Using Neutrinos as a Probe of the Strong Interaction

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

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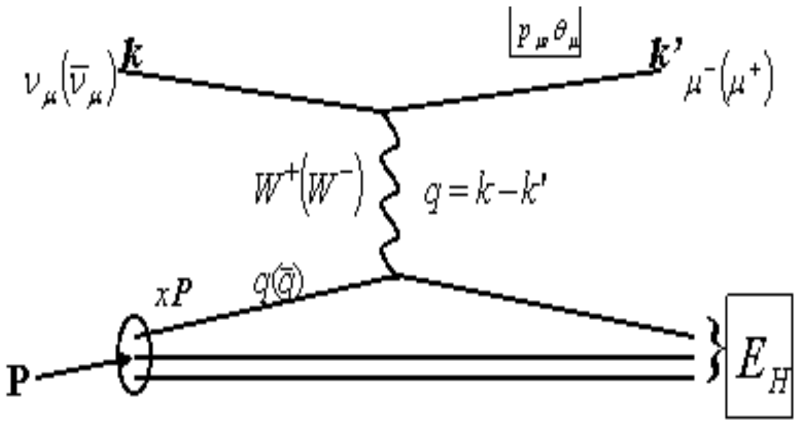
With thanks to the many publications and presentations of Martin Tzanov, U. Colorado

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 $\Delta xF_3 = 4x(s\text{-}c)$, 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.**

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)

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

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

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

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.

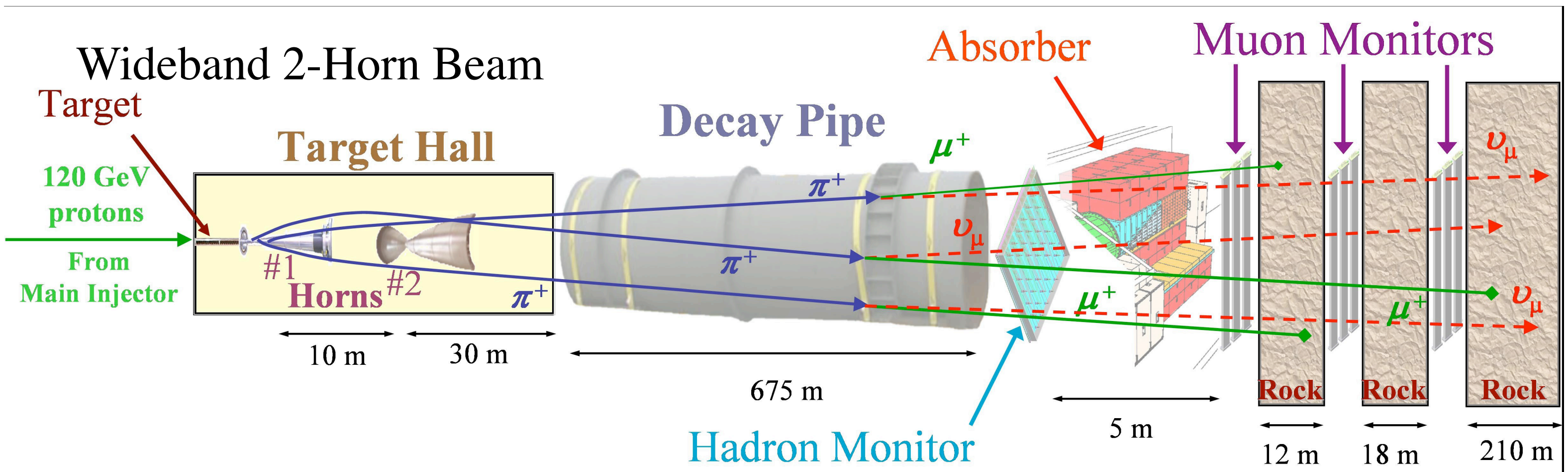
Most "Recent" DIS Experiments

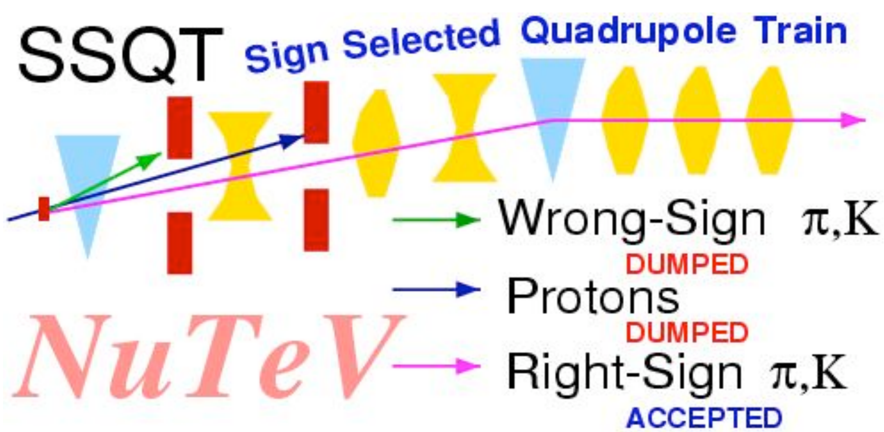
- There followed a long string of ν scattering experiments with **increasing statistics** and **decreasing systematic errors** ….

	E_ν range (< E_ν>) (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)	--	---	Fine-grained
CHORUS	10-200(27)	95-98	Pb	2%	5%	Fine-grained
MINOS	3-15	05-10	Fe	2.5%	5.6%	Coarse

Neutrino Beamlines

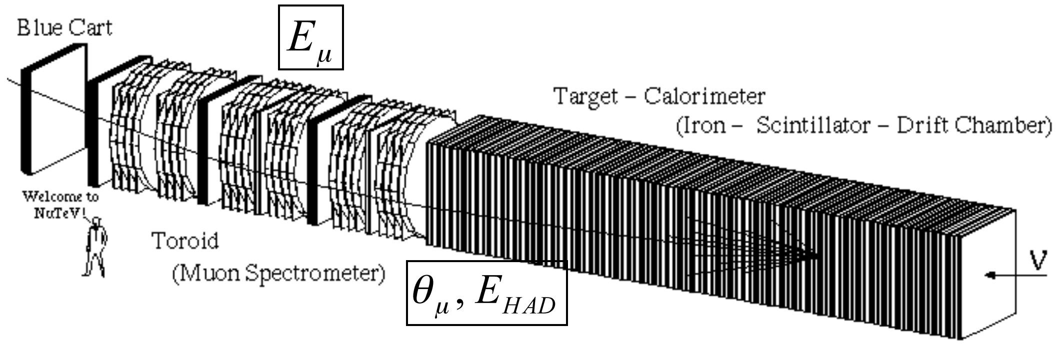
- Intense proton beam on a target. Collect π and K and steer into a decay area. Absorb hadrons and muons from beam leaving only neutrinos.



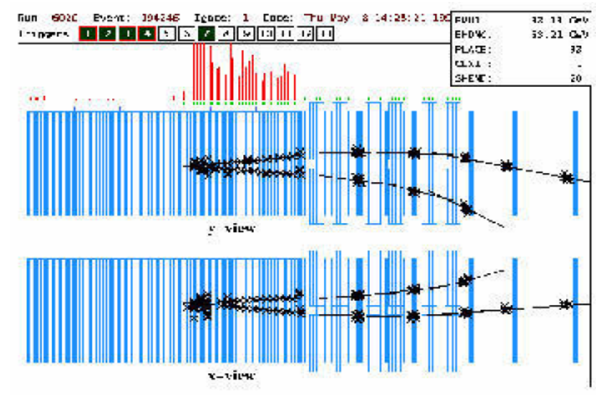


The NuTeV Experiment: 800 GeV Protons

> 3 million neutrino/antineutrino events with $20 \le E_\nu \le 400\ GeV$



Refurbished CCFR detector



Target Calorimeter:

- Steel-Scintillator Sandwich (10 cm)

$$\frac{\delta E}{E} \approx \frac{0.86}{\sqrt{E}} \text{ -resolution}$$

- Tracking chambers for muon track and vertex

- Muon Spectrometer:

  Three toroidal iron magnets with five sets of drift chambers

$$\langle B_\varphi \rangle \approx 1.7T,\ p_t \approx 2.4GeV/c$$

$$\delta(1/p)/(1/p) \sim 11\% \text{ MCS dominated}$$

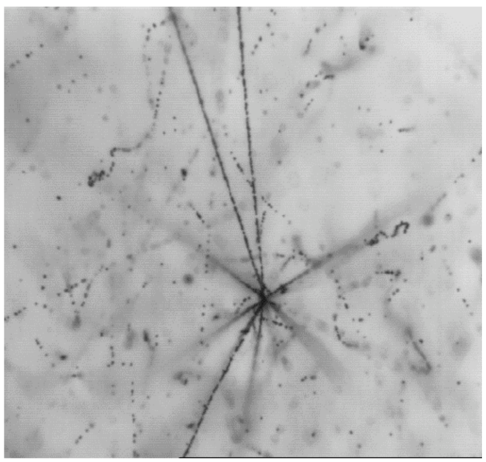
- Always focusing for leading muon

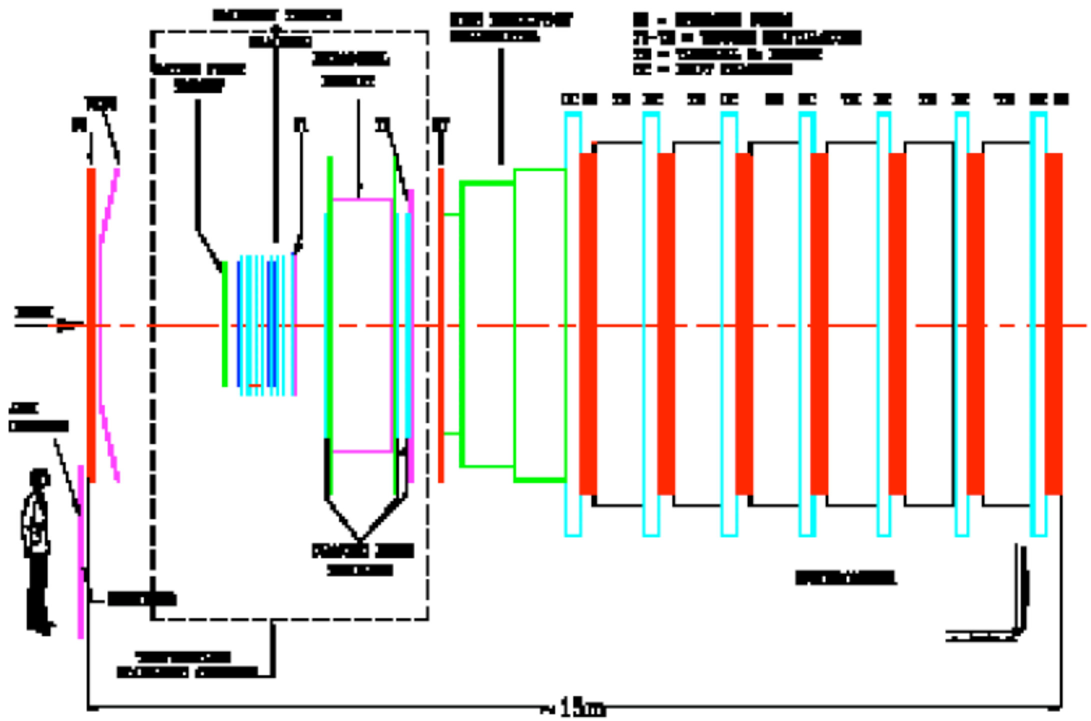
To confront leading systematic errors, there was a continuous calibration beam that yielded

Hadron energy scale $\frac{\Delta E_{HAD}}{E_{HAD}} = 0.43\%$ Muon energy scale $\frac{\Delta E_\mu}{E_\mu} = 0.7\%$

CHORUS Experiment – nuclear emulsions

- 450 GeV protons -→ 10 – 200 GeV ν, 6% wrong-sign background
- Nuclear Emulsion Target (Pb, Fe, Ca and C)
- Scintillating Fiber tracker





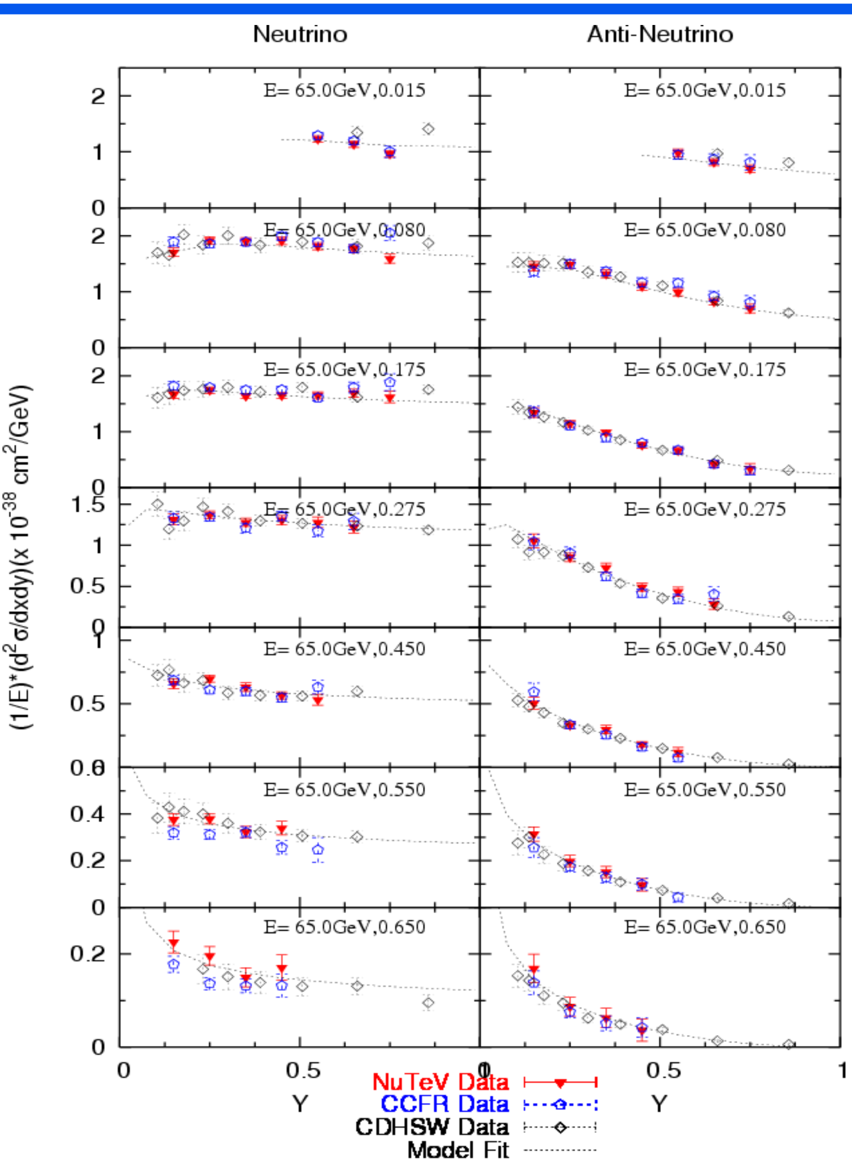
Muon energy scale – 2.5%

Hadron Energy Scale - 5%

(test beam exposure)

NuTeV CC Differential Cross Section

$d\sigma/dy$ for different E_ν



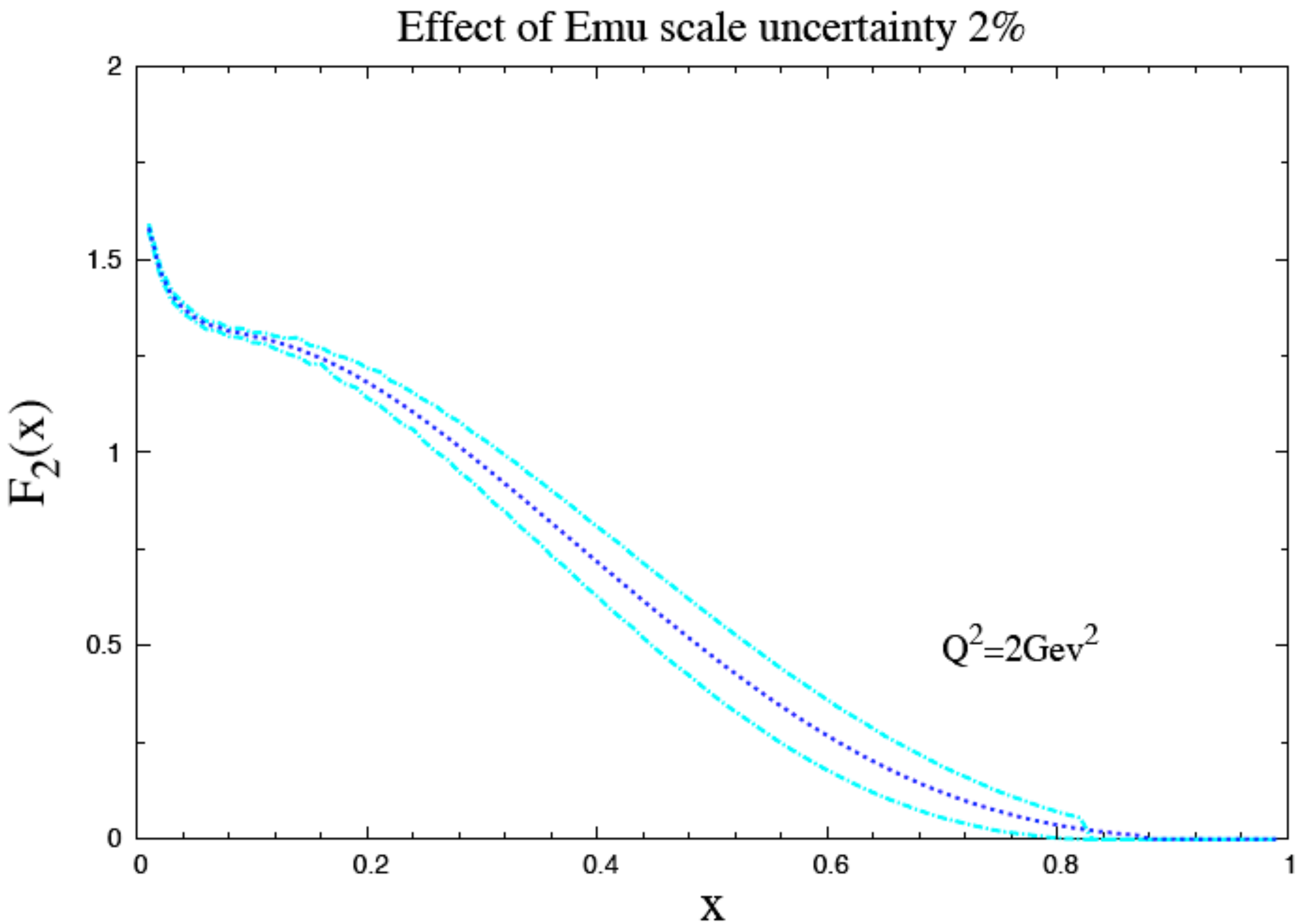
	E_μ scale	E_{HAD} scale	E_ν range (GeV)
CDHSW	2%	2.5%	20-200
CCFR	1%	1%	30-360
NuTeV	0.7%	0.43%	30-360

◆ NuTeV has increased statistics compared to other ν-Fe experiments.

◆ Significant reduction in the largest systematic uncertainties : - E_μ and E_{HAD} scales

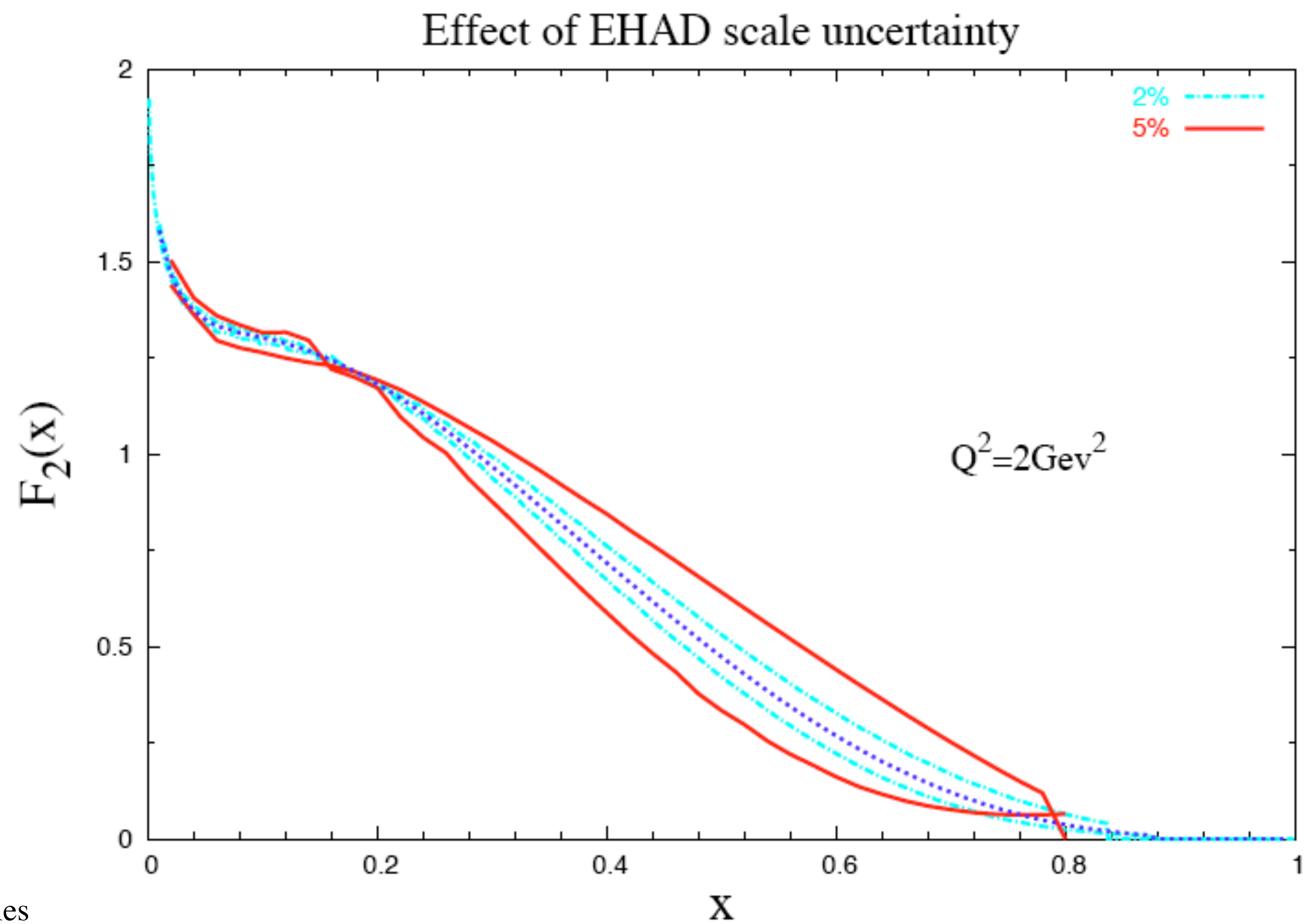
Estimated systematic error: E_μ scale

NuTev achieved 0.7%



Estimated systematic error: E_{had} scale

NuTev achieved 0.43%



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

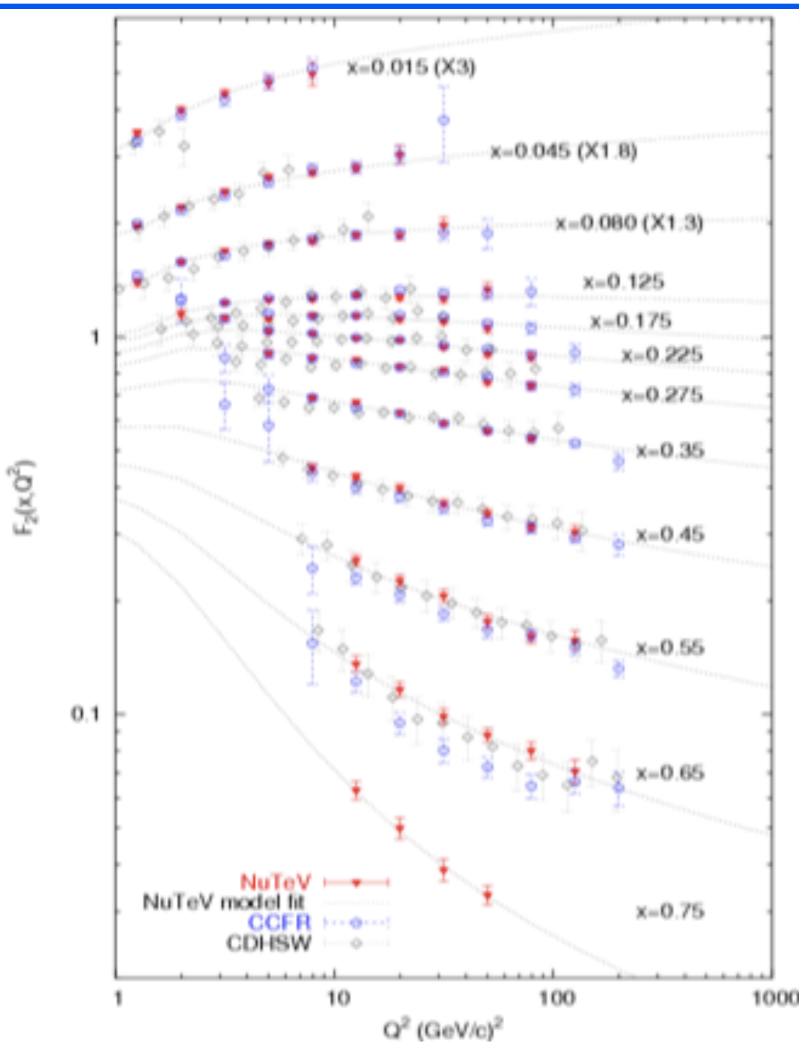
$$\left[\frac{d^2\sigma}{dx\,dy}^{\nu} - \frac{d^2\sigma}{dx\,dy}^{\bar{\nu}}\right]\frac{\pi}{G_F^2 ME} =$$

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

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

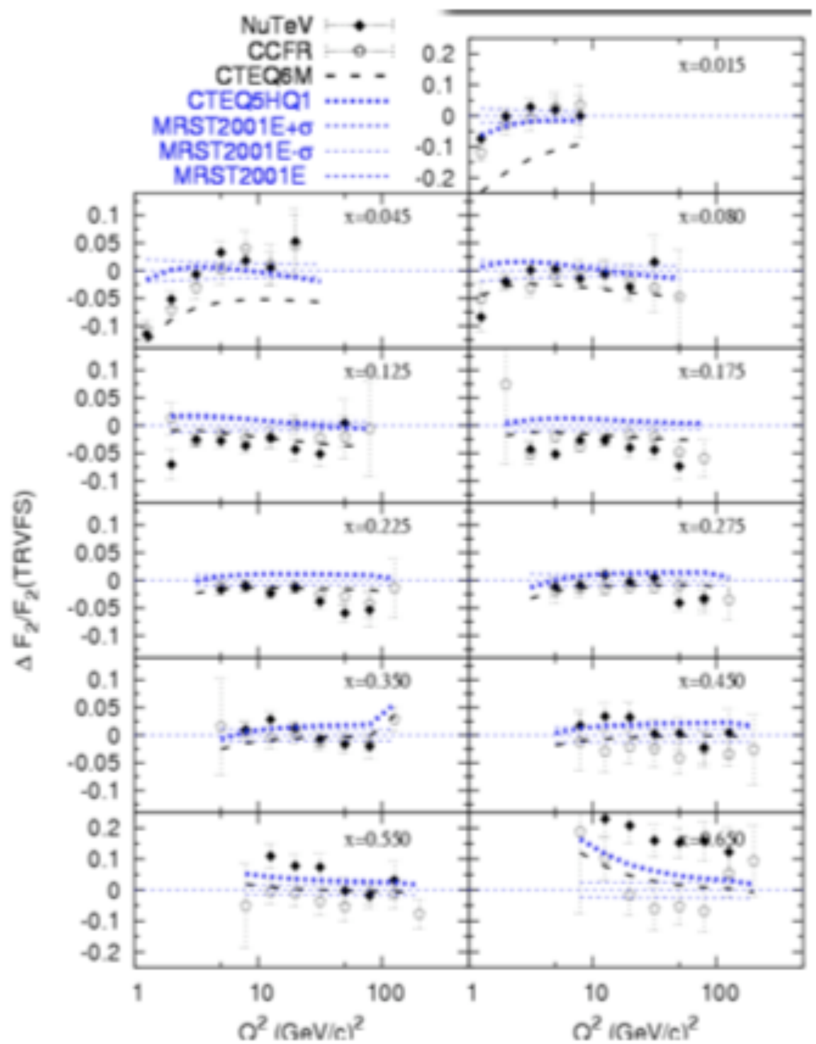
- Radiative corrections applied
- Isoscalar correction applied

NuTeV F_2 Measurement

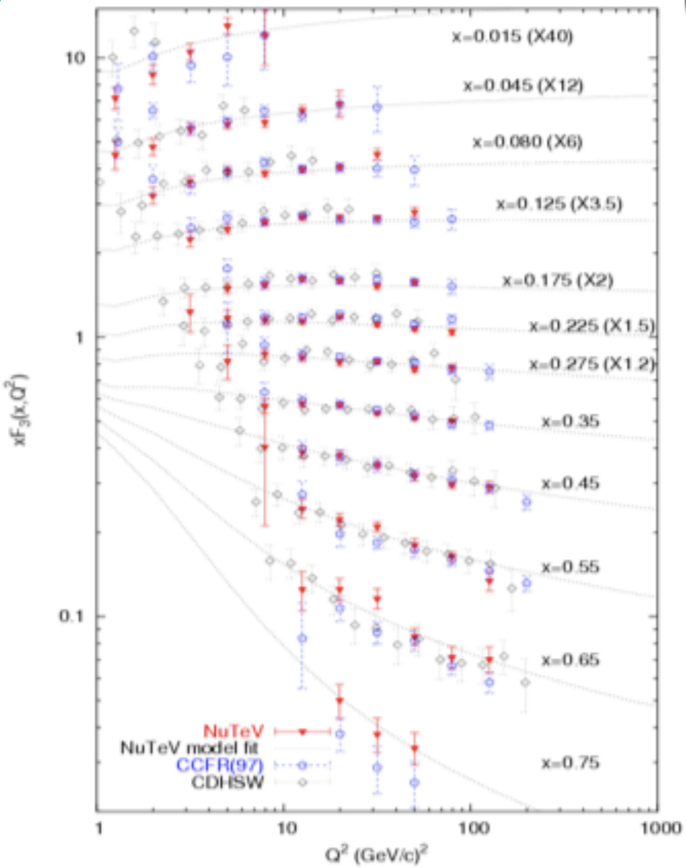


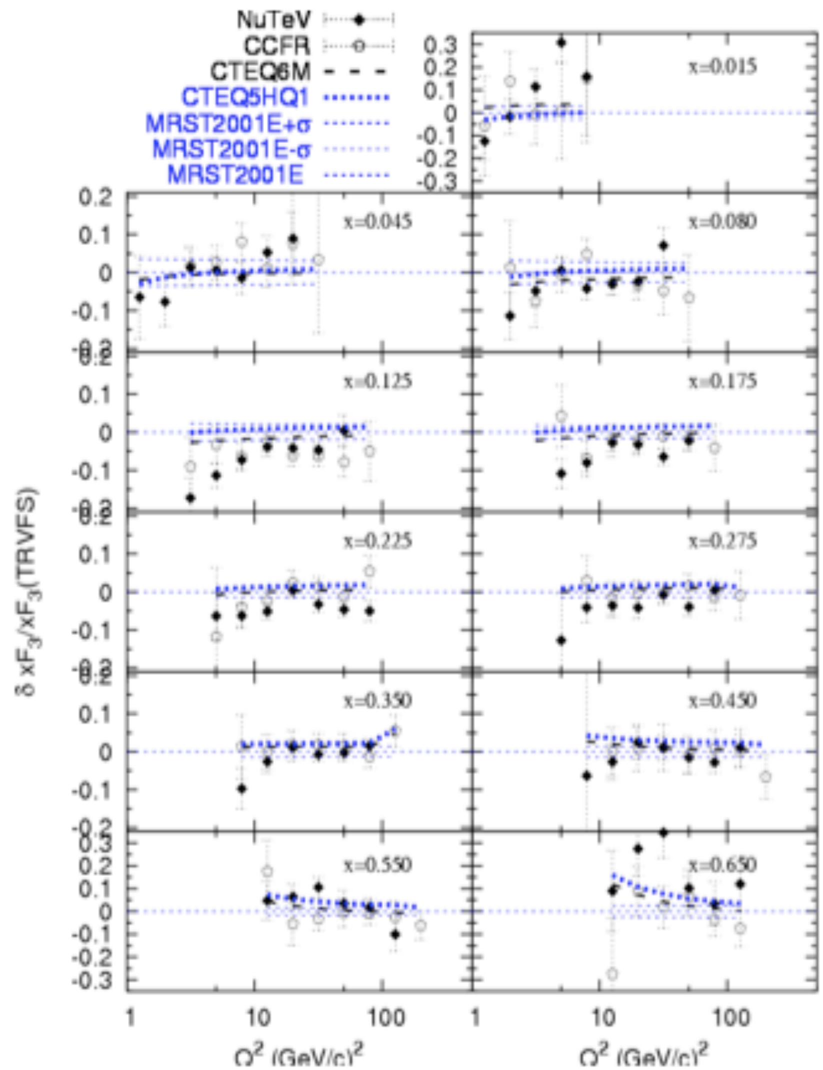
◆ At $x>0.4$ NuTeV is systematically above CCFR

◆ Comparison of NuTeV F_2 with global fits



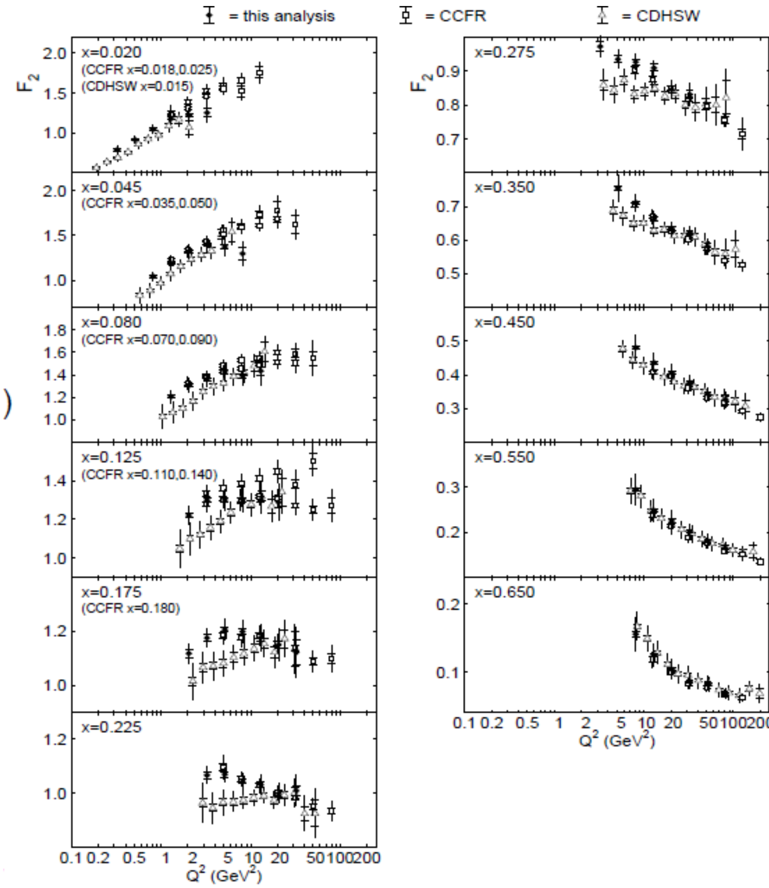
NuTeV xF_3 Measurement

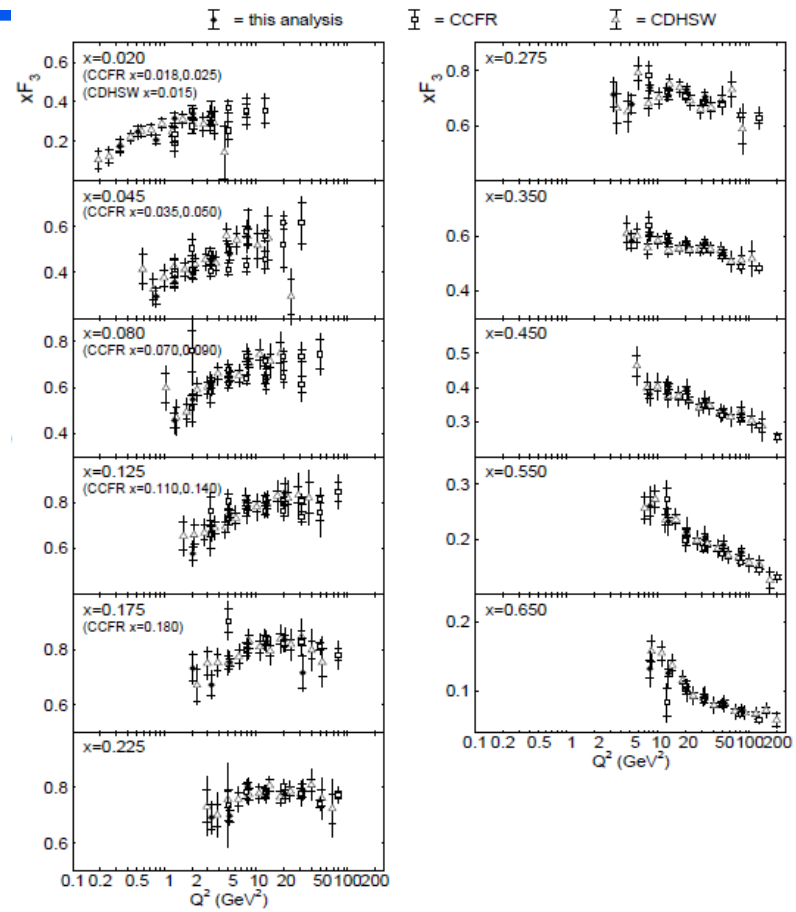




- At $x>0.5$ NuTeV is systematically above CCFR
- NuTeV F_2 agrees with theory for medium x.
- At low x different Q^2 dependence.
- At high x (x>0.5) NuTeV is systematically higher.

CHORUS Structure Functions: ν Pb





- First ν-Pb differential cross section and structure functions
- CHORUS measurement favors CCFR over NuTeV
- Much larger systmatic errors than the NuTeV experiment

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, d and s.

Using Leading order expressions:

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

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

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

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

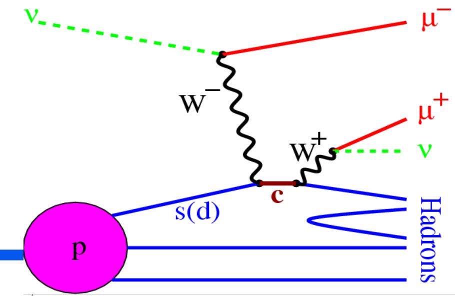
Taking combinations of the Structure functions

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

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

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

Charm Production by Neutrinos
a direct look at strange sea.

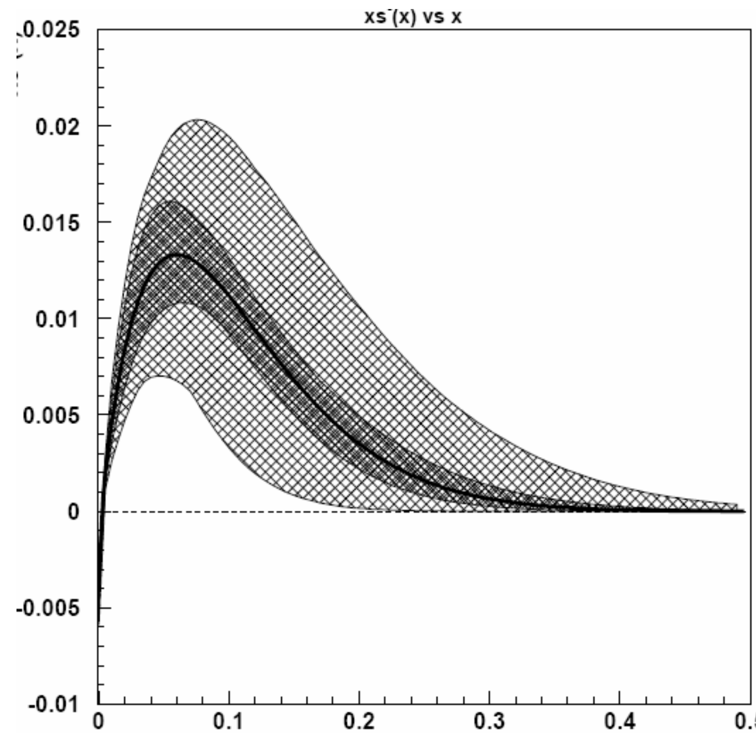


- Charm quark is produced from CC neutrino interaction with s(d) quark in the nucleon. d-quark interaction is CKM suppressed
- Detect charm via the semi-leptonic decay which yields a very clear signature – two opposite sign muons
- It is sensitive to m_c through E_ν dependence.
- With high-purity ν and $\bar{\nu}$ 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.

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

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

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>0.6) NuTeV is systematically higher.

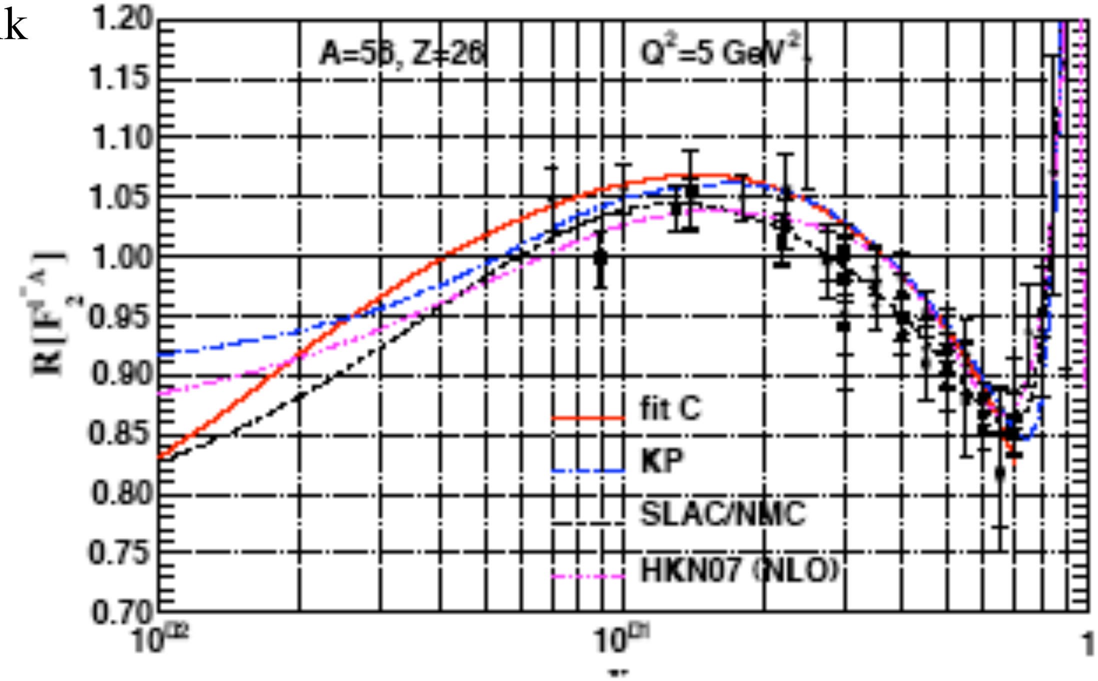
NuTeV extracts the **strange quark** distribution via charm production using both ν and $\bar{\nu}$ and gets a value of $S^-(x)$

All of the NuTeV Results are for ν – Fe interactions and where necessary have assumed the nuclear corrections for neutrino interactions are the same as $l^\pm$. <u>Is this really the case?</u>

Nuclear Structure Function Corrections

ℓ± (Fe/D_2)

See yesterday's talk by Solvignon !



- 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.**

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

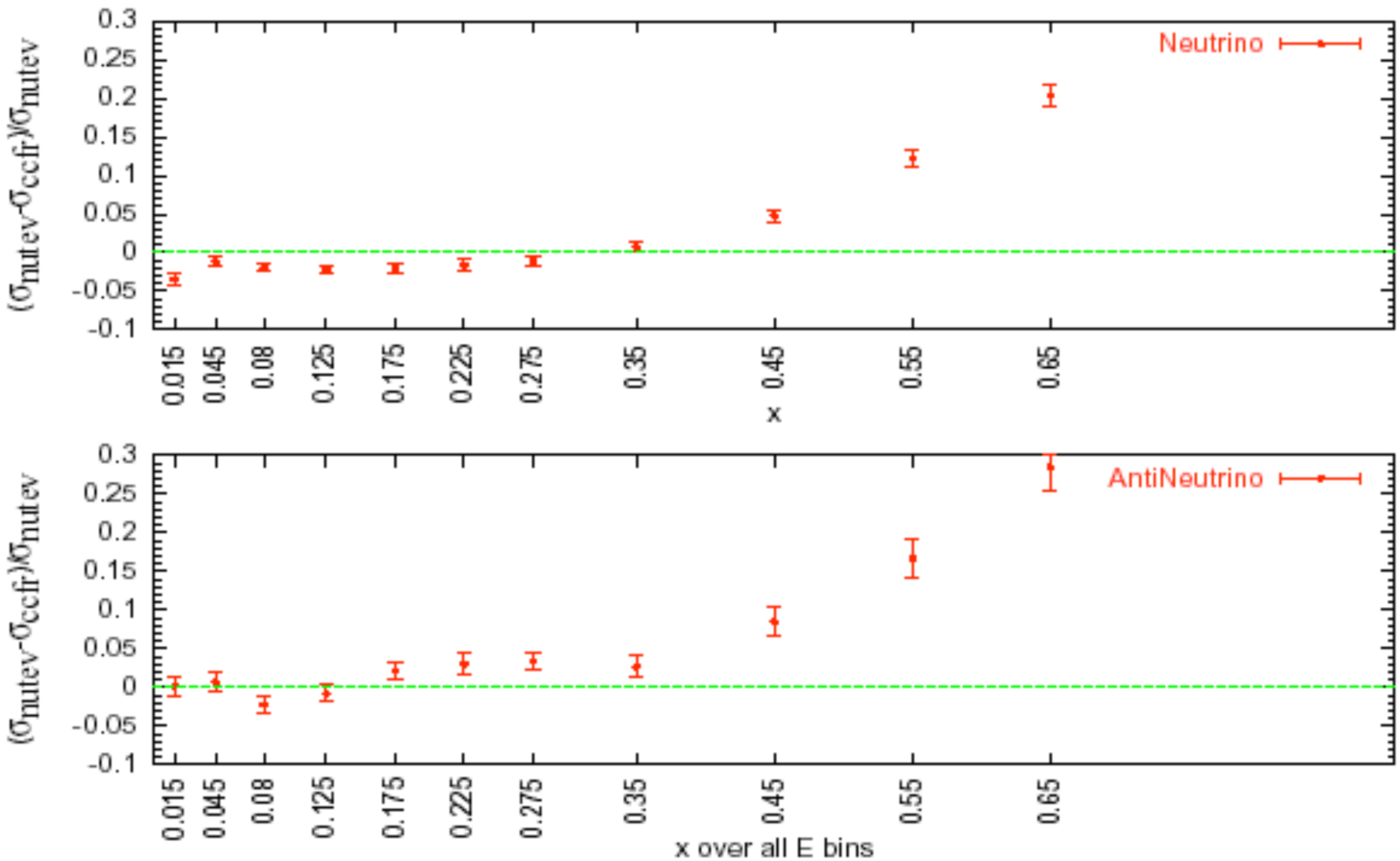
Joey Huston - MSU, Cynthia Keppel - Hampton, Steve Kuhlmann - ANL,
JGM - Fermilab, Fred Olness - SMU, Jeff Owens - Florida State,
Jon Pumplin and Dan Stump - MSU

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?



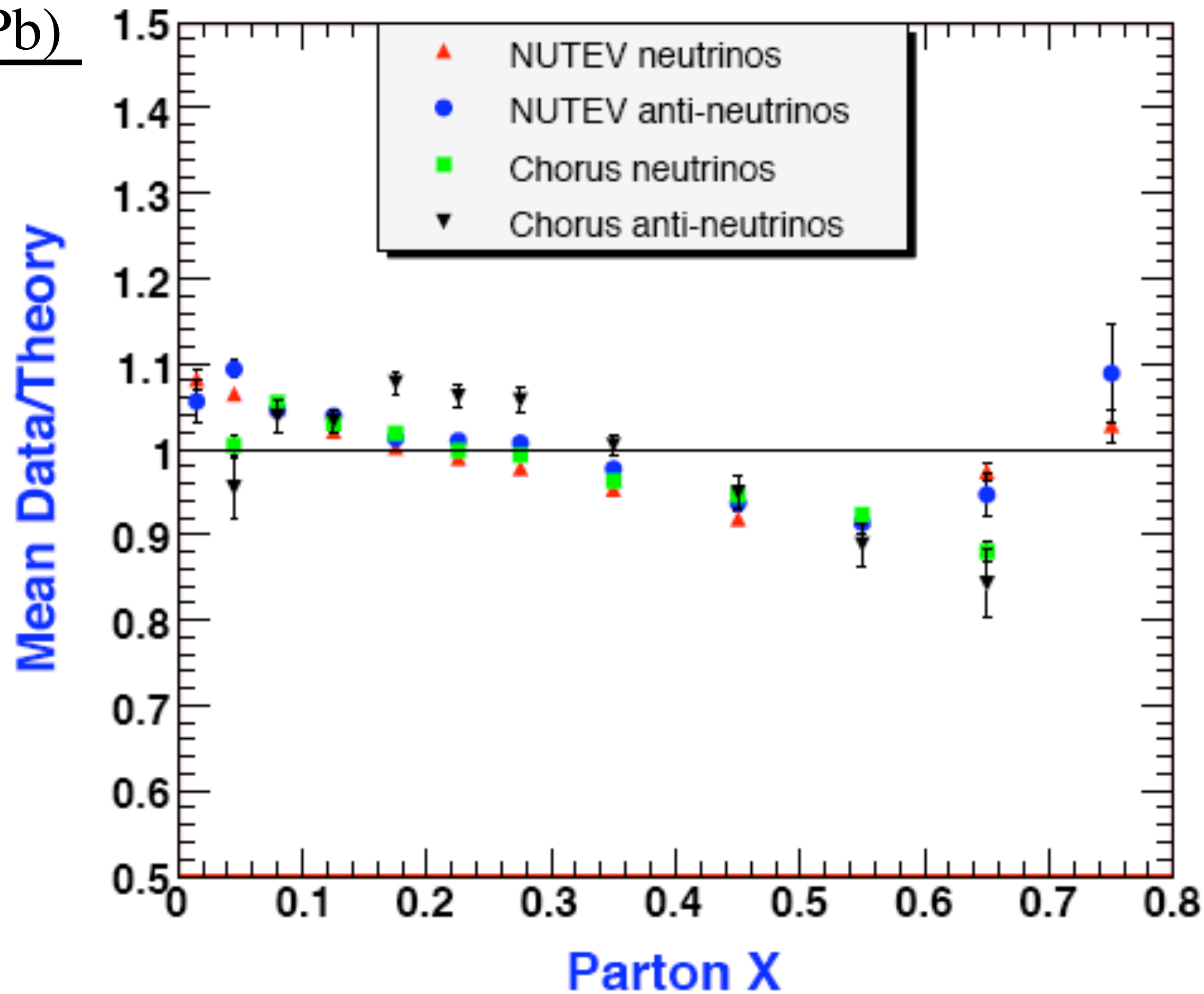
CTEQ High-x Study: nuclear effects
No high-statistics D2 data – "make it" from PDFs

- 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

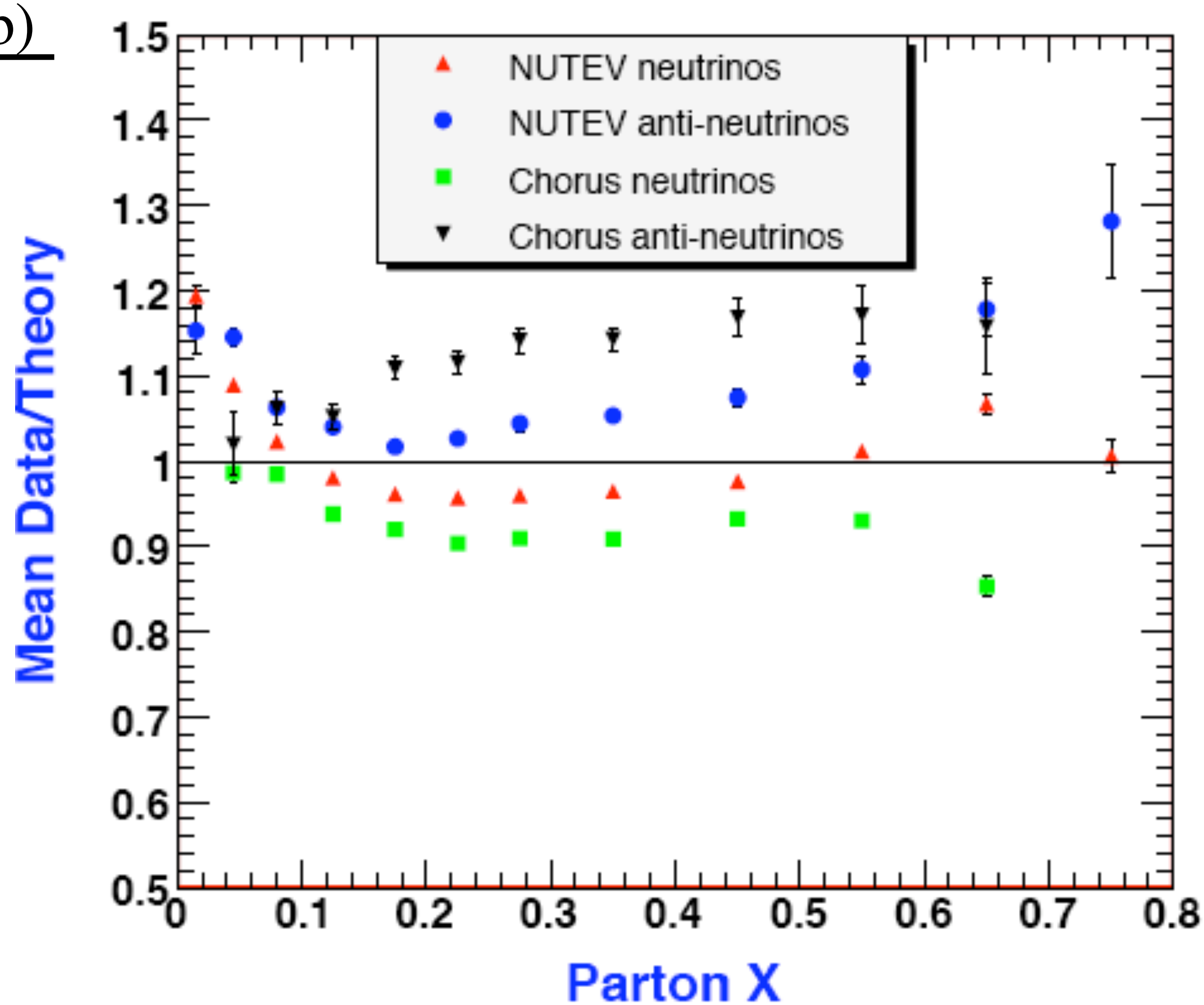
$$\frac{\sigma(\nu Fe \text{ or } \nu Pb)}{\sigma(\nu\text{"}D_2\text{"})}$$



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

Kulagin-Petti nuclear corrections

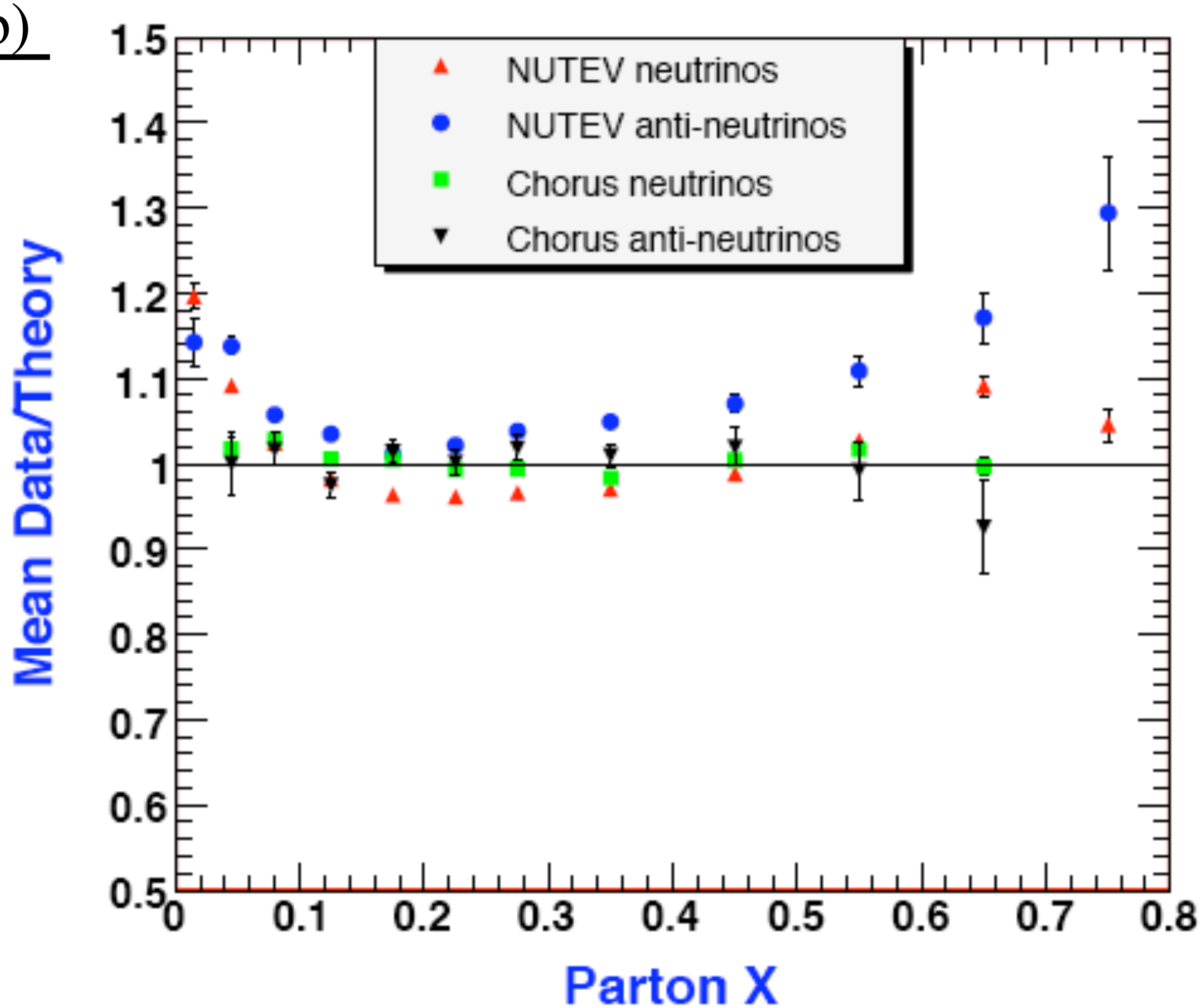
$$\frac{\sigma(\text{Fe or Pb})}{\sigma(D_2)}$$



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

Kulagin-Petti nuclear corrections

$$\frac{\sigma(\text{Fe or Pb})}{\sigma(D_2)}$$



Nuclear PDFs from neutrino deep inelastic scattering

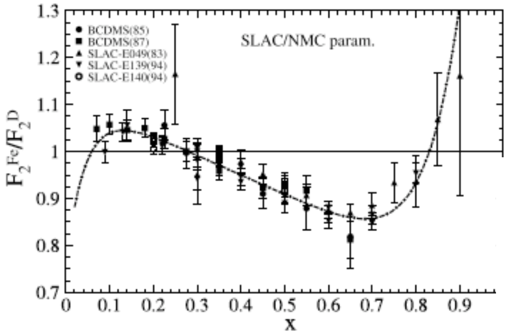
I. Schienbein (SMU & LPSC-Grenoble, J-Y. Yu (SMU)
C. Keppel (Hampton & JeffersonLab) J.G.M. (Fermilab),
F. Olness (SMU), J.F. Olness (Florida State U)

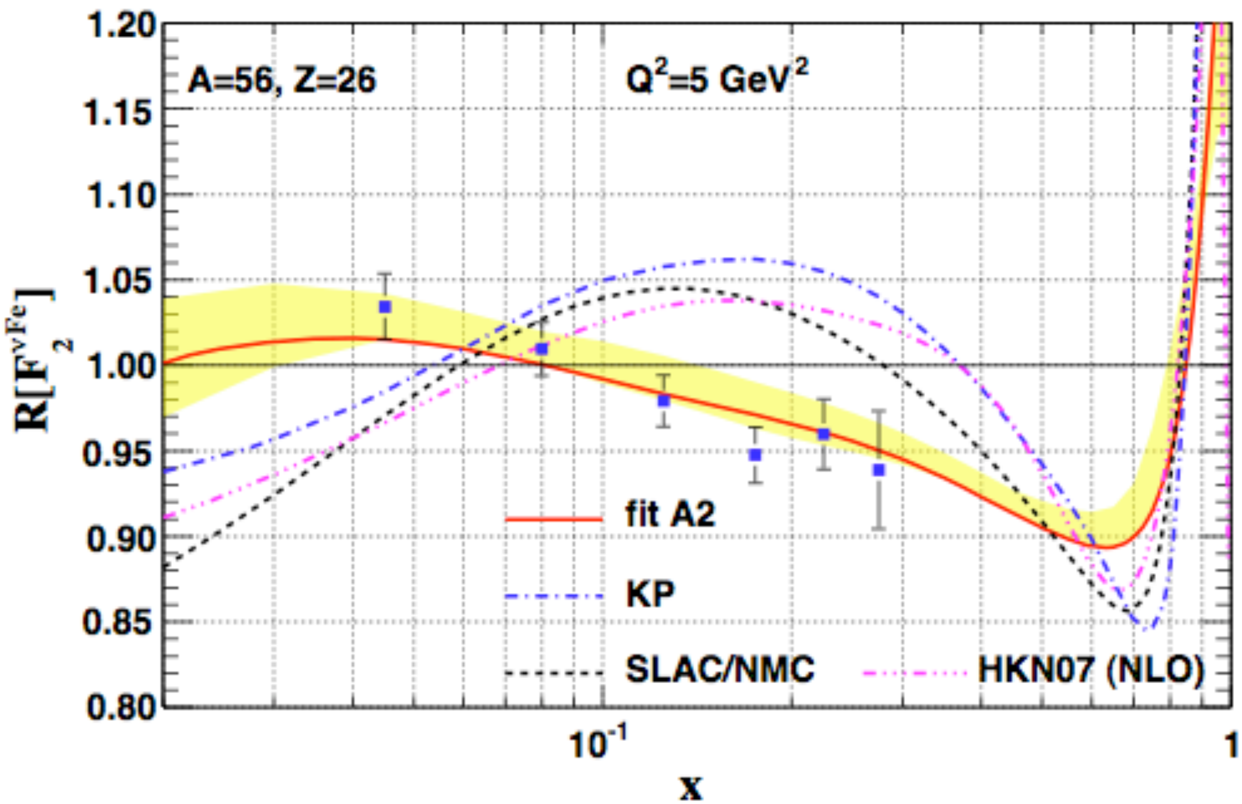
e-Print: **arXiv:0710.4897** [hep-ph]

Same Reference Fit as Earlier Analysis

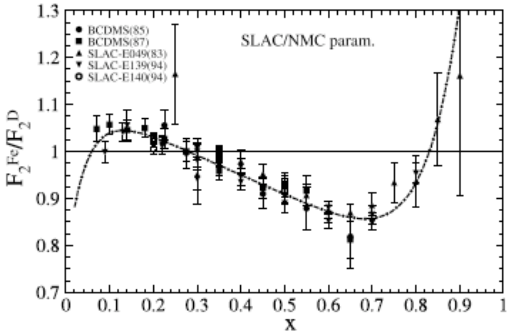
- Form reference fit mainly nucleon (as opposed to nuclear) scattering results:
  - BCDMS results for F_2^p and F_2^d
  - NMC results for F_2^p and F_2d/F_2^p
  - H1 and ZEUS results for F_2^p
  - CDF and DØ result for inclusive jet production
  - CDF results for the W lepton asymmetry
  - E-866 results 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

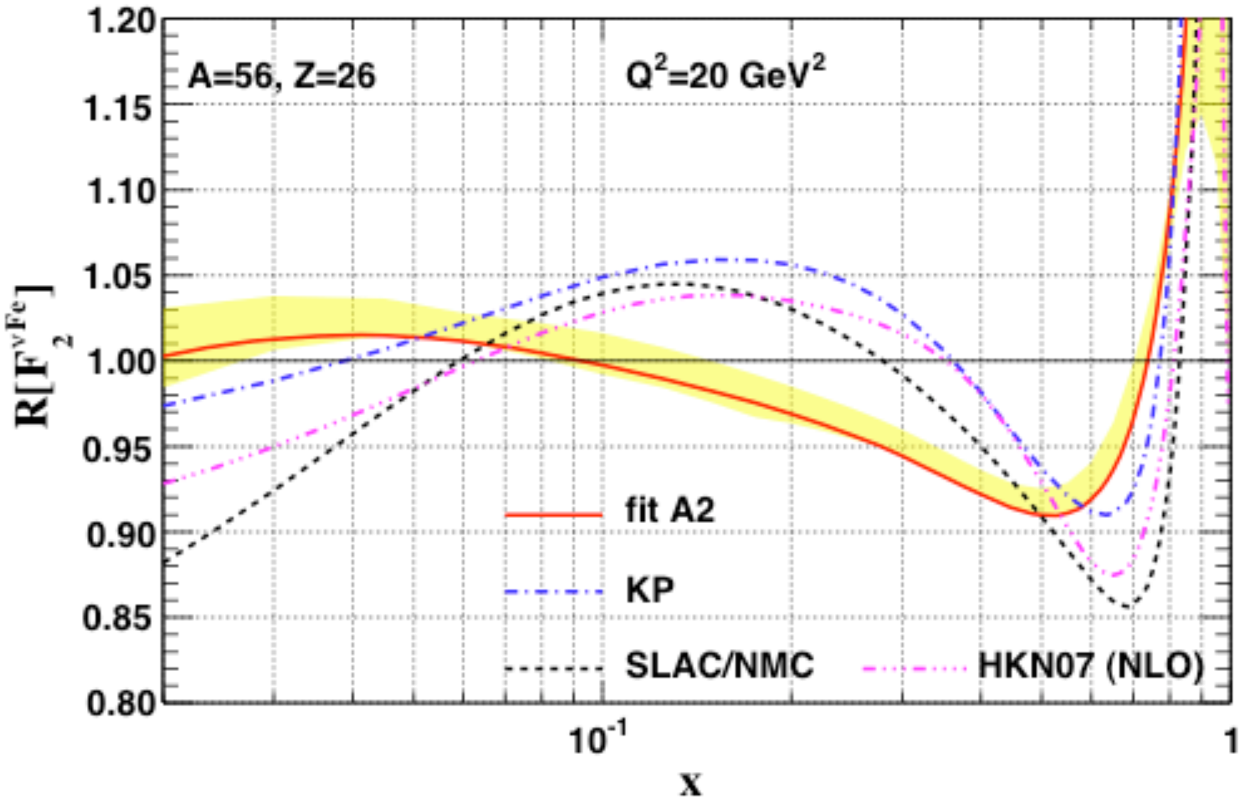
F_2 Structure Function Ratios: ν-Iron



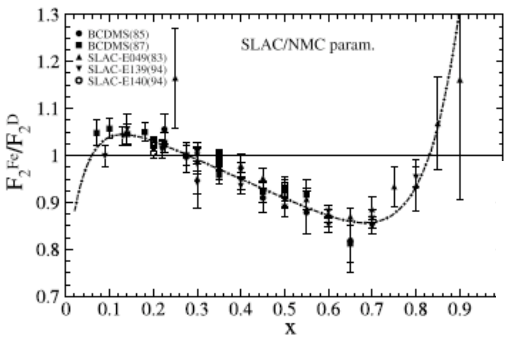


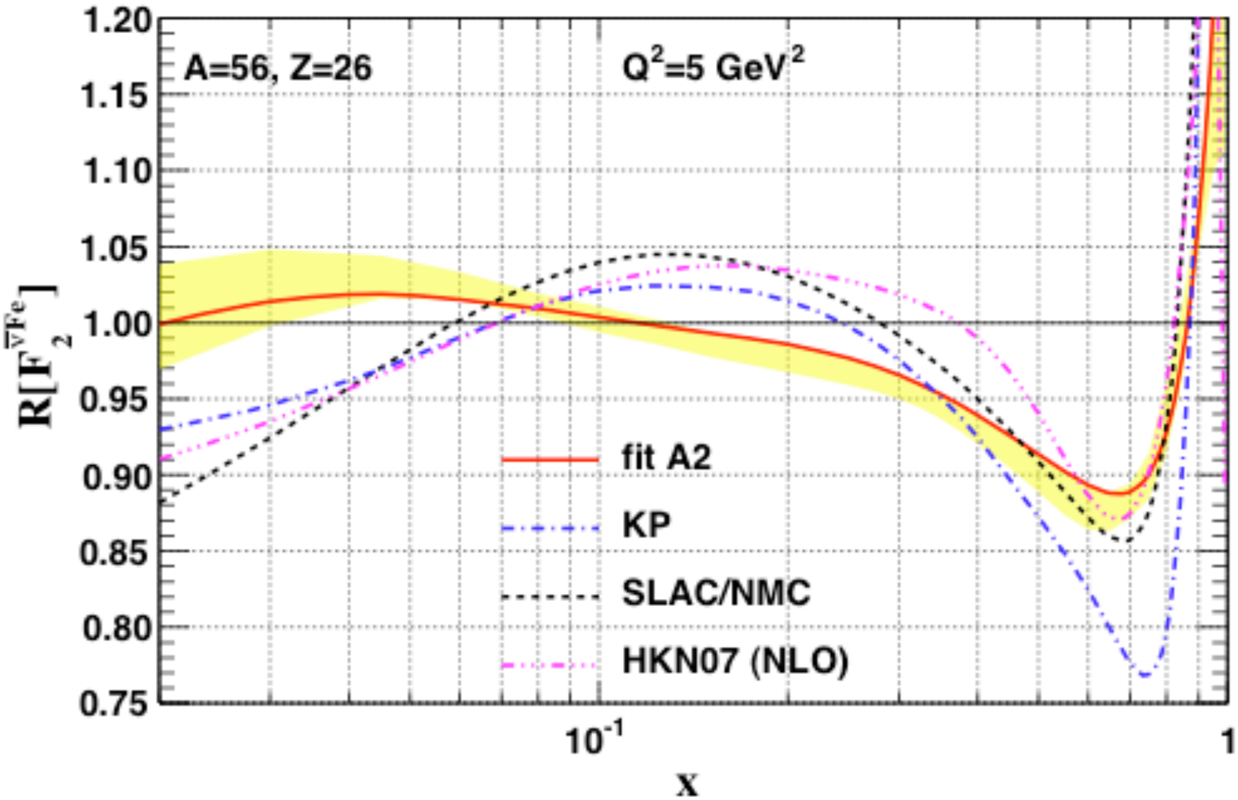
F_2 Structure Function Ratios: ν-Iron



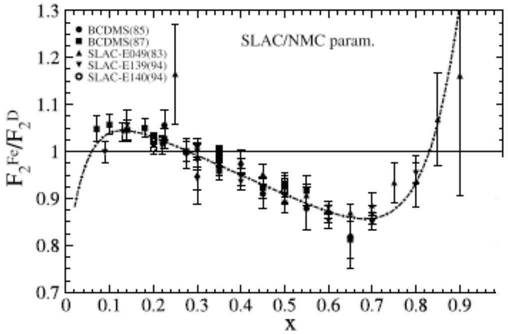


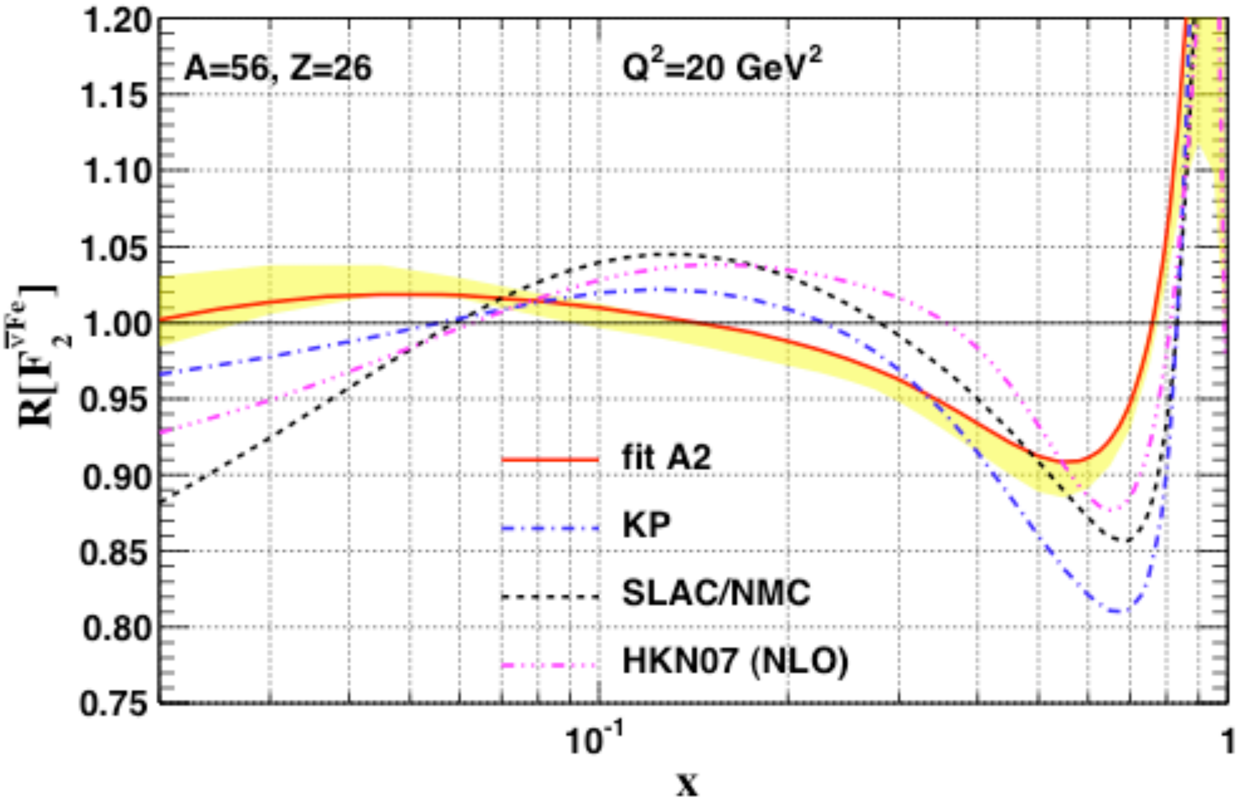
F_2 Structure Function Ratios: $\bar{\nu}$-Iron





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





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

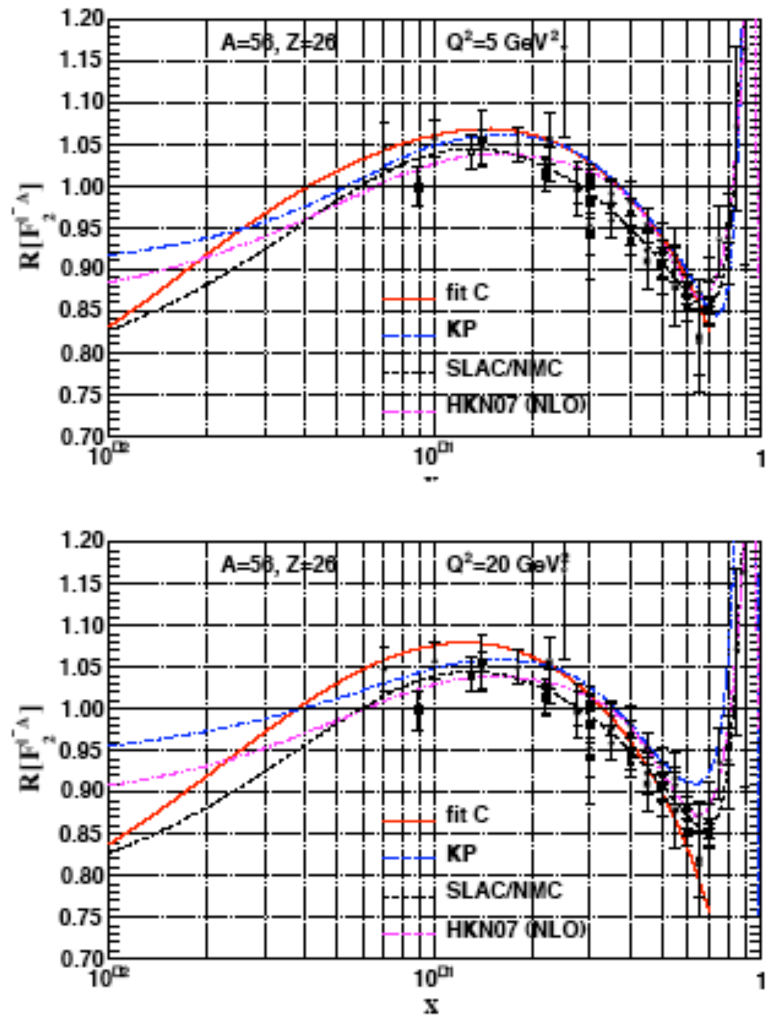
Work in progress: **Kovarik**, Yu, Keppel, Morfin, Olness, Owens, **Schienbein**, Stavreva

- 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).

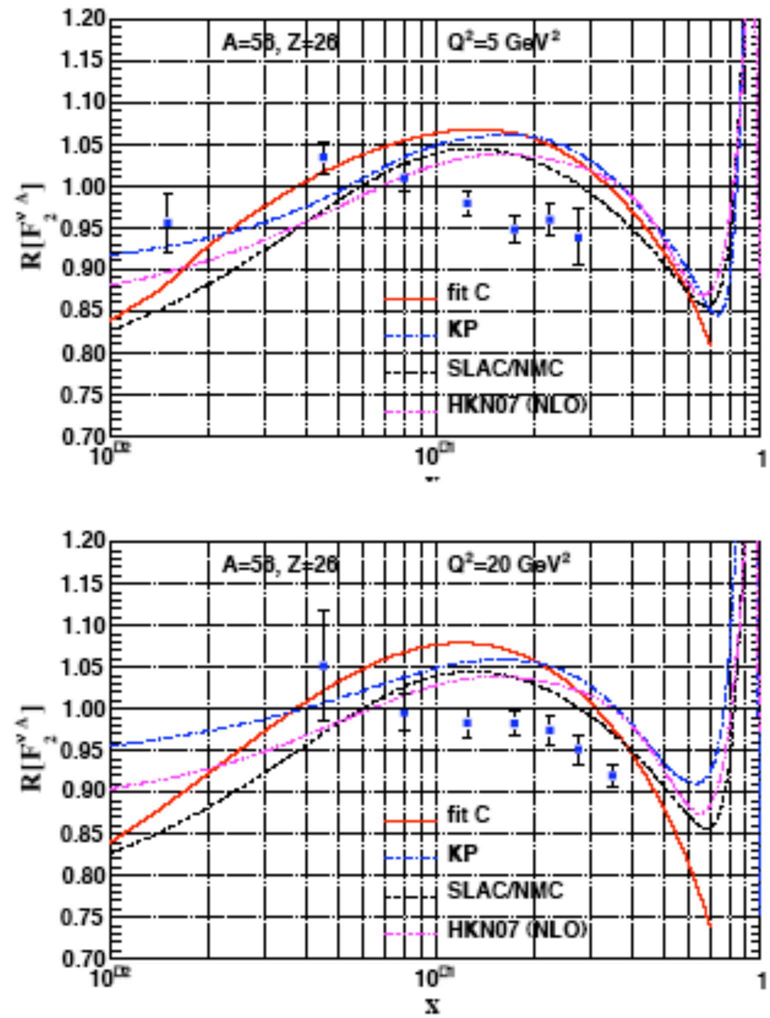
Use the usual procedure of observing the behavior of the fits as you adjust the "weight" of the dominant data sample

W = 0

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

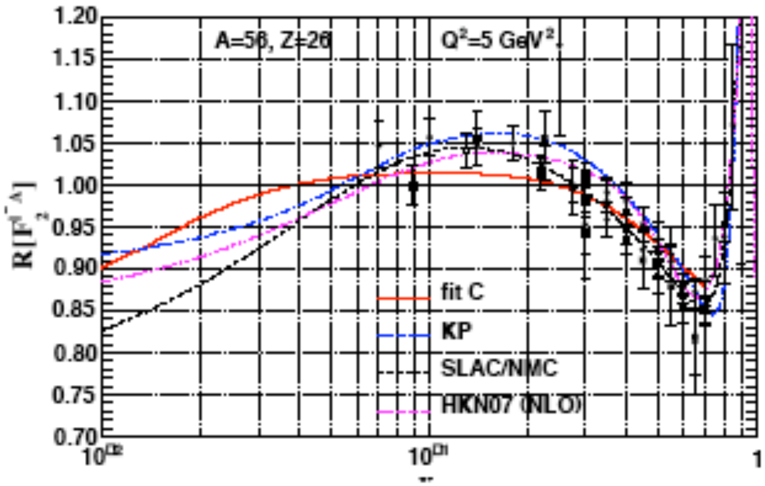


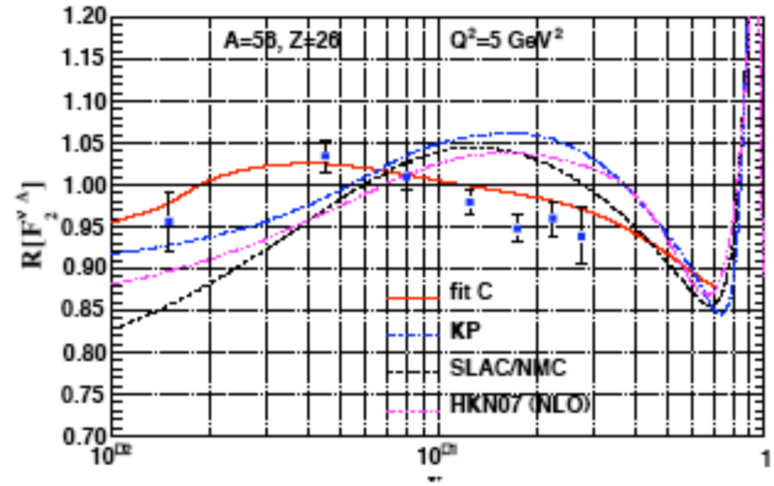
$R[F_2(\nu\ Fe)]$

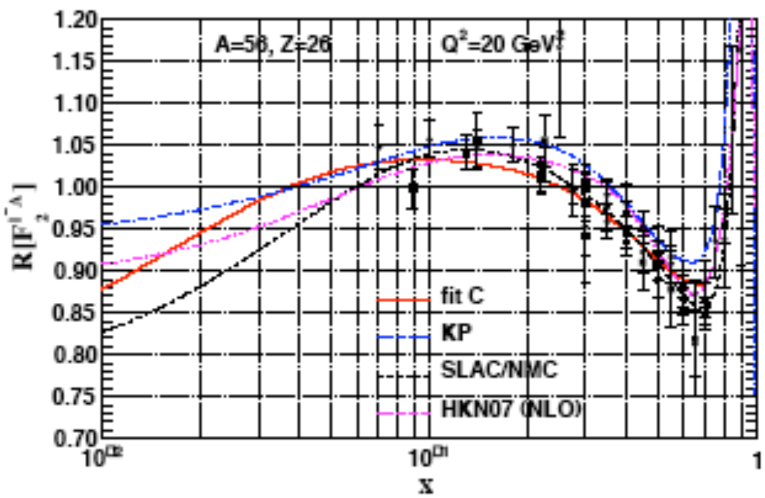


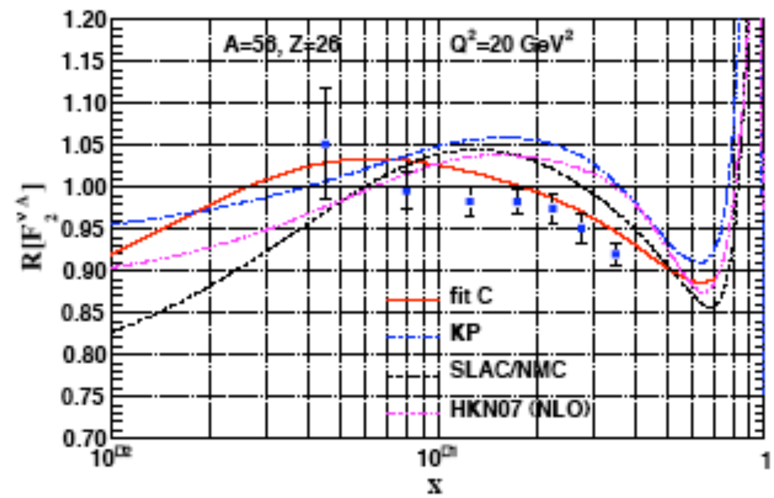
W = 1/2

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



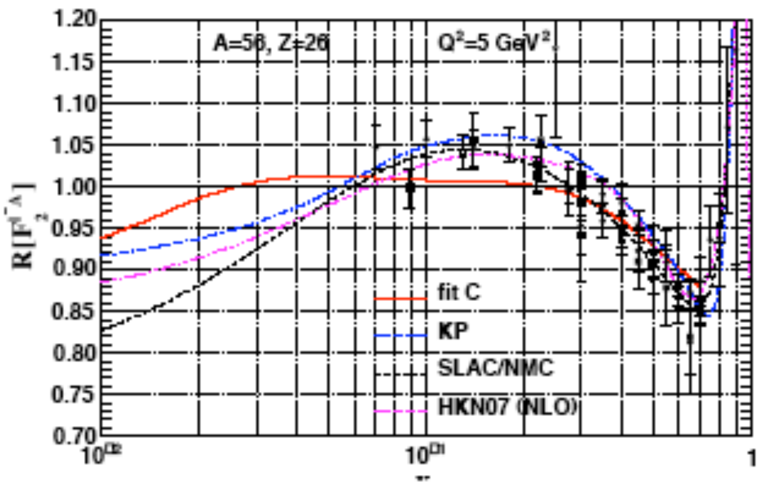


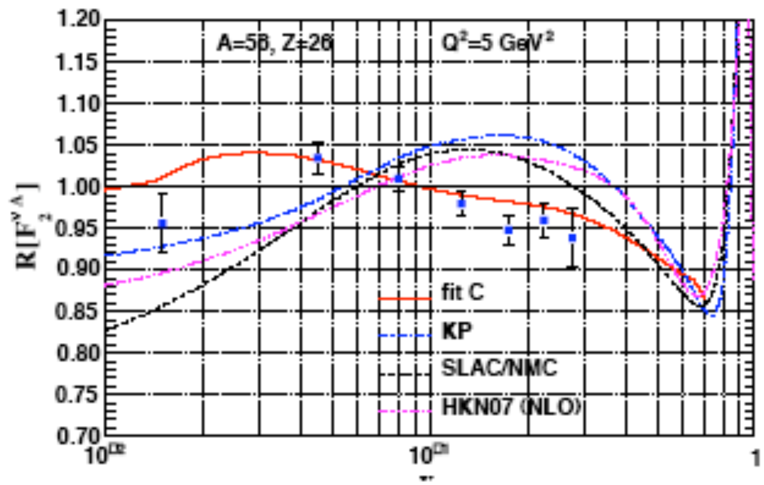


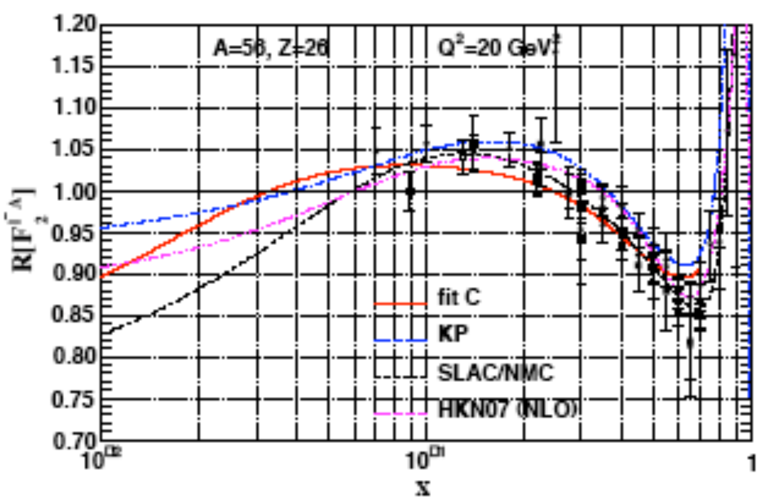


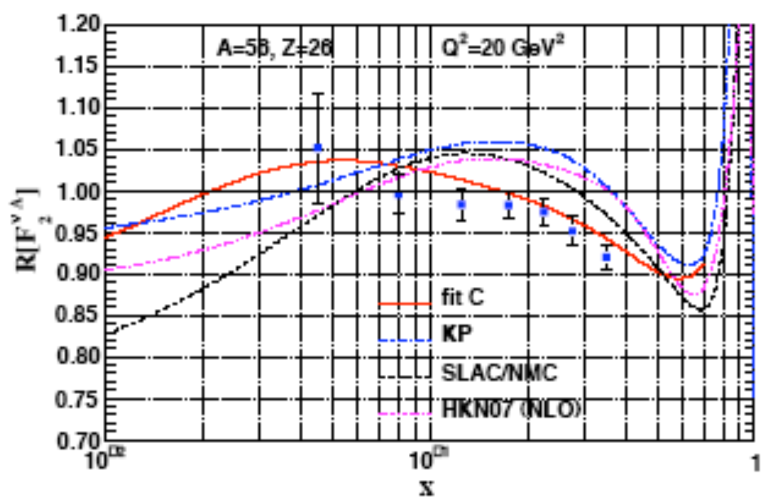
W = 1

R[F_2($\ell^\pm$ Fe)] R[F_2(ν Fe)]



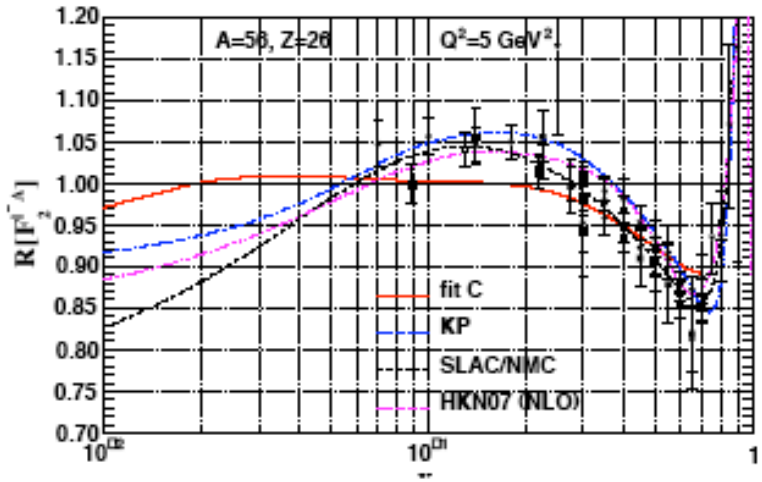


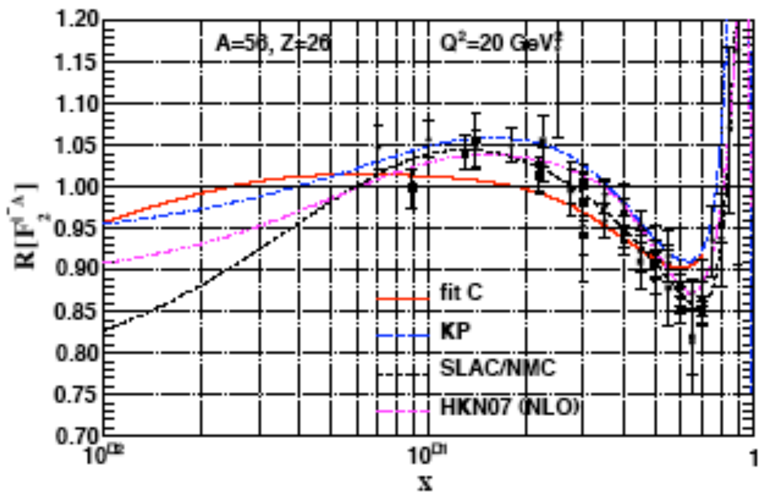




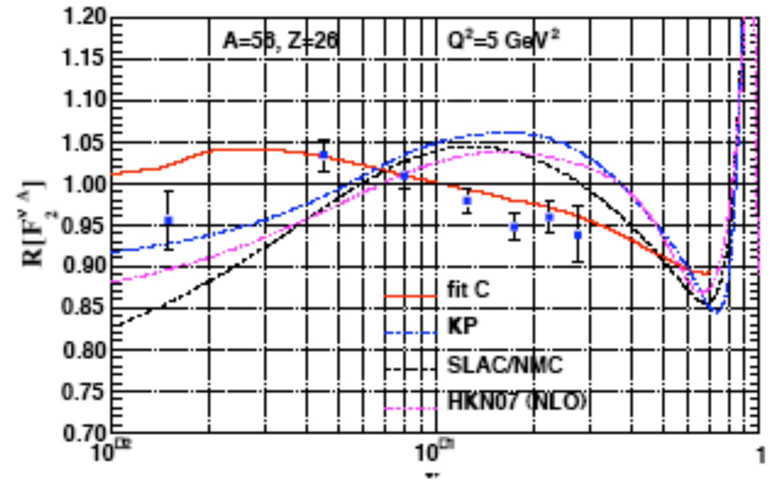
$W = \infty$

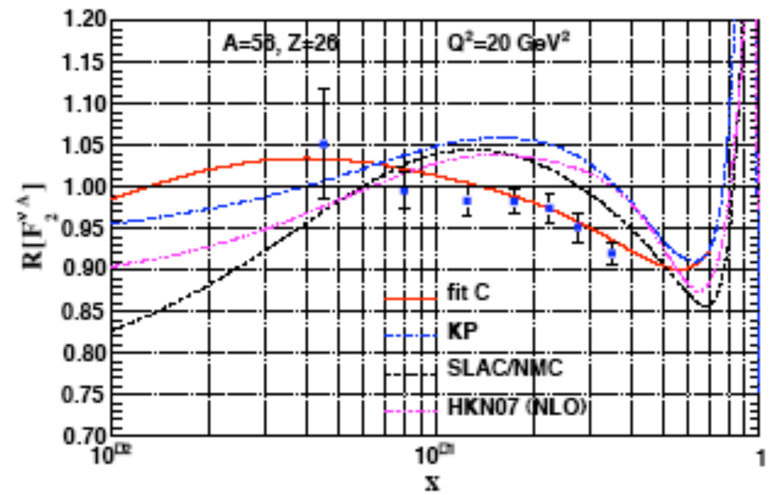
$R[F_2(\ell^{\pm}\ \mathrm{Fe})]$





$R[F_2(\nu\ \mathrm{Fe})]$





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)

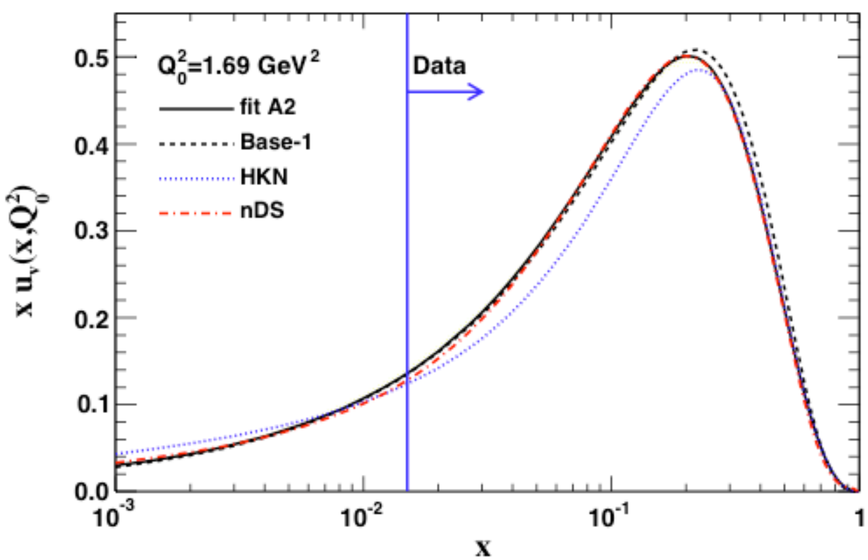
Weight	Fit name	ℓ data	χ^2	ν data	χ^2	total χ^2 (/pt)
$w = 0$	decut3	708	639 T?	-	nnnn T? **NO**	639 (0.90)
$w = 1/7$	glofac1a	708	645 **YES**	3134	4710 **NO**	5355 (1.39)
$w = 1/4$	glofac1c	708	654 **YES**	3134	4501 **NO**	5155 (1.34)
$w = 1/2$	**glofac1b**	708	680 **YES**	3134	4405 **NO*** **	5085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

Summary and Conclusions

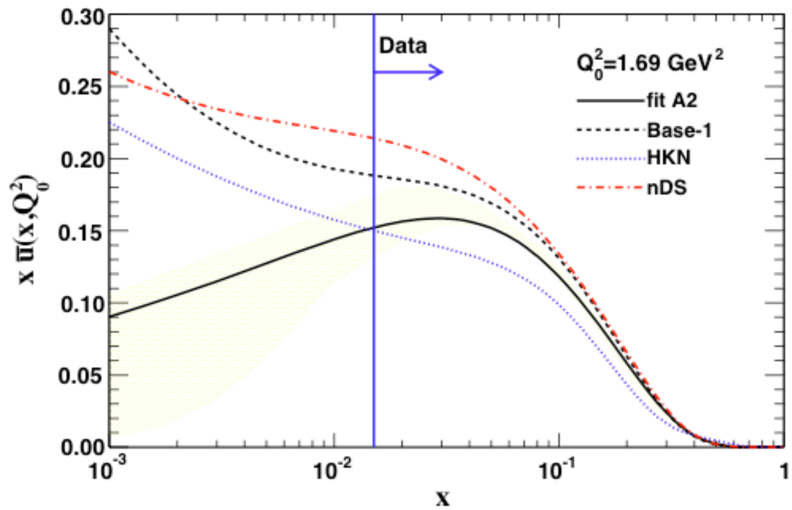
- Neutrino scattering can provide an important look at the nucleon from a different (and complimentary) angle than electro-production.
  - The ability of neutrinos and anti-neutrinos to taste particular flavors of quarks can help isolate PDFs
- To understand the neutrino (oscillations, mixing, matter 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}**. Are and nuclear effects 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 a systematic **experimental** study of **ν-induced nuclear effects (next talk).**
- **Need collaborative NP input to fully and correctly analyze crucial high-accuracy neutrino experiments!**

Additional Details

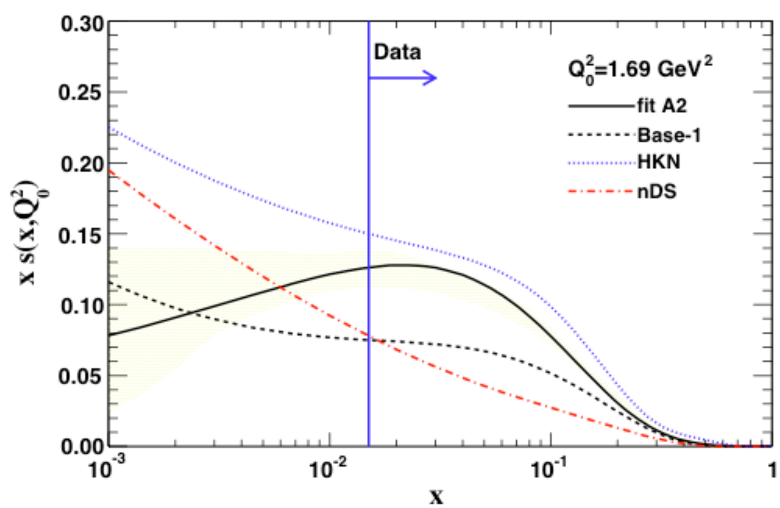
Iron PDFs



Q_0^2=1.69 GeV^2
fit A2
Base-1
HKN
nDS
Data
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 $\sigma_{\rm DY}^{pA}/\sigma_{\rm DY}^{pA'}$: 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)		

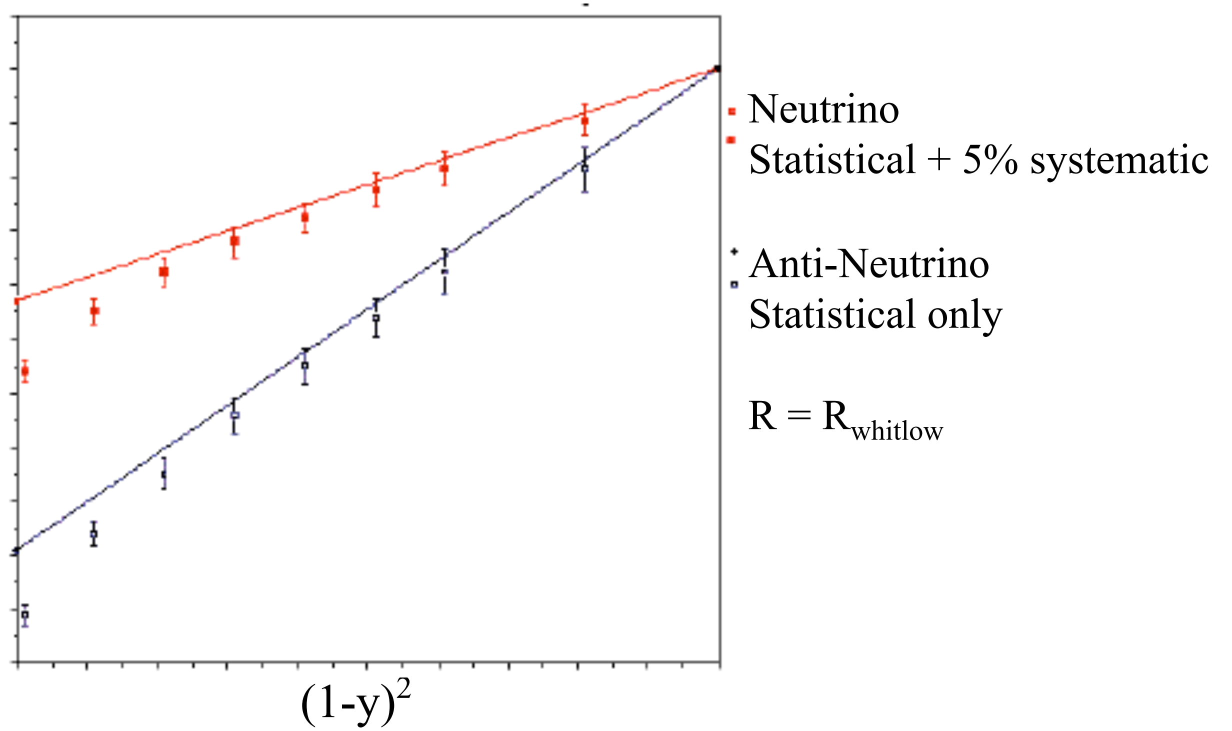
Physics Results: Six Structure Functions for Maximal Information on PDF's

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

$+ y^2 F_L$

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

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



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

Meant to give an impression only!

Kinematic cuts in (1-y) not shown.

High-x PDFs
ν - p Scattering

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

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

At high x

$$\boxed{\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} = \frac{d}{u}}$$

Add in…

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

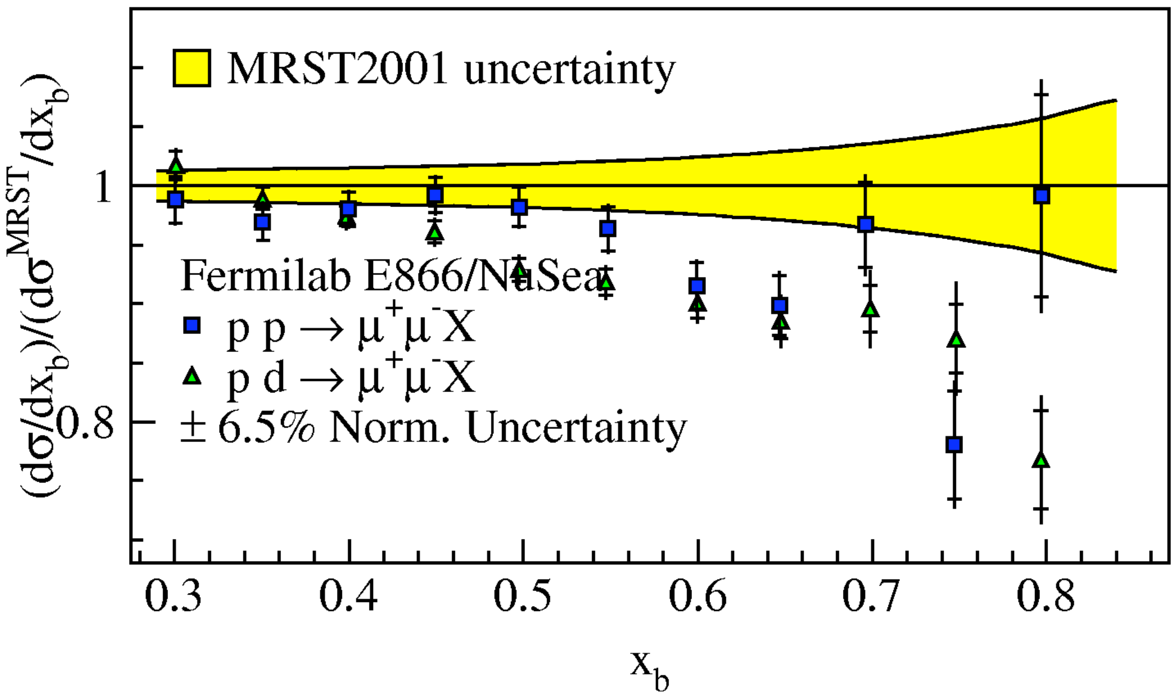
$$xF_3^{\bar{\nu} p} = 2x\,(-\bar{d} + u - \bar{s})$$

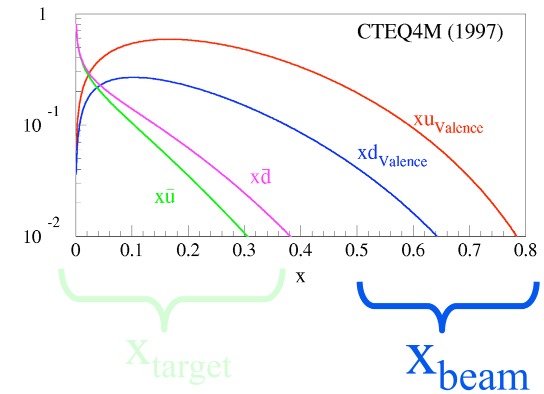
$$F_2^{\nu p} - xF_3^{\nu p} = 4x\bar{u}$$

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

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

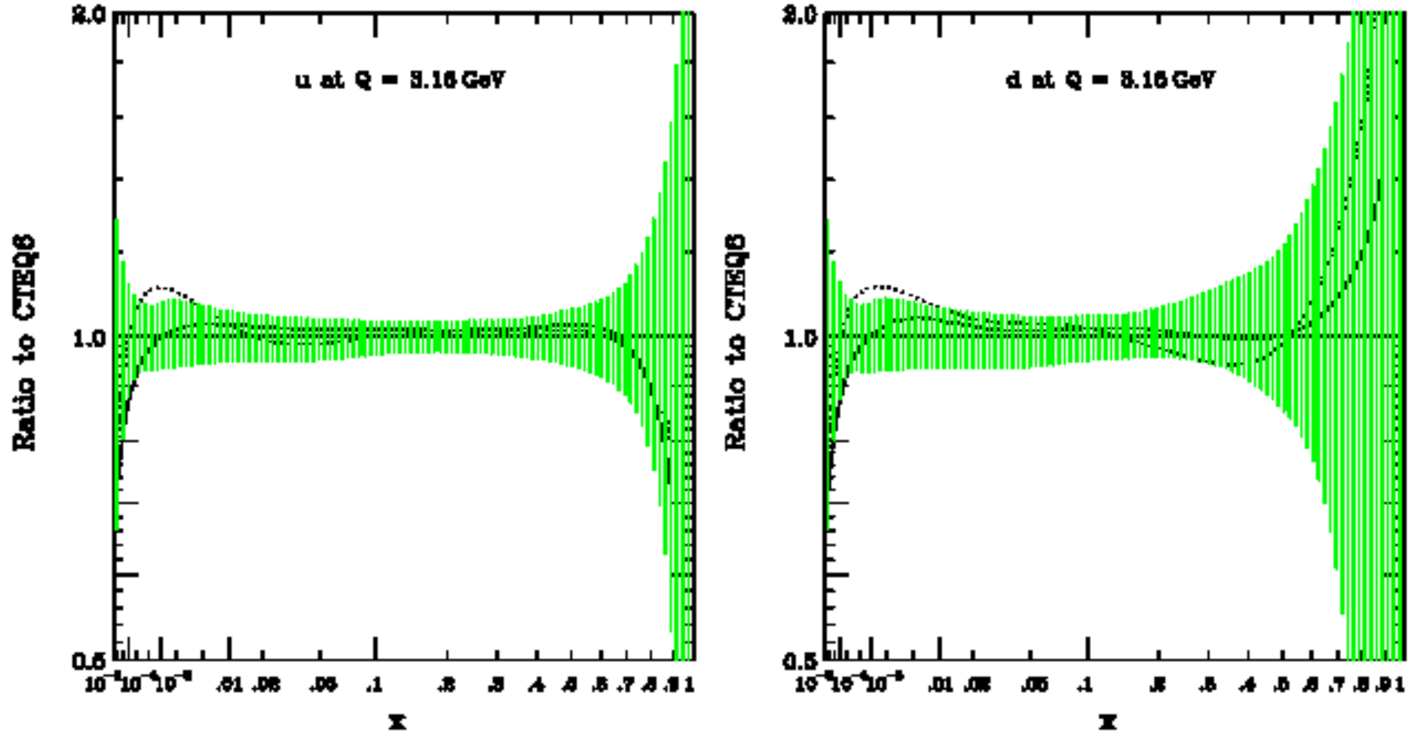
E866 -Drell-Yan Preliminary Results (R. Towell - Hix2004)





- 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)*

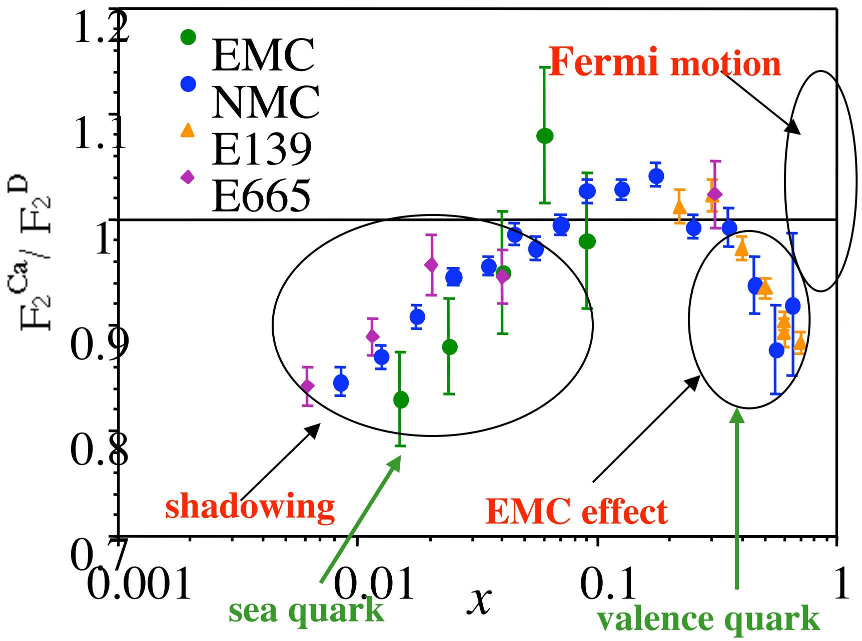
Present Status: ν-scattering
High x_{Bj} parton distributions

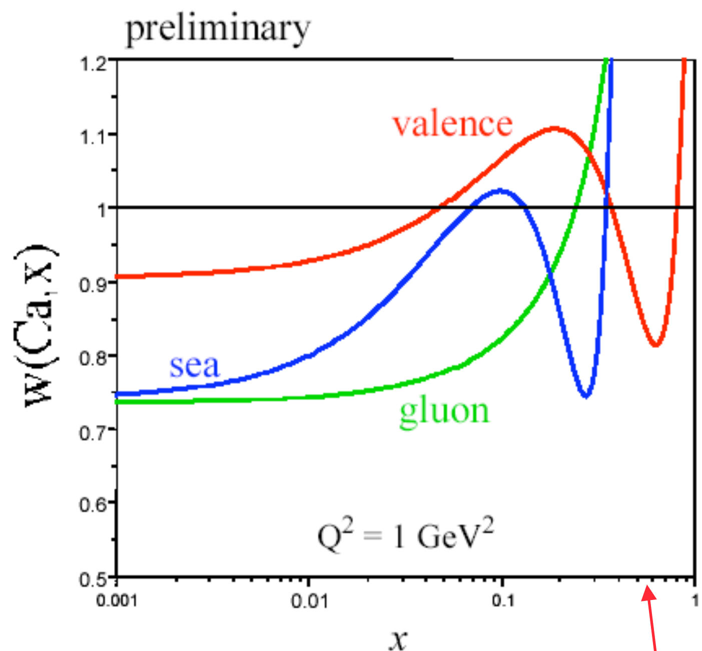


- Ratio of CTEQ5M (solid) and MRST2001 (dotted) to CTEQ6 for the u and d quarks at $Q^2 = 10\ GeV^2$. The shaded green envelopes demonstrate the range of possible distributions from the CTEQ6 error analysis.

- 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

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

- 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::

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