JPG Review of SIS and DIS Scattering

Invited by guest editors for a volume on ν-A scattering

$\nu(\bar{\nu})$-Nucleus Interactions in the Shallow- and Deep-Inelastic Scattering Regions

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We work with following definitions

- SIS_t: is defined as non-resonant meson (pion) production with $Q^2 < 1$ GeV^2 (rather arbitrary).
- As Q^2 grows and surpasses this1 GeV^2 threshold…
- DIS: non-resonant (pion) production via interactions on quarks within the nucleon.

- Experimentally we cannot tell the difference between resonant and non-resonant pion production.
- SIS practically defined to include resonant production as well.
- Set W = 2 GeV as border to separate resonant pion production from quark-fragmented pion production.

- **SIS_e: Inclusive π production: $(M_N + M_\pi) < W < 2$ GeV and $Q^2 < 1$ GeV^2 with $W > 2$ GeV**
- **DIS: $Q^2 > 1$ GeV^2 and $W > 2$ GeV**

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Inclusive SIS studies and "Quark-Hadron Duality"
How did the concept of duality originate?

Many examples of duality tests in e-N/A and ν-N/A

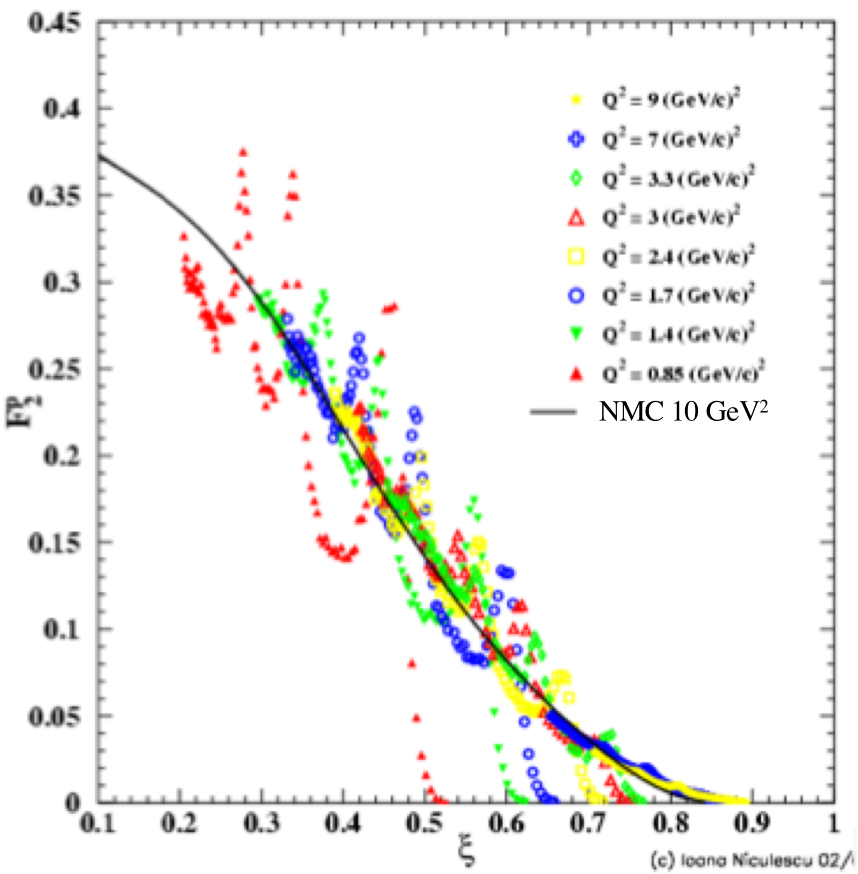
- How does the SIS region transition to DIS?
  - How does the physics (language) of quark/partons from DIS meet the physics of nucleons/pions of SIS → **quark-hadron duality**
  - Do the nuclear effects measured in the DIS region extend down into the SIS region or do they suddenly/slowly turn off.
- Quark–hadron duality is a general feature of strongly interacting landscape.
  - Relationships between meson–nucleon and quark–gluon degrees of freedom.
- Quark-hadron duality originally studied and confirmed in e-N scattering. With ν-N scattering, no data need to use theory models!

- **Show why it is absolutely essential to include non-resonant pion production in any evaluation of duality!**

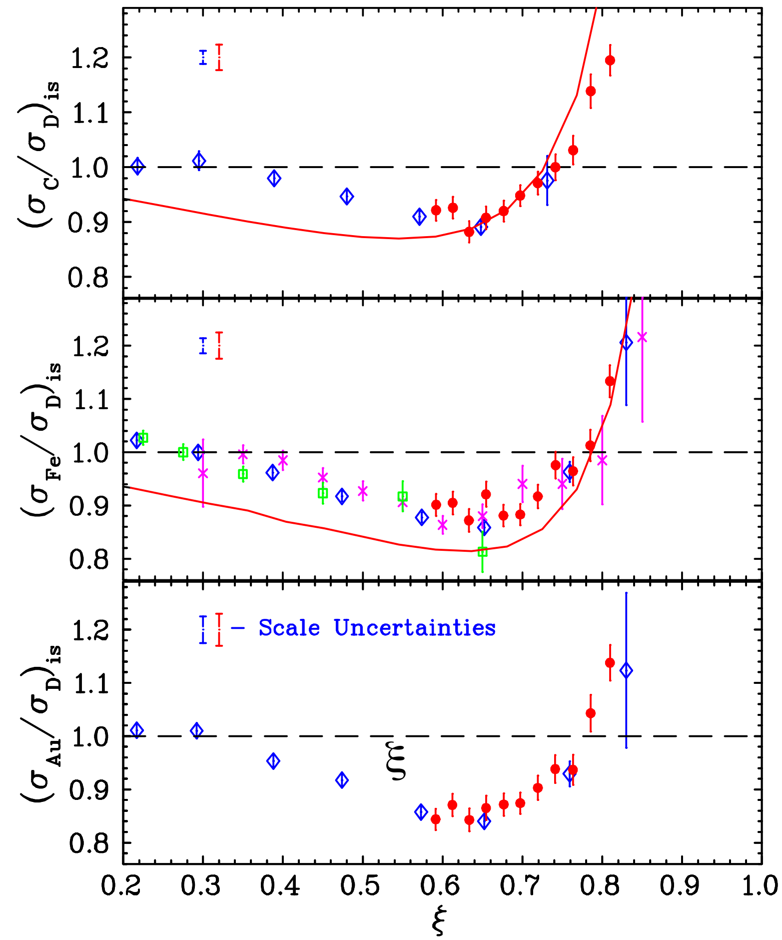
Duality works well in e-N/A.

Present multiple examples

Early Jefferson Lab 6 GeV
<u>e-Nucleon</u> study of duality

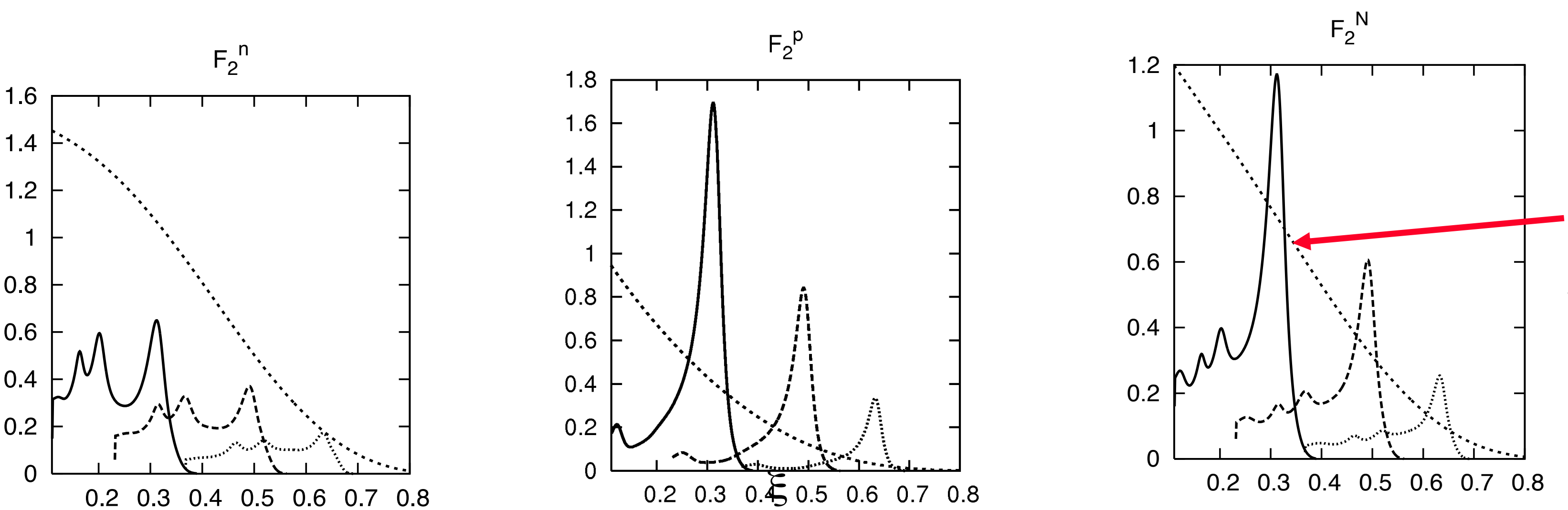


EMC effect in Resonance Region! The solid red circles are Jefferson Lab data taken in the **resonance region 1.2 < W^2 < 3.0 GeV and Q^2 = 4 GeV^2.** Oher data points from DIS.



…. Not so well for ν-N/A - Jan et al. study

- Comparison to Rein-Sehgal SIS structure functions for n, p and N at $Q^2 = 0.4$, 1.0 and 2.0 GeV^2 (W < 2.0 GeV) with the LO DIS curve at 10 GeV^2 .



However there is reasonable evidence of duality for the region around the Delta with F_2^N

- Many other examples using models from GiBUU and Ghent presented.

Summary: Quark-Hadron Duality for e-N/A and ν-N/A

- $F_2^{ep\ en}$: Qualitative and quantitative duality HOLDS in electron–nucleon scattering.
- $F_2^{\nu p\ \nu n}$: In neutrino–nucleon scattering, duality roughly holds for the average nucleon but NOT individually for neutron and proton. NOT SURPRISING see below!
- $F_2^{\nu A}$: Not at all clear how duality works here, or if it should with FSI. Particularly questionable for nuclei with an excess number of neutrons.

- In general for neutrinos, the resonance structure functions for **proton are much larger than for neutrons** and in the case of DIS structure functions **the situation is opposite.**

- Although to some extent model dependent, a general tendency is that for larger W, DIS structure functions are much larger than the resonance contribution at lower W.

- Can duality be used to suggest problems with current ν-N models via the sum of (1 + n pi) resonance plus non-resonant continuum – try it with GENIE and nuWro,

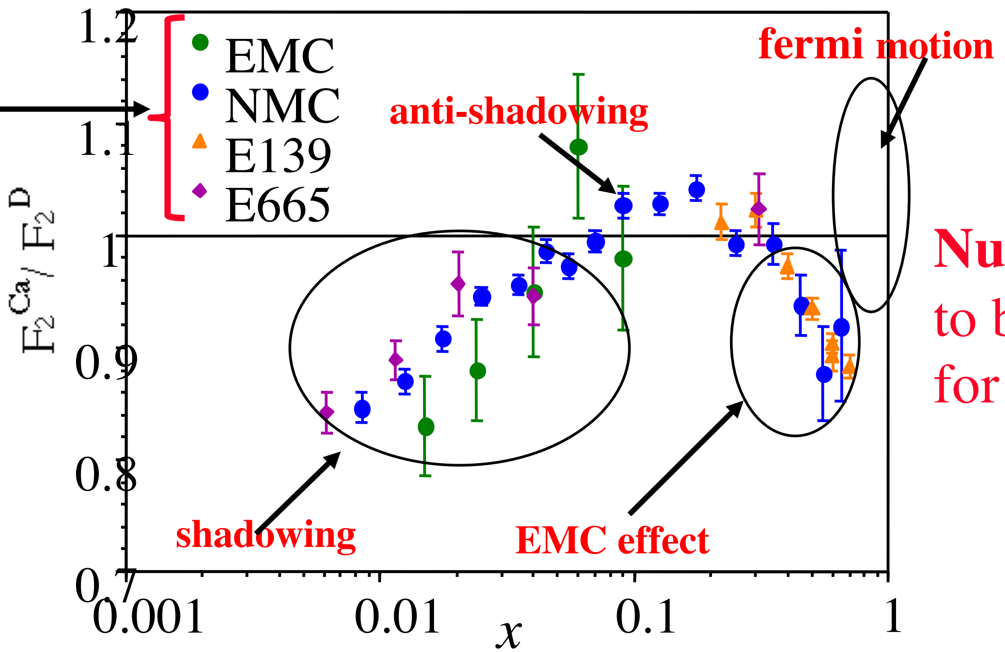
- There is now fresh suggestions that these so-called DIS nuclear effects **(EMC effect) continue down into the SIS region with W < 2.0 GeV!**

Phenomenology/Experiment – DIS

Detailed presentation of ν-A DIS experiments

Why and how of **Nuclear Correction Factors** and fits for **nuclear PDFs**

Charged Lepton
e/μ – A Scattering



Nuclear Correction Factor
to bring e/μ A to e/μ N
for fitting free N PDFs

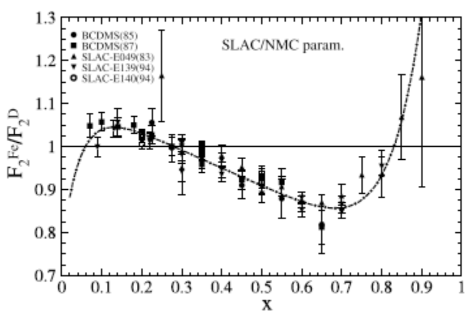
- **<u>In early CTEQ free nucleon PDF fits – *terrible tension* at low-x when including $\nu / \overline{\nu}$ – A corrected with $l^{\pm}$ NCF. Had to ignore $\nu / \overline{\nu}$ – A input !!</u>**

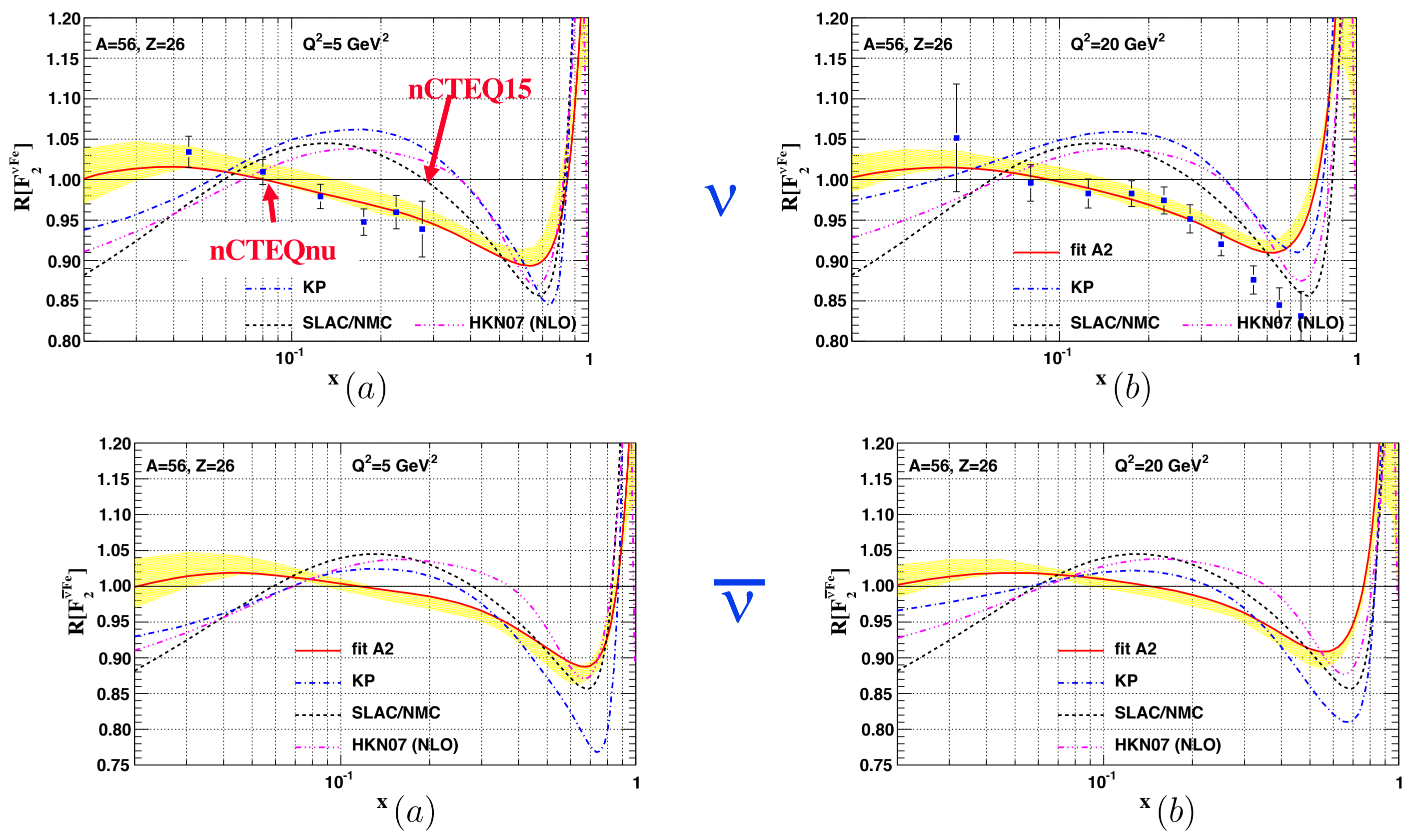
- Conclusion the **neutrino nuclear correction factors are <u>different</u>** than the charged lepton nuclear correction factor?

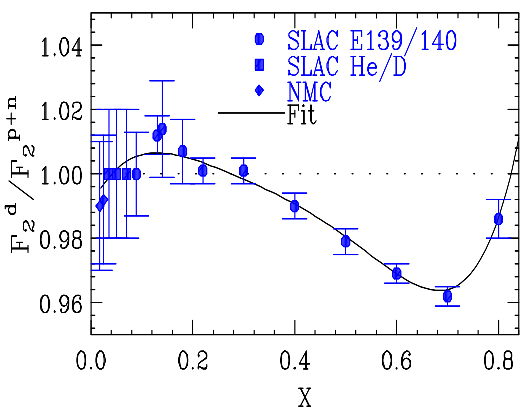
Neutrino Nuclear Correction Factors (NCF)!!

nCTEQnu NCFs: ν and $\bar{\nu}$ $F_2(\nu\text{–Fe}) / F_2[\nu\text{–}(n+p)]$

Show how fits yield ν–based nuclear PDFs







- **NO compromise (χ^2 with tolerance) fit with both ν and e/μ results!**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A.**
  - Presence of axial-vector current. Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.

Nuclear PDFs
Detailed description of how nPDFs extracted

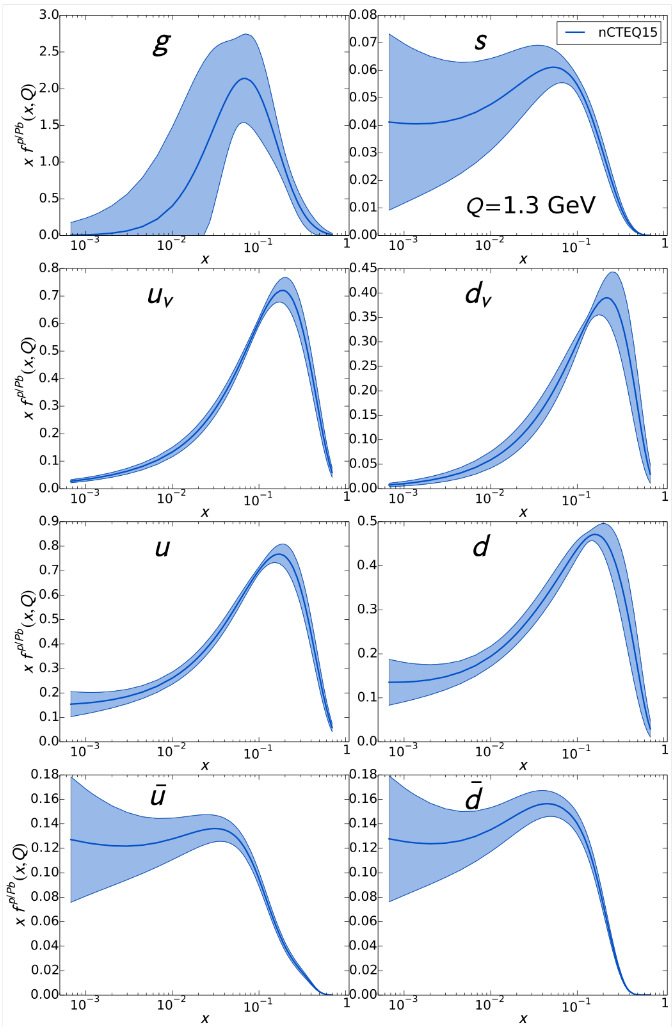


Figure 37. Results of the nCTEQ fit displaying the actual PDFs at the Q_0 scale of $Q = 1.3$ GeV. **P in Pb**

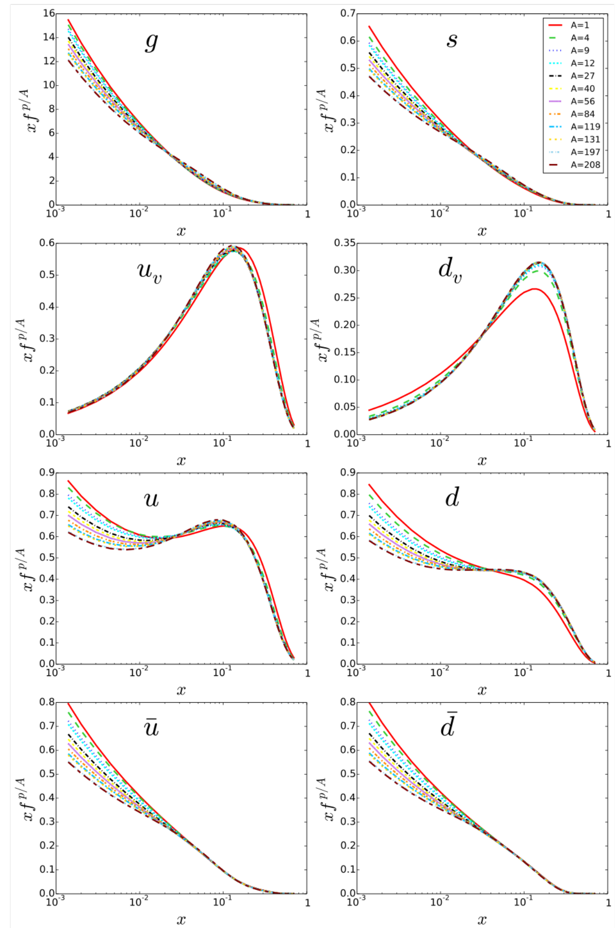
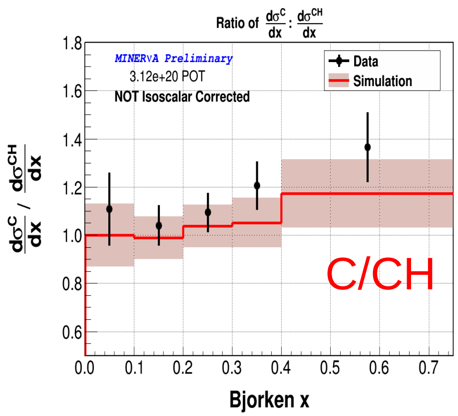
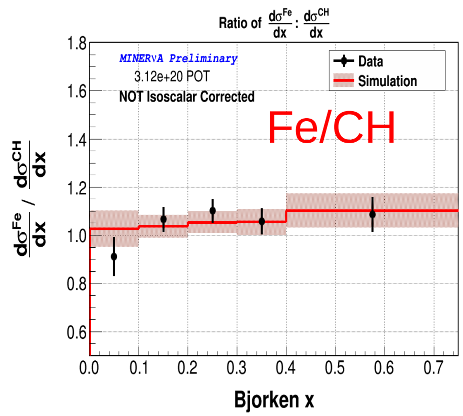
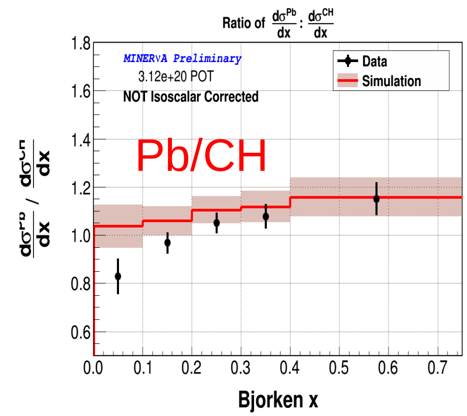


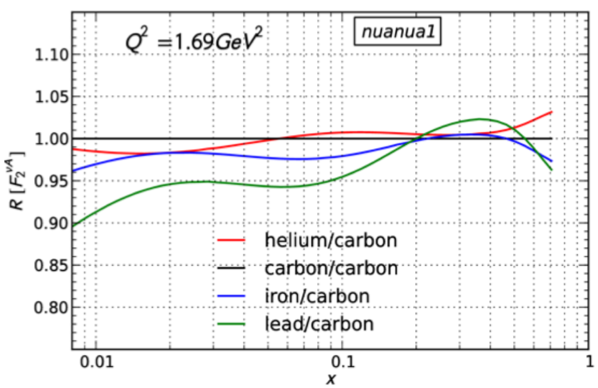
Figure 36. The A-dependence of the nCTEQ nuclear proton PDFs at 10 GeV for a range of nuclei from the free proton $(A = 1)$ to lead $(A = 208)$

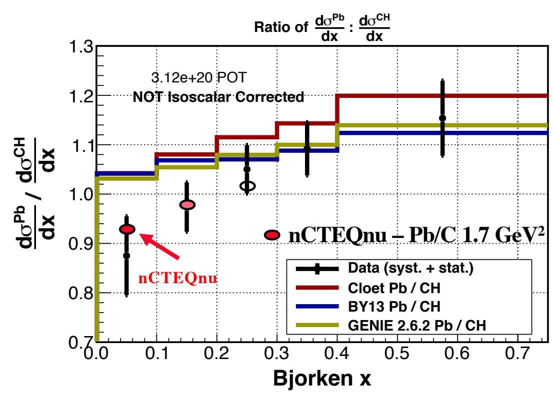
Present most recent relative results. What does MINERνA see?
LE DIS Cross Section Ratios – dσ/dx.
Compare to nuclear PDFs from neutrino fit.











Conclude: Fits and Predictions - Fe

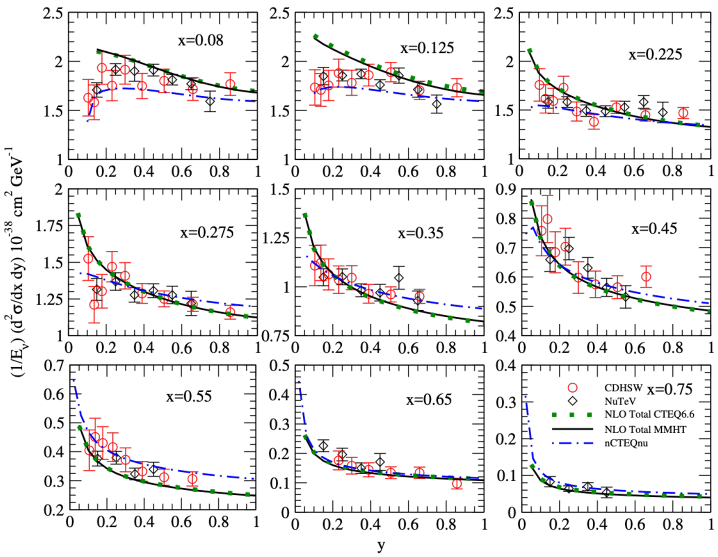


Figure 49. Results of the differential scattering cross section vs y, at different x for ν induced reaction on Fe at $E_\nu = 65$ GeV. The results are obtained by using (i) CTEQ6.6 nucleon PDFs at NLO in the MS-bar scheme (dotted line), (ii) MMHT nucleon PDFs at NLO (solid line). The experimental points are the data from CDHSW and NuTeV experiments. Here iron is treated as isoscalar target. The blue dash-dotted line is the result from nCTEQnu nPDFs with $Q^2 \geq 1.0\ GeV^2$.

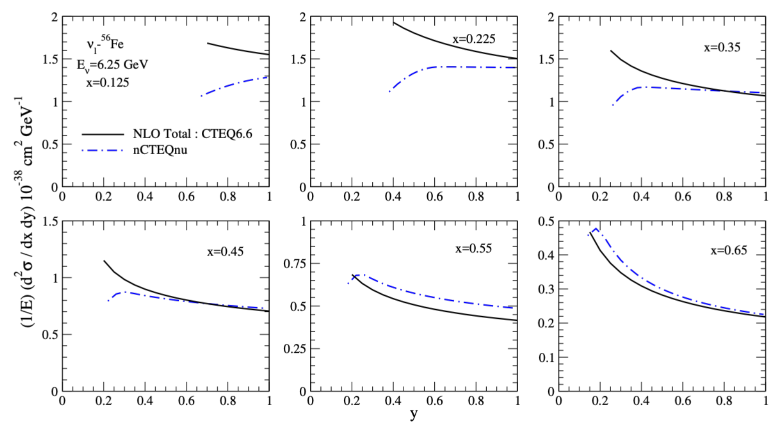


Figure 51. Results of the differential scattering cross section vs y, at different values of x for 6.25 GeV ν induced reaction on Fe treated as an isoscalar target. The results are obtained with a $Q^2 \geq 1.0\ GeV^2$ cut by the Aligarh-Valencia model using CTEQ6.6 nucleon PDFs at NLO in the MS-bar scheme (solid line). The nCTEQnu nuclear PDFs based prediction is the blue dash-dotted line. The lower-y downward curve of the prediction at a given x corresponds to the extrapolation of the nCTEQnu global fit below $Q_0^2 = 1.69\ GeV^2$.

Prediction - Ar

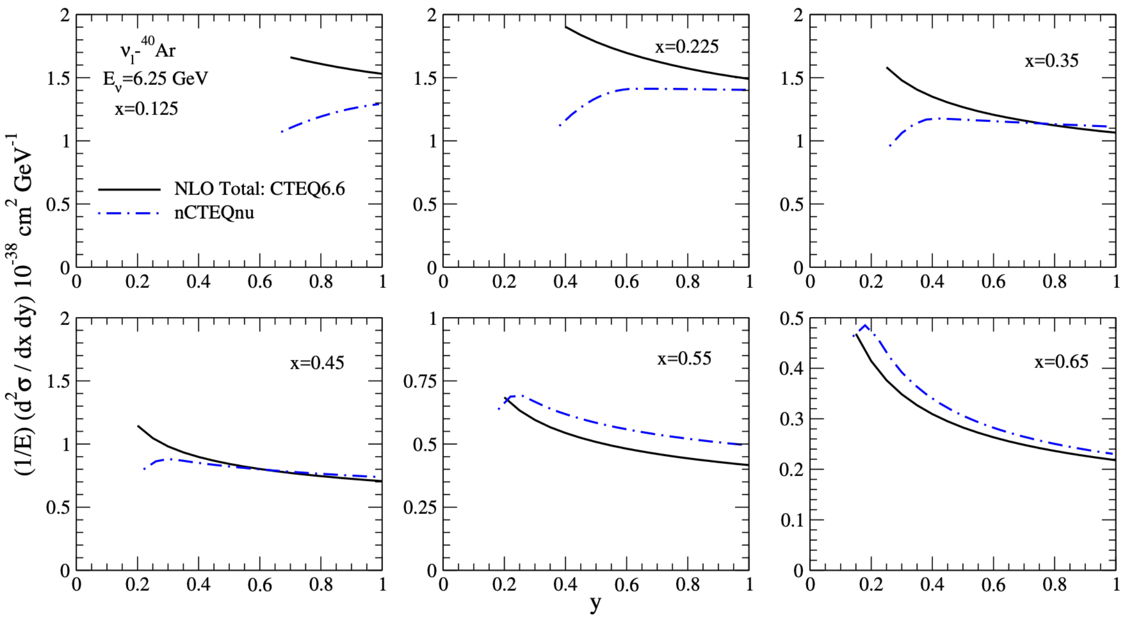


Figure 53. Results of the differential scattering cross section vs y, at different values of x for 6.25 GeV ν induced reaction on Ar treated as an isoscalar target. The results are obtained with a $Q^2 \geq 1.0\ GeV^2$ cut by the Aligarh-Valencia model using CTEQ6.6 nucleon PDFs at NLO in the MS-bar scheme (solid line). The nCTEQnu nuclear PDFs based prediction is the blue dash-dotted line. The lower-y downward curve of the prediction at a given x corresponds to the extrapolation of the nCTEQnu global fit below $Q_0^2 = 1.69\ GeV^2$.