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Non-global logarithms with jet trimming in Z+jet production in proton-proton collisions

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Abstract: We investigate the role of non-global logarithms in the trimmed jet mass distribution in the process of Z+jet production in pp collisions. While some grooming techniques completely eliminate these non-global logarithms, their presence persists with the trimming algorithm, which we select for the current work. Our study involves an analytical fixed-order calculation up to second order in the strong coupling and an all-orders resummation for the non-global logarithms in the invariant mass distribution of the trimmed leading-p_T jet. We also present a fully resummed result for the distribution of the trimmed jet mass, including global logarithms, valid at NLL accuracy.

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1. Introduction

Jets can emerge from the hadronic decays of heavy particles, such as the $Z/W^{\pm}$ bosons, the Higgs boson, and top quarks, or possibly through the decay of potential new particles at the electroweak scale. When these particles are produced with a large boost, their hadronic decays become collimated, and the resulting particles are reconstructed as a single jet. Jets can also arise from the fragmentation of quarks and gluons generated in hard-scattering events, commonly referred to as QCD jets. Due to soft and collinear emissions, jets exhibit complex internal structures.

Jet substructure techniques are instrumental in disentangling these structures, enabling a discrimination between jets originating from heavy particle decays and those arising from QCD fragmentation. At the LHC, these techniques have revolutionized our understanding of jets, offering valuable insights into their properties and underlying dynamics [1–4]. Additionally, they have proven to be invaluable in mitigating non-perturbative effects such as pileup contamination, thereby facilitating more precise studies of QCD, including measurements of the strong coupling constant [5, 6]. Jet substructure methods have become standard tools in new physics searches by both the CMS and ATLAS collaborations at the LHC, as demonstrated in refs. [7, 8]. The significance of these techniques will grow even further with the operation of future high-luminosity colliders, where the demands for precision are higher. Common grooming algorithms include trimming [9], pruning [10, 11], mass-drop filtering [12], and soft-drop [13], each characterized by a distinct perturbative structure. In this work, we focus on the trimming algorithm with full radius R, transverse momentum cut parameter z_{cut} and substructure radius R_{sub}. We leave the exploration of other substructure methods for future studies.

A widely studied observable in jet substructure analyses is the invariant mass of a jet, m_j. This work addresses the resummation of the jet mass in the process $pp \to Z + \text{jet}$. The incomplete cancellation of soft and collinear singularities between real and virtual contributions to the distribution of this observable generates large logarithmic terms in the ratio of the jet mass to its transverse momentum p_t, causing fixed-order calculations to become unreliable. To overcome this, resummation techniques are employed to systematically sum these logarithms to all orders, resulting in more reliable theoretical predictions.

The jet mass is classified as a non-global observable. In contrast to global observables, which are sensitive to radiation across the entire event, non-global observables depend on radiation within a limited phase space region, creating complicated emission patterns that challenge theoretical calculations. Resummation of the jet mass distribution requires accounting for towers of logarithms known as non-global [14, 15] and clustering [16] logarithms (NGLs and CLs). The resummation of NGLs poses significant challenges as they involve the consideration of correlated soft gluon emissions at all orders, necessitating the use of Monte Carlo methods and the large-N_c limit.

The resummed expression for the integrated (cumulative) jet mass distribution in the Z+jet process can be written as

$$\sigma(\rho) = \sum_{\delta} \int \mathrm{d}\mathcal{B}_{\delta} \frac{\mathrm{d}\sigma_{0\delta}}{\mathrm{d}\mathcal{B}_{\delta}} \Omega_{\mathcal{B}} \left(1 + \alpha_s C_1(\mathcal{B}_{\delta}) + O(\alpha_s^2)\right) f_{\mathcal{B},\delta}(\rho) \mathcal{S}_{\delta}(\rho) C_{\delta}(\rho), \tag{1}$$

where $\rho = m_j^2/p_t^2$, δ denotes the partonic channels, $\mathrm{d}\sigma_{0\delta}/\mathrm{d}\mathcal{B}_{\delta}$ is the differential Born cross-section for the born configuration $\mathcal{B}_{\delta}$, $\Omega_{\mathcal{B}}$ represents experimental cuts, and C_1 accounts for fixed-order corrections. In this equation, $f_{\mathcal{B},\delta}(\rho)$ represents the resummed global form factor, while $\mathcal{S}_\delta(\rho)$ and $C_\delta(\rho)$ represent the resummed non-global and clustering logarithmic effects.

Our goal is to resum NGLs at $O(\alpha_S^2)$ and to all orders within the large-N_c approximation for the trimmed jet mass distribution. By including both non-global and global logarithms, we present fully resummed results at next-to-leading logarithmic (NLL) accuracy.

2. NGLs with trimming

While some grooming algorithms, such as the modified mass-drop tagger (mMDT) [17], eliminate these logarithms entirely [17, 18], trimming retains the presence of NGLs. At second order in the strong coupling α_s, the NGLs arise from the correlated emission of an untrimmed soft gluon k_2 inside the jet from a harder gluon k_1 emitted outside the jet. The non-global contribution to the jet mass distribution under trimming is expressed as

$$\begin{aligned} f_{\mathcal{B},\delta}^{\mathrm{trim},(2),\mathrm{NG}}(\rho) = -\frac{1}{2}\,\bar{\alpha}_S^2\,\mathrm{C_A}\sum_{(i\ell)} C_{i\ell}\Bigg(&\ln^2\min\left[\frac{R^2}{\rho},\frac{1}{z_{\mathrm{cut}}}\right]\mathcal{G}_{2,(i\ell)}^{\mathrm{ak_t}}(R^2,R^2)\\ &+\Theta(R^2 z_{\mathrm{cut}}-\rho)\left[\ln^2\frac{R^2}{\rho}-\ln^2\frac{1}{z_{\mathrm{cut}}}\right]\mathcal{G}_{2,(i\ell)}^{\mathrm{ak_t}}(R^2,\max[\rho/z_{\mathrm{cut}},R_{\mathrm{sub}}^2])\\ &+\Theta(R_{\mathrm{sub}}^2 z_{\mathrm{cut}}-\rho)\ln^2\frac{R_{\mathrm{sub}}^2 z_{\mathrm{cut}}}{\rho}\Big[\mathcal{G}_{2,(i\ell)}^{\mathrm{k_t}}(R_{\mathrm{sub}}^2,R_{\mathrm{sub}}^2)-\mathcal{G}_{2,(i\ell)}^{\mathrm{k_t}}(R_{\mathrm{sub}}^2,\rho/z_{\mathrm{cut}})\\ &+\mathcal{G}_{2,(i\ell)}^{\mathrm{k_t}}(R^2,\rho/z_{\mathrm{cut}})-\mathcal{G}_{2,(i\ell)}^{\mathrm{k_t}}(R^2,R_{\mathrm{sub}}^2)\Big]\Bigg). \end{aligned} \tag{2}$$

The sum runs over dipoles formed by the three hard legs in the Born event: the incoming partons a and b, and the outgoing parton j initiating the jet. The color factors $C_{i\ell}$ depend on the parton species: $C_{i\ell} = 2\,\mathrm{C_F} - \mathrm{C_A}$ for dipoles involving quarks only, and $C_{i\ell} = \mathrm{C_A}$ for dipoles involving a quark and a gluon. The standard QCD color factors are $\mathrm{C_F} = 4/3$ and $\mathrm{C_A} = 3$. The anti-k_t clustering non-global factors $\mathcal{G}_2^{\mathrm{ak_t}}$ for the various dipoles are given by

$$\begin{aligned} \mathcal{G}_{2,(ab)}^{\mathrm{ak_t}}(R^2,R_{\mathrm{sub}}^2) &= -\frac{1}{2}\,R^2\ln R^2+\frac{1}{2}\left(R^2-R_{\mathrm{sub}}^2\right)\ln\left(R^2-R_{\mathrm{sub}}^2\right)\\ &\quad+\frac{1}{2}\,R_{\mathrm{sub}}^2+\frac{1}{8}\,R^2R_{\mathrm{sub}}^2-\frac{1}{576}\,R^4R_{\mathrm{sub}}^2-\frac{1}{576}\,R^2R_{\mathrm{sub}}^4+O(R^8)\,, \end{aligned} \tag{3a}$$

$$\begin{aligned} \mathcal{G}_{2,(aj)}^{\mathrm{ak_t}}(R^2,R_{\mathrm{sub}}^2) = \mathcal{G}_{2,(bj)}^{\mathrm{ak_t}}(R^2,R_{\mathrm{sub}}^2) &= \left(\frac{R^2-R_{\mathrm{sub}}^2}{8}+\frac{R^4-R_{\mathrm{sub}}^4}{576}\right)\ln\frac{R^2-R_{\mathrm{sub}}^2}{R^2}\\ &\quad+\frac{1}{2}\,\mathrm{Li}_2\frac{R_{\mathrm{sub}}^2}{R^2}+\frac{5}{576}\,R^2R_{\mathrm{sub}}^2-\frac{1}{192}\,R_{\mathrm{sub}}^4+O(R^8)\,. \end{aligned} \tag{3b}$$

For the k_t algorithm, the corresponding factors are

$$\begin{aligned} &\mathcal{G}_{2,(ab)}^{\mathrm{k_t}}(R^2,R_{\mathrm{sub}}^2) = \mathcal{G}_{2,(ab)}^{\mathrm{ak_t}}(R^2,R_{\mathrm{sub}}^2)\\ &-\Theta(2\,R_{\mathrm{sub}}-R)\left[\chi_2(R_{\mathrm{sub}}/R)\,R^2+\chi_4(R_{\mathrm{sub}}/R)\,R^4+\chi_6(R_{\mathrm{sub}}/R)\,R^6+O(R^8)\right], \end{aligned} \tag{4a}$$

$$\begin{aligned} &\mathcal{G}_{2,(aj)}^{\mathrm{k_t}}(R^2,R_{\mathrm{sub}}^2) = \mathcal{G}_{2,(bj)}^{\mathrm{k_t}}(R^2,R_{\mathrm{sub}}^2) = \mathcal{G}_{2,(aj)}^{\mathrm{ak_t}}(R^2,R_{\mathrm{sub}}^2)\\ &-\Theta(2\,R_{\mathrm{sub}}-R)\left[\psi_0(R_{\mathrm{sub}}/R)+\psi_2(R_{\mathrm{sub}}/R)\,R^2+\psi_4(R_{\mathrm{sub}}/R)\,R^4+\psi_6(x)\,R^6+O(R^8)\right]. \end{aligned} \tag{4b}$$

Details of the functions $\chi(R_{\text{sub}}/R)$ and $\psi(R_{\text{sub}}/R)$ can be found in ref. [19].

The resummation of NGLs to all orders is performed in the large-N_c limit using the Monte Carlo program described in refs. [14, 15], adapted to include trimming. The result, as a function of the evolution parameter

$$t(\rho) = -\frac{1}{4\pi\beta_0} \ln\left(1 - 2\alpha_s\beta_0 \ln(R^2/\rho)\right), \tag{5}$$

is shown in Figure 1. This figure presents the NGL form factor $\mathcal{S}(t)$ for trimmed jets, alongside the ungroomed k_t (with $R = 0.2$) and anti-k_t (with $R = 0.7$) clustered jet. At small values of t, the NGLs distribution for trimmed jets resembles that of the anti-k_t algorithm, but as t increases, it approaches the behavior observed for the k_t algorithm.

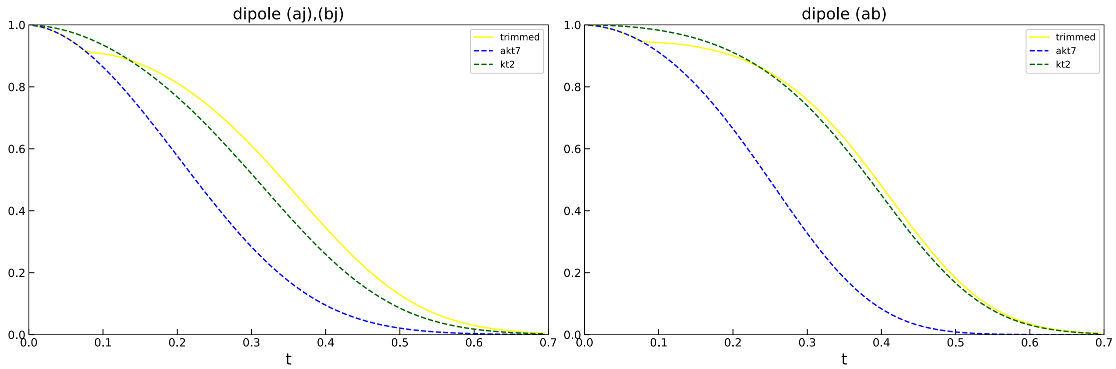

Figure 1: The resummed NGLs factor $\mathcal{S}(t)$ for dipole (ab) (left) and dipoles (aj) and (bj) (right).

3. Resummed jet mass spectrum

In this section, we present the numerical results for the convolution of the resummed form factor, including resummed NGLs at large N_c, with the Born cross-section. The details of the resummation of the global form factor $f_{\mathcal{B},\delta}$ at NLL accuracy along with the $\mathcal{O}(\alpha_s C_1)$ NLO correction term are presented in ref. [19]. In order to perform the convolution in eq. (1), we use the Monte Carlo program `MadGraph5_aMC@NLO` [20, 21] to generate Born-level events for the process $pp \to Z$+jet at parton level. The resulting `LHE` file is then passed to MadAnalysis [22] to analyse the events and extract the kinematics and weigh the events with the resummed form factor at each bin of the ρ variable.

The obtained results are shown in figure 2. We observe from the plots that trimming has no effect on the resummed distribution at NLL accuracy in the region $\rho > R^2 z_{\text{cut}}$. Below this region, the trimming has a strong effect on the distribution and the effect of NGLs remain moderate. In the intermediate region the double logarithms in ρ freeze to a constant and are restoed for $\rho < R_{\text{sub}}^2 z_{\text{cut}}$.

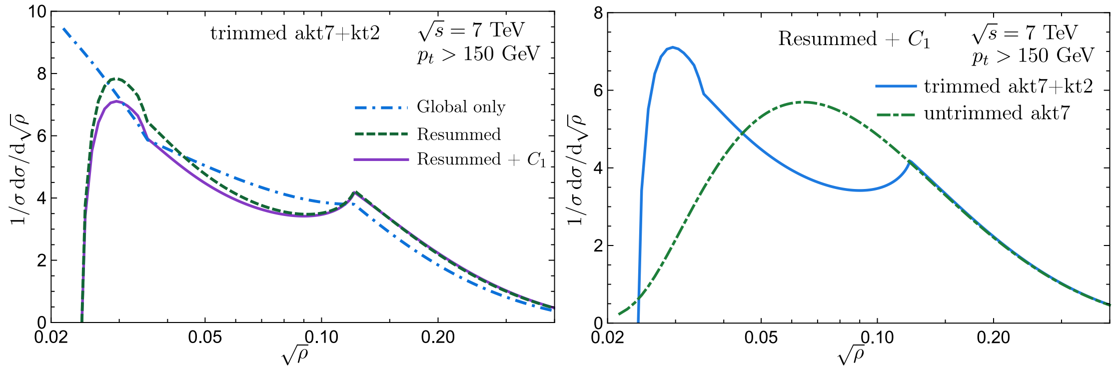

Figure 2: Resummed trimmed and untrimmed jet mass distributions.

4. Conclusion

In this paper, we have analytically computed and resummed NGLs in the jet mass distribution for the process $pp \to Z + \text{jet}$, incorporating jet trimming as a grooming algorithm. Our results provide a detailed account of how trimming retains these logarithms at the second order in the strong coupling, unlike other grooming techniques that effectively mitigate or eliminate them.

We provided a fully resummed result valid at NLL accuracy for the trimmed jet mass distribution. Further refinements in our predictions could involve the inclusion of higher-order NLO corrections through the matching procedure as well as and the exploration of the impact of non-perturbative effects with trimming.

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