PB TMD fits at NLO with dynamical resolution scale

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Abstract

Parton branching solutions of QCD evolution equations have recently been studied to construct both collinear and transverse momentum dependent (TMD) parton distributions. In this formalism a soft-gluon resolution scale is introduced to separate resolvable and non-resolvable branchings, and to take into account soft-gluon coherence effects. In this talk, results of fits to the high precision deep inelastic scattering (DIS) structure function measurements are shown including for the first time the effects of dynamical, i.e. branching-scale dependent, resolution scales at Next-to-Leading-Order (NLO) accuracy in the strong coupling.

1 Introduction

QCD resummations [1] to all orders in the strong coupling are an essential aspect of theoretical predictions for precision physics at high-energy hadron colliders. Transverse momentum dependent (TMD) parton distributions [2] provide a theoretical framework to both accomplish resummed perturbative calculations and include non-perturbative dynamics. In Refs. [3, 4] a method which is based on the unitarity picture of parton evolution [5, 6] has been presented to define TMDs in a parton branching (PB) formalism. In this method color coherence of soft-gluon radiation [7, 8, 9, 10] and transverse momentum recoils are taken into account. The soft-gluon resolution scale is introduced to separate resolvable branchings from non-resolvable ones, and Sudakov form factors are used to describe explicit partonic probabilities for no resolvable branchings in a given evolution interval. Since the transverse momentum generated radiatively in the branching is sensitive to the treatment of the non-resolvable region [11], an additional condition can be applied to relate the transverse momentum recoil and the scale of the branching. This relation incorporates the property of angular ordering, and implies that the soft-gluon resolution scale can be dynamical, i.e., dependent on the branching scale.

In this work, the effects of dynamical resolution scales on TMD evolution and on collider observables are discussed. The PB evolution equations are solved numerically with dynamical resolution scale by applying the Monte Carlo solution techniques [3, 12], and fits to precision deep inelastic scattering (DIS) measurements [13] are performed at Next-to-Leading-Order (NLO) accuracy in the strong coupling.

The paper is organized as follows. In Sec.2 the PB evolution equation and dynamical soft-gluon resolution scale are described. The results of DIS fits with dynamical resolution scale are shown in Sec.3. Conclusions are given in Sec.4.

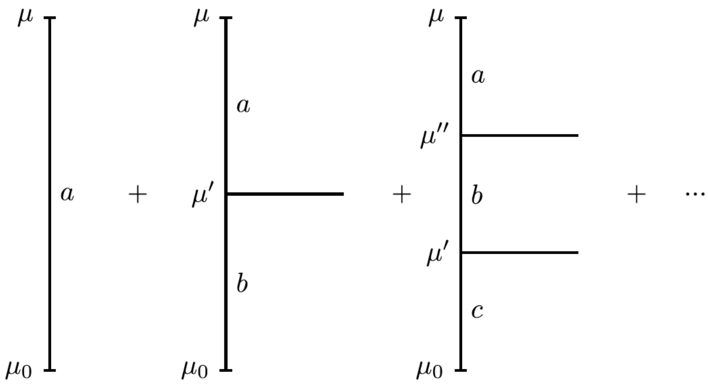

Figure 1: Solution of the branching equation by iteration.

2 Parton Branching TMDs and angular ordering

In the Parton Branching approach, the TMD evolution equations can be written as [4]

$$\begin{aligned}\tilde{A}_a\left(x,k,\mu^2\right) = &\tilde{A}_a\left(x,k,\mu_0^2\right)\Delta_a\left(\mu^2,\mu_0^2\right)\\ &+\sum_b\int\frac{\mathrm{d}^2\mu'}{\pi\mu'^2}\Theta\left(\mu^2-\mu'^2\right)\Theta\left(\mu'^2-\mu_0^2\right)\\ &\times\int_x^1 dz\Theta\left(z_m(\mu')-z\right)\frac{\Delta_a\left(\mu^2,\mu_0^2\right)}{\Delta_a\left(\mu'^2,\mu_0^2\right)}P^R_{ab}\left(z,\alpha_s\left(b\left(z\right)^2\mu'^2\right)\right)\tilde{A}_b\left(x/z,k+a(z)\mu',\mu'^2\right)\end{aligned} \tag{1}$$

where $\tilde{A}_a\left(x,k,\mu^2\right) = xA_a\left(x,k,\mu^2\right)$ is the momentum-weighted TMD distribution of flavor a, carrying the longitudinal momentum fraction x of the hadron's momentum and transverse momentum k at the evolution scale μ; z and μ' are the branching variables, with z being the longitudinal momentum transfer at the branching, and μ' the momentum scale at which the branching occurs; P^R_{ab} are the real-emission splitting kernels; Δ_a is the Sudakov form factor, given by

$$\Delta_a\left(\mu^2,\mu_0^2\right) = \exp\left(-\sum_b\int_{\mu_0^2}^{\mu^2}\frac{\mathrm{d}\mu'^2}{\mu'^2}\int_0^1 \mathrm{d}z\Theta\left(z_m\left(\mu'\right)-z\right)zP^R_{ba}\left(z,\alpha_s\left(b\left(z\right)^2\mu'^2\right)\right)\right). \tag{2}$$

The initial evolution scale in Eq. (1) is denoted by μ_0.

An iterative Monte Carlo solution of Eq. (1) is obtained in [3], and is represented pictorially in Fig. 1. Collinear PDFs can be obtained from Eq. (1) as well by integration over the transverse momentum k. The distribution of flavor a at scale μ is written, as a function of x and k, as a sum of terms involving no branching between μ_0 and μ, then one branching, then two branchings, and so forth. The transverse momentum k, in particular, arises from this solution by combining the intrinsic transverse momentum (in the first term on the right hand side of Eq. (1)) with the transverse momenta emitted in all branching.

Due to colour coherence, soft gluons fulfill angular ordering (AO) in the evolution cascade, with the angle of the emitted gluon with respect to the beam axis increasing at each branching. The PB method incorporates the AO [14] through i) the relation between the branching scale μ' and the transverse momentum q of the emitted parton, $|q| = (1-z)\mu'$; ii) the scale in the running coupling $\alpha_s(q^2) = \alpha_s((1-z)\mu'^2)$; iii) the resolution scale $z_m = 1-q_0/\mu'$, where q_0 is the minimum transverse momentum with which a parton can be resolved. Based on four-momentum conservation, the constraint on the minimum transverse momentum of the emitted

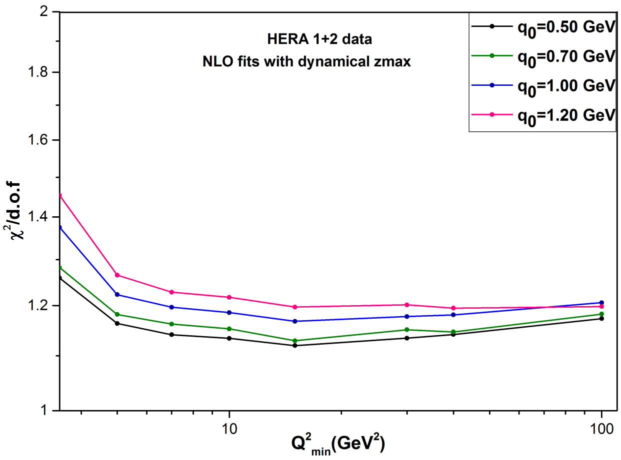

Figure 2: The fit results with dynamical z_m at NLO with HERA 1 + 2 data set, using xFitter

parton q_0 results, using the ordering relation, in the maximum z value, z_m, as a function of the branching scale. Taking q_0 to be large enough compared to $\Lambda_{\rm QCD}$ allows one to stay in the weak coupling region avoiding the Landau pole of α_s. Extending the work [15], in this study we present for the first time fits of PB TMD parton densities with q_0 larger than $\Lambda_{\rm QCD}$ and dynamical resolution scale.

3 Fits at NLO with dynamical resolution scale

In this section, numerical results for fits with dynamical resolution scale at NLO are discussed. The fits to inclusive DIS cross section combined H1 and ZEUS measurements [13] are performed in a wide range of Q^2 and x using χ^2 minimization, by means of the open-source QCD platform xFitter [16, 17]. We follow the same strategy as in [15] for parameterization, systematic and experimental uncertainty calculations, use of NLO coefficient functions and heavy flavour treatment. The experimental uncertainties on each of the fitted parameters are calculated within the xFitter package. The model uncertainty is obtained by varying m_c, m_b and initial evolution scale. In Fig. 2 results for the $\chi^2/d.o.f$ as a function of the minimum Q^2 of the data included in the fit are shown. In this figure, different fits with different q_0 values are plotted. It is observed that for each value of q_0 there is a reasonably good χ^2 in a wide range of Q^2, with the lowest q_0 giving the best $\chi^2/d.o.f$.

In Fig. 3, predictions for the inclusive DIS cross section from $q_0 = 0.5GeV$ and $q_0 = 1.0GeV$ are shown and compared with the measurements from HERA [13] for different values of the evolution scale $\mu^2 = Q^2$. The agreement with data is excellent for these two different q_0s.

In Fig. 4 the gluon and $\bar{u}$ densities as a function of the transverse momentum are shown at $\mu = 100$GeV and $x = 0.01$, for $q_0 = 0.5GeV$ and $q_0 = 1.0GeV$, together with the uncertainty band coming from the experimental and model sources.

4 Summary and outlook

The PB method [3, 4] has been used for angular-ordered TMD evolution, to obtain fits to the high precision DIS structure function measurements, including for the first time the effects of

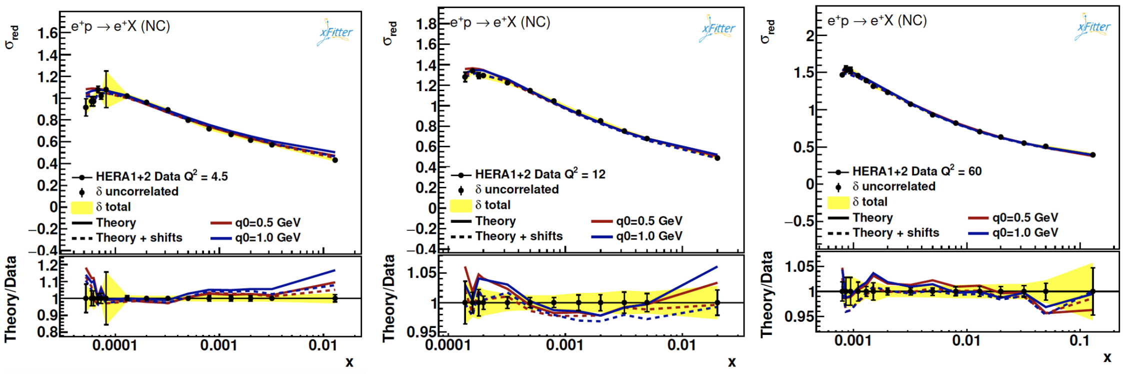

Figure 3: Measurement of the reduced cross section obtained at HERA compared to predictions using $q_0 = 0.5GeV$ and $q_0 = 1.0GeV$.

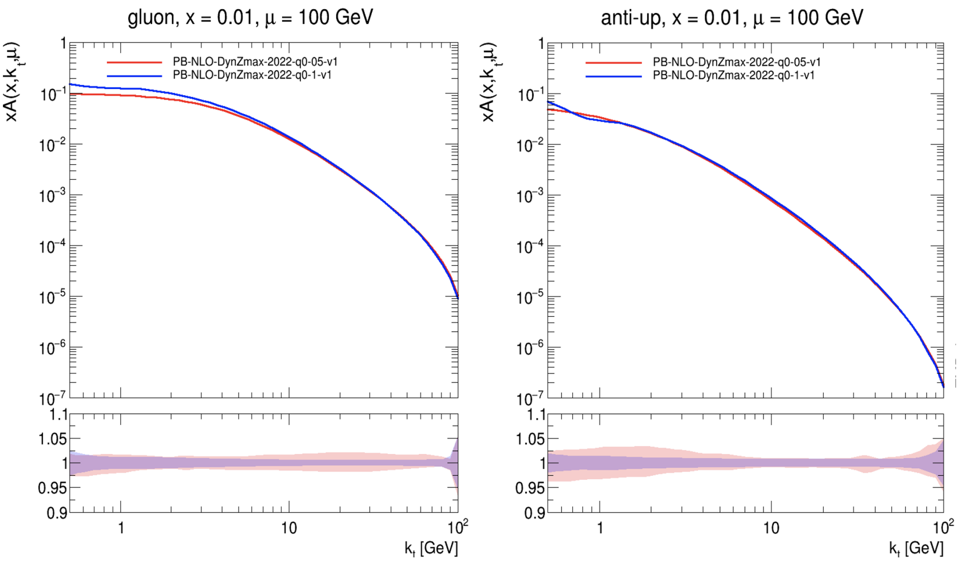

Figure 4: Transverse Momentum Dependent parton densities for $\bar{u}$ and gluon from $q_0 = 0.5GeV$ and $q_0 = 1.0GeV$ as a function of k_t for $\mu = 100$GeV at $x = 0.01$. In the below panel, the relative uncertainty coming from the total of experimental and model uncertainties are shown.

dynamical, i.e. branching-scale dependent, resolution scales. The fits have been obtained at NLO accuracy in the strong coupling. Uncertainties on TMD distributions, including experimental and model sources, have been determined. Good agreement with the measurements is observed when angular ordering is applied.

The NLO TMD parton distributions determined from these fits, with the associated uncertainties, will be released this year, and will be made available in the TMDlib library [18, 19].

These distributions can be used for physics studies in hadronic collisions and phenomenological applications. It was noted in [20, 21] that the low transverse-momentum part of the Drell-Yan lepton-pair production spectrum is sensitive to angular ordering effects in the QCD running coupling, and an analogous observation was made [22] for di-jet angular correlations at large azimuthal angles. The results presented in this work will enable investigations of angular ordering effects in soft-gluon resolution scales as well.

Also Drell-Yan + jets final states can be studied with PB TMDs, e.g. by NLO matching [23] or multi-jet merging [24] approaches. For such studies, it will be possible to use the TMD distributions obtained in this work along with the Monte Carlo event generator [25] implementing the PB method. Dynamical resolution scale effects are currently being examined also in the context of generalized PB evolution equations involving TMD splitting functions [26, 27] defined by high-energy factorization [28].

A future development of the work in this paper will be to extend the fits to larger data sets. This will apply both to data from current experiments such as LHC and fixed-target experiments, and to data from future collider programs such HL-LHC [29], EIC [30], LHeC [31].

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