Jet charge modification in dense QCD matter

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In these proceedings we report a recent calculation of the jet charge modification in heavy-ion relative to proton collisions at the LHC. Jets have played an essential role in constraining theories of in-medium parton shower evolution and in determining the properties of the quark-gluon plasma created in ultra-relativistic nuclear reactions. It is important to extend these studies to flavor-tagged jets and explore observables that are sensitive to their partonic origin. The average jet charge, introduced early on in the history of quantum chromodynamics, is a proxy for the electric charge of the quark or gluon that initiates the jet. In the framework of soft-collinear effective theory, we show how to evaluate the jet charge in a dense strongly-interacting matter environments. We identify observables that can isolate the contribution of in-medium branching from isospin effects and present predictions for the transverse momentum dependence of the jet charge distribution in nucleus-nucleus collisions and its modification relative to the proton case.

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1. Introduction

The jet charge is a substructure observable designed to approximate the electric charge of the hard scattered parton that initiates the jet. It was introduced in the late 1970s [1] and is defined as the transverse momentum-weighted sum of the charges of particles within the jet cone

\[ Q_{\kappa,\text{jet}} = \frac{1}{(p_T^{\text{jet})})^\kappa} \sum_{i \in \text{jet}} Q_i (p_i^T)\kappa. \]  

(1)

Here, \( Q_i \) and \( p_i^T \) are the electric charge and the transverse momentum of particle \( i \), and \( \kappa > 0 \) is a free parameter. From the point of view of heavy-ion physics, the ability to identify the partonic origin of jets is extremely useful, as the modification in nuclear matter is different for quark and gluon jets [2].

Jet charge calculations for lead-lead (Pb+Pb) collisions at the LHC have been performed using a Monte Carlo approach [3] and the framework of soft-collinear effective theory (SCET) [4]. In these proceedings we review the latter. First measurements of the jet charge in heavy-ion collisions have also appeared and have been used to isolate the fraction of gluon-like jets [5].

Starting with the definition Eq. (1) and realizing that gluons do not contribute to the average jet charge, this observable can be expressed as follows:

\[ \langle Q_{\kappa,\text{q}} \rangle = \int dz \, z^\kappa \sum_h \frac{\sigma_{\text{q}\text{jett}}} {\sigma_{\text{q}\text{jett}}} \frac{d\sigma_{\text{q}\text{jett}}}{dz}, \quad \langle Q_{\kappa,\text{q}} \rangle = \frac{\tilde{J}_{qq}(E, R, \kappa, \mu)}{J_q(E, R, \mu)} \tilde{D}_Q^Q(\kappa, \mu), \]  

(2)

where \( J_q(E, R, \mu) \) is a jet function. \( \tilde{J}_{qq}(E, R, \kappa, \mu) \) is the Wilson coefficient for matching the quark fragmenting jet function onto a quark fragmentation function and \( \tilde{D}_Q^Q(\kappa, \mu) \) is a fragmentation function [6]. The \((\kappa + 1)\)-th Mellin moments of the jet matching coefficient and fragmentation function are defined as

\[ \tilde{J}_{qq}(E, R, \kappa, \mu) = \int_0^1 dz \, z^\kappa J_{qq}(E, R, z, \mu), \quad \tilde{D}_Q^Q(\kappa, \mu) = \int_0^1 dz \, z^\kappa \sum_h Q_h D_h^Q(z, \mu). \]  

(3)

In Eq. (3) \( z = p_i^T/p_T \), \( E \) is the jet energy, \( R \) is the jet radius, and \( \mu \) is the factorization scale. An important property of the jet charge is that it is sensitive to scaling violations in QCD

\[ \frac{p_T}{\langle Q_{\kappa,\text{q}} \rangle} \frac{d}{dp_T} \langle Q_{\kappa,\text{q}} \rangle = \frac{\alpha_s}{\pi} \tilde{P}_{qq}^{(\kappa)}, \]  

(4)

where \( \tilde{P}_{qq}^{(\kappa)} \) is the \((\kappa + 1)\)-th Mellin moment of the leading order splitting function. The effect has been measured in proton-proton collisions [7] and this serves as a strong motivation to extend the observable to heavy-ion collisions.

2. Theoretical formalism in heavy ion collisions and numerical results

Before we proceed to the evaluation of the jet charge in Pb+Pb collisions we will validate the SCET formalism in the simpler p+p reactions. The ATLAS collaboration has performed measurements of back-to-back jets at \( \sqrt{s} = 8 \) TeV, denoting them as a more forward and a more central jet, and extracted the flavor dependent jet charge

\[ \langle Q_{\kappa}^{f/c} \rangle = (f_\alpha^{f/c} - f_\alpha^{f/c})\langle Q_{\kappa}^\alpha \rangle + (f_d^{f/c} - f_d^{f/c})\langle Q_{\kappa}^d \rangle. \]  

(5)
In Eq. (5) $f_q^j/\kappa^j$ is the fraction of $q$-flavored jets for the more forward/central jets and $\langle Q^2_j \rangle$ is the average charge for the $q$ jet. Our theoretical results for the average jet charge and the up- and down-quark jet charges as a function of jet $p_T$ are shown in Fig. 1. The average jet charge only relies on one non-perturbative parameter/boundary condition for a given $\kappa$ and the jet type, which we obtain through PYTHIA simulations. The uncertainties are evaluated by varying the factorization scale $\mu$ by a factor of two. The left panel of Fig. 1 gives the average jet charge for more central jets and its absolute value decreases with $\kappa$, as expected from Eq. (1). The right panel of Fig. 1 gives the flavor-separated charges for up- and down-quark jets. The predictions agree very well with the measurements by ATLAS [7], even though the data have large experimental uncertainties.

Propagation of partons in QCD matter adds a medium-induced component to the parton showers that characterize simpler reactions. The in-medium branching processes relevant to shower formation can be calculated order-by-order in powers of the mean number of scatterings [9]. An important characteristic of medium-induced showers, which persists to higher orders in $\alpha_s$ [8], is that they are softer and broader than the vacuum ones. Jet production and jet substructure in reactions with nuclei can be evaluated in a systematic and improvable fashion using a generalization of SCET to include interactions between its degrees of freedom and QCD matter mediated by Glauber gluons (SCET$_G$). Thus, the ingredients of SCET factorization receive medium corrections where relevant. For example, QGP contribution to the the matching coefficients can be expressed in terms of the in-medium splitting kernels

$$J_{qq}^{\text{med}}(E, R, x, \mu) = \frac{\alpha_s(\mu)}{2\pi^2} \int_0^{2E x(1-x)\tan R/2} \frac{d^2k_\perp}{k_\perp^2} P_{qg,qq}^{\text{med}}(x, k_\perp).$$

The medium correction to the full quark jet function reads

$$J_q^{\text{med}}(E, R, \mu) = \int_0^1 dx x \left( J_{qq}^{\text{med}}(E, R, x, \mu) + J_{qg}^{\text{med}}(E, R, x, \mu) \right)$$

$$= \frac{\alpha_s(\mu)}{2\pi^2} \int_0^1 dx \int_0^{2E x(1-x)\tan R/2} \frac{d^2k_\perp}{k_\perp^2} P_{qg,qq}^{\text{med, real}}(x, k_\perp),$$

Figure 1: Left: transverse momentum dependence of the average jet charge distribution with $\kappa = 0.3, 0.5$ and 0.7 for the more central jets in $\sqrt{s_{NN}} = 8$ TeV p+p collisions at the LHC. Right: average charge of up and down-quark jets as a function of jet $p_T$. Data is from ATLAS [7].
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Figure 2: Left: The average jet charge in \( \sqrt{s_{NN}} = 5.02 \) TeV central Pb+Pb collisions for more central jets and its modification relative to p+p collisions. Calculations for \( \kappa = 0.3, 1 \) and \( 2 \) are shown. Right: Modification of the up-jet charge due to in-medium evolution as a function of transverse momentum.

see also [10]. Finally, in a QCD medium the evolution of the charge-weighted fragmentation function becomes

\[
\frac{d}{d \ln \mu} \tilde{D}^Q_{\text{full}}(\kappa, \mu) = \frac{\alpha_s(\mu)}{\pi} \left( \tilde{P}_{qq}(\kappa) + \tilde{P}_{\text{med}}^{qq}(\kappa, \mu) \right) \tilde{D}^Q_{\text{full}}(\kappa, \mu),
\]

(9)

where \( \tilde{P}_{\text{med}}^{qq}(\kappa, \mu) \) is the \((\kappa + 1)\)-th Mellin moment of the medium splitting kernel. The additional scale dependence in the medium-induced part of Eq. (9) reflects the difference in the \( k_\perp \) dependence of the vacuum and in-medium branching processes [11].

The jet charge and its modification in central Pb+Pb collisions at the LHC are shown in the left panel of Fig. 2. At very high transverse momenta it is completely dominated by isospin effects. However, for \( p_T < 200 \) GeV one begins to observe the effects of in-medium evolution. The uncertainty bands correspond to the variation of the coupling \( g \) between the jet and the medium in the interval \((1.8, 2.0)\). The need to cleanly isolate the contribution of in-medium evolution to jet charge modification led us to propose a new observable – the modification of individual flavor jet charge in heavy-ion versus proton collisions. This can be seen in the right panel of Fig. 2 where we show the medium modifications to the up-quark jet charge. The only difference between the up- and down-quark jet charges is the fragmentation function boundary condition, hence their modification is the same

\[
\frac{\langle Q^{Pb+Pb}_{\kappa, \text{up}}(p_T) \rangle}{\langle Q^{Pb+Pb}_{\kappa, \text{up}}(p_T) \rangle} = \frac{\langle Q^{Pb+p}_{\kappa, \text{up}}(p_T) \rangle}{\langle Q^{Pb+p}_{\kappa, \text{up}}(p_T) \rangle}.
\]

(10)

The individual jet charge modification eliminates the initial-state isospin effects and helps reveal the final-state medium-induced parton shower contribution to the jet function and the fragmentation function evolution. For this reason, the medium corrections are larger for smaller energy jets - a kinematic region where the medium-induced splitting functions are more important. Furthermore, when \( \kappa \) is large the \((\kappa + 1)\)-th Mellin moment of the medium splitting function is more sensitive to soft-gluon emission.
3. Conclusions

We presented recent calculation of the jet charge distributions in heavy-ion collisions in the SCET\(_G\) effective field theory framework [4]. In the presence of nuclear matter the jet functions, jet matching coefficients, and the evolution of the fragmentation functions are constructed with the help of the medium-induced splitting kernels. The jet charge observable is particularly interesting because of its ability to discriminate between jets of various flavors, for example up-quark jets, down-quark jets and gluon jets. This discriminating power remains valid in nucleus-nucleus collisions. Furthermore, the charge of jets can provide novel insight into the Mellin moments of medium-induced splitting functions and the in-medium evolution of the non-perturbative fragmentation functions.

The jet charge definition is independent of the hard process. Thus, jet charge modification can be studied in other types of nuclear matter such as e+A collisions at the future electron-ion collider (EIC). Recent calculations of light and heavy meson production at the EIC have shown that with appropriate choice of center-of-mass energies and rapidity domains jet quenching effects in cold nuclear matter can be large and observable [12]. We plan to evaluate the jet charge in e+A reactions in the future.

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