Physics Letters B 769 (2017) 242–248

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Inclusive production of small radius jets in heavy-ion collisions

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ARTICLE INFO

Article history:
Received 31 January 2017
Received in revised form 23 March 2017
Accepted 28 March 2017
Available online 31 March 2017
Editor: A. Ringwald

ABSTRACT

We develop a new formalism to describe the inclusive production of small radius jets in heavy-ion collisions, which is consistent with jet calculations in the simpler proton–proton system. Only at next-to-leading order (NLO) and beyond, the jet radius parameter R and the jet algorithm dependence of the jet cross section can be studied and a meaningful comparison to experimental measurements is possible. We are able to consistently achieve NLO accuracy by making use of the recently developed semi-inclusive jet functions within Soft Collinear Effective Theory (SCET). In addition, single logarithms of the jet size parameter $\alpha_s^n \ln^n R$ are resummed to next-to-leading logarithmic ($\mathrm{NLL_R}$) accuracy in proton–proton collisions. The medium modified semi-inclusive jet functions are obtained within the framework of SCET with Glauber gluons that describe the interaction of jets with the medium. We present numerical results for the suppression of inclusive jet cross sections in heavy ion collisions at the LHC and the formalism developed here can be extended directly to corresponding jet substructure observables.

1. Introduction

In heavy-ion collisions at RHIC and LHC, a quark–gluon plasma (QGP) can be created and studied by using both hard and soft probes [1]. Jets are produced in hard-scattering events and constitute one of the most frequently studied examples of hard probes in heavy-ion collisions. Jets traverse the hot and dense QCD medium and are identified as energetic and collimated sprays of particles in the detectors. Examination of their properties can, therefore, provide information about the QGP. The LHC experimental collaborations ALICE [2], ATLAS [3] and CMS [4], have provided precise data sets for the inclusive production of jets in both proton–proton and heavy-ion collisions. In heavy-ion collisions jets are modified, or quenched, due to the interaction with the QCD medium [5]. Most commonly, the quenching of jet production yields is studied using the nuclear modification factor R_{AA}, which is given by the ratio of the respective cross section in heavy-ion collisions normalized by the corresponding proton–proton baseline. In order to reliably extract information about the QGP from the available data sets, it is important that the experimentally achieved precision is matched with corresponding theoretical calculations. This is precisely what we are going to address in this work.

The identification of jets relies on a jet algorithm that specifies when particles are clustered together into the same jet. Typical algorithms used by the experimental analyses involve, for example, the anti-k_T and the cone algorithms [6,7]. In addition, jets are defined by the jet parameter R which represents the size of the identified jets, see e.g. [8,9] for more details. The first non-trivial order in the perturbative expansion of the cross section where these specifications play a role is next-to-leading order (NLO) in QCD. Therefore, full NLO is the minimally required perturbative order allowing meaningful comparisons between theory and the experimental measurements.[1] In addition, parton distribution functions (PDFs) are fitted at NLO, typically for larger values of $R \sim 0.7$. For the analyses of heavy-ion collisions, however, the jet size parameter is typically chosen to be relatively small, $R \sim 0.2$–0.4, in order to minimize the heavy-ion background and its fluctuations. The perturbative series exhibits a single logarithmic structure $\alpha_s^n \ln^n R$ to all orders in the QCD strong coupling constant, which have to be resummed to render the convergence of the perturbative calculations.

Such a $\ln R$-resummation has recently been achieved for proton–proton collisions to next-to-leading logarithmic ($\mathrm{NLL_R}$) accuracy [10] within the framework of Soft Collinear Effective Theory

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[1] Fixed order calculations can be matched to parton showers and our statement is inclusive of those approaches.

http://dx.doi.org/10.1016/j.physletb.2017.03.067

(SCET) [11–14]. See [15–18] for related work along these lines. It was also demonstrated that the cross section for inclusive jets can be factorized into convolution products of PDFs, hard functions and so-called semi-inclusive jet functions $J_i(z, \omega_J R, \mu)$ (siJFs) [10]. The siJFs describe the formation of a jet with energy ω_J and jet parameter R originating from a parent parton i at scale μ. They satisfy the same timelike DGLAP equations that govern the scale evolution of fragmentation functions. By solving the DGLAP equations, the resummation of logarithms $\ln R$ can be achieved. For values of R in the range of 0.2–0.4, fixed NLO calculations fail to describe the experimental data in proton–proton collisions [4]. When the resummation of $\ln R$ terms is included, good agreement can be achieved, as we will show below. The improved proton–proton baseline makes this the ideal starting point to also study inclusive jet production in heavy-ion collisions. In this work, we extend our earlier calculations for proton–proton collisions to heavy-ion collisions. See for example [5,19–25] for earlier work on the description of jets in heavy-ion collisions.

We address the medium modification within the effective field theory (EFT) framework of SCET with Glauber gluons, which is generally denoted by SCET_G [26,27]. The interaction of collinear quarks and gluons with the hot and dense QCD medium can be described via the exchange of Glauber gluons. Within SCET_G, the relevant interaction terms are included at the level of the Lagrangian. By making use of the collinear-Glauber sector of the corresponding EFT, the full collinear in-medium splitting functions have been derived in the past years to first order in opacity [28–31]. When finite quark masses are neglected, the in-medium splitting functions are given by the vacuum splitting functions times a modification factor that depends on the properties of the medium. The opacity expansion for the medium interactions is analogous to the traditional Gyulassy–Levai–Vitev (GLV) approach to parton energy loss in the QCD medium [32]. At first order in opacity, an average number of uncorrelated interactions with the medium is taken into account. Higher orders in the opacity expansion correspond to correlations between the interactions, which are yet to be calculated beyond the soft gluon emission limit, and are neglected in this work. In the traditional GLV approach, all radiated gluons in the splitting processes are approximated to be soft. Within SCET_G, one can go beyond this approximation and obtain full control of the collinear dynamics of splitting processes in the medium. For example, the in-medium splitting functions have already been successfully applied to describe the modification of light hadrons [33,34] as well as heavy flavor mesons [31] in heavy-ion collisions.

In this work, we derive an analogous treatment of the in-medium effects for inclusive jets by defining in-medium siJFs. In the vacuum, the siJFs can be written in terms of collinear vacuum splitting functions. In the medium, we need to include additional contributions to the siJFs that can be expressed in terms of collinear in-medium splitting functions derived from SCET_G. In general, both radiative and collisional energy loss can play a role in modifying jet production in the medium. In this work, we concentrate on the high-p_T jets and a consistent NLO calculation of the siJFs. Thus, we will leave collisional energy loss for future publications.

The remainder of this paper is organized as follows. In Section 2, we recall the basic framework for inclusive jet production in proton–proton collisions for small-R jets. We outline a consistent extension of the jet cross section to heavy-ion collisions using the in-medium collinear splitting functions obtained within SCET_G. In Section 3, we present numerical results for the nuclear modification factor R_{AA} and we compare to recent data from the LHC. Finally, we draw our conclusions in Section 4.

2. Theoretical framework

We start by summarizing the main results of [10] for inclusive jet production in proton–proton collisions. We then outline how this framework can be extended to the heavy-ion case.

2.1. Proton–proton collisions

The factorized form of the double differential cross section for inclusive jets with a given transverse momentum p_T and rapidity η is given by

$$\frac{d\sigma^{pp\to \text{jet}\,X}}{dp_T d\eta} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^c \otimes J_c \,. \tag{1}$$

Here, we suppressed the arguments of the various functions for better readability. See [10] for more details. The symbols $\otimes$ denote convolution products and we are summing over all relevant partonic channels. The $f_{a,b}$ denote the PDFs, H_{ab}^c are hard-functions and the J_c are the siJFs. The hard-functions are evaluated up to NLO and were shown [10] to be the same as the hard-functions for inclusive hadron production $pp \to hX$, see [35,36]. Note that Eq. (1) is a factorization of purely hard-collinear dynamics, i.e. no soft function is needed. The siJFs are perturbatively calculable functions that describe the formation of the observed jet originating from a parent parton.

If both H_{ab}^c and J_c are expanded to NLO, we get back to the standard NLO results for inclusive jets as derived in [37,38,9]. Within the framework developed in [10], we can go beyond the fixed order approach. Using the siJFs in Eq. (1) represents an additional final state factorization. As pointed out in [15,16], fixed order jet cross sections can have a vanishing, unphysical scale dependence. This problem is overcome by using the factorized form of the cross section in Eq. (1), where the interpretation of the QCD scale uncertainty as a measure of missing higher order corrections is restored. See [10] for numerical results concerning the scale dependence.

In [10], the siJFs $J_i(z, \omega_J R, \mu)$ were calculated to NLO from their operator definition within SCET. We have $z = \omega_J/\omega$, where ω_J (ω) denotes the jet (initiating parton) energy. Here, we summarize only the results for quark initiated jets to keep the discussion short. Up to NLO, one has to consider the diagrams presented in Fig. 1 for jets that are initiated by an outgoing quark. (A) corresponds to the leading-order (LO) diagram. To LO, one finds $J_q^{(0)}(z, \omega_J R, \mu) = \delta(1-z)$. At NLO, one has to consider the contributions (B)–(E). Here (B) corresponds to a splitting process, where both final state partons are in the jet. (C) is a virtual correction and (D), (E) are the contributions, where one of the final state partons exits the jet. All contributions (B)–(E) can be written in terms of integrals over the quark-to-quark or quark-to-gluon LO Altarelli–Parisi splitting functions [39]. We make use of this fact below when deriving the in-medium siJFs. For completeness, we present here the result for the quark siJF in dimensional regularization up to NLO for the anti-k_T algorithm

$$\begin{aligned} J_q(z, \omega R, \mu) &= \delta(1-z) \\ &+ \frac{\alpha_s}{2\pi}\left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{\omega^2 \tan^2(R/2)}\right) - 2\ln z\right)\left[P_{qq}(z) + P_{gq}(z)\right] \\ &- \frac{\alpha_s}{2\pi}\left\{ C_F\left[2(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + (1-z)\right]\right. \\ &\left. - \delta(1-z) C_F\left(\frac{13}{2} - \frac{2\pi^2}{3}\right) + 2P_{gq}(z)\ln(1-z) + C_F z\right\}, \end{aligned} \tag{2}$$