Measurements of F_2 at Low x and Q^2 in νN DIS at the Tevatron and a Possible Resolution of the νN μN Discrepancy

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DIS 2001
Bologna, IT

- *Outline of this Talk*

§1. CCFR Beam And Detector

§2. This F_2 Measurement

§3. Old F_2 Measurements,
Errors and Corrections

§4. Comparison to Charged Lepton Data:
Contradictions and Resolution

§5. PCAC and the ν/μ Difference

§6. Interpretation and Conclusion

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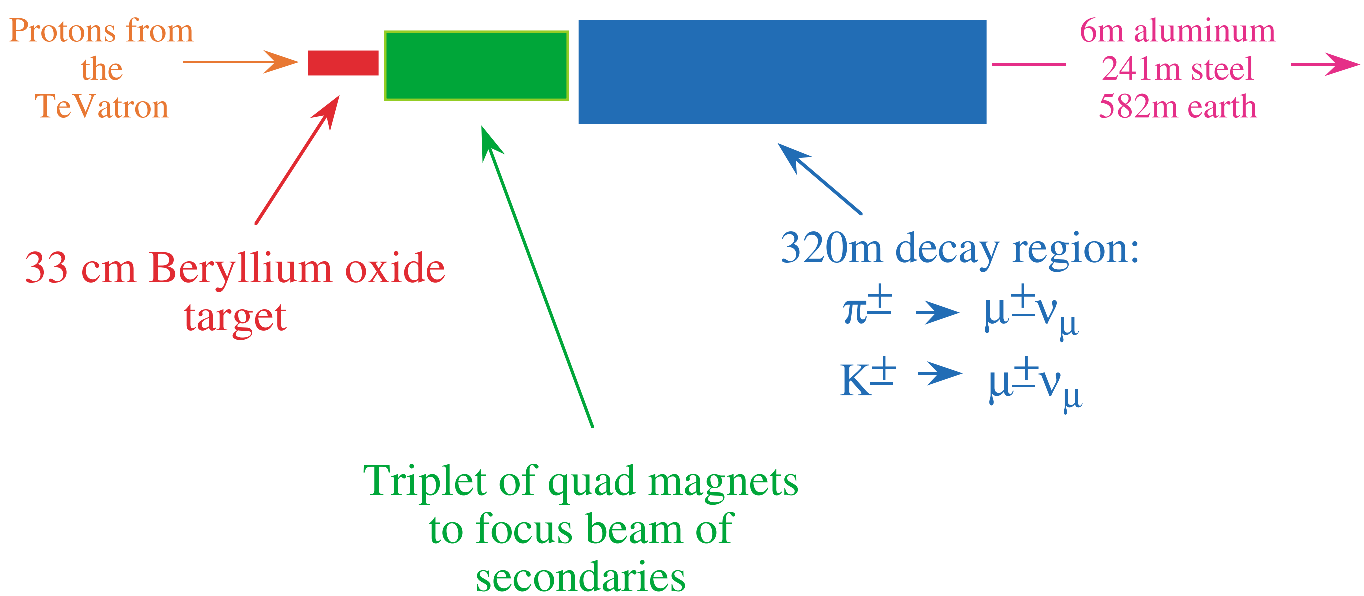
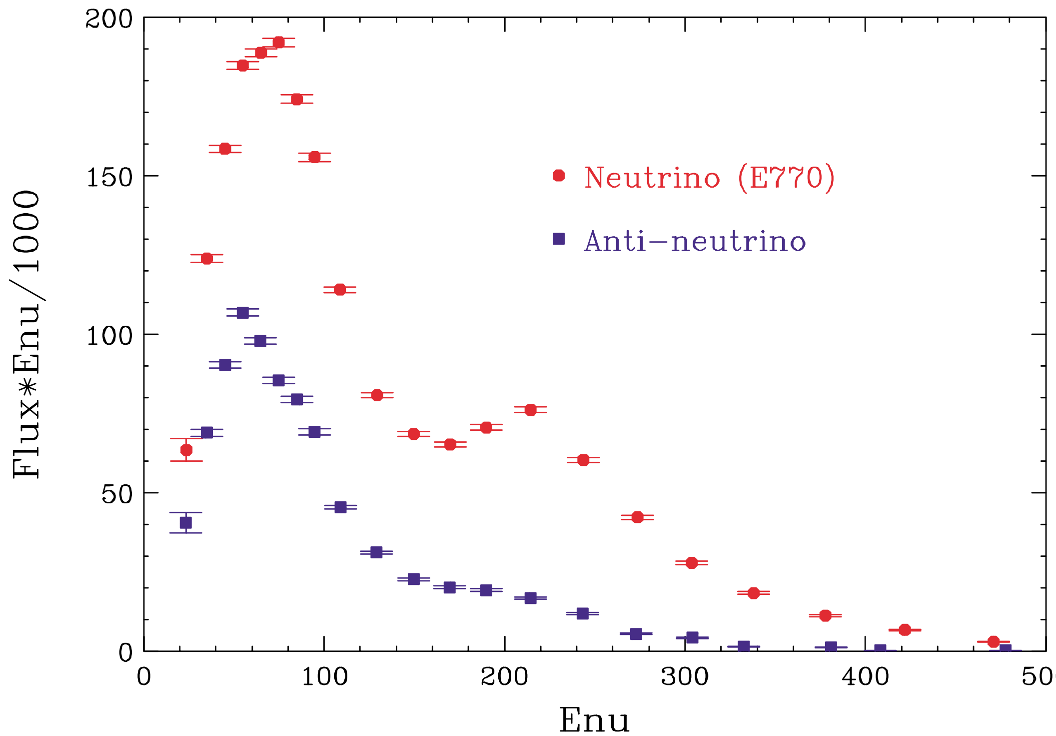
Target and Decay Region

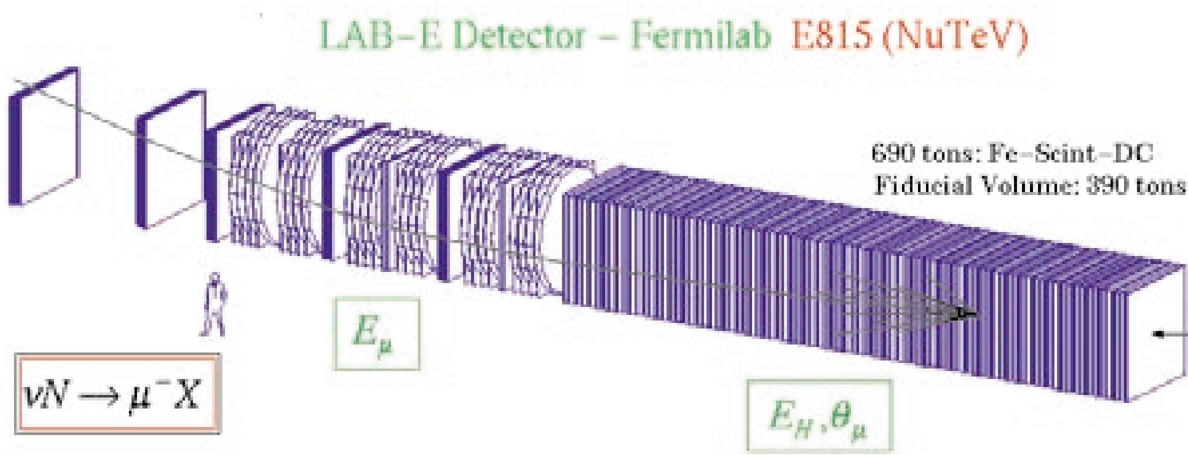
- CCFR Quadrupole Triplet
  not same as NuTeV
  (M. Goncharov, this conf.)
- 1.4 km to detector



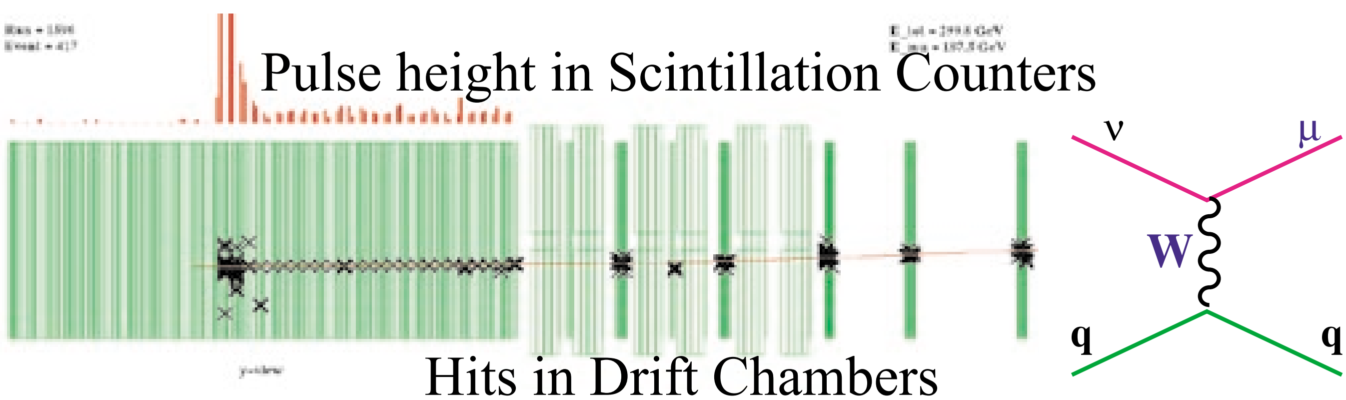


- $< E_\nu > \approx 140$ GeV
- Statistics of the Sample

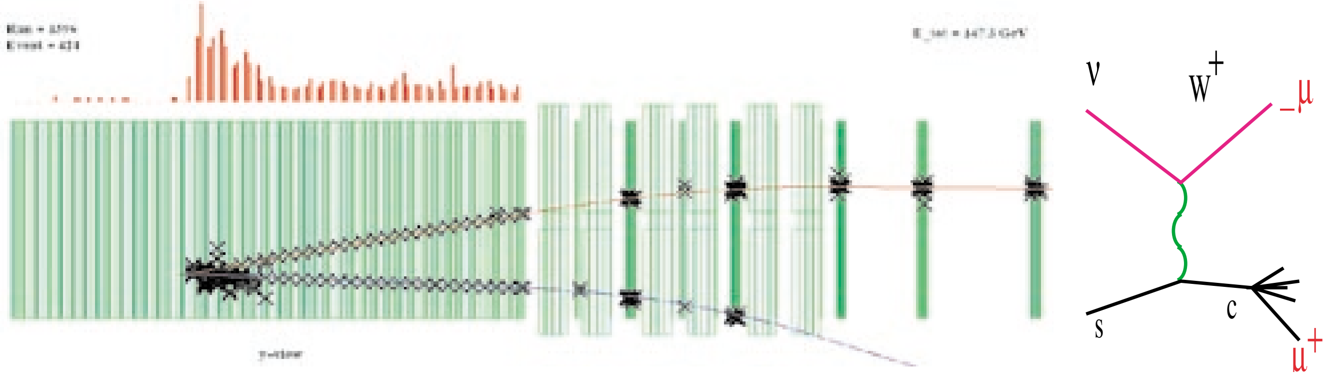
Experiment	Neutrino	AntiNeutrino
CCFR	1,030,000	179,000
CDHSW	640,000	550,000



Charged Current



Opposite Sign Dimuon



CCFR detector

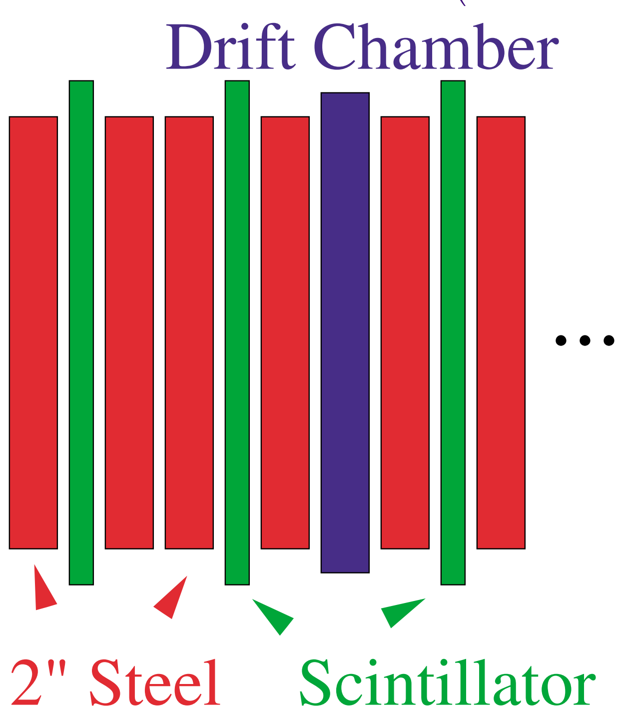
Target

- Measures energy of hadronic system

$$\frac{\sigma_E}{E} \approx \frac{0.85}{\sqrt{E\ (\mathrm{GeV})}}$$

- 10 ft by 10 ft, no transverse segmentation
- Tracks final state muon

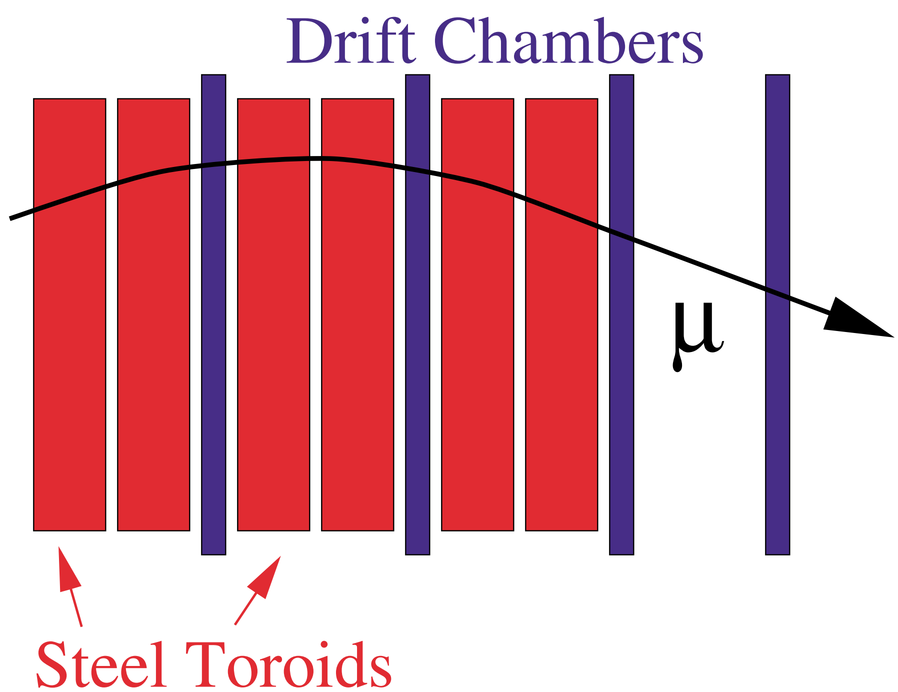
$$\sigma_\theta \sim \left(0.3 + \frac{60\ \mathrm{GeV}}{p}\right)\ \mathrm{mr}$$



Toroid

- Magnetic field bends muon
- Curvature measures muon momentum

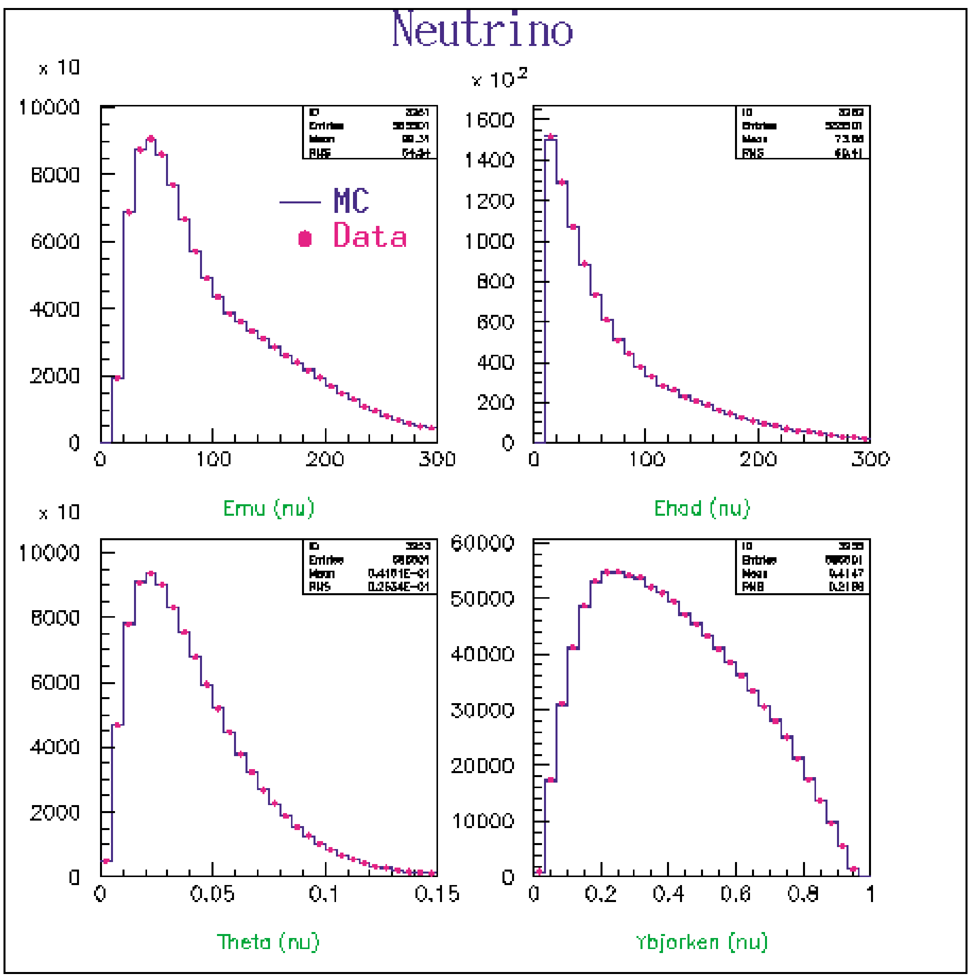
$$\frac{\sigma_p}{p} \approx 0.11$$



How well do we model our detector?

§1. Monte Carlo Describes Data Well

§2. Smearing is based on a parameterization from test beam data



How do we measure F_2^ν?

$$N^{\nu,\overline{\nu}}\left(x,Q^2\right) = \rho L N^A \int_{xbin} dx \int_{Q^2bin} dQ^2 \int_{allenergies} dE \frac{d\sigma^{\nu,\overline{\nu}}}{dxdQ^2}\Phi^{\nu,\overline{\nu}}\left(E\right)$$

$$\frac{d^2\sigma^{\nu,\overline{\nu}}}{dxdQ^2} = \frac{G_F^2 M E_\nu}{\pi}\left(\left(1 - y - \frac{Mxy}{2E}\right)F_2 + \frac{y^2}{2}2xF_1 \pm y\left(1-\frac{y}{2}\right)xF_3\right)$$

- Cuts on the data:
  - ▷ Hadron shower containment
    - ∗ Hadron shower within fiducial volume cut
  - ▷ Muon momentum resolution
    - ∗ Enough hits in target DCs
    - ∗ Muon track within toroid with enough hits in DCs and good fit to track
    - ∗ Muon passes through at least 2/3 of toroid

Cuts and Corrections

- Energy and Angular Resolution
  - ▷ $E_{\mathrm{HAD}} > 10$ GeV
  - ▷ $E_\mu > 15$ GeV
  - ▷ 30 GeV $< E_\nu <$ 360 GeV
  - ▷ $\theta_\mu < 150$ mrad
- Corrections to the data:
  - ▷ Radiative effects
    - ∗ D. Yu. Bardin and V. A. Dokuchaeva, JINR–E2–86–260 (1986)
  - ▷ Isoscalar
  - ▷ Propagator
  - ▷ Bin-center

Flux Extraction: Fixed ν Method

- Basic Equations:

$$\frac{1}{E}\,\frac{d^2\sigma}{dx\,dy}(\nu N) \sim q + (1-y)^2\bar{q}$$
$$\frac{1}{E}\,\frac{d^2\sigma}{dx\,dy}(\bar{\nu} N) \sim \bar{q} + (1-y)^2 q$$

  where $y = 1 - E_\mu/E_\nu$

  ▷ So $y = 0$ means μ has all the energy, hadron shower has none

  ▷ Experimentally very clean

- At $y = 0$:

$$\frac{1}{E}\,\frac{d^2\sigma}{dx\,dy}(\nu N) = q + \bar{q}$$
$$\frac{1}{E}\,\frac{d^2\sigma}{dx\,dy}(\bar{\nu} N) = q + \bar{q}$$

Differential Cross Section For $\nu, \bar{\nu} =, \propto F_2$

- Flux extraction relies on CC events with low hadronic energy ($E_{\rm had} < 20$ GeV)
- Variation Gives Relative Flux: if $\nu = E_{\rm had}$ then after some algebra:

1. Term Proportional to Flux

$$N(E_\nu, \nu < \nu_o) = \Phi(E_\nu) \int_0^{\nu_o} d\nu \; A\times$$

2. Term Of Order ν/E (once again, small y)

$$\left[1 + \left(\frac{B}{A}\right)\left(\frac{\nu}{E}\right) - \frac{\nu^2}{2E^2}\left(\frac{B}{A} - \frac{\int F_2 \bar{R}}{\int F_2}\right)\right]$$

with

$$A = \frac{G_F^2 M}{\pi} \int dx\, F_2(x, Q^2)$$

$$B = -\frac{G_F^2 M}{\pi} \int dx\, F_2(x, Q^2) \pm x F_3(x, Q^2)$$

$$C = B - \frac{G_F^2 M}{\pi} \int dx\, F_2(x, Q^2) \bar{R}(x, Q^2)$$

$$\bar{R} = \frac{E + 2Mx}{(1+R)E} - \frac{Mx}{E} - 1$$

- So We See Amidst the Algebra:

  §1. Number(E) $\propto \Phi(E)$ in $\nu \to 0$ limit

  §2. Corrections Are
  Weakly Energy Dependent

- We Do Need to Iterate
  Structure Function and Flux

- Don't Get Normalization

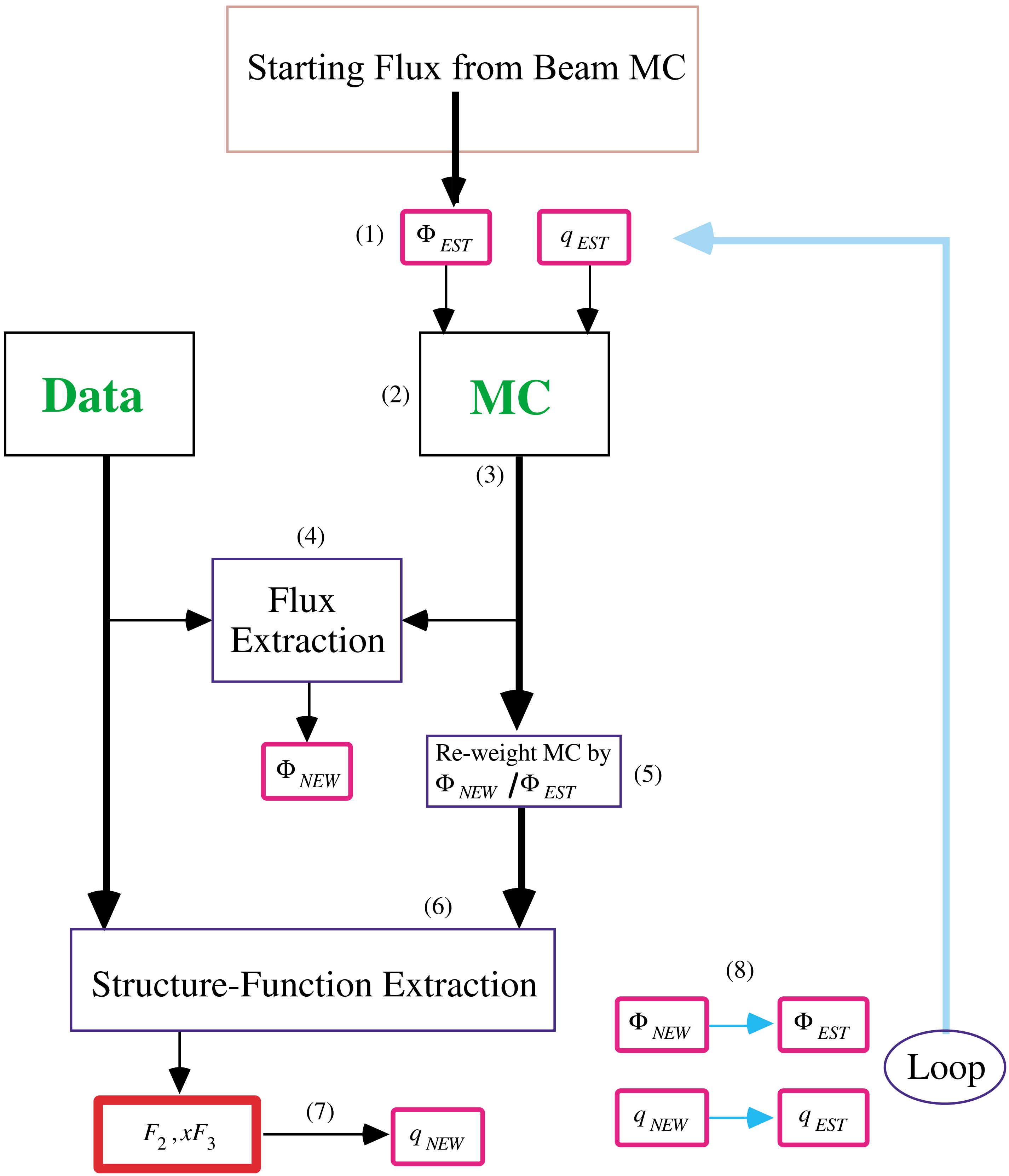
- Use world average

$$\sigma_\nu = 0.677 \pm 0.014 \times 10^{-38} \ \frac{\mathrm{cm}^2}{\mathrm{GeV}}$$

$$\sigma_{\overline{\nu}}/\sigma_\nu = 0.499 \pm 0.007$$

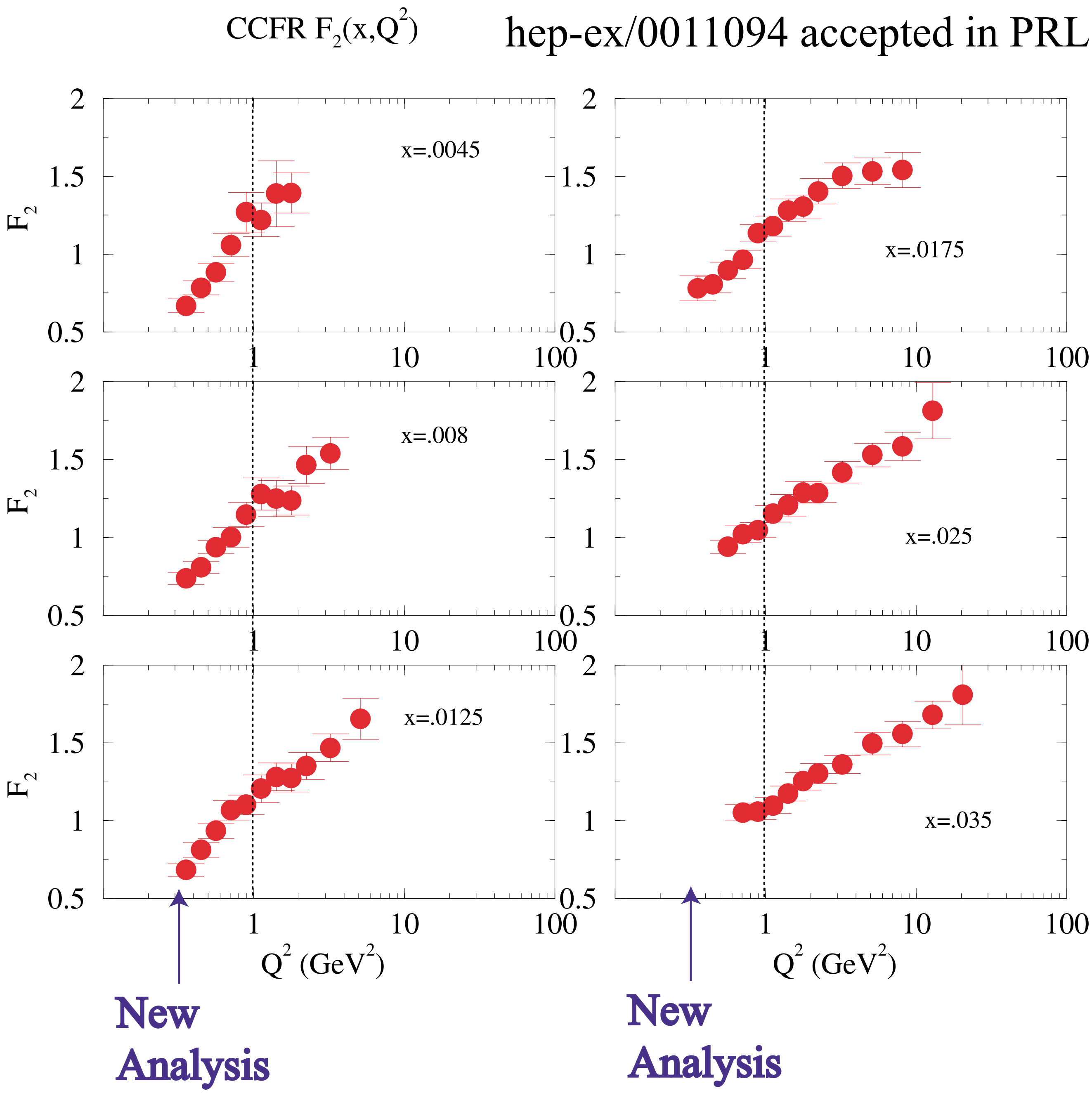
  to get absolute normalization of flux

- But then F_2 Normalization Yields Error



Starting Flux from Beam MC
(1)
Φ_{EST}
q_{EST}
Data
(2)
MC
(3)
(4)
Flux Extraction
Φ_{NEW}
Re-weight MC by Φ_{NEW}/Φ_{EST}
(5)
(6)
Structure-Function Extraction
F_2, xF_3
(7)
q_{NEW}
(8)
Φ_{NEW}
Φ_{EST}
q_{NEW}
q_{EST}
Loop

First measurement of F_2^ν at low x, low Q^2 in νN DIS

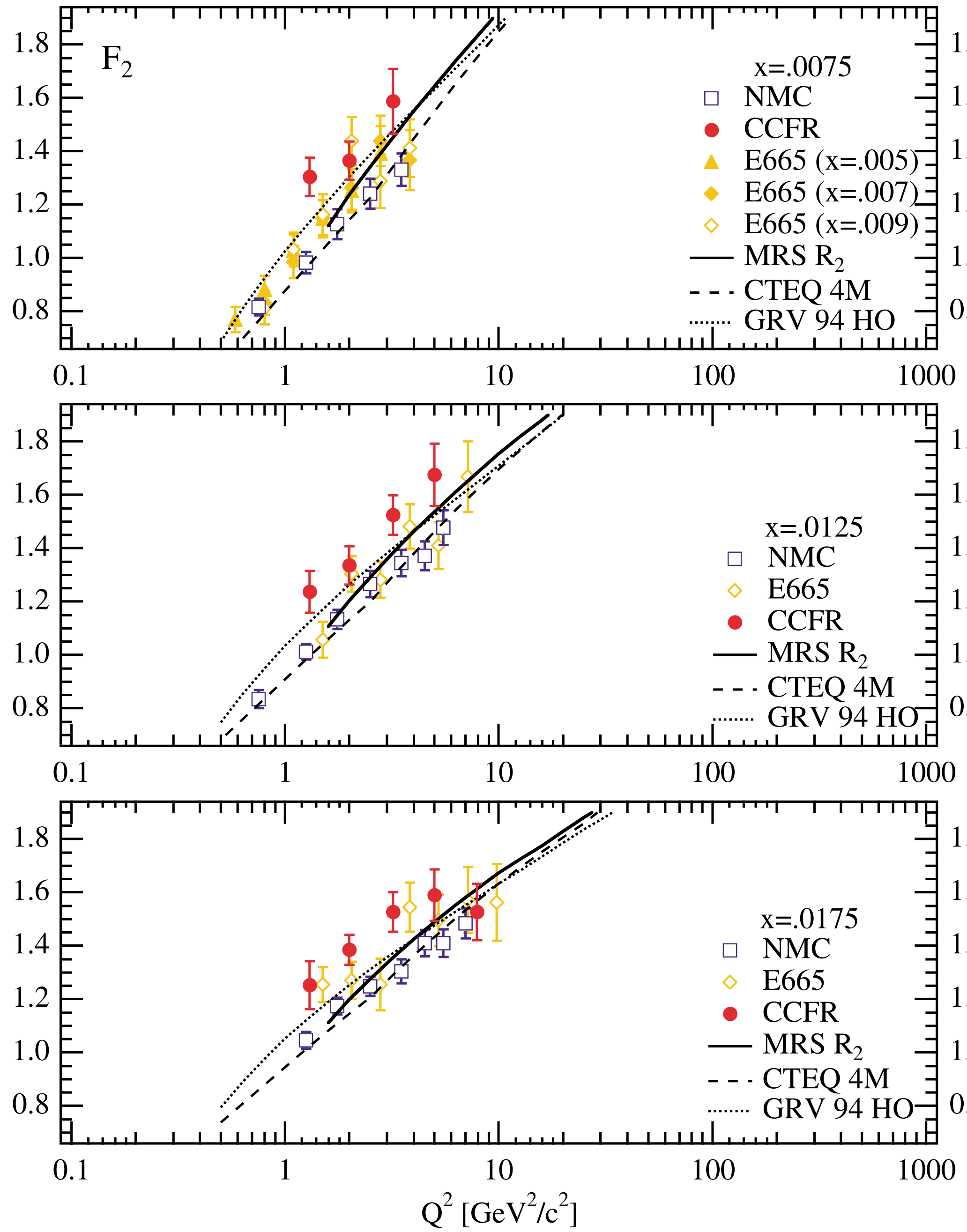


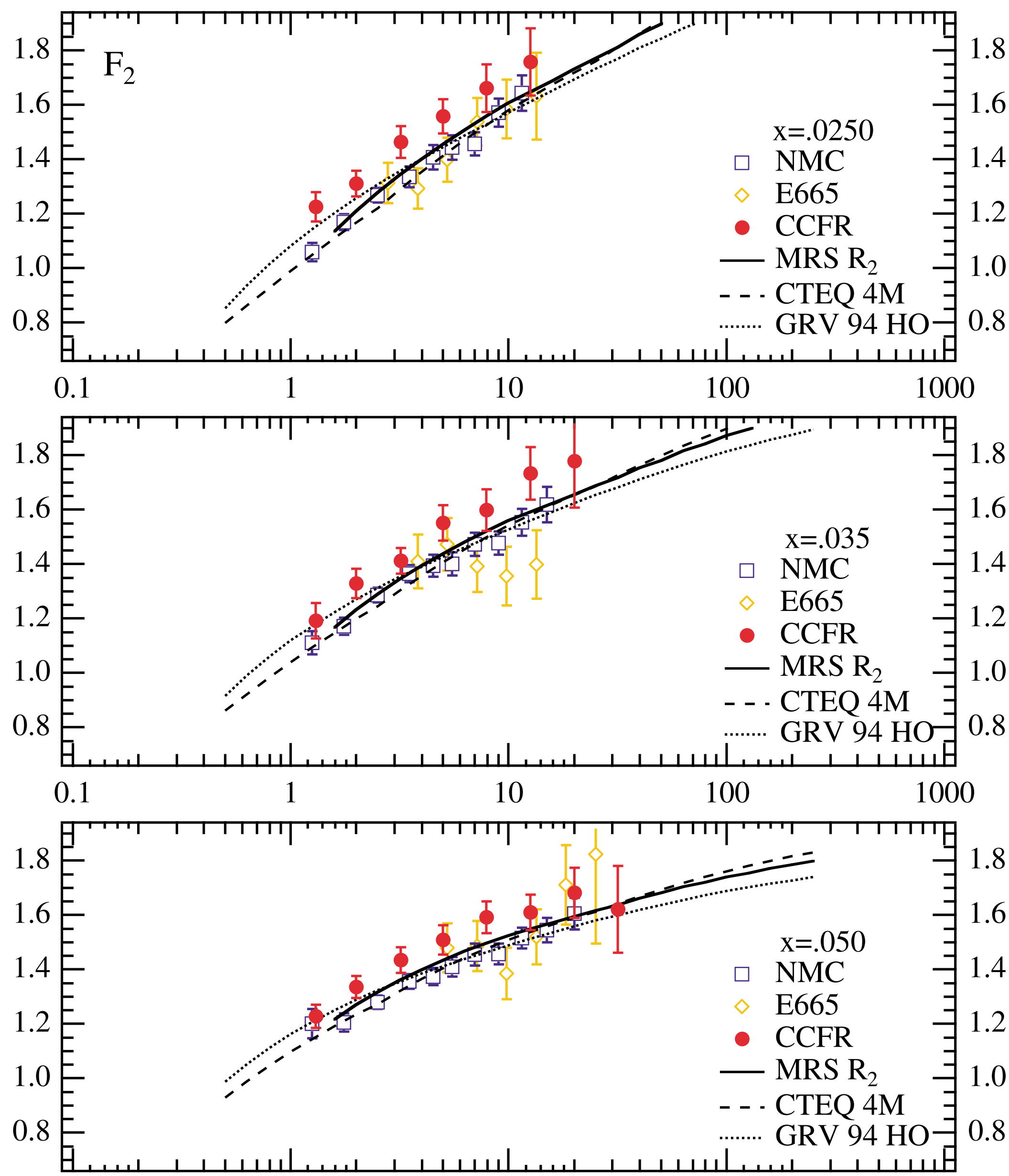
Statistical and Systematic errors

SOURCE OF UNCERTAINTY		$\delta\ F_2^\nu$
Statistics:	low x	2-3%
	higher x	$\sim$ 1%
Energy Calibrations:	Hadron ($\pm$1%)	1-2%
	Muon ($\pm$1%)	2-3%
Physics Models:	Charm Mass ($\pm$18%)	1-2 %
	Charm Branching Ratio ($\pm$7%)	$<$ 1%
	Strange Sea Normalization ($\pm$12%)	$<$ 1%
	Strange Sea Shape ($\pm$26%)	$<$ 1%
	Cross section normalization ($\pm$2.1%)	2-3%
	Cross section ratio ($\pm$1.4%)	$<$ 1%
	PDF Choices ($\pm 1\sigma$)	3-5%
	R world ($\pm$15%)	$<$ 2%
	ΔxF_3 model,low x	5%
	ΔxF_3 model, higher x	$\sim$ 1%
	Radiative corrections model ($\pm 1\sigma$) low x	3%
	Radiative corrections model ($\pm 1\sigma$), higher x	$\sim$ 1%

Previous CCFR F_2 Measurements

There has been a $\sim 10-20\%$ discrepancy at low region ($x < 0.1$) between F_2^ν(CCFR) and F_2^μ(NMC) (Seligman *et al.*)





F2
x=.0250
x=.035
x=.050
NMC
E665
CCFR
MRS R2
CTEQ 4M
GRV 94 HO
0.8
1.0
1.2
1.4
1.6
1.8
0.1
1
10
100
1000
Q2 [GeV2/c2]

Charged Lepton Data Comparisons:

- The strange sea correction to

  $5/18 F_2^{\nu}$ is 10$\pm$2% at $x = 0.01$

$$F_2^{\mu} = \frac{5}{18} F_2^{\nu} - \frac{1}{6}(s + \bar{s} - c - \bar{c})$$

- The nuclear correction to

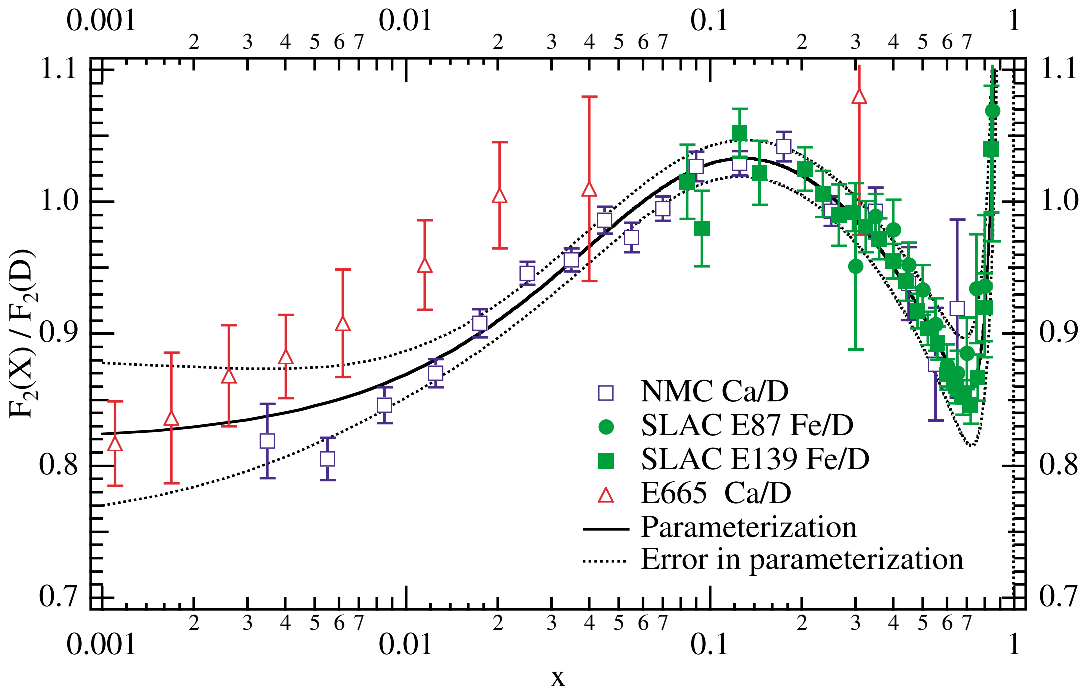
  $F_2(\mathrm{Fe})$ is 15$\pm$2% at $x = 0.01$

  from NMC/E665/SLAC[μ, e]

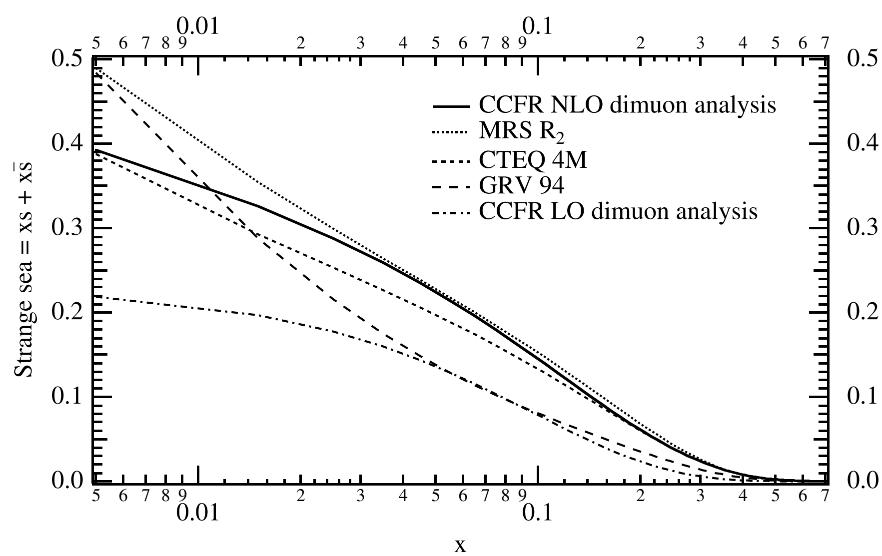
- The slow-rescaling correction to account for massive charm threshold effects is

  6$\pm$2% at $x = 0.01$

• Nuclear correction (EMC effect)

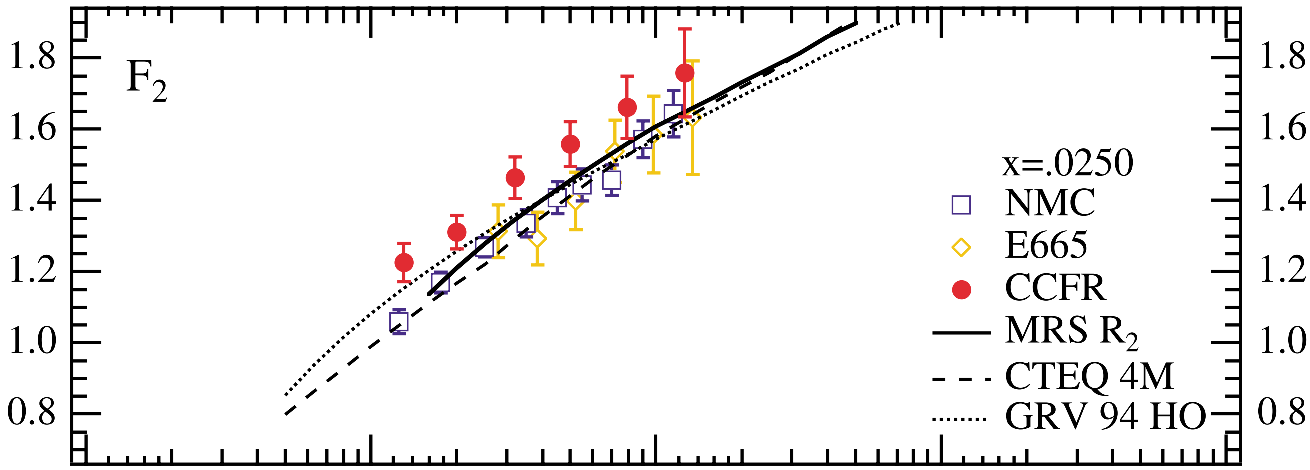


• Strange sea correction



Attempts have been made

to resolve this discrepancy



- Wrong strange sea at low x ?
  Sea would have to be
  increased by factor of two
- $s(x) \neq \overline{s}(x)$?
  $\overline{s}(x)$ would have to be negative
- Different nuclear effects ?
  Has been studied by Boros et al.(hep-ph/9804410)
  $\leq 5\%$, not enough

- Charge symmetry violation?

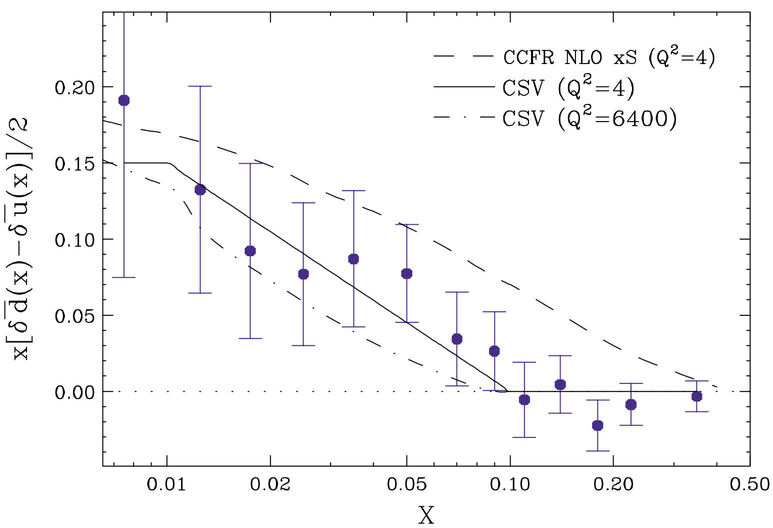
$$\delta\overline{d} = \overline{d}^p - \overline{u}^n \neq 0$$
$$\delta\overline{u} \neq 0$$

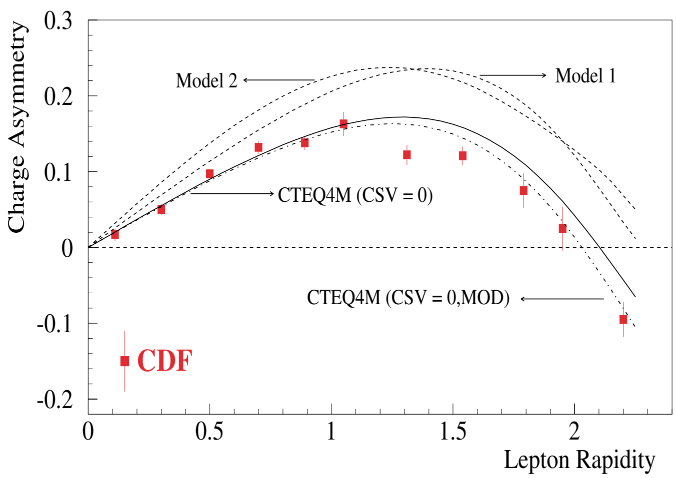
Ruled out by Bodek et al.
using CDF W asymmetry data

- Effects of massive charm used in the extraction procedure? (e.g. slow rescaling effects, ΔxF_3 correction).

Charge symmetry violation

- Charge symmetry violation, $d^n \neq u^p$
  $\delta\bar{d} = \bar{d}^p - \bar{u}^n \simeq 0.5s$
  $\delta\bar{u} = \bar{u}^p - \bar{d}^n \simeq 0.5s$





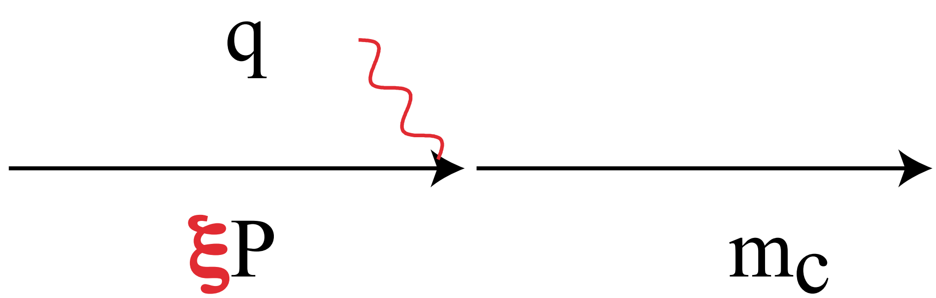
The CDF W asymm. data do not agree with the CSV model.

Bodek et al., PRL 83, 2892(1999)

Slow-Rescaling Correction

- What is Slow-Rescaling?

  Kinematic Penalty
  for Massive Quark Production



$$(\xi P + q)^2 = m_c^2$$

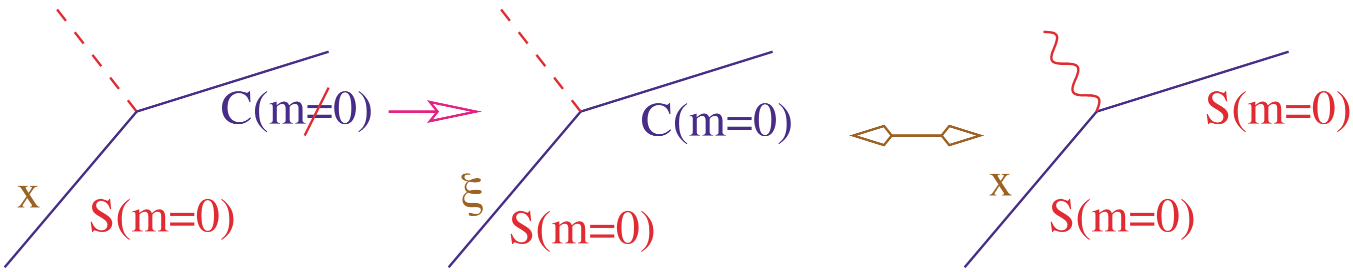
$$\xi = x + \frac{m_c^2 - m_i^2}{2P \cdot q}$$

$$\xi \approx x\left(1 + \frac{m_c^2}{Q^2}\right)$$

Obviously Crude Approximation

- Initial State Quark Mass
- Threshold Effects
- Gluon Scattering

Slow rescaling $[x \longrightarrow \xi = x(1 - m_c^2/Q^2)]$

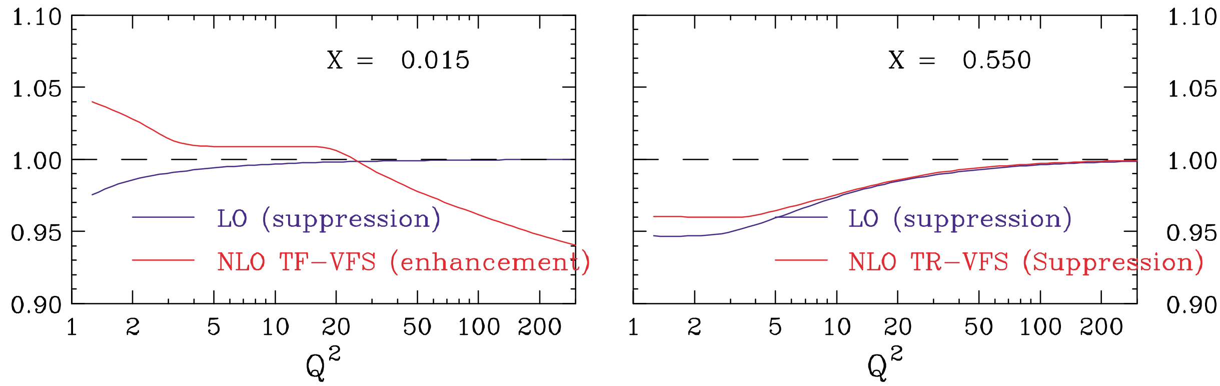


OK For Dimuons, but not for NLO PDFs...

- Previous CCFR F_2 analysis
  applied slow rescaling correction

- F_2^{ν} could be directly compared with F_2^{μ}
- Recent NLO calculations including massive charm production are very different from the LO, slow rescaling corrections used in the previous CCFR analysis

F2[Heavy/Light]



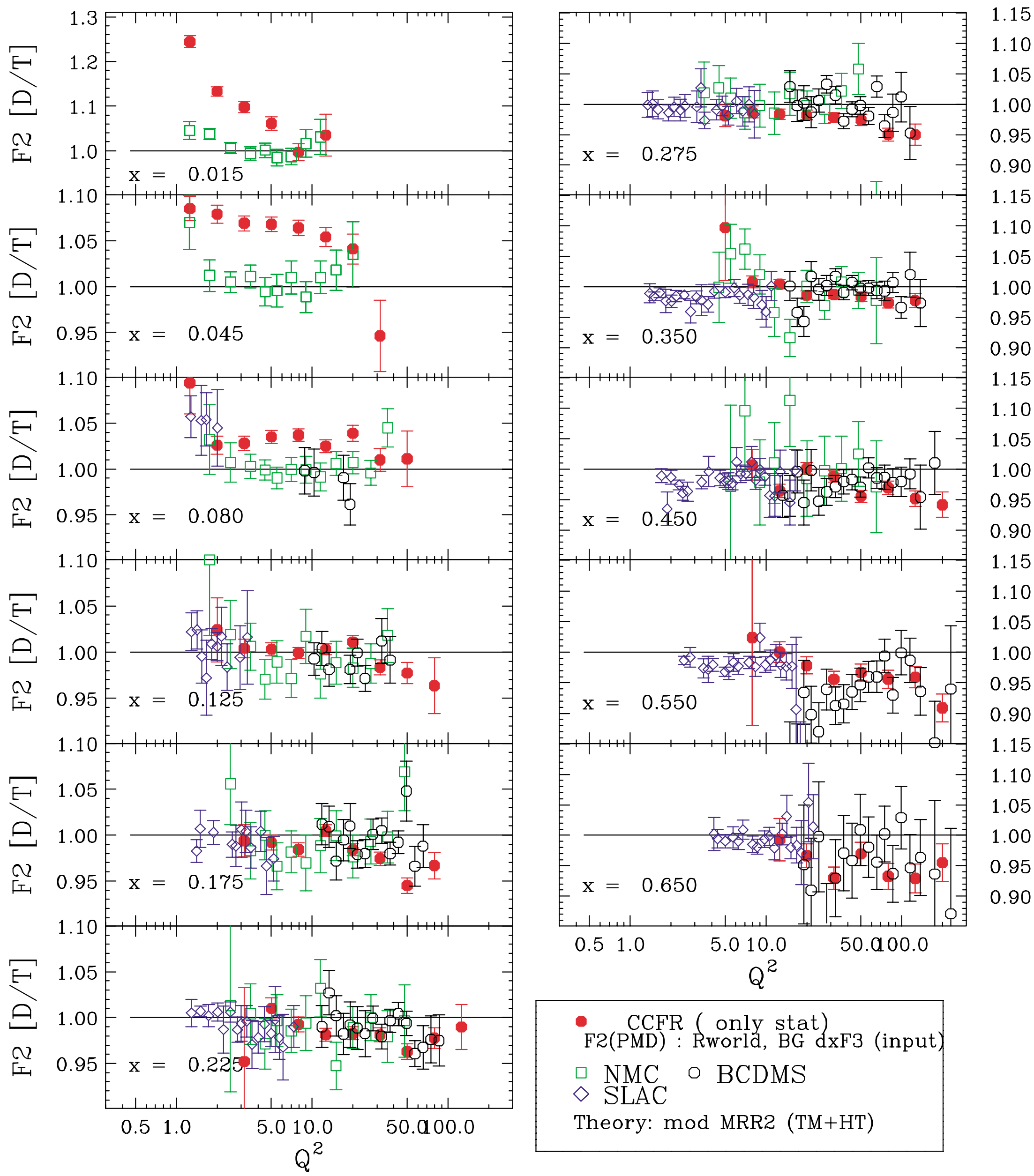
- LO calculations are too simplistic
- Large uncertainty
  in the slow rescaling correction
- *Do not apply slow rescaling corrections*
- Rephrase Question:

Does the Same PDF/Model Describe Both μ and ν DIS?

- Compare data to theory:
  Neutrino case: $\dfrac{Data(m_c \neq 0)}{Theory(m_c \neq 0)}$
  Muon case: $\dfrac{Data(\mu)}{Theory(\mu)}$

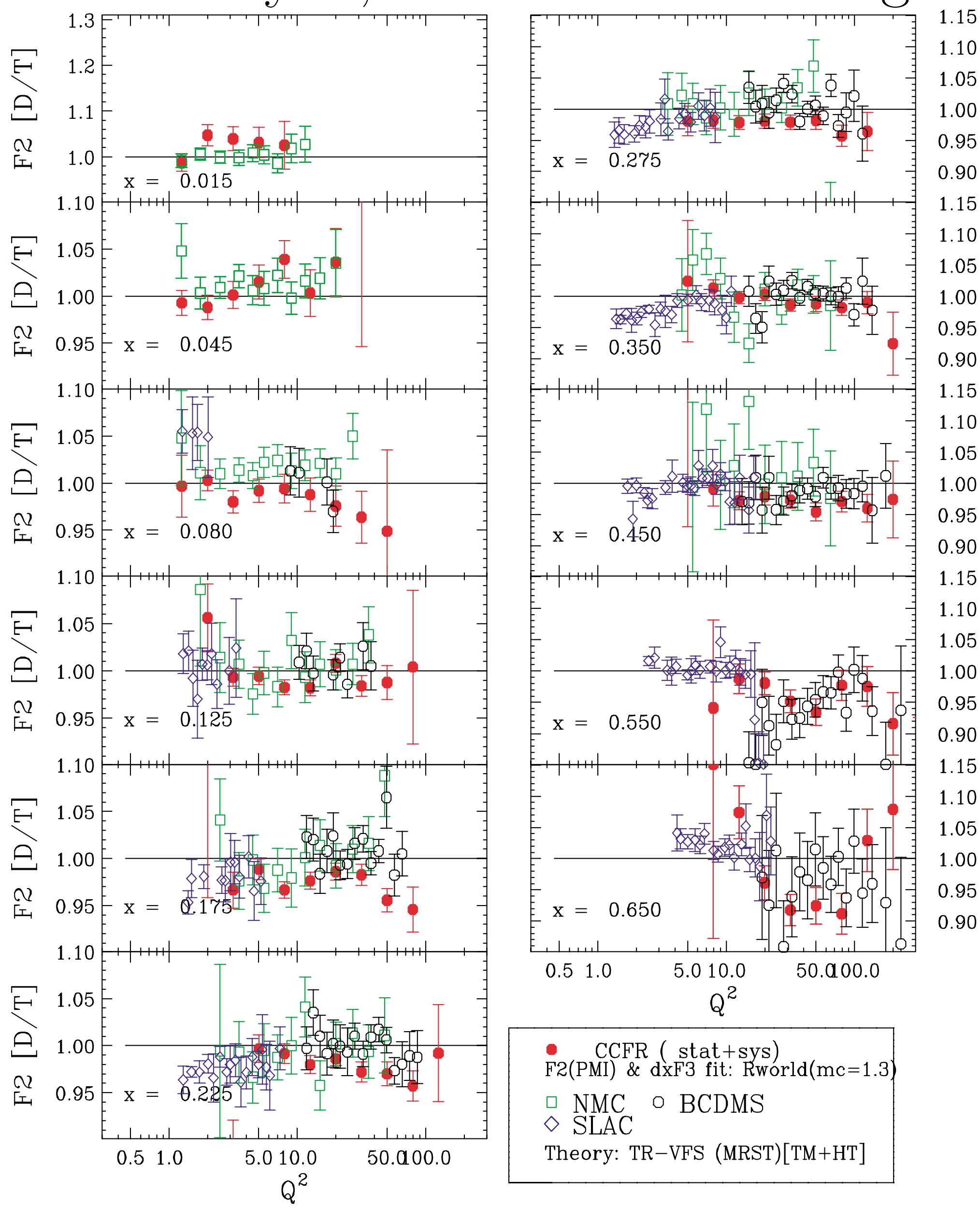
Comparison of F_2^{ν} and F_2^{μ}

- Before this analysis,
  with LO Slow-Rescaling Applied



Comparison of F_2^ν and F_2^μ

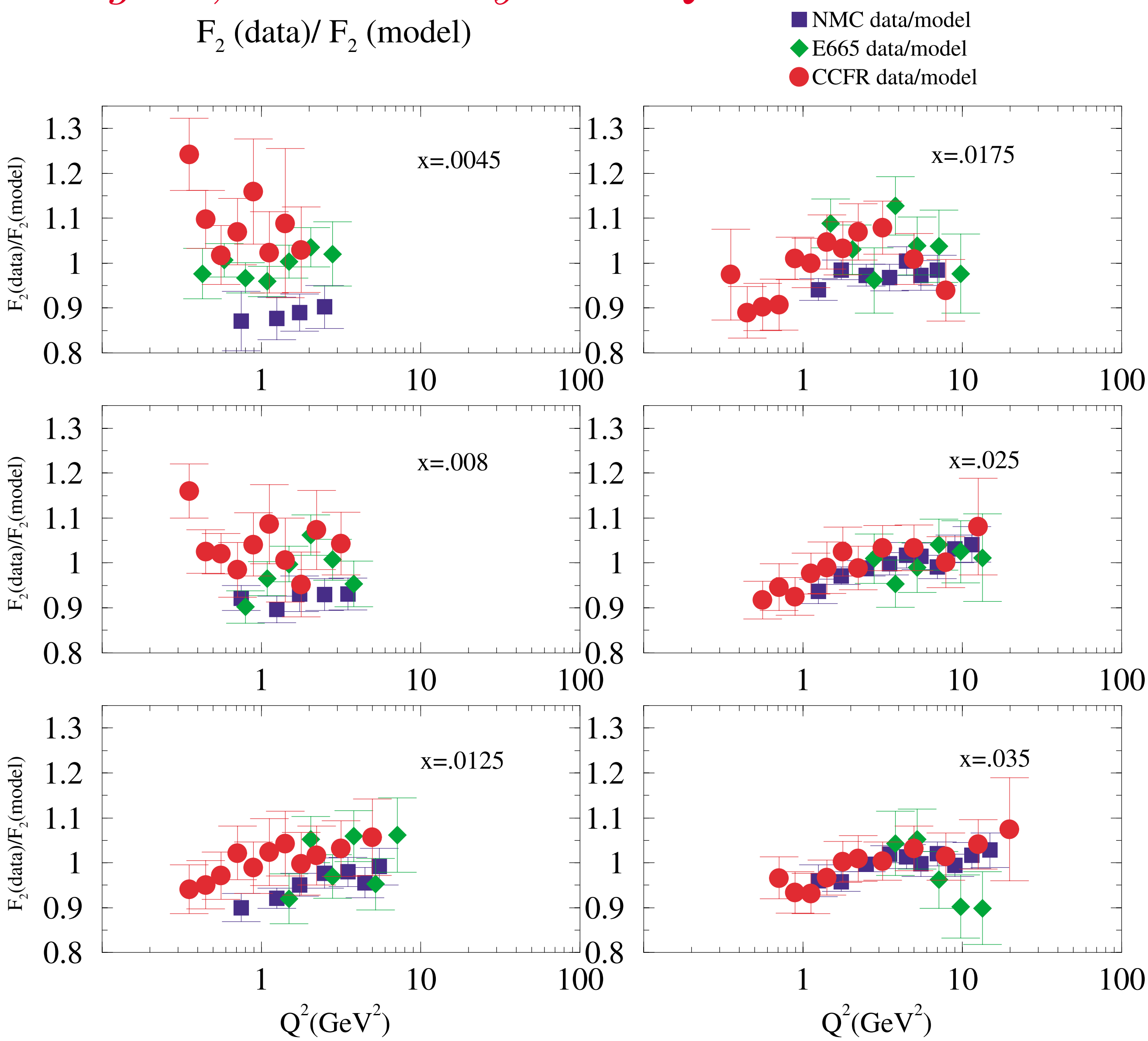
- This analysis, NO Slow-Rescaling Applied



- Discrepancy Gone

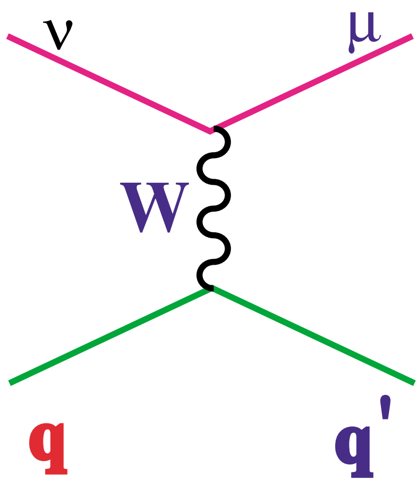
Lower x and lower Q^2

Again, New Analysis is $Q^2 < 1$

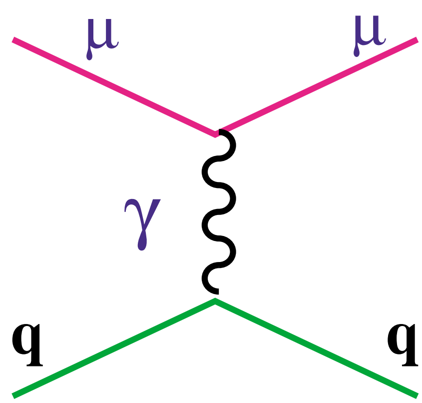


Should F_2^{ν} and F_2^{μ} behave differently as $Q^2 \rightarrow 0$?

- How Are νN and μN Scattering Different?



νN



μN

- F_2 must Vanish at $Q^2 = 0$ for Photon Exchange:

$$\frac{d^2\sigma}{dQ^2\,dx}\Big|_{\mu N} \propto \frac{4\pi\alpha}{Q^4}\frac{F_2(x,Q^2)}{x}$$

- But Not For Neutrinos:

$$\frac{d^2\sigma}{dQ^2\,dx}\Big|_{\nu N} \propto \frac{G_F^2}{2\pi x}$$

In The Olden Days

- The Partially Conserved Axial Current hypothesis[1] connects the axial part of
  weak hadronic current
  to the charged pion field
- Adler proposed to test the PCAC hypothesis using high energy neutrinos[2]
  $\hookrightarrow \sigma^{\nu N}$ can be expressed in terms of $\sigma^{\pi N}$
- A consequence of Adler's prediction: at low Q^2, W, mediating neutrino interaction, can fluctuate to a π whose cross section will not vanish at $Q^2 = 0$
- F_2^{ν} approaches a constant as $Q^2 \rightarrow 0$

[1] M. Gell-Mann, M. Levy, *Nuovo Cim.* **16**, 705 (1960)
[2] S. Adler, *Phys. Rev.* **135**, B963 (1964)

How can we test this prediction?

- Fit the data to a form predicted by
  A. Donnachie and P.V. Landshoff
  Z. Phys. **C61**: 139 (1994).
- Donnachie and Landshoff have
  proposed simple parameterizations
  - ▷ components are movitivated by physical considerations
  - ▷ describe the behavior of F_2^μ and F_2^ν in this Q^2 limit.

Muon Scattering	Neutrino Scattering
$C\left(\frac{Q^2}{Q^2+A^2}\right)$	$C\left(\frac{Q^2}{Q^2+A^2}+\frac{Q^2+B}{Q^2+D^2}\right)$
As $Q^2 \to 0,\ F_2^\mu \to 0$	As $Q^2 \to 0,\ F_2^\nu \to$ constant

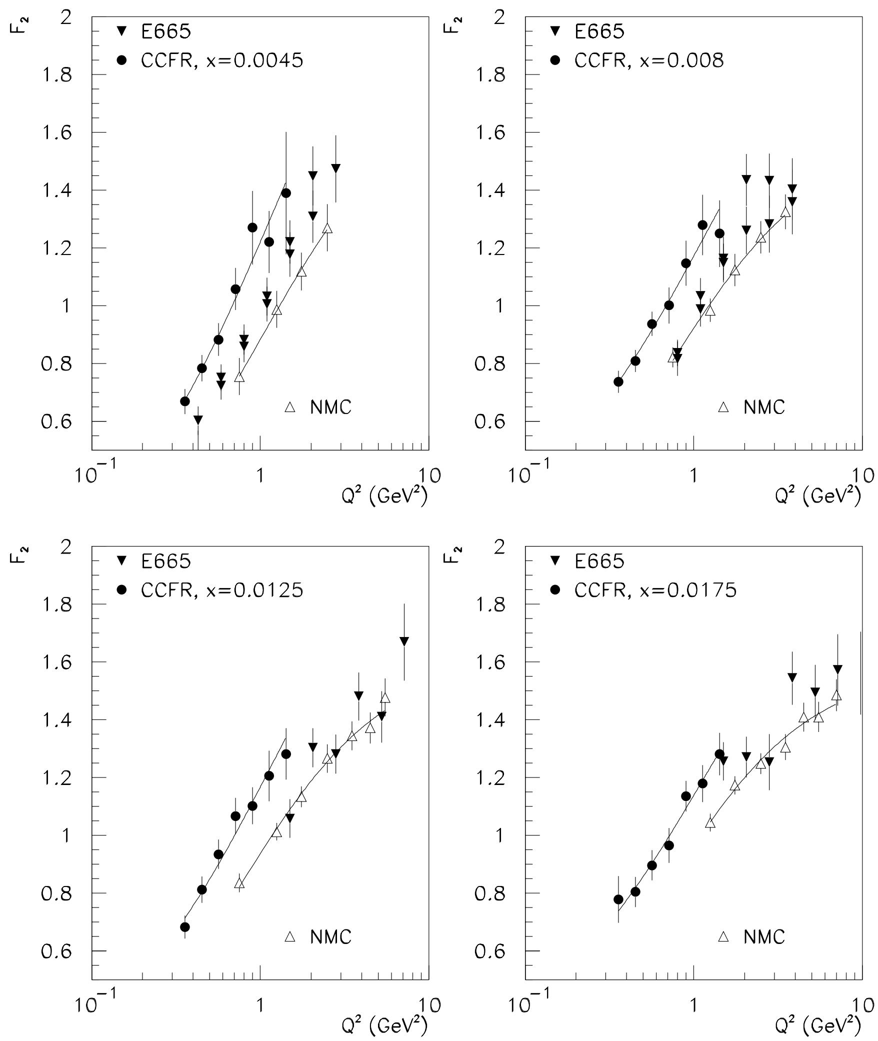
Do CCFR data follow this form?

Extract axial component of the weak interaction

Fit to data using form predicted by

Donnachie and Landshoff

$$C\left(\frac{Q^2}{Q^2+A^2}+\frac{Q^2+B}{Q^2+D^2}\right)$$



Fit Results

- A = .83 ± 0.06 GeV:

  determined from a fit to NMC data above.

x	B	C	D	$F_2^\nu(Q^2=0)$	χ^2/N
0.0045	1.49 ± 0.02	2.62 ± 0.26	0.06 ± 0.17	0.04 ± 0.10	0.5
0.0080	1.63 ± 0.05	2.32 ± 0.05	0.50 ± 0.05	0.22 ± 0.03	0.5
0.0125	1.63 ± 0.05	2.39 ± 0.05	0.40 ± 0.05	0.18 ± 0.03	1.0
0.0175	1.67 ± 0.05	2.20 ± 0.05	0.65 ± 0.07	0.26 ± 0.03	0.5

- $F_2\left(Q^2=0\right)$ statistically significant
- In agreement

§1. Within 1σ in three highest x bins

§2. Lowest x bin $\longrightarrow$ 2σ deviation

- Conclusions:

§1. First Extraction of F_2 in νN
for $x < .01$, low Q^2

§2. By Comparing Data to Theory,
Solve ν/μ N discrepancy in F_2
$\Rightarrow$ *LO Slow Rescaling Big Effect*

§3. F_2^{μ} and F_2^{ν} agree with D&L PCAC Model