QCD Formulation of Charm Production in Deep-Inelastic Scattering and the Sea-Quark–Gluon Dichotomy

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Gluon-initiated contributions to deep-inelastic scattering 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 dependences 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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Total inclusive deep-inelastic scattering of electrons, muons, and neutrinos on nucleons has 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. 1(a)].

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.[3] However, a realistic assessment of the reliability of the existing strange-quark analyses does not, so far, exist.

Existing data on charm production in neutral-current (muon) scattering[4] were originally interpreted in the simple parton model as scattering off charm quarks in the target, similar to the charged-current case above. They were alternatively reinterpreted[5] as the result of the "gluon-fusion mechanism"[6] [cf. Fig. 1(b)]. Studies of heavy-flavor production at the DESY *ep* collider HERA also used the later mechanism.[7] This approach does not count the heavy quark as an active parton inside the nucleon at all; it cannot be the dominant mechanism at high energies.

In the QCD framework, the two interaction mechanisms discussed above, Figs. 1(a) and 1(b), are not distinct and exclusive. Rather, they correspond to the first two terms in the perturbative series for charm production in deep-inelastic scattering. A quantitative treatment of these processes must incorporate both in a consistent way.[8] It is easy to see that, although corrections due to the gluon-fusion diagram [Fig. 1(b)] are nominally of "higher order" than the simple quark scattering mechanism [Fig. 1(a)], these two contributions can, in fact, be of the same order of magnitude. The one extra power of α_s in the hard cross section for the gluon-fusion contribution is easily compensated by the gluon distribution which is 1 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 above 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[9] and several sets of representative parton distributions. In Figs. 2(a) and

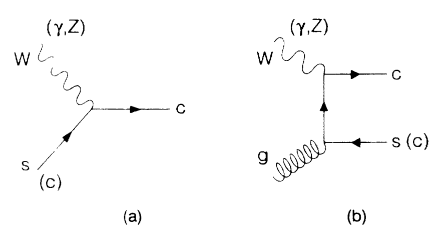

FIG. 1. Mechanisms that contribute to charm production in deep-inelastic scattering: (a) leading-order quark–vector-boson scattering, and (b) next-to-leading-order gluon–vector-boson scattering.

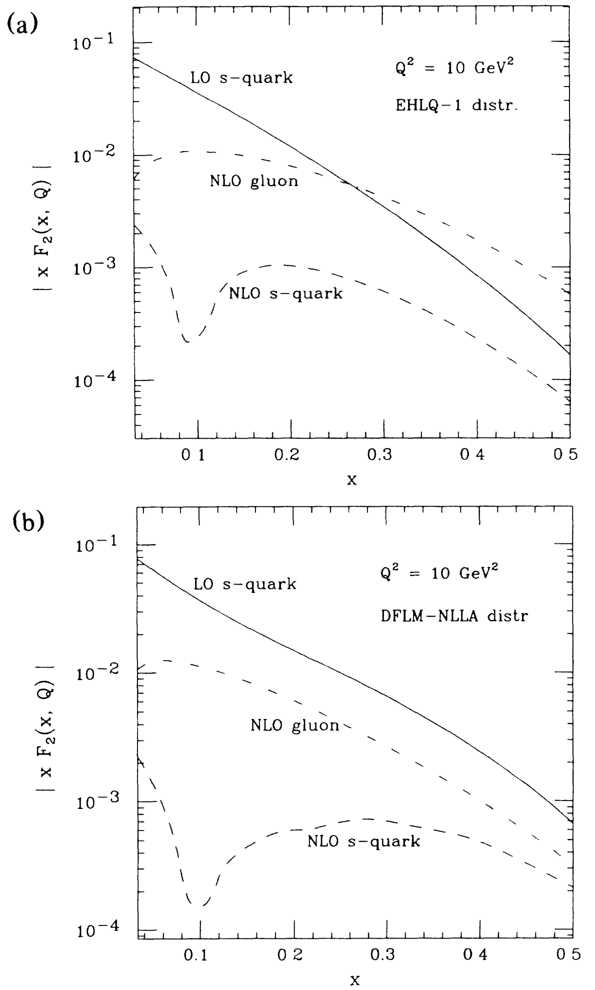

FIG. 2. LO and NLO s-quark and gluon contributions to charm-production structure function xF_2 using (a) Eichten-Hinchliffe-Lane-Quigg set 1 distributions, and (b) Diemoz-Ferroni-Longo-Martinelli next-to-leading-logarithm-approximation distributions.

2(b) we show the magnitudes of the three contributions at $Q^2 = 10$ GeV over the range $0.05 < x < 0.5$. 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 distributions* 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—modified minimal subtraction ($\overline{\rm MS}$) and deep-inelastic scattering (DIS).[10] 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 Letter. The complete calculation, including the explicit formulas, will be given in a full length paper.[11]

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 + 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.

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[12] of replacing the Bjorken x with ξ emerges naturally in the above factorization formula. Of equal importance, but mostly overlooked in the existing literature, 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 LO quark scattering contribution to the partonic structure functions ω due to Fig. 1(a) is straightforward to compute. By using the QCD-evolved quark distributions, this term already incorporates that part of Fig. 1(b) with the internal quark line in the collinear on-shell configuration. Thus, the calculation of the proper NLO gluon contribution, Fig. 1(b), requires a suitable subtraction of this (long-distance) piece, which is characterized by an associated mass singularity when the quark-parton mass approaches zero. We choose to perform the calculation using a nonzero quark-parton mass and identify the subtraction term as the singular piece (see next paragraph) in the zero-mass limit.[13,14] The calculation, consisting of squaring two diagrams of the type shown in Fig. 1(b), with general vector-boson coupling and both quark masses nonzero, is quite involved. Several independent methods were used to cross-check the results.

In our subtraction procedure, the analytic expression for the subtraction 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 $\overline{\rm MS}$ scheme) which is given simply by the well-known gluon splitting function multiplied by $\alpha_s \ln(\mu/m)$, 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 noncollinear 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).[15] 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 order higher in α_s. Hence the sum is relatively insensitive to the choice of this parameter.

In general, the complete calculation fully confirms the qualitative estimate that the (usually ignored) 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 $\nu+N\to\mu+X$. The most important quark parton in this case is the strange quark. (The d quark also contributes in principle. However, since its contribution to the total cross section is not significant, it can be left out for our current purposes.) In order to quantify the gluon contribution and to delineate the distinctive features of the quark and gluon terms, we need to use some input parton distributions. The detailed results clearly depend on the particular input. We will present some typical results.

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 the right-handed one in antineutrino 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).

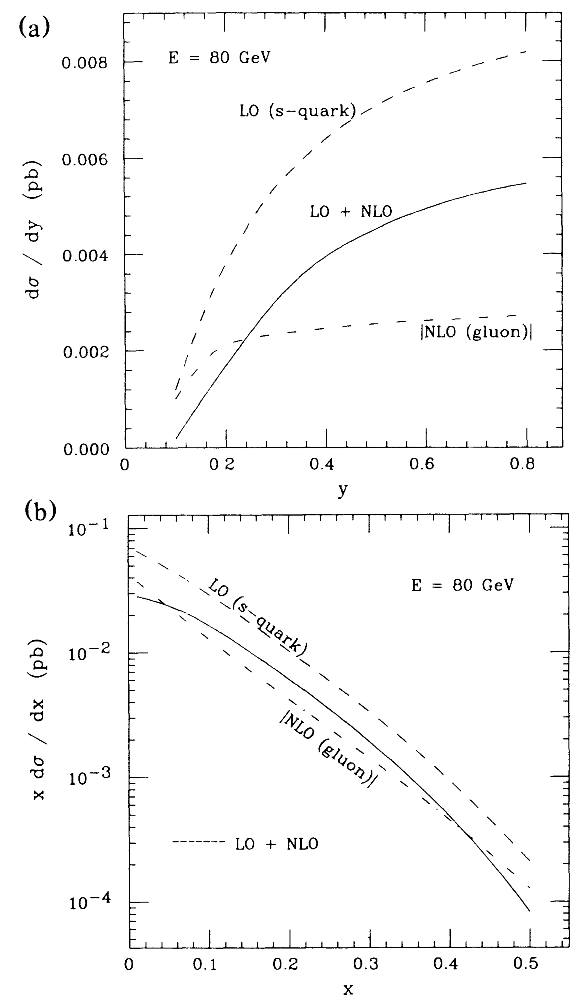

FIG. 3. Charm-production cross section at a typical fixed-target energy: (a) $d\sigma/dy$ (integrated over $0.1<x<0.6$), and (b) $x\,d\sigma/dx$ (integrated over $0.1<y<0.8$).

In Figs. 3(a) and 3(b) we show the cross sections $d\sigma/dy$ and $x\,d\sigma/dx$ for incoming neutrino energy $E=80$ GeV, using a recent parton distribution test.[16] 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 (40–100)% effect depending on the kinematical variables, especially y. The variation of the correction with y reflects the non-negligible contribution from 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, and the LO and NLO terms are expected to resume their expected relative size—differing by a factor of α_s. This is verified by our calculation at the HERA energy. In Fig. 4 we show the cross sections $d\sigma/dy$ for c.m. energy $\sqrt{s}=314$ GeV (corresponding to a fixed-target energy of

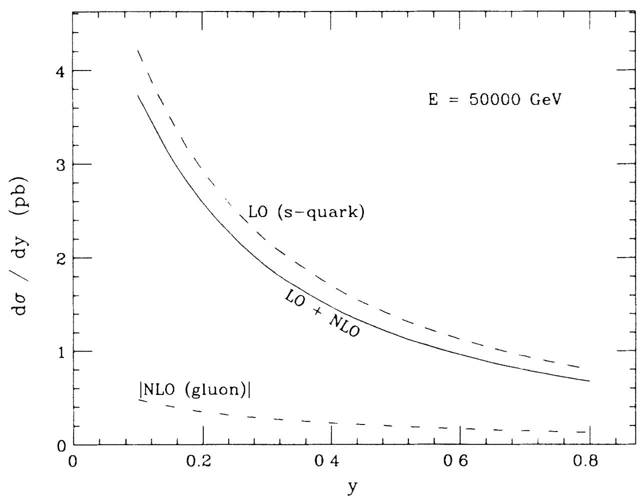

FIG. 4. Same as Fig. 3(a), except that $E = 50$ TeV.

$E \sim 50$ TeV). The lines have the same meanings as before.

It is well known that the quark scattering contribution to the cross section at the 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 $m_c = 1.5$ GeV. The charm-mass dependence of the NLO term is rather different from that of 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.[11]

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 dependences of the structure functions for the overall process. Our results are clearly illustrative only. The proper way to make use of these results is to reanalyze the relevant experimental results (dimuon 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 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 may other quantitative standard-model studies of W and Z physics at the colliders all depend on these quantities, this reanalysis 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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