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QCD Formulation of Charm Production in Deep Inelastic Scattering and the Sea-quark—Gluon Dichotomy

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ABSTRACT

Gluon initiated contributions to DIS processes, such as charm production, can be *comparable* in magnitude to the "leading-order" sea-quark processes. A proper next-to-leading order calculation in QCD confirms this and yields distinct dependencies of these two contributions on the kinematic variables and on the charm quark mass. These results imply that previous analyses of charm production data to extract the strange and charm content of the nucleon, as well as the precise determination of Standard Model parameters based on these analyses, need to be reassessed.

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1 Introduction

Total inclusive deep inelastic scattering of electrons, muons, and neutrinos on nucleons have been the main source of information on parton distributions in general. Global analysis of the total inclusive data does not, however, provide a good handle on the strange and charm quark content of the nucleon since they only make a very small contribution to the measured structure functions. In the framework of the simple parton model, it is clear that a more direct determination of the strange quark distribution of the nucleon can be provided by the semi-inclusive process of charm production in charged-current deep inelastic neutrino scattering; and of the charm quark distribution by the semi-inclusive process of charm production in neutral current muon and neutrino scattering, *cf.* Fig. 1a.

Most work on the strange quark distribution is indeed based on this simple idea applied to charm production in charged current neutrino scattering.[1] Results obtained in this way play an important role in a wide range of phenomenological analyses, including the precise determination of the Weinberg angle and the top quark mass limit.[2] It has been emphasized that the uncertainty of the strange quark distribution currently represents the largest source of error in this important area of basic Standard Model phenomenology.[4] However, a realistic assessment of the reliability of the existing strange quark analyses does not, so far, exist.

The situation with the study of charm production in neutral current processes is rather different. Because of the higher threshold for producing the charm quark pair, an alternative mechanism for interpreting the charm-production (experimentally, opposite-sign dimuon production) data in muon scattering has been adopted[3]— "gluon fusion" with the virtual vector boson, Fig. 1b. This approach avoids the use of the charm quark as an active parton inside the nucleon altogether. Although this picture may seem reasonable just above the charm threshold, the leading order vector-boson—charm-quark scattering mechanism (Fig. 1a) must become dominant in the high energy domain. When and how does the transition from one mechanism to the other take place? There is no answer to this question in the literature. In the meantime, the question of the charm content of the proton has become critical in the proper interpretation of the increasingly precise measurements of the W- and Z-production cross-sections and cross-section ratios in the very high energy hadron colliders.[5]

Since perturbative Quantum Chromodynamics provides a comprehensive framework to describe these processes, both uncertainties mentioned above can be resolved by a systematic analysis. In this framework, the interaction mechanisms depicted in Fig.1a and Fig.1b are not distinct and exclusive. Indeed, *both are part of the QCD perturbative series contribution to charm production in deep inelastic scattering.* It is easy to see that, although the gluon-fusion mechanism (Fig. 1b) is nominally of "higher order" than the simple quark scattering mechanism (Fig. 1a) these two contributions are in fact of the same order of magnitude! The one extra power of α_s in the hard cross-section for the gluon-fusion mechanism is easily compensated by the gluon distribution which is one order of magnitude larger than the sea-quark distribution.

This is in fact a general phenomenon associated with all processes conventionally thought to be sea-quark-initiated, as the argument is not specific to any process. We can verify this quantitatively by examining the zero quark mass case for which the leading order (LO) results are familiar and the next-to-leading order (NLO) formulas are readily available in the literature. For this purpose, we computed the charm production (zero-mass) F_2 structure function due to the strange quark parton in LO and NLO and the gluon parton in NLO, using known hard scattering formulas [6] and several sets of representative parton distributions. In Fig. 2a,b we show the magnitudes of these three contributions at $Q^2 = 10\ GeV$ over the range $0.05 < x < 0.5$ obtained with EHLQ-1 and DFLM-NLLA distributions, respectively. We see that numerically the gluon contribution is indeed substantial as compared to the LO quark term; whereas the NLO quark contribution remains small (of order α_s or less) as compared to both. The precise ratios are sensitive to the choice of distribution functions, as illustrated by the two plots.

This example demonstrates that, without *a priori* knowledge of the parton distributions, it is imperative to include the NLO gluon contributions in any meaningful QCD analysis of processes previously thought to be dominated solely by sea quarks. This point also implies that, the very notion of *sea quark distribution* is highly *renormalization scheme dependent.* In fact, the NLO terms shown in Fig. 2 represent precisely the difference between the same sea quark distribution in the two most often used schemes—$\overline{\text{MS}}$ and DIS. It is not possible to make quantitative statements about the sea quark distribution without specifying the scheme used, as the difference may be of the same order of magnitude as the distribution itself—in contrast to conventional expectation (which does hold for valence quarks).

It is obvious then that a proper analysis of charm production in deep inelastic scattering must be carried out to NLO in QCD which includes *both* mechanisms depicted in Fig. 1. It is the purpose of this paper to present results of such an analysis, including the effects of the charm quark mass. Although a complete calculation should also include the NLO quark contribution, this term is not numerically as significant (cf. Fig. 2). Hence we leave it out in this short communication. The complete calculation, including the explicit formulas, will be given in a full length paper.[7]

2 The QCD Formalism

The basic QCD (factorization) formula for the inclusive vector-boson—hadron scattering tensor structure function is:

$$W_H^{\mu\nu}(q,p) = \sum_a f_H^a(\xi,\mu) \otimes \omega_a^{\mu\nu}(q,k,\mu) \tag{1}$$

where H is the target hadron label; a is the parton label; (q, p, k) are the momenta of the electroweak vector boson, the hadron, and the parton respectively; μ is the renormalization scale; and $\xi = k^+/p^+$ is the fractional light-cone plus "+" component carried by the parton with respect to that of the hadron. The symbol $\otimes$ denotes a convolution of the parton distribution function f_H^a and the hard vector-boson-parton scattering tensor $\omega_a^{\mu\nu}$ over the variable ξ. For zero mass quarks and to leading order, the convolution variable ξ reduces to the Bjorken x.

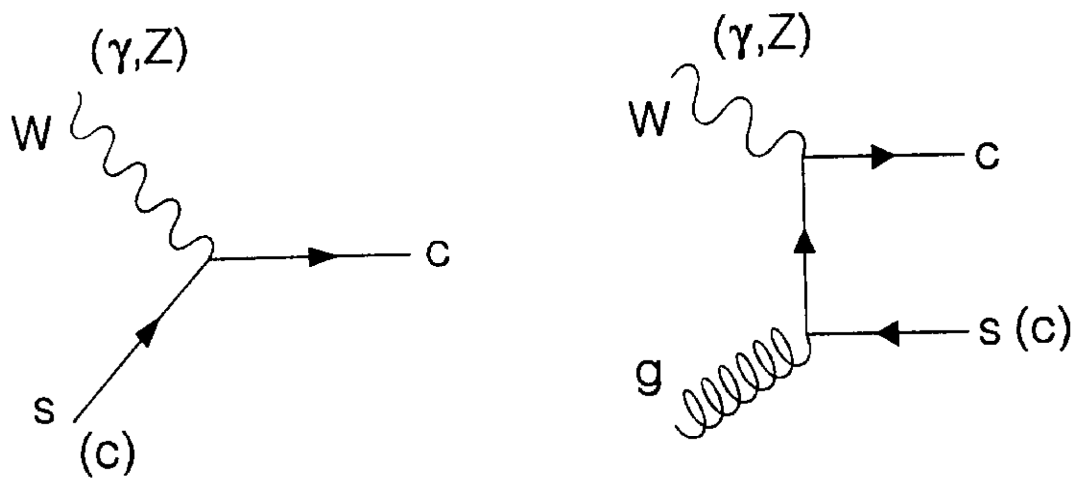

Figure 1: Mechanisms that contribute to charm production in DIS: (a) LO quark-vector-boson scattering, and (b) NLO gluon-vector-boson scattering.

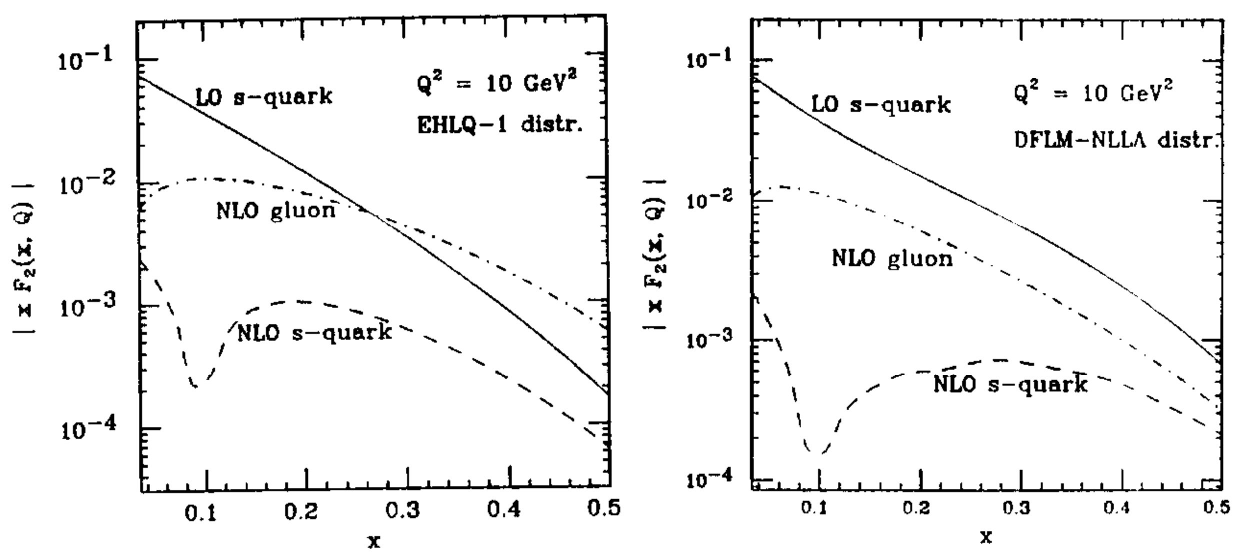

Figure 2: LO and NLO s-quark and gluon contributions to charm production structure function xF_2 using (a) EHLQ-1 distributions, and (b) DFLM-NLLA distributions.

Since the charm quark mass is not negligible in the region of phase space where most current data on charm production in deep inelastic scattering is to be interpreted, the familiar zero-mass QCD parton model formalism must be properly extended. The well-known "slow-rescaling" prescription[8] of replacing the Bjorken x with ξ emerges naturally in the above factorization formula. Of equal importance, but mostly overlooked, is the modification of the hard scattering tensor $\omega_a^{\mu\nu}(q,k,\mu)$ due to the charm quark mass which changes the helicity dependence of the structure functions for the overall process, even in LO. (For instance, the Callan-Gross relation no longer holds.) This needs to be treated correctly.

The familiar structure functions $\{W_1, W_2, W_3\}$ are obtained from $W^{\mu\nu}$ by contracting the $\{\mu, \nu\}$ indices with appropriate tensors formed from (q,p) while the corresponding parton-level quantities $\{\omega_1, \omega_2, \omega_3\}$ are defined in terms of (q,k). The two sets are distinct when the incoming quark-parton mass is non-zero, and are, in general, related by a set of rather non-trivial transformations. However, a simple correspondence does exist between the *helicity structure functions* (W_{R}, W_{L}, W_{Long}) and the corresponding parton-level quantities because these are obtained from $W^{\mu\nu}$ by contracting with the helicity (polarization) vectors $\{e_\lambda\}$ of the gauge boson. It is not hard to prove that the polarization vectors $\{e_\lambda(q,p)\}$ for the overall process are identical to the $\{e_\lambda(q,k)\}$ for the parton process, provided that the initial state parton is collinear to the hadron—as indeed it is by definition. This direct relationship is independent of any assumptions about the quark mass and simplifies the necessary calculations considerably.

The LO quark scattering contribution to the partonic structure functions ω due to Fig. 1a is straightforward to compute. The calculation of the NLO gluon contribution, Fig. 1b, requires a suitable subtraction of the collinear singularity in order to factor out the long-distance part of the amplitude which is already contained in the quark distribution function in the LO term. We choose to perform the calculation using a non-zero quark-parton mass and identify the subtraction term as the singular piece (see next paragraph) as this mass tends to zero.[9,10] The actual calculation consists of computing two box and two crossed-box diagrams obtained by squaring two diagrams of the type Fig. 1b. With general vector boson coupling and both quark masses non-zero, the calculation is quite involved in practice. The Dirac algebra is done with the program ASHMEDAI. The integration over phase space is done both analytically (with Mathematica©) and numerically. The results agree.

Qualitatively, the subtraction term originates from summing final states of the gluon scattering diagram, Fig. 1b, over that region of phase space where the internal quark line is close to the mass-shell and collinear to the gluon parton—thus it represents the overlap of the two basic parton interaction mechanisms depicted in Fig. 1, which must be subtracted in order to avoid double-counting. In our subtraction procedure, the analytic expression for this term is:

$$W^\lambda = f^g \otimes \tilde{f}_g^q \otimes \omega_q^\lambda \tag{2}$$

where we have suppressed all inessential indices and variables. Here ω_q^λ is the LO quark partonic helicity structure function, and $\tilde{f}_g^q$ denotes the perturbative quark-distribution inside the gluon (calculated in the $\overline{\mathrm{MS}}$ scheme) which is given simply by the well-known gluon splitting function multiplied by $\alpha_s \log(\mu/m)$ where μ is the subtraction scale and m is the quark-parton mass. The origin of the subtraction term discussed above suggests that the subtraction scale μ has a natural physical interpretation as the scale marking the boundary of the collinear and non-collinear regions in the P_T integration over the final states. We choose this scale to be a fixed fraction c of the maximum P_T for given kinematic variables (x, Q).[11] The same scale appears in the parton distribution function of the LO term. When the factor c is varied, the variation of the subtraction term and the LO term compensate each other; the difference is of one high order in α_s. Hence the sum is relatively insensitive to the choice of this parameter.

3 Results

In general, the complete calculation fully confirms the qualitative estimate that the gluon contribution to charm production is of the same order of magnitude as the conventional quark contribution in deep inelastic scattering. To be specific, we shall focus on the charged-current interactions process $\nu + N \rightarrow \mu + X$. The most important quark-parton in this case is the strange quark. The d-quark also contributes to a lesser extent and it should be included in a full-fledged phenomenological analysis. Since we find that it does not contribute significantly to the total cross section, we leave it out for the sake of clarity.

To obtain specific results, we need to use some input parton distributions. The results will then depend on the strange quark and gluon distributions of the chosen set. The proper procedure is, of course, to utilize the sensitivity of the differential cross-sections on the parton distributions to determine the latter by comparison with charm-production measurements. For the purpose of illustrating the importance of the gluon contribution and to delineate the distinctive features of the two types of terms, we shall use a set of parton distributions obtained from global fits to current total inclusive deep inelastic scattering and Drell-Yan data which assumes that the strange quark to non-strange sea-quark ratio to be one-half[12] as suggested by existing experiments.[2]

We find the NLO correction to the dominant ("*correct*") helicity structure function for charm production (*i.e.* the left-handed one in neutrino scattering, and right-handed one in anti-neutrino scattering) to be negative—the *same* as for the zero quark mass case—and to be *of the same order of magnitude* as the LO term. In contrast, the corrections to the "wrong" helicity and the longitudinal structure functions are *positive* and, as one would expect, *considerably larger* than the corresponding LO terms (which vanish in the limit of zero charm quark mass).

In Fig. 3a and 3b we show the cross-section $d\sigma/dy$ and $x\ d\sigma/dx$ for incoming neutrino energy $E = 80\,\mathrm{GeV}$. The NLO correction due to the gluon fusion diagram with subtraction is negative, reflecting the behavior of the dominant helicity structure function, and is shown here in absolute magnitude. We see the importance of this correction—a 40% to 100% effect depending on the kinematical variables, especially y. The variation of the correction with y reflects the non-negligible contribution from

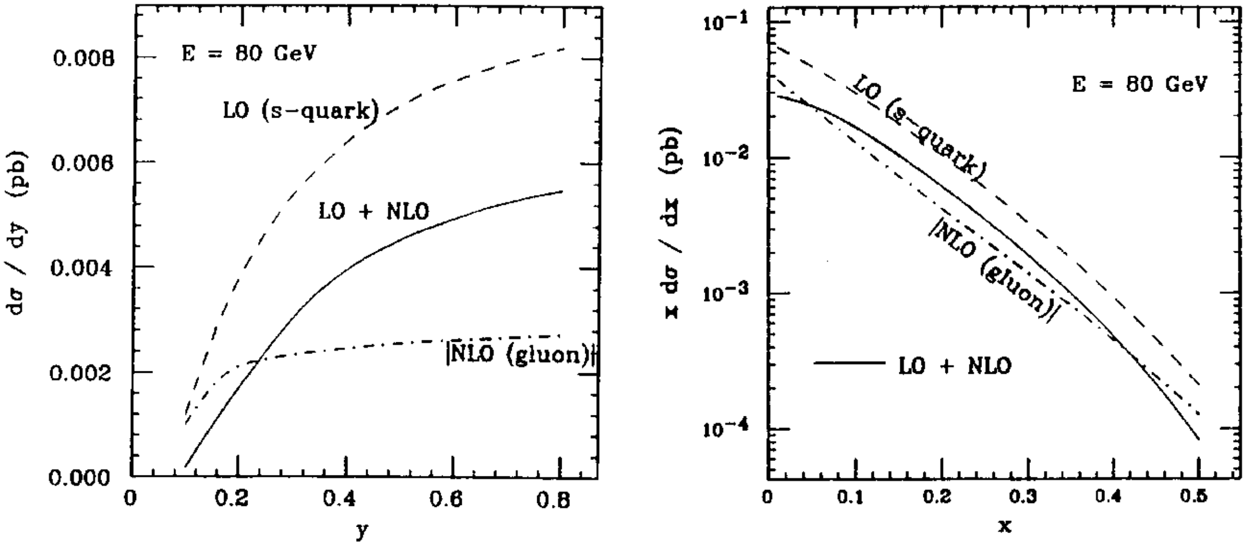

Figure 3: Charm production cross-section at a typical fixed-target energy: (a) $\mathrm{d}\sigma/\mathrm{d}y$ (integrated over $0.1 < x < 0.6$); and (b) $x\ \mathrm{d}\sigma/\mathrm{d}x$ (integrated over $0.1 < y < 0.8$).

the "wrong" helicity and longitudinal structure functions from the NLO term.

At very high energies, the sea quark distributions become more comparable to the other distributions, the LO and NLO terms are expected to resume their expected relative size—differing by a factor α_s. This is verified by our calculation at the HERA energy. In Fig. 4a and 4b we show the cross-sections $d\sigma/dy$ and $x\ d\sigma/dx$ respectively for CM energy $\sqrt{s} = 314\,\mathrm{GeV}$, (corresponding to a fixed target energy of $E \sim 50\,\mathrm{TeV}$). The lines have the same meanings as before.

It is well-known that the quark scattering contribution to the cross-section at current fixed-target experimental range is sensitive to the assumed mass of the charm quark. The same is true of the gluon contribution which we just showed to be important. The results presented above are obtained with $m_C = 1.5\,\mathrm{GeV}$. The charm mass dependence of the NLO term is rather different from the LO term. This will be reflected in the combined cross-section because the correction term is important. Details on this effect will be presented in the full-length paper.[7]

4 Implications and Discussions

This study demonstrates that the two basic mechanisms for producing charm in DIS—the scattering of the vector boson off the quark and the gluon constituents of the nucleon—are both important in the QCD parton framework. These two fundamental processes also lead to different helicity compositions and kinematical dependencies of the structure functions for the overall process. As mentioned earlier, the proper way to make use of these results is to re-analyze the relevant experimental results (di-muon final states in DIS) using the complete QCD formalism described here. Such an analysis may lead to different results on the strange and charm quark distributions

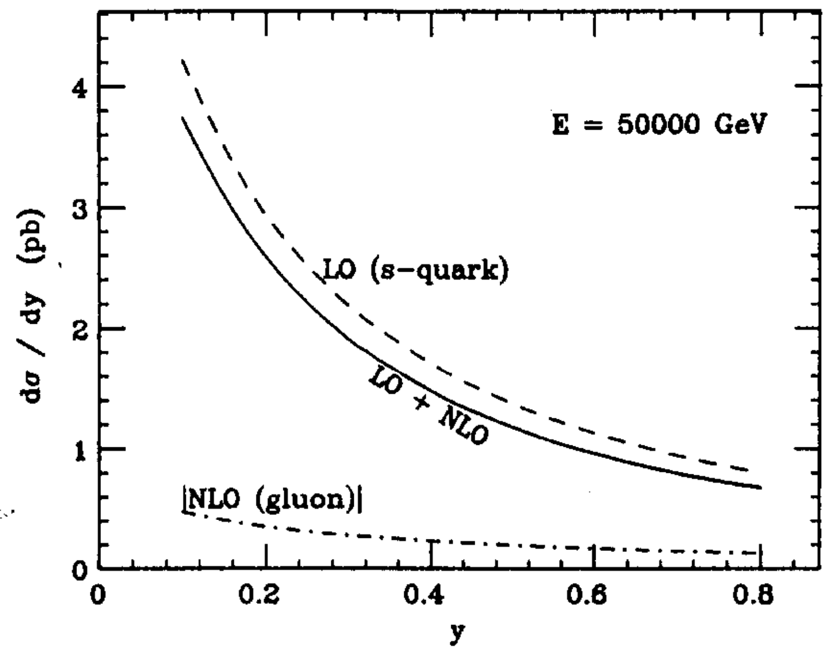

Figure 4: Same as Fig.3; except that $E = 50\ TeV$

of the proton and, perhaps, the value of the charm quark mass, compared to those obtained previously with the neglect of the NLO gluon contribution. To the extent that the precise determination of the Weinberg angle from DIS scattering, the related estimate of top-quark mass, and many other quantitative Standard Model studies of W- and Z-physics at the colliders all depend on these quantities, this re-analysis should have significant consequences in many areas.

Since the NLO gluon term can be numerically significant compared to the LO sea-quark terms, it is necessary to define the sea-quark distributions *always* to next-to-leading-order in QCD. This also requires attention to the choice of renormalization scheme both in the definition and in the use of these distributions, so that meaningful and consistent results can be obtained. All these issues need further quantitative study.

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References

[1] U. Amaldi, *et. al. Phys. Rev.* **D36**, 1385 (1987); G.L. Fogli and D. Haidt, *Z. Phys.* **C40**, 379 (1988); J. Ellis, and G.L. Fogli, *Phys. Lett.* **B232**, 139 (1989); See also, J. Feltesse, *Proceedings of the 1989 International Symposium on Lepton and Photon Interactions at High Energies*, Stanford, August 1989, Ed. M. Riordan, p. 13, (1990).

[2] M. Arneodo, *et al.*, *Z. Phys.* **C35**, 1 (1987); J.J. Aubert,*et al.*, *Phys. Lett.* **167B**, 127 (1986); *Phys. Lett.* **94B**, 101 (1980) (EMC); H. Abramowicz, *et al.*, *Phys. Rev. Lett.*, **57**, 298 (1986); *Z. Phys.* **C28**, 51 (1985) (CDHSW); K. Lang, *et al.*, *Z. Phys.* **C33**, 483 (1987); S.R. Mishra, et al., preprint NEVIS-R-1410 (14th Rencontres de Moriond) Mar. 1989 (CCFR); D. Bogert, *et al.*, *Phys. Rev. Lett.*, **55**, 1969 (1985) (FMMF); J.V. Allaby, *et al.*, *Z. Phys.* **C36**, 611 (1987) (CHARM).

[3] Cf. Arneodo *et al.*, *op. cit.*

[4] R. Brock, Talk delivered at the *New Directions in Neutrino Physics at Fermilab* workshop, Batavia, Illinois, September 1988.

[5] F. Halzen and D. A. Morris, *Phys. Lett.* **B237**, 107 (1990).

[6] See, for instance, W. Furmanski and R. Petronzio, *Z. Phys. C*, **11**, 293 (1982).

[7] M. Aivazis, F. Olness, and W.K. Tung, (to be published)

[8] R. M. Barnett, *Phys. Rev.* **D14**, 70 (1976).

[9] F.I. Olness and Wu-Ki Tung, *Nucl. Phys.* **B308**, 813 (1988).

[10] For an alternate approach to the non-zero quark mass problem, *c.f.*, R. M. Barnett, H. E. Haber, and D. E. Soper, *Nucl. Phys.* **B306**, 697 (1988).

[11] A naive choice of the subtraction scale might appear to be Q. However, this choice has no relation to the origin of the subtraction term as described in the text. From a practical point of view, setting $\mu = Q$ results in gross over-subtraction in the lower end of the convolution integral which, in turn, leads to very unstable results and even to negative cross-sections for the overall process in some kinematical regions. *C.f.*, M. A. G. Aivazis and J. C. Collins, Illinois Institute of Technology preprint (in preparation).

[12] J.G. Morfin and Wu-Ki Tung, preprint Fermilab-PUB 90/24, IIT 90/11.