Impact of Soft Resummation on Structure Functions

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CERN TH

1. Introduction
2. Soft resummation in the coefficient function for charged-current Deep Inelastic Scattering
3. Results for resummed structure functions
4. Preliminary comparison with NuTeV data
5. Conclusions and outlook

G.C. and A.D. Mitov, Nucl. Phys. B676 (2004) 346
G.C. and L. Magnea, in progress

For reliable structure function measurements, precise QCD calculations are necessary

Gluon radiation in Deep Inelastic Scattering

Two issues:

1) Soft-gluon radiation (large-x resummation)

2) Heavy quark production in DIS and consistent inclusion of quark mass effects

Soft resummation for massless quark production:

S. Catani and L. Trentadue, NPB327 (1989) 323

S. Catani, G. Marchesini and B.R. Webber, NPB349 (1991) 635

A. Vogt, PLB 497 (2001) 228

Soft resummation for heavy quark production in NC events:

E. Laenen and S. Moch, PRD 59 (1999) 0340027

More recently: soft resummation for heavy quark production in CC DIS

Kinematics

$$\nu_\mu(k)N(P) \to \mu(k')X(P')$$

Parton-level hard scattering process:

$$q_1(p_1)W(q) \to q_2(p_2)$$

$$p_1^2 = 0, \quad p_2^2 = m^2, \quad Q^2 = -q^2 \quad x = \frac{Q^2}{2P \cdot q} \quad y = \frac{P \cdot q}{P \cdot k}$$

$$P = \left(P^{(0)}, 0, 0, P^{(3)}\right), \quad p_1 = \left(p_1^{(0)}, 0, 0, p_1^{(3)}\right) \quad z = \frac{p_1^{(0)} + p_1^{(3)}}{P^{(0)} + P^{(3)}}$$

M: target mass

Large Q^2 ($m/Q \ll 1$; $M/Q \ll 1$):

$$0 < x \leq 1 \quad , \quad x = z$$

Heavy quark q_2 and small Q^2:

m and M taken into account

$$x = \frac{\lambda z}{1 - M^2\lambda^2 z^2/Q^2} \quad \lambda = \frac{Q^2}{Q^2 + m^2} \quad 0 < x \leq \frac{\lambda}{1 - M^2\lambda^2/Q^2}$$

Structure functions $\mathcal{F}_i$ as convolution of $\overline{\mathrm{MS}}$ coefficient functions and parton distribution functions

$$\mathcal{F}_i(x,Q^2) = \int_z^1 \frac{d\xi}{\xi}\left[C_i^q(\xi,\mu^2,\mu_F^2,\lambda) q_1\left(\frac{z}{\xi},\mu_F^2\right) + C_i^g(\xi,\mu^2,\mu_F^2,\lambda) g\left(\frac{z}{\xi},\mu_F^2\right)\right],$$

Differential cross section in CC DIS is parametrized in terms of three structure functions:

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 ME}{\pi(1+Q^2/m_W^2)^2}\left\{y^2 xF_1 + \left[1-\left(1+\frac{Mx}{2E}\right)y\right]F_2 \pm y\left(1-\frac{y}{2}\right)xF_3\right\}$$

Relation between F_i and $\mathcal{F}_i$

$$F_1 = \mathcal{F}_1 \qquad F_2 = \frac{2x}{\lambda\rho^2}\mathcal{F}_2 \qquad F_3 = \frac{2}{\rho}\mathcal{F}_3$$

$$\rho = \sqrt{1+\left(\frac{2Mx}{Q}\right)^2}$$

NLO $\overline{\mathrm{MS}}$ coefficient function:

M. Glück, S. Kretzer and E. Reya, PLB 380 (1996) 171

Soft-gluon radiation

Quark-initiated coefficient function contains terms which get large once $z \to 1$ (soft-gluon emission)

$$C^{\rm soft}(z,\mu_F^2,\lambda) = 2C_F \left\{ 2\left[\frac{\ln(1-z)}{1-z}\right]_+ - \left[\frac{\ln(1-\lambda z)}{1-z}\right]_+ + \frac{1}{4}\left[\frac{1-z}{(1-\lambda z)^2}\right]_+ + \frac{1}{(1-z)_+}\left(\ln\frac{Q^2+m^2}{\mu_F^2} - 1\right)\right\}$$

In Mellin space:

$$f_N = \int_0^1 dz z^{N-1} f(z)$$

$$\frac{1}{(1-z)_+} \to \ln N \qquad \left[\frac{\ln(1-z)}{1-z}\right]_+ \to \ln^2 N \quad \text{for } N\to\infty$$

Massive case: $m/Q \sim \mathcal{O}(1)$, $\lambda = Q^2/(Q^2+m^2) < 1$, $\lambda z \simeq \lambda$

$$C_N^{\rm soft}|_{\lambda<1} = 1 + \frac{\alpha_S(\mu^2)C_F}{\pi}\left\{\ln^2 N + \left[2\gamma_E + 1 - \ln\frac{T^2}{\mu_F^2}\right]\ln N\right\}$$

$$T^2 = m^2\left(1+\frac{Q^2}{m^2}\right)^2$$

Massless approximation: $m/Q \ll 1$, $\lambda \simeq 1$, $\lambda z \to 1$

$$C_N^{\rm soft}|_{\lambda=1} = 1 + \frac{\alpha_S(\mu^2)C_F}{\pi}\left\{\frac{1}{2}\ln^2 N + \left[\gamma_E + \frac{3}{4} - \ln\frac{Q^2}{\mu_F^2}\right]\ln N\right\}$$

Gluon fusion coefficient function: no soft-enhanced terms

$g \to q\bar{q}$ splitting is not soft divergent

Soft resummation in the coefficient function

Heavy quark in the final state:

$$\Delta_N = \exp\left\{ \int_0^1 dz \frac{z^{N-1}-1}{1-z}\left[\int_{\mu_F^2}^{T^2(1-z)^2} \frac{dk^2}{k^2} A\left[\alpha_S(k^2)\right] + S\left[\alpha_S\left(T^2(1-z)^2\right)\right]\right]\right\} = \exp\left[\log N g_1 + g_2\right]$$

$k^2 = (p_1+p_g)^2(1-z) = 2E_g^2(1-\cos\theta_{1g}) \simeq E_g^2 \sin^2\theta_{1g} \quad T^2 = m^2\left(1+Q^2/m^2\right)^2$

$$A(\alpha_S) = \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n A^{(n)} \;;\; A^{(1)} = C_F \;;\; A^{(2)} = \frac{1}{2}C_F\left[C_A\left(\frac{67}{18}-\frac{\pi^2}{6}\right)-\frac{5}{9}n_f\right]$$

$$S(\alpha_S) = \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n S^{(n)} \;;\; S^{(1)} = -C_F$$

$g_1 \log N$ **resums LL** $A^{(1)}$ **:** $\alpha_S \log^2 N, \alpha_S^2 \log^4 N \ldots \alpha_S^n \log^{n+1} N;$
g_2 **resums NLL** $A^{(2)}, S^{(1)}$ **:** $\alpha_S \log N, \alpha_S^2 \log^2 N \ldots \alpha_S^n \log^n N$

Light quark in the final state $(m/Q \ll 1)$:

$$\Delta_N|_{m/Q\to 0} = \exp\left\{\int_0^1 dz \frac{z^{N-1}-1}{1-z}\int_{\mu_F^2}^{Q^2(1-z)}\left[\frac{dk^2}{k^2}A\left[\alpha_S(k^2)\right] + \frac{1}{2}B\left[\alpha_S\left(Q^2(1-z)\right)\right]\right\}\right]$$

$$B(\alpha_S) = \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n B^{(n)} \quad B^{(1)} = -\frac{3}{2}C_F$$

Matching resummation and $\mathcal{O}(\alpha_S)$ exact calculation

$$H_N^{\rm res} = \Delta_N - [\Delta_N]_{\alpha_S} + C_N(\alpha_S)$$

Charm quark production at HERA and NuTeV

Hard processes: $dW \to c \;\; sW \to c$

$$q_1(z,Q^2)|_{\rm HERA} = |V_{cd}|^2 d(z,Q^2) + |V_{cs}|^2 s(z,Q^2)$$

$$q_1(z,Q^2)|_{\rm NuTeV} = |V_{cd}|^2 \frac{d(z,Q^2)+u(z,Q^2)}{2} + |V_{cs}|^2 s(z,Q^2)$$

$u_p = d_n$, $s_p = s_n$, $V_{cd} \simeq 0.223$, $V_{cs} \simeq 0.974$

$sW \to c$: **strange quark density**

Dimuon events at NuTeV: $\nu_\mu s \to \mu^- cX$, $c \to \mu^+ X'$
M. Goncharov et al., PRD 64 (2001) 112006

NuTeV: small Q^2 in CC events is possible

$Q^2 = 2$ **and** 5 GeV^2 **at NuTeV: massive calculation**

HERA: $Q^2 \geq 100$ **GeV**^{2} **in CC events** $\;Q^2 = P^2_{T,h}/(1-y)$

$Q^2 = 300$ **and** 1000 GeV^2**: massless calculation**

HERA I: 1500 **CC events;** ~ 150 **charm events;** $\sim 10\%$ **decay into** $K\pi\pi$, 50% **reconstructed, i.e.** ~ 10 **events (C. Kiesling)**

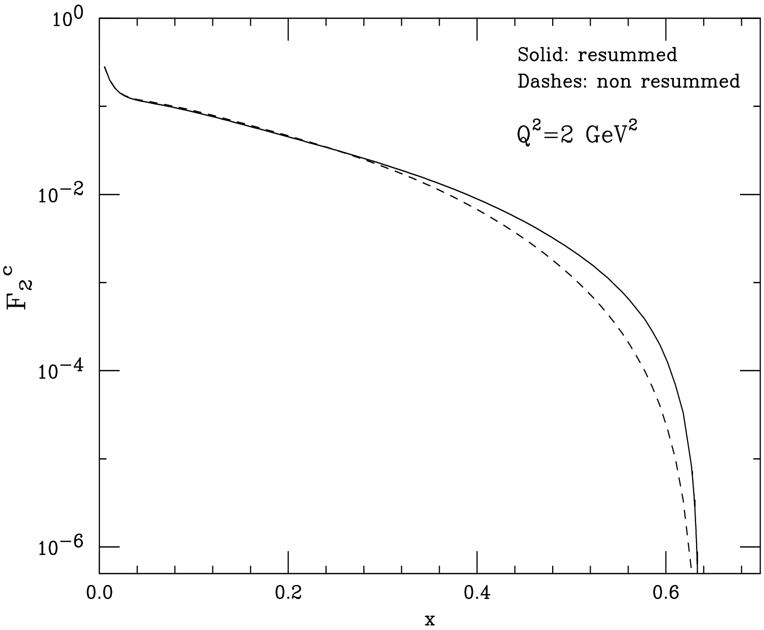
HERA II: 10 **times more statistics,** ~ 100 **charm CC events**

CTEQ NLO $\overline{\rm MS}$ parton distribution functions (CTEQ6M)

Possible future pdf fits with resummed coefficient function

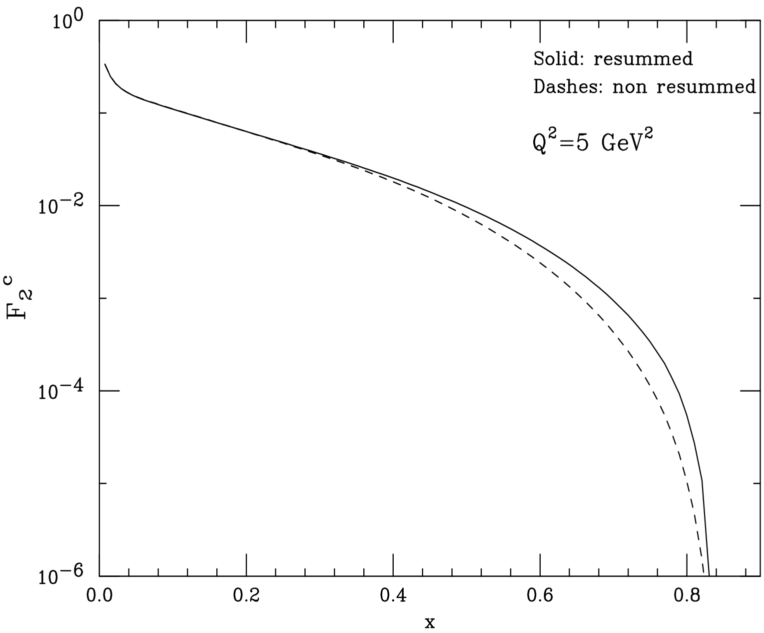
$\Lambda_4^{\overline{\rm MS}} = 326$ **MeV,** $\Lambda_5^{\overline{\rm MS}} = 226$ **MeV,** $\alpha_S(m_Z) = 0.118$,
$m_c = 1.3$ GeV, $m_b = 4.5$ GeV

Results at NuTeV



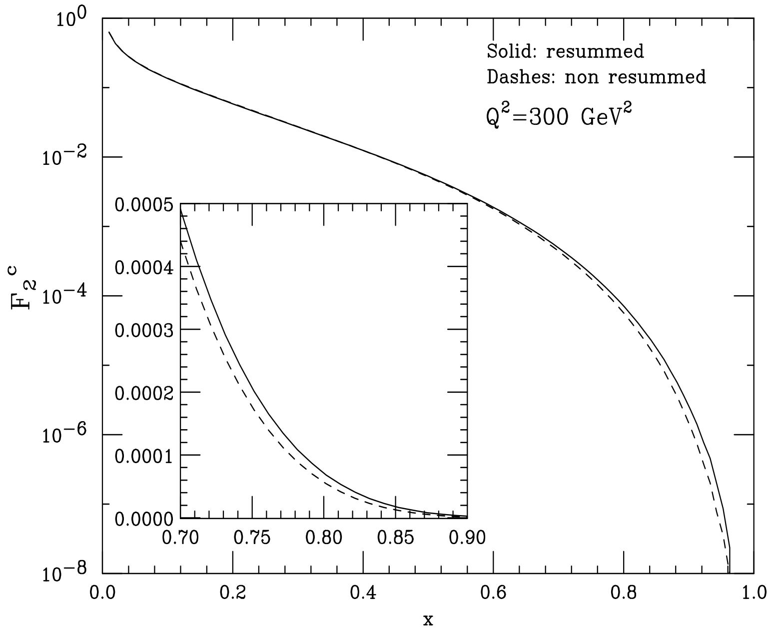
$Q^2 = 2$ GeV^2, $\mu = \mu_F = Q$

$x = 0.5$: **factor of 2;** $x = 0.6$: **factor of 5**



$Q^2 = 5$ **GeV^2**, $x = 0.7$: **factor of 2;** $x = 0.8$: **factor of 5**

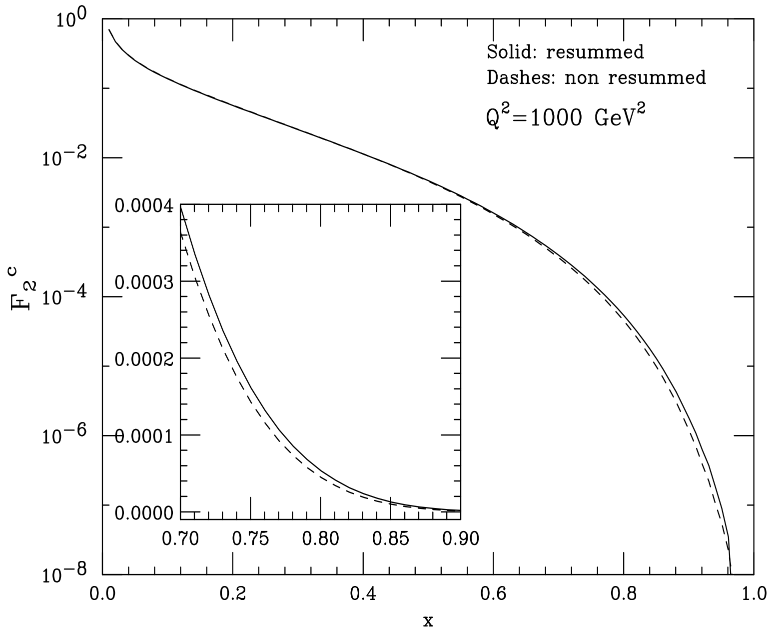
Results at HERA



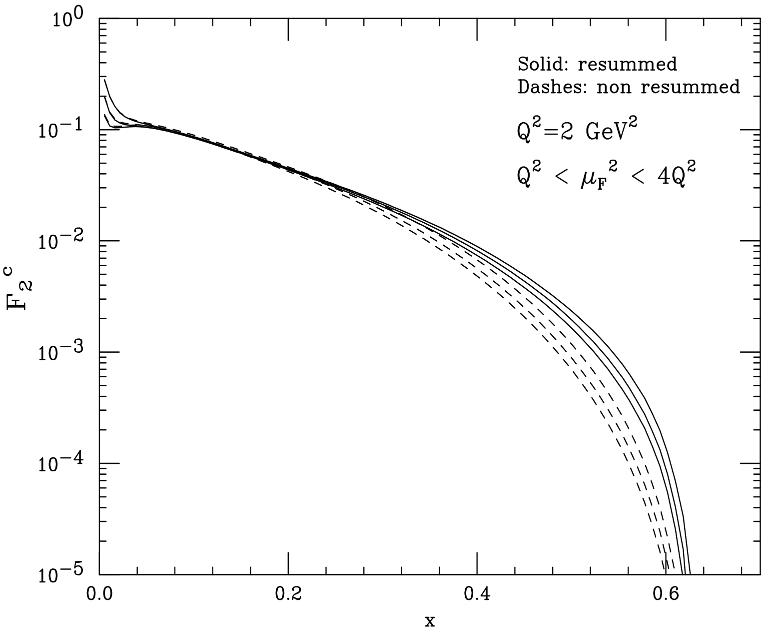
Small impact of resummation

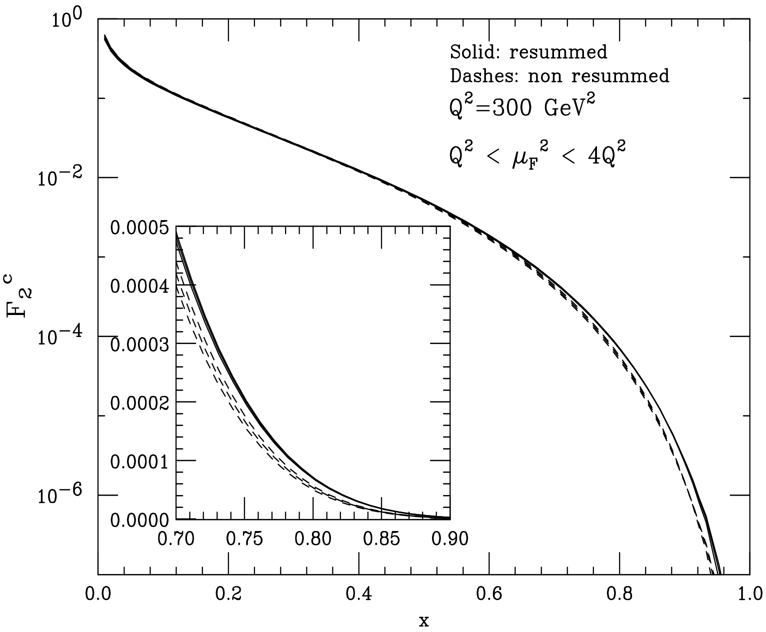
$\alpha_S(2\ \mathrm{GeV}^2) \simeq 3\ \alpha_S(300\ \mathrm{GeV}^2)$

$x > 0.6$: **effect of** $10 - 20\%$



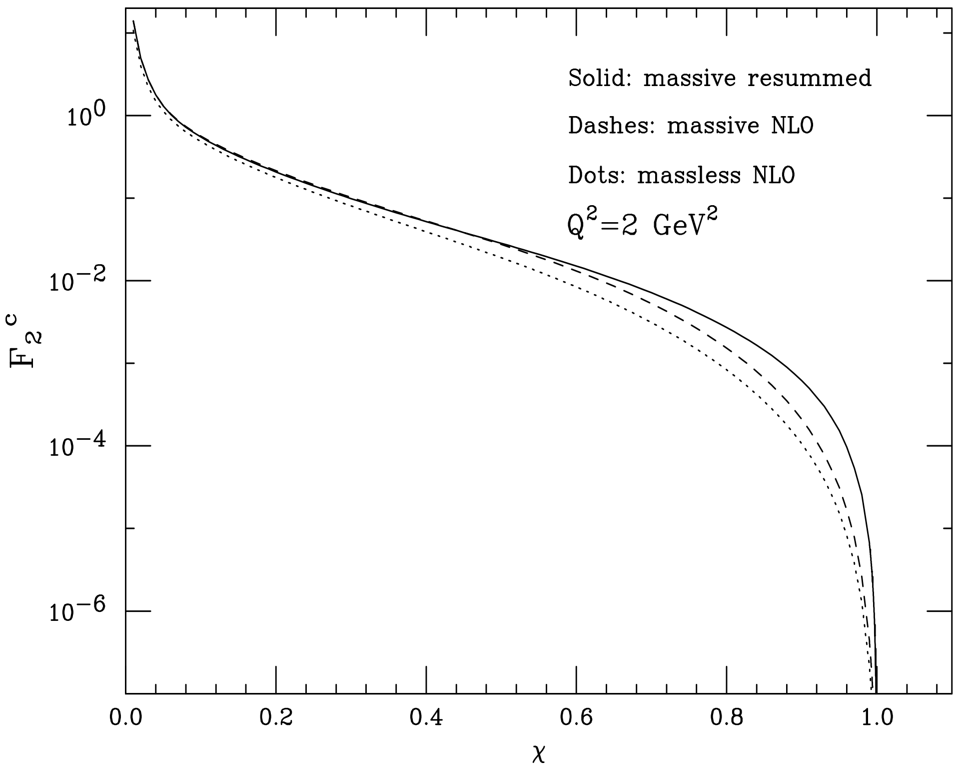
Dependence on the factorization scale





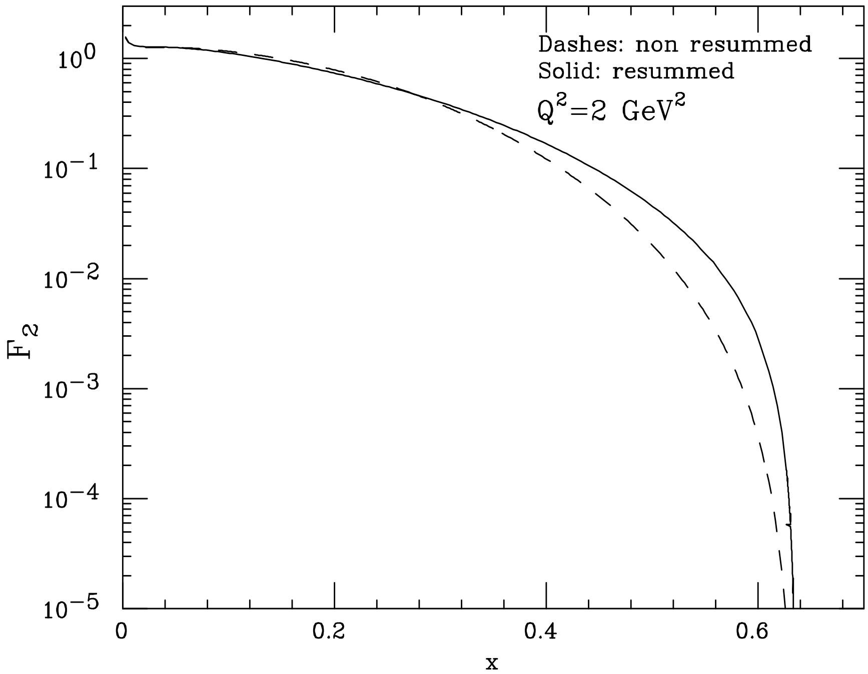
Smaller dependence on factorization scales after soft resummation

Comparison of soft-gluon and mass effects

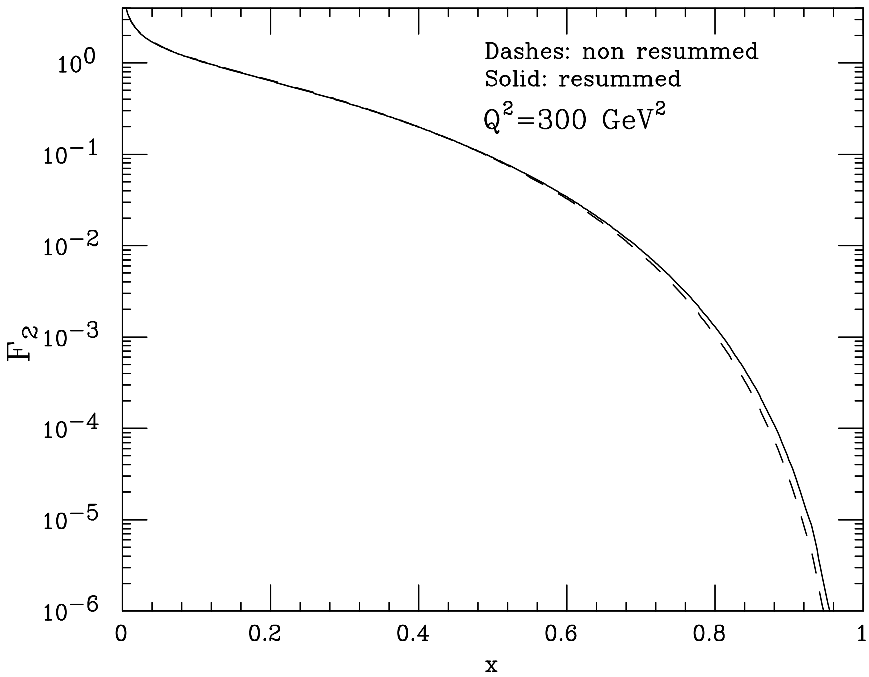


At large x soft-resummation effects are larger than mass corrections

Inclusive structure functions

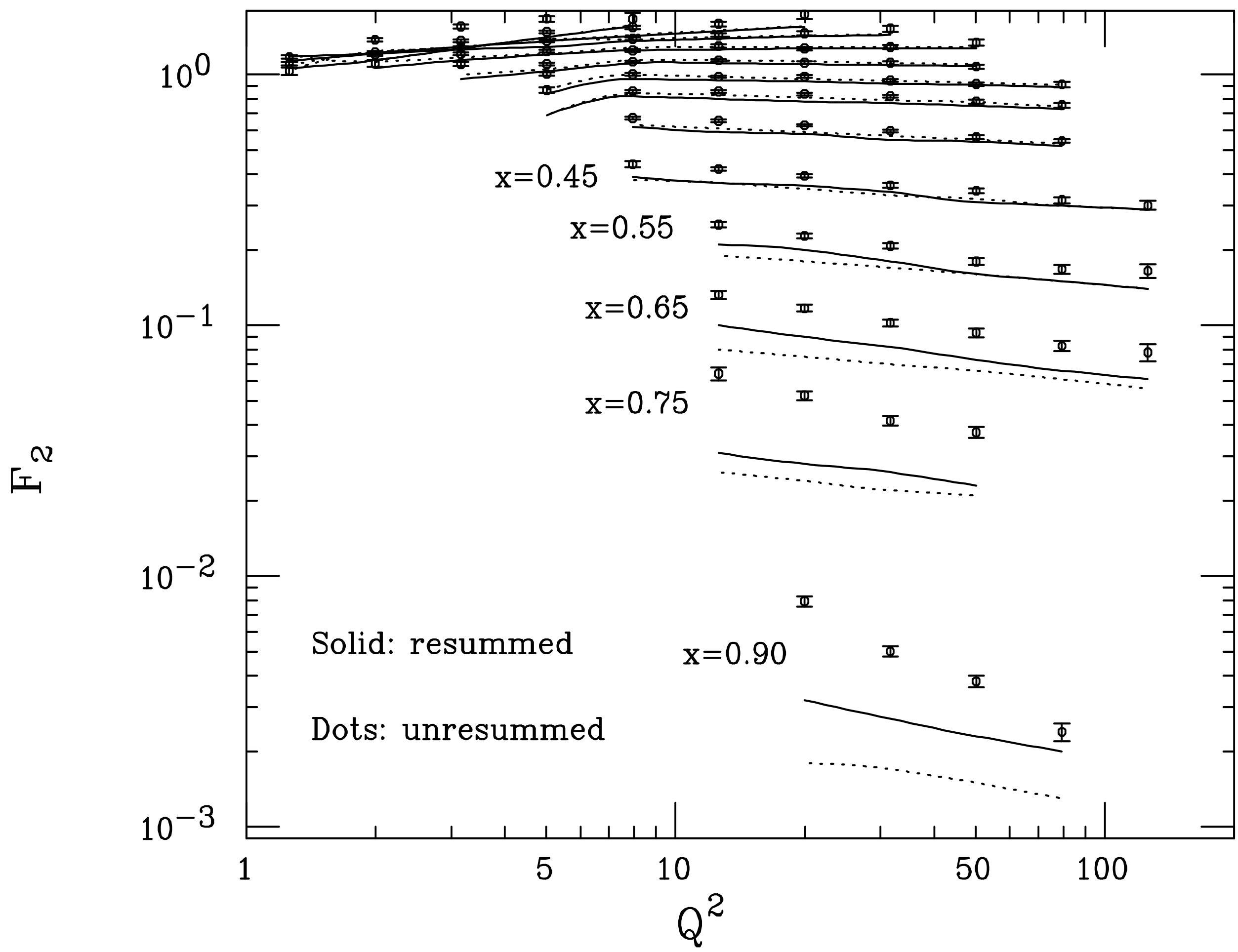


$x = 0.5$: **factor of 2;** $x = 0.6$: **factor of 8**



$x = 0.8$: 20%; $x = 0.9$: 60%

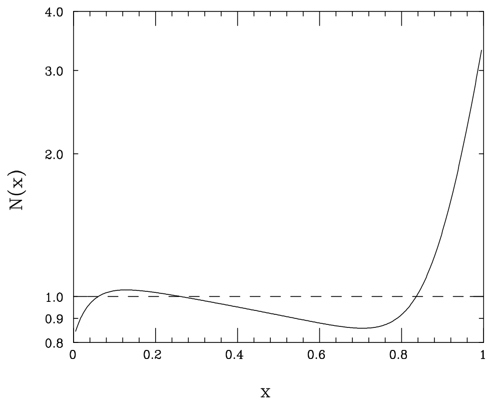
Comparison with NuTeV data (NLO pdf)



Nuclear correction factor:

$N(x) = 1.10 - 0.36\,x - 0.28\exp(-21.94\,x) + 2.77\,x^{14.41}$

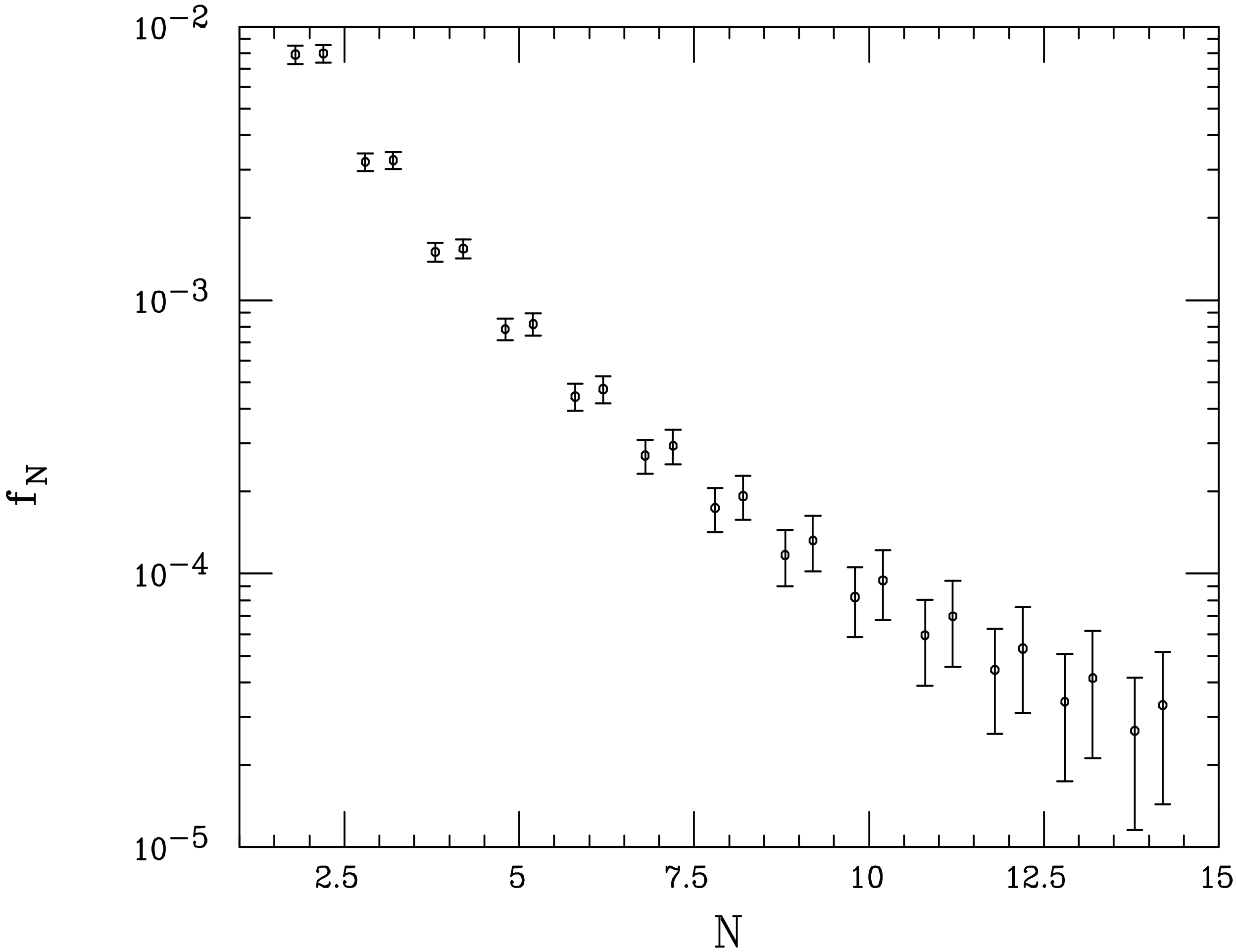
W. Seligam, Ph.D. Thesis, fit to F_2^{Fe}/F_2^D



Preliminary fits of non-singlet pdfs in moment space using BCDMS and NMC neutral-current DIS data

S. Forte, L. Garrido, J.I. Latorre, A. Piccione,
Neural network parametrization of DIS structure functions
JHEP 0205 (2002) 062

$Q^2 = 25$ GeV^2



Conclusions and outlook

Soft-gluon resummation in CC DIS coefficient function to NLL accuracy

Results for massive quarks and massless approximation

Charm-quark and inclusive structure functions at NuTeV and HERA

Big effect of resummation at small Q^2

Smaller dependence on factorization scale

Comparison with NuTeV data

In progress:

Fits of parton densities with resummed coefficient function for CC and NC DIS

We shall consider structure function data from NuTeV, HERA, BCDMS and NMC