High-energy QCD at colliders: semi-hard reactions and unintegrated gluon densities

Letter of Interest for SnowMass 2021

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The search for evidence of New Physics is in the viewfinder of current and forthcoming analyses at the Large Hadron Collider (LHC) and at future hadron, lepton and lepton-hadron colliders. This is the best time to shore up our knowledge of strong interactions though, the high luminosity and the record energies reachable widening the horizons of kinematic sectors uninvestigated so far. A broad class of processes, called *diffractive semi-hard* reactions [1], *i.e* where the scale hierarchy, $s \gg \{Q^2\} \gg \Lambda^2_{\rm QCD}$ (s is the squared center-of-mass energy, $\{Q\}$ a (set of) hard scale(s) characteristic of the process and $\Lambda_{\rm QCD}$ the QCD scale), is stringently preserved, gives us a faultless chance to test perturbative QCD in new and quite original ways. Here, a genuine fixed-order treatment based on collinear factorization fails since large energy logarithms enter the perturbative series in the strong coupling, α_s, with a power that increases with the order. In particular, large final-state rapidities (or rapidity distances), typical of single forward emissions (or double forward/backward emissions) with colorless exchanges in the t-channel, directly enhance the weight of terms proportional to $\ln(s)$. The Balitsky-Fadin-Kuraev-Lipatov (BFKL) approach [2] performs an all-order resummation of these large energy logarithms both in the leading approximation (LLA), which means inclusion of all terms proportional to $\alpha_s^n \ln(s)^n$, and in the next-to-leading approximation (NLA), including all terms proportional to $\alpha_s^{n+1} \ln(s)^n$. Over the last few years, predictions for observables in a wide range of semi-hard final states have been given. Among them, azimuthal correlations between two Mueller-Navelet jets [3] have been identified as favorable observables in the discrimination between BFKL- and fixed-order-inspired calculations [4]. This channel is characterized by hadroproduced jets with high transverse momenta, a large difference in rapidity, and a secondary undetected gluon system. Several phenomenological studies have been conducted so far [5–13] and they are in fair agreement with data collected by the CMS collaboration [14]. However, the contingency that the same data could be concurrently portrayed at the hand of fixed-order, DGLAP-based calculations, has been pointed out recently, but not yet punctually addressed. Taking advantage of the richness of configurations gained by combining the acceptances of CMS and CASTOR detectors and making use of disjoint intervals for the transverse momenta of the emitted objects, it was recently highlighted [15] how high-energy resummed and fixed-order driven predictions for semi-hard sensitive observables can be decisively discriminated in the kinematic ranges typical of current and forthcoming analyses at the LHC. With the aim of deepen our knowledge of the BFKL dynamics, a notable variety of final states has been recently proposed: the inclusive multi-jet hadroproduction [16, 17], the inclusive emission of two light-charged hadrons [18, 19], J/Ψ-jet [20], hadron-jet [21], Higgs-jet [22, 23], Drell–Yan-jet [24] and heavy-flavored di-jet photo- [25] and hadroproduction [26].

The BFKL resummation still represents a powerful tool to improve our understanding of the proton structure at small-x. First, it allowed us to define and study an *unintegrated gluon distribution* (UGD), written as a convolution of the gluon Green's function and the non-perturbative proton impact factor. Then, it gave us the chance to improve the description of collinear parton distribution functions (PDFs) with next-to-leading (NLO) and next-to-NLO accuracy through the inclusion of NLA resummation effects [27]. Ultimately, it permitted us to predict the small-x behavior of *transverse-momentum-dependent* (TMD) gluon distributions [28].

The UGD has been subject of intense studies since the early days both in exclusive and inclusive channels. Originally employed in the study of DIS structure functions [29], the UGD has then probed through the exclusive diffractive vector-meson leptoproduction [30–32] at HERA, the single-bottom quark production [33] at the LHC and the inclusive forward Drell-Yan dilepton production [34, 35] at LHCb. Notably, exclusive emissions of forward meson states at moderately low energy scales offer a unique chance to compare predictions done in the high-energy resummmation formalism with results obtained at the hand of the generalized-parton-distribution (GPD) formalism. Recent analyses on the diffractive electroproduction of ρ mesons [31] have corroborated the underlying assumption [36] that the small-size dipole scattering mechanism is at work, thus validating the use of the UGD formalism, which holds when observable transverse momenta are large. Nonetheless, a significant sensitivity of polarized cross sections to intermediate values of the meson transverse momenta, where, in the case of inclusive emissions, a description at the hand of TMD factorization starts to be most appropriate framework, has been observed. All these features brace the message that the development of a unified formalism, where both the CSS [37] and the BFKL evolution mechanisms are consistently integrated in the definition of small-x gluon-TMD distributions, needs to be carried on with high priority in the medium-term future. The extension of these studies to the production of (single) forward heavy-quark bound states certainly represents a substantial step forward towards a deeper understanding of the proton structure in wider kinematic ranges. Leading-order (LO) impact factors describing the production of forward heavy-quark pairs [26, 38] are the landmark for the study of emissions of heavy-flavored open states in collisions of hadrons [26] or quasi-real photons [25]. Still they can serve as a common basis for the analytic calculation of LO impact factors depicting the emission of forward heavy-light mesons and quarkonia.

The research lines presented above are relevant in the search for high-energy effects via the description of an increasing number of hadronic and lepto-hadronic reactions at the LHC and at new-generation colliders, like the Electron-Ion Collider (EIC). At the same time, the BFKL resummation serves as a tool to address more general aspects of QCD, from the hadronic structure to other resummations and to the production mechanism of hadronic bound states. We believe that the inclusion of these topics in the *SnowMass 2021* scientific program would accelerate progress of our understanding of both formal and phenomenological aspects of strong interactions at high energies.

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