

Ground state correlations in deep inelastic scattering and the Drell-Yan process

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Abstract. Such high energy processes as deep inelastic scattering (DIS) and Drell-Yan heavy lepton pair production are among the most important tools to probe the quark and gluon interaction. We calculated non-perturbative corrections to the LO cross section formulae for DIS and the Drell-Yan process. The interaction of partons was taken into account via dressing the incoming quark lines with spectral functions. We found that the effect of ground state correlation in DIS is large in the region of small Bjorken x and low momentum transfer Q^2 . For a quark width of the order of 200 MeV, the cross section deviation reaches as much as 50% for $Q^2 = 10 \text{ GeV}^2$. On the other hand, for the values of Q^2 well above the resonance region, e. g. 200 GeV^2 , the effect of the initial quark off-shellness turned out to be small in DIS, but still substantial for the triple differential Drell-Yan cross section. Semi-inclusiveness of the latter process opens a possibility to extract from the experimental data important information on the shape of the quark spectral function in the nucleon. From the comparison to recent data on the Drell-Yan cross section from the NuSea collaboration, we obtained for the width of the quark spectral function the value about 200 MeV. The performed off-shell DIS and Drell-Yan cross section calculations allow for a better understanding of the quark and gluon interaction in the nucleon and, thus, the nucleon structure.

PACS. 13.60.Hb Total and inclusive cross sections (including deep-inelastic processes) – 13.85.Qk Inclusive production with identified leptons, photons, or other nonhadronic particles

1 Introduction

One of the major goals of present day research is to study the structure of the nucleon and other hadrons in terms of the fundamental quark-gluon dynamics. One would like to gain as good an understanding of hadron structure as our understanding of the compositeness of the nucleus in terms of nucleons and their interaction.

In high energy hadronic processes like deep inelastic scattering (DIS), the Drell-Yan process, jet production, etc. the soft and hard subprocesses can be disentangled. This allows one to apply the well established methods of perturbative QCD for the extraction of the information about the non-perturbative quark and gluon properties in a bound state from the experimental data. In this way, for instance, the distributions of partons, having different hadron light cone momentum fractions (parton distribution functions), are found [2].

The described method, based on factorization principle, is analogous to the plane wave impulse approximation (PWIA) for the quasi-elastic (e,e'p) scattering in nuclear physics.

In the theory of nuclei the importance of the effects beyond the PWIA, e.g. photon radiation, initial state in-

teraction (ISI), and final state interaction (FSI) is well understood. Semi-exclusive processes offer an opportunity to study these effects. Cross section measurements, in which energy and momentum of the nucleon can be determined from the final state kinematics, can thus probe nuclear structure via the spectral function.

The neglected in PWIA initial and final state quark interaction effects on the observable hard scattering cross sections has not been studied yet. The primordial transverse momentum of the quarks in the nucleon has been considered in some works [1], but the effect of the parton virtuality on the observed inclusive and semi-exclusive processes has not been calculated so far.

As we show below, the off-shellness effects have the same order of magnitude as those of the intrinsic transverse momentum. Thus, the consistent treatment of the both off-shellness and non-collinearity is necessary.

By properly taking into account the ISI and off-shell kinematics of quarks, we succeeded to simultaneously describe the experimentally measured fully inclusive (for example, DIS) as well as semi-inclusive (triple-differential cross section of the Drell-Yan process) cross sections very well.

The applied technique and obtained results are presented in the following sections.

2 Method

The basic tool in the calculation of hard processes is the factorization into hard and soft physics:

$$d\sigma = f(Q^2, \xi) \otimes d\hat{\sigma}(\xi).$$

We additionally took into account the initial state interaction via dressing the incoming quark lines with a spectral function and used the generalized factorization:

$$d\sigma = f(Q^2, p_T, \xi) \otimes d\hat{\sigma}(\xi, m) \otimes Sp(m, \Gamma),$$

where: $d\hat{\sigma}(\xi, m)$ - off-shell partonic cross section, $Sp(m, \Gamma)$ - quark spectral function(s), $f(Q^2, p_T, \xi)$ - unintegrated quark distribution, ξ - hadron light cone momentum fraction carried by the struck parton, m - quark virtuality, Γ - quark width.

The hard part, i.e., partonic cross section is calculated using the rules of perturbative quantum chromodynamics (pQCD). We have calculated the pQCD cross section of electron scattering off a virtual quark and the cross section of the annihilation of an off-shell quark-antiquark pair into a pair of dileptons.

Both off-shell cross sections turn out to be gauge invariant. So, the modification of the vertex by the Ward identity was not necessary.

The full kinematics was taken into account as well. In case of DIS it reads:

$$\xi = \frac{x}{Q^2} (Q^2 - 2\mathbf{k}_\perp \cdot \mathbf{q}_\perp - m_i^2),$$

Thus, the struck quark's virtuality and the hadron light cone momentum fraction, carried by this quark, are linearly connected. This is not the case in the Drell-Yan process. For the kinematics of Drell-Yan process in the hadron center of mass system, we obtained the following relations:

$$M_{DY}^2 = m_1^2 + m_2^2 + \xi_1 \xi_2 P_1^+ P_2^- + \frac{(m_1^2 + \mathbf{p}_{1\perp}^2)(m_2^2 + \mathbf{p}_{2\perp}^2)}{\xi_1 \xi_2 P_1^+ P_2^-}$$

$$x_F = \frac{1}{\sqrt{S}} \left(\xi_1 P_1^+ - \xi_2 P_2^- - \frac{(m_1^2 + \mathbf{p}_{1\perp}^2)}{\xi_1 P_1^+} + \frac{(m_2^2 + \mathbf{p}_{2\perp}^2)}{\xi_1 P_2^-} \right)$$

In the target rest frame, the connection between the observable mass (M_{DY}^2), Feynman variable (x_F), and transverse momentum (p_T) of the lepton pair on one hand side and the partonic variables on the other hand side is simpler. However, factorization in the usual form is not applicable in this system of [3].

The following parameterization is commonly used for the unintegrated parton distributions:

$$f(Q^2, p_T, \xi) = f(p_T) \cdot q(Q^2, \xi),$$

where $f(p_T)$ - a Gaussian, $q(Q^2, \xi)$ - conventional parton distribution functions. For the latter, we used the latest parameterizations by Glueck, Reya, Vogt [2].

In our calculations, a Breit-Wigner parameterizations for the quark spectral function was applied. The width was considered constant for a constant hard scale of the process (Q^2 for DIS and $M_{DY}^2 + p_T^2$ for Drell-Yan).

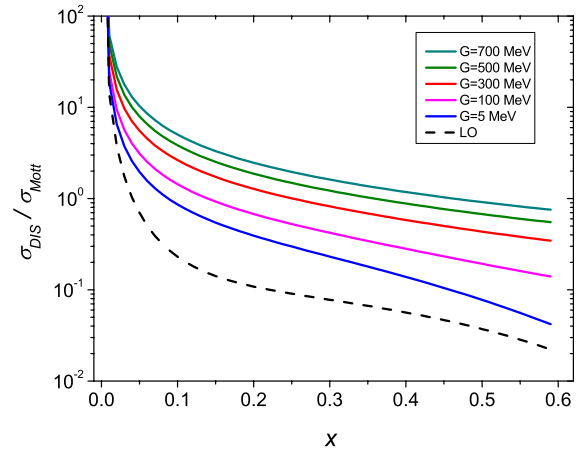


Fig. 1. DIS cross section for the range of quark spectral function widths from 5 MeV to 1 GeV and the parton model (dashed line)

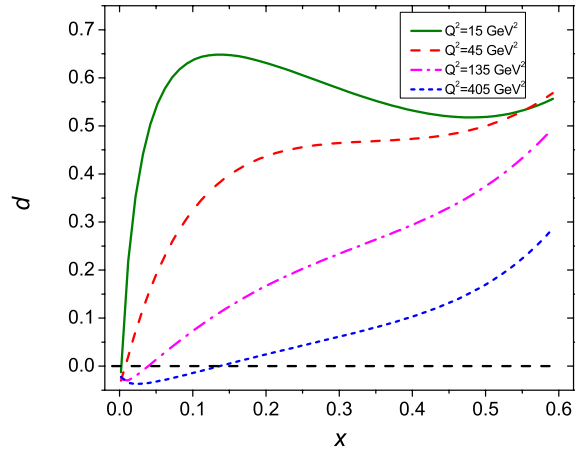


Fig. 2. Relative deviation of calculated cross section of DIS off the proton from parton model, $d = (\sigma_{ISI} - \sigma_{LO}) / (\sigma_{ISI} + \sigma_{LO})$, for different Q^2

3 Results

The result of our calculations for DIS for a range of widths as compared to the parton model is shown in Fig. 1.

We found that the effect of the initial state interaction in DIS is large in the region of small Bjorken x and low momentum transfer Q^2 . For the quark width 200 MeV, the cross section deviation reaches as much as 50% for $Q^2 = 10 \text{ GeV}^2$.

On the other hand, for the values of Q^2 well above the resonance region, e. g. 200 GeV^2 , the effect of the initial quark off-shellness accounts only to at most 10% of the LO cross section.

The found effect of the parton virtuality in DIS is Q^2 -suppressed (Fig. 2). For the most of the experimentally investigated values of Q^2 , the ambiguity in the parton distribution function parameterizations due to the renormalization scale uncertainty is of the same order as the ISI effect in DIS.

Thus, the value of the quark width in the nucleon cannot be extracted from the DIS data. This is the result

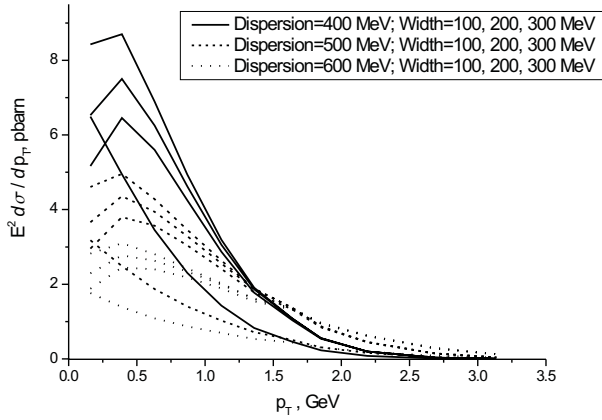


Fig. 3. Calculated distribution of the Drell-Yan lepton pair's transverse momentum for different values of the quark primordial transverse momentum dispersion and spectral function width

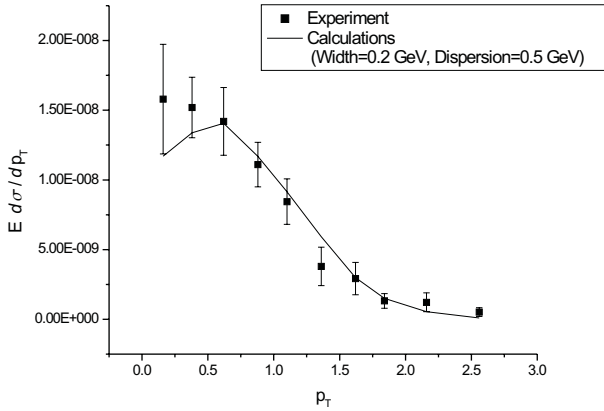


Fig. 4. Calculation result, compared to the data of the Fermilab experiment 866 for the continuum dimuon production in 800 GeV/c proton collision, $6.2 \leq M \leq 7.2$ GeV, $-0.05 \leq x_F \leq 0.2$. Only statistical errors shown

which was expected by an analogy to nuclear physics, because the DIS cross section is fully inclusive.

In contrast, for such a semi-exclusive observable as the transverse momentum distribution of the Drell-Yan lepton pair, we have found a substantial dependence on both the dispersion of the quark primordial transverse momentum and the spectral function width (Fig. 3). The LO QCD prediction for this distribution is the δ -function around 0, while the experimentally measured distribution is rather broad.

In the Figs. 5 and 4, an example of our description of the experimental data is presented. In this data set, the mass of the Drell-Yan pair is around 7 GeV and $0 < x_F < 0.2$. The optimal parameters for these values of M_{DY} and x_F are 500 MeV for the dispersion and 200 MeV for the width. The data are reproduced very well over the two orders of magnitude. The slight underestimation at $p_T > 2.5$ GeV is caused by the considerable contribution of the gluon Compton scattering process to the measurable cross section at these high p_T . Note that the convex shape of the distribution at small p_T cannot be described without the inclusion of the off-shell effects (Fig. 3).

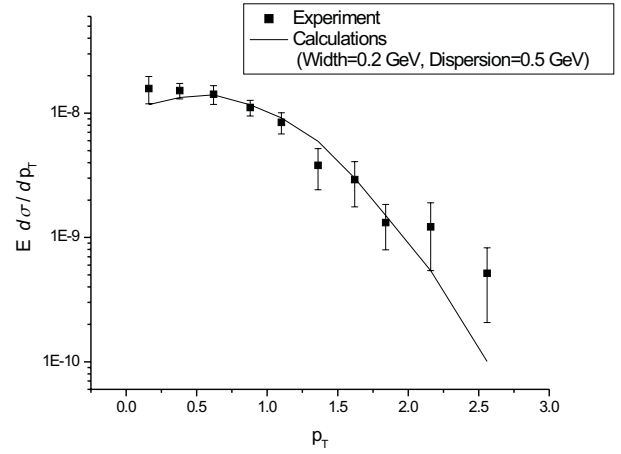


Fig. 5. Calculation result, compared to the data of the Fermilab experiment 866 for the continuum dimuon production in 800 GeV/c proton collision, $6.2 \leq M \leq 7.2$ GeV, $-0.05 \leq x_F \leq 0.2$. Only statistical errors shown

In addition, by other models, neglecting off-shellness, the magnitude of the cross section is not correctly obtained and an additional overall K-factor is used. Our calculations yield not only the experimentally measured form of the cross section but also its amplitude without any K-factor.

4 Summary and outlook

We developed a formalism to study the quark and gluon structure of hadrons going further than the well known picture of collinear non-interacting partons and applied it to calculate cross sections of several high-energy processes. In this paper, the deep inelastic scattering and Drell-Yan pair production are considered.

We explicitly took into account the quark initial state interaction, missed in the standard perturbative consideration, by dressing the quark lines with spectral functions and using the method of generalized factorization.

There was discovered a substantial contribution of the quark off-shellness to the transverse momentum distribution of high-mass virtual photons produced in high-energy hadron-hadron collisions. The quark width in proton was estimated from comparison to resent data of the experiment E866 at Fermilab. For the mass of the Drell-Yan pair around 7 GeV and $0 < x_F < 0.2$, the quark width is 200 MeV. More details about the method and the results can be found in the long write-up by the same authors [3].

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