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

Martin Tzanov

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

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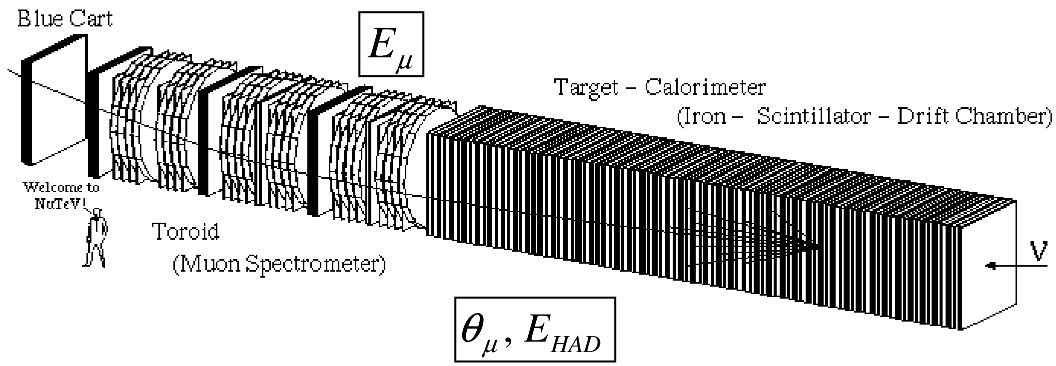
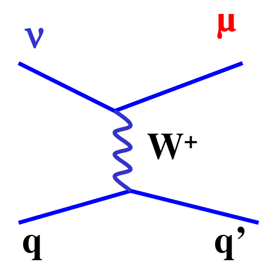
NuTeV Detector





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**

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

$$\delta(1/p)/(1/p) \sim 11\%$$ **MCS dominated**

- **Always focusing for lead muon**

New feature: Continuous Calibration Beam

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

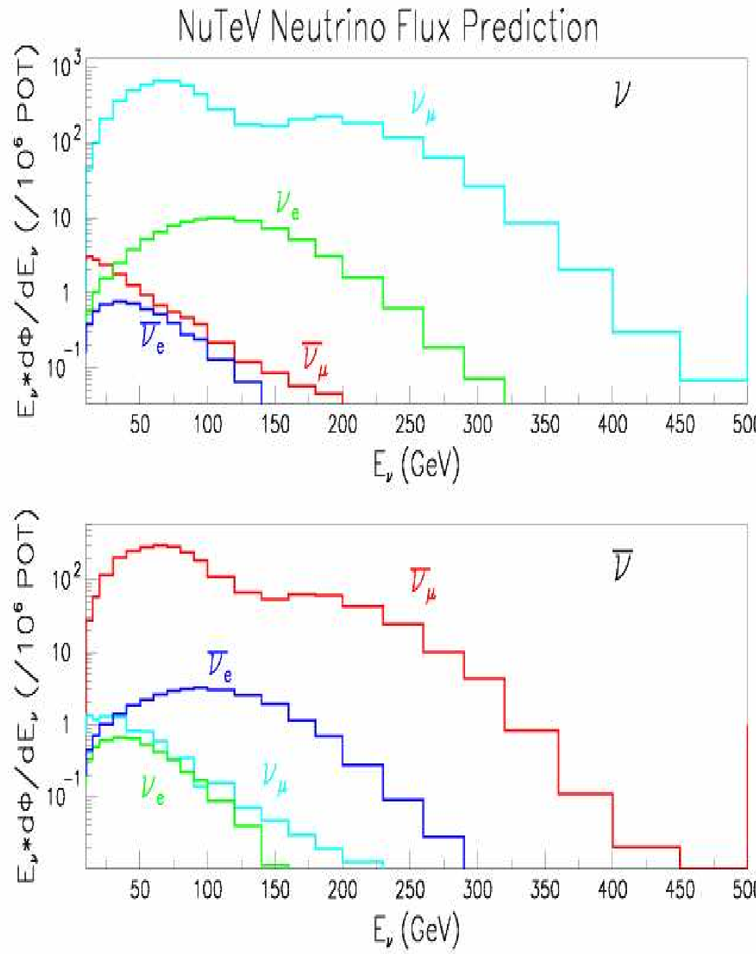
Muon energy scale $\frac{\Delta E_\mu}{E_\mu} = 0.7\%$

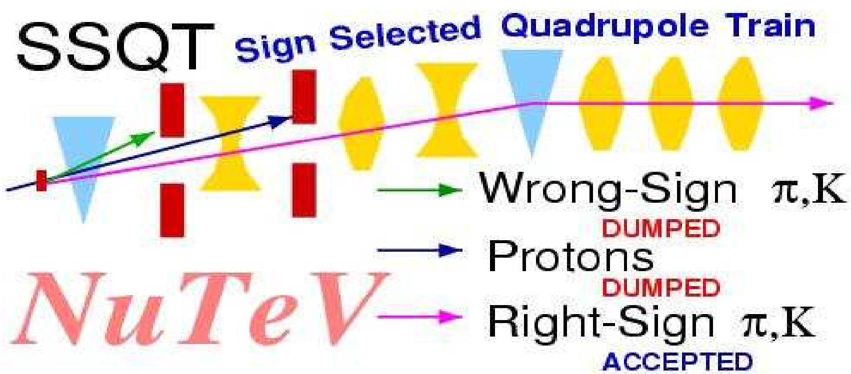
Neutrino Beamline

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

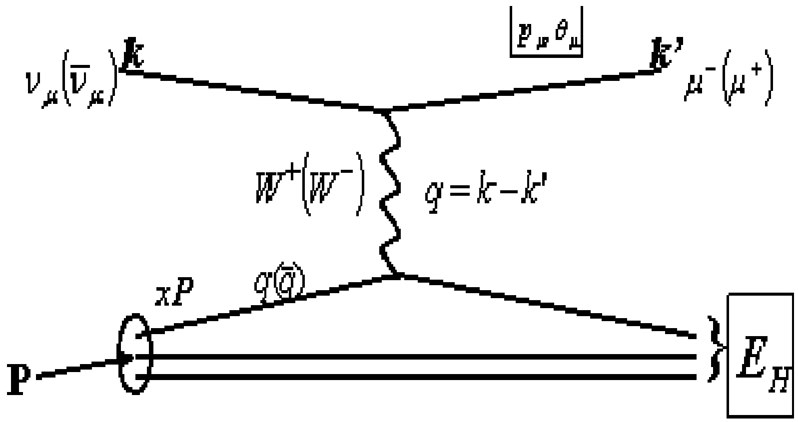
  $20 \leq E_\nu \leq 400$ GeV
- Wrong-sign $\pi^{\pm}/K^{\pm}$ are dumped

  NuTeV selects neutrinos or antineutrinos
- High purity separate neutrino and antineutrinos
  - 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

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

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

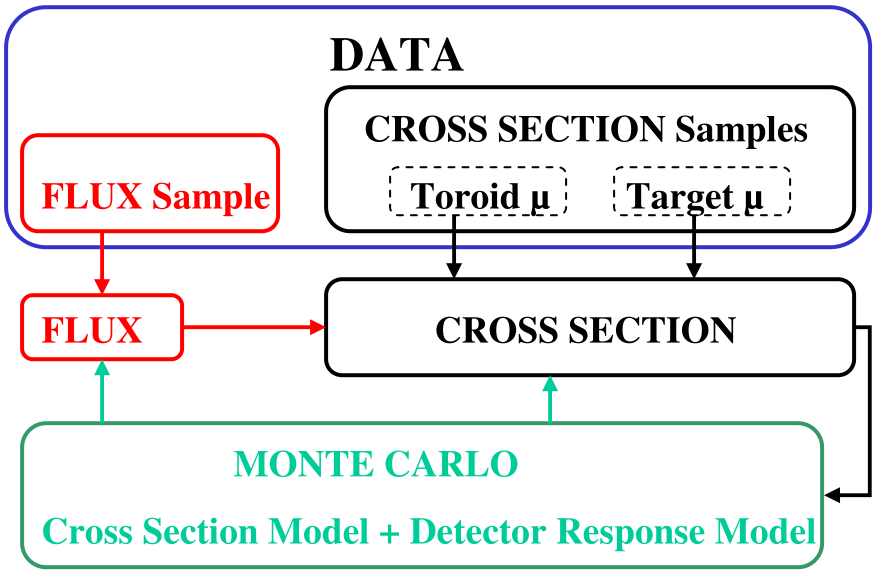
$$\Delta xF_3 = x\left(F_3^{\nu} - F_3^{\bar{\nu}}\right) = 4x\left(s(x)-c(x)\right)$$

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

Extraction of the Differential Cross Section

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

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



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

Events selection criteria:

- **Toroid muon :Good muon track, containment,** $E_\mu>15GeV$, $E_{HAD}>10GeV$, $30<E_\nu<300\ GeV$ $Q2>1\ GeV^2/c^2$
- **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))*

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.

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

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

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

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

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

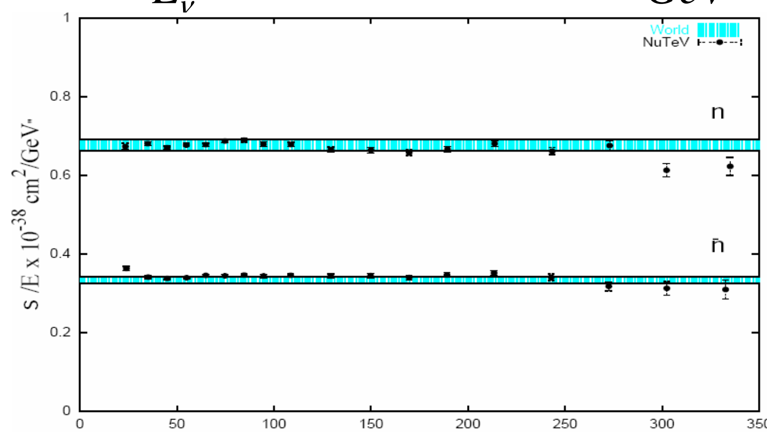
$$\frac{dN_{\nu,\bar{\nu}}}{d\nu} \xrightarrow{\nu\to 0} \Phi(E_\nu)A_{\nu,\bar{\nu}}$$

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

Normalizing the relative flux

- using world average neutrino cross section for $30\text{GeV} < E_\nu < 200\text{GeV}$

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



- 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

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 B/A are important for the relative flux extraction

$$m_c = 1.4 \pm 0.13$$

$$B/A^{\nu} = -0.27 \pm 0.03, \quad B/A^{\bar{\nu}} = -1.64 \pm 0.03$$

- 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

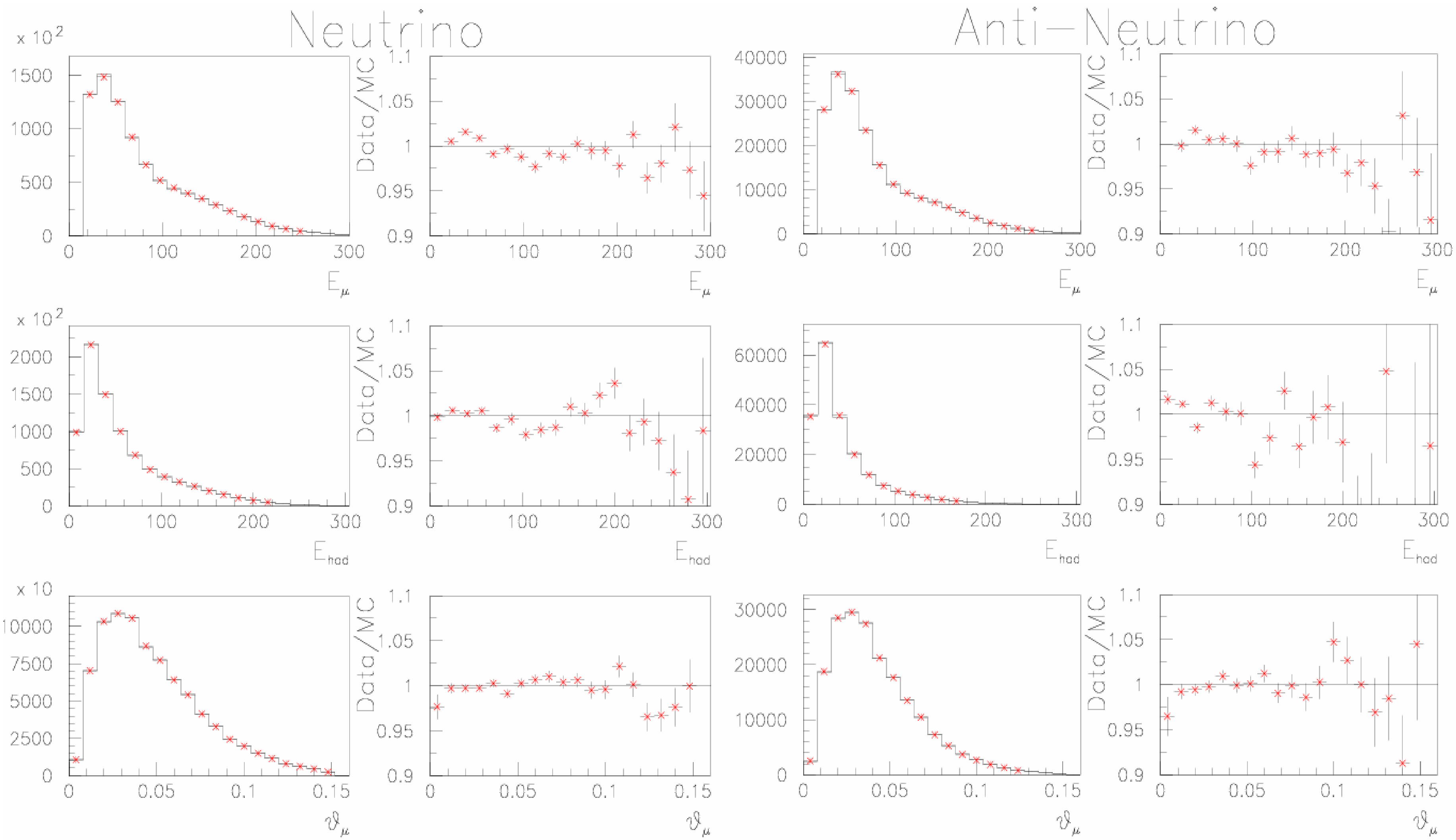
$\sigma_{\alpha i}$ - the size of systematic uncertainty i at data point α

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

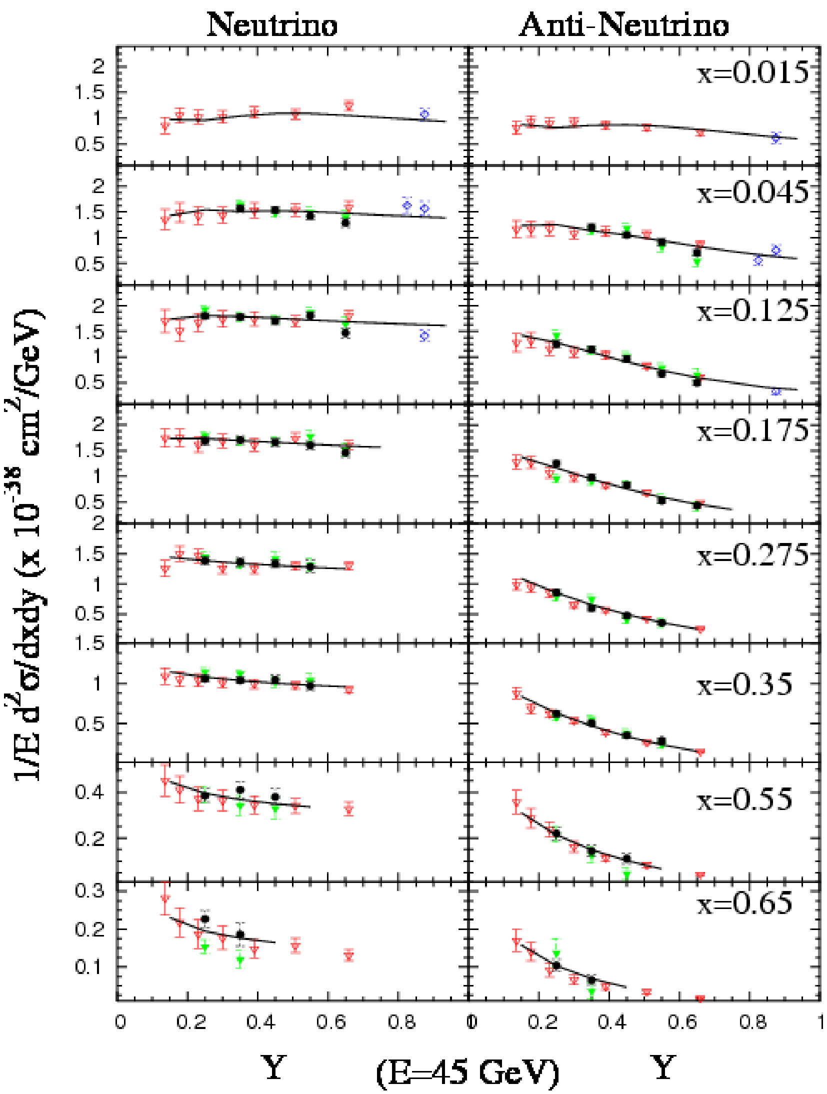
$$\partial_{i\alpha} = \frac{\frac{d^2\sigma}{dxdy}(x,y,E)(S_i+\varepsilon_i) - \frac{d^2\sigma}{dxdy}(x,y,E)(S_i-\varepsilon_i)}{2\varepsilon_i}$$

- 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%	30-350
NuTeV	0.43%	0.7%	30-300

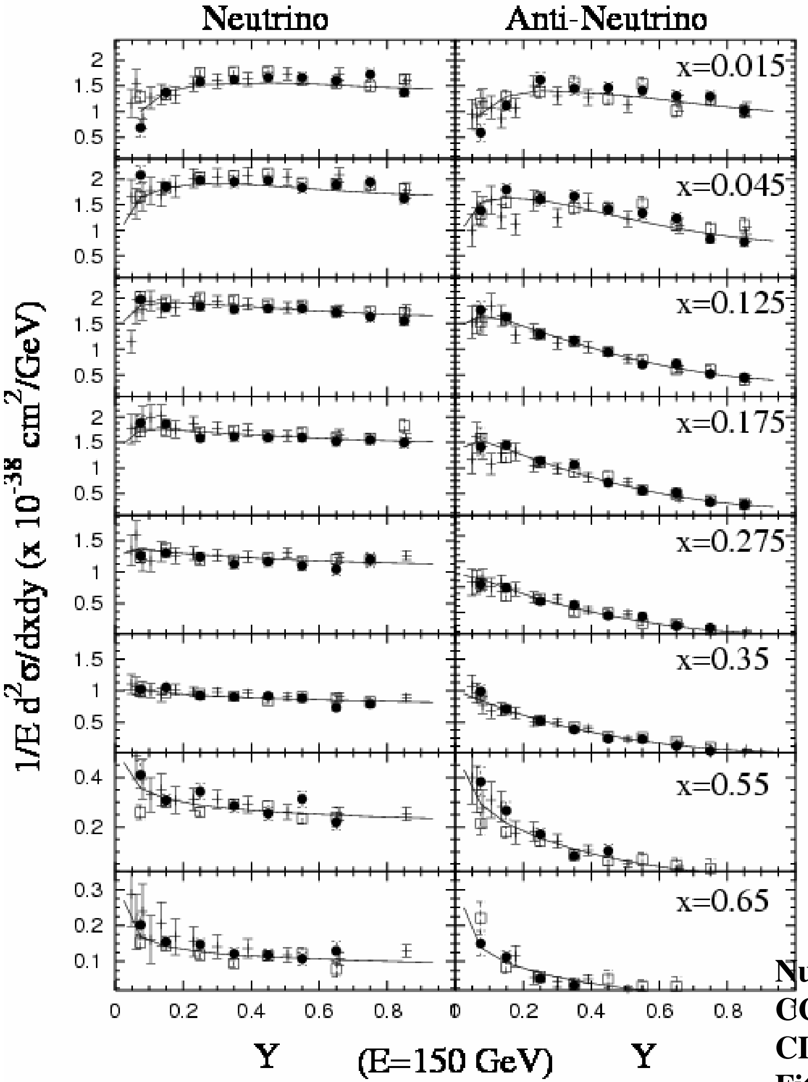
- **all major systematics are included**
- **new high-*y* cross section at low *x* and low E_{ν} (different systematics – not included)**
- **NuTeV has comparable statistics to the other ν-Fe experiments.**
- **Reduction in the largest systematic uncertainties : E_{μ} and E_{HAD} scales**

Other ν-Fe data shown on the plot:

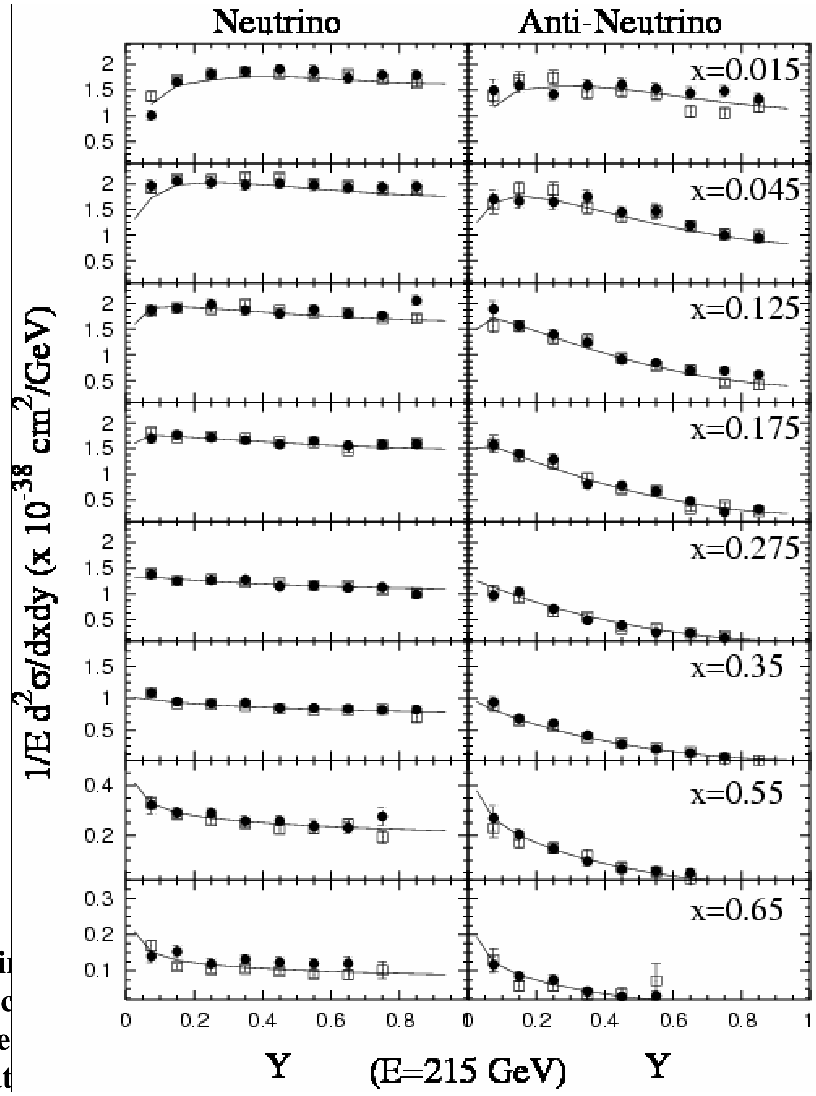
CDHSW(Z. Phys. C49 187, 1991)

U. K. Yang CCFR Ph.D. Thesis

Preliminary NuTeV's CC Cross Section



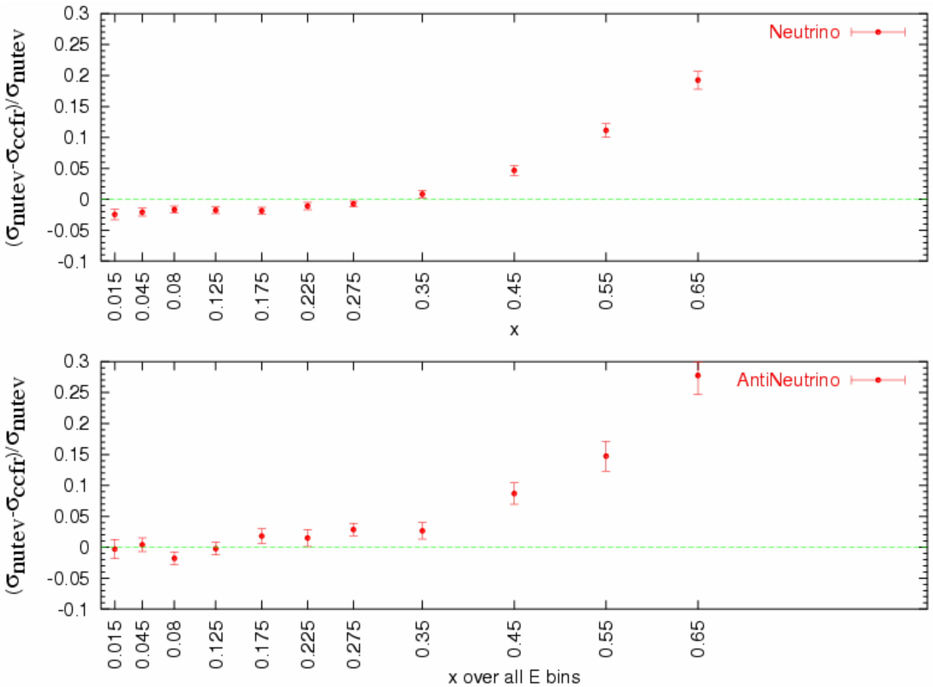
NuTeV – filled ci
CCFR - open circ
CDHSW – crosse
Fit to NuTeV Dat



NuTeV CC Cross Section Result

- it agrees well with other ν-Fe experiments for x<0.4
- for x>0.4 it agrees in level, but not in shape with CDHSW

- for x>0.4 NuTeV result is increasingly higher than CCFR
  - x=0.45 - 5%
  - x=0.55 - 10%
  - x=0.65 - 20%



Investigating the discrepancy with CCFR

- similar detectors and techniques
- NuTeV has improved calibration
  - 3% effect at x=0.65
- Different model fit parameters
  - 3% effect at x=0.65
- 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^-

F_2 and xF_3 Measurement

F_2

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

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

- **Perform 1-parameter fit for F_2**
- **[2]R_w and model for ΔxF_3 are used**

[1]TR-VFS ΔxF_3 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

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

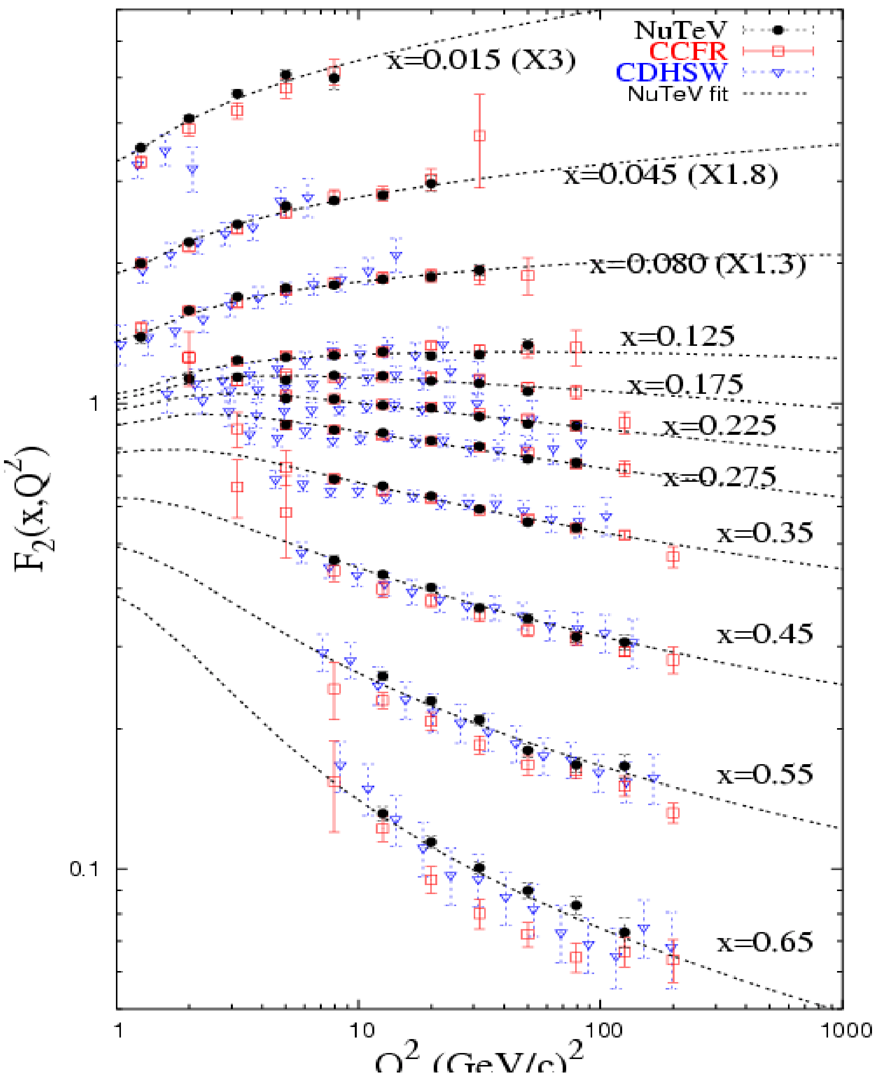
$$=\Delta F_2\left(1-y-\frac{Mxy}{2E}+\frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right)+2y\left(1-\frac{y}{2}\right)\quad x\bar{F}_3$$

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

- **Radiative corrections applied**

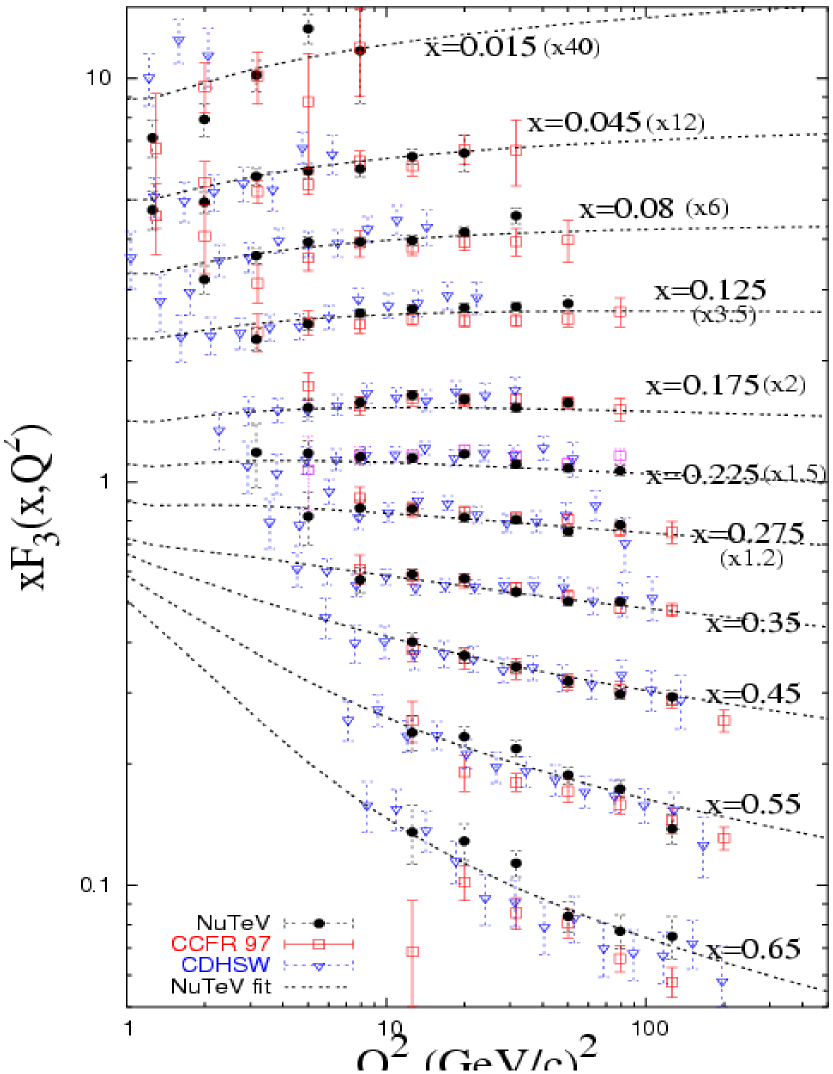
  (D. Y. Bardin and Dokuchaeva, JINR-E2-86-260 (1986))
- **Isoscalar correction applied**
- **Bin centering correction for Q^2**

F_2 Measurement



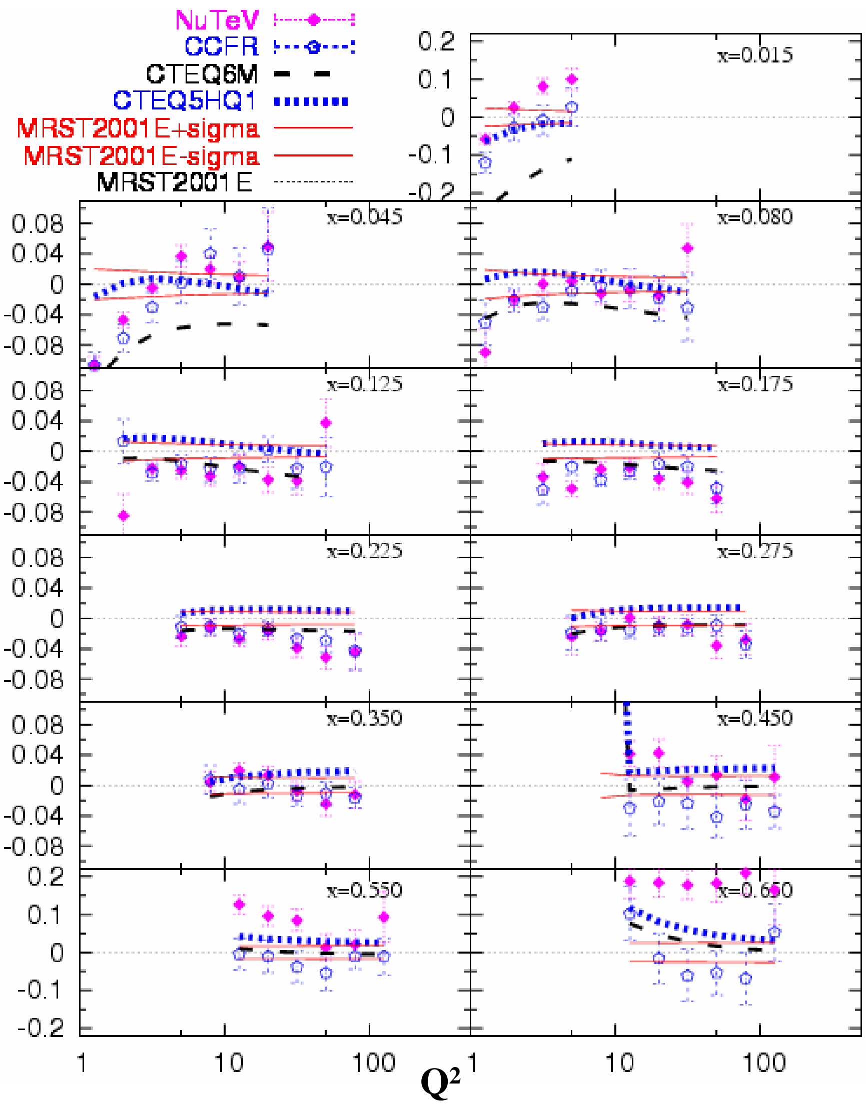
- **Isoscalar ν-Fe F_2**
- **NuTeV F_2 is compared with CCFR and CDHSW results**
  - the line is a fit to NuTeV data
- **All systematic uncertainties are included**
- **All data sets agree for *x<0.4.***
- **At *x>0.4* NuTeV agrees in level with CDHSW, but not in shape**
- **At *x>0.4* NuTeV is systematically 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**
- **All systematic uncertainties are included**
- **All data sets agree for $x<0.4$.**
- **At $x>0.4$ NuTeV agrees in level with CDHSW, but not in shape**
- **At $x>0.4$ NuTeV is systematically above CCFR**

Comparison with Theory

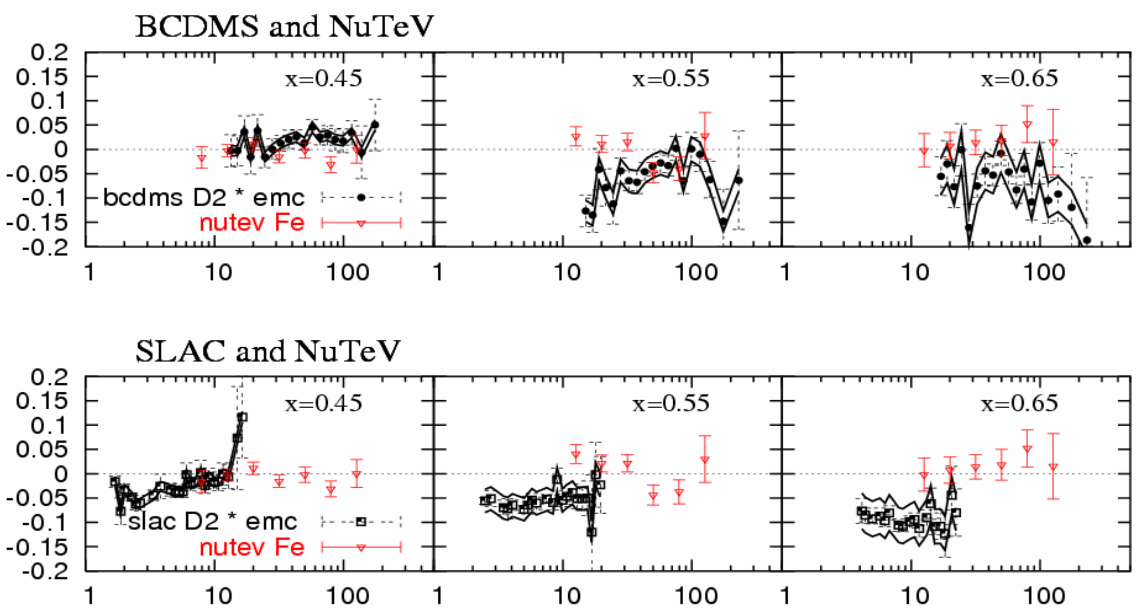


- base line is TRVFS(MRST2001E)
- NuTeV and CCFR F_2 are compared to

TRVFS(MRST99) $\dfrac{F_2^{NuTeV} - F_2^{TRVFS}}{F_2^{TRVFS}}$

- Other 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

Comparison with Charge Lepton Data for *x>0.4*



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

•NuTeV is higher than BCDMS(D_2) (top 3 plots)

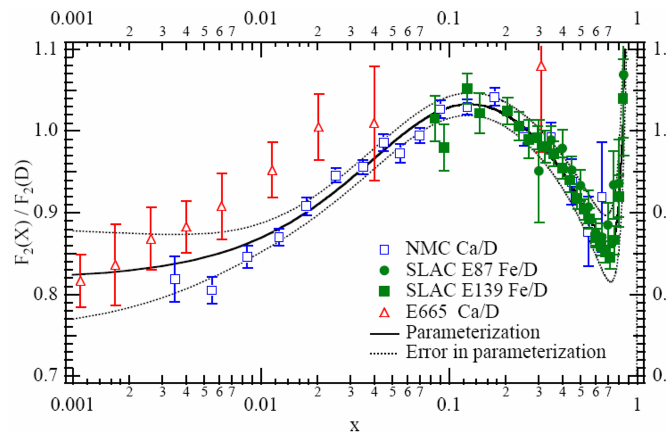
- *7%* at *x=0.55*, and *x=0.65*

• NuTeV is higher than SLAC(D_2) (bottom 3 plots)

- *5%* at *x=0.55*, and *7%* at *x=0.65*

NuTeV data favors smaller nuclear correction.

- **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**

Conclusions

- NuTeV has extracted high precision $\nu - Fe$ and $\bar{\nu} - Fe$ differential cross section

- The **S**ign **S**elected **Q**uadrupole **T**rain is unique feature for NuTeV:
  - NuTeV measured differential cross section for inaccessible before high-y kinematic region.

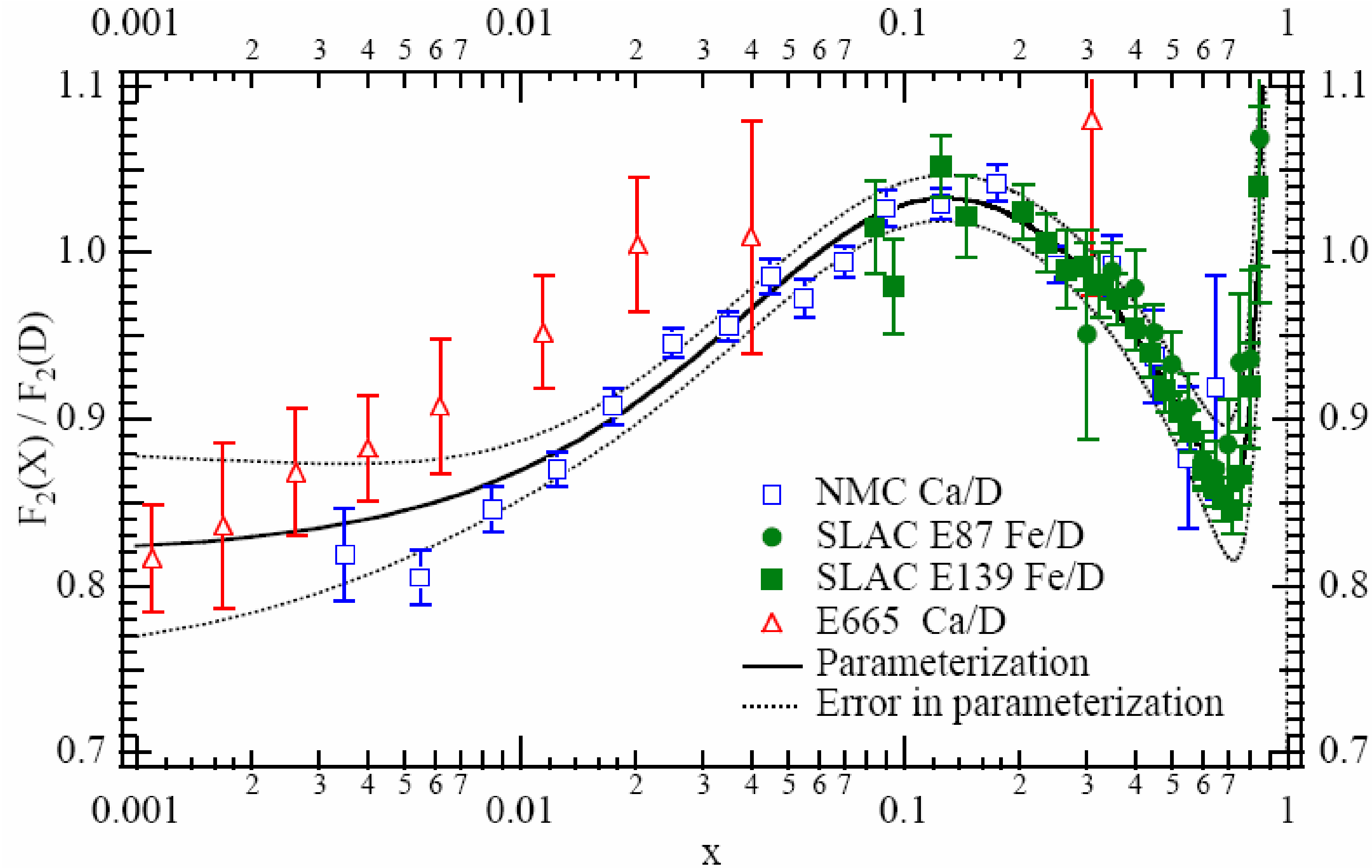
- NuTeV measurement is in a good agreement with previous $\nu - Fe$ experiments (CCFR, CDHSW) for x<0.4. For x>0.4 NuTeV is systematically higher than CCFR:
  5% at *x=0.45*, *10%* at *x=0.55*, *20%* at *x=0.65*

- comparison with charge lepton data and theory shows that NuTeV favors smaller nuclear correction at high-x.

Future:

- final checks
- QCD fits

Nuclear Correction



Buras-Gaemers Parameterization

- **Valence quark distributions parameterization:**

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

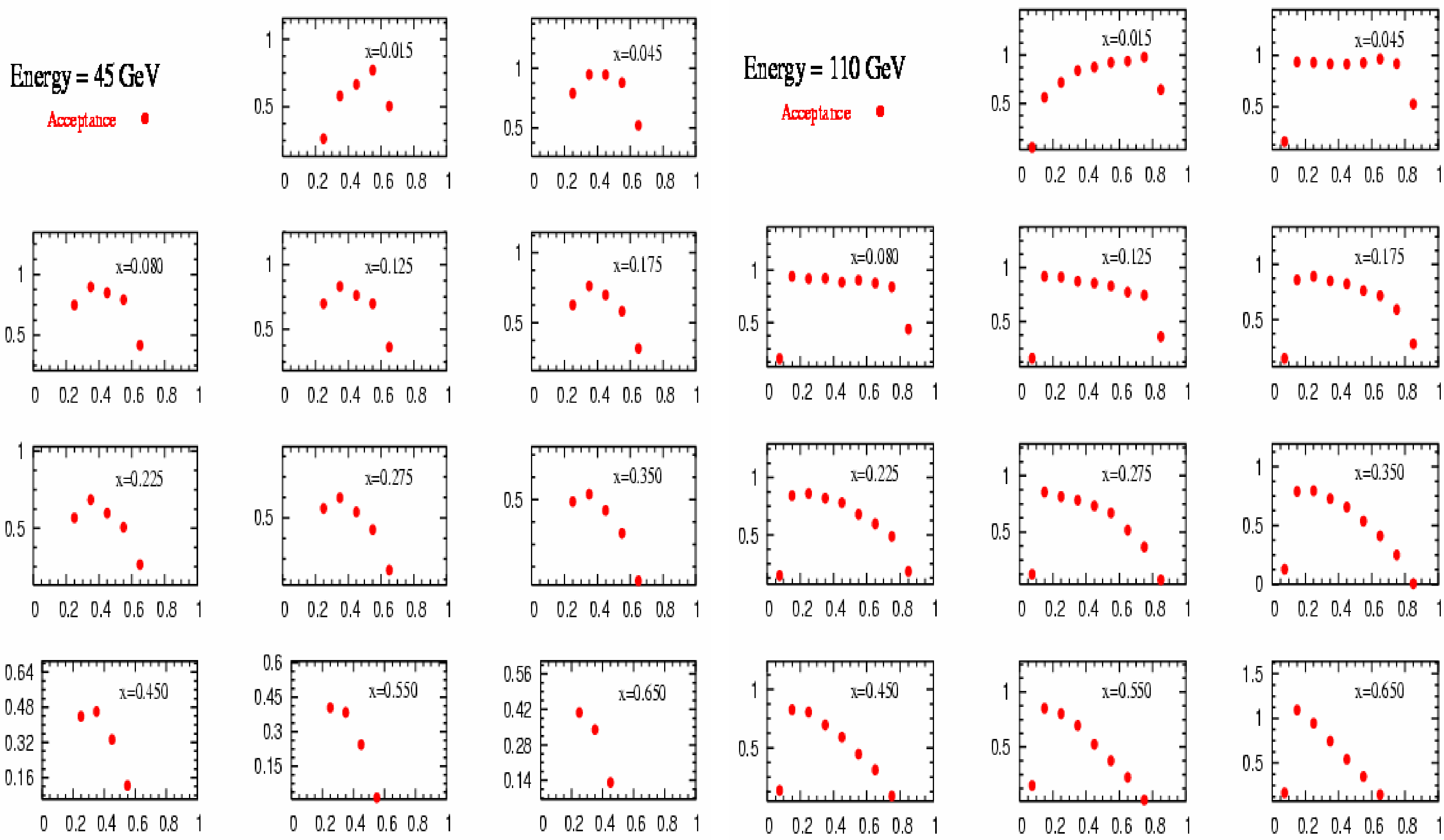
- **Sea quark distributions parameterization:**

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

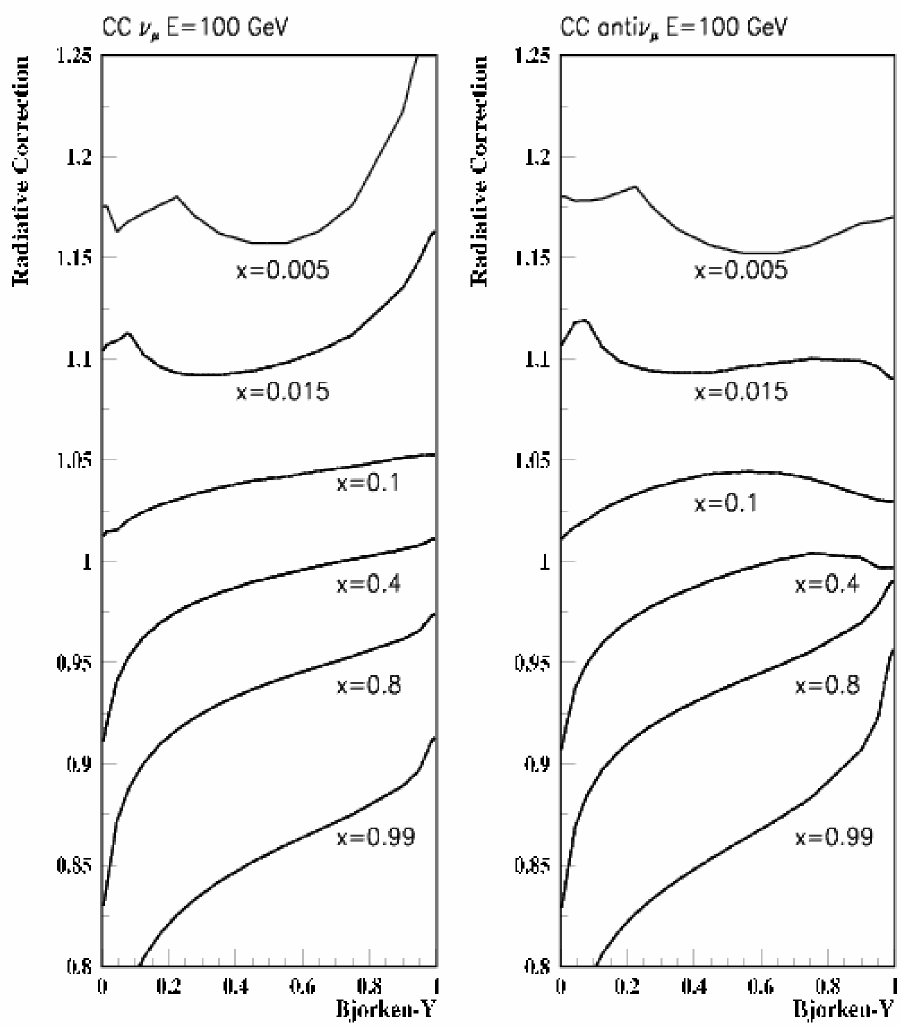
- **The exponents E_i and ES_i and the normalization coefficients AV_i and AS_i are fitted to NuTeV differential cross section data.**

- **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

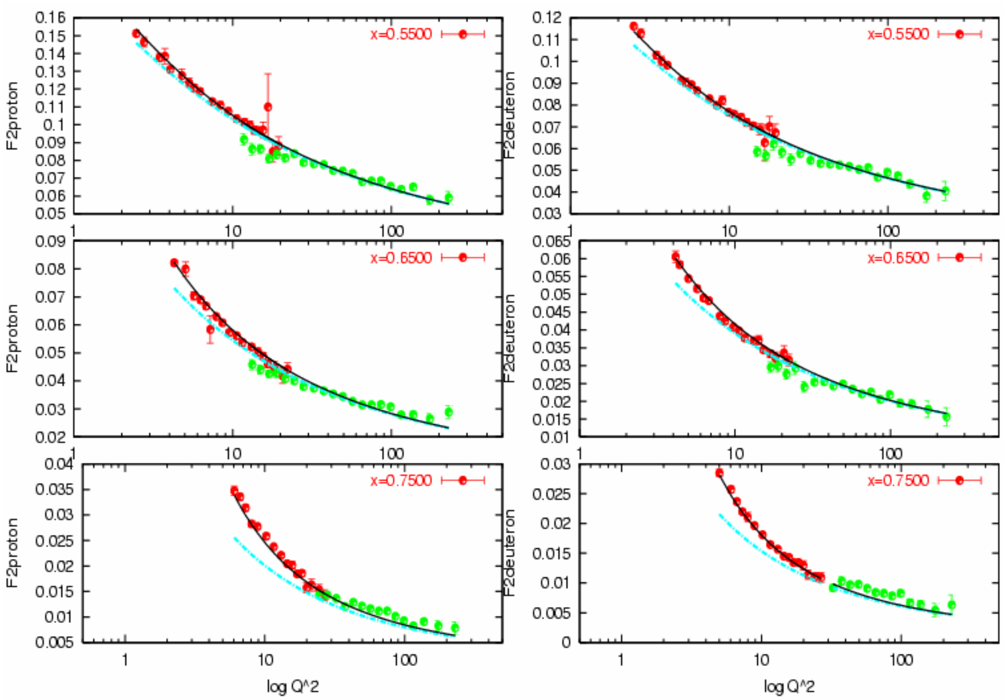


Radiative Correction



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