NuTeV Final Structure Function Results

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Outline:

- NuTeV experiment
- Method and results:
  - Differential Cross Section
  - Structure Functions
- Comparisons to other data and theory
- Summary

NuTeV Experiment:

- NuTeV is a precision neutrino DIS experiment
- Data taking: 1996-97 FermiLab fixed target run
  $E_\nu \in (30\ ,\ 360)$ GeV and $Q^2 \in (1\ ,\ 600)$ GeV^2
- Charged Current events: $8.6 \times 10^5\ \nu$ and $2.3 \times 10^5\ \overline{\nu}$

NuTeV Collaboration:

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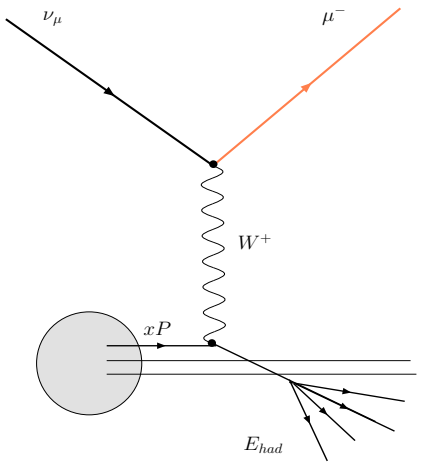
CC Deep Inelastic Neutrino Scattering:



- Lorentz-invariant quantities in terms of measured $E_\mu,\ \theta_\mu,\ E_{had}$:

$$\begin{cases} Q^2 = 4(E_\mu + E_{had})E_\mu sin^2\frac{\theta_\mu}{2} \\ x = \frac{Q^2}{2ME_{had}} \\ y = \frac{E_{had}}{E_\mu + E_{had}} \\ \nu = E_{had} \end{cases}$$

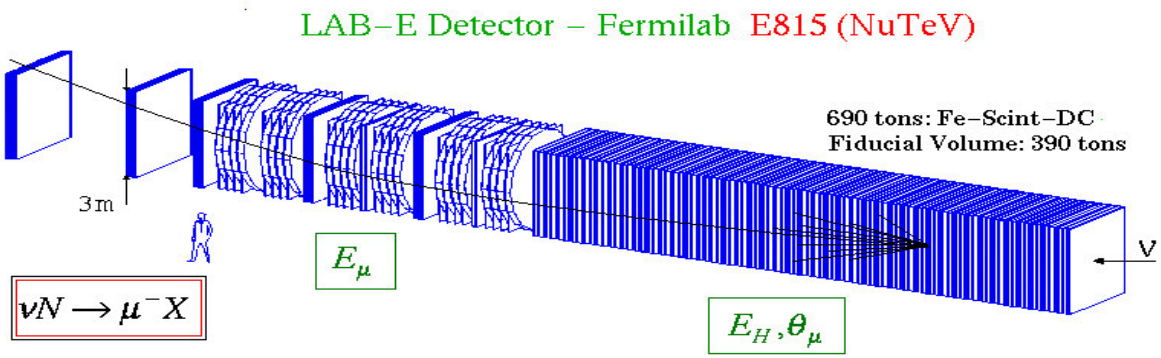
Neutrino Differential Cross-Section:

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

Neutrino Structure Functions in terms of quark compositions of target:

- $2xF_1^{\nu(\overline{\nu})}(x,Q^2) = \Sigma\left[xq^{\nu(\overline{\nu})} + \overline{x}q^{\nu(\overline{\nu})}\right]$
- $F_2^{\nu(\overline{\nu})}(x,Q^2) = \Sigma\left[xq^{\nu(\overline{\nu})} + x\overline{q}^{\nu(\overline{\nu})} + 2xk^{\nu(\overline{\nu})}\right]$
- $xF_3^{\nu(\overline{\nu})}(x,Q^2) = \Sigma\left[xq^{\nu(\overline{\nu})} - x\overline{q}^{\nu(\overline{\nu})}\right]$
  - powerful tool for testing pQCD and measuring Λ_{QCD}

NuTeV Detector:



Target Calorimeter:

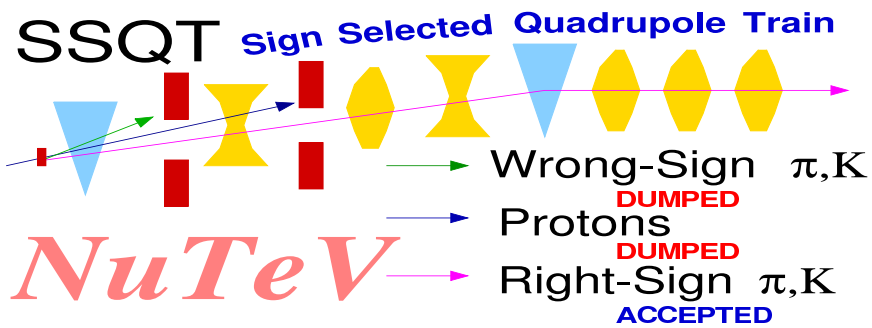
- 690 ton Fe target
- liquid scintillator counters:
  - triggering information
  - hadron resolution:
    $\frac{\sigma}{E} \sim 0.022 + \frac{0.86}{\sqrt{E}}$
- drift chambers:
  - track μ
  - determine vertex position

Muon Spectrometer:

- 420 ton toroidal Fe magnets:
  - $B_\phi \sim 15$ kG
  - $p_t = 2.4$ GeV/c
- drift chambers:
  - momentum resolution: $\frac{\sigma}{p} \sim 11\%$
- two modes of operation: ν and $\bar{\nu}$
  - polarity always set to focus the muon from primary vertex

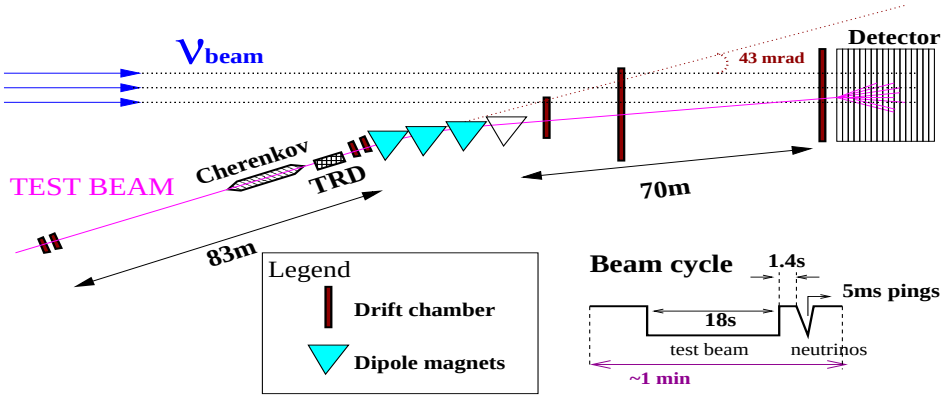
NuTeV Features:

Sign Selected Beam:



- high purity ν or $\overline{\nu}$ beams:
  - in ν mode: $3 \times 10^{-}4\ \overline{\nu}$
  - in $\overline{\nu}$ mode: $4 \times 10^{-}3\ \nu$
- charge of leading μ known

Calibration Beam:



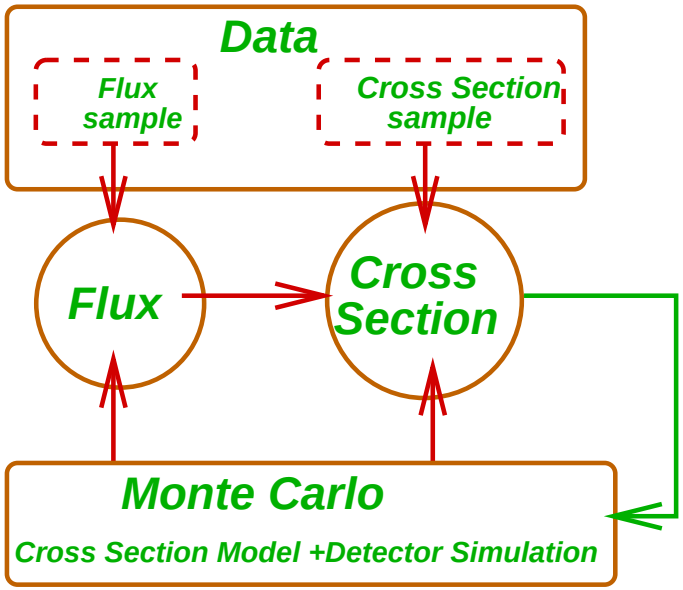
- measures the absolute energy scale:
  - muons: $\frac{\delta E_\mu}{E_\mu} = 0.70\%$
  - hadrons: $\frac{\delta E_{had}}{E_{had}} = 0.43\%$

Extracting Differential Cross Section:

Differential Cross Section in terms of flux and number of events: $\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{1}{\Phi(E_\nu)}\frac{d^2N^{\nu(\overline{\nu})}}{dxdy}$

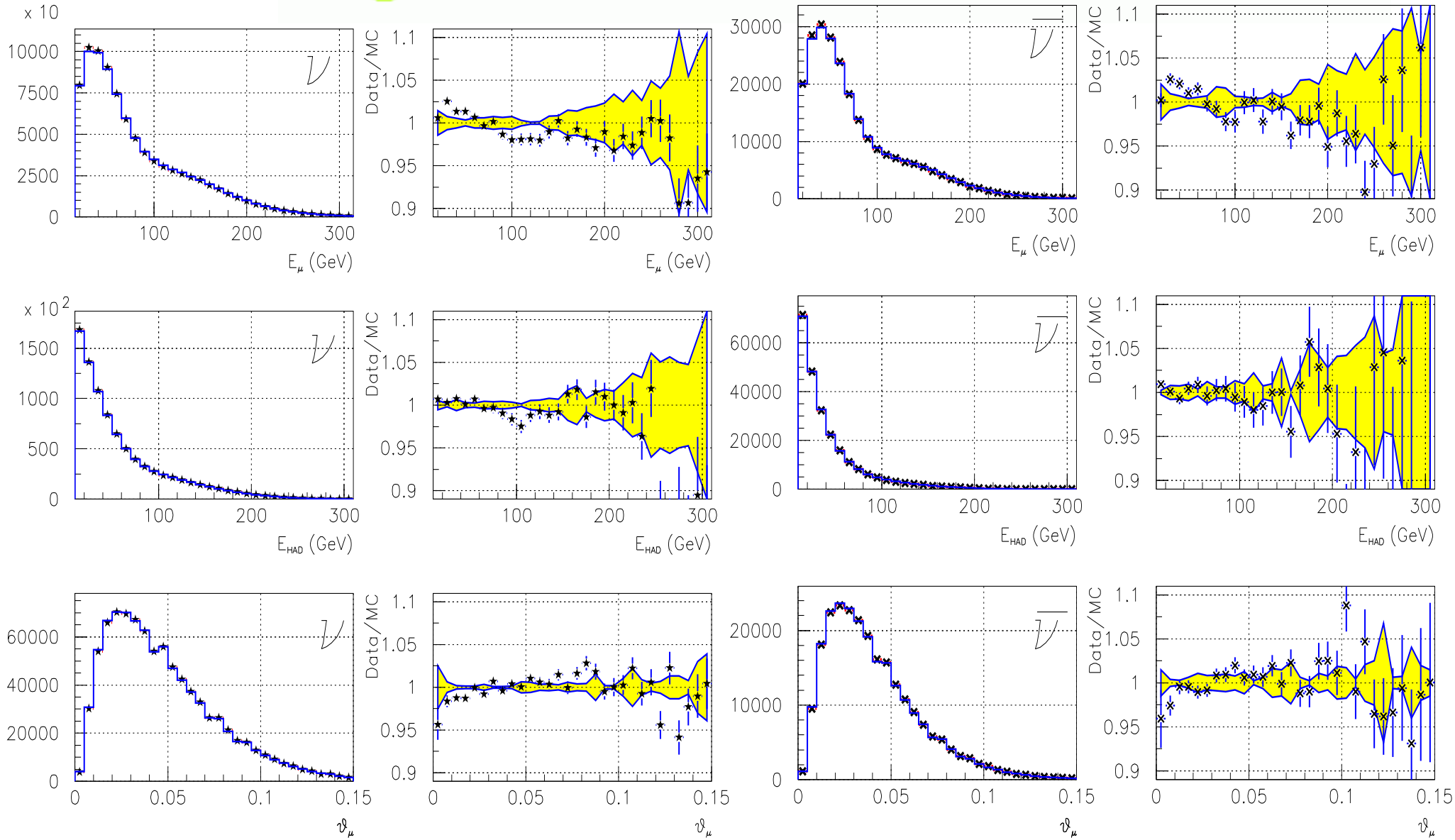
- **Data:**
  - Flux Sample: data set of $E_{had} < 20\ GeV$
  - Cross Section Sample: toroid analyzed muon
    - containment and good muon track
    - $E_\mu > 15\ GeV,\ E_{had} > 10\ GeV,\ E_\nu \in (30\ ,\ 360)\ GeV,$ $Q^2 > 1\ GeV^2$
- **Monte Carlo:**
  - used only for acceptance and smearing corrections
  - Cross-Section Model
    - LO QCD inspired parametrization: fit to data :

      [A.Buras, K.Gaemers; Nucl.Phys.B132,249(1978)]
      - includes HT parametrization for Q^2 dependence at x>0.4 (SLAC,NMC,BCDS).
      - for $Q^2 < 1.35\ GeV^2$ use GRV Q^2 evolution
  - Detector model:
    - E_μ and E_{had} resolution functions param. using TB
    - θ_μ parametrized using GEANT hit level MC



- Process is iterated:
  - use CCFR for initial input (loop 0)
  - convergence occurs after 3 loops:
    - the change in the average cross-section is $< 0.1\%$
  - 20% acceptance cut on final sample

Modeling of Data:



- Monte Carlo/Data in good agreement over all kinematic region

Cross Section Systematic Uncertainties:

- 7 sources of systematics:
  - E_μ and E_{had} scales
  - uncertainties in the smearing models of E_μ and E_{had}
  - uncertainties in flux extraction: m_c and flux uncertainty
  - uncertainty in the cross-section model
- overall normalization uncertainty 2.1% (flux normalization)
- each systematic error evaluated separately and correlations between them is taken into account
- the statistical errors are added in quadrature to the diagonal elements of covariance matrix

$$\chi^2 = \sum_{\alpha,\beta=1}^{N_{DATA}^{\nu(\bar{\nu})}} \left(F_\alpha^{th} - D_\alpha^{data}\right) M_{\alpha\beta}^{-1} \left(F_\beta^{th} - D_\beta^{data}\right)$$

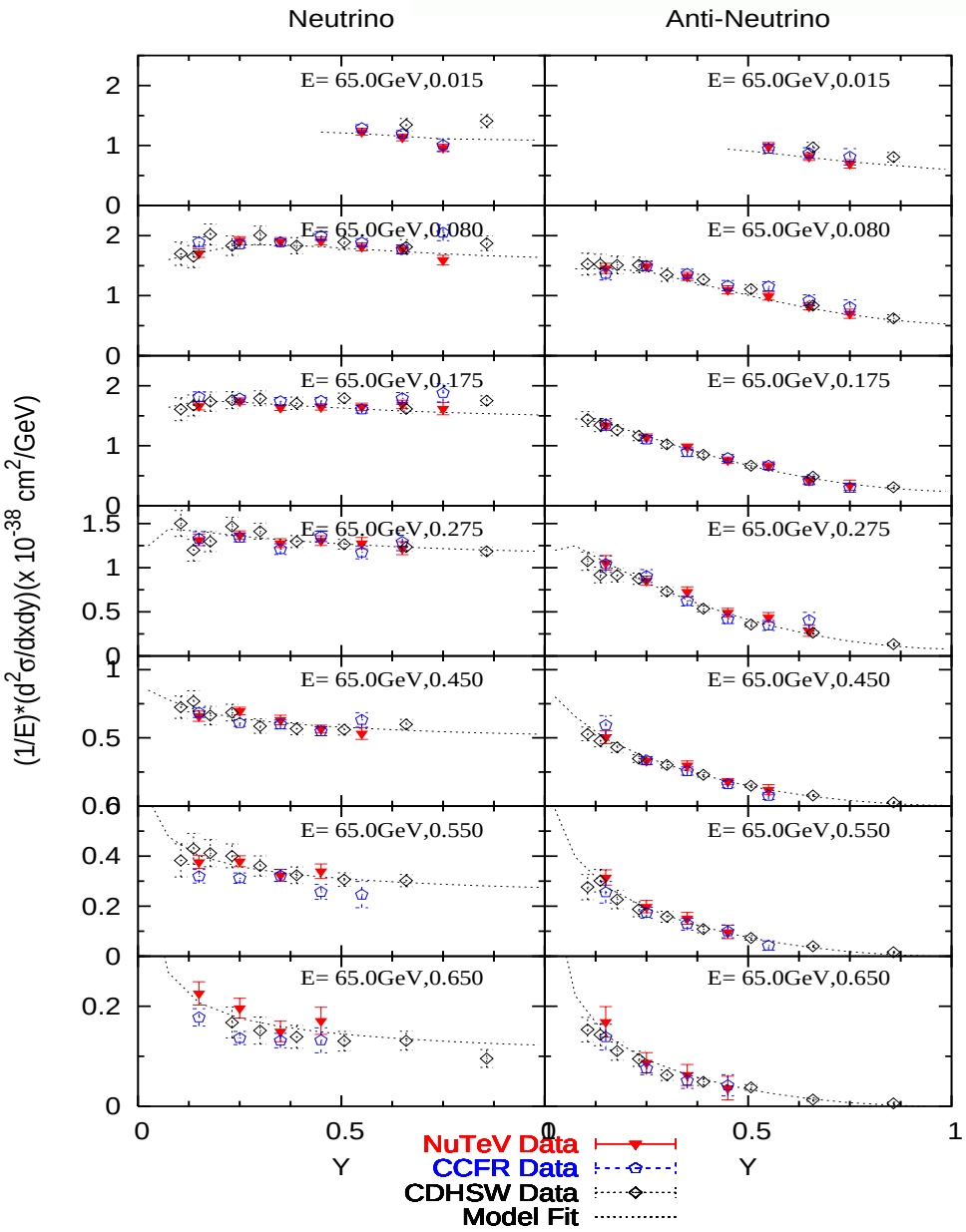
- $M_{\alpha\beta}$ point to point covariance matrix

$$M_{\alpha\beta} = \sum_i^7 \sigma_{i|\alpha}\partial_{i|\alpha}\sigma_{i|\beta}\partial_{j|\beta}$$

  - $\sigma_{i|\alpha}$ is the size of systematic i at the data point α
  - each derivative obtained by varying each systematic S_i by a small value ϵ_i

$$\partial_{i|\alpha} = \frac{\frac{d^2\sigma}{dxdy}(S_i + \epsilon_i) - \frac{d^2\sigma}{dxdy}(S_i - \epsilon_i)}{2}$$

NuTeV Final Differential Cross Section:



- plots show extracted $\nu(\overline{\nu}) - Fe$ Cross-Sections as function of y for various x bins at $E_\nu = 65\ GeV$, $110\ GeV$ and $190\ GeV$
- NuTeV is compared to other $\nu - Fe$ data:
  - CDHSW (Z. Phys C49 187, 1991)
  - CCFR (U. K. Yang PhD. Thesis)
- NuTeV has better understanding of largest systematics:

data	E_μ scale	E_{had}	range
CDHSW	2%	2.5%	20-200 GeV
CCFR	1%	1%	30-360 GeV
NuTeV	0.7%	0.43%	30-360 GeV

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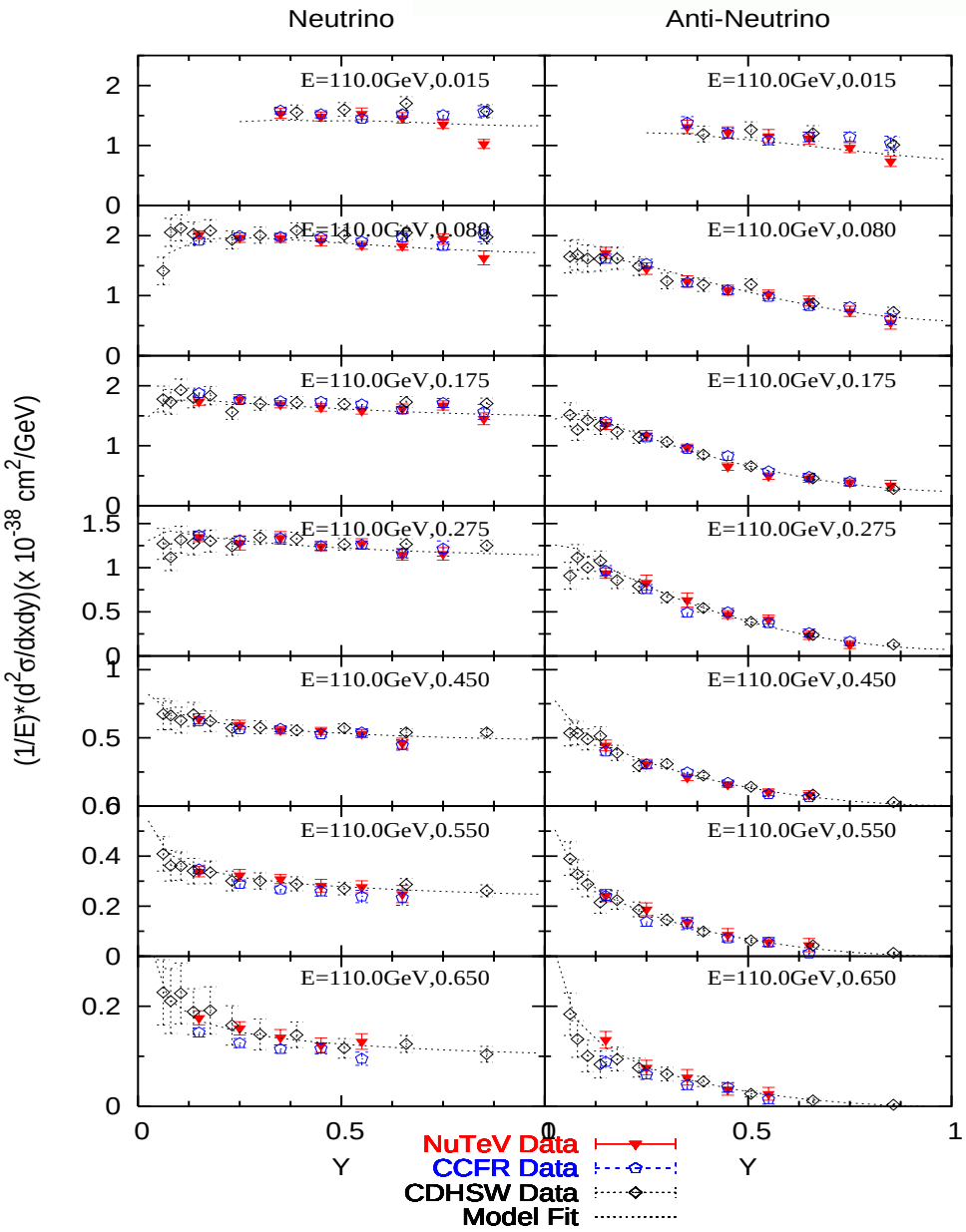

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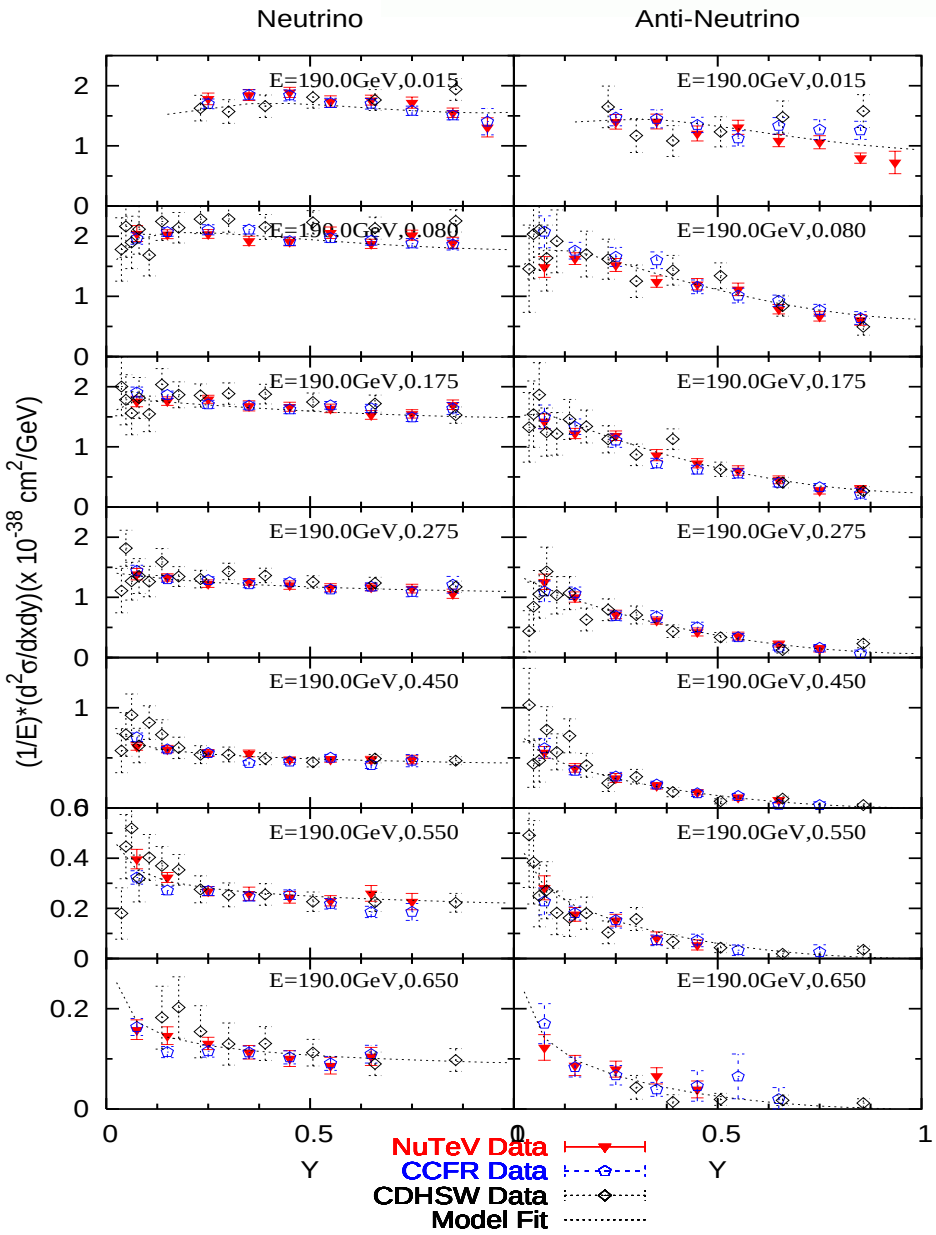

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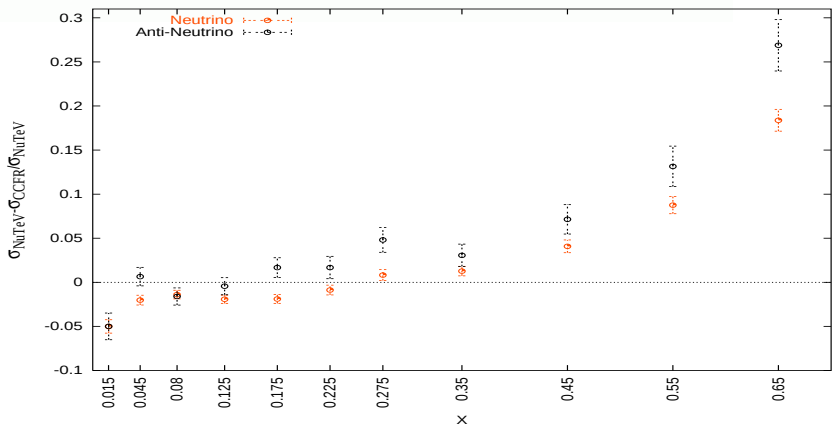
NuTeV vs CCFR



- good agreement at low and medium x in shape and level
- at $x > 0.4$ NuTeV above CCFR over all E_ν and y:
  up to $\approx 20\%$ difference at $x = 0.65$

The sources of differences with CCFR:

- NuTeV has an improved energy calibration:
  - maps the whole toroid with TB muons $\Longrightarrow$ magnetic field (E_μ scale) more accurately determined:
    accounts for $+5\%$ difference at $x = 0.65$
  - includes non-linearity in E_{had} scale (not taken into account by CCFR):
    accounts for $1 - 2\%$ at $x = 0.65$
- NuTeV has an improved E_μ smearing model (using TB data): accounts for $+2\%$ difference at $x = 0.65$
- Model difference between NuTeV and CCFR:accounts for $+3\%$ difference at $x = 0.65$

All these account for $\approx 2/3$ of the differences at high $x \Longrightarrow$ results in 1.2σ agreement

- NuTeV had separate ν and $\bar{\nu}$ beam; CCFR had simultaneous beams
- NuTeV set always to focus on μ from primary vertex, CCFR had focusing and defocusing modes.

Extraction of $F_2(x,Q^2)$ and $xF_3(x,Q^2)$

- Cross-Sections corrected for isoscalar target and QED effects [D.Y.Bardin, Dokuchaeva,JINR-E2-86-260(1986)]
- Structure Functions determined from fits to linear combination of the diff. cross-sections:

$$\left[\frac{d^2\sigma^\nu}{dxdy}+\frac{d^2\sigma^{\overline{\nu}}}{dxdy}\right]\frac{\pi}{2MG^2E_\nu}=\left(1-y-\frac{Mxy}{2E}+\frac{1+(\frac{2Mx}{Q})^2}{1+R_L}\frac{y^2}{2}\right)F_2^{avg}+y(1-\frac{y}{2})\Delta xF_3$$

$$\left[\frac{d^2\sigma^\nu}{dxdy}-\frac{d^2\sigma^{\overline{\nu}}}{dxdy}\right]\frac{\pi}{2MG^2E_\nu}=\Delta F_2\left(1-y-\frac{Mxy}{2E}+\frac{1+(\frac{2Mx}{Q})^2}{1+R_L}\frac{y^2}{2}\right)+\left(y-\frac{y^2}{2}\right)xF_3^{avg}$$

- $F_2^{avg}(x,Q^2)=\frac{1}{2}\left(F_2^\nu(x,Q^2)+F_2^{\overline{\nu}}(x,Q^2)\right)$
- perform 1-parameter fit for $F_2^{avg}(x,Q^2)$
- input model for $R_L(x,Q^2)$, $\Delta xF_3(x,Q^2)$:
  - R_L from a fit to the world's data

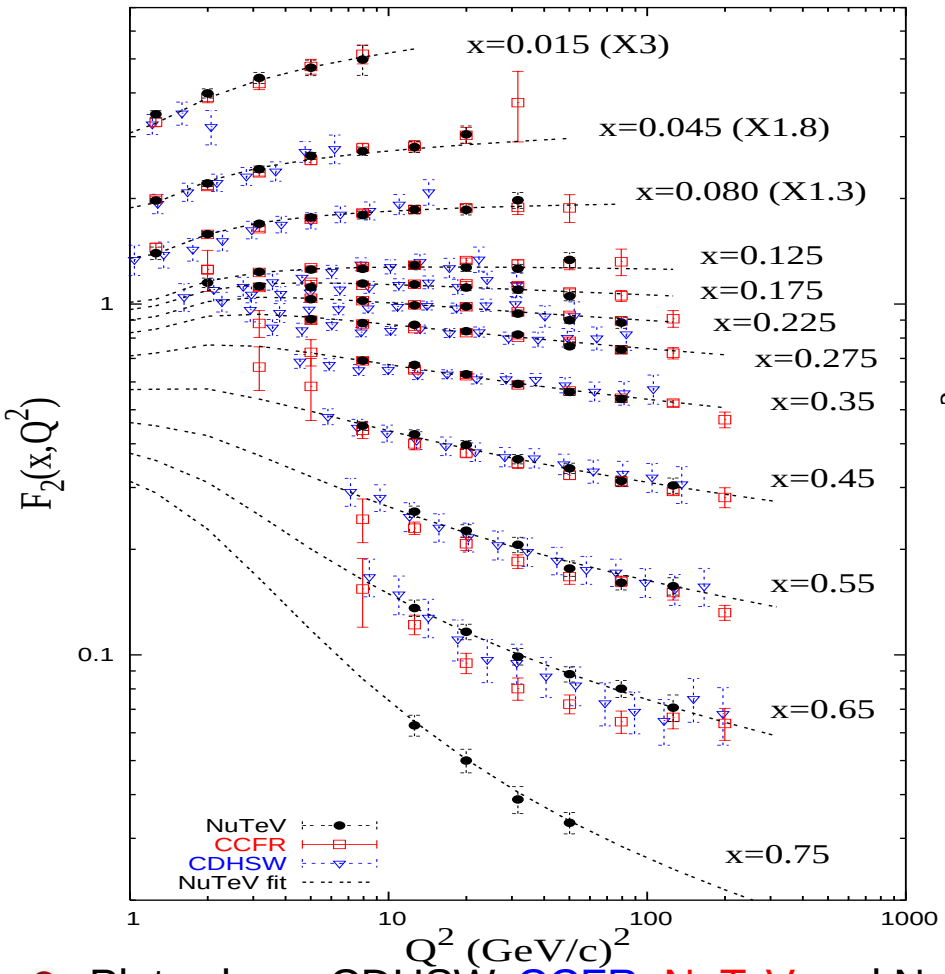
    [L.W.Whitlow $et.al.$ Phys.Lett. B250(1990) 193]
  - $\Delta xF_3=xF_3^\nu-xF_3^{\overline{\nu}}=4x(s-c)$ from NLO QCD model(TR- VFS)

    [R.Thorne and R.Roberts, Phys.Lett. B 421 (1998)]

- $xF_3^{avg}(x,Q^2)=\frac{1}{2}\left(xF_3^\nu(x,Q^2)+xF_3^{\overline{\nu}}(x,Q^2)\right)$
- perform 1-parameter fit for $xF_3^{avg}(x,Q^2)$
- $\Delta F_2=F_2^\nu(x,Q^2)-F_2^{\overline{\nu}}(x,Q^2)\approx 0$
  - no inputs required

One parameter final fit results:

Structure Function $F_2(x, Q^2)$:



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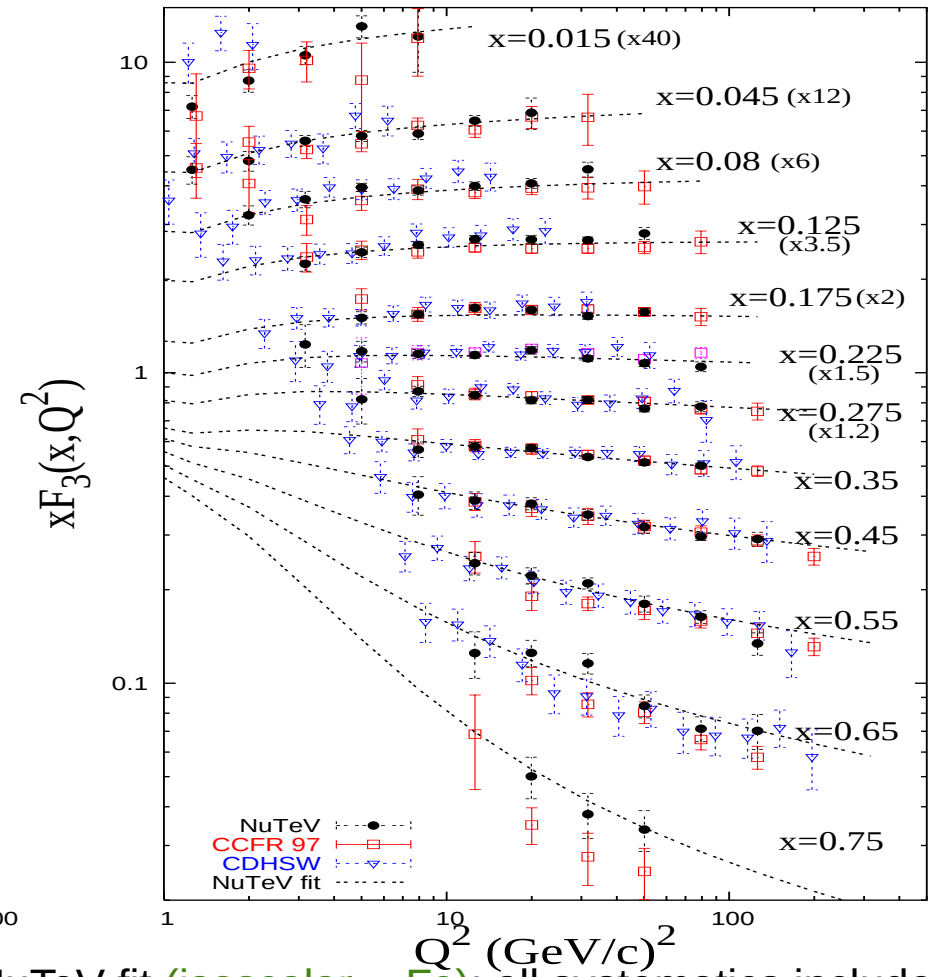
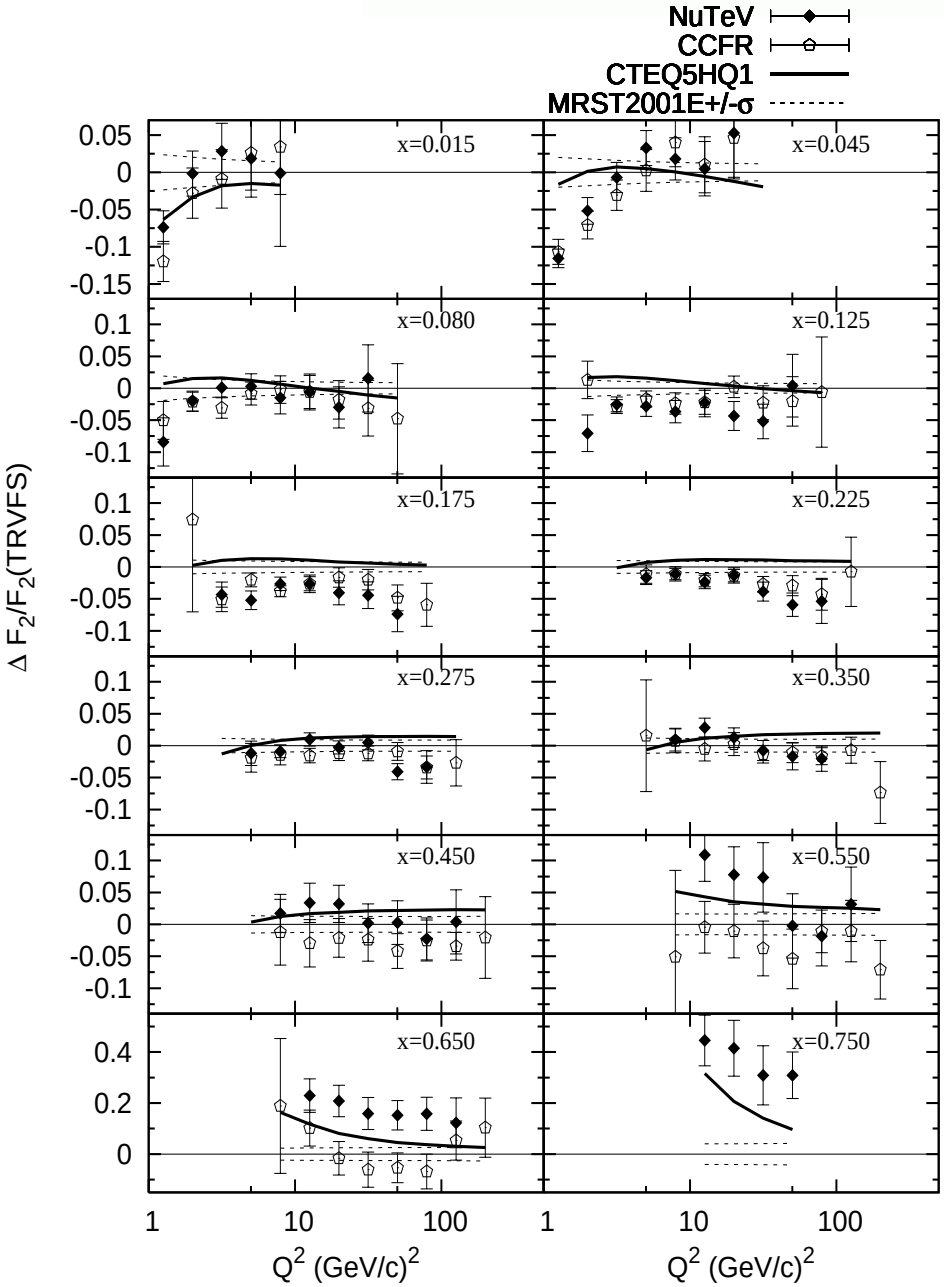


- Plots show: CDHSW, CCFR, NuTeV and NuTeV fit (isoscalar ν-Fe); all systematics included
- the same characteristics seen as at the cross-section level results

Comparison with NLO theory models:



$$\frac{F_2^{DATA} - F_2^{MRST2001}}{F_2^{MRST2001}}$$

- NuTeV and CCFR compared to NLO models:
  - TR-VFS MRST-2001E (dotted line)
  - ACOT (FFS) with CTEQ5HQ1 (solid line)
- different Q^2 dependence at low x
- good agreement at medium x
- at high x NLO models are $15 - 20\%$ bellow NuTeV
- Theory models corrected for:
  - Target Mass: important at high x, low Q^2

    [H.Georgi& H.D.Politzer, Phys.Rev D14 1829]
  - Nuclear Effects ...

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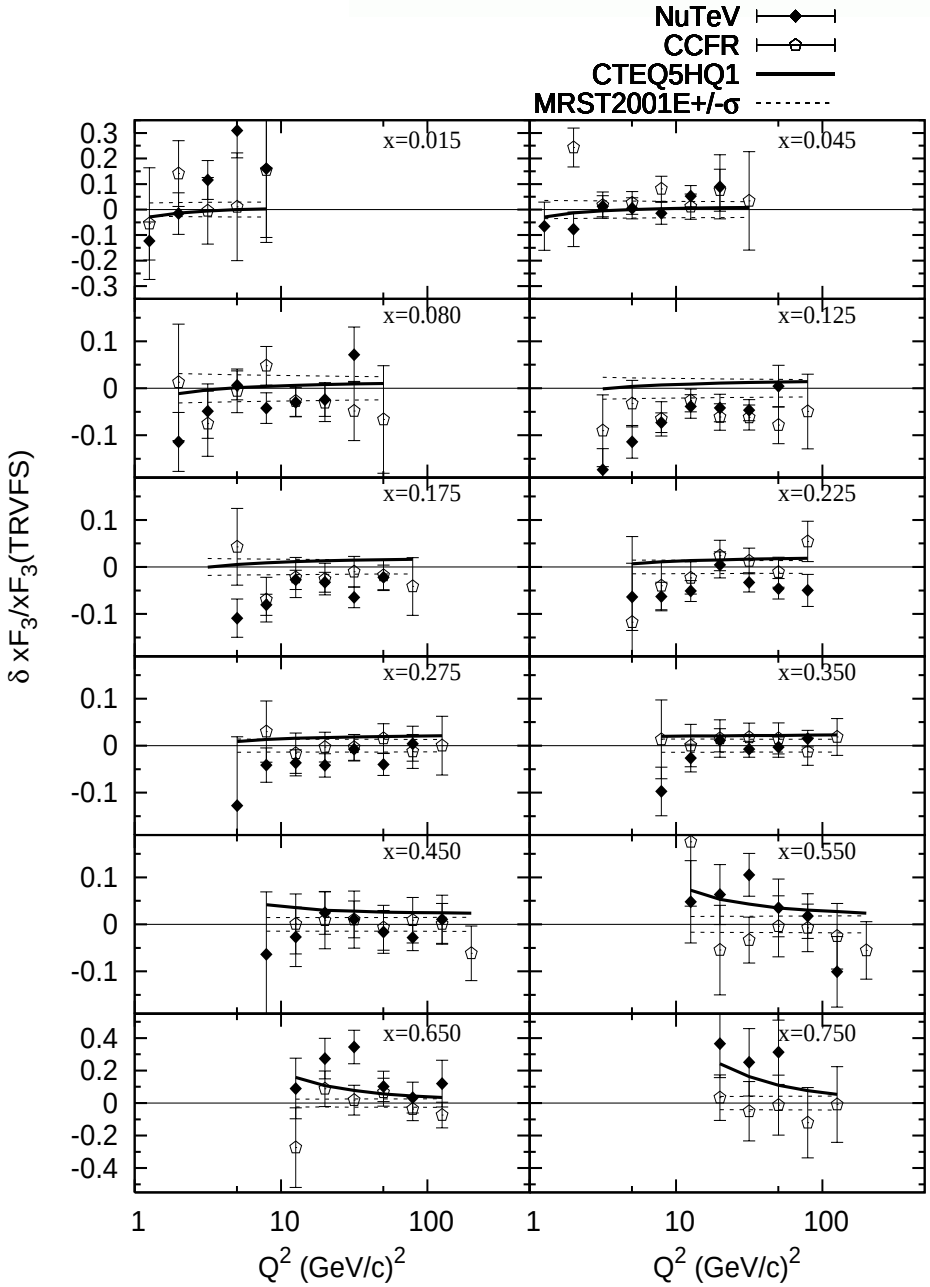

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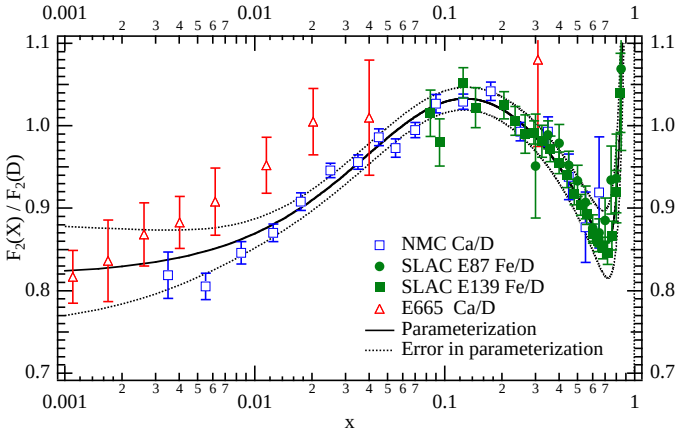
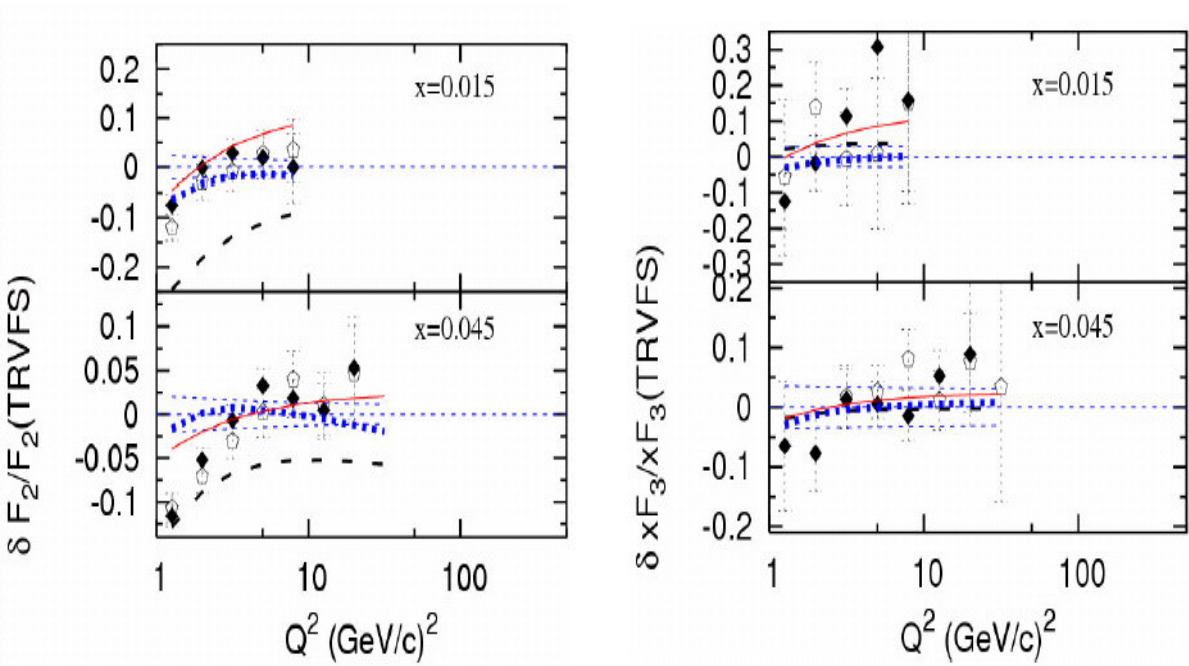
Nuclear Corrections:

- correction measured from charged-lepton data on nuclear targets
- standard way: assume for neutrino case same correction
- we use a parametrization fit to charged lepton data independent of Q^2 to data (dominated at $x > 0.4$ by Q^2 SLAC data):



- perhaps NuTeV favours smaller nuclear effects

- recent calculations show that in the shadowing region (low x) nuclear correction has a Q^2 dependence:
  - S.A. Kulagin, R. Petti hep-ph/0412425
  - J.W. Qiu, I. Vitev hep-ph/0410062 [Phys.Lett.B 587 (2004)]



(red curve is TRVFS(MRST2001) with new nucl. correct.)

Summary:

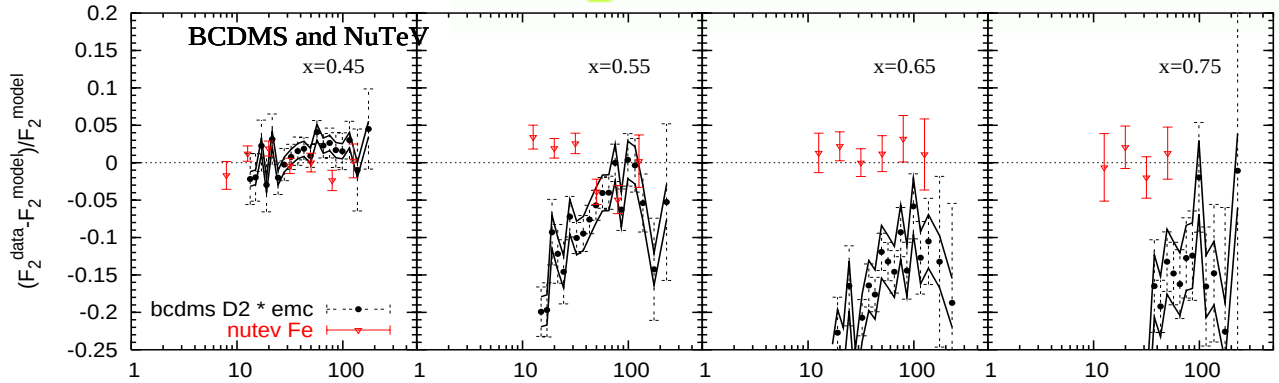
- Final differential Cross Section and Structure Functions measurements have been presented
  - results compared with other neutrino measurements:
    - at large x NuTeV is higher than CCFR data (up to 20% at $x = 0.65$ mainly due to calibration effects)
  - results compared with NLO theory models:
    - at low x different Q^2 dependence
    - at high x NuTeV above theory models (up to 15% at $x = 0.65$)
      - assumption for nuclear corrections (large for charged lepton data);
      - new nuclear corrections available at low x (Q^2 dependence)
- user friendly interface to access NuTeV differential cross section available at: $http://www-nutev.phyast.pitt.edu/results_2005/nutev_sf.html$
- Future:
  - QCD fits to extract α_S
  - inclusion of high-y sample and extract $R_L(x, Q^2)$ from 2 parameter fits

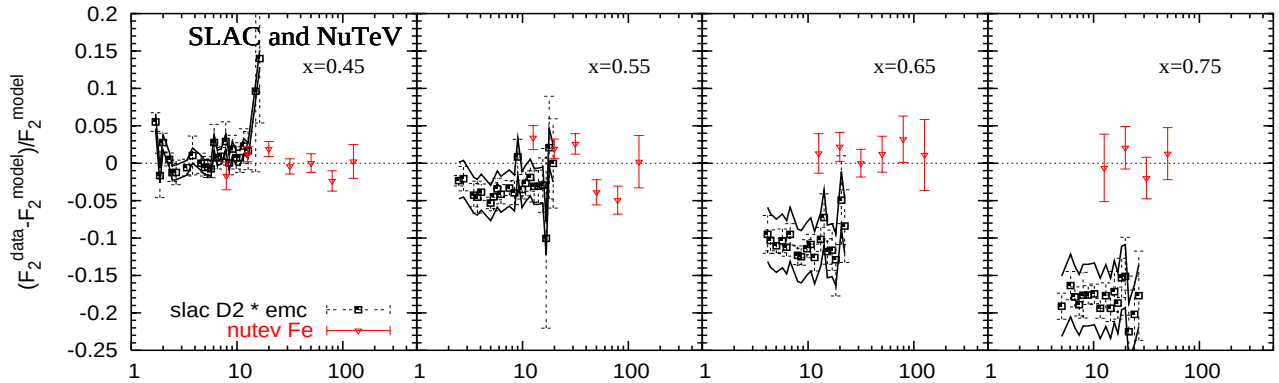
NuTeVPack:

- user friendly interface to access NuTeV differential cross section available at:
  $http://www-nutev.phyast.pitt.edu/results_2005/nutev_sf.html$

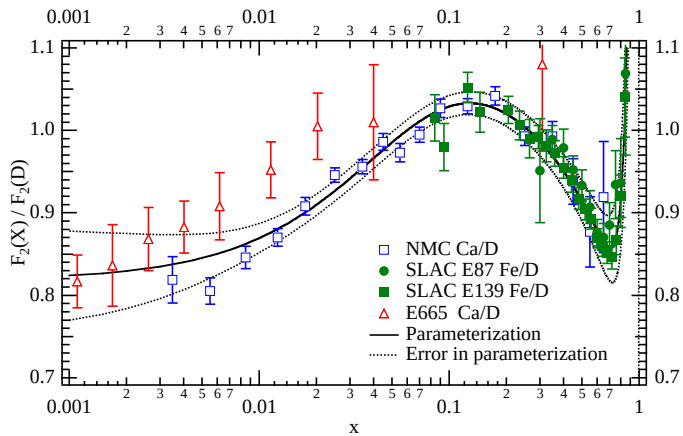
- NuTeV provides:
  - data table (differential cross section on Fe)
  - covariance matrix (with all systematics included)
- no corrections applied to data;
- data binned in x,y, E bins;
- allows access to each systematic error separately, as well as the combination of sytematic errors;
- statistical error added in quadrature to the diagonal

Comparison with Charged Lepton Data at high x:





- 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)



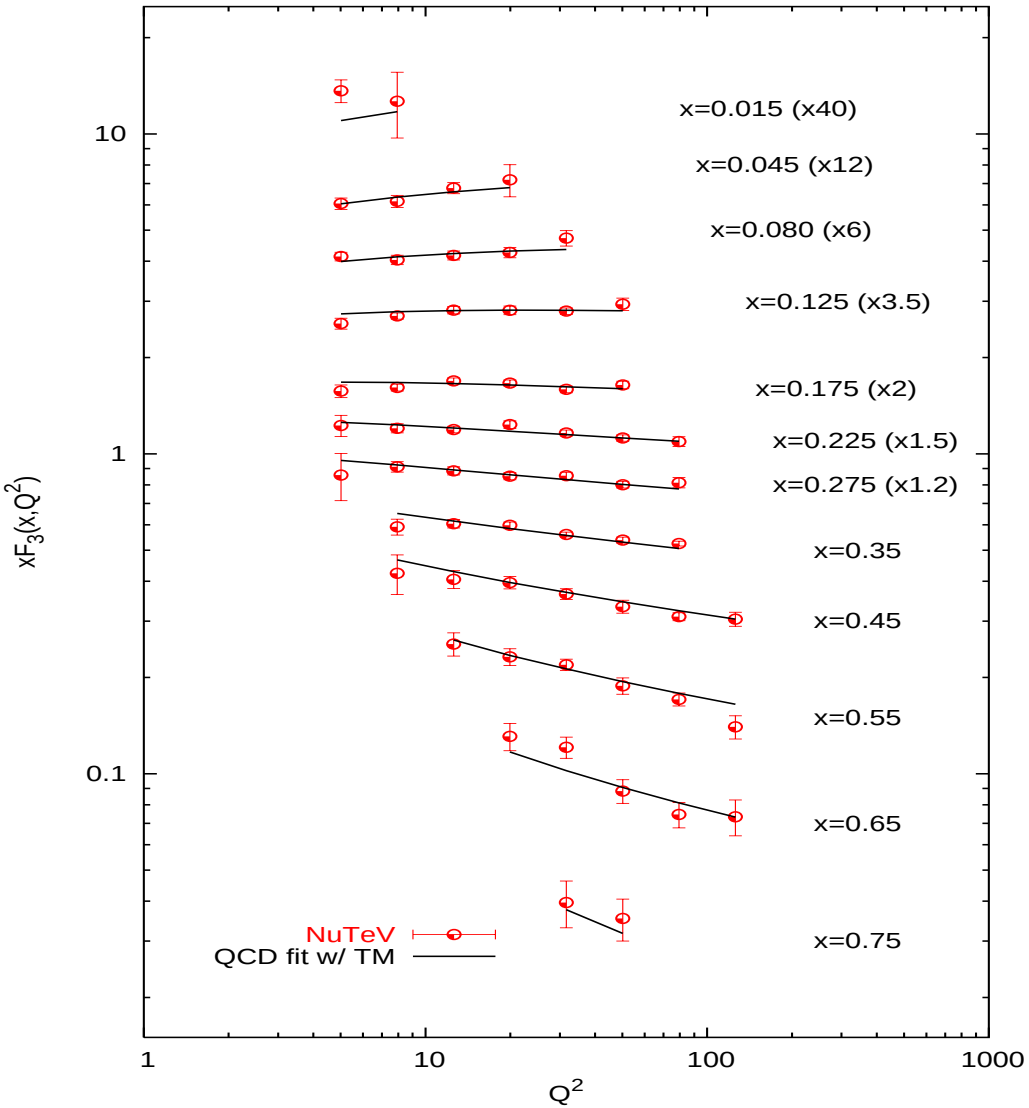
- plots show $\frac{F_2^l - F_{2BG}^\nu}{F_{2BG}^\nu}$ in high x bins
- data sets: NuTeV(Fe), BCDMS(D_2), SLAC(D_2)
  - NuTeV above BCDMS(D_2) by $\approx 7\%$ at $x = 0.55$, $\approx 12\%$ at $x = 0.65$ and $\approx 15\%$ at $x = 0.75$
  - NuTeV above SLAC(D_2) by $\approx 4\%$ at $x = 0.55$, $\approx 10\%$ at $x = 0.65$ and $\approx 17\%$ at $x = 0.75$

ν-scattering favors perhaps smaller nuclear effects at high x

Non Singlet QCD preliminary fits

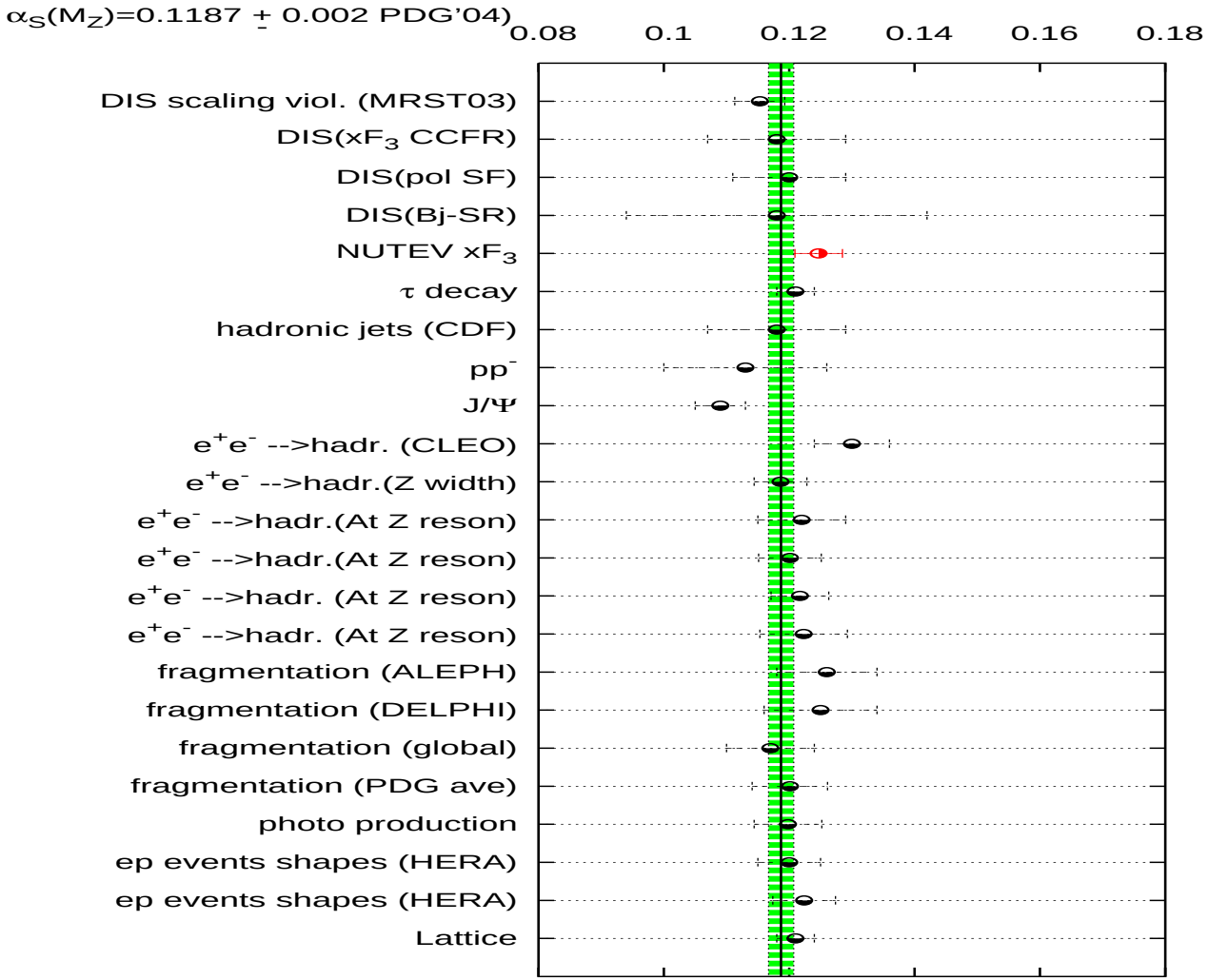
- $xF_3^{\nu(\overline{\nu})}(x,Q^2) = \Sigma\left[xq^{\nu(\overline{\nu})} - x\overline{q}^{\nu(\overline{\nu})}\right]$
  - available to neutrino scattering due to parity-violation
  - its evolution does not depend on gluon
- NLO QCD evolution code [J. Owens]
  - Non-Singlet evolution starts at $Q_0^2 = 5GeV^2$
  - Data is fitted for $Q^2 > 5\ GeV^2,\ \ W^2 > 10\ GeV^2$
  - $\Lambda_{\overline{MS}}^{(5)}$ is a fit parameter: provides a parametrization of the scale dependence on α_S
  - Corrections applied to theory:
    - Target Mass: important at high x, low Q^2

      [H.Georgi& H.D.Politzer, Phys.Rev D14 1829]
  - currently massless evolution:
    - include heavy quark production piece [F. Olness code]

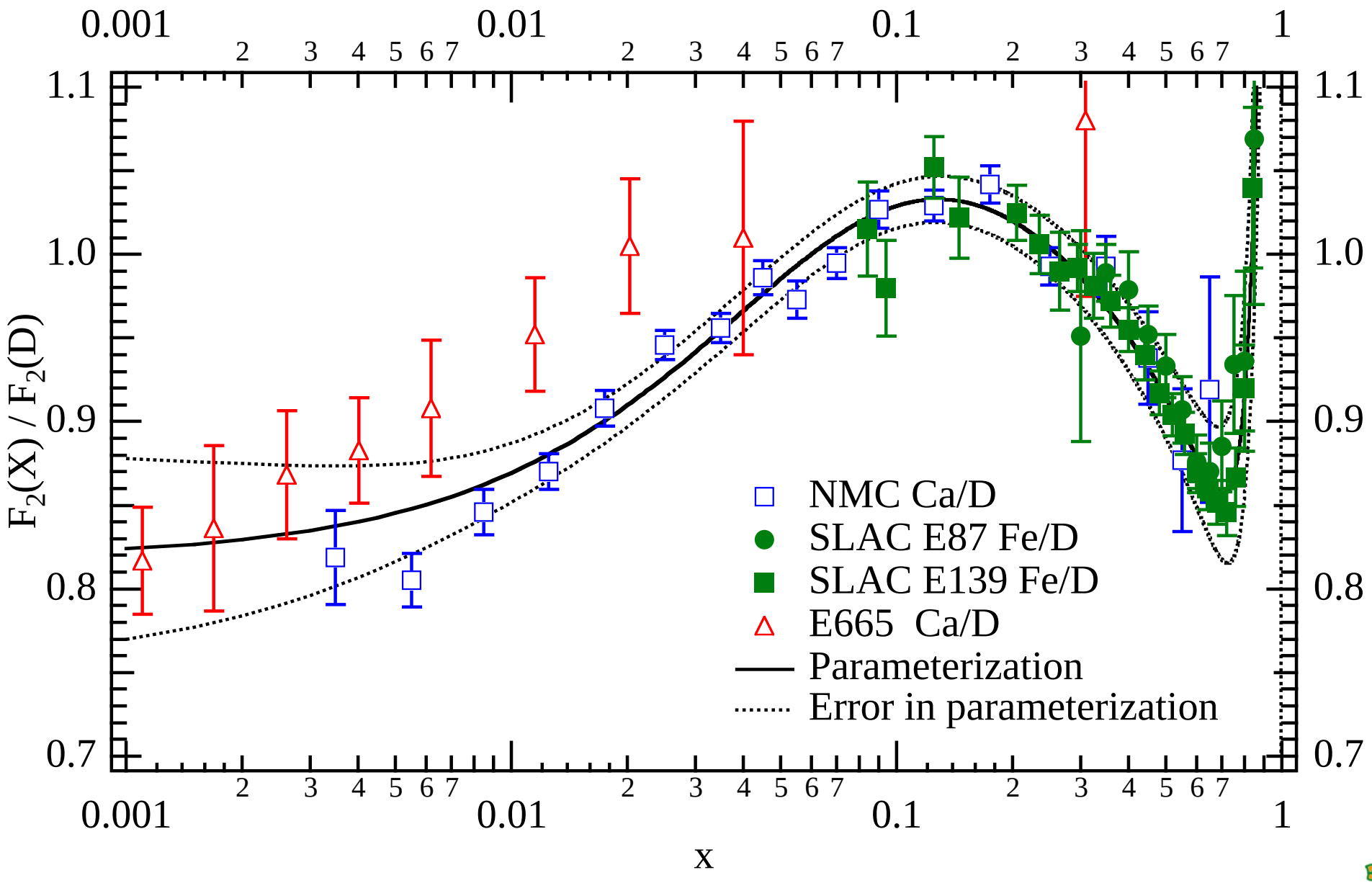


Preliminary α_S from NS Fit:

- $\Lambda^{(5)}_{\bar{M}S} = 324 \pm 61 MeV \Longrightarrow \alpha_S(M^2_{Z^0}) = 0.1247 \pm 0.0038$
- world average: $\alpha_S(M_{Z^0}) = 0.1187 \pm 0.002$ [PDG 2004]



Nuclear Correction



Extracting Relative Flux:

"Fixed ν_0 method": Integrate data at low ν

- derived from the general form of cross section, integrated over x with fixed $y = \frac{\nu}{E_\nu}$:

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

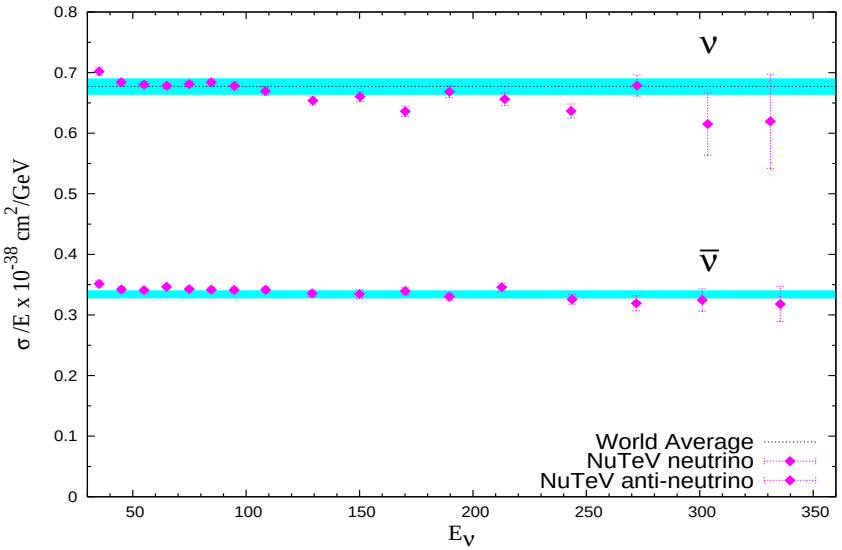
$$\begin{cases} A = \frac{G_F^2 M}{\pi} \int F_2(x, Q^2) dx \\ B = -\frac{G_F^2 M}{\pi} \int \left[F_2(x, Q^2) \mp x F_3(x, Q^2)\right] dx \\ C = B - \frac{G_F^2 M}{\pi} \int F_2(x, Q^2) \left(\frac{1 + \frac{2Mx}{\nu}}{1 + R(x, Q^2)} - \frac{Mx}{\nu} - 1\right) dx \end{cases}$$

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

$\frac{B}{A}$ ($\frac{C}{A}$) determined from the fit to $\frac{dN}{d\nu}$ data

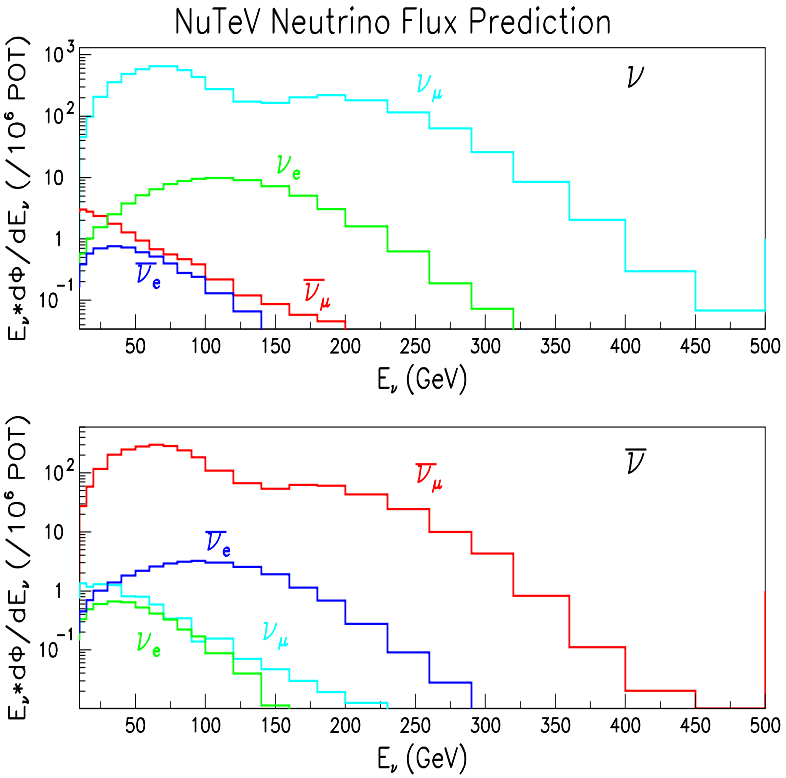
- Absolute flux obtained by normalizing our cross-section to the world average value: $\frac{\sigma^\nu_{WORLD}}{E_\nu} = 0.677 \pm 0.014 \times 10^{-38} \frac{cm^2}{GeV}$

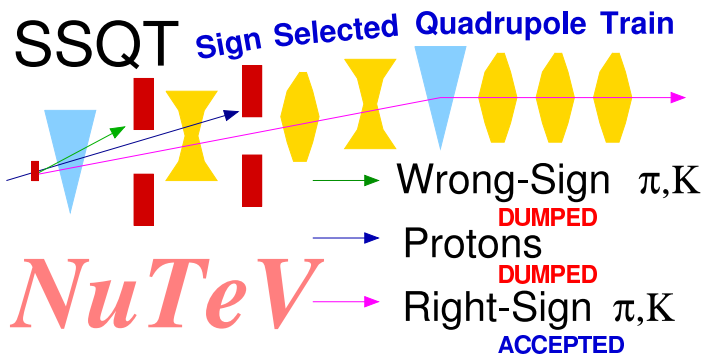
- Test of Flux extraction:



- $\frac{\sigma^\nu}{E_\nu}$ is flat as function of E_ν within $\pm 2.1\%$
- $\frac{\sigma^\nu}{\sigma^{\bar{\nu}}}$ agrees with world average

Neutrino Beam





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