Unintegrated sea quark at small x and vector boson production

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Parton-shower event generators that go beyond the collinear-ordering approximation at small x have so far included only gluon and valence quark channels at transverse momentum dependent level. In this contribution we provide a definition of a transverse momentum depend (TMD) sea quark distribution valid in the small x region, which is based on the TMD gluon-to-quark splitting function. As an example process we consider vector boson production in the forward direction of one of the protons. The $qq^* \to Z$ matrix element (with one off-shell quark) is calculated in an explicit gauge invariant way, making use of high energy factorization.

1 Introduction

Scattering processes with a single hard scale are well described within the framework of collinear factorization. The treatment of multi-scale processes is on the other hand more involved. In this case, generalized factorization formula are needed to gain control over large logarithms in higher orders of perturbation theory [?]. Such generalized factorization formulas typically involve transverse-momentum dependent (TMD), or "unintegrated" parton distribution and parton decay functions. A broad class of such multiple-scale events is given by small-x processes. The latter are one of the main sources of final states in the central region at the LHC and lead to sizeable rates of forward large-$p_\perp$ jet production at the LHC [?,?]. At small x, TMD parton distributions arise naturally as a consequence of high energy factorization and BFKL evolution [?]. k_T-factorization[?,?] provides then the matching of these high energy factorized TMD distributions to collinear factorized distributions. For Monte Carlo applications a convenient description is given in terms of the CCFM evolution equation [?] which interpolates for inclusive observables between DGLAP and BFKL evolution [?]. It therefore provides a natural basis for a Monte-Carlo realization of k_T-factorization which is provided by the Monte Carlo event generator Cascade [?].

Computational tools based on TMD parton densities have so far been developed within a quenched approximation where only gluons and valence quarks are taken into account [?,?]. While this captures correctly the leading contributions at small x, it is mandatory to go beyond this approximation in order to include preasymptotic effects and to treat final states associated with quark-initiated processes such as Drell-Yan production.

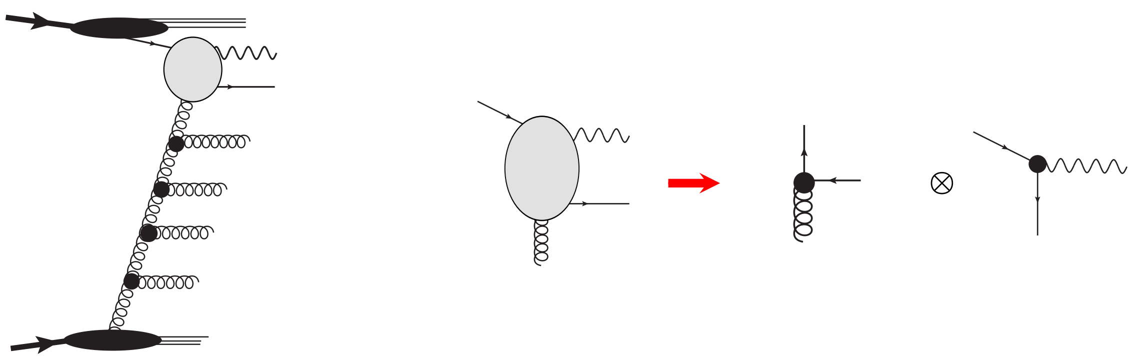
In this contribution we present first steps in this direction, through providing a definition for a TMD sea quark distribution at small x. As an example process we examine forward Drell-Yan production. For a detailed description we refer to [?].

2 Definition of a TMD sea quark distribution and off-shell $qq^* \to Z$ coefficient

The following definition of an unintegrated sea-quark distribution at small x is based on the off-shell TMD gluon-to-quark splitting function [?]. It is obtained by generalizing the expansion in two-particle irreducible kernels of [?] to finite transverse momenta. It reads

$$P_{qg}\left(z, \frac{\boldsymbol{k}^2}{\boldsymbol{\Delta}^2}\right) = T_R \left(\frac{\boldsymbol{\Delta}^2}{\boldsymbol{\Delta}^2 + z(1-z)\boldsymbol{k}^2}\right)^2 \left[(1-z)^2 + z^2 + 4z^2(1-z)^2 \frac{\boldsymbol{k}^2}{\boldsymbol{\Delta}^2}\right]. \tag{1}$$

Here $\boldsymbol{\Delta} = \boldsymbol{q} - z \cdot \boldsymbol{k}$ with $\boldsymbol{k}$ and $\boldsymbol{q}$ transverse momenta of the off-shell gluon and quark respectively, while z is the fraction of the 'minus' light cone momentum of the gluon which is carried on by the t-channel quark. Although evaluated off-shell, the splitting probability is universal. In combination with the gluon Green's function, it takes into account the full small x enhanced transverse momentum dependence to all orders in the strong coupling. The transverse momenta of the sea quark arises therefore as a consequence of subsequent small x enhanced branchings which are not strongly ordered in their transverse momenta. To relate this parton splitting



(a) (b)

Figure 1: (a): If the vector boson is produced in the forward region, the sea quark density becomes sensitive to multiple small x enhanced gluon emissions, leading to a k_T-dependent gluon density (b): Schematic factorization of the partonic $qg^* \to Zq$ process of a) into the $g^* \to q^*$ splitting and the $qq^* \to Z$ coefficient.

kernel to forward vector boson production, we analyze the flavor exchange process $g^*q \to Zq$, see Fig. **??**. At high (partonic) center of mass energy, this process can be treated according to the "reggeized quark" calculus [?,?]. The latter extends the effective action formalism [?], currently explored at NLO [?], to amplitudes with quark exchange in terms of effective degrees of freedom, the so-called reggeized quarks [?,?]. The use of the effective vertices [?,?] ensures gauge invariance of the coefficients relevant to perform the high-energy factorization [?,?] for vector boson production, despite the off-shell parton. If taken literally, the reggeized quark calculus leads for the $g^*q \to Zq$ process to a rather crude approximation to the $g^* \to q^*$ splitting function. This is due to a strong ordering condition which sets the 'plus' momenta of the off-shell quark for the $g^* \to q^*$ splitting to zero. For Eq. (**??**) this corresponds to the limit $z \to 0$. It is however possible to relax this kinematic restriction and to keep z finite, while maintaining the gauge invariance properties of the original vertex. For the $g^* \to q^*$ splitting this yields then precisely the splitting function Eq. (**??**).

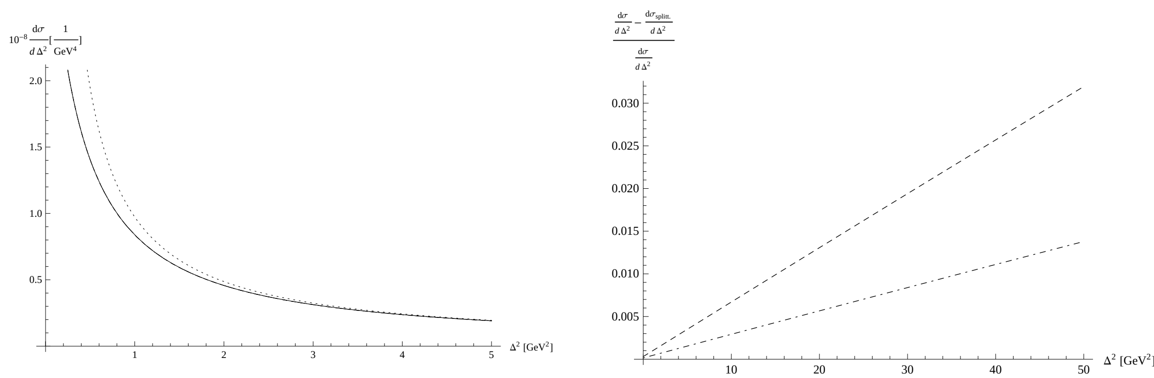
For the $qq^* \to Z$ coefficient, the high energy limit sets the 'minus' component of the quark momentum to zero. While it is possible to relax the ordering prescription also in this case, both versions are in agreement with collinear factorization and will be therefore considered in the following. We obtain

$$\hat{\sigma}_{qq^* \to Z} = \sqrt{2} G_F M_Z^2 (V_q^2 + A_q^2) \frac{\pi}{N_c} \delta(z x_1 x_2 s + T - M_Z^2). \tag{2}$$

Here the variable T parametrizes the off-shellness of the t-channel quark. In the collinear limit $T = 0$ and Eq. (**??**) agrees with the conventional $qq \to Z$ coefficient. For the general off-shell case, T coincides with the squared transverse momentum of the off-shell quark if strong minus momentum ordering is fulfilled. If this condition is on the other hand relaxed, T agrees with the absolute value of the squared four momentum of the off-shell quark. These two possibilities then factorize the $qg^* \to qZ$ process as convolutions in the modulus of transverse (k_T) and four momentum (t) respectively. For further details we refer to the paper [?].

3 Numerical analysis

In the following section we compare the different off-shell factorized expressions with the full $qg^* \to qZ$ matrix element result and an expression which uses only the collinear splitting function. For small $|\boldsymbol{\Delta}|$, the differences between t and k_T-factorized expressions are numerically



(a) (b)

Figure 2: (a): $\boldsymbol{\Delta}^2$ dependence of the differential cross section $d\sigma/d\boldsymbol{\Delta}^2$ for small $|\boldsymbol{\Delta}|$: (solid) full; (dashed) no plus-momentum ordering; (dot-dashed) no plus-momentum and minus-momentum ordering; (dotted) collinear approximation. All but the last curve overlap in this region. We set $x_1 x_2 s = 2.5 M_Z^2$, $\boldsymbol{k}^2 = 2$ GeV^2. (b): Relative deviations in the differential cross section $d\sigma/d\boldsymbol{\Delta}^2$: (dashed) no plus-momentum ordering; (dot-dashed) no plus-momentum and minus-momentum ordering.

small. Both expressions are close to the full result; as $|\boldsymbol{\Delta}|$ increases, we find that the deviations due to the kinematic contributions by which both versions differ become non-negligible, and that the t-factorized expression gives a better approximation to the full result.

Future extensions of the above results concern at first large-x corrections, likely to be important for Drell-Yan phenomenology, see [?,?,?,?]. Another direction addresses the inclusion of full quark emissions to the evolution of the unintegrated parton densities. The latter are naturally contained in both leading-order DGLAP evolution and unintegrated parton densities which taken into account full next-to-leading order BFKL evolution, see [?] for related work. The results in this paper can be implemented in a parton shower Monte Carlo generator including transverse-momentum dependent branching, such as [?]. Work along these lines is in progress.

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