Elucidating the Internal Structure of Jets at the LHC Using Soft-Collinear Effective Theory

Jet Shape Resummation [1] *and Medium Modification*

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Abstract

The jet shape is a classic jet substructure observable that probes the average transverse energy profile inside a reconstructed jet. The studies of jet shapes in proton-proton collisions have served as precision tests of perturbative Quantum Chromodynamics (QCD). They have also recently become the baseline for studying the in-medium modification of parton showers in ultra relativistic nucleus-nucleus collisions. The jet shape is a function of two angular parameters R and r which can be at hierarchical scales. Its calculation suffers from large logarithms of the ratio between the two scales, and these phase space logarithms can conveniently be resummed in the framework of soft-collinear effective theory (SCET). We find that, up to power corrections, the integral jet shape can be expressed in a factorized form which involves only the ratio between two jet energy functions. Resummation is performed at next-to-leading logarithmic (NLL) order using renormalization-group evolution techniques. The modification of jet shapes in heavy ion collisions is calculated at leading order in opacity using SCET with Glauber gluon interactions in the medium. Comparisons to the jet shape measurements at the LHC are presented to verify the dominant role of the collinear parton shower and to identify the kinematic region in which power-suppressed soft modes and non-perturbative effects may play a role.

Introduction

The jet shape probes the transverse energy distribution inside a jet and is very different for quark-initiated and gluon-initiated jets. It is useful in quark-gluon discrimination which is important in new physics searches. On the other hand, in heavy ion physics the modification of jet shapes provides unique information about the properties of the hot, dense medium that is produced in ultra-relativistic nuclear collisions which is referred to as the quark-gluon plasma (QGP).

Given a jet with an axis $\hat{n}$, its integral jet shape $\Psi_J(r)$ is defined as follows,

$$\Psi_J(r) = \frac{\sum_{i,\, d_{i\hat{n}}<r} E_T^i}{\sum_{i,\, d_{i\hat{n}}<R} E_T^i}\,, \tag{1}$$

which is the fraction of the transverse energy of the jet within an angle r from the jet axis. Here, $d_{i\hat{n}}$ is the Euclidean distance between the two directions along the i-th particle and the jet axis $\hat{n}$ on the rapidity-azimuthal angle plane: ${d_{i\hat{n}}}^2 = (y_i - y_{jet})^2 + (\phi_i - \phi_{jet})^2$. In experiment, we measure the *averaged* integral jet shape, $\Psi(r) = \frac{1}{N_J}\sum_{J=1}^{N_J}\Psi_J(r)$. The differential jet shape is then defined to be its derivative, $\psi(r) = \frac{d\Psi(r)}{dr}$. The jet shape was introduced and calculated in QCD at leading-order in [2]. Large logarithms of the form $\ln r/R$ were later resummed using the modified leading logarithmic approximation [3], including the contributions from initial state radiation and non-perturbative effects. To go beyond these approximations and address the precision of the jet shape calculations in a systematically improvable way, we will use effective field theory techniques in SCET [4].

Soft-Collinear Effective Theory

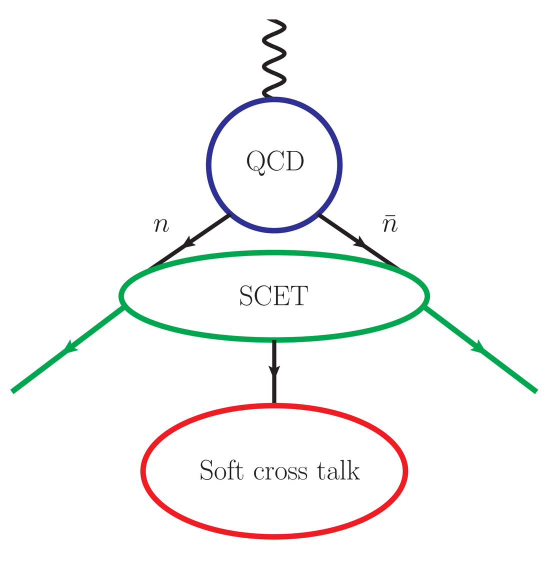

Figure 1: Factorization in SCET

SCET is an effective field theory of QCD with a systematic power counting. In events with highly collimated jets, the power counting parameter is small and the leading power contribution calculated in SCET is a very good approximation of the full QCD result. SCET separates physics at different energy scales, and the factorization of the hard, collinear and soft sectors is more transparent. The hard, jet and soft functions involved in the factorization theorem of a physical cross section, as well as their anomalous dimensions, can be calculated order by order at each characteristic scale. Large logarithms of the ratio between hierarchical energy scales are resummed through the renormalization-group evolution of these functions. In heavy ion collisions with the creation of the QGP, SCET is extended to include the Glauber gluon interaction with the medium [5].

Factorized Expression for the Jet Shape

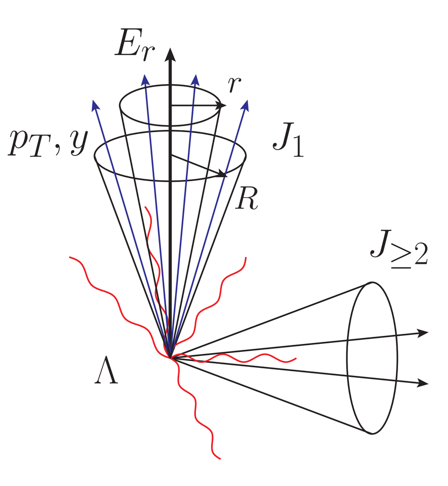

Figure 2: Schematic event topology of N-jet production

For concreteness, let us consider the shapes of jets from a N-jet configuration in e^+e^- collisions without loss of generality. Jets are reconstructed using a jet algorithm with a parameter R that is parametrically small. An energy cutoff Λ outside the jets is imposed to ensure the N-jet configuration. We also measure the energy E_r inside a cone of size r in one jet (labeled by 1), as well as the transverse momenta p_{Ti} and rapidity y_i of all the jets. The differential cross section of N-jet production with the measurement of E_r and the energy cutoff Λ is,

$$\frac{1}{\sigma_0}\frac{d\sigma}{dE_r dp_{T_i} dy_i} = H(p_{T_i}, y_i, \mu) J_{\omega_1}(E_r,\mu) J_{\omega_2}(\mu)\dots J_{\omega_N}(\mu) S_{n_1\dots n_N}(\Lambda,\mu) \tag{2}$$

$+\mathcal{O}(\frac{\Lambda}{Q}) + \mathcal{O}(R)$. Here, $H(p_{T_i}, y_i, \mu)$ is the hard function which contains the information about the N-jet production at the hard scale. $J_\omega(E_r,\mu) = \sum_{X_c}\langle 0|\bar{\chi}_\omega(0)|X_c\rangle\langle X_c|\chi_\omega(0)|0\rangle\delta(E_r - \hat{E}^{<r}(X_c))$ is a newly defined jet function, which is the probability of measuring an energy E_r inside the subcone of size r. Here χ_ω is the collinear jet field in SCET, and the operator $\hat{E}^{<r}$ returns the energy of the collinear particles X_c inside the r cone. All the other jet functions without the jet energy measurements are the unmeasured jet functions [6]. After integrating out the collinear modes we are left with a soft sector which is described by soft Wilson lines along the jet directions. The soft function is, $S_{n_1\dots n_N}(\Lambda,\mu) = \sum_{X_s}\langle 0|\mathcal{O}_s^\dagger(0)|X_s\rangle\langle X_s|\mathcal{O}_s(0)|0\rangle\Theta(\Lambda - \hat{E}^{>R}(X_s))$, where $\mathcal{O}_s(0)$ consists of N soft Wilson lines along the $n_{1,\dots,N}$ directions intersecting at the origin 0. The operator $\hat{E}^{>R}$ returns the energy of the soft particles X_s outside all N jets. Note that the factorized expression is a simple product of the hard, jet and soft functions. The *averaged* energy inside the cone of size r in jet 1 is

$$\langle E_r\rangle_{\omega_1} = \frac{\int dE_r E_r \frac{1}{\sigma_0}\frac{d\sigma}{dE_r dp_{T_i} dy_i}}{\frac{1}{\sigma_0}\frac{d\sigma}{dp_{T_i}dy_i}} = \frac{\cancel{H(p_{T_i}, y_i,\mu)} J^{E_r}_{\omega_1}(\mu) \cancel{J_{\omega_2}(\mu)\dots J_{\omega_N}(\mu) S_{n_1\dots n_N}(\Lambda,\mu)}}{\cancel{H(p_{T_i}, y_i,\mu)} J_{\omega_1}(\mu) \cancel{J_{\omega_2}(\mu)\dots J_{\omega_N}(\mu) S_{n_1 2\dots n_N}(\Lambda,\mu)}} = \frac{J^{E_r}_{\omega_1}(\mu)}{J_{\omega_1}(\mu)}\,. \tag{3}$$

$J^{E_r}_\omega(\mu) = \int dE_r\, E_r\, J_\omega(E_r,\mu)$ is referred to as the jet energy function. The integral jet shape needs another average over the jet production cross sections, with proper phase space cuts on p_T and y,

$$\Psi(r) = \frac{1}{\sigma_{\rm total}}\sum_{i=q,g}\int_{PS} dp_T dy \frac{d\sigma^i}{dp_T dy}\Psi^i_\omega(r)\,,\ \text{where}\ \Psi_\omega(r) = \frac{\langle E_r\rangle_\omega}{\langle E_R\rangle_\omega} = \frac{J^{E_r}_\omega(\mu)/J_\omega(\mu)}{J^{E_R}_\omega(\mu)/J_\omega(\mu)} = \frac{J^{E_r}_\omega(\mu)}{J^{E_R}_\omega(\mu)}\,, \tag{4}$$

which is the ratio between two jet energy functions. As we can see, the jet shape is insensitive to the hard process and the soft radiation, and it depends only on the partonic origin and the energy of the jet.

Renormalization-Group Evolution and Resummation

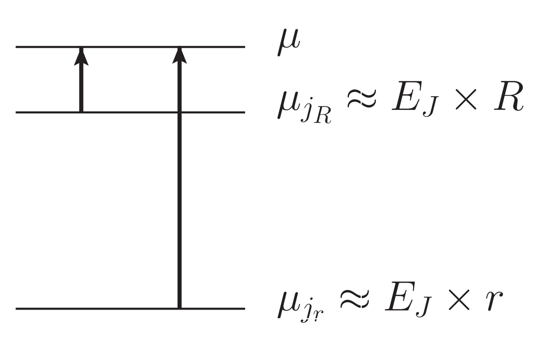

Figure 3: RG evolution of the jet energy function

The renormalization-group equation satisfied by the jet energy function is the following,

$$\frac{dJ^{iE_r}_\omega(\mu)}{d\ln\mu} = \left[-C_i\Gamma_{\rm cusp}(\alpha_s)\ln\frac{\omega^2\tan^2\frac{R}{2}}{\mu^2} - 2\gamma^i(\alpha_s)\right] J^{iE_r}_\omega(\mu)\,, \tag{5}$$

where $\Gamma_{\rm cusp}$ is the cusp anomalous dimension. The equation can be solved and the jet energy function can be evolved from its natural scale μ_{j_r} to the renormalization scale μ. The resummed integral jet shape is therefore

$$\Psi^i_\omega(r) = \frac{J^{iE_r}_\omega(\mu)}{J^{iE_R}_\omega(\mu)} = \frac{J^{iE_r}_\omega(\mu_{j_r})}{J^{iE_R}_\omega(\mu_{j_R})}\exp[-2C_iS(\mu_{j_r},\mu_{j_R}) + 2A_i(\mu_{j_r},\mu_{j_R})]\left(\frac{\mu^2_{j_r}}{\omega^2\tan^2\frac{R}{2}}\right)^{C_iA_\Gamma(\mu_{j_R},\mu_{j_r})}\,. \tag{6}$$

where $i = q, g$ with $C_q = C_F$ and $C_g = C_A$ the Casimir operators of the fundamental and adjoint representations in QCD. Here $S(\nu,\mu) = -\int_{\alpha_s(\nu)}^{\alpha_s(\mu)} d\alpha\frac{\Gamma_{\rm cusp}(\alpha)}{\beta(\alpha)}\int_{\alpha_s(\nu)}^{\alpha}\frac{d\alpha'}{\beta(\alpha')}$, $A_i(\nu,\mu) = -\int_{\alpha_s(\nu)}^{\alpha_s(\mu)} d\alpha\frac{\gamma^i(\alpha)}{\beta(\alpha)}$ and $A_\Gamma(\nu,\mu) = -\int_{\alpha_s(\nu)}^{\alpha_s(\mu)} d\alpha\frac{\Gamma_{\rm cusp}(\alpha)}{\beta(\alpha)}$ are the renormalization-group evolution kernels in SCET.

Medium Modification of the Jet Shape

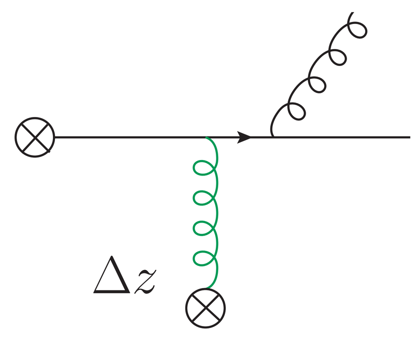

Figure 4: Parton splitting induced by Glauber gluons

In heavy ion collisions, jets are produced and subsequently quenched as they propagate through the medium. The medium induced splitting [7] causes the jet shape to be modified,

$$\Psi(r) = \frac{J_r^{E,vac} + J_r^{E,med}}{J_R^{E,vac} + J_R^{E,med}} = \frac{J_r^{E,vac}}{J_R^{E,vac}}\frac{J_R^{E,vac}}{J_R^{E,vac} + J_R^{E,med}} + \frac{J_r^{E,med}}{J_R^{E,vac} + J_R^{E,med}}\,.$$

Because of the Landau-Pomeranchuk-Migdal effect the modification is a power correction, and there are no large logarithms in $J_r^{E,med}$ at first order in opacity. For illustration, in the small x limit the medium induced splitting function for the $q\to qg$ channel is

$$\frac{dN_{q\to qg}}{dxd^2k_\perp} = \frac{C_F\alpha_s}{\pi^2}\frac{1}{x}\int_0^L\frac{d\Delta z}{\lambda}\int d^2q_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2q_\perp}\frac{2k_\perp\cdot q_\perp}{k_\perp^2(q_\perp - k_\perp)^2}\left[1 - \cos\left(\frac{(q_\perp - k_\perp)^2\Delta z}{x\omega}\right)\right]\,, \tag{7}$$

and we use the effective cross section $\frac{1}{\sigma_{el}}\frac{d\sigma_{el}}{d^2q_\perp} = \frac{m^2}{\pi(q_\perp^2+m^2)^2}$ in the simple model of the static QGP. There is no extra soft-collinear divergence when integrating over the final state phase space, and the renormalization-group evolution of the jet energy function is the same as in vacuum.

Results and Conclusions

Here we present the comparison of our jet shape calculation with the CMS measurements of differential jet shapes in proton-proton and lead-lead collisions with nucleon-nucleon center of mass energy at $\sqrt{s_{\rm NN}} = 2.76$ TeV [8]. Jets are reconstructed using the anti-$k_{\rm T}$ algorithm with $R = 0.3$, and the cuts $p_T^{\rm jet} > 100$ GeV, and $0.3 < |y^{\rm jet}| < 2$ are imposed. The theoretical uncertainties are estimated by varying the jet scales in the resummed expressions, shown as the colored boxes in the plots. For medium calculations we use the following parameters of QGP: the gluon mean free path $\lambda_g = 1$ fm, the size of QGP $L = 3$ fm, and the inverse range of the glauber gluon interaction $m = 0.75$ GeV.

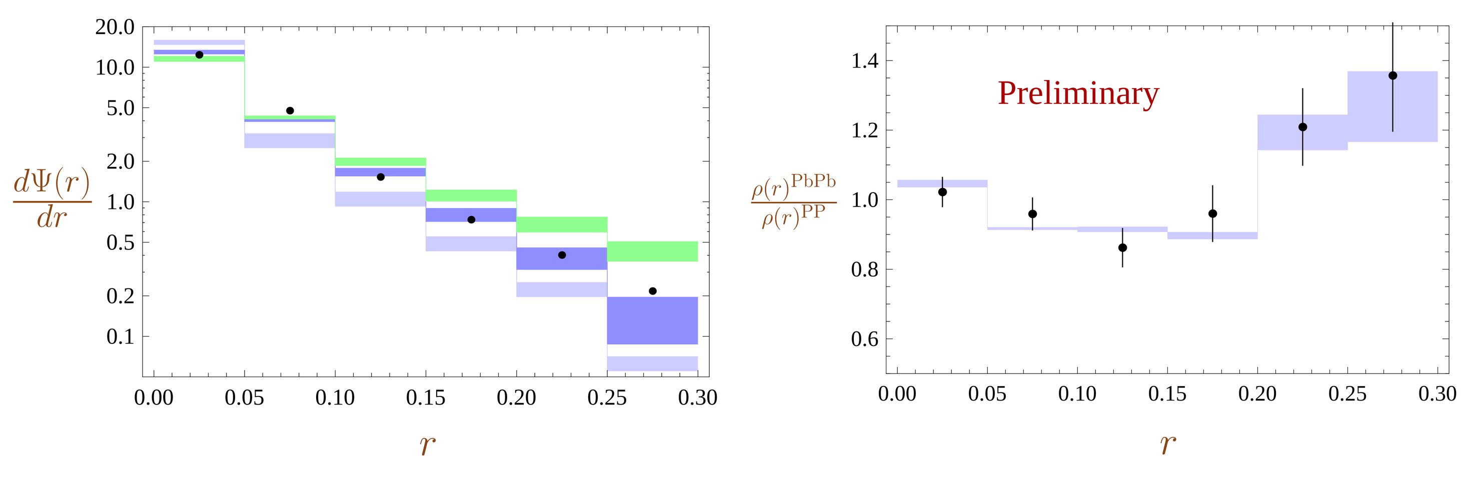

Figure 5: (Left) The differential jet shape for anti-$k_{\rm T}$ jets at leading order and next-to-leading logarithmic accuracy, as well as cone jets at NLL. The NLL results agree much better with the data than the LO results. The resummation and the algorithm dependence of the jet shape are important. (Right) Medium modification of jet shapes in lead-lead collisions with centrality 0 - 10%. It is sensitive to the QGP parameters which will allow us to probe the properties of the medium more precisely. The attenuation at mid r and the enhancement at the periphery of the jet agree with the data very well.

We find very good agreement between our calculations and the data. To conclude, the jet shape is resummed at NLL accuracy using the renormalization-group techniques in SCET. The baseline calculation in proton-proton collisions has been established and it can be systematically improved to higher precisions. The LO calculation can not describe the data well and the resummation is essential. The effect of medium modification is captured by the Glauber gluon interactions, which is an important power correction. The precision measurements of the QGP properties will be possible in the future.

Y.-T. Chien and I. Vitev are supported by the US Department of Energy, Office of Science.

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