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# Initial-state splitting kernels in cold nuclear matter

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ABSTRACT

We derive medium-induced splitting kernels for energetic partons that undergo interactions in dense QCD matter before a hard-scattering event at large momentum transfer $Q^2$. Working in the framework of the effective theory SCET$_G$, we compute the splitting kernels beyond the soft gluon approximation. We present numerical studies that compare our new results with previous findings. We expect the full medium-induced splitting kernels to be most relevant for the extension of initial-state cold nuclear matter energy loss phenomenology in both p+A and A+A collisions.



## 1. Introduction

Initial-state cold nuclear matter (CNM) effects in A+A and in particular in p+A collisions have received growing attention in recent years [1,2]. Various CNM effects have been discussed extensively in the literature [3–21]. Coherent and incoherent scattering, which lead to power corrections in the production cross sections and the Cronin effect, are limited to small and moderate transverse momenta $p_T$. Nuclear shadowing effects and inelastic multi-parton processes in a QCD medium can lead to modification of the production cross sections for particles and jets at large transverse momenta. In particular, the effect of CNM energy loss can be amplified at high mass or $p_T$ near the kinematic bounds [15,21]. Here, energy loss refers to the medium-induced soft bremsstrahlung processes that redistribute part of the energy of fast partons in a shower of soft gluons. Generally speaking, this can happen before or after the hard-scattering. The beam jets of the incoming nucleon can also lose energy via Bertsch–Gunion bremsstrahlung in a process that contributes to the generation of the underlying event multiplicity for the hadronic collisions [22].

Renewed interest in CNM effects was sparked by recent experimental results that revealed a large and highly non-trivial nuclear modification of jet production yields in p+Pb collisions at the LHC [23,24], as well as in d+Au at RHIC [25,26]. These nuclear modifications manifested themselves in a suppression of the jet production cross section for central collisions, whereas the experiments found an enhancement for peripheral collisions. While it is not yet clear how much of these effects arise from centrality bias, CNM energy loss can contribute to the jet suppression in central and semi-central collisions. In particular, the scaling behavior of the observed suppression as a function of $p_T \cosh(y)$ can be understood in this picture, where $y$ is the rapidity of the observed jet. CNM energy loss may also be a non-negligible effect in describing nuclear modifications in A+A collisions, even though it is suppressed compared to final-state energy loss. In the framework of the reaction operator approach [8], CNM energy loss was first computed in [14] and applied to Drell–Yan production [15]. These initial-state energy loss calculations are an extension of the Gyulassy–Levai–Vitev approach to energy loss for the final state, which successfully predicted and described the magnitude, centrality and energy dependence of jet quenching in A+A collisions, e.g. see [27,28]. It is certainly of great relevance to theory and experiment to further improve the framework of inelastic parton scattering in nuclear matter, which we address in this work.

Advances in understanding inelastic parton processes in dense QCD matter are enabled by Soft Collinear Effective Theory [29–33] (SCET) and its extension to accommodate jet propagation in a nuclear medium. In recent years SCET has become a valuable tool for describing energetic particle and jet production at present-day collider experiments [34–41]. An effective theory describing the interaction of collinear partons with a QCD medium, Soft Collinear Effective Theory with Glauber gluons (SCET$_G$), was developed in [42,43] and theoretical results for the elastic and inelastic soft parton scattering processes given in [44–46]. The basic idea is to include a “Glauber mode” in the effective theory that describes the interaction of energetic partons in matter only by a transverse

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momentum exchange. In the traditional approach to energy loss, medium-induced splittings were derived only in the small-$x$, or soft gluon limit. Here, $x$ denotes the large lightcone momentum fraction carried away by the emitted parton and $x \ll 1$ denotes the approximation in which non-Abelian energy loss is well defined and discussed in the literature. SCET$_\mathrm{G}$ allows to systematically go beyond this approximation to finite values of $x$ and understand in detail the formation of an in-medium parton shower. In [43,45,46] the full medium-induced splitting kernels were derived for final-state parton showers. They describe the branching processes that follow a large $Q^2$ hard-scattering and result in energetic particles and jets seen in the detectors. The obtained full splitting kernels have been successfully applied in order to improve the theoretical precision of the computation of various observables in A+A collisions, including jet and hadron production cross sections [47,48] as well as jet cross sections and shapes [49,50]. Applications in deep inelastic scattering have been discussed in [51,52]. In this work, we derive the analogous finite-$x$ medium-induced splitting kernels for the initial state, relevant to parton shower formation in cold nuclear matter. In the future, we plan to extend the existing CNM energy loss phenomenology using our new results. In addition, as was pointed out in Ref. [53], another potential application of medium-induced splitting kernels is to derive the medium modification of jet and beam functions in SCET, by integrating the corresponding dense QCD matter splitting functions.

The remainder of this paper is organized as follows. In Section 2, we recall the basic framework of SCET$_\mathrm{G}$ and rederive the vacuum splitting kernels. In Section 3, we present our results for the full in-medium splitting kernels in the initial state, as well as their soft-gluon emission limit. In particular, we point out important differences to earlier initial-state results. We present numerical studies comparing the new splitting kernels with their small-$x$ approximations in Section 4. Finally, we draw our conclusions in Section 5.

## 2. Theoretical framework

The effective theory SCET$_\mathrm{G}$ as derived in [43] is based on the following Lagrangian

$$\mathcal{L}_{\mathrm{SCET_G}}(\xi_n, A_n, A_G) = \mathcal{L}_{\mathrm{SCET}}(\xi_n, A_n) + \mathcal{L}_{\mathrm{G}}(\xi_n, A_n, A_G)\ , \tag{1}$$

where the first term is the usual SCET Lagrangian [29–32] and the second term describes the physical interaction of collinear partons with the QCD medium via the exchange of Glauber gluons. The explicit form of the Lagrangians as well as the corresponding Feynman rules can be found in [43]. In this work, we present results for the initial-state splitting processes $q \to qg$, $q \to gq$, $g \to gg$ and $g \to q\bar{q}$. Their respective amplitudes are given by

$$\begin{aligned} A_{q\to ab} &= \langle a(p)b(k)|\, T\, \mathrm{e}^{iS}\, \bar{\chi}_n(x_0)\, |q(p_0)\rangle\ , \\ A_{g\to ab} &= \langle a(p)b(k)|\, T\, \mathrm{e}^{iS}\, \mathcal{B}_n^{\lambda c}(x_0)\, |g(p_0)\rangle\ , \end{aligned} \tag{2}$$

where $\chi$, $\mathcal{B}$ are collinear gauge invariant SCET fields for quarks and gluons respectively [54,55] and $S$ is the SCET$_\mathrm{G}$ action. The partons after the splitting are labeled as $a$, $b$, which is representative for the two possible splittings of a quark or a gluon as listed above. The momenta of the involved partons are given in parentheses in Eq. (2) and are related by momentum conservation $p_0 = p + k$. The parton with momentum $k$ carries away a fraction $x = k^+/p_0^+$ of the energy of the initial parton with momentum $p_0$. In this work, we are considering massless partons only. Using the on-shell conditions $p_0^2 = k^2 = 0$, we may parametrize the involved momenta as

$$\begin{aligned} p_0 &= \left[p_0^+, 0, \mathbf{0}_\perp\right], \\ k &= \left[x p_0^+, \frac{\boldsymbol{k}_\perp^2}{x p_0^+}, \boldsymbol{k}_\perp\right], \\ p &= p_0 - k = \left[(1-x)p_0^+, \frac{-\boldsymbol{k}_\perp^2}{x p_0^+}, -\boldsymbol{k}_\perp\right], \end{aligned} \tag{3}$$

where we have adopted the following notation for light-cone four-vectors $q = [q^+, q^-, \boldsymbol{q}_\perp] = [\bar{n}\cdot q, n\cdot q, \boldsymbol{q}_\perp]$ for any vector $q$ and $n^\mu = (1,0,0,1)$, $\bar{n}^\mu = (1,0,0,-1)$. Note that in Eqs. (3), we have chosen the positive light-cone direction along the momentum direction of the parent parton.

Using only the SCET Lagrangian, we can reproduce again the results for the vacuum leading-order Altarelli–Parisi splitting kernels [56]. As in [45], we obtain

$$\left(\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x}\frac{1}{\boldsymbol{k}_\perp^2}, \tag{4}$$

$$\left(\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}^2\boldsymbol{k}_\perp}\right)_{g\to gg} = \frac{\alpha_s}{2\pi^2} 2C_A \left(\frac{1-x}{x} + \frac{x}{1-x} + x(1-x)\right)\frac{1}{\boldsymbol{k}_\perp^2}, \tag{5}$$

$$\left(\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}^2\boldsymbol{k}_\perp}\right)_{g\to q\bar{q}} = \frac{\alpha_s}{2\pi^2} T_R \left(x^2+(1-x)^2\right)\frac{1}{\boldsymbol{k}_\perp^2}, \tag{6}$$

$$\left(\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}^2\boldsymbol{k}_\perp}\right)_{q\to gq} = \left(\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}^2\boldsymbol{k}_\perp}\right)_{q\to qg} (x \to 1-x). \tag{7}$$

In this work, we are only considering real splitting processes away from the endpoints at $x = 1$ and $x = 0$. However, in future phenomenological applications, we are going to employ generalized QCD evolution techniques using the in-medium initial-state splitting kernels. An analogous technique for the final-state splitting kernels was used in [47,48] for studies of jet quenching phenomenology in A+A collisions. In this context, the in-medium virtual contributions (at $x = 0$ in our notation) were derived from momentum and flavor sum rules satisfied by the splitting kernels. The same techniques can be used for the initial-state splitting kernels.

## 3. Initial-state parton splittings

In Ref. [43], it was shown that a particularly simple gauge choice for calculations of jets in the medium is the so-called hybrid gauge. In this gauge the collinear gluons are treated in the light-cone gauge, while the Glauber gluons are treated in the covariant gauge. With this choice both the collinear Wilson line as well as the transverse gauge link which appear in the effective theory reduce to unity. This choice simplifies our calculations considerably. In order to compute the splitting kernels to first order in opacity, we need to consider single- and double-Born diagrams. The topology of the relevant diagrams for initial-state splitting processes is shown in Fig. 1. In the first line of Fig. 1, the single-Born diagrams are shown, which have to be squared. In the second row, the non-zero double-Born diagrams are shown which appear as interference terms with the vacuum Born amplitude.

We now present our results for the initial-state in-medium splitting kernels, which constitutes the main result of this paper. In order to simplify our notation, we define the following two dimensional transverse vectors $\boldsymbol{A}_\perp$, $\boldsymbol{B}_\perp$, $\boldsymbol{C}_\perp$ and phases $\Omega_{1,2,3}$ similar to the notation in [43,45]