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Factorization for substructures of boosted Higgs jets

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ABSTRACT

We present a perturbative QCD factorization formula for substructures of an energetic Higgs jet, taking the energy profile resulting from the $H \to b\bar{b}$ decay as an example. The formula is written as a convolution of a hard Higgs decay kernel with two b-quark jet functions and a soft function that links the colors of the two b quarks. We derive an analytical expression to approximate the energy profile within a boosted Higgs jet, which significantly differs from those of ordinary QCD jets. This formalism also extends to boosted W and Z bosons in their hadronic decay modes, allowing an easy and efficient discrimination of fat jets produced from different processes.

The Higgs boson, which is responsible for the electroweak symmetry breaking mechanism in the Standard Model (SM), has been discovered at the Large Hadron Collider (LHC) with its mass around 125 GeV. Though its couplings to other particles seem to be consistent with the SM, the ultimate test as to whether this observed particle is the SM Higgs boson relies on the measurement of the trilinear Higgs coupling that appears in Higgs pair production. A Higgs boson is predominantly produced via gluon fusion processes at the LHC. It has been shown [1] that the cross section of the Higgs pair production increases rapidly with center-of-mass energy of hadron colliders. With much higher collision energy in the partonic process, preferred for exploring the trilinear Higgs coupling, the Higgs boson and its decay products will be boosted. An energetic Higgs boson can also be associately produced with other SM particles, such as W, Z bosons, top quarks and jets [2].

The SM Higgs boson decays into a pair of bottom quark and antiquark dominantly. When the Higgs boson is highly boosted, this pair of bottom quarks may appear as a single jet and cannot be unambiguously discriminated from an ordinary QCD jet. A similar challenge applies to the identification of other boosted heavy particles, e.g., W bosons, Z bosons, and top quarks, when decaying via hadronic modes. Hence, additional information on internal structures of these boosted jets (such as their masses, energy profiles, and configurations of subjets) is required for the experimental identification. Many theoretical efforts were devoted to the exploration of heavy particle jet properties based on event generators [3–5]. As to the study of QCD jets in perturbative QCD (pQCD), the fixed-order calculation for their energy profiles was completed in [6], and the leading-logarithm resummation was performed in [7]. Recently, the pQCD formalism, including fixed-order evaluations [8] and the next-to-leading-logarithm resummation technique [9], was employed to investigate jet substructures. The alternative approach based on the soft-collinear effective theory and its application to jet production at an electron-positron collider were presented in Refs. [10,11]. For the application to jet profiles in proton-proton collisions, see, for example, Ref. [12].

In this Letter we develop a pQCD factorization formula to describe the internal jet energy profile (JEP) of the boosted jet resulting from the $H \to b\bar{b}$ decay, with energy E_{J_H} and invariant mass m_{J_H}. The basic idea of our theoretical approach is as follows. A Higgs boson is a colorless particle, while its decay products, the bottom quark and antiquark, are colored objects and dressed by multiple gluon radiations to form a system with mass of $\mathcal{O}(m_{J_H})$ and energy of $\mathcal{O}(E_{J_H})$. The invariant mass m_J of the bottom quark and its collimated gluons, with energy of $\mathcal{O}(E_{J_H})$, typically satisfies the hierarchy $E_{J_H} \gg m_{J_H} \gg m_J$. Based on the factorization theorem, QCD dynamics characterized by different scales must factorize into soft, collinear, and hard pieces, separately. First, the Higgs jet function J_H is factorized from a Higgs boson production process at the leading power of m_{J_H}/E_{J_H}. Then the b-quark jet function is defined at the leading power of m_J/m_{J_H} [9], soft gluons with energy of $\mathcal{O}(m_{J_H})$ are absorbed into a soft function S, and the remaining energetic gluons with energy $\mathcal{O}(E_{J_H})$ and invariant mass of $\mathcal{O}(m_{J_H})$ go into the hard Higgs decay kernel H.

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The Higgs JEP is then factorized at leading power of m_J/m_{J_H} into a convolution of the hard kernel with two b-quark jet functions and a soft function that links colors of the two b quarks. We will demonstrate a simple scheme, in which the soft gluons are absorbed into one of the b-quark jets, forming a fat jet, and the soft function reduces to unity. The other b-quark jet is a thin jet to avoid double counting of soft radiation. Since a Higgs boson is massive and a color singlet, its JEP dramatically differs from that of ordinary QCD jets. Below, we present the derivation of the JEP of a Higgs boson decaying into a bottom-quark pair. We shall evaluate the hard decay kernel at the leading order (LO) and substitute the light-quark jet function, as obtained in Ref. [9], for the b-quark jet functions to predict the Higgs JEP up to the accuracy of next-to-leading logarithms.

The four-momentum of the Higgs jet can be written as $P_{J_H} = E_{J_H}(1, \beta_{J_H}, 0, 0)$, with $\beta_{J_H} = \sqrt{1-(m_{J_H}/E_{J_H})^2}$. We define the Higgs jet function at the scale μ as

$$J_H(m_{J_H}^2, E_{J_H}, R, \mu^2) = \frac{2(2\pi)^3}{E_{J_H}} \sum_{N_J} \langle 0|\phi(0)|N_J\rangle\langle N_J|\phi^\dagger(0)|0\rangle \quad (1)$$

$$\times\delta(m_{J_H}^2 - \hat{m}_{J_H}^2(N_J, R))\delta(E_{J_H} - E(N_J))\delta^{(2)}(\hat{n}_{J_H} - \hat{n}(N_J)),$$

where the coefficient has been chosen to satisfy $J_H^{(0)} = \delta(m_{J_H}^2 - m_H^2)$ at the zeroth order in the Yukawa coupling. m_H represents the Higgs boson mass, and R the Higgs jet cone radius. The three δ-functions in the above definition specify the Higgs jet invariant mass, energy, and unit momentum direction of the set N_J of final-state particles, respectively. After applying the aforementioned factorization procedure, J_H is written as

$$\begin{aligned}
&J_H(m_{J_H}^2, E_{J_H}, R, \mu^2)\\
&= \frac{1}{E_{J_H}} \Pi_{i=1,2} \int dm_{J_i}^2 dE_{J_i} d^2\hat{n}_{J_i}\\
&\times \int d\omega S(\omega, R, \mu_f^2) J_i(m_{J_i}^2, E_{J_i}, R_i, \mu_f^2)\\
&\times H(P_{J_1}, P_{J_2}, R, \mu^2, \mu_f^2)\delta(m_{J_H}^2 - P_{J_1}\cdot P_{J_H} - P_{J_2}\cdot P_{J_H} - \omega)\\
&\times\delta(E_{J_H} - E_{J_1} - E_{J_2})\delta^{(2)}(\hat{n}_{J_H} - \hat{n}_{J_1+J_2}), \qquad (2)
\end{aligned}$$

where the factorization scale μ_f is introduced by the b-quark jet functions J_i. m_{J_i} (E_{J_i}, P_{J_i}, R_i) is the invariant mass (energy, momentum, radius) of the b-quark jets, and the soft function takes the form $S^{(0)} = \delta(\omega)$ at LO with the variable $\omega \equiv P_S \cdot P_{J_H}$, where P_S is the soft gluon momentum.

To describe the Higgs JEP, we define the jet energy function $J_H^E(m_{J_H}^2, E_{J_H}, R, r, \mu^2)$ by including in Eq. (2) a step function $\Theta(r-\theta_j)$ for every final-state particle j. The final-state particles with non-vanishing step functions (i.e., emitted within the test cone of radius r) and associated with the b-quark jet J_i are grouped into the b-quark jet energy function $J_i^E(m_{J_i}^2, E_{J_i}, R_i, r_i, \mu_f^2)$. The energetic final-state particles outside the b-quark jets and within the test cone are absorbed into the hard kernel H^E. The other final-state particles outside the test cone are absorbed back into their original functions. In this work, we will consider only the LO hard kernel, from which the hard gluon contribution to the JEP is absent, i.e., $J_1 \times J_2 \times H^E = 0$. We then arrive at

$$\begin{aligned}
&J_H^E(m_{J_H}^2, E_{J_H}, R, r, \mu^2)\\
&= \frac{1}{E_{J_H}} \Pi_{i=1,2} \int dm_{J_i}^2 dE_{J_i} d^2\hat{n}_{J_i} \int d\omega S(\omega, R, \mu_f^2)\\
&\times \sum_{i\neq j} J_i^E(m_{J_i}^2, E_{J_i}, R_i, r_i, \mu_f^2) J_j(m_{J_j}^2, E_{J_j}, R_j, \mu_f^2)\\
&\times H^{(0)}(P_{J_1}, P_{J_2}, R, \mu^2, \mu_f^2)\\
&\times \delta(m_{J_H}^2 - P_{J_1}\cdot P_{J_H} - P_{J_2}\cdot P_{J_H} - \omega)\delta(E_{J_H} - E_{J_1} - E_{J_2})\\
&\times \delta^{(2)}(\hat{n}_{J_H} - \hat{n}_{J_1+J_2}), \qquad (3)
\end{aligned}$$

where the LO hard kernel is

$$H^{(0)} = \frac{N_c}{2\pi^3}\left(\frac{m_b}{v}\right)^2 \frac{(E_{J_1}E_{J_2})^2[1-\cos(\theta_{J_1}+\theta_{J_2})]}{(P_{J_H}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}, \qquad (4)$$

with the number of colors N_c, the b-quark mass m_b, the vacuum expectation value v, the Higgs decay width Γ_H, and the polar angle θ_{J_i} of the b-quark jet J_i relative to the Higgs jet axis.

We have the freedom to choose the jet parameters R_i and r_i, whose values depend on the scheme adopted to factorize the soft radiation in the Higgs jet into different convolution pieces in Eq. (3). A simple scheme is to take J_1 as a thin jet, such that its entire energy is counted when a sufficient amount of the thin jet is within the test cone as specified below. For that, we set $R_1 = r_1 = r$, which increases from the minimal value 0.1 in our numerical analysis. This choice leads to the simplification of J_1^E, $J_1^E(m_{J_1}^2, E_{J_1}, r, r, \mu_f^2) = E_{J_1} J_1(m_{J_1}^2, E_{J_1}, r, \mu_f^2)\Theta(ar - \theta_{J_1})$, with $a \sim \mathcal{O}(1)$ being a geometric factor. The scheme also includes a fat jet J_2 with a large cone radius $R_2 = R$, which then absorbs all soft radiation in the Higgs jet. The energy function of the fat jet $J_2^E(m_{J_2}^2, E_{J_2}, R, r_2 = r, \mu_f^2)$, which contributes to the Higgs JEP as $\theta_{J_2} \le ar$, will take the result derived in the resummation technique [9,13].

Next, we integrate out the dependence on the Higgs jet invariant mass by taking the first moment in the Mellin transformation of J_H^E, defined as $\bar{J}_H^E(1, E_{J_H}, R, r, \mu^2) \equiv \int J_H^E(m_{J_H}^2, E_{J_H}, R, r, \mu^2) dm_{J_H}^2/(RE_{J_H})^2$. To perform the integration over $\hat{n}_{J_2}$, we write the corresponding δ-function as

$$\begin{aligned}
\delta^{(2)}(\hat{n}_{J_H} - \hat{n}_{J_1+J_2}) &= \delta\left(\frac{\mathbf{P}_{J_H}}{|\mathbf{P}_{J_H}|} - \frac{\mathbf{P}_{J_1}+\mathbf{P}_{J_2}}{|\mathbf{P}_{J_1}+\mathbf{P}_{J_2}|}\right),\\
&= \frac{|\mathbf{P}_{J_1}+\mathbf{P}_{J_2}|}{|\mathbf{P}_{J_2}|}\delta\Bigg(\frac{|\mathbf{P}_{J_1}+\mathbf{P}_{J_2}|}{|\mathbf{P}_{J_H}||\mathbf{P}_{J_2}|}\mathbf{P}_{J_H}\\
&\qquad - \frac{\mathbf{P}_{J_1}}{|\mathbf{P}_{J_2}|} - \hat{n}_{J_2}\Bigg), \qquad (5)
\end{aligned}$$

where the ratio is given by $|\mathbf{P}_{J_1}+\mathbf{P}_{J_2}|/|\mathbf{P}_{J_2}| = (E_{J_1}\cos\theta_{J_1} + E_{J_2}\cos\theta_{J_2})/E_{J_2}$. The angular relation $E_{J_1}\sin\theta_{J_1} = E_{J_2}\sin\theta_{J_2}$ is then demanded. The integration over E_{J_2} is trivial. The b-quark jet masses m_{J_i}, whose typical values are much smaller than m_H, are negligible in the hard kernel. The integrations over $m_{J_H}^2$ and $m_{J_i}^2$ can then be done trivially, with $\int dm_{J_i}^2 J_i(m_{J_i}^2, E_{J_i}, R_i, \mu_f^2) = 1 + O(\alpha_s) \approx 1$.

The soft function is defined as a vacuum expectation value of two Wilson links in the directions $\bar{\xi}_{J_i} = (1, \hat{n}_{J_i})/\sqrt{2}$ with $\hat{n}_{J_i} = \mathbf{P}_{J_i}/|\mathbf{P}_{J_i}|$, $i = 1, 2$. An explicit next-to-leading-order (NLO) calculation in the Mellin (N) space gives

$$S^{(1)} = \frac{\alpha_s C_F}{\pi(RE_{J_H})^2} \ln\frac{\bar{\xi}_{J_1}^2\bar{\xi}_{J_2}^2}{4(\bar{\xi}_{J_1}\cdot\bar{\xi}_{J_2})^2}\left(\frac{1}{\epsilon} + \ln\frac{4\pi\mu_f^2\bar{N}^2}{R^4E_{J_H}^2 e^{\gamma_E}}\right), \qquad (6)$$

where the color factor $C_F = 4/3$ and the moment $\bar{N} \equiv N\exp(\gamma_E)$, with γ_E being the Euler constant. The off-shellness $\bar{\xi}_{J_i}^2$ associated with the b-quark jets implies that $S^{(1)}$ contains the collinear dynamics which has been absorbed into the jet functions. Hence, the subtraction of the collinear divergences from the soft function is