PROCEEDINGS OF SCIENCE

Heavy-flavored emissions in hybrid collinear/high-energy factorization

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Heavy-flavored emissions have been always considered as an excellent channel to test properties of Quantum chromodynamics (QCD) at present and future colliders. Among different regimes, in which heavy-flavor production can be investigated, we focus our attention on the semi-hard one, where $s \gg Q^2 \gg \Lambda_{\rm QCD}$ (s is the squared center-of-mass energy, Q^2 a (set of) hard scale(s) characteristic of the process and $\Lambda_{\rm QCD}$ the QCD mass scale). Here, we build predictions in a hybrid collinear/high-energy factorization, in which the standard collinear description is supplemented by the Balitsky-Fadin-Kuraev-Lipatov resummation of large energy logarithms. The definition and the study of observables sensitive to high-energy dynamics in the context of heavy-flavor physics has the double advantage of (*i*) allowing to get a stabilization of the BFKL series under higher-order corrections and (*ii*) providing us with an auxiliary tool to investigate heavy-flavor production in wider kinematical ranges. Hence, we propose a scientific program on heavy-flavor physics at high energy with the goal of considering both open (heavy-jet) and bound states (Λ baryons, heavy-light mesons and quarkonia).

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

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PoS(EPS-HEP2021)389

1. Introduction

In the TeV-range, which is to be considered at modern colliders, hadronic reactions can be explored in new kinematic regimes. A particularly interesting one is the so-called *semi-hard regime*, characterized by a center-of-mass energy, $\sqrt{s}$, much larger than the hard scales of the process, $\{Q\}$, which are, in turn, much larger than the QCD mass scale, $\Lambda_{\rm QCD}$. Here, large logarithms of the energy enter the perturbative series with powers increasing with the perturbative order, thus systematically compensating the smallness of the coupling. Therefore, a resummation to all orders which takes into account the effects of these large logarithms is required. The consolidated tool for this resummation is the Balitsky-Fadin-Kuraev-Lipatov (BFKL) approach [1–4], which allows for the inclusion of large energy logarithms both in the leading logarithmic approximation ($(\alpha_s \ln s)^n$ terms are resummed), LLA, and in the next-to-leading logarithmic approximation ($(\alpha_s \ln s)^n$ and $\alpha_s(\alpha_s \ln s)^n$ terms are resummed), NLA. In this framework, the cross sections of processes take a peculiar factorized form, given by the convolution of two process-dependent impact factors, related to the transition of colliding particles into a precise final-state (in their fragmentation region), and a process-independent Green's function. A selection of reactions that can be considered at NLA level includes: the inclusive hadroproduction of two jets well separated in rapidity (Mueller–Navelet channel [5]), for which several phenomenological analyses have appeared so far [6–16], the inclusive detection of two light-charged rapidity-separated hadrons [17–20] or of a rapidity-separated pair formed by a light-charged hadron and a jet [21–23], the inclusive production of rapidity-separated Λ-Λ or Λ-jet pairs [24]. Settling for only a partial inclusion of next-to-leading effects, new channels open up, such as three- and four-jet hadroproduction [25–29], J/Ψ-jet [30], Drell–Yan-jet [31], Higgs-jet [32], and heavy-quark pair production [33–36]. In these reactions two objects with a large separation in rapidity are inclusively tagged, together with an undetected hadronic system. They can be investigated via the so-called *hybrid* collinear/high-energy factorization, where collinear ingredients, such as parton distribution functions (PDFs), fragmentation functions (FFs) and jet functions (JFs), enter the definiton of BFKL impact factors. Another class of reactions that can be studied in the BFKL approach are the so-called single-forward emissions, where the gluon content in the proton is accessed via the *unintegrated gluon distribution* (UGD) [37–39]. Below, we will focus on heavy flavored emissions, in particular to Λ_c-baryon productions. The reason for our interest lies in the fact that these reactions present a novel feature in BFKL phenomenology, allowing for a (partial) stabilization of the series, under inclusion of high-order corrections and scale variations.

2. Λ_c-Λ_c and Λ_c-jet production in VFNS: Theoretical set-up

We considered two hadronic reactions:

$$\text{proton}(P_a) + \text{proton}(P_b) \longrightarrow \Lambda_c^{\pm}(p_1, y_1) + X + \Lambda_c^{\pm}(p_2, y_2) \; , \tag{1}$$

$$\text{proton}(P_a) + \text{proton}(P_b) \longrightarrow \Lambda_c^{\pm}(p_1, y_1) + X + \text{jet}(p_2, y_2) \; , \tag{2}$$

We consider these channels in the high p_T-regime, which justifies the use of a *zero-mass variable flavor number scheme* (ZM-VFNS), in which all five active quarks are considered as massless, and therefore the fragmentation in the Λ_c occurs from light particles. At variance with the standard collinear approach, in our treatment we start from a high-energy factorization which emerges inside the BFKL formalism and we then add collinear ingredients at the level of impact factors. In fact, the "pure" BFKL treatment allows us to build partonic distributions, which are not infrared-safe quantities. We need to reabsorb divergences associated with initial and also final (since we are not totally inclusive) state radiation, at the level of impact factors, thus defining "hadronic impact factors", given by a convolution of BFKL partonic impact factors with PDFs and FFs. It is convenient to write the cross section as a Fourier series of the azimuthal-angle coefficients, $C_{n\geq 0}$

$$\frac{d\sigma}{dy_1 dy_2 d|\vec{p}_1| d|\vec{p}_2| d\varphi_1 d\varphi_2} = \frac{1}{(2\pi)^2}\left[C_0 + 2\sum_{n=1}^{\infty}\cos(n\varphi)\, C_n\right], \tag{3}$$

where $\varphi_{1,2}$ are the azimuthal angles of the tagged objects and $\varphi \equiv \varphi_1 - \varphi_2 - \pi$. The definition of C_n in the $\overline{\text{MS}}$-scheme can be found in [40]. We remark that the description of Λ_c particles in terms of light-hadron impact factors is adequate, provided that energy scales are much larger than the Λ_c mass. This condition is guaranteed by the transverse-momentum ranges of our interest.

3. Λ_c production: Phenomenology and stabilization effects

To show the stabilization mechanism that occurs in the production of heavy species such as Λ_c, we will compare its cross section summed over azimuthal angles with the corresponding ones for lighter species. Key ingredients to build our distributions are the azimuthal coefficients integrated over rapidity and transverse momenta of the two tagged objects, and differential in the rapidity difference $\Delta Y \equiv y_1 - y_2$

$$C_n = \int_{y_1^{\min}}^{y_1^{\max}} dy_1 \int_{y_2^{\min}}^{y_2^{\max}} dy_2 \int_{p_1^{\min}}^{p_1^{\max}} d|\vec{p}_1| \int_{p_2^{\min}}^{p_2^{\max}} d|\vec{p}_2|\; \delta(\Delta Y - y_1 + y_2)\; C_n\left(|\vec{p}_1|, |\vec{p}_2|, y_1, y_2\right). \tag{4}$$

Here, we consider just C_0, whereas a more detailed analysis on the azimuthal correlation can be found in Ref. [40]. We impose LHC-typical kinematic cuts for both Λ-particles and jets, allowing the transverse momenta of the Λ to range between 10 GeV and $p_\Lambda^{\max} \simeq 21.5$ GeV and the jets one between 35 GeV and 60 GeV. As for the rapidities, we set $|y_\Lambda| < 2.0$ and $|y_J| < 4.7$. We fix the center-of-mass energy at $\sqrt{s} = 13$ TeV. We perform our phenomenological studies by making use of the `JETHAD` modular interface [41] under development at our Group. We depict the parton fragmentation into Λ_c baryons in terms of the `KKSS19` NLO FF set [42], while lighter-hadron emissions (Λ hyperons) are described in terms of `AKK08` NLO FFs [43]. In upper panels of Fig. 1 we show the ΔY-dependence of the φ-summed cross section, C_0, in the double Λ_c channel, together with corresponding predictions for the detection of Λ hyperons. We note that NLA bands are almost nested (except for very large values of ΔY) inside LLA ones and they are generally narrower in the Λ_c case. This is a clear effect of a (partially) reached stability of the high-energy series, for both hadron emissions. However, while predictions for hyperons lose almost one order of magnitude when passing from natural scales to the expanded BLM ones (from left to right panel), results for Λ_c baryons are much more stable, the NLA band becoming even wider in the BLM case. The stability is partially lost when a Λ_c particle is accompanied by a jet, as shown in lower panels of Fig. 1. Here, LLA and NLA bands are almost disjoined at natural scales (left panel), while in the BLM case (right panel) they come closer to each other for hyperon plus jet, and almost entirely contained for Λ_c plus jet. In Fig. 2 we study C_0 for the double production of Λ_c baryons (left) or

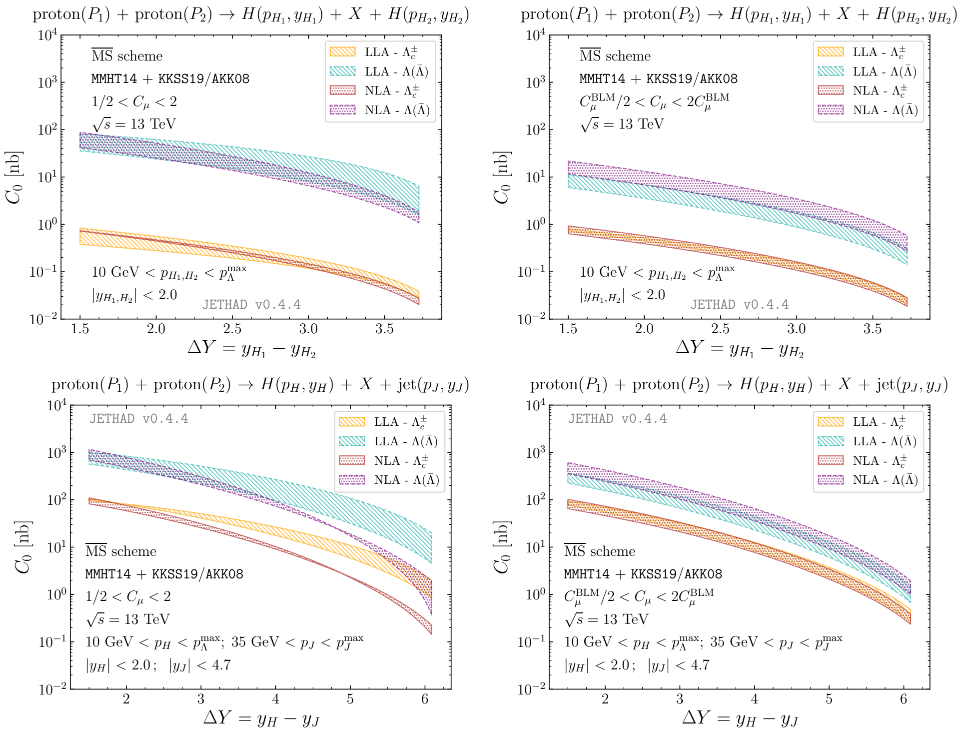

Figure 1: Behavior of the φ-summed cross section, C_0, as a function of ΔY, in the double Λ_c (upper) and in the Λ_c plus jet channel (lower), at natural scales (left) and after BLM optimization (right), and for $\sqrt{s} = 13$ TeV. Error bands provide with the combined uncertainty coming from scale variation and numerical integrations. Predictions for Λ_c emissions are compared with configurations where Λ hyperons are detected.

Λ hyperons (right) under a progressive variation of energy scales in a wider range that includes the typical BLM ones, $1 < C_\mu < 30$. C_0 exhibits a fair stability under progressive scale variation both in the Λ_c, while its sensitivity spans over almost one order of magnitude in the hyperon case. These studies on C_0 clearly highlight how Λ_c emissions allow for a stabilization of the resummed series, that cannot be obtained with lighter hadrons. Further studies in [40, 44] have evidenced how the stability effect is due to the smooth- and non-decreasing with μ_F behavior of Λ_c FF. We plan to extend our program on semi-hard phenomenology by considering inclusive production of heavy-light mesons and quarkonia at the LHC and at new-generation colliding facilities [45–48].

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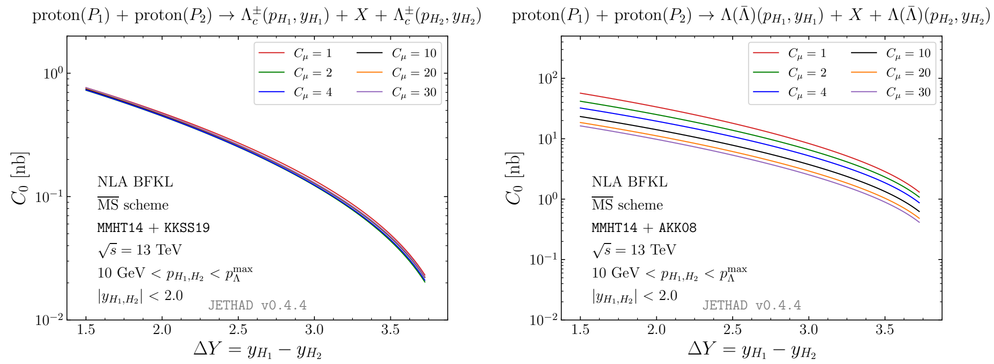

Figure 2: Behavior of the φ-summed cross section, C_0, as a function of ΔY, in the dihadron production channel, and for $\sqrt{s}$ = 13 TeV. A study on progressive energy-scale variation in the range $1 < C_\mu < 30$ is done for Λ_c emissions (left) and for Λ detections (right).

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