Hydrogen single pion data in Δ region

Genie

UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

vs.

Who will win?

GENIE vs BEBC H single pion data, who will win?

The GENIE model for resonances, especially form factors
has become untethered from H and D data
and what it does is not really documented

The BEBC Q2 data on hydrogen at 10 < Ev < 200 GeV
is a powerful dataset with ~7% systematic uncertainty

GENIE vs BEBC H single pion data, who will win?

The GENIE model for resonances, especially form factors
has become untethered from H and D data
and what it does is not really documented

The BEBC Q2 data on hydrogen at 10 < Ev < 200 GeV
is a powerful dataset with ~7% systematic uncertainty

1π anchors resonance rate and pion multiplicity ND constraints

The combination implies uncertainty in the energy dependence
that we should be applying to DUNE and within nusystematics

Technical notes available (skip this slide)

Many components to this nearly complete work

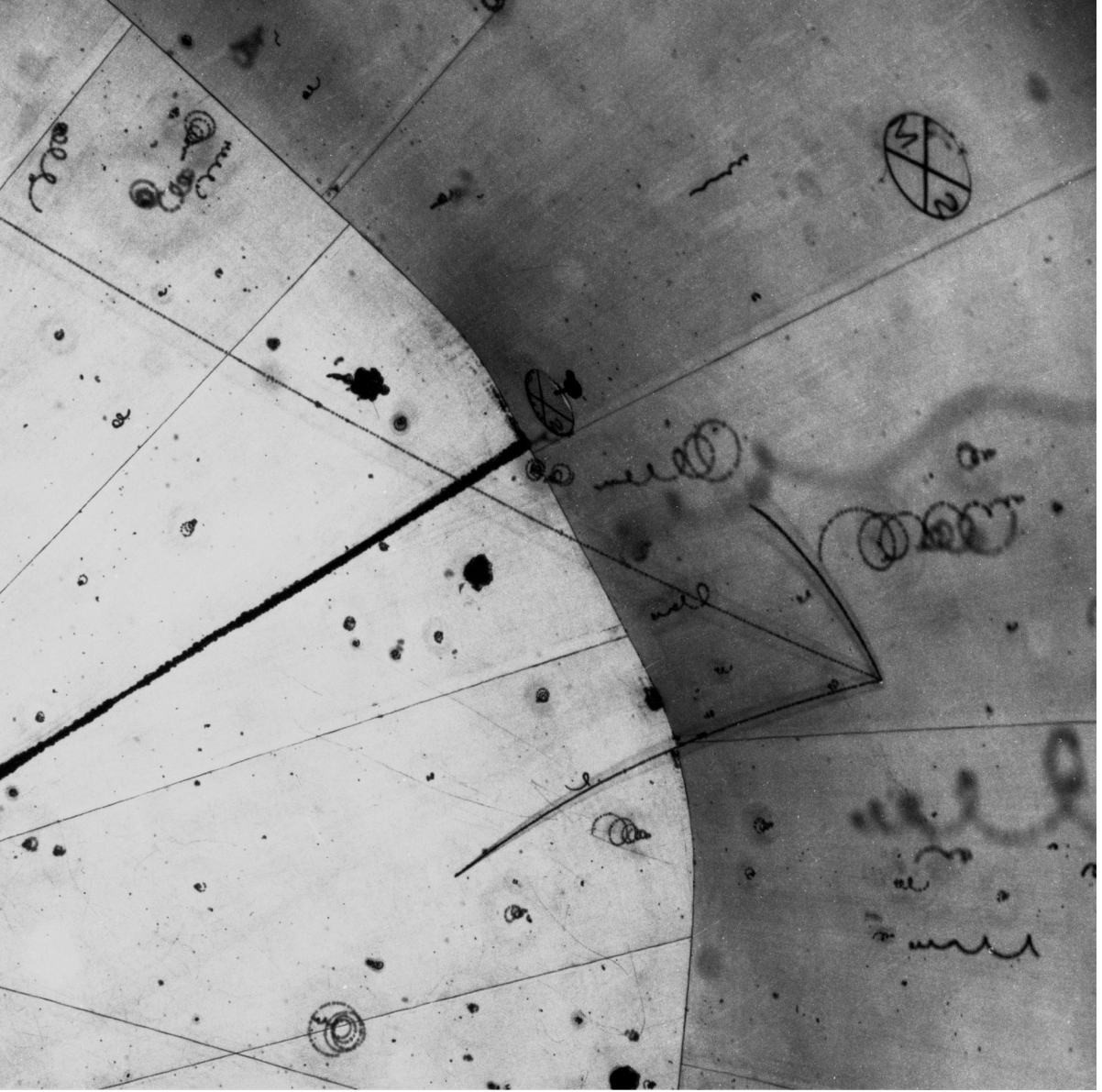
Main tech note in MINERvA docdb:32216

Side note on Diffractive process MINERvA docdb:32152

Side note on SIS region MINERvA docdb:32234

Studies by Bode Applegate and Ben Utt: 30791, 32249

Energy dependence MS theses by
Ishmam Mahbub and Asit Srivastava



Three prong event on H

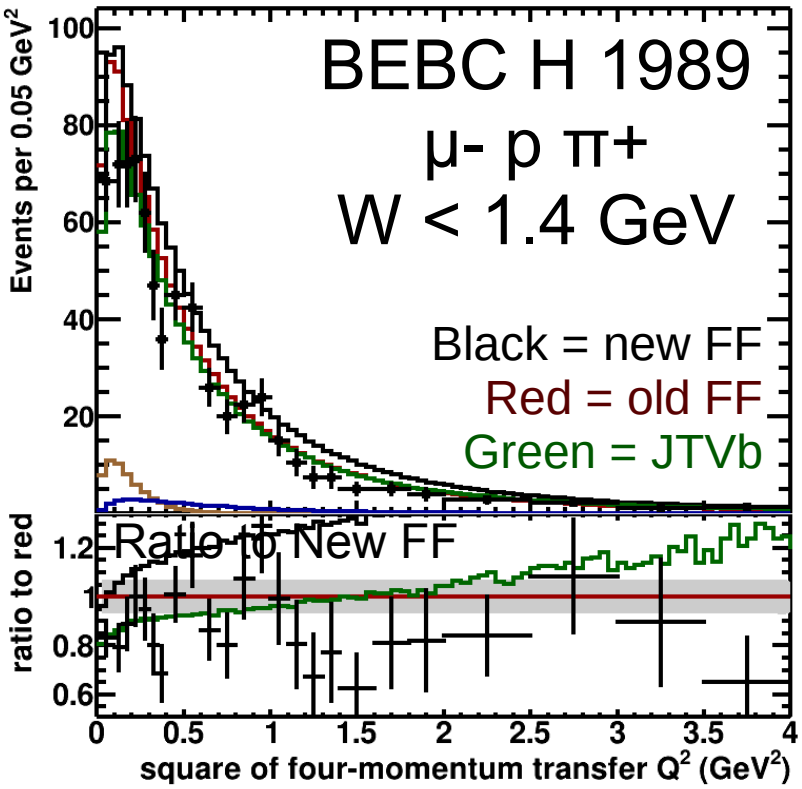
This one from ANL 1970
Featured in Physics Today
Todays analysis BEBC 1980s

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

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

No missing P, no neutrons
No FSI, no backgrounds
95% scanning efficiency

Before going into the details, this is one end result



GT Jones WA21 ZPhysC 43 (1989) p.527
Rebinned for resolution, statistics

1056 events on H from Jones:1989
reevaluated normalization on σ
Transfer norm to Q2 event rate
add estimated Q2 smearing effects

GENIE 3.4.0 with several configs
no nuclear effects for hydrogen
no neutrons in the final state
diffractive and DIS components

Cross section at 30 GeV is all from
The W2 structure function
Practically constant with Ev

Need the best BEBC data σH for one pi+ W < 1.4

Two papers, two normalizations presented, effectively two fluxes

Allen:1986 takes the flux from beam monitors in wide band beam
9% uncertain on integrated flux plus acceptance errors

Jones:1989 7% bootstraps the integrated flux using inclusive narrow band beam σNe/E and measured σH/σNe in WBB

I updated σNe/E to use Seligman's "world average" σIsoscalar/E
They seem independent & consistent, so averaged the two results.

Final σH (one pi W < 1.4) = 57.2 ± 1.8 stat ± 3.9 syst x 10-40 cm2

Transfer the normalization from σ to Q2 event rate

Final σH (one pi W < 1.4) = 57.2 ± 1.8 stat ± 3.9 syst x 10-40 cm2

GENIE has a value for this for every model configuration
Energy dependence is so mild, flux weighted average is precise
For example, old form factors give 66.5 x 10-40 cm2

Since the Q2 event rate are the same events
(and acceptance effects are approximately flat)

so ok to scale GENIE to the integrated Q2 data so that
The ratio (1.16 in this case) between GENIE and data is preserved

(Scale can be reused for other W regions, I think, not sure)

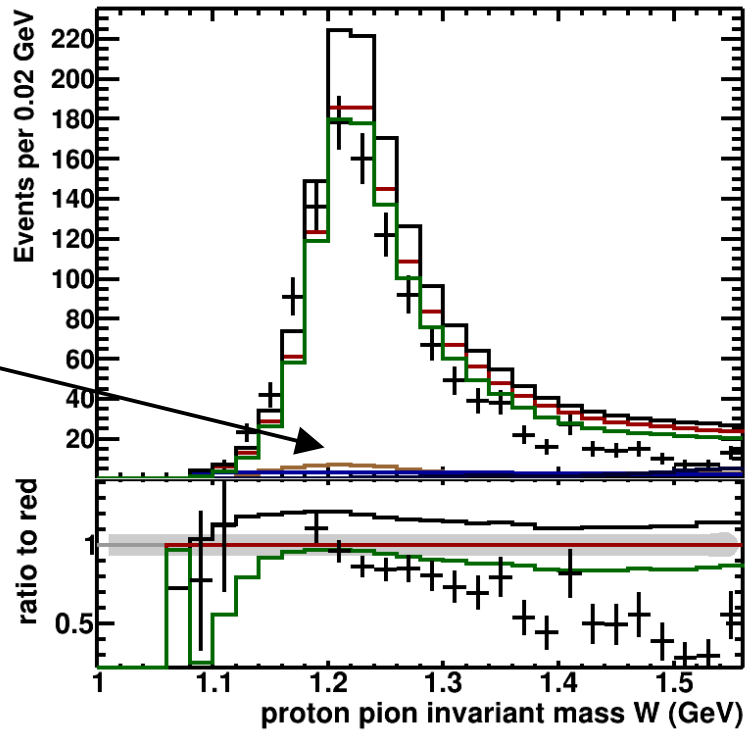
Check the uncertainty on the W(pπ) cut

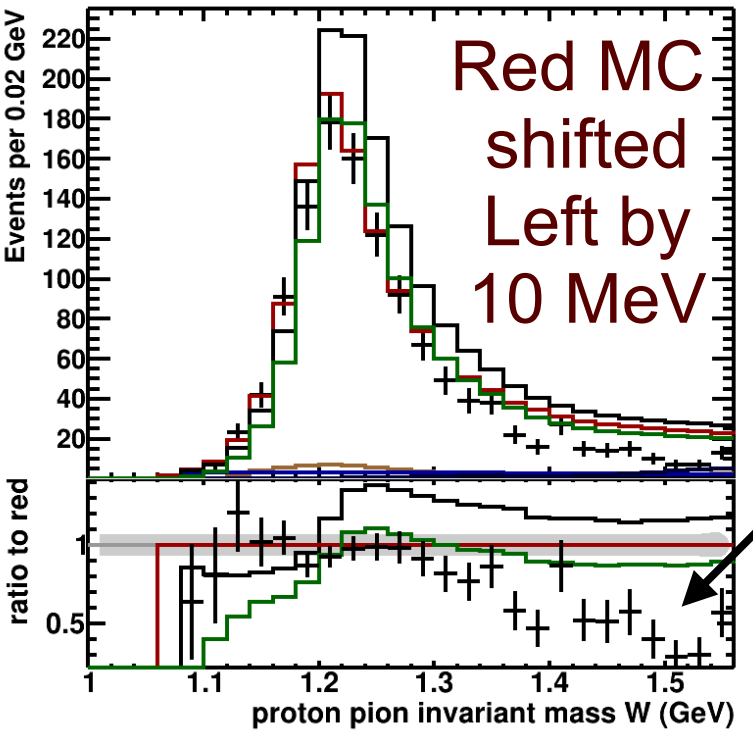
For deuterium, nuclear effects might make this a tricky cut

Hydrogen is ok except data peaks at 1220 not 1232 MeV

Jones WA21 1989

DIS DFR nonΔ too small to see



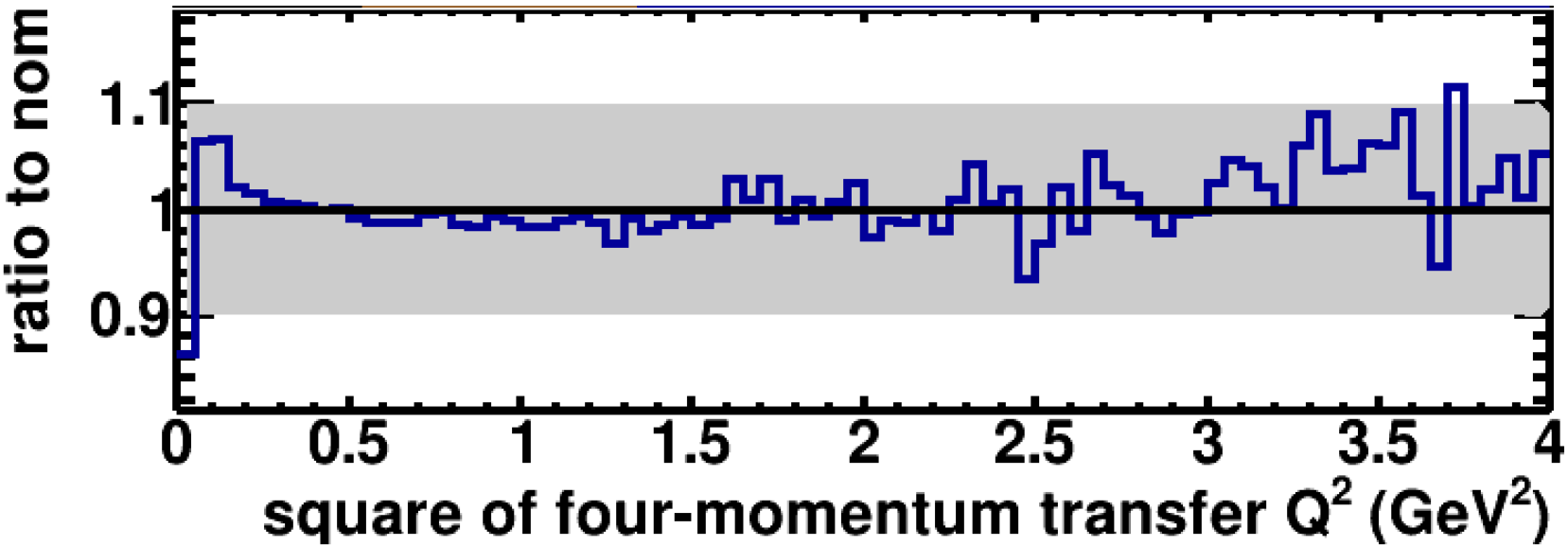


Δ++ tail MC too high

Real or 3% bias in proton pion momenta ? Only 1% on selection

Check smearing effects and choose binning

For the fully inclusive process (for σ/E) the resolution on Q2 in Jones:1987 to be 20% at high Q2 and 0.02 GeV at low Q2



gray ± 10% guide the eye

It narrows the peak? The three-prong sample should be better!

Hint that Emu resolution becomes dQ2/Q2 ~ 10% at high Q2

Using this “worst case” and forward fold !

Other systematics via GENIE sample (can skip slide)

A 0.5% magnetic field bias has negligible effect.

If a large = 3% Ehad bias solves W bias
implies some additional Q2 bias, not evaluated

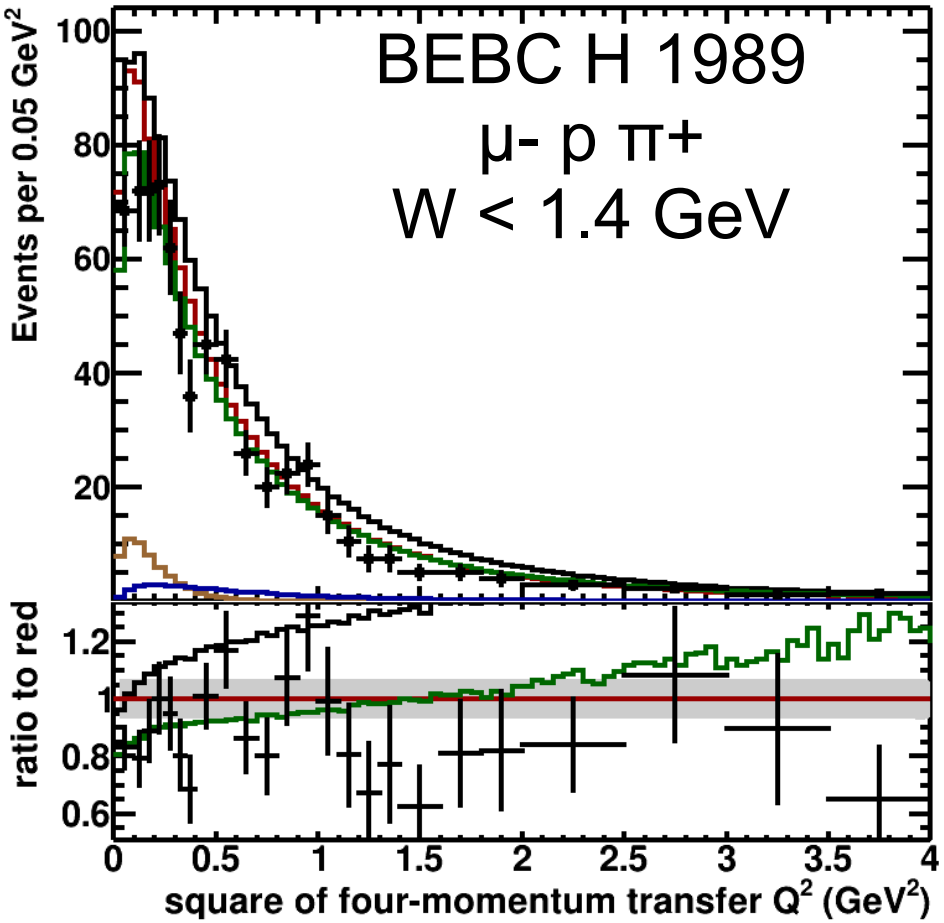
Flux shape has negligible effect
Tried NuMI/MINERvA-like distortions at peak and in tail

Didn't try hard to reconstruct resolution from Ehad and Emu
Except that Q2 resolution ≈ 2 x Emu resolution

Did not try to reproduce the 3C (missing momentum) constraints
important for neutron final states in D, not for H

Did not try unseen inner Bremsstrahlung or radiative photon

Here is that first plot again and model descriptions



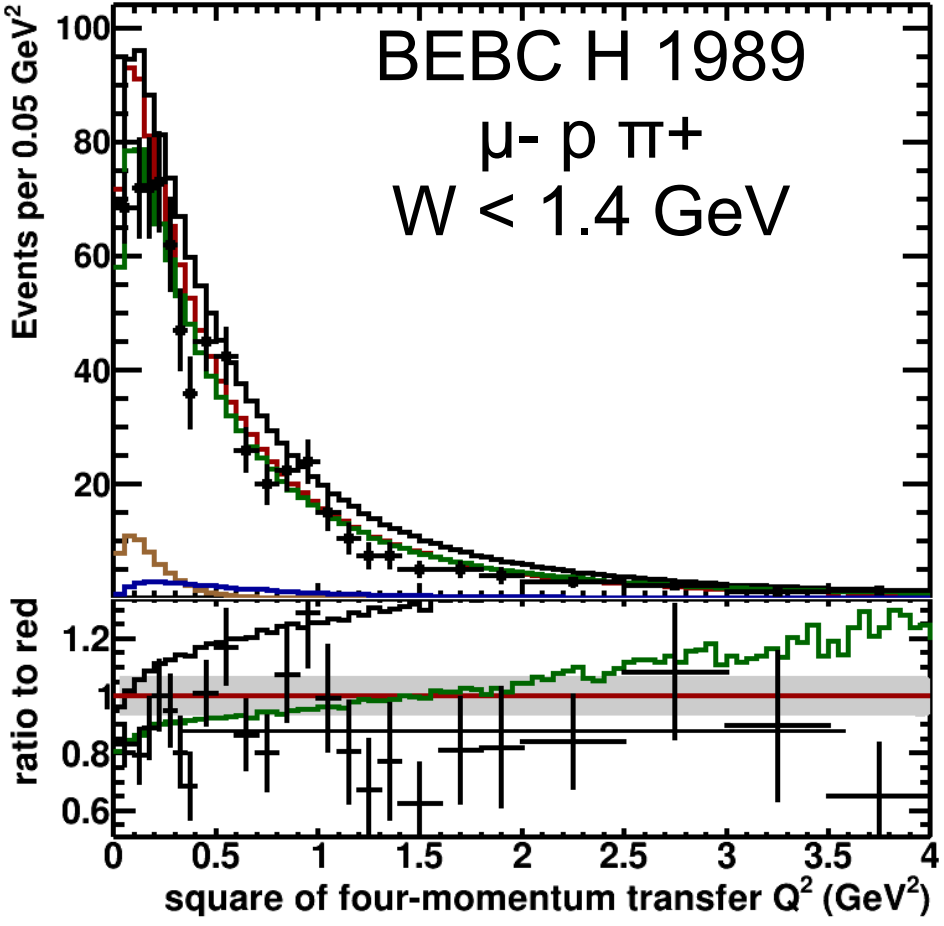
Note: lowQ2 rolloff feature

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

The red line is an ok fit, green on the other side of ok



Black new FF is G18 out of the box
Red is old FF, GENIE v2
Green is JTVb tune like AR23_20i

Lower, black horizontal line in ratio is fitting the residual data/MC

Constant 0.88 is an ok fit
Pvalue ~ 0.05 including flux error
Slope+Intercept fit is NOT better
Meh P-value mostly the jumpy data

JTVb is worse χ2 by 2 units

Who needs a new, best tune? Want best uncertainties

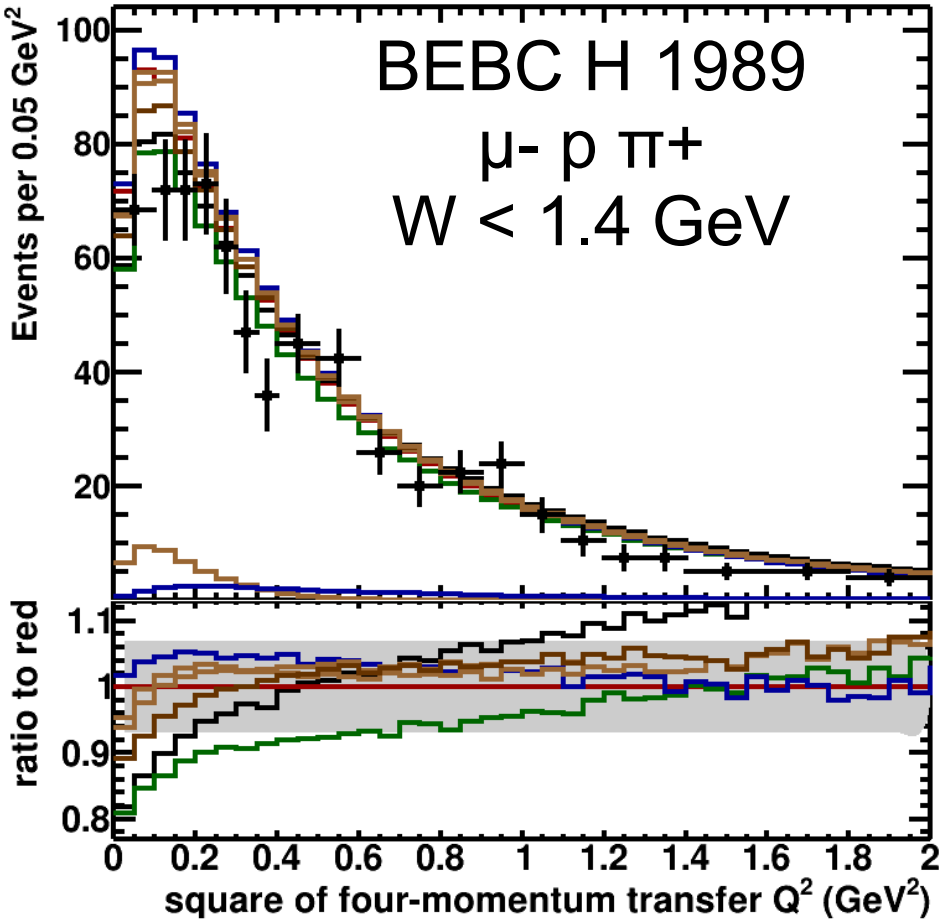
Taking an unexpected point of view in the next few slides.
I want to tune to the red model (old FF, tuned GENIE2-like)
in the range 0.3 < Q2 < 1.5 GeV2
as if the GENIE2 model is Nature, mock data.

What are all the ways to modify GENIE3 to look like Nature
and how does it compare to what the red model really does?

Don't have fitting apparatus yet, doing it by hand this time

Data is plausibly described, learned Q2 < 0.3 is weird
want creativity with model before more work with data

Zoom in & plot other pseudo-tunes of the black model



Red is old form factors
"tune" is roughly to red (not data)
So I didn't plot data in ratio here

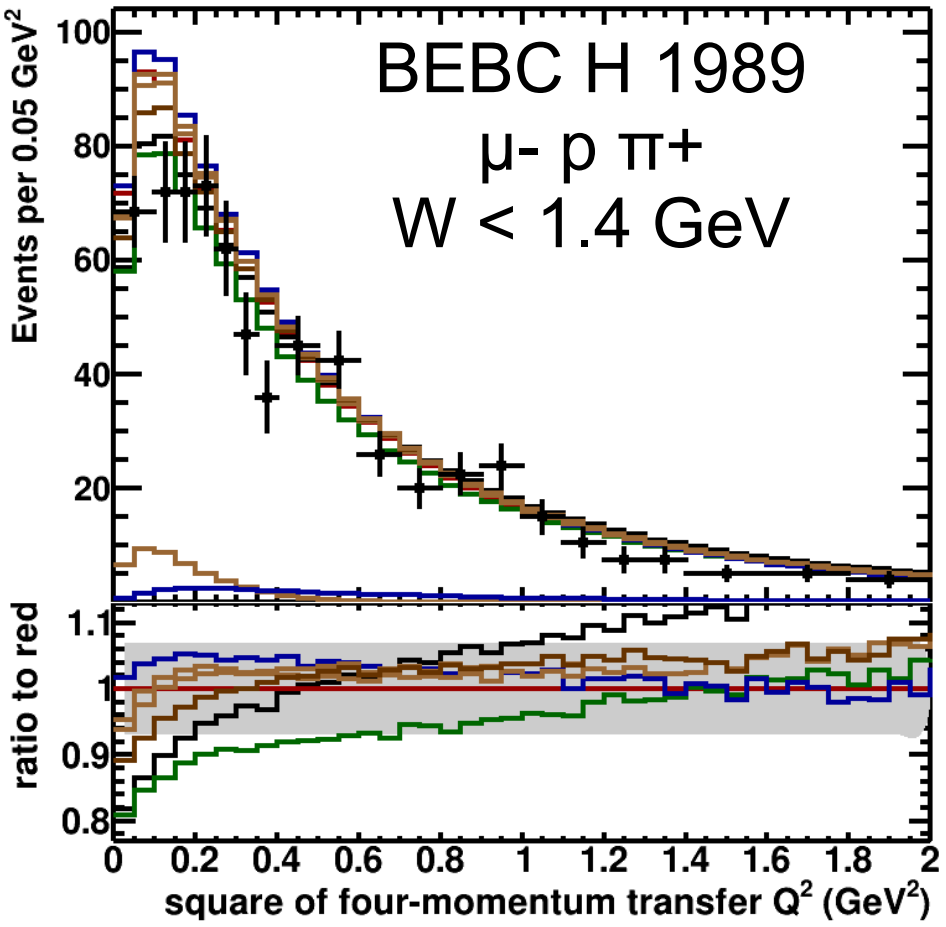
Black line is base scaled 0.85
Green is Tena Vidal 02_11b

Lt browns: MA=1.0 or MV=0.7733
Dk brown: MA=1.0 & half diffractive

Blue: QE Zexpansion axial FF

Most line up in middle, all diverge for Q2 < 0.3 GeV2

Take-home message we already probably knew



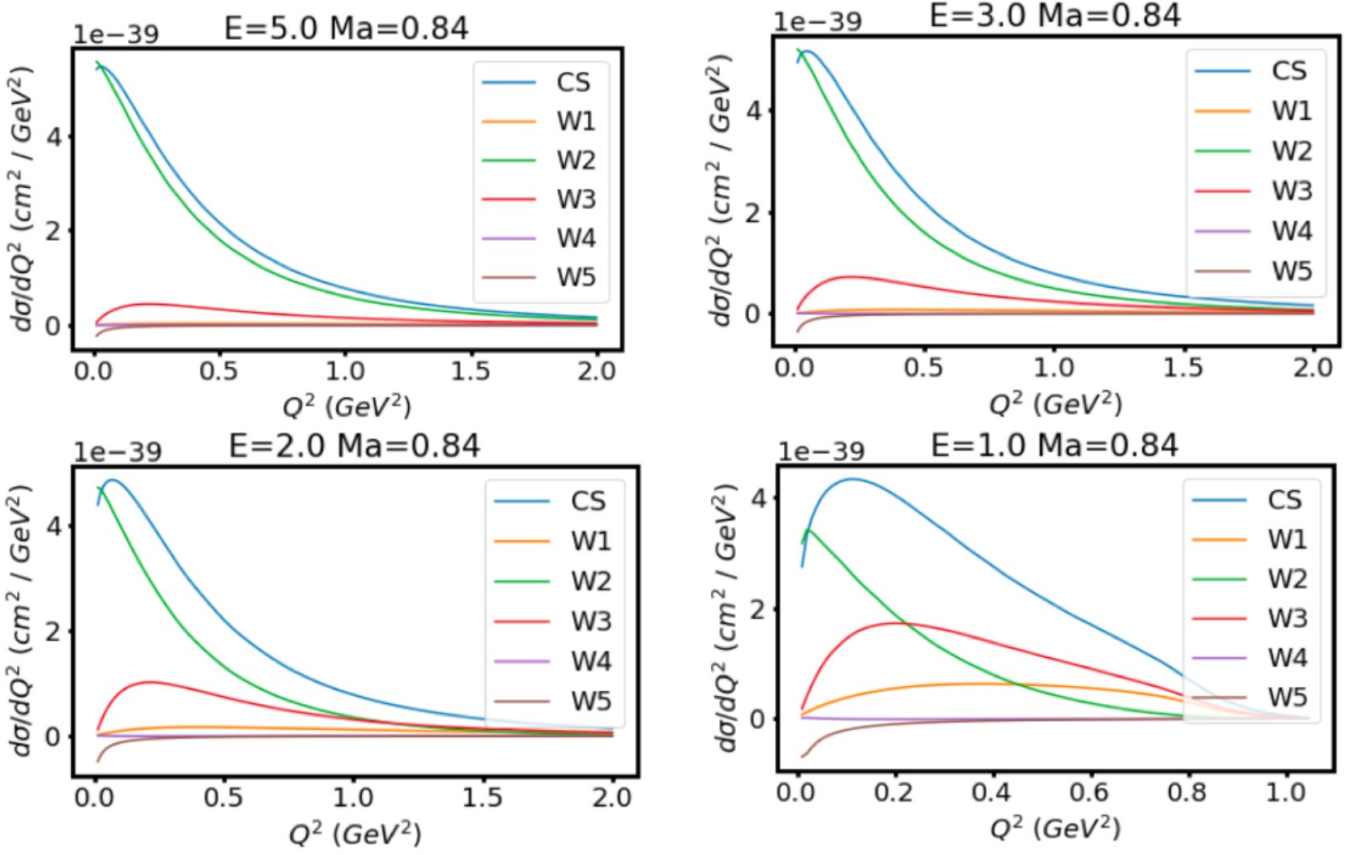
If Red was Nature

Multiple parameter combinations
Will successfully describe nature.

These data constrain them
just b.o.e'd these numbers so far
MA 0.99 ± 0.05ish, MV 0.76 ± 0.04
Zexp + Diffractive + DIS scale.
want some kind of covariance

Nusystematics needs parameters
and some version of the covariance
probably simplified. Ugh.

Constraining the W2 structure function to 7% syst



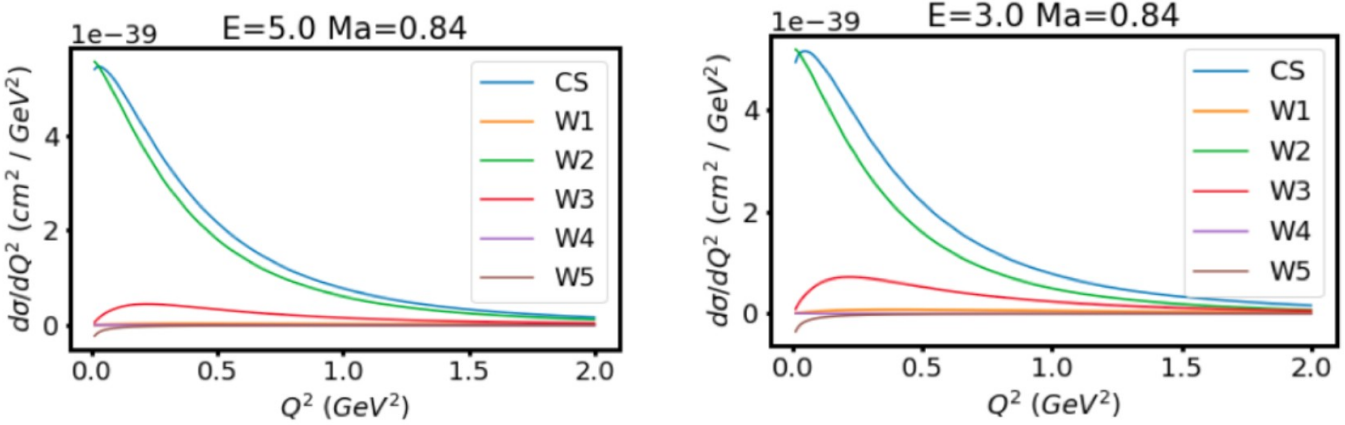
Structure functions get multiplied by factors of 1/E^2 and 1/E and 1

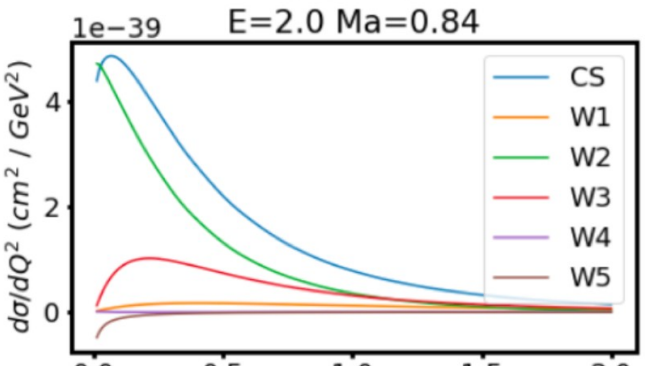
Form factors are inside structure fun

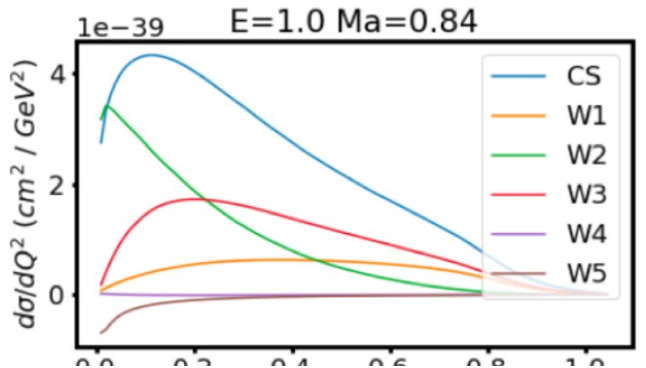
Kinematic boundary
High Q2 reach
Decreases at low E

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

Goal is to go beyond form factors as only uncertainty







Even the W2 structure function all that remains at high energy on its own is complicated This is simplified form factor C5V=0 but really its not

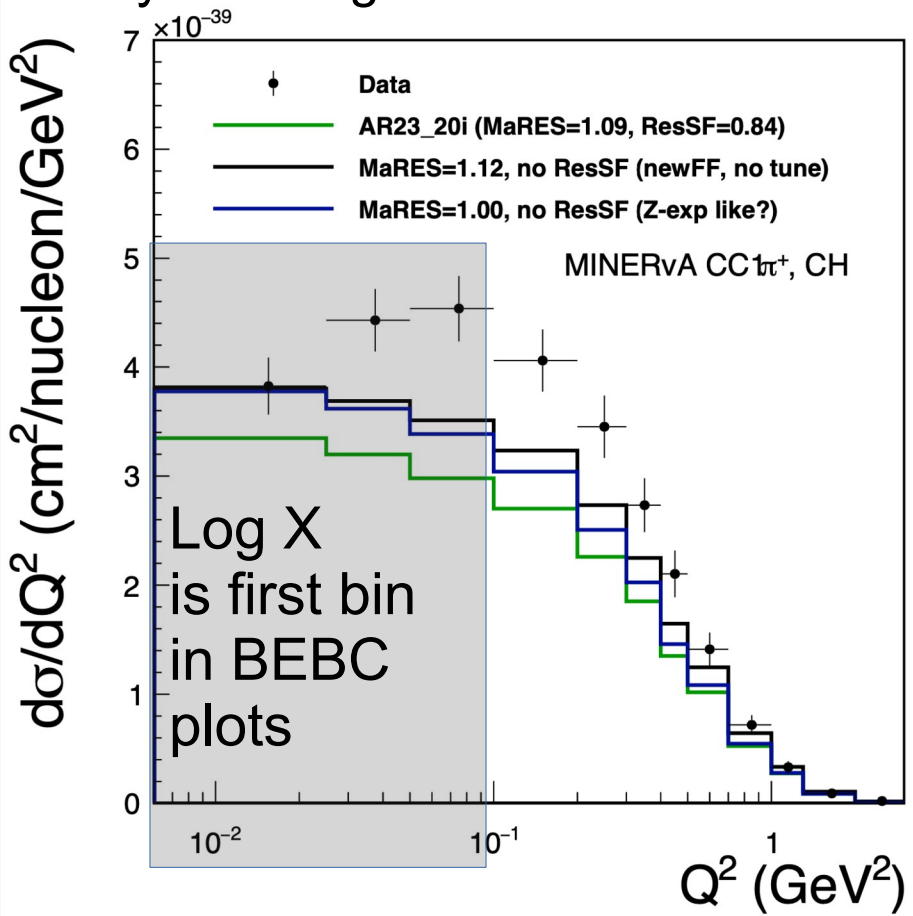
$$\frac{V_2}{3} = (C_3^V)^2 \frac{2}{3M_R^2} Q^2[q\cdot p + m_N^2 + M_R^2] + \frac{(C_4^V)^2}{m_N^2}\frac{2}{3} Q^2[q\cdot p + m_N^2 - m_N M_R] + \frac{C_3^V C_4^V}{m_N}\frac{2}{3M_R} Q^2[q\cdot p + (M_R - m_N)^2]$$

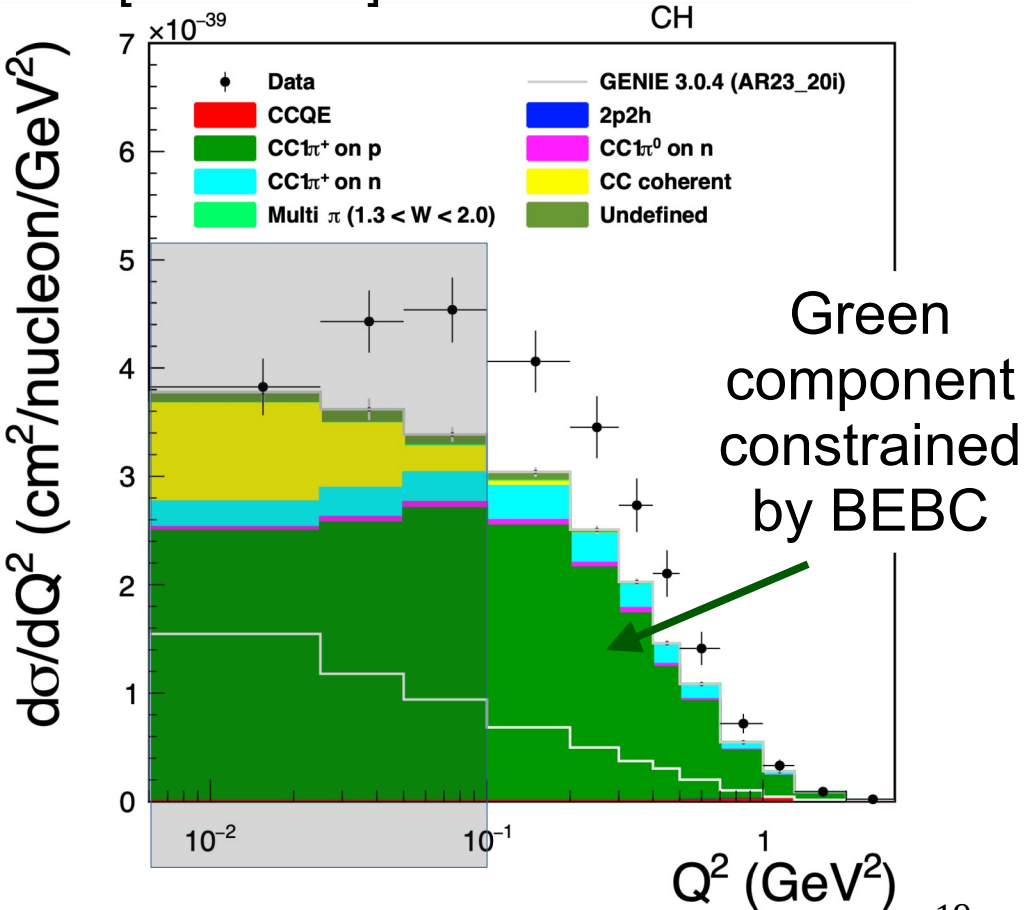
$$+ \frac{2}{3}\left[(C_5^A)^2 \frac{m_N^2}{M_R^2} + \frac{(C_4^A)^2}{m_N^2} Q^2\right][q\cdot p + m_N^2 + m_N M_R] \quad \text{(A2)}$$

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

Pause before going on. What parameters?

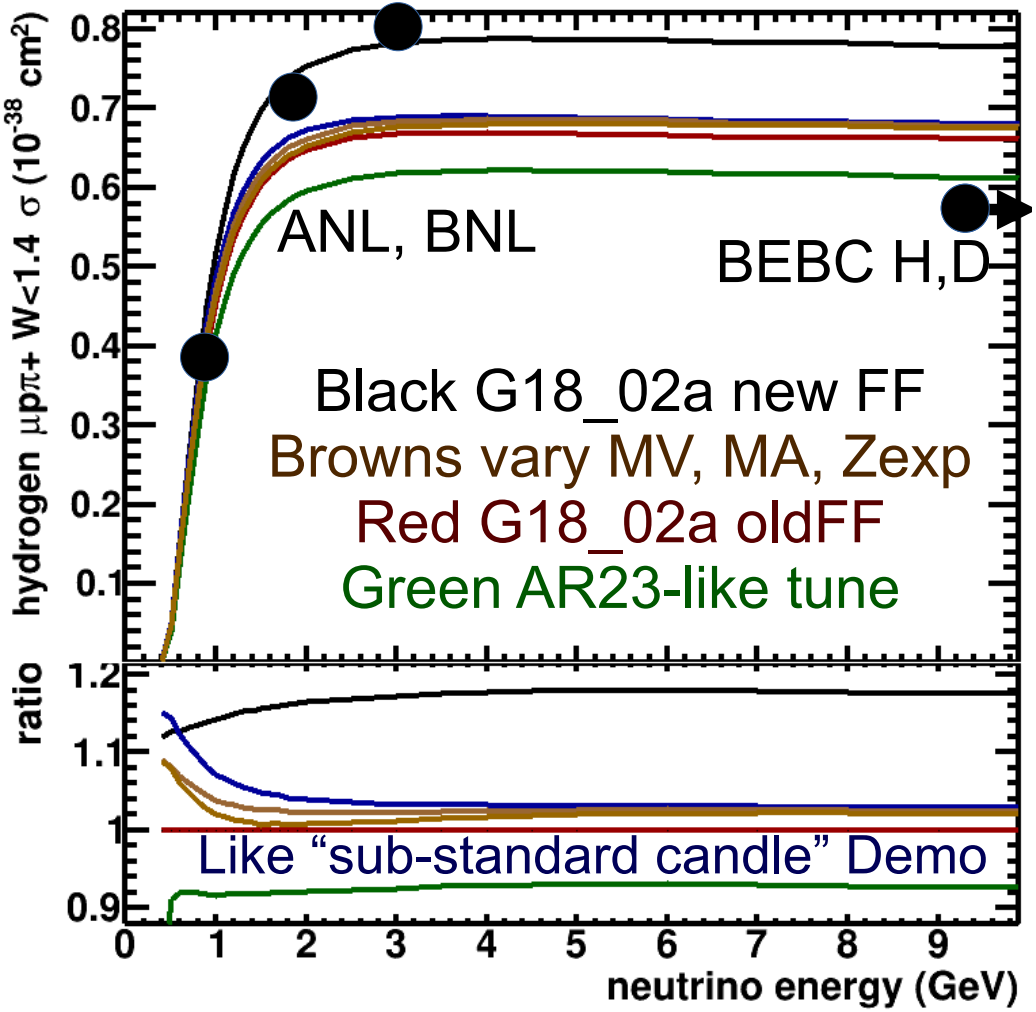
Can use MA, MV, scale Diffractive, scale DIS, scale RES
Old vs. new FF expressions. What about W = 1220 ?
Unless MV really is pinned by electron data, no independent MA.

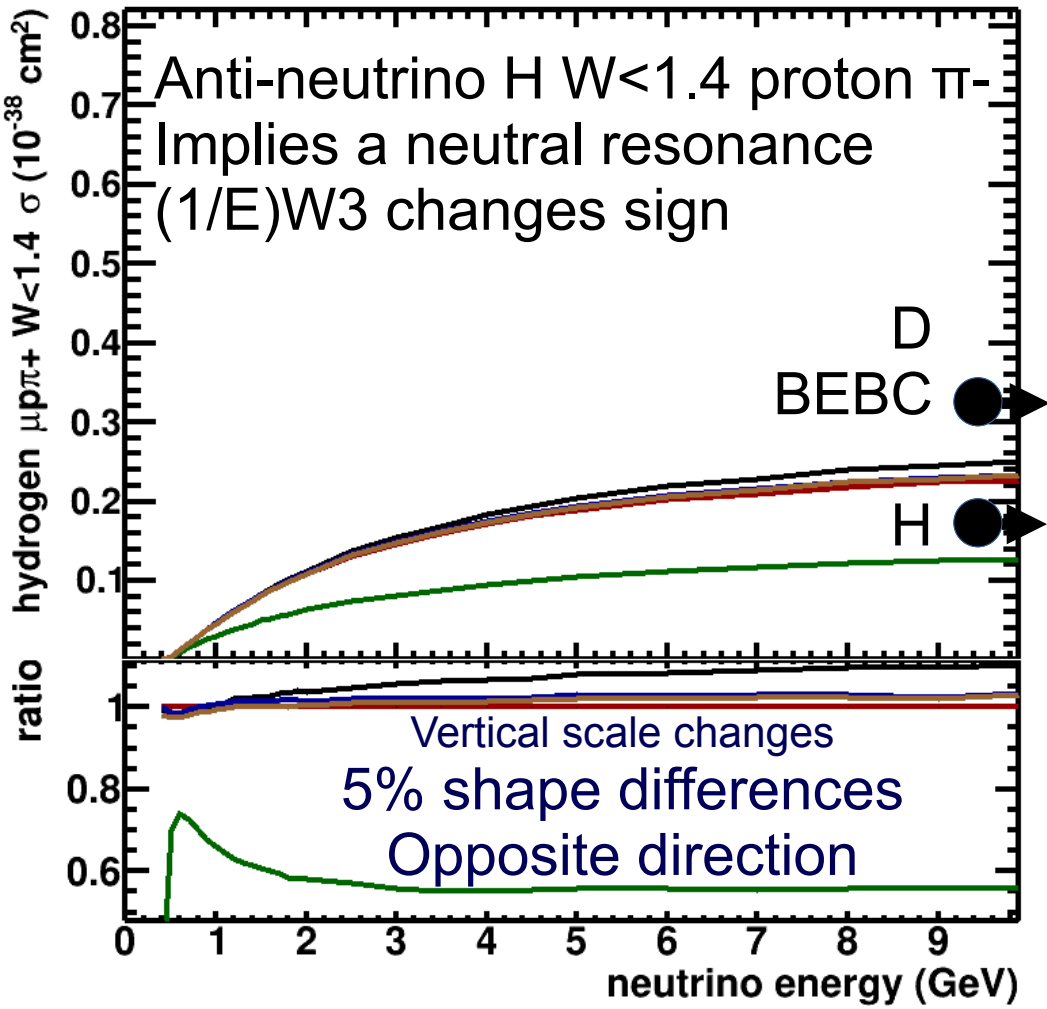
Data is so jumpy (for unknown reasons, fluctuations we guess)
Dubious we would get a serious constraint anyway.

Demo using Z expansion for axial form factor for blue line.
Wondering if further hack lets me use Abi's uncertainties
To give more freedoms to the fit compared to just MA?

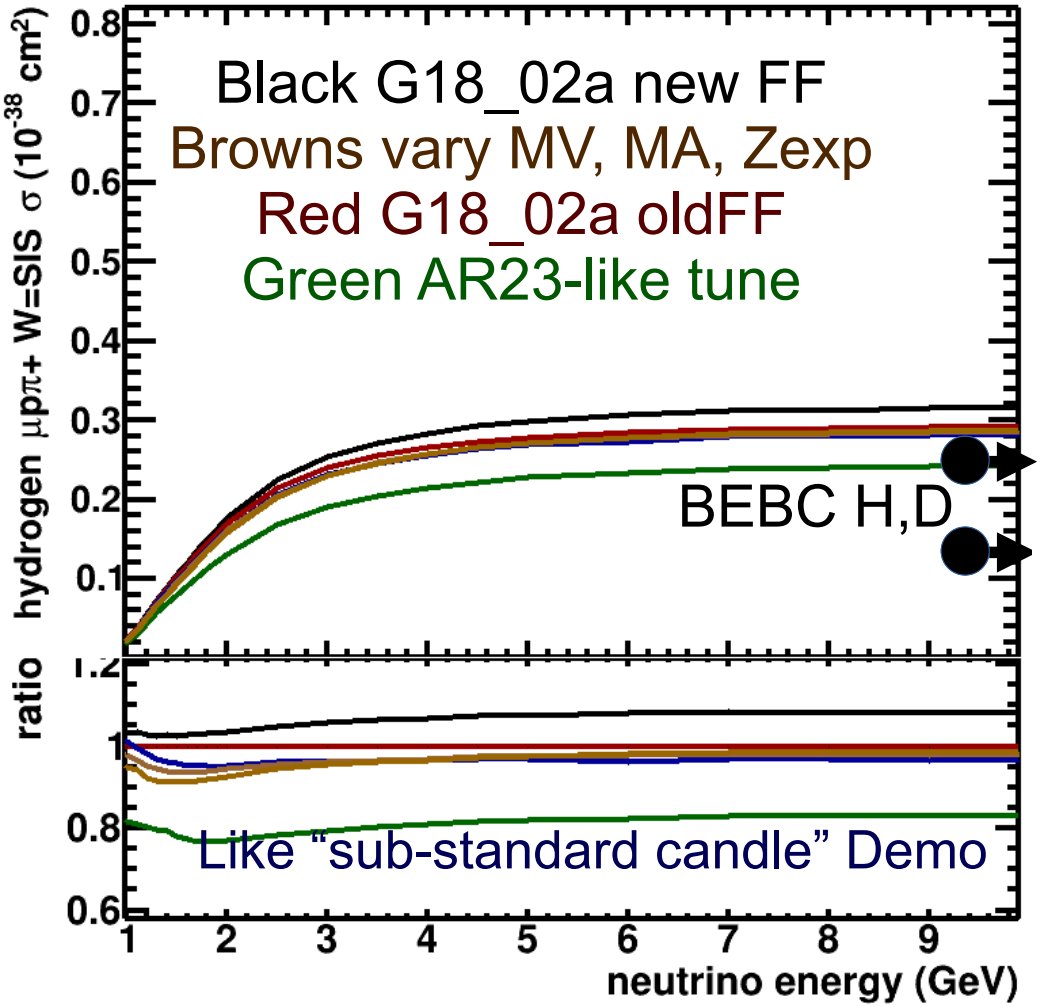
Difficult design situation. Does 30 GeV data affect DUNE?

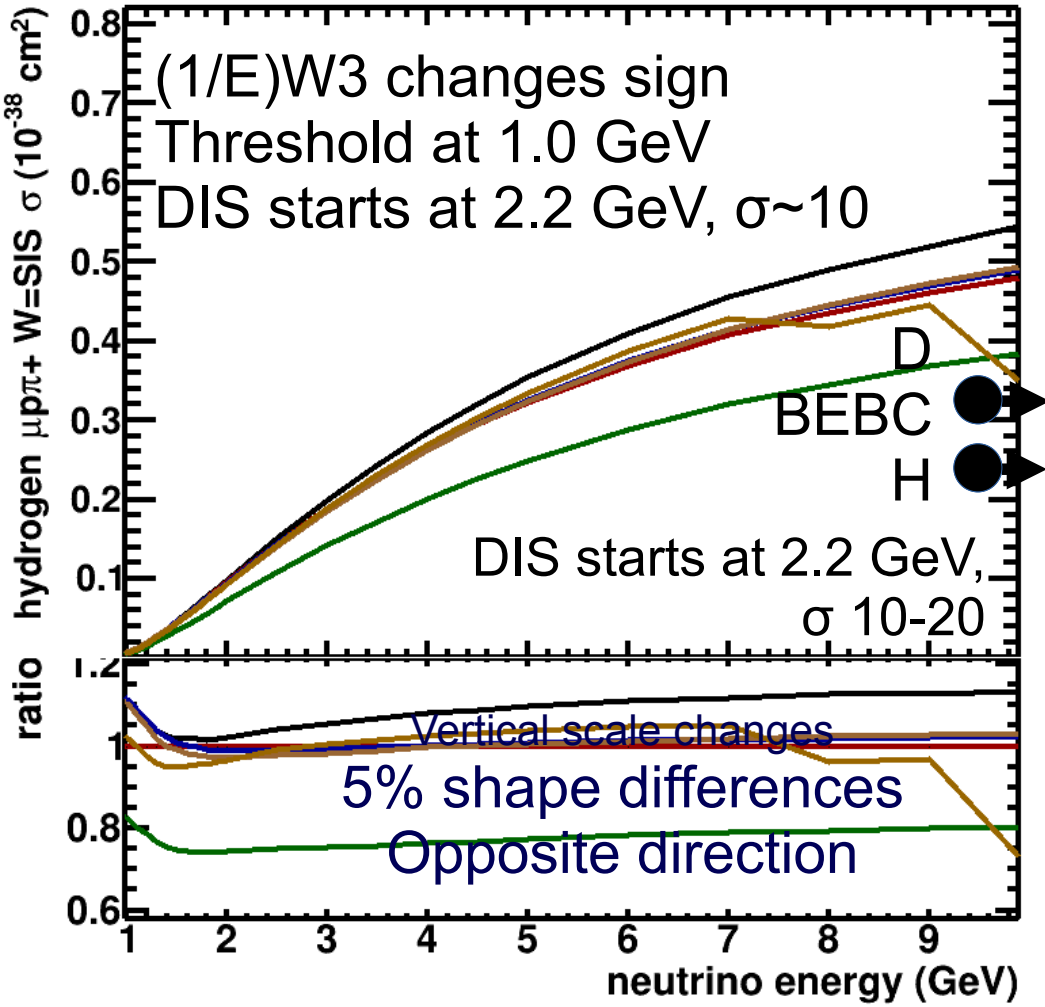
Projected onto oscillation region, 10% effects



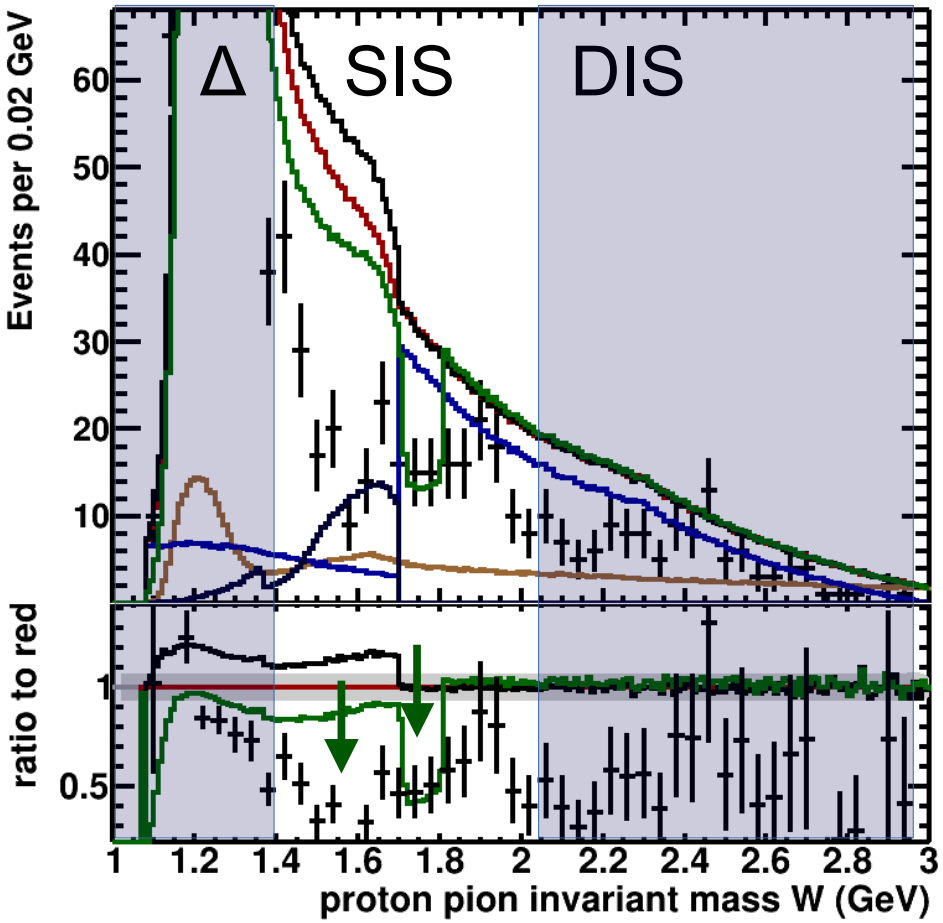


1.4 < W < 2.0 SIS 1π+ region energy dependence





What about higher W but still single π+ sample?



Adequate. By design! ™

Focus on the near Δ region today
1.3 < W < 1.5 or so
suppressed vertical axis

This p π+ channel has a
resonance desert
only the tail of the Δ contributes

GENIE rate is off by x2
Δ tail is too high, too long

More to see here
Save for future SIS DIS talk

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

They give 5 to 10% different predictions in 1-2 GeV region

Next goals
Some lightweight fitting that gives parameter ranges
and a covariance we can use in nusystematics

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.

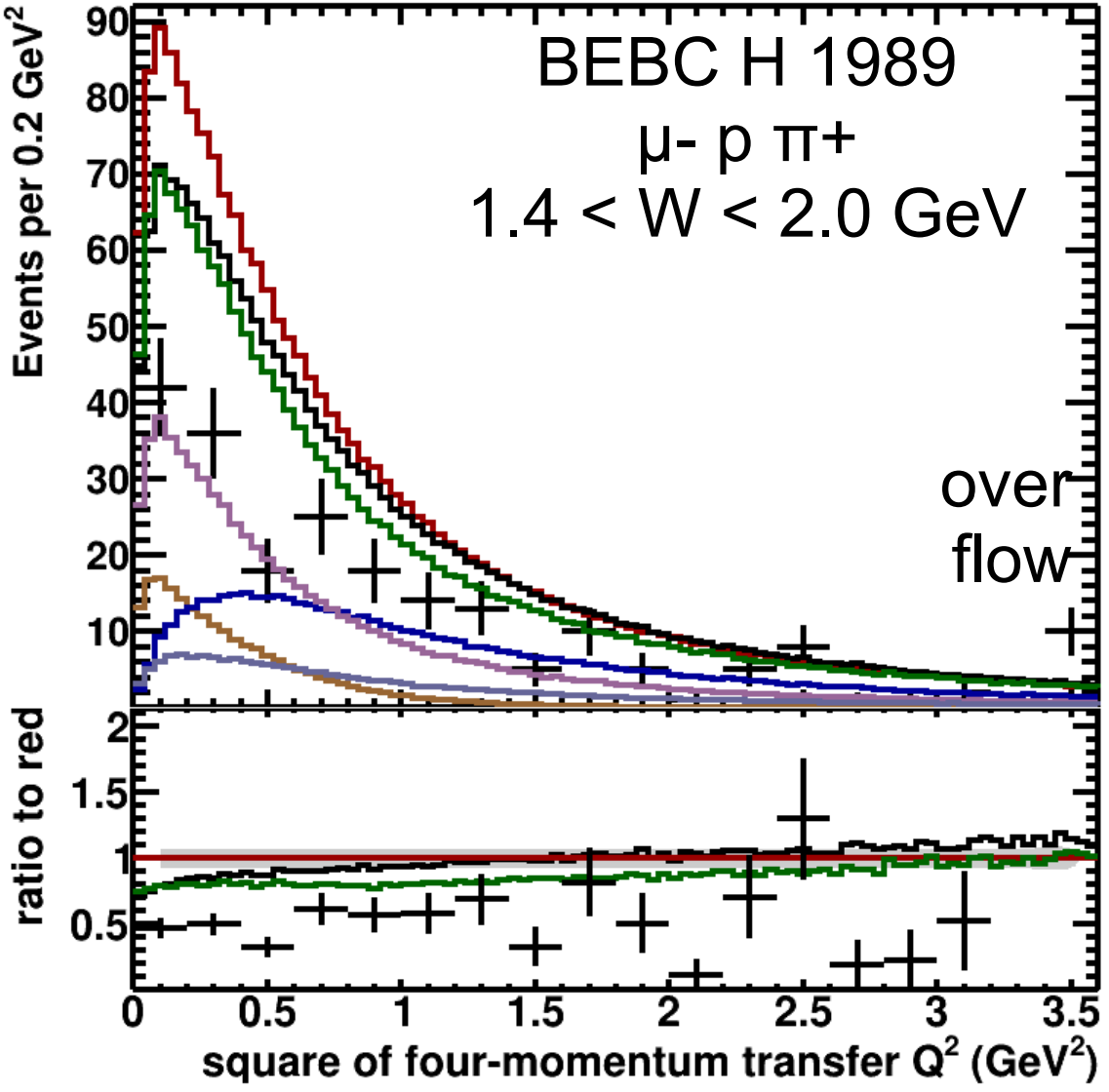
Some of the material here goes in that paper as illustration

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

Backups and old material

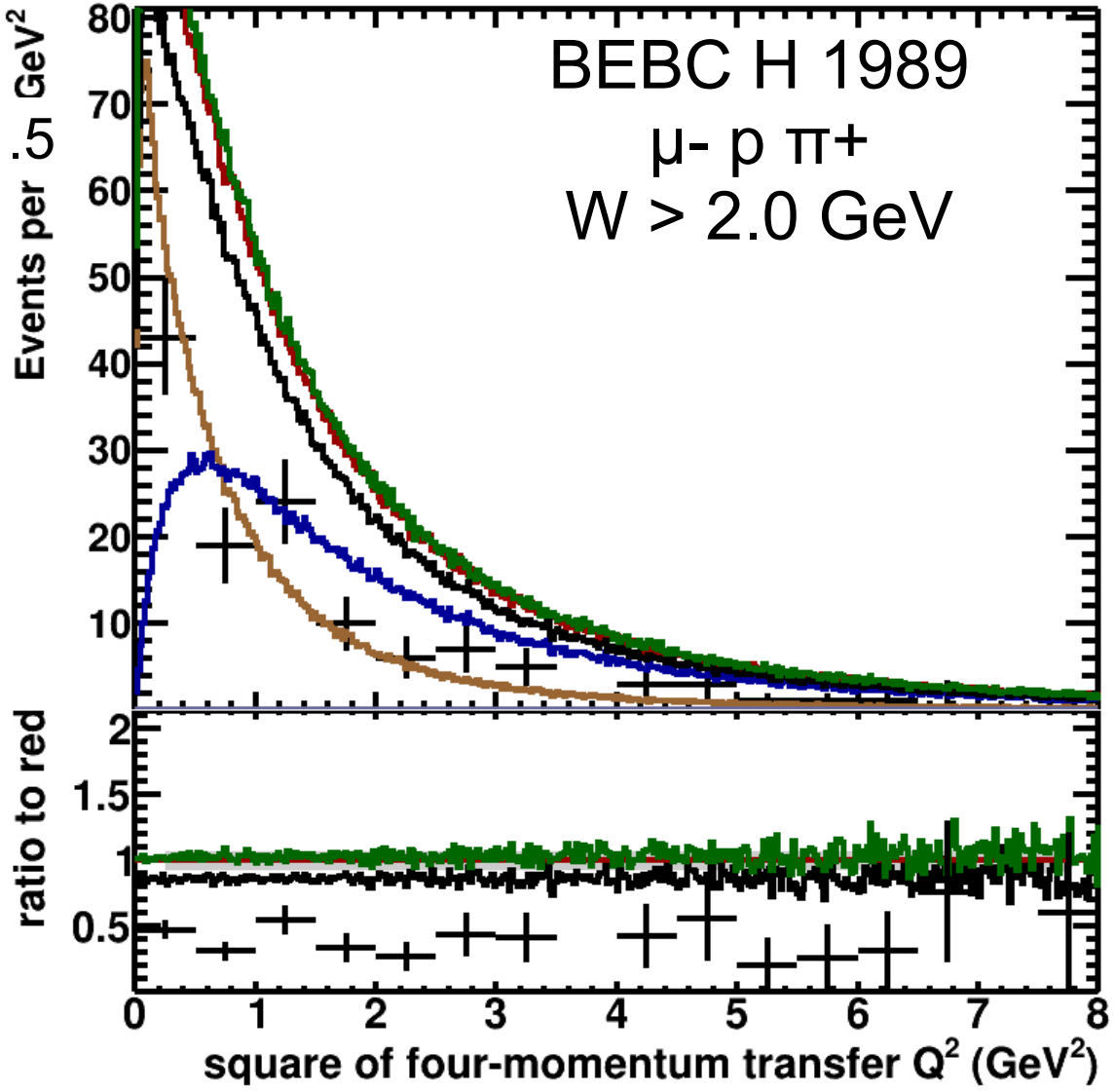


Q2 distribution in SIS 1.4 < W < 2.0 one π+

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%



Q2 distribution in DIS
W > 2.0 one π+

Only components
Brown = diffractive
Blue = DIS

Normalization seems ok
Need to check

Cant see ~10% norm error

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

Same high W information in table form: skip this

	1.4 < W < 2.0	W > 2.0	1.4 < W < 2.0	W > 2.0
	neutrino		anti-neutrino	
Data average	14.6 ± 1.5	9.8 ± 1.5	24.1 ± 2.9	15.5 ± 2.6
Data Allen:1986	14.0 ± 1.4	9.4 ± 1.4	18.7 ± 2.2	12 ± 2
MC oldFF	29.9	16.9	62.5	33.1
DIS	10.7	9.5	33.6	25.8
Diffractive	3.5	7.4	3.5	7.4
MC JTVb	25.0	17.1	51.5	33.8
DIS	5.5	9.8	15.1	26.6
Diffractive	3.5	7.3	3.5	7.2

Higher W problems for anti-neutrino μpπ- too. Future task.

Diffractive and SIS comments

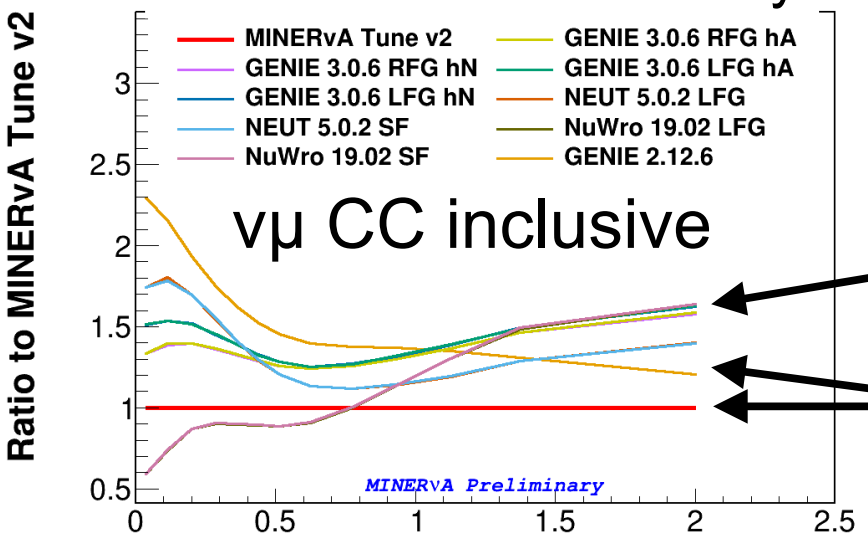
GENIE models old Form Factors (red) and JTVb (green) 2x high

Diffractive alone at W > 2.0 is almost data, before adding DIS

Though Rein paper sorta-hinted model was ~3x too high

Only data on diffractive until another experiment with a lot of H

MINERvA SIS sensitivity



Slope in Q2 with new form factors

Is more dramatic at higher W

Causes this divergence in predictions

Offset from Wilkinson & Rodrigues

Genie3

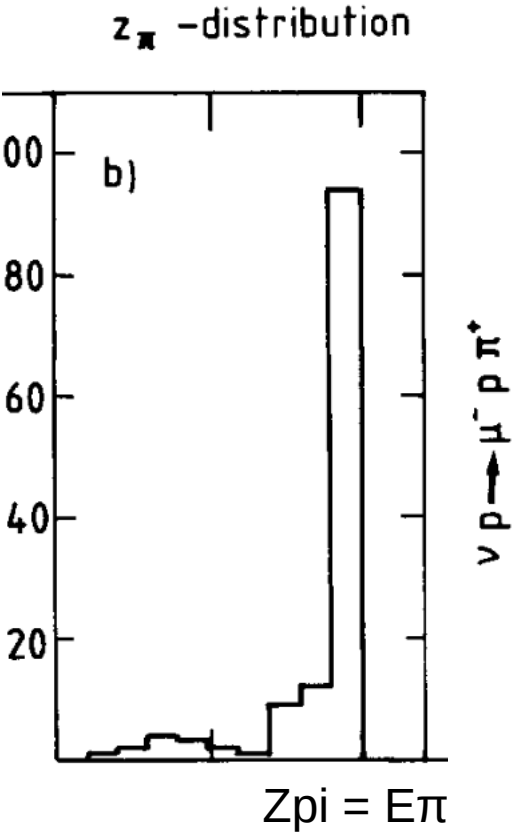
Genie2

Lots of structure here!

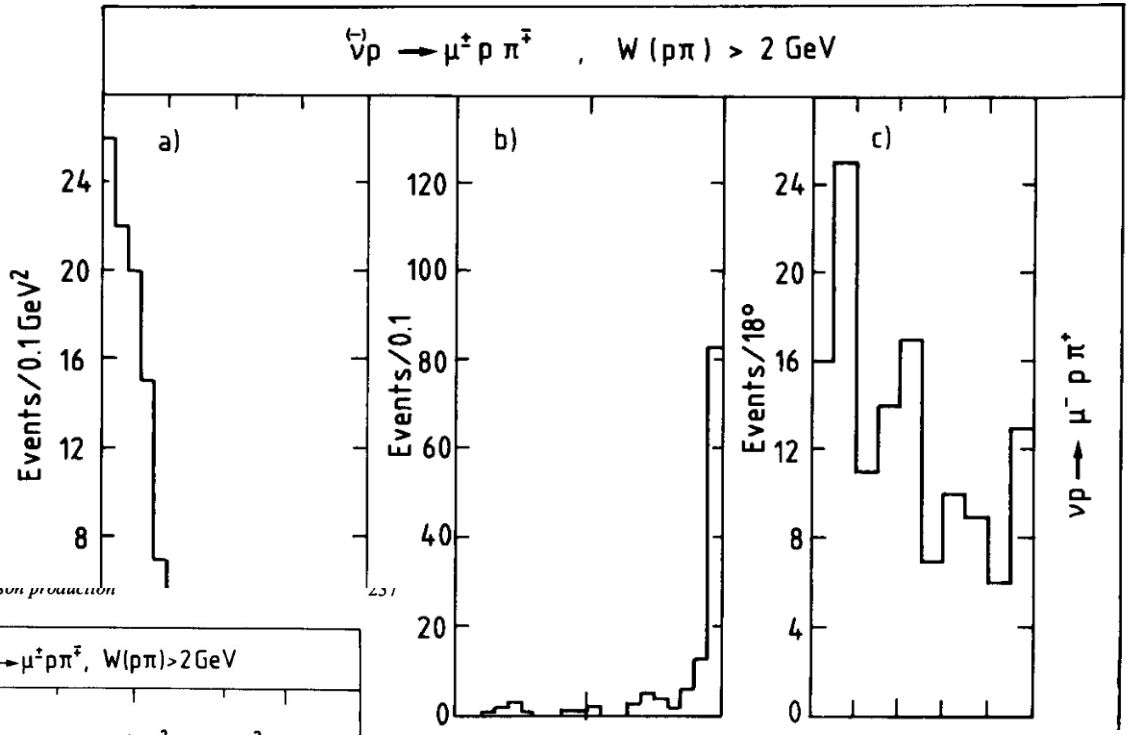
MINERvA SIS results expected at NuInt24

Muon pT trends = similar to Q2

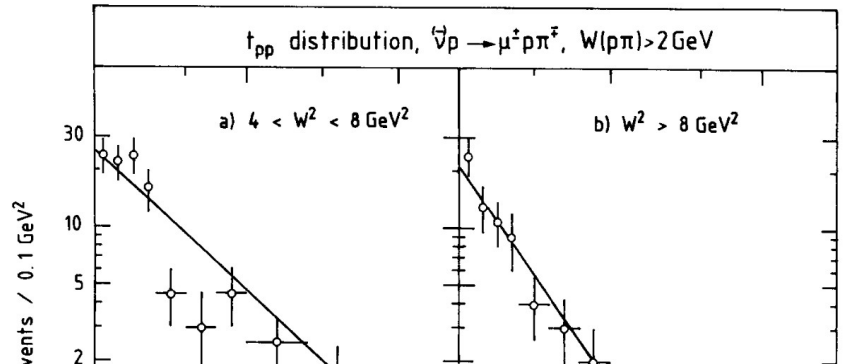
Allen:1986 has four more W>2 distributions



Zpi = Eπ

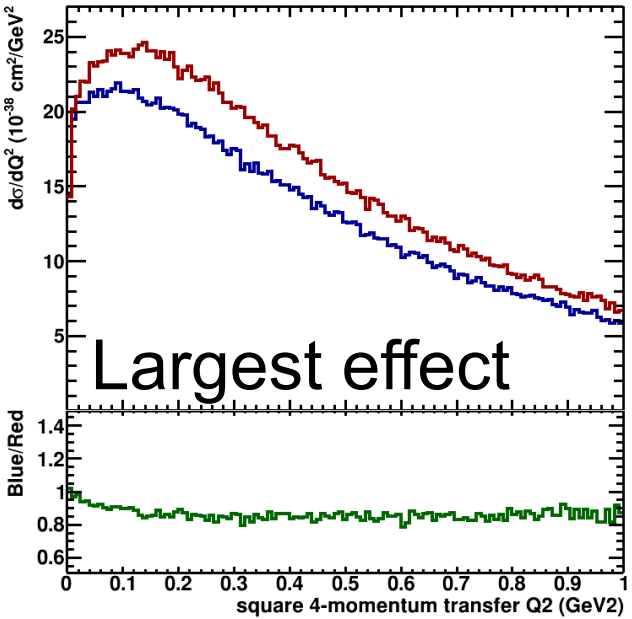


cosθπ Φπ

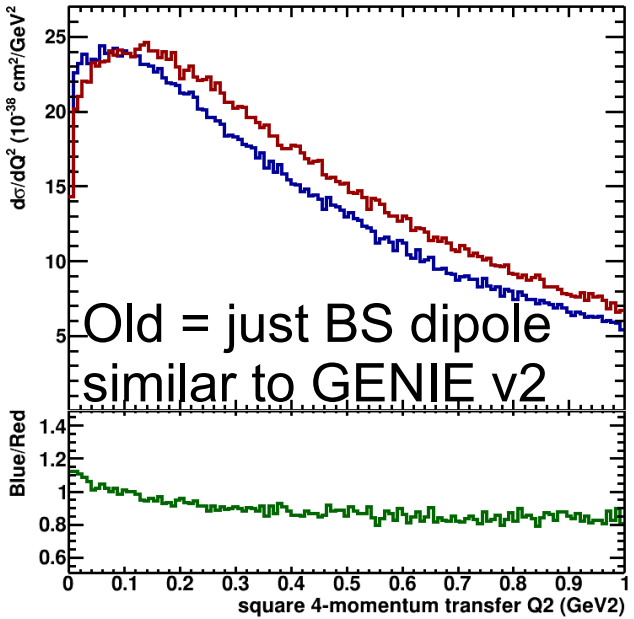


Separate the vector and axial form factor effects

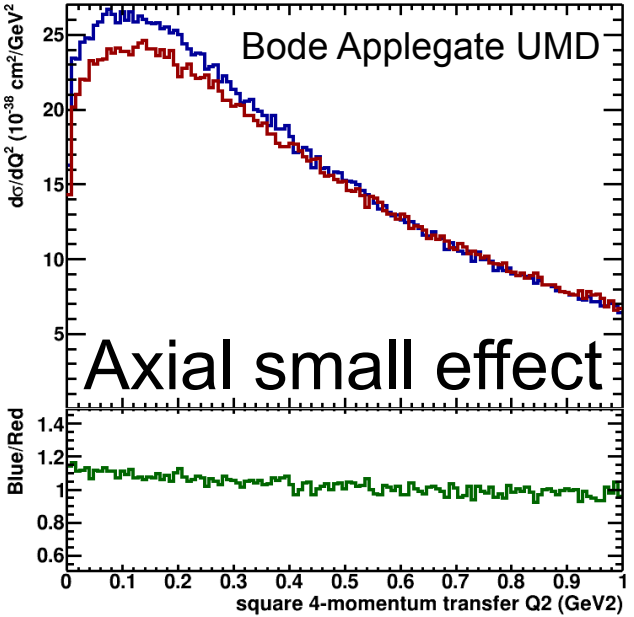
Red: default GENIE3 newFF Argon Δ++ 3 GeV no FS selection



Old Vector FF
But same MV



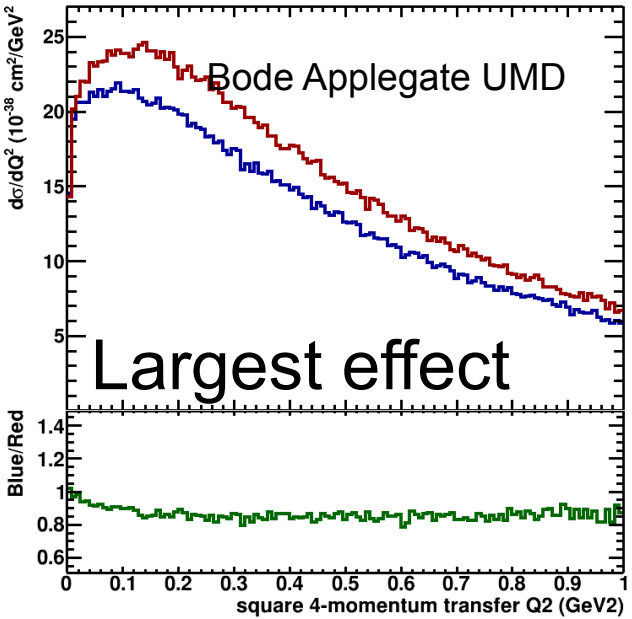
Old Axial & Vector
but same MA, MV



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.

What do we know about the Rein diffractive model?

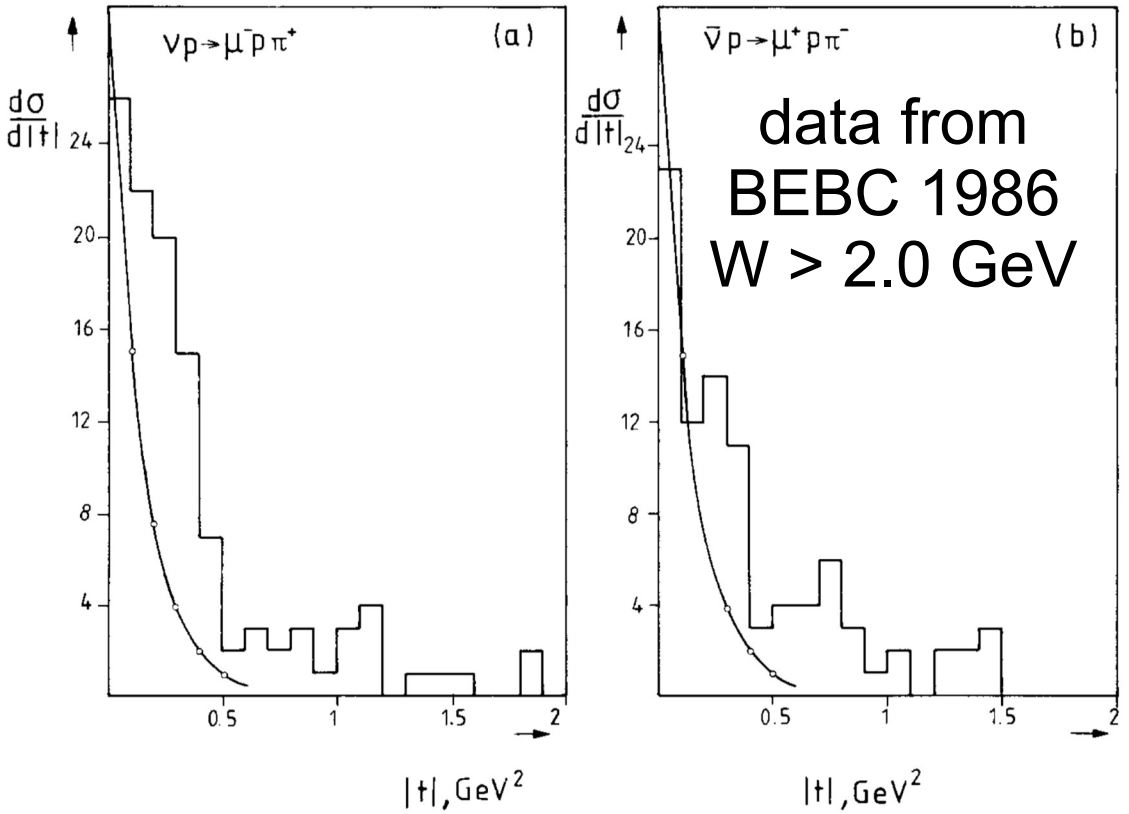


Fig. 7. t-distributions compared with data (from ref. [8]) (a) for neutrino reaction (b) for antineutrino reaction; $W > 2$ GeV, $b = 7$ GeV^{-2}, $m_A = 1.1$ GeV/c^2.

data from
BEBC 1986
W > 2.0 GeV

Complicated what Rein did
And what GENIE did.

Rein's model (and GENIE)
Integrates to this distribution
And 9.4 ± 1.4 10e-40 cm2

This distribution is
Arbitrary normalized

Now I can make the real
comparison with GENIE

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

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

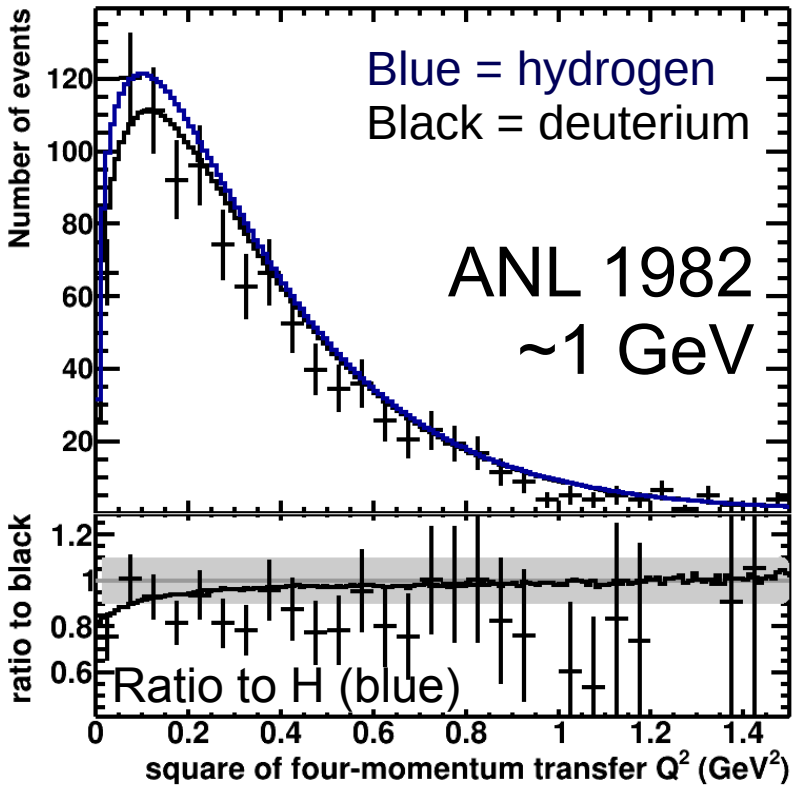
These were done before working on BEBC
They are still approximately correct

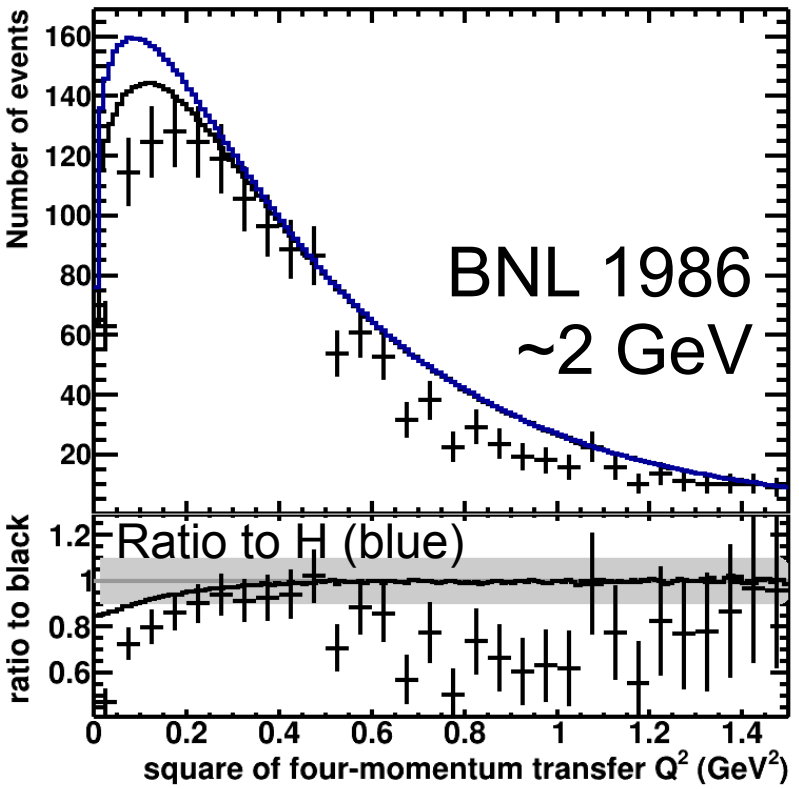
But many adjustments to backport from BEBC experience

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



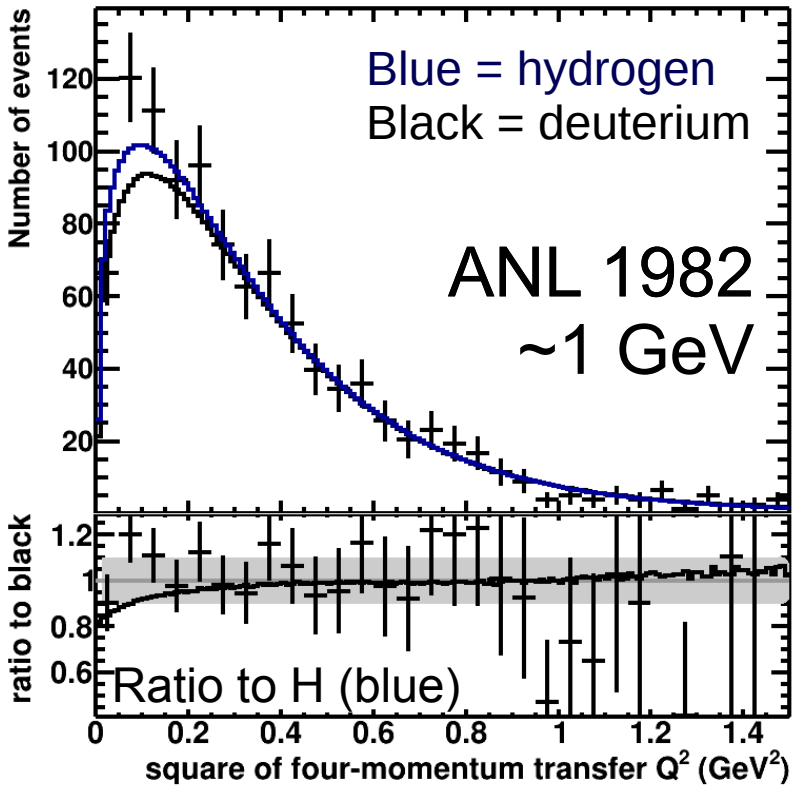


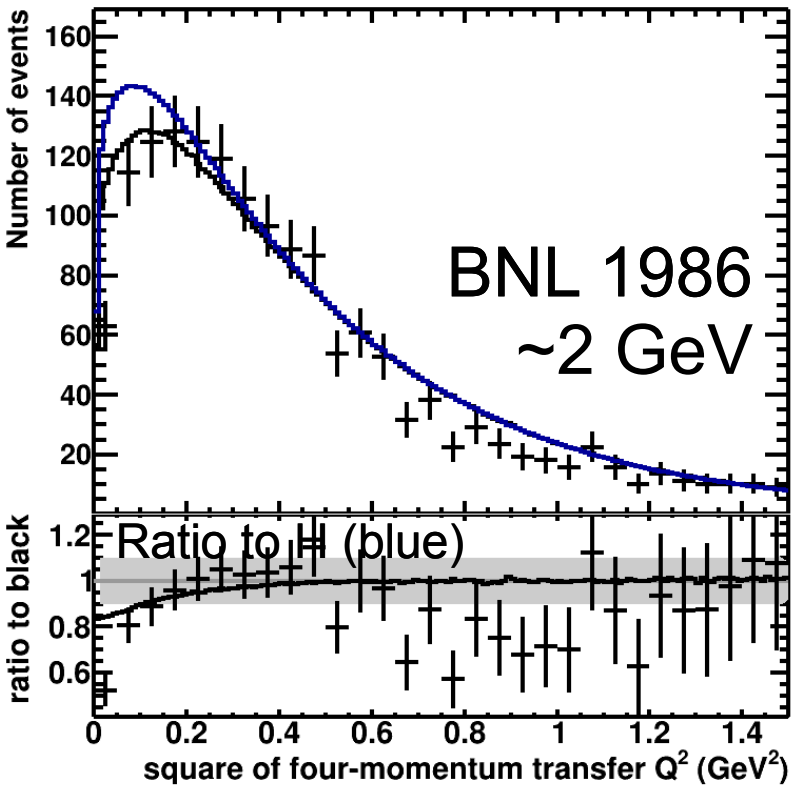
Showed this last time. Similar discrepancy to BEBC despite energy.

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