Deep-and-Shallow Inelastic Scattering with Neutrinos
Experimental and Phenomenological Overview

SIS / DIS Review – S.A. 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/**

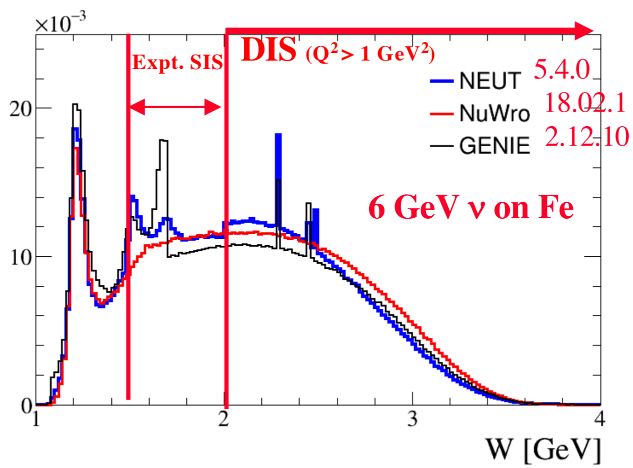
Snowmass Workshop on Theoretical Tools for Neutrino Scattering…

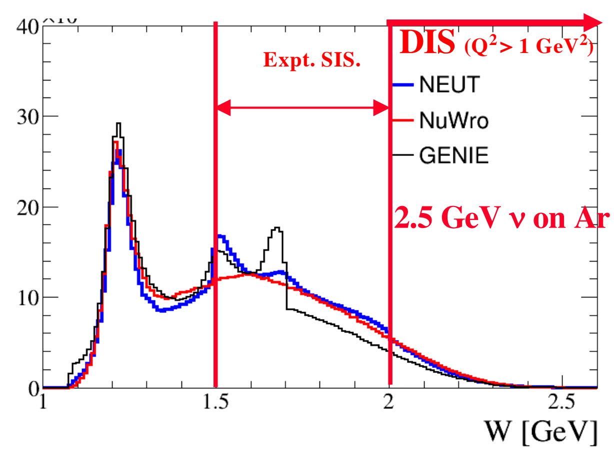
Jorge G. Morfín
Fermilab

The General **SIS + (true) DIS** Landscape – Comparison of Generators

DIS is the community definition of $W > 2$ GeV with $Q^2 > 1$ GeV^2

- **Shallow Inelastic Scattering (SIS)** is non-resonant meson production ($W > m_N + m_\pi$)
- Since we cannot experimentally separate non-resonant from resonant meson production, we practically define **SIS** as inclusive meson production with $W < 2.0$ GeV.
- By far the majority of contemporary studies in ν-nucleus interactions have been of Quasielastic and 1 π (mainly Δ) production.
- For this summary **let's define experimental SIS as the unexplored kinematic region $1.5 < W < 2.0$ GeV**
- **Significance for DUNE** - 45 % of ν_μ CC events have $W > 1.5$ GeV.



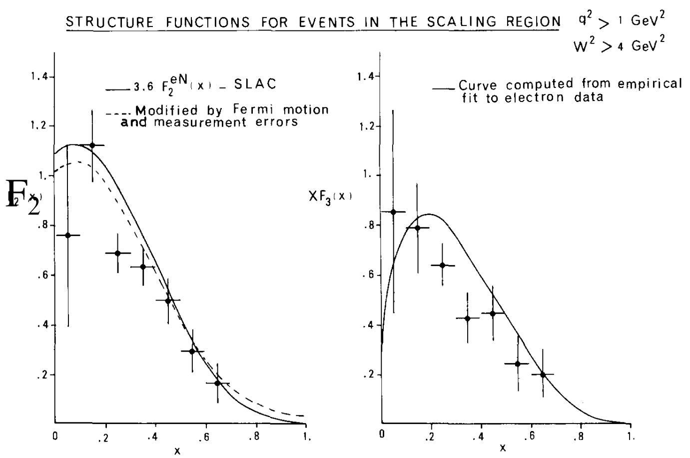


C. Bronner- 2018

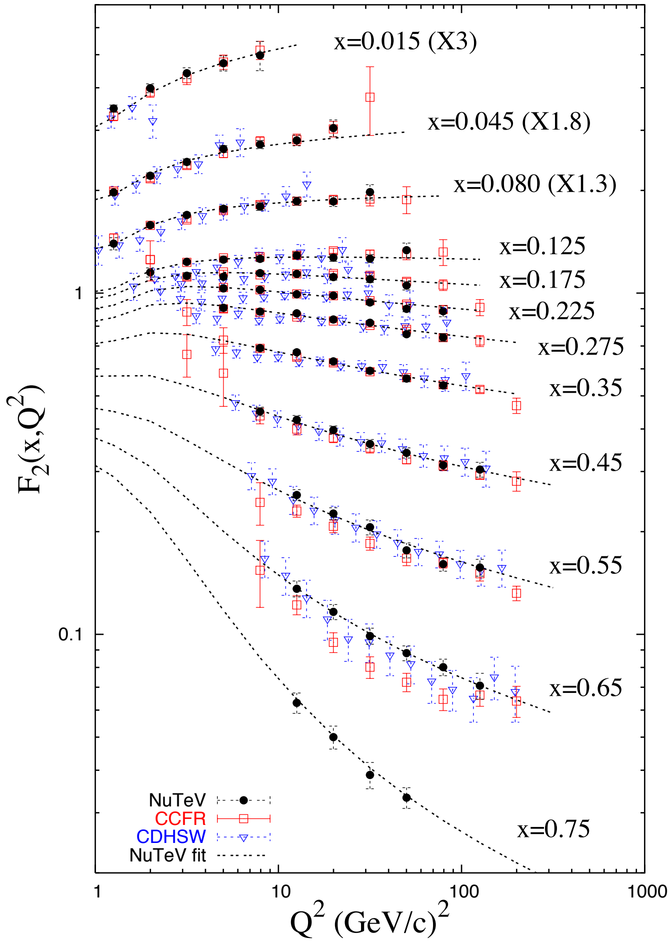
Start this overview with Deep-Inelastic Scattering (DIS)

Neutrinos: studying the structure of the nucleon (mainly PDFs) with DIS for **50 years (>15 major experiments)**!

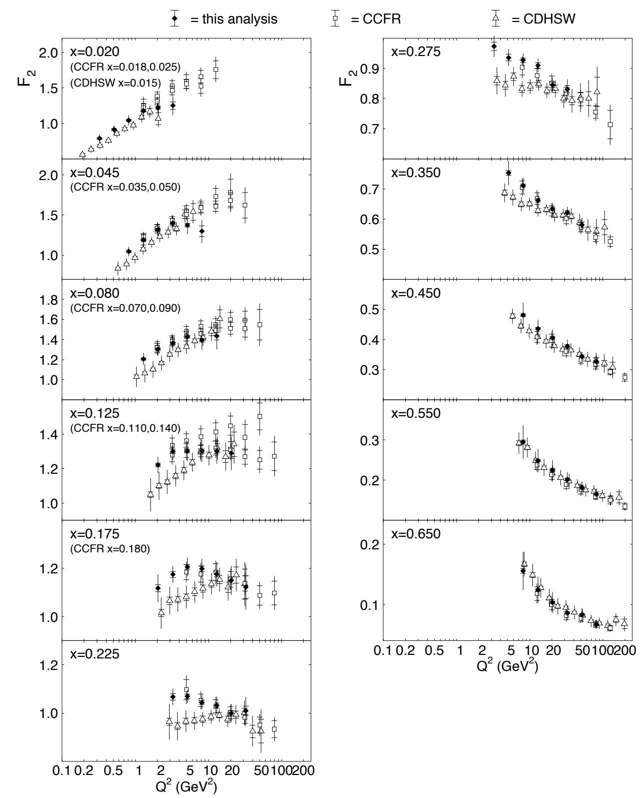
First (early 70's) Gargamelle (CF_3Br) measurement of F_2 and xF_3 for initial neutrino verification of scaling then recently discovered at SLAC.



NuTeV (Fe) measurement of F_2 compared to CCFR (Fe) and CDHSW (Fe).



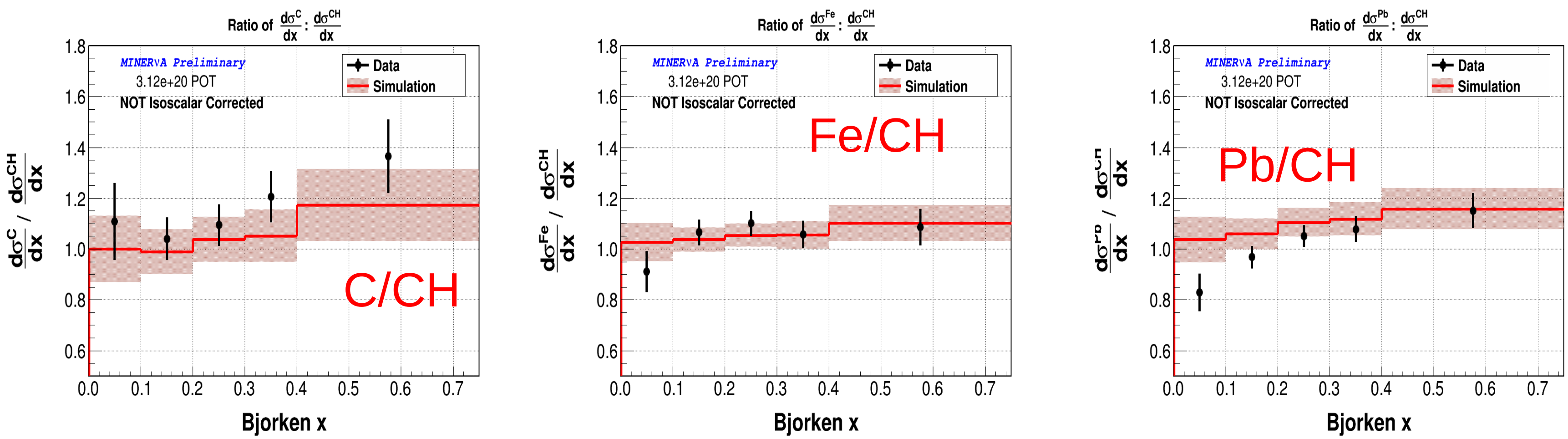
CHORUS (Pb) measurement of F_2 compared to CCFR (Fe) and CDHSW (Fe).



MINERνA LE Measured Neutrino Nuclear Correction Factors

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

(Not included in nCTEQ neutrino fits: $Q^2 > 4$ GeV^2, W> 3.5 GeV)



J. Mousseau

- Red shaded histogram is GENIE prediction based on charged-lepton NCFs.
- MINERνA LE Measurement of DIS Cross Section Ratios suggest we need improved understanding of low-x, low-Q^2 ν–A interactions.
- **Much improved MINERνA ME beam nuclear target ratios soon to be released!**

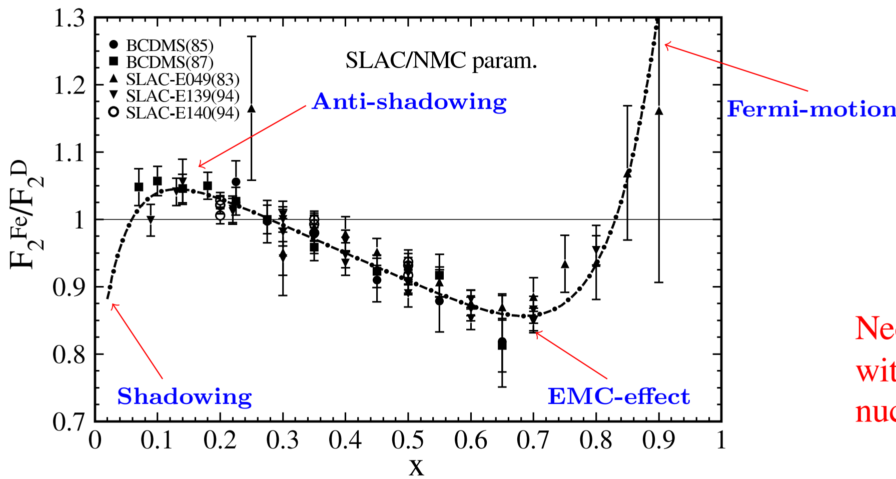
Along the way in the ‘80s, a discovery with nuclear ratios...

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

EMC(1983) - measurement changed the scene dramatically!

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

(Charged-lepton)
Nuclear
Correction
Factor



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

- **The structure of the nucleon in the nuclear environment (F_2(A) / A) is not the same as the free nucleon F_2(N)/2 and the deviations are a function of x_{Bj}.**
  - Suggesting nPDFs in the nuclear environment ≠ free nucleon PDFs!

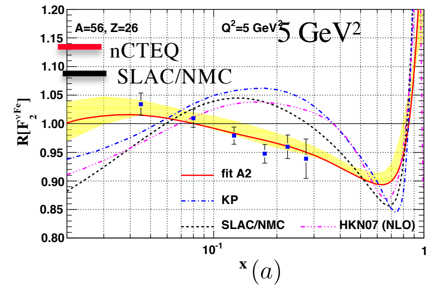
- **Do neutrino interactions with nuclei show the same effect?**
  - Hints of difference: ν-A with $l^{\pm}$A NCF in CTEQ **Nucleon** PDF fits
  - Address this question with nCTEQ studies but also studied by other groups):
    - » DeFlorian, Sassot, Stratmann and Zurita & Paukkunen and Salgado & ….

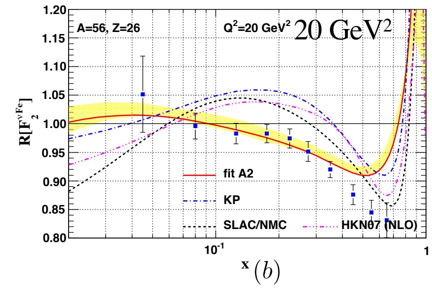
Determination of Neutrino ($\nu/\bar{\nu}$) Nuclear Correction Factors
Original (≈2010) and Ongoing (2021) nCTEQ Fits

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

R = F_2(ν – Fe; measured) / F_2[ν – (n+p); PDFs]

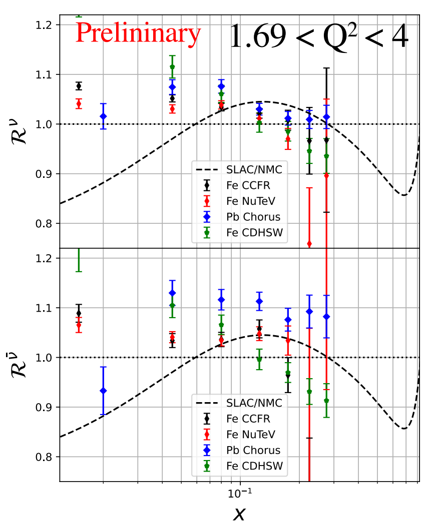
NO compromise (χ^2 with tolerance) fit for ν (dominated by NuTeV) and e/μ results.

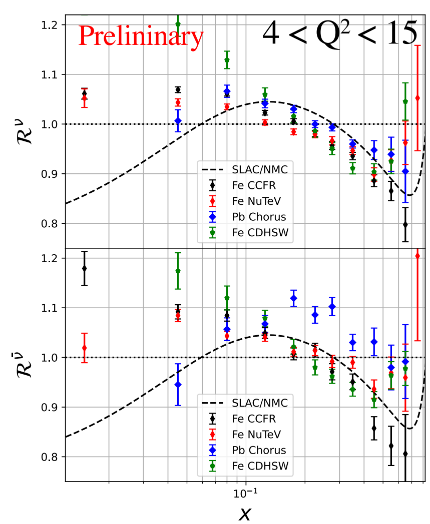


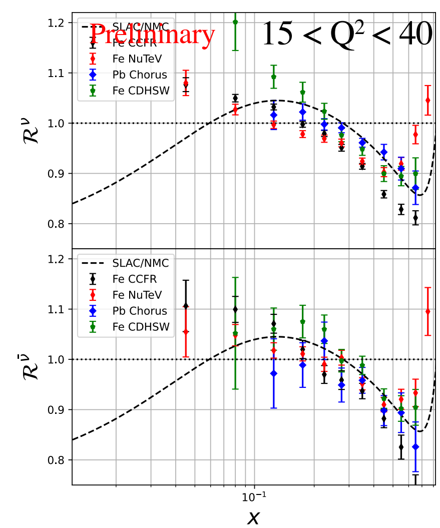


- Ongoing 2021 nCTEQ fit R = σ(ν – A); measured / σ[ν – (n+p); CTEQ6 PDFs]
- Expanded data sets: Dimuon: CCFR & NuTeV and DIS: CCFR, NuTeV. CDHSW, CHORUS (Q > 2 GeV, W> 3.5 GeV)
- More careful treatment of cross experiment normalization uncertainties and the R denominator.
- **Tension still exists between ($l^{\pm}$ …) and neutrino data. Tension maximal at x ≤ 0.1, to lesser extent at x ~ 0.6 (mainly NuTeV). Confirm nCTEQ (≈2010) low-x conclusion but softened at higher x!**

K.F. Muzakka



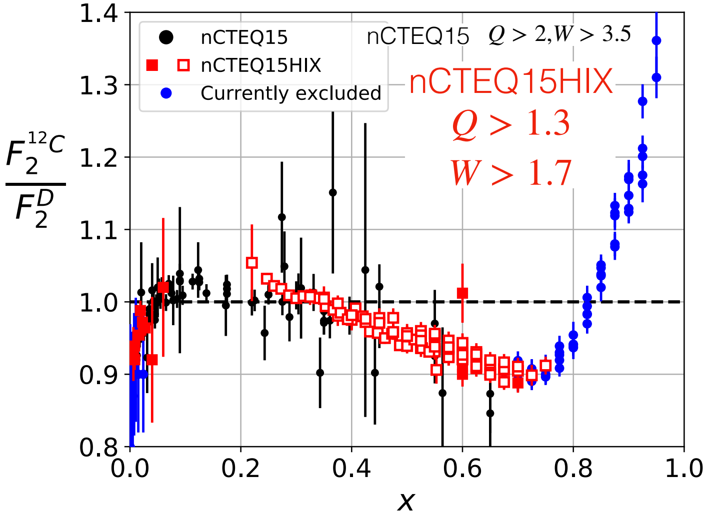


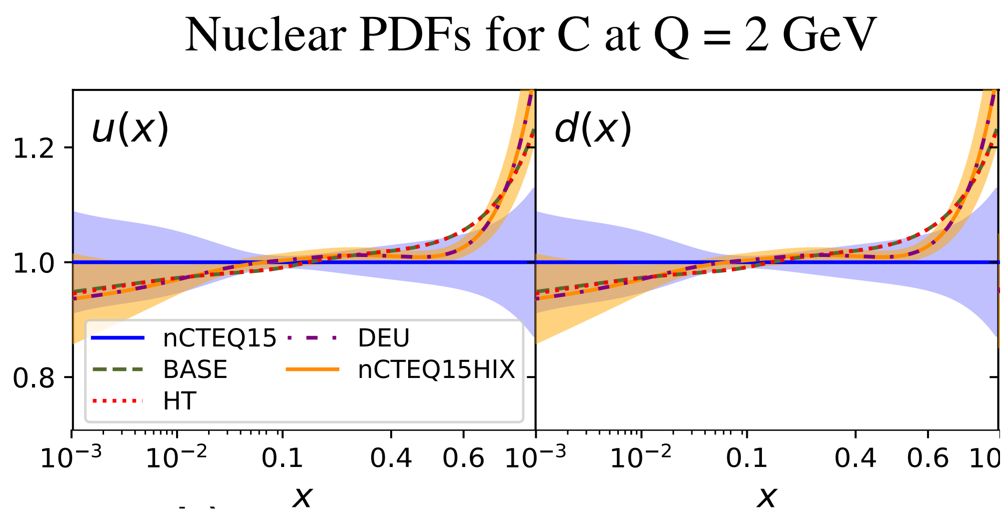


NOTE: First nCTEQ fit into the **SIS transition region**

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

nCTEQ15HIX gives $l^{\pm}$A nPDFs for **W>1.7 GeV, Q > 1.3 GeV**





- TMC (Target Mass Correction) sub-leading M^2/Q^2 corrections to leading twist structure function.

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

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

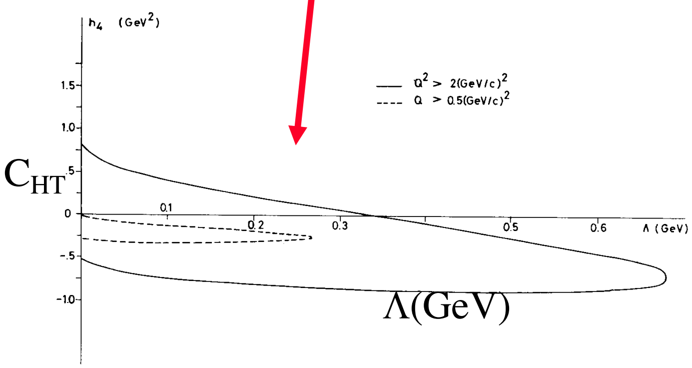
e-Print: 2012.11566 [hep-ph]

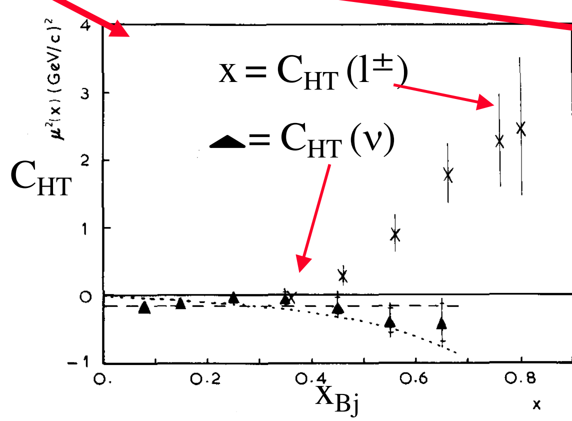
Speaking of Higher Twist…
From DIS, Transition to the SIS Region…
Entering the (SIS) Non-perturbative Region

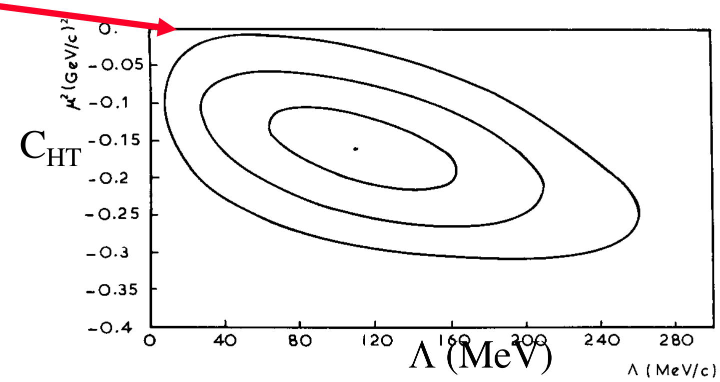
- From pQCD, with Q^2 evolution proportional to $1/\log(Q^2/\Lambda^2)$, extend into the non-pQCD regime and consider $1/Q^2$ effects.
  - Target Mass Corrections (TMC) well understood theoretically, accounted for with the help of the Nachtmann variable. $\xi = 2x/[1 + (1 + 4\, M^2x^2 / Q^2)^{1/2}]$.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

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

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







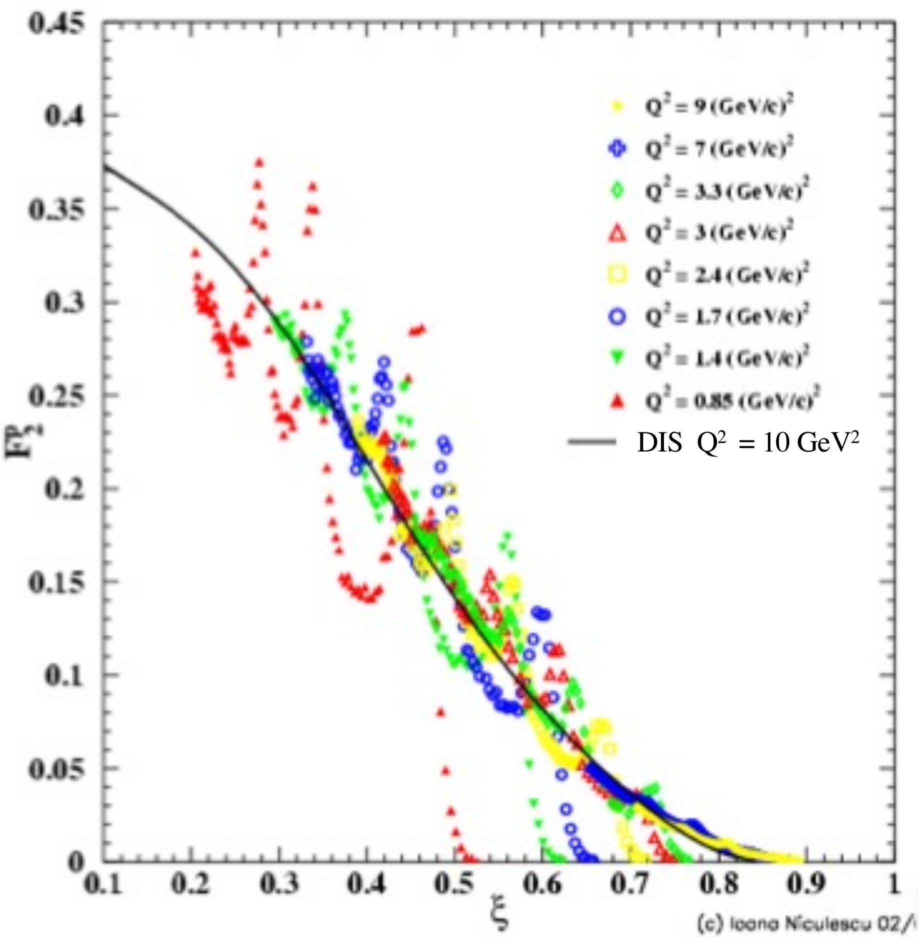
- That is C^A_{HT} in neutrino scattering: **smaller & negative**!
- **What about additional NUCLEAR higher twists, A-dependence of HT?**

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/partons from DIS meet the physics of nucleons/mesons (pions) of SIS → **quark-hadron duality**
  - Relationships between meson–nucleon and quark–gluon degrees of freedom.
- In the 60's the concept of "Duality" began with the total pion-proton cross section being compared to Regge fits to higher energy data and concluding low-E hadronic cross sections on average could be described by high-energy behavior.
- 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 – how about $\nu/\bar{\nu}$-N scattering or more realistically $\nu/\bar{\nu}$-A scattering?

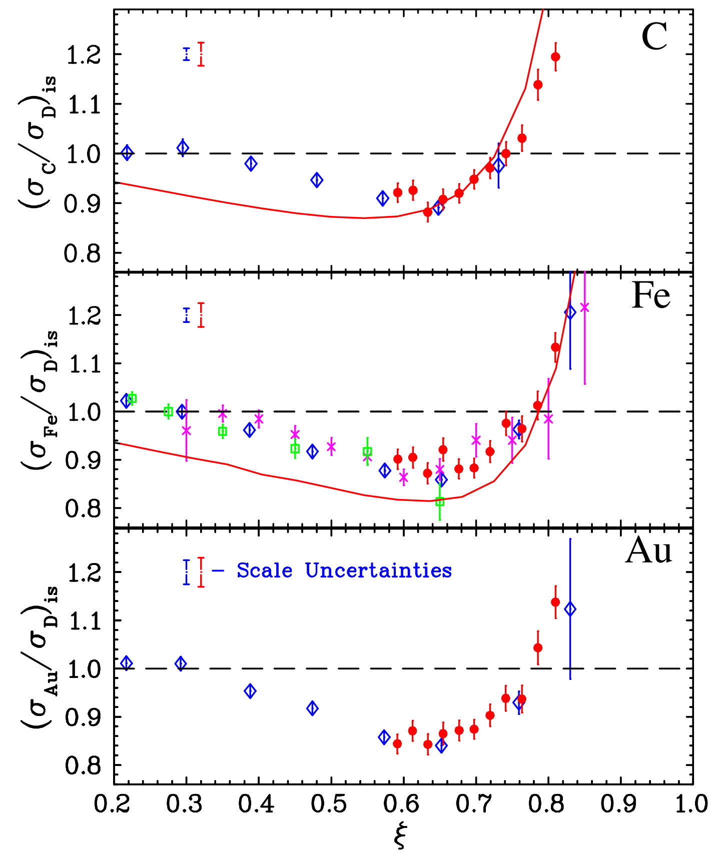
What does Quark-Hadron Duality "Look Like" Experimentally?

Jlab **e-proton** Study



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

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



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?

Quantitative test of Quark-Hadron Duality:

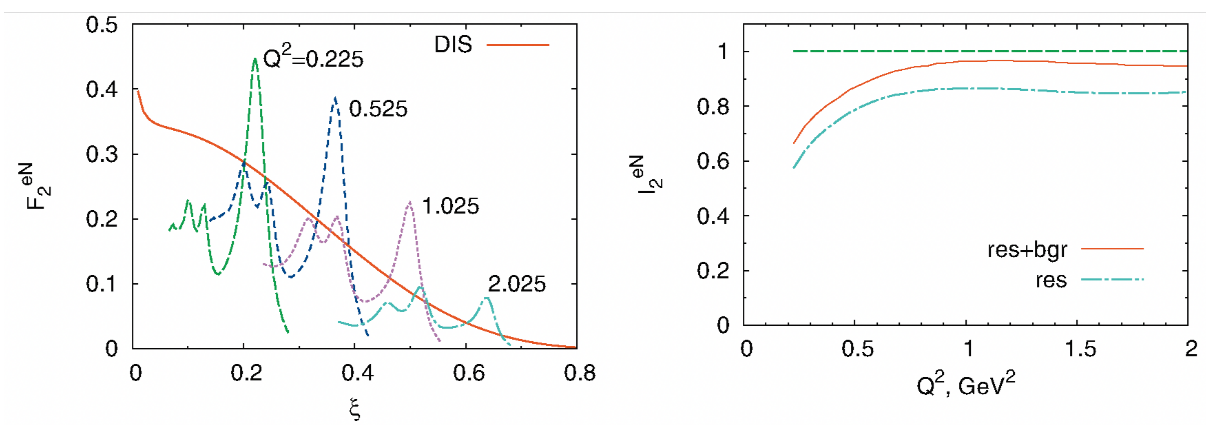
Ratio of integrals over a finite ξ interval

e - Nucleon

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

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

- Using Giessen fit to e-N scattering – 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 $I(Q^2)$.



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

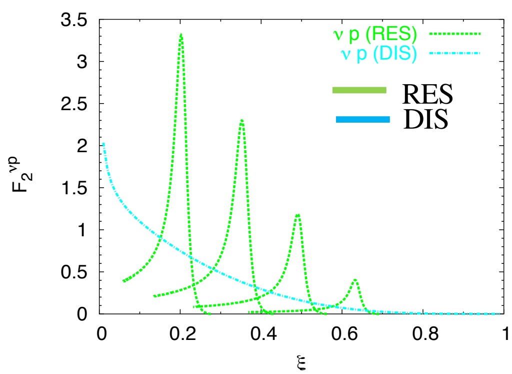
Now for **Neutrinos – NO HIGH STATISTIC NUCLEON DATA** – must rely on models for ν-n, ν-p and ν-N scattering

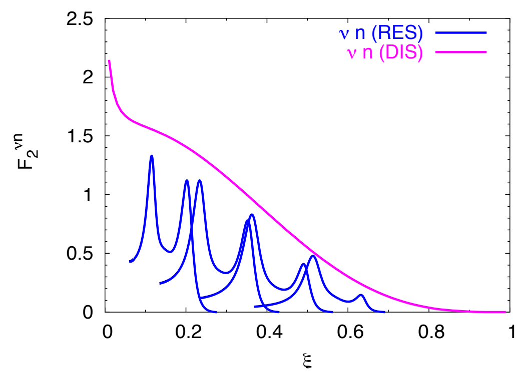
Low-lying resonances: $F_2^{\nu n(res)} < F_2^{\nu p(res)}$, DIS: $F_2^{\nu n(DIS)} > F_2^{\nu p(DIS)}$

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

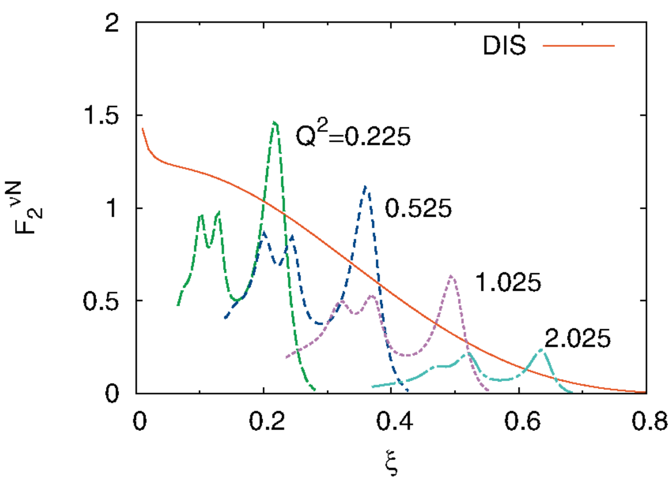
$$F_2^{\nu p(res-3/2)} = 3F_2^{\nu n(res-3/2)}$$
$$F_2^{\nu p(res-1/2)} \equiv 0$$

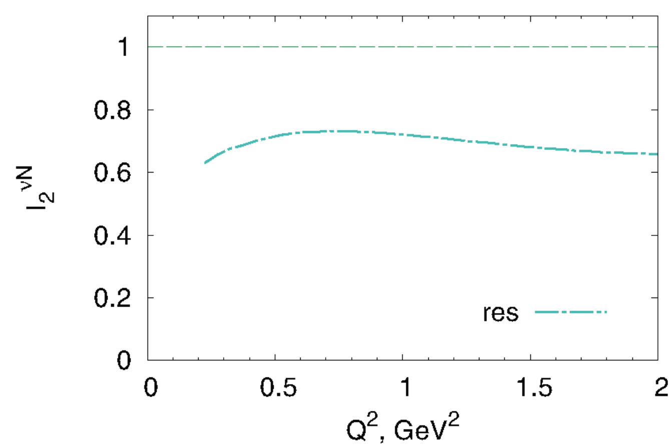
$F_2^{\nu n(res)}$: finite contributions from isospin 3/2 and -1/2 resonances





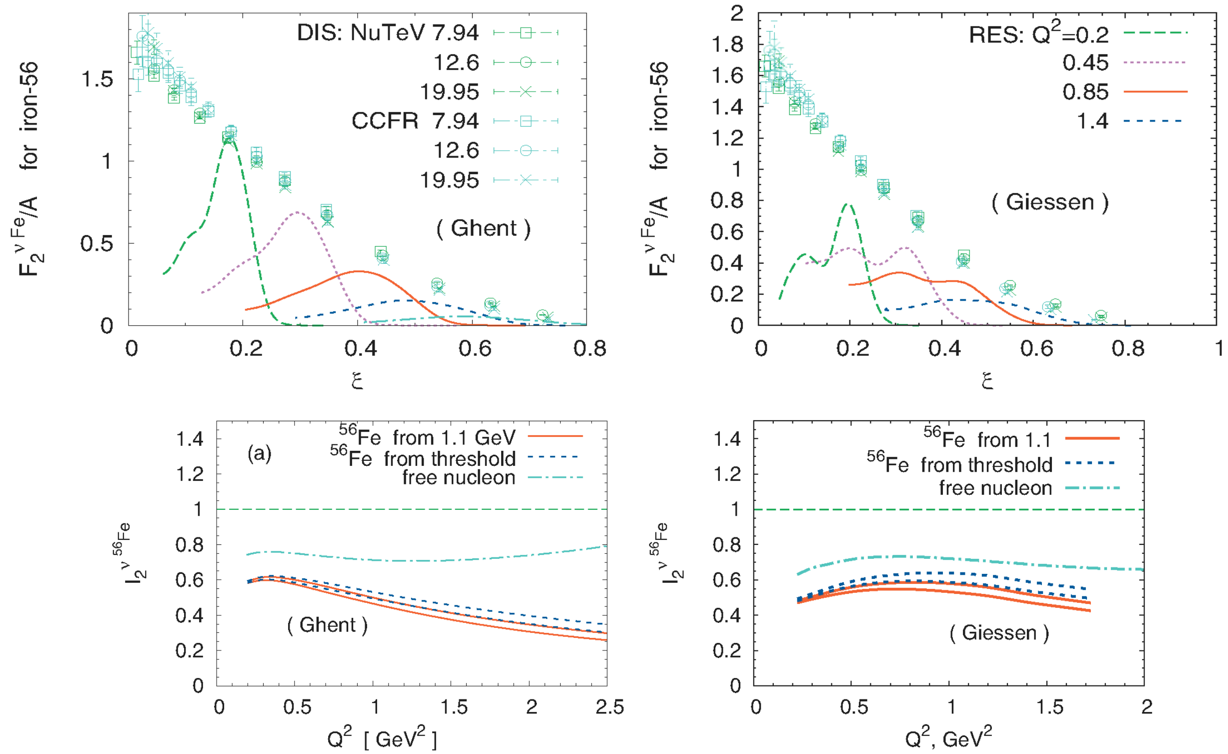
Resonance estimates from GiBUU Model for ν-N scattering.
DIS at 10 GeV^2. No non-resonant π included





Even more concerning when talking of NUCLEI not NUCLEON- Is the problem for Fe the neutron excess?

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.**
- for larger W, DIS F_i's are much larger than the resonance contribution at lower W.
- How duality should be applied with neutrinos is still unknown, however…
- **Has the duality concept led to predicting SIS behavior from DIS measurements…?**

(Updated) Bodek-Yang Model

Attempt to (a la Duality) 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 **for e-N interactions**.
- They include TMC and HT effects by replacing x_{Bj} with 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.

$$\xi_W = \frac{Q^2 + B}{\{M\nu[1+\sqrt{(1+Q^2/\nu^2)}] + A\}}$$

- They introduce quark flavor dependent K factors to extend the values of PDFs at $Q^2 = 0.8$ GeV^2 down to to $Q^2 \approx 0$
  - Like this $F_2(x, Q^2 < 0.8) = K(Q^2) * F_2(\xi w, Q^2=0.8)$ example $F_2(x,Q^2) \rightarrow \frac{Q^2}{Q^2+C} F_2(\xi_w, Q^2)$

- **All initial development and checks of the B-Y model performed with e/μ-n and e/μ-p. Thus, the V contribution to ν scattering is well modeled!**
- Updated: axial vector introduced making sure that as $Q^2 \rightarrow 0$, A does not disappear like V.
- **Introduce nuclear effects as measured in electroproduction!**
- **Used in GENIE to estimate non-resonant π and higher W resonances.**

Updated Bodek-Yang Model

- B-Y effective LO model with ξw describe all e/μ DIS and resonance data as well as photo-production data (down to $Q^2 = 0$): provide a good reference for vector SF for neutrino cross section.

- Introduce new K factors for axial vectors based on PCAC and agree with CCFR F2 Q2=0 measurement

- **Updated B-Y model provides a good reference for both neutrino and anti-neutrino nucleon cross sections with W > 1.8 GeV.**
  - **How about checking B-Y vs nCTEQ15HIX (W> 1.7 GeV) for e-N scattering??**

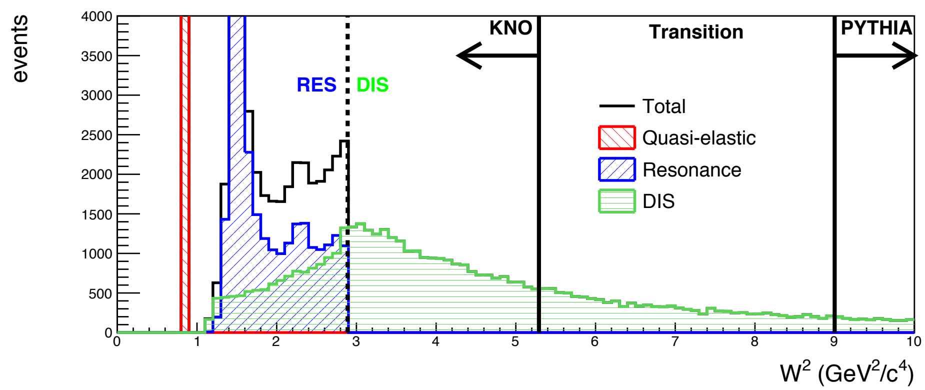
- **Model also works on-average down to W > 1.4 GeV, providing some overlap with resonance models but not the Δ resonance.**

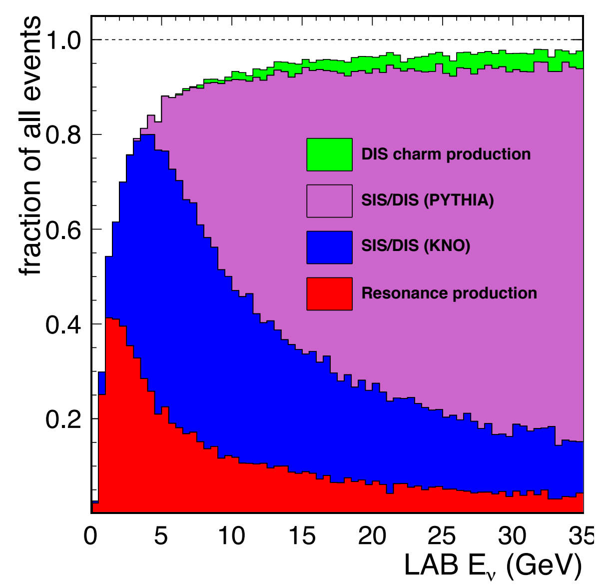
Another Global Concept Hadronization

Use recent GENIE study to start discussion

e-Print: 2106.05884 [hep-ph]

- Why is it important?
  - 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
  - KNO scaling - dispersion of multiplicities around $<n_{ch}>$ with a general scaling function
  - PYTHIA - Lund string fragmentation best at higher energies - needs low W modifications.
  - Tuned to BEBC & 15’ bubble chamber H and D data. However, there can be nuclear modifications.





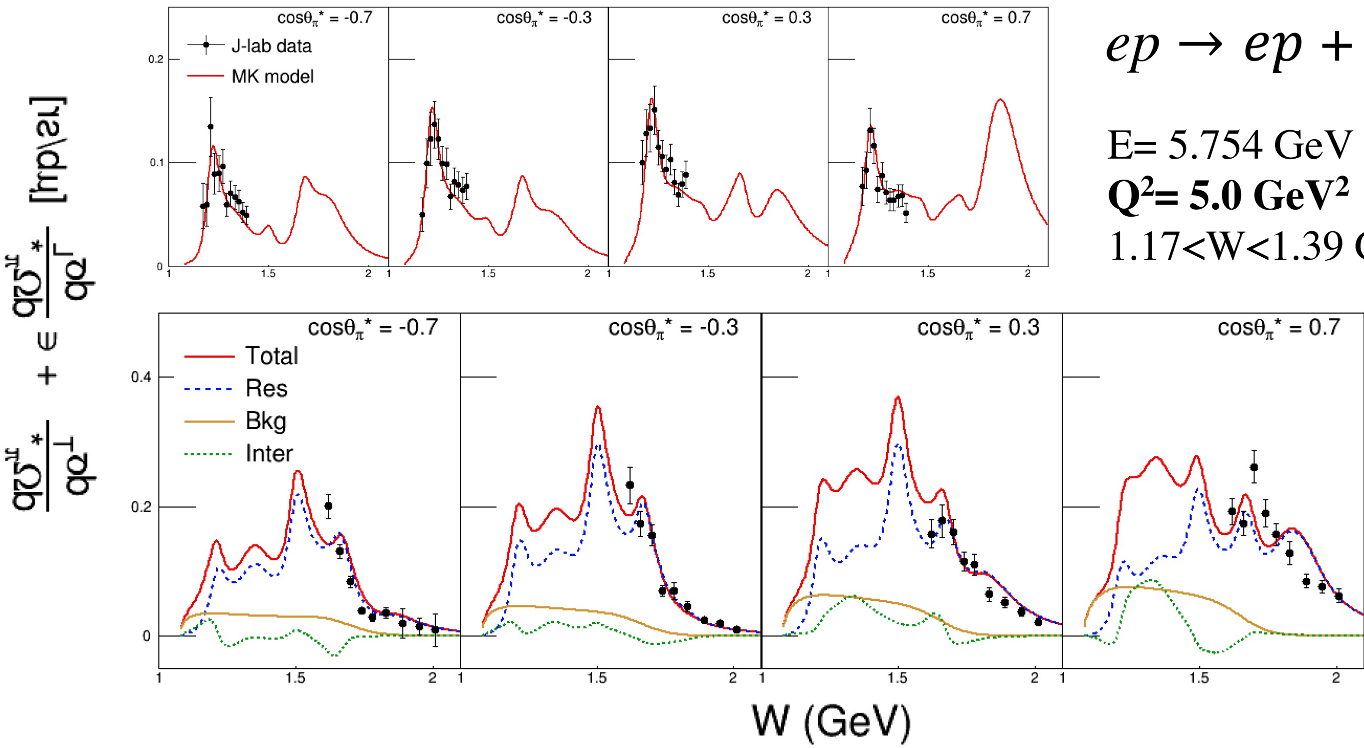
Global fit results.
Errors not quoted!

	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 contributing 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 **with ν–N interactions coming soon**.



$ep \rightarrow ep + \pi^0$

E= 5.754 GeV
Q^2= 5.0 GeV^2
1.17<W<1.39 GeV

$ep \rightarrow en + \pi^+$

E= 5.449 GeV
Q^2= 4.0 GeV^2
1.62<W<2.01 GeV

How about multi-pion production?

Multiple Resonances above the Δ 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]

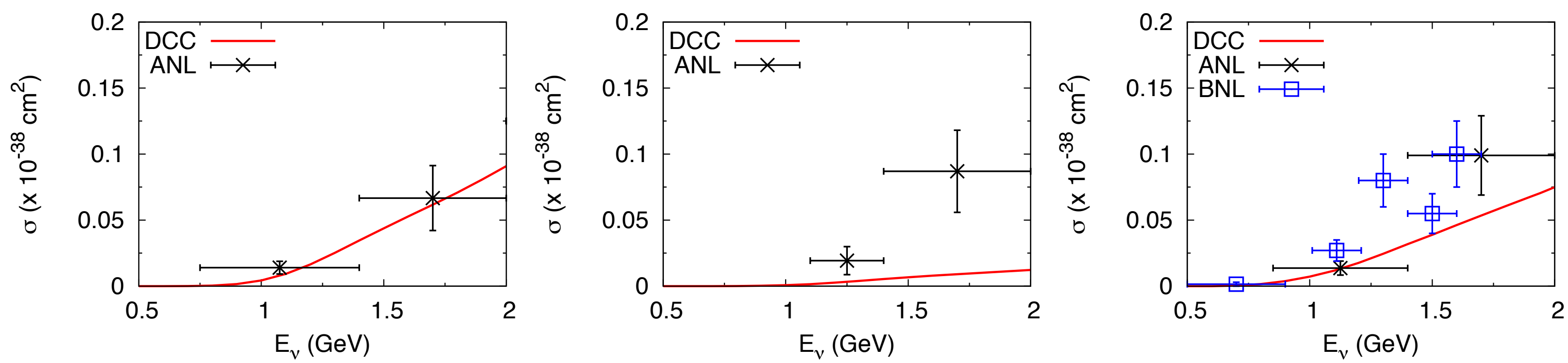


FIG. 19. (Color online) Comparison of the DCC-based calculation with data for $\nu_\mu p \to \mu^- \pi^+ \pi^0 p$ (left), $\nu_\mu p \to \mu^- \pi^+ \pi^+ n$ (middle) and $\nu_\mu n \to \mu^- \pi^+ \pi^- p$ (right). ANL (BNL) data are from Ref. [93] ([13]).

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

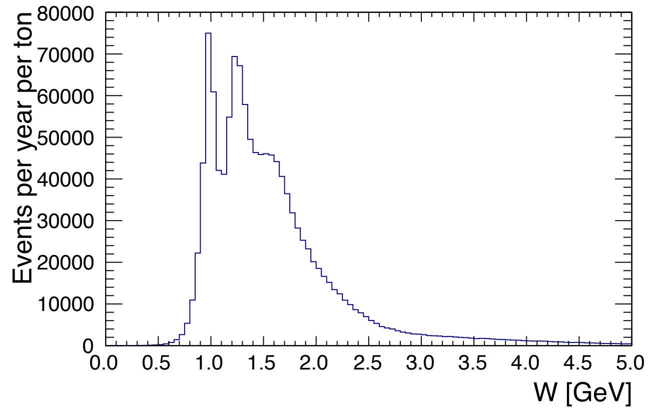
- There is essentially no high-statistics ν-N/A experimental data within the kinematic range of interest - $1.5 < W < 2.0$ GeV - for testing these models!

- What experimental data for comparison can we expect in the (near) future

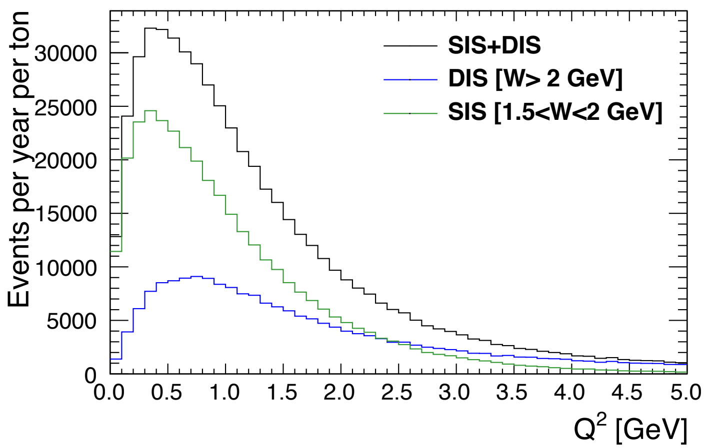
- MINERνA starting the high-statistics expt. Study for $\nu/\bar{\nu}$ -**A**!
  - Measure total and differential inclusive σ's with Q^2, ξ and W in the SIS region.
  - Measure multiplicities of charged hadron in increasing W bins from SIS to and in DIS.
  - Compare the cross sections derived in the DIS with the SIS equivalents.
  - Measure single/multiple pion production in the kinematic region $1.4 < W < 2.0$ GeV
  - With ν and $\bar{\nu}$ extract the SIS structure functions $F_i(\xi, Q^2)$, compare to DIS $F_i(\xi, Q^2_{DIS})$.
  - Determine nuclear effects by ratios of σ off nuclei in the SIS region…

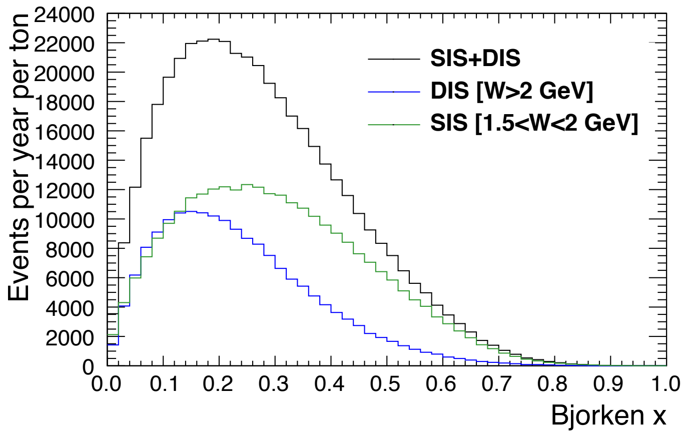
DUNE – 45 % of ν_μ CC events have W>1.5 GeV

latest ND flux – GENIE 3



S. Dolan - 2021

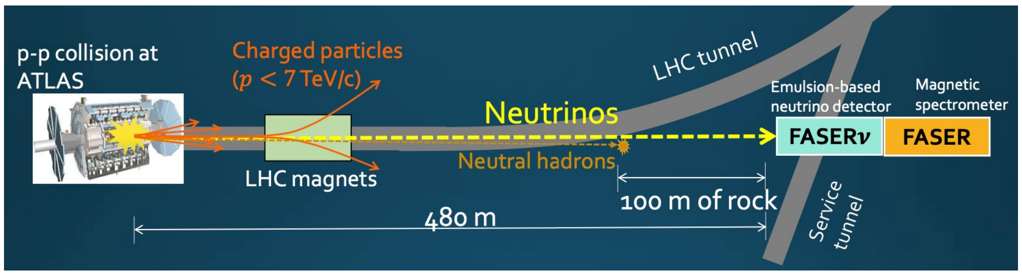


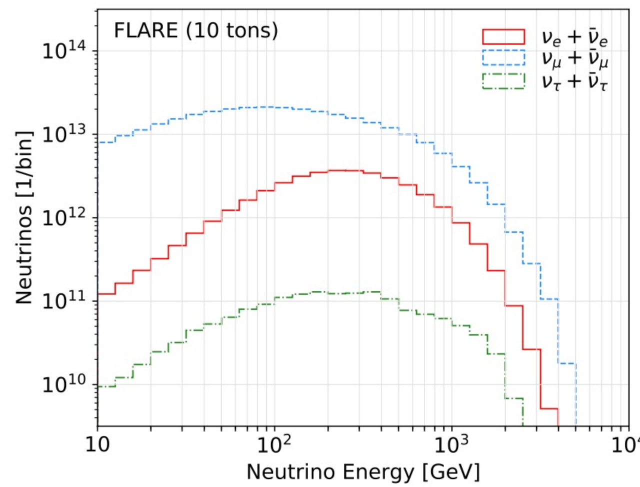


- DUNE should have millions of events in this unexplored SIS region as well as a huge DIS sample for detailed hadronization and nPDF studies.

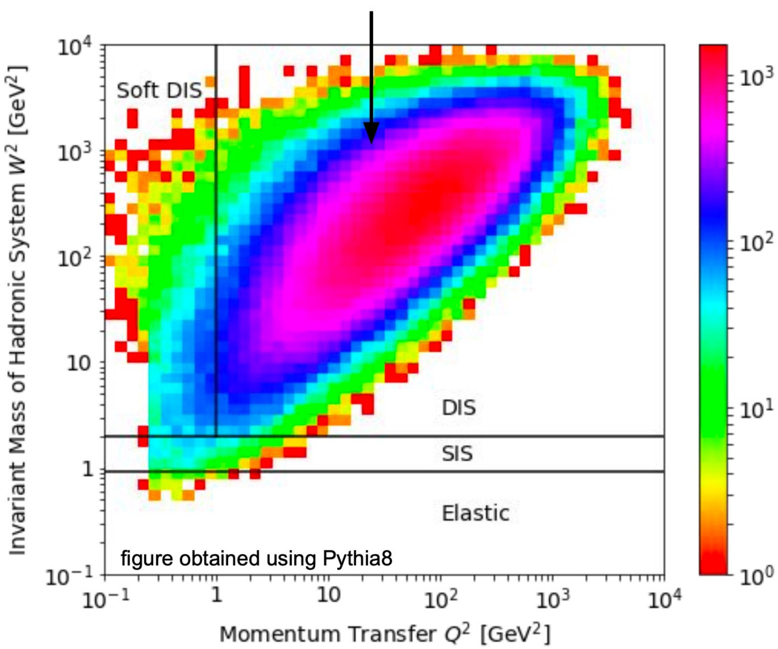
A newcomer - the CERN FPF neutrino beams to expand the studied W and Q^2 regions

- 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**.

WHAT DO 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 nuclear effects particularly the EMC effect.

  - Experimental1- a large statistics **hydrogen AND deuterium experiment**!
    - **Separate Snowmass LOI on needs and possibilities of H/D experiment!**
    - Improved tuning for hadronization models (lower W PYTHIA) in the DIS region.
    - Provide experimental basis for DIS nuclear effect studies.
    - Provide experimental results to check Theory1 (estimate nuclear HT?) and Theory2 ($x \rightarrow 1.0$) efforts without nuclear effects.
    - Detailed study of SOFT DIS (W > 2.0 GeV and Q < 1.0 GeV) without nuclear effects.
  - Experimental2 - Large statistics measured data sets on LIGHTER nuclei
  - Experimental3 – high statistics $d\sigma/dxdy$, multiπ production off neutrons and protons, general hadronization studies and nuclear effects over wide range of low-to-high A.

WHAT DO 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 cross sections as a function of W and ξ for Duality studies across a broad range of nuclear targets.

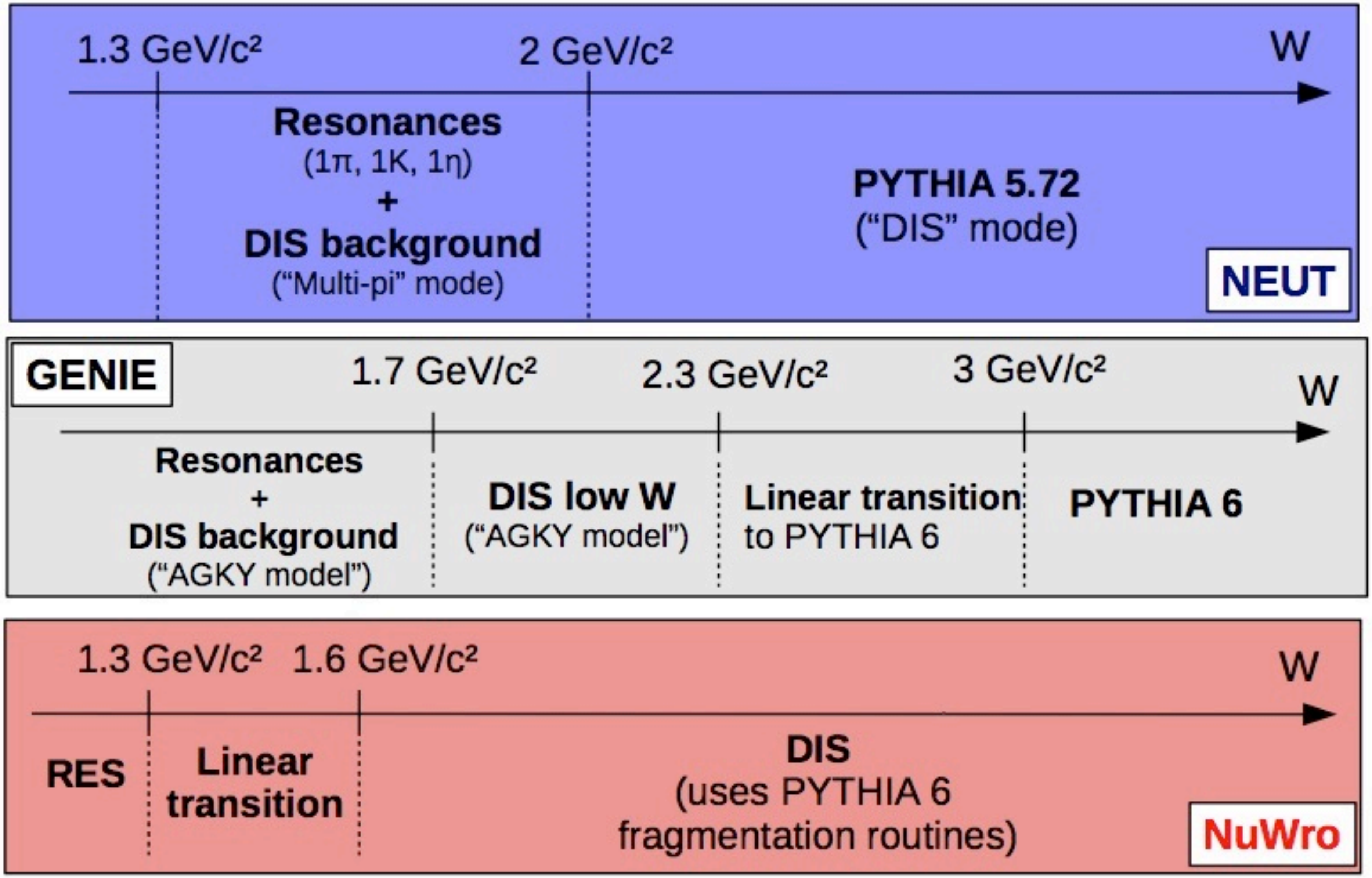
Additional Details

Start this overview with Deep-Inelastic Scattering (DIS)

Neutrinos: studying the structure of the nucleon (mainly PDFs) with DIS for **50 years**!

- From the early 70's with bubble chambers
  - Gargamelle - heavy liquid (CF_3BR)
  - BEBC – H/D and mixed with Ne
  - 15' – H/D and mixed with Ne
- Somewhat later than Gargamelle but with much higher statistics electronic detectors
  - CDHS(W) - iron
  - CHARM / CHARM II - marble/glass
  - CF/CFR - iron
  - HPWF - liquid scintillator
  - IHEP-JINR - liquid scintillator / Al
- These early experiments were followed by:
  - CCFR - iron
  - NuTeV - iron
  - CHORUS - lead
  - NOMAD - carbon/aluminum/iron (no released differential cross sections).
  - MINERvA – CH + (lower statistics) He, H_2O C, Fe and Pb.

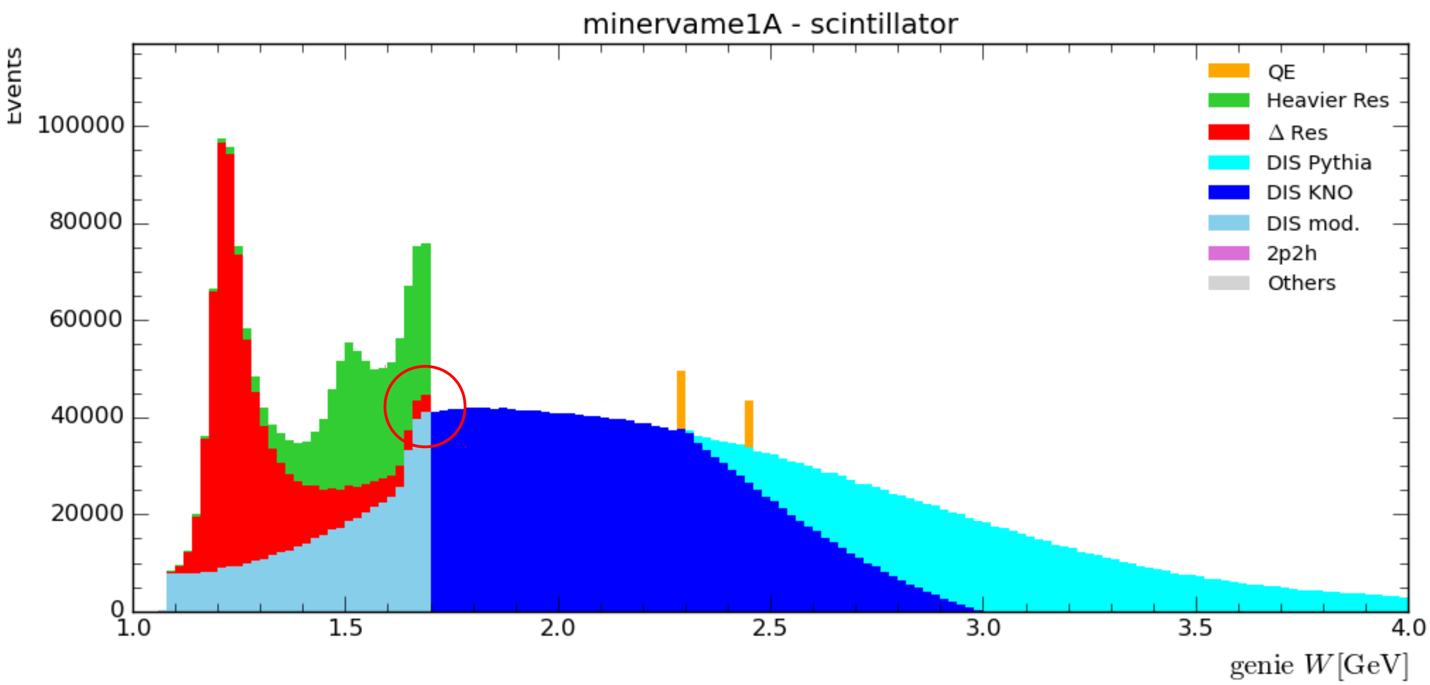
SIS/DIS Regions in Generators



GENIE (2.12.6) application of B-Y model

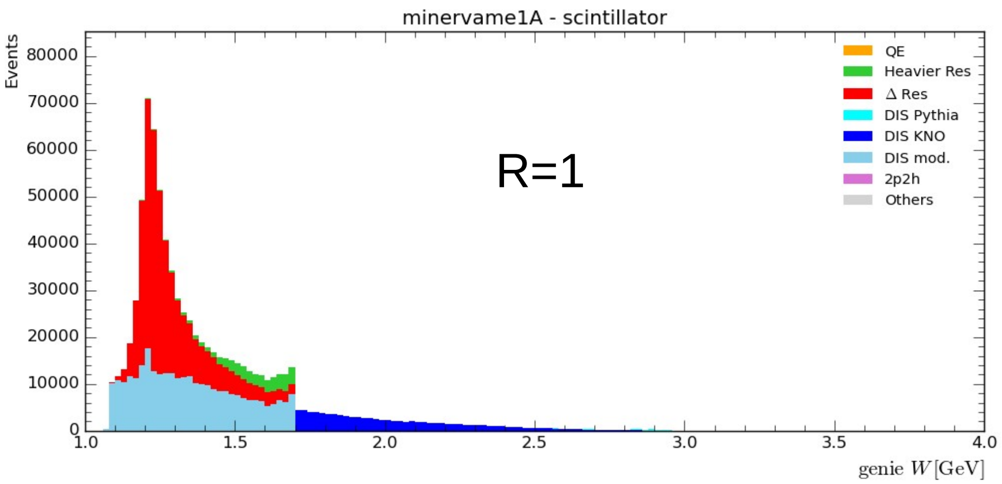
Study from Gilson Correia Silva (then CBPF Rio de Janeiro, now Hamburg)

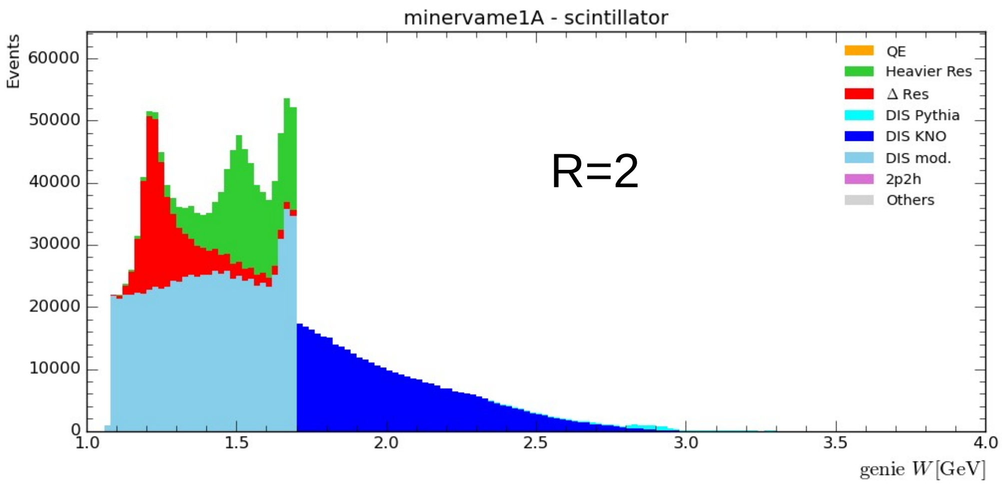
- Careful of double counting (R-S) resonances and resonances in inclusive B-Y model.
  - GENIE applies weight to B-Y to avoid double counting for 1π production



Hadronic System Multiplicity (m) = 2 (for example-1N + 1π)

No weight applied to avoid double counting resonances (R-S & B-Y)

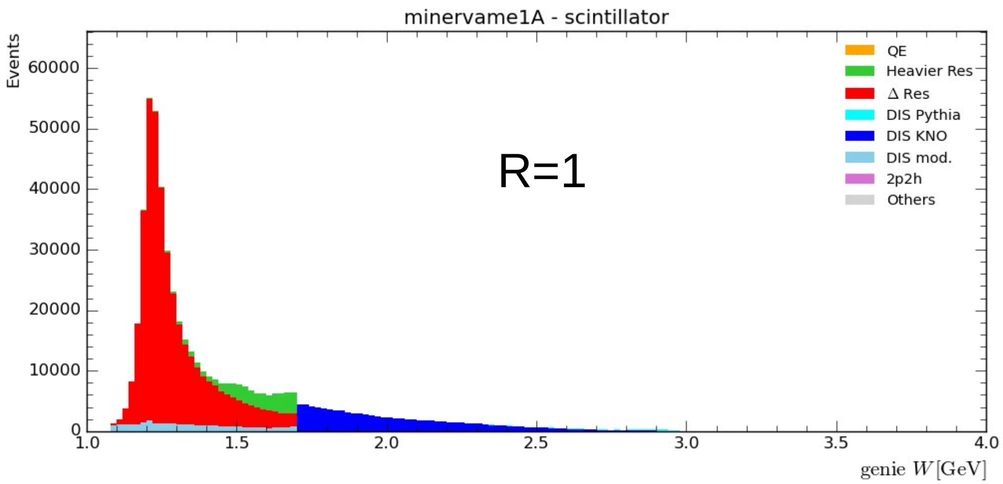


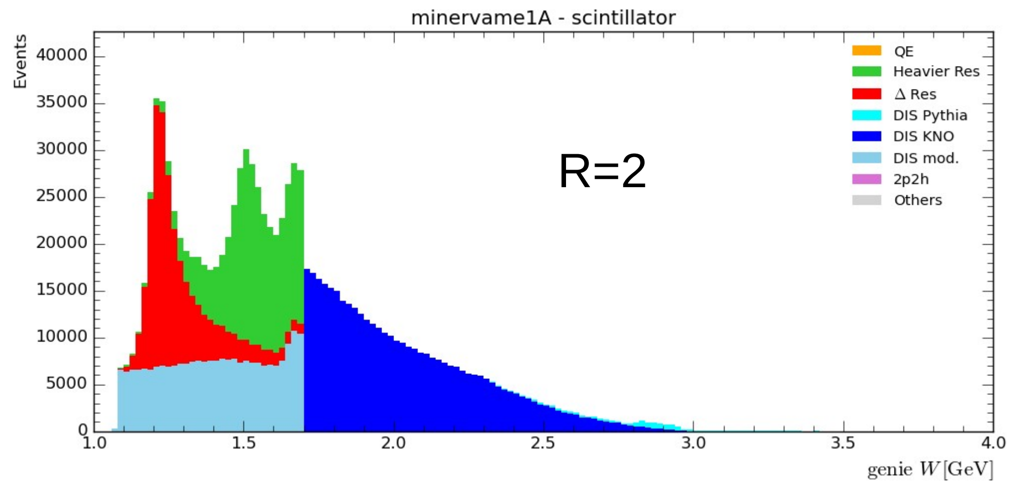


R=1: (νp) or $(\bar{\nu} n)$
R=2: (νn) or $(\bar{\nu} p)$

Hadronic System Multiplicity (m) = 2 (for example-1N + 1π)

Indicated weight applied to avoid double counting resonances (R-S & B-Y)



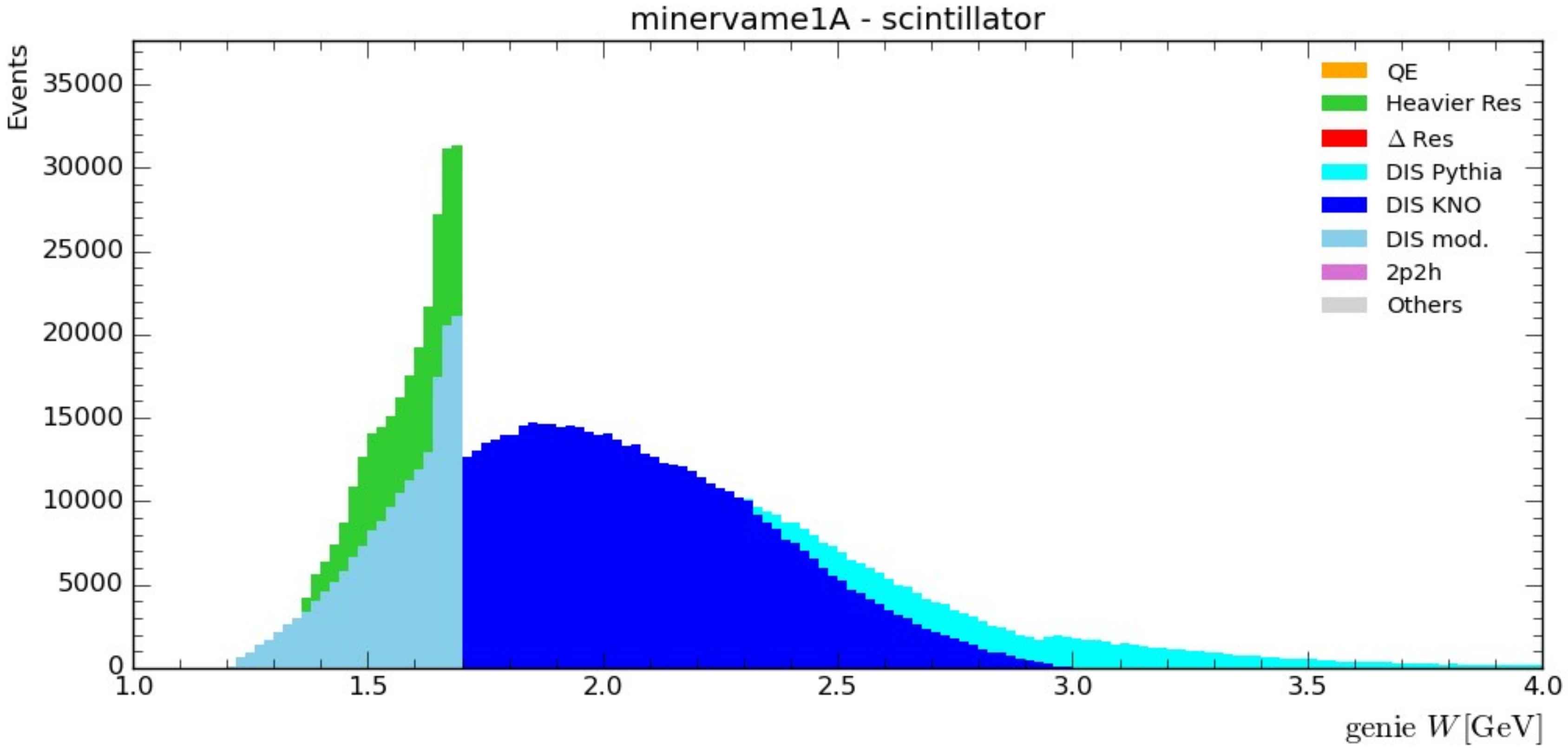


R=1: (νp) or $(\bar{\nu} n) \rightarrow$ weight in DIS mod.=0.1

R=2: (νn) or $(\bar{\nu} p) \rightarrow$ weight in DIS mod.=0.3

Hadronic System Multiplicity (m) = 3

No weight applied to avoid double counting resonances (RES vs B-Y)



How do we determine these nPDFs? - Global Fits

- Use experimental data at cross section level (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

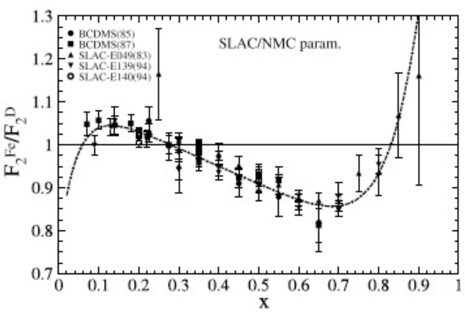
- Use DGLAP equation to evolve $f_i(x, Q)$ from Q_0 to desired Q.
- Calculate theory predictions corresponding to the data (σDIS, σDY, etc.).
- Calculate $\chi 2$ function – compare data with correlated errors and theory.
- Minimize $\chi 2$ function with respect to parameters c_0, c_1 … c_5 .
- A-dependent 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

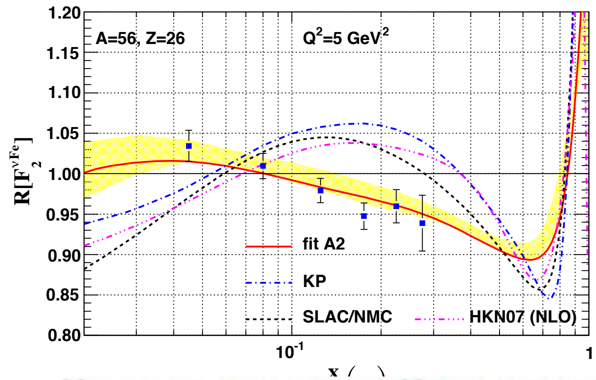
Determination of Neutrino ($\nu/\bar{\nu}$) Nuclear Correction Factors

First ($\leq$ 2012) nCTEQ Fit:

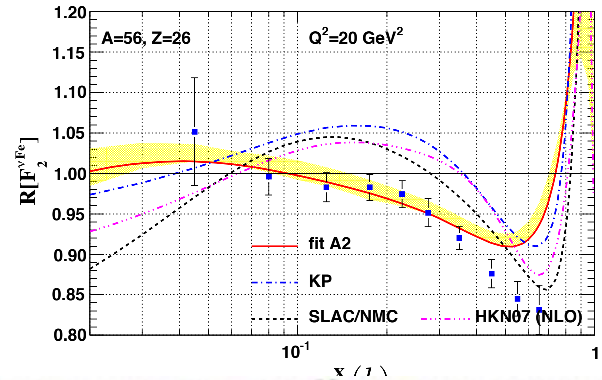
$R = F_2(\nu - Fe;\ \text{measured}) / F_2[\nu - (n+p);\ \text{PDFs}]$ (dominated by NuTeV)

Use NuTeV & CHORUS DIS σ + NuTeV and CCFR dimuon σ



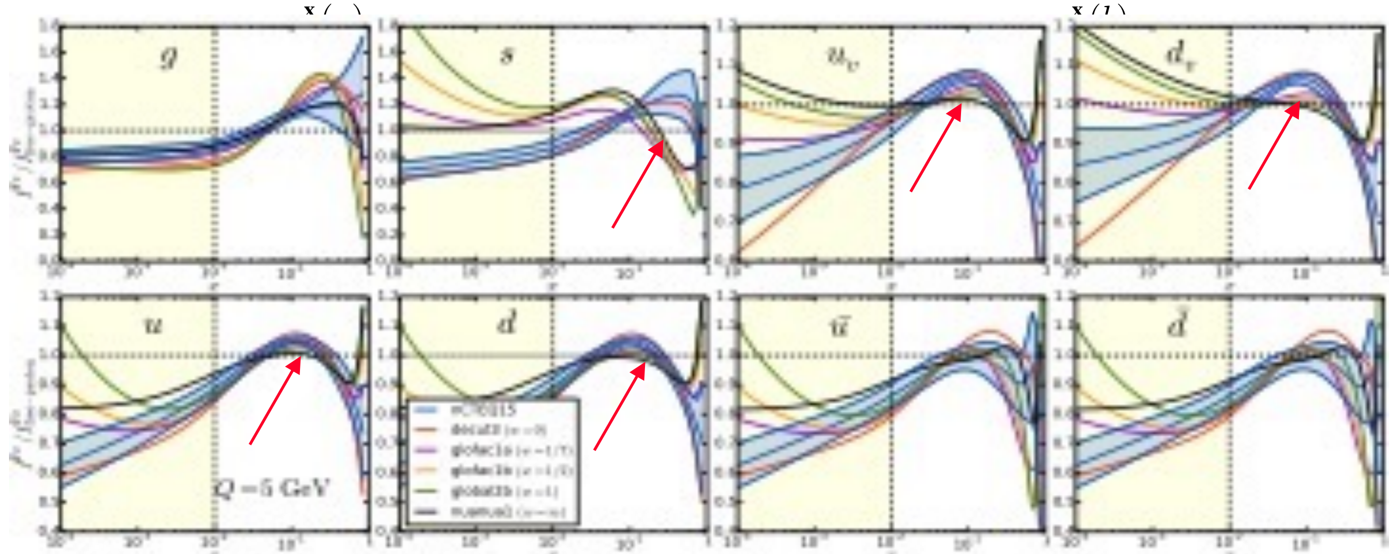


ν



Blue shaded curve (with errors) nCTEQ15 nPDFs fit to $l^{\pm}$+DY.

Black line ν nPDFs from fit to NuTeV & CHORUS DIS + NuTeV & CCFR dimuon



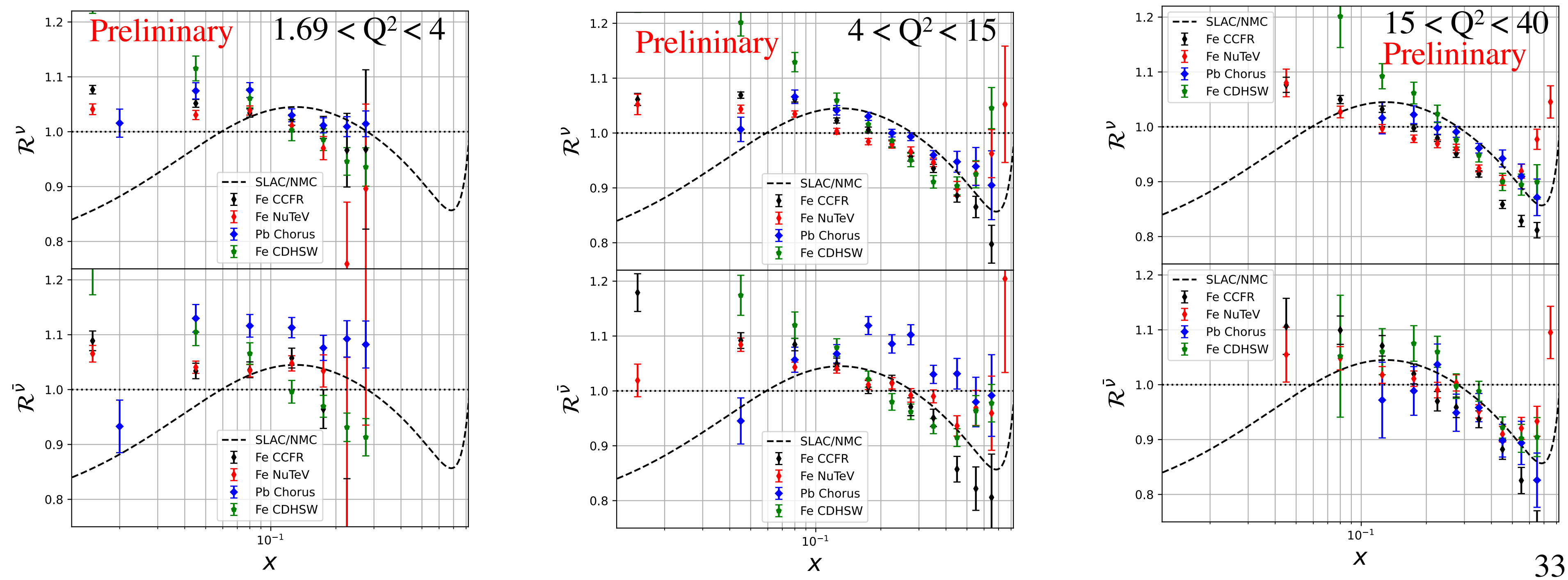
Could NOT find a compromise (χ^2 with tolerance) fit for <u>either F_2 or nPDFs</u> with ν (dominated by NuTeV) and e/μ results using cross sections with covariant errors.

Determination of Neutrino ($\nu/\bar{\nu}$) Nuclear Correction Factors

Ongoing (2021) nCTEQ Fit

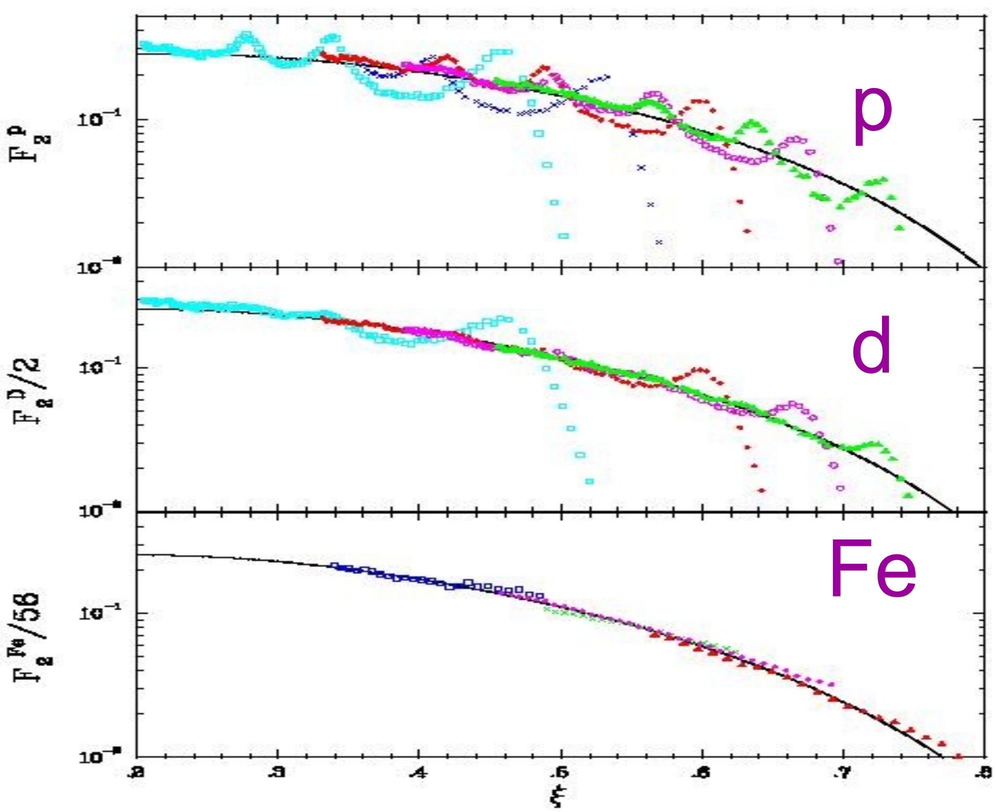
R = σ(ν – A); measured / σ[ν – (n+p); CTEQ6 PDFs]

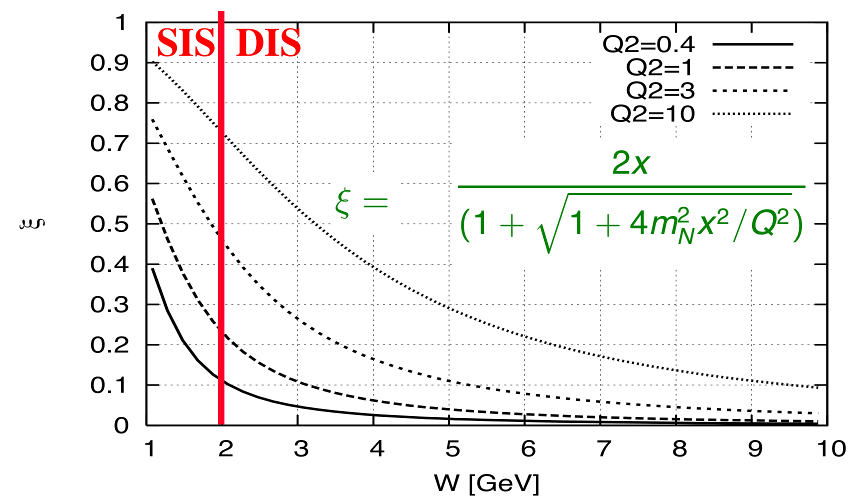
- Expanded data sets: Dimuon: CCFR & NuTeV, DIS: CCFR, NuTeV. CDHSW, CHORUS (Q > 2 GeV, W> 3.5 GeV - 4060 data points)
- More careful treatment of normalization uncertainties and the R denominator.
- Tension still exists between the fit of ($l^{\pm}$& DY) data and neutrino data. The tension is maximal at x ≤ 0.1 and to a lesser extent at x ~ 0.6 (mainly NuTeV). Confirm nCTEQ (2012) low-x conclusion but softened higher x differences!



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

- 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 at 10 GeV^2** with **EMC effect** for Fe applied.

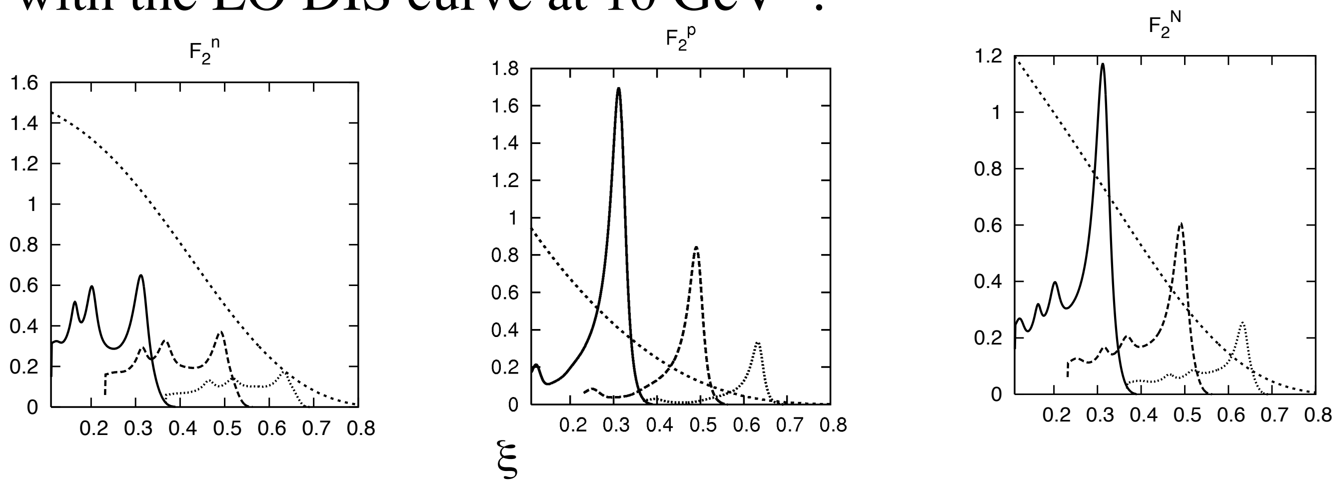




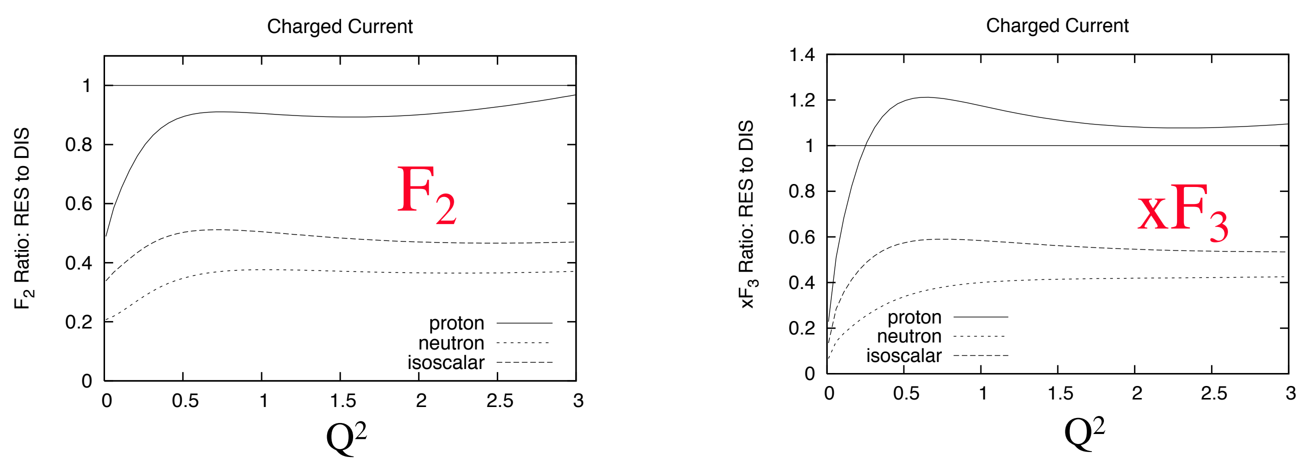
Now for **Neutrinos -** our "favorite" Rein-Sehgal Model

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

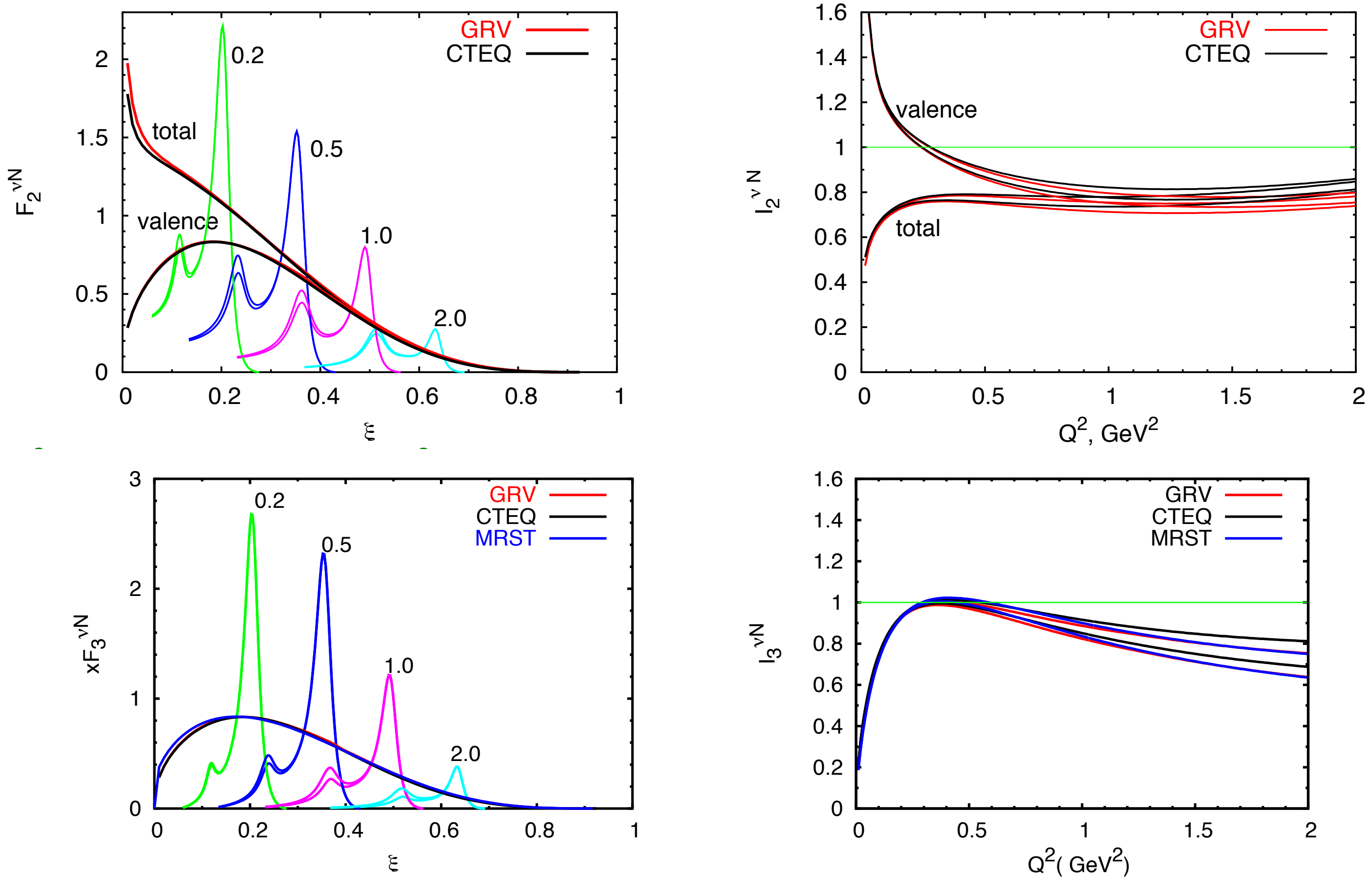
- Comparison to Rein-Sehgal structure functions for n, p and N at $Q^2 = 0.4$, 1.0 and 2.0 GeV^2 with the LO DIS curve at 10 GeV^2 .



- 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.**



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!!



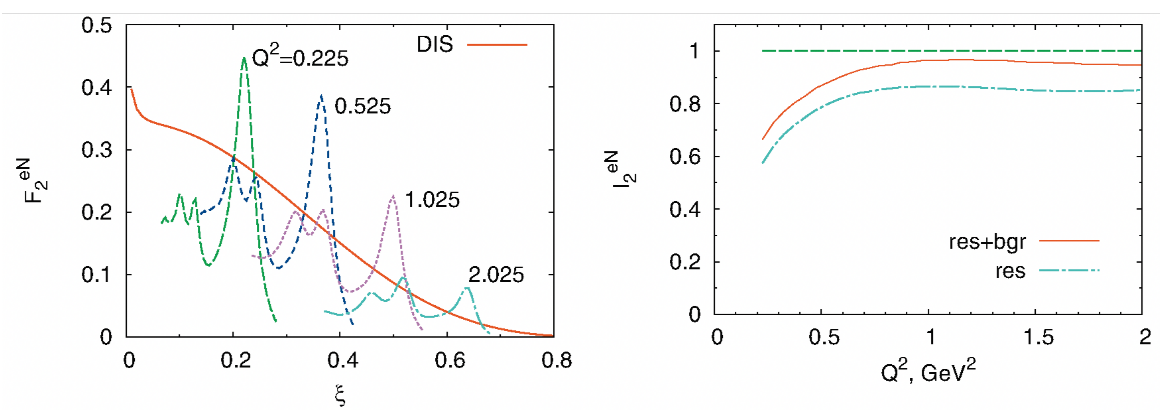
- Global Duality-on the average the resonances appear to oscillate around and slide down the DIS curve. Similar results with the Sato-Lee model
- Local duality in ν-N scattering is worse than in electron scattering: the ratio does not grow appreciably with Q^2

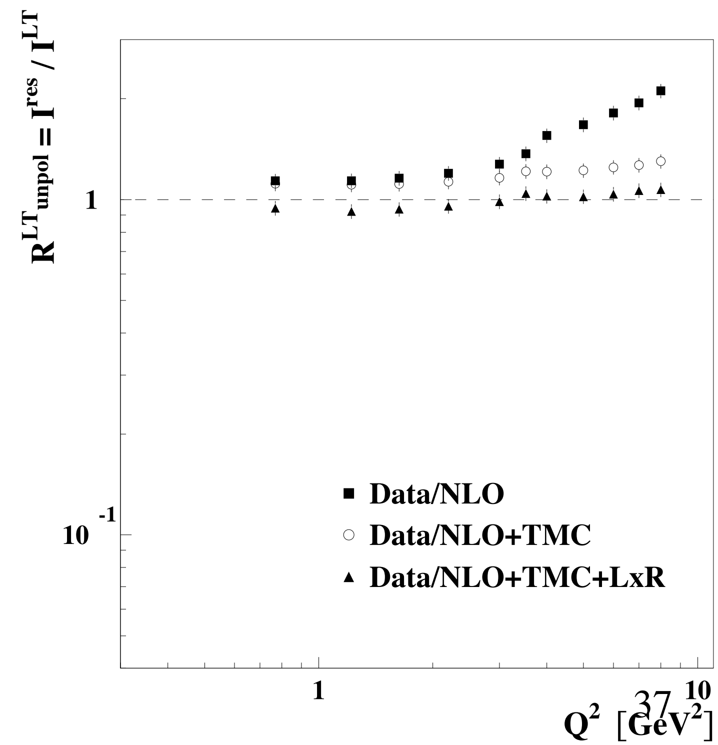
Duality and Higher Twist

- Does the fact that duality holds so well for e N resonance scattering compared to LO, **leading twist** DIS results suggest there is little room for higher twist contributions for $Q^2 > 1$ GeV^2 and $x < 0.65$??

- Multiple studies of this available in the literature and all seem to agree with the above statement. For example from: 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.

- 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





How about multi- π

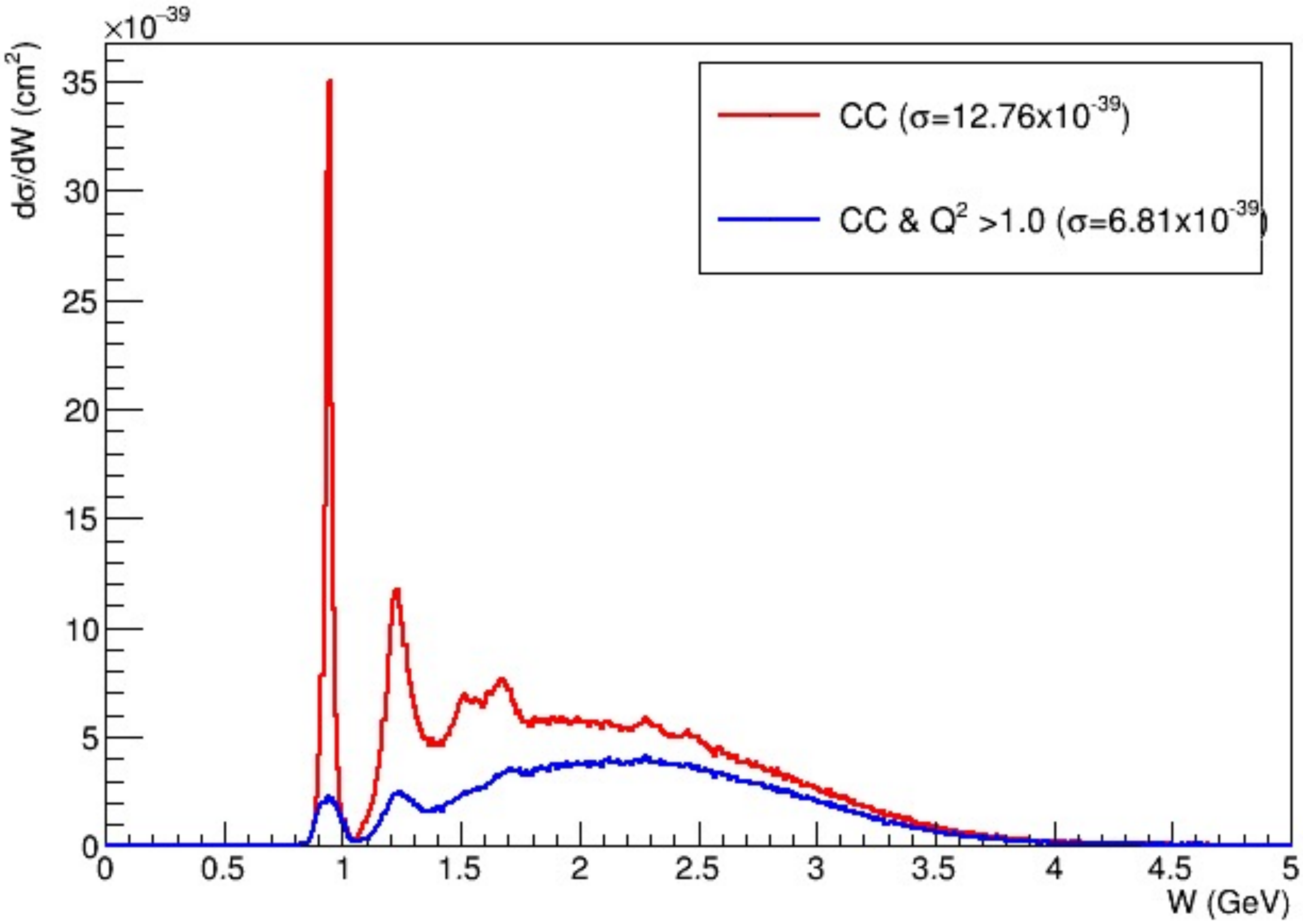
Words of Caution from Nakamura and Sato when including the single and multi π resonances beyond the Δ – much more difficult!

	$\Delta(1232)$ region	Beyond $\Delta(1232)$ region ($W \lesssim 2$ GeV)
Resonance	$\Delta(1232)$ dominates No other resonances	No single resonance dominate Several comparable resonances overlap
Non-resonant	Much smaller than $\Delta(1232)$ ChPT works → well-controlled	Comparable to resonant contributions ChPT not work
Relative phases among mechanisms	(fairly) well-controlled	Crucially important but not easy to control
Coupled-channels	Only πN	πN and $\pi\pi N$ are comparable and strongly coupled ηN, $K\Lambda$, $K\Sigma$ channels are also coupled

Multiple Resonances above the Δ with 2π decay states: D(1520, 1675) **$2\pi > 25\%$,** D(1700) **$2\pi >$ 10-55%,** S(1620) **$2\pi > 55\%$,** P(1720 and 1900) **$2\pi > 40\%$,**

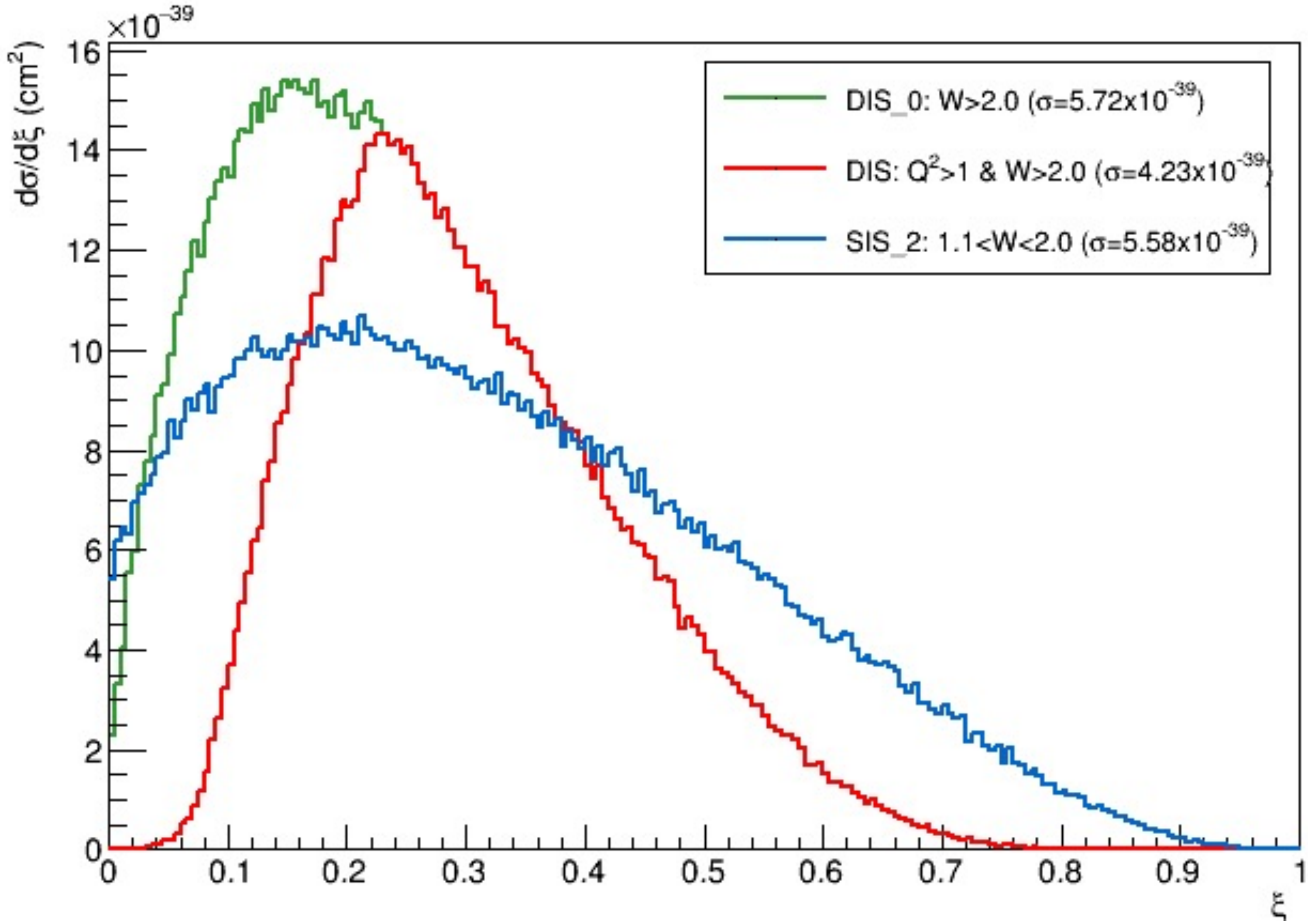
What about GENIE?

NuMI ME ν beam on Deuterium



Gian Caceres

What about GENIE?
NuMI ME ν beam on Deuterium



Gian Caceres