Determination of α_s from Neutrino-Nucleon Deep-Inelastic Scattering

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Outline

- α_s determination in Neutrino DIS
- Neutrino-Nucleon DIS
  - kinematics, cross-section
- α_s extraction from SF evolution
- α_s from GLS Sum Rule
- Summary

CCFR & NuTeV Collaborations

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α_s determination in Neutrino DIS

Neutrino–Nucleon Deep Inelastic Scattering provides very precise methods of measuring α_s

α_s from SF Scaling Violations completely inclusive; free of hadronization and jet definition uncertainties.

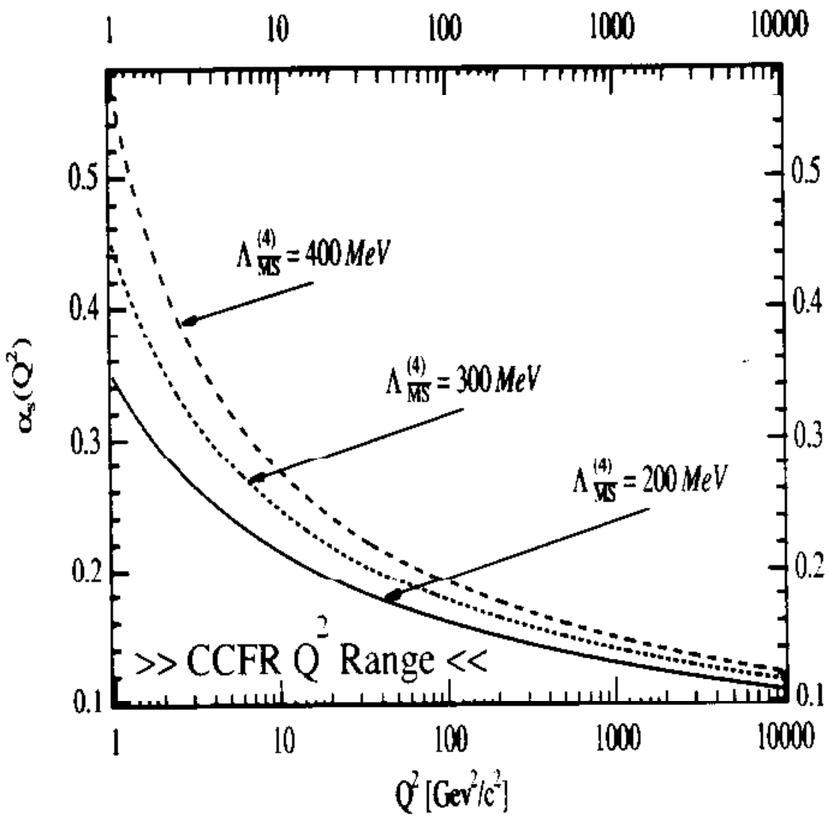
xF_3 purely non-singlet $\Rightarrow$ α_s determination independent of gluon.

Non-perturbative effects $\sim 1/Q^2$ In contrast, e^+e^- fragmentation function scaling violations $\sim 1/Q$.

x-section weak Q^2 dependence $\Rightarrow$ less sensitivity to experimental resolution. In contrast, l^{+-} DIS x-section $\sim 1/Q^4 \rightarrow$ sensitive to resolution effects.

Also, α_s from GLS Sum Rule $\Rightarrow$ depends only on valence distribution; theoretical framework to $\sim \alpha_s^3$.

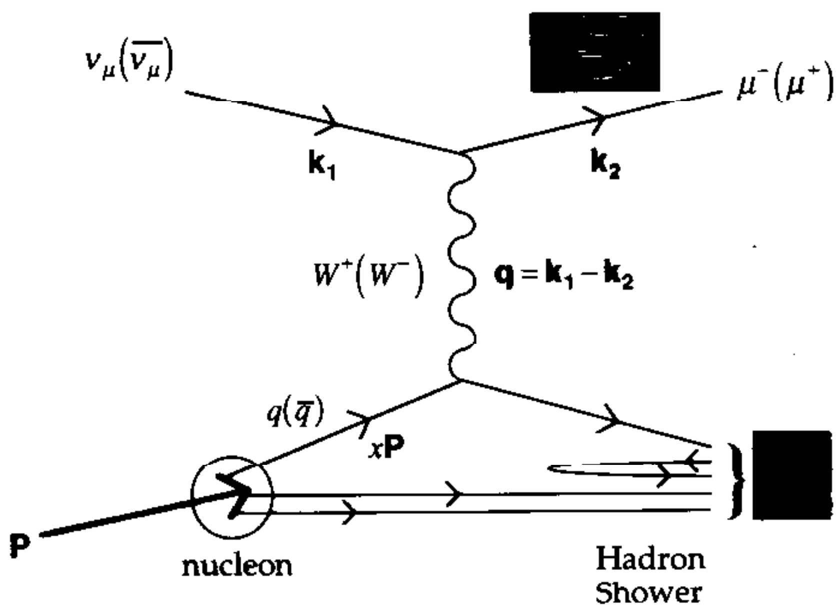
CCFR sensitivity in α_s determination



- CCFR α_s determination from both scaling violations and GLS Sum Rule
- CCFR data have small statistical and systematic errors, thus providing the most precise determination of α_s from DIS.

ν-N DIS kinematics & cross sections

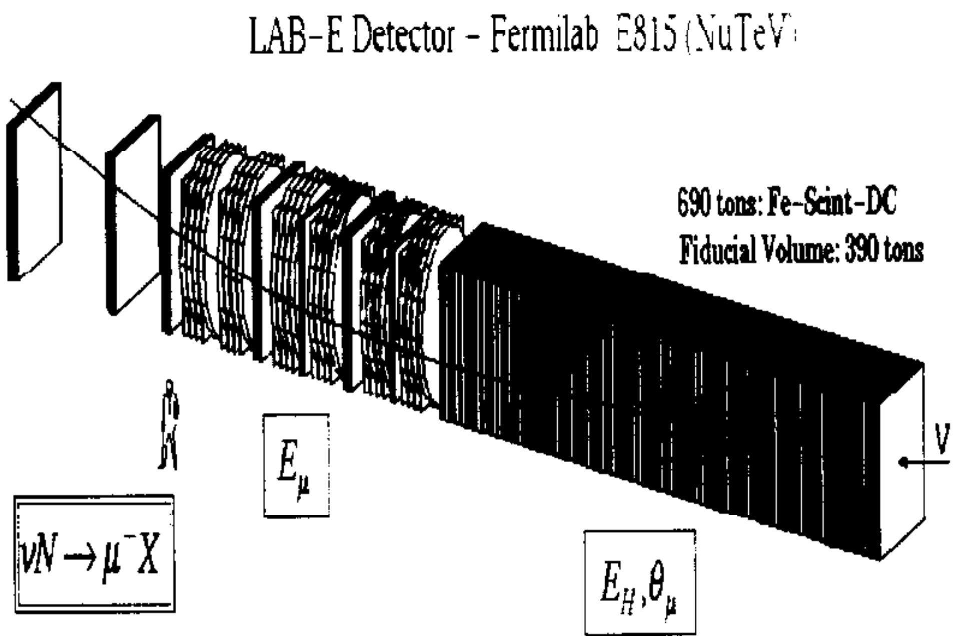
Tree-level diagram for CC νN scattering.



$$
\begin{aligned}
\nu &= (p\cdot q)/M = E_{had} - M \\
y &= p\cdot q/p\cdot k_1 = \frac{E_{had} - M}{E_{had} + E_\mu} \\
Q^2 &= -q^2 = (E_{had} - M + E_\mu)E_\mu\theta^2 \\
x &= Q^2/(2p\cdot q) = \frac{(E_{had} - M + E_\mu)E_\mu\theta^2}{2M(E_{had} - M)}
\end{aligned}
$$

$$
\begin{aligned}
\frac{d^2\sigma^{\nu(\overline{\nu})N}}{dxdy} = \; & \frac{G_F^2 M E_\nu}{\pi\left(1 + Q^2/M_W^2\right)^2}\left[F_2^{\nu(\overline{\nu})N}(x,Q^2)\left(\frac{y^2 + (2Mxy/Q)^2}{2 + 2R_L^{\nu(\overline{\nu})N}(x,Q^2)} + 1 - y - \frac{Mx}{2E_\nu}\right.\right. \\
& \left.\pm x F_3^{\nu(\overline{\nu})N}(x,Q^2)\,y\left(1 - \frac{y}{2}\right)\right]
\end{aligned}
$$

Structure Functions with ν's (CCFR/NuTeV)



CCFR $\nu\&\bar{\nu}$ beam:

- Wide Band Beam, Simultaneous $\nu\&\bar{\nu}$
- Energy Range: $30\,GeV$ to $500\,GeV$

CCFR Data Sample (SF analysis)	ν	$\bar{\nu}$
Events	9.5×10^5	1.7×10^5

Target Calorimeter:

- $\frac{\Delta E_H}{E_H} = \frac{0.89}{\sqrt{E_H(GeV)}}$, $\Delta\theta \cong .3 + \frac{60\,mr}{E_\mu(GeV)}$

Toroid Spectrometer:

- $15\,kG$ Field ($P_T = 2.4\,GeV/c$)
- $\frac{\Delta p_\mu}{p_\mu} = 0.11$

α_S from F_2 and xF_3 scaling violations

Decompose SFs into singlet and non-singlet parts:

$$F_i(x, Q^2) = aF_i^{NS}(x, Q^2) + bF_i^{SI}(x, Q^2)$$

Relate F_i^{NS} and F_i^{SI} to quark distributions (NLO):

$$F_i^{NS} \sim \{xq^{NS},\ C_i,\ \alpha_s \textstyle\int_x^1 q^{NS} f_{iq}\}$$

$$F_i^{SI} \sim \{xq^{SI},\ C_i^1,\ \alpha_s \textstyle\int_x^1 q^{SI} f_{iq},\ C_i^2,\ \alpha_s \textstyle\int_x^1 G f_{iG}\}$$

In pQCD the Q^2 evolution of q and G governed by DGLAP equations:

$$\frac{dq^{NS}}{dln(Q^2)} \sim \{\alpha_s,\ \textstyle\int_x^1 P^{NS} q^{NS}\}$$

$$\frac{dq^{SI}}{dln(Q^2)} \sim \{\alpha_s,\ \textstyle\int_x^1 (P_{qq} q^{SI} + C_q P_{qG} G)\}$$

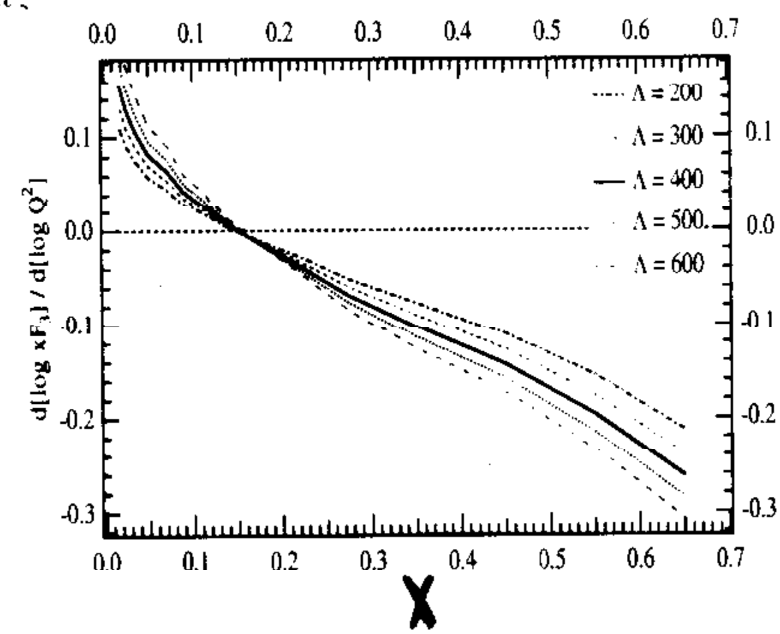
$$\frac{dG}{dln(Q^2)} \sim \{\alpha_s,\ \textstyle\int_x^1 (P_{GG} G + P_{Gq} q^{SI})\}$$

α_s from SF scaling violations in practice

Use an iterative Procedure

- Parameterize the x dependence of q^{NS}, q^{SI}, G
- Start with a value of $\alpha_s$at $Q^2 = Q_0^2$.
- Compute SFs at $Q^2 = Q_0^2$.
  Use DGLAP and renormalization group equation to get SFs over the whole x and Q^2 domain.
- Optimize the agreement in x, Q^2 between the **measured** and the **computed** SFs

At the end of the day, obtain the parameters for q^{NS}, q^{SI}, G and α_s



CCFR α_S from SF scaling violations

- Both F_2 and xF_3, and xF_3 only fits
- NLO QCD evolution program from Duke and Owens
- Fit included target-mass. higher-twist, and $R_{L,QCD}$ effects.
- Data cuts: $Q^2 > 5$ GeV^2, $W^2 > 10$ GeV^2, and $x < 0.7$. Drop bins with statistical error $> 50\%$
- Systematic errors studied by shifting F_2 and xF_3 1σ and re-fitting.

PDF parameterization used:

$$xq_{NS}(x, Q_0^2) = A_{NS} x^{\eta_1}(1 - x)^{\eta_2}$$

$$xq_S(x, Q_0^2) = xq_{NS}(x, Q_0^2) + A_S(1 - x)^{\eta_S}$$

$$xG(x, Q_0^2) = A_G(1 - x)^{\eta_G}$$

No constrains from:

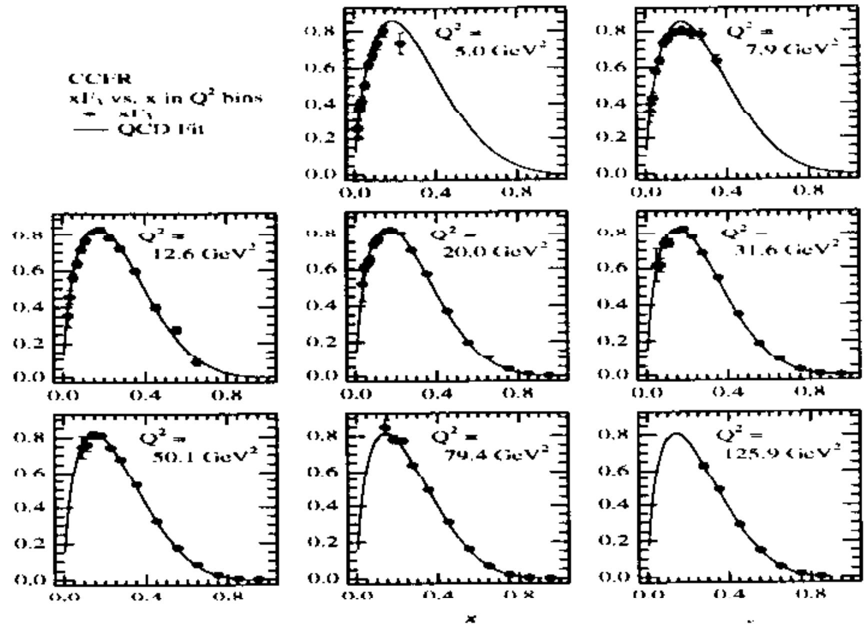
1. Fermion Conservation Sum Rule (presense of HO corrections)
2. Momentum Sum Rule (x range not (0,1))

CCFR α_S from SF scaling violations

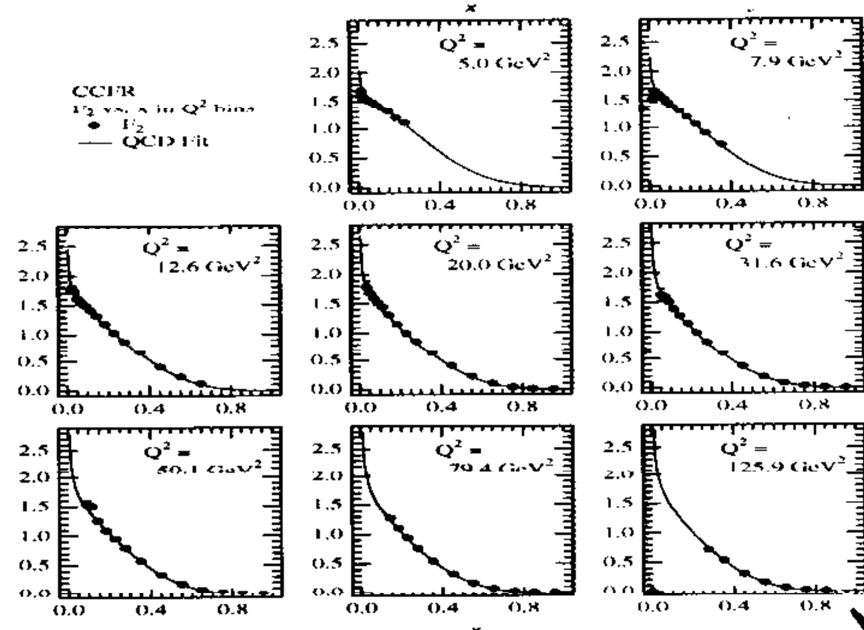
Different methods:

1. Tests of pQCD
   - pQCD prediction compared to SF slopes
   - Error determined by SFs varied by 1σ of each systematic
2. Fit assuming the validity of pQCD
   - Incorporate experimental systematic uncertainties as parameters of the QCD fit

xF_3



F_2



X

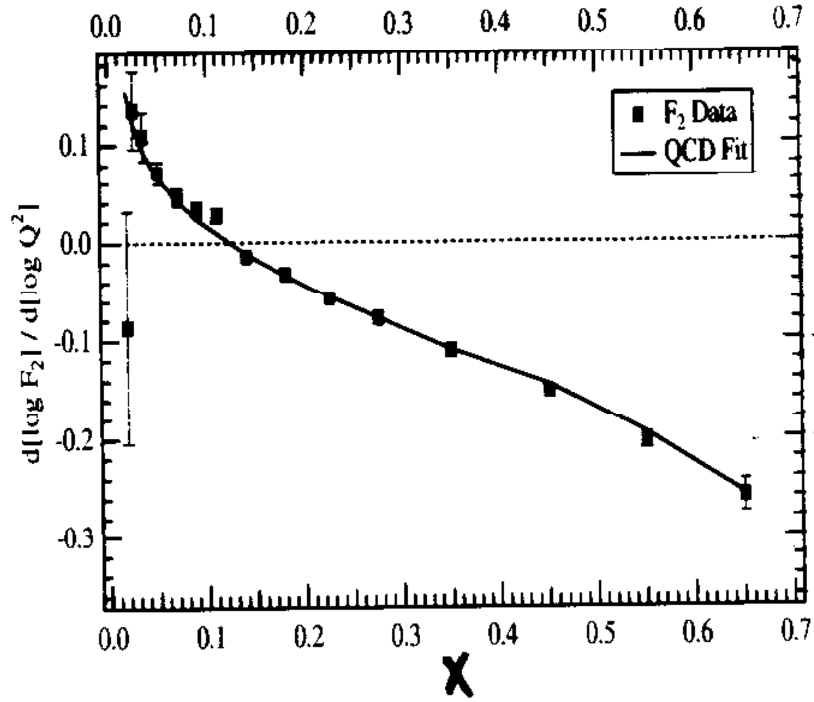
$\Lambda_{\overline{MS}}^{(4),NLO} = 381 \pm 23(\text{stat.}) \pm 58(\text{syst}) MeV$, ($F_2$ and xF_3, no systematics included in the fit)

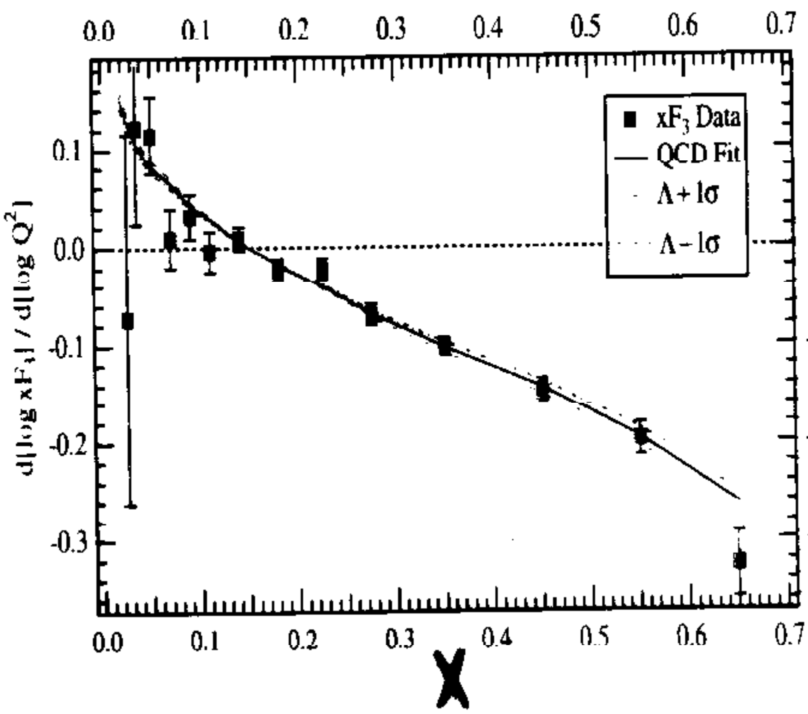
$\chi^2/\text{dof} = 190/164$

xF_3 only fit: $\Lambda_{\overline{MS}}^{(4),NLO} = 387 \pm 42 \pm 93$ MeV

$\chi^2/\text{dof} = 81/82$

QCD fit comparison with $d(F_2)/d[ln(Q^2)]$ and $d(xF_3)/d[ln(Q^2)]$





CCFR Global Systematic QCD fit

Use QCD to constrain the systematic uncertainties

1. Incorporate Systematic Uncertainties into the QCD fit
2. χ^2 fit to the theoretical prediction compared to data in x and Q^2
3. Systematics included introducing parameter δ_k in the fit:

$$\begin{aligned}\mathbf{F}^{diff} &= \mathbf{F}^{data} - \mathbf{F}^{theory} + \sum_k \delta_k(\mathbf{F}^k - \mathbf{F}^{data}) \\ \chi^2 &= (\mathbf{F}^{diff})\mathbf{V}^{-1}(\mathbf{F}^{diff})^T + \sum_k \delta_k^2.\end{aligned}$$

$\mathbf{F} = (F_2, xF_3)$ and $\mathbf{V} = (\sigma_{ij})$

4. $\mathbf{F}^k$ value of extracted SFs with kth systematic shifted by 1σ.

Systematic Uncertainties

Largest experimental contributions:

Systematic	Shift	$\delta(\Lambda_{\overline{MS}})$
Muon Energy	1%	32 MeV
Hadron Energy	1%	25 MeV
Hadron Energy shift	150 MeV	23 MeV

If systematics are included in the QCD fit:

Parameter	Fit Results	Parameter	Fit Results
$\Lambda_{\overline{MS}}$	$337 \pm 28\ MeV$	A_G	2.22 ± 0.34
η_1	0.805 ± 0.009	η_G	4.65 ± 0.68
η_2	3.94 ± 0.03	$\delta\left(C_{HAD}^{744}\right)$	0.95 ± 0.42
A_{NS}	8.60 ± 0.18	$\delta\left(C_{HAD}^{770}\right)$	0.28 ± 0.27
A_S	1.47 ± 0.04	$\delta\left(C_\mu\right)$	0.21 ± 0.18
η_S	7.67 ± 0.13	$\delta\left(\sigma^{\overline{\nu}}/\sigma^{\nu}\right)$	0.04 ± 0.50

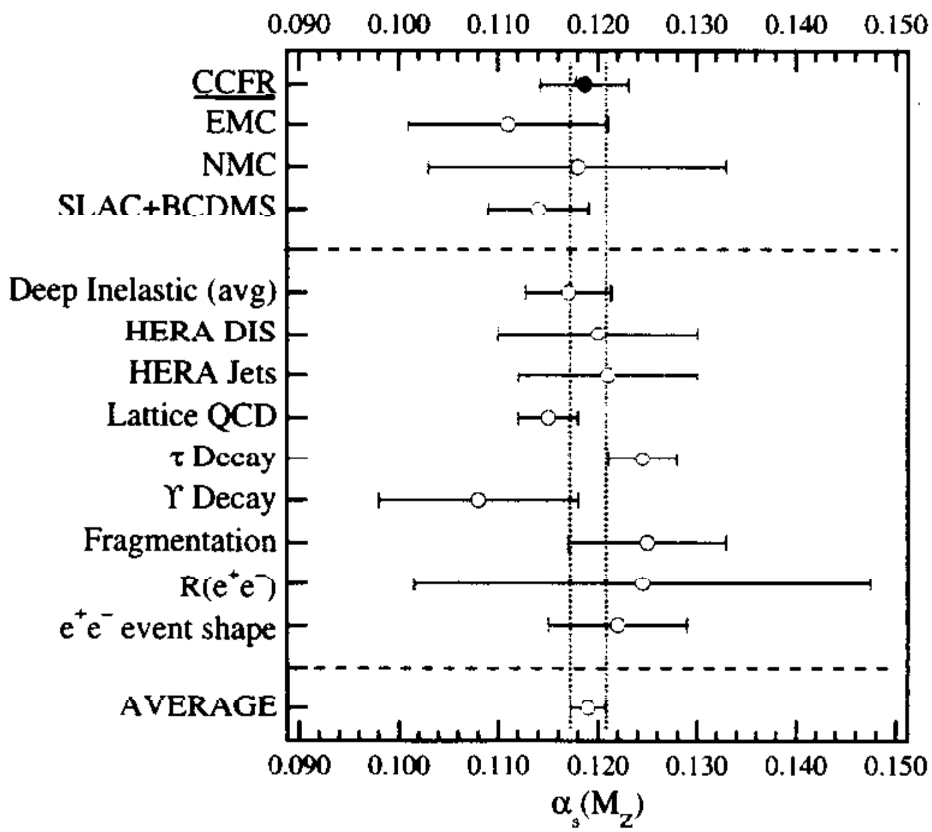
$\rightarrow$ units of $\sigma_{\text{systematic}}$

CCFR "Global Systematic" QCD fit Results

$$\Lambda_{\overline{MS}}^{(4),NLO} = 337 \pm 28(\mathrm{stat.} + \mathrm{syst.}) \pm 13(\mathrm{HT}) MeV$$

$$(\chi^2/DOF = 157/164)$$

$$\alpha_s^{NLO}(M_Z^2) = 0.119 \pm 0.002(\exp) \pm 0.001(HT) \pm 0.004(\mathrm{scale})$$



α_s from the Gross-Llewellyn-Smith Sum Rule

With Higher-Order pQCD corrections, GLS integral is

$$\int_0^1 xF_3(x,Q^2)\frac{dx}{x} = 3\left(1-\frac{\alpha_s}{\pi}-a(n_f)\left(\frac{\alpha_s}{\pi}\right)^2-b(n_f)\left(\frac{\alpha_s}{\pi}\right)^3\right)-\Delta HT$$

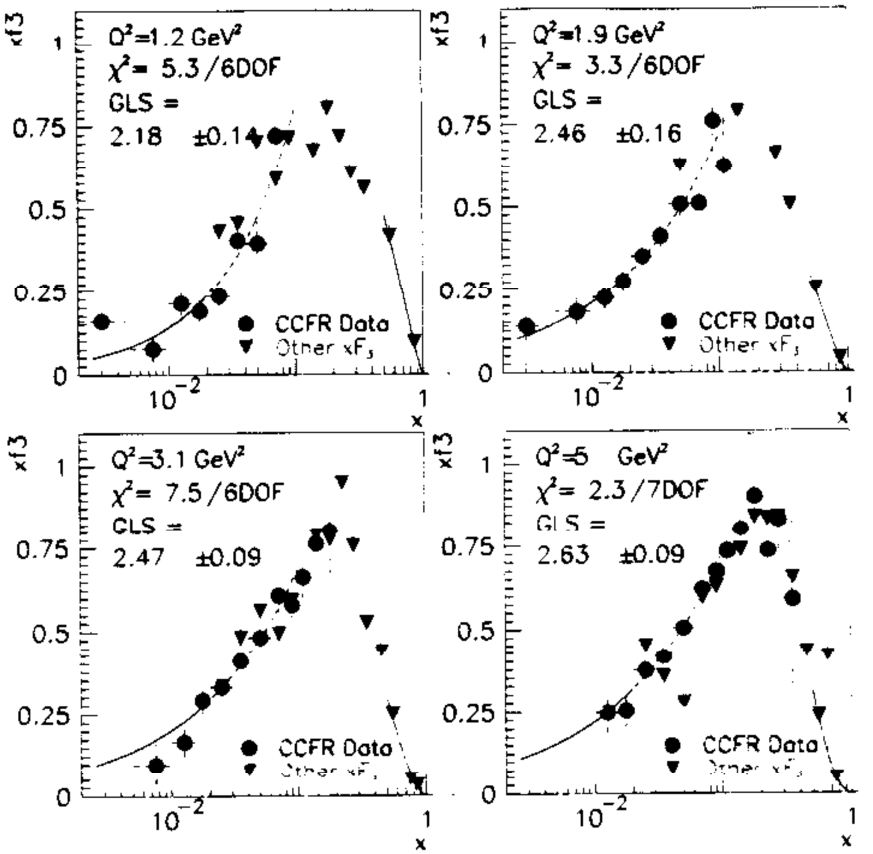
for $Q^2 = 3GeV^2$. $a \approx 3.3$. $b \approx 12$

ΔHT = Higher Twist Corrections $\left(\frac{0.27\pm 0.14}{Q^2}\right)$

Ref: Braun & Kolesnichenko, *Nucl. Phys.* **B283** (1987)

$$\boxed{\text{GLS Sum Rule}(Q^2) \Rightarrow \alpha_s(Q^2) \rightarrow \alpha_s(M_Z^2)}$$

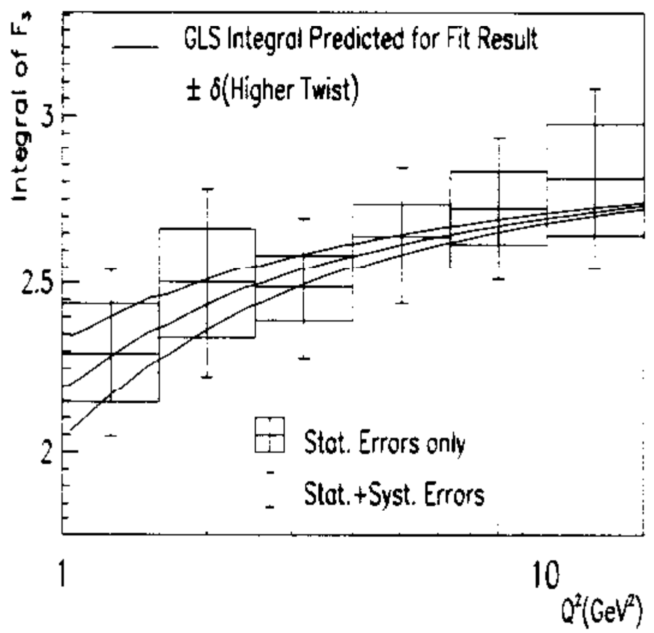
xF_3 vs x at low Q^2



- Use other ν−N DIS data - WA59, WA25, SKAT,FNAL-E180, BEBC, together with the CCFR data.
- Data fit to power-law for $x < 0.1$ and for $x > 0.5$
- Integrate using the fit for $x < 0.02$ and $x > 0.5$

Summary of Errors and Results

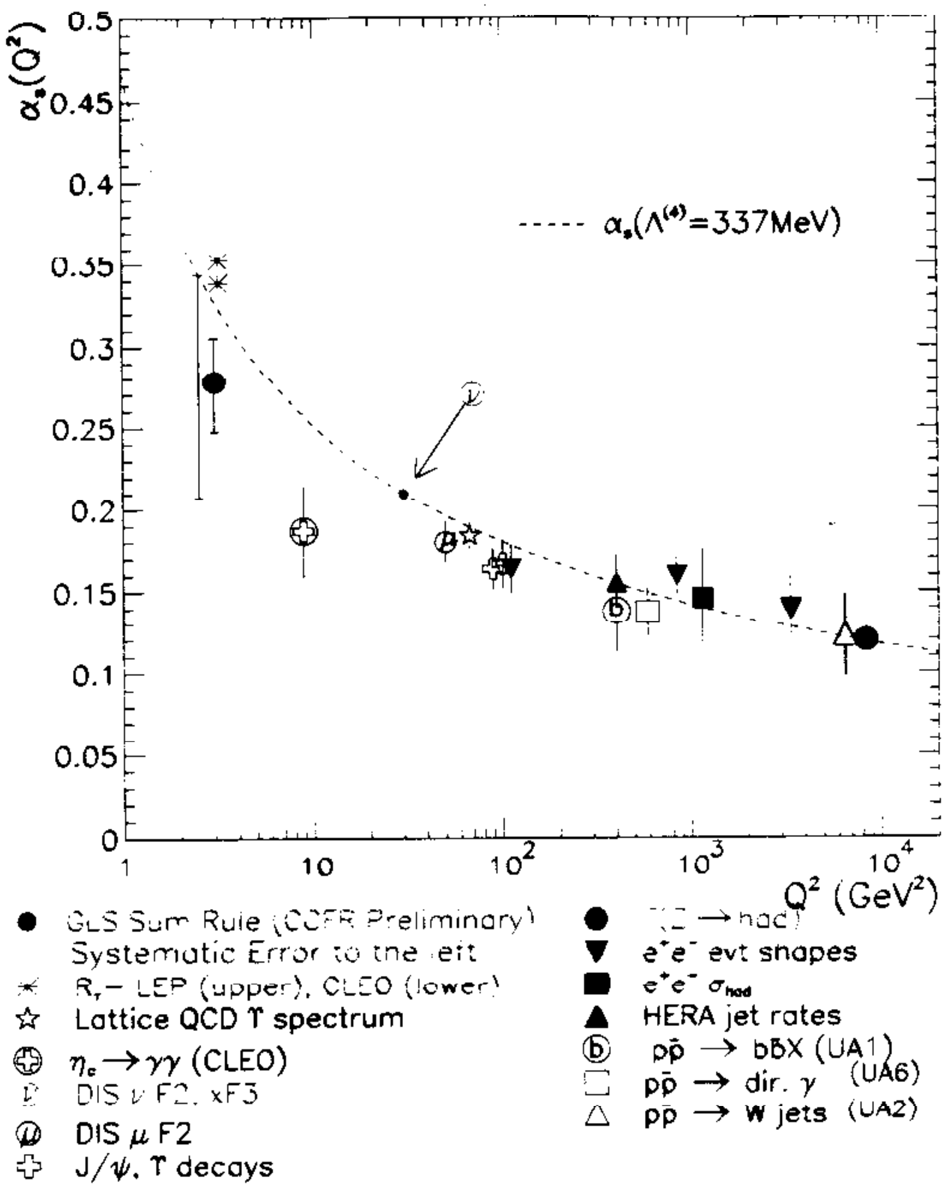
- Statistical Uncertainty : 0.005
- Experimental Systematics : 0.008
- Low x acceptance Model error : 0.008 (Preliminary)
- Renormalization Scale : 0.001
- Higher Twist : 0.005



$$\alpha_s(MZ^2) = 0.112^{+0.004}_{-0.005}(stat.)^{+0.006}_{-0.008}(syst.) \pm 0.008(Model)^{+0.004}_{-0.005}$$

Preliminary

World α_S



Summary

- $\Lambda_{\overline{MS}}^{(4),NLO}$ determined from QCD fit including systematic error matrix:

  $$\Lambda_{\overline{MS}}^{(4),NLO} = 337 \pm 28(stat. + syst.) \pm 13(HT)$$

  which corresponds to

  $$\alpha_s(M_Z^2) = 0.119 \pm 0.002(exp.) \pm 0.004(Theory)$$

  This is one of the most precise measurements of α_s

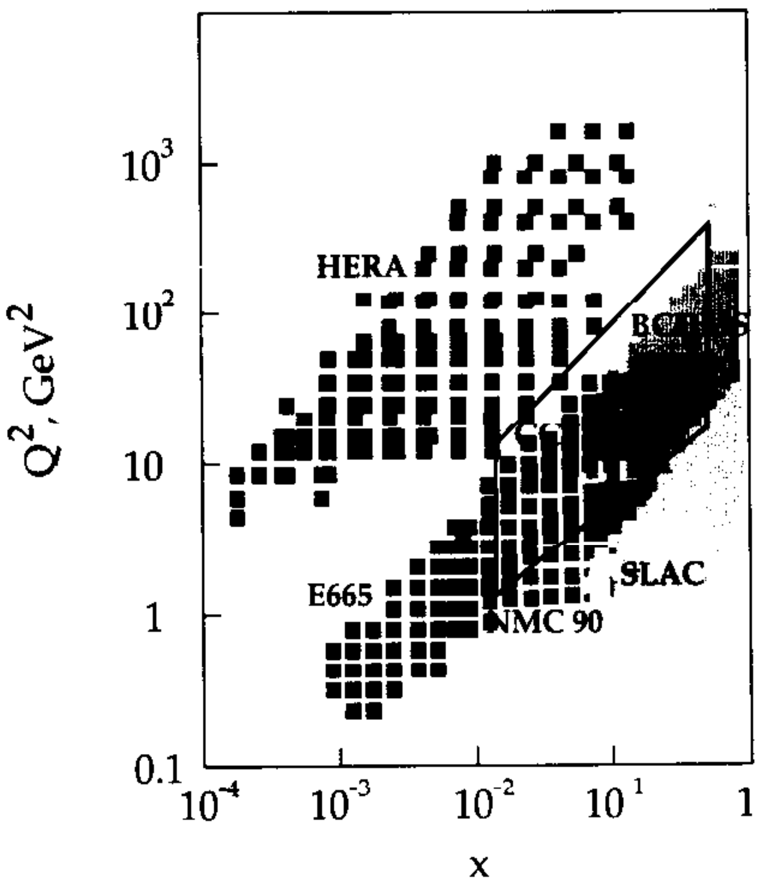
- NNLO α_s has been determined from GLS sum rule :

  $$\alpha_s(M_Z^2) = 0.112^{+0.011}_{-0.013}(combined)$$

  preliminary

- Improvements expected from NuTeV
  - Sign-Selected beam $\Rightarrow$ increase $\overline{\nu}$ statistics and eliminate ν $\overline{\nu}$ confusion at low-x
  - Continuous test beam $\Rightarrow$ better determination of E_H and E_μ calibration and resolution including time variations

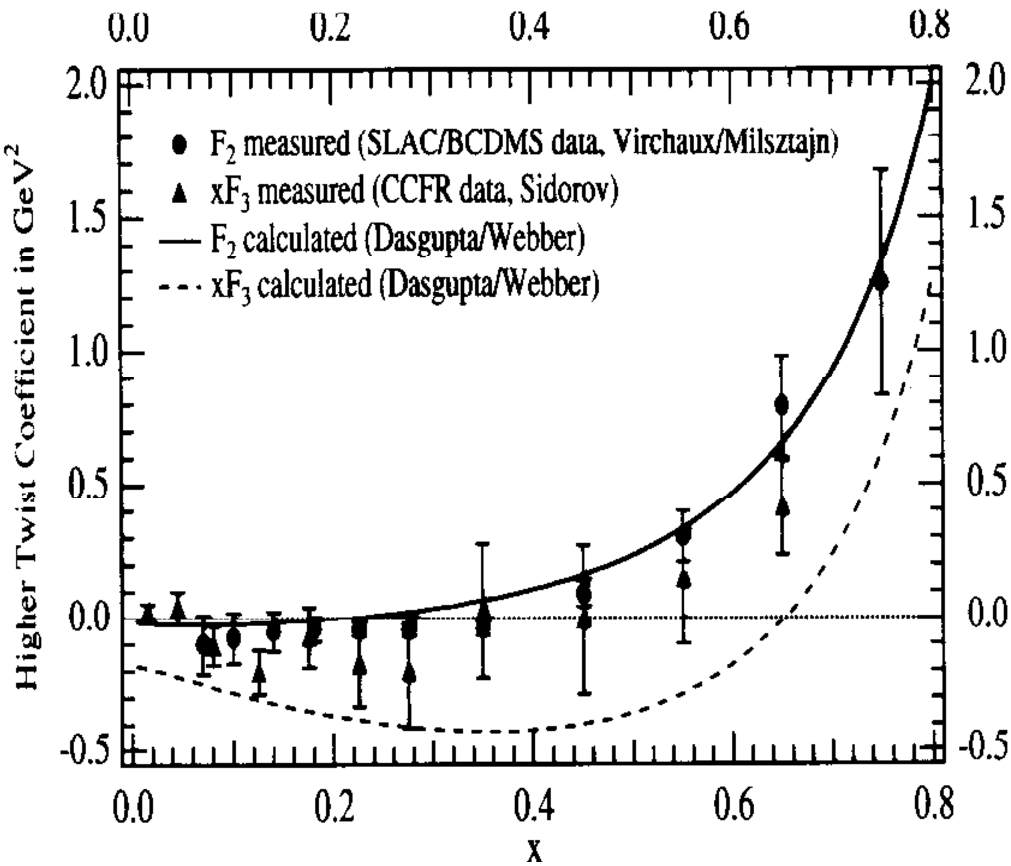
Kinematic region accessible to high statistics DIS experiments



$\Lambda^{(4),\,NLO}_{\overline{MS}} = 381 \pm 53$ MeV xF_3 only , $\chi^2/\text{dof} = 69/89$

Higher-Twist Effects

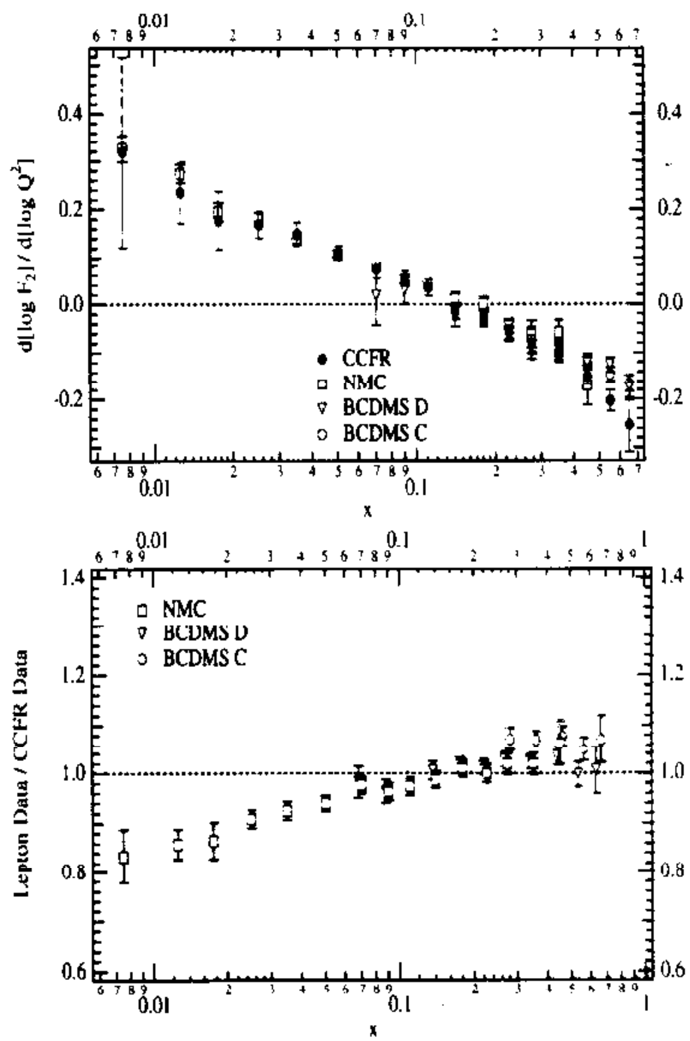
$$F^{measured} = F^{pQCD}\{1 + \frac{D_2(x)}{Q^2} + \frac{D_4(x)}{Q^4}\}$$

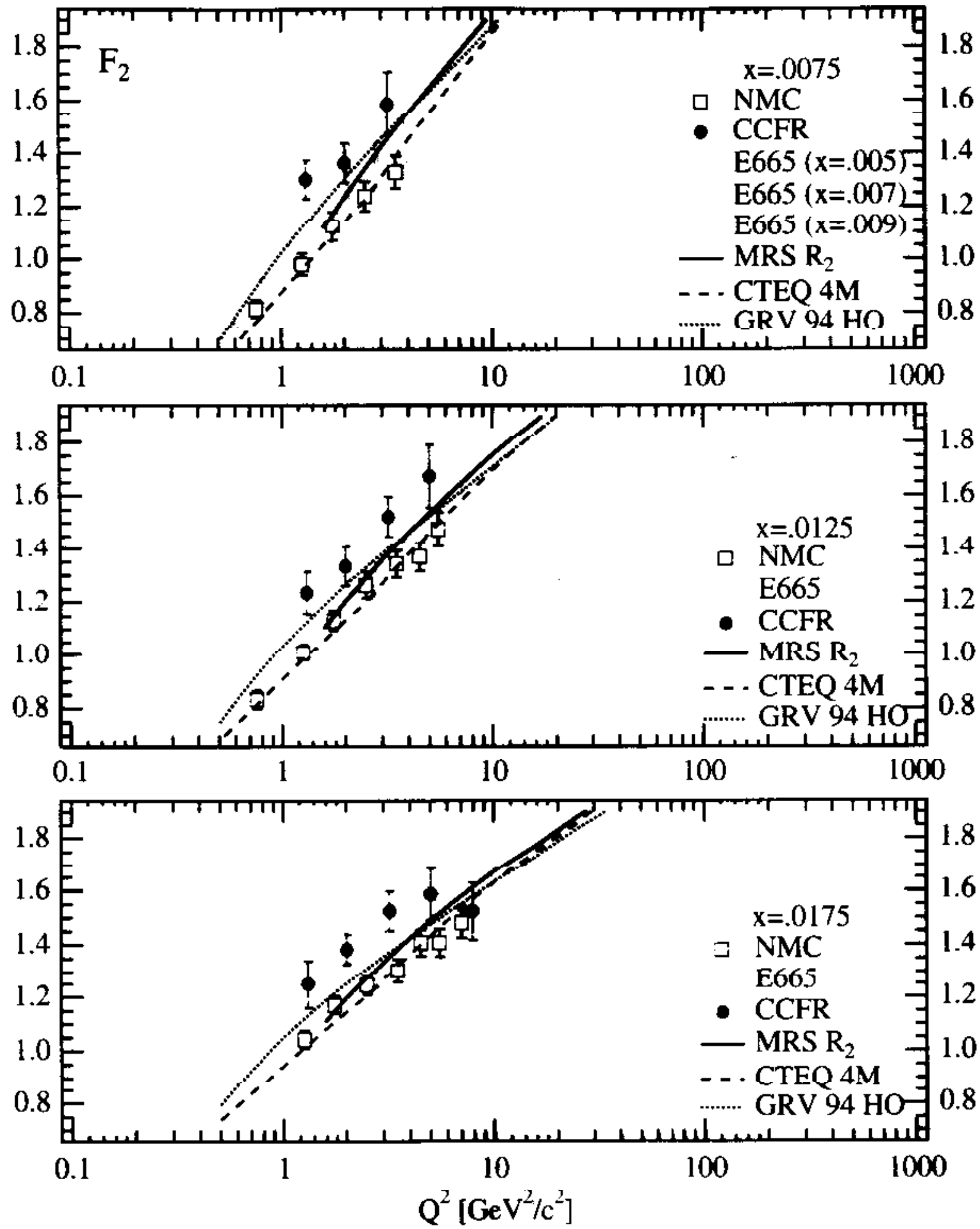


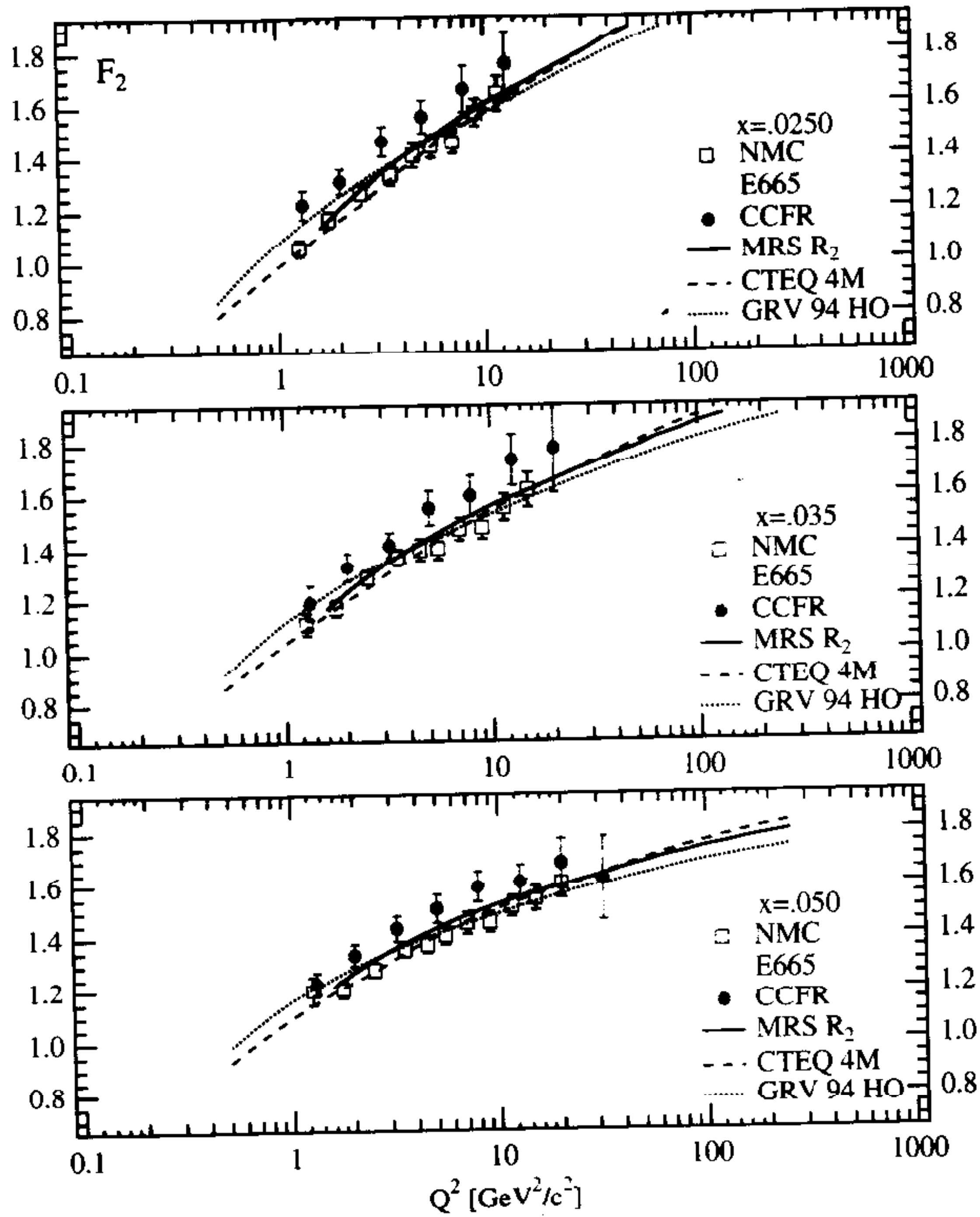
- D_2 from F_2: lower α_s than CCFR, xF_3 D_2 used previous CCFR SFs
- Central fit value with $\frac{1}{2}\times$ calculation. HT error using 0 and full contribution.

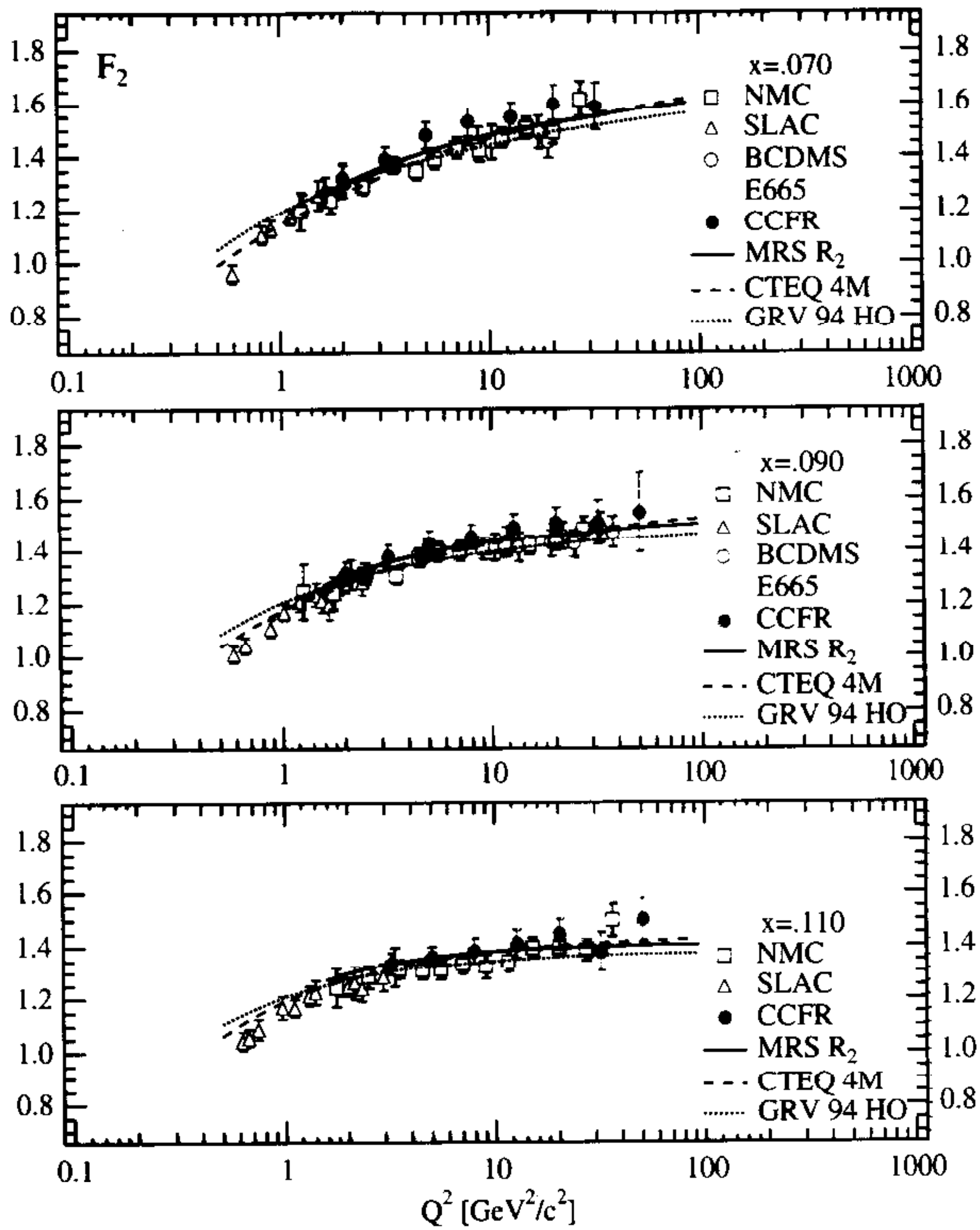
Comparison of CCFR F_2 logarithmic Q^2 slopes with charged-lepton scattering results

- Correct charged-lepton F_2 for quark-charge and nuclear effects
- Fit F_2 to a power law form: $F_2 = A \times (Q^2)^C$




F2
x=.0075
NMC
CCFR
E665 (x=.005)
E665 (x=.007)
E665 (x=.009)
MRS R2
CTEQ 4M
GRV 94 HO
x=.0125
NMC
E665
CCFR
MRS R2
CTEQ 4M
GRV 94 HO
x=.0175
NMC
E665
CCFR
MRS R2
CTEQ 4M
GRV 94 HO
Q2 [GeV2/c2]


F2
x=.0250
NMC
E665
CCFR
MRS R2
CTEQ 4M
GRV 94 HO
x=.035
NMC
E665
CCFR
MRS R2
CTEQ 4M
GRV 94 HO
x=.050
NMC
E665
CCFR
MRS R2
CTEQ 4M
GRV 94 HO
Q2 [GeV2/c2]


F_2
x=.070
NMC
SLAC
BCDMS
E665
CCFR
MRS R_2
CTEQ 4M
GRV 94 HO
x=.090
NMC
SLAC
BCDMS
E665
CCFR
MRS R_2
CTEQ 4M
GRV 94 HO
x=.110
NMC
SLAC
CCFR
MRS R_2
CTEQ 4M
GRV 94 HO
Q^2 [GeV^2/c^2]