Precise Measurement of the Differential Cross Section for $\nu - Fe$ and $\bar{\nu} - Fe$ Scattering (Final Result)

Martin Tzanov
University of Pittsburgh

Introduction

- NuTeV experiment
- $\nu | \bar{\nu} | - N$ Differential cross section and structure functions

Method

- Differential cross section extraction
- F_2 and xF_3 measurement

Results

Conclusions

NuTeV Collaboration

T. Adams [4], A. Alton [4], S. Avvakumov [8], L. de Barbaro [5], P. de Barbaro [8], R. H. Bernstein [3], A. Bodek [8], T. Bolton [4], S. Boyd [7], J. Brau [6], D. Buchholz [5], H. Budd [8], L. Bugel [3], J. Conrad [1], R. B. Drucker [6], B. T. Fleming [1], J. Formaggio [1], R. Frey [6], J. Goldman [4], M. Goncharov [4], D. A. Harris [8], J. H. Kim [1], S. Koutsoliotas [1], R. A. Johnson [2], M. J. Lamm [3], W. Marsh [3], D. Mason [6], J. McDonald [7], K. S. McFarland [8], C. McNulty [1], D. Naples [7], P. Nienaber [3], V. Radescu [7], A. Romosan [1], W. K. Sakumoto [8], H. Schellman [5], M. H. Shaevitz [1], P. Spentzouris [1], E. G. Stern [1], N. Suwonjandee [2], N. Tobien [3], M. Tzanov [7], A. Vaitaitis [1], M. Vakili [2], V. Wu [2], U. K. Yang [8], J. Yu [3], G. P. Zeller [5]

[1] *Columbia University, New York, NY*

[2] *University of Cincinnati, Cincinnati, OH*

[3] *Fermi Nat'l Accelerator Lab, Batavia, IL*

[4] *Kansas State University, Manhattan, KS*

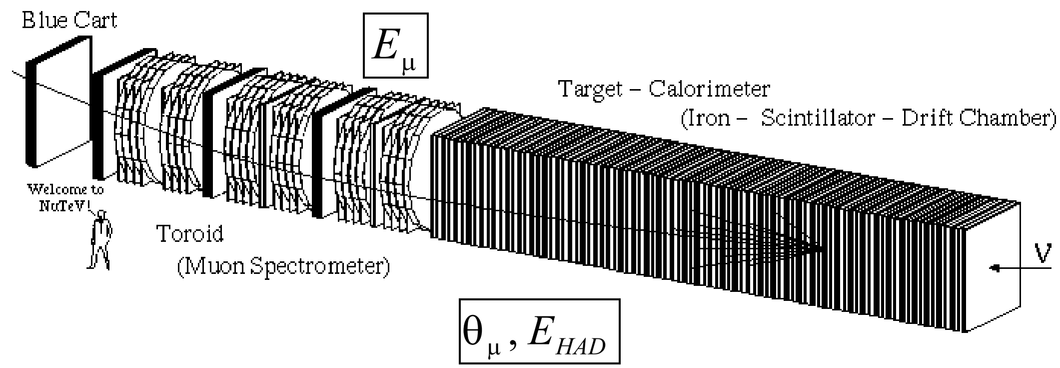
[5] *Northwestern University, Evanston, IL*

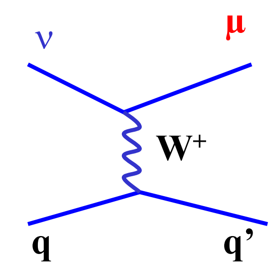
[6] *University of Oregon, Eugene, OR*

[7] *University of Pittsburgh, Pittsburgh, PA*

[8] *University of Rochester, Rochester, NY*

NuTeV Detector





Target Calorimeter:

- **Steel-Scintillator Sandwich (10 cm)**

  $\frac{\delta E}{E} \approx \frac{0.86}{\sqrt{E}}$ **-resolution**
- **Tracking chambers for muon track and vertex**

Muon Spectrometer:

- **Three toroidal iron magnets with five sets of drift chambers**

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

  $\delta(1/p)/(1/p) \sim 11\%$ **MCS dominated**
- **Always focusing for leading muon**

New feature: Continuous Calibration Beam

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

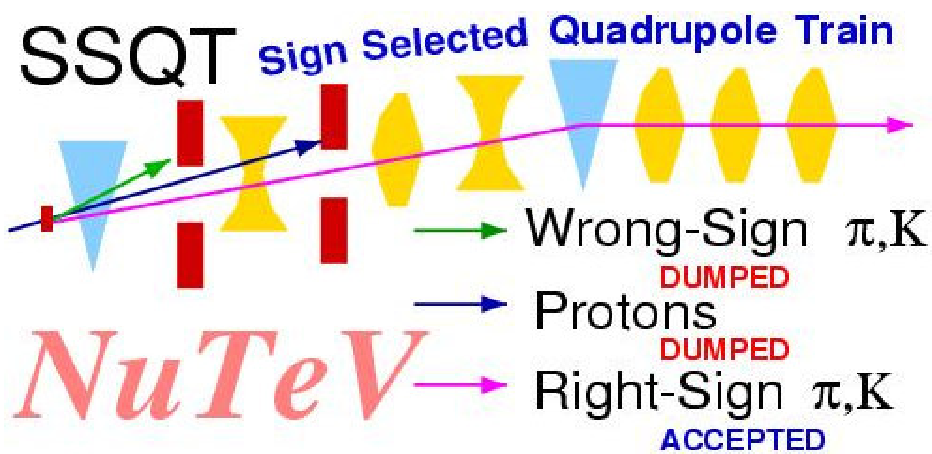
Muon energy scale $\frac{\Delta E_\mu}{E_\mu} = 0.7\%$

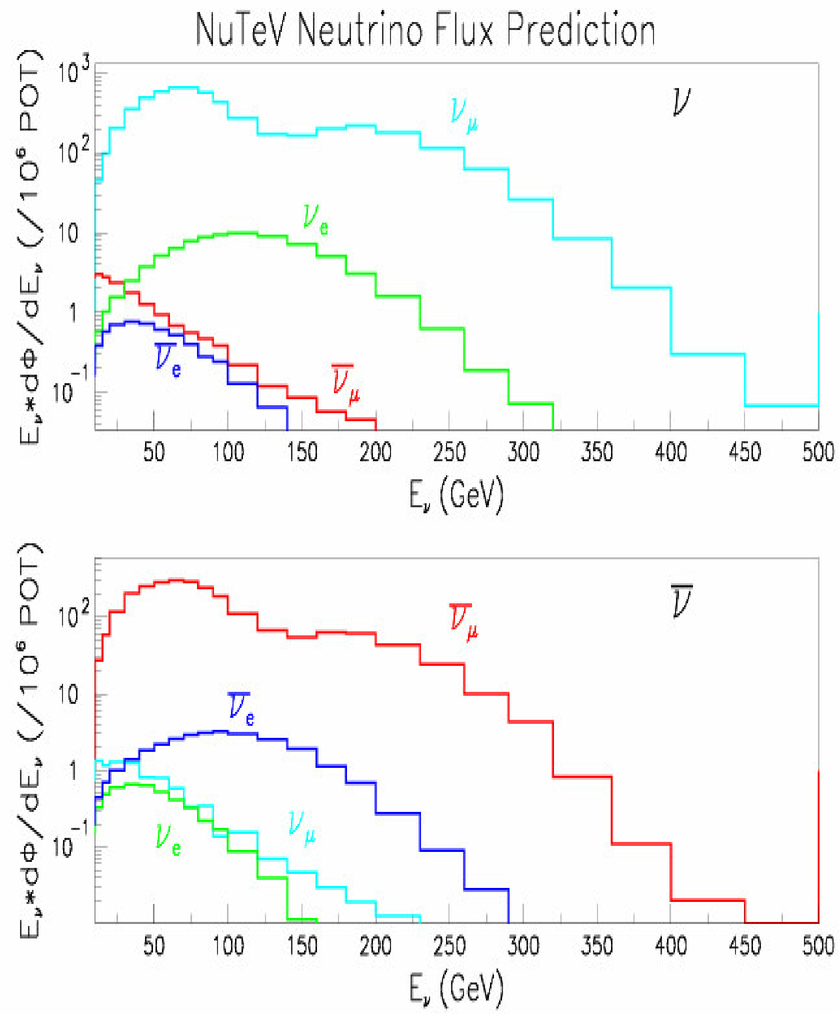
Neutrino Beamline

- NuTeV accumulated over 3 million neutrino/ antineutrino events in 1996-1997

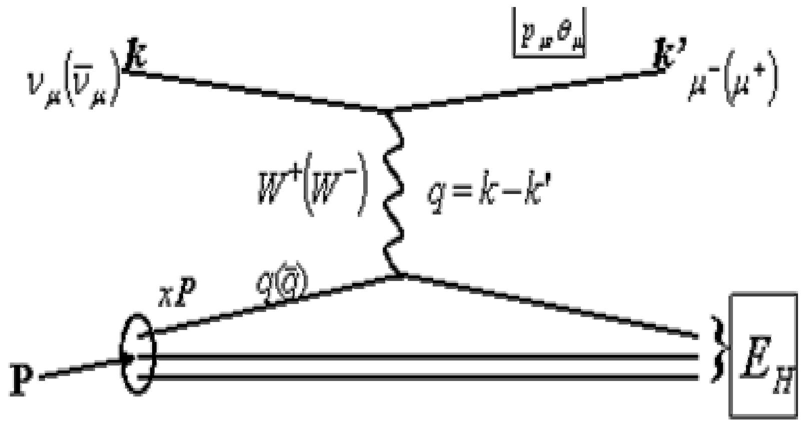
  $20 \leq E_\nu \leq 400\ GeV$
- Wrong-sign $\pi^{\pm}/K^{\pm}$ are dumped

  NuTeV selects neutrinos or antineutrinos
- High purity neutrino or antineutrino beam
  - high y CC sample
  - tag leading muon





Neutrino-Nucleon Scattering



$Q^2 = 4E_\nu E_\mu \sin^2\frac{\theta}{2}$,	**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

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

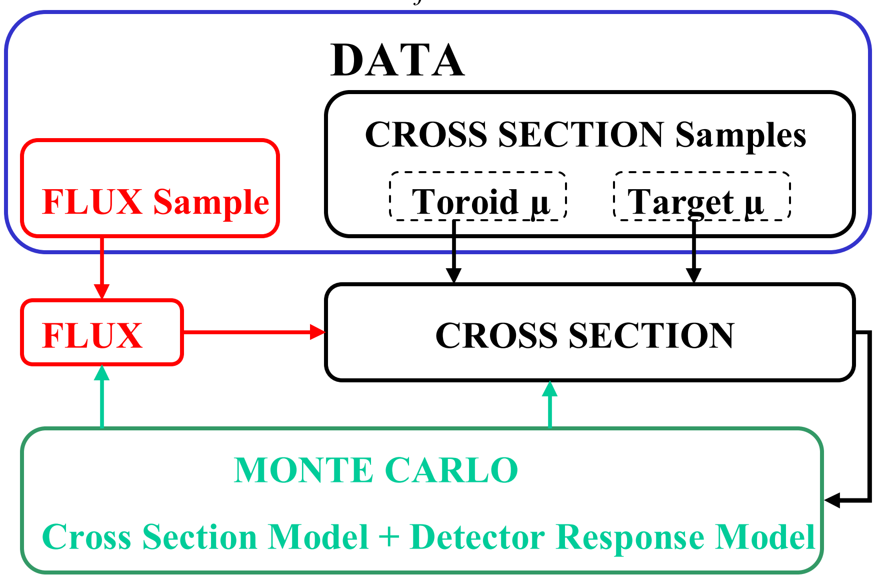
$$xF_3^{\nu(\bar{\nu})N} = \sum\left[xq^{\nu(\bar{\nu})N}(x) - x\bar{q}^{\nu(\bar{\nu})N}(x)\right] = x\left(d_V(x) + u_V(x)\right) \pm 2x\left(s(x) - c(x)\right),$$ **ν-scattering only**

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

Extraction of the Differential Cross Section

Differential Cross Section in terms of number of events and the flux:

$$\left(\frac{1}{E}\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy}\right)_{ijk} = \frac{1}{\Phi(E_k)}\frac{N_{ijk}^{\nu(\bar{\nu})}}{\Delta x_i \Delta y_j}$$



Data sample (E_{HAD}<20 GeV) is used to extract the FLUX

Events selection criteria:

- **Toroid muon :Good muon track, containment,** $E_\mu>15GeV$, $E_{HAD}>10GeV$, $30<E_\nu<360\ GeV$ $Q2>1\ GeV^2/c^2$
- **Target muon:** $4<E_\mu<12GeV$

Monte Carlo event generator is used for acceptance:

- **Cross section model:**

-QCD inspired fit using Buras – Gaemers[1] param.

-Q^2 evolution from GRV for $Q^2<1.35$ GeV/c. Includes fit for x>0.4 to SLAC, NMC and BCDMS to account for non-perturbative behavior at low Q^2 and high x

- **Detector model:**

- E_μ and E_{HAD} resolution functions are parameterized using Test Beam (TB) muons and hadrons

- θ_μ is parameterized as a function of E_{HAD} and event position using GEANT hit level Monte Carlo

[1](*A. Buras, K. Gaemers, Nucl. Phys.* **B132**, *249 (1978)*)

Systematic Uncertainties

There are **23 systematic uncertainties** which are considered:

- E_μ and E_{HAD} energy scales affect both the flux and the diff. cross section extraction

$$\frac{\Delta E_\mu}{E_\mu} = 0.7\% \qquad \frac{\Delta E_{HAD}}{E_{HAD}} = 0.43\%$$

- m_c and **flux uncertainty** are important for the relative flux extraction

$$m_c = 1.4 \pm 0.13$$

- neutrino **world average cross section** has **2.1%** uncertainty – used to normalize the flux. (included as overall normalization)

- the uncertainty in the E_μ and E_{HAD} energy smearing models.

- **16** model fit parameters.

The χ^2 including all systematic uncertainties is given by

$$\chi^2 = \sum_{\alpha\beta} \left(D_\alpha - Theory \right) M^{-1}_{\alpha\beta} \left(D_\beta - Theory \right)$$

$$M_{\alpha\beta} = \sum_{ij} \rho_{ij} \partial_{\alpha i} \partial_{\beta j} \sigma_{\alpha i} \sigma_{\beta j}$$

$M_{\alpha\beta}$ - point to point covariance matrix

ρ_{ij} - 22x22 correlation matrix of all uncertainties

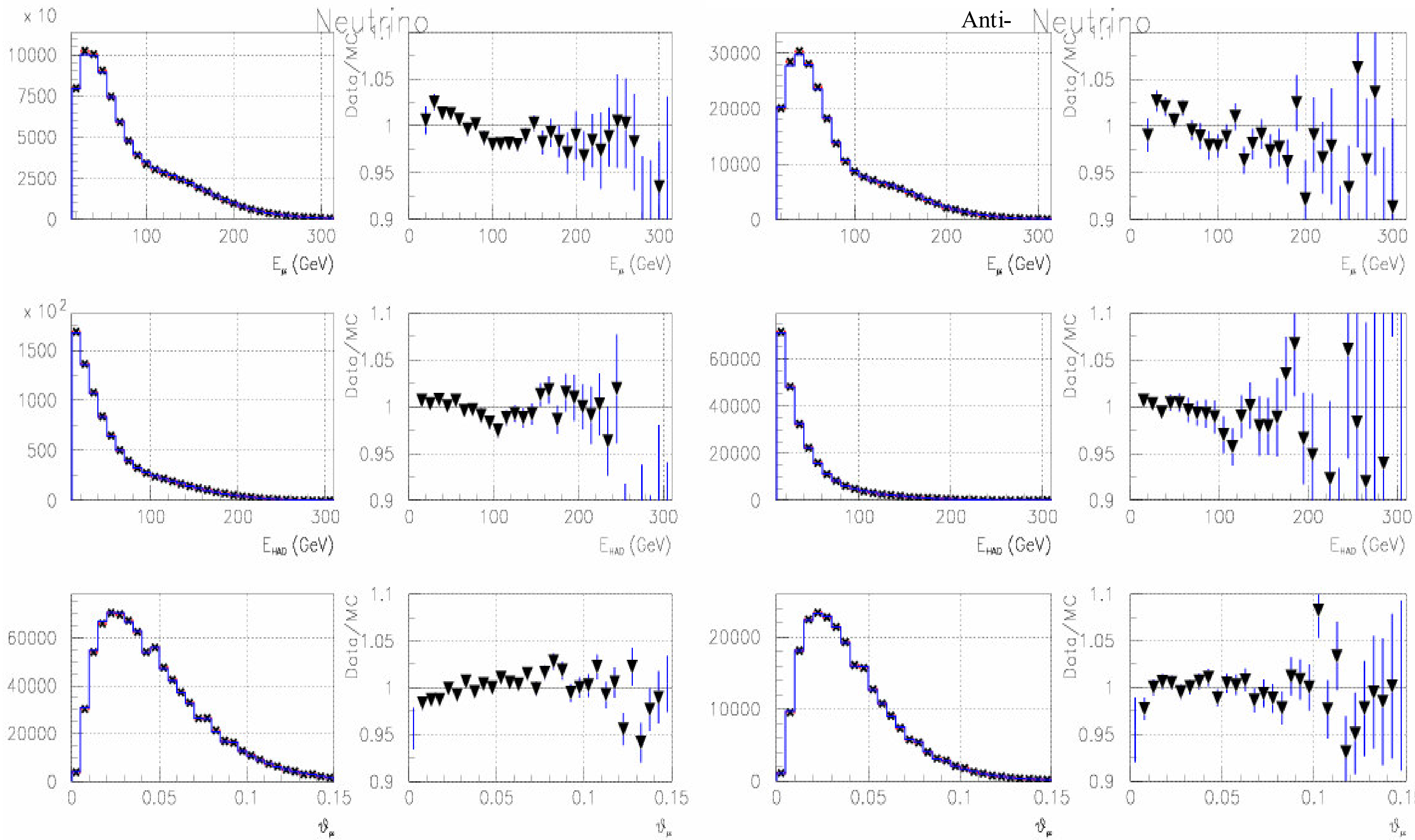
$\sigma_{\alpha i}$ - the size of systematic uncertainty i at data point α

Each derivative is calculated by varying the corresponding systematic S_i by a small ε_i using:

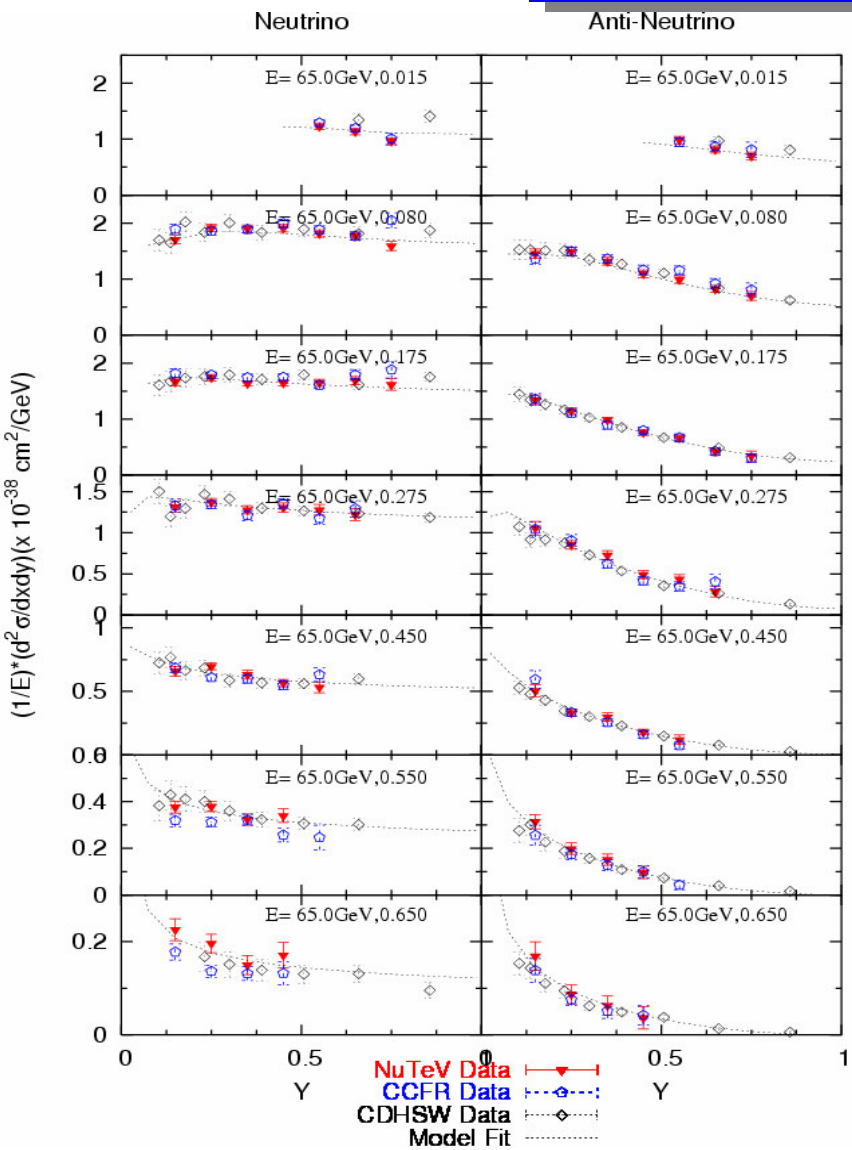
$$\partial_{i\alpha} = \frac{\frac{d^2\sigma}{dxdy}\left(x,y,E \mid S_i+\varepsilon_i\right) - \frac{d^2\sigma}{dxdy}\left(x,y,E \mid S_i-\varepsilon_i\right)}{2\varepsilon_i}$$

•statistical uncertainty is added in quadrature to the diagonal element of the matrix

Monte Carlo Modeling of Data



NuTeV CC Cross Section



	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

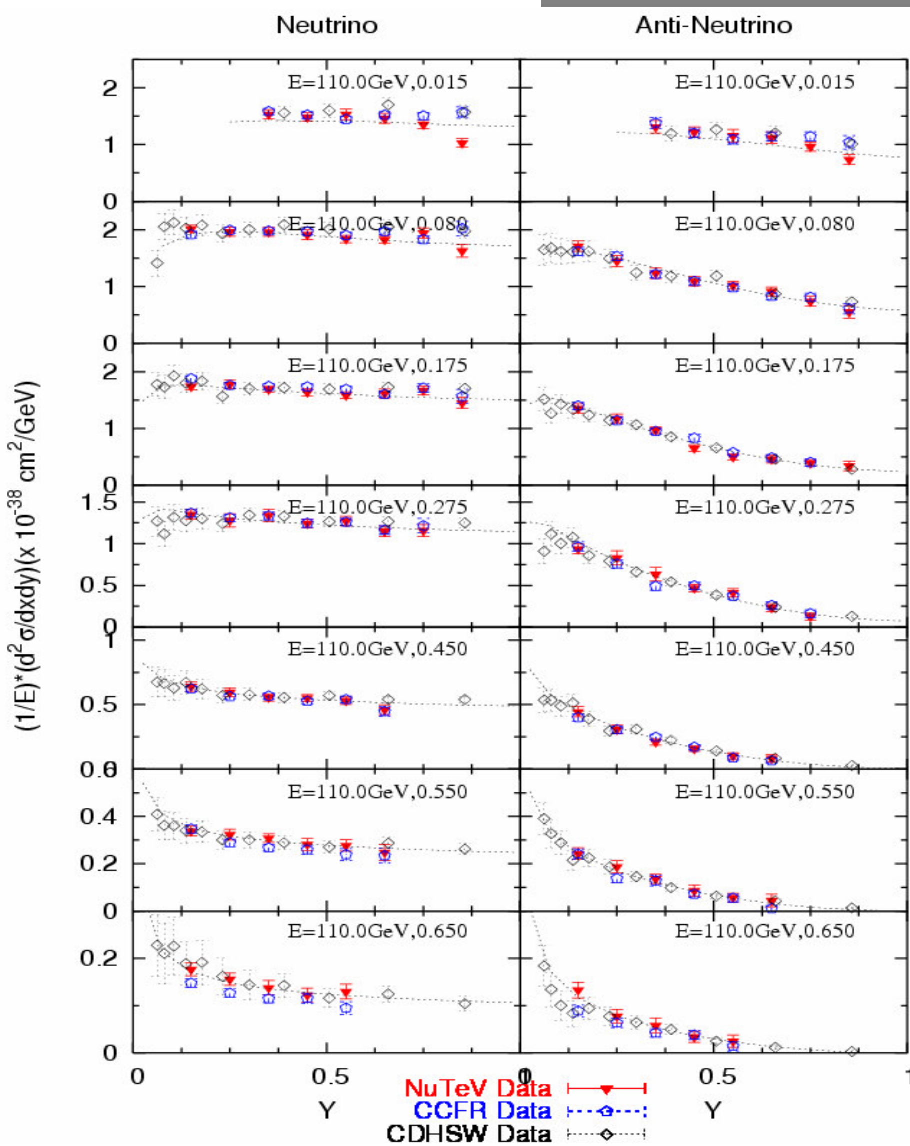
- **All systematics are included.**
- **NuTeV has comparable statistics to other ν-Fe experiments.**
- **Reduction in the largest systematic uncertainties :**
  - E_μ and E_{HAD} scales

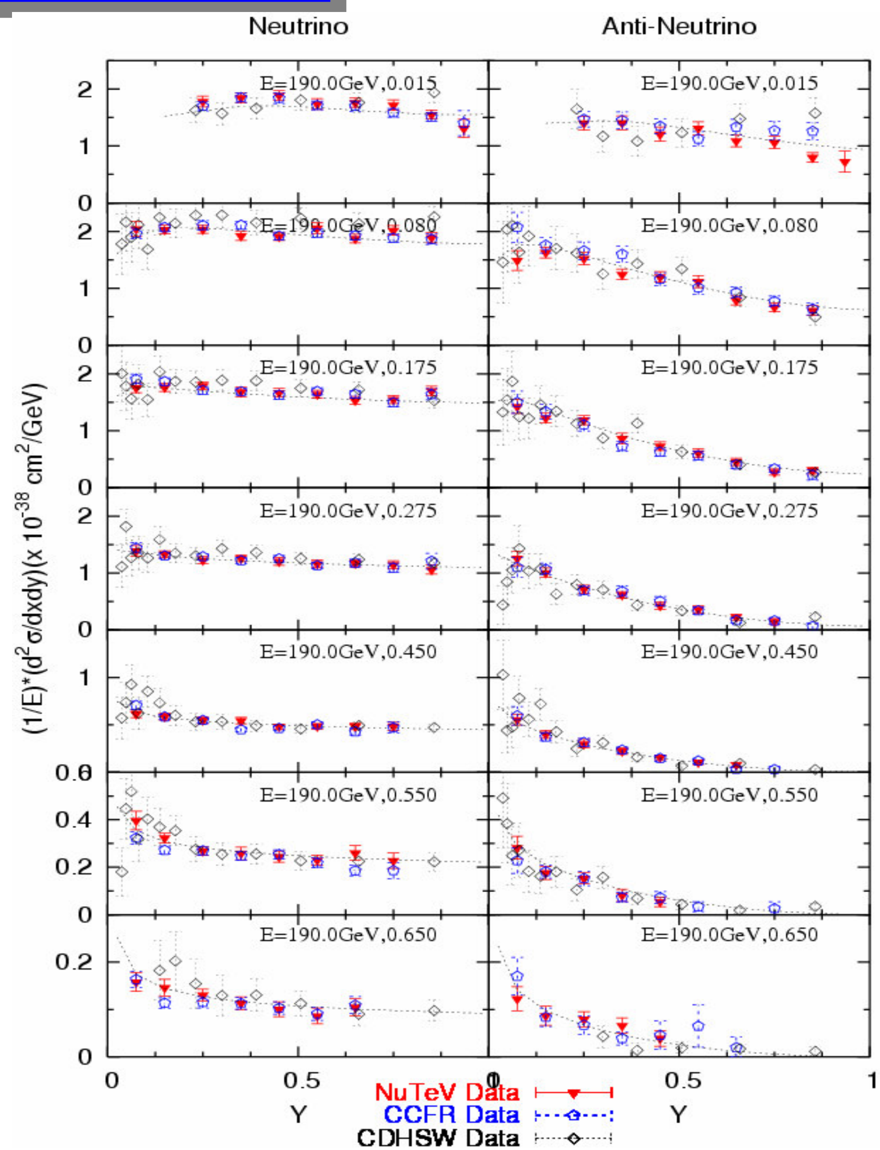
Other ν-Fe data shown on the plot:

CDHSW(Z. Phys. C49 187, 1991)

U. K. Yang CCFR Ph.D. Thesis

NuTeV's CC Cross Section

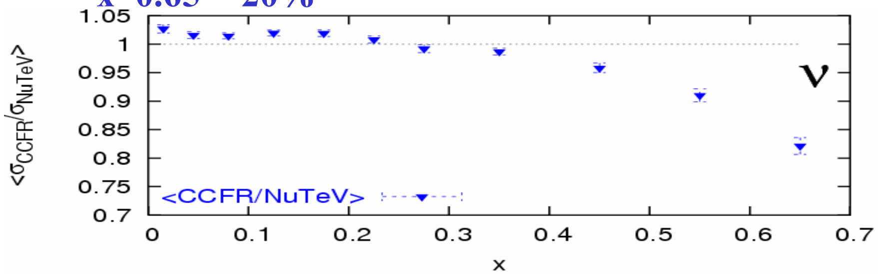


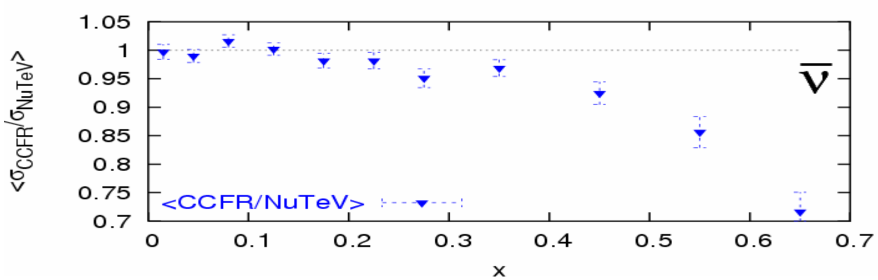


NuTeV vs CCFR

- NuTeV agrees with CCFR for x<0.4.

- Increasingly higher than CCFR at x> 0.4
  - x=0.45 - 4%
  - x=0.55 - 10%
  - x=0.65 - 20%





•Other differences are:
- NuTeV had separate neutrino and antineutrino beams
- NuTeV - always focusing for the "right-sign" muon
- CCFR – simultaneous neutrino and antineutrino runs
- CCFR toroid polarity was half of the time focusing for μ^+ and half of the time μ^-

Investigating the discrepancy with CCFR:
- similar detectors and techniques
- NuTeV has improved hadron energy calibration
  - 1-2% effect at x=0.65

- precise calibration of the muon spectrometer
  - the difference in the CCFR and NuTeV magnetic field models is an effective 0.8% shift in the muon energy scale
  - 5% at the x=0.65

- improved muon energy smearing model
  - 2% at x=0.65

- different model fit parameters
  - 3% effect at x=0.65

All together account for 11% of the 20% difference at x=0.65. Systematic errors are 6-7% at x=0.65. The two results will be in 1.5 σ agreement.

F_2 and xF_3 Measurement

F_2

$$\left[\frac{d^2\sigma}{dxdy}^{\nu}+\frac{d^2\sigma}{dxdy}^{\bar{\nu}}\right]\frac{\pi}{G_F^2ME}=$$
$$=2\bar{F}_2\left(1-y-\frac{Mxy}{2E}+\frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right)+y\left(1-\frac{y}{2}\right)\Delta xF_3$$

- Perform 1-parameter fit for F_2
- [1]TR-VFS ΔxF_3 model
- [2]R_w model

[1](R. S. Thorne and R. G. Roberts, Phys. Lett. B 421, 303 (1998)).

[2](L.W.Whitlow et. al. Phys. Lett. B250, 193 (1990)).

xF_3

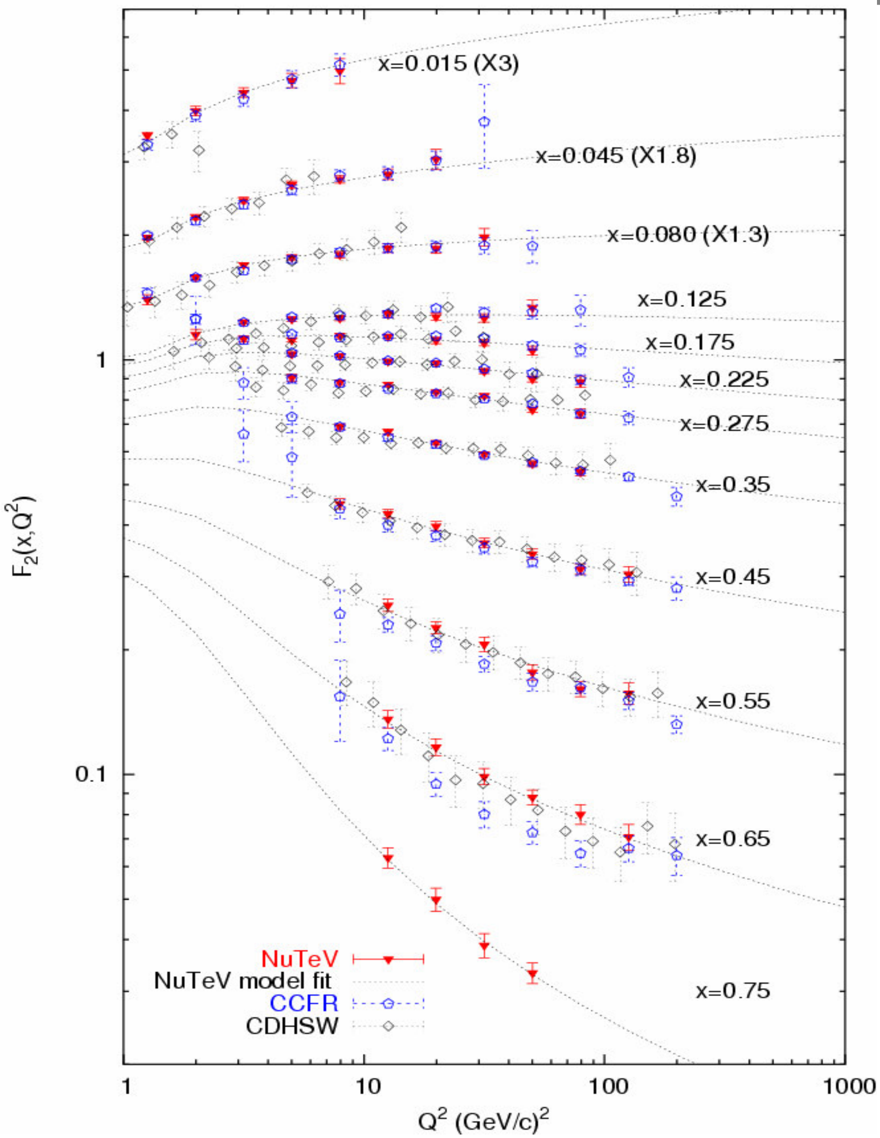
$$\left[\frac{d^2\sigma}{dxdy}^{\nu}-\frac{d^2\sigma}{dxdy}^{\bar{\nu}}\right]\frac{\pi}{G_F^2ME}=$$
$$=\Delta F_2\left(1-y-\frac{Mxy}{2E}+\frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right)+2y\left(1-\frac{y}{2}\right)x\bar{F}_3$$

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

- **Radiative corrections applied**

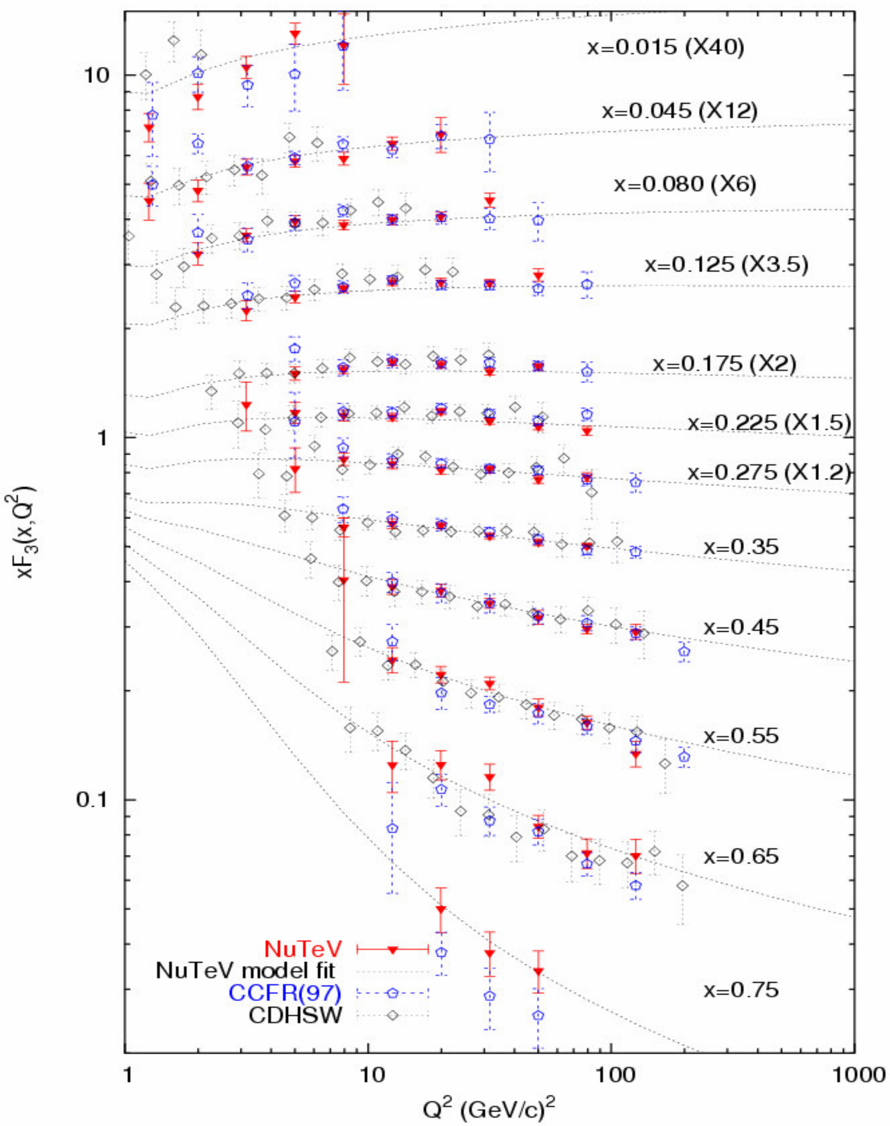
  (D. Y. Bardin and Dokuchaeva, JINR-E2-86-260 (1986))
- **Isoscalar correction applied**
- **Bin centering correction for Q^2**

F_2 Measurement



- **Isoscalar ν-Fe F_2**
- **NuTeV F_2 is compared with CCFR and CDHSW results**
  - the line is a fit to NuTeV data
- **All systematic uncertainties are included**
- **All data sets agree for *x<0.4*.**
- **At *x>0.4* NuTeV agrees with CDHSW**
- **At *x>0.4* NuTeV is systematically above CCFR**

xF_3 Measurement



- Isoscalar ν-Fe xF_3
- NuTeV xF_3 is compared with CCFR and CDHSW results
  - the line is a fit to NuTeV data
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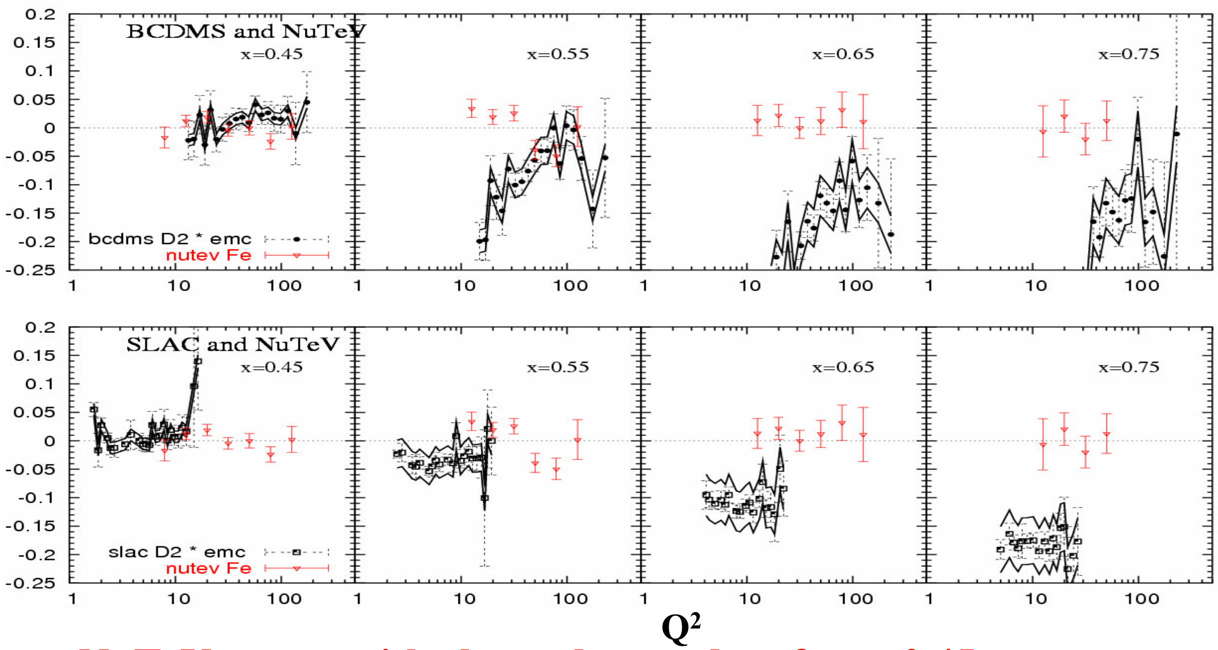
- All data sets agree for $x<0.4$.
- At $x>0.4$ NuTeV agrees with CDHSW
- At $x>0.4$ NuTeV is systematically above CCFR

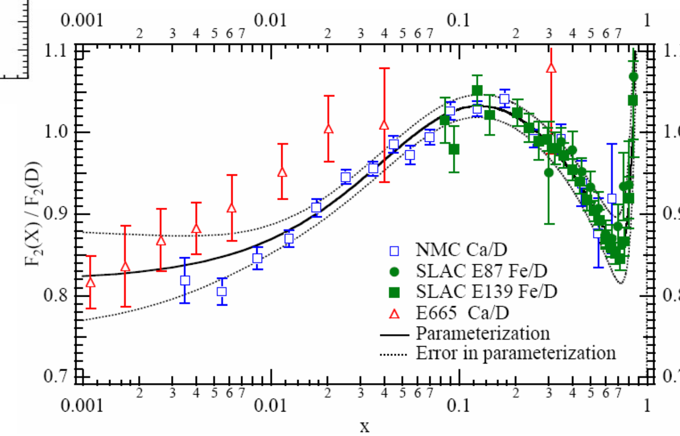
Comparison with Charge Lepton Data for *x>0.4*



- Baseline is NuTeV model fit
- data points are $\frac{F_2^{DATA} - F_2^{BG}}{F_2^{BG}}$

•charge lepton data is corrected for:

- $\frac{F_2^{\nu}}{F_2^{l}}$ using CTEQ4D
- heavy target $\frac{F_2^{N}}{F_2^{D}}$

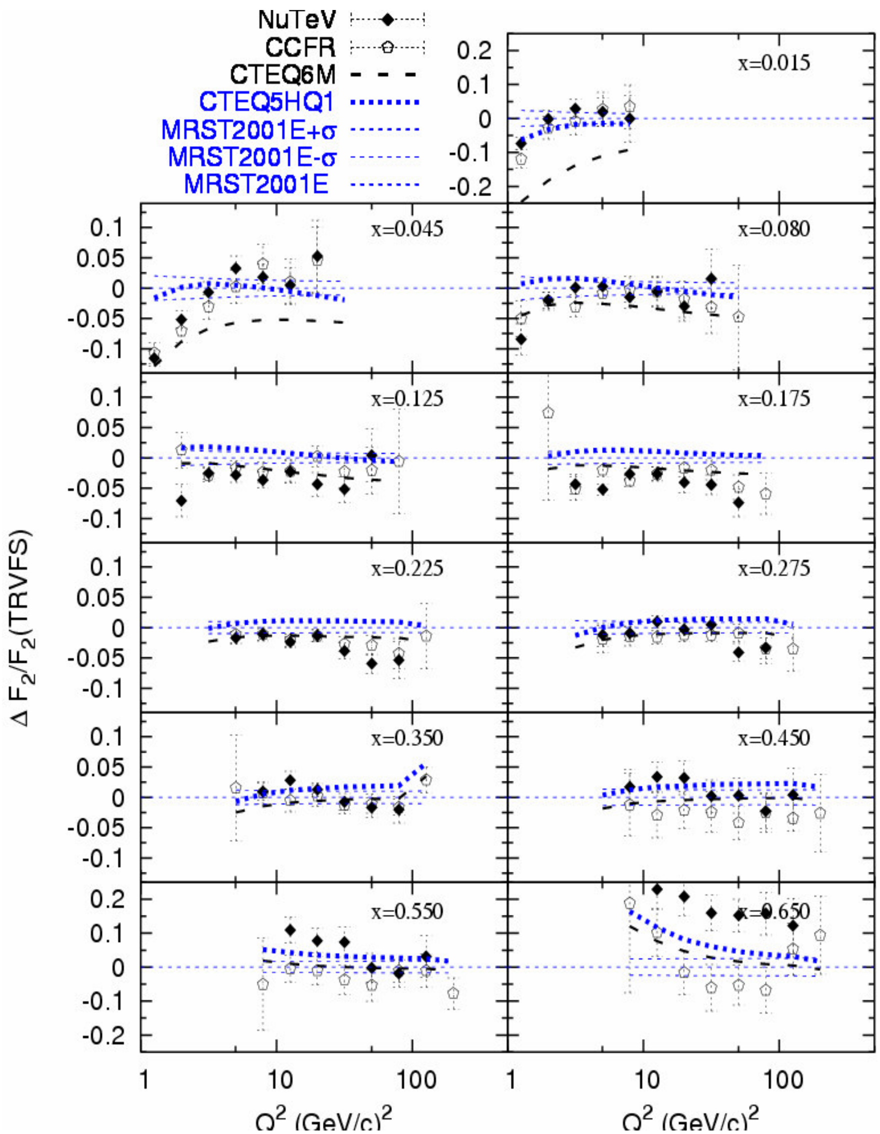


- the nuclear correction is dominated by SLAC data, which is at lower Q^2 from NuTeV in this region

- 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*

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

Comparison with Theory for F_2



- Baseline is TRVFS(MRST2001E)

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

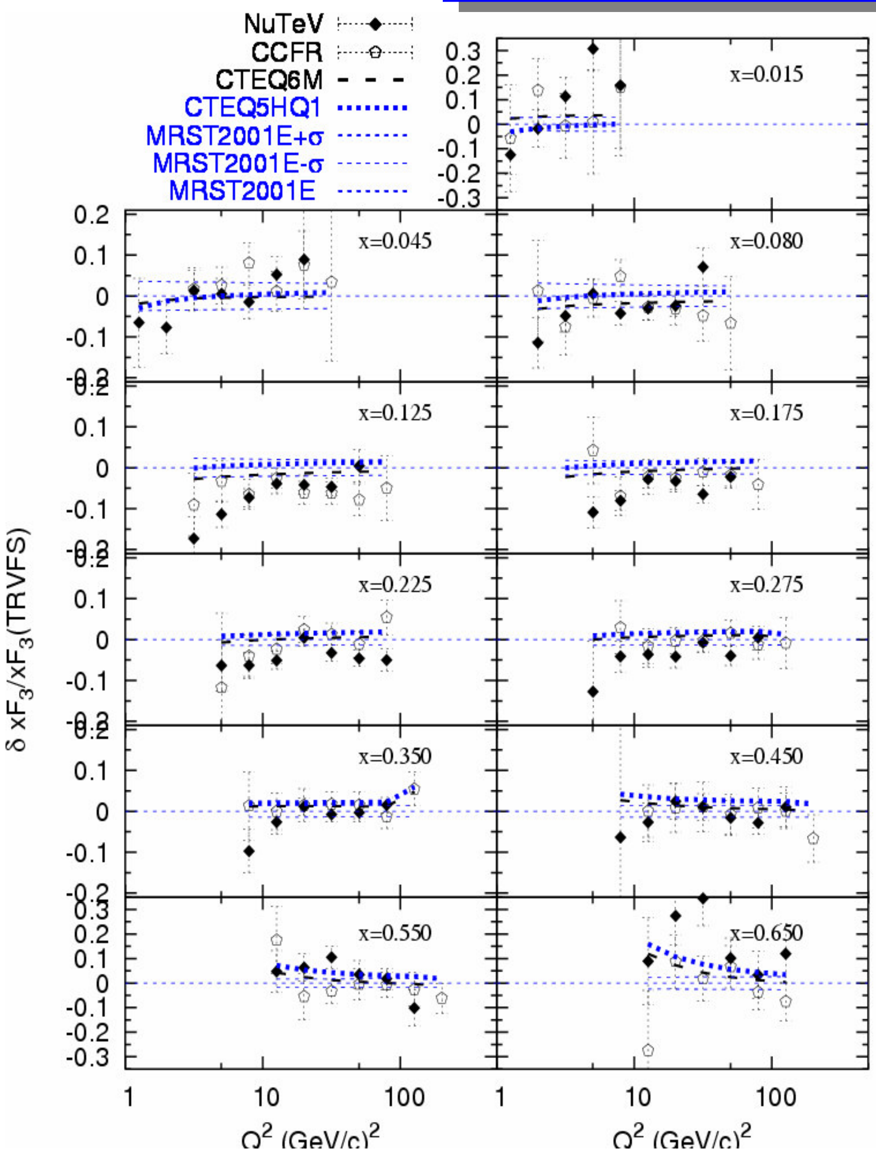
$$\frac{F_2^{NuTeV} - F_2^{TRVFS}}{F_2^{TRVFS}}$$

- 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>0.6) NuTeV is systematically higher.

Comparison with Theory for xF_3



- Baseline is TRVFS(MRST2001E).

- NuTeV and CCFR xF_3 are compared to TRVFS(MRST2001E)

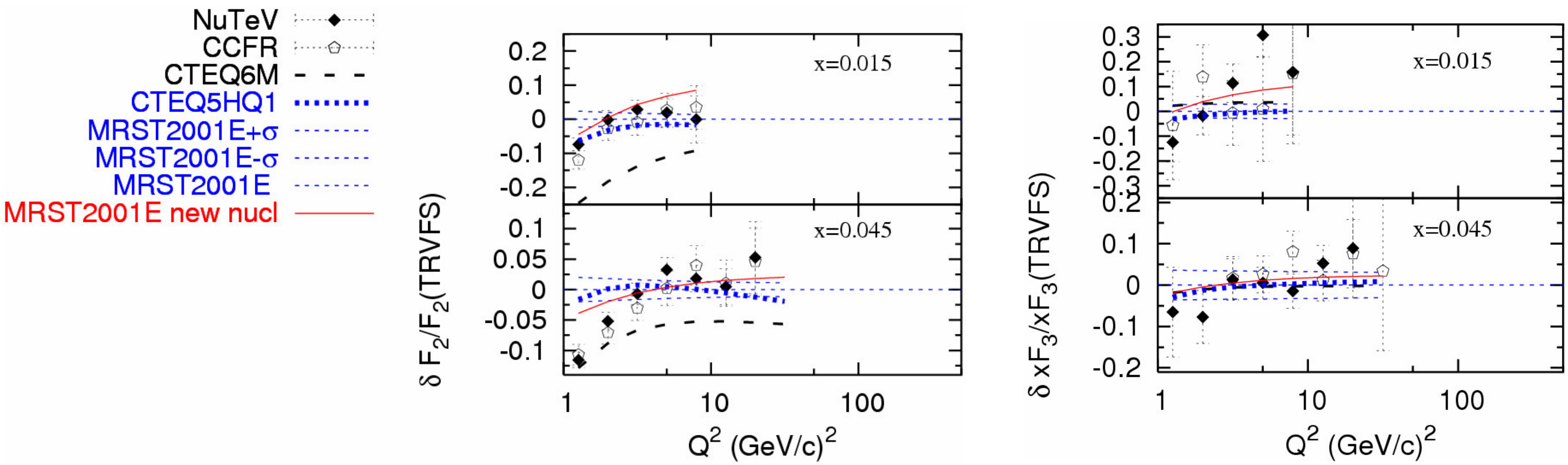
$$\frac{xF_3^{NuTeV} - xF_3^{TRVFS}}{xF_3^{TRVFS}}$$

- 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 xF_3 agrees with theory for medium x.
- At low x different Q^2 dependence.
- At high x (x>0.6) NuTeV is systematically higher.

Comparison with Theory at Low x



- both NuTeV and CCFR agree in level with theory in the shadowing region (except CTEQ6M)

- the red curve is TRVFS(MRST) using the following model for nuclear correction:

NUCLEAR SHADOWING IN NEUTRINO NUCLEUS DEEPLY INELASTIC SCATTERING.
By Jianwei Qiu, Ivan Vitev (Iowa State U.),. Jan 2004. 7pp.
Published in Phys.Lett.B587:52-61,2004
e-Print Archive: hep-ph/0401062

NuTeVPack

- NuTeVPack is a user friendly interface to access NuTeV cross section data

- The data represents the NuTeV neutrino and anti-neutrino differential cross section on IRON, along with a full covariance matrix containing all systematic errors. There are no corrections applied to the data. (all radiative effects are in). Data is binned in 12 x-bins, 13 y-bins and 17 E-bins.

- A new version of the package allows access to each systematic error separately, as well as combination of systematic errors. (requested by theorists)
  It will return the covariance (or inverse covariance) matrix for the chosen set of systematic errors. The statistical error is always added in quadrature to the diagonal. Will be available by the end of DIS2005.
  We strongly recommend the use of the full covariance matrix. Even in a case of one systematic error there is a bin-to-bin correlation in the data.

The NuTeVPack is available for download here:
http://www-nutev.phyast.pitt.edu/results_2005/nutev_sf.html

Conclusions

- NuTeV has extracted high precision $\nu - Fe$ differential cross section.
- NuTeV measurement is in an agreement with previous $\nu - Fe$ experiments
  - agrees with CDHSW
  - agrees with CCFR for x<0.4 and systematically higher at high x
    4% at *x=0.45*, *10%* at *x=0.55*, *20%* at *x=0.65*
  - NuTeV has an improved detector calibration compared to CCFR.
    - accounts for *11%* of the *20%* discrepancy at x=0.65.
      Both results would be in 1.5 σ agreement.

- NuTeV agrees with charge lepton data for x<0.5.
  - perhaps the nuclear correction at high-x is smaller for neutrino scattering.

- NuTeV agrees with theory for medium x.
  - at low x different Q^2 dependence. Q^2 dependent nuclear shadowing.
  - differs in level at x>0.6.

- NuTeVPack is available on the web:
  http://www-nutev.phyast.pitt.edu/results_2005/nutev_sf.html

Future:

- Target sample cross section and QCD fits.

Flux Extraction

Relative flux extraction using "fixed ν_0 method"

- We can rewrite the differential cross section in terms of $\nu=E_{HAD}$ integrate over x.

$$\frac{d^2\sigma^{\nu\bar{\nu}}}{dx\,d\nu} = \frac{G^2 M}{\pi}\left[F_2 - \frac{\nu}{E}\left(F_2 \pm xF_3\right) + \frac{\nu^2}{2E^2}\left(F_2 \pm xF_3 + R_{TERM}F_2\right)\right],$$

$$where\, R_{TERM}\left(x,Q^2\right) = \frac{1+2Mx/\nu}{1+R_L\left(x,Q^2\right)} - \frac{Mx}{\nu} - 1$$

$$\frac{dN_{\nu,\bar{\nu}}}{d\nu} = \Phi\left(E_\nu\right)\left(A_{\nu,\bar{\nu}} + B_{\nu,\bar{\nu}}\left(\nu/E_\nu\right) + \frac{C_{\nu,\bar{\nu}}}{2}\left(\nu/E_\nu\right)^2\right),$$

$$A = \frac{G_F^2 M}{\pi}\int_0^1 F_2\left(x,Q^2\right)dx,\quad B = -\frac{G_F^2 M}{\pi}\int_0^1\left(F_2\left(x,Q^2\right) \mp xF_3\left(x,Q^2\right)\right)dx,$$

$$C = -B + \frac{G_F^2 M}{\pi}\left(\int_0^1 F_2\left(x,Q^2\right)dx\right)R_{TERM}\left(x,Q^2\right) = -B + A\, R_{TERM}$$

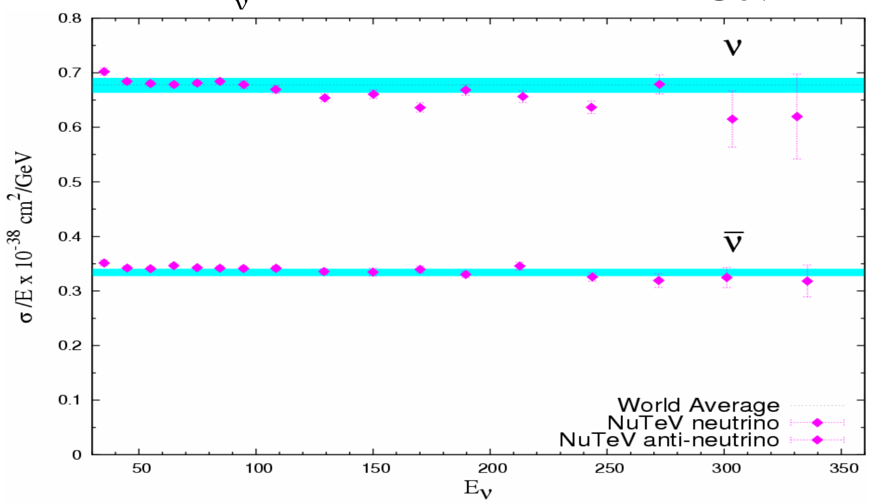
$$\frac{dN_{\nu,\bar{\nu}}}{d\nu} \xrightarrow{\nu\to 0} \Phi\left(E_\nu\right)A_{\nu,\bar{\nu}}$$

$$\Phi\left(E_\nu\right) = \int_0^{\nu_0/E_\nu}\left(\frac{dN\left(E_\nu\right)}{dy}\Bigg/\left(1+\frac{B}{A}y+\frac{C}{A}\frac{y^2}{2}\right)\right)dy$$

Normalizing the relative flux

- using world average neutrino cross section for 30GeV < E_ν <200GeV

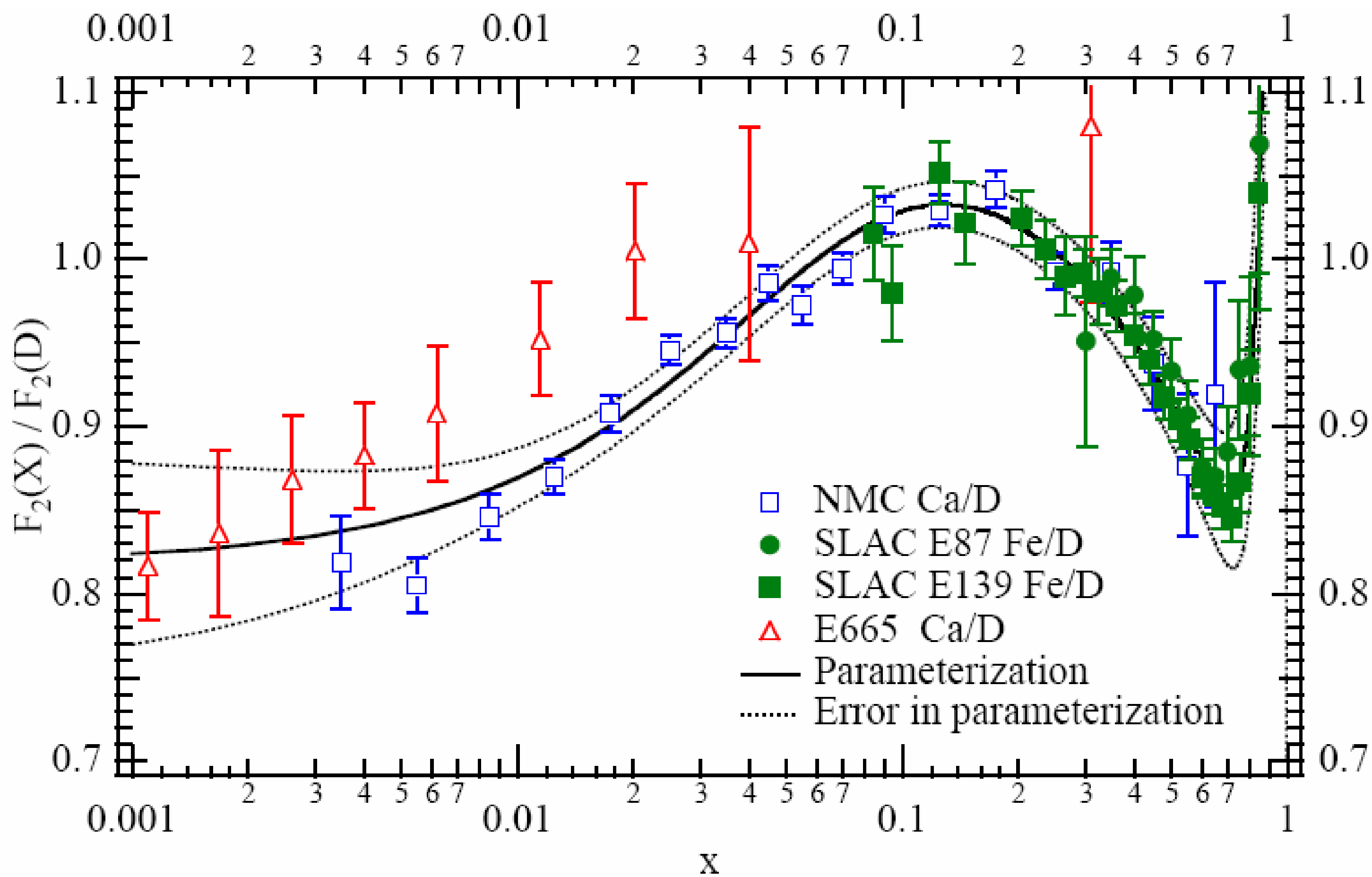
$$\frac{\sigma}{E_\nu} = 0.677 \pm 0.014 \times 10^{-38}\,\frac{cm^2}{GeV}$$



- the neutrino cross section $\frac{\sigma}{E_\nu}$ is flat as a function of E_ν within less than 2%

- the relative antineutrino cross section agrees with the world average

Nuclear Correction



Buras-Gaemers Parameterization

- **Valence quark distributions parameterization:**

$$x^{E_1} \times (1-x)^{E_2} + AV_2 \times x^{E_3} \times (1-x)^{E_4} + AV_3 \times x^{E_5} \times (1-x)^{E_6}$$

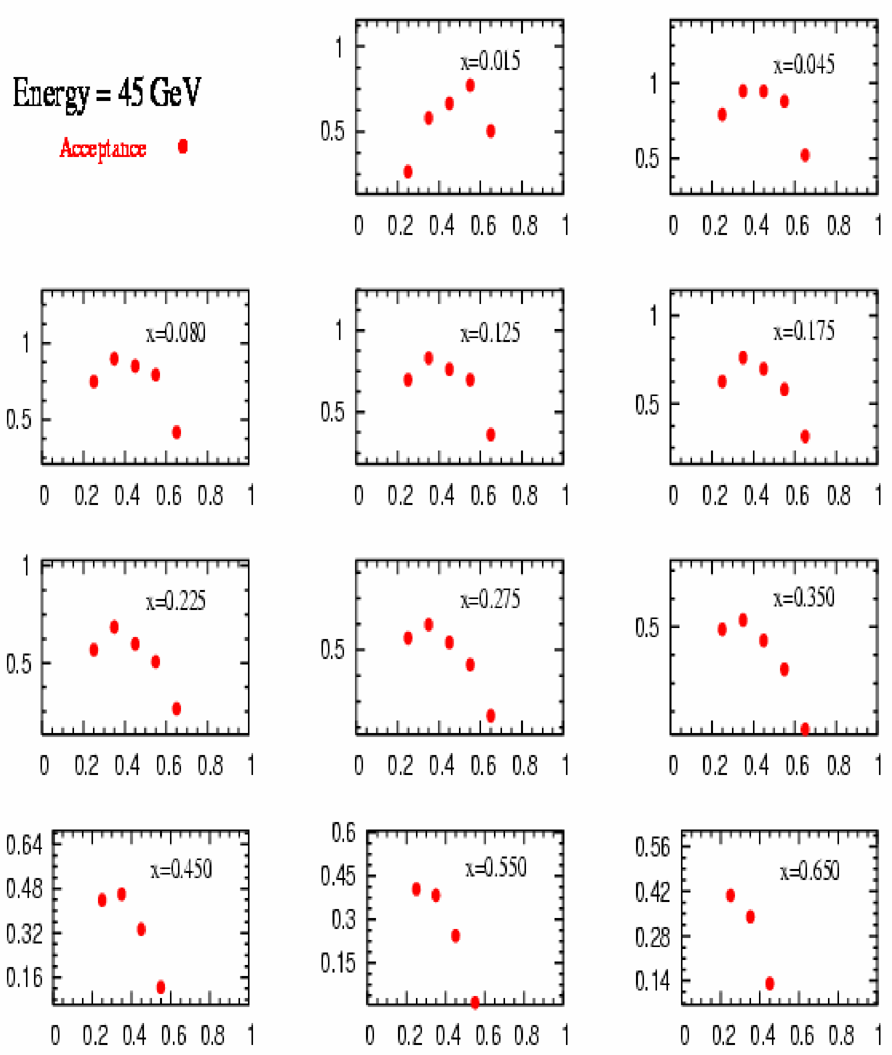
- **Sea quark distributions parameterization:**

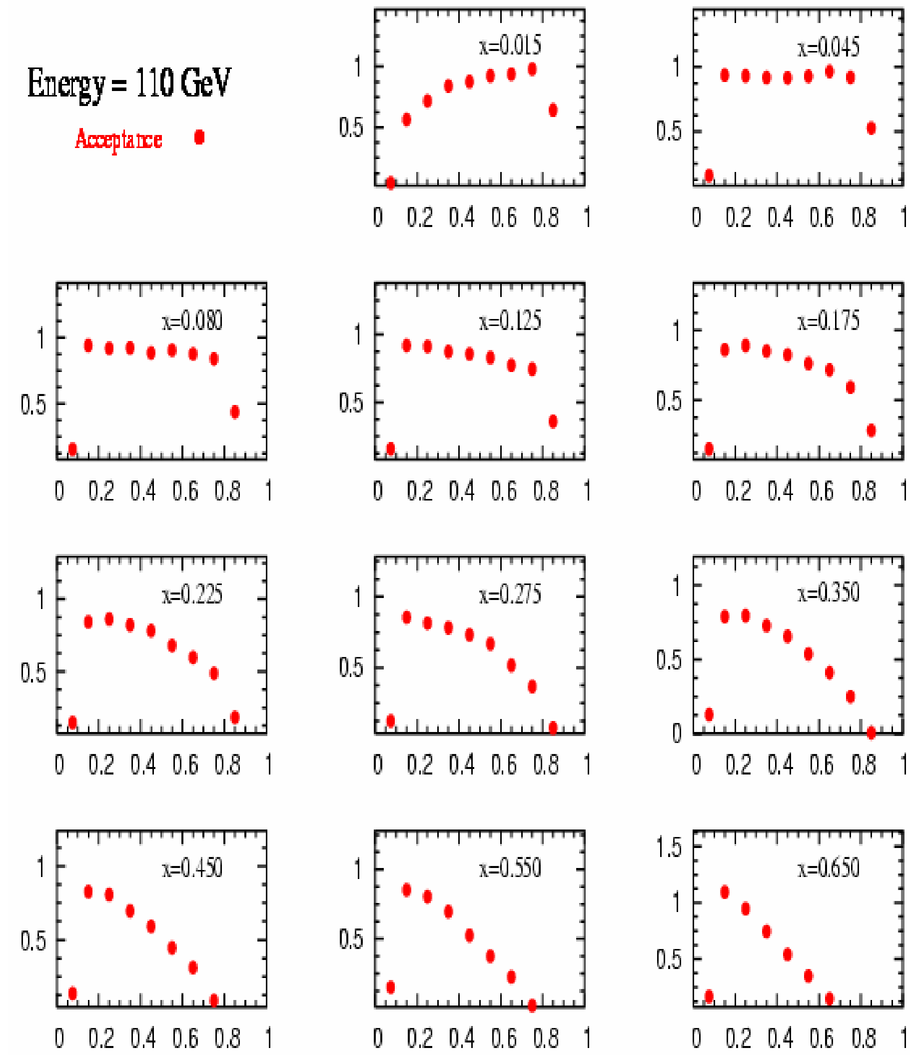
$$AS_1 \times (1-x)^{ES_1} + AS_2 \times (1-x)^{ES_2}$$

- **The exponents E_i and ES_i and the normalization coefficients AV_i and AS_i are fitted to NuTeV differential cross section data.**

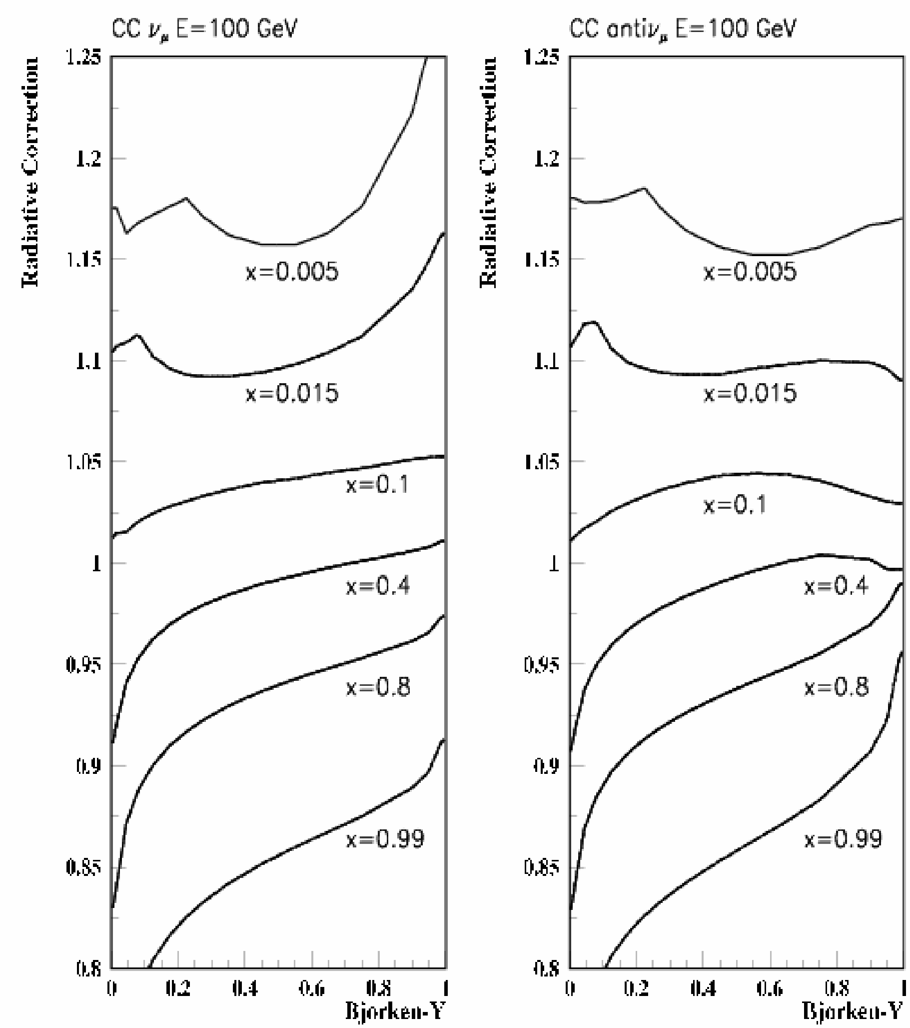
- **13 parameters to fit. Fit includes standard QCD evolution, assumes $R=R_{world}$, charm mass, W-mass and sea constraint from dimuon data.**

Acceptance Correction



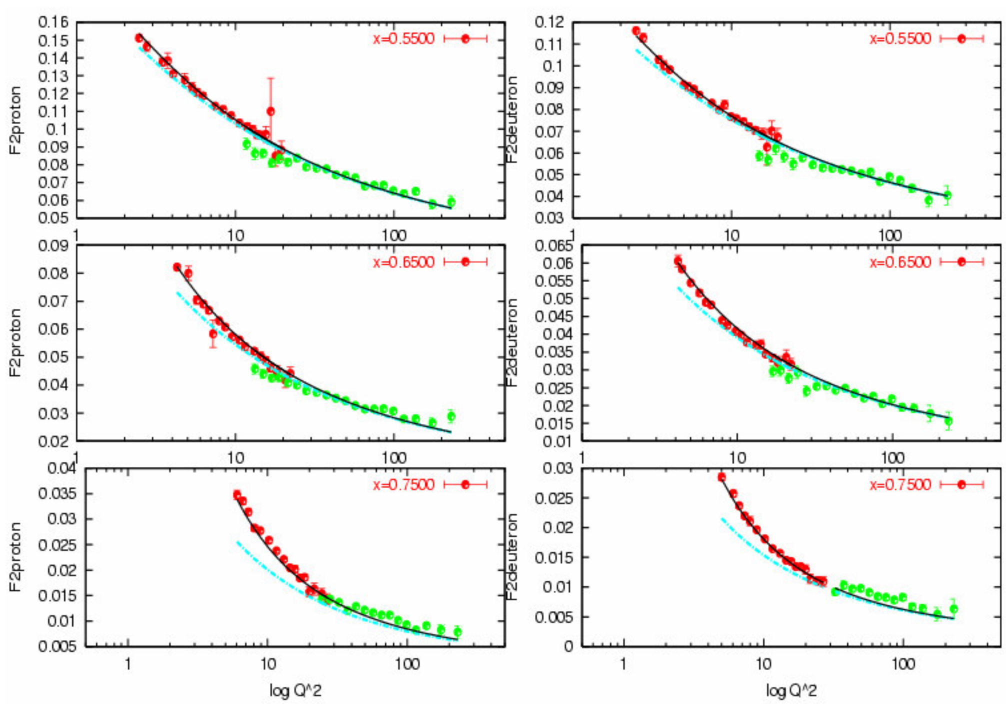


Radiative Correction



Higher Twist

- fit to ep, ed data (SLAC, NMC,BCDMS) to account for Target Mass and Higher-Twist effects in parton level cross section model
- important at high x and low Q^2



$$x' = x\frac{Q^2+B}{Q^2+Ax}$$

$$F_2 \rightarrow \left(\frac{Q^2}{Q^2+C}\right)F_2(x', Q^2)$$

A	0.57
B	0.22
C	0.06
χ^2/dof	792/312