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A Remark on the Q^2 Evolution of Intrinsic Charm in the Proton

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Abstract

The Q^2 evolution of the charmed structure function ("Intrinsic Charm") of the proton was considered. It is shown that the numerical results of the paper [6] overestimate the QCD evolution of the heavy quark distribution inside the proton about 2.5 times. This observation leads to result that QCD evolution of the intrinsic charm structure function can in practice be neglected at $x_B \geq 0.1$. The main effect comes from the threshold behaviour ("mass corerctions" to the structure function) of the charm distribution. The correct calculations agree better both with the physical expectations and with the experimental data of the EMC collaboration on diffractive charm production in μN–scattering. Fit to the EMC data gives the IC normalization equal to 0.5%. It is concluded that the contribution from neutral current scattering on the intrinsic charmed quark should significantly exceed the contribution from photon–gluon fusion process at small values of the momentum transfer, $Q^2 \leq 20\,GeV^2$ and $x_B \geq 0.1$ and can be observed at HERA collider.

1 Introduction

The results of the EMC Collaboration on muon–nucleon scattering [1] showed that there exists a visible excess of the charmed particles yield at $x \geq 0.15$ and $Q^2 \leq 40\ GeV^2$ over the conventional photon–gluon fusion (PGF) model expectations. Evidence for an excess of charm production at high x was also found in hadron–hadron collisions [2].

Following the experimental results on diffractive production of charmed particles the existence of the so called "intrinsic charm" (IC) in the nucleon has been suggested, i.e. there is a non–zero probability to find the $|\,uud\bar{c}c>$ component in the nucleon Fock wave function. Such a $\bar{c}c$ pair is created nonpertubatively "*before*" the interaction in distinction to "extrinsic charm" created by a large momentum transfer from the photon to the proton in the scattering process. The standard pertubative contribution in the charmed structure function of the proton is being described by the PGF mechanism (Fig.1(a), 1(b)). At the same time a nonpertubative charmed component of the proton will lead to the direct scattering of the electron on the charmed quark from the proton sea (Fig.1(c)) giving a charmed current jet in the final state.

The first theoretical estimate for the charmed particles production due to nonpertubative charm component inside the proton has been made by S.Brodsky et al. in [5] using old–fashioned pertubation theory to obtain the momentum distribution of c component:

$$c(x) \;=\; 18\,x^2\,\{\,\frac{1}{3}\,(1-x)\,(1\,+\,10x\,+\,x^2)\,+\,2x\,(1\,+\,x)\,\ln x\}, \qquad (1)$$

with the normalization of 1% for sum of $\bar{c}$ and c quark. This distribution is much harder than the distribution of the light sea u and d quarks. If the quarks inside the nucleon should

[1] supported by the Deutsche Forschungsgemeinschaft (DFG) and DESY

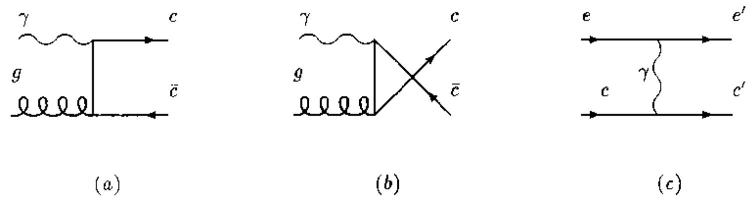

Figure 1: The diagrams contributing to the charm structure function. (a),(b) photon–gluon fusion; c) the zeroth–order diagram for the electron scattering on the intrinsic charmed quark.

"stay together", i.e., they should have the same velocity, it is clear, that a massive charmed quark should carry a larger fraction of the proton momentum than the light quarks. From Eq.(1) one obtains for the average x of charmed quarks the value $< x > \approx \frac{2}{7}$ to be compared with $< x > \approx \frac{1}{7}$ for light sea quarks.

The possibility to observe the ep scattering on the intrinsic charm (the diagram (c) in the Fig.1) at the HERA collider has been analyzed in [3, 4]. The calculations made in [3, 4] show that it is possible to separate the intrinsic charm contribution from the ordinary photon–gluon fusion contribution in the total charm yield within the range $10 \leq Q^2 \leq 10^3\ GeV^2$ where Q^2 is the momentum transfer squared. The authors of papers [3, 4] used the standard $\log\log$ approximation for extrapolating the numerical results on c quark evolution from paper [6], in which the sub–leading corrections to the structure function of the c quark were determined. Such a $\log\log$ behaviour follows from the ordinary evolution equations and is not necessarily correct for heavy quarks. The mass corrections, coming from non–zero charm and nucleon masses, were also neglected in [3, 4]; they play a very important role [6] at sufficiently low Q^2, where the main part of the total cross–section is found.

In the present note the results of a careful check of the numerical calculations of the paper [6] are presented and it is shown that the original results of [6] overestimate the QCD evolution of the intrinsic charmed quarks structure function. The correct calculations lead to a much slower Q^2 evolution of the c–quark structure function and allow to improve the agreement of the IC model with the experimental data. The calculations presented here are also in better agreement with the expectations for the QCD evolution of heavy quarks.

The question about the Q^2 evolution of heavy quarks is greater general interest, because the standard Altarelli–Parisi evolution equations are valid in leading order of the pertubation theory for massless partons only. There are no detailed experimental data yet to study the behaviour of the heavy quark distributions (if they do exist). HERA gives the opportunity to investigate this problem over a large range in Q^2.

2 Sub–leading corrections to IC structure function

For the sake of clarity we first recapitulate the main results of paper [6], where the sub–leading corrections to IC structure function $F_2^c\,(x, Q^2)$ have been calculated. These corrections come from two sources. The first one results from the nonzero masses of the proton and c quark.

The second source are the first-order QCD radiative corrections (see Fig.2).

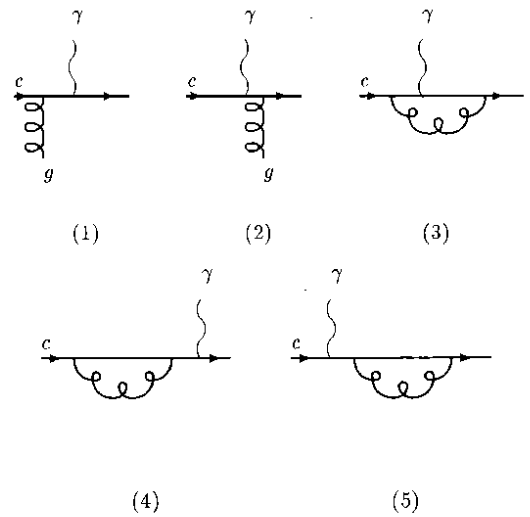

Figure 2: $O(\alpha_s)$ corections to the intrinsic charm distribution: (1), (2) — gluon bremsstrahlung and (3), (4), (5) — virtual gluon corrections. The diagrams (4) and (5) do not contribute in the on-shell renormalization scheme.

The diagrams (4) and (5) in Fig.2 are canceled if one chooses the on-shell renormalization scheme. We follow [6] and give explicitly the final formulae for mass and radiative corrections to the c quark structure function for further references.

- **mass corrections**

The form of the IC structure function with mass corrections only is (the authors of [6] extended the method suggested in paper [7]):

$$F_2^{c(0)}(x) = \frac{8x^2}{9(1+4\rho x^2)^{\frac{3}{2}}}\Big[\frac{(1+4\lambda)}{\zeta} + 3\,\hat{g}(\zeta,\gamma)\Big], \tag{2}$$

where,

$$\hat{g}(\zeta,\gamma) = \frac{2\rho x}{1+4\rho x^2}\int_\zeta^\gamma dt\,\frac{c(t,\gamma)}{t}(1-\frac{\lambda}{\rho t^2})[1+2\rho x t+\frac{2\lambda x}{t}]. \tag{3}$$

Function $c(t,\gamma)$ is being determined by:

$$c(t,\gamma) = \begin{cases} c(t) - \frac{t}{\gamma}c(\gamma), & t \le \gamma \\ 0, & t \ge \gamma. \end{cases}$$

The parameters ρ, ζ, $\hat{x}$, λ, γ are the following:

$$\begin{aligned} \rho &= \tfrac{m_p^2}{Q^2}; & \lambda &= \tfrac{m_c^2}{Q^2}; \\ \gamma &= \tfrac{2a\hat{x}}{1+\sqrt{1+4\rho\hat{x}^2}}; & \hat{x} &= \tfrac{1}{1+4\lambda-\rho}; \\ \zeta &= \tfrac{2ax}{1+\sqrt{1+4\rho x^2}} & a &= \tfrac{\sqrt{1+4\lambda}+1}{2} \end{aligned} \tag{4}$$

- **radiative corrections**

The expression for the first-order radiative corrections has the form:

$$\begin{aligned} \sigma_2^{(1)}(z,\lambda) &= \tfrac{2\alpha_s}{3\pi}\delta(1-z)\,\{4\ln\lambda - 2 + \sqrt{1+4\lambda}\,L \\ &+ \tfrac{(1+2\lambda}{\sqrt{1+4\lambda}}[3L^2+4L+4Li_2(\tfrac{-d}{a})+2L\ln\lambda-4L\ln(1+4\lambda)+2Li_2(\tfrac{d^2}{a^2})]\} \\ &+ \tfrac{\alpha_s}{3\pi}\tfrac{1}{(1+4\lambda z^2)^2}\Big\{\tfrac{1}{[1-(1-\lambda)z]^2}[(1-z)(1-2z-6z^2+8z^4) \\ &+ 6\lambda z(1-z)(3-15z-2z^2+8z^3) + 4\lambda^2 z^2(8-77z+65z^2-2z^3)+ \\ &+ 16\lambda^3 z^3(1-21z+12z^2)-128\lambda^4 z^5] \\ &- \tfrac{2\hat{L}}{\sqrt{1+4\lambda z^2}}[(1+z)(1+2z^2)-2\lambda z(2-11z-11z^) - 8\lambda^2 z^2(1-9z)]\Big\} \\ &- \tfrac{8z^4(1+\lambda)^2}{(1-z)_+} - \tfrac{4z^4(1+2\lambda)(1+4\lambda)^2\hat{L}}{\sqrt{1+4\lambda z^2}(1-z)_+}, \end{aligned} \tag{5}$$

with the definitions:

$$\hat{L} = \ln\frac{4\lambda z[1-(1-\lambda)z]}{(1+2\lambda z+\sqrt{1+4\lambda z^2})^2};\; L = \ln\frac{a}{d};\; d = a-1;\; Li_2 = -\int_0^x dz\,\frac{\ln(1-z)}{z}. \tag{6}$$

The flavour conservation leads to the condition:

$$\int_0^1 dz\,\sigma_2^{(1)}(z) = 0. \tag{7}$$

Then, the first-order correction to the structure function $F_2^{c(0)}(x,Q^2)$ can be represented as a convolution of the c quark distribution $c(t,\gamma)$ with the radiative corrections (5):

$$F_2^{c(1)}(x,Q^2) = \frac{8}{9}\zeta\int_\zeta^\gamma \frac{dy}{y}\,c(y,\gamma)\sigma_2^{(1)}(\frac{\zeta}{y},\lambda). \tag{8}$$

For simplicity reasons the so-called "full ζ-scaling" was assumed in Eq.(8), namely, that the zeroth-order structure function $F_2^{c(0)}(x,Q^2)$ has the simplified form:

$$F_2^{c(0)}(x,Q^2) \approx \frac{8}{9}\zeta\,c(\zeta,\gamma). \tag{9}$$

As was shown in [6], such a "full ζ–scaling" is a very good approximation for the exact expression (2) at $Q^2 \geq 3\,GeV^2$. Therefore, the corrected IC structure function is a sum of two terms:

$$F_2^c(x,Q^2) \;=\; F_2^{c(0)}(x,Q^2) \;+\; F_2^{c(1)}(x,Q^2). \qquad (10)$$

3 Numerical check of the analytical expressions

Let us first consider some qualitative arguments on the Q^2 evolution of the heavy quark structure function. The numerical results of paper [6] predict that the Q^2 evolution of the heavy c quark is larger than the evolution of light quark, calculated from ordinary Altarelli–Parisi equations (see Fig.3(a)). The curve "2" in Fig.3(a) presents the results of the $O(\alpha_s)$ radiative corrections to $F_2^c(x,Q^2)$; the curve "3" is the prediction of the Altarelli–Parisi equations and the curve "4" shows the variation of the charmed structure function within the range $10 \geq Q^2 \geq 70\ GeV^2$ following from the calculations made in paper [6]. Those curves are taken from the original paper [6].

As one can see the results of [6] predict higher evolution of the c quark distribution than for massless partons (Altarelli–Parisi equations suggest a zero quark mass).

Such a conclusion disagrees with present understanding of the quark evolution by gluon radiation. It is clear that a heavy quark radiating a gluon looses a lesser fraction of its momentum, than a light quark. Therefore a heavy quark should evolve "slower" than a light one. The faster evolution of heavy quark conradicts also the well–established experimental results about quark fragmentation functions. The fragmentation function of a light quark peaks at small values of its fractional momentum z. While charmed particles carry around 75% of the momentum of the initial charmed quark, and the b particles around 90% of the initial momentum. Due to the fact that the physical mechanisms of the Q^2 evolution and the hadronization of a quark are closely related (emission of gluons), a light quark should evolve "faster", than a heavy one. This fact apparently contradicts the numerical results of the paper [6] (our calculations show that the formulae of the paper [6] really predict "faster"evolution for light quarks again in disagreement with the numerical results from that paper[2]).

Above observations encouraged us to carry out a careful check of the numerical results of [6]. This was done as follows:

- the numerical calculations were made according to Eq.(8);
- the expression (8) was calculated after the substitution $u = \frac{\zeta}{y}$, i.e., using an independent code. Both methods gave the same results (the relative integration accuracy was chosen equal to 10^{-6} for both methods);
- the calculation of the integral (7) gives zero value within the integration accuracy (i.e., there are no apparent bugs in codes for Eq.(5));
- to be sure that the numerical integration evaluates correctly the singularity $(1-z)_+^{-1}$ in Eq.(5) at $z = 1$, the following procedure was used. Performing two subsequent analytical integrations of the integral (8) one obtains an integral which does not contain anymore the singularity $(1-z)_+^{-1}$. We do not give these expressions here owing to their complicated structure. The further numerical calculations of the regular integral again leads to the same results as the original expression (8);
- because the expression for $\alpha_s(Q^2)$ has not been given explicitly in [6], the calculations were carried out for two numbers of flavours, $N_f = 3$ and $N_f = 4$ and with two values of the QCD parameter — $\Lambda = 0.2\ GeV$ and $\Lambda = 0.5\ GeV$. The results, in practice, are not changed for the chosen range of the momentum transfer $(3 \leq Q^2 \leq 70)\,GeV^2$. The value of α_s was calculated for the argument value $(Q^2+20)\,GeV$ in accord with the papers [1] and [6];
- the distributions of the integrand in the integral (8) were analized. These expressions do not contain any singularities (except the integrated singularity $(1-z)_+^{-1}$). Thus one can be sure that no "peaks" have been "missed" by the integration program (the code *GAUSS2* was used).

The mass of the charmed quarks was chosen equal to $m_c = 1.35\ GeV$ according to [6]. All calculations were perfomed with double precision.

The comparison of the above calculations with the results of [6] at $Q^2 = 70\,GeV^2$ is shown in Fig.3(a) by the curve "1".

The correct results are about 2.5 times less than the results from [6] at its maximum value (at $x \approx 0.4$) and less than the predictions of ordinary Altarelli–Parisi evolution equations at high momentum ($x \geq 0.2$), which fact agrees better with physical expectations mentioned above.

The contribution of the radiative corrections to the IC structure function is demonstrated in Fig.3(b). The IC structure functions for various Q^2 are shown in Fig.3(c). It is clear from these figures that the radiative corrections can play an important role at low $x \leq 0.1$ and can be negleted within the region of interest, $x \geq 0.15$. The main variation of the charmed structure function comes from the mass corrections due to non–zero masses of the c quark and the proton and is restricted mainly by the range $Q^2 \leq 20\ GeV^2$. At higher Q^2 the evolution of the $F_2^c(x,Q^2)$ is small. Thus, the IC structure function above the charm threshold depends only little on Q^2 and one can neglect such a dependence in practical calculations. This result will lead to softer distributions of the final products of the charm fragmentation and decays at low Q^2 and to harder ones at high Q^2 in comparison with, e.g., the results of the papers [3, 4].

4 Comparison with the experimental data

A fit of the correct calculations for IC structure function together with PGF contribution has been made to estimate the normalization for intrinsic charm component. The EMC data from [1] on the charm structure function were used. The only free parameter of the fit is the normalization of the intrinsic charm distribution (remember that Eq.(1) is normalized on 1%). The mass for charmed quark for the fit and for further calculations was taken equal to $m_c = 1.35\ GeV$.

The charm structure function due to PGF contribution is defined by [8]:

[2] I thank G.Ingelman for his advice to check this fact.

$$F_2^{c(PGF)}(x,Q^2) = \int_{ax}^{1} \frac{dz}{z} G(z,Q^2)\, f_2(\frac{x}{z},Q^2), \quad (11)$$

where, $a = 1+4\lambda$, $\lambda = m_c^2/Q^2$ and

$$\begin{aligned} f_2(z,Q^2) &= \frac{\alpha_s(\hat{s})e_q^2}{\pi} z \left\{ \sqrt{1-\lambda\frac{z}{(1-z)}}\left[-\frac{1}{2} + 2z(1-z)(2-\lambda)\right] \right. \\ &+ \left. \left[1-2z(1-z)+4\lambda z(1-3z) - 8\lambda^2 z^2\right] \log\frac{1+\sqrt{1-4\lambda\frac{z}{(1-z)}}}{1-\sqrt{1-4\lambda\frac{z}{(1-z)}}} \right\}. \end{aligned} \quad (12)$$

In the above expressions e_q is the charge of the c quark and the value $\hat{s} = Q^2(\frac{z}{x}-1)$ was used as the QCD scale [8]. For the intrinsic charm structure function the QCD scale has been chosen according to [1], [6], i.e., $\alpha_s(Q^2+20\,GeV)$.

Four parameterizations were exploited for the gluon distribution: $3\,(1-x)^5$, following ordinary counting rules; parametrization DO (set 2) [10]; EHLQ (set 1) [11] and the parametrization MTB2 [9]. The last parametrization (MTB2) gives the best value of $\chi^2/DOF \approx 1.5$. Fig.4(a) shows the results of the fit for four values of the momentum transfer. The curves represent the sum of contributions PGF + 0.5% IC for each Q^2. One observes reasonable agreement with the experimental data (the PGF model without IC contribution gives the $\chi/DOF = 3.80$).

The deep-inelastic cross section is proportional to [4]:

$$\frac{d\sigma}{dxdQ^2} \sim \frac{[1+(1-y)^2]}{Q^4 x} F_2^c(x,Q^2). \quad (13)$$

The summary (PGF + 0.5%IC) cross section is shown in Fig.4(b) (arbitrary units). It is seen that the IC contribution significantly exceeds the PGF one at $x \geq 0.15$ and $Q^2 < 20\ GeV^2$.

For the simulation of the ep scattering *PYTHIA 5.6* Monte Carlo generator was used with *MTB2* parametrization for the gluon distribution (for the PGF model) and with intrinsic c quark distributions according to Eq.(10). The evaluation of the total cross sections for deep-inelastic scattering with uncorrected, Eq.(1), and "ζ-scaled", Eq.(9), charm distributions gives the following results (with inclusion of the resolved-photon components scattering):

$$\begin{array}{lll} \sigma_{tot}^{\text{noncorrected}} & (ep \to cX \text{ on intrinsic charm}) & \approx\ 615\ \text{pb}, \\ \sigma_{tot}^{\zeta\ \text{scaling}} & (ep \to cX \text{ on intrinsic charm}) & \approx\ 289\ \text{pb}. \end{array}$$

The Fig.5 illustrates the x_B, $W = \sqrt{(P+q)^2}$ and E_T distributions for scattering on the non-corrected intrinsic charmed quarks (open area), "ζ-scaled" distribution (close dashed area) and the standard PGF predictions (dashed area). The cut $Q^2 > 1\ GeV^2$ has been used for all the variants. The total cross sections after the above cut on Q^2 are the following:

$$\begin{array}{lll} \sigma_{tot}^{\text{noncorrected}} & (ep \to cX \text{ on intrinsic charm}) & \approx\ 548\ \text{pb}, \\ \sigma_{tot}^{\zeta\ \text{scaling}} & (ep \to cX \text{ on intrinsic charm}) & \approx\ 244\ \text{pb}, \\ \sigma_{tot} & (ep \to cX \text{ by PGF}) & \approx\ 5.0\cdot 10^4\ \text{pb}. \end{array}$$

The Monte Carlo estimations show that the scattering on the charmed component of the proton gives leptons from charmed particle decays within the angular range $\theta_{lep} < 20°$ (see Fig.6). Thus the signature of the events is very clear — scattered electron with small energy loss in backward direction and energetic decay lepton (electron or muon) in forward direction. For the integrated luminocity $L_{int} = 20\ pb^{-1}$ one can expect after the 'beam-pipe' cut ($4° \leq \theta_{lep} \leq 176°$, $E_{lep} \geq 0.5\ GeV^2$) about 150 events and about 90 events after an additional cut $x_B \geq 0.01$. This additional cut is expected to significantly suppress the contribution from the photon-gluon fusion process. Open area in the Fig.6 presents the angular and energy distributions for the scattered electron and for the decay leptons after the 'beam-pipe' cut. The dashed area in this figure shows the effect of the additional cut on Bjorken variable $x_B \geq 0.01$. The simulation was carried out for the energy of the incoming electron $E_e = 30\ GeV$ and for the energy of the proton $E_p = 820\ GeV$.

5 Conclusion

We conclude that the numerical results of [6] overestimate the QCD evolution of the intrinsic charm structure function. On another hand, the analytical expressions from that paper are correct and can be used for the description of the mass and radiative corrections to the heavy quark distributions. The QCD evolution of the IC structure function is slow. Thus, for the simulation of the deep-inelastic scattering on intrinsic charmed quarks the omission of the QCD evolution gives a good approximation and it is sufficient to calculate the IC structure function only with the mass corrections according to Eq.(9) (so-called ζ-scaling).

The fit to the EMC data gives the value of 0.5% for the normalization of the intrinsic charm distribution in the proton. The admixture of the IC component in the proton structure function is small but its contribution in charm production at low Q^2 can significantly exceed the contribution of the standard PGF mechanism and such an excess can be observable at HERA.

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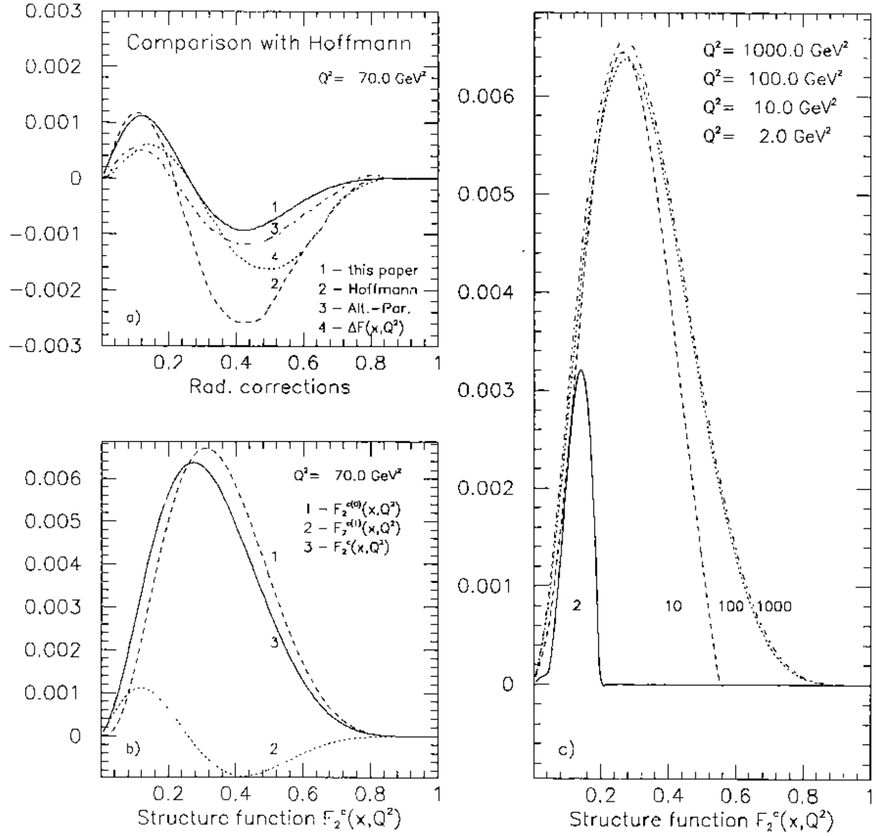

Figure 3: a) The comparison of the numerical results from paper [6] with the results obtained in present paper: 1 — the radiative corrections calculated in present paper; 2 — the same results from [6]; 3 — the predictions of the standard QCD evolution and 4 — the difference $\Delta F_2^c = [F_2^{c(1)}(x,70) - F_2^{c(1)}(x,10)]$ (last three curves were taken from [6]). b) The radiative corrections contribution to $F_2^c(x,Q^2)$ at $Q^2 = 70\,GeV^2$: 1 — the zeroth-order uncorrected distribution $F_2^{c(0)}(x,Q)$; 2 — radiative corrections $F_2^{c(1)}(x,Q^2)$; 3 — corrected distribution $F_2^c(x,Q^2)$. c) The corrected structure function $F_2^c(x,Q^2)$ for four values of momentum transfer: $Q^2 = 2\,GeV^2$; $Q^2 = 10\,GeV^2$; $Q^2 = 100\,GeV^2$ and $Q^2 = 1000\,GeV^2$.

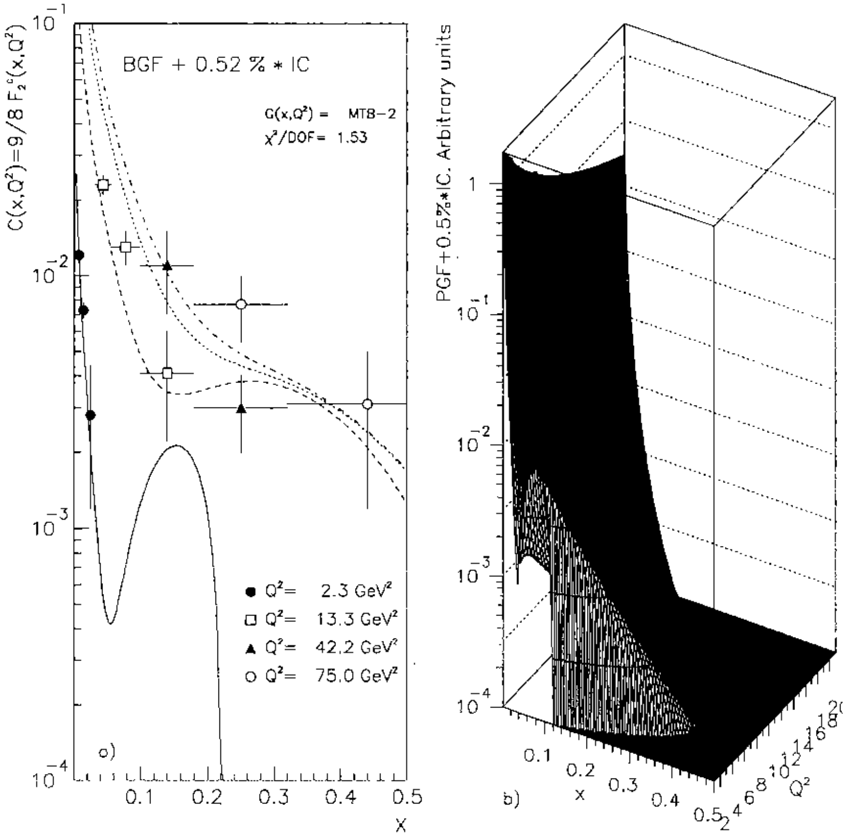

Figure 4: a) The results of the fit of the intrinsic charm normalization to EMC data. b) The summary cross-section (arbitrary units) (PGF + 0.5%IC). For gluon distribution the MTB2 [9] parametrization was used.

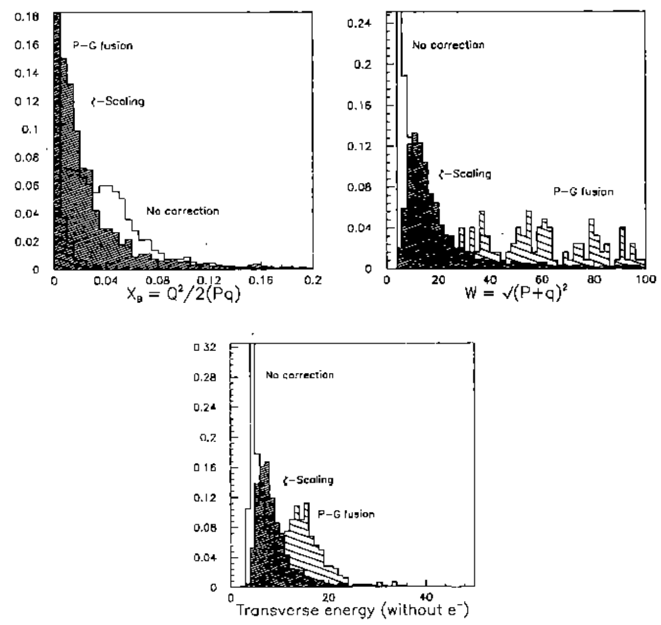

Figure 5: The results of the Monte Carlo simulation for scattering on the intrinsic charmed quarks. The scattering of the resolved photon components has been included. The histograms show the results for non-corrected IC distribution, Eq.(1); ζ-scaling, Eq.(9); and predictions of the photon-gluon fusion model. All histograms are normalized to the unit and a cut $Q^2 > 1\ GeV^2$ has been applied. For the gluon distribution the MTB2 [9] parametrization was used.

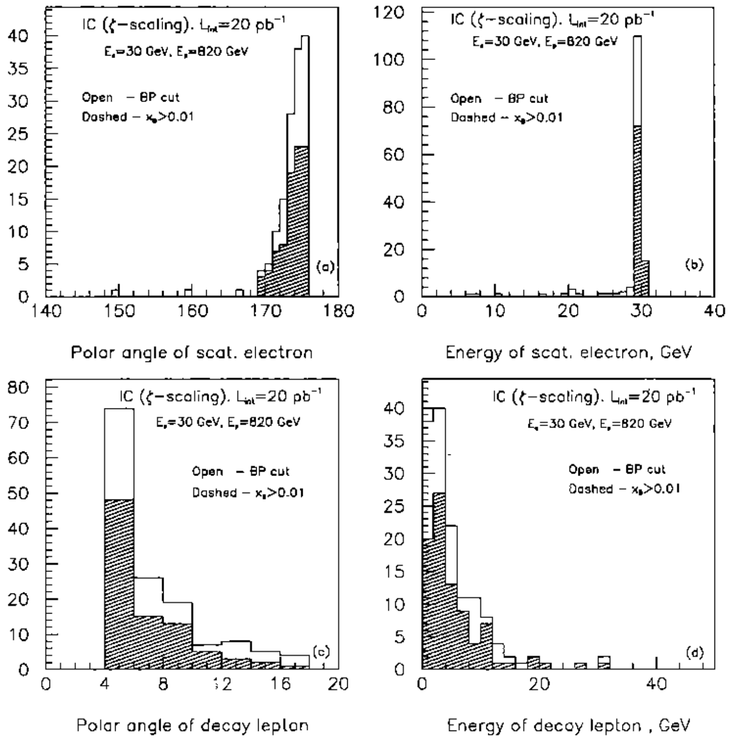

Figure 6: The angular (a,c) and energy (b,d) distributions for scattered electron and for leptons from charm decays respectively. The histograms show the results for the corrected IC distribution, Eq.(9) (ζ-scaling). The open area — the 'beam—pipe cut' only ($4^\circ \leq \theta_\mu \leq 176^\circ$, $E_\mu \geq 0.5\,GeV$). Dashed area — an additional cut $x_B \geq 0.01$. The histograms are normalized on the integrated luminocity $L_{int} = 20\ pb^{-1}$.