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Phenomenology of threshold corrections for inclusive jet production at hadron colliders

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ABSTRACT

We study one-jet inclusive hadro-production and compute the QCD threshold corrections for large transverse momentum of the jet in the soft-gluon resummation formalism at next-to-leading logarithmic accuracy. We use the resummed result to generate approximate QCD corrections at next-to-next-to leading order, compare with results in the literature and present rapidity integrated distributions of the jet's transverse momentum for Tevatron and LHC. For the threshold approximation we investigate its kinematical range of validity as well as its dependence on the jet's cone size and kinematics.

We study the hadro-production of jets focusing on one-jet inclusive cross sections. This important scattering process probes parton interactions at very high scales and has been measured at the LHC as well as at the Tevatron collider in the past with very good accuracy [1–4]. At large momentum transfer the available jet cross section data have not only allowed to set limits in the TeV range on the scales of various models for new physics, but have also offered access to the determination of a number of parameters in Quantum Chromodynamics (QCD). These include the strong coupling constant α_s as well as the gluon distribution in the proton at medium to large values of the parton momentum fractions x.

In all cases, precise theoretical predictions for the measured rates are an essential prerequisite and demand good control of the higher order QCD corrections in particular. It is well known that these can be sizable and, moreover, are dominated by soft gluon emission in the kinematical region where the transverse momentum of the observed jet is large. At such boundary of phase space the imbalance between virtual corrections and real emission contributions gives rise to large logarithms which need to be controlled to high orders in perturbation theory and, potentially, require resummation. While the exact next-to-leading order (NLO) results to the $2 \to 2$ parton scattering process underlying the one-jet inclusive hadro-production are available since long [5–7], the computation of the next-to-next-to-leading order (NNLO) cross section predictions for $2 \to 2$ parton scattering is yet to be completed. In this situation, the threshold logarithms for the one-jet inclusive cross section have been used as a means of estimating the size of the exact NNLO QCD corrections [8] and all-order resummation of soft gluon effects at large transverse momentum of the identified jet has been achieved [9–11]. Recently, the NNLO QCD corrections in the purely gluonic channel to one-jet inclusive and di-jet production at hadron colliders have been performed [12].

In the present Letter we perform a phenomenological study of threshold corrections to the inclusive jet production at both, Tevatron and LHC for the rapidity integrated transverse momentum distributions of the jets. To that end, we compute those threshold logarithms in the soft-gluon resummation formalism [13,14] and compare our results at next-to-leading logarithmic (NLL) accuracy with the available literature [8]. Given the widespread use of those QCD corrections, e.g., in experimental analysis of one-jet inclusive data [15,16] and in the determination of parton distribution functions (PDFs) from global fits [17–19], we are particularly interested in assessing the kinematical range of validity of the NLL threshold logarithms.

For hadro-production of jets the precise definition of the threshold is an important issue, because the boundary of phase space for soft gluon emission depends on the details of jet definition, i.e., on the jet algorithm, on the jet's cone size and on assumptions of the jet's mass. As we will see, the resummation of threshold logarithms in [8] assumes massless jets in the small cone approximation, see [11]. In order to scrutinize the threshold approximation, we perform a comparison to the exact QCD results at NLO, available, e.g., through the programs `NLOJET++` [20,21] or `MEKS` [22]. We find that threshold corrections provide a valid description of the parton dynamics, although, within a kinematical range being limited to rather large transverse momenta of jet and to very small jet cone sizes. Since the latter

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turn out to be typically much smaller than the currently chosen values at LHC and Tevatron, the dependence on finite cone sizes, which is unaccounted for in [8], introduces a large additional systematic uncertainty in the threshold approximation. This is unlike the case of soft-gluon resummation for single-particle inclusive hadro-production at high transverse momentum [23,24] or for heavy-quark hadro-production (see, e.g., [25–27]), where soft-gluon emission is considered relative to a final state composed of on-shell particle(s) and the threshold logarithms are found to provide extremely precise predictions through NNLO.

We are considering the following process in proton (anti-)proton collisions at hadron colliders,

$$P + P(\bar{P}) \to J + X, \tag{1}$$

where J denotes the observed jet and X the system recoiling against J. At the parton level, a total of 9 different subprocesses contributes, namely,

$$\begin{aligned}
&q(p_1) + q'(p_2) \to q(p_3) + q'(p_4),\\
&q(p_1) + \bar{q}(p_2) \to q'(p_3) + \bar{q}'(p_4),\\
&q(p_1) + \bar{q}(p_2) \to q(p_3) + \bar{q}(p_4),\\
&q(p_1) + q(p_2) \to q(p_3) + q(p_4),\\
&q(p_1) + \bar{q}'(p_2) \to q(p_3) + \bar{q}'(p_4),\\
&q(p_1) + \bar{q}(p_2) \to g(p_3) + g(p_4),\\
&q(p_1) + g(p_2) \to q(p_3) + g(p_4),\\
&g(p_1) + g(p_2) \to q(p_3) + \bar{q}(p_4),\\
&g(p_1) + g(p_2) \to g(p_3) + g(p_4).
\end{aligned} \tag{2}$$

The Mandelstam invariants are $s = (p_1 + p_2)^2$, $t = (p_1 - p_3)^2$ and $u = (p_2 - p_3)^2$. It is to be noted that either of the partons in the final state can give rise to the observable jet and the other will be inclusive, implying that the observable can be computed either by symmetrizing the matrix elements between t and u or, alternatively, by running the jet-algorithm while doing the phase space integration. With these Mandelstam invariants, the relation $s_4 = s + t + u \geqslant 0$ holds where s_4 is the invariant mass of the system recoiling against the observed jet and $s_4 = 0$ at threshold.

The perturbative expansion of the partonic cross section $\hat{\sigma}$ in powers of the strong coupling constant α_s reads

$$\hat{\sigma} = \sum_{l=0}^{\infty} \hat{\sigma}^{(l)}, \tag{3}$$

where $\hat{\sigma}^{(0)}$ denotes the Born term. At higher orders the parton cross section $\hat{\sigma}^{(l)}$ contains plus-distributions of the type $\alpha_s^l [\ln^{2l-1}(s_4/p_T^2)/s_4]_+$ that lead to the Sudakov logarithms upon integration. In a physical interpretation s_4 denotes the additional energy carried away by real emission of soft gluons above the partonic threshold.

The generic l-loop expanded resummed results can be written as

$$\begin{aligned}
\frac{d^2\hat{\sigma}^{(l)}}{dt\,du} = {}& \sum_{k=0}^{2l-1} C_{l,k} \left[\frac{\ln^{(2l-1)-k}(s_4/p_T^2)}{s_4}\right]_+ \\
&+ C_{l,\delta}\,\delta(s_4) + \mathcal{O}(s_4),
\end{aligned} \tag{4}$$

and at each loop order, the coefficients $C_{l,0}$ determine the leading logarithm (LL), the coefficients $C_{l,1}$ determine the NLL contributions and so on. It is well-established, that the threshold logarithms exponentiate and at the differential level (one-particle inclusive kinematics [28]) this exponentiation has been performed to NLL accuracy in [8], where the resummed result has been used to generate the results in fixed-order perturbation theory through NNLO.

The resummation is based on the factorization of the partonic cross section near threshold into various functions, each of which organizes the large corrections stemming from a particular region of phase space. The full dynamics of collinear gluon emission from initial or final state partons are summarized in so-called jet functions $\mathcal{J}^I$ and $\mathcal{J}^F$ which contain all LL and some NLL enhancements. Additional soft gluon dynamics at NLL accuracy which are not collinear to one of the external partons are summarized by the soft function S, which is governed by anomalous dimension Γ_S [9]. Finally, the effects of off-shell partons are collected in a so-called hard function H, where both H and S are matrices in the space of color configurations for the respective underlying $2 \to 2$ scattering process in Eq. (2).

The resummation is conveniently carried out in the space of moments N. The formal definition of Laplace moments as

$$\tilde{f}(N) = \int \frac{ds_4}{s} e^{-Ns_4/s} f(s_4/s), \tag{5}$$

establishes the correspondence between the plus-distributions for $s_4 \to 0$ and the moments $N \to \infty$, that is $[\ln^{2l-1}(s_4/p_T^2)/s_4]_+ \leftrightarrow \ln^{2l} N$, see, e.g., [29] for details. Thus, the parton level resummed cross section for a generic subprocess in Eq. (2) is given by [8,28]

$$\begin{aligned}
&d\hat{\sigma}^{\text{res}}_{12\to 34}(N)\\
&\quad = \exp\left[-\sum_{a=1,2} 2 \int_{\mu_F}^{2p_a\cdot\zeta} \frac{d\mu}{\mu} C_{(f_a)} \frac{\alpha_s(\mu^2)}{\pi} \ln N_a\right]\\
&\qquad \times \exp\left[\sum_{a=1,2} \mathcal{J}^I_a(N_a)\right] \times \exp\left[\sum_{b=3,4} \mathcal{J}^F_b(N)\right]\\
&\qquad \times \exp\left[2 \sum_{a=1,2} \int_{\mu_F}^{p_T} \frac{d\mu}{\mu} \gamma_a\big[\alpha_s(\mu^2)\big]\right]\\
&\qquad \times \exp\left[4 \int_{\mu_R}^{p_T} \frac{d\mu}{\mu} \beta\big(\alpha_s(\mu^2)\big)\right]\\
&\qquad \times \mathrm{Tr}\left\{H\big(\alpha_s(\mu_R^2)\big)\bar{P}\exp\left[\int_{p_T}^{p_T/N} \frac{d\mu}{\mu} \Gamma_S^\dagger\big(\alpha_s(\mu^2)\big)\right]\right.\\
&\qquad \left.\times S\big(\alpha_s(p_T^2/N^2)\big) P \exp\left[\int_{p_T}^{p_T/N} \frac{d\mu}{\mu} \Gamma_S\big(\alpha_s(\mu^2)\big)\right]\right\},
\end{aligned} \tag{6}$$

where the trace operation acts on the matrices S, H and Γ_S in color space and P, $\bar{P}$ denote (complex) ordered matrix products. The function β is the standard QCD beta function, $\gamma_q = (\alpha_s/\pi)(3C_F/4)$ and $\gamma_g = (\alpha_s/\pi)(\beta_0/4)$ are the anomalous dimensions for quarks and gluons needed to 1-loop accuracy here. $C_{(f_a)}$ is the quadratic Casimir operator with $C_f = C_F = (N_c^2 - 1)/(2N_c)$ for an external quark/antiquark and $C_f = C_A = N_c$ for an external gluon with N_c being the number of colors. The renormalization and factorization scale are given by μ_R and μ_F. Moreover, ζ_μ is a dimensionless vector specifying the kinematics, see [28], so that in single-particle inclusive kinematics it can be taken as $\zeta_\mu = p_J/p_T$ and, likewise, the moments N_a $(a = 1, 2)$ are given by $N_1 = N(-u/s)$ and $N_2 = N(-t/s)$.