Parton distribution functions at small momentum fractions

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Parton distribution functions (PDFs) quantify the nonperturbative structure of hadrons in a wide range of computations for high-energy processes. In common phenomenological approaches such as the one used by CTEQ-TEA collaboration [1], the PDFs are parameterized at an initial scale Q_0 as functions of the partonic momentum fraction x and free parameters a_N:

$$xf_a(x,Q_0) = x^{a_1}(1-x)^{a_2}P_a(x;a_3,...). \tag{1}$$

In this parametric form, the $x \to 0$ limit of this form is guided by the term x^{a_1} suggested by the Regge theory [2]. The $x \to 1$ limit is dominated by the $(1-x)^{a_2}$ term suggested by quark counting rules [3]. Slowly varying, smooth functions $P_a(x)$ modify the behavior at intermediate x. It is commonly accepted that PDFs can be used to make predictions in the QCD formalism valid at $x \gtrsim 0.01$ and obey the DGLAP evolution equations [4]. At $x \ll 0.01$ and small Q, k_T-ordered QCD radiation typical for DGLAP factorization no longer dominates because of parton saturation effects. In perturbative expansions, large logarithms $\alpha_s^k \log^n(1/x)$ emerge. The large logarithms can be resummed according to BFKL equations [5].

It is still unclear where, in the x and Q kinematic plane, one expects transition from DGLAP to BFKL, and then to the full saturation dynamics. When the $\alpha_s^k \log^n(1/x)$ terms become large, we enter gluon saturation region very quickly [6]. In the global QCD analyses by the NNPDF [7] and xFitter [8] groups, the BFKL resummation approach improves the description of the HERA DIS data in the corner of small x and Q in the kinematic phase space. As an alternative, the CT group has introduced an x-dependent DIS factorization scale $\mu^2_{\mathrm{DIS},x} = a_1(Q^2 + a_2/x^{a_3})$ [1], motivated by saturation models. The parameters $a_{1,2,3}$ are determined by global fits. When compared to the existing DIS data, the CT approach based on the saturation scale provides the same level of agreement between the theory and data as the NNPDF and xFitter analyses that implement the BFKL resummation. Both the saturation scale and BFKL approaches enhance (reduce) the gluon (singlet) PDF at small x and small Q (~ 2 GeV). At higher factorization scales, such as $Q = 10$ GeV, the small-x effect disappears. Within the currently accessible experimental region, the PDFs and the predicted cross section agree well between the two approaches.

The goal for the proposed study is to extend comparisons between the two approaches to new kinematical regions. We expect that, at the smallest x and Q, the full saturation dynamics becomes markedly different from its large-log approximation based on the BFKL formalism. Our goal is to use the comparisons between the DGLAP, BFKL, and saturation approaches to delineate the boundaries between the three theoretical formalisms. The other goal is to understand implications to phenomenological predictions at the FCC-hh collider and in cosmic ray experiments.

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