Update to the Bodek-Yang Unified Model for Electron- and Neutrino- Nucleon Scattering Cross sections

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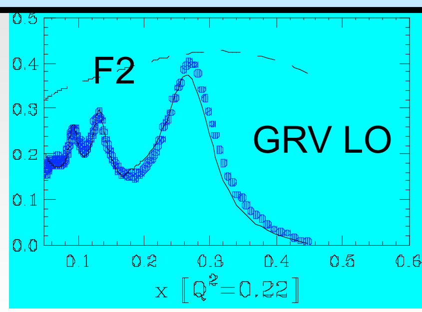
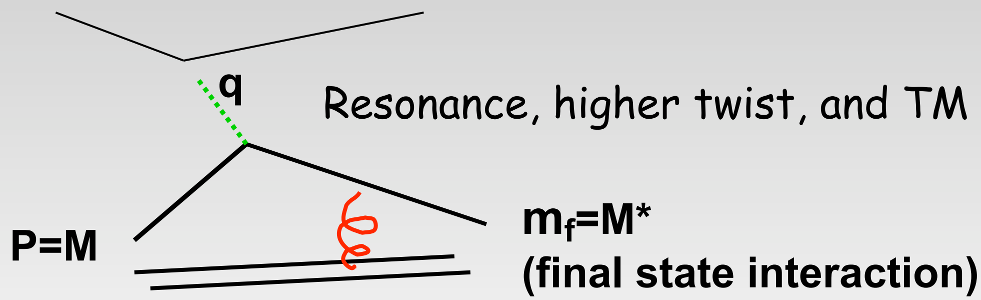
Modeling neutrino cross sections

- Describe DIS, resonance, even photo- production (Q^2=0) in terms of quark-parton model. With PDFS, it is straightforward to convert charged-lepton scattering cross sections into neutrino cross section.
- Challenge:
  - Understanding of high x PDFs at very low Q^2?
  - Understanding of resonance scattering in terms of quark-parton model?
  - What happens near Q^2=0?



- Bodek-Yang LO approach (pseudo NNLO)
  Use effective LO PDFs with a new scaling variable, ξw to absorb target mass, higher twist, missing QCD higher orders

  \+ add low Q2 K factors



$$\xi\, W = \frac{Q^2+m_f^2+O(m_f^2-m_i^2)+A}{M\nu\,(1+(1+Q^2/\nu^2))^{1/2}+B} \longrightarrow X_{bj}= Q^2/2M\nu$$

Bodek -Yang Effective LO PDF model - 2004 (2003)

1. Start with GRV98 LO (Q^2_{min}=0.80 GeV^2)
   - dashed line- describe F2 data at high Q^2
2. Replace the Xbj with a new scaling, ξ_w

3. Multiply all PDFs by **K factors for** photo prod. limit and higher twist
   $[\ \sigma(\gamma)= 4\pi\alpha/Q^2 * F_2(x, Q^2)\ ]$
   Ksea = $Q^2/[Q^2+Csea]$
   Kval = $[1- G_D{}^2 (Q^2)\ ] * [Q^2+C2V] / [Q^2+C1V]$ motivated by Adler Sum rule
   where $G_D{}^2 (Q^2) = 1/ [\ 1+Q^2 / 0.71\ ]^4$

4. Freeze the evolution at $Q^2 = Q^2_{min}$
   - $F_2(x, Q^2 < 0.8) = K(Q^2) * F_2(Xw, Q^2=0.8)$

- Fit to all DIS F2 P/D (with low x HERA data)
  A=0.418, B=0.222

Csea = 0.381,C1V = 0.604, C2V= 0.485
χ^2/DOF = 1268 / 1200 Solid Line

For 2xF1 use R1998

Fit only precise charged lepton scattering data.
<u>No neutrino data and No Resonance data included in the fit.</u>

2004 update:
Separate K factors for uv, dv,us,ds

For XF3 : we assumed V=A in 2003-2004

A : initial staete binding/TM+ higher order QCD

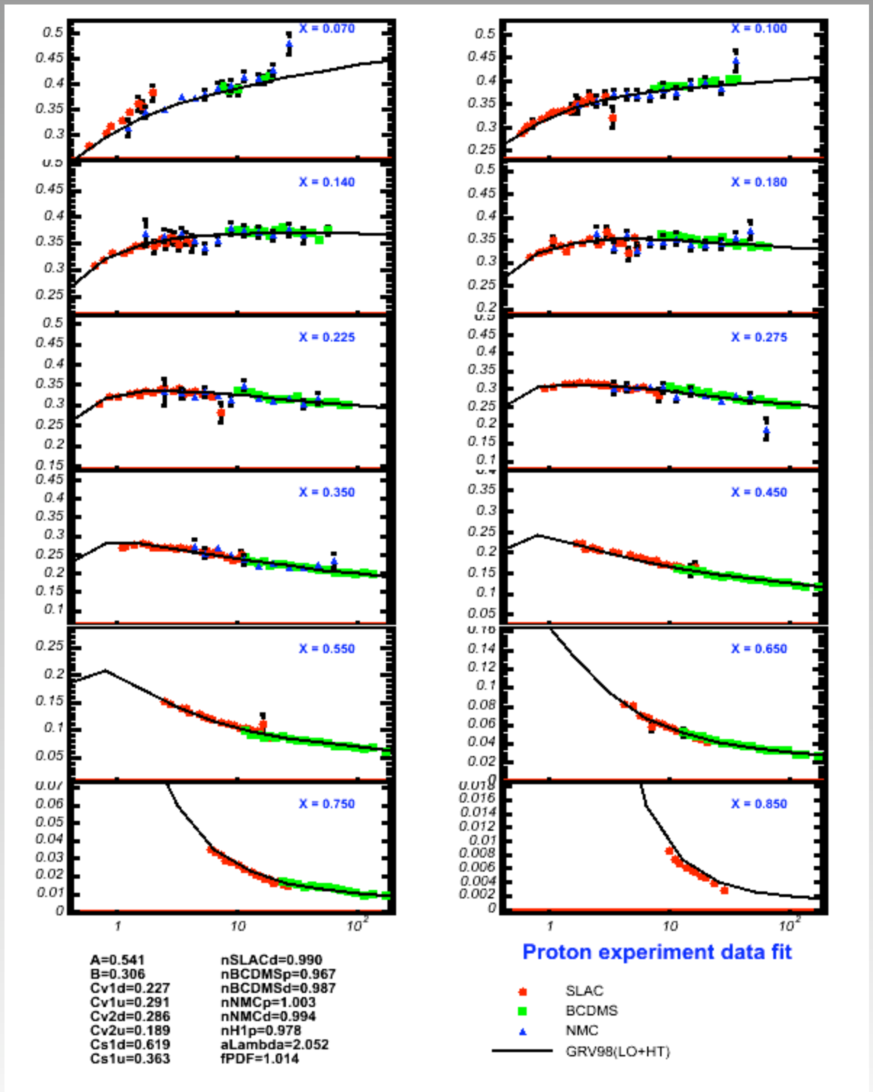
B : final state mass m_f^2, Δm^2,

K Factor: Photo-prod limit (Q^2 =0), Adler sum-rule

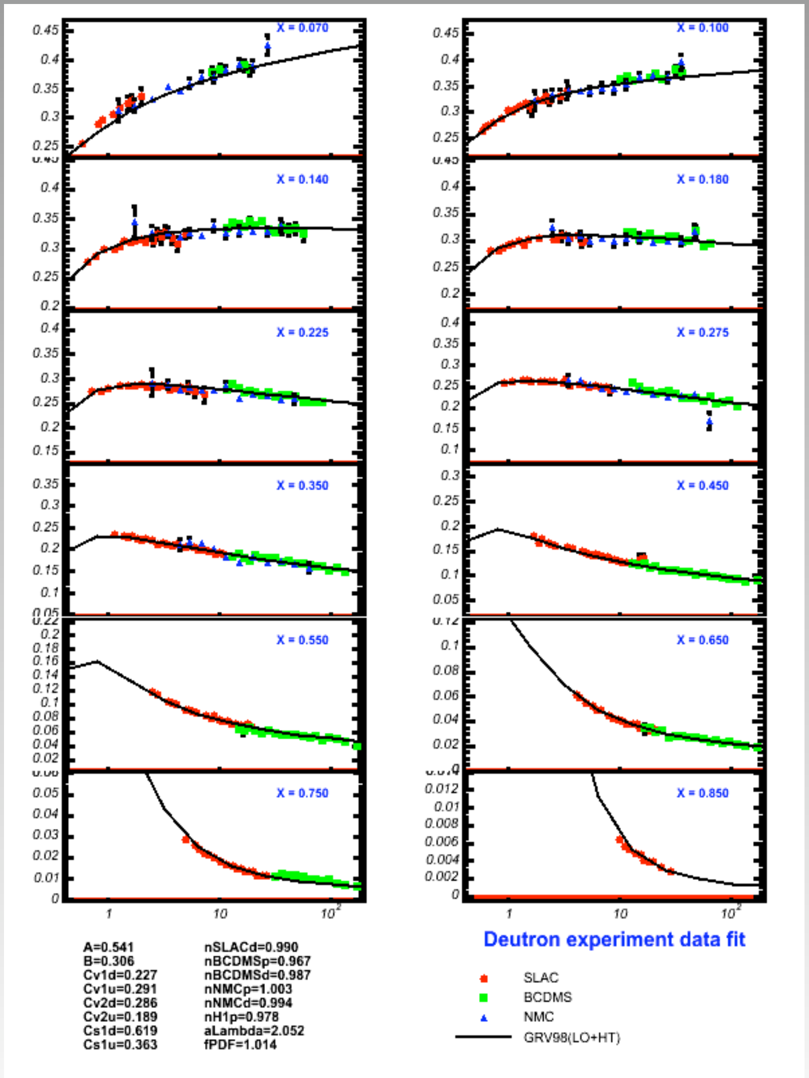
Xbj= Q^2 /2 Mν

$$\xi_W = \frac{Q^2+m_f{}^2+O(m_f{}^2-m_i{}^2) +A}{M\nu\ (1+(1+Q^2/\nu^2)\ )^{1/2} +B}$$

Fit results GRV98 + B-Y 2004 (SLAC, BCDMS, NMC) H + D

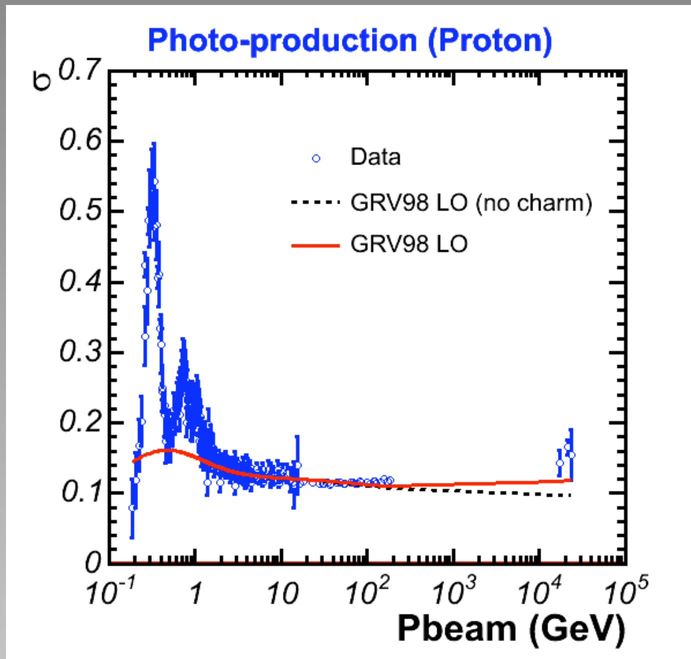


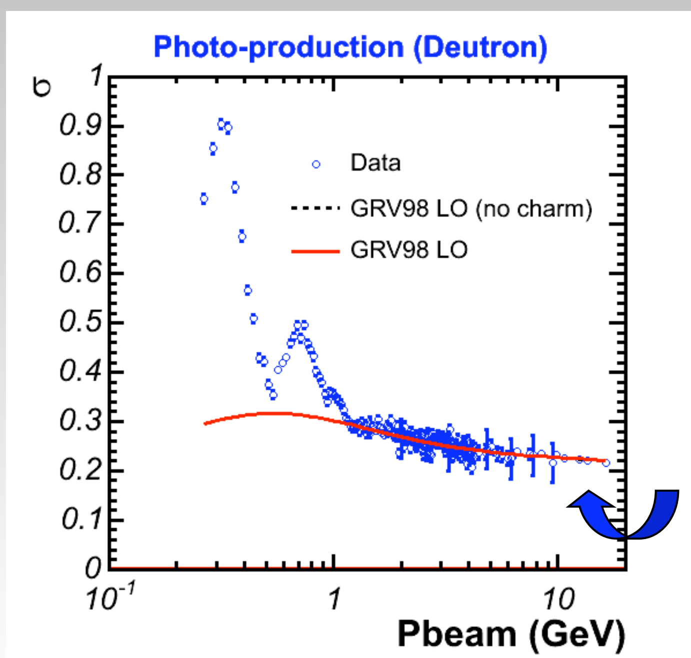
F2 proton

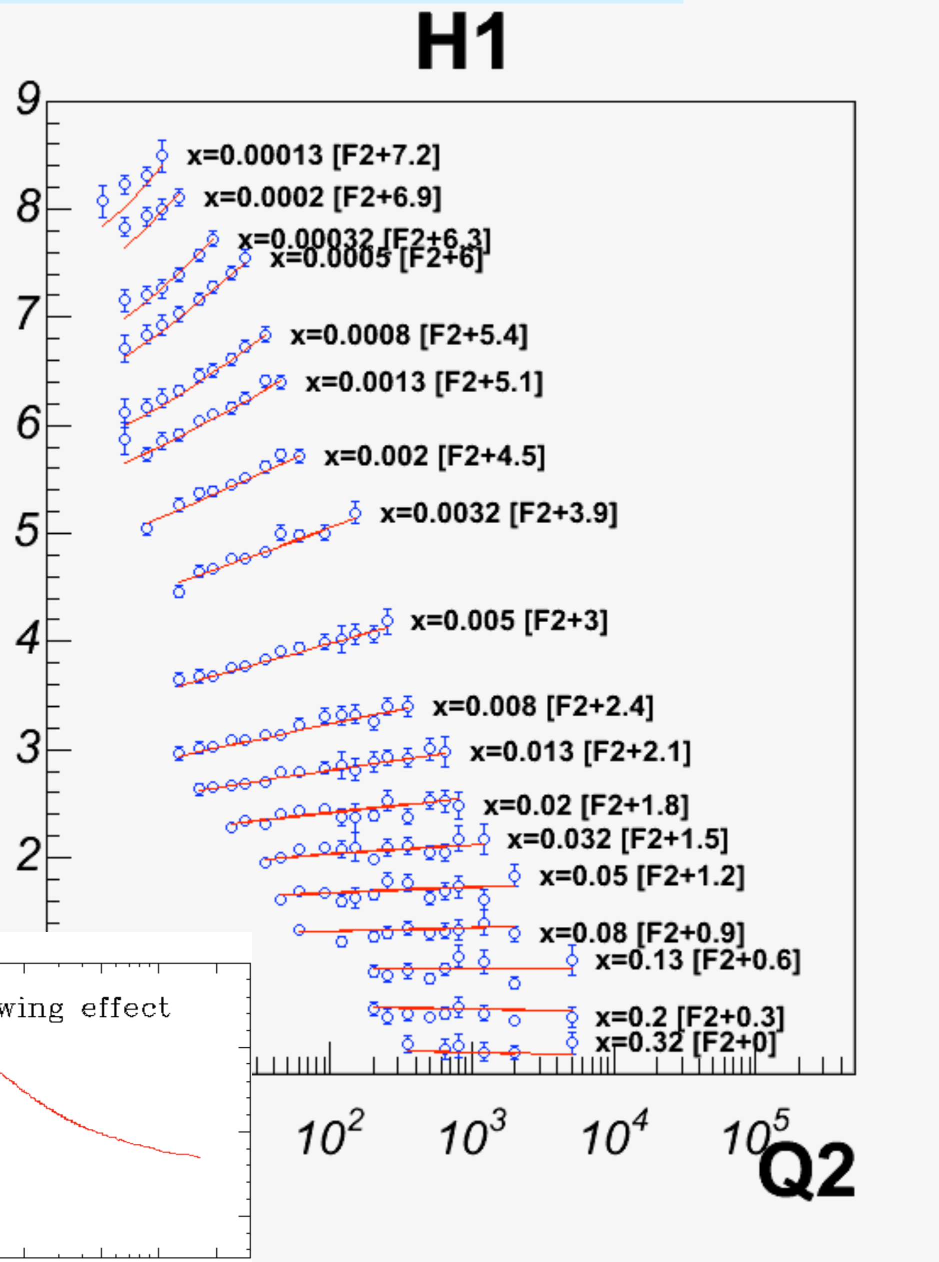


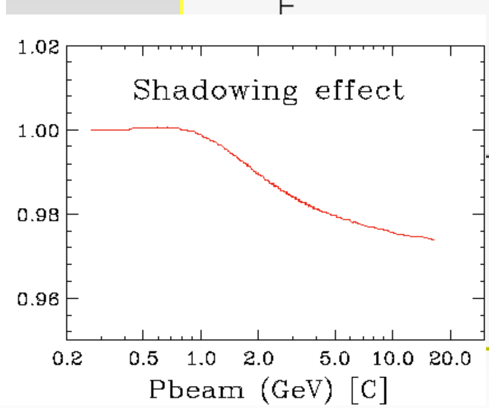
F2 deuterium

Fit results GRV98 + B-Y 2004



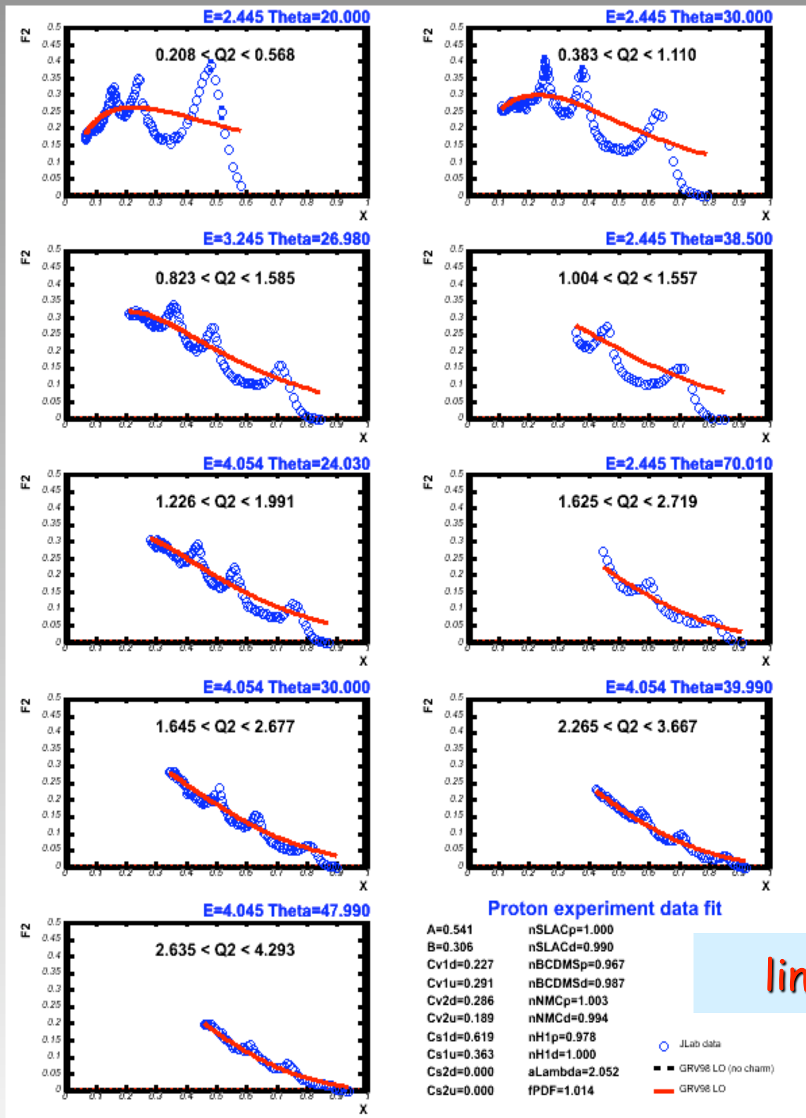


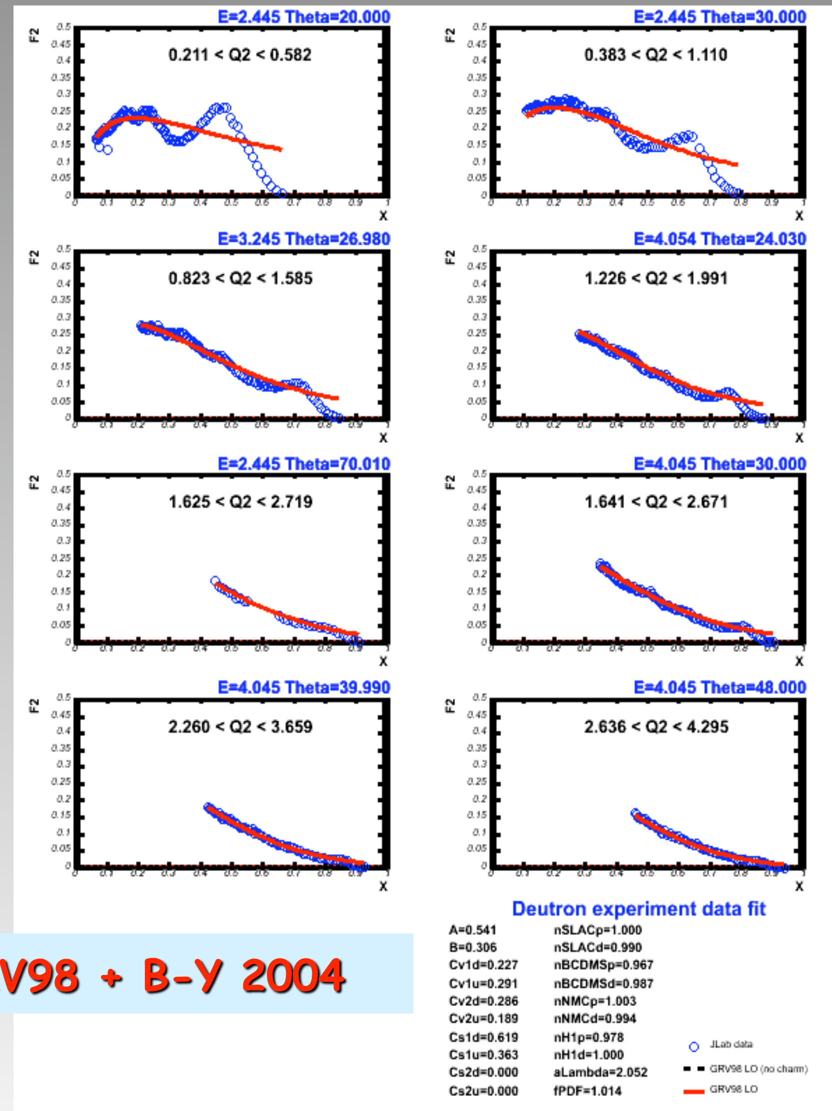




Resonance F2 proton

Resonance F2 deuterium





line GRV98 + B-Y 2004

Fit works on resonance region -Resonance data are not included in the fit!!!

How model uses only H and D data.

For lepton/muon cross sections on nuclear targets - need to correct for Nuclear Effects measured in e/muon expt. Use also for neutrino expt.

(Note nuclear effects can be different for neutrinos)

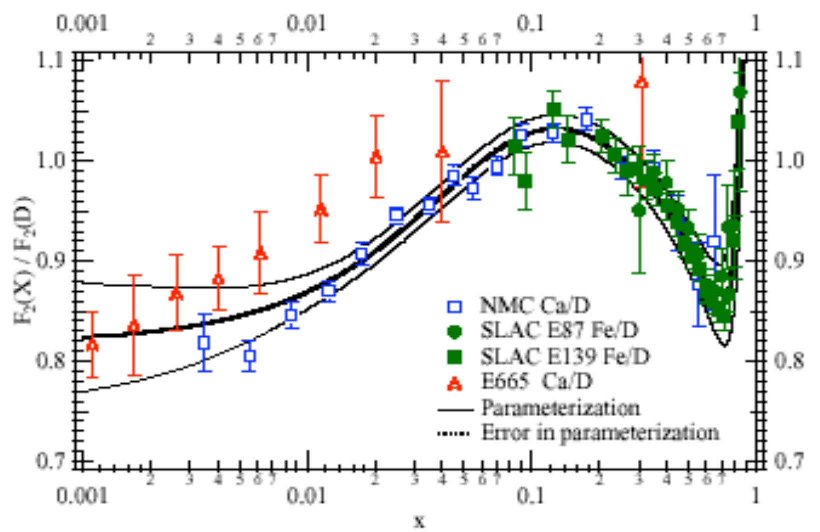
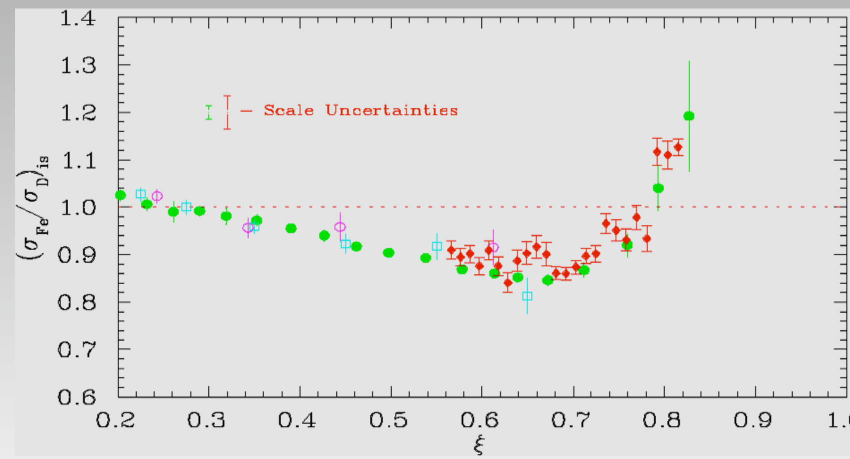


Figure 5. The ratio of F_2 data for heavy nuclear targets and deuterium as measured in charged lepton scattering experiments(SLAC,NMC, E665). The band show the uncertainty of the parametrized curve from the statistical and systematic errors in the experimental data [16].



Comparison of Fe/D F2 data

In resonance region (JLAB)

Versus DIS SLAC/NMC data

In ξ_{TM} (C. Keppel 2002).

The BY model is used for the inelastic part of the cross section

People use the 2004 Bodek-Yang model above W=1.8 and other other models for quasielastic, the delta, and the 1520 resonance region and matche to Bodek-Yang in the W=1.8 region .

- Find that predicted total neutrino and antineutrino cross sections are lower than high energy measurements (5%).
- The antineutrino to neutrino ratio is also a little low.

2009 updates:

1. Correct for the difference in scaling violations for F2 and XF3
2. Correct for Vector is not equal to Axial at low Q2.
3. Make model work down to W=1.1 to provide smoother matching

For higher precision:

Need to apply radiative corrections to F2

Need to include c-cbar sea high energy (no c-cbar sea in GRV98).

Need to account for the differences in nuclear effects between electrons and neutrinos

2009 Update 1: H(x) = NLO Correction to xF_3

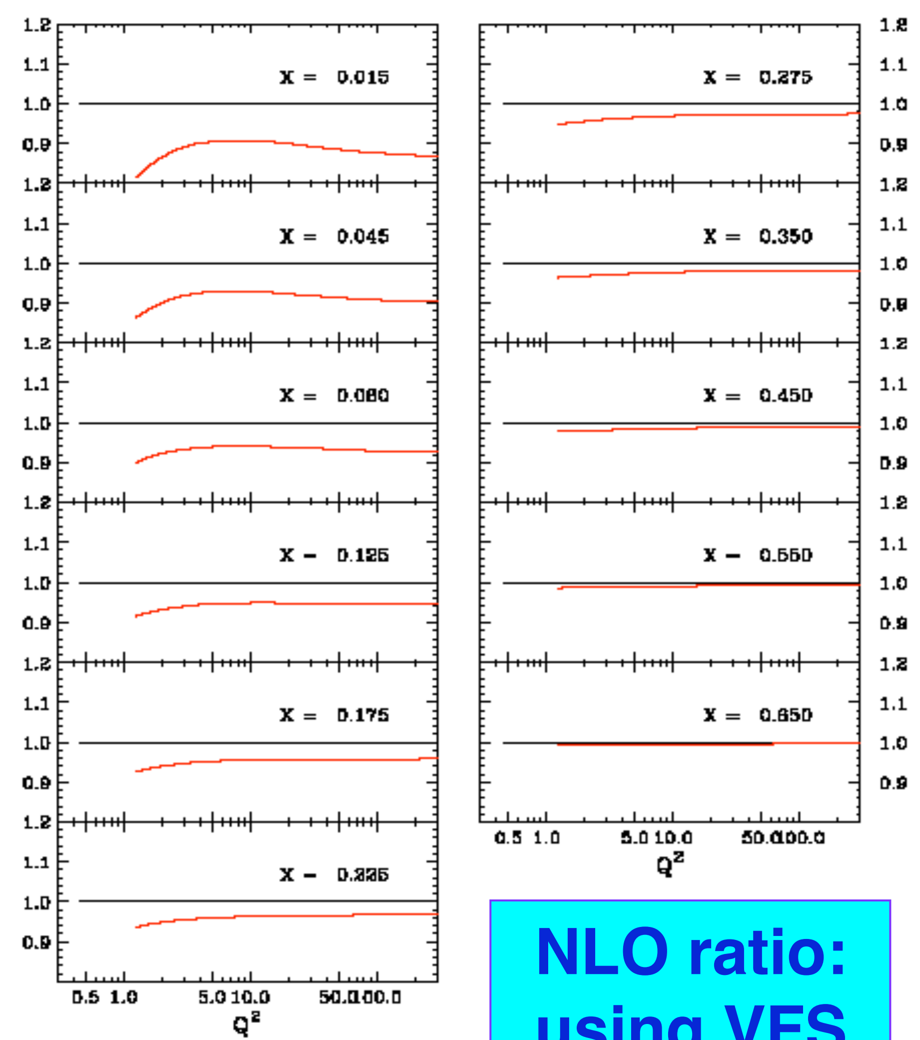
- Scaling variable, ξw absorbs higher order QCD and higher twist in F_2, but xF3 may be different.

(F_2 data was used in the fitting our corrections to leading order PDF)

- 1st Update: Use double ratio correction H(x) from QCD

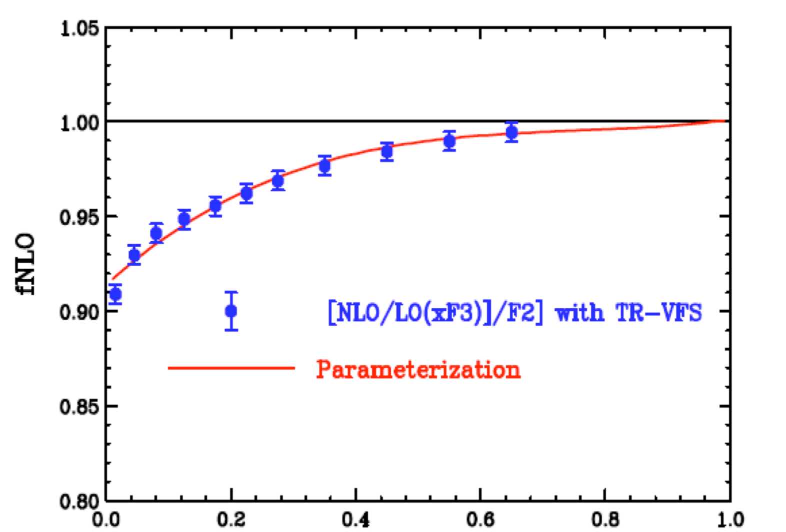
$$\frac{xF_3(\mathrm{NLO})}{xF_3(\mathrm{LO})} \Big/ \frac{F_2(\mathrm{NLO})}{F_2(\mathrm{LO})}$$

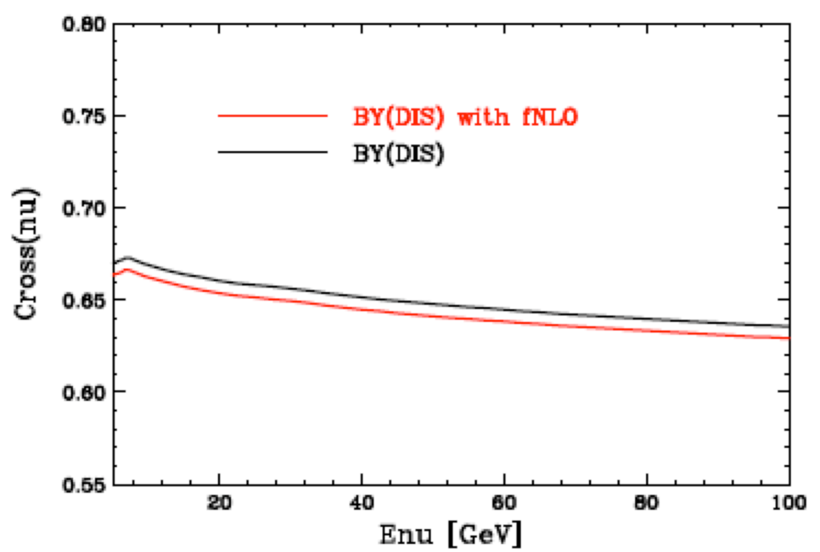
=> not 1 but indep. of Q^2

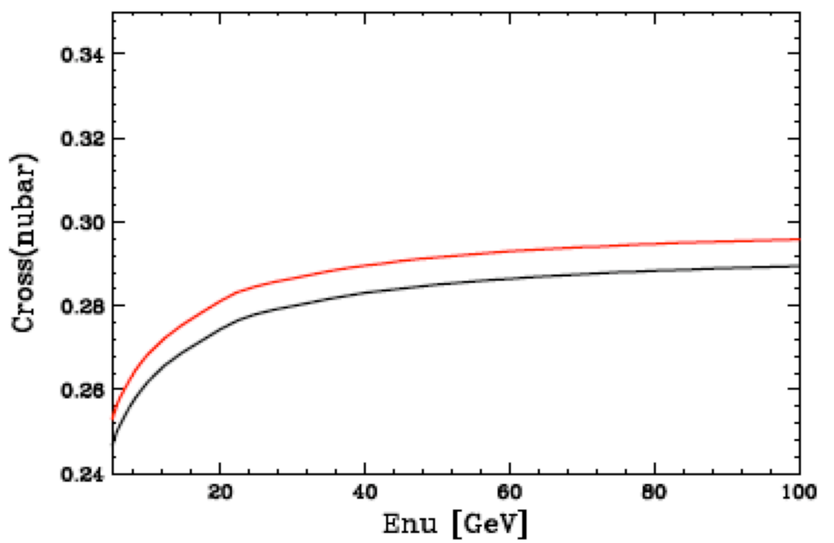


NLO ratio: using VFS

Effect of xF_3 NLO correction H(x)







- Parameterized xF_3 correction as a function of x = H(x)
- Neutrino cross section down by 1%
- Anti-neutrino cross section up by 3%

2009 update 2: Axial contribution at low Q2

$$K_i^{\text{vector}}(Q^2) = \frac{Q^2}{Q^2 + C}, \quad K_i^{\text{axial}}(Q^2) = \frac{Q^2 + C_1}{Q^2 + C_2},$$

$$F_2^{\nu}(x,Q^2) = \Sigma_i \left[K_i^{\text{vector}}(Q^2) + K_i^{\text{axial}}(Q^2) \right] \times \xi_w \left[q_i(\xi_w, Q^2) + \bar{q}_i(\xi_w, Q^2) \right]$$

$$xF_3^{\nu}(x,Q^2) = 2\Sigma_i \left[\sqrt{K_i^{vector}(Q^2) K_i^{axial}(Q^2)} \right] \times H(x,Q^2) \left[xq_i(\xi_w, Q^2) - x\bar{q}_i(\xi_w, Q^2) \right],$$

- In our neutrino previous cross section model we assumed $K^{axial} = K^{vector}$.

This is only true for free quarks (which is a correct assumption for Q2> 0.5 GeV2)

- However: We expect that axial-vector is not suppressed at Q2=0
  - 2009 Update 2 : $K^{axial} = 1$ as a first try

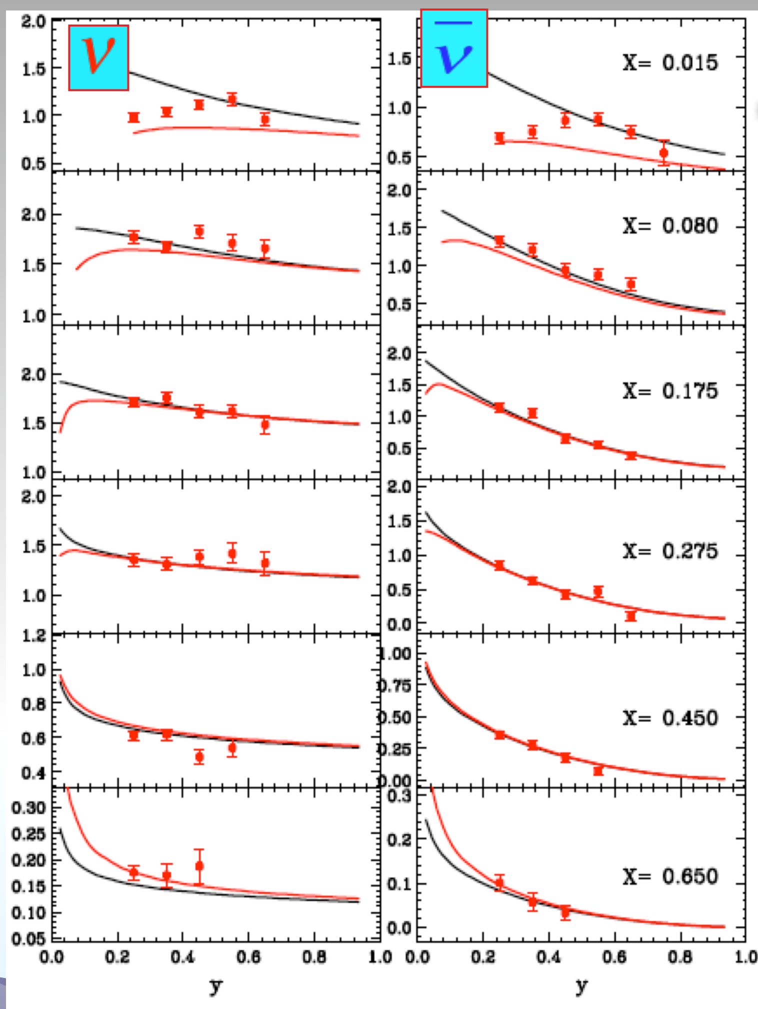
Axial-contribution

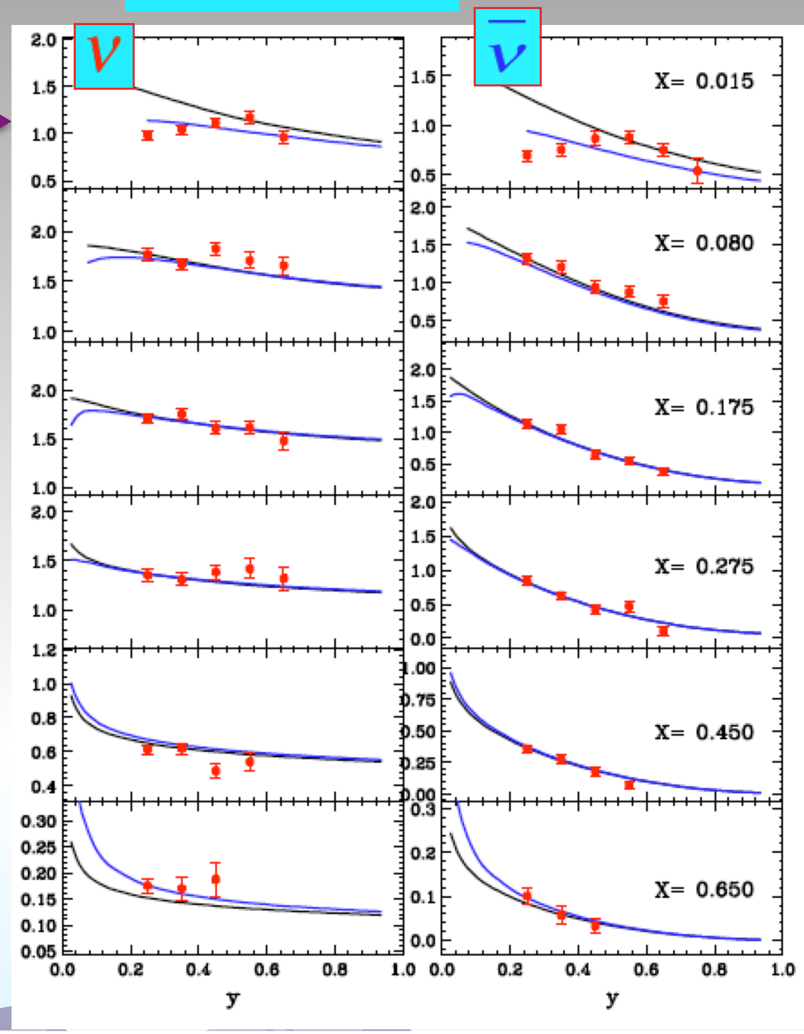
CCFR diff. cross at Eν= 55 GeV

$K_{axial} = Q^2/(Q^2+C)$

$K_{axial} = 1$

better





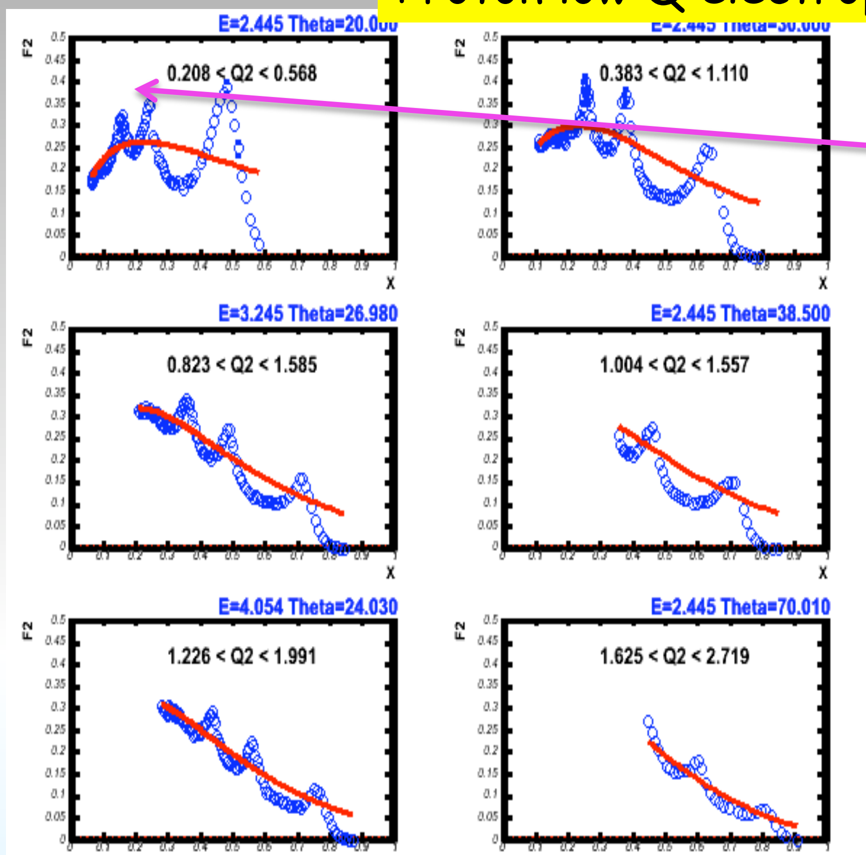
Black line GRV98; red line with B-Y 2004 and Kaxial=Kvector, blue Kaxial=1

Update 3: In resonance region, duality works down to Q2=0.5 GeV2, but breaks down at Q2=0.
Not important for the Vector part, since Q2=0 contributes zero to the vector part of the neutrino cross section.

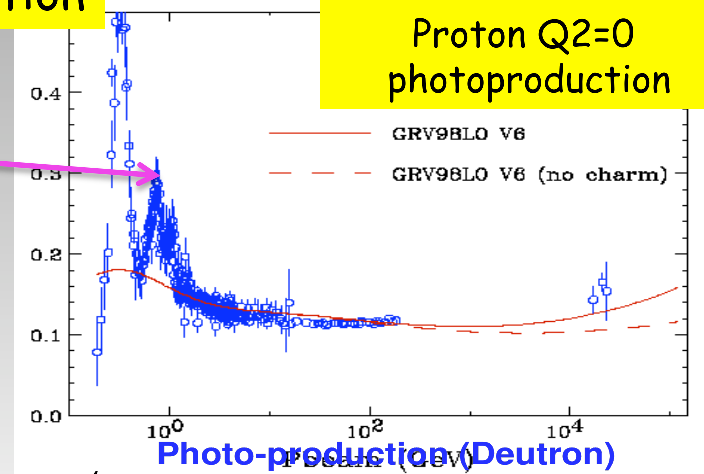
$\sigma(\gamma\text{-proton}) = 4\pi\alpha/Q^2 * F_2(\xi_w, Q^2)$

where $F_2(\xi_w, Q^2) = Q^2/(Q^2 + C) * F_2(\xi_w)$

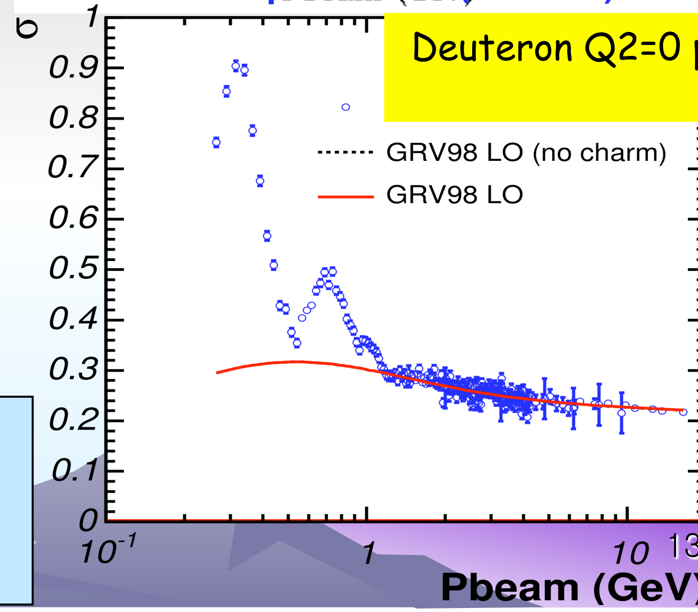
Proton low Q electroproduction



Proton Q2=0 photoproduction



Deuteron Q2=0 photo



Update 3: Improve the model so that it is also valid in the resonance region at Q2=0
We will fix it by applying a low Ehad K factor
Important for axial part

Update (3): apply a low ν (Ehad) K factor
$K(\nu) = (\nu^2 + C2nu) / \nu^2$
Where C2nu = 0.20
It make duality work for resonance all the way to Q2=0.
So vector part is now modeled everywhere including resonance region down to very low Nu and very low Q2.

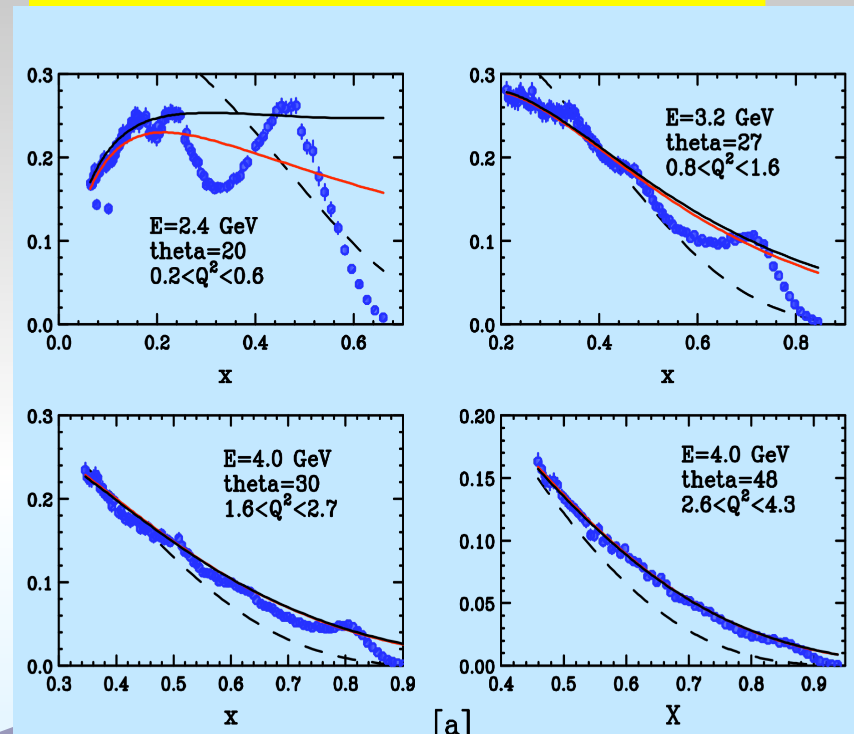
$\sigma(\gamma\text{-deuteron}) = 4\pi\alpha/Q^2 * F_2(\xi_w, Q^2)$

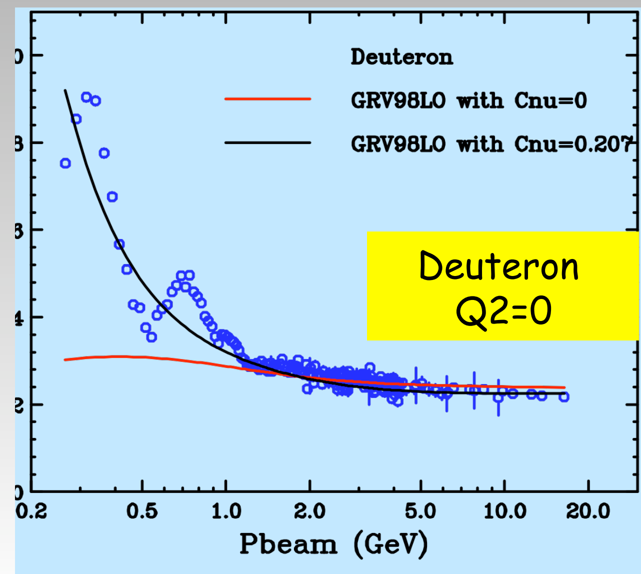
where $F_2(\xi_w, Q^2)$

$= Q^2 /(Q^2 + C) * F_2(\xi_w)$

Photo-production Q2=0

Deuteron Resonances Electroproduction





Black line includes Low Ehad K factor

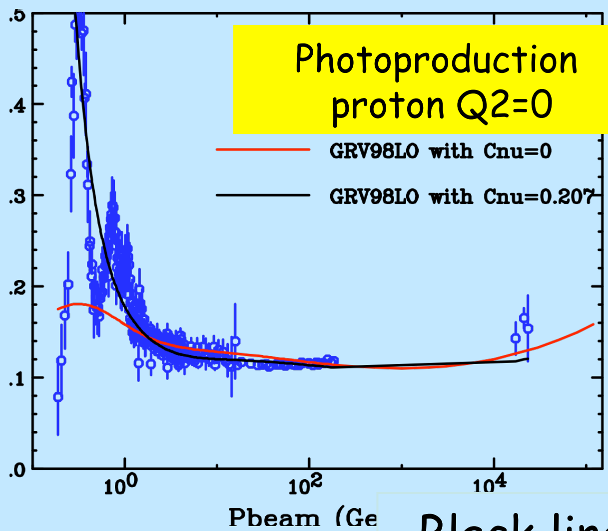
Red line – no low ν (Ehad) K factor

For a heavy nucleus, Fermi motion will smear all of the resonances

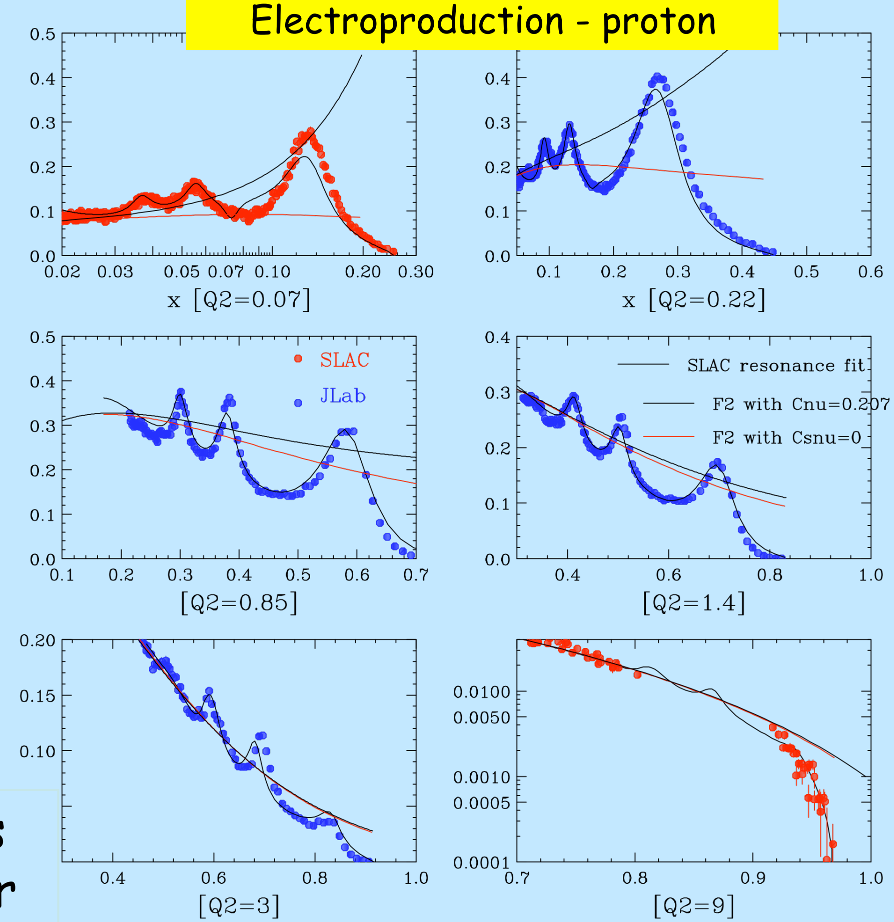
Low Ehad K(ν) factor extends the validity of the model for electron scattering in the resonance region down to Q2=0

- Proton data
- (note that for nuclear targets the resonances will be smeared by Fermi Motion)

Photo-production Q2=0



Electroproduction - proton



Black line includes Low Ehad K factor

Red line no Low ν K factor

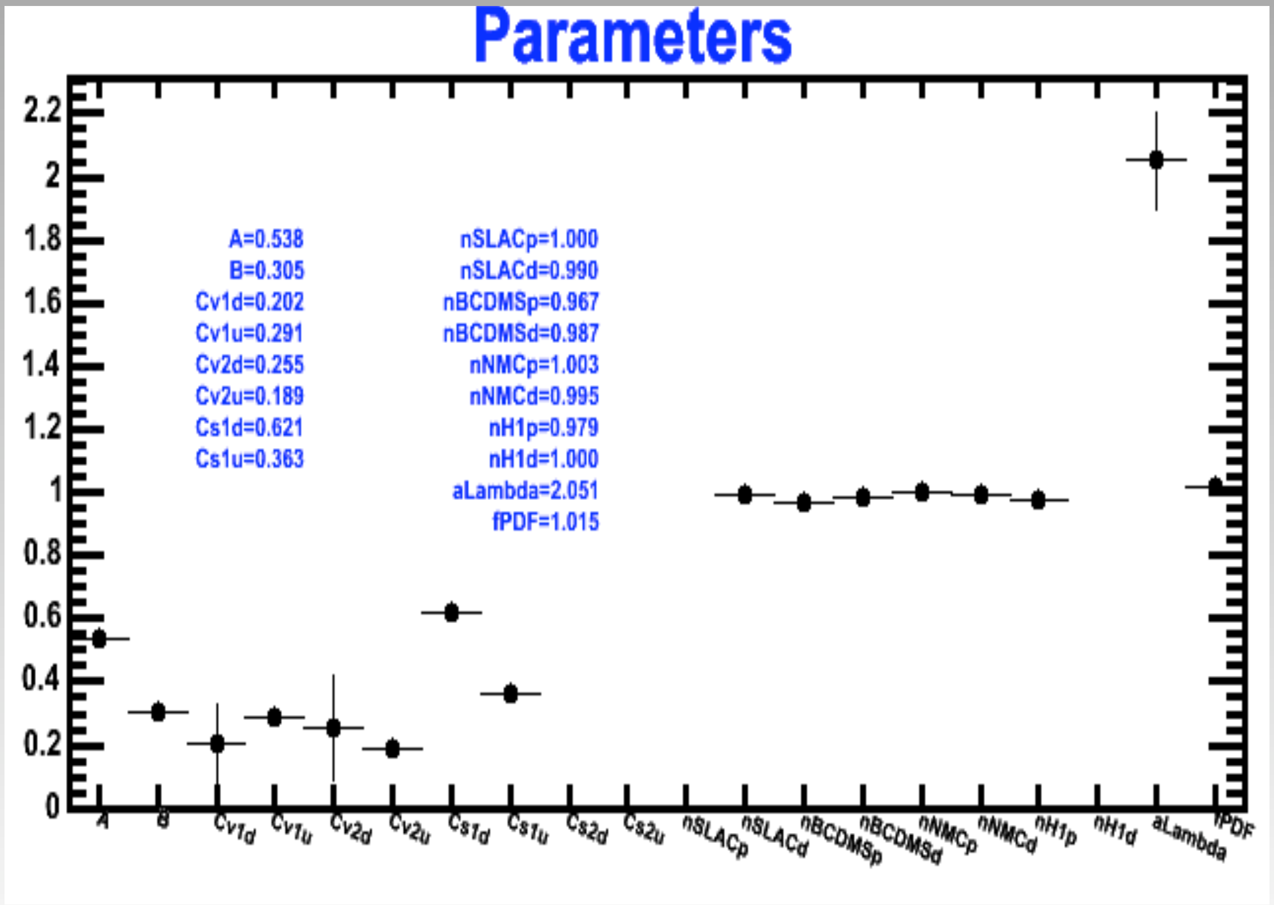
Bodek-Yang - 2010

Summary and Discussions

- We updated our Effective LO model with ξw and K(Q2) factors.
- (1) Updated to account for the difference in the higher order QCD corrections between F2 and XF3. This is accounted for with a H(x) factor Therefore, the axial part is also well described for Q2>1 GeV2, where axial and vector are expected to be the same
- (2) Updated to use K_axial (Q^2)=1 for both the resonance and inelastic continuum region. This is expected since we know that neutrino quasielastic and resonance production form factor are not zero at Q2=0.
- The lowest Q2 bins in the neutrino and antineutrino measured differential cross sections favor K_axial (Q^2)=1.The total cross section as measured in high energ y neutrino scattering favors K_axial (Q^2) =1. -->To be investigated in MINERvA
- (3) Updated to include a low Ehad factor K(ν) to describe all charged lepton inelastic continuum as well as all resonance data including photo-production data down to Q2=0. The vector part of the neutrino cross section is now modeled very well. Note: By Gauge Invariance, the vector structure functions must go to zero at Q2=0 for both resonances and inelastic continuum.

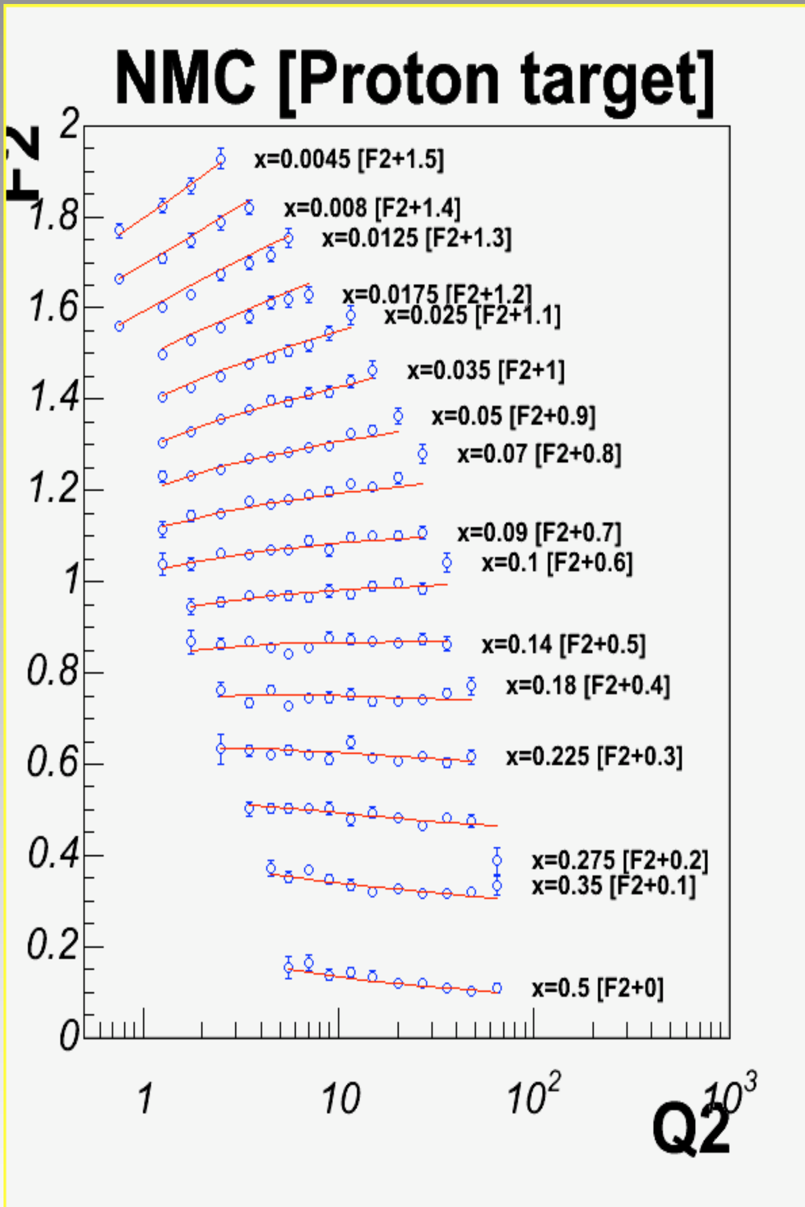
Backup-slides

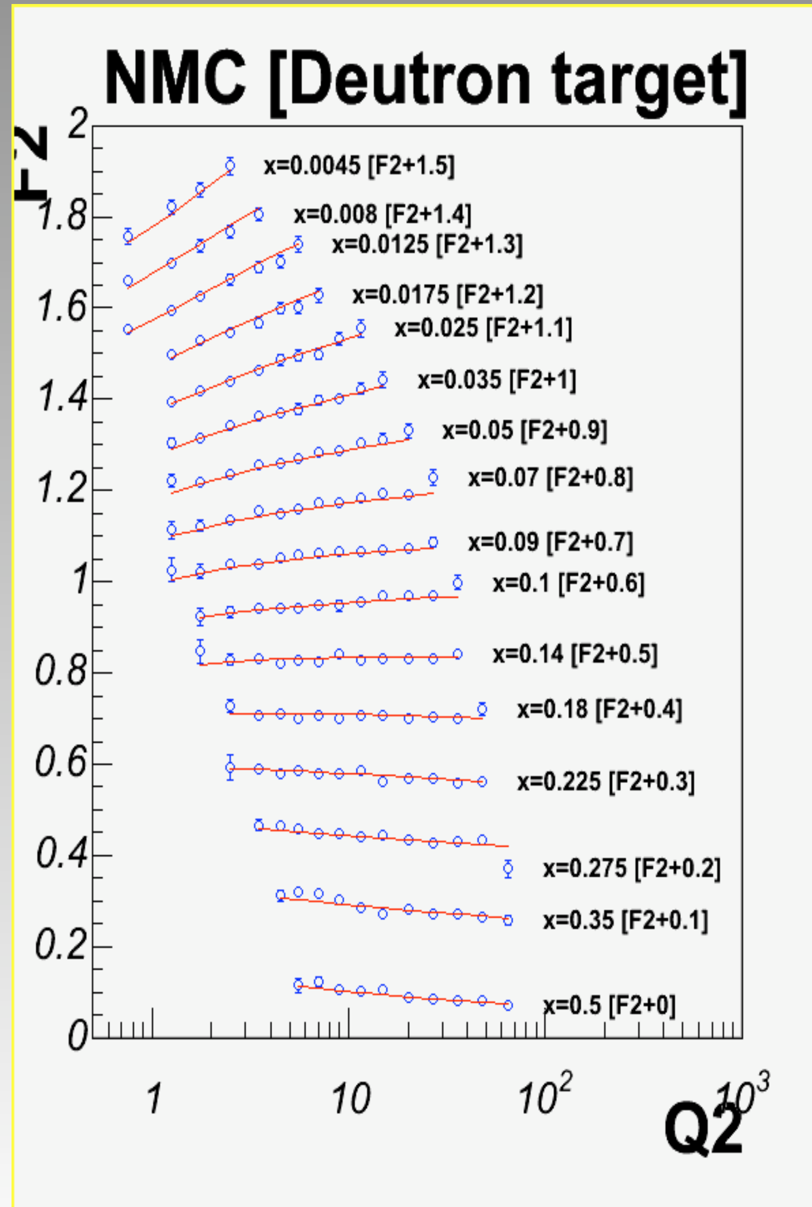
GRV98 + B-Y 2004 Fit results
separate K factors
for uv, dv,us,ds



Separate K factors for uv, dv,us,ds provided additional parameters. They provide separate tuning for H and D data, but are not important for Heavy nuclei.

Fit results GRV98 + B-Y 2004 muon scattering





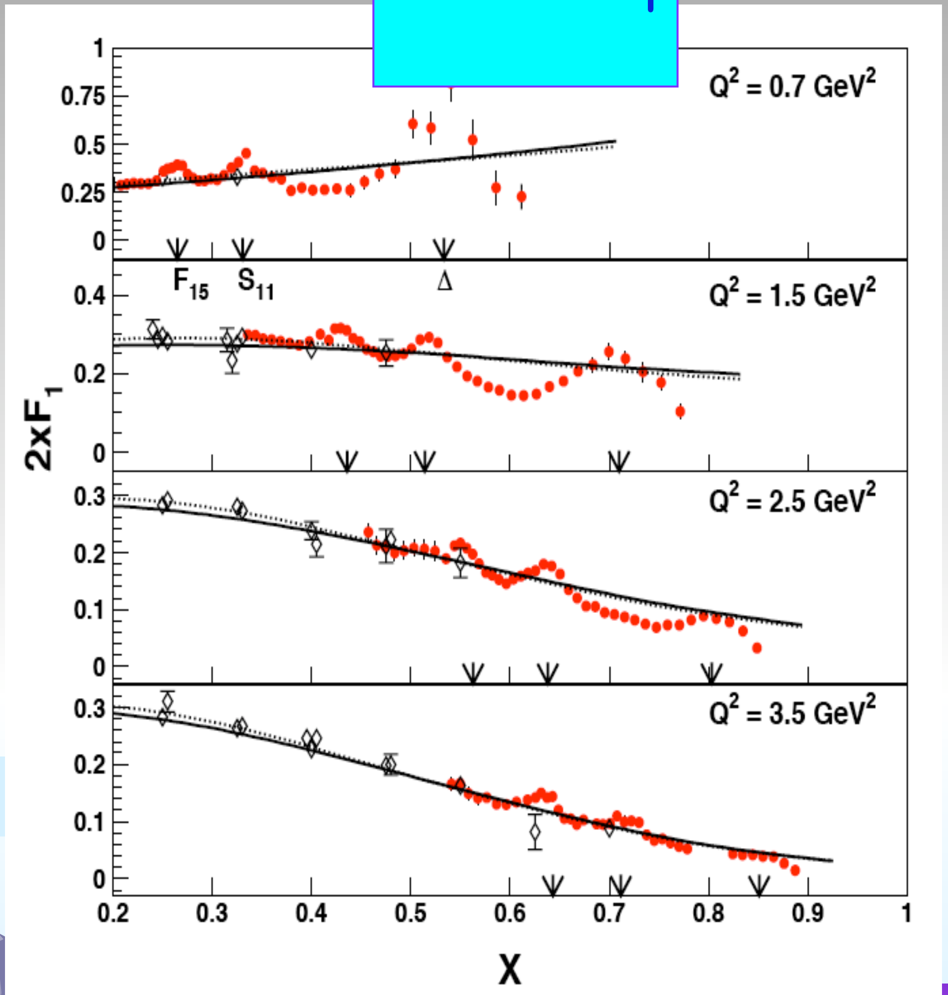
$2xF_1$ data

- All DIS e/μ F_2 data are well described
- Photo-production data (Q^2=0) also work: thus included in the latest fit
- 2xF1 data (Jlab/SLAC) also work:

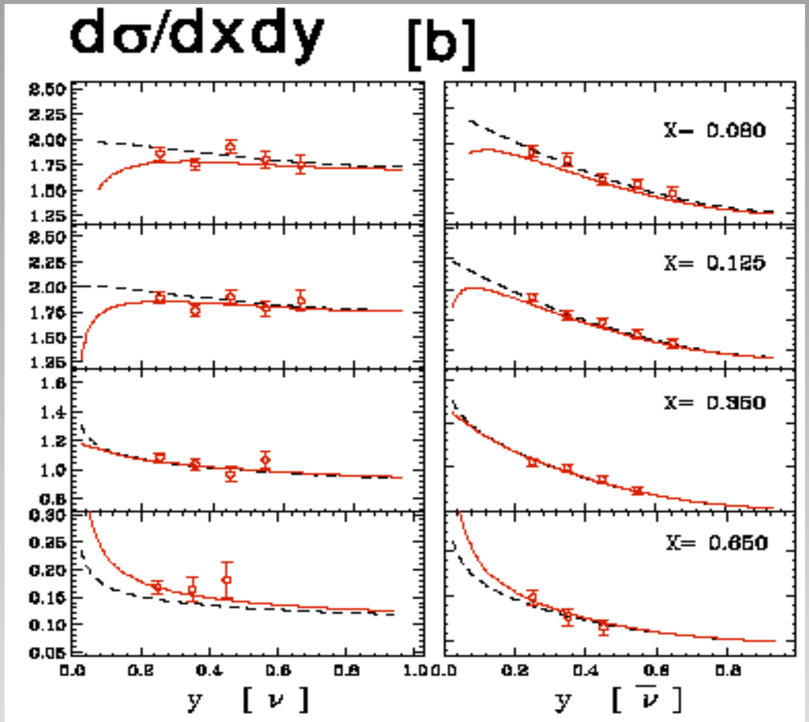
  using $F_2(\xi_w)$+R1998

line GRV98 + B-Y 2004

Jlab $2xF_1$



Comparison with CCFR neutrino data (Fe) (assume V=A) apply nuclear corrections



- Apply nuclear corrections using e/m scattering data.
- Calculate F_2 and xF_3 from the modified PDFs with ξw
- Use R=Rworld fit to get $2xF_1$ from F_2
- Implement charm mass effect through ξw slow rescaling algorithm, for F_2 $2xF_1$, and XF_3

Red line GRV98 + B-Y 2004

--ξw PDFs GRV98 modified (red line)

---- GRV98 (x,Q^2) unmodified (black)

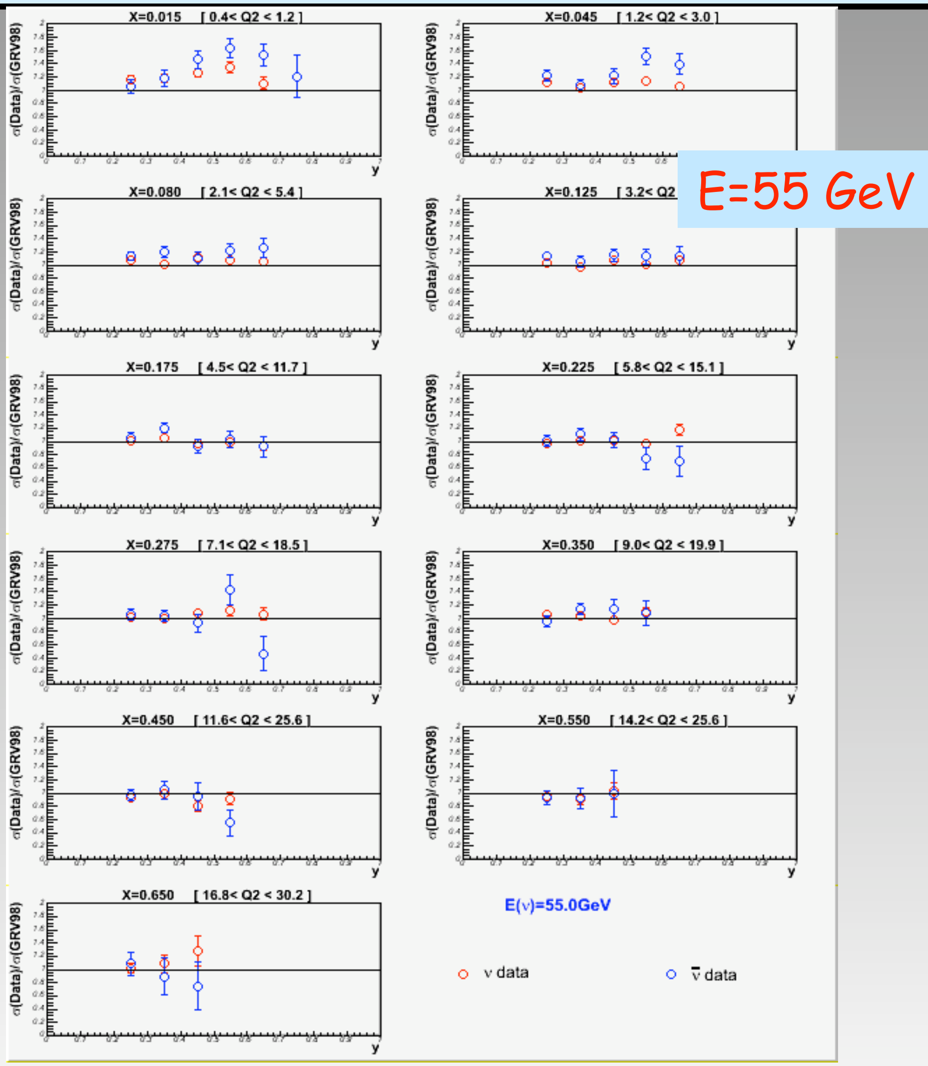
Left: CCFR neutrino data -55 Gev

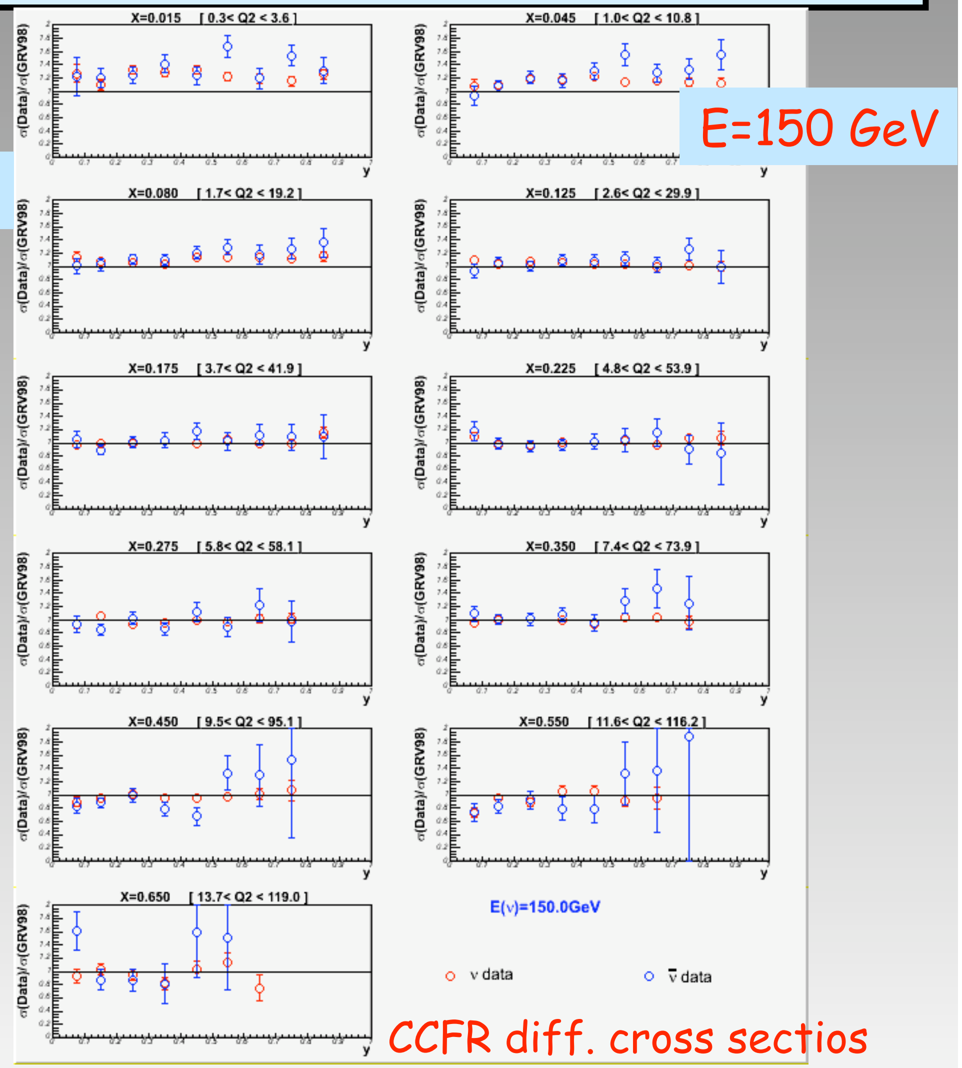
Right : CCFR anti-neutrino data ,-55 GeV

(NuFact03 version)

Our model describes **CCFR** diff. cross sect. (Eν=30–300 GeV) well Note that no neutrino data was included in fit. (However, Lets look in more detail).

Comparison with updated model (assume V=A)
CCFR Fe data/ (GRV98 + B-Y 2004)

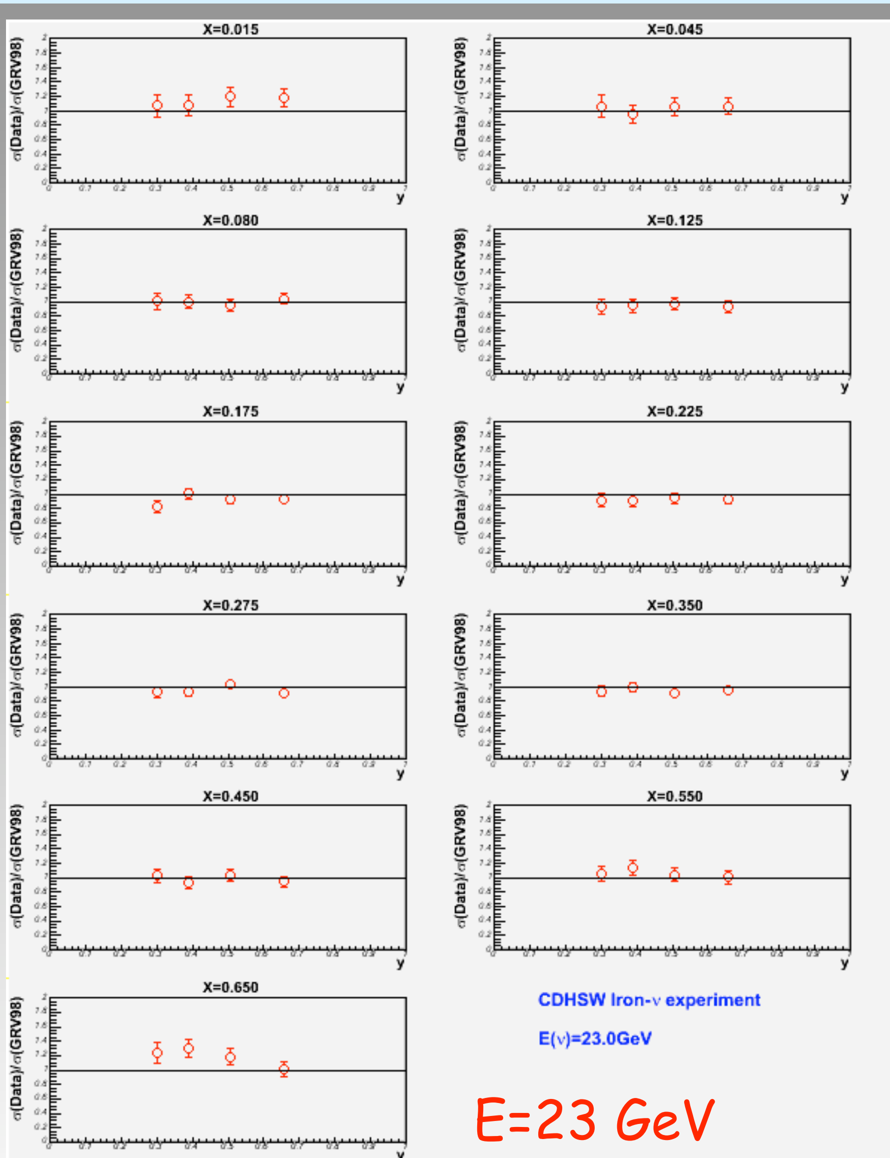


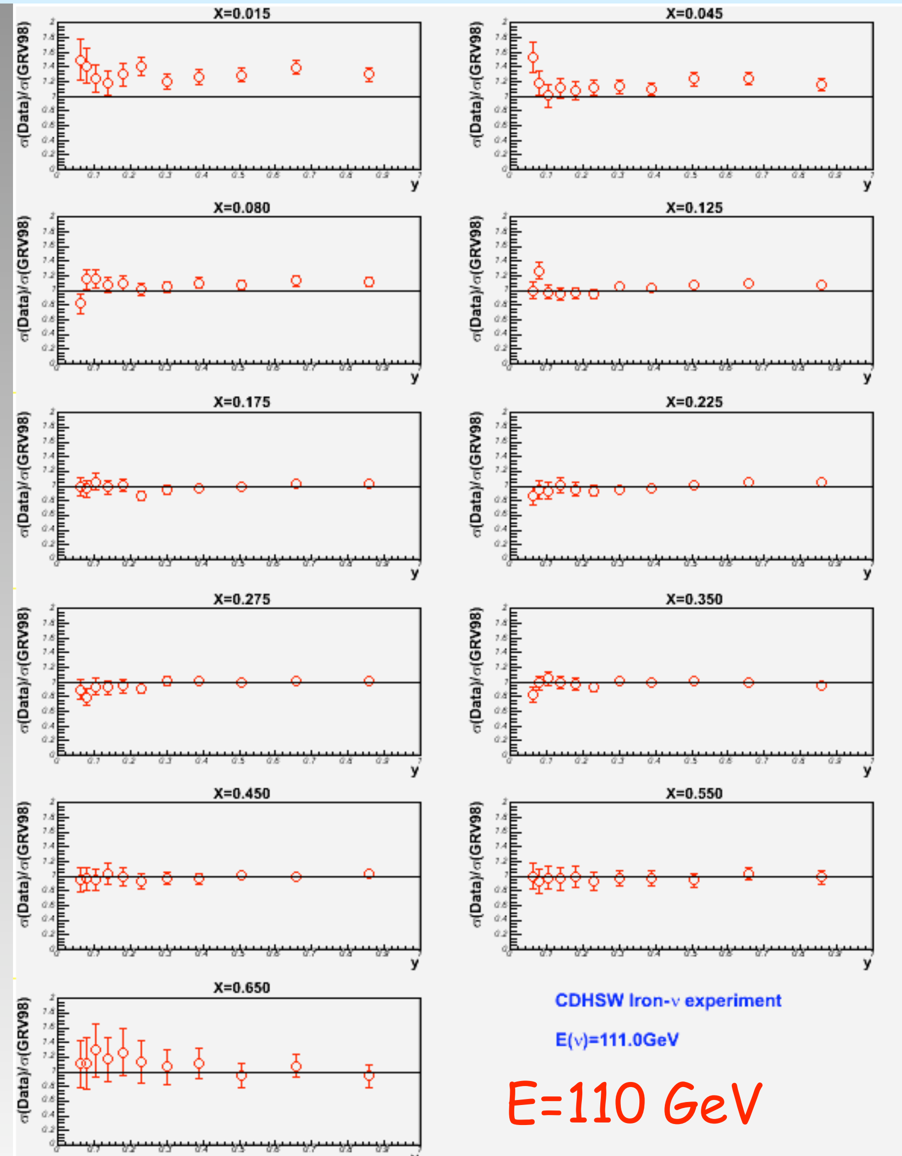


CCFR diff. cross sectios

Model underestimates neutrino data at lowest x bin. At high energy, some may be from missing radiative corrections and c-cbar contribution

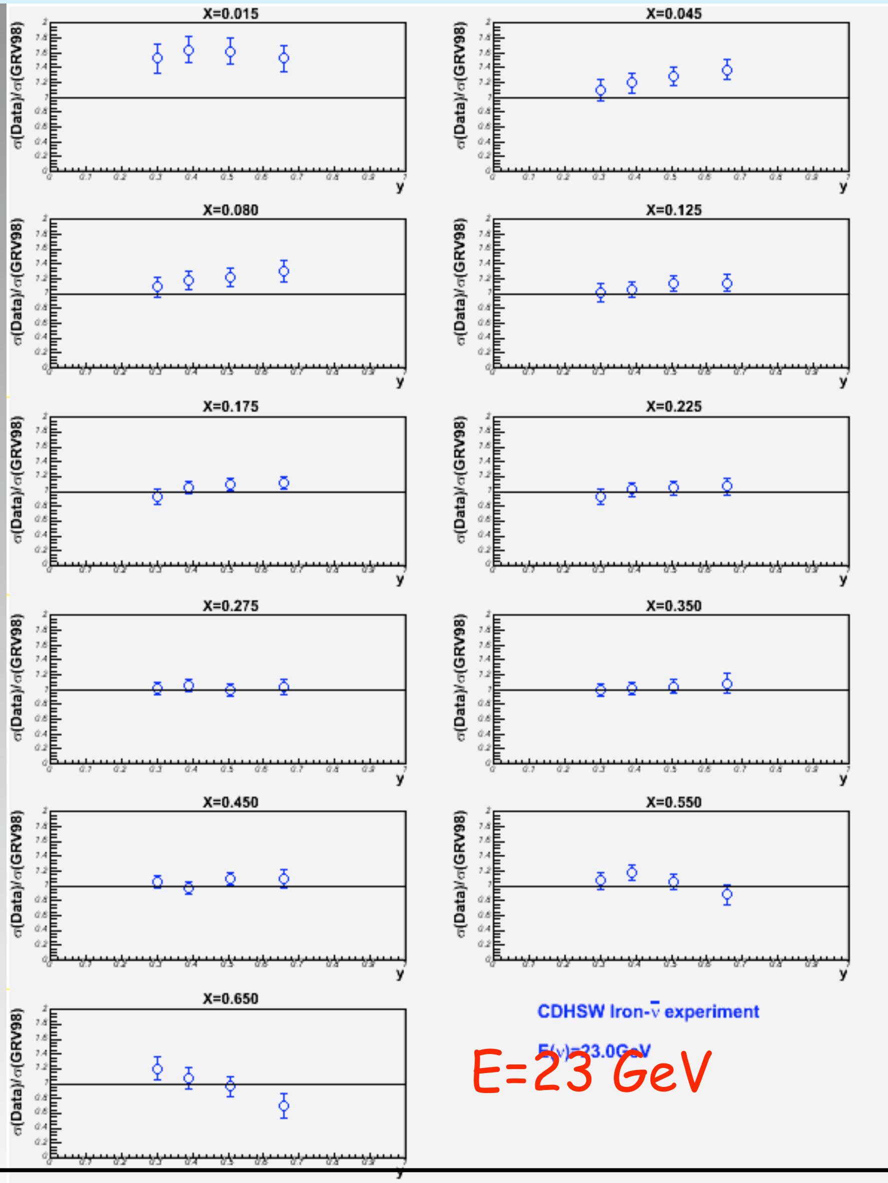
Comparison with CDHSW neutrino data (Fe)

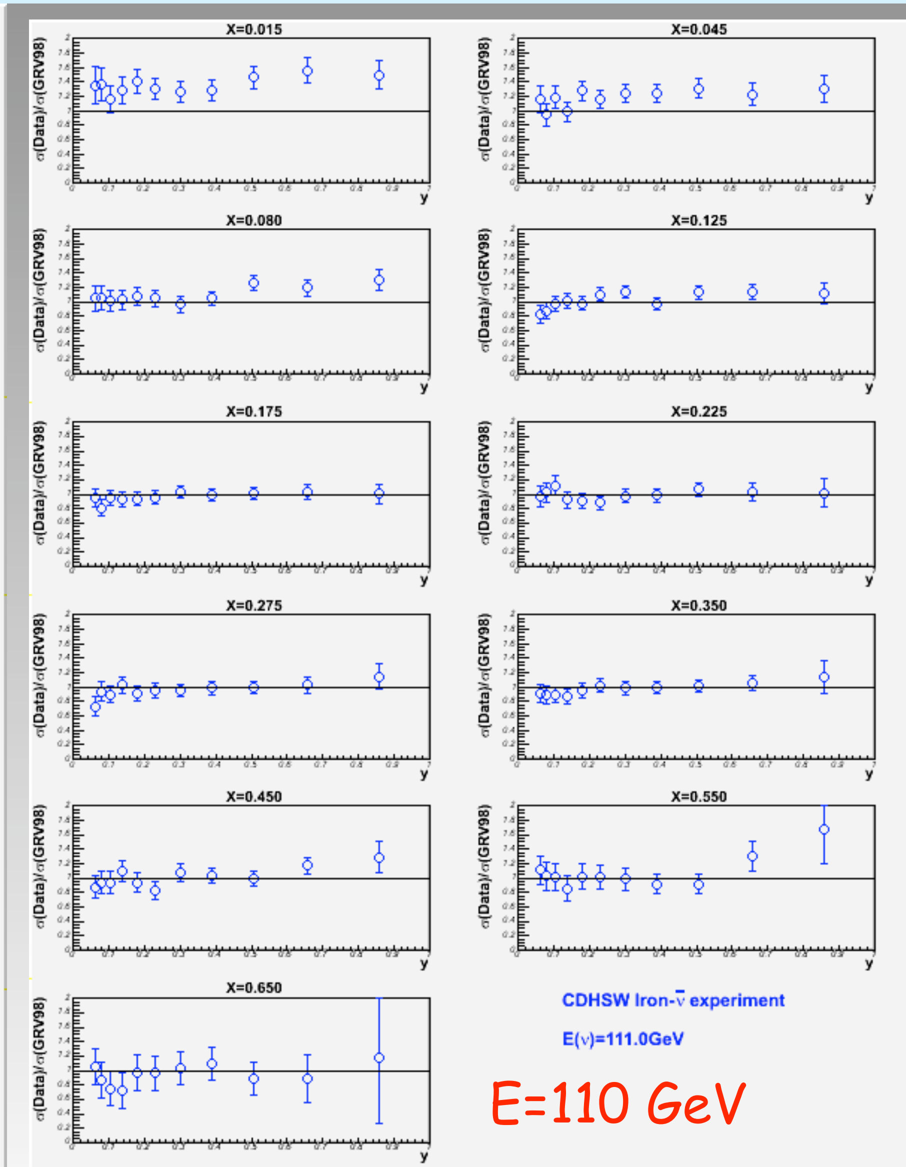




Model underestimates neutrino data at lowest x bin. At high energy, some may be from missing radiative corrections and c-cbar contribution

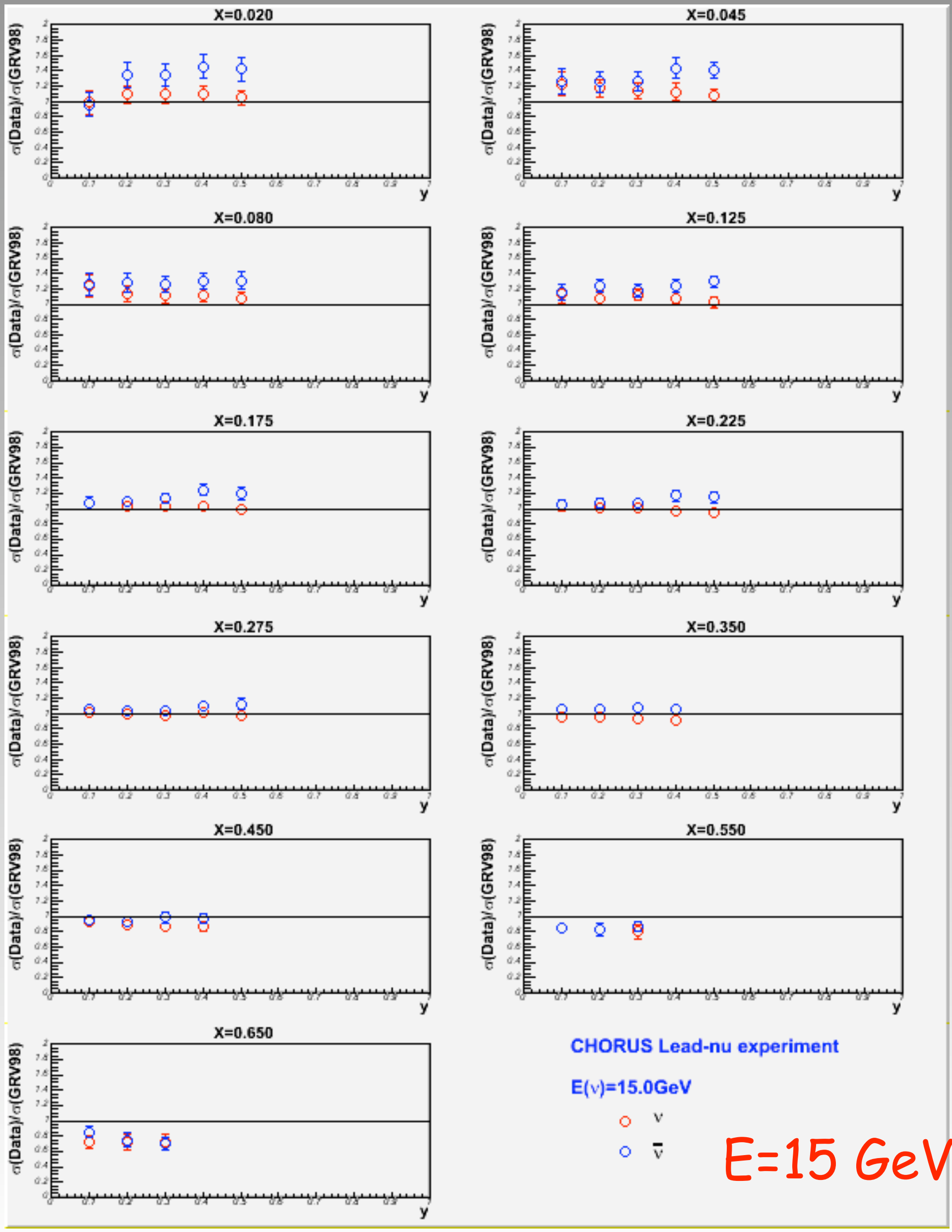
Comparison with CDHSW anti-neutrino data (Fe)



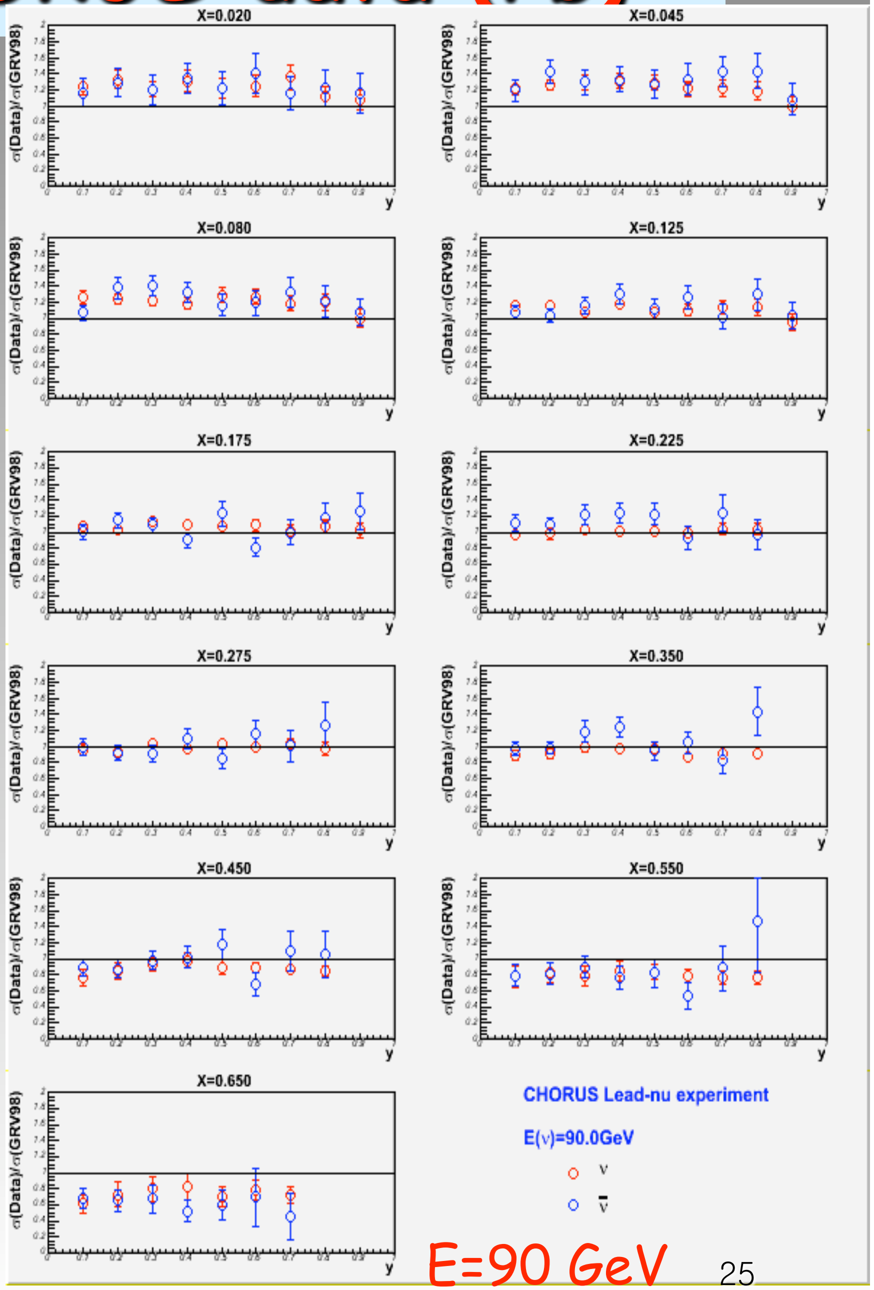


Model underestimates antineutrino data at lowest x bin –also lowest Q2. At high energy, some may be from missing radiative corrections and c-cbar contribution

Comparison with CHORUS data (Pb)



E=15 GeV

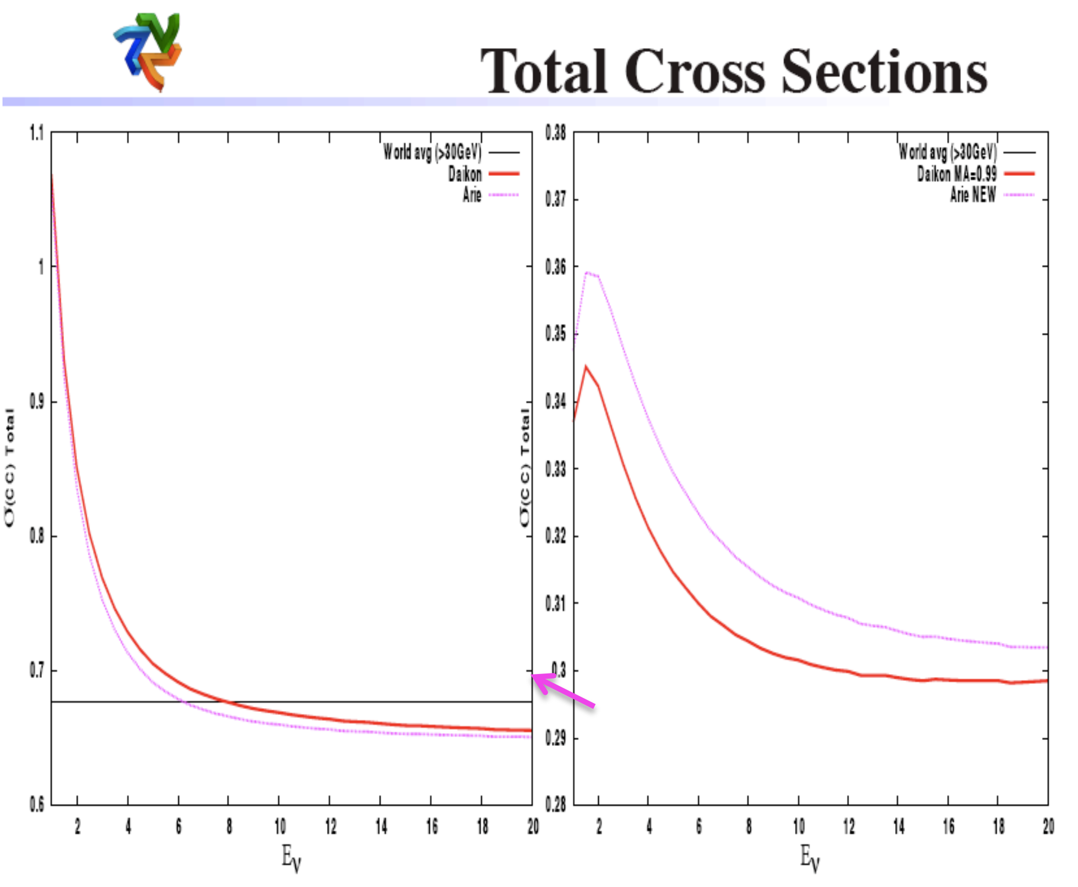


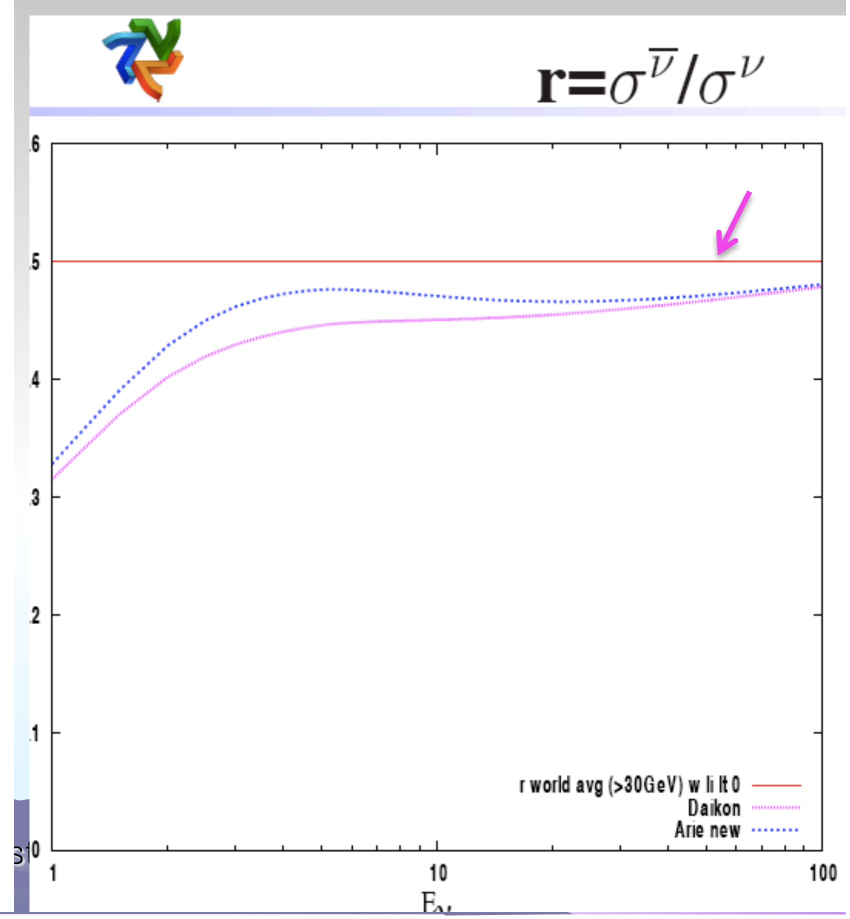
E=90 GeV

How is the model be used

- Duality is not expected to work for quasielastic or the delta
This is because these cross section have definite isospin final states. Therefore PDFs will not give the correct ratio of neutrino vs antineutrino and proton versus neutron scattering for quasielastic and delta production.
- Duality should work in the region of higher resonances since these regions include several resonances with different isospins..
- People use the 2004 Bodek-Yang model above W=1.8
- They used other models for quasielastic, the delta, and the 1520 resonance region and matched them to Bodek-Yang in the W=1.8 region .
- 2009 -> make it work in the delta region

Total cross sections
Bodek-Yang 2004 used above W=1.8 AND
matched to resonance and quaselastic models.
Find that predicted total neutrino and antineutrino cross sections are lower than high energy measurements (5%). The antineutrino to neutrino ratio is also low.
Some may come from the need to apply radiative corrections and include the c-cbar sea at very high energy (no c-cbar sea in GRV98). Some may be differences in nuclear effects between electrons and neutrinos- But is this all?





Note: GRV98 + B-Y 2004 is for free nucleons (H+D). Electron and muon data are corrected for radiative corretions. In addition, GRV98 has no charm sea.

Published neutrino differential cross sections:

(1) Have no radiative corrections

(2) Are on nuclear targets

(3) Have contributions from XF3 and include both axial and vector contributions.

(4) Some are at very high energy which include a contribution from the charm sea.

In order to compare to neutrino data:

(1) We need to account for difference in the scaling violations in XF3 and F2 (2009 update 1)

(2) We need to make duality work in the resonance region at very low Q2 if we want to match to the resonance region, (2009 update 2)

(3) We need to account for difference in axial and vector structure functions at low Q2 (2009 update 3)

(4) We need to apply an X dependent nuclear correction to convert from H-D to nuclei.

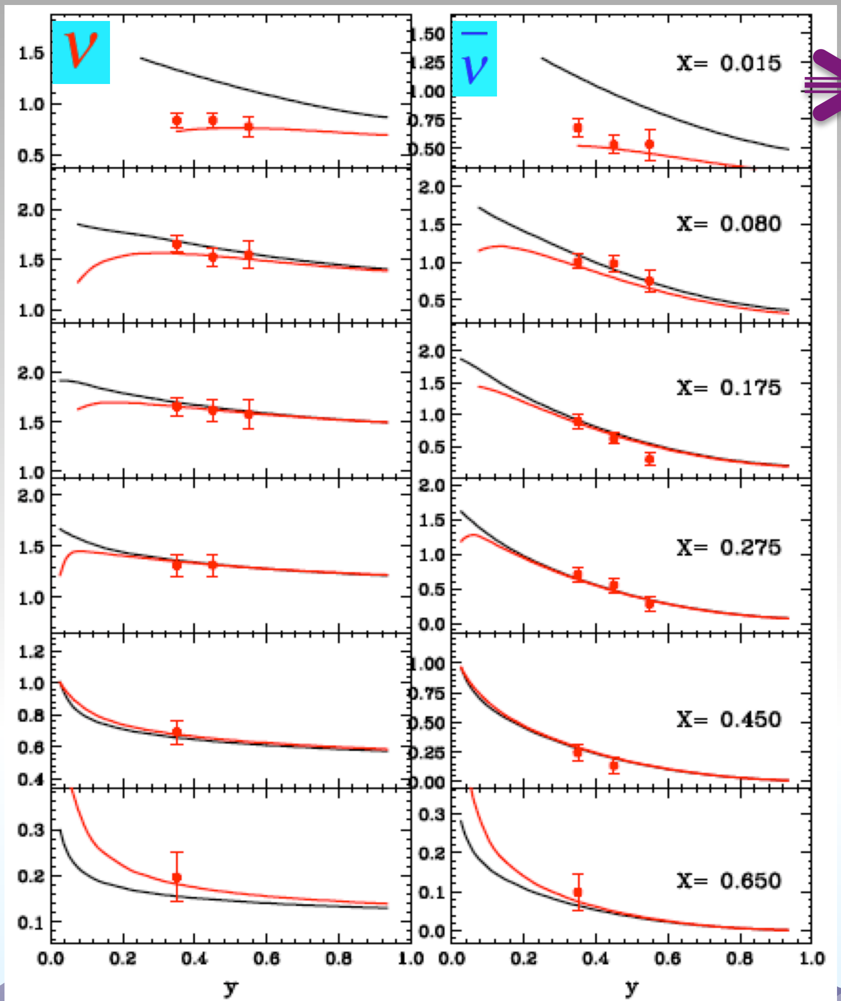
(1) However, nuclear effects may be different for muons and neutrinos, different for axial versus vector, different for F2, XF3 (will be studied in MINERva)

(2) We should to add radiation to GRV98 + B-Y 2004 (or radiatively correct the neutrino data) - not done

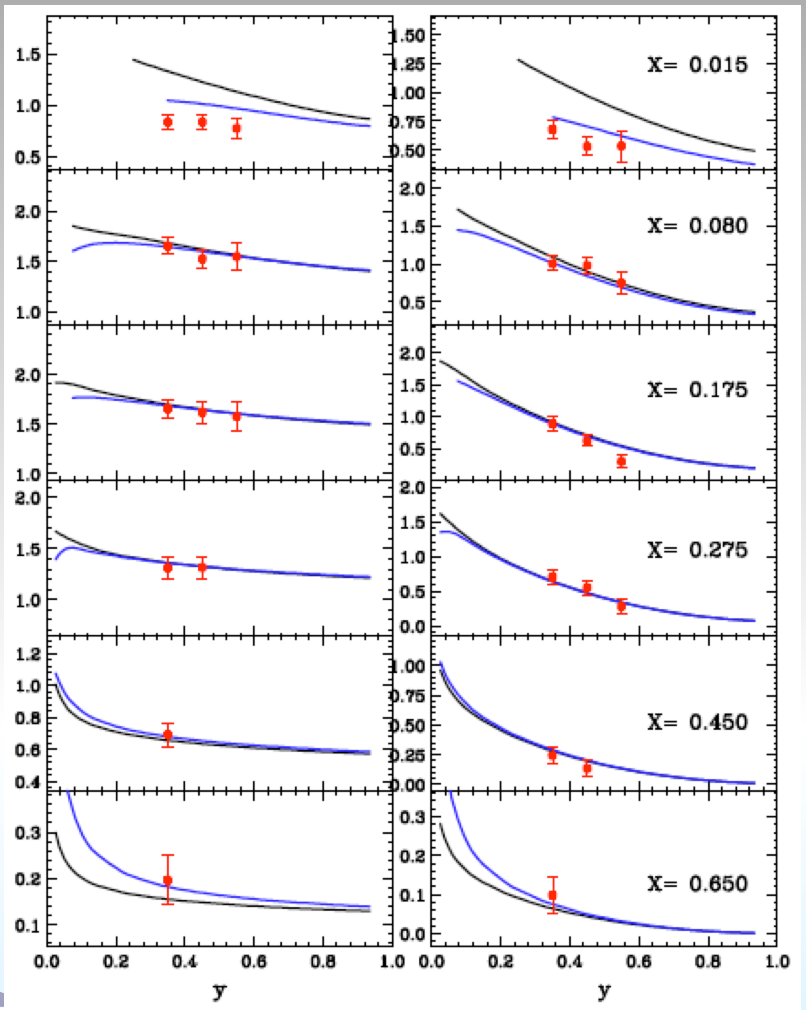
(3) We should add charm sea contribution at very large energy (not done)

CCFR diff. cross at Eν= 35 GeV

$K_{axial} = K_{vector} = Q^2/(Q^2+C)$



$K_{axial} = 1$



Black line GRV98; red line with B-Y 2004

And Kaxial=Kvector, blue Kaxial=1

Things left to do

- Use Kaxial (Q2)=1 for now, but it will be tuned further in the future.
- We can tune the axial vector K factor by including low Q2 neutrino and antineutrino differential cross sections in the fit

  However, the electron data has been radiatively corrected. A proper comparison to neutrino differential cross sections needs to include both radiative corrections and the c-cbar contribution at high energies (which are not included in the GRV98 PDFS). And what about the nuclear effects?

We plan tune Kaxial (Q2) to get better agreement with the neutrino and antineutrino measured total cross sections (Here we need to separately add the quasielastic, delta and c-cbar contributions, (but no need to include the radiative corrections since these integrate away in the total cross section). We will have this comparison soon

- In the future more detailed information on the axial form factor would come from MINERνA: by combining JUPITER Jlab (e-N vector) with the MINERνA (neutrino-N vector+axial) data.
- There could be different nuclear effects (e vs ν), F2 vs xF3, and for axial F2 versus vector F2. This will also be studied in MINERνA