Shallow-and-Deep Inelastic Scattering with Neutrinos

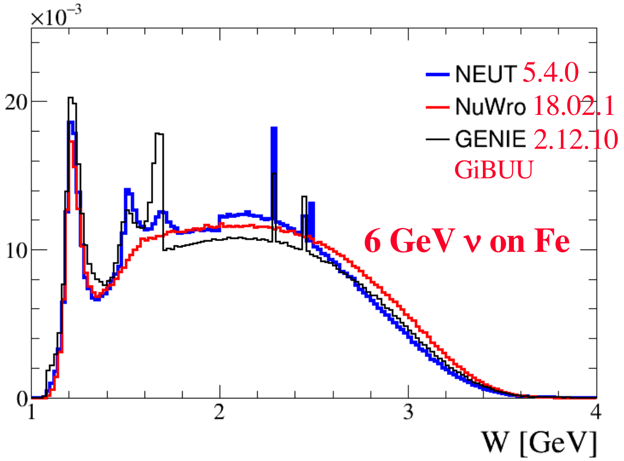
SIS / DIS Review – M.Sajjad Athar. and JGM - arXiv:2006.08603 **[hep-ph]**

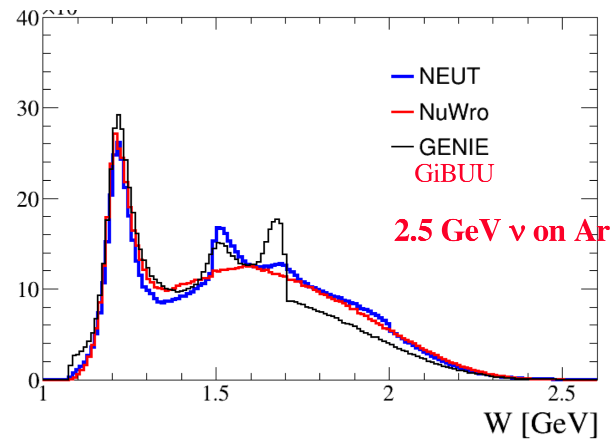
NuSTEC Workshop on SIS and DIS - https://indico.cern.ch/event/727283/
NuSTEC Workshop on Pion Production - https://indico.fnal.gov/event/20793/

NuFact 2021 – Cagliari, Italy – 7 September 2021

Jorge G. Morfín
Fermilab

The SIS and DIS Overall Landscape vs W





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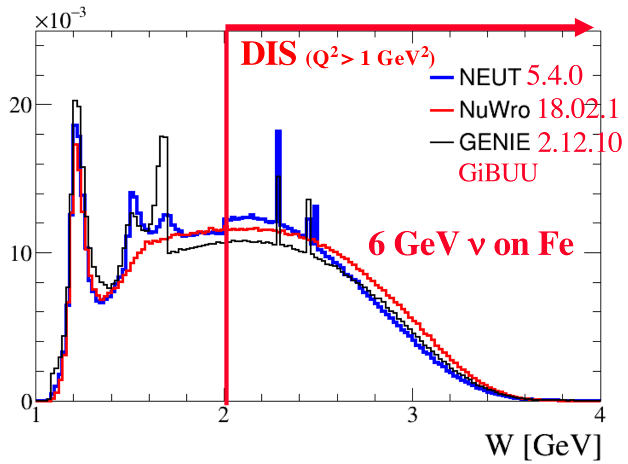

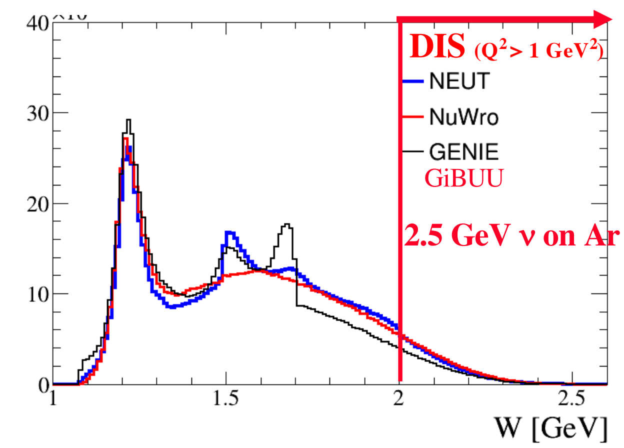

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- **DIS:** community definition of W > 2 GeV with $Q^2 > 1$ GeV^2 (Untouched! – "soft DIS" $Q^2 < 1$ GeV^2)

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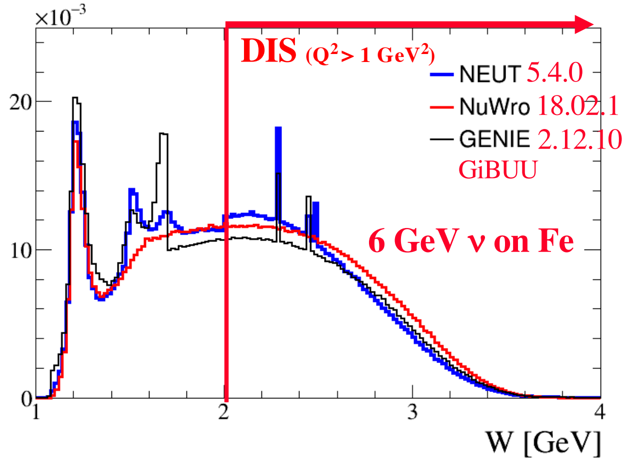

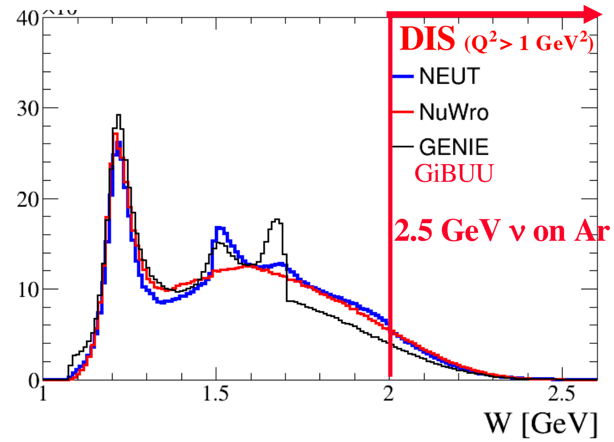

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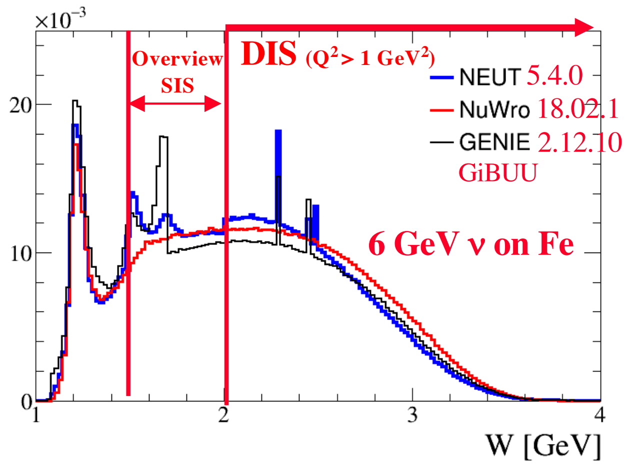
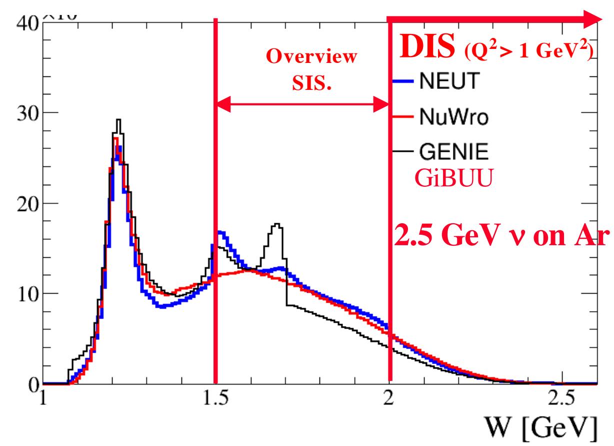
- **SIS: Shallow Inelastic Scattering** is non-resonant meson production with $W > M_N + m_\pi$
- We cannot experimentally separate non-resonant from resonant meson production. We practically define **SIS** as inclusive meson production with $W < 2.0$ GeV.
- The majority of contemporary studies in ν-nucleus interactions have been of Quasielastic and 1 π (mainly Δ) production.

The SIS and DIS Overall Landscape vs W





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- The majority of contemporary studies in ν-nucleus interactions have been of Quasielastic and 1 π (mainly Δ) production.
- For this overview define **"SIS"** as meson (pion) production the **unexplored kinematic region:** **$1.5 < W < 2.0$ GeV.**
- **SIS/DIS significance for DUNE** - 45 % of ν_μ CC events have $W > 1.5$ GeV.

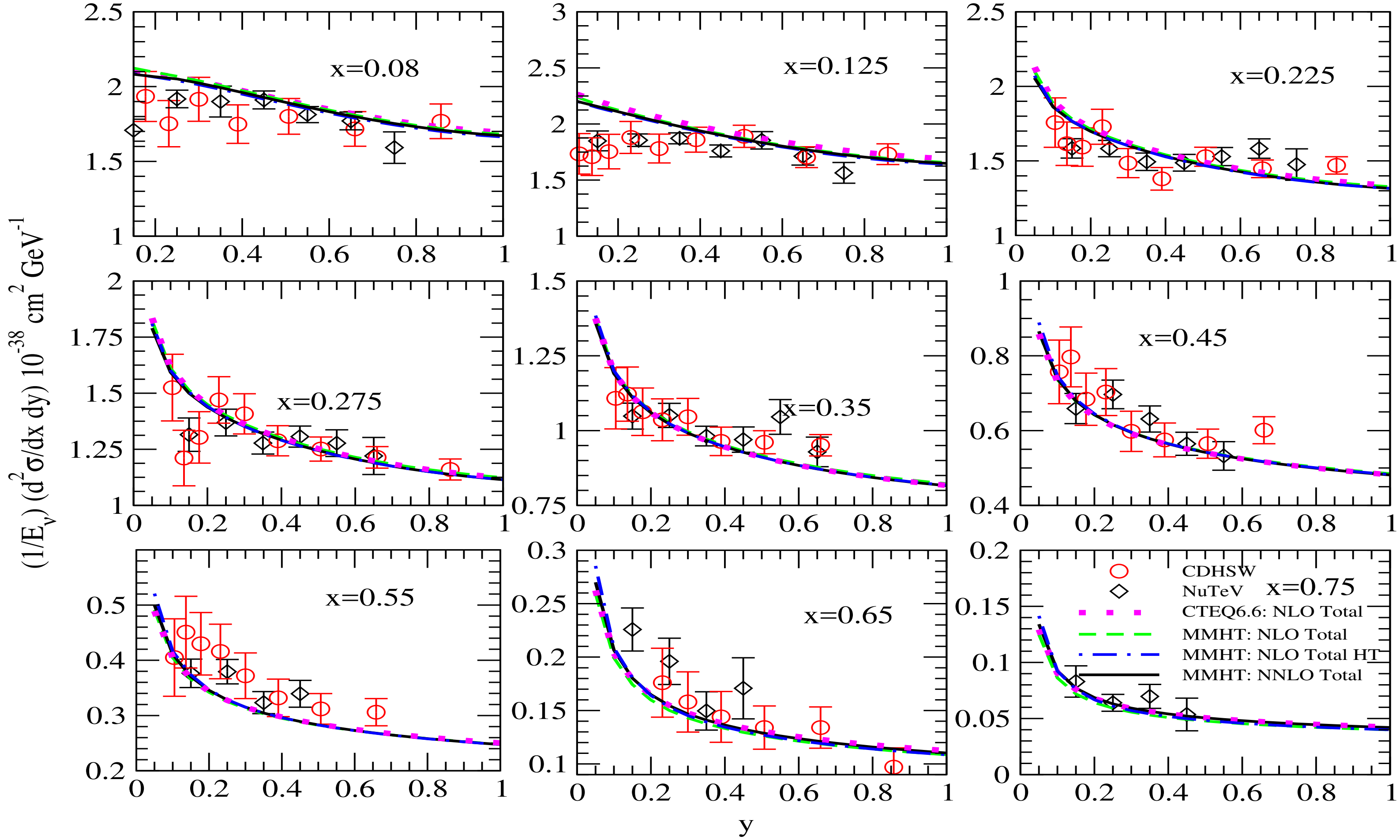
Overview of the Theoretical Picture for SIS/DIS

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

- $\nu/\bar{\nu}$ -Nucleon Scattering
  - ν-Nucleon Scattering: Shallow Inelastic Scattering
    - » Resonant, non-resonant and interference contributions
  - ν-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
- ν/ν -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



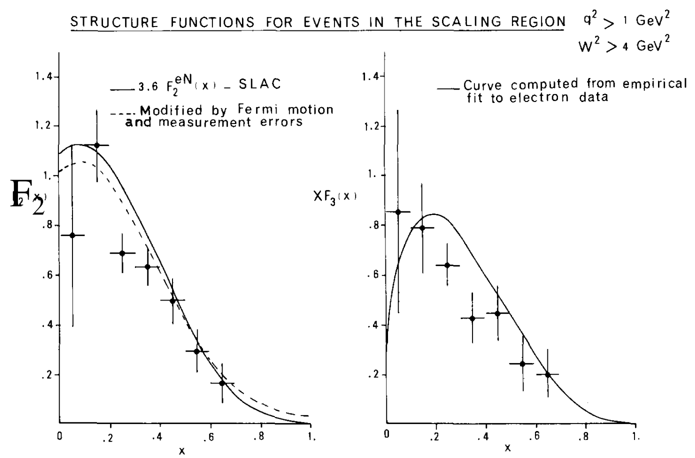
Results using the full Aligarh nuclear model with nucleon PDFs at NLO from CTEQ 6.6 (dotted line) and MMHT (dashed line). Also MMHT with HT effect as well as at NNLO (solid line) are shown. The experimental points are the data from CDHSW ⭕ and NuTeV ◇ experiments.

Experimental / Phenomenological overview

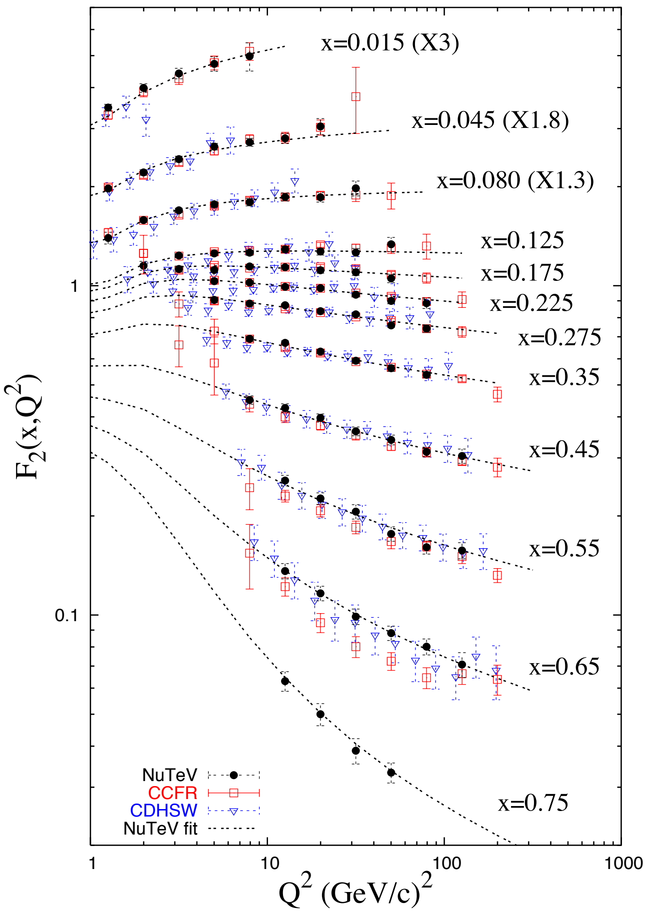
Start with Deep-Inelastic Scattering (DIS)

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

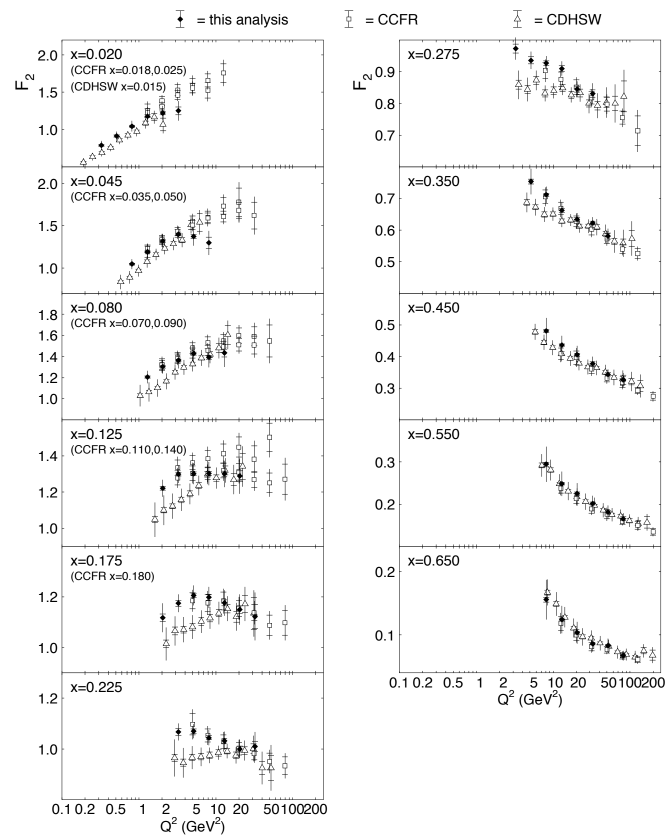
First (early 70's) Gargamelle (CF_3Br) measurement of F_2 and xF_3 (650 ν and 1050 $\bar{\nu}$) for initial neutrino verification of scaling then recently discovered at SLAC.



NuTeV (Fe) measurement (3 million ν and $\bar{\nu}$ events) of F_2 compared to CCFR (Fe) and CDHSW (Fe).



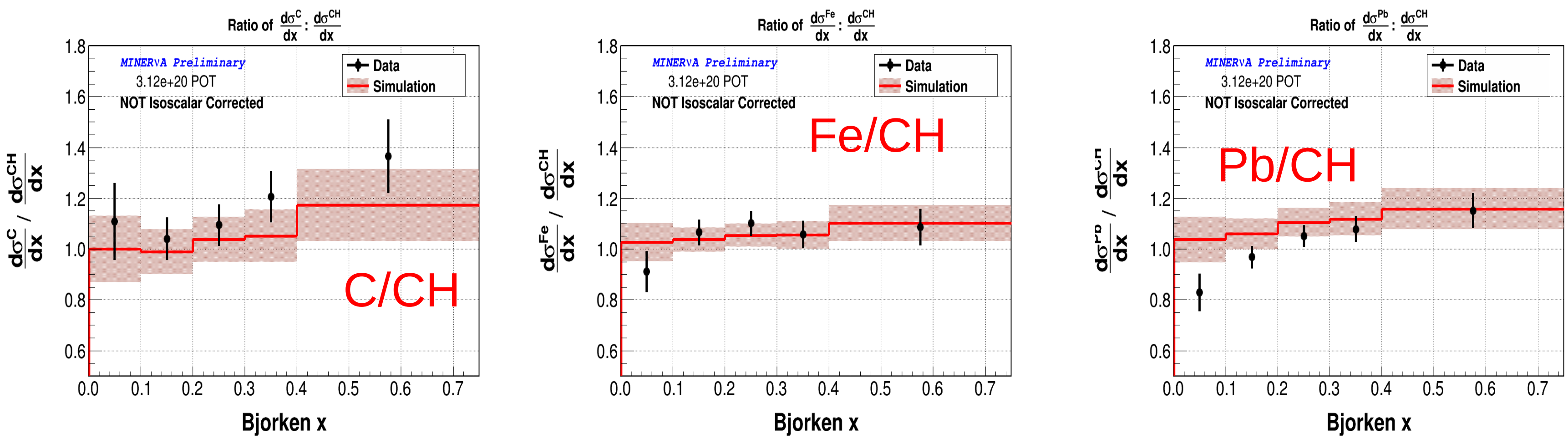
CHORUS (Pb) measurement (1.5 million ν and $\bar{\nu}$ events) of F_2 compared to CCFR (Fe) and CDHSW (Fe).



Most recent ν DIS measurements

MINERvA LE Beam: Measured DIS Neutrino Nuclear Ratios

$Q^2 > 1.0\ GeV^2$ and $W > 2.0\ GeV$



J. Mousseau

- Red shaded histogram are GENIE predictions using charged-lepton measurements of nuclear effects.
- MINERvA LE Measurement of DIS Cross Section Ratios will be useful for improved understanding of the low-Q^2 and low-W ν–A DIS interactions.
- Results from the MINERvA higher-statistics DIS nuclear target analysis (using the higher-energy ME beam) soon to be released! More from MINERvA in the next talk from Michael Kordosky.
- **Why did MINERvA measure ratios?**

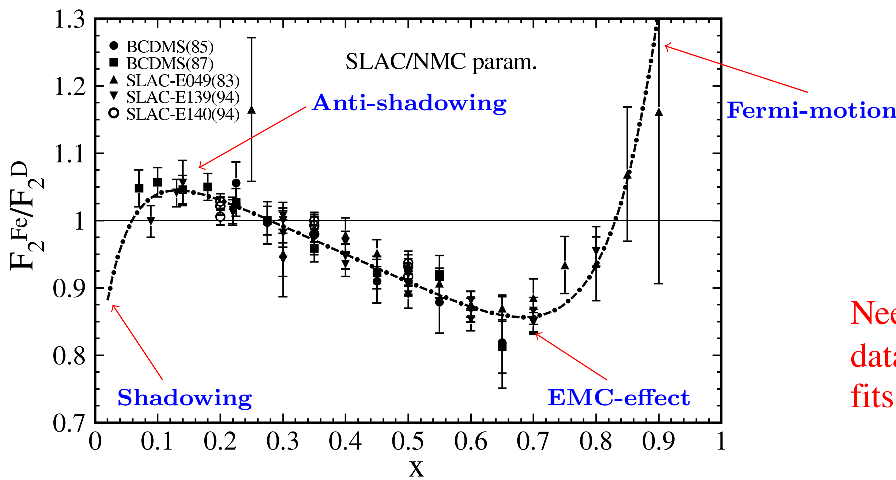
Along the way in the '80s, a discovery with nuclear ratios...

Charged lepton ($l^{\pm}$) - Nucleus Interactions

EMC(1983) - measurement changed the scene dramatically!

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

Charged-lepton) **N**uclear **C**orrection **F**actor (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 & ….

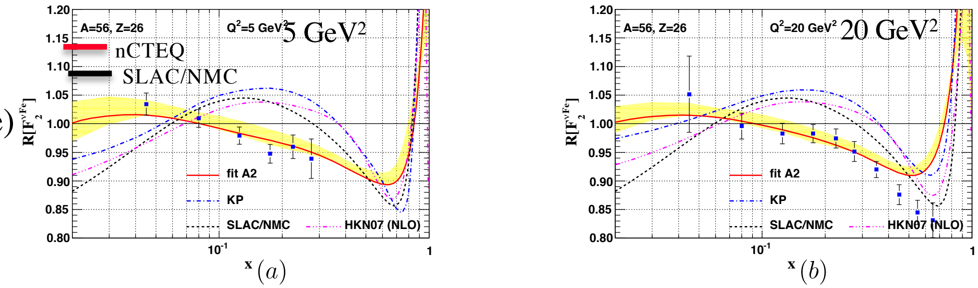
Determination of Neutrino ($\nu/\bar{\nu}$) Nuclear Correction Factors
Original (≈2010) and Ongoing (2021) nCTEQ Fits

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

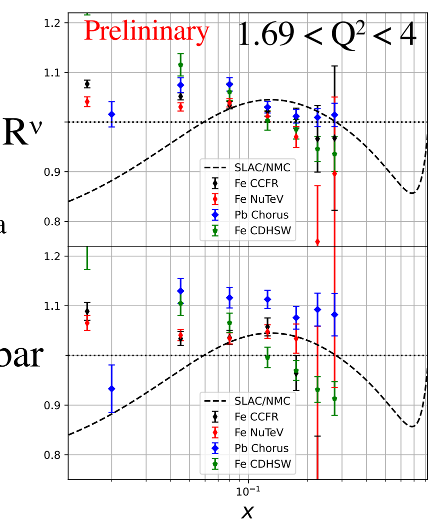
$R = F_2(\nu - \mathrm{Fe};\ \text{measured}) / F_2[\nu - (n+p);\ \text{PDFs}]$

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

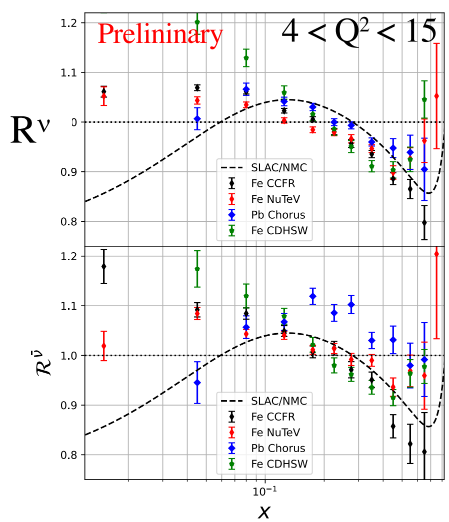
NCF(Fe)

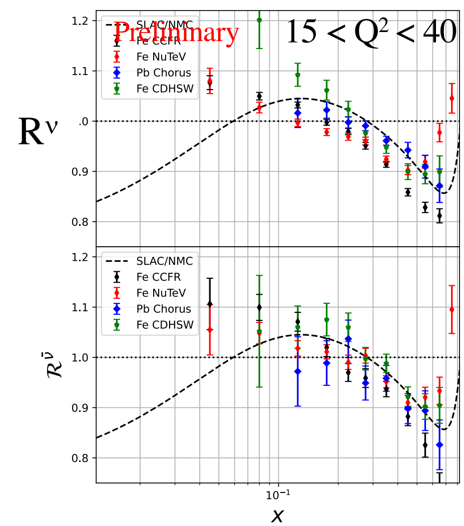


- **UPDATE: Ongoing** 2021 nCTEQ fit $R = \sigma(\nu - A);\ \text{measured} / \sigma[\nu - (n+p);\ \text{CTEQ6 PDFs}]$
- Expanded data sets: Dimuon: CCFR & NuTeV and DIS: CCFR, NuTeV. CDHSW, CHORUS (Q > 2 GeV, W> 3.5 GeV). MINERvA Data does not (yet) make the cut.
- Improved treatment of cross experiment normalization uncertainties and the R denominator.
- **Tension still exists** between ($1^{\pm}$ …) and neutrino data. **Tension maximal at x ≤ 0.1,** to **lesser extent at higher x** (mainly NuTeV). **Confirm nCTEQ (≈2010) low-x conclusion but softened at higher x!**



K.F. Muzakka

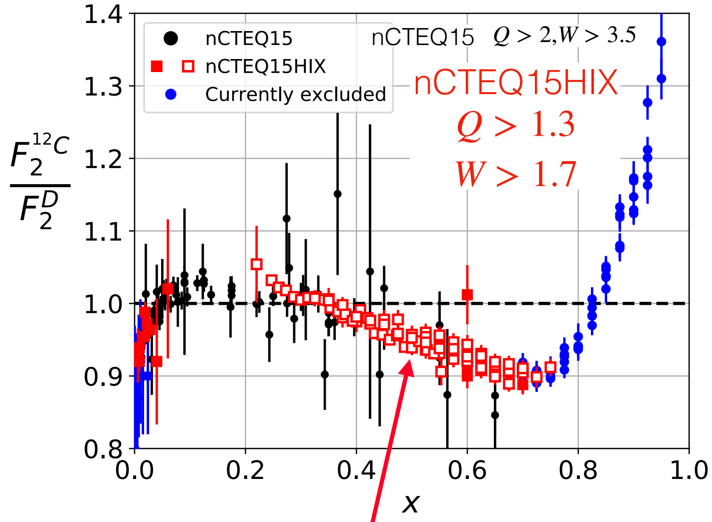


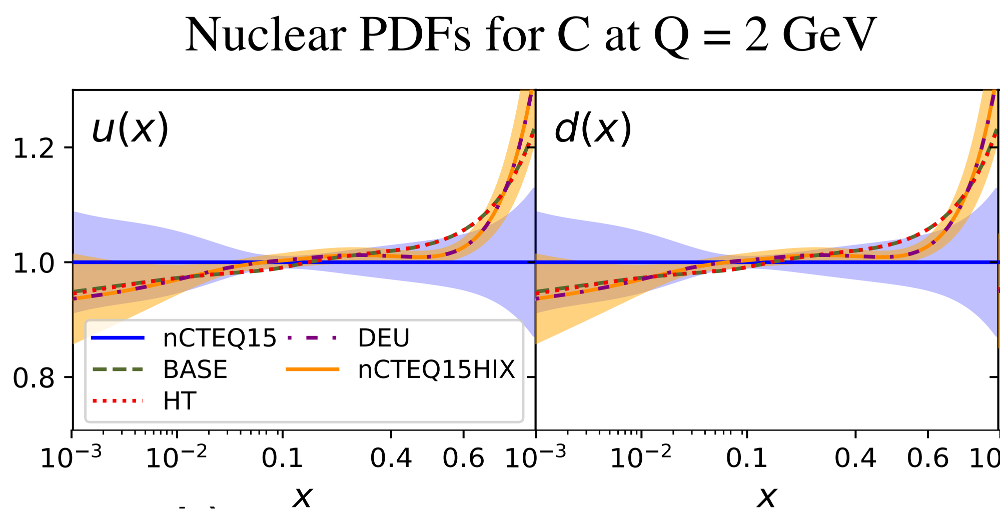


Important Note: First nCTEQ fit into the **SIS transition region**

nCTEQ15HIX (https://ncteq.hepforge.org) Charged lepton nPDFs for

W > 1.7 GeV, Q > 1.3 GeV²





- Using higher–x, lower Q Jefferson Lab **($l^{\pm}$)** nuclear ratio measurements

- TMC (Target Mass Correction) sub-leading M^2/Q^2 corrections to leading twist structure function. Often referred to as "kinematic HT", Accounted for with help of the Nachtmann variable.
  $\xi = 2x/[1 + (1 + 4 M^2x^2 / Q^2)^{1/2}]$.

- HT (Higher Twist) - Non-perturbative multi-quark interactions, theoretically not well understood, often experimentally parametrized and fitted for e-N/A with:

$$F_2^A \rightarrow F_2^{A\,\mathrm{LT}}\left[1 + \frac{C_{HT}^A}{Q^2}\right]$$

e-Print: 2012.11566 [hep-ph]

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

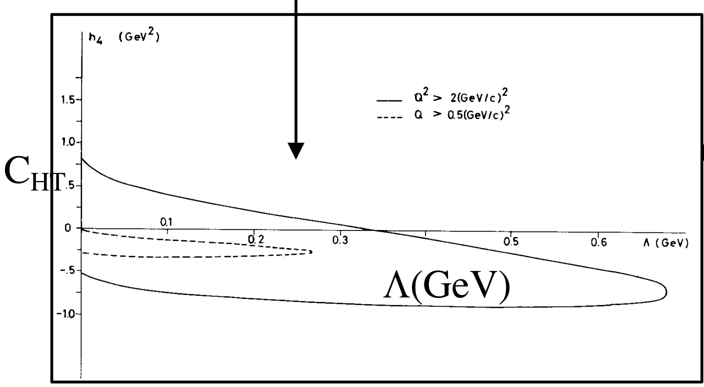
From DIS as we transition into the SIS Region…

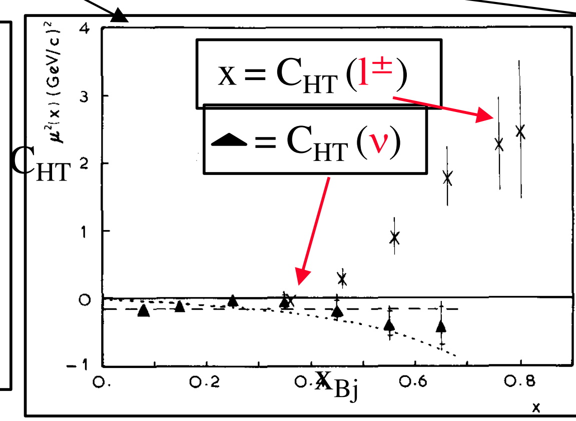
We pass through the Non-perturbative QCD Region

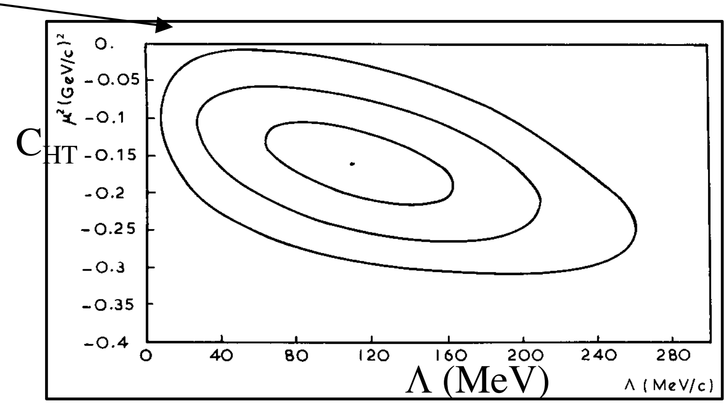
- From pQCD, with Q^2 evolution proportional to $1/\log(Q^2/\Lambda^2)$, extend into the non-pQCD regime and consider $1/Q^2$ effects.
  - Target Mass Corrections (TMC) - leading twist effect well understood theoretically, accounted for with the help of the Nachtmann variable. **$\xi = 2x/[1 + (1 + 4 M^2x^2 / Q^2)^{1/2}]$.**
  - **"Higher Twist" (HT) in neutrino scattering parameterized with the same form:**

$$F_2^A \rightarrow {}^{LT}F_2^A \left[1 + \frac{C_{HT}^A}{Q^2}\right]$$

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



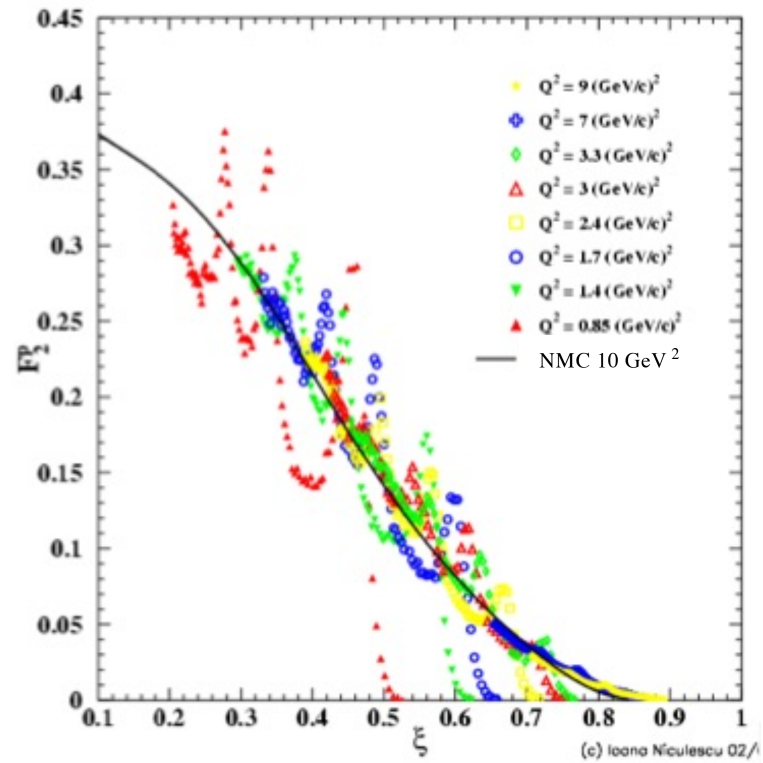




- That is $C^{\nu A}_{HT}$ in neutrino scattering: smaller & negative!

Continuing study of The DIS ⟶ SIS Transition!
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 <u>average</u> over resonance production.**
- Quark-hadron duality originally studied and confirmed in e-N scattering – **what does duality "look like"** (Jlab **<u>e-proton</u>** Study) **?**
- **How about a quantitative test of "duality"?**

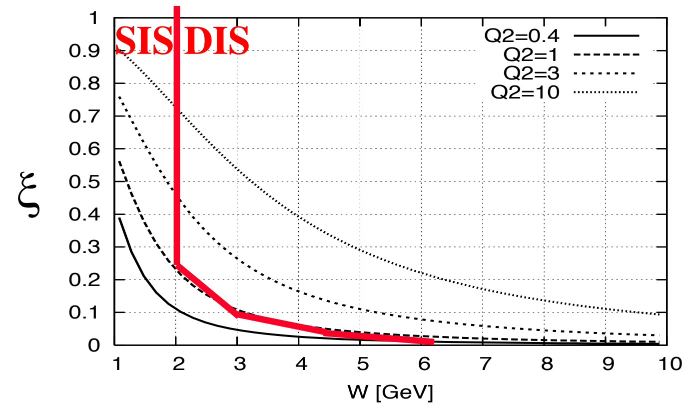


Quantitative test of Quark-Hadron Duality:
Ratio of integrals over a finite ξ interval
e - Nucleon

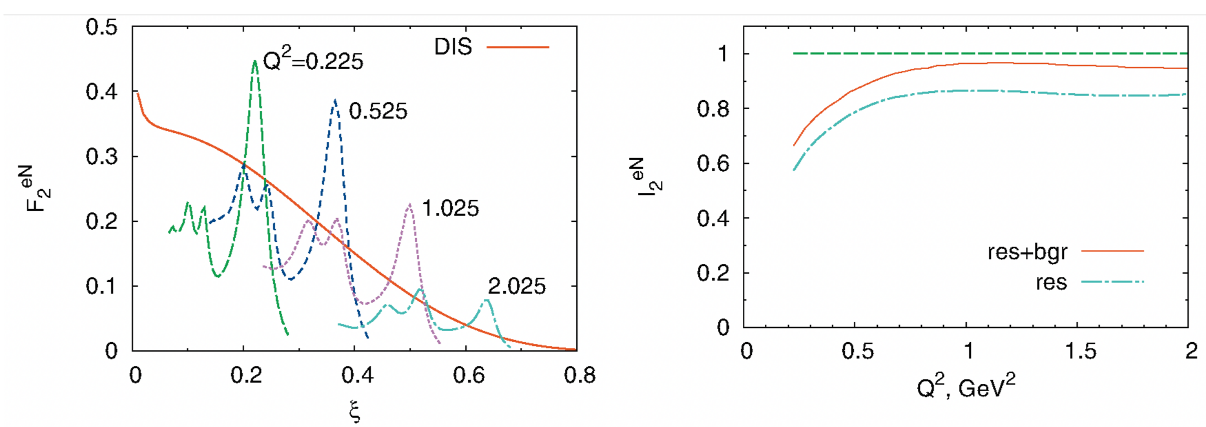
- Ratio of the strength of the SIS to DIS region. Ideal Duality I = 1.0 .

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

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



- Using Giessen fit to e-N scattering – $F_2^{eN}(\xi)$ 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).



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

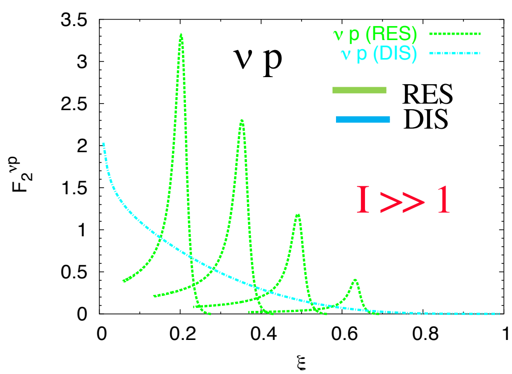
Resonance estimates from Lalakulich, Melnitchouk and Paschos for ν-n and ν-p scattering.

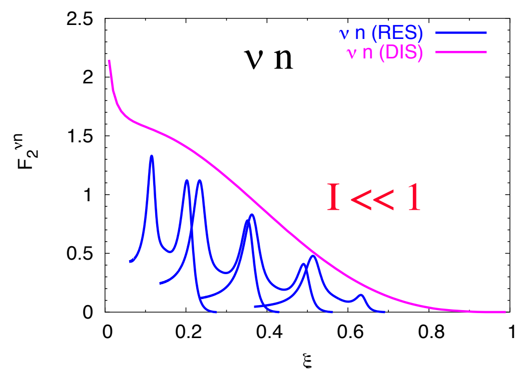
Low-lying resonances: $F_2^{\nu n(res)} < F_2^{\nu p(res)}$, DIS: $F_2^{\nu n(DIS)} > F_2^{\nu p(DIS)}$

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

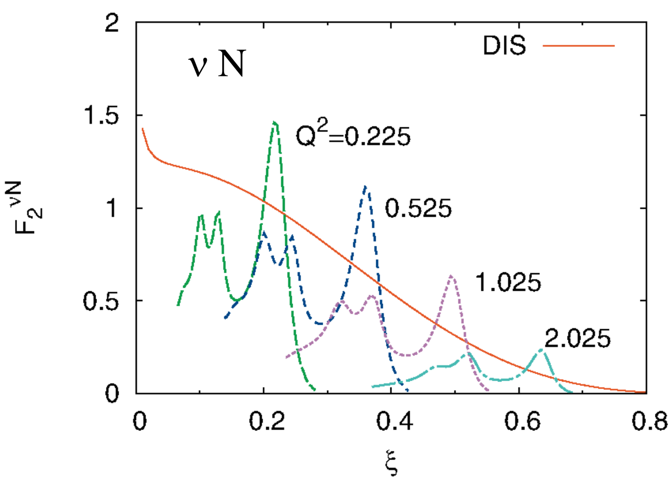
$F_2^{\nu p(res-1/2)} \equiv 0$

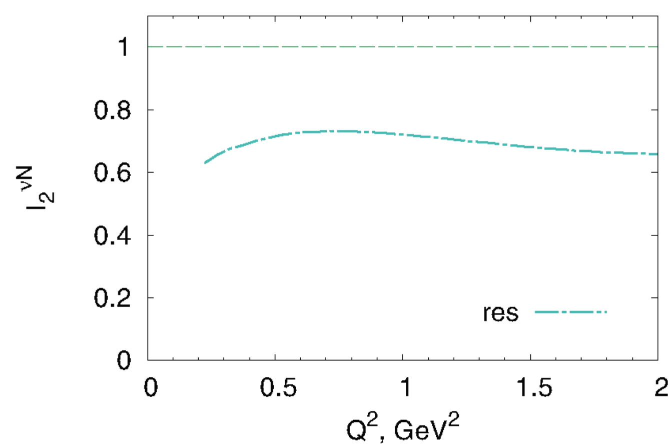
$F_2^{\nu n(res)}$: finite contributions from isospin 3/2 and -1/2 resonances



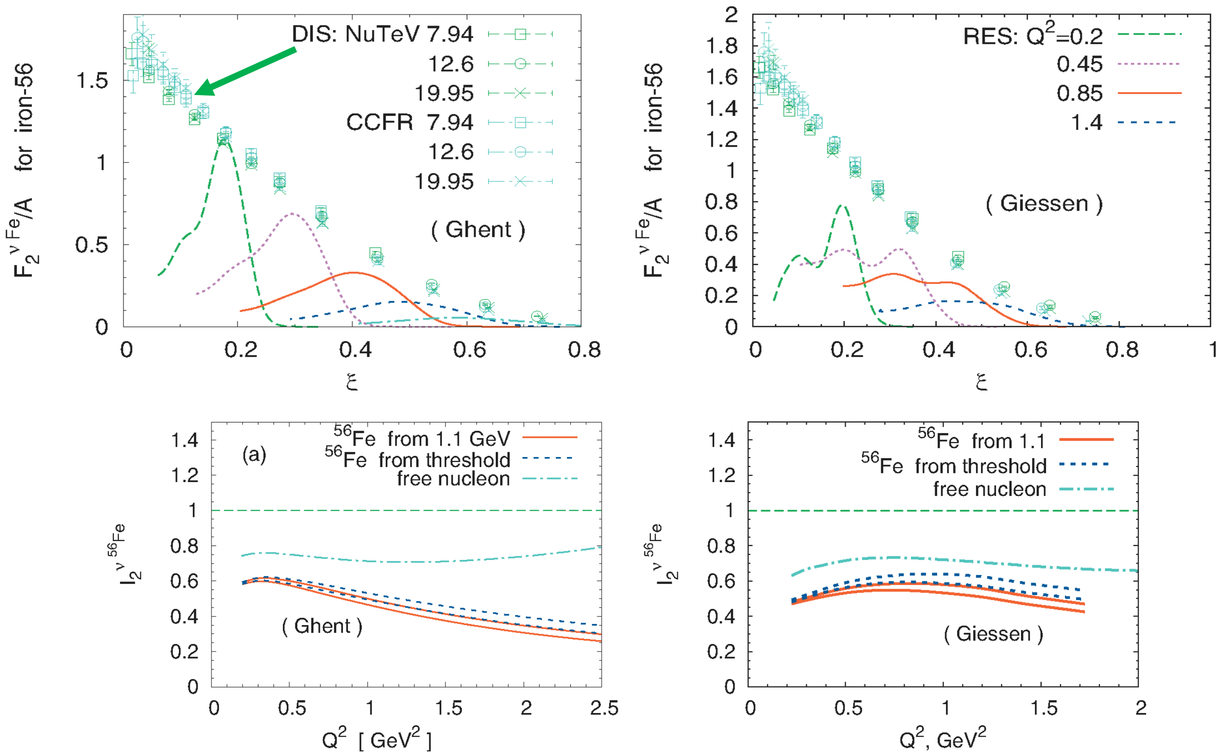


Resonance estimates from GiBUU Model for ν-N scattering compared To DIS at 10 GeV^2.
<u>No non-resonant π included</u>





Even more concerning 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 resonance structure functions for **proton are much larger than for neutrons** and in the case of DIS structure functions **the situation is opposite.**
- Higher W DIS F_i's are much larger than the resonance contribution at lower W.
- How duality should be applied with neutrinos is still **an open question**, however, ask…
- **Has the duality concept led to predicting SIS behavior from DIS measurements…?**

Bodek-Yang Model

Use the spirit of Duality to extrapolate DIS phenomena to the inclusive SIS region
B-Y is used in many/most neutrino event generators

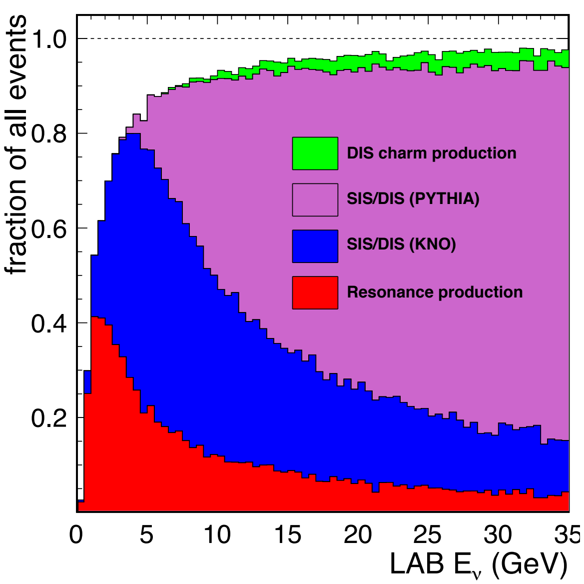
- B-Y model keeps Duality in mind by extending GRV LO PDFs that describes DIS for W > 2 GeV, $Q^2 > 0.8$ GeV^2 further down in Q^2 and W to the SIS region.
- They include TMC and HT effects by replacing x_{Bj} with $\xi_W = \frac{Q^2 + B}{\{M\nu[1+\sqrt{(1+Q^2/\nu^2)}]+A\}}$ that also accounts for missing higher order QCD (NLO..).
  - B allows extrapolation to photoproduction limit at $Q^2 = 0$.
  - A allows this enhanced TMC term to account for HT.
- They introduce quark flavor dependent K factors to extend the values of PDFs at $Q^2 = 0.8$ GeV^2 down to to $Q^2 \approx 0$.
- All initial development and checks of the B-Y model performed **with e/μ-n and e/μ-p. The V contribution to ν–N** well modeled and **B-Y then added the A contributions!**
- Introduce nuclear effects as measured **in electroproduction!**
- Updated B-Y model provides a good reference for both neutrino and anti-neutrino nucleon cross sections with W > 1.8 GeV.
  - **How about comparing B-Y and nCTEQ15HIX (W> 1.7 GeV) for e-N scattering??**
- Used in GENIE to estimate non-resonant π and transition W resonances.

Another Important SIS/DIS Concept - Hadronization

Recent GENIE (3.0) study.

e-Print: 2106.05884 [hep-ph]

- Why is it important? (See also Mike Kordosky's MINERvA talk)
  - Gives multiplicities and kinematics of the hadrons before final state interactions, consequently
  - Impacts the estimation of backgrounds and calorimetric energy reconstruction!
- Empirical observation of average charged multiplicities: $< n_{ch} >= a + b \cdot ln(W^2/GeV^2)$
- GENIE uses AGKY model based on KNO model at low W and PYTHIA at high W
  - W < 2.3 GeV - KNO model - dispersion of multiplicities around $<n_{ch}>$ with general scaling function
  - W > 3.0 GeV - PYTHIA - Lund string model best at higher energies - needs low W modifications.
  - Tuned to BEBC & 15' bubble chamber H and D data. However, there can be nuclear modifications.



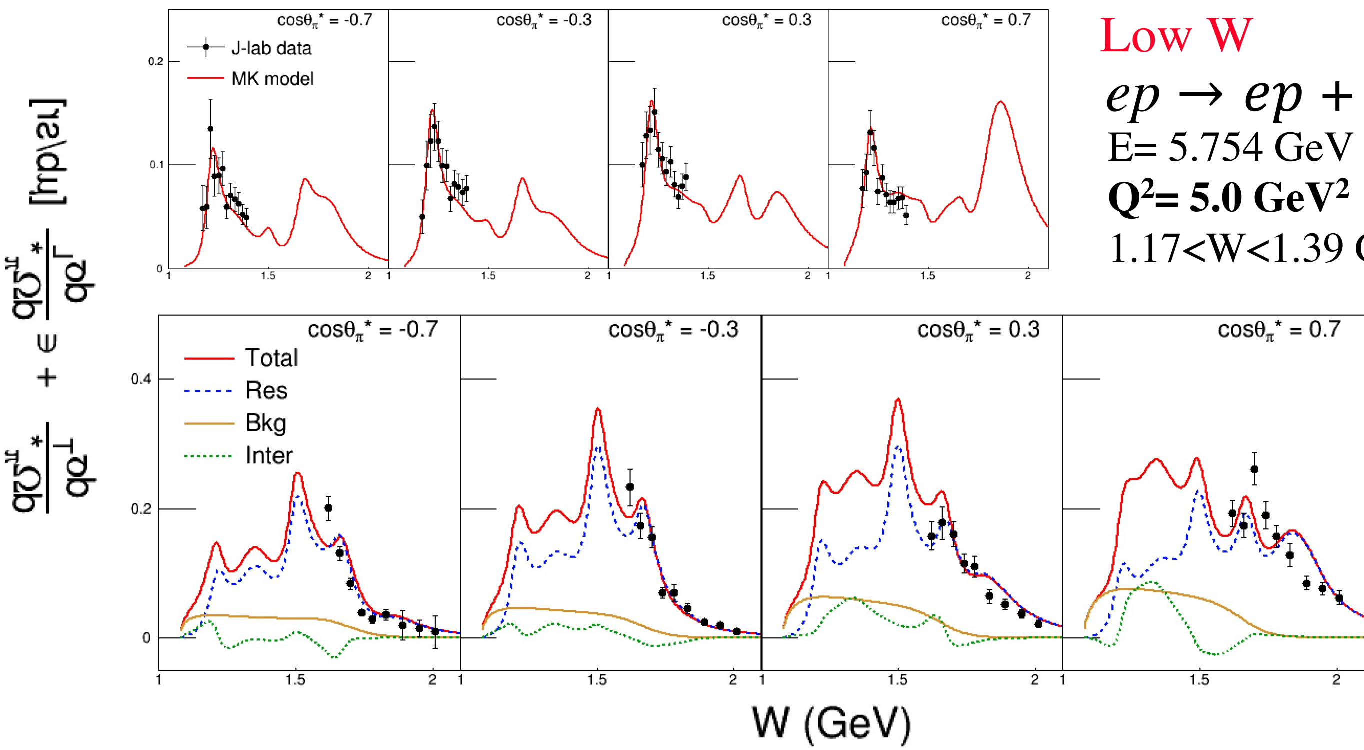
Global fit results.
Errors not quoted!

	νp	νn	$\bar{\nu} p$	$\bar{\nu} n$
a	1.1	1.75	1.32	1.11
b	0.79	0.5	0.8	0.88

What about individual channels that make up this multiplicity and contribute to this inclusive SIS phenomena?

New Minoo Kabirnezhad (MK) single π model

- MK Model for single pion production, which includes resonant and non-resonant interactions including interference effects.
- Uses the Rein-Sehgal framework but the more sophisticated Rarita-Schwinger formalism for the first four resonances and Rein-Sehgal for the higher resonances up to W = 2 GeV.
- **Latest update extends the model to high W and higher Q^2!**
- Currently for e-N interactions only. **However, ν–N interactions coming soon!**



Low W

$ep \rightarrow ep + \pi^0$

E= 5.754 GeV

Q^2= 5.0 GeV²

1.17<W<1.39 GeV

High W

$ep \rightarrow en + \pi^+$

E= 5.449 GeV

Q^2= 4.0 GeV²

1.62<W<2.01 GeV

How about multi-pion production?

Multiple Resonances above the Δ in the highlighted (1.5 – 2.0) GeV with 2π decay states: D(1520, 1675) **2π > 25%,** D(1700) **2π > 10-55%,** S(1620) **2π > 55%,** P(1720 and 1900) **2π > 40%,**

Nakamura, Kamano and Sato take on the challenge!

- Starting with dynamical coupled-channel (DCC) model developed for π-N, γN→ πN,…
- Extend the modeling of the V-current to model e-N and compare with data.
- Use PCAC to include A-current and develop a (DCC) for ν-N resonances.
  - Interference between resonant and non-resonant amplitudes uniquely determined.
- Result for single pion agrees reasonably well with data.
- First DCC model to give double-pion production (resonant, non-resonant and interference). e-Print: 1506.03403 [hep-ph]

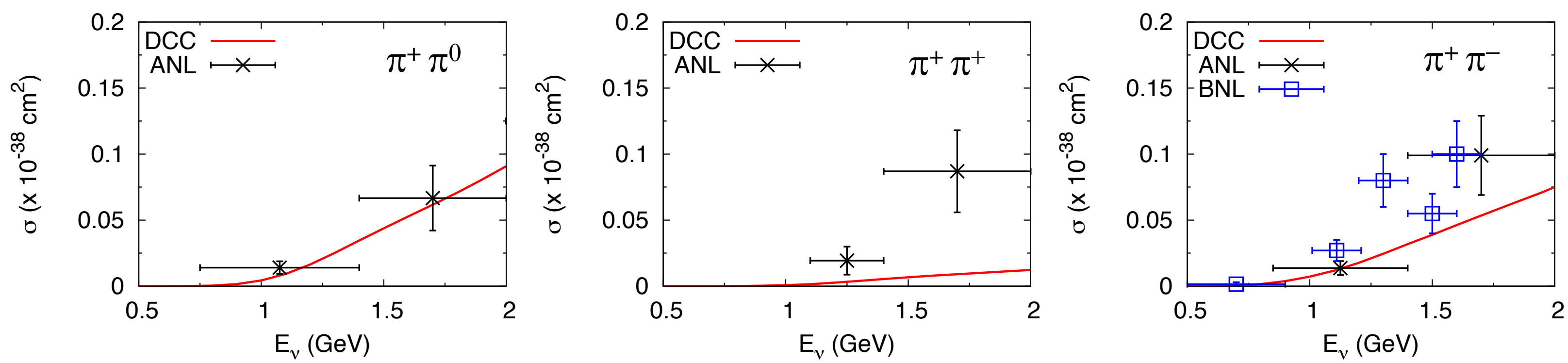


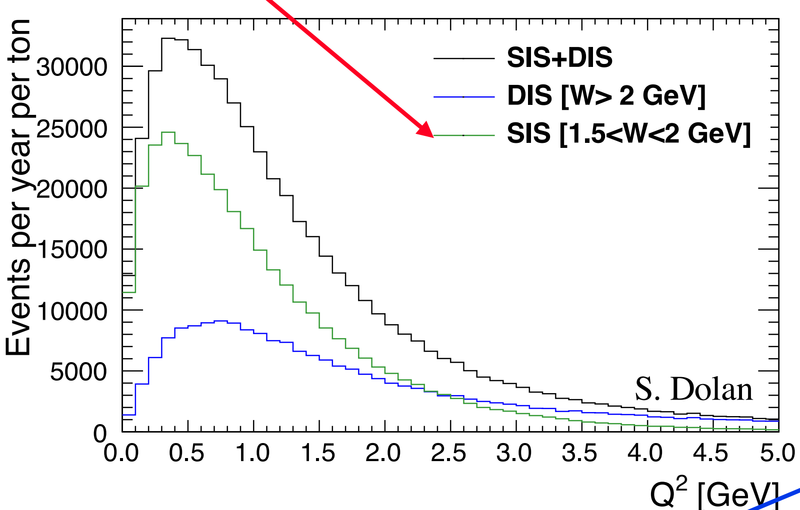
FIG. 19. (Color online) Comparison of the DCC-based calculation with data for $\nu_\mu p \to \mu^-\pi^+\pi^0 p$ (left), $\nu_\mu p \to \mu^-\pi^+\pi^+ n$ (middle) and $\nu_\mu n \to \mu^-\pi^+\pi^- p$ (right). ANL (BNL) data are from Ref. [93] ([13]).

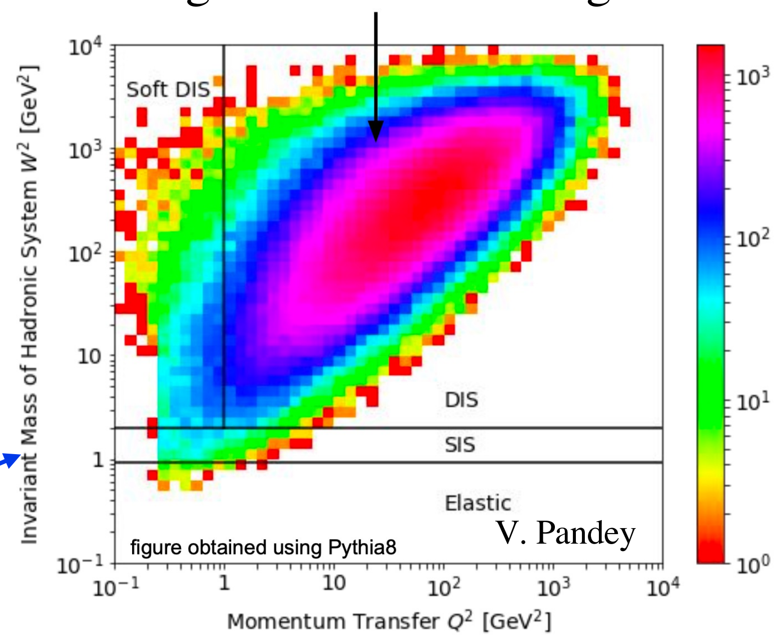
Yes, we are getting increasingly sophisticated models covering SIS and DIS, however…

- **There is minimal high-statistics ν-N/A experimental data within the kinematic range of interest - 1.5 < W < 2.0 GeV – available for testing models!**
  What experimental data can we expect in the (near) future?

- MINERvA finishing the study of 1.5 < W < 2.0 GeV for $\nu/\bar{\nu}$ - CH!
  - Measure total and differential inclusive σ's with Q^2, ξ and W in the SIS region.
  - Measure multiplicities of charged hadron in increasing W bins from SIS to and in DIS.

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





- CERN Forward Physics Facility neutrino beams to expand the studied W and Q^2 regions

As prepared for a Snowmass Workshop….
A FEW ITEMS WE NEED TO ADDRESS THE MANY OPEN QUESTIONS?

- DIS –
  - Theory1 – Study of non-perturbative QCD effects for neutrino (high x–low Q)!
  - Theory2 – Better understanding of x > 1.0 region for nuclear targets!
  - Theory3 – Better understanding of partonic nuclear effects!
  - Experimental1- a large statistics **hydrogen AND deuterium experiment**!
    - High statistics dσ/dxdy and single and multi π production off neutrons and protons.
    - Improved tuning for hadronization models (lower W PYTHIA) in the DIS region.
    - Provide experimental results to check Theory1 (estimate nuclear HT?) and Theory2 (x → 1.0) efforts without nuclear effects.
    - Detailed study of SOFT DIS (W > 2.0 GeV and Q < 1.0 GeV) without nuclear effects.
  - Experimental2 - Large statistics measurements over wide range of low-to-high A, particularly LIGHTER nuclei.
    - high statistics dσ/dxdy for nPDF global fits,
    - nπ production to study fragmentation length and nuclear effects from low-to-high A.

A FEW ITEMS WE NEED TO ADDRESS THE MANY OPEN QUESTIONS?

- SIS (1.5 – 2.0 GeV)
  - Theory1 – Better understanding of how duality works with neutrinos.
  - Theory2 – Continued development of resonant-nonresonant single and multi-π models on nucleons
  - Theory3 – Bring these models into the nuclear environment. Increased investigations of **Final State Interactions**
  - Experimental1 - Measure single and multi-pion production on nucleons in a large statistics **hydrogen AND deuterium experiment**!
    - » Improved tuning for the KNO hadronization models in the SIS region
  - Experimental2 - Measure SIS Inclusive and exclusive cross sections as a function of W and ξ for Duality studies across a broad range of nuclear targets.
  - Experimental3 – high statistics $d\sigma/dxdy$, multi π production off neutrons and protons, general hadronization studies and nuclear effects over wide range of low-to-high A.