QCD results from NuTeV

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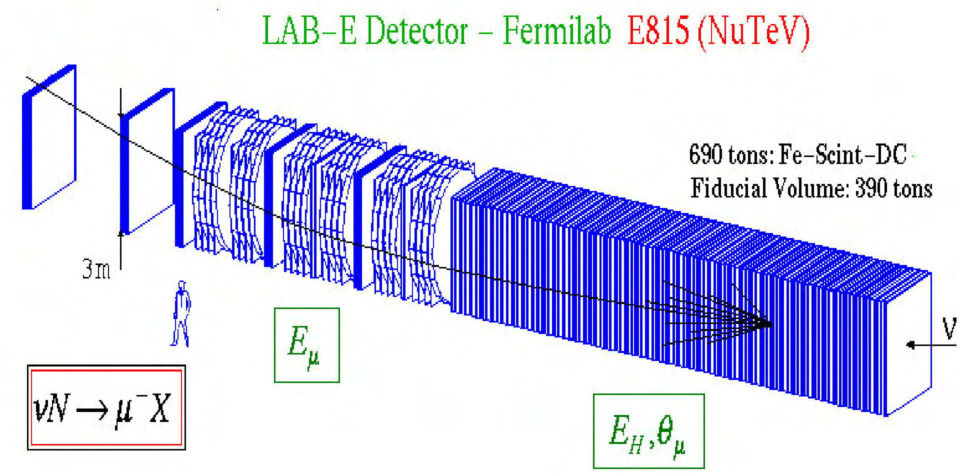
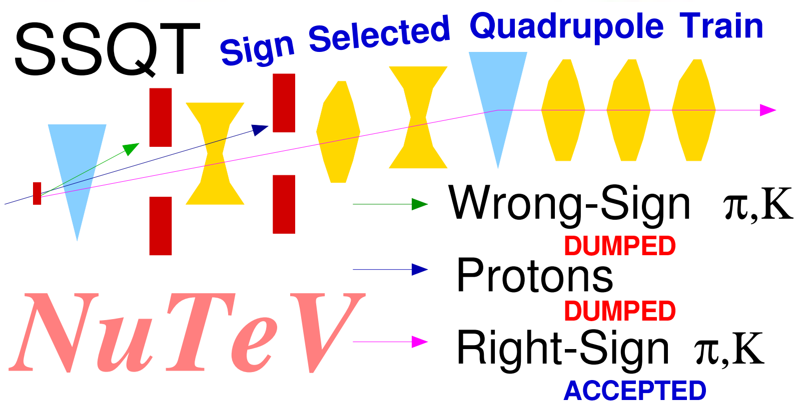
Outline :

- NuTeV experiment
- Methods of extraction of the Structure Functions
- NLO Theory Models for the QCD fits
- QCD results
- Remarks on the Target Mass Corrections
- Conclusions

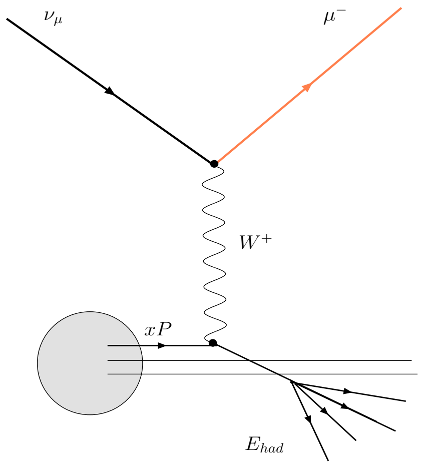
NuTeV Experiment:





- a precision $\nu - Fe$ DIS experiment: Iron Calorimeter + Muon Spectrometer
- Data taking: 1996-97 FNAL fixed target $< E_\nu >\sim 120$ GeV, $< Q^2 >\sim 25$ GeV^2
- Sign Selected Beams: 99.9% pure ν_μ, and 99.7% pure $\overline{\nu}_\mu$
- Calibration beam throughout run: μ, e^-, hadrons (4.5 - 190 GeV)
  - muons: $\frac{\delta E_\mu}{E_\mu} = 0.70\%$
  - hadrons: $\frac{\delta E_{HAD}}{E_{HAD}} = 0.43\%$
- CC events: 8.6×10^5 ν and 2.3×10^5 $\overline{\nu}$

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:

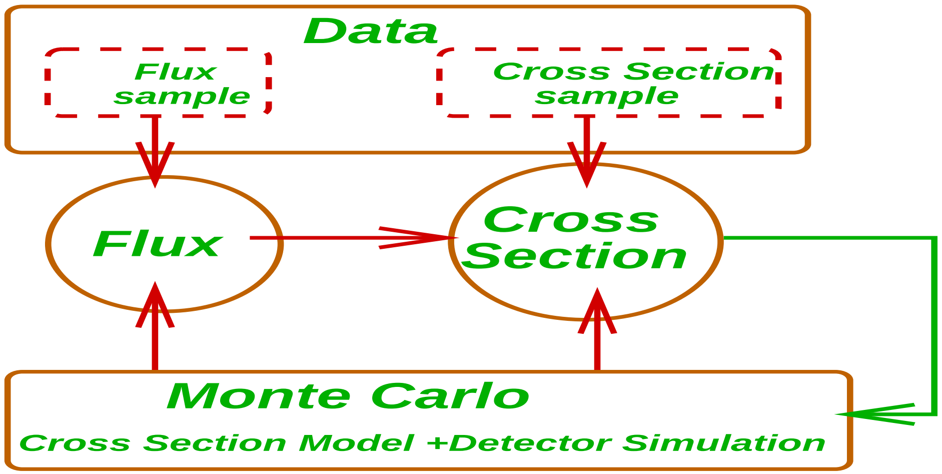
$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+\frac{Q^2}{M_W^2})^2}\left[\left(1 - y - \frac{Mxy}{2E_\nu}\right) F_2^{\nu(\overline{\nu})} + \frac{y^2}{2} 2xF_1^{\nu(\overline{\nu})} \pm y(1-\frac{y}{2})xF_3^{\nu(\overline{\nu})}\right]$$

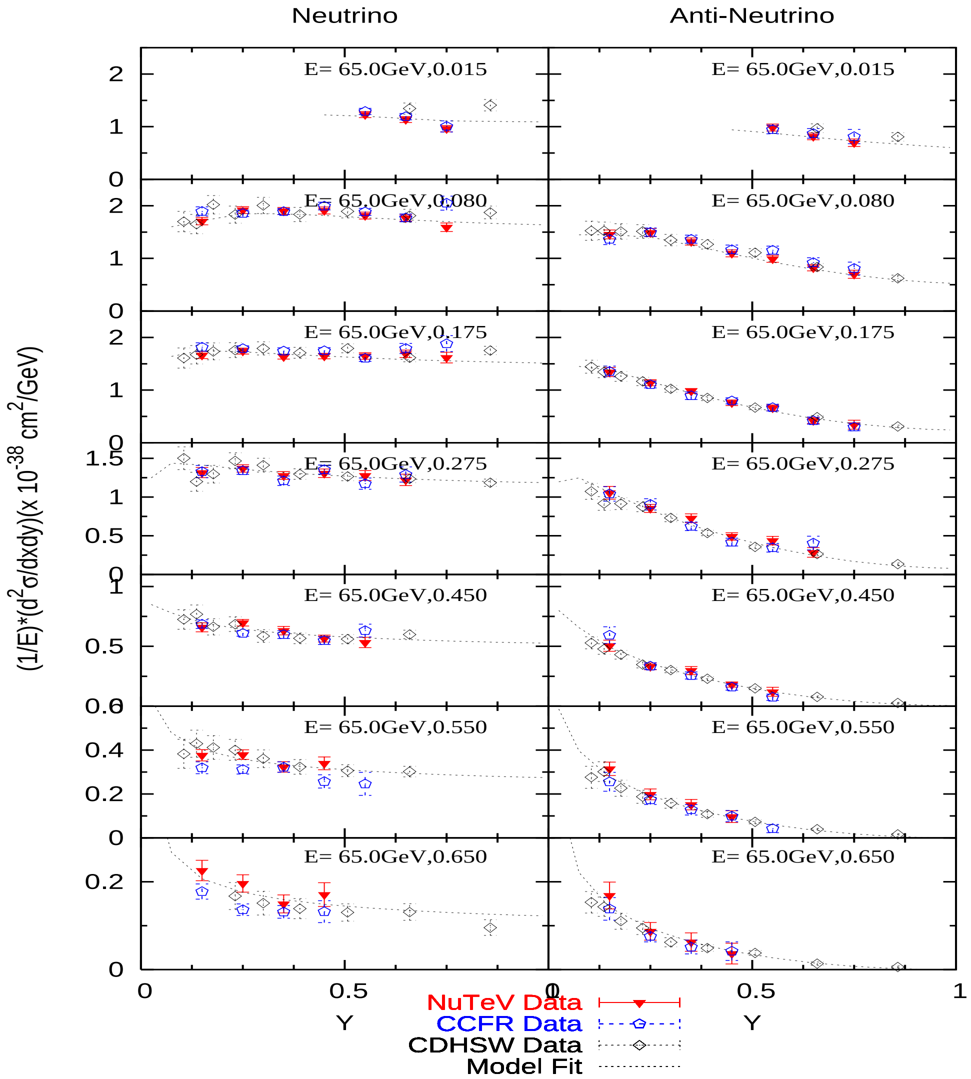
Neutrino Structure Functions in terms of quark compositions of target:

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

Extracting Differential Cross Section:

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





- Data:
  - Flux Sample: data set of $E_{had} < 20\ GeV$
  - Cross Section Sample:
    - $E_\mu > 15\ GeV,\ E_{had} > 10\ GeV,$ $E_\nu \in (30\ ,\ 360)\ GeV,\ Q^2 > 1\ GeV^2$
- Monte Carlo:
  - for acceptance and smearing corrections only
- [M.Tzanov et al., hep-ex/0509010]

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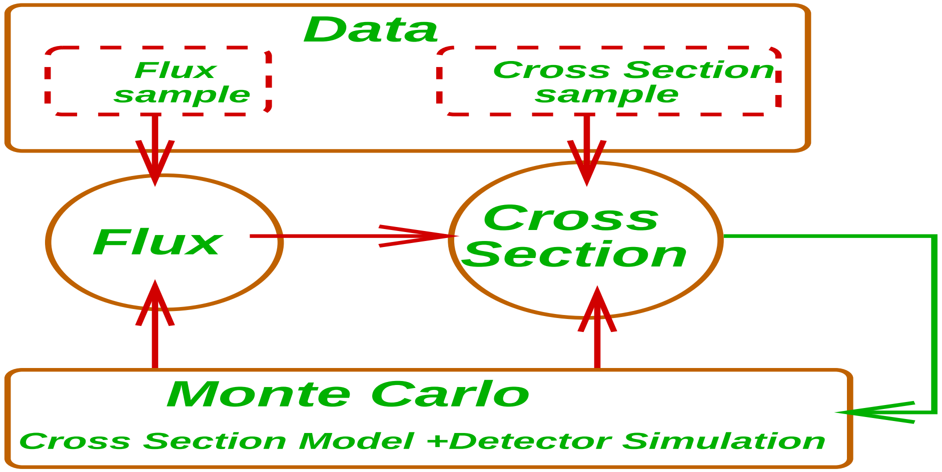

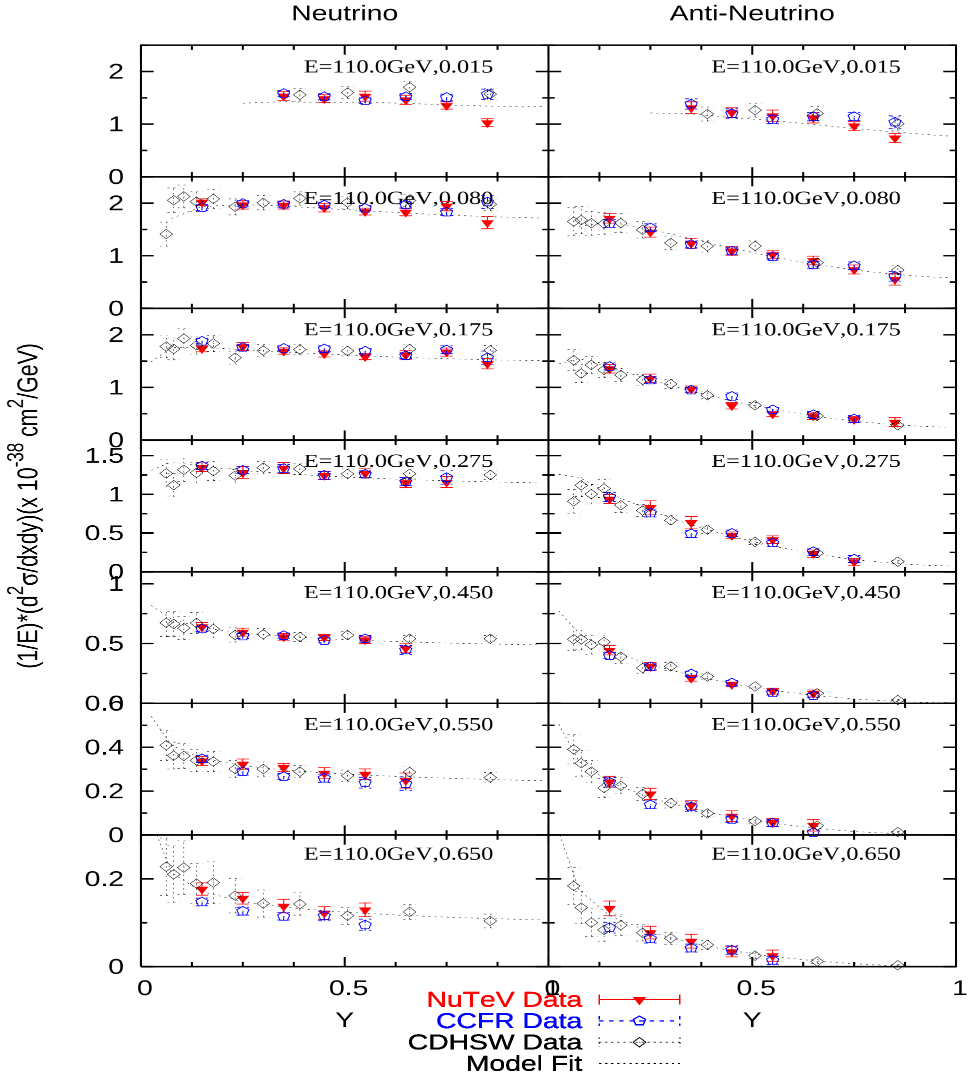

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Extracting Structure Functions:

GOAL: determine Λ_{QCD} from the NLO QCD fits to SF's

- For the xF_3 only NLO QCD fit: 1p fits to the Diff. Cross sections:

$$\left[\frac{d^2\sigma^{\nu}}{dxdy} - \frac{d^2\sigma^{\overline{\nu}}}{dxdy}\right] \frac{\pi}{2MG^2E_{\nu}} \approx \left(y - \frac{y^2}{2}\right) xF_3^{avg}$$

$$\Delta F_2 = F_2^{\nu} - F_2^{\overline{\nu}} \approx 0; \quad \text{no model input needed}$$

- For the xF_3 and F_2 NLO QCD fit: 2p fits to y-dependence of cross sections:
  - use cross section error matrix :
  - obtain correlations between F_2 and xF_3

$$\frac{d^2\sigma^{\nu}}{dxdy} = \frac{2MG^2E_{\nu}}{\pi}\left[\left(1-y-\frac{Mxy}{2E}+\frac{1+\frac{4M^2x^2}{Q^2}}{1+R_L}\frac{y^2}{2}\right)\left(F_2^{avg}+\frac{\Delta F_2}{2}\right)+y\left(1-\frac{y}{2}\right)\left(xF_3^{avg}+\frac{\Delta xF_3}{2}\right)\right]$$

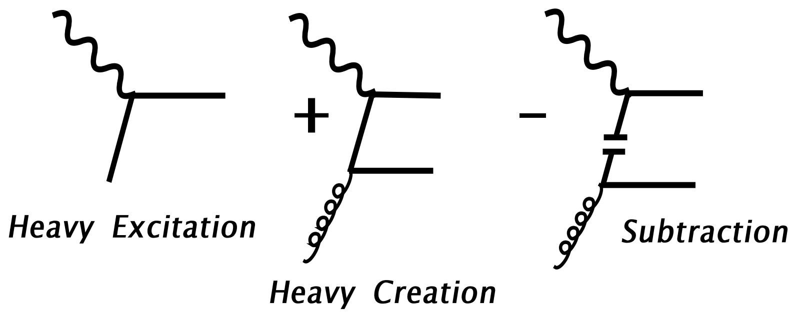
$$\frac{d^2\sigma^{\overline{\nu}}}{dxdy} = \frac{2MG^2E_{\nu}}{\pi}\left[\left(1-y-\frac{Mxy}{2E}+\frac{1+\frac{4M^2x^2}{Q^2}}{1+R_L}\frac{y^2}{2}\right)\left(F_2^{avg}-\frac{\Delta F_2}{2}\right)+y\left(1-\frac{y}{2}\right)\left(xF_3^{avg}-\frac{\Delta xF_3}{2}\right)\right]$$

$$F_2^{avg}(x,Q^2) = \frac{1}{2}\left(F_2^{\nu}(x,Q^2)+F_2^{\overline{\nu}}(x,Q^2)\right) \quad xF_3^{avg}(x,Q^2) = \frac{1}{2}\left(xF_3^{\nu}(x,Q^2)+xF_3^{\overline{\nu}}(x,Q^2)\right)$$

$\Delta xF_3 = xF_3^{\nu} - xF_3^{\overline{\nu}}$; $\Delta F_2 = F_2^{\nu} - F_2^{\overline{\nu}}$; Input model for R_L [fit to world data], ΔxF_3 [NLO TR-VFNS]

NLO Theory models:

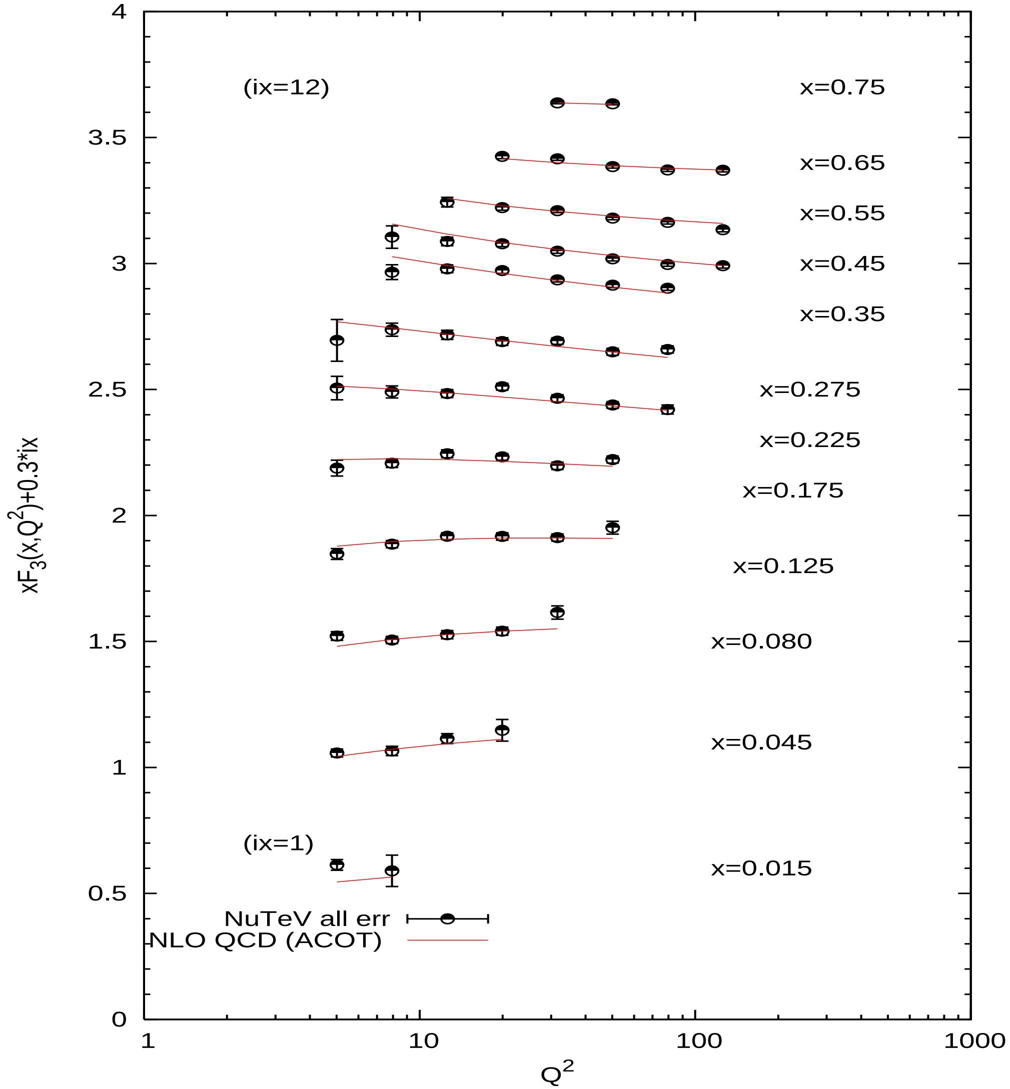
- massless $\overline{MS}$: J.F. Owens' program
  [ref: J.F. Owens, private communication; A. Devoto, D.W. Duke, J.F. Owens, and R.G. Roberts, Phys. Rev. D27, 508 (1983)]
- massive ACOT scheme: F. Olness, S. Kretzer base program
  [ref:F. Olness, private communication; Phys.Rev. D50 (1994)]
  - belongs to the VFNS factorization schemes
  - uses CWZ renormalization method: a hybrid of $\overline{MS}$ & zero momentum renorm.



  - smooth transition from the $M_H >> \mu_F$ to $M_H << \mu_F$ regions
- massless evolution: [ref: J. F. Owens' program]
  - no gain of information from a mass dependent evolution [ref: F.Olness, Phys.Rev.D V57 (1998)]
  - starts at $Q_0^2 = 5$ GeV^2
- $m_b = 4.3 \pm 0.2$ GeV, $m_c = 1.4 \pm 0.2$ GeV

Preliminary NLO QCD fits:

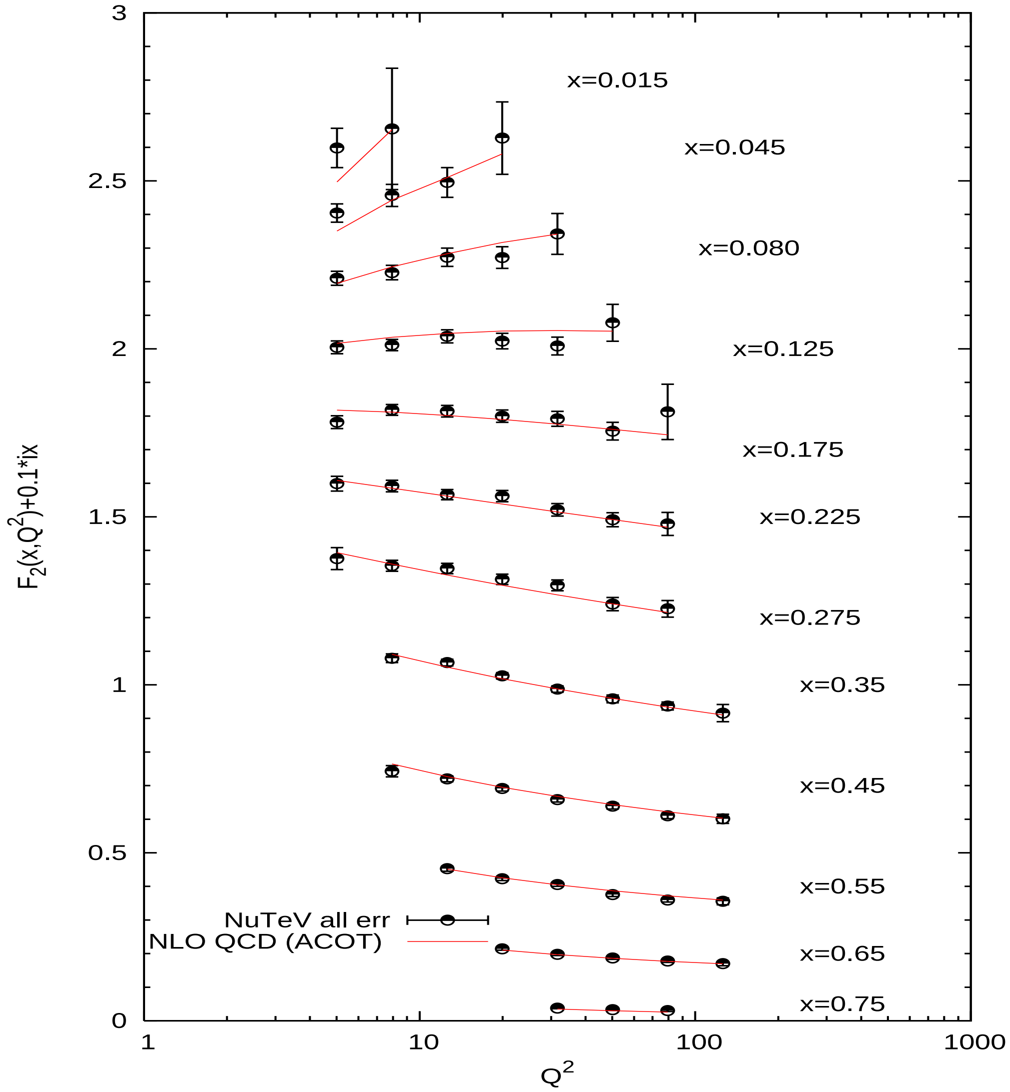
xF_3 from non-singlet fit results:



- Perform NLO QCD fits to:
  1. $xF_3(x, Q^2)$ only
  2. $F_2(x, Q^2)$ and $xF_3(x, Q^2)$
- PDF's evolved using DGLAP equations
- $\Lambda_{QCD}^{n_f=4}$ free parameter in the fit
- Requirements:
  - $Q^2 > 5$ GeV^2, $x < 0.8$, $W^2 > 10$ GeV^2
- apply Target Mass Correction [Next]

Preliminary NLO QCD fits:

F_2 from combined fit results:



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Remarks on the Target Mass corrections:

$$F_1^{TM}(x,Q^2) = \frac{x}{\xi}\frac{F_1^{(0)}(\xi,Q^2)}{k} + \frac{M_p^2 x^2}{Q^2 k^2}\int_\xi^1 \frac{F_2^{(0)}(u,Q^2)}{u^2}du + \frac{2M_p^4 x^3}{Q^4 k^3}\int_\xi^1 du \int_u^1 \frac{F_2^{(0)}(v,Q^2)}{v^2}dv$$

$$F_2^{TM}(x,Q^2) = \frac{x^2}{\xi^2}\frac{F_2^{(0)}(\xi,Q^2)}{k^3} + \frac{6M_p^2 x^3}{Q^2 k^4}\int_\xi^1 \frac{F_2^{(0)}(u,Q^2)}{u^2}du + \frac{12M_p^4 x^4}{Q^4 k^5}\int_\xi^1 du \int_u^1 \frac{F_2^{(0)}(v,Q^2)}{v^2}dv$$

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$$k = \sqrt{1 + \frac{4x^2 M_p^2}{Q^2}}, \quad \xi = \frac{2x}{1+k}$$

- General relations, holding to all orders in α_S:
  - no use of the Callan - Gross relation
- F_i^{TM} are functions of (x, Q^2)
- Quark masses effects included in $F_i^{(0)}$.
- $F_i^{(0)}$ are experimental SF's in the limit $M_P \to 0$

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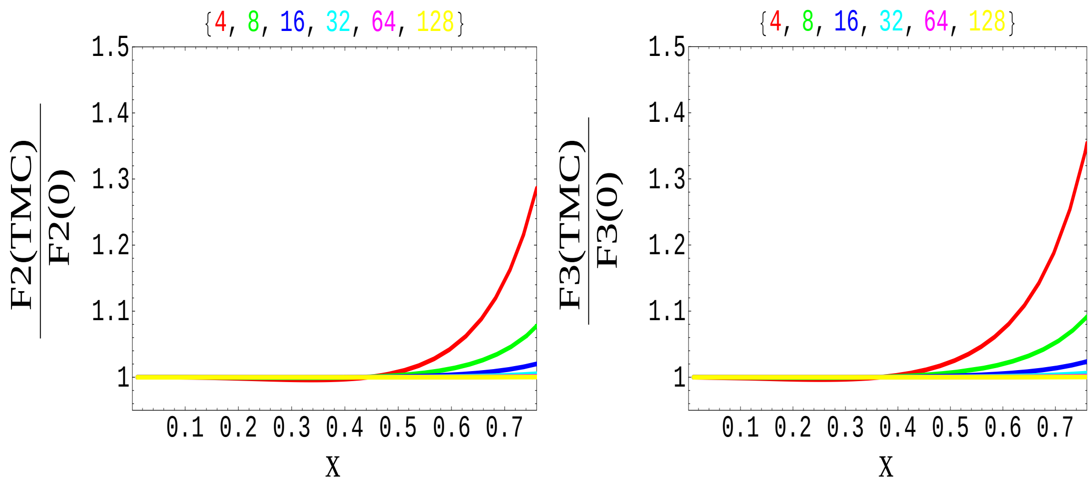


NLO QCD results:

SFs	Parameter	xF_3 only $\overline{MS}$	xF_3 only ACOT	$F_2 + xF_3$ $\overline{MS}$	$F_2 + xF_3$ ACOT
	$\Lambda^{(n_f=4)}$(MeV)	476 ± 60	488 ± 59	433 ± 51	458 ± 41
NS	$A1_{u_v}$	0.73 ± 0.01	0.73 ± 0.01	0.71 ± 0.02	0.72 ± 0.02
	$A2_{u_v}$	3.47 ± 0.06	3.47 ± 0.06	3.50 ± 0.05	3.49 ± 0.05
	$A0_{u_v} + A0_{d_v}$	4.74+2.37	4.73+2.36	4.47+2.23	4.50+2.25
S	$A0_{ud}$			0.68 ± 0.03	0.67 ± 0.03
	$A2_{ud}$			6.74 ± 0.20	6.83 ± 0.21
G	$A0_g$			2.42	2.21
	$A2_g$			4.83 ± 1.38	4.30 ± 0.41
	χ^2/dof	78/59	77/59	79/125	76/125
	$\alpha_S(M_{Z^0})$	0.1257 ± 0.0029	0.1260 ± 0.0028	0.1236 ± 0.0026	0.1247 ± 0.0020

- Errors include statistical and all experimental system. uncertainties
- Full Covariance Error Matrix taking into account all the correlations has been used

Contributing Systematics

- Experimental systematics:
  - energy scales: E_μ, E_{had}
  - energy smearing models
  - flux uncertainties: $\frac{B}{A}$, m_c
  - input models: ΔxF_3, R_W

xF_3		scale		smear model		flux uncert.	
(MeV)	stat.	E_μ	E_{had}	E_μ	E_{had}	m_c	$\frac{B}{A}$
$\Lambda^{n_f=4}_{ACOT} = 454$	± 57	$^{+76}_{-38}$	$^{-10}_{+65}$	-28	$^{+3}_{0}$	$^{-2}_{0}$	$^{-6}_{+4}$

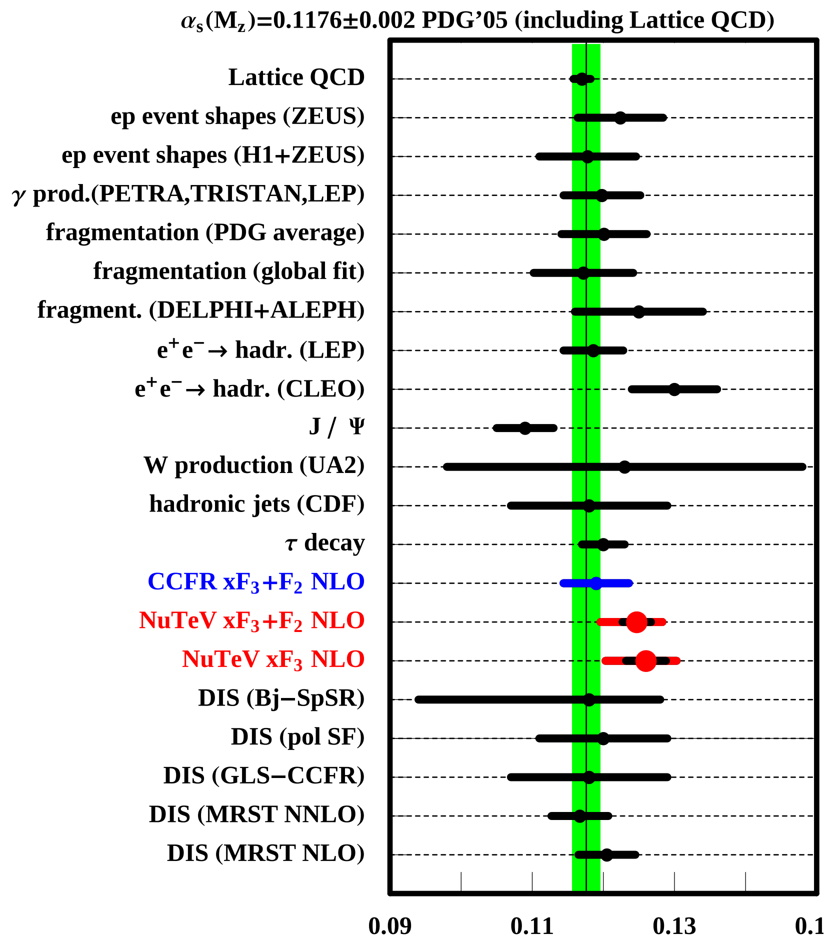
F_2 & xF_3		scale		smear model		flux uncert.		input model	
(MeV)	stat	E_μ	E_{had}	E_μ	E_{had}	m_c	$\frac{B}{A}$	R_W	ΔxF_3
$\Lambda^{n_f=4}_{ACOT} = 434$	± 22	$^{+21}_{-8}$	$^{-10}_{+26}$	-22	$^{-13}_{+8}$	$^{+28}_{-15}$	$^{+2}_{-11}$	$^{+8}_{-13}$	$+31$

- Theoretical Uncertainty:
  - scale dependence: $\mu_F^2 = C_i Q^2$, $C_i = 1/2, 1, 2 ...$:

C_i	xF_3 only	$xF_3 + F_2$
2	$+74$ MeV	$+61$ MeV
0.5	-113 MeV	-87 MeV

NuTeV on the World Map:

- NuTeV (ACOT scheme) Preliminary Results:
  - xF_3 Fit Result:
    $\alpha_S(M_Z) = 0.1260 \pm 0.0028(exp)^{+0.0034}_{-0.0050}(th)$
  - $F_2 + xF_3$ Fit Result:
    $\alpha_S(M_Z) = 0.1247 \pm 0.0020(exp)^{+0.0030}_{-0.0047}(th)$
- WORLD AVERAGE
  $\alpha_S(M_Z) = 0.1176 \pm 0.0020$ [PDG 2005]
  (excluding Lattice QCD:
  $\alpha_S(M_Z) = 0.1185 \pm 0.0020$)
- DIS points from the scaling violations are summarized here by the MRST NLO(and NNLO) global fits analysis [PDG 2005]
  - MRST04 NLO: $\alpha_S(M_Z) = 0.1205 \pm 0.004$



Conclusions:

- First $\Lambda_{QCD}^{nf=4}$ from $\nu - DIS$ including full NLO treatment of charm production
  NLO QCD fits to $xF_3(x,Q^2)$ and $F_2(x,Q^2)$
  - Use of the full covariance differential cross section error matrix [NuTeVpack - M.Tzanov et al., hep-ex/0509010];
  - Results above other DIS measurements;
  - Error dominated by the theoretical uncertainty
    - largest experimental uncertainty due to the E_μ scale [$\frac{\delta E_\mu}{E_\mu} = 0.7\%$]
- Target Mass Corrections:
  - incorporated into the NLO $sin^2\theta_W$ results
  - plan a brief report in collaboration with H. Reno, S. Kretzer, F. Olness, I. Schienbein, C. Keppel, W. Melnitchouk, ...
- Many thanks to J .F. Owens and F. Olness

Backup 1: PDF parametrization:

Parametrization of the PDF's:

$$xq^{NS} = xu_v + xd_v = (A0_{u_v} + A0_{d_v})x^{A1_{u_v}}(1-x)^{A2_{u_v}}$$

$$xq^S = \underbrace{xu_v + xd_v}_{xq^{NS}} + 2A0_{ud}(1-x)^{A2_{ud}}$$

$$xG = A0_g(1-x)^{A2_g}$$

$A0_{u_v}$, $A0_{d_v}$, and $A0_g$ are constrained by the QCD sum rules.

Backup 2: NuTeV vs. CCFR

- CCFR quotes: $\alpha_S(M_Z) = 0.119 \pm 0.002(stat + syst) \pm 0.001(HT) \pm 0.004(th)$
- prelim. NuTeV: $\alpha_S(M_Z) = 0.125 \pm 0.002(stat + syst))^{+0.003}_{-0.005}(th)$

Notes on the comparisons:

- CCFR analysis used a different method of extracting the SF's and had used a LO correction for charm production
- no QCD constraints used in CCFR analysis
- consistent way to compare: use CCFR F_2 (PMI) [Phys.Rev.Lett.86(2001)]vs. NuTeV F_2:
  - CCFR: $\Lambda^{n_f=4} = 330 \pm 64$ MeV; NuTeV: $\Lambda^{n_f=4} = 425 \pm 71$ MeV
  - (errors added in quadrature)
- theoretical uncertainty for CCFR is quoted from MRST paper, NuTeV evaluates it by varying the factorization scale in the program