How Can We Use Neutrinos as a Probe of the Strong Interaction?

Neutrino / Anti-neutrino Deep-Inelastic Scattering off of Massive Nuclear Targets

NuFact11 – Working Group 2
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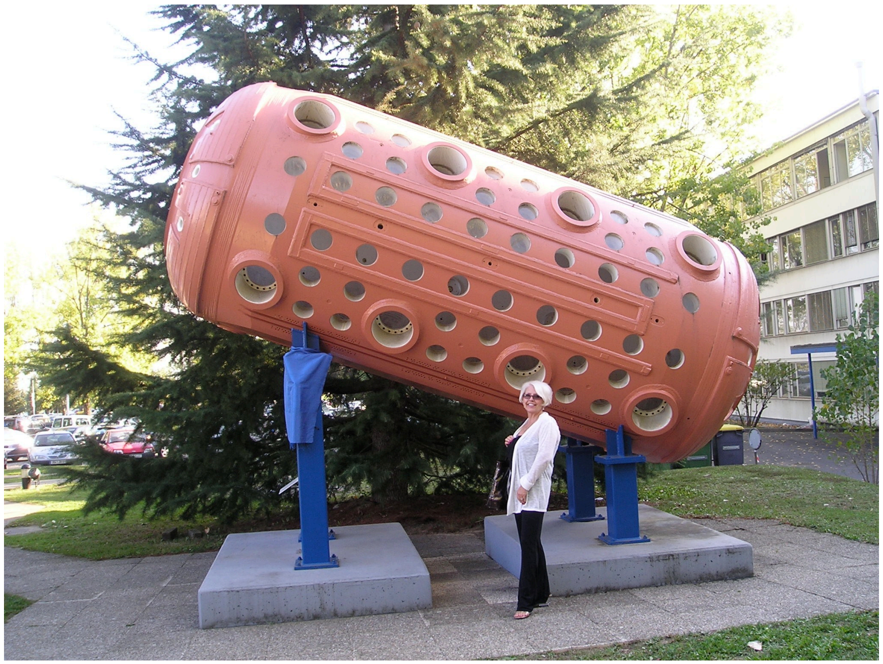
Neutrino Experiments have been studying QCD for about 40 years



- For example, Gargamelle made one of the first measurements of Λ_{ST} in the early 1970's using sum rules and the x-Q^2 behavior of the structure functions F_2 and xF_3 measured off heavy liquids.
- BEBC followed with QCD studies using ν + p and ν + D scattering.

Most "Recent" DIS Experiments

- There followed a long string of ν scattering experiments with **increasing statistics** and **decreasing systematic errors** ….

	E_ν range ($<E_\nu>$) (GeV)	Run	Target A	E_μ scale	E_{HAD} scale	Detector
NuTeV (CCFR)	30-360(120)	96-97	Fe	0.7%	0.43%	Coarse
NOMAD	10-200(27)	95-98	Various (mainly C)	0.2%	≈ 0.5%	Fine-grained
CHORUS	10-200(27)	95-98	Pb	2%	5%	Fine-grained
MINOS	3-15	05-10	Fe	2.5%	5.6%	Coarse

F_2 and xF_3 Measurement

F_2

$$\left[\frac{d^2\sigma}{dx\,dy}^{\nu} + \frac{d^2\sigma}{dx\,dy}^{\bar\nu}\right]\frac{\pi}{G_F^2 ME} =$$

$$= 2\,\overline{F}_2\left(1 - y - \frac{Mxy}{2E} + \frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right) + y\left(1-\frac{y}{2}\right) \quad \Delta xF_3$$

- Perform 1-parameter fit for F_2
- ΔxF_3 model
- R_L model

xF_3

$$\left[\frac{d^2\sigma}{dx\,dy}^{\nu} - \frac{d^2\sigma}{dx\,dy}^{\bar\nu}\right]\frac{\pi}{G_F^2 ME} =$$

$$= \Delta F_2\left(1 - y - \frac{Mxy}{2E} + \frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right) + 2\,y\left(1-\frac{y}{2}\right) \quad x\overline{F}_3$$

- Perform 1-parameter fit for xF_3
- ΔF_2 is very small and is neglected

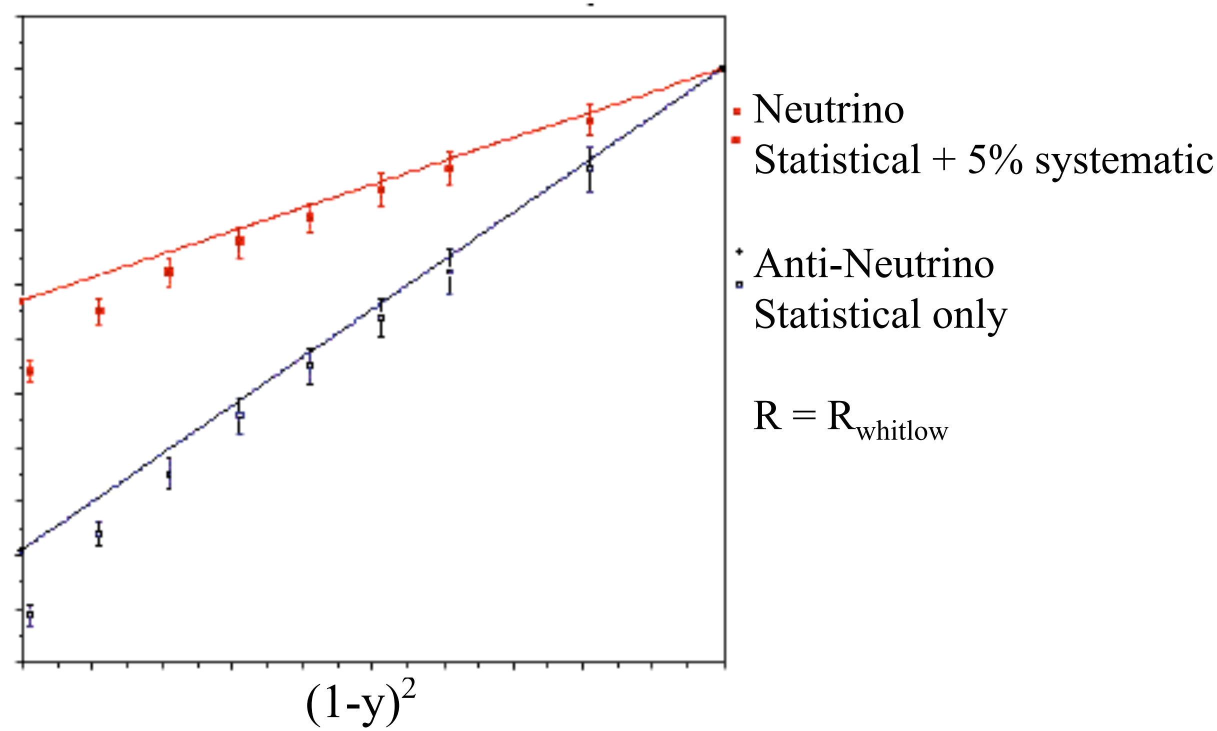
- Radiative corrections applied
- Isoscalar correction applied

Physics Results: Six Structure Functions for Maximal Information on PDF's

$$\frac{d\sigma^{\nu A}}{dx\,dQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{1}{2}\left(F_2^{\nu A}(x,Q^2) + xF_3^{\nu A}(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^{\nu A}(x,Q^2) - xF_3^{\nu A}(x,Q^2)\right) + y^2 F_L\right]$$

$$\frac{d\sigma^{\bar{\nu} A}}{dx\,dQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{1}{2}\left(F_2^{\bar{\nu} A}(x,Q^2) - xF_3^{\bar{\nu} A}(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^{\bar{\nu} A}(x,Q^2) + xF_3^{\bar{\nu} A}(x,Q^2)\right)\right]$$

$$\frac{\sigma\left(x,Q^2,(1-y)^2\right)}{G^2/2\pi x}$$

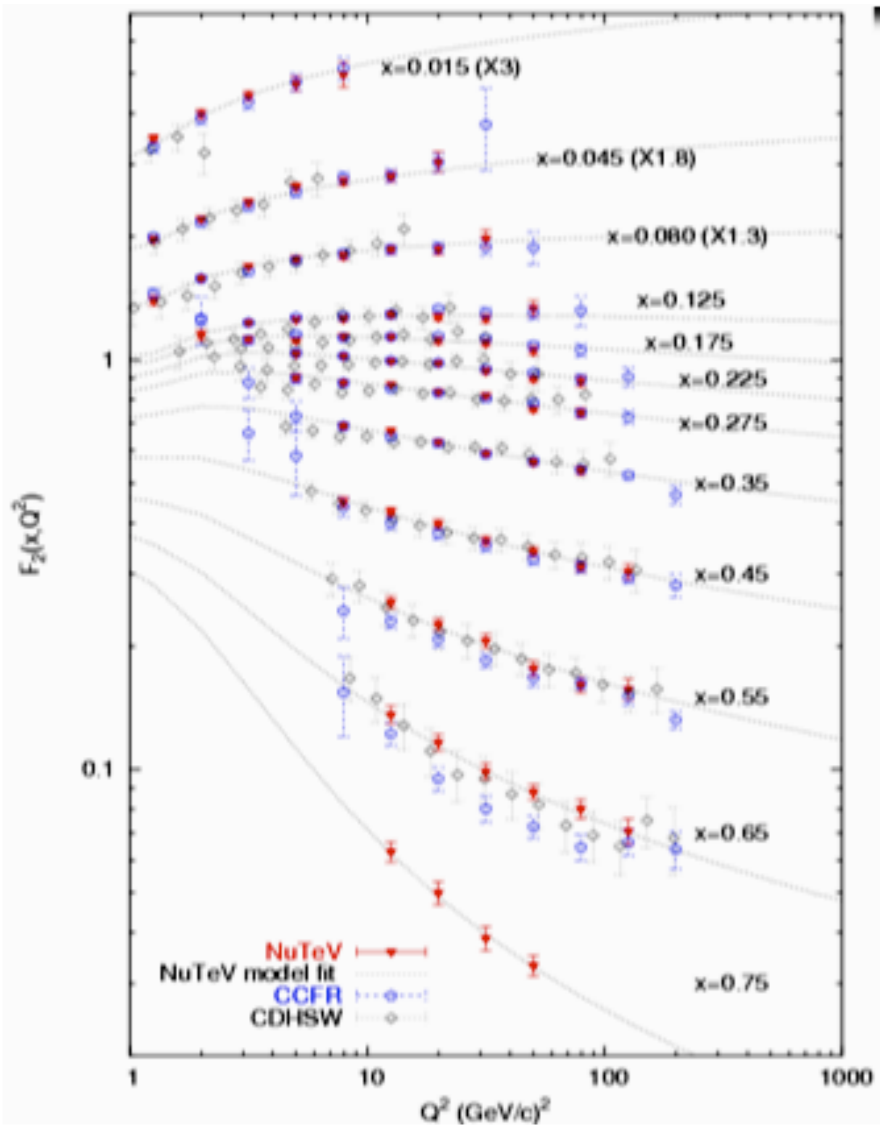


$R = R_{whitlow}$

$X = 0.1 - 0.125$
$Q^2 = 2 - 4\ GeV^2$

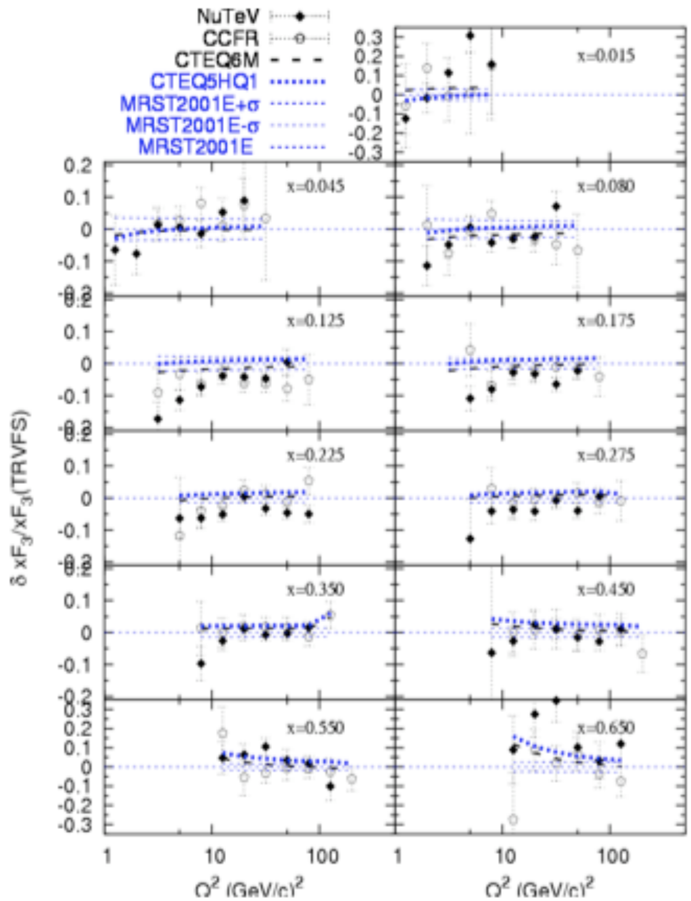
Meant to give an impression only!
Kinematic cuts in (1-y) not shown.

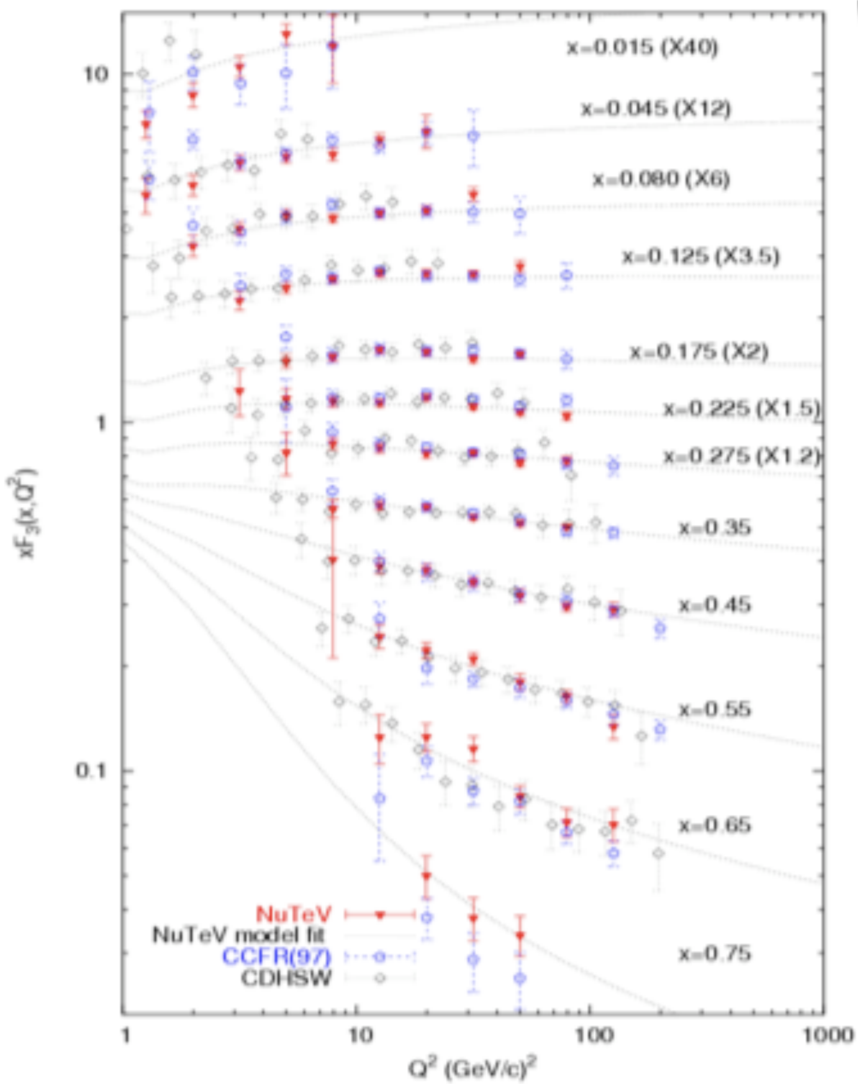
NuTeV F_2 Measurement



◆ At $x>0.4$ NuTeV is Systematically above CCFR

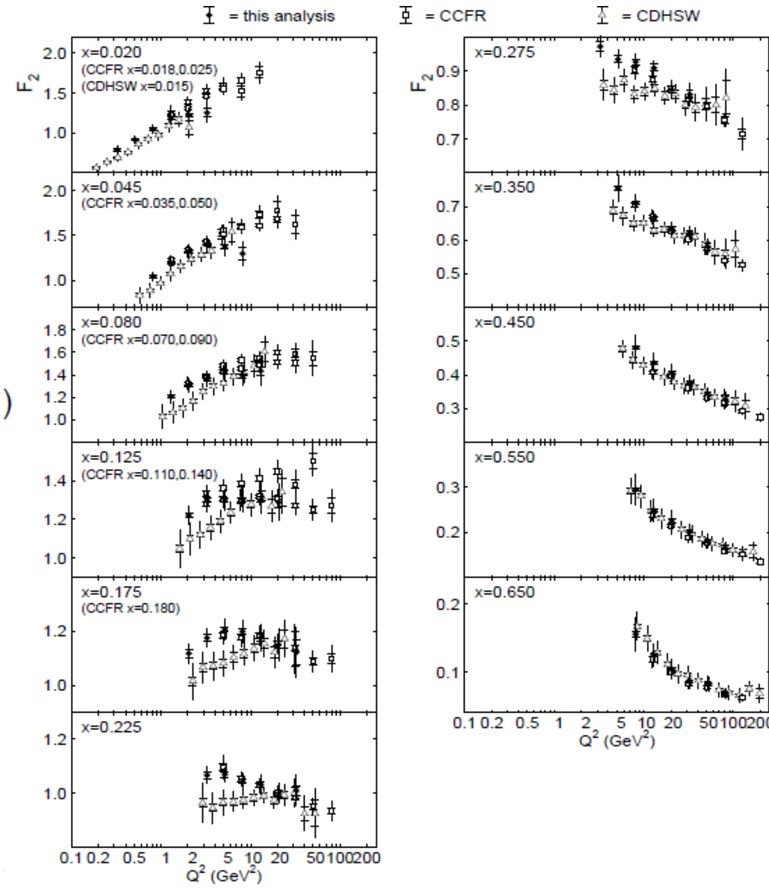
NuTeV xF_3 Measurement

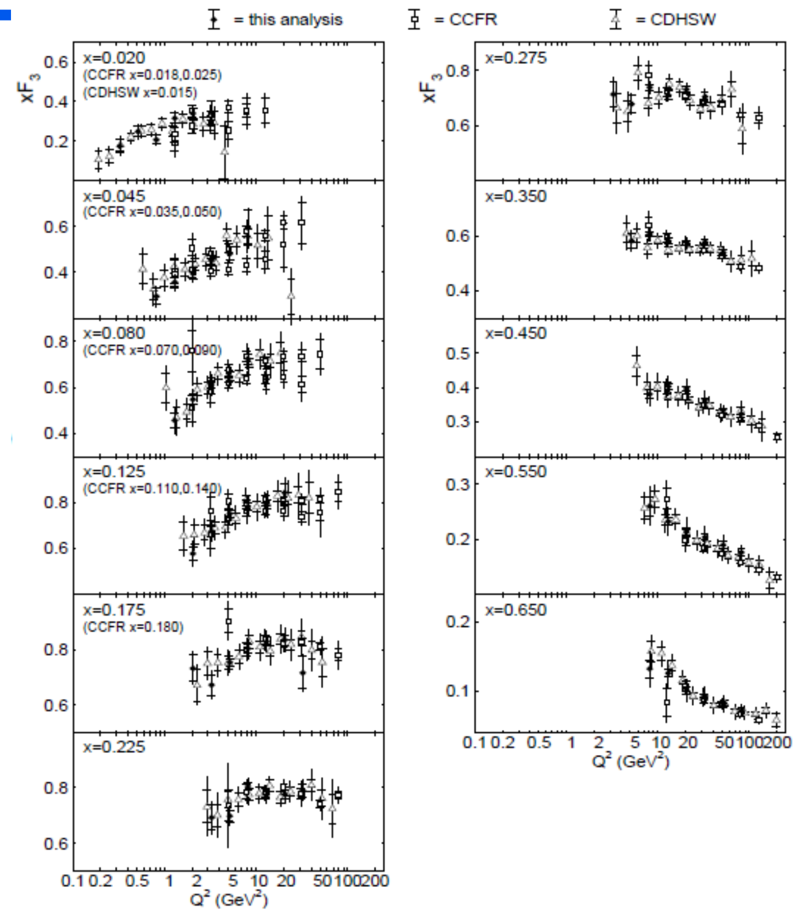




- At $x>0.5$ NuTeV is systematically above CCFR
- NuTeV xF_3 agrees with theory for medium x.
- At low x different Q^2 dependence

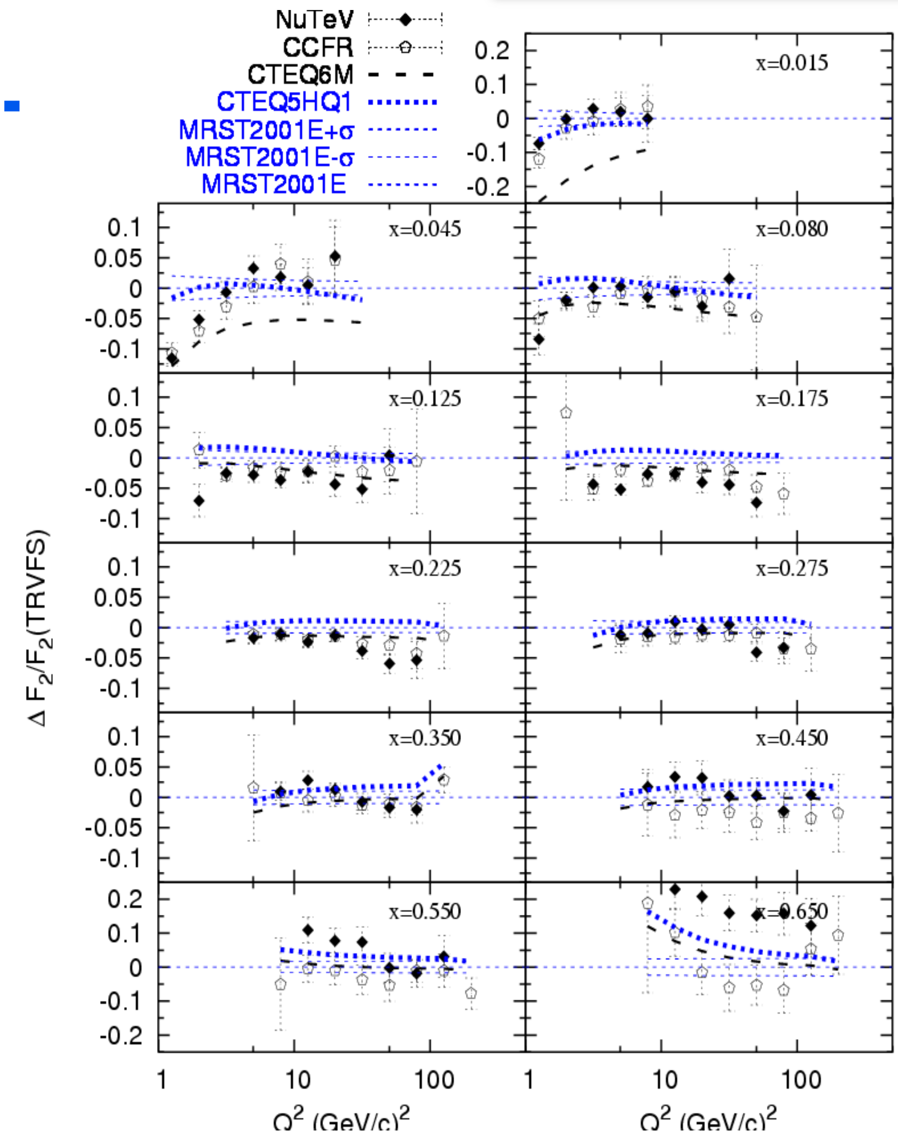
CHORUS Structure Functions: ν Pb





- First ν-Pb differential cross section and structure functions.
- CHORUS measurement somewhat favors CCFR over NuTeV at high x.
- Much larger systematic errors than the NuTeV experiment.

Comparison with Global Fits for F_2



- Baseline is TRVFS(MRST2001E)

- NuTeV and CCFR F_2 are compared to TRVFS(MRST2001E)

$$\frac{F_2^{NuTeV} - F_2^{TRVFS}}{F_2^{TRVFS}}$$

- Theoretical models shown are:
  - ACOT(CTEQ6M)
  - ACOT(CTEQ5HQ1)
  - TRVFS (MRST2001E)

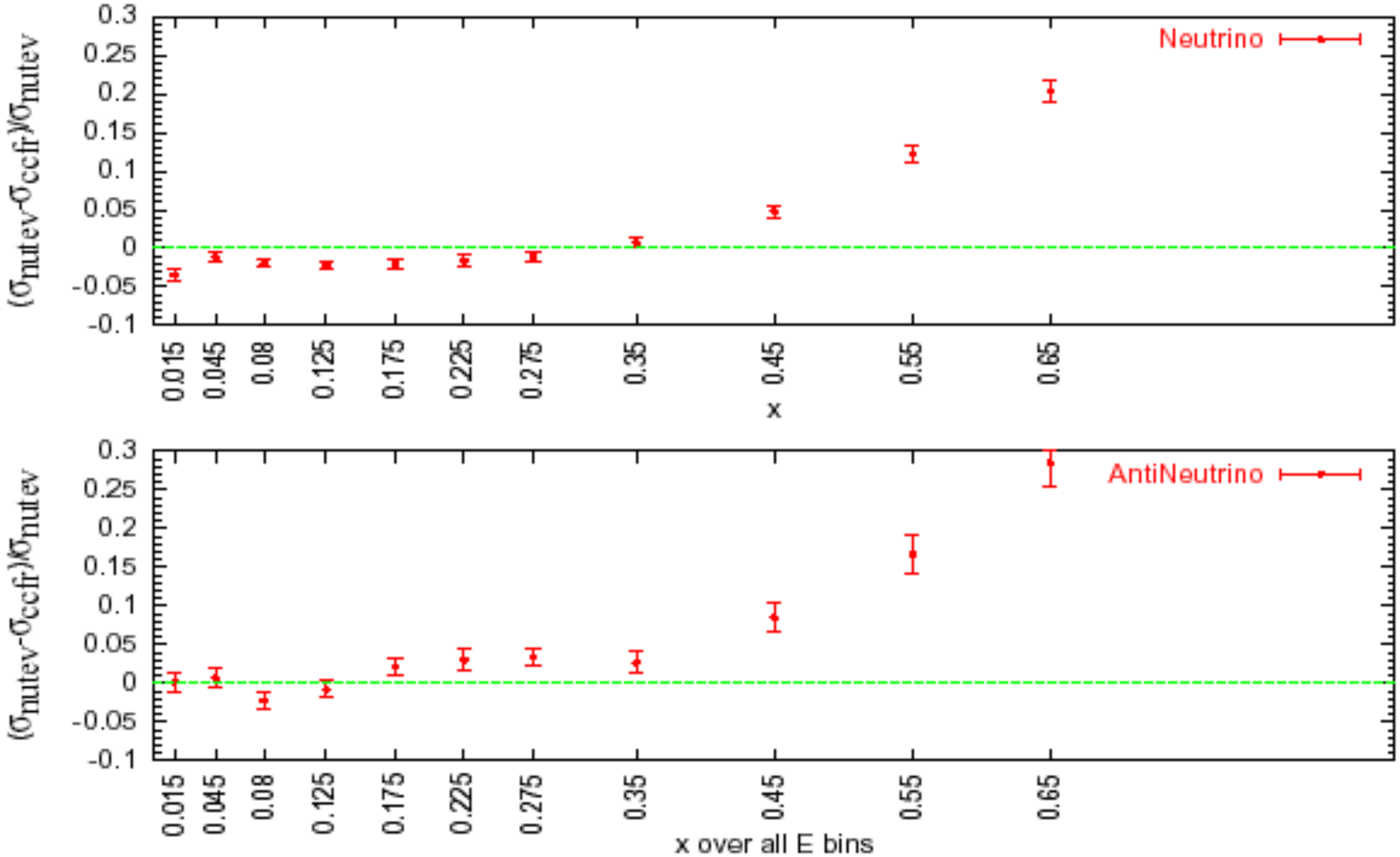
- Theory curves are corrected for:
  - target mass
    (H. Georgi and H. D. Politzer, Phys. Rev. D14, 1829)
  - nuclear effects – parameterization from charge lepton data, assumed to be the same for neutrino scattering (no Q^2 dependence added) nuclear effects parameterization is dominated by SLAC (lower Q^2 in this region) data at high-x

- NuTeV F_2 agrees with theory for medium x.
- At low x different Q^2 dependence.
- At high x (x>0.5) NuTeV is systematically higher.

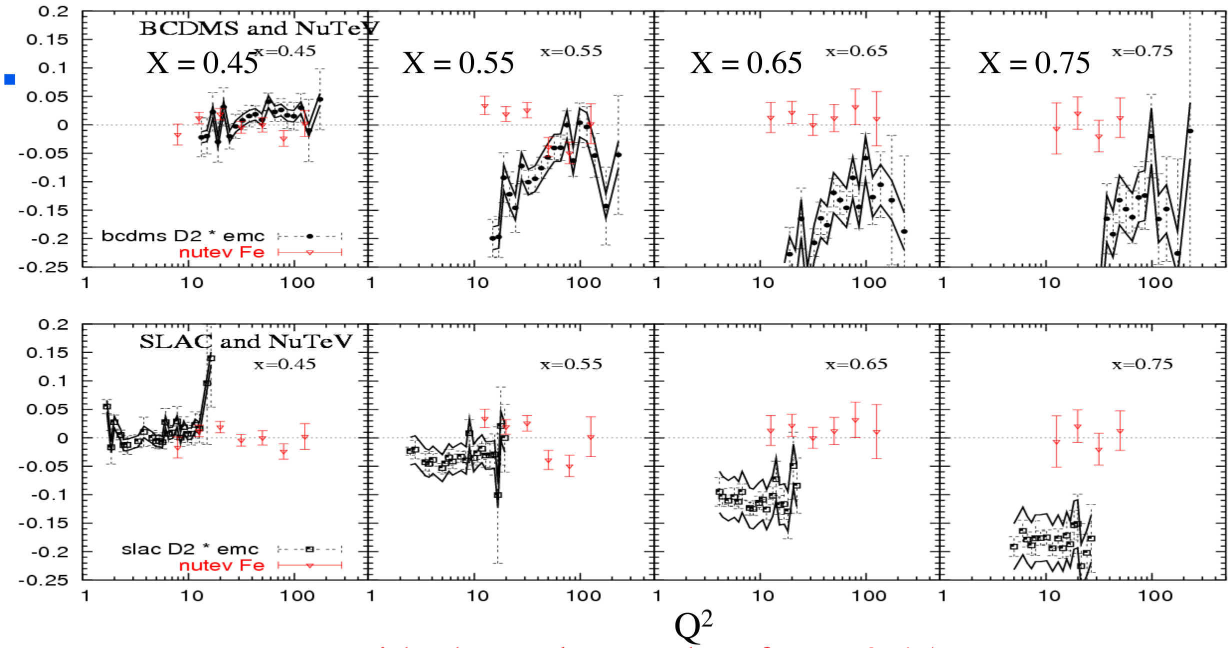
Martin Tzanov

NuTeV (ν-Fe) Compared to CCFR.

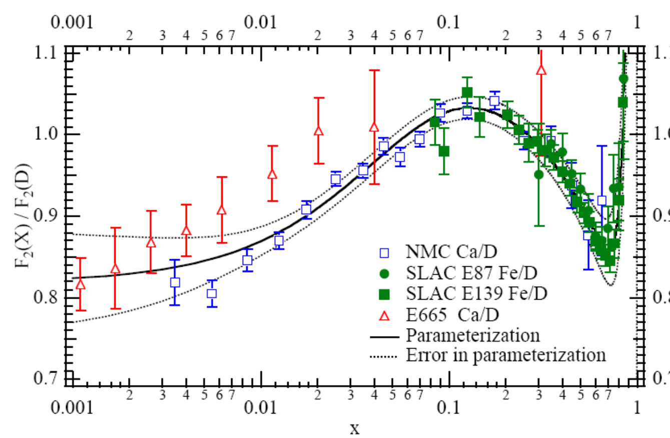
(CHORUS (ν-Pb) in between CCFR and NuTeV at high x)



Comparison with Charge Lepton Data for *x>0.4*



- Baseline is NuTeV model fit
- data points are $\dfrac{F_2^{DATA} - F_2^{BG}}{F_2^{BG}}$
- charge lepton data is corrected for:
  - $\dfrac{F_2^{\nu}}{F_2^{l}}$ using CTEQ4D
  - heavy target $\dfrac{F_2^{N}}{F_2^{D}}$



- NuTeV agrees with charge lepton data for x=0.45.
- NuTeV is higher than BCDMS(D_2), different Q^2 dependence
  - *7%* at *x=0.55*, *12%* at *x=0.65*, and *15%* at *x=0.75*
- NuTeV is higher than SLAC(D_2) (bottom 4 plots)
  - *4%* at *x=0.55*, *10%* at *x=0.65*, and *17%* at *x=0.75*

the nuclear correction is dominated by SLAC data, which is at lower Q^2 than NuTeV in this region

"Perhaps the nuclear correction is smaller for neutrino scattering at high x."
Martin Tzanov

Summary ν Scattering Results – NuTeV

NuTeV accumulated over 3 million neutrino / antineutrino events with $20 \leq E_\nu \leq 400$ GeV.

NuTeV considered 23 systematic uncertainties.

NuTeV σ agrees with other ν experiments and theory for medium x.

At low x different Q^2 dependence.

At high x (x>0.5) NuTeV is systematically higher.

All of the NuTeV Results are for $\nu/\bar{\nu}$ – Fe interactions and where necessary have assumed the nuclear corrections for neutrino interactions are the same as those for charged leptons.

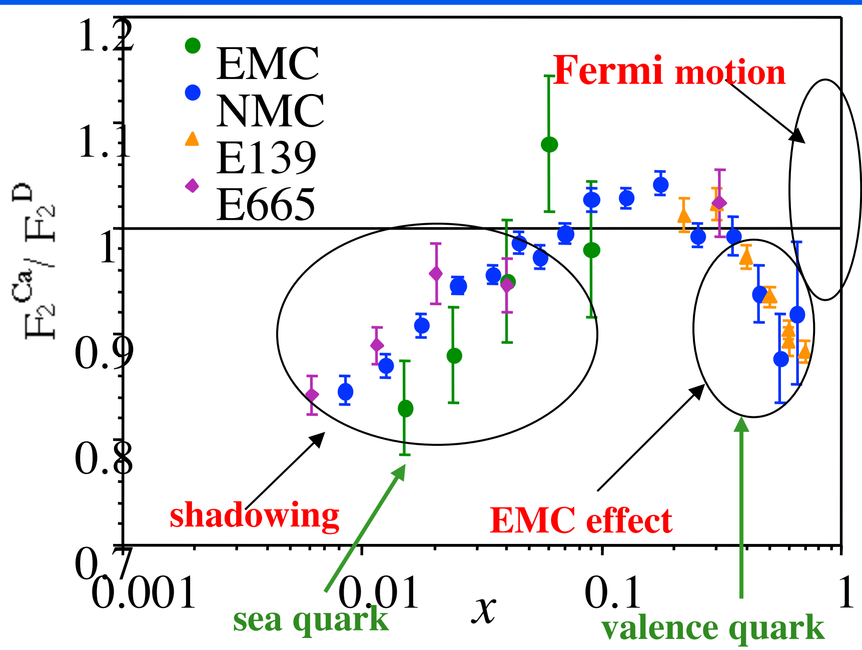
Is this really the case?

Nuclear Effects in Neutrino Interactions

- Target nucleon in motion - spectral functions (Benhar et al.)
- Certain reactions prohibited - Pauli suppression
- Quasi-elastic form factors are modified within the nuclear environment. (Butkevich / Kulagin, Tsushima et al.)
- Meson exchange currents
- Produced topologies are modified by final-state interactions modifying topologies and reducing detected energy.
  - Convolution of $\delta\sigma(n\pi)$ $\otimes$ formation zone uncertainties $\otimes$ π-absorption uncertainties yield larger oscillation-parameter systematics
- **Cross sections and structure functions are modified and parton distribution functions within a nucleus are different than in an isolated nucleon. Observations from an on-going CTEQ analysis.**

Experimental Studies of Nuclear Effects with Neutrinos:

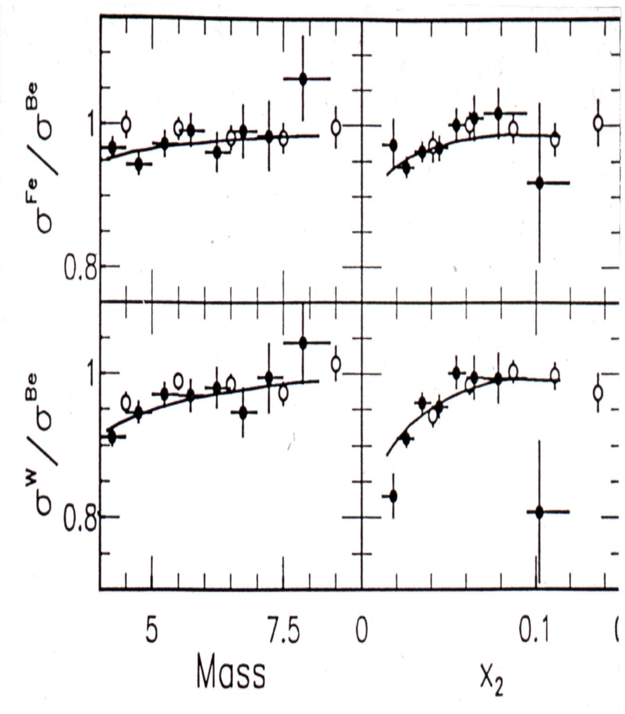
until recently - essentially NON-EXISTENT

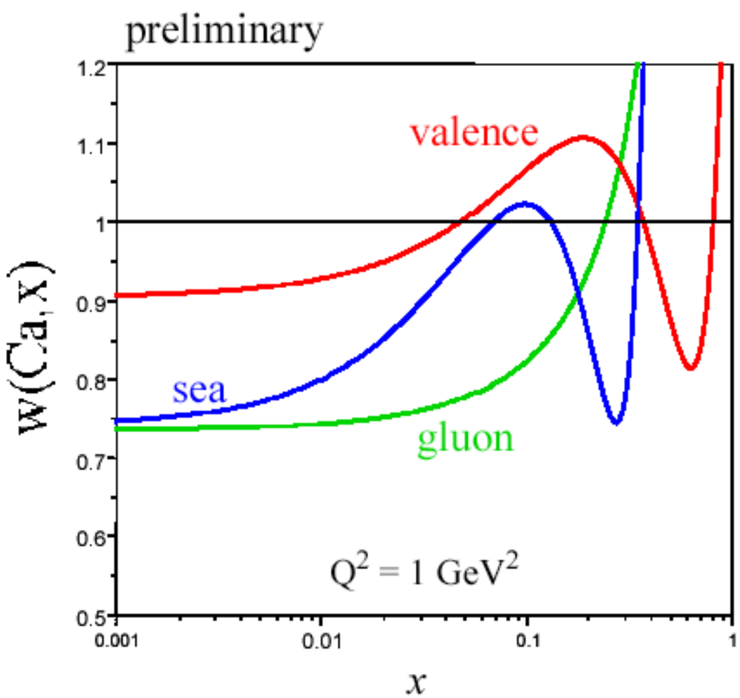


- F_2 / nucleon changes as a function of A. Measured in μ/e - A, **not in ν − A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A.**
  - **Presence of axial-vector current.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**

Nuclear Effects

A Difference in Nuclear Effects of Valence and Sea Quarks?





- Nuclear effects similar in Drell-Yan and DIS for x < 0.1. Then no "anti-shadowing" in D-Y while "anti-shadowing" seen in DIS (5-8% effect in NMC).
- This quantified via **Nuclear Parton Distribution Functions**: K.J. Eskola et al and S. Kumano et al. Currently, K. Kovarik, I. Schienbein and Ji Young Yu + CTEQ nPDF fits
- **Sergei Kulagin and Roberto Petti have also provided a look at ν + A effects**

Kulagin-Petti Model of Nuclear Effects

hep-ph/0412425

- Global Approach -aiming to obtain quantitative calculations covering the complete range of x and Q^2 available with thorough physics basis for fit to data.
- Different effects on structure functions (SF) are taken into account:

$$F_i^A = F_i^{p/A} + F_i^{n/A} + F_i^{\pi/A} + \delta F_i^{\mathrm{coh}}$$

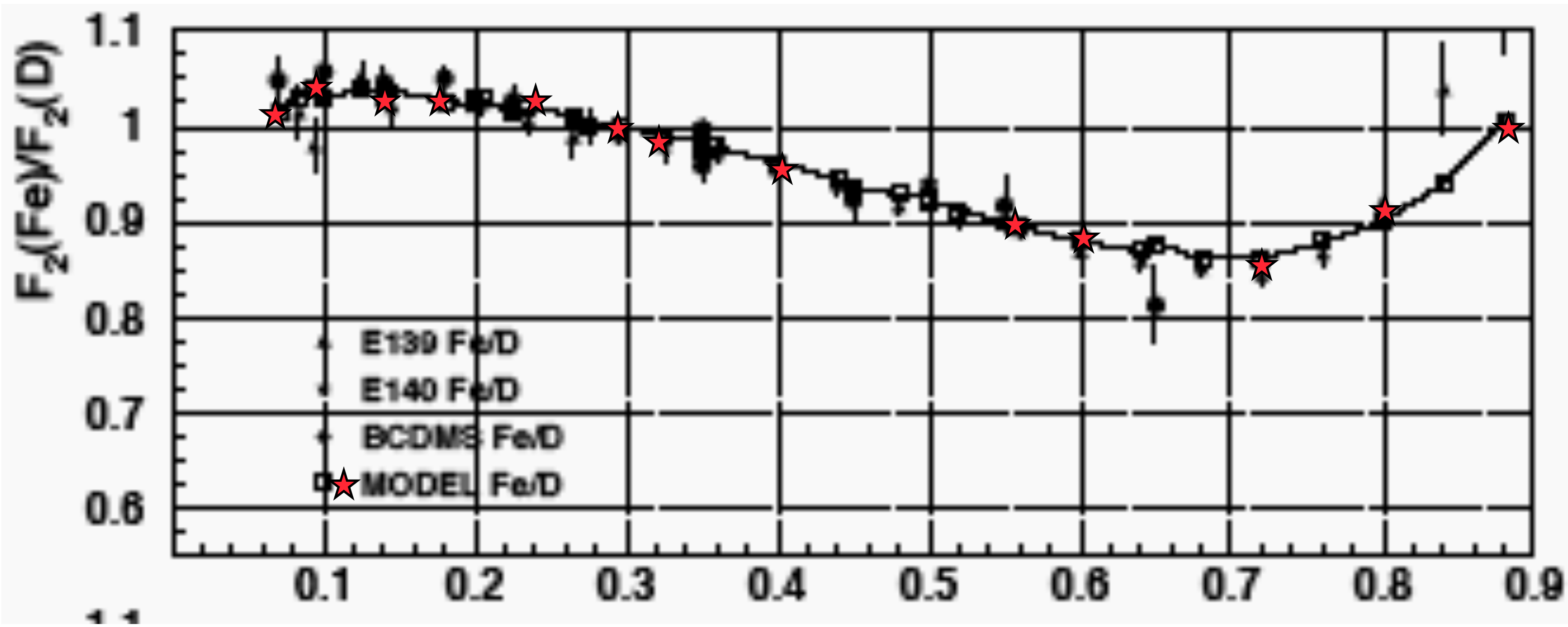
- $F_i^{p(n)/A}$ bound proton(neutron) SF with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)
- $F_i^{\pi/A}$ nuclear Pion excess correction (PI)
- $\delta F_i^{\mathrm{coh}}$ contribution from coherent nuclear interactions: Nuclear Shadowing (NS)

- **Fermi Motion** and **Binding** in nuclear structure functions is calculated from the convolution of nuclear spectral function and (bound) nucleon SFs:
- Since bound nucleons are off-mass shell there appears dependence on the nucleon virtuality $\kappa^2 = (M + \varepsilon)^2 - k^2$ where we have introduced an **off-shell structure function $\delta f_2(x)$**

$$F_2(x, Q^2, k^2) = F_2(x, Q^2)\left(1 + \delta f_2(x)(k^2 - M^2)/M^2\right)$$

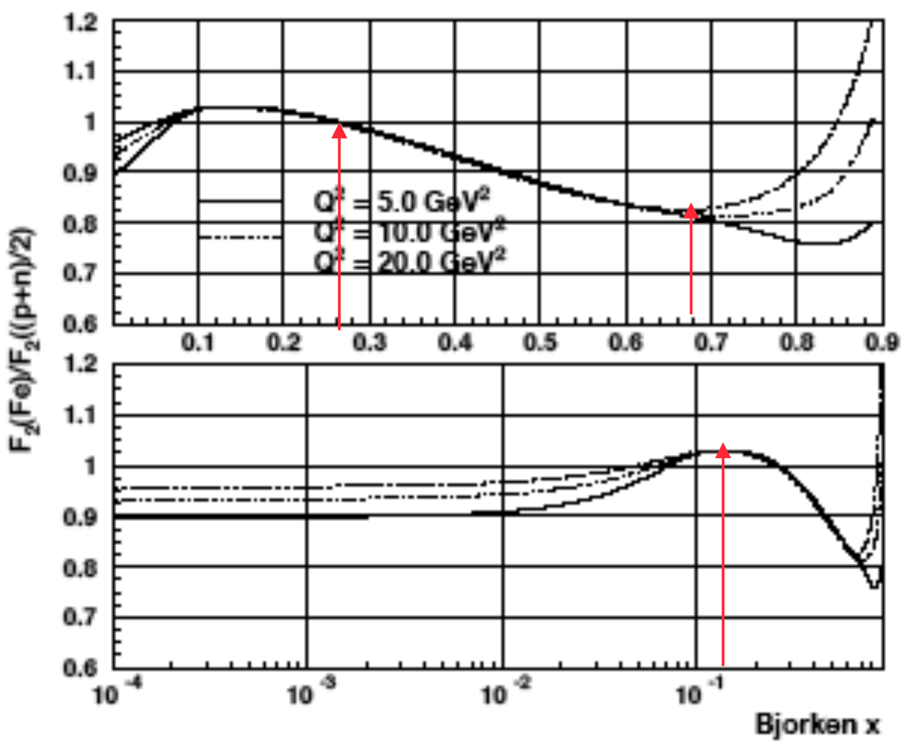
- Leptons can scatter off mesons which mediate interactions among bound nucleons yielding a **nuclear pion correction**

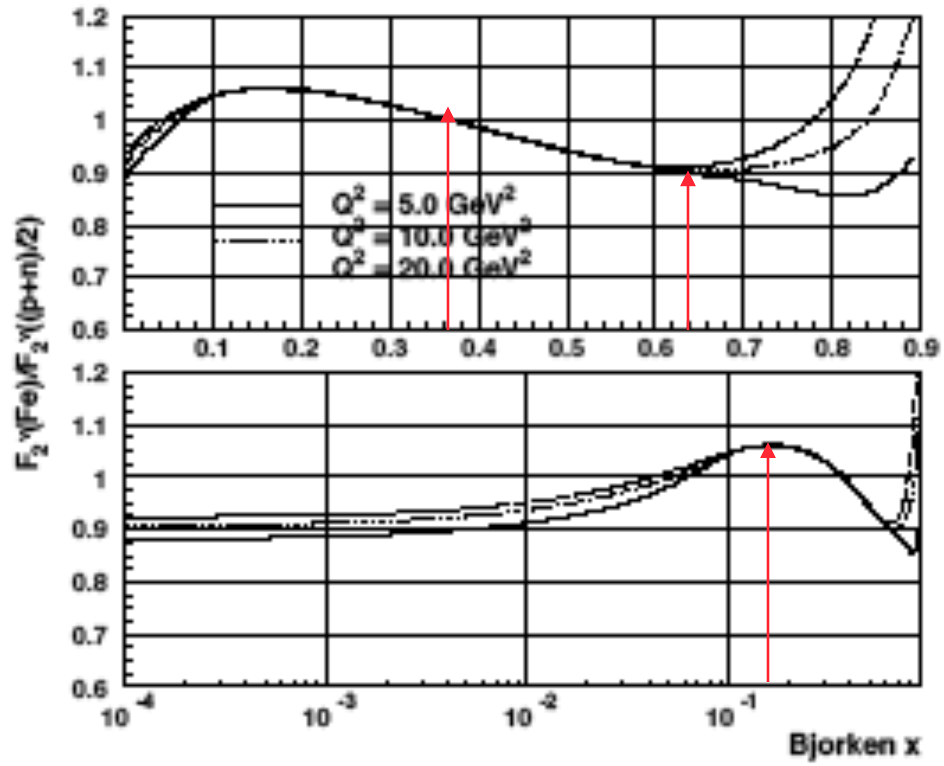
Kulagin-Petti compared to e/μ+Fe data
F_2 (e/μ+Fe) / F_2 (e/μ+D)



Charged Lepton

$F_2\,(\mu+Fe)\,/\,F_2\,(\mu+N)$ compared to $F_2\,(\nu+Fe)\,/\,F_2\,(\nu+N)$



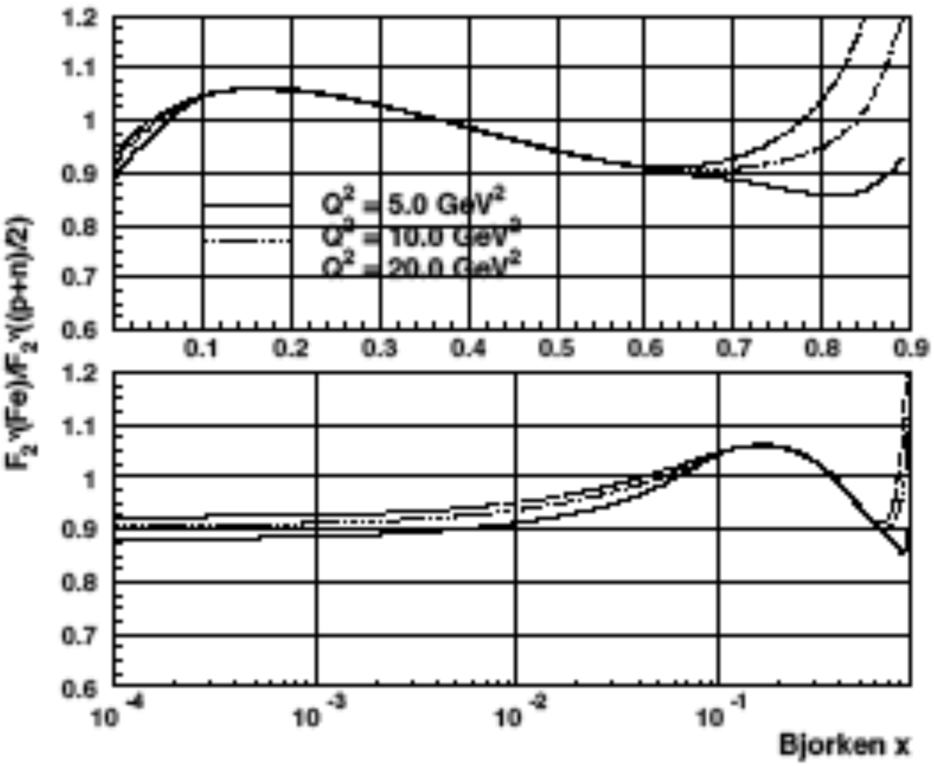


Charged Lepton

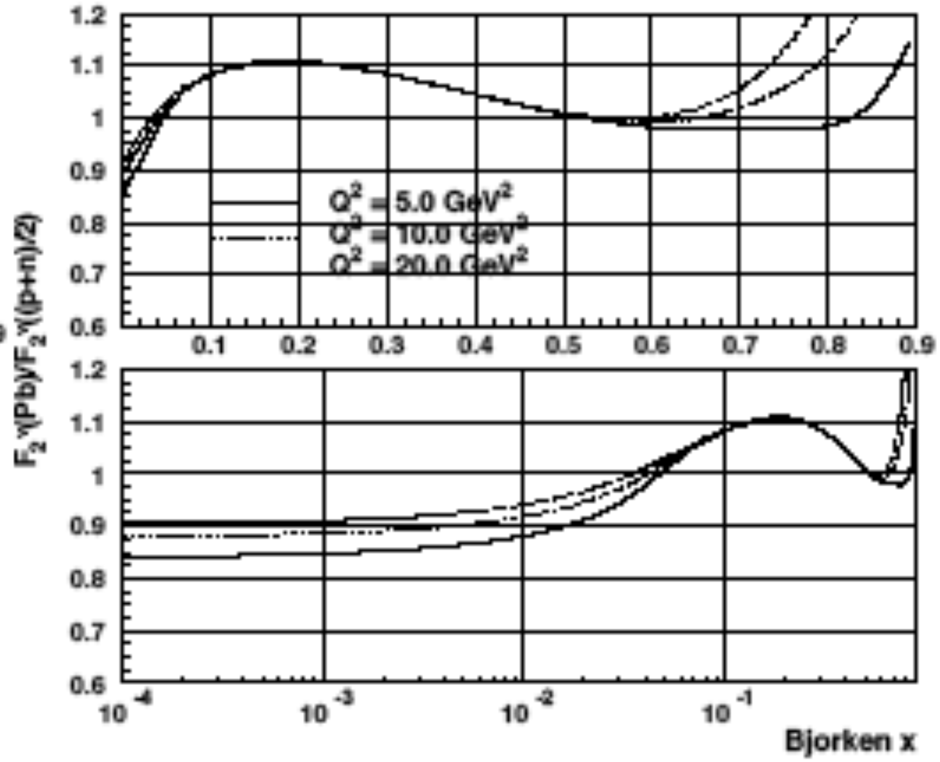
Neutrino

$F_2\,(\nu+A)\,/\,F_2\,(\nu+N)$

(n excess included in effect)

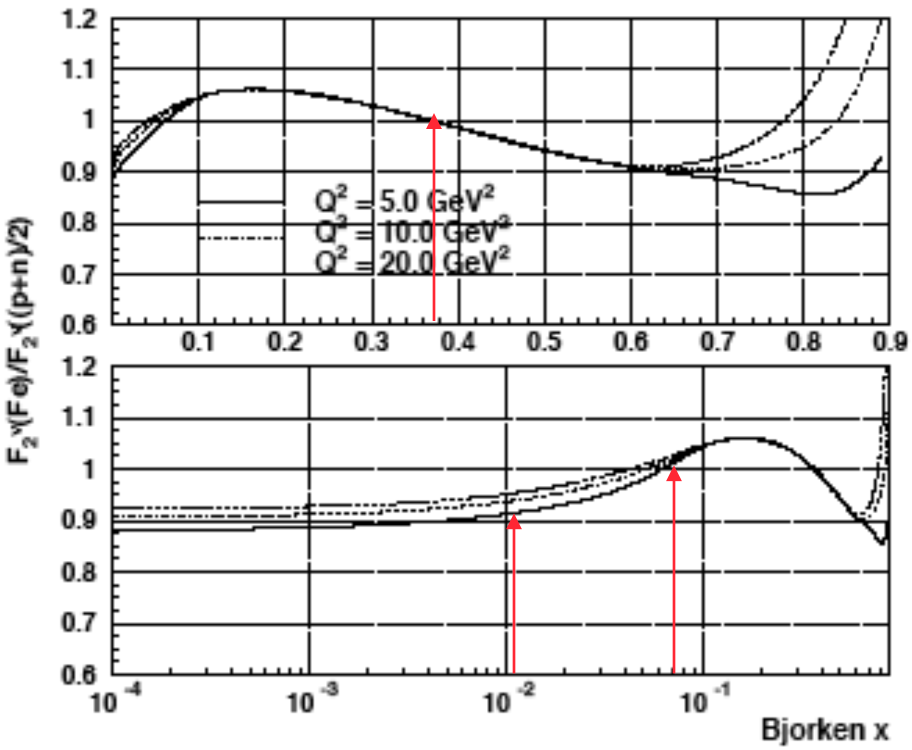


Fe

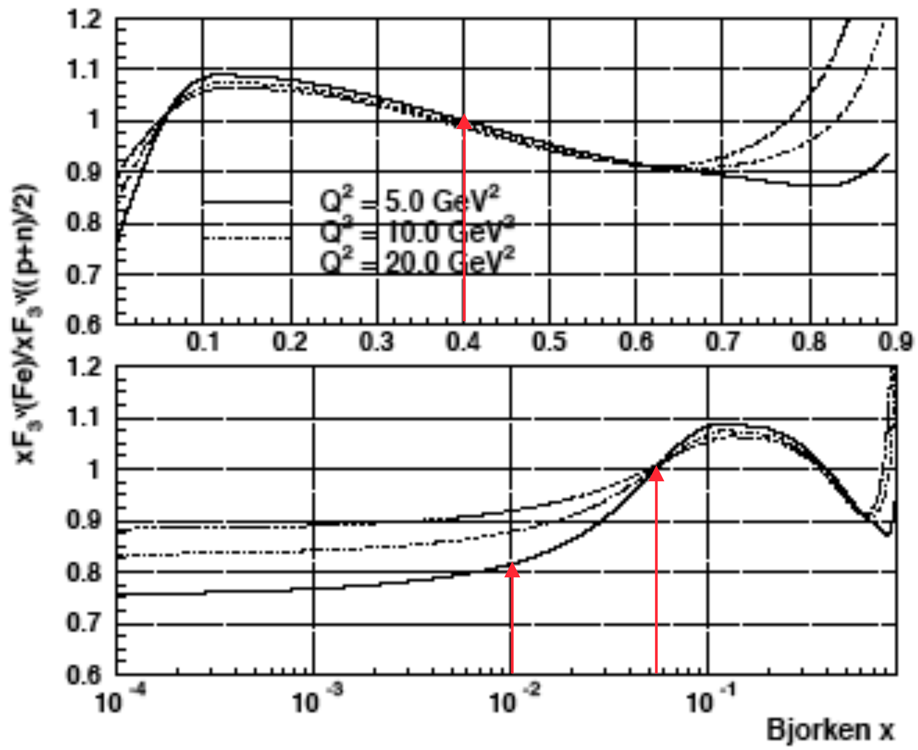


Pb

Kulagin-Petti: ν-Fe Nuclear Effects

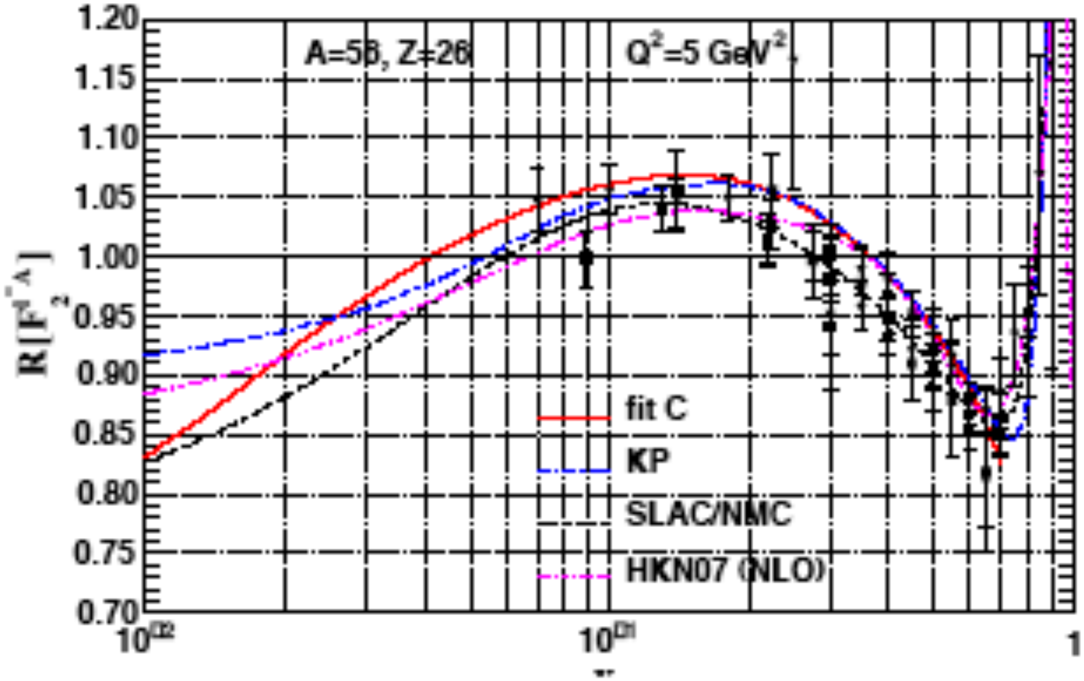


F_2



xF_3

Nuclear Structure Function Corrections
$\ell^{\pm}$ (Fe/D_2)



- F_2 / nucleon changes as a function of A. Measured in μ/e - A, **not in ν − A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A.**
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  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**

CTEQ study: The Impact of new neutrino DIS and Drell-Yan data on large-x parton distributions

Joey Huston - MSU, Cynthia Keppel - Hampton, Steve Kuhlmann - ANL,
JGM - Fermilab, Fred Olness - SMU, Jeff Owens - Florida State,
Jon Pumplin and Dan Stump - MSU

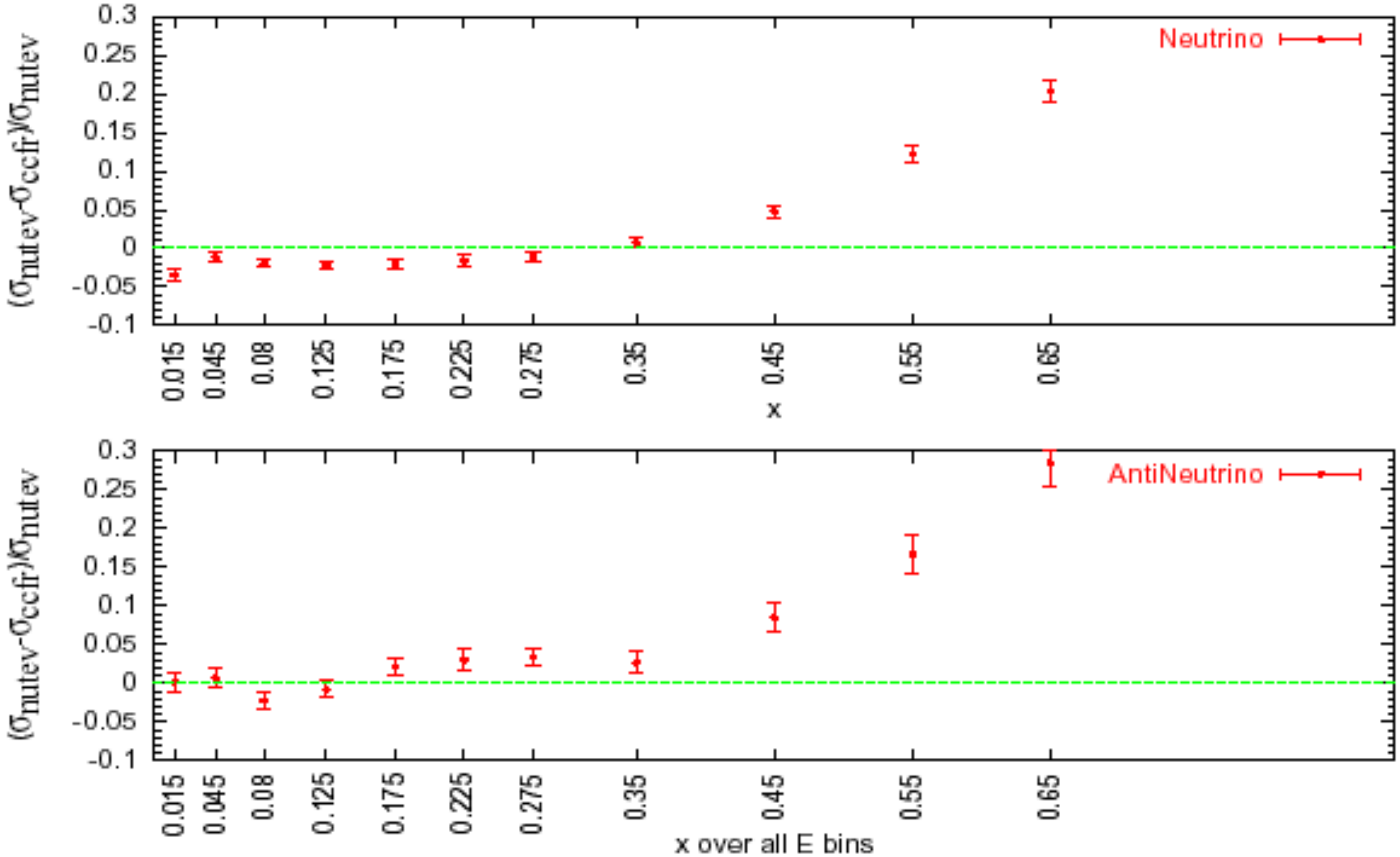
Published in **Phys.Rev.D75:054030,2007**.
e-Print: **hep-ph/0702159**

Had to use $l^{\pm}$-Fe correction factors to combine NuTeV ν-Fe results with E866 p-H and p-D Drell-Yan results.
Tension between NuTeV and E866 started us on a rather convoluted path to extracting **nuclear effects from neutrino interactions**.

NuTeV (ν-Fe) Compared to CCFR (in PDF fits). At High-x NuTeV Indicates Effect **Opposite** to E866 D-Y.

(CHORUS (ν-Pb) in between CCFR and NuTeV at high x)

Is the tension between NuTeV and E866 coming from applying $l^{\pm}$-Fe nuclear corrections to the NuTeV ν-Fe measurements?



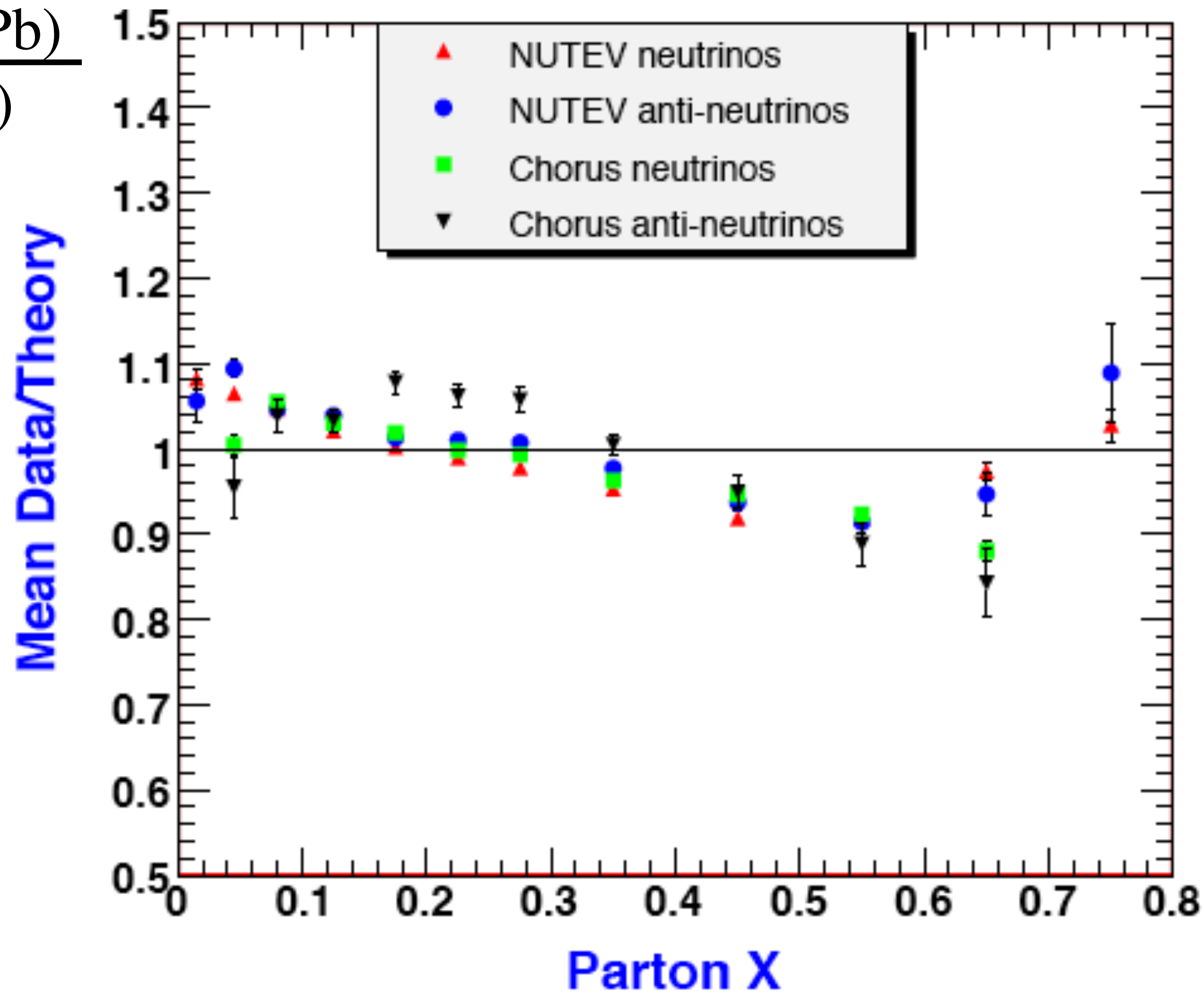
CTEQ High-x Study: nuclear effects
No high-statistics D_2 data – "make it" from PDFs

- Form reference fit mainly nucleon (as opposed to nuclear) scattering results:
  - BCDMS results for F_2^p and F_2^d
  - NMC results for F_2^p and F_2d/F_2^p
  - H1 and ZEUS results for F_2^p
  - CDF and DØ result for inclusive jet production
  - CDF results for the W lepton asymmetry
  - E-866 results for the ratio of lepton pair cross sections for pd and pp interactions
  - E-605 results for dimuon production in pN interactions.
- Correct for deuteron nuclear effects

NuTeV(Fe) and CHORUS (Pb) ν scattering (unshifted) σ results compared to reference fit

no nuclear corrections

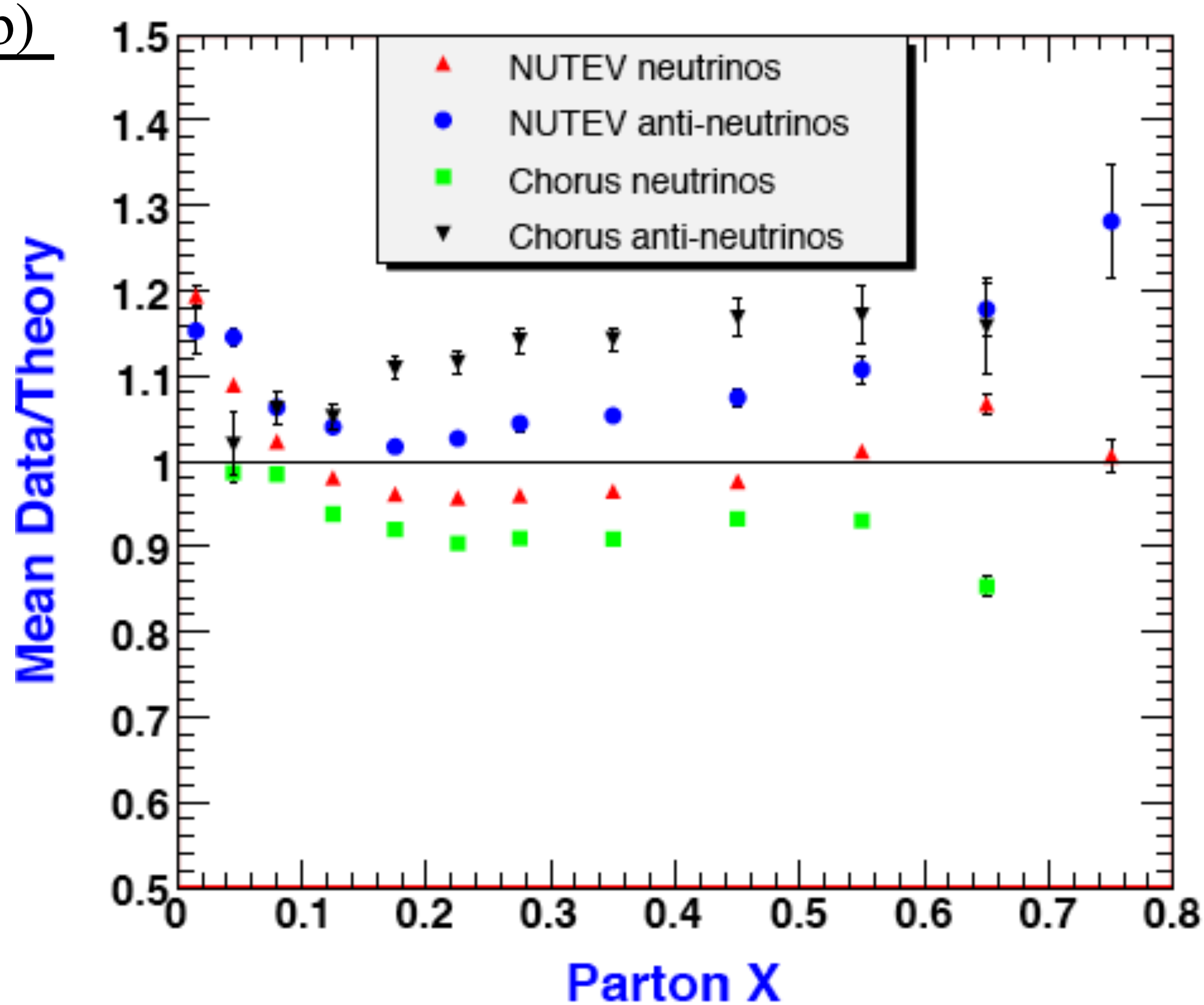
$$\frac{\sigma(\nu\mathrm{Fe}\ \mathrm{or}\ \nu\mathrm{Pb})}{\sigma(\nu\text{"}n+p\text{"})}$$



NuTeV σ(Fe) & CHORUS σ(Pb) ν scattering (un-shifted) results compared to reference fit

Kulagin-Petti nuclear corrections

$$\frac{\sigma(\text{Fe or Pb})}{\sigma(n+p)}$$



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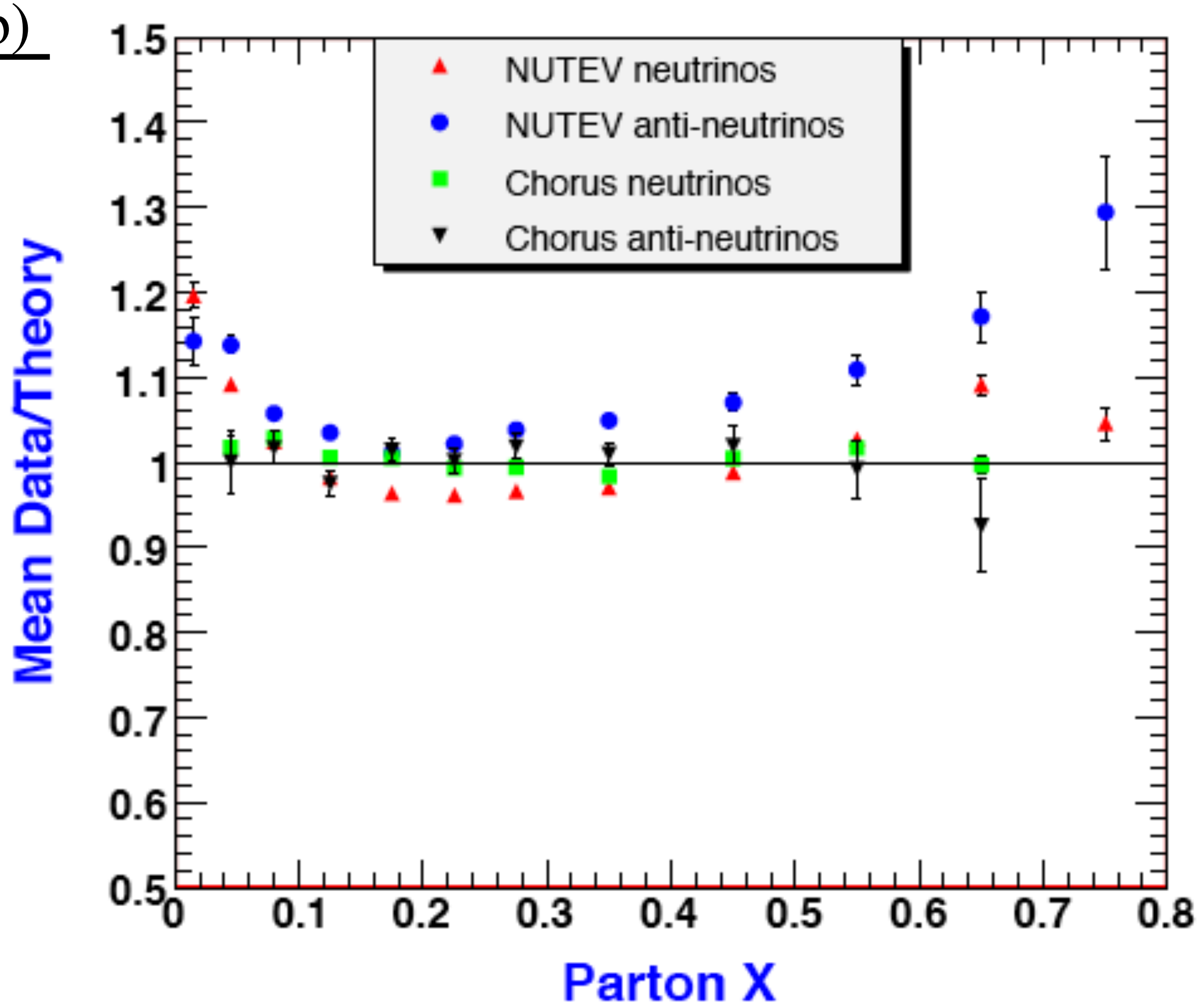

Nuclear PDFs from neutrino deep inelastic scattering

I. Schienbein (SMU & LPSC-Grenoble, J-Y. Yu (SMU)
C. Keppel (Hampton & JeffersonLab) J.G.M. (Fermilab),
F. Olness (SMU), J.F. Olness (Florida State U)

e-Print: **arXiv:0710.4897** [hep-ph]

Formalism

- PDF Parameterized at Q_0 = 1.3 GeV as

$$xf_i(x,Q_0) = \begin{cases} A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1+e^{A_4}x)^{A_5} & : i = u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s}\,, \\ A_0 x^{A_1}(1-x)^{A_2} + (1+A_3 x)(1-x)^{A_4} & : i = \bar{d}/\bar{u}\,, \end{cases}$$

- PDFs for a nucleus are constructed as:

$$f_i^A(x,Q) = \frac{Z}{A}\, f_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, f_i^{n/A}(x,Q)$$

- Resulting in nuclear structure functions:

$$F_i^A(x,Q) = \frac{Z}{A}\, F_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, F_i^{n/A}(x,Q)$$

- The differential cross sections for CC scattering off a nucleus::

$$\begin{aligned} \frac{d^2\sigma}{dx\,dy}^{\overset{(-)}{\nu}A} &= \frac{G^2 M E}{\pi}\left[(1-y-\frac{Mxy}{2E})F_2^{\overset{(-)}{\nu}A}\right. \\ &+ \left.\frac{y^2}{2} 2xF_1^{\overset{(-)}{\nu}A} \pm y(1-\frac{y}{2})xF_3^{\overset{(-)}{\nu}A}\right] \end{aligned}$$

Same Reference Fit as Earlier Analysis

- Form reference fit mainly nucleon (as opposed to nuclear) scattering results:
  - BCDMS results for F_2^p and F_2^d
  - NMC results for F_2^p and $F_2 d/F_2^p$
  - H1 and ZEUS results for F_2^p
  - CDF and DØ result for inclusive jet production
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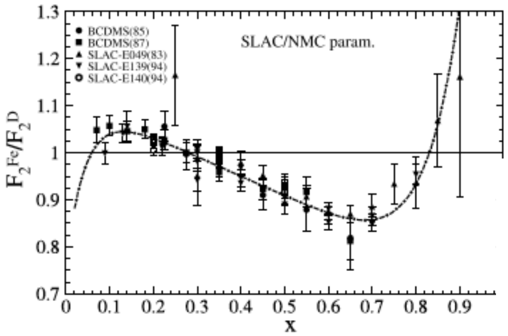
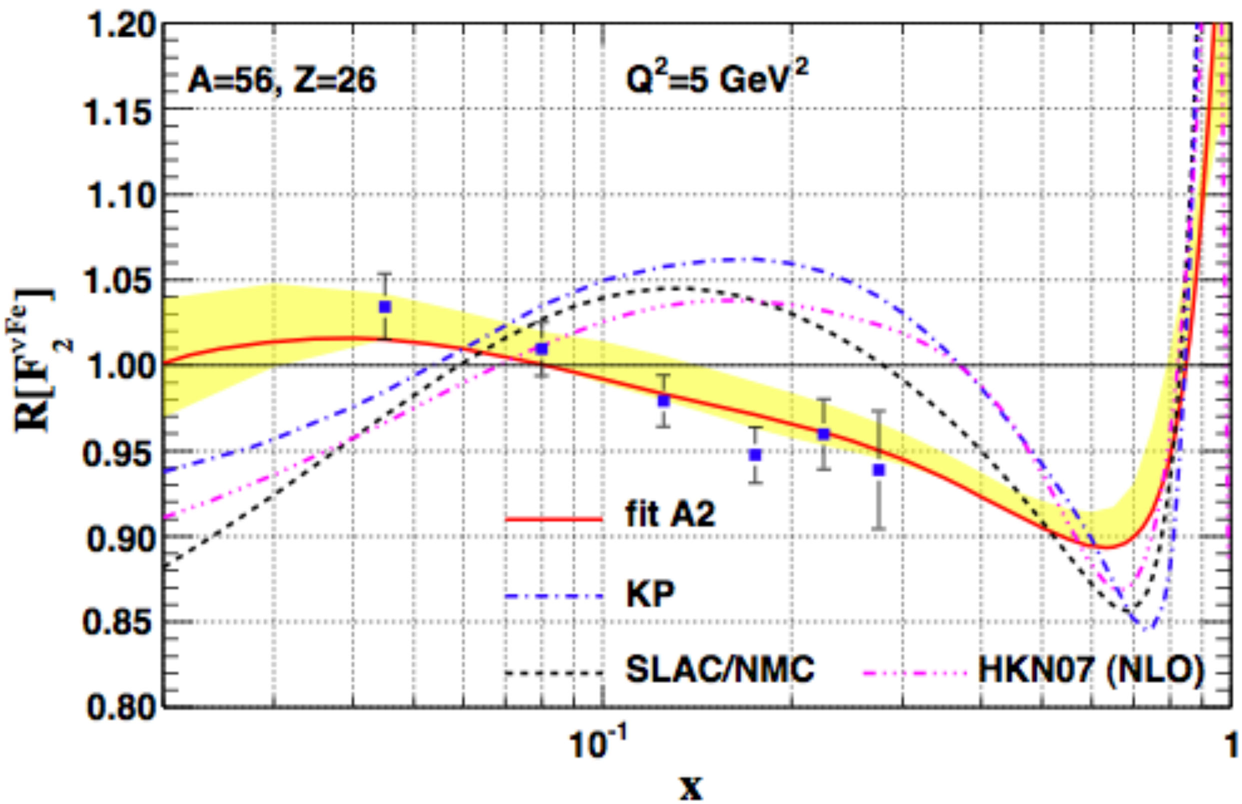
- Correct for deuteron nuclear effects

F_2 Structure Function Ratios: ν-Iron



$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



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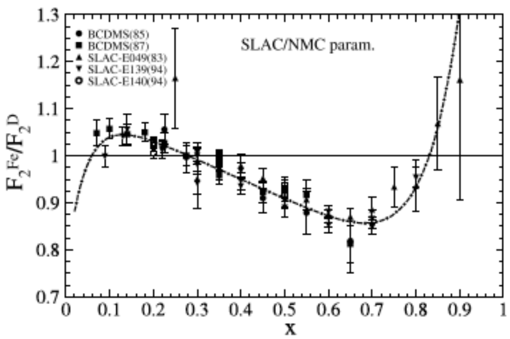
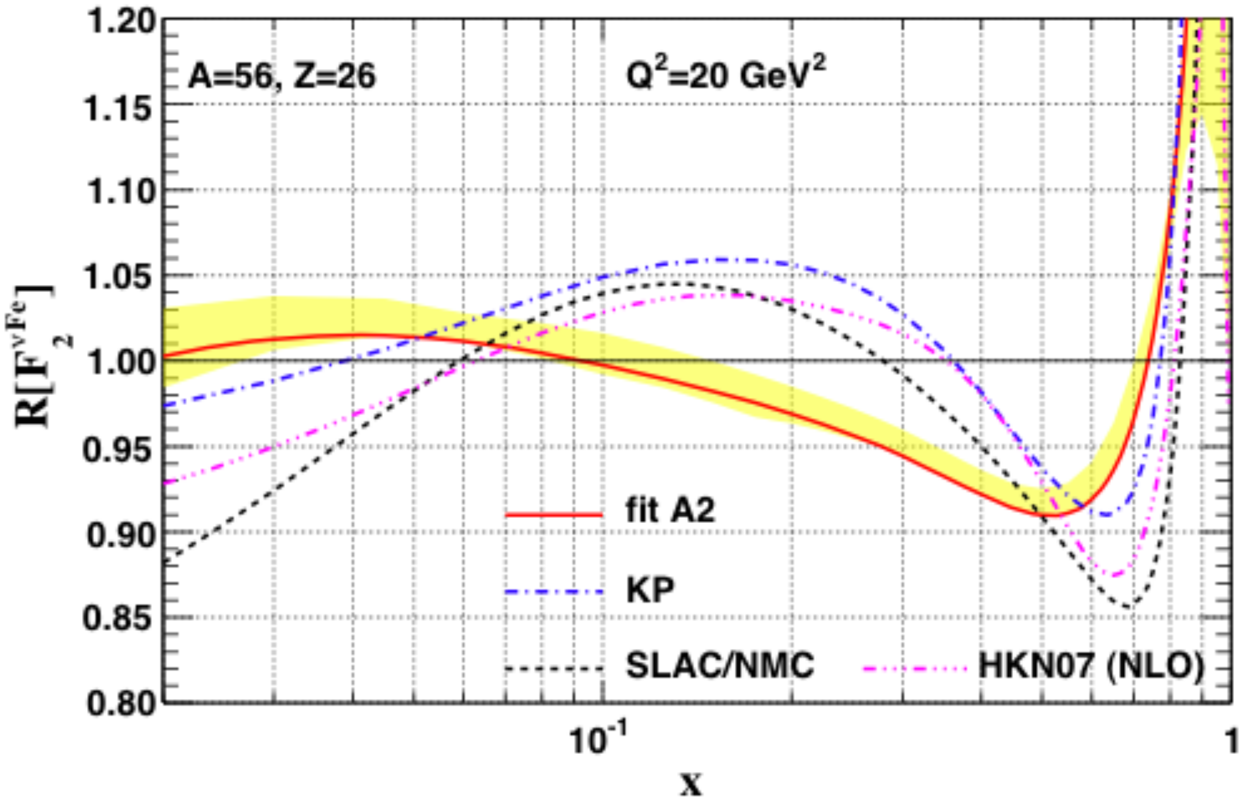
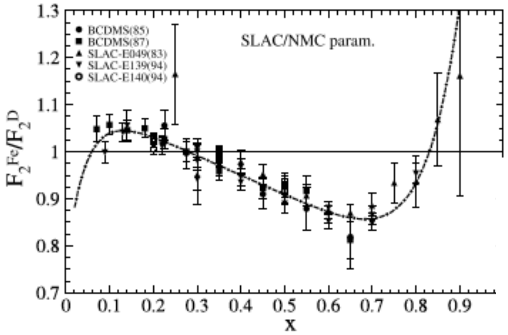
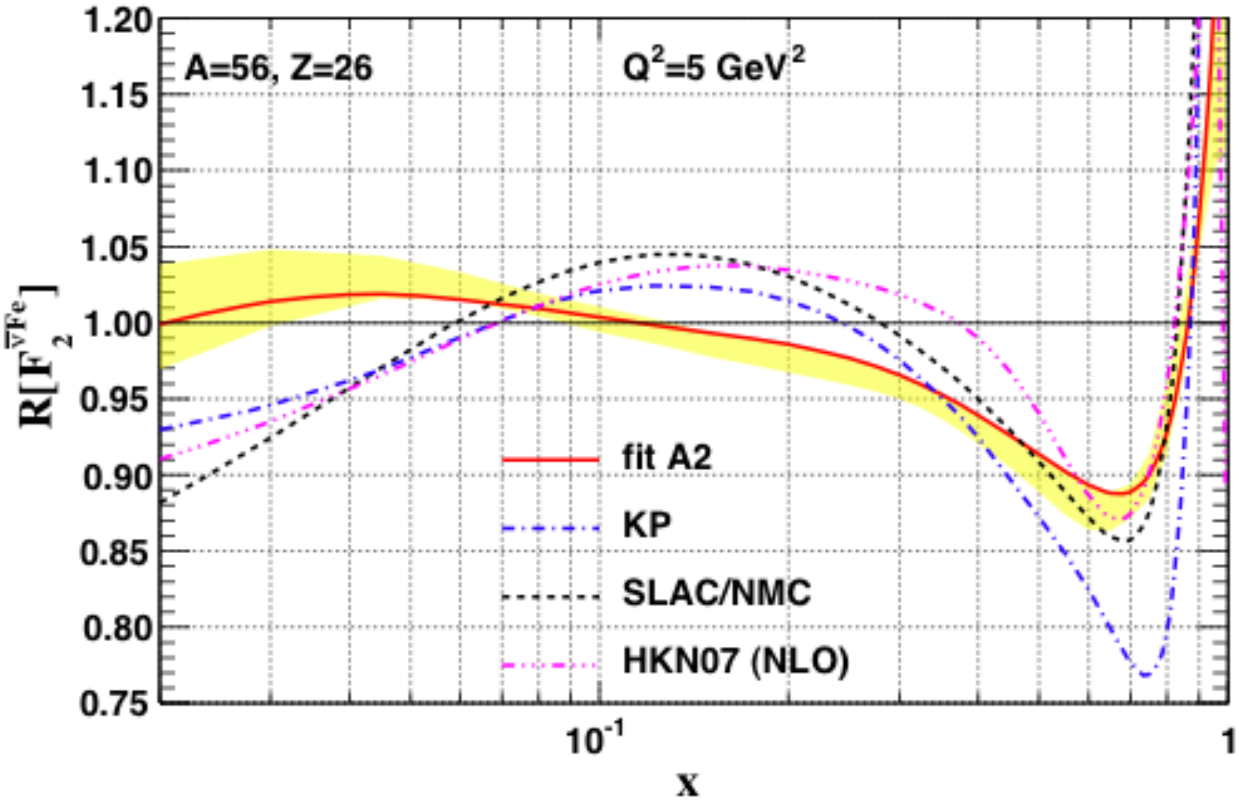


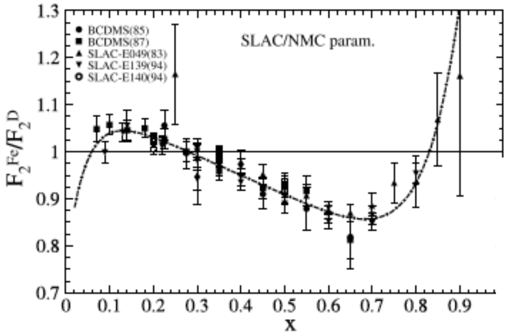


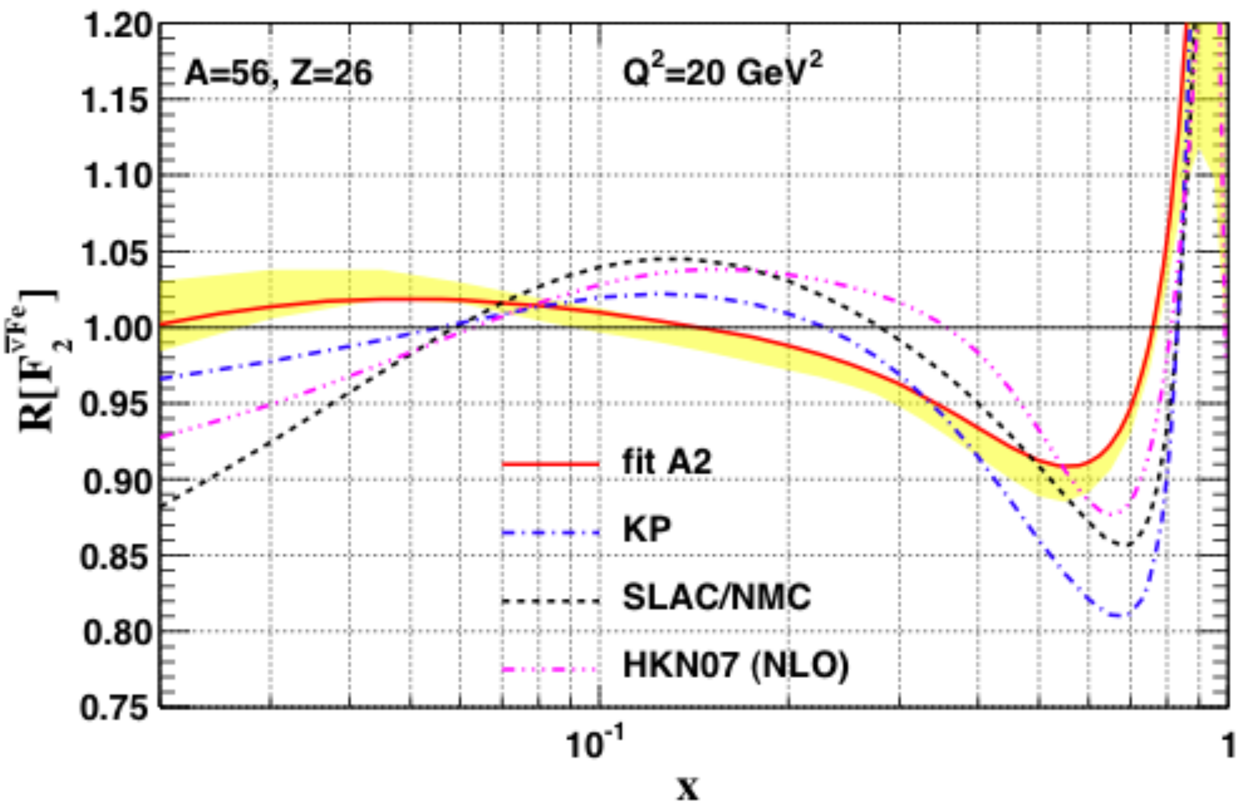
F_2 Structure Function Ratios: $\bar{\nu}$-Iron





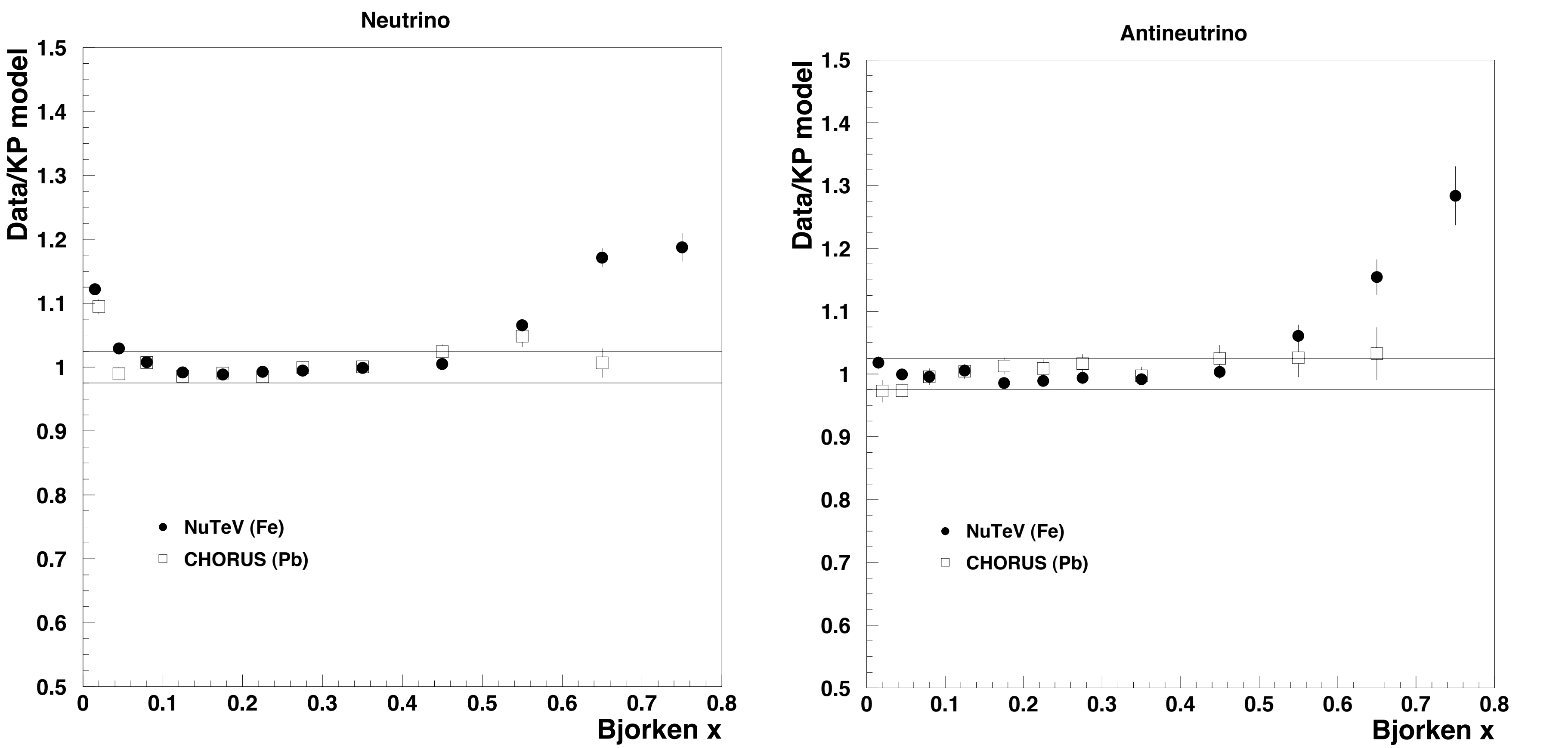
F_2 Structure Function Ratios: $\bar{\nu}$-Iron





Comparison of Data to the Kulagin-Petti Model

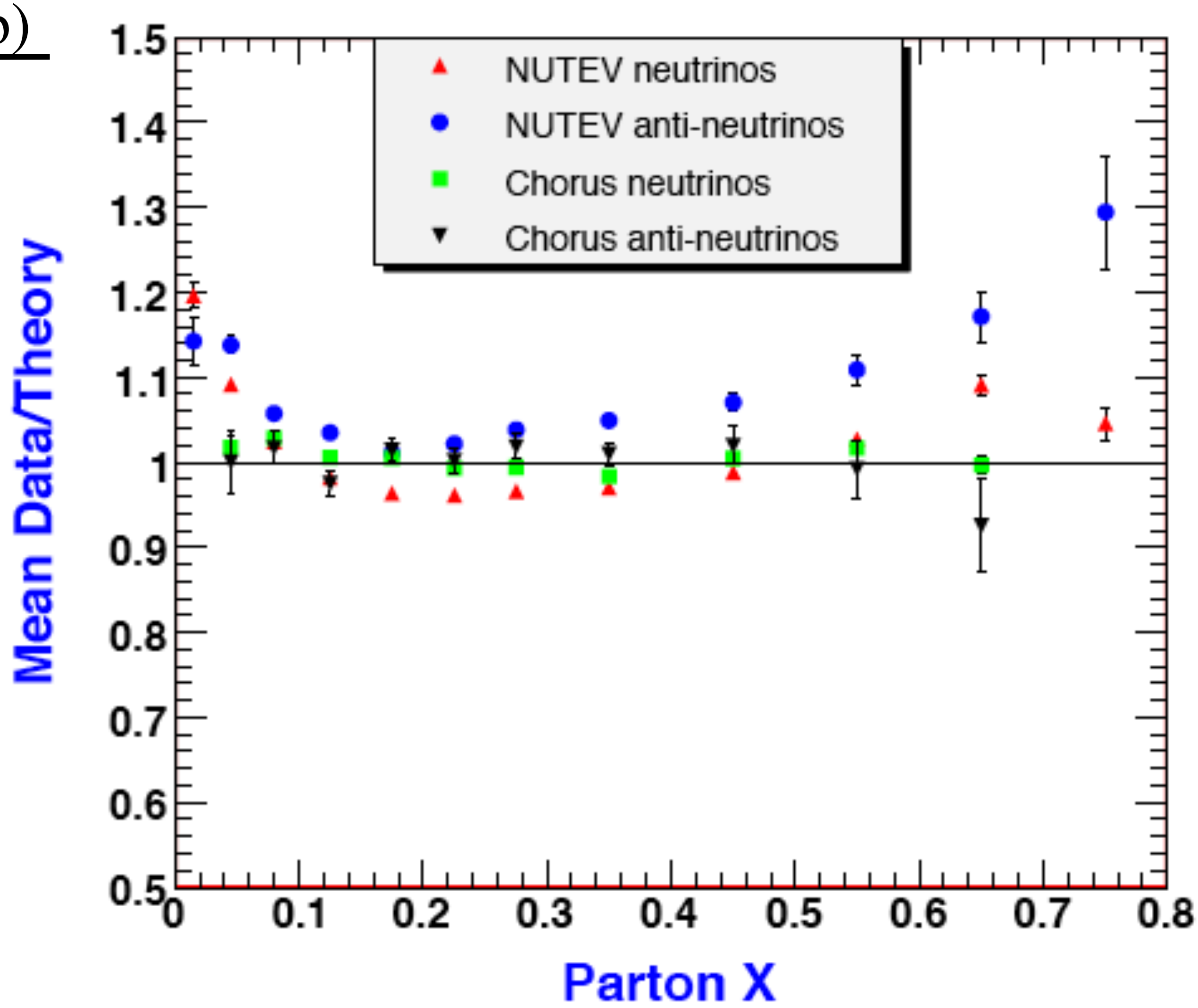
thanks to Roberto Petti



NuTeV σ(Fe) & CHORUS σ(Pb) ν scattering (shifted) results compared to reference fit

Kulagin-Petti nuclear corrections

$$\frac{\sigma(\text{Fe or Pb})}{\sigma(n+p)}$$



First Conclusions

- All high-statistics neutrino data is off nuclear targets. Need nuclear correction factors to include data off nuclei in fits with nucleon data.

- Nuclear correction factors (R) different for neutrino-Fe scattering compared to charged lepton-Fe.

- **Results from one experiment on one nuclear target… careful**.

- If we combine ν-nucleus with charged $l^{\pm}$-nucleus results and D-Y in a single global fit can we find a common description acceptable to both?

Combined Analysis of ν A, ℓA and DY data

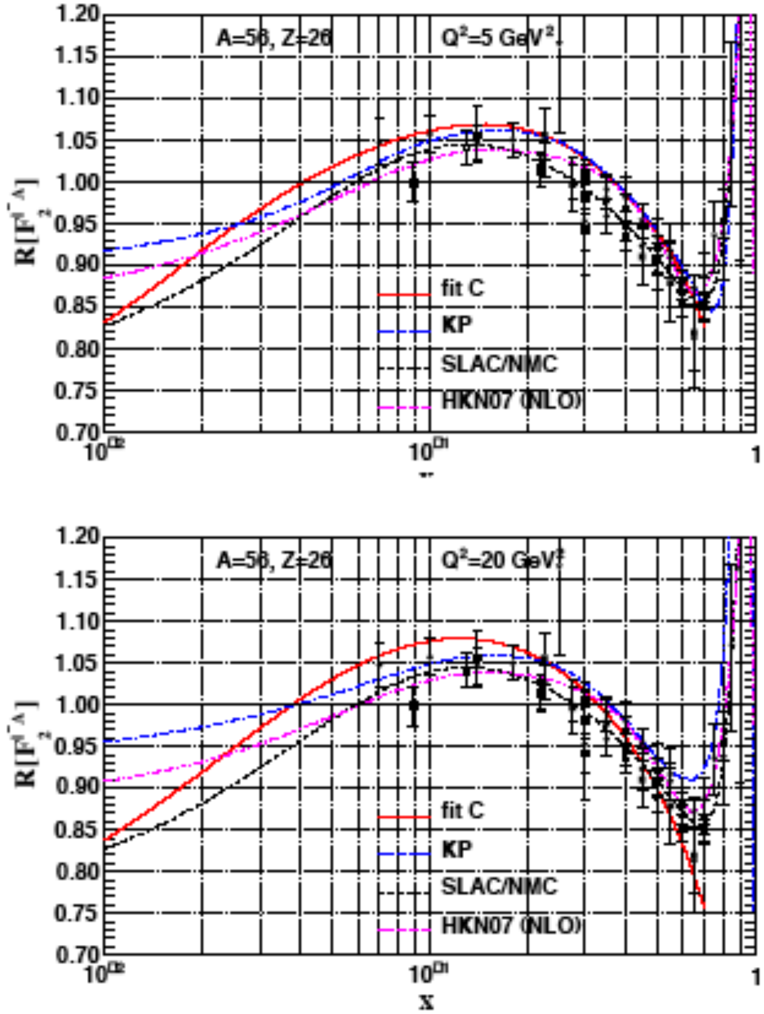
Kovarik, Yu, Keppel, Morfin, Olness, Owens, **Schienbein**, Stavreva

- Take an earlier analysis of $\ell^{\pm}$A data sets (built in A-dependence)
  - Schienbein, Yu, Kovarik, Keppel, Morfin, Olness, Owens,
  - PRD80 (2009) 094004
- For $\ell^{\pm}$A take $F_2(A)$ /$F_2(D)$ and $F_2(A)$ /$F_2(A')$ and DY $\sigma(pA)/\sigma(pA')$
  - 708 Data points with $Q > 2$ and $W > 3.5$
- Use **8 Neutrino data sets**
  - NuTeV cross section data: $\nu\, Fe$, $\overline{\nu}\, Fe$
  - NuTeV dimuon off Fe data
  - CHORUS cross section data: $\nu\, Pb$, $\overline{\nu}\, Pb$
  - CCF*R* dimuon off Fe data
- Initial problem, with standard CTEQ cuts of $Q > 2$ and $W > 3.5$ **neutrino data points (3134) far outnumber $\ell^{\pm}$A (708)**.

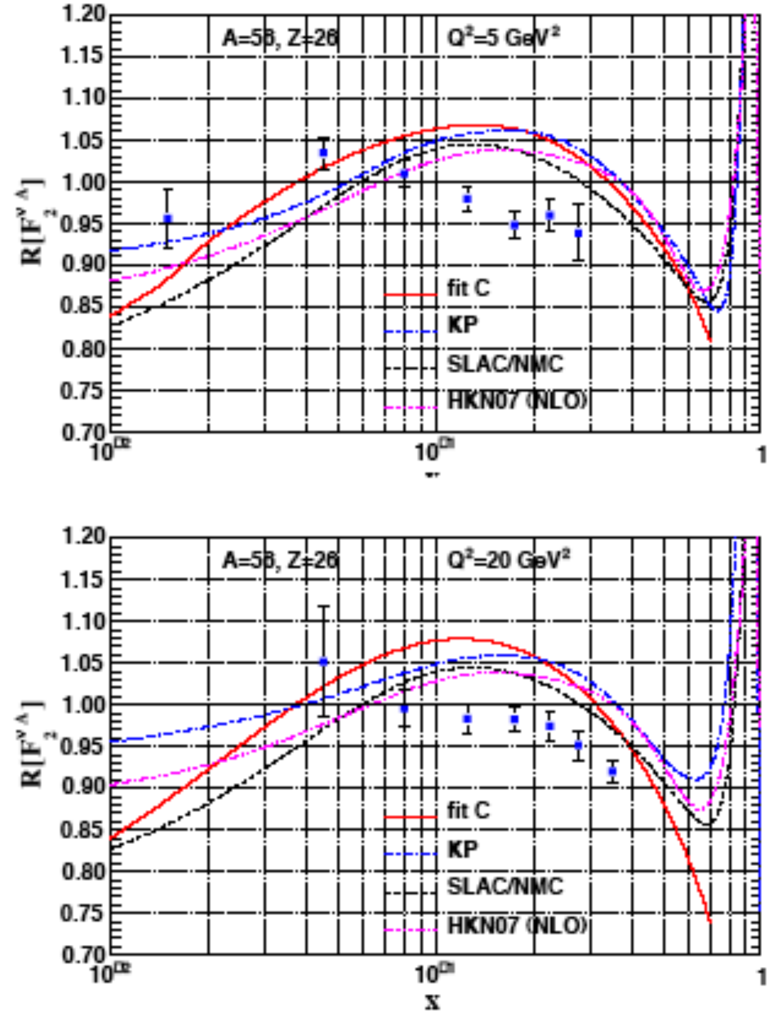
Use the usual procedure of observing the behavior of the fits as you adjust the "weight" of the dominant data sample

W = 0

$R[F_2(\ell^\pm\ Fe)]$

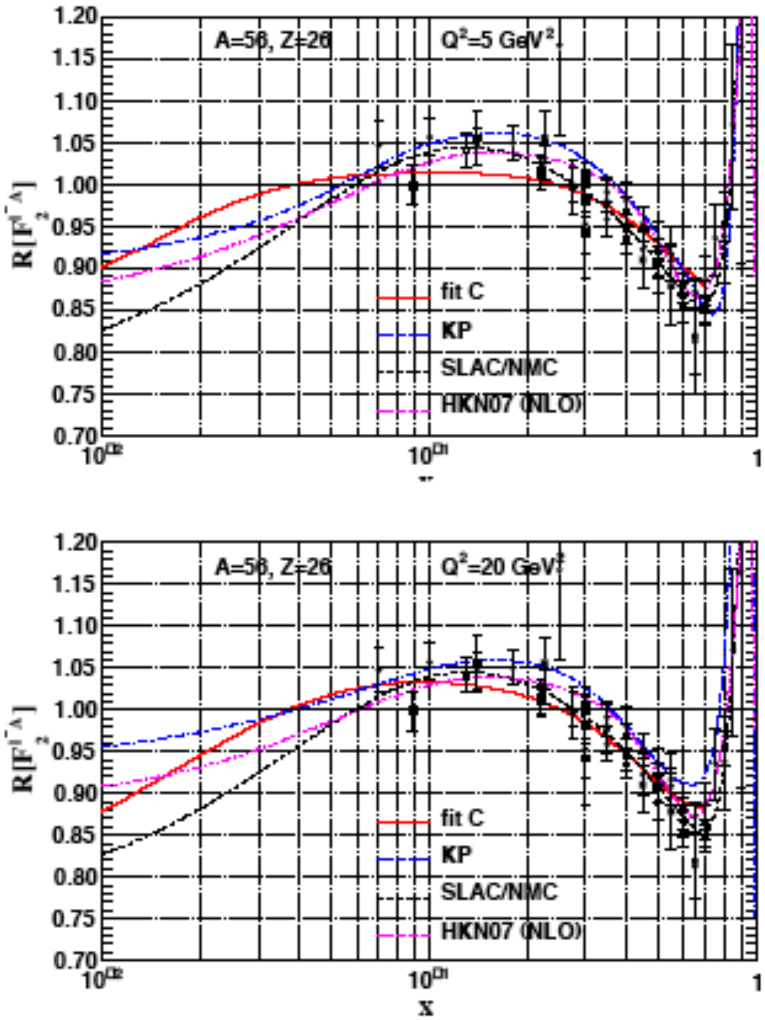


$R[F_2(\nu\ Fe)]$

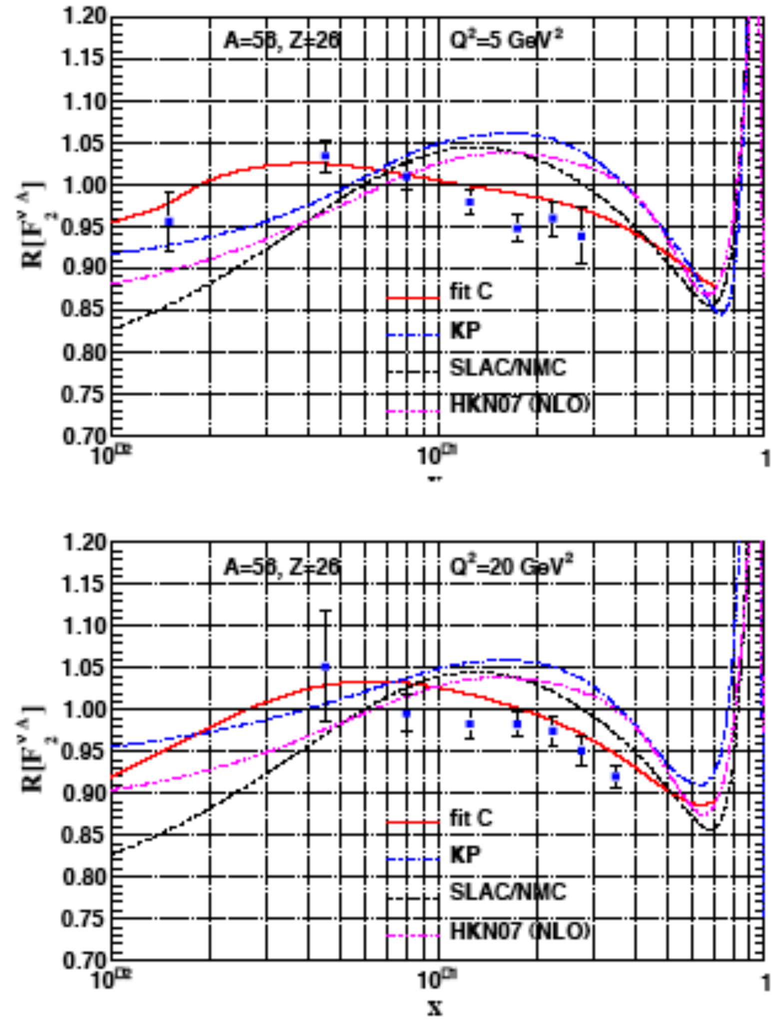


W = 1/2

R[F$_2$(ℓ$^\pm$ Fe)]

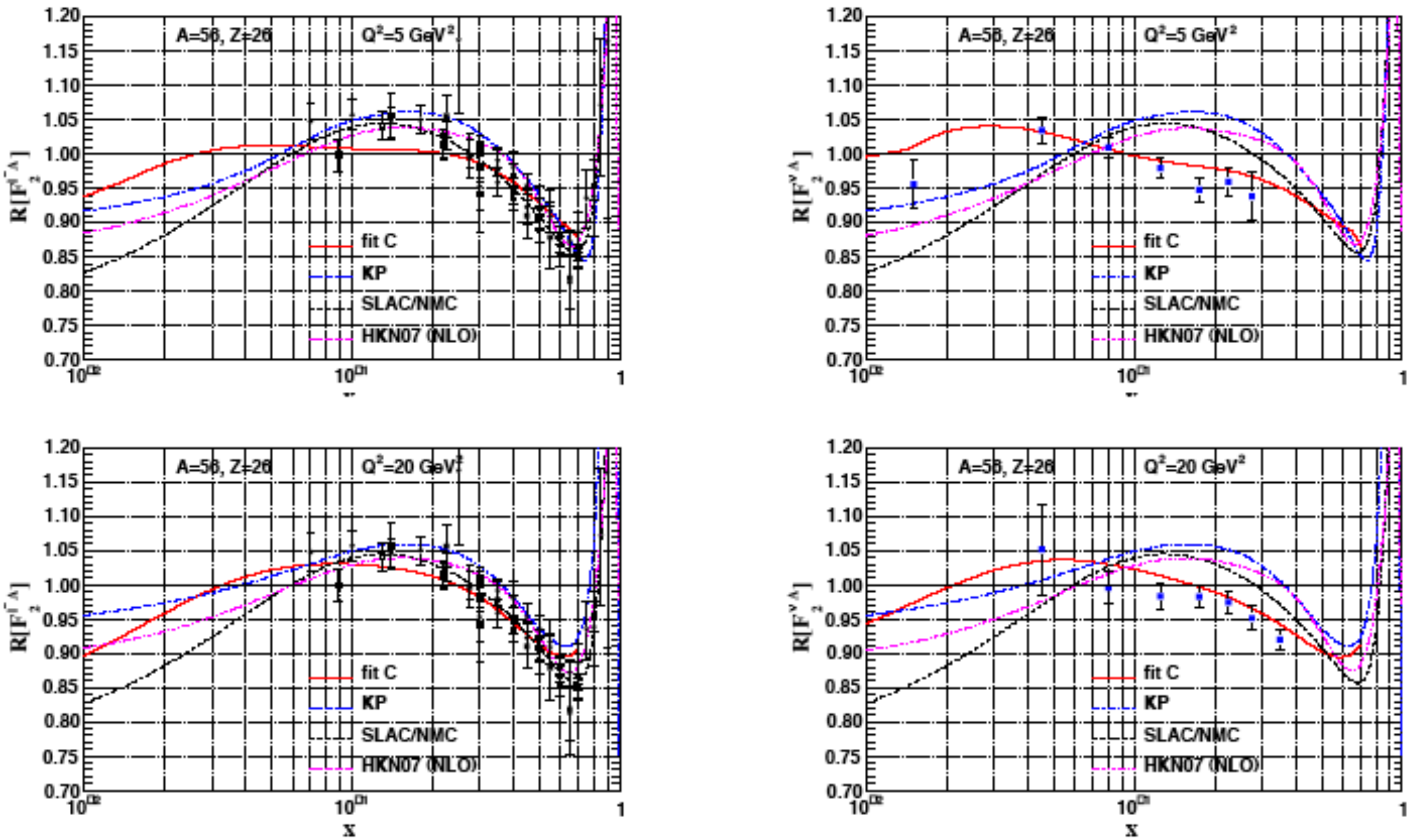


R[F$_2$(ν Fe)]



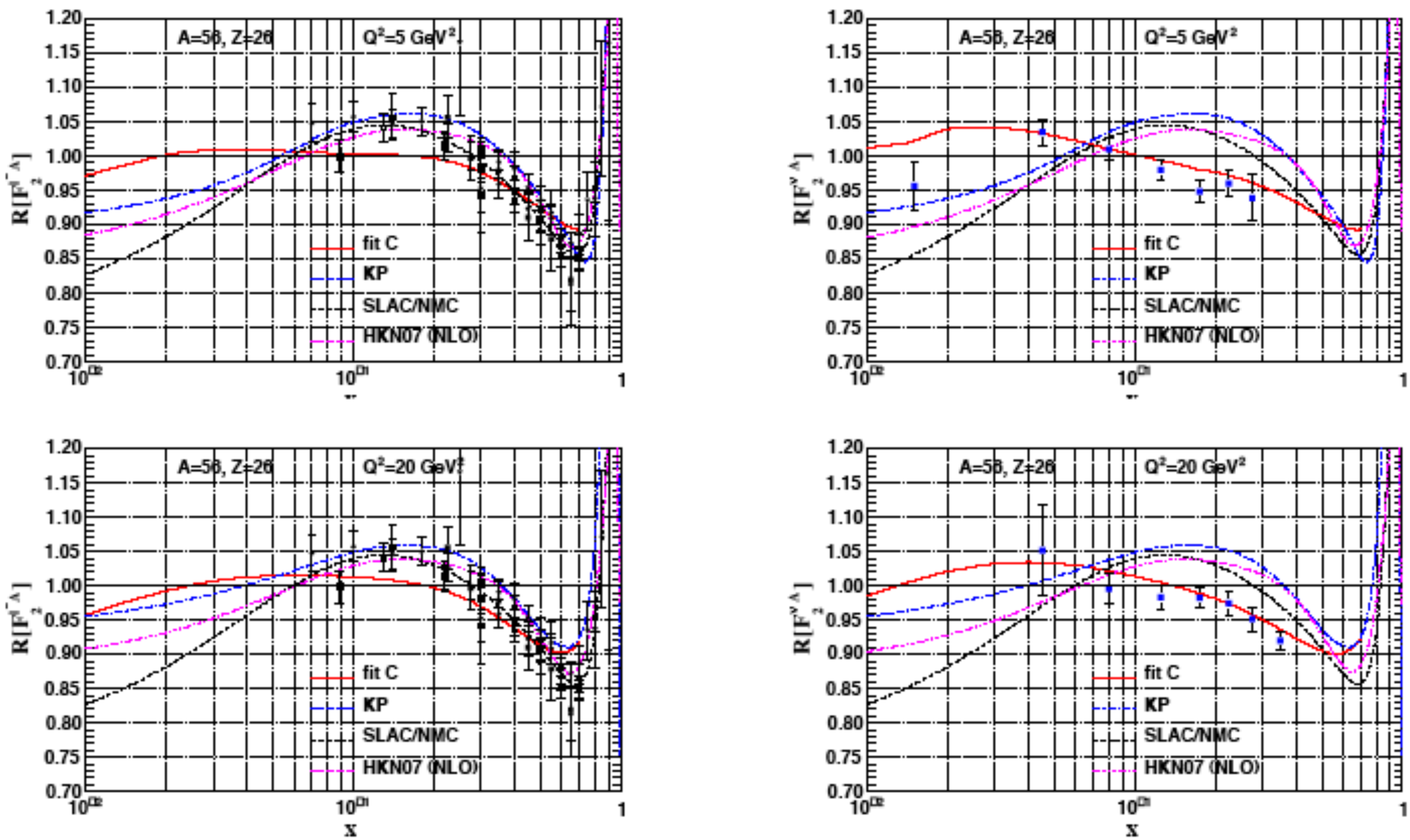
W = 1

$R[F_2(\ell^{\pm}\ Fe)]$ $R[F_2(\nu\ Fe)]$



$W = \infty$

$R[F_2(\ell^{\pm}\ Fe)]$ $R[F_2(\nu\ Fe)]$



Fit results

Weight	Fit name	ℓ data	χ^2 (/pt)	ν data	χ^2 (/pt)	total χ^2 (/pt)
$w = 0$	decut3	708	639 (0.90)	-	-	639 (0.90)
$w = 1/7$	glofac1a	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
$w = 1/4$	glofac1c	708	654 (0.92)	3134	4501 (1.43)	5155 (1.34)
$w = 1/2$	glofac1b	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
$w = 1$	global2b	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
$w = \infty$	nuanua1	-	-	3134	4192 (1.33)	4192 (1.33)

- w = 0: **No**. Problem: R[F_2(ν Fe)].
- w = 1/7: **No**. Problem: R[F_2(ν Fe)].
- w = 1/4; 1/2: **No**.
  - Q2 = 5: Undershoots R[F_2($\ell^\pm$ Fe)] for x < 0:2. Overshoots R[F_2(ν Fe)] for x 2 [0:1; 0:3].
  - Q2 = 20: R[F_2($\ell^\pm$ Fe)] still ok. Overshoots R[F_2(ν Fe)].
- w = 1: **No**. Possibly there is a compromise if more strict Q2 cut?
  - Q2 = 5: Undershoots R[F_2($\ell^\pm$ Fe)] for x < 0:2. R[F_2(ν Fe)] ok.
  - Q2 = 20: R[F_2($\ell^\pm$ Fe)] still ok. R[F_2(ν Fe)] ok.
- w = ∞: **No**. Problem: R[F_2($\ell^\pm$ Fe)].

Quantitative χ^2 Analysis

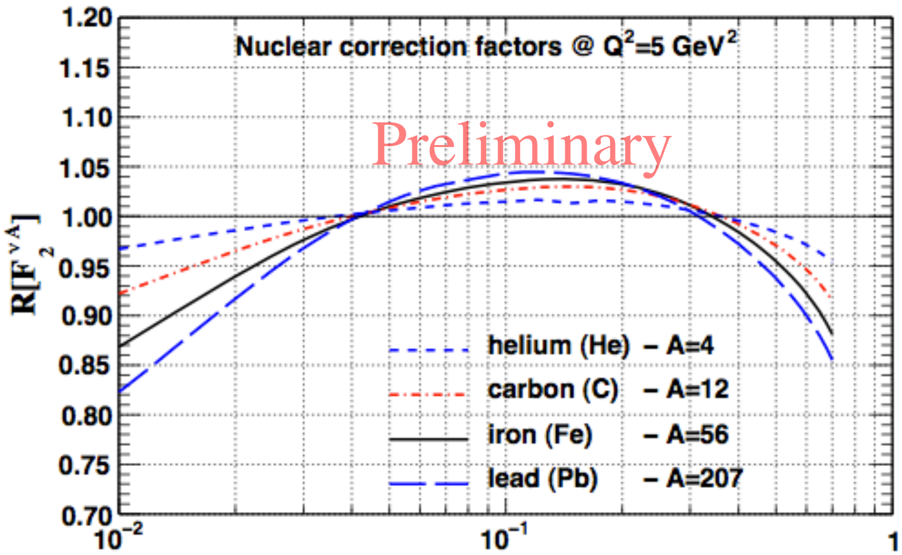
- Up to now we are giving a qualitative analysis. Consider next quantitative criterion based on χ^2
- Introduce "tolerance" (T). Condition for compatibility of two fits:

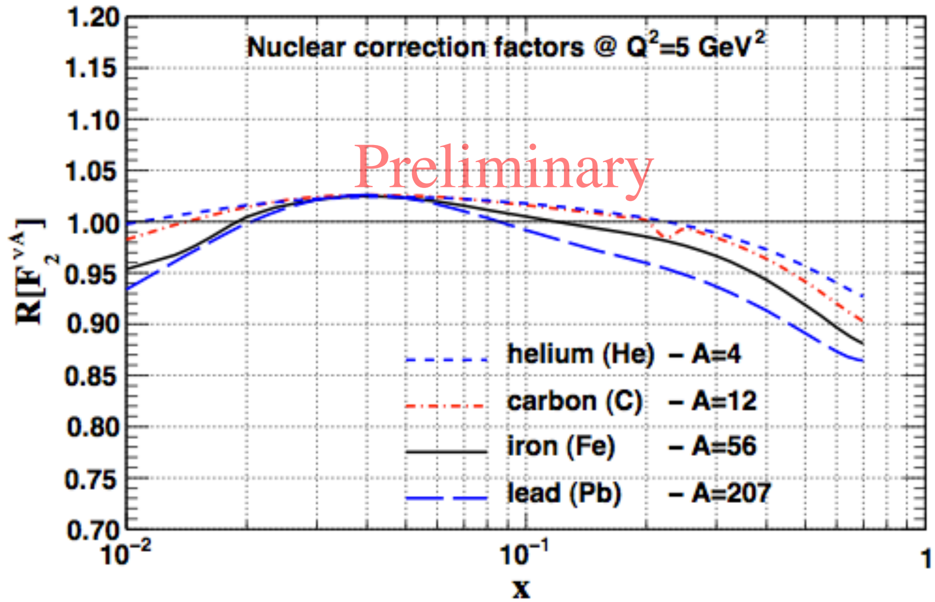
The 2nd fit χ^2 should be within the 90% C.L. region of the first fit χ^2

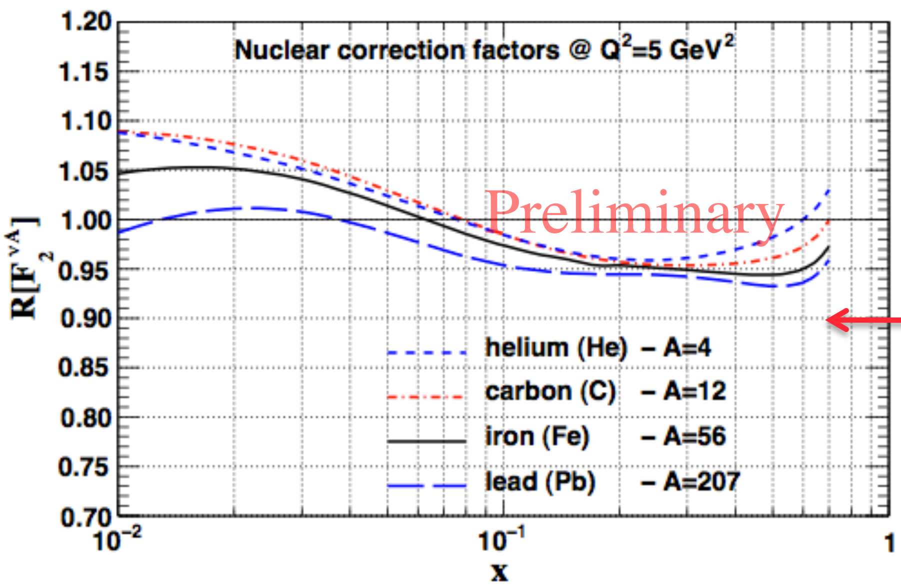
- Charged: 638.9 ± 45.6 (best fit to charged lepton and DY data)
- Neutrino: 4192 ± 138 (best fit to only neutrino data)

Weight	Fit name	ℓ data	χ^2	ν data	χ^2	total χ^2 (/pt)
$w = 0$	decut3	708	639	-	nnnn **NO**	639 (0.90)
$w = 1/7$	glofac1a	708	645 **YES**	3134	4710 **NO**	5355 (1.39)
$w = 1/4$	glofac1c	708	654 **YES**	3134	4501 **NO**	5155 (1.34)
$w = 1/2$	**glofac1b**	708	680 **YES**	3134	4405 **NO*** **	5085 (1.32)
$w = 1$	global2b	708	736 **NO**	3134	4277 **YES**	5014 (1.30)
$w = \infty$	nuanua1	-	nnn **NO**	3134	4192	4192 (1.33)

Few Days Old - VERY Preliminary Predictions for MINERνA Targets







Careful! Based on analysis of NuTeV ν-Fe results and scaled in A **as charged lepton nucleus** scattering results!

(Karol Kovarik – Katlsruhe)

Summary and Conclusions

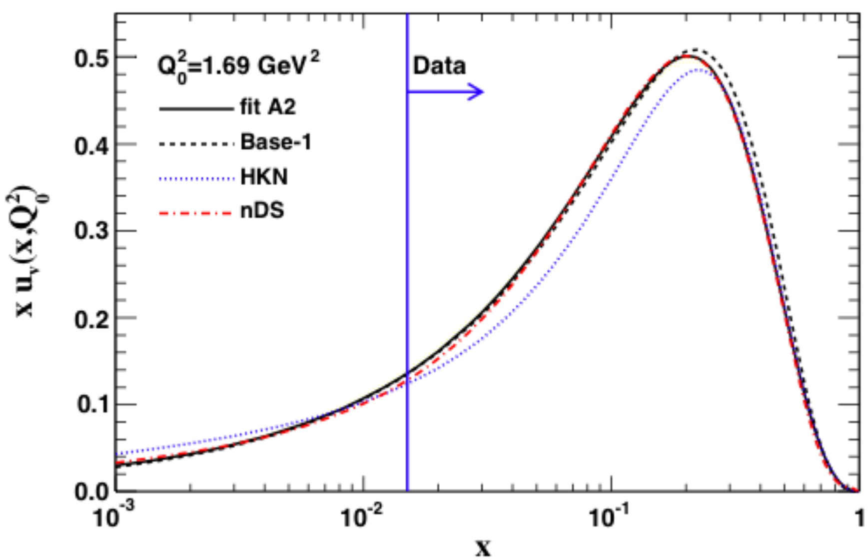
- Neutrino scattering can provide an important look at the nucleon from a different (and complimentary) angle than electro-production.
  - The ability of neutrinos and anti-neutrinos to taste particular flavors of quarks can help isolate PDFs
- To understand the neutrino (oscillations, mixing, matter effects and δ^{CP}) neutrino experiments use heavy nuclear targets to obtain statistics. **Need to understand ν-induced nuclear effects!**
  - **Use the difference between ν and $\bar{\nu}$ to measure** δ^{CP}**. Nuclear effects are NOT the same?**
- There are indications from **one** experiment using **one** nucleus that **ν-induced nuclear effects are different** than $\ell^{\pm}$-nuclear effects.
  - Based on nuclear corrections factors R and the tolerance criterion, there is no good compromise fit to the $\ell^{\pm}$A + DY + νA data.
- Need systematic **experimental** study of **ν-induced nuclear effects in A and D_2.**
- **MINERνA** – 4.9 x10^{20} POT in LE and 12.0 x10^{20} POT in ME configuration:
  - If ME beam **all neutrino** expect **produced (NEUGEN)** ≈ 4.3 x 10^{6} DIS events in 3 tons plastic, over 1 million DIS events in Fe and Pb and ½ million DIS events in water.

Additional Details

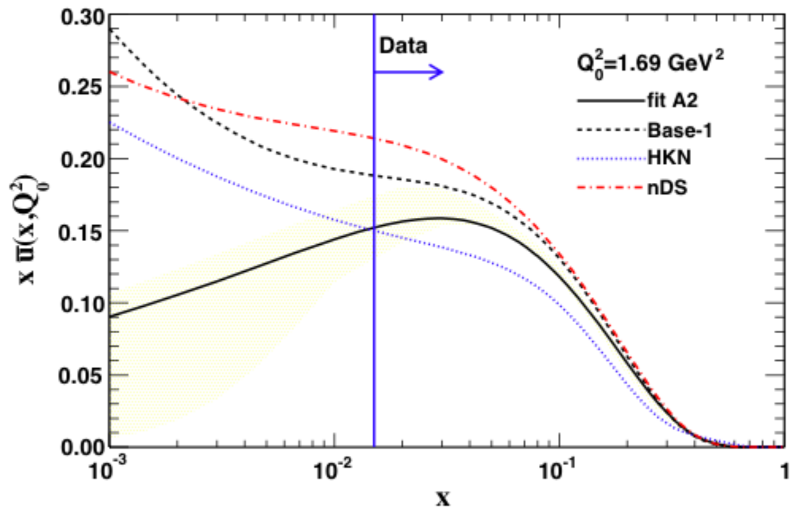
Motivation for Studying ν DIS

- Interacting with the weak current means a **much smaller interaction rate** than e/μ scattering
  - Need huge, higher-A detectors and intense neutrino beams
  - The neutrino flux is difficult to predict and measure.
- However **can select which set of quarks involved in the interaction via ν or $\overline{\nu}$**
- While F_2 is measured precisely by the charge lepton scattering, **xF_3 is accessible by neutrino DIS**.
  - ΔxF_3 yields increased sensitivity to the **valence quark distributions.**
  - However, through $\Delta xF_3 = 4x(s-c)$, ΔxF_3 is **also sensitive to heavy quarks.**
- Speaking of heavy quarks, examining charm production with neutrinos also gives us insight into the **strange quark distribution**.
- **Electroweak physics** has been a rich neutrino subject for decades.
- Finally, recent phenomenological / experimental work is indicating some interesting **differences concerning nuclear effects with neutrinos compared to charged lepton scattering.**

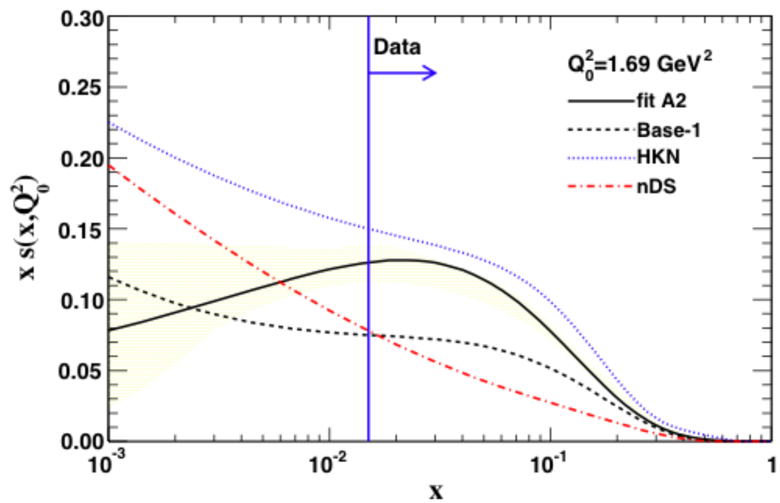
Iron PDFs



Q_0^2=1.69 GeV^2
Data
fit A2
Base-1
HKN
nDS
$x\, u_v(x,Q_0^2)$
x



Data
Q_0^2=1.69 GeV^2
fit A2
Base-1
HKN
nDS
$x\, \bar{u}(x,Q_0^2)$
x



Data
Q_0^2=1.69 GeV^2
fit A2
Base-1
HKN
nDS
$x\, s(x,Q_0^2)$
x

Charged lepton data points

- DIS F_2^A/F_2^D data sets: 862 points (before cuts)
- DIS $F_2^A/F_2^{A'}$ data sets: 297 points (before cuts)
- DY data sets $\sigma_{\mathrm{DY}}^{pA}/\sigma_{\mathrm{DY}}^{pA'}$: 92 points (before cuts)

Table from Hirai et al.,arXiv:0909.2329

	R	Nucleus	Experiment	EPS09	HKN07	DS04
DIS		D/p	NMC		O	
	A/D	4He	SLAC E139	O	O	O
			NMC95	O (5)	O	O
		Li	NMC95	O	O	
		Be	SLAC E139	O	O	O
		C	EMC-88, 90		O	
			NMC 95	O	O	O
			SLAC E139	O	O	O
			FNAL-E665		O	
		N	BCDMS 85		O	
			HERMES 03		O	
		Al	SLAC E49		O	
			SLAC E139	O	O	O
		Ca	EMC 90		O	
			NMC 95	O	O	O
			SLAC E139	O	O	O
			FNAL-E665		O	
		Fe	SLAC E87		O	
			SLAC E139	O (15)	O	O
			SLAC E140		O	
			BCDMS 87		O	
		Cu	EMC 93	O	O	
		Kr	HERMES 03		O	
		Ag	SLAC E139	O	O	O
		Sn	EMC 88		O	
		Au	SLAC E139	O	O	O
			SLAC E140		O	
		Pb	FNAL-E665		O	
	A/C	Be	NMC 96	O	O	O
		Al	NMC 96	O	O	O
		Ca	NMC 95		O	
			NMC 96	O	O	O
		Fe	NMC 96	O	O	O
		Sn	NMC 96	O (10)	O	O
		Pb	NMC 96	O	O	O
	A/Li	C	NMC 95	O	O	
		Ca	NMC 95	O	O	
DY	A/D	C	FNAL-E772	O	O	O
		Ca		O (15)	O	O
		Fe		O (15)	O	O
		W		O (10)	O	O
	A/Be	Fe	FNAL E866	O	O	
		W		O	O	
π pro	dA/pp	Au	RHIC-PHENIX	O (20)		

High-x PDFs

ν - p Scattering

$$F_2^{\nu p} = 2x\,(d + \bar{u} + s)$$

$$F_2^{\bar{\nu} p} = 2x\,(\bar{d} + u + \bar{s})$$

$$\xrightarrow{\text{At high x}} \quad \boxed{\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} = \frac{d}{u}}$$

Add in…

$$xF_3^{\nu p} = 2x\,(d - \bar{u} + s)$$

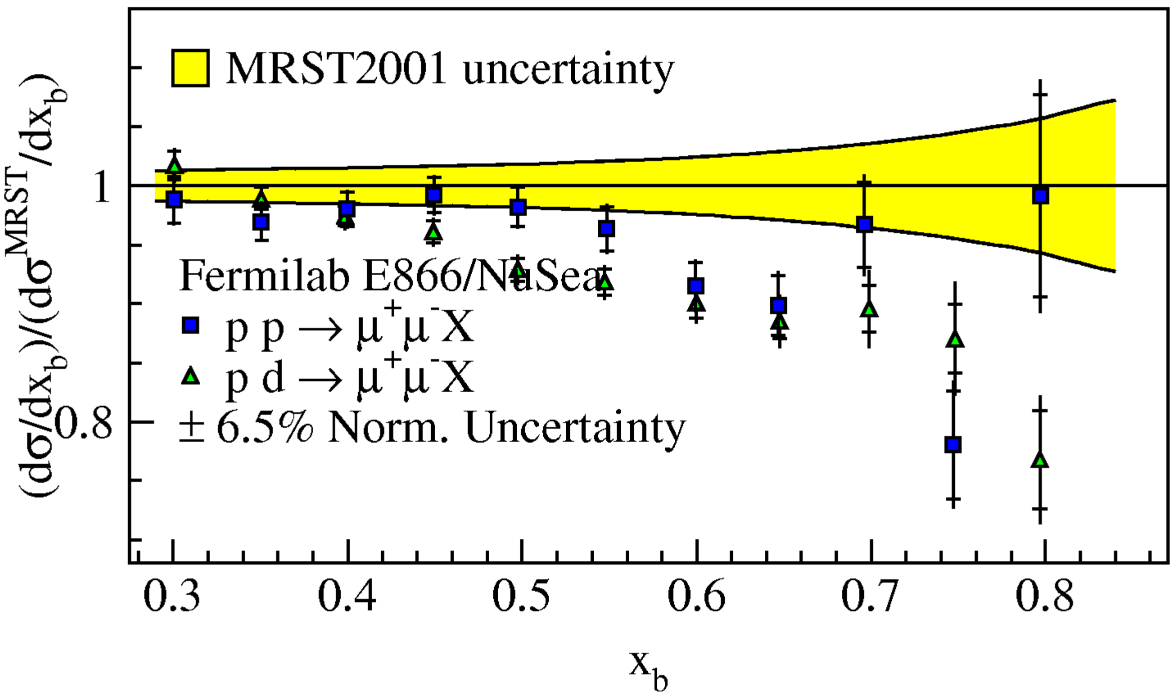
$$xF_3^{\bar{\nu} p} = 2x\,(-\bar{d} + u - \bar{s})$$

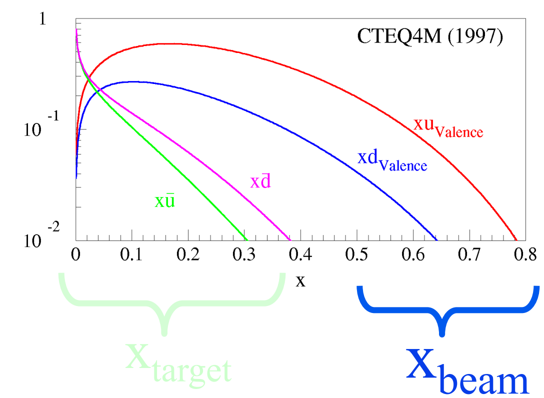
$$\longrightarrow \quad F_2^{\nu p} - xF_3^{\nu p} = 4x\bar{u}$$

$$F_2^{\bar{\nu} p} + xF_3^{\bar{\nu} p} = 4xu$$

Further indications that the valence quarks not quite right at high-x??

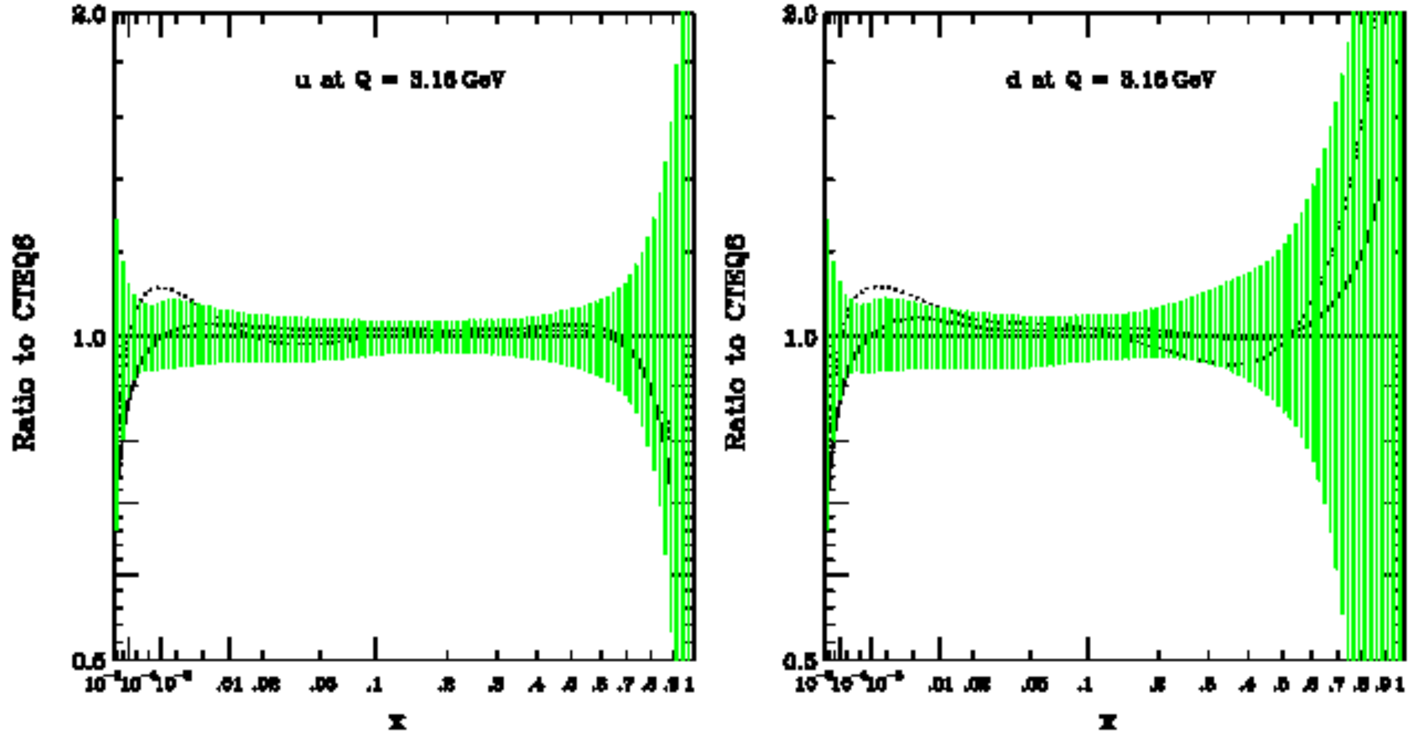
E866 -Drell-Yan Preliminary Results (R. Towell - Hix2004)





- x_{beam} **distribution measures** ***4u + d*** **as** ***x--> 1*****.**
- **Both MRST and CTEQ** ***overestimate*** **valence distributions as** ***x --> 1*** **by 15-20%.**
- **Possibly related to** ***d/u*** **ratio as** ***x --> 1*****, but requires full PDF-style fit.**
- *Radiative corrections have recently been calculated. (Not yet fully applied)*

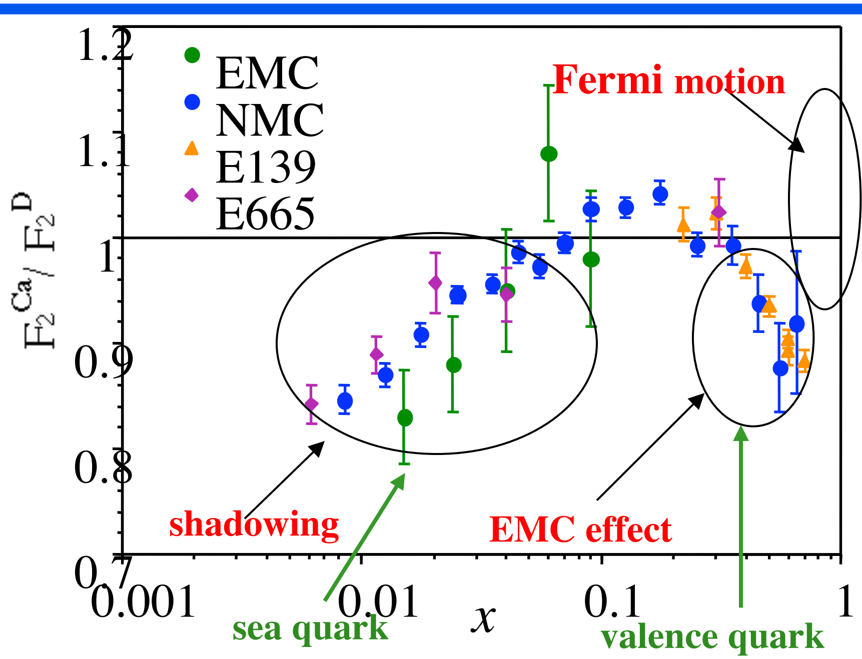
Present Status: ν-scattering
High x_{Bj} parton distributions

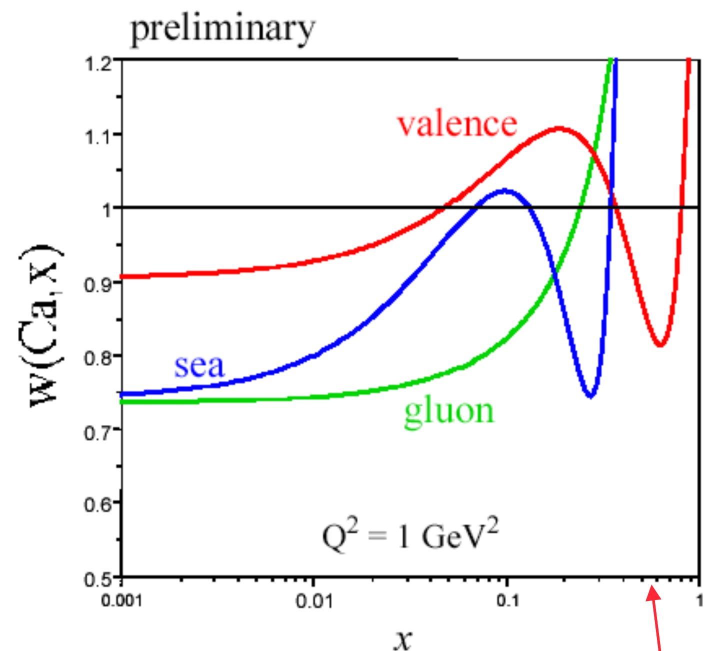


- Ratio of CTEQ5M (solid) and MRST2001 (dotted) to CTEQ6 for the u and d quarks at $Q^2 = 10\ \text{GeV}^2$. The shaded green envelopes demonstrate the range of possible distributions from the CTEQ6 error analysis.

- CTEQ / MINERνA working group to investigate high-x_{Bj} region.

Knowledge of Nuclear Effects with Neutrinos: essentially NON-EXISTENT





- F_2 / nucleon changes as a function of A. Measured in μ/e - A **not in ν − A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A**.
  - **Presence of axial-vector current.**
  - **SPECULATION: Much stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**
  - **Different nuclear effects for d and u quarks.**

Formalism

- PDF Parameterized at Q_0 = 1.3 GeV as

$$x f_i(x, Q_0) = \begin{cases} A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1+e^{A_4} x)^{A_5} & : i = u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s}\,, \\ A_0 x^{A_1}(1-x)^{A_2} + (1+A_3 x)(1-x)^{A_4} & : i = \bar{d}/\bar{u}\,, \end{cases}$$

- PDFs for a nucleus are constructed as:

$$f_i^A(x,Q) = \frac{Z}{A}\, f_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, f_i^{n/A}(x,Q)$$

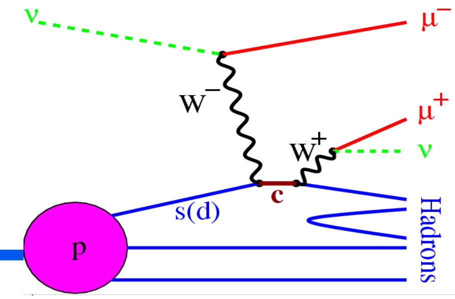
- Resulting in nuclear structure functions:

$$F_i^A(x,Q) = \frac{Z}{A}\, F_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, F_i^{n/A}(x,Q)$$

- The differential cross sections for CC scattering off a nucleus::

$$\frac{d^2\sigma}{dx\,dy}^{\overset{(-)}{\nu} A} = \frac{G^2 M E}{\pi}\left[(1 - y - \frac{Mxy}{2E})F_2^{\overset{(-)}{\nu} A} + \frac{y^2}{2} 2xF_1^{\overset{(-)}{\nu} A} \pm y(1-\frac{y}{2})xF_3^{\overset{(-)}{\nu} A}\right]$$

Charm Production by Neutrinos
a direct look at strange sea.



- Charm quark is produced from CC neutrino interaction with s(d) quark in the nucleon. d-quark interaction is CKM suppressed
- Detect charm via the semi-leptonic decay which yields a very clear signature – two opposite sign muons
- It is sensitive to m_c through E_ν dependence.
- With high-purity ν and $\bar{\nu}$ beams, NuTeV made high statistics separate s and $\bar{s}$ measurements: 5163 ν and 1380 $\bar{\nu}$
- Could then make a measurement of $s - \bar{s}$.

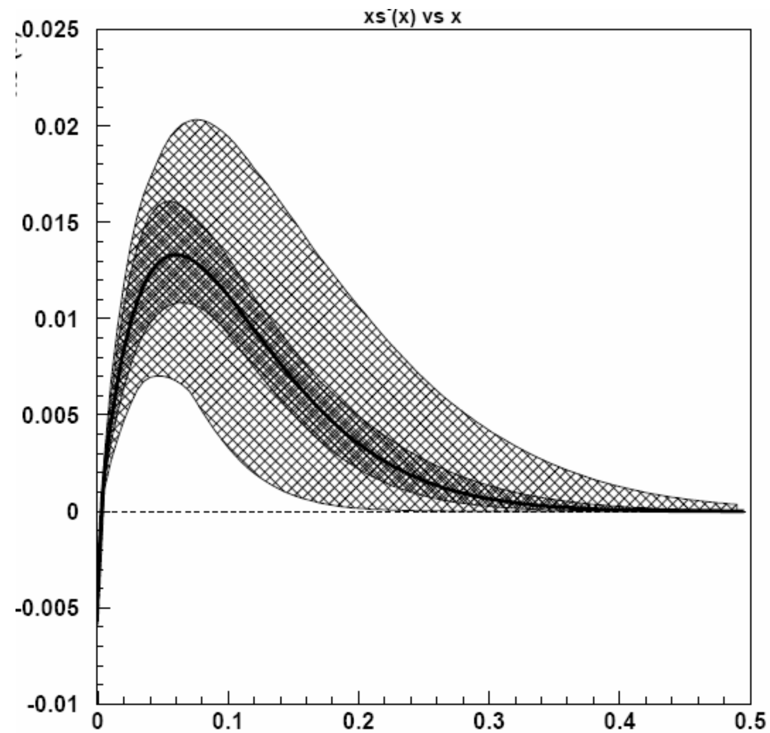
Strange Sea Asymmetry

$$s^- = (s - \bar{s})$$

$$S^- = \int_0^1 xs^-(x)dx = 0.00196 \pm \underset{\text{(stat)}}{0.00046} \pm \underset{\text{(syst)}}{0.00045} \pm \underset{\text{(external)}}{0.00128}$$

- CTEQ inspired NLO model,
- in the fit net strangeness of the nucleon is forced to 0.

$m_c = 1.41 \pm 0.10\text{(stat)} \pm 0.008\text{(syst)} \pm 0.12\text{(ext) GeV}/c^2$



This is an anlysis of strange quarks in an Fe nucleus!
Are ν nuclear effects known? Are they the same for ν and $\bar{\nu}$?

Parton Distribution Functions:
What Can We Learn With All Six Structure Functions?

Recall Neutrinos have the ability to directly resolve flavor of the nucleon's constituents: ν interacts with d, s, $\bar{u}$, and $\bar{c}$ while $\bar{\nu}$ interacts with u, c, $\bar{d}$ and $\bar{s}$.

Using Leading order expressions:

$$F_2^{\bar{\nu}N}(x,Q^2) = x\left[u+\bar{u}+d+\bar{d}+2\bar{s}+2c\right]$$

$$F_2^{\nu N}(x,Q^2) = x\left[u+\bar{u}+d+\bar{d}+2s+2\bar{c}\right]$$

$$xF_3^{\bar{\nu}N}(x,Q^2) = x\left[u+d-\bar{u}-\bar{d}-2\bar{s}+2c\right]$$

$$xF_3^{\nu N}(x,Q^2) = x\left[u+d-\bar{u}-\bar{d}+2s-2\bar{c}\right]$$

Taking combinations of the Structure functions

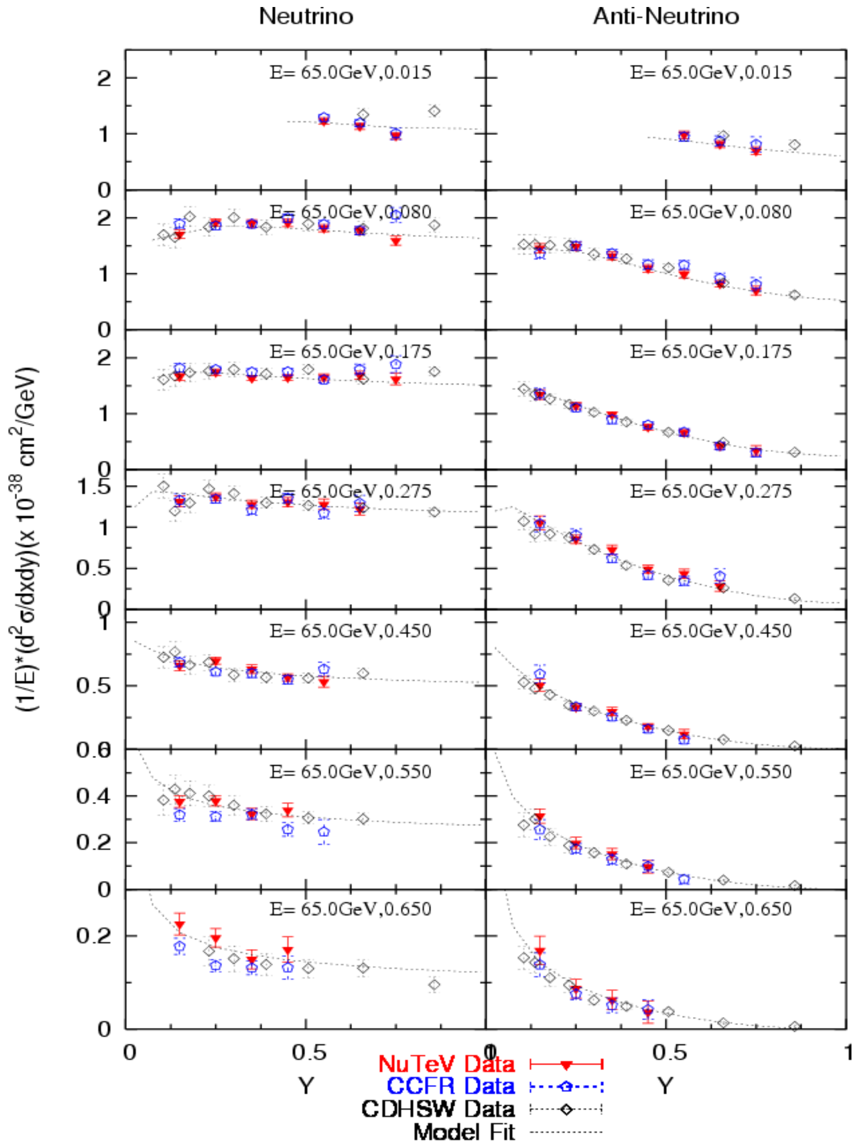
$$F_2^{\nu} - xF_3^{\nu} = 2\left(\bar{u}+\bar{d}+2\bar{c}\right)$$

$$F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} = 2\left(\bar{u}+\bar{d}+2\bar{s}\right)$$

$$xF_3^{\nu} - xF_3^{\bar{\nu}} = 2\left[\left(s+\bar{s}\right)-\left(\bar{c}+c\right)\right]$$

NuTeV CC Differential Cross Section

$d\sigma/dy$ for different E_ν

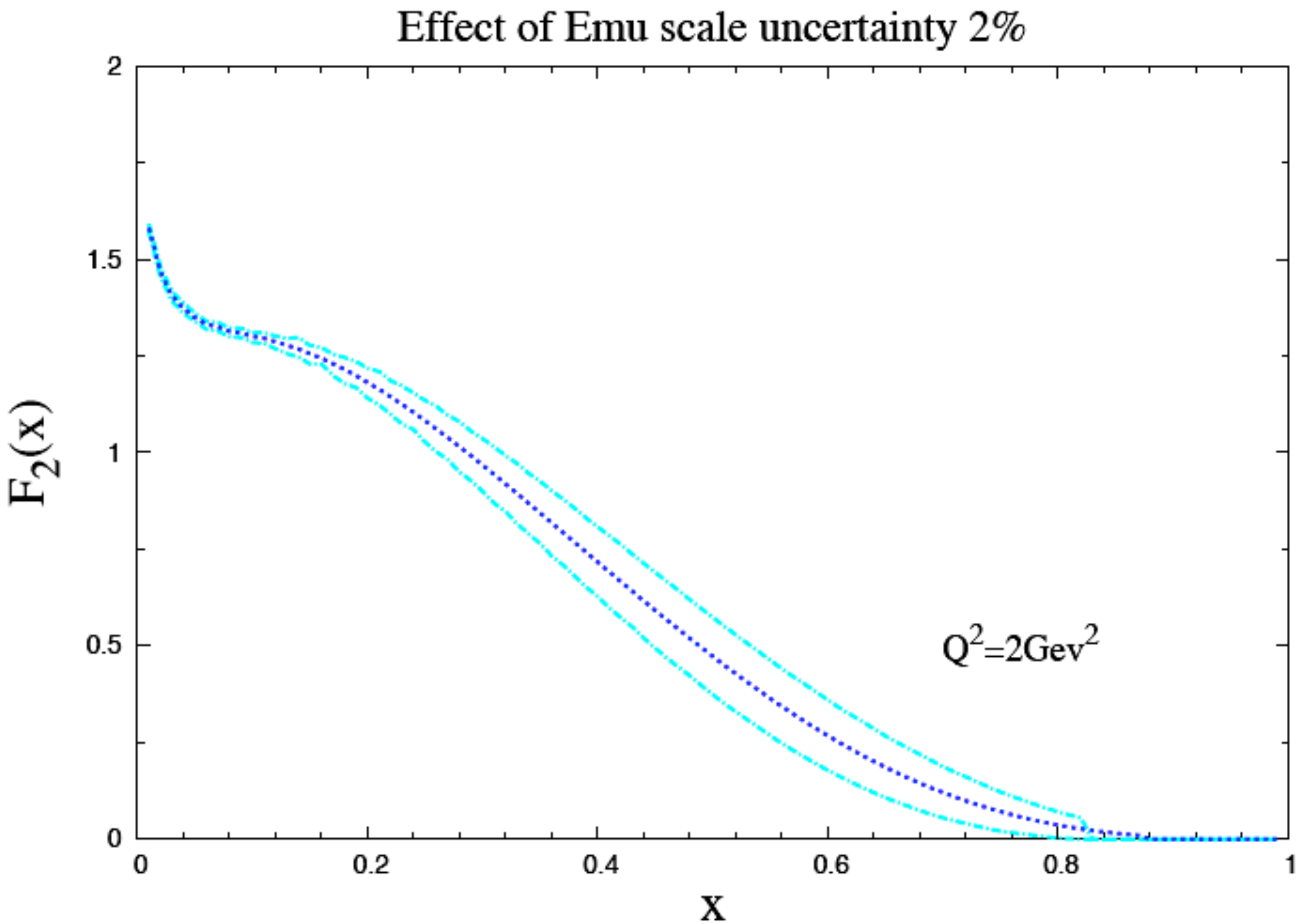


	E_μ scale	E_{HAD} scale	E_ν range (GeV)
CDHSW	2%	2.5%	20-200
CCFR	1%	1%	30-360
NuTeV	0.7%	0.43%	30-360

- NuTeV has increased statistics compared to other ν-Fe experiments.
- Significant reduction in the largest systematic uncertainties : - E_μ and E_{HAD} scales

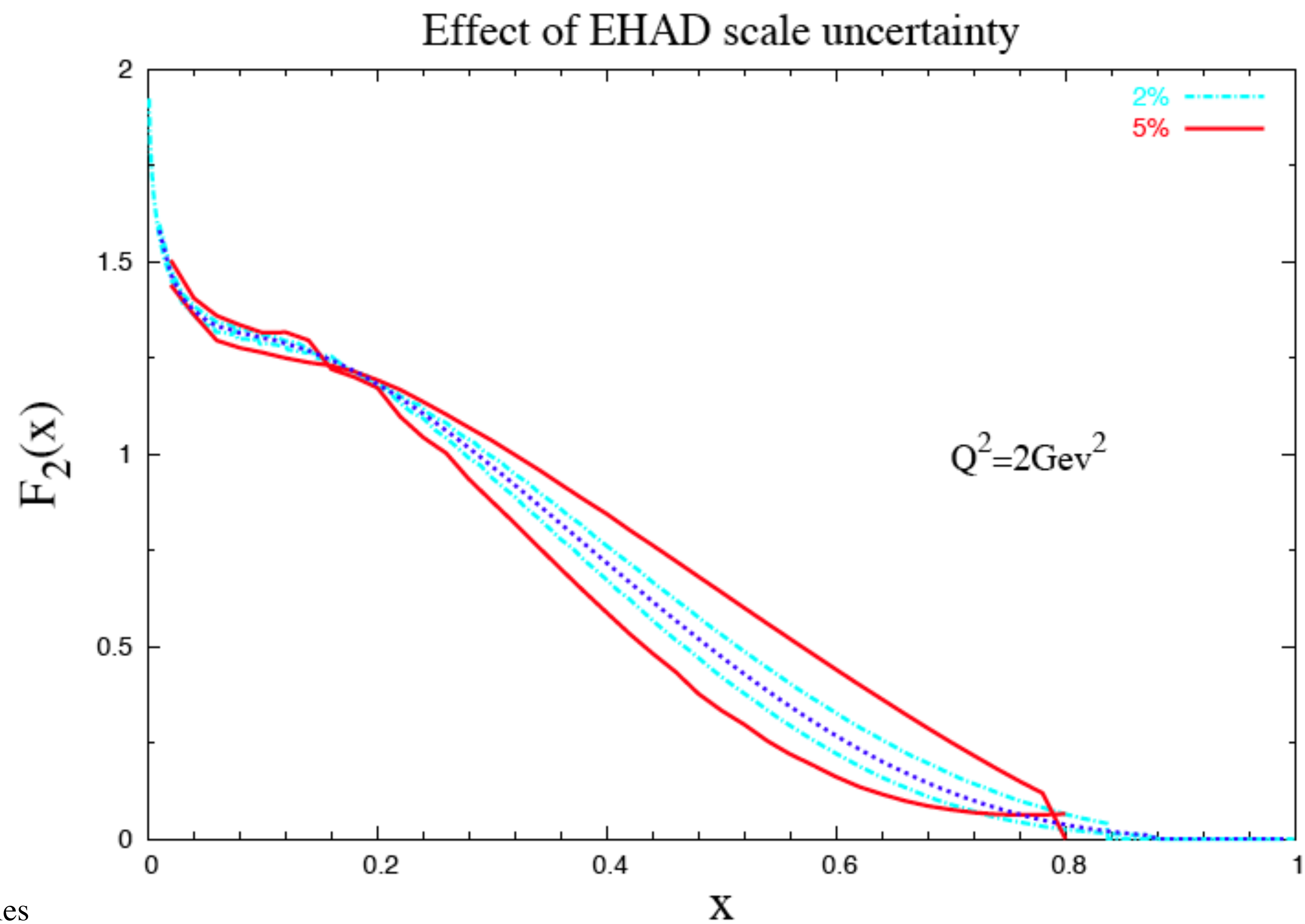
Estimated systematic error: E_μ scale

NuTev achieved 0.7%

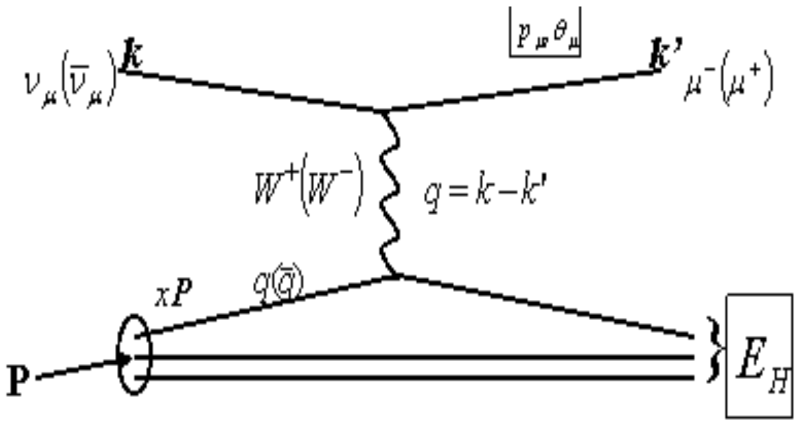


Estimated systematic error: E_{had} scale

NuTev achieved 0.43%



The Parameters of ν DIS



$Q^2 = 4E_\nu E_\mu \sin^2\frac{\theta}{2},$	Squared 4-momentum transferred to hadronic system
$x = \frac{Q^2}{2ME_{HAD}},$	Fraction of momentum carried by the struck quark
$y = \frac{\nu}{E_\nu} = \frac{E_{HAD}}{E_\nu},$	Inelasticity

Differential cross section in terms of structure functions:

$$\frac{1}{E_\nu}\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M}{\pi\left(1+Q^2/M_W^2\right)^2}\left[\left(1-y-\frac{Mxy}{2E_\nu}+\frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R(x,Q^2)}\right)F_2^{\nu(\bar{\nu})} \pm \left(y-\frac{y^2}{2}\right)xF_3^{\nu(\bar{\nu})}\right]$$

Structure Functions in terms of parton distributions (for ν-scattering)

$$F_2^{\nu(\bar{\nu})N} = \sum\left[xq^{\nu(\bar{\nu})N}(x) + x\bar{q}^{\nu(\bar{\nu})N}(x) + 2xk^{\nu(\bar{\nu})N}(x)\right],$$

$$xF_3^{\nu(\bar{\nu})N} = \sum\left[xq^{\nu(\bar{\nu})N}(x) - x\bar{q}^{\nu(\bar{\nu})N}(x)\right] = x\left(d_V(x) + u_V(x)\right) \pm 2x\left(s(x) - c(x)\right),$$

$$R = \frac{\sigma_L}{\sigma_T}$$