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Factorization of jet cross sections in heavy-ion collisions

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We propose a new phenomenological approach to establish QCD factorization of jet cross sections in the heavy-ion environment. Starting from a factorization formalism in proton-proton collisions, we introduce medium modified jet functions to capture the leading interaction of jets with the hot and dense QCD medium. A global analysis using a Monte Carlo sampling approach is performed in order to reliably determine the new jet functions from the nuclear modification factor of inclusive jets at the LHC. We find that gluon jets are significantly more suppressed due to the presence of the medium than quark jets. In addition, we observe that the jet radius dependence is directly related to the relative suppression of quark and gluon jets. Our approach could help to improve the extraction of medium properties from data.

Introduction. In heavy-ion collisions (HIC) at the LHC and RHIC hard probes such as highly energetic jets and hadrons are used to extract information about the created hot and dense QCD medium, the quark-gluon plasma (QGP) [1, 2]. Since no parton is observed in isolation, QCD factorization is necessary to separate the physics that live at different scales and to link the quarks and gluons in hard collisions to the hadrons observed in the detectors [3]. The factorization has been applied successfully at collider and fixed target experiments. In particular, it is possible to consistently extract universal parton distribution functions (PDFs) within global analyses from different processes and experiments [4–8]. These phenomenological results support the validity of QCD factorization in proton-proton ($p+p$) collisions and the universality of PDFs, which ensures the predictive power of the approach.

However, QCD factorization for observables in hadron-hadron collisions is an approximation with corrections typically suppressed by inverse powers of the large momentum transfer of the hard scattering. Although the proof of factorization theorems at the leading power of the large momentum transfer is independent of the details of the identified hadrons, the corrections to the factorized formalism are very much sensitive to what hadrons are colliding or observed in the final-state. This is because the subleading power contributions to the hadronic observables are very sensitive to QCD multiple scattering and, therefore, depend on where the collision is taking place, in a proton, a heavy ion, or a QGP-like hot medium. That is, the kinematic regime where the leading power formalism is applicable could be very different for $p+p$, proton-ion, or ion-ion ($A+A$) collisions. Tremendous efforts have been devoted to study multiple scatterings in QCD, and their medium modifications to hadronic observables, such as jet quenching, from which medium properties were extracted [9–15]. Since only the first subleading power contributions to hadronic observables can be factorized to all orders in perturbative QCD (pQCD) in a similar way to the leading power contributions [16–18], some kind of model dependence is needed for studying QCD multiple scatterings which can introduce a model bias of the extracted medium properties.

Given the importance of jet quenching observables for extracting QGP properties in HIC, we explore in this Letter the validity of the leading power, model independent QCD factorization formalism for inclusive single jet production in $A+A \to \text{jet}+X$. Using the leading power factorization formalism and the same partonic hard parts and jet evolution for $p+p$ collisions, we demonstrate for the first time that we are able to interpret the jet suppression $R_{\text{AA}}^{\text{jet}}$ data from the LHC by fitting medium induced jet functions. We use a Monte Carlo (MC) sampling approach to reliably determine the new medium modified jet functions and to identify the kinematic regime where this factorization approach is indeed feasible. This data driven approach to verify factorization in HIC may open a new door toward extractions of medium properties with a reduced model bias. Eventually, a global analysis of different observables is needed to establish more rigorously the universality of these nonperturbative functions; and a consistent treatment of medium sensitive power corrections is required to extend the predictive power of our formalism to HIC at lower energies.

Theoretical framework. Inclusive single jet cross section in $p+p$ collisions, differential in the transverse momentum p_T and rapidity η, can be factorized as [19]

$$\frac{d\sigma^{pp\to\text{jet}+X}}{dp_T d\eta} = \sum_{ab} f_{a/p} \otimes f_{b/p} \otimes \mathcal{H}_{ab}^{\text{jet}} \tag{1}$$

$$= \sum_{ab} f_{a/p} \otimes f_{b/p} \otimes \Big[\sum_c \hat{\sigma}_{ab\to c} \otimes J_c + \hat{\sigma}_{ab}^{\text{Jet}}\Big] \,. \tag{2}$$

Here $f_{i/p}(x_i)$ with $i=a,b$ are the PDFs, $\otimes$ indicates appropriate integrals over parton momentum fractions and $\mathcal{H}_{ab}^{\text{jet}}$ are partonic hard parts for the colliding partons of flavor a and b to produce the observed jet, which are perturbatively calculable depending on the jet algorithm. When the observed jet is very energetic and narrow in cone size R, the partonic hard parts $\mathcal{H}_{ab}^{\rm jet}$ are dominated by large logarithms in $\ln(R)$. Since the $\ln(R)$ are due to the sensitivity to collinear final-state radiation that forms the jet, the resummation of $\alpha_s^n \ln^n(R)$ is needed which can be consistently achieved by reorganizing $\mathcal{H}_{ab}^{\rm jet}$ analogous to [20]. The separation of $\mathcal{H}_{ab}^{\rm jet}$ into a "jet-independent" partonic hard part, $\hat{\sigma}_{ab\to c}(z,\mu)$, for producing a parton c of transverse momentum $p_T^c = p_T/z$ at a factorization scale $\mu \sim p_T$ and a "jet-dependent" jet function, $J_c(z, p_T R, \mu)$, which accounts for the formation of the observed jet from the parton c, as indicated in Eq. (2) allows for the resummation of $\ln(R)$ terms to all orders [21–24]. The $\hat{\sigma}_{ab}^{\rm Jet}$ in Eq. (2) are either R-independent or suppressed by powers of R^2 [25], and can be neglected if R is sufficiently small. Therefore, we do not consider $\hat{\sigma}_{ab}^{\rm Jet}$ in our analysis. Terms which are further suppressed by inverse powers of p_T are also neglected as they are beyond the factorization formulas in Eqs. (1) and (2).

When $\mathcal{H}_{ab}^{\rm jet}$ is reorganized for deriving Eq. (2), we can choose the "jet-independent" $\hat{\sigma}_{ab\to c}(z,\mu)$ to be the same as the partonic hard part for inclusive single hadron production at high p_T [26, 27], which is factorized as [28],

$$\frac{d\sigma^{pp\to h+X}}{dp_T d\eta} = \sum_{abc} f_{a/p} \otimes f_{b/p} \otimes \hat{\sigma}_{ab\to c}(z,\mu) \otimes D_c^h(z,\mu)\,. \tag{3}$$

Here D_c^h are the single hadron fragmentation functions (FFs), and the dependence on the initial-state partonic momentum fractions and the factorization scale are left implicit. Since the physically observed cross section on the left hand side is independent of the factorization scale, the μ-dependence of the FFs follows the DGLAP evolution where the evolution kernels are uniquely determined by the μ-dependence of $\hat{\sigma}_{ab\to c}(z,\mu)$, order-by-order in pQCD. Since $\hat{\sigma}_{ab\to c}(z,\mu)$ is the same in both Eqs. (2) and (3), the jet functions obey the same DGLAP evolution equation,

$$\mu\frac{d}{d\mu} J_c(z, p_T R, \mu) = \sum_d P_{dc}(z) \otimes J_d(z, p_T R, \mu)\,, \tag{4}$$

with the same $P_{dc}(z)$ as for FFs. Solving the DGLAP evolution equation from the jet invariant mass $\mu_J \sim p_T R$ to $\mu \sim p_T$, the scale of the hard collision, effectively resums single logarithms in the jet radius $\alpha_s^n \ln^n(R)$. Although the J_c in Eq. (2) play the same role as the D_c^h in Eq. (3), they are calculable order-by-order in pQCD, while the FFs are nonperturbative and need to be extracted from experimental data. The factorized formalism in Eq. (2) has been successfully tested for single inclusive jet production in $p+p$ collisions at the LHC [29].

When we apply Eq. (2) to narrow-cone jet production in HIC, only the PDFs and the jet functions should be modified since $\hat{\sigma}_{ab\to c}$ is insensitive to the long-distance physics. Although nuclear PDFs (nPDFs) differ from nucleon PDFs, we note that their impact is generally small which is consistent with the expectation that jet quenching is a final state effect [30–33]. That is, the main source of jet quenching is likely to be multiple scattering and medium induced energy loss as the jet traverses the QGP, which modify the J_c in $p+p$ collisions into medium sensitive and nonperturbative jet functions ($J_c^{\rm med}$),

$$J_c(z, p_T R, \mu) \to J_c^{\rm med}(z, p_T R, \mu)\,. \tag{5}$$

The factorization of jet production in HIC in terms of $J_c^{\rm med}$ was first proposed in [34, 35] where a model calculation [36] was performed. In [37], the medium modification was taken to be a function of the jet p_T and the jet energy loss was determined at the cross section level. Other recent data driven approaches can be found in [38–40]. The factorization formalism in Eq. (2) with $J_c^{\rm med}$ allows us to directly work at the parton level to study how the parton shower (PS) gets modified due to the presence of the QGP. In [41] a new approach at the level of jet cross sections was introduced.

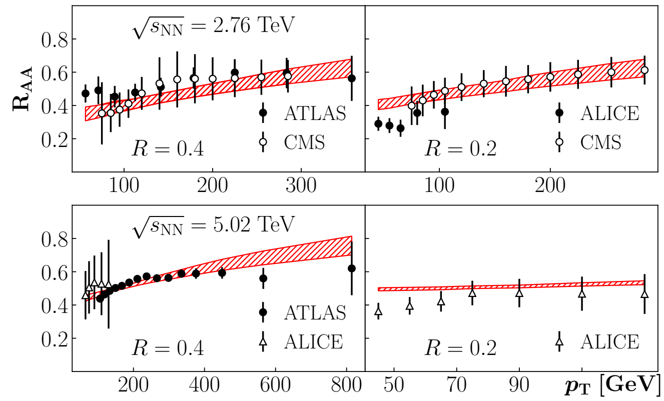

FIG. 1. The $R_{\rm AA}^{\rm jet}$ for inclusive jet production (0-10% centrality) at $\sqrt{s_{\rm NN}} = 2.76$ TeV (upper panels) and $\sqrt{s_{\rm NN}} = 5.02$ TeV (lower panels). We show the comparison with the data from ALICE [42, 43], ATLAS [44, 45] and CMS [46].

We stress that the proposed factorization approach is complementary to others in the literature, see for example [47] and references therein. In-medium calculations based on analytical techniques or PS event generators rely on some kind of factorization in HIC. With the leading power factorization formalism used here, our approach reduces the model bias to a minimum. The success of our framework, as demonstrated below, can help us to focus on how the medium modifies the jet functions in order to develop microscopic models of the QGP and its interaction with hard probes.

To be consistent with QCD factorization at leading power, we leave the DGLAP evolution equation and the corresponding kernels in Eq. (4) unmodified and only change the initial condition of the evolution. In a PS picture this corresponds to keeping the shower between the hard scale p_T and the jet scale $p_T R$ to be the same as that in the vacuum. Instead, only the physics at lower scales is affected by the QCD medium, which is captured effectively by fitting $J_c^{\rm med}$ to the data at the jet scale $\mu_J \sim p_T R$. This is consistent for example with the PS developed in [48–52] where the shower is unmodified relative to the vacuum case at sufficiently large scales. In principle, it is possible to extend our calculation to include a medium modified evolution which can be constrained from data and which we leave for future work [53].

Our analysis here is similar to the global analyses of nPDFs [54–56] and nuclear fragmentation functions in cold nuclear matter [57]. Since the J_c are perturbatively calculable, we choose an ansatz where the $J_c^{\rm med}$ are written in terms of the vacuum ones convolved with weight functions $W_c(z)$,

$$J_c^{\rm med}(z, p_T R, \mu_J) = W_c(z) \otimes J_c(z, p_T R, \mu_J)\,. \tag{6}$$

This approach effectively assumes that the QGP introduces a factorizable modification of the J_c, which recovers the vacuum case, for example, for very peripheral interactions, by having $W_c(z) \to \delta(1-z)$. We adopt the following flexible parametrization,

$$W_c(z) = \epsilon_c \delta(1-z) + N_c\, z^{\alpha_c}(1-z)^{\beta_c}\,, \tag{7}$$

for the weight functions. As the dependence on the factorization scale μ of the J_c is associated with the leading $\ln(R)$ contribution to the jet cross sections, one finds $\mu\frac{d}{d\mu}\int_0^1 dz\, z\, J_c(z, p_T R, \mu) \propto \sum_d \int_0^1 dz\, z\, P_{dc}(z) = 0$. That is, the first moment of J_c is independent of the factorization scale. Due to momentum conservation of the fragmenting parton p_T^c, the J_c satisfy the sum rule

$$\int_0^1 dz\, z\, J_c(z, p_T^c R, \mu) = 1\,, \tag{8}$$

which provides constraints for the evolution of the jet functions both in the vacuum and the medium. The convolution structures in Eqs. (2) and (6) can be handled conveniently in Mellin moment space [58]. The parameters of the weight functions are determined by a MC sampling of the likelihood function $\rho(\mathbf{a}|\text{data}) \propto \mathcal{L}(\mathbf{a},\text{data})\pi(\mathbf{a})$ with $\mathcal{L}(\mathbf{a},\text{data}) = \exp\left[-\frac{1}{2}\chi^2(\mathbf{a},\text{data})\right]$, where the data resampling method (NNPDF [7], JAM [8]) is used in order to obtain the MC ensemble for the parameters.

Phenomenological results. We consider inclusive jet data in HIC from the LHC, with the nuclear modification factor defined as

$$R_{\rm AA}^{\rm jet} = \frac{d\sigma^{\rm PbPb\to jet+X}}{\langle T_{\rm AA}\rangle\, d\sigma^{pp\to {\rm jet}+X}}\,, \tag{9}$$

where $\langle T_{\rm AA}\rangle$ is the average nuclear overlap function over a given $A+A$ centrality class [59]. The $J_c^{\rm med}$ need to be extracted separately for different centrality classes and center-of-mass (CM) energies. We include all available data sets from the LHC and limit ourselves here to the most central collisions (0-10%). At $\sqrt{s_{\rm NN}} = 2.76$ TeV we include the data from ALICE [42], ATLAS [44] and CMS [46] and at $\sqrt{s_{\rm NN}} = 5.02$ TeV we consider the ATLAS data of [45] and the preliminary ALICE data of [43]. For all data sets the anti-k$_T$ algorithm [60] was used with jet radii in the range of $R = 0.2$-0.4. The data sets cover different rapidity ranges which we take into account without listing them here. We add correlated and uncorrelated uncertainties in quadrature. For all numerical results presented here we use the CT14 PDF set of [5], and we work at next-to-leading order supplemented with resummation at next-to-leading logarithmic accuracy. In Fig. 1, we present a comparison of data from the LHC for the $R_{\rm AA}^{\rm jet}$ and our theoretical results using the fitted $J_c^{\rm med}$. We show the results at $\sqrt{s_{\rm NN}} = 2.76$ TeV (upper panels) and $\sqrt{s_{\rm NN}} = 5.02$ TeV (lower panels). For both CM energies we find good agreement with a χ^2/d.o.f. of 1.1 (2.76 TeV) and 1.7 (5.02 TeV). At low jet p_T there may be an indication for a medium modified DGLAP evolution, while the precision of current data does not require it yet. More insights could be obtained from analyzing hadron and jet substructure observables.

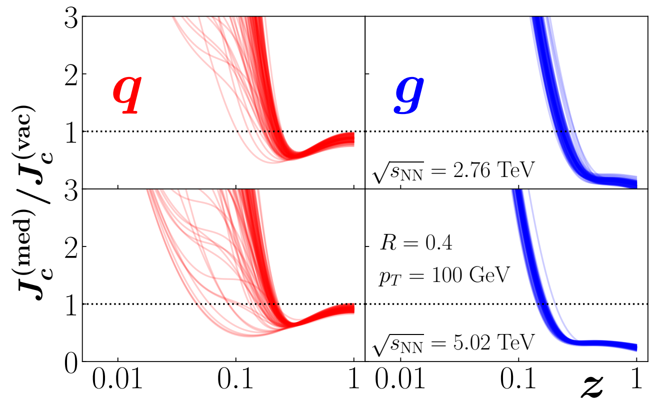

FIG. 2. Ratio of the extracted $J_c^{\rm med}$ and J_c at $\sqrt{s_{\rm NN}} = 2.76$ TeV (upper panels) and $\sqrt{s_{\rm NN}} = 5.02$ TeV (lower panels) evaluated for $R = 0.4$ jets at $\mu = p_T = 100$ GeV for quarks (left) and gluons (right).

In Fig. 2, we present the ratio of the extracted $J_c^{\rm med}$ and their vacuum analogues for $\sqrt{s_{\rm NN}} = 2.76$ TeV (upper panels) and $\sqrt{s_{\rm NN}} = 5.02$ TeV (lower panels) separately for quark (left) and gluon (right) jets with $R = 0.4$ at the scale $\mu = p_T = 100$ GeV. We find that the uncertainty at the higher CM energy is reduced significantly. This is mainly due to the very precise data set from ATLAS at 5.02 TeV [45] which dominates the corresponding fit.

At large-z the suppression of the jet functions indicates that it is less likely to form a jet carrying a large momentum fraction of the fragmenting parton in HIC. This is consistent with existing parton energy loss models [9, 10]. The suppression of $J_c^{\rm med}$ at large-z leads to the suppres-

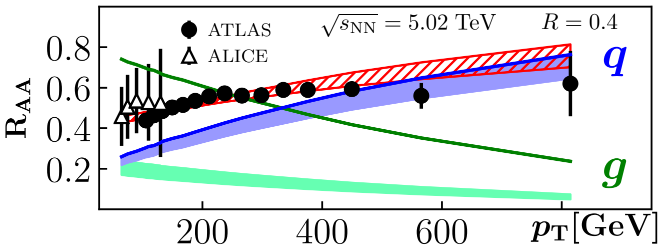

FIG. 3. The suppression of the quark (blue) and gluon (green) cross sections for the lower left panel of Fig. 1 as an example. The individual suppression (bands) can be seen relative to the vacuum fractions (lines).

sion of the inclusive jet cross section. On the other hand, the large-z suppression is compensated by an enhancement at small-z, see also Eq. (8). We note that the HIC jet data puts more significant constraints on the large-z region of the $J_c^{\rm med}$. This is due to the convolution structure of the jet cross section, which forces the phase space with a combination of small $x_{a,b}$ and large z to dominate the jet production rate. A possibility to constrain the small-z behavior more directly is the measurement of the energy distribution of inclusive subjets [61].

In Fig. 2 we also observe a significant difference between $J_q^{\rm med}$ and $J_g^{\rm med}$ where gluon jets are significantly more suppressed at large-z than quark jets. This behavior is generally expected from model calculations. In fact, we find that it is not possible to fit the experimental data with the same weight function for quarks and gluons in Eq. (7), while retaining a probabilistic interpretation (positivity) of the $J_c^{\rm med}$. We investigated this large difference at the level of the cross section which requires us to define quark and gluon jets beyond leading-order. This can be achieved by introducing the jet functions J_{cd} that not only keep track of the parton c initiating the jet but also of the flavor content $d = q, g$ such that [62, 63]

$$\sum_d J_{cd}(z, p_T R, \mu) = J_c(z, p_T R, \mu)\,. \qquad (10)$$

In Fig. 3 we show the separation of the vacuum cross section into quark (blue line) and gluon (green line) jets using the $\sqrt{s_{\rm NN}} = 5.02$ TeV setup (lower left panel of Fig. 1) along with the corresponding separation in the medium (blue and green bands). We observe that gluon jets are significantly more suppressed than quark jets in the medium. Some jet substructure observables indeed support this observation, see for example [64–67]. In the future it will be possible to better pin down differences between quark and gluon jets by including $\gamma/Z+$jet [68, 69] and hadron + jet [70, 71] data in a global analysis. We thus conclude that the leading power factorization formalism with medium jet functions not only captures the feature of in-medium interactions of jets with the QGP but also allows for a clear physical interpretation.

An intriguing aspect of jet quenching studies is the jet radius dependence. While the current experimental

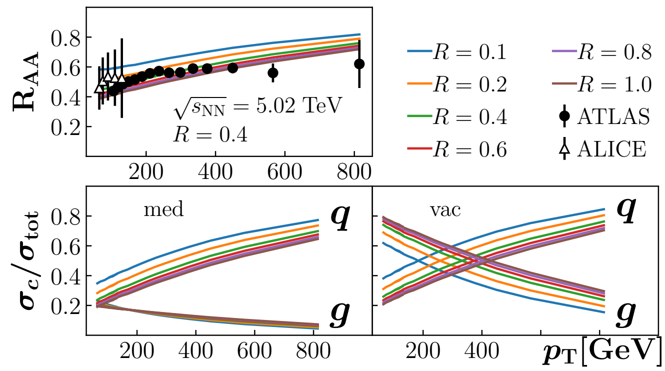

FIG. 4. The dependence of the $R_{\rm AA}^{\rm jet}$ at $\sqrt{s_{\rm NN}} = 5.02$ TeV on the jet radius R (upper panel), and quark and gluon jet contributions in the medium (lower left) and vacuum (lower right).

data remains inconclusive, different model calculations in the literature predict the $R_{\rm AA}^{\rm jet}$ to either increase or decrease with R. In general, a non-monotonic behavior is expected: the $R_{\rm AA}^{\rm jet}$ increases at both formal limits $R \to 0, \infty$. In the limit $R \to 0$, the $R_{\rm AA}^{\rm jet}$ is expected to approach the hadron $R_{\rm AA}^h$ which is generally above the $R_{\rm AA}^{\rm jet}$ [72]. For large R the energy lost by partons due to medium interactions should eventually all be contained in a very large cone. However, both limits are formally not covered by the factorization formalism in Eq. (2). For $R \to 0$, the jet scale $\mu_J \sim p_T R \to 0$, and the evolution starts at $\mu_J \sim 1$ GeV with a nonperturbative J_c. For the experimentally accessible R values it is thus a priori not clear if the $R_{\rm AA}^{\rm jet}$ increases or decreases with R. In Fig. 4 we show the R-dependence obtained within our framework at $\sqrt{s_{\rm NN}} = 5.02$ TeV. In the vacuum the gluon fraction of the jets decreases with smaller R, caused by more phase space to evolve and the J_g evolving faster, which leads to the increase of the quark fraction (lower right). In the medium, gluon jets are more significantly quenched (lower left), which is why the $R_{\rm AA}^{\rm jet}$ (upper panel) effectively inherits the R-dependence of the quark jets. It will be interesting to see if these findings will be confirmed by more precise data in the future.

Conclusions. In this Letter, we proposed an approach to phenomenologically establish QCD factorization of jet cross sections in HIC. We considered inclusive jet production at the LHC and found that it is indeed possible to describe the $R_{\rm AA}^{\rm jet}$ by the leading power factorization formalism for $p + p$ collisions with medium modified jet functions. Our results thus support the notion of QCD factorization in the HIC environment. Since our framework operates at the parton level, it is possible to separate quark and gluon jets. We found that gluon jets are significantly more suppressed than quark jets; and there is a direct link between the relative suppression of quark and gluon jets and the jet radius dependence of the $R_{\rm AA}^{\rm jet}$.

In the future it will be important to investigate universality aspects of the jet functions by analyzing γ/Z tagged jet data as well as hadron and jet substructure observables in a similar way. The intuitive physical interpretation of the extracted medium jet functions may facilitate comparisons with model calculations available in the literature. Our proposed factorization approach helps to identify the impact of the medium modification at the parton level, and may serve as guidance for constructing microscopic models of the QGP and its interaction with hard probes. We hope that the factorization framework may help to explore how the formation and the evolution of a parton shower gets modified due to the presence of the hot and dense QCD medium created in HIC, from which the properties of the QGP can be better extracted.

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