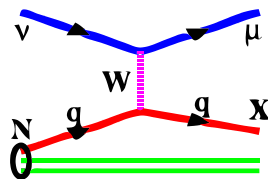


NuTeV



Differential Cross Section Results from NuTeV

Voica Radescu

University of Pittsburgh
for the NuTeV Collaboration
April, DIS 2004

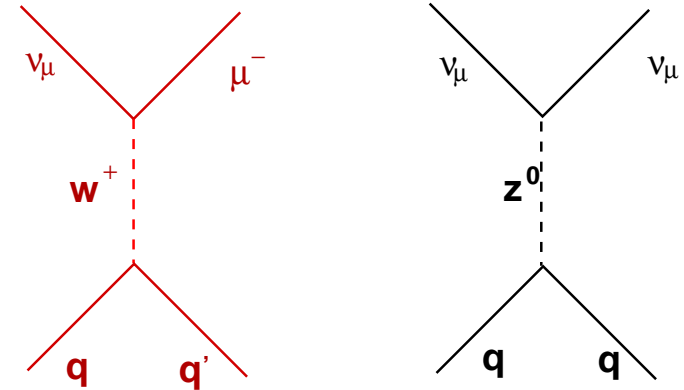


Outline:

- ▶ About NuTeV:
 - ▶ NuTeV Detector
 - ▶ NuTeV Beam
- ▶ Differential Cross-Section
 - ▶ Results and Comparisons with past data
- ▶ Structure Function Measurement
 - ▶ Results and Comparisons with past data and theory
- ▶ Conclusions and Future

About NuTeV:

- ▶ NuTeV is a precise neutrino DIS experiment
- ▶ Data taking: 1996-97 FermiLab fixed target run
 $E_\nu \in (20, 400)\text{GeV}$ and $Q^2 \in (1, 600)\text{GeV}^2$
- ▶ Type of interactions:
 - ▶ NC: $\nu(\bar{\nu})N \rightarrow \nu(\bar{\nu})X$
 - ▶ CC: $\nu(\bar{\nu})N \rightarrow \mu^-(\mu^+)X$



The NuTeV collaboration:

T. Adams⁴, A. Alton⁴, S. Avvakumov⁸, L. de Barbaro⁵, P. de Barbaro⁸, R. H. Bernstein³, A. Bodek⁸, T. Bolton⁴, S. Boyd⁷, J. Brau⁶, D. Buchholz⁵, H. Budd⁸, L. Bugel³, J. Conrad², R. B. Drucker⁶, B. T. Fleming², R. Frey⁶, J.A. Formaggio², J. Goldman⁴, M. Goncharov⁴, D. A. Harris⁸, R. A. Johnson¹, J. H. Kim², S. Koutsoliotas², M. J. Lamm³, W. Marsh³, D. Mason⁶, J. McDonald⁷, K. S. McFarland^{8,3}, C. McNulty², D. Naples⁷, P. Nienaber³, V. Radescu⁷, A. Romosan², W. K. Sakumoto⁸, H. Schellman⁵, M. H. Shaevitz², P. Spentzouris², E. G. Stern², N. Suwonjandee¹, M. Tzanov⁷, M. Vakili¹, A. Vaitaitis², U. K. Yang⁸, J. Yu³, G. P. Zeller⁵ and E. D. Zimmerman²

¹ University of Cincinnati, Cincinnati, OH 45221

² Columbia University, New York, NY 10027

³ Fermi National Accelerator Lab., Batavia, IL 60510

⁴ Kansas State University, Manhattan, KS 66506

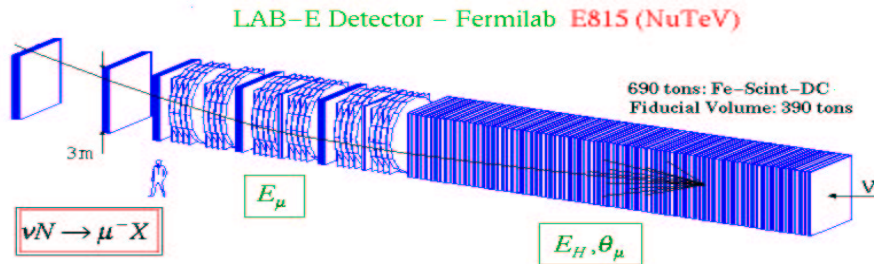
⁵ Northwestern University, Evanston, IL 60208

⁶ University of Oregon, Eugene, OR 97403

⁷ University of Pittsburgh, Pittsburgh, PA 15260

⁸ University of Rochester, Rochester, NY 14627

NuTeV Apparatus:



Target Calorimeter:

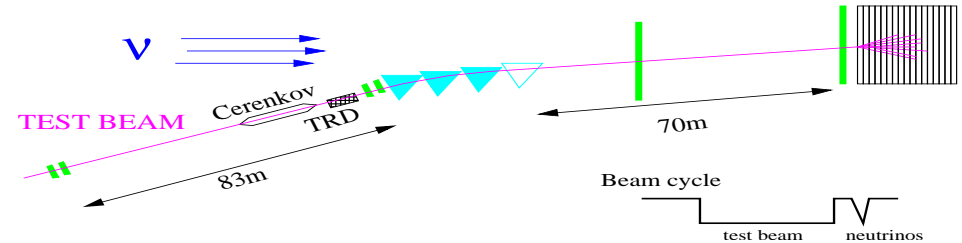
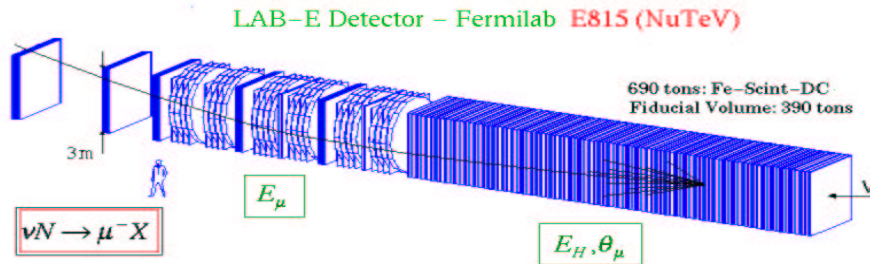
- ▶ 690 ton Fe target
- ▶ liquid scintillator counters:
- ▶ hadron resolution: $\frac{\sigma E}{E} \sim \frac{0.86}{\sqrt{E}}$
- ▶ drift chambers: track μ and determine vertex position

Muon Spectrometer:

- ▶ 420 ton toroidal Fe magnets ($B_\phi \sim 15$ kG)
- ▶ drift chambers
- ▶ momentum resolution: $\frac{\sigma p}{p} \sim 11\%$
- ▶ **polarity always set to focus the muon from primary vertex (CC)**

NuTeV Apparatus:

NuTeV Features:



Target Calorimeter:

- ▶ 690 ton Fe target
- ▶ liquid scintillator counters:
- ▶ hadron resolution: $\frac{\sigma E}{E} \sim \frac{0.86}{\sqrt{E}}$
- ▶ drift chambers: track μ and determine vertex position

Muon Spectrometer:

- ▶ 420 ton toroidal Fe magnets ($B_\phi \sim 15$ kG)
- ▶ drift chambers
- ▶ momentum resolution: $\frac{\sigma p}{p} \sim 11\%$
- ▶ **polarity always set to focus the muon from primary vertex (CC)**

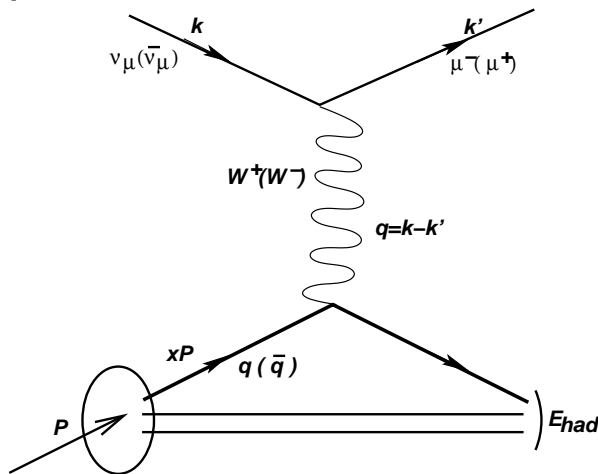
Calibration Beam:

- ▶ detector calibrated every minute
- ▶ $\mu, e^-,$ hadrons (4.5 - 190 GeV)
- ▶ measures the absolute energy scale:
 - ▶ muons: $\frac{\delta E_\mu}{E_\mu} = 0.70\%$
 - ▶ hadrons: $\frac{\delta E_{HAD}}{E_{HAD}} = 0.43\%$

Sign Selected Quadrupole Train: 🌸

- ▶ high purity ν or $\bar{\nu}$ beams
- ▶ the muon from primary vertex tagged (doesn't require μ charge)
- ▶ access to low E_μ data (high-y)

Charged Current Neutrino Scattering:



▶ Lorentz-invariant quantities in terms of measured E_μ , θ_μ , E_{HAD} :

- ▶ $Q^2 = 4(E_\mu + E_{HAD})E_\mu \sin^2 \frac{\theta_\mu}{2}$ → negative square of 4-momentum transfer
- ▶ $x = \frac{Q^2}{2ME_{HAD}}$ → Bjorken scaling variable
- ▶ $y = \frac{E_{HAD}}{E_\mu + E_{HAD}}$ → fraction of total leptonic energy transferred to the hadronic system)
- ▶ $\nu = E_{HAD}$ → energy transferred to hadronic system

Neutrino Differential Cross-Section:

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1 + \frac{Q^2}{M_W^2})^2} \left[\left(1 - y - \frac{Mxy}{2E_\nu}\right) F_2^{\nu(\bar{\nu})} + \frac{y^2}{2} 2xF_1^{\nu(\bar{\nu})} \pm y\left(1 - \frac{y}{2}\right) xF_3^{\nu(\bar{\nu})} \right]$$

Structure Functions in Neutrino interactions in terms of quark compositions of target:

- ▶ $2xF_1^{\nu(\bar{\nu})}(x, Q^2) = \sum 2x[q^{\nu(\bar{\nu})} + \bar{q}^{\nu(\bar{\nu})}]$
- ▶ $F_2^{\nu(\bar{\nu})}(x, Q^2) = \sum 2x[q^{\nu(\bar{\nu})} + \bar{q}^{\nu(\bar{\nu})} + 2k^{\nu(\bar{\nu})}]$
- ▶ $xF_3^{\nu(\bar{\nu})}(x, Q^2) = \sum 2x[q^{\nu(\bar{\nu})} - \bar{q}^{\nu(\bar{\nu})}]$ (only in neutrino scattering!)
- ▶ $R_L(x, Q^2) = \frac{\sigma_L}{\sigma_T} = \frac{F_L}{2xF_1} = \frac{F_2}{2xF_1} \left(1 + \frac{4M^2x^2}{Q^2}\right)$ (sensitive to pure QCD effects)

Extracting Differential Cross Section:

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

$$\frac{d^2 \sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{1}{\Phi(E_\nu)} \frac{d^2 N^{\nu(\bar{\nu})}}{dx dy}$$

▶ Flux Sample:

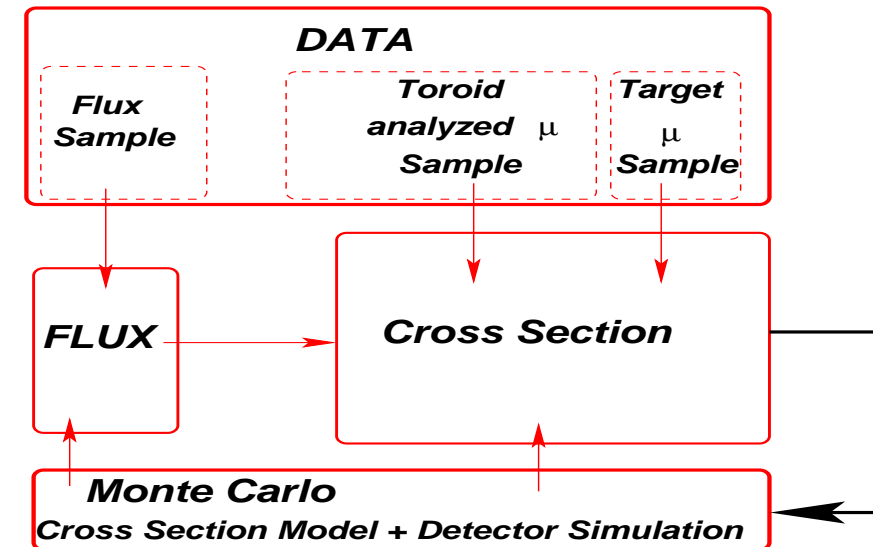
- ▶ nearly independent data set ($E_{\text{HAD}} < 20 \text{ GeV}$)
- ▶ extract flux (see next slide)

▶ Cross Section Sample:

- ▶ Main Sample: toroid analyzed muon
 - ▶ containment and good muon track
 - ▶ $E_\mu > 15 \text{ GeV}$, $E_{\text{HAD}} > 10 \text{ GeV}$,
 $E_\nu \in (30, 360) \text{ GeV}$
 - ▶ $Q^2 > 1 \text{ GeV}^2$
- ▶ New sample: target μ
 - ▶ SSB: allows low $E_\mu (\leq 12 \text{ GeV})$ data (high-y)
 - ▶ $E_\mu > 4 \text{ GeV}$

▶ Cross-Section Model

- ▶ used only for acceptance and smearing corrections
- ▶ QCD inspired LO parametrization: **fit to data** :
(A.Buras, K.Gaemers; Nucl.Phys.B132,249(1978))
 - ▶ includes higher twist parametrization for Q^2 dependence at $x > 0.4$ (SLAC, NMC, BCDS data).
 - ▶ for $Q^2 < 1.35 \text{ GeV}^2$ uses GRV Q^2 evolution



▶ Process is iterated:

- ▶ use CCFR for initial input (loop 0)
- ▶ convergence occurs after 2 loops:
 - ▶ average cross-section change is $\sim 1\%$ after loop 1 (loop2 $< 0.3\%$)
- ▶ acceptance cut on last iteration (20%)

Extracting Relative Flux:

- ▶ Relative flux in energy bins extracted
- ▶ Absolute flux obtained by normalizing our cross-section to the world average value:

$$\frac{\sigma_{\text{WORLD}}^{\nu}}{E_{\nu}} = 0.677 \pm 0.014 \times 10^{-38} \frac{\text{cm}^2}{\text{GeV}}$$
- ▶ Flux Determined from low ν data ($< 20 \text{ GeV}$)

“Fixed ν_0 method”: Integrate data at low ν 🌸

- ▶ polynomial expansion of the differential cross section in $y = \frac{\nu}{E_{\nu}}$

$$\frac{dN}{d\nu} = \Phi(E_{\nu})A \left(1 + \frac{B}{A} \frac{\nu}{E_{\nu}} - \frac{C}{A} \frac{\nu^2}{2E_{\nu}^2} \right) \xrightarrow{\nu \rightarrow 0} \Phi(E_{\nu})A$$

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

$$B = -\frac{GM}{\pi} \int [F_2(x, Q^2) \mp xF_3(x, Q^2)] dx$$

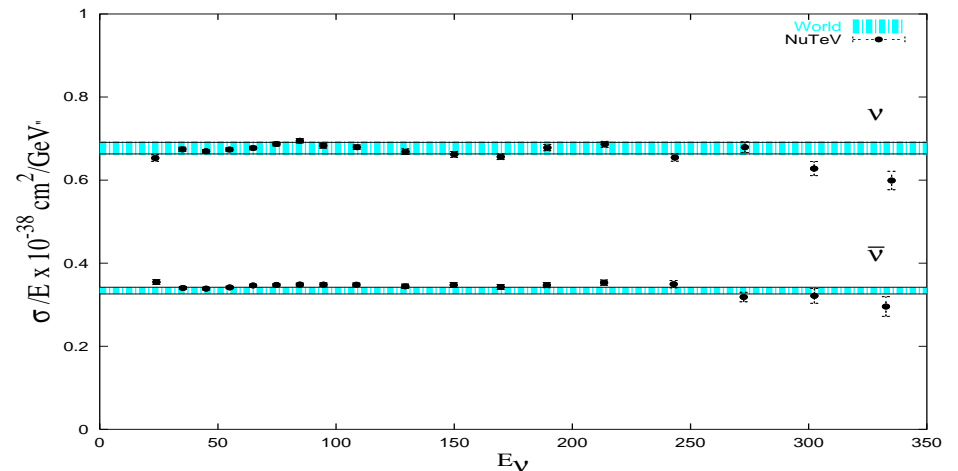
$$C = B - \frac{GM}{\pi} \int F_2(x, Q^2) \left(\frac{1 + \frac{2Mx}{\nu}}{1 + R(x, Q^2)} - \frac{Mx}{\nu} - 1 \right) dx$$

- ▶ Determine relative flux from:

$$\Phi(E_{\nu}) = \int_0^{\nu_0} \frac{\frac{dN}{d\nu}}{1 + \underbrace{\frac{B}{A} \frac{\nu}{E_{\nu}}}_{\text{small}} - \underbrace{\frac{C}{A} \frac{\nu^2}{2E_{\nu}^2}}_{\text{small}}} d\nu$$

- ▶ $\frac{B}{A}, \frac{C}{A}$ determined from the fit to $\frac{dN}{d\nu}$ data

- ▶ Test of Flux extraction:



- ▶ NuTeV's $\frac{\sigma^{\nu}}{E_{\nu}}$ is flat as function of E_{ν} within $< \pm 2\%$
- ▶ $\frac{\sigma^{\nu}}{\sigma^{\bar{\nu}}}$ agrees with world average



Cross Section Systematic Uncertainties:

- ▶ 17 sources of systematics
 - ▶ E_μ and E_{HAD} scales
 - ▶ $m_c, \frac{B}{A}$ used to extract flux
 - ▶ 13 parameters used in cross-section model
- ▶ each systematic error evaluated separately and correlations between them taken into account
- ▶ overall normalization uncertainty **2.1%** (flux normalization)
- ▶ the statistical errors are added in quadrature to the diagonal elements of covariance matrix

How to use the Data Set:

- ▶ χ^2 for all systematic uncertainties:

$$\chi^2 = \sum_{\alpha\beta} (D^\alpha - f^{theory}) M_{\alpha\beta}^{-1} (D^\beta - f^{theory})$$

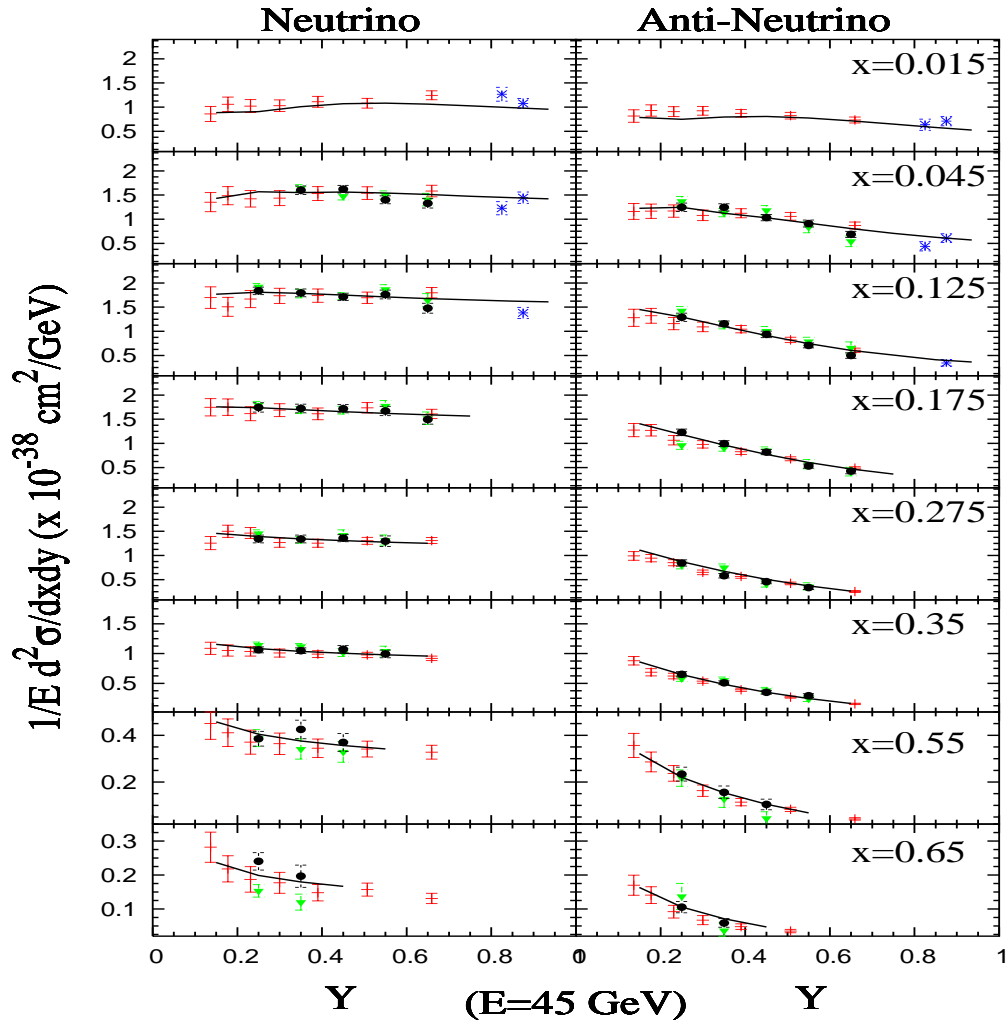
- ▶ $M_{\alpha\beta}$ is point to point covariance matrix:

$$M_{\alpha\beta} = \sum_{ij} \rho_{ij} \delta_{i|\alpha} \delta_{j|\beta}$$

- ▶ ρ_{ij} is 17×17 correlation matrix
- ▶ $\delta_{i\alpha}$ is symmetrized error:

$$\delta_{i|\alpha} = \frac{\frac{d^2\sigma}{dx dy} (S_i + \sigma_i) - \frac{d^2\sigma}{dx dy} (S_i - \sigma_i)}{2}$$

NuTeV Differential Cross Section:



LABEL:

black circles - NuTeV (long muon); blue circles - NuTeV (short muon)

green triangles - CCFR; red crosses - CDHSW; line - NuTeV model

▶ plots show extracted $\nu(\bar{\nu}) - \text{Fe}$ Cross-Sections as function of y for different x bins at $E_\nu = 45 \text{ GeV}$ and $E_\nu = 150 \text{ GeV}$

▶ NuTeV has extended y region data:

▶ new data at high- y and low x

▶ major systematics included:
 $E_\mu, E_{HAD}, m_c, \frac{B}{A}$
 (not yet for high- y data)

▶ NuTeV is compared to other Fe neutrino data:

- ▶ CDHSW (Z. Phys C49 187, 1991)
- ▶ CCFR (U. K. Yang PhD. Thesis)

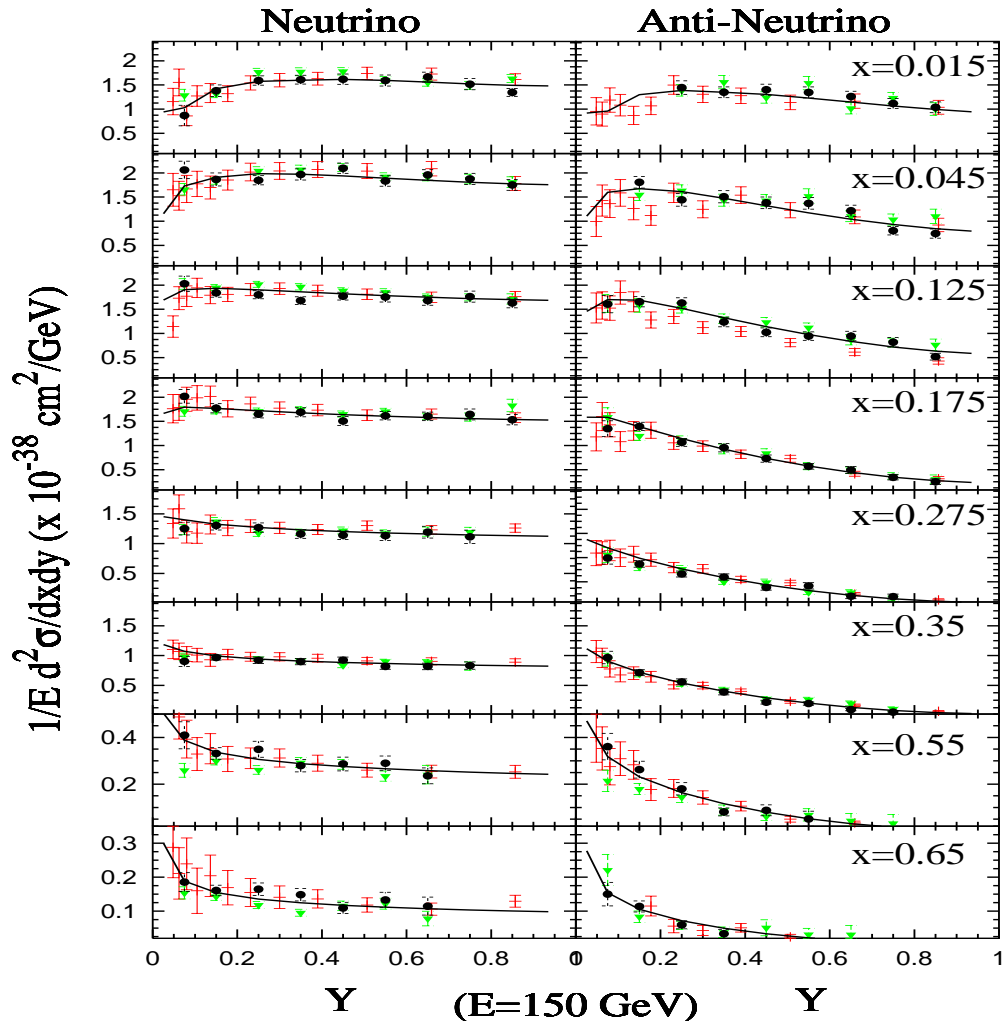
▶ NuTeV has comparable statistics

▶ Better control of largest systematics.

▶ E_μ and E_{HAD} energy scales:

CDHSW	2%	2.5%	20-200 GeV
CCFR	1%	1%	30-350 GeV
NuTeV	0.7%	0.43%	30-350 GeV

NuTeV Differential Cross Section:



LABEL:

black circles - NuTeV (long muon); blue circles - NuTeV (short muon)

green triangles - CCFR; red crosses - CDHSW; line - NuTeV model

- ▶ plots show extracted $\nu(\bar{\nu}) - \text{Fe}$ Cross-Sections as function of y for different x bins at $E_\nu = 45 \text{ GeV}$ and $E_\nu = 150 \text{ GeV}$

- ▶ NuTeV has extended y region data:

▶ new data at high- y and low x

- ▶ major systematics included:

$E_\mu, E_{HAD}, m_c, \frac{B}{A}$
(not yet for high- y data)

- ▶ NuTeV is compared to other Fe neutrino data:

▶ CDHSW (Z. Phys C49 187, 1991)

▶ CCFR (U. K. Yang PhD. Thesis)

- ▶ NuTeV has comparable statistics


- ▶ Better control of largest systematics.

▶ E_μ and E_{HAD} energy scales:

CDHSW	2%	2.5%	20-200 GeV
CCFR	1%	1%	30-350 GeV
NuTeV	0.7%	0.43%	30-350 GeV



Characterize NuTeV result:

- ▶ At low and medium x NuTeV in good agreement with other $\nu - \bar{\nu} - \text{Fe}$ data over entire energy and y
- ▶ For $x > 0.4$ NuTeV cross-sections is above the CCFR measurement over the entire energy range
- ▶ This difference increases with x : 
 - ▶ at $x=0.45 \sim 5\%$; at $x=0.55 \sim 10\%$; at $x=0.65 \sim 20\%$
- ▶ At high x NuTeV agrees in level with CDHSW measurement (large uncertainties)

Investigating the source of differences with CCFR:

- ▶ CCFR and NuTeV similar in design and analysis method
- ▶ NuTeV has an improved energy calibration:
 - ▶ includes nonlinearity in E_{HAD} (accounts for $\sim +3\%$ difference at high x)
- ▶ Model (fit to NuTeV data) difference (accounts for $\sim +3\%$ difference at $x=0.65$)
- ▶ Another difference between CCFR and NuTeV experiments:
 - ▶ NuTeV had separate neutrino and antineutrino runs (SSB)
 - ▶ NuTeV always set to focus the “right-sign” muon: better acceptance
 - ▶ CCFR had simultaneous neutrino and antineutrino runs
 - ▶ CCFR had toroid polarity $\sim 50\%$ set to focus on μ^+ and $\sim 50\%$ set on μ^-

Extraction of Structure Functions: $F_2(x, Q^2)$

- ▶ Structure Functions determined from fits to linear combination of the differential cross-sections:

$$\frac{d^2\sigma^\nu}{dx dy} + \frac{d^2\sigma^{\bar{\nu}}}{dx dy} = \frac{2MG^2 E_\nu}{\pi} \left[\left(1 - y - \frac{Mxy}{2E} + \frac{1 + (\frac{2Mx}{Q})^2}{1 + R(x, Q^2)} \frac{y^2}{2} \right) F_2^{AVG}(x, Q^2) + y \left(-\frac{y}{2}\right) \Delta x F_3(x, Q^2) \right]$$

- ▶ where $F_2^{AVG}(x, Q^2) = \frac{1}{2}(F_2^\nu(x, Q^2) + F_2^{\bar{\nu}}(x, Q^2))$
- ▶ perform 1-parameter fit for $F_2^{AVG}(x, Q^2)$
- ▶ input model for $R_L, \Delta x F_3$ where:
 - ▶ R_L from a fit to the world's data (L.W.Whitlow *et. al.* Phys.Lett. B250(1990) 193)
 - ▶ $\Delta x F_3 = xF_3^\nu - xF_3^{\bar{\nu}} = 4x(s - c)(\text{QPM assuming symmetric seas})$ from NLO QCD model(T-R VFS) (R.Thorne and R.Roberts, Phys.Lett. B 421 (1998))

Cross-Sections corrected to :

- ▶ isoscalar target (5.67% excess of n over p in Fe target)
- ▶ QED radiative effects (D.Y.Bardin and Dokuchaeva, JINR-E2-86-260(1986))



Extraction of Structure Functions: $x F_3(x, Q^2)$

- ▶ Structure Functions determined from fits to linear combination of the differential cross-sections

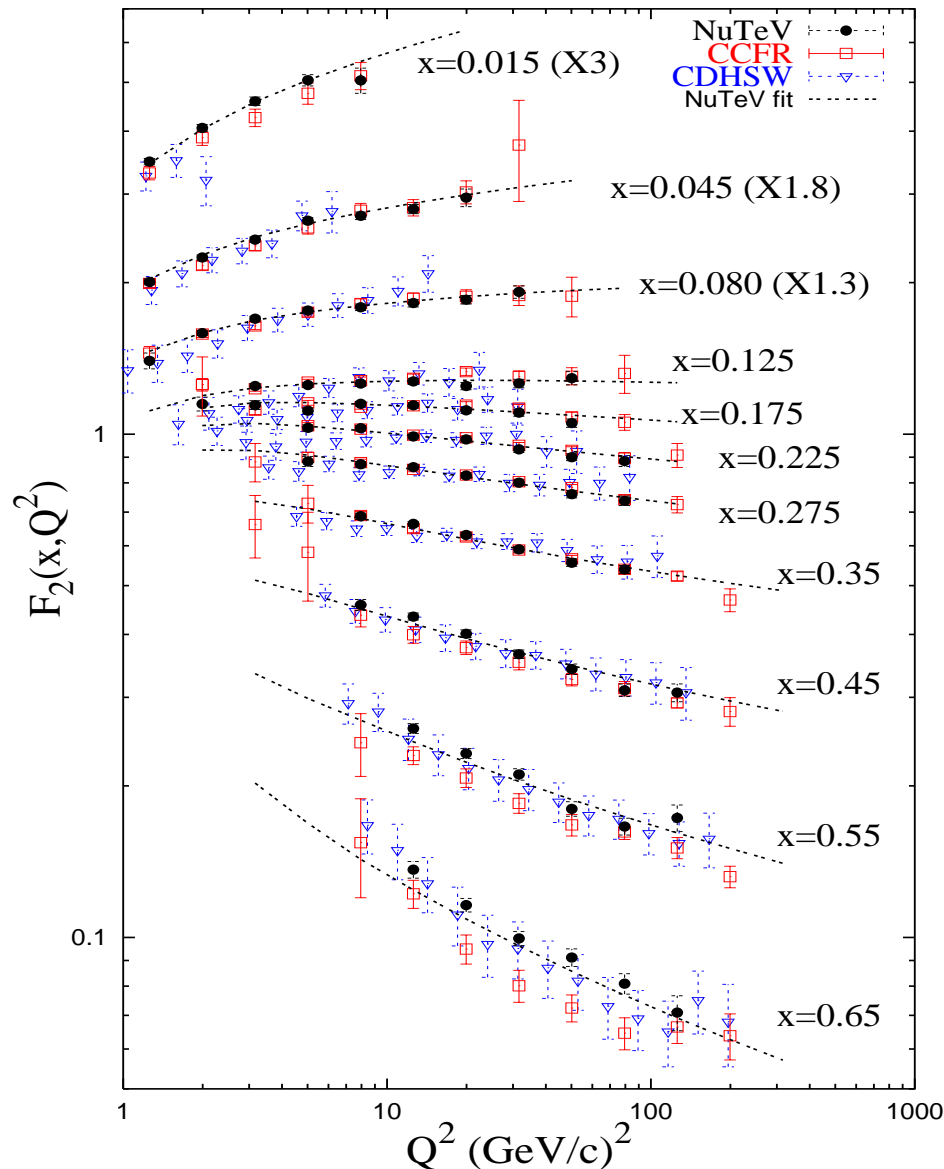
$$\frac{d^2\sigma^\nu}{dx dy} - \frac{d^2\sigma^{\bar{\nu}}}{dx dy} = \frac{2MEG^2}{\pi} \left(y - \frac{y^2}{2} \right) x F_3^{AVG}(x, Q^2)$$

- ▶ where $x F_3^{AVG}(x, Q^2) = \frac{1}{2} (x F_3^\nu(x, Q^2) + x F_3^{\bar{\nu}}(x, Q^2))$
- ▶ perform 1-parameter fit for $x F_3^{AVG}(x, Q^2)$
- ▶ $F_2^\nu(x, Q^2) \sim F_2^{\bar{\nu}}(x, Q^2) \longrightarrow$ no inputs required 🌸

Cross-Sections corrected to :

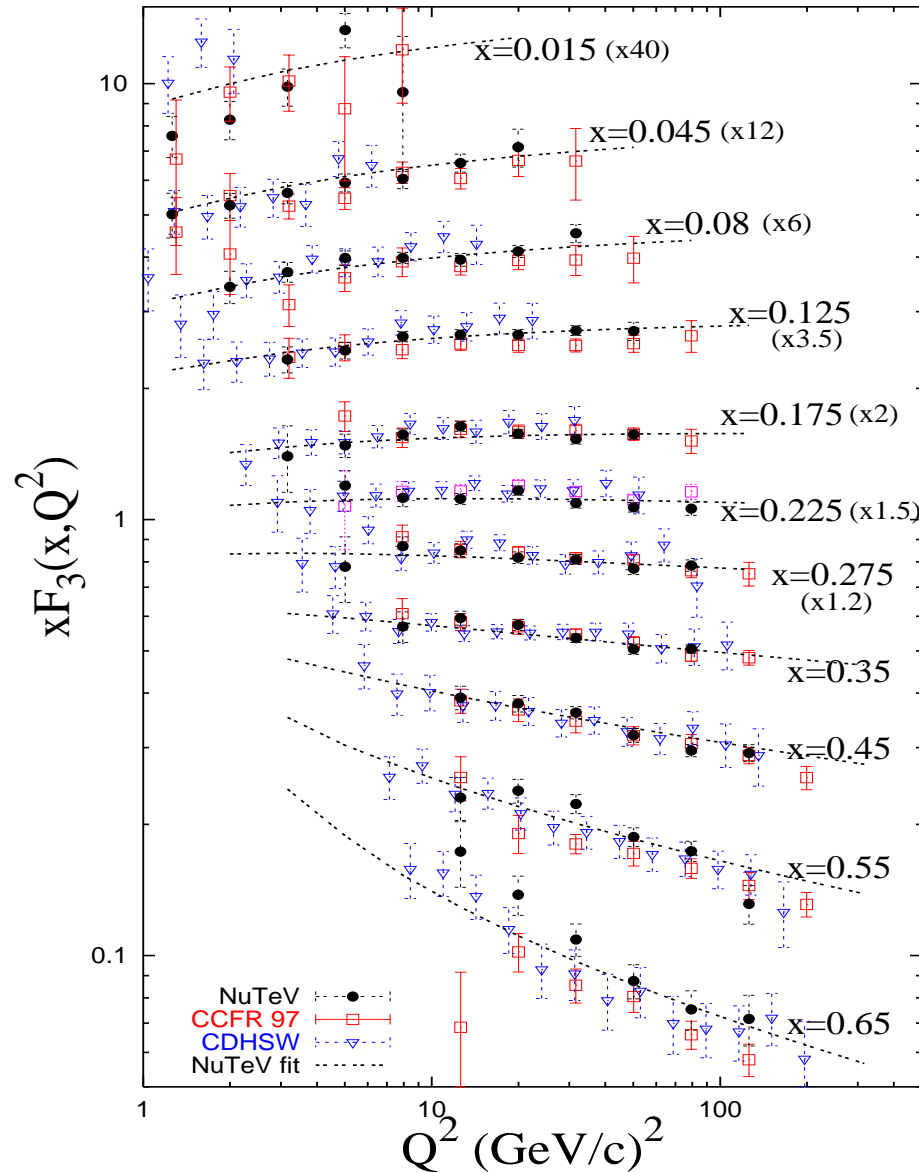
- ▶ isoscalar target (5.67% excess of n over p in Fe target)
- ▶ QED radiative effects (D.Y.Bardin and Dokuchaeva, JINR-E2-86-260(1986))

Comparison to other neutrino data



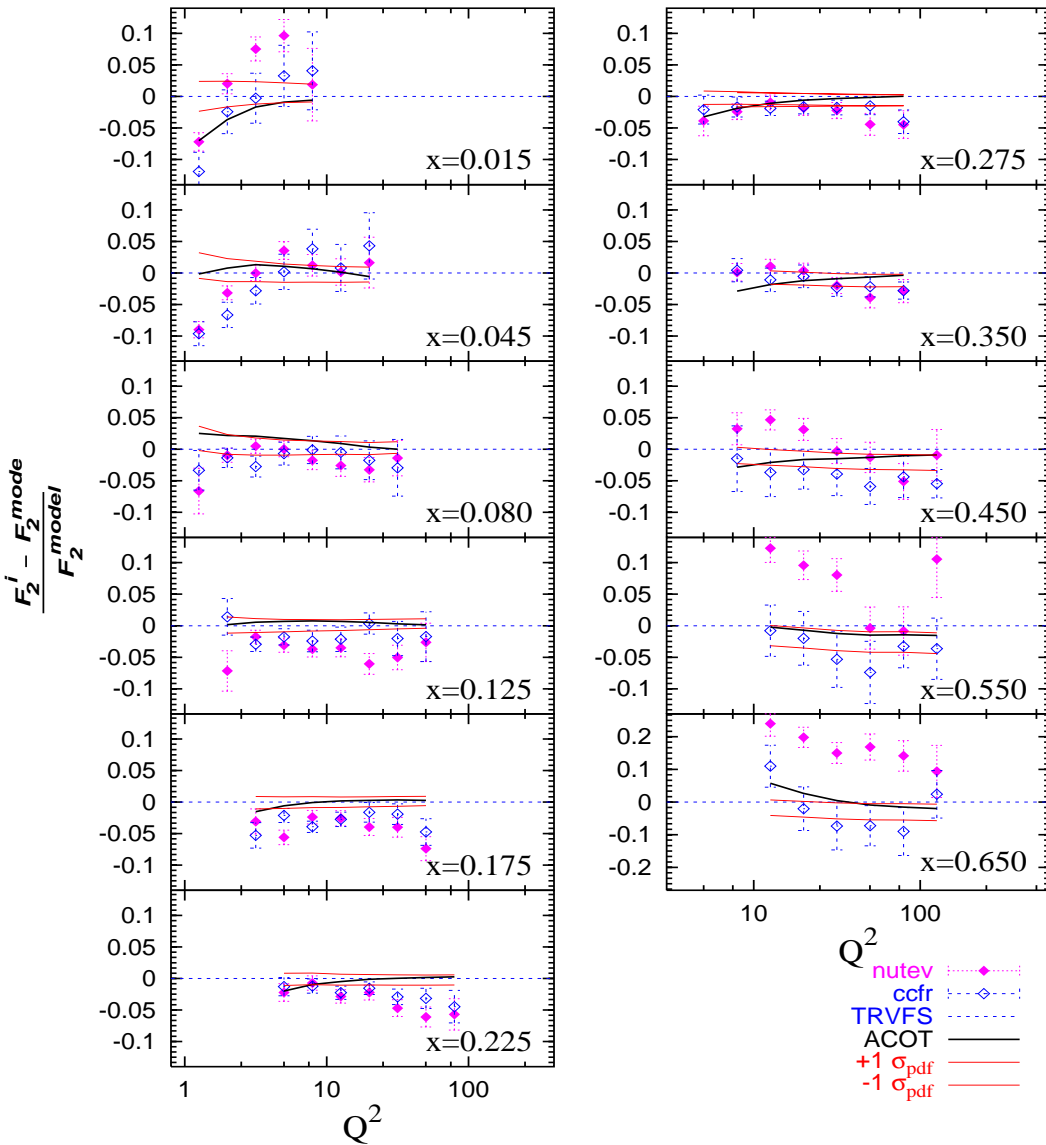
- ▶ Data sets shown: CCFR, CDHSW, NuTeV for isoscalar $\nu - \text{Fe}$ F_2
- ▶ The line is F_2 from our model
- ▶ Data has major systematics included:
 - ▶ $R_{\text{WORLD}}, \Delta x F_3$ (model systematics)
 - ▶ $E_\mu, E_{\text{HAD}}, m_c, \frac{B}{A}$
- ▶ at $0.015 < x < 0.5$ all data sets are in good agreement
- ▶ at high x NuTeV is systematically above CCFR
- ▶ at high x NuTeV is in agreement with CDHSW

Comparison to other neutrino data



- ▶ Data sets shown: CCFR, CDHSW, NuTeV for isoscalar $\nu - \text{Fe}$ xF_3
- ▶ The line is xF_3 from our model
- ▶ Data has major systematics included:
 - ▶ $E_\mu, E_{\text{HAD}}, m_c, \frac{B}{A}$
- ▶ at $0.015 < x < 0.5$ all data sets are in good agreement
- ▶ at high x NuTeV is systematically above CCFR
- ▶ at high x NuTeV is in agreement with CDHSW

Comparison to theory



▶ plots show NuTeV and CCFR F_2 data ratios to TR-VFS (MRST-99 pdf) curve in all x bins

▶ Other Models shown:

- ▶ TR-VFS with MRST-2001 $E \pm 1\sigma$ pdf
- ▶ ACOT with CTEQ4HQ

▶ Theory curves corrected for:

- ▶ Target Mass (H.Georgi & H.D.Politzer, Phys.Rev D14 1829)
- ▶ Nuclear Effects:
 - ▶ correction measured in charged-lepton experiments from nuclear targets
 - ▶ standard way: apply the same correct. to neutrino scattering
 - ▶ we use a parametrization fit to data, independent of Q^2

(dominated at $x > 0.4$ by SLAC (low Q^2))

- ▶ new analysis with JLAB data using Nachtmann variable: $\xi = \frac{2x}{1 + \sqrt{1 + \frac{4M^2 x^2}{Q^2}}}$ (high x or low Q^2)

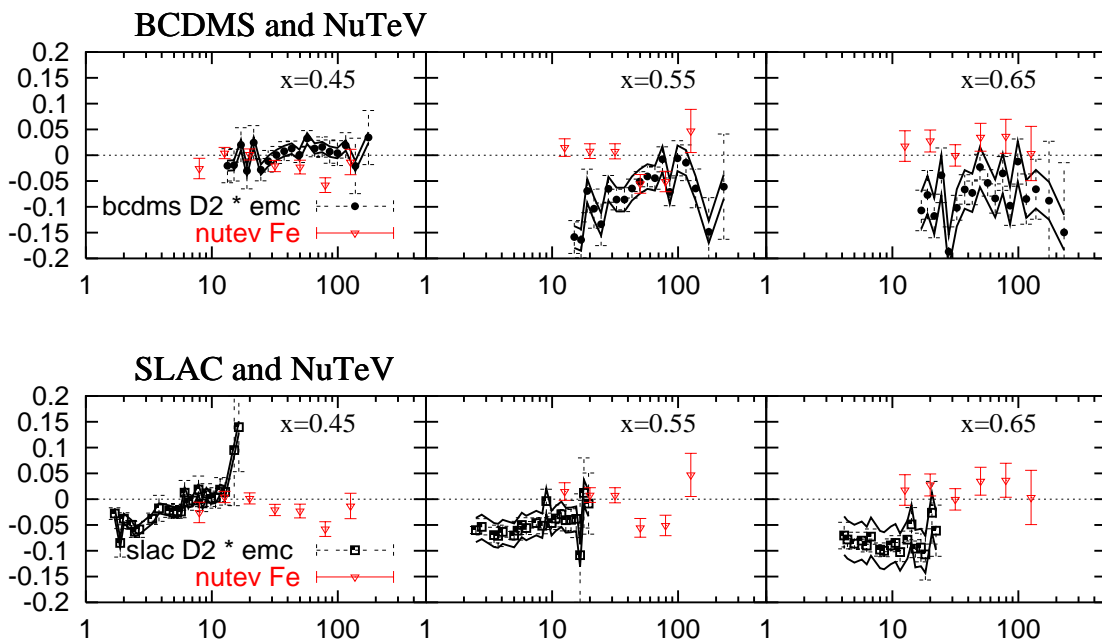
favors slightly smaller correction

(J. Arrington *et al.*:nucl-ex/0307012 v2)

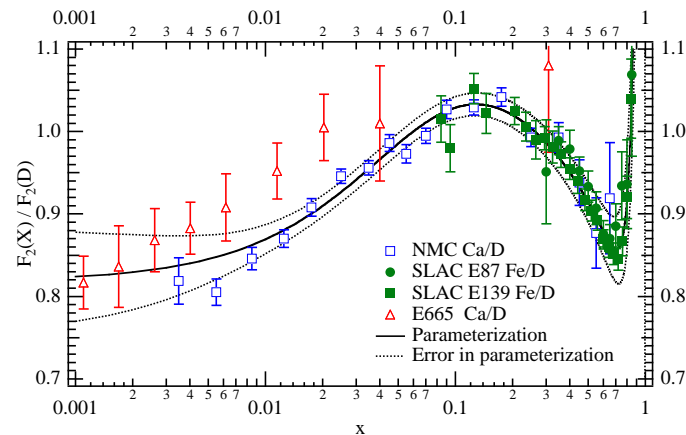
Comparison with Charged Lepton Data at high x:

Compare with charged lepton data at high x where nuclear effects are large:

▶ e-D and μ -D data corrected to ν -Fe:



- ▶ apply $\frac{F_2^l}{F_2^\nu}$ corr. (using CTEQ4D)
- ▶ apply $\frac{F_2^N}{F_2^D}$ corr. (heavy target)



▶ plots show $\frac{F_2^l - F_2^\nu}{F_2^\nu}$ in high x bins

▶ data sets: **NuTeV(Fe)**, BCDMS(D_2), SLAC(D_2)

▶ NuTeV differs from BCDMS(D_2) \times emc_{corr} by $\sim 7\%$ at x=0.55 and 0.65

▶ NuTeV differs from SLAC(D_2) \times emc_{corr} by $\sim 5\%$ at x=0.55 and $\sim 7\%$ at x=0.65

▶ From comparisons to F_2^{THEORY} and charged lepton F_2^{DATA} we could conclude that ν -scattering favors smaller nuclear effects at high x

▶ EMC corr. dominated by SLAC data (at high x)

▶ NuTeV data is in a higher Q^2 region



Conclusions:

- ▶ NuTeV has extracted the most precise neutrino and antineutrino differential cross-section to date;
- ▶ NuTeV has a unique feature: **SignSelected Beam**:
 - ▶ high- y data previously unaccessible;
- ▶ NuTeV has good agreement with previous neutrino experiments in all kinematic region except for high x where NuTeV favors a higher differential cross-section than CCFR :
 - at $x = 0.45$: 5% ● at $x = 0.55$: 10% ● at $x = 0.65$: 20%;
- ▶ At large x NuTeV is higher than theory curves:
 - ▶ assumption for nuclear corrections (large for charged lepton data);
 - ▶ reanalysis of nuclear effects using JLAB data are now undergoing:
 - ▶ favors slightly smaller nuclear corrections at high x
- ▶ We are performing the final checks.

Future:

- ▶ 2 parameters fits;
- ▶ QCD fits.

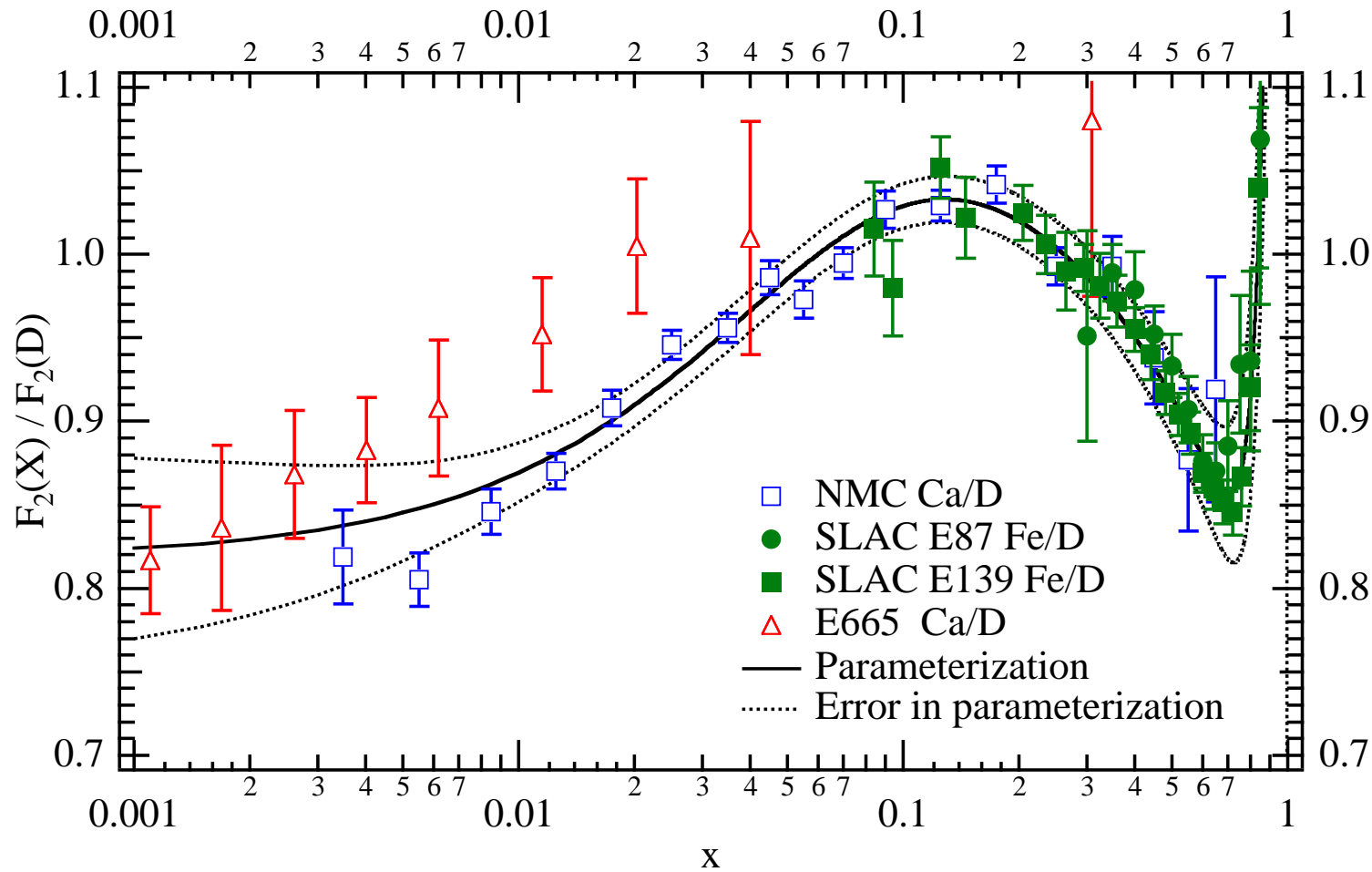


That's all

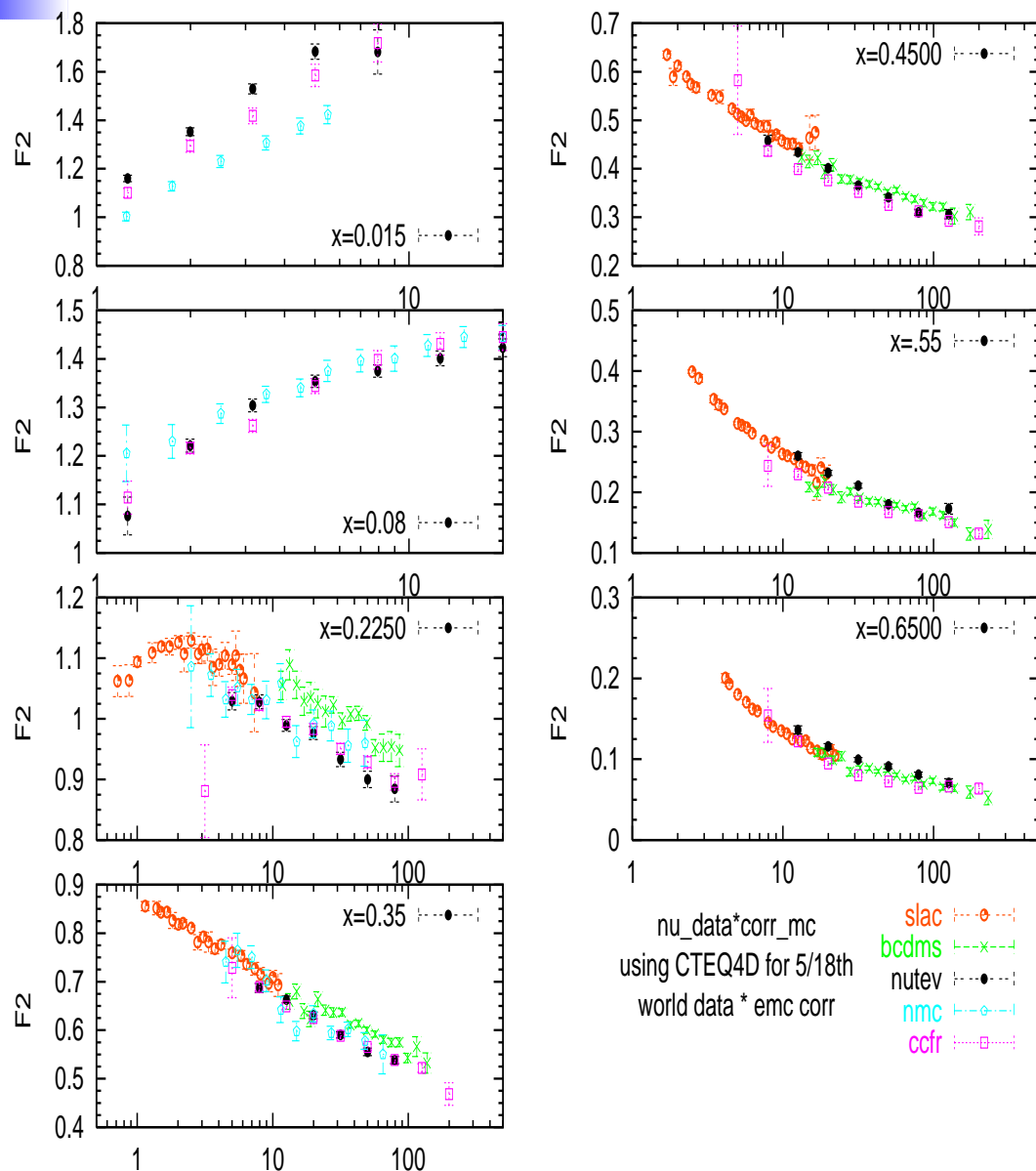
next: additional details

Nuclear Correction

Parametrization fit to the data:



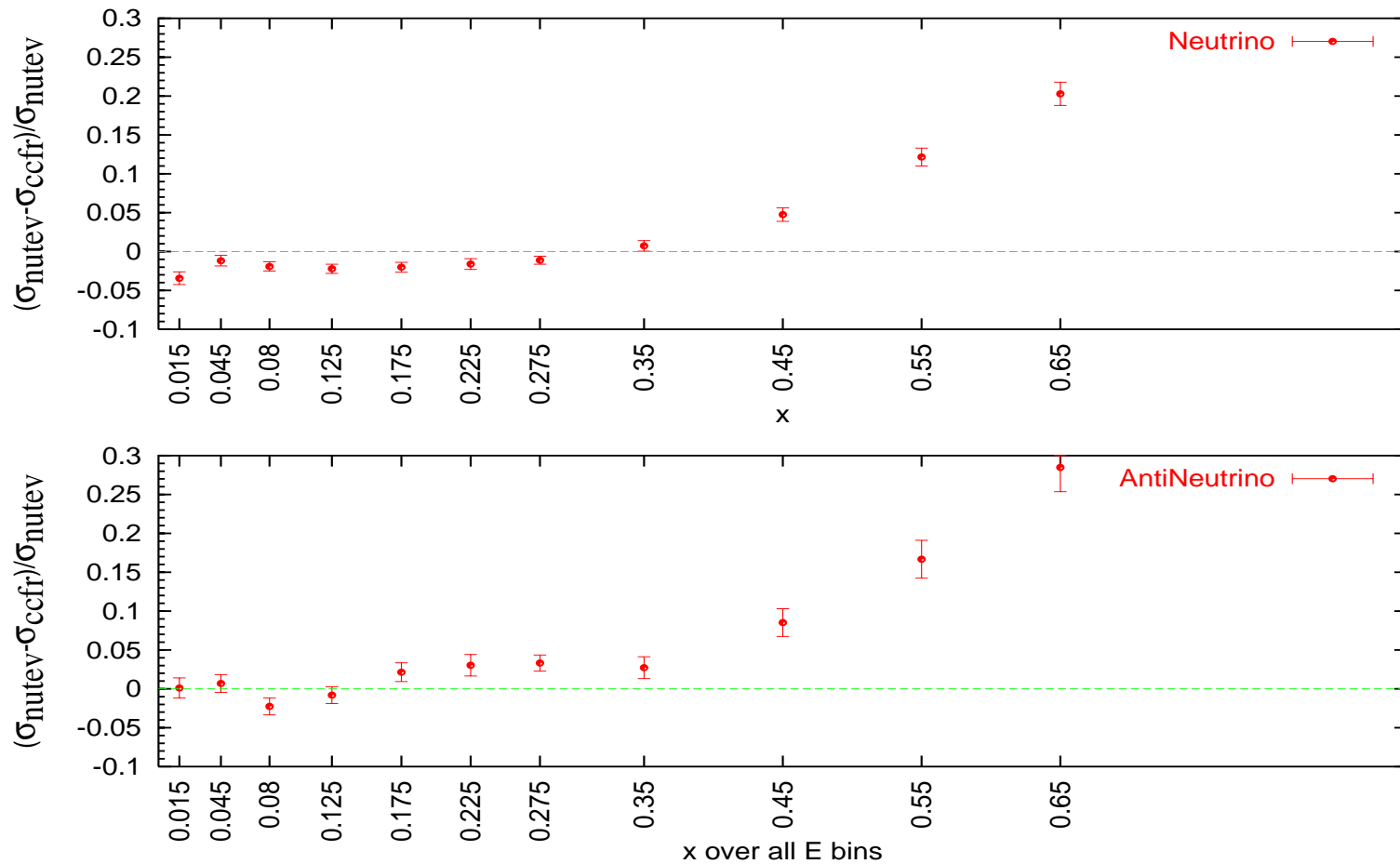
Comparison with Charged Lepton Data:



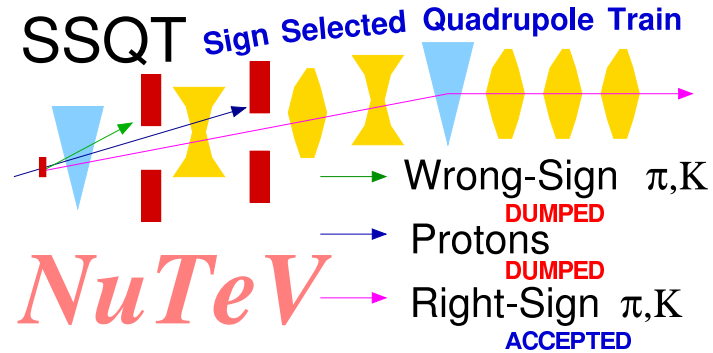
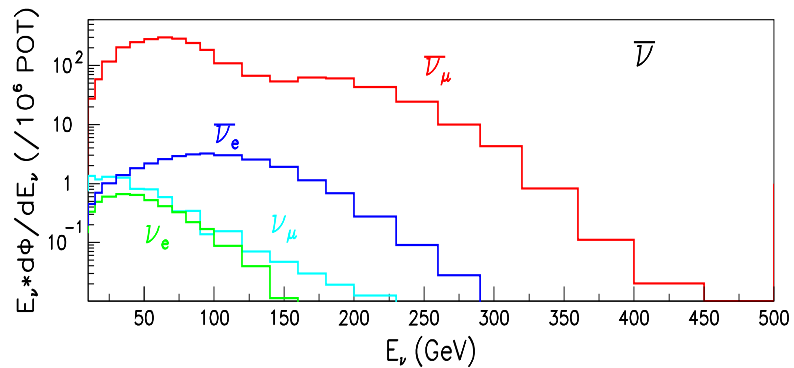
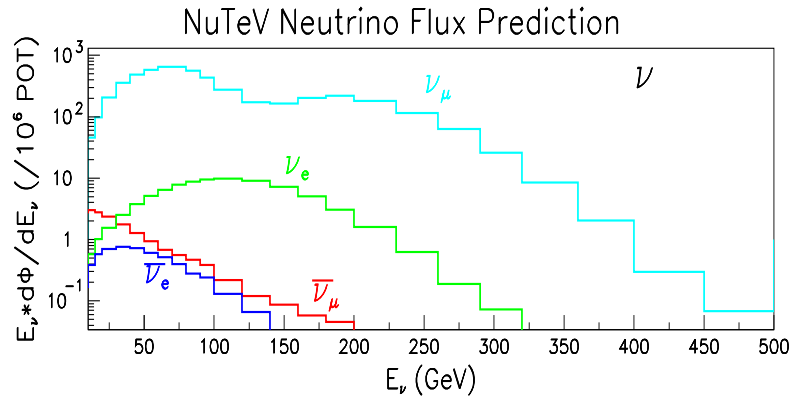
- ▶ Data sets considered: NMC, SLAC, BCDMS deuteron data
- ▶ In order to compare these data sets with neutrino:
 - ▶ Corrections to charged lepton data:
 - ▶ apply $\frac{F_2^l}{F_2^V}$ (using CTEQ4D pdfs)
 - ▶ apply $\frac{F_2^N}{F_2^D}$ (heavy target)
- ▶ NuTeV in good agreement with CCFR at low and medium x
- ▶ NuTeV in good agreement in medium x with charged lepton data
- ▶ NuTeV systematically above at high x
- ▶ NuTeV favors smaller nuclear effect

Differences with CCFR

Weighted average over all energies and y bins in each x bin of the relative ratio between CCFR and NuTeV at the level of the cross-section, for neutrinos and antineutrinos:



Neutrino Beam



- ▶ selects ν or $\bar{\nu}$: $\nu \bar{\nu}$
 - ▶ in ν mode: $3 \times 10^{-4} \bar{\nu}$
 - ▶ in $\bar{\nu}$ mode: $4 \times 10^{-3} \nu$
- ▶ tag leading muon
- ▶ access to high y data



Cross-Section Model

▶ BG parametrization of the valence:

$$xu_v(x, Q^2) = u_v^{\text{tot}} x^{E_1} (1-x)^{E_2} + AV_2 x^{E_3} (1-x)^{E_4} + AV_3 x^{E_5} (1-x)^{E_6}$$

$$xd_v(x, Q^2) = d_v^{\text{tot}} xu_v(x, Q^2) \cdot (1-x)$$

$$E_i = E_{i0} + E_{i1} \ln \frac{\ln Q^2 / A_0^2}{\ln Q_0^2 / A_0^2}$$

▶ BG parametrization of the sea:

$$x\bar{u}(x, Q^2) = x\bar{d}(x, Q^2) = \frac{1}{2(\kappa+2)} (AS(1-x)^{ES} + AS_2(1-x)^{ES_2})$$

$$xs(x, Q^2) = x\bar{s}(x, Q^2) = \frac{k}{2(\kappa+2)} \frac{AS}{ES+1} (ES + \alpha + 1)(1-x)^{ES+\alpha}$$

$$AS = (ES + 1) \left(\frac{SQ_2 - AS_2 / (ES_2 + 1)}{SQ_3 - AS_2 / (ES_2 + 1)(ES_2 + 2)} \right) - 2$$

$$AS = (ES + 1) \left(\frac{SQ_2 - AS_2}{ES_2 + 1} \right)$$

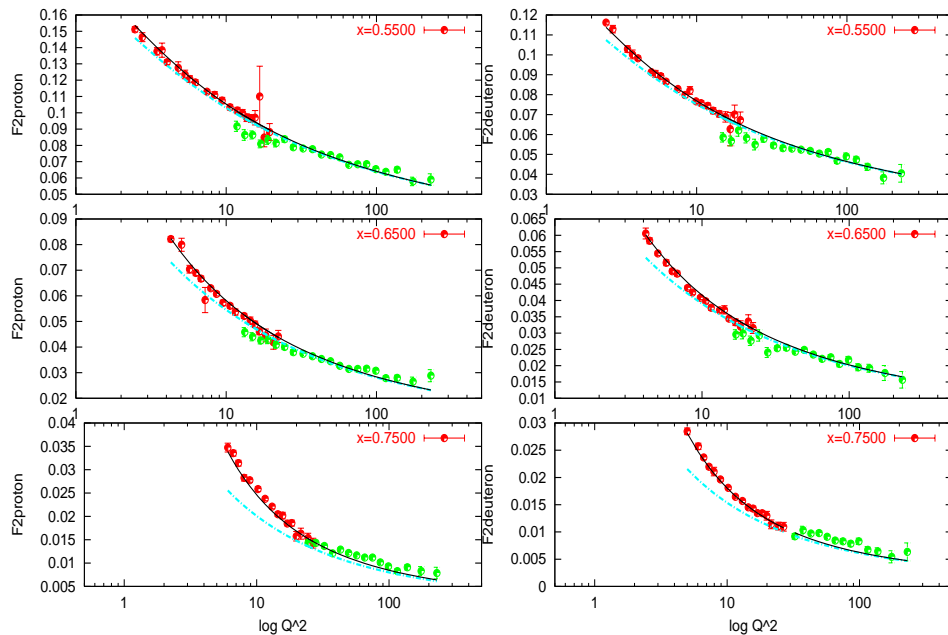
$$AS_2 = AS_{20} + AS_{21} \ln(Q^2)$$

$$ES_2 = ES_{20} + ES_{21} \ln(Q^2)$$

- ▶ Exponents (E_i) and normalization terms are fitted to NuTeV differential cross-section data every loop of iteration.
- ▶ for Q^2 assume GRV evolution
- ▶ assume $m_c = 1.4 \text{ GeV}$, the standard W-mass and $R_L = R_{\text{WORLD}}$

Higher Twist

- ▶ Fit to ep, ed data (SLAC,BCDMS) to parameterize Target Mass and Higher Twist effects in parton-level cross section model
- ▶ important at high x and low Q^2 .
([hep-ex/0203009](#) May 2002 A.Bodek and U.K.Yang)
 - ▶ At high x and low Q^2 have to take into account the nucleon mass \rightarrow redefine x including these corrections which come as $1/Q^2$ term (Target Mass effect)
 - ▶ At low Q^2 the lepton-nucleon scattering involves a double parton scattering. The contributions from HT diagrams are suppressed by powers of $1/Q^2$ as compared to the leading twist diagrams.

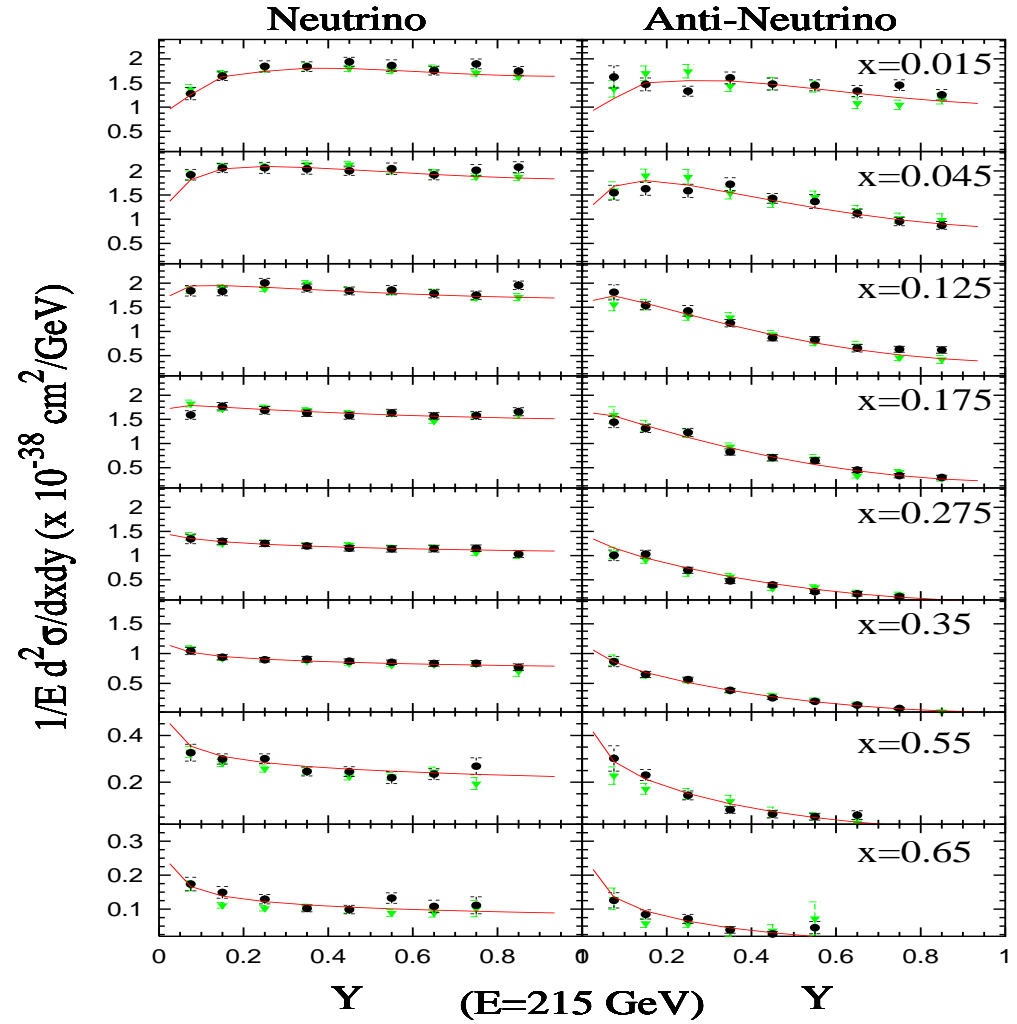
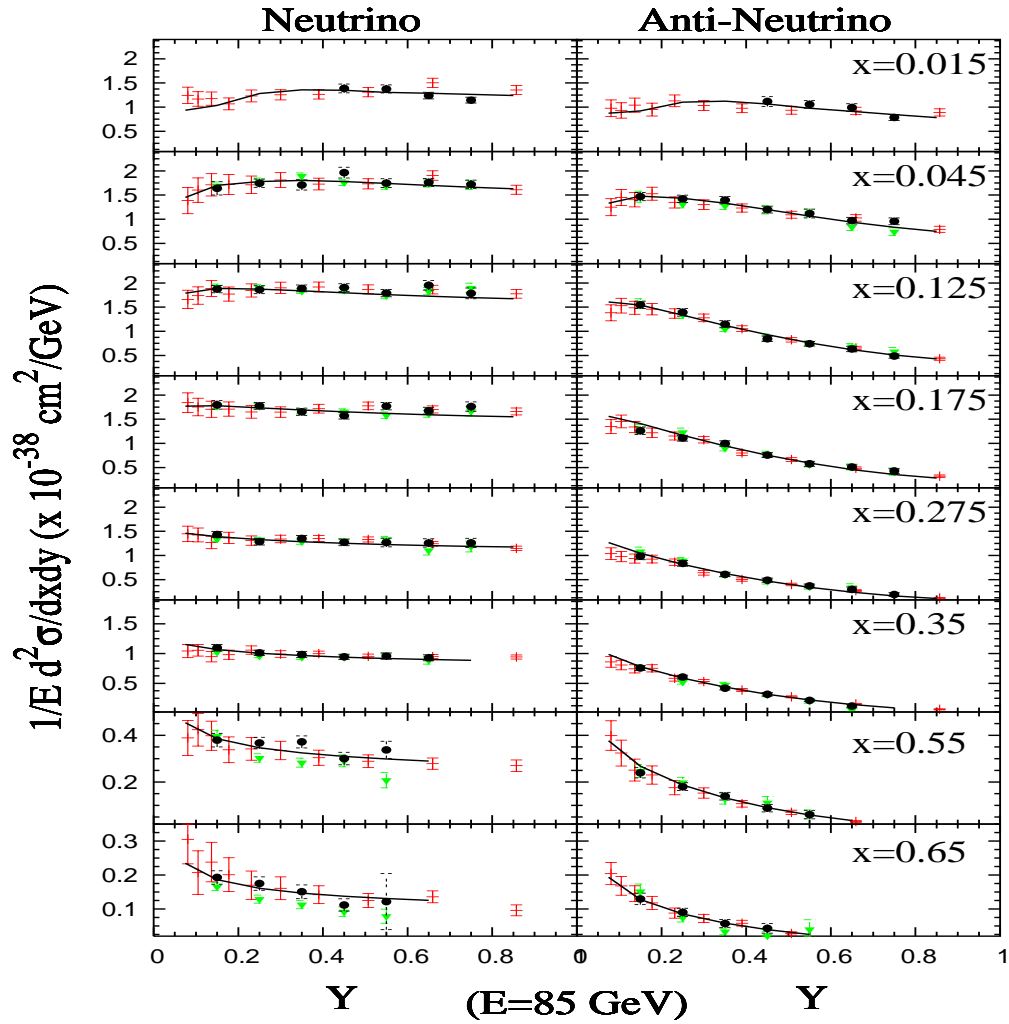


$$x' = x \frac{Q^2 + B}{Q^2 + Ax}$$

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

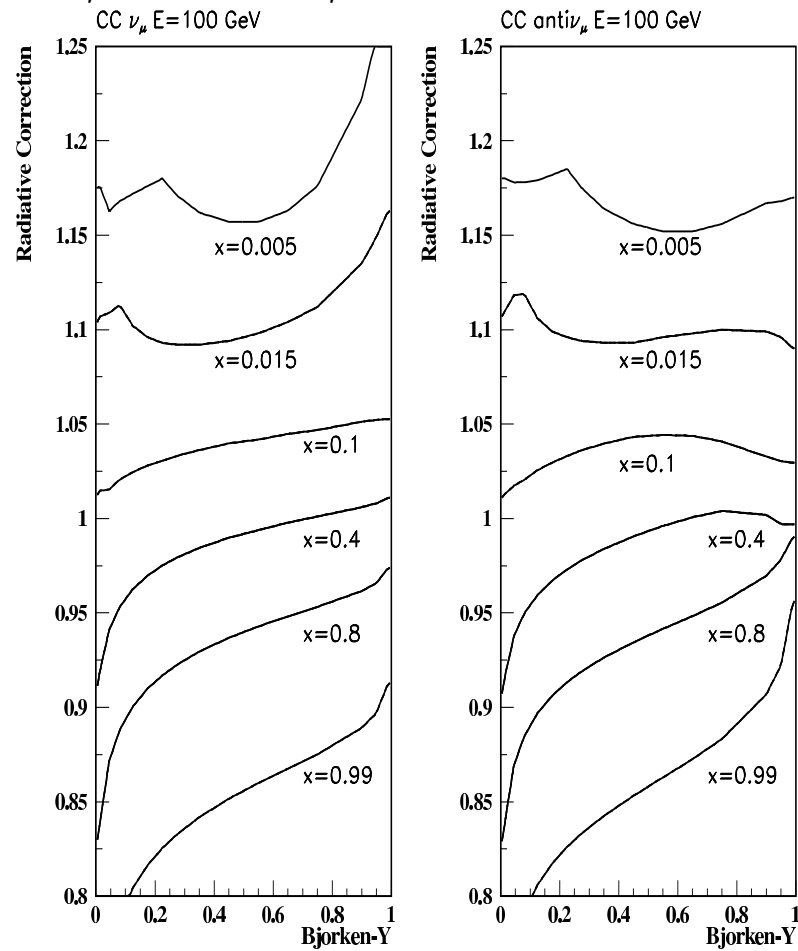
A	0.57
B	0.22
C	0.06
χ^2/dof	792/312

NuTeV Cross-Section at different energies:

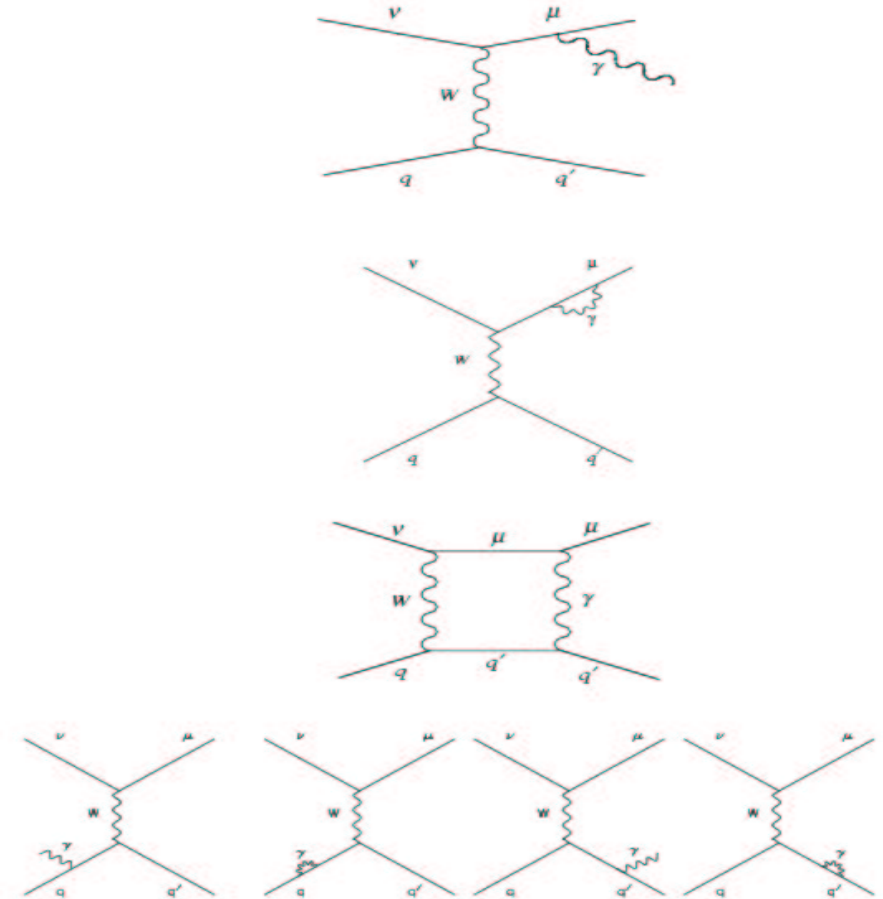


Radiative corrections

Total size of the QED radiative corrections for ν_μ (left) and $\bar{\nu}_\mu$ (right) CC scattering as function of Bjorken-Y



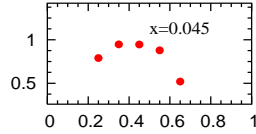
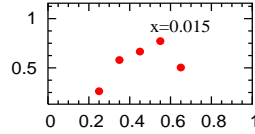
Bardin, D. Y. and Dokuchaeva, JINR-E2-86-260



Acceptance plots for main sample

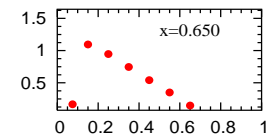
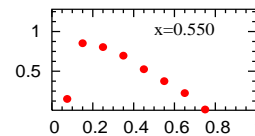
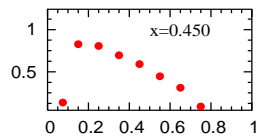
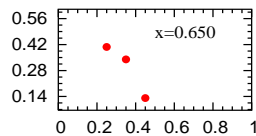
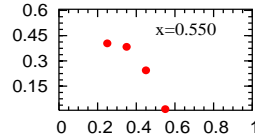
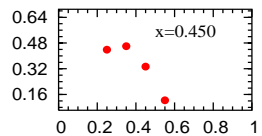
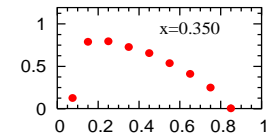
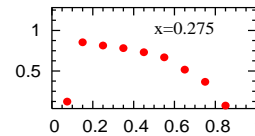
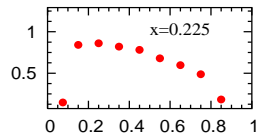
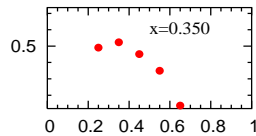
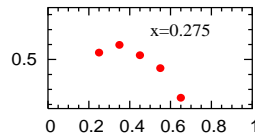
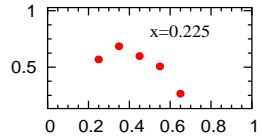
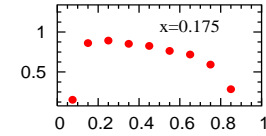
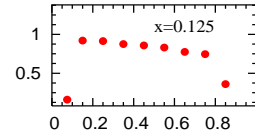
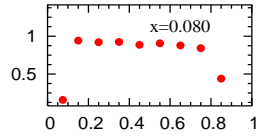
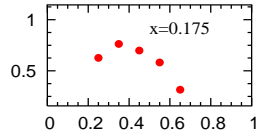
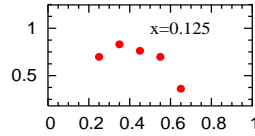
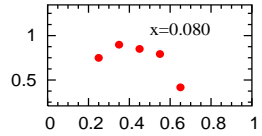
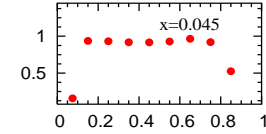
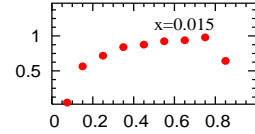
Energy = 45 GeV

Acceptance ●



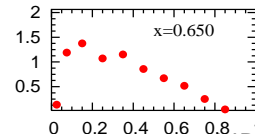
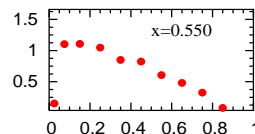
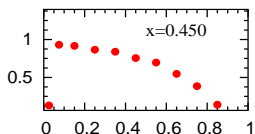
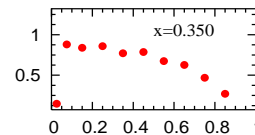
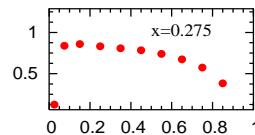
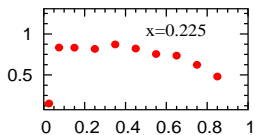
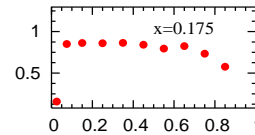
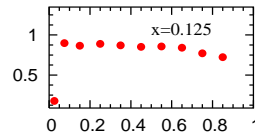
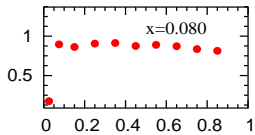
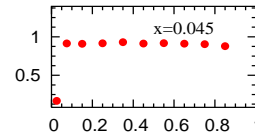
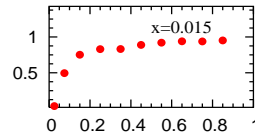
Energy = 110 GeV

Acceptance ●



Energy = 245 GeV

Acceptance ●





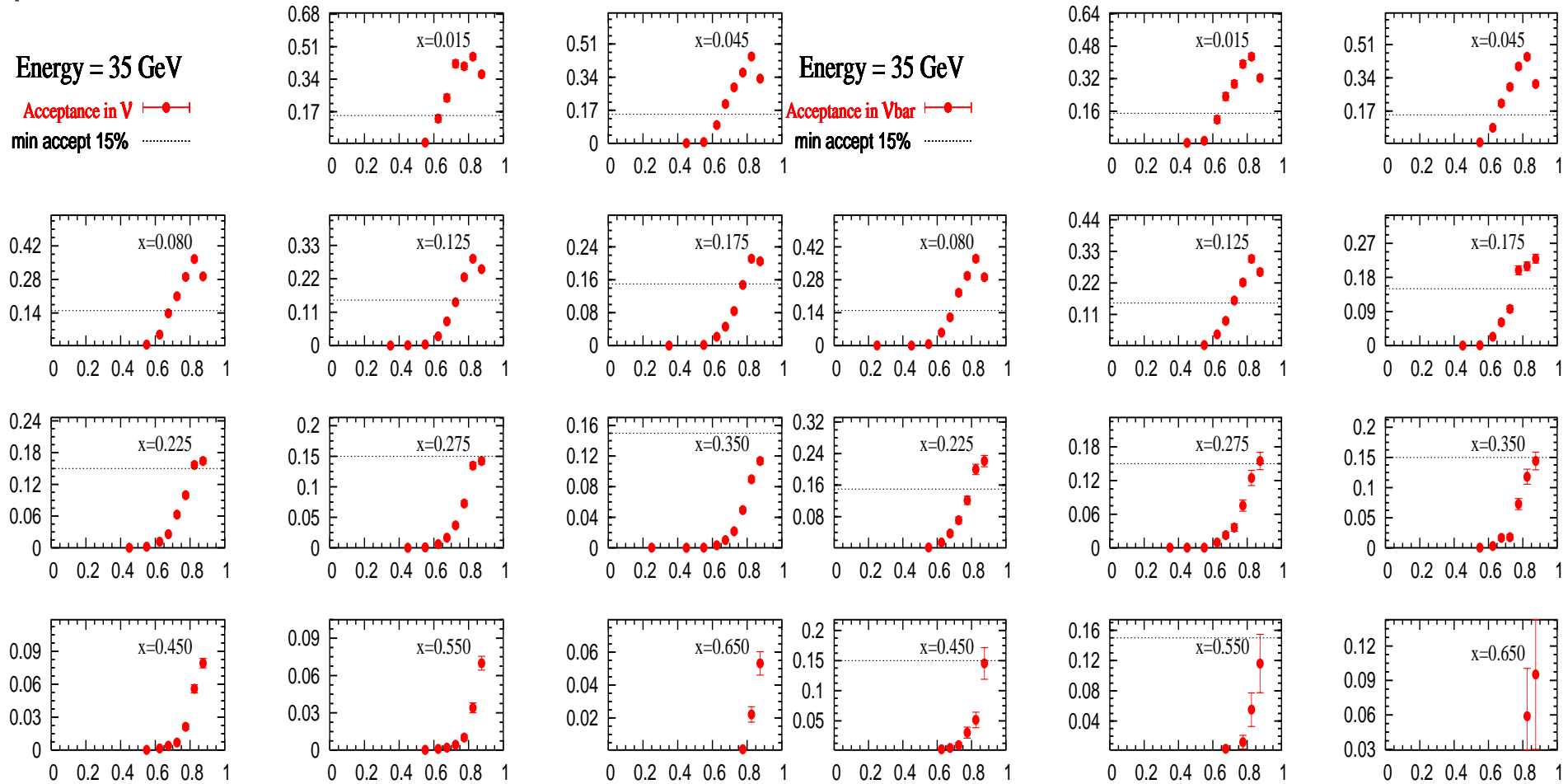
Acceptance plots for high- Y (new sample)

Energy = 35 GeV

Acceptance in V 
 min accept 15% 

Energy = 35 GeV

Acceptance in Vbar 
 min accept 15% 



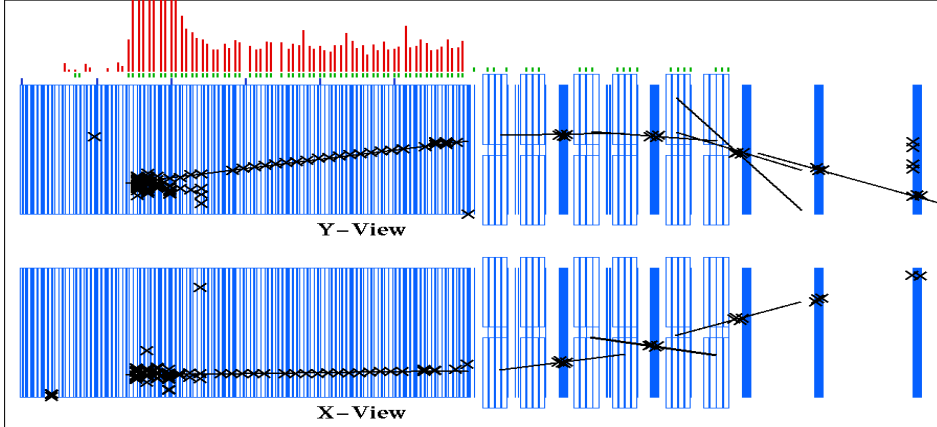
Event Display

For Toroid analyzed muon:

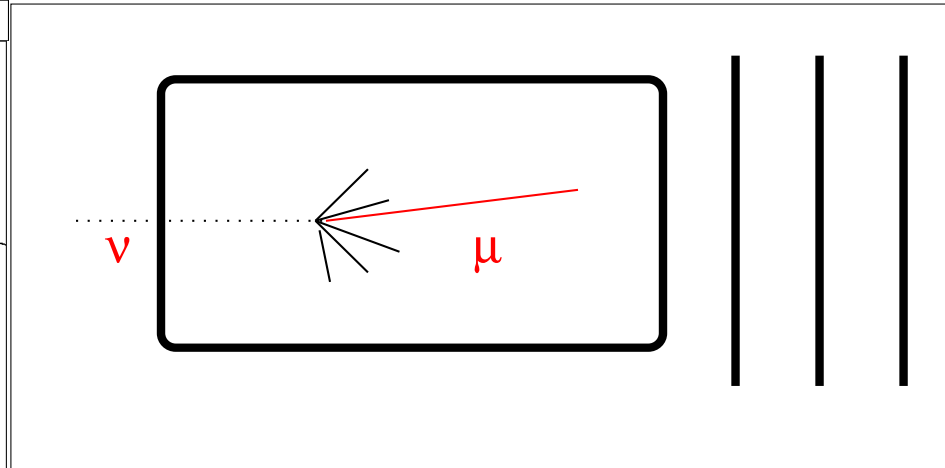


Run: 5153 Event: 1105 Date: Sat Jun 22 22:55:32 1996
Triggers: 1 2 3 4 5 6 7 8 9 10 11 12 13

EHAD0: 117.06 GeV
EMU1: 26.40 GeV

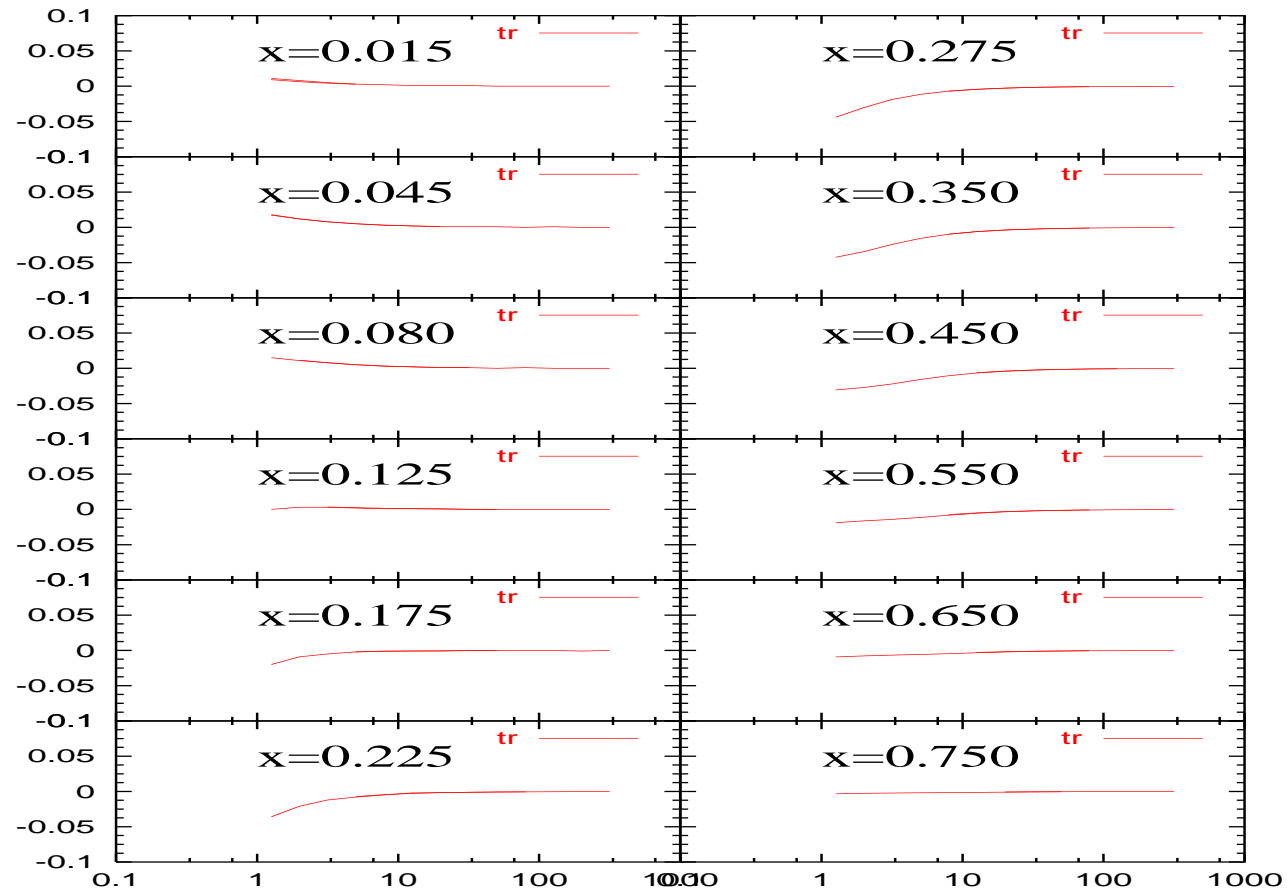


For Target muon:

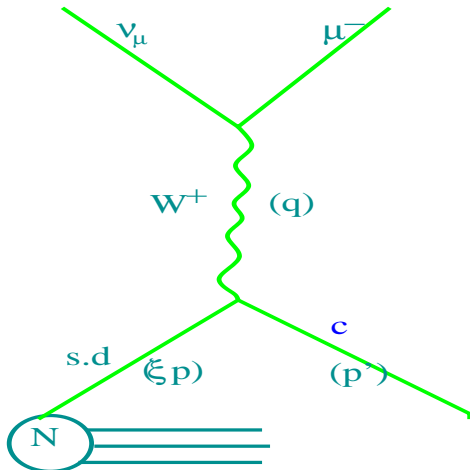


ΔF_2 model

$$\Delta F_2 = (F_2^\nu(x, Q^2) - F_2^{\bar{\nu}}(x, Q^2)) = \left(\frac{1+R(x, Q^2)}{1+(4Mx^2/Q^2)} \right) V_{cd}^2 \left[\frac{(u_\nu + d_\nu)}{2} \right]$$



R^ν vs R^μ



LO slow rescaling:

$$(q + \xi p)^2 = p'^2 = m_c^2$$

$$q^2 + 2\xi pq + \xi^2 M^2 = m_c^2$$

$$\xi = x(1 + \frac{m_c^2}{Q^2})(1 - \frac{x^2 M^2}{Q^2}) \stackrel{x^2 M^2 \rightarrow 0}{\simeq} x(1 + \frac{m_c^2}{Q^2})$$

Write separately: the charm and non-charm producing piece:

- ▶ $2xF_1^{cp+ncp}(x) = 2xF_1^{ncp}(x) + \frac{x}{\xi} 2\xi F_1^{cp}(\xi)$
- ▶ $xF_3^{cp+ncp}(x) = xF_3^{ncp}(x) + \frac{x}{\xi} \xi F_3^{cp}(\xi)$
- ▶ $F_2^{cp+ncp}(x) = \frac{1+R(x)}{1+\frac{4M^2x^2}{Q^2}} 2xF_1^{ncp}(x) + \frac{1+R(\xi)}{1+\frac{4M^2\xi^2}{Q^2}} 2\xi F_1^{cp}(\xi)$

where $R(x) = R_{world}(x)$ and $R(\xi) = R_{world}(\xi)$

$R_{world}(i.e. R^{e/\mu})$ corrected for heavy flavor contribution:

$$R^{eff} = \frac{F_2^{cp+ncp}(x)}{2xF_1^{cp+ncp}(x)} (1 + \frac{4M^2x^2}{Q^2}) - 1$$

Cross-Section Systematic Uncertainties

Systematic	Value	σ Vector
E_μ	0.7%	$0.007*(1-y)E_\nu$
E_{HAD}	0.43%	$0.0043*yE_\nu$
$\nu(\bar{\nu})$ Flux B/A correction	-0.45 ± 0.035 (-1.73 ± 0.027)	0.035 (0.027)
m_c	1.40 ± 0.13	0.13
BGPARG1 A0	0.34 ± 0.17	0.17
BGPARG2 A1	0.25 ± 0.33	0.33
BGPARG3 A2	0.92 ± 2.47	2.47
BGPARG4 AV2	$-0.108E-2 \pm 0.75E-2$	0.75E-2
BGPARG5 E10	0.745 ± 0.10	0.10
BGPARG6 E11	0.089 ± 0.40	0.40
BGPARG7 E20	3.15 ± 0.44	0.44
BGPARG8 E21	2.47 ± 2.0	2.0
BGPARG9 S2	$0.14 \pm 0.11E-1$	0.11E-1
BGPARG10 S3	$0.125E-1 \pm 0.32E-2$	0.32E-2
BGPARG11 G3	$0.236E-1 \pm 0.38E-1$	0.38E-1
BGPARG12 AS20	0.45 ± 1.46	1.46
BGPARG13 AS21	0.50 ± 1.78	1.78
Flux normalization: σ_W	$\pm 2.1\%$	