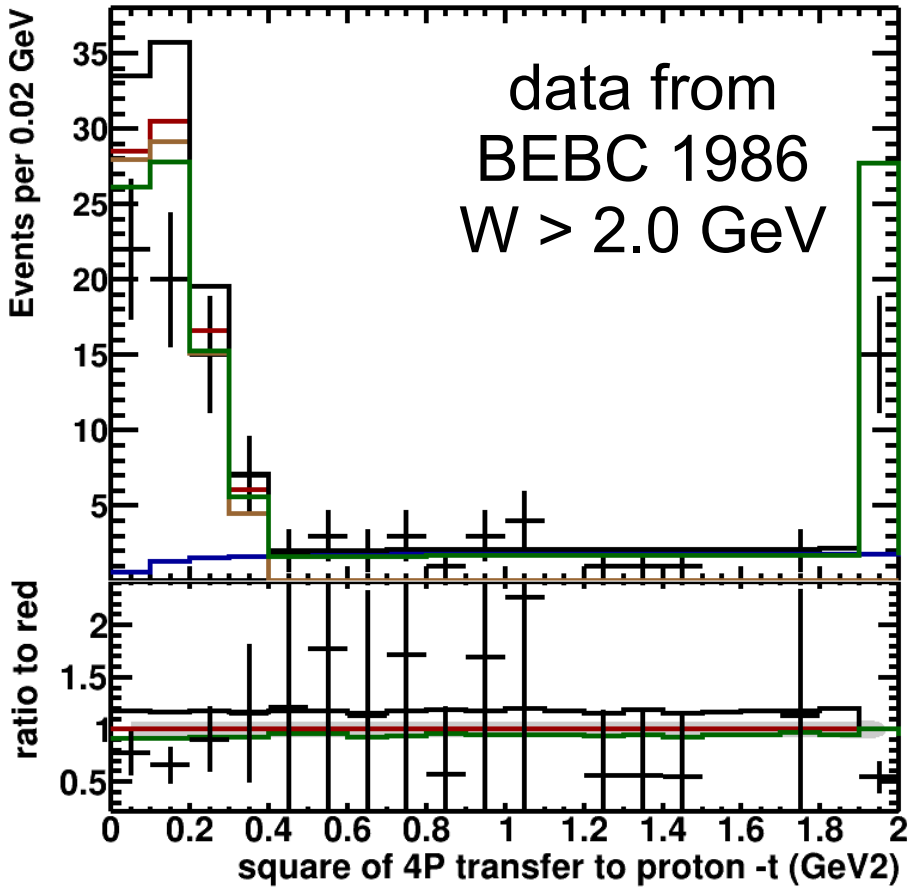
Complicated what Rein did
And what GENIE did
but these are literally the data

This distribution is
Arbitrary normalized
unlike previous slide

I should be able to make this
directly with right norm
but high teaching load.

Model D. Rein Nucl.Phys.B 278 (1986) p.61
Data P. Allen Nucl.Phys.B 264 (1986) p.221

Comparison of |t| to GENIE



This is close, but new as of the last 24 hours

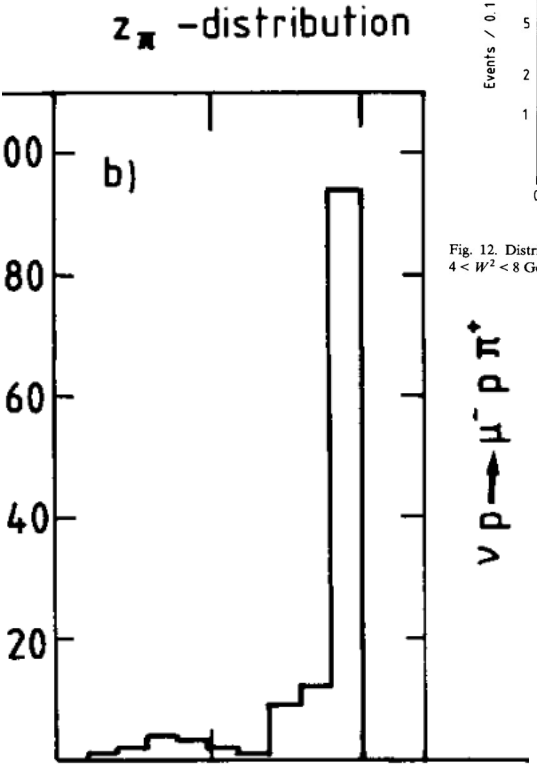
Basic overprediction appears split between diffractive and the DIS parts

Like the Q2 distributions there are things that are not quite right.

Need some time

Model GENIE's version Rein Nucl.Phys.B 278 (1986) p.61
Data P. Allen Nucl.Phys.B 264 (1986) p.221

Allen:1986 has six more W>2 distributions



Zpi = Eπ / (Ev-Eμ)

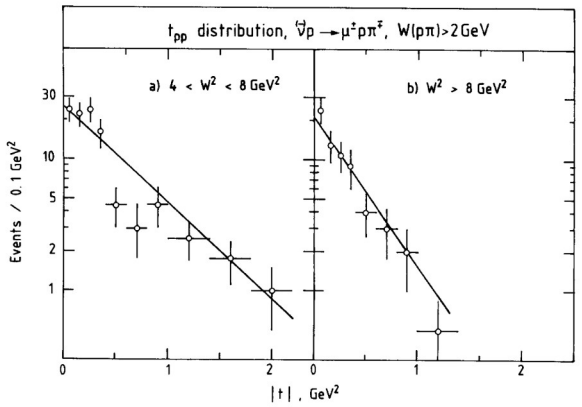
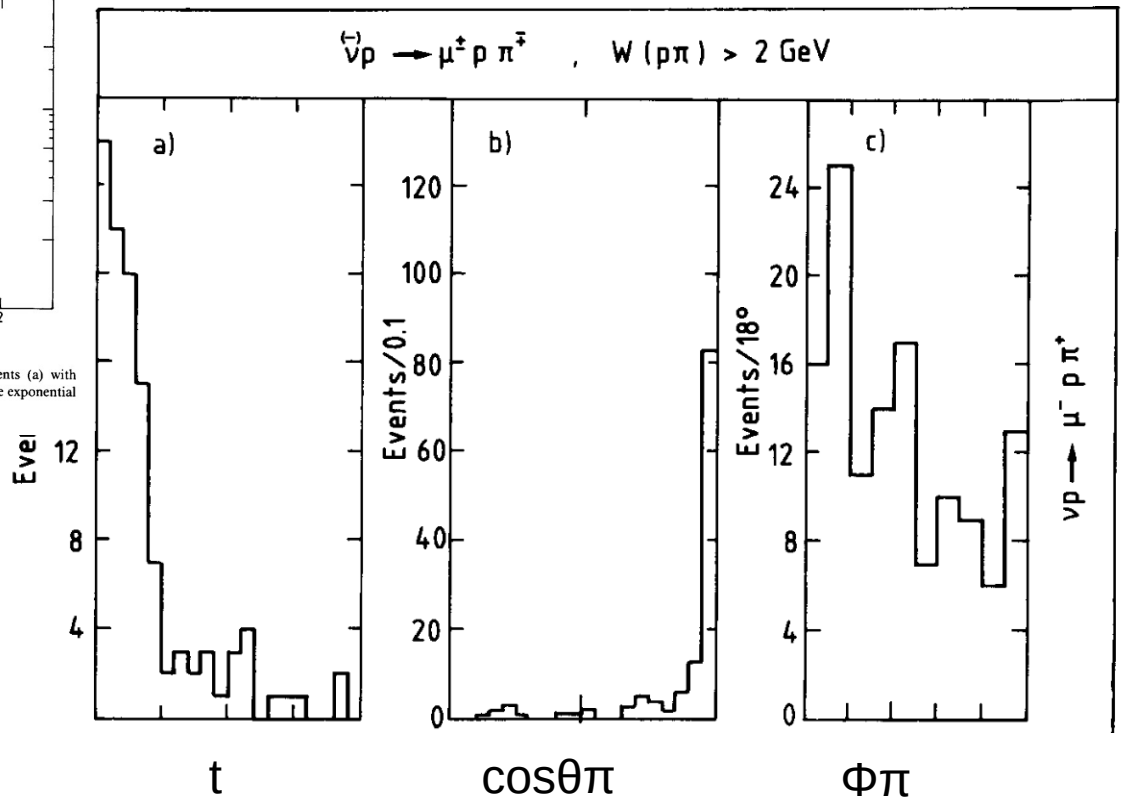


Fig. 12. Distribution of $|t|$ for the combined samples of reactions (1) and (2) for events (a) with $4 < W^2 < 8$ GeV^2 and (b) with $W^2 > 8$ GeV. The straight lines on these logarithmic plots are exponential fits to the data.



Plus anti-nu H → μ+ p π- samples

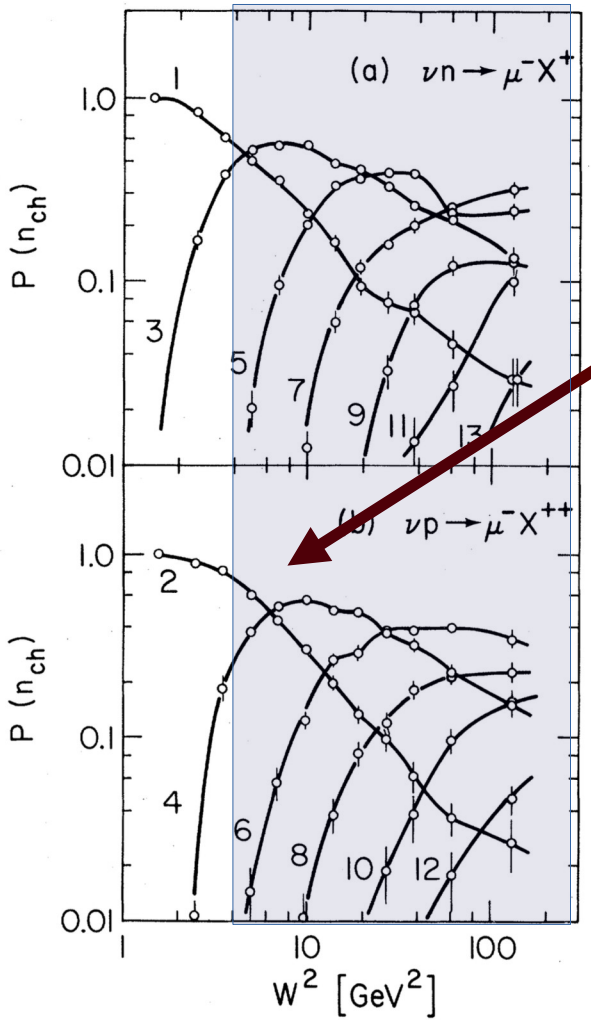


FIG. 3. Normalized topological cross sections versus W^2 for charged-hadron multiplicities. (a) $\nu n \rightarrow \mu^- + (n_{ch})^+$. (b) $\nu p \rightarrow \mu^- + (n_{ch})^{++}$. The lines are drawn between experimental points to guide the eye.

Hadronization was tuned to these and similar data, but ...

In that era of GENIE2 there was
No diffractive model for H
and not sure the status of coherent for D

Which apparently are half the single π rate for W > 2

So we have something to think about

D. Zieminska et al. FNAL 15' PRD 27 (1983) p. 47

Conclusions

BEBC H data has 7% systematics
Published a lot of basic distributions

Tuned versions of GENIEs can describe Q2 data
for W < 1.4 by construction
But overestimate single pion production at higher W

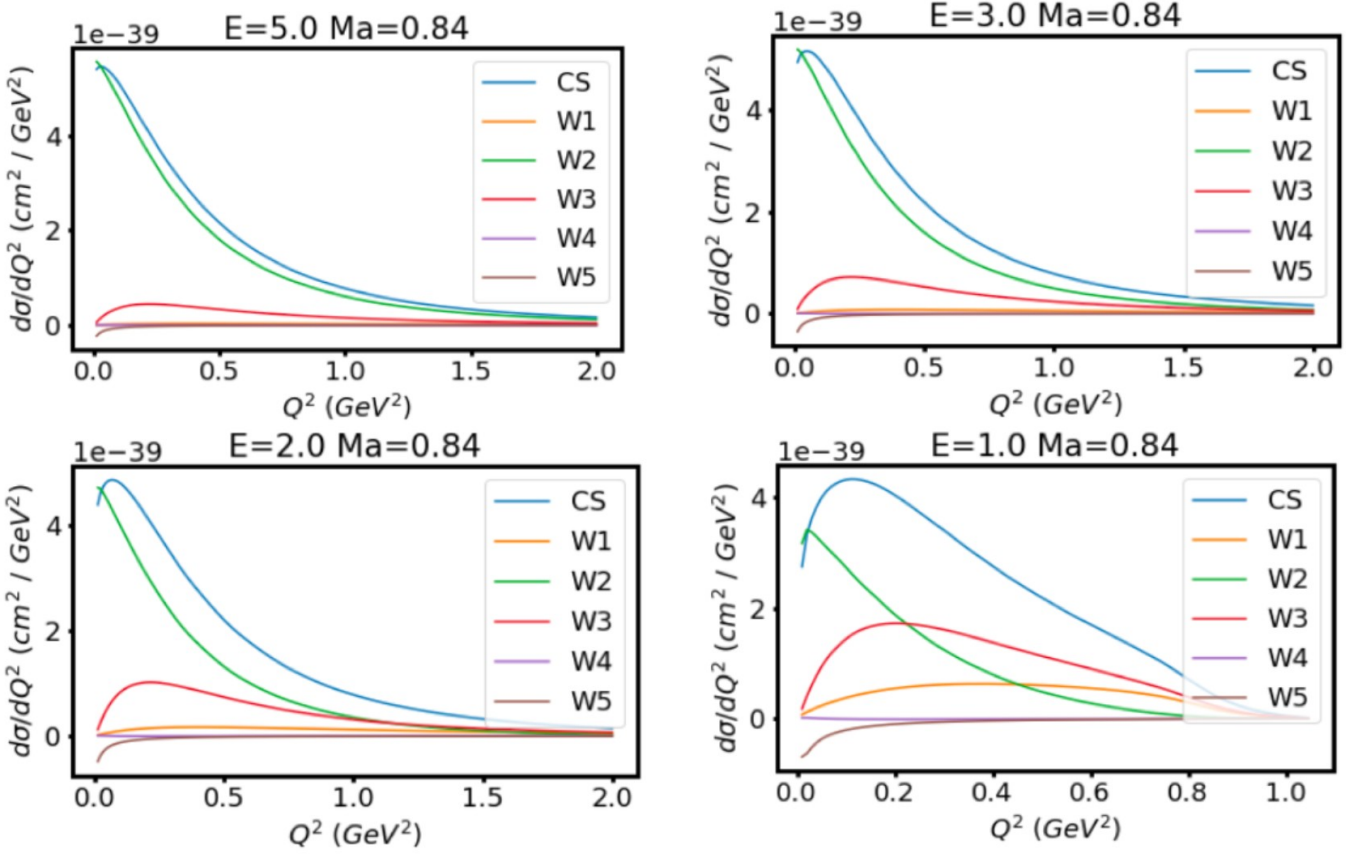
New inclusive data on MINERvA support GENIE3
Resonance model (and duality) at higher W and high Q2

Pretty clear what knobs we will want to make for DUNE

Slowed down by my teaching load since January, now...

Backups and old material

Constraining the W2 structure function to 7% syst



Structure functions get multiplied by factors of 1/E^2 and 1/E and 1

Form factors are inside structure fun

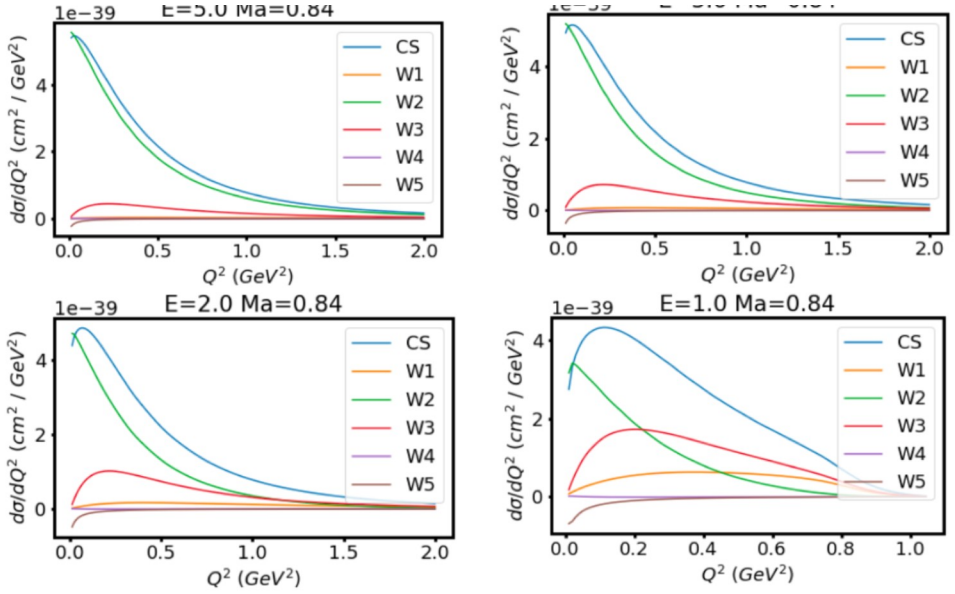
Kinematic boundary
High Q2 reach
Decreases at low E

Ishmam Mahbub MS thesis Duluth 2021
Delta model by Lalakulich and Paschos 2005

Constraining the W2 structure function to 7% syst

$$\frac{V_2}{3} = (C_3^V)^2 \frac{2}{3M_R^2} Q^2[q\cdot p + m_N^2 + M_R^2] + \frac{(C_4^V)^2}{m_N^2}\frac{2}{3} Q^2[q\cdot p + m_N^2 - m_N M_R] + \frac{C_3^V C_4^V}{m_N}\frac{2}{3M_R} Q^2[q\cdot p + (M_R$$

$$+ \frac{2}{3}\left[(C_5^A)^2 \frac{m_N^2}{M_R^2} + \frac{(C_4^A)^2}{m_N^2} Q^2\right][q\cdot p + m_N^2 + m_N M_R]$$



1/E^2 and 1/E and 1

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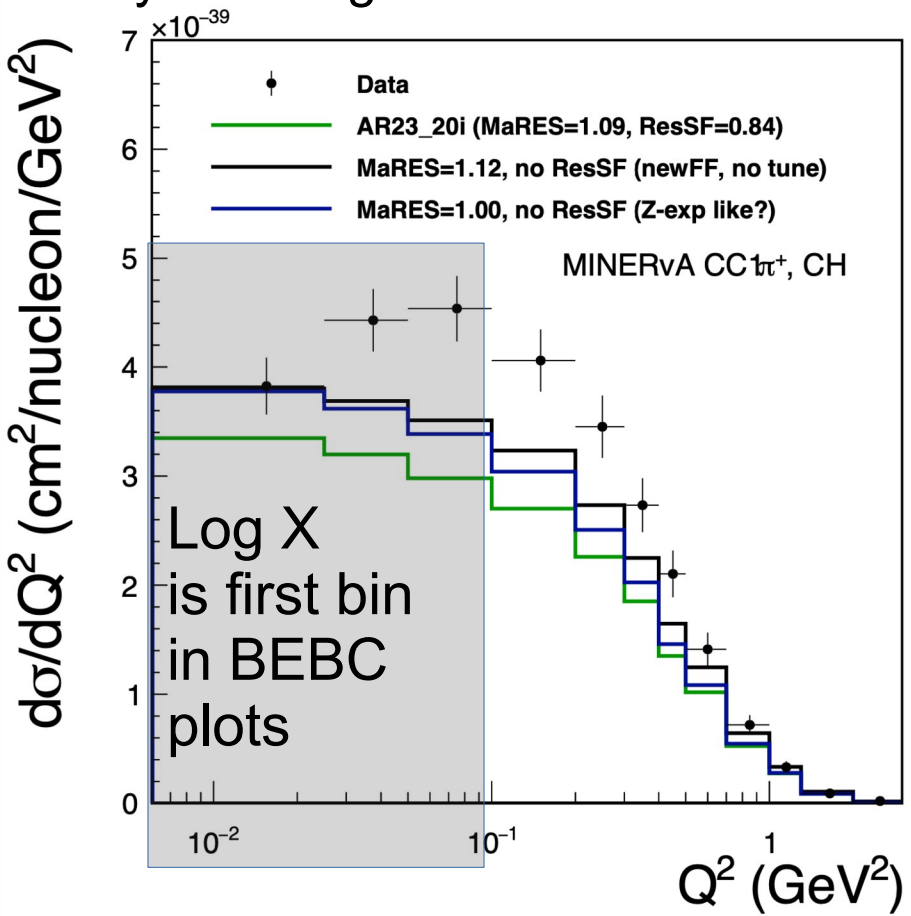
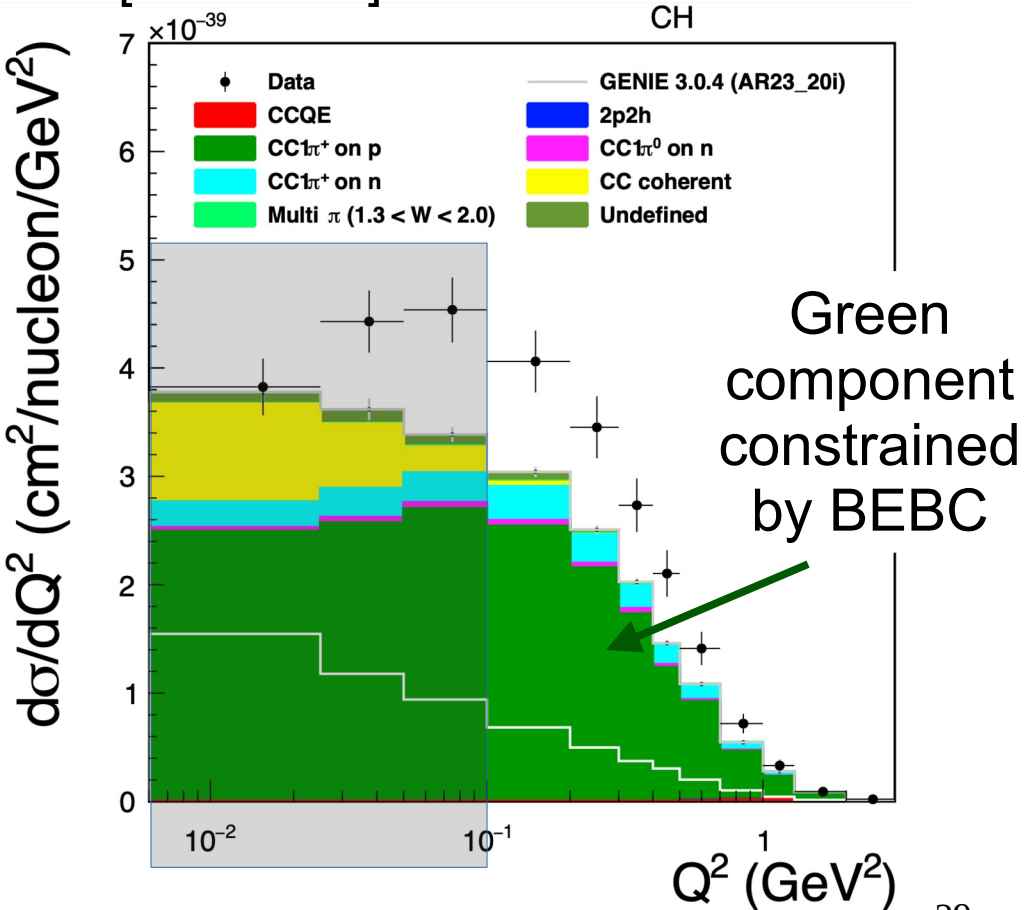
Delta model by Lalakulich and Paschos 2005

Compare to related configurations on CH & MINERvA

Plots by Jaesung Kim Data from Bercellie et al. [MINERvA] 2023: 35 < KEπ < 350 MeV





MidQ2 models 20-30% low vs MINERvA CH, <10% high vs BEBC H

Upcoming tasks

Jarek Nowak and I are trying to describe (for a paper)
How the new form factors relate to the non-Rein Sehgal framework
and to electron scattering data.

Some of the material here goes in that paper as illustration

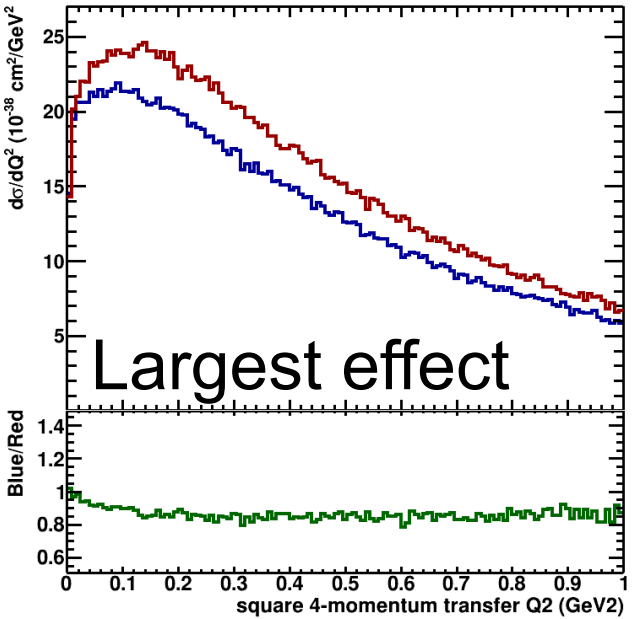
Finish something that looks like a fit + covariance for NIUWG

Want to try again the results on deuterium
ANL, BNL, FNAL, and the other BEBC WA25 papers

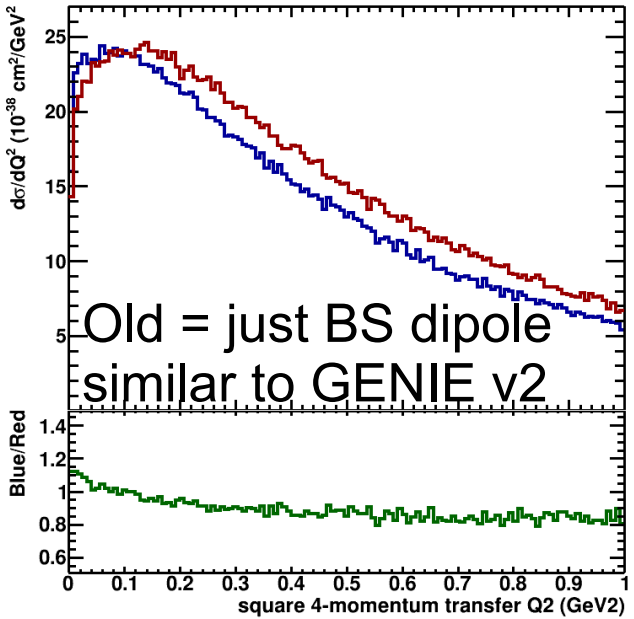
Pretty easy (lack of mental strain) to add the anti-neutrino Q2
except the anti-nu flux choices have 2-sigma tension

Separate the vector and axial form factor effects

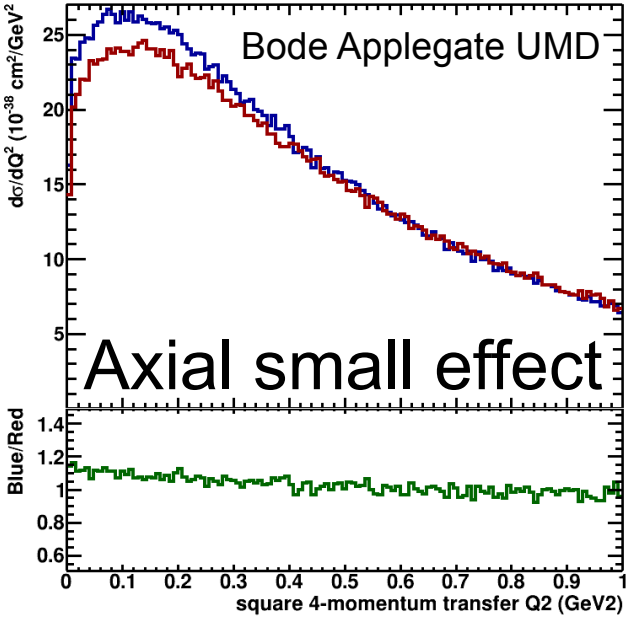
Red: default GENIE3 newFF Argon Δ++ 3 GeV no FS selection



Old Vector FF
But same MV



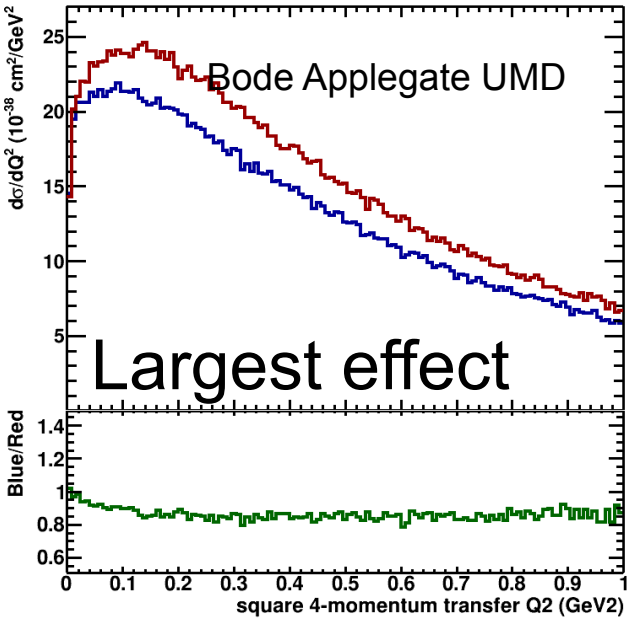
Old Axial & Vector
but same MA, MV



Old Axial FF
But same MA

Both V & A contribute to a low-Q2 rolloff vs. GENIE2

But the MA was tuned to data with old Vector FF



Old Vector FF
But same MV
MA needs to go down

New VectorFF from Lalakulich
Obtained from LT analysis near Delta peak
Old axial MA tuned by Kuzmin and others.

New FF are too high because MA needs to be retuned to data, or something.

Options: Graczyk and Sobczyk did it
Julia Tena Vidal and GENIE sorta did it
changed 15% normalization and 3% MA

Use the QE Zexpansion Meyer et al.

Vector form factors

Still trying to isolate what Lalakulich form factors are like she extracted them from (e,e') data in the Delta region working with Jarek Nowak on that

They should not necessarily look like the QE form factors

Lalakulich got them from data, but how do they compare to more recent work on QE vector form factors ?

Do they look like the QE form factors ? Not sure yet. (Should they?)

ANL and BNL plots

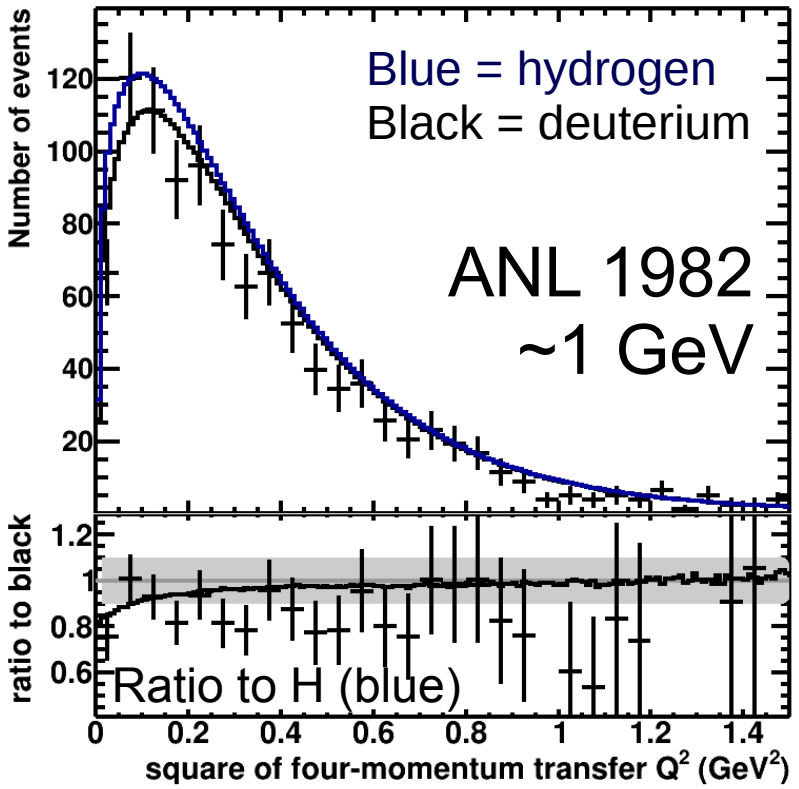
These were done before working on BEBC
They are still approximately correct

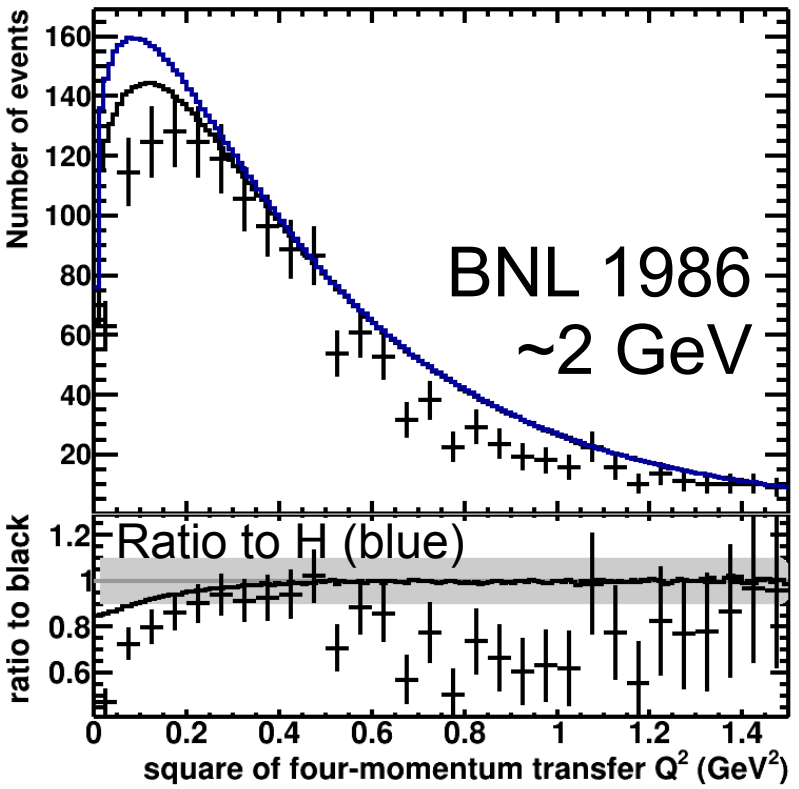
But many adjustments to backport from BEBC experience

Could be surprises.

And there is a spline problem that comes from a surprise GENIE build feature that requires developers to make clean was few % and fixed already for BEBC

G18_02a (RFG+hA) with new (default) form factors



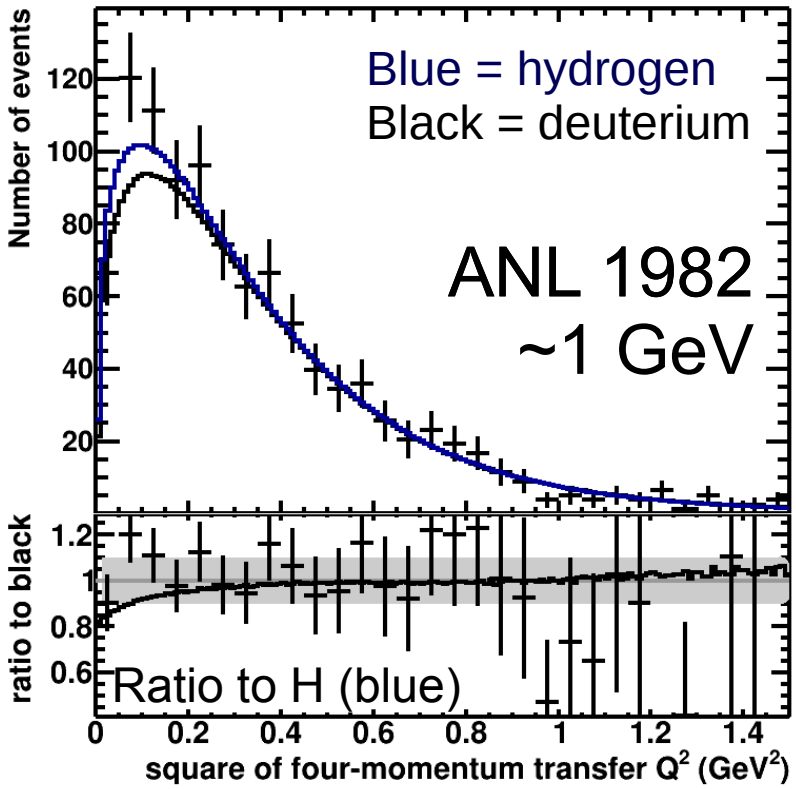


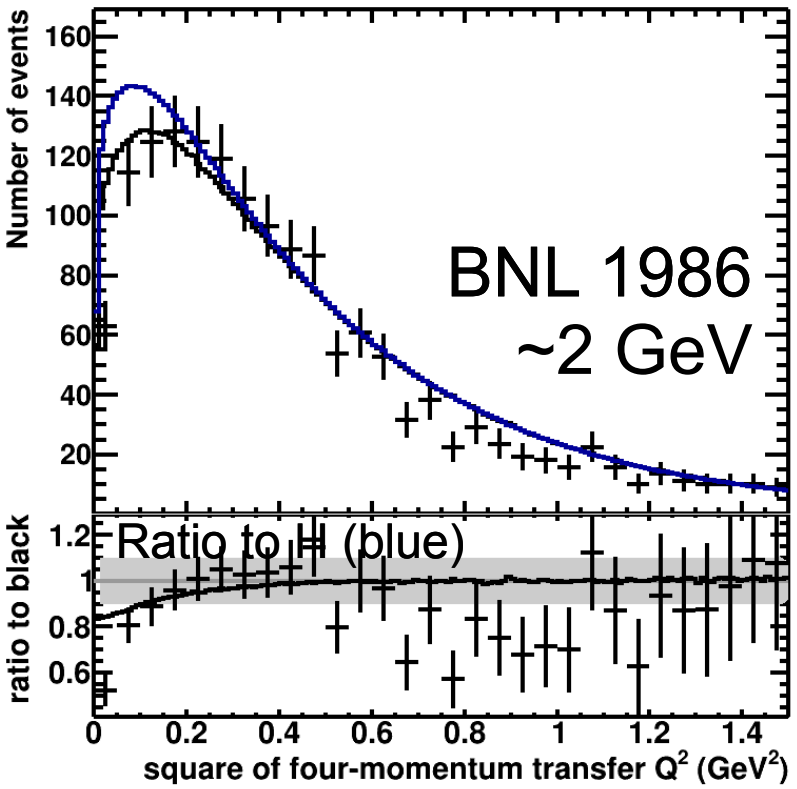
Showed this last time. Similar discrepancy to BEBC despite energy.

Hay! Blue has Diffractive but Black does NOT have coherent. Should it?

Naive test, true W(~~p~~d pi) > 2.0 . Need to test assuming reco proton

G18_02a (RFG+hA) with old Rein Sehgal Form Factors





This prediction is a lot lower. Hard to tell by eye, but the shape is different.
MA=1.12 fit this model to these data, before the Callum+Phil modification.
and according to people not literally using GENIE (Naumov et al.)

$$\frac{\overline{L}_{\mu\nu}\overline{W}^{\mu\nu}}{E_\nu^2} = \frac{1}{E_\nu^2}\left[W_1\left(Q^2+m_l^2\right) - \frac{W_2}{2}\left(m_l^2+Q^2\right) \mp \frac{q_0 W_3}{2M}\left(m_l^2+Q^2\right) + \frac{W_4}{M^2}\left(\frac{Q^2 m_l^2 + m_l^4}{2}\right)\right] + \frac{1}{E_\nu}\left[-2q_0 W_2 \pm \frac{W_3 Q^2}{M} - \frac{W_5 m_l^2}{M}\right] + 2W_2$$

Are deuterons (from the coherent/diffractive process) Reco'd as protons ?

Fermi motion and removal energy effects

Some spectator neutrons have enough momentum to Fail the 3C requirement.

There is some FSI, GENIE predicts some, its uncertain

Shape of flux will show up, but will still be small

Many structure function terms contribute, not just W2