Abstract
We review a recently proposed phenomenological framework to establish the notions of QCD factorization and universality of jet cross sections in heavy-ion collisions. First results of a global analysis of the nuclear modification factor of inclusive jets are presented where we extract medium modified jet functions using a Monte Carlo sampling approach. We observe that gluon jets are significantly more suppressed than quark jets. In addition, we study the jet radius dependence of the inclusive jet cross section in heavy-ion collisions and comment on a recent measurement from CMS. By considering for example jet substructure observables it will be possible to test the universality of the extracted medium jet functions. We thus expect that the presented results will eventually allow for extractions of medium properties with a reduced model bias.

Keywords:
Jets, QCD factorization, heavy-ion collisions

1. Introduction
The quark-gluon plasma (QGP) produced in heavy-ion collisions at the LHC and RHIC has been conjectured to have filled our universe shortly after the big bang. Highly energetic particles and jets that are also produced in these collisions serve as important probes of the hot and dense medium. These so-called hard probes traverse the QGP and carry information about the medium properties. One of the most striking signatures of the QGP is jet quenching. It is often quantified in terms of the nuclear-modification factor \(R_{AA}\) which is given by the ratio of the jet yield in heavy-ion and a rescaled proton-proton baseline. One of the main advantages of hard probes is that the relevant cross sections can be calculated perturbatively in proton-proton collisions by making use of factorization theorems [1,2] which allow for a consistent separation of perturbative and nonperturbative but universal ingredients such as parton distribution and fragmentation functions. By analyzing heavy-ion cross sections in terms of leading power proton-proton factorization theorems, we eventually aim to answer the question of how much information factorization theorems established in the vacuum tell us about the corresponding heavy-ion cross sections. While it is generally accepted...
that the main reasons for jet quenching are parton energy loss and multiple scatterings with spectator partons in the medium, the exact mechanism remains unknown which can introduce a significant model bias for extractions of medium properties from data.

Since there are no first principles proofs of QCD factorization and universality in heavy-ion collisions, we recently proposed in Ref. [3] to establish these concepts phenomenologically. Instead of designing a general purpose parton shower, we employ factorization theorems of jet cross sections which involve jet functions that have been developed for proton-proton collisions over the last decade. If jets are sufficiently collimated, the dynamics of the formation and evolution of jets can be expressed in terms jet functions up to corrections which are power suppressed by $O(R^2)$. These jet functions are perturbatively calculable in the vacuum and we perform a first extraction of the analogue nonperturbative functions in heavy-ion collisions. We employ a Monte Carlo sampling technique to reliably extract these jet functions from the available data. Eventually, the universality of the obtained jet functions will have to be tested by considering other cross sections as well. An important example are jet substructure observables where the extracted medium jet functions are needed to calculate the relevant quark/gluon fractions [4]. Therefore, the results presented here constitute only a first step in this direction.

2. Theoretical framework

At leading power, the factorized cross sections for inclusive jets differential in the jet transverse momentum $p_T$ and rapidity $\eta$ in proton-proton collisions can be written as [5][6][7]

$$\frac{d\sigma_{pp\rightarrow \text{jet}+X}}{dp_T d\eta} = \sum_{abc} f_{a/p} \otimes f_{b/p} \otimes H_{ab}^c \otimes J_c ,$$

(1)

where $f_{a/p}$ denote the PDFs, $H_{ab}^c$ are hard-scattering functions of partons $ab \rightarrow c$ and the functions $J_c$ take into account the formation and evolution of the inclusive jet sample originating from parton $c$. The symbols $\otimes$ denote appropriate integrals over the longitudinal momentum fractions of the involved partons. The jet functions $J_c(z, p_T R, \mu)$ depend on the momentum fraction $z$ of the identified jet relative to the initial parton $c$, the jet transverse momentum $p_T$, the jet radius $R$ and the renormalization scale $\mu$. The jet functions satisfy the usual timelike DGLAP evolution equations similar to fragmentation functions

$$\mu \frac{d}{d\mu} J_c = \sum_d P_{dc} \otimes J_d .$$

(2)

For the kinematics considered here, we expect that the only relevant modification in heavy-ion collisions is the final state jet function. This assumption is based, for example, on the fact that the photon yield in heavy-ion collisions is consistent with no modification. Therefore, we make the following ansatz for the corresponding heavy-ion cross section where we replace the vacuum jet function in Eq. (1) as

$$J_c(z, p_T R, \mu) \rightarrow J_{c}^{\text{med}}(z, p_T R, \mu) = W_c(z) \otimes J_c(z, p_T R, \mu) .$$

(3)
Here we write the medium jet functions $F_{j}^{\text{med}}$ in terms of the vacuum ones convolved with weight functions $W_z$, which we fit to the available data. See also [10] [11]. We choose a suitable functional form for $W_z$, see [3] for more details. A related analysis of fragmentation functions in cold nuclear matter was carried out in [12]. We note that in heavy-ion collisions both the initial condition of the evolution at scale $\sim p_T R$ can be modified as well as the evolution of the jet functions to the hard scale $\sim p_T$. Here we start with the minimal assumption that the jet function gets affected by energy scales around $\sim p_T R$ which sets the initial scale for the evolution and constitutes the lowest scale relevant for this process. We discuss the implications of this assumption in more detail below.

3. Phenomenological results

We consider the available data from ATLAS [8] and ALICE [9] at $\sqrt{s_{NN}} = 5.02$ TeV for central collisions (0-10%) and $R = 0.2, 0.4$. A similar analysis of the data sets at $\sqrt{s_{NN}} = 2.76$ TeV can be found in [3]. We employ the data resampling technique used in PDF fits such as [13] [14]. In Fig. 1 (left panel), we present the experimental data and our theoretical results using the extracted medium jet functions $F_{j}^{\text{med}}$. Overall we observe good agreement and we find $\chi^2/d.o.f = 1.7$. In the right panel of Fig. 1, we show the ratio of the medium and the vacuum jet functions for $p_T = 100$ GeV and $R = 0.4$. We observe a suppression at large values of $z$ and an enhancement at small-\(z\), which effectively requires the colliding partons to have a larger average momentum fractions $x$ in heavy-ion collisions than that in vacuum in order to produce the same $p_T$ jet, and leads to an overall suppression of the jet cross section in heavy-ion collisions. We note that the uncertainty of the extracted jet functions is larger at small-$z$ which is due to the convolution structure of the cross section in Eq. (1). In addition, we observe a more significant modification of the gluon jet function (right) compared to the quark case (left). We explore the strong gluon suppression at the cross section level by studying the quark/gluon fractions in the vacuum and medium in more detail [13]. Fig. 2 (left) shows the vacuum quark/gluon fractions as a function of the jet transverse momentum $p_T$ for different values of the jet radius. For smaller jet radii, more evolution makes the jet functions larger at small-$z$, which requires a larger average $x$ and increases the fraction of quark jets. Similarly, the right panel shows the medium case where we use the extracted medium jet functions for the same center of mass energy. We observe a significant shift toward quark jets in heavy-ion collisions relative to the vacuum due to the enhancement of jet functions at small-$z$. We note that the $R$ dependence of the quark/gluon fractions is reduced in the medium but the ordering compared to the vacuum is preserved.

Recently, CMS published preliminary inclusive jet data for jet radii in the range of $R = 0.2-1.0$ [15]. The experimental data for the ratios of cross sections with different $R$ is very precise and can provide important constraints on the extracted medium jet functions discussed here. While a more in-depth analysis of the new data set is necessary, we note that preliminary studies indicate that a modification of the DGLAP evolution equations in heavy-ion collisions could alter the $R$ dependence of the nuclear modification factor $R_{AA}^{jet}$. So far we have assumed that the evolution equations are the same as in the vacuum, see Eq. (2). The new data set for different jet radii will thus allow for precision determinations of the medium jet functions and more definitive conclusions about the structure of jet cross sections in heavy-ion collisions can be obtained.

Fig. 2. The fractions of quark (blue) and gluon (green) jets in proton-proton (left) and heavy-ion collisions (right). We show the results for three values of the jet radius $R$ (different dashing).
4. Conclusions and outlook

In heavy-ion collisions the yield of high transverse momentum jets is suppressed which is known as jet quenching. We employed a factorization ansatz for the jet cross section in heavy-ion collisions in terms of hard-scattering and medium modified jet functions which can be determined from data. We have presented results of a first global analysis of the available data from the LHC. We observed a significant difference between the suppression of quark and gluon jets. Ultimately, the goal of our analysis is to test or establish the notions of QCD factorization and universality in heavy-ion collisions. We expect that the analysis performed here can eventually lead to definitive and model independent conclusions about the modification of the final state parton cascade in heavy-ion collisions and, thus, provide constraints on models of the QGP and its interaction with hard probes. This can be achieved by extending the presented framework to other processes such as inclusive hadrons, jet substructure observables and photon-jet correlations.

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References

[1] J. C. Collins, D. E. Soper, G. F. Sterman, Factorization of Hard Processes in QCD, Adv. Ser. Direct. High Energy Phys. 5 (1989) 1–91. arXiv:hep-ph/0409313 doi:10.1142/97898145032660001

[2] G. C. Nayak, J.-W. Qiu, G. F. Sterman, Fragmentation, NRQCD and NNLO factorization analysis in heavy quarkonium production, Phys. Rev. D72 (2005) 114012. arXiv:hep-ph/0509021 doi:10.1103/PhysRevD.72.114012

[3] J.-W. Qiu, F. Ringer, N. Sato, P. Zurita, Factorization of jet cross sections in heavy-ion collisions, Phys. Rev. Lett. 122 (25) (2019) 252301. arXiv:1903.01993 doi:10.1103/PhysRevLett.122.252301

[4] F. Ringer, B.-W. Xiao, F. Yuan, Can We Observe Jet $p_T$-broadening in Heavy-Ion Collisions at the LHC? arXiv:1907.12541

[5] T. Kaufmann, A. Mukherjee, W. Vogelsang, Hadron Fragmentation Inside Jets in Hadronic Collisions, Phys. Rev. D92 (2015) 054015. arXiv:1506.04140 doi:10.1103/PhysRevD.92.054015

[6] Z.-B. Kang, F. Ringer, I. Vitev, The semi-inclusive jet function in SCET and small radius resummation for inclusive jet production, JHEP 10 (2016) 125. arXiv:1606.06732 doi:10.1007/JHEP10(2016)126

[7] L. Dai, C. Kim, A. K. Leibovich, Fragmentation of a Jet with Small Radius, Phys. Rev. D94 (11) (2016) 114023. arXiv:1606.07411 doi:10.1103/PhysRevD.94.114023

[8] M. Aaboud, et al., Measurement of the nuclear modification factor for inclusive jets in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, Phys. Lett. B790 (2019) 108–128. arXiv:1805.05635 doi:10.1016/j.physletb.2018.10.076

[9] S. Acharya, et al., Measurements of inclusive jet spectra in pp and central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV Phys. Lett. B769 (2017) 242–248. arXiv:1701.05899 doi:10.1016/j.physletb.2017.03.067

[10] Y. He, L.-G. Pang, X.-N. Wang, Bayesian extraction of jet energy loss distributions in heavy-ion collisions, Phys. Rev. Lett. 122 (25) (2019) 252302. arXiv:1808.05310 doi:10.1103/PhysRevLett.122.252302

[11] R. Sassot, M. Stratmann, P. Zirnita, Fragmentations Functions in Nuclear Media, Phys. Rev. D81 (2010) 054001. arXiv:0912.1311 doi:10.1103/PhysRevD.81.054001

[12] R. D. Ball, et al., Parton distributions from high-precision collider data, Eur. Phys. J. C77 (10) (2017) 663. arXiv:1706.00428 doi:10.1140/epjc/s10052-017-5199-5

[13] A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens, N. Sato, Constraints on large-$x$ parton distributions from new weak boson production and deep-inelastic scattering data, Phys. Rev. D93 (11) (2016) 114017. arXiv:1602.03154 doi:10.1103/PhysRevD.93.114017

[14] A. Banfi, G. F. Salam, G. Zanderighi, Infrared safe definition of jet flavor, Eur. Phys. J. C47 (2006) 113–124. arXiv:hep-ph/0601139 doi:10.1140/epjc/s2006-02552-4

[15] C. Collaboration, Measurement of Jet Nuclear Modification Factor in PbPb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV with CMS.