Understanding the transition from Shallow-to-Deep Inelastic Scattering with Neutrinos

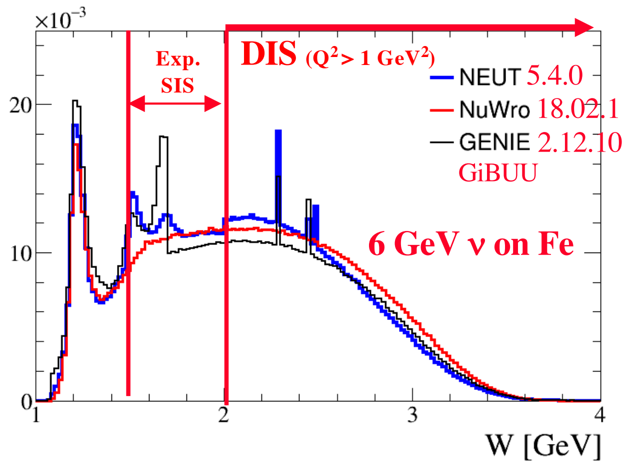
SIS / DIS Review – M.Sajjad Athar. and JGM - arXiv:2006.08603 **[hep-ph]**

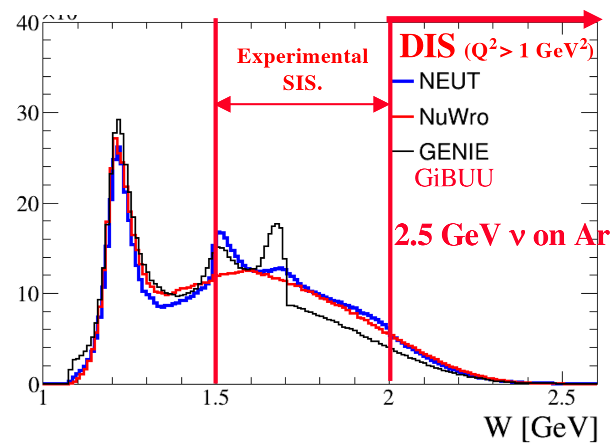
NuSTEC Workshop on SIS and DIS - https://indico.cern.ch/event/727283/
NuSTEC Workshop on Pion Production - https://indico.fnal.gov/event/20793/

NuInt 2022 – Seoul, Korea – October 2022

Jorge G. Morfín
Fermilab

The SIS and DIS Overall Landscape vs W

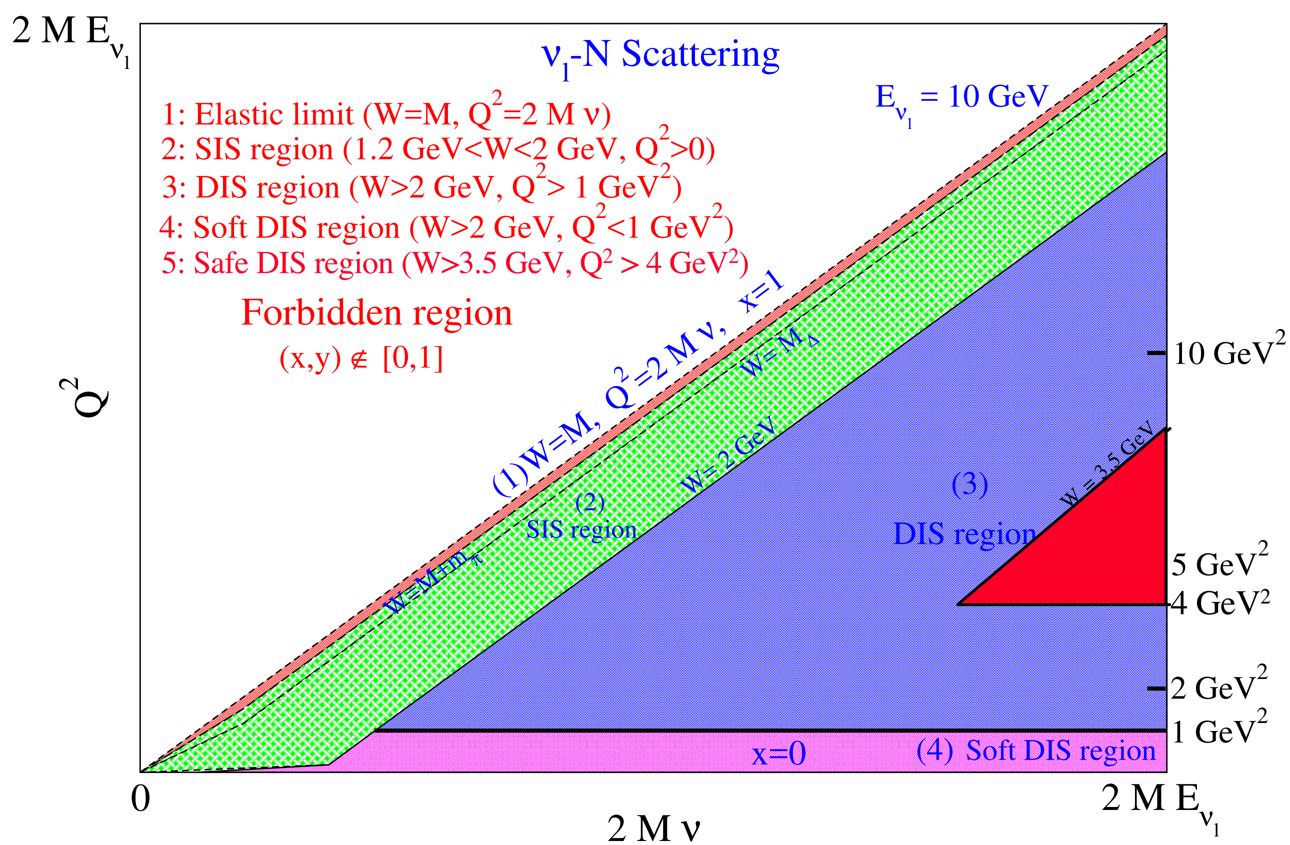




C. Bronner- 2018

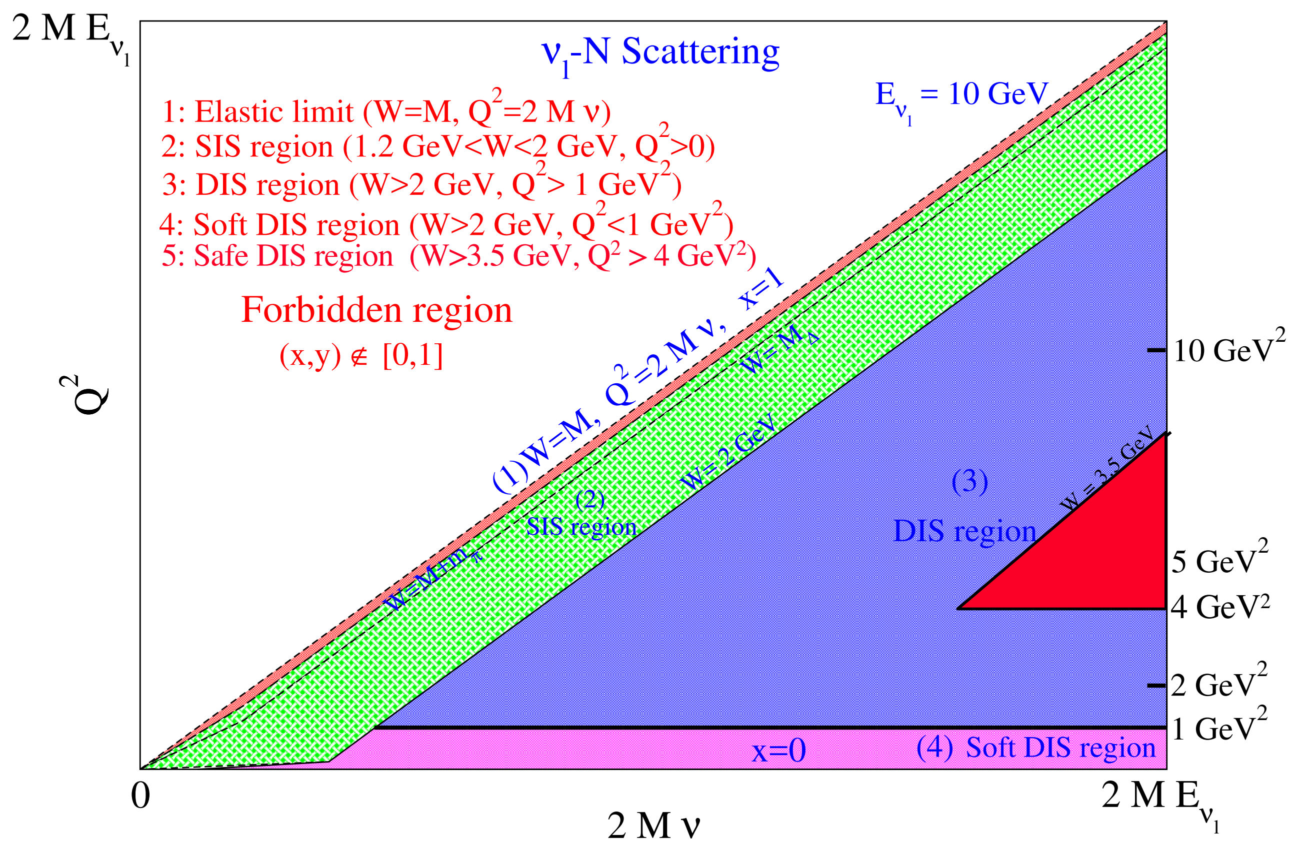
- **DIS:** community definition of $W > 2$ GeV with $Q^2 > 1$ GeV^2 (Global PDF Fits more restrictive)
- **SIS: Shallow Inelastic Scattering** is non-resonant meson production with $W > M_N + m_\pi$
- We cannot experimentally separate non-resonant from resonant meson production. We practically define **SIS** as inclusive meson production with $W < 2.0$ GeV.
- However, the majority of contemporary studies in ν-nucleus interactions have been of Quasielastic and 1 π (mainly Δ) production.
- So we define **"SIS"** as meson (pion) production the **unexplored kinematic region:** **$1.5 < W < 2.0$ GeV.** This is the definition used in MINERvA SIS analyses.
- **SIS/DIS significance for DUNE -** 45 % of ν_μ CC events have $W > 1.5$ GeV.

Let's bring in Q^2 that actually determines true DIS



- "Safe" DIS region chosen for (nCTEQ) Global QCD fits for determining PDFs.
- "Safe" suggests minimizing non-perturbative ($1/Q^2$) effects (more coming soon).
- This Safe DIS region ≈ out of reach for modern neutrino experiments.
  - For example, MINERvA ME loses another factor of 8 events going from blue to red above!

How do we use information from the safe DIS region to predict behavior in the SIS region?



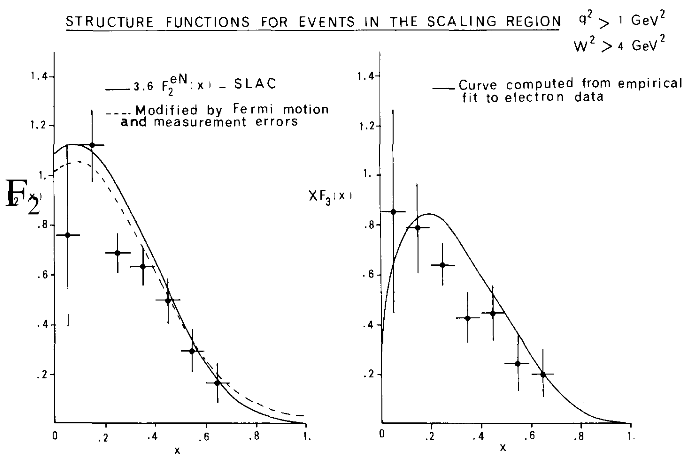
- Can we start with the measured ν-A scattering in the "safe DIS" region to gain an understanding/prediction of what to expect in the SIS region?
- Possibility 1: Quark-Hadron **Duality** (DIS → SIS)
- Possibility 2: High Q,W (DIS) **Perturbative QCD** →
  Lower Q,W (SIS) **non-Perturbative QCD**

Let's first review status of Experimental Data in the "safe" region

Deep-Inelastic Scattering (DIS)

Neutrinos have been using DIS to study the structure of the nucleon for **50 years (> 15 major experiments)**!

First (early 70's) Gargamelle (CF_3Br) measurement of F_2 and xF_3 (650 ν and 1050 ν̄) for initial neutrino verification of scaling then recently discovered at SLAC.



From Gargamelle to MINERvA: Exploring the structure of the nucleon with neutrinos

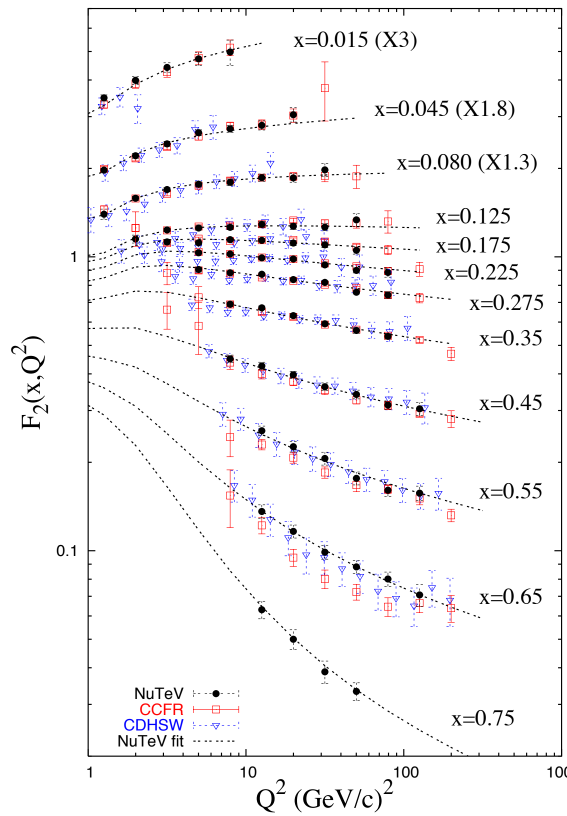
Jorge G. Morfín[a]

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

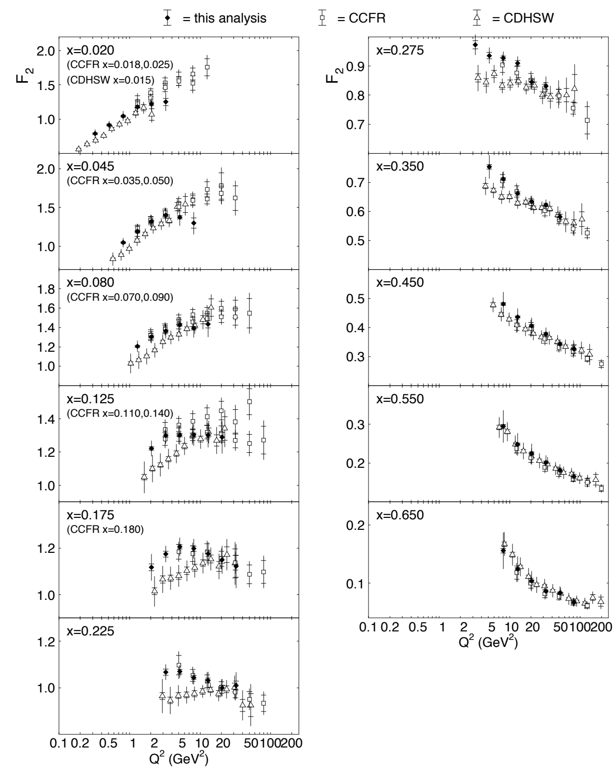
Eur.Phys.J.ST 230 (2021) 24, 4221-4241

MINERvA-doc-30806,

NuTeV (Fe) measurement (3 million ν and ν̄ events) of F_2 compared to CCFR (Fe) and CDHSW (Fe).



CHORUS (Pb) measurement (1.5 million ν and ν̄ events) of F_2 compared to CCFR (Fe) and CDHSW (Fe).



Compatibility of neutrino DIS data and its impact on nuclear parton distribution functions, (nCTEQ) K.F. Muzakka et al. e-Print 2204.13157:

Fine, we have a good start with **global safe DIS results for neutrino.**

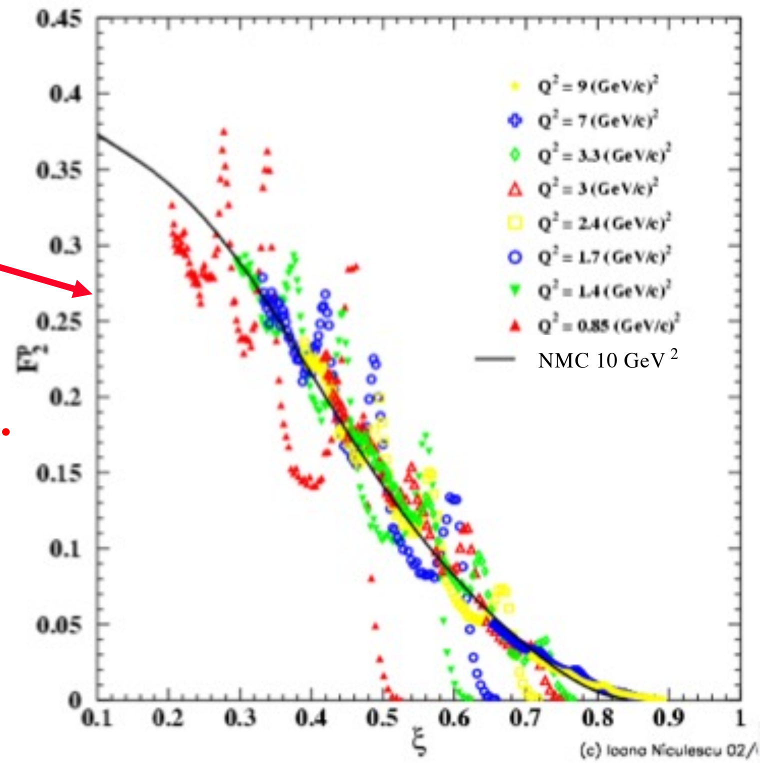
Now let's start the study of the DIS ⟶ SIS Transition!

Possibility 1: **Quark – Hadron Duality**

- Quark–hadron duality is a general feature of strongly interacting landscape
  - How does the physics (language) of quark/gluons from DIS meet the physics of nucleons/mesons (pions) of SIS → **quark-hadron duality**
- In the 70's Bloom and Gilman defined duality by studying structure functions from e-N scattering and noting that **the leading QCD formulation of DIS is approximately equal to the average over resonance production.**
- Quark-hadron duality originally studied and confirmed in **e-N scattering – what does duality "look like" ?** (Jlab e-proton Study)
- ξ **is known as the Nachtmann variable**
  - **Important for treating low Q^2/higher-x data (later)..**

$$\xi = \frac{2x}{1 + \sqrt{1 + 4m_N^2 x^2 / Q^2}}$$

- **How about a quantitative test of "duality"?**



Quantitative test of Quark-Hadron Duality:

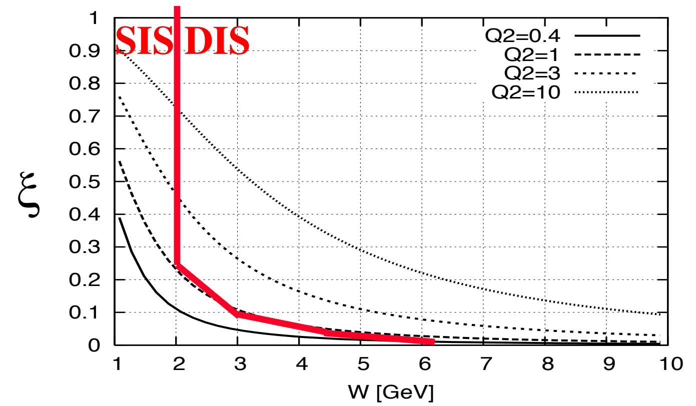
Ratio of integrals over a finite ξ interval

e - Nucleon

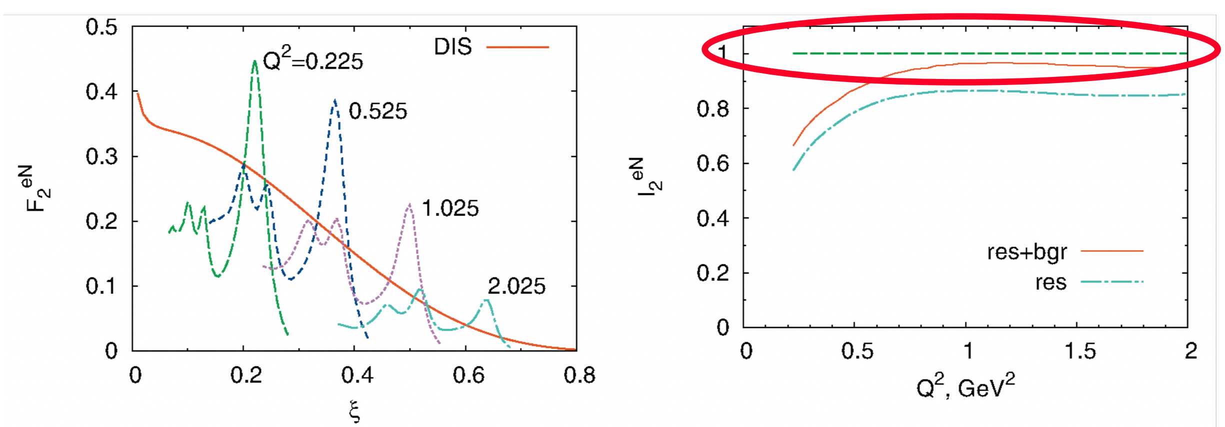
- Ratio of the strength of the SIS to DIS region. Ideal Duality I = 1.0 .

$$\mathcal{I}_{|}(Q^2, Q^2_{DIS}) = \frac{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{RES}(\xi, Q^2)}{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{DIS}(\xi, Q^2_{DIS})}$$

$$\xi = \frac{2x}{(1 + \sqrt{1 + 4m_N^2 x^2/Q^2})}$$



- F_2^{eN} (ξ) for values of Q^2 indicated on spectra compared to LO DIS QCD fit at Q^2 = 10 GeV^2. Value of integral I(Q^2). Duality works well for eN scattering!



Stress the importance of including the **non-resonant** pion production!

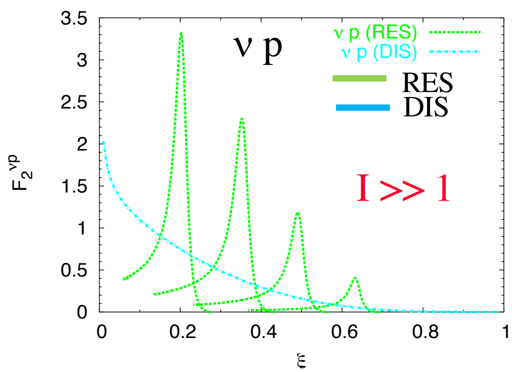
Now for **Neutrinos** – NO HIGH STATISTIC NUCLEON DATA – must rely on models for ν-n, ν-p and ν-N scattering

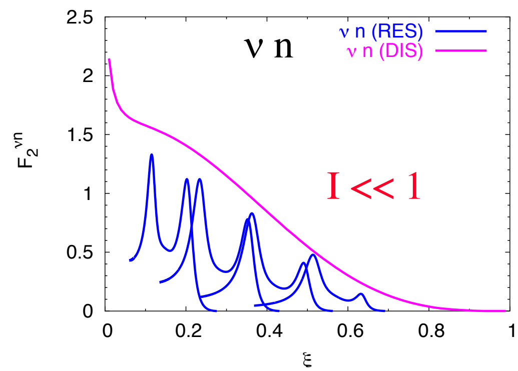
Low-lying resonances: $F_2^{\nu n(res)} < F_2^{\nu p(res)}$, DIS: $F_2^{\nu n(DIS)} > F_2^{\nu p(DIS)}$

Resonance estimates from Lalakulich, Melnitchouk and Paschos for ν-n and ν-p scattering.

$F_2^{\nu p(res-3/2)} = 3F_2^{\nu n(res-3/2)}$
$F_2^{\nu p(res-1/2)} \equiv 0$

$F_2^{\nu n(res)}$: finite contributions from isospin 3/2 and -1/2 resonances





In general, for neutrinos the **resonance structure functions** for **proton are much larger than for neutrons** however **DIS structure functions the situation is opposite.**

Strong suggestion here that **for neutrinos**:
duality holds for isoscalar nucleon $(F_2^{\nu p} + F_2^{\nu n})/2$.

What does that imply for **duality for nuclei with large neutron excess??**

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 ν*p* : In neutrino–nucleon scattering, duality seems to roughly holds for the **average** nucleon but NOT individually for neutron and proton.
- F_2 *eA* : Different story, looks good but quantitative check in e–A not as good as e–n/p
- **F_2 νA : Not at all clear how duality works here, particularly in 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 DIS structure functions are **much larger** than the resonance contribution at lower W.
- **For neutrinos: not yet at all clear how duality should be applied!**

Possibility 2 - **High Q,W (DIS) Perturbative QCD → Lower Q,W (SIS) non- Perturbative QCD**

- The "Infinite Momentum Frame" or "DEEP Deep Inelastic Region" → perturbative QCD region.
  - Certainly, does not describe the environment of our 1 - 10 GeV neutrino beams! How do we know we are there or at least getting close…?
- When we are in a region where **M^2x^2/Q^2** terms are negligible, we are in the region of perturbative QCD (and Q^2 evolution is given by pQCD).
- As **Q^2** gets smaller and/or **x_{Bj}** gets larger, we need to include **M^2x^2/Q^2** corrections to the theory. Often characterized as "1 / **Q^2** effects"
  - TARGET MASS (TMC) - kinematic corrections due to non-negligible mass of targets. To be more precise the mass M of the target modifies the scattering kinematics and therefore the DIS structure functions. Applied to the theory!
  - HIGHER TWIST (HT) – dynamic corrections due to parton-parton correlations. HT corrections to DIS processes account for non-perturbative multiquark/parton interactions and are mainly extracted experimentally!

Language of non-perturbative QCD

- **Target Mass Correction** –TMCs were first calculated by Nachtmann yielding the "Nachtmann Variable". This is only the first term in a full TMC expression:

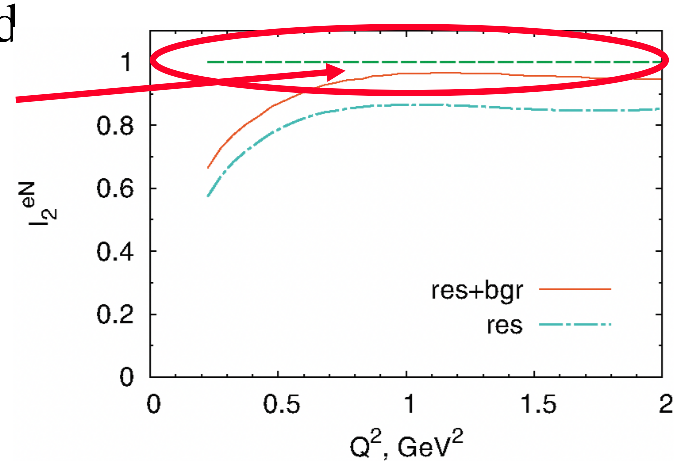
$$\xi = \frac{2x}{(1+\sqrt{1+4m_N^2 x^2/Q^2})} \rightarrow \text{ TMCs vanish, } \xi \rightarrow x, \text{ when } M^2/Q^2 \rightarrow 0 \text{ as we want.}$$

  - TMC has been calculated for the **nucleon.** nCTEQ is at the paper stage of TMC for **Nuclei**!

- **Higher Twist** – HT effects are extracted experimentally by fitting data to a pQCD + HT:

$$\mathbf{F_2(x, Q^2) = F_2^{pQCD}(x, Q^2)\ [\ 1 + C_{HT}(x) / Q^2\ ]}$$

- **Duality and Higher Twist** - Can Duality further inform us about HT and TMC? Does duality holding for e-N scattering compared to LO, **leading twist** DIS **suggest** HT is minimal?



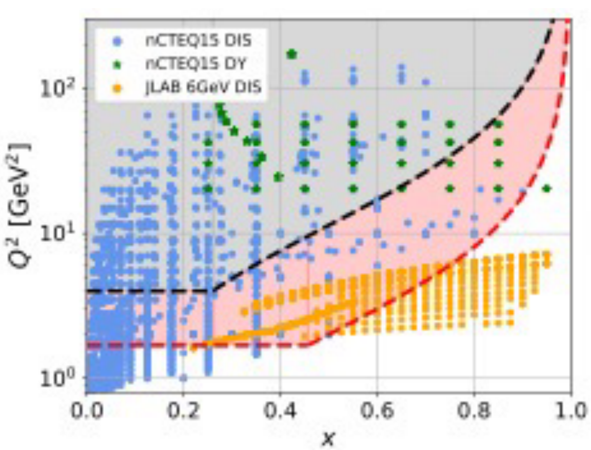
A. Fantoni, N. Bianchi, and S. Liuti. Quark-hadron duality and higher twist contributions in structure functions. *AIP Conf. Proc.*, 747(1):126–129, 2005.

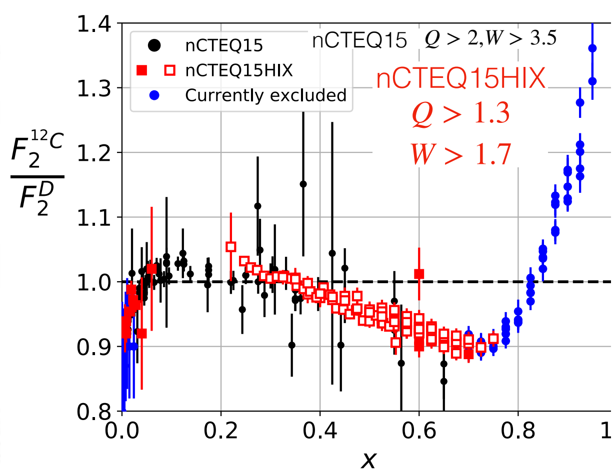
Possibility 2 – Applied!

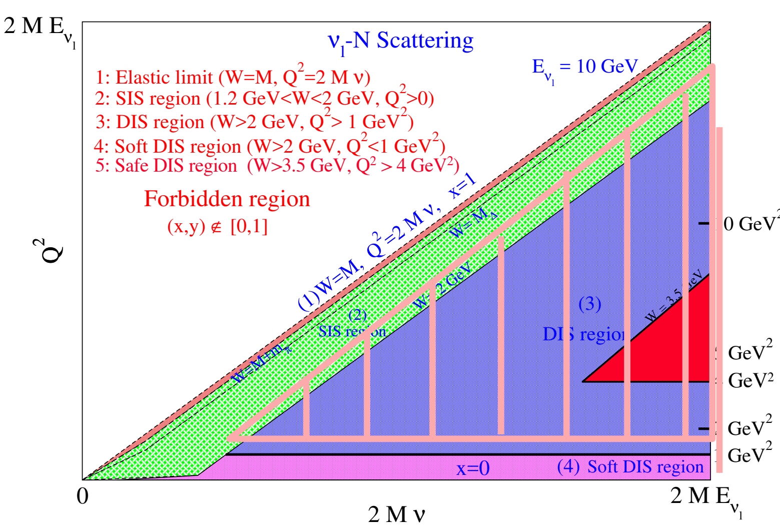
Extrapolating from DIS to SIS - from pQCD to non-pQCD

- Start with a familiar attempt. As we just heard, **Bodek-Yang model** keeps **Duality** in mind by extending GRV LO DIS PDFs for W > 2 GeV, $Q^2 > 0.8$ GeV^2 down in Q^2 and W into the SIS region.
  - They include Target Mass Correction (TMC) and Higher Twist (HT) effects by replacing x_{Bj} with ξ_W an enhanced TMC term to account for both TMC and HT….

- Now, a more rigorous extrapolation to SIS transition, non-pQCD region. The first nCTEQ global fit of **nuclear ratios** into the **SIS transition region:** e-Print: 2012.11566 [hep-ph]:
- Adding higher–x, lower Q Jefferson Lab **(eA)** nuclear **ratio** measurements to perform a global fit:
- e/μ nuclear ratios **F_2^A/F_2^D and σ^A/σ^D** for **W > 1.7 GeV, $Q^2 > 1.69$ GeV**





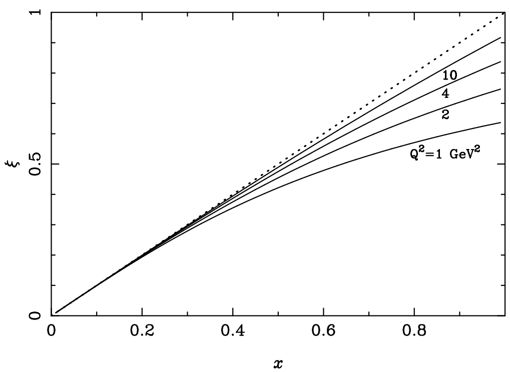


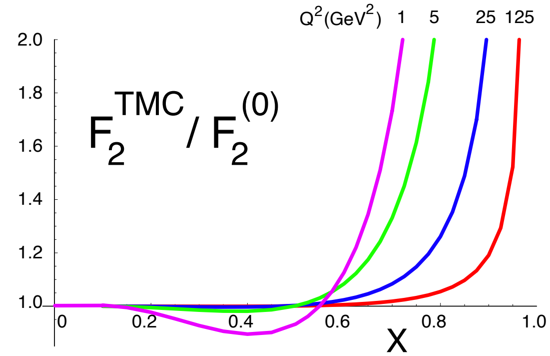
1/ Q^2 Corrections Entering the nCTEQ Global Fit

(also improved CJ15 Deuteron for ratios F_2^A/F_2^D and σ^A/σ^D)

e-Print: 2012.11566 [hep-ph]

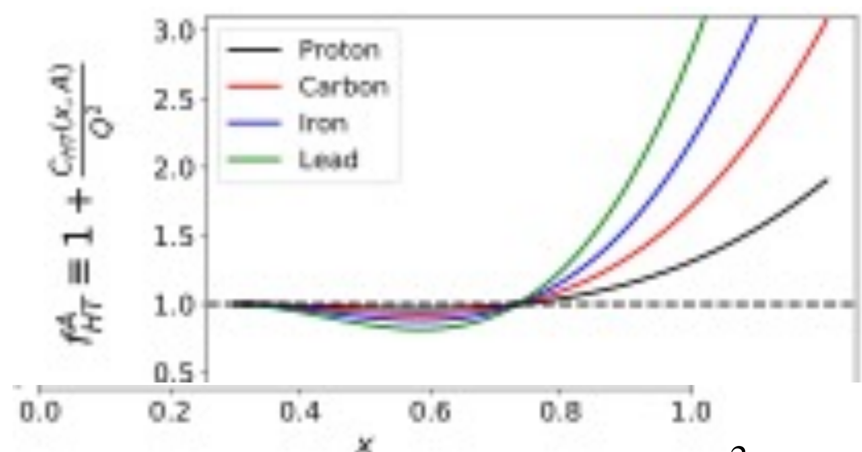
- **TMC** - Schienbein et al. Review of Target Mass Corrections: e-Print: 0709.1775 [hep-ph]
  Kretzer-Reno - Target Mass Corrections to Electro-Weak Structure Functions e-Print: hep-ph/0307023 [hep-ph]





- **HT** – Accardi et al (CJ15) - Constraints on large-x PDFs, eprint:1602.03154 [hep-ph].
  Qiu-Sterman - QCD and re-scattering in nuclear targets, eprint: hep-ph/0111002.

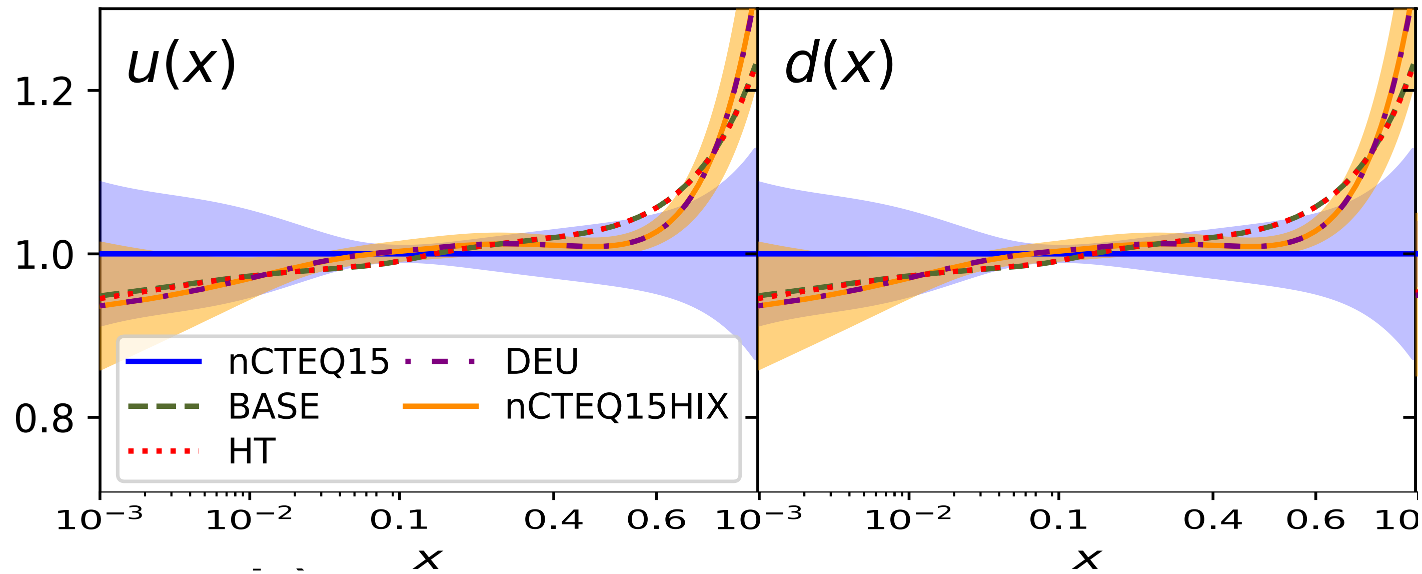
e/μ=A scattering HT correction factor for nuclei as a function of x at $Q^2 = 4.0$ GeV^2 :



Effective Results for e/μ – A scattering PDFs pQCD → non-pQCD for electroproduction

nCTEQ15HIX (https://ncteq.hepforge.org)

Nuclear PDFs for C at $Q^2 = 4\ GeV^2$



- Comparing the nCTEQ15 (safe DIS) and nCTEQ15hix (lower W and Q) fits to the same expanded data set shows an improvement of 15% in χ^2 / N_{dof} for hix fit.
- Confirms that as long as TMC is applied, the contribution of HT for $x < 0.7$ and $Q^2 > 1.69\ GeV^2$ is minimal for electroproduction!
  - Further Jlab studies now show that with TMC applied, HT minimal for $x < 0.7$ and **$Q^2 > 1.0\ GeV^2$** for e/μ – A scattering.
- **What about performing the extrapolated fits for Neutrinos?**

To perform the extrapolated fits for Neutrinos we need **MINERνA (ME) SIS and DIS Analyses**

- **SIS** – 1.5 < W < 2.0 GeV – First Inclusive Cross sections in this restricted W region. $d\sigma/dp_\mu^t$ and $d\sigma/dp_\mu^z$ for both ν and $\bar{\nu}$ completed, $d\sigma/dx$ and $d\sigma/dQ^2$ underway.

- **DIS** – (W>2 GeV and $Q^2 > 1$ GeV^2): $d\sigma/dx$ and $d\sigma/dE_\nu$ in nuclear targets for nuclear ratios with both ν and $\bar{\nu}$

- **DIS** – (W>2 GeV and $Q^2 > 1$ GeV^2): $d\sigma/dxdy$ (maybe for E_ν regions) for ν and $\bar{\nu}$. These expressions can be included directly in (nCTEQ) global fits to study **higher-twist** with neutrinos.

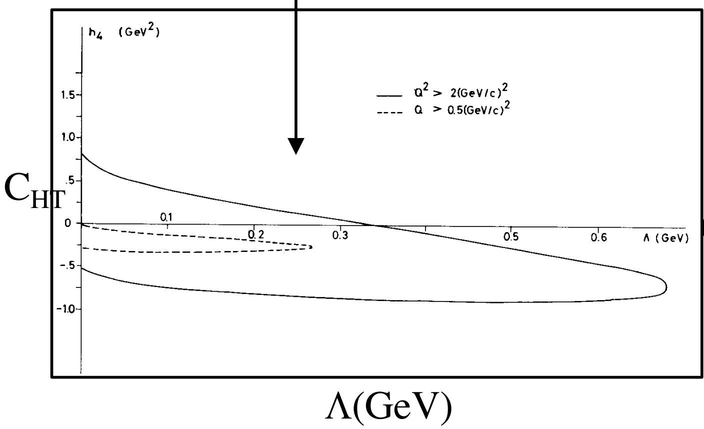
However….

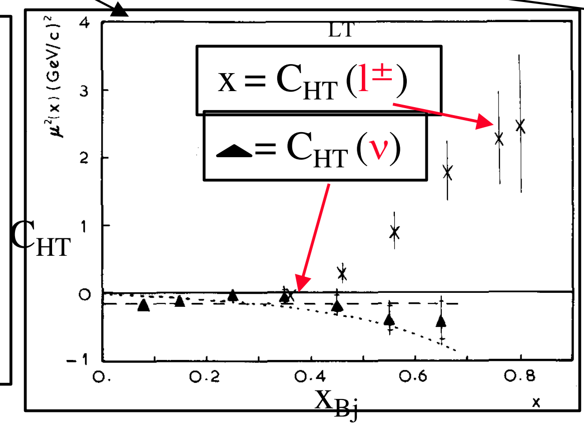
Speaking of Higher Twist – what about HT ν - A?

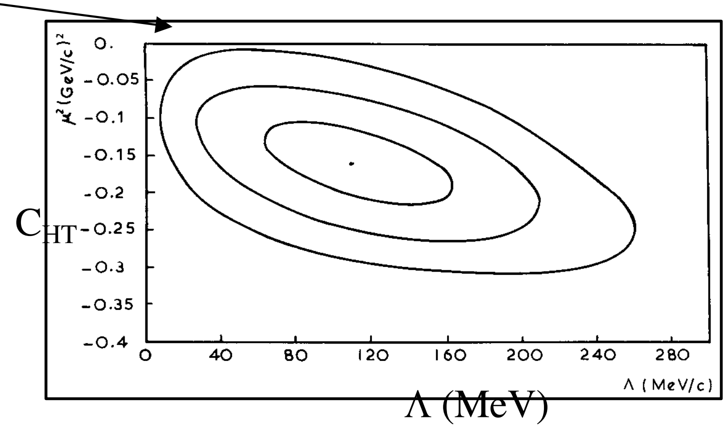
Growing evidence suggesting HT for ν - A is **NOT** the same as e-A

- From pQCD, with Q^2 evolution proportional to $1/\log(Q^2/\Lambda^2)$, extend into the non-pQCD regime and consider $1/Q^2$ effects: TMC and HT: $F_2^A \rightarrow F_2^A\left[1 + \frac{C_{HT}^A}{Q^2}\right]$

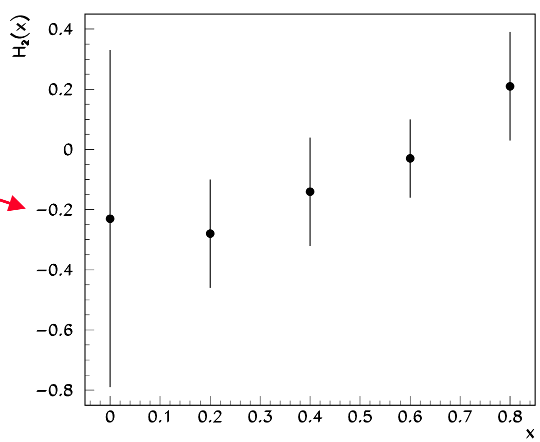
- Gargamelle (CF_3Br) & BEBC (Ne/H) SPS experiments, LO QCD & TMC applied:







- Alekhin and Kataev – Higher Twist from CCFR F_2 and xF_3



- That is C_{HT} in neutrino scattering:

smaller & negative!

Summary
Understanding the DIS to SIS Transition Region

- Extrapolating from DIS to the SIS Transition Region using Duality:

Additional study needed to understand how duality should be applied to neutrino scattering!

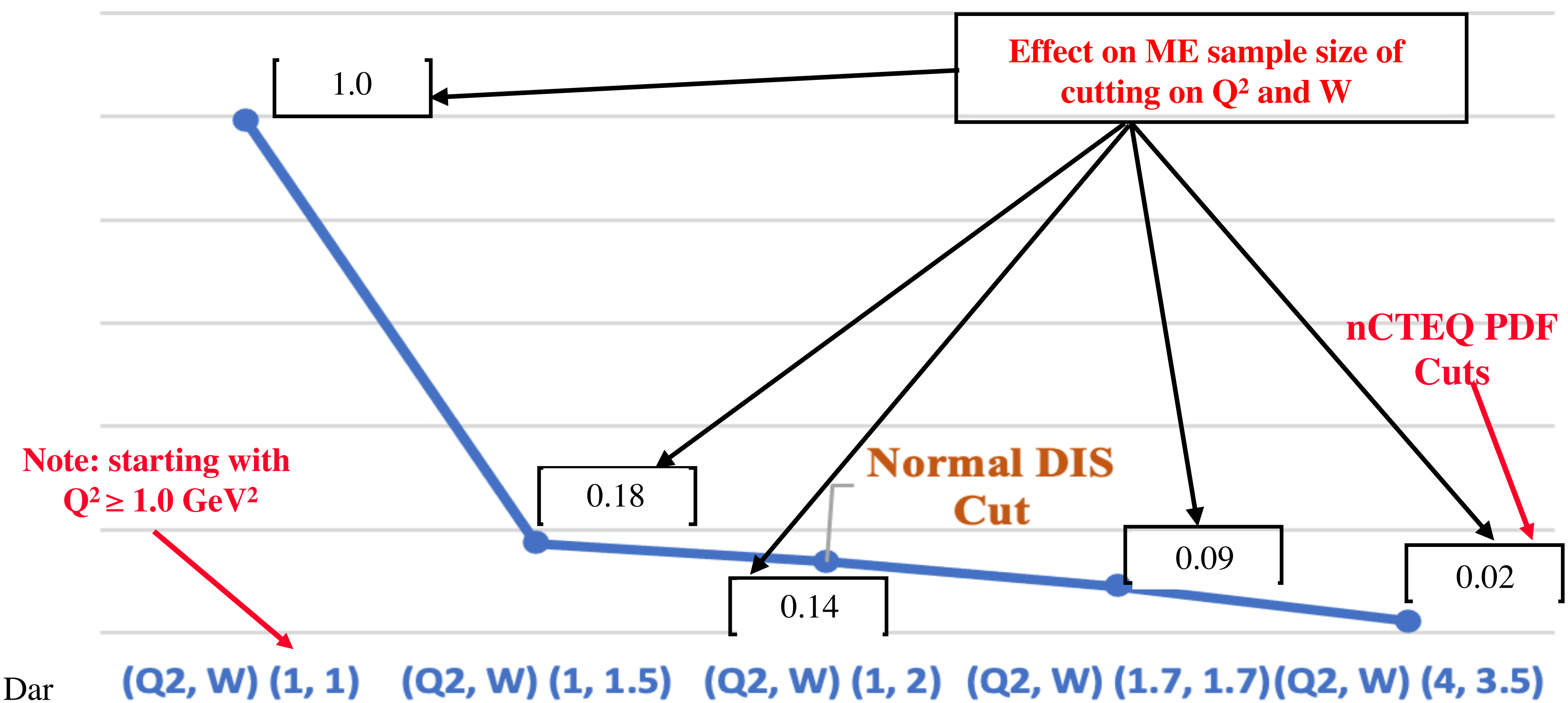
- Extrapolating from (safe) DIS (pQCD) to the SIS Transition Region (non-pQCD) using additional $1/\ Q^2$ contributions:

Need completed MINERvA SIS and DIS analyses and better understanding of HT in neutrino scattering!

Extras

These nCTEQ cuts of $Q^2 > 4$ GeV^2, W> 3.5 GeV – A Big Cut even for the MINERvA ME beam!

- BIG Gain if we can include lower Q^2 and W events in the global analysis
- However we then need to then bring in additional lower Q^2 effects in the fit.
  - Target Mass Effects and Higher Twist



Ahmad Dar

Overview of the Theoretical Picture for SIS/DIS

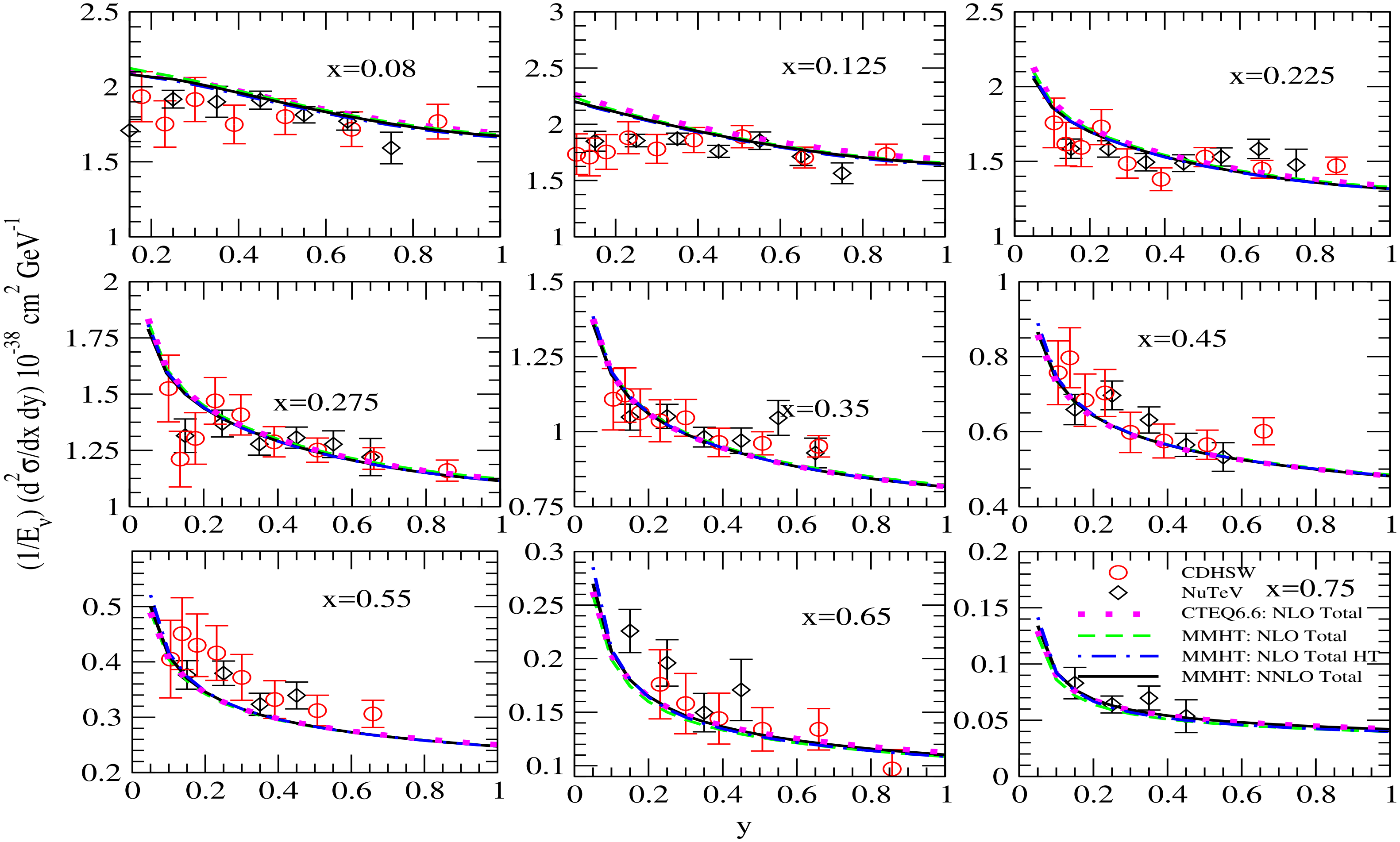
M. Sajjad Athar – Aligarh Muslim University, India – SA, JGM SIS/DIS Review
Huma Haider – More details Thursday WG2 Parallel

- □/□ -Nucleon Scattering
  - □-Nucleon Scattering: Shallow Inelastic Scattering
    - » Resonant, non-resonant and interference contributions
  - □-Nucleon Scattering: Deep-Inelastic Scattering
    - » Introduction of the structure functions and parton distribution functions
  - DIS QCD Corrections
    - » NLO and NNLO Evolutions
    - » Target Mass Correction Effect – Important for low Q^2 DIS and Transition to SIS
    - » Higher Twist Effect - Low Q^2 transition from DIS pQCD to non pQCD
- □/$\bar{\nu}$ -Nucleus Scattering : Deep-Inelastic Scattering Theory
  - Aligarh-Valencia Formulation
    - » Fermi motion, binding and nucleon correlation effects
    - » Mesonic effect – virtual meson cloud associated with nucleons within the nucleus
    - » Shadowing, Antishadowing and EMC effects
    - » Isoscalarity Corrections

Theoretical Picture

Full Aligarh-Valencia formulation: $d^2\sigma/dxdy$ vs experimental results

for E_ν = 65 GeV on Iron

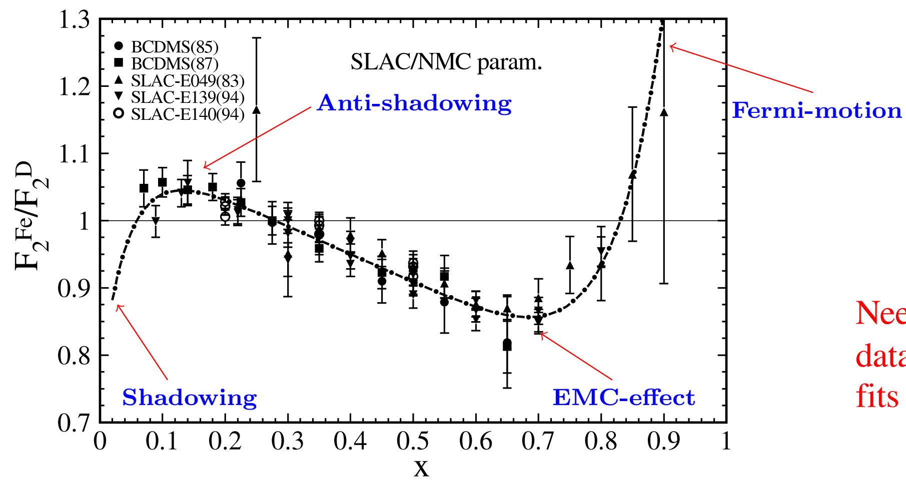


Results using the full Aligarh nuclear model with nucleon PDFs at NLO from CTEQ 6.6 (dotted line) and MMHT (dashed line). Also MMHT with HT effect as well as at NNLO (solid line) are shown. The experimental points are the data from CDHSW ⭘ and NuTeV ◇ experiments.

Important to point out that along the way in the '80s EMC, with μ-A scattering, made a discovery with **nuclear ratios** that **changed the scene dramatically!**

$$F_2^A(x) \neq Z F_2^p(x) + N F_2^n(x)$$

Charged-lepton
Nuclear
Correction
Factor (NCF)



Need NCFs to combine nuclear data with nucleon data in global fits to nucleon PDFs.

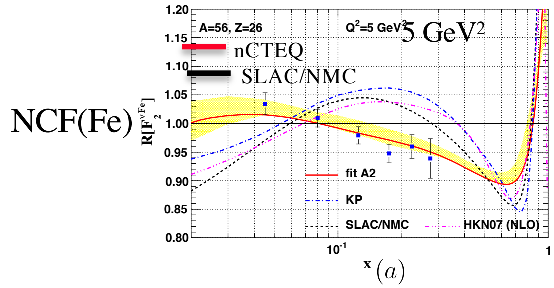
- Ratio shows that for $l^{\pm}$ - A, the structure of the nucleon in the nuclear environment ($F_2(A)/A$) **not the same** as the free nucleon and deviations are a function of x_{Bj}.
  - PDFs of nucleons in the nuclear environment (nuclear nPDFs) ≠ free nucleon PDFs!
- **Do neutrino interactions with nuclei show the same effect?**
  - **Early hints of difference**: ν-A vs. $l^{\pm}$A NCF in CTEQ global **Nucleon** PDF fits
  - Address this question with **nCTEQ studies** but also studied by other groups):
    - » DeFlorian, Sassot, Stratmann and Zurita & Paukkunen and Salgado & ….

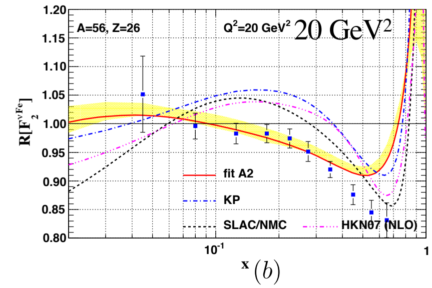
Determination of Neutrino ($\nu/\overline{\nu}$) Nuclear Correction Factors
Original (≈2010) and Ongoing (2021) nCTEQ Fits

Previous nCTEQ (≈ 2010): NuTeV and CHORUS DIS and NuTeV dimuon σ for the strange sea

$R = F_2(\nu - Fe; \text{measured}) / F_2[\nu - (n+p); \text{PDFs}]$

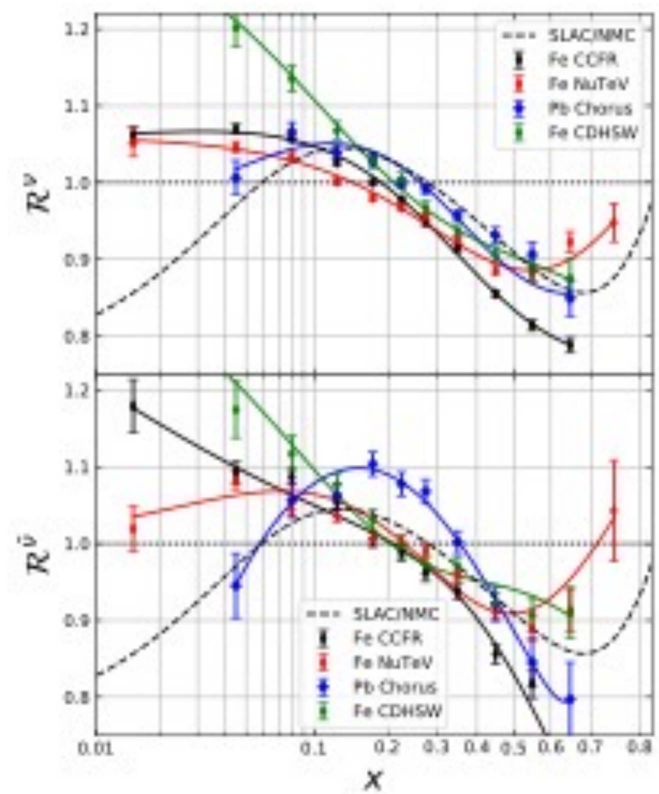
NO compromise (χ^2 with tolerance) fit for ν (dominated by NuTeV) and e/μ results.





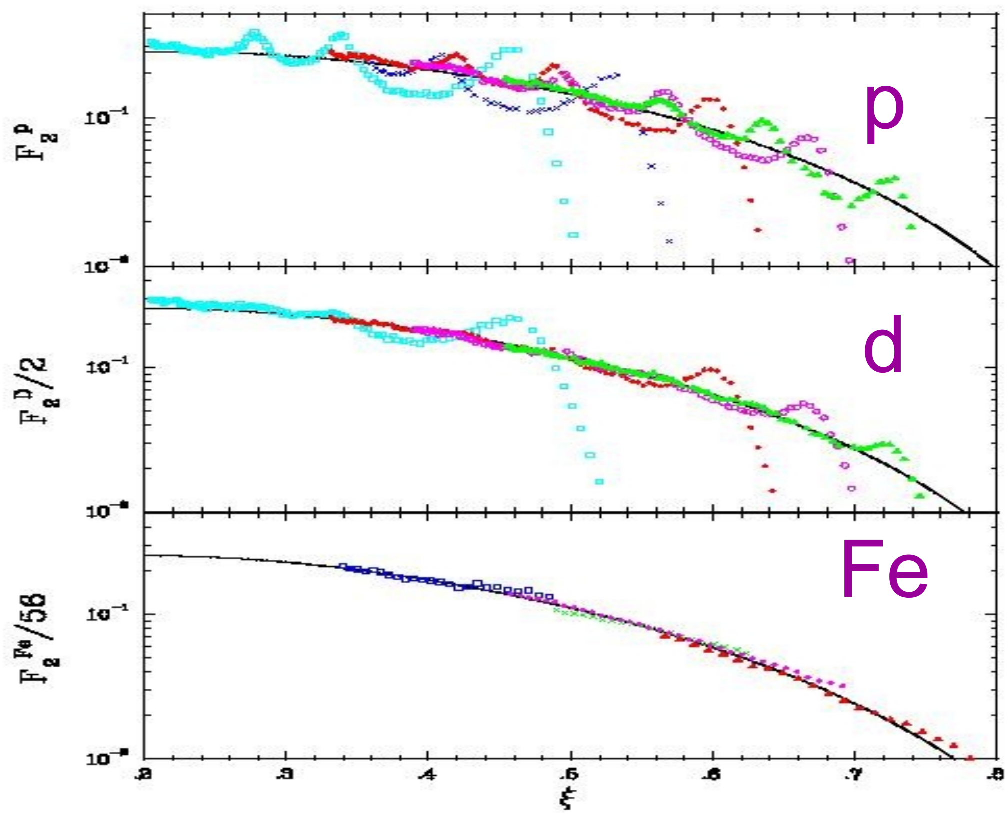
UPDATE: Compatibility of neutrino DIS data and its impact on nuclear parton distribution functions, K.F. Muzakka et al. e-Print 2204.13157:
nCTEQ fit $R = \sigma(\nu - A); \text{measured} / \sigma[\nu - (n+p); \text{CTEQ6 PDFs}]$

- Expanded data sets: Dimuon: CCFR & NuTeV and DIS: CCFR, NuTeV. CDHSW, CHORUS (**Q > 2 GeV, W> 3.5 GeV**). (Minimal MINERvA Data survives this cut.)
- Improved treatment of cross experiment normalization uncertainties and the R denominator.
- **Tension still exists** between (l$^{\pm}$ A) and neutrino data. **Tension maximal at x ≤ 0.1,** to **lesser extent at higher x**
- **Confirm nCTEQ (≈2010) low-x conclusion but softened at higher x with more data sets! NuTeV still quite different than SLAC/NMC.**

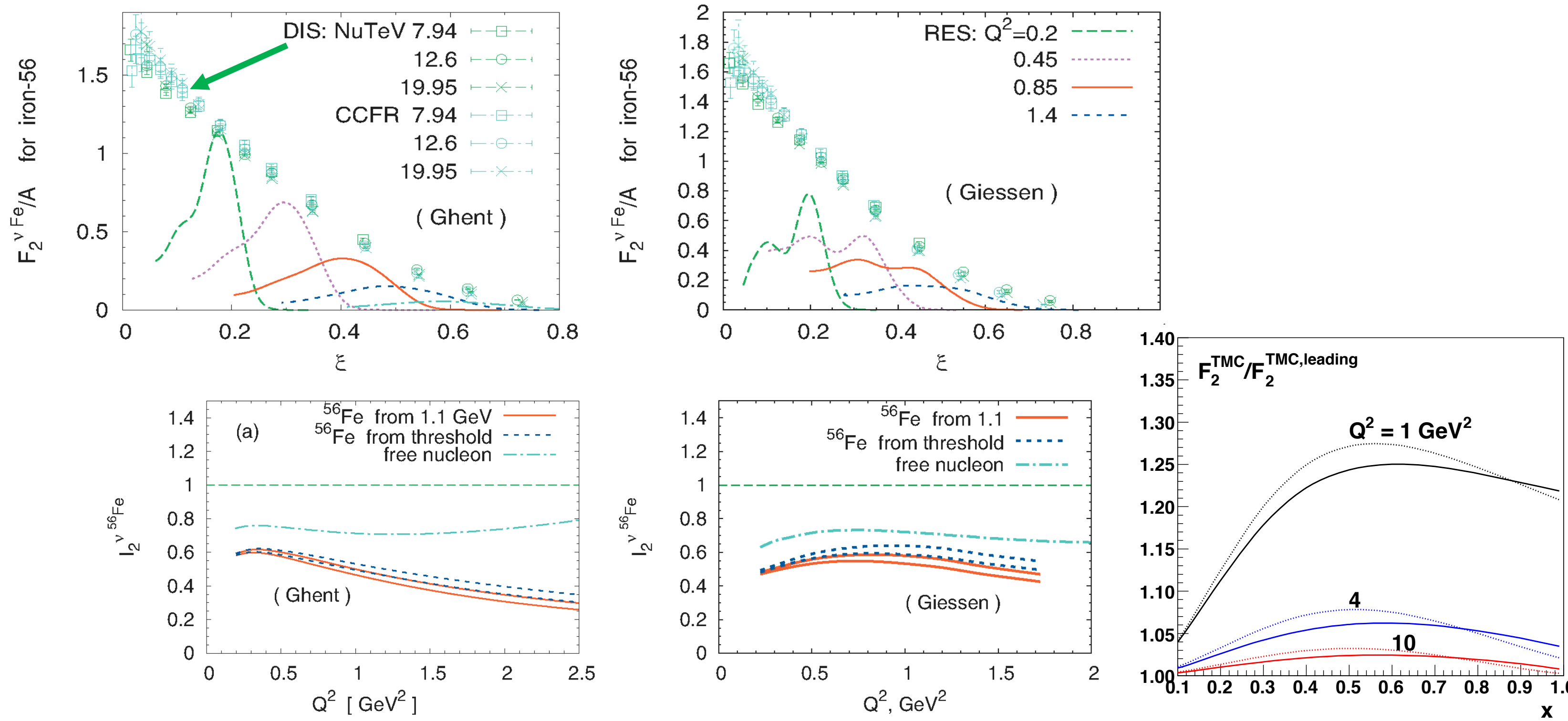


Now Nucleus not Nucleon Qualitative look at Q-H Duality: e-A results

- Now **e-nucleus** – individual resonances visible in e-P, somewhat less in e-D and mostly smeared out by e-Fe. Curved line is from MRST global **DIS fits** with **EMC effect** for Fe applied.



Even more uncertain when talking of NUCLEI not NUCLEON- Is the problem for Fe the neutron excess and/or **models for Final State Interactions?**

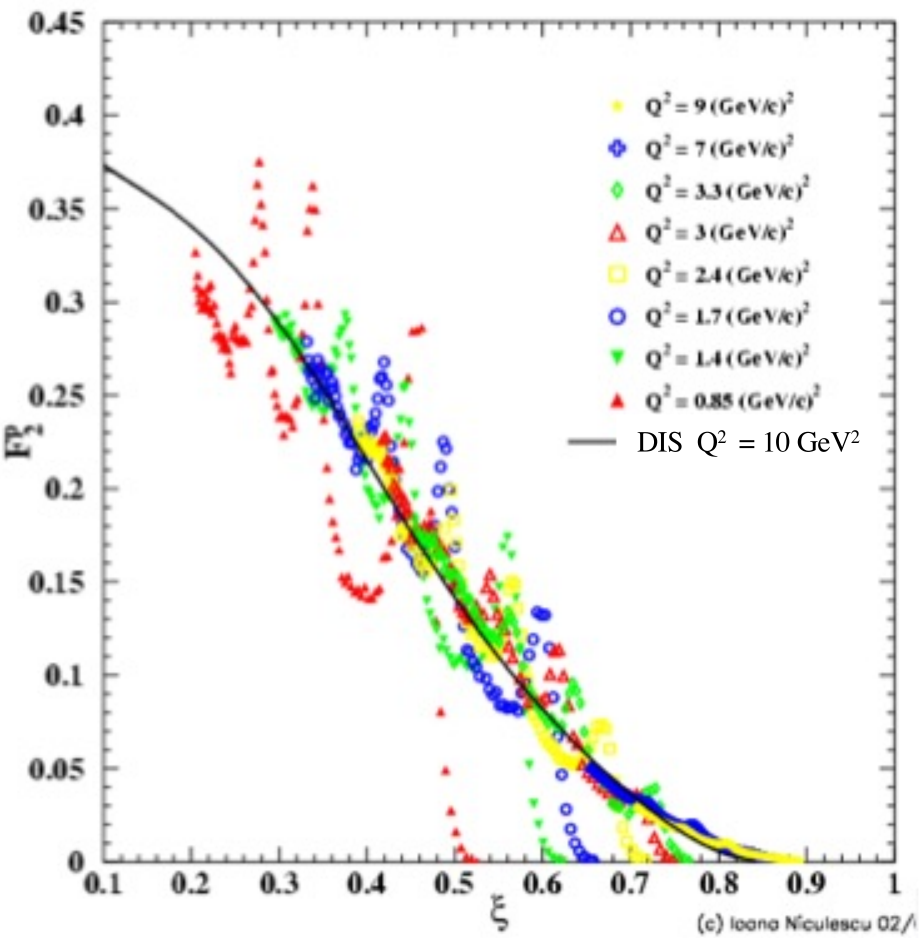


- In general, for neutrinos the **<u>resonance structure functions</u>** for **proton are much larger than for neutrons** and in the case of **<u>DIS structure functions</u> the situation is opposite.**
- Although to some extent model dependent, a general tendency is that **DIS structure functions** are much larger than the **resonance contribution** at lower W.
- **How duality should be applied with neutrinos is still an open question**

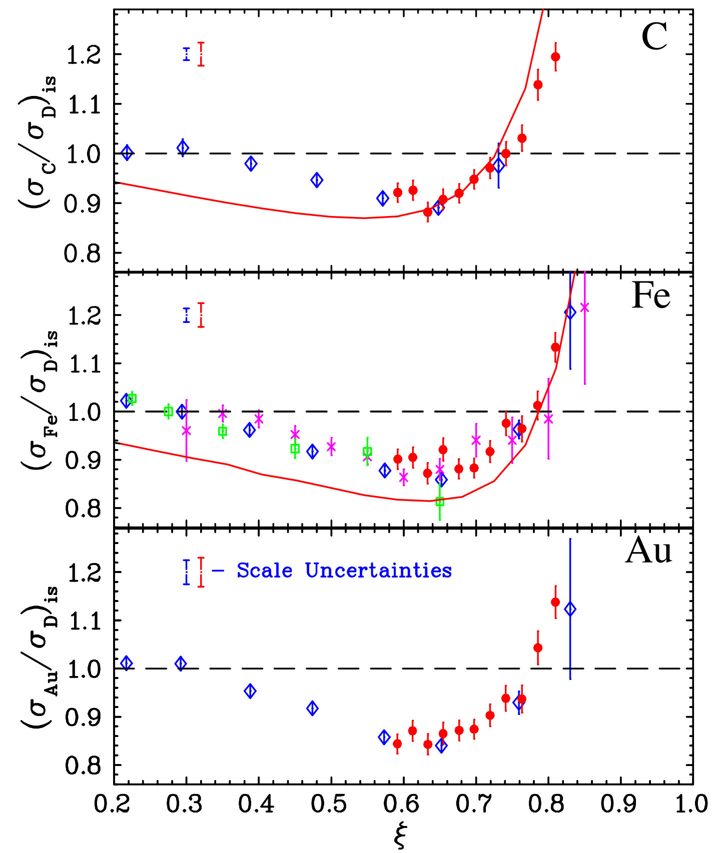
What does Quark-Hadron Duality "Look Like" Experimentally?

Jlab **e-proton** Study

EMC Effect in the **e-A Resonance Region**

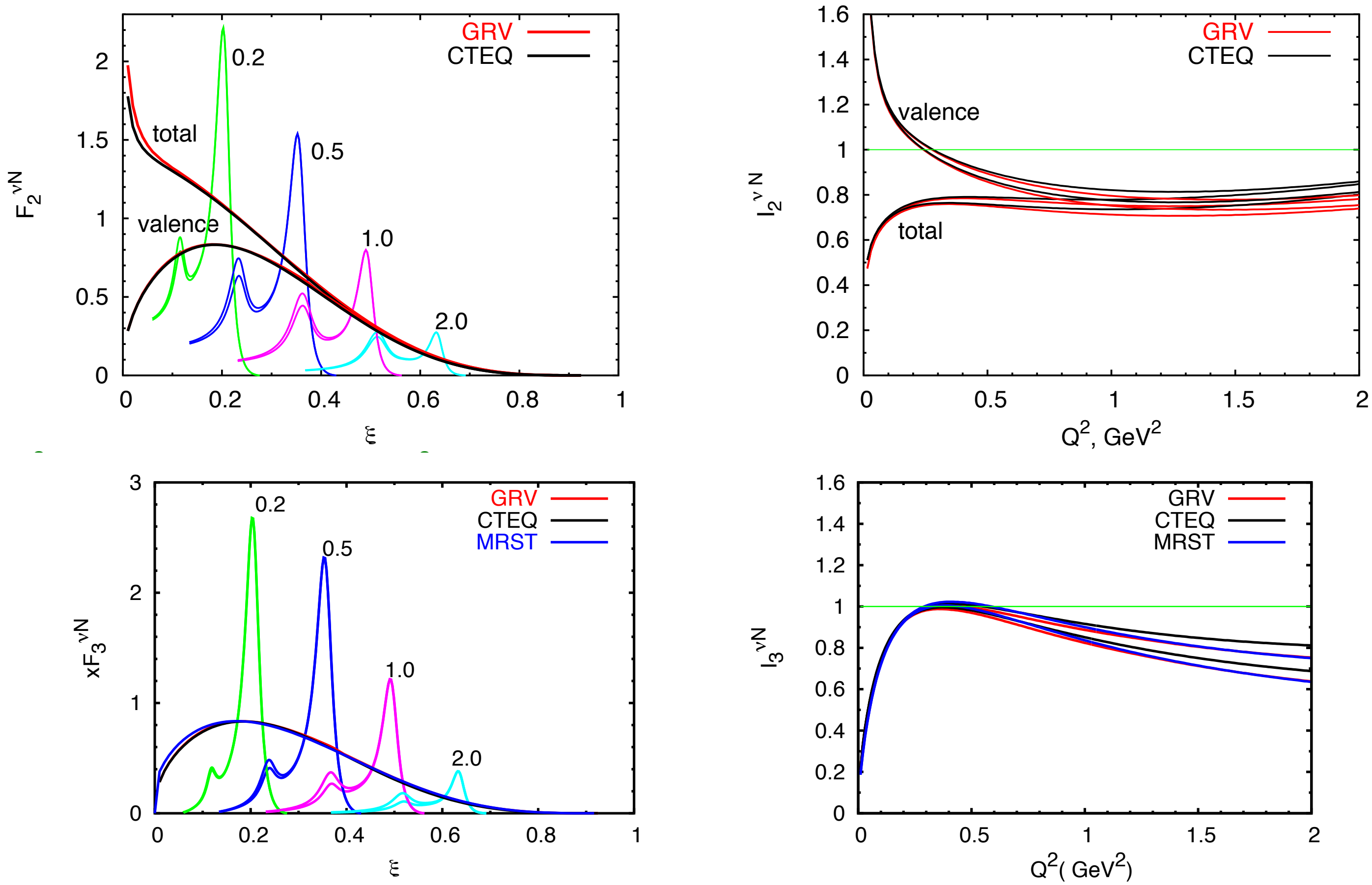


$$\xi = \frac{2x}{(1 + \sqrt{1 + 4m_N^2 x^2 / Q^2})}$$



The solid red circles are Jefferson Lab data taken in the **resonance region** **1.1 < W < 1.7 GeV and Q^2 = 4 GeV^2**. All other data points from DIS region. Evidence for Duality?

From work of Olga Lalakulich - Local duality appears to holds for the averaged neutrino $F_2^N = (F_2^n + F_2^p) / 2$ (to the 20% level) . Introduce "two-component duality" and resonances dual with valence quarks and non-resonant with sea quarks!!

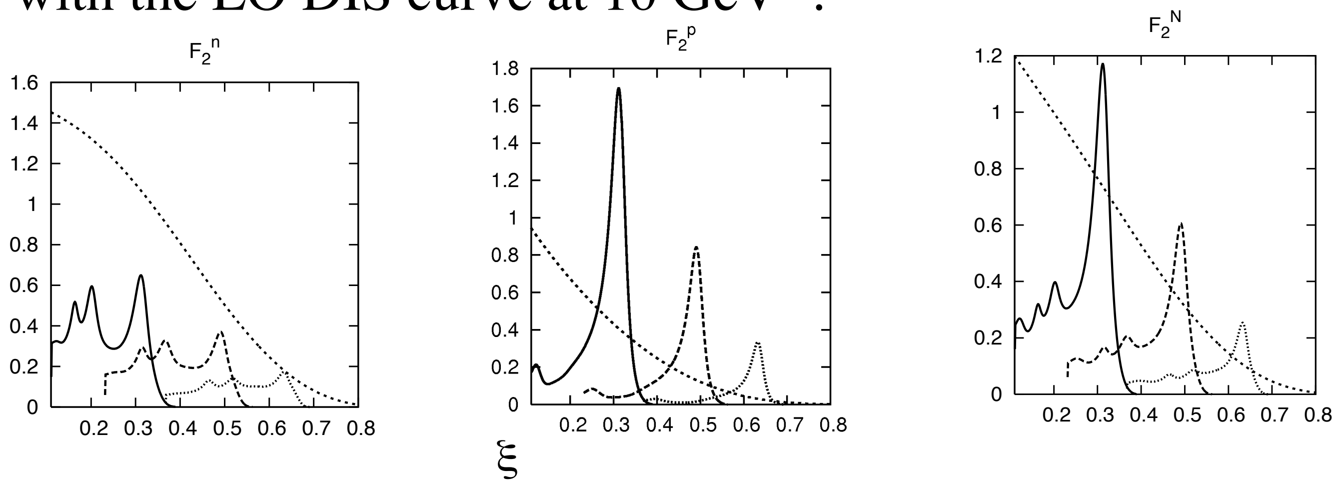


- Global Duality-on the average the resonances appear to oscillate around and slide down the DIS curve. Similar results with the Sato-Lee model
- Local duality in ν-N scattering is worse than in electron scattering: the ratio does not grow appreciably with Q^2

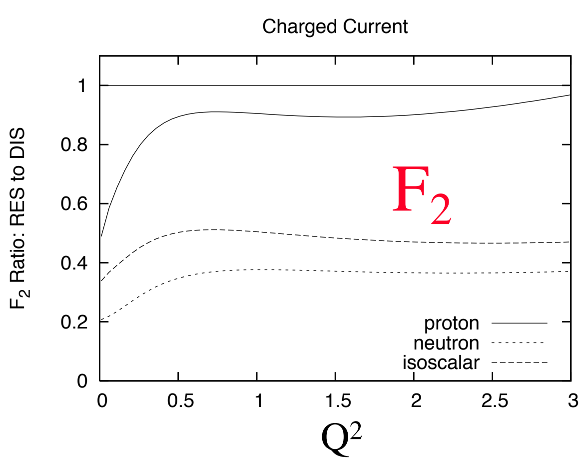
Now for **Neutrinos -** our "favorite" Rein-Sehgal Model

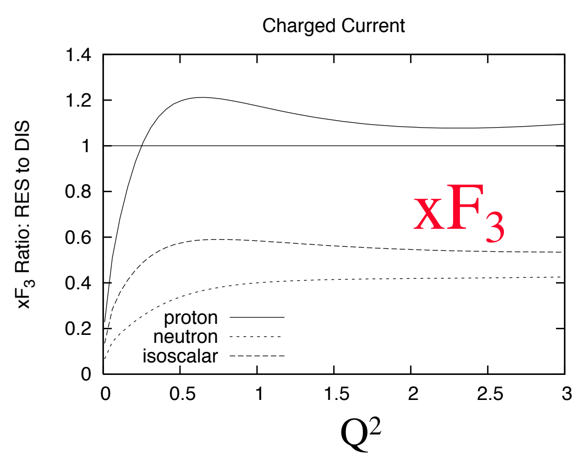
ν-n, ν-p and **ν-N** Resonances (J. Sobczyk et al.-NuWro)

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



- The I integral over the whole W region for the R-S model for resonances off neutron (dotted), proton (solid) and isoscalar (dashed). **Limited multi-pi resonances and ? non-resonant pi.**





How do we determine these nPDFs? - Global Fits

- Use experimental data at <u>cross section level</u> (DIS, DY, W/Z etc.).
- Parametrize proton in nuclear environment PDFs at initial scale Q_0 = 1.3 GeV.

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}, \qquad i = u_v, d_v, g, \ldots$$

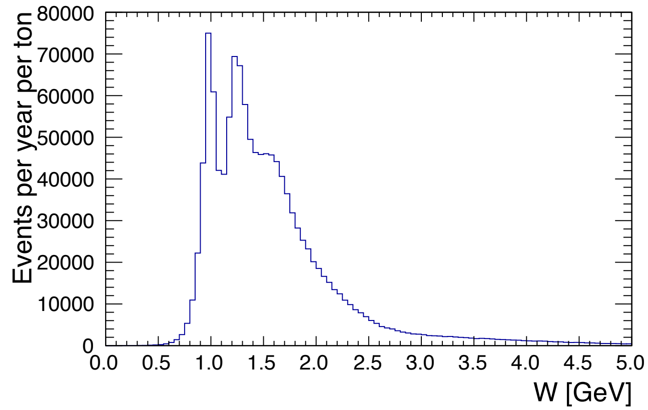
$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} + (1+c_3 x)(1-x)^{c_4}$$

C_i are A-dependent

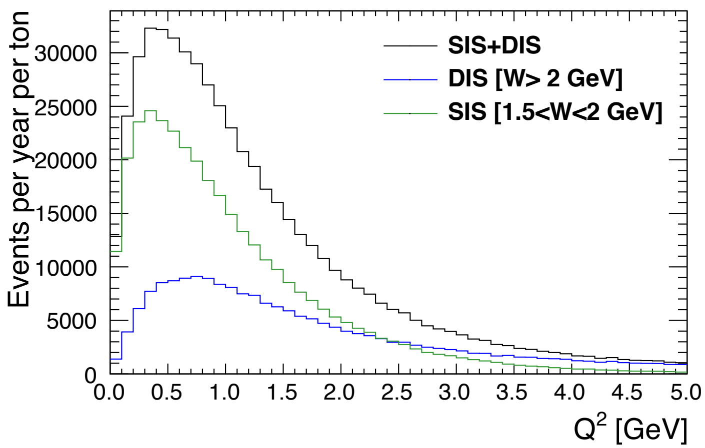
- Use DGLAP equation to evolve $f_i(x, Q)$ from Q_0 to desired Q.
- Calculate theory predictions corresponding to the data (DIS, DY, etc.).
- Calculate χ^2 function – compare data with correlated errors and theory.
- Minimize χ^2 function with respect to parameters c_0, c_1 … c_5 .
- A-dependent fit parameters $c_i(A)$ reduces to free proton PDF fit for A = 1.
- Calculations:
  - NLO in (leading twist) QCD including heavy quark mass effects (ACOT scheme)
  - Include Target Mass Corrections

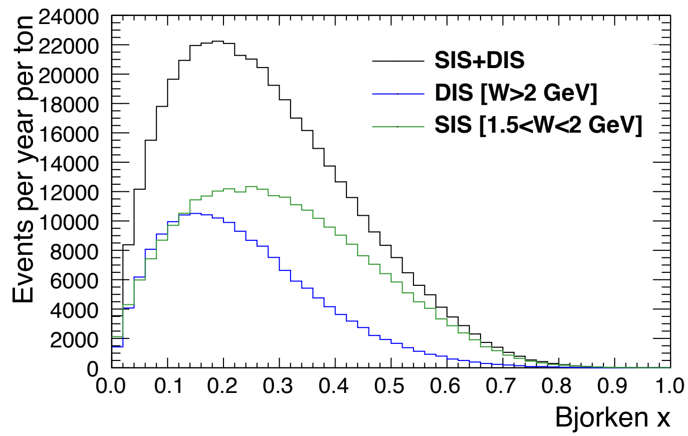
DUNE – 45 % of ν_μ CC events have W>1.5 GeV

latest ND flux – GENIE 3



S. Dolan - 2021





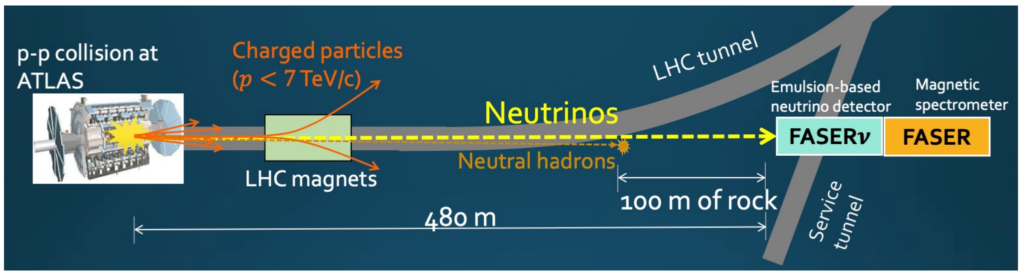
- DUNE should have millions of events in this unexplored SIS region as well as a huge DIS sample for detailed hadronization and nPDF studies.

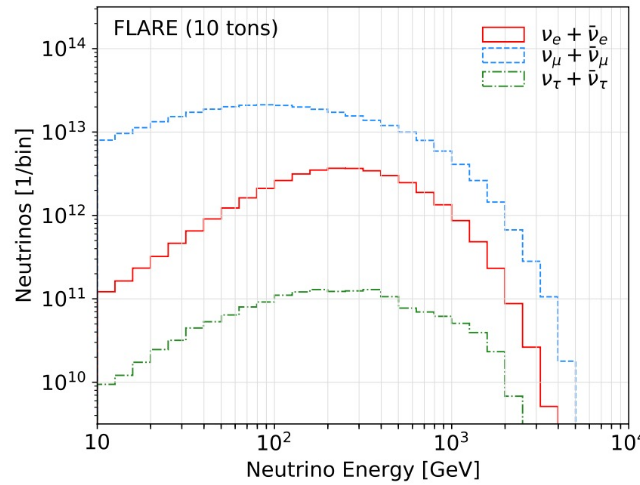
Expected MINERvA Results

15:45	Inclusive Antineutrinos in Targets (1d)	Anežka Klustová	None
16:15	Inclusive Antineutrinos in Plastic (2d)	Maria Mehmood	None
09:00	DIS Neutrinos in Targets (2d)	Zubair Ahmad Dar	None
09:30	DIS Antineutrinos in Targets (1d)	Vaniya Ansari	None
10:00	DIS Neutrinos in Targets (1d)	Amy Filkins	None
13:50	Helium Update	Christian Nguyen	None
14:20	Machine Learning Multiplicity	Luis Bonilla	None
09:00	DIS Antineutrinos in Targets (2d)	Sayeed Akhter	None
09:30	Inclusive Antineutrinos in Targets (2d)	Prameet Kumar Gaur	None
09:30	SIS Analysis Update	Adrian L. Sánchez	

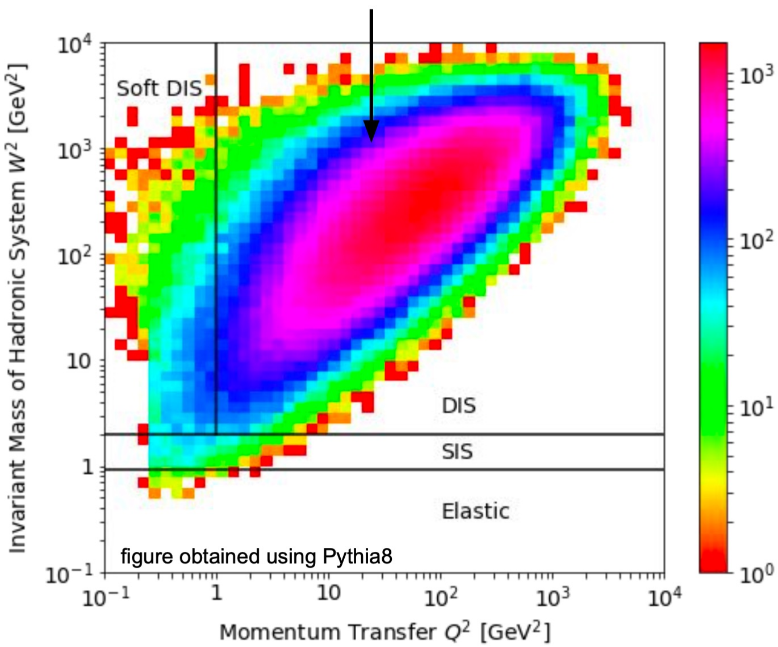
A newcomer - the CERN FPF neutrino beams to expand the studied W and Q^2 regions

- LHC produces an intense and strongly collimated beam of highly energetic neutrinos of **all three flavors** in the far-forward direction. A **Forward Physics Facility (FPF)** is created to house a suite of experiments for the High Luminosity-LHC (HL-LHC) era.





- Expected events for CC $\nu_\mu -^{40} Ar$ scattering in FLArE-10 (10 ton LArTPC) during HL-LHC. Sum is order 100's K $\nu_\mu + \nu_\mu$. Pilot experiments for LHC3



- FPF will measure high statistics CC and NC neutrino-nucleon/nucleus cross sections on a **variety of nuclear targets** during LHC Run 3 (2022 - 2024) and HL-LHC (2027 - 2036) era.
  - DIS cross section measurements cover **uncharted energy region** between the accelerator and IceCube neutrino energies.
  - Phase space covers 1000s of expected events in the SIS/DIS transition (and Soft DIS) region and would provide a unique opportunity to study **quark-hadron duality in the weak sector**.