PROCEEDINGS OF SCIENCE

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

$$Q_{\kappa,\text{jet}} = \frac{1}{\left(p_T^{\text{jet}}\right)^\kappa} \sum_{\text{i}\in\text{jet}} Q_i \left(p_T^i\right)^\kappa \ . \tag{1}$$

Here, Q_i and p_T^i 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:

$$\langle Q_{\kappa,q}\rangle = \int dz\, z^\kappa \sum_h Q_h \frac{1}{\sigma_{\text{q-jet}}} \frac{d\sigma_{h\in\text{q-jet}}}{dz} \, , \quad \langle Q_{\kappa,q}\rangle = \frac{\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{J_q(E,R,\mu)} \tilde{D}_q^Q(\kappa,\mu) \, , \tag{2}$$

where here $J_q(E,R,\mu)$ is a jet function. $\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)$ 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

$$\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu) = \int_0^1 dz\, z^\kappa \mathcal{J}_{qq}(E,R,z,\mu) \, , \quad \tilde{D}_q^Q(\kappa,\mu) = \int_0^1 dz\, z^\kappa \sum_h Q_h D_q^h(z,\mu) \, . \tag{3}$$

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

$$\frac{p_T}{\langle Q_{\kappa,q}\rangle} \frac{d}{dp_T} \langle Q_{\kappa,q}\rangle = \frac{\alpha_s}{\pi} \tilde{P}_{qq}(\kappa) \, , \tag{4}$$

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

$$\langle Q_\kappa^{f/c}\rangle = (f_u^{f/c} - f_{\bar{u}}^{f/c})\langle Q_\kappa^u\rangle + (f_d^{f/c} - f_{\bar{d}}^{f/c})\langle Q_\kappa^d\rangle \, . \tag{5}$$

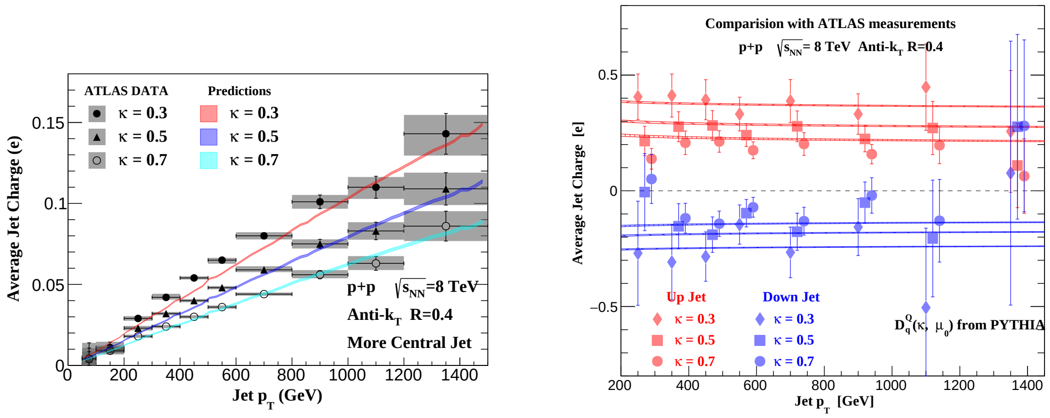

Figure 1: Left: transverse momentum dependence of the average jet charge distribution with κ =0.3, 0.5 and 0.7 for the more central jets in $\sqrt{s_{\rm NN}}$ = 8 TeV p+p collisions at the LHC. Right: average charge of up and down-quark jets as a function of jet p_T. Data is from ATLAS [7].

In Eq. (5) $f_q^{f/c}$ is the fraction of q-flavored jets for the more forward/central jets and $\langle Q_\kappa^q \rangle$ 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 κ and the jet type, which we obtain through PYTHIA simulations. The uncertainties are evaluated by varying the factorization scale μ 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 κ, 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 α_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$_{\rm G}$). 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

$$\mathcal{J}^{\rm med}_{qq,(qg)}(E,R,x,\mu) = \frac{\alpha_s(\mu)}{2\pi^2}\int_0^{2Ex(1-x)\tan R/2} \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2} P^{\rm med}_{q\to qg,(gq)}(x,\mathbf{k}_\perp)\,. \tag{6}$$

The medium correction to the full quark jet function reads

$$J_q^{\rm med}(E,R,\mu) = \int_0^1 dx\, x\left(\mathcal{J}^{\rm med}_{qq}(E,R,x,\mu) + \mathcal{J}^{\rm med}_{qg}(E,R,x,\mu)\right) \tag{7}$$

$$= \frac{\alpha_s(\mu)}{2\pi^2}\int_0^1 dx \int_0^{2Ex(1-x)\tan R/2} \frac{d^2\mathbf{k}_\perp}{\mathbf{k}_\perp^2} P^{\rm med,real}_{q\to qg}(x,\mathbf{k}_\perp)\,, \tag{8}$$

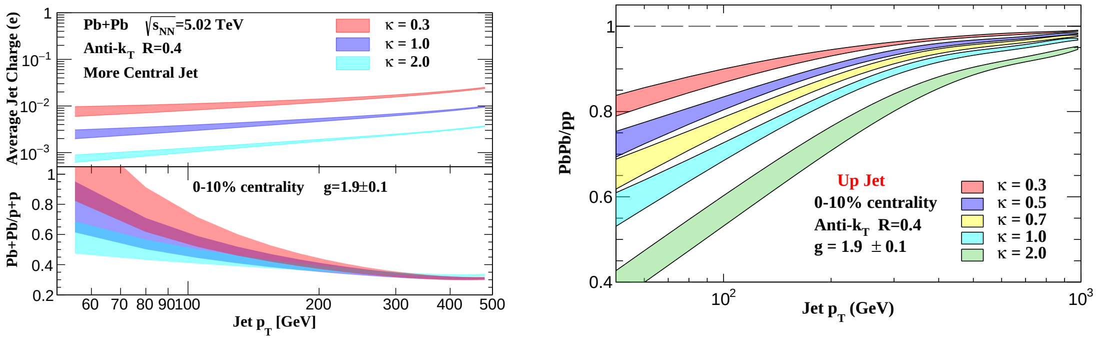

Figure 2: Left: The average jet charge in $\sqrt{s_{\text{NN}}} = 5.02$ TeV central Pb+Pb collisions for more central jets and its modification relative to p+p collisions. Calculations for κ =0.3, 1 and 2 are shown. Right: Modification of the up-jet charge due to in-medium evolution as a function of transverse momentum.

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

$$\frac{d}{d\ln\mu}\tilde{D}_q^{Q,\text{full}}(\kappa,\mu) = \frac{\alpha_s(\mu)}{\pi}\left(\tilde{P}_{qq}(\kappa) + \tilde{P}_{qq}^{\text{med}}(\kappa,\mu)\right)\tilde{D}_q^{Q,\text{full}}(\kappa,\mu)\,, \tag{9}$$

where $\tilde{P}_{qq}^{\text{med}}(\kappa,\mu)$ 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

$$\frac{\langle Q_{\kappa,u}^{\text{Pb+Pb}}(p_T)\rangle}{\langle Q_{\kappa,u}^{\text{p+p}}(p_T)\rangle} = \frac{\langle Q_{\kappa,d}^{\text{Pb+Pb}}(p_T)\rangle}{\langle Q_{\kappa,d}^{\text{p+p}}(p_T)\rangle}\,. \tag{10}$$

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 κ 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 $\mathrm{SCET_G}$ 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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