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Open heavy-flavor measurements in ultra-relativistic nuclear collisions

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Abstract

Recent results from open heavy-flavor measurements in proton-proton (*pp*), proton/deuteron-nucleus (*p*/d-A), and nucleus-nucleus collisions (A-A) at RHIC and at the LHC are presented. Predictions from theoretical models are compared with the data, and implications for the properties of the hot and dense medium produced in ultra-relativistic heavy-ion collisions are discussed.

Keywords: Strongly interacting matter, Heavy quarks, Energy loss, Collectivity

1. Introduction

Heavy-flavor hadrons carrying charm or beauty quarks are unique probes of the hot and dense, strongly interacting Quark-Gluon Plasma (QGP) produced in ultra-relativistic heavy-ion collisions at RHIC and at the LHC [1, 2]. Owing to the large quark masses, heavy quark-antiquark pairs are produced almost exclusively in the earliest phase of a heavy-ion collision via partonic hard scattering processes. Since their formation time is small compared to the timescale of QGP formation/thermalization [2, 3] heavy quarks experience the full evolution of the system while they propagate through the medium and interact with its constituents. Because the strong interaction preserves the quark flavor, the total charm and beauty yields remain unaffected, *i.e.* they should scale with the nuclear overlap function in nuclear collisions, and only their phase-space distributions are modified. Two experimental observables are commonly investigated to study the interaction of heavy quarks with the medium: the nuclear modification factor R_{AA}, which is the ratio of the momentum distributions of heavy-flavor hadrons or their decay products in AA and *pp* collisions (properly scaled by the nuclear overlap function), and their azimuthal anisotropy quantified via the elliptic flow parameter v_2, which is the second harmonic of the Fourier expansion of the momentum distributions in azimuth with respect to the relevant symmetry plane of the collision. In principle, the simultaneous measurement of R_{AA} and v_2 can give access to the heavy-quark transport coefficients in the QGP [4].

Heavy quarks lose energy via radiative [5] and collisional processes [6] while traversing the dense medium. However, differences between the energy loss of heavy and light quarks are expected. Due to the dead-cone effect, the parton energy loss via medium-induced gluon emission is expected to decrease with increasing parton mass [7]. Additional collisional energy loss should be reduced for heavy quarks compared

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to light quarks [8]. This ordering of heavy- and light-quark energy loss is reinforced by the fact that, at RHIC and LHC energies, light-flavor hadrons mostly originate from gluon fragmentation [9] while heavy-flavor hadrons are produced via the fragmentation of heavy quarks. Since the color coupling of gluons is larger than the one of quarks, gluons suffer a larger radiative energy loss in the deconfined medium. Therefore, a mass hierarchy is expected for the parton energy loss, $\Delta E_{\rm parton}$, in the kinematic regimes where the mass can not be neglected with respect to the parton momentum: $\Delta E_{\rm gluon} > \Delta E_{\rm light\,quark} > \Delta E_{\rm charm} > \Delta E_{\rm beauty}$. When confronting the measured nuclear modification factors $R_{\rm AA}$ of light-flavor and heavy-flavor hadrons with this expected hierarchy, a number of additional caveats have to be considered [9], including the differences between the primordial spectral shapes of the produced partons and their fragmentation functions, which are harder for heavy quarks compared to light quarks. Furthermore, at low $p_{\rm T}$ light-flavor hadrons are mostly produced via soft processes, which is not the case for heavy-flavor hadrons.

The interaction of heavy quarks with the medium contributes to the azimuthal anisotropy of their momentum distributions in a twofold way: since the collision zone is azimuthally asymmetric in position space, v_2 reflects the path-length dependence of heavy-quark energy loss [10, 11], and, at low $p_{\rm T}$, v_2 is sensitive to the rescattering of heavy quarks in the medium. There, a positive v_2 would indicate that heavy quarks participate in the collective motion of the medium, which is a prerequisite for thermalization with the latter [12].

In order to fully exploit the potential of heavy-flavor measurements in heavy-ion collisions, it is mandatory to conduct additional reference measurements in elementary *pp* collisions and in *p*/d-A collisions. Heavy-flavor measurements in these small collision systems do not only provide the crucial references for the heavy-ion program, they are also interesting in their own right. Since a hard scale is introduced already by the quark mass, perturbative QCD methods are applicable even for the calculation of low-momentum heavy-quark production via hard scattering processes. Therefore, heavy-flavor measurements in *pp* collisions provide a sensitive testing ground for QCD at the high-energy frontier. In d-Au and *p*-Pb collisions at RHIC and at the LHC, respectively, effects due to the presence of a heavy nucleus in the initial state can be investigated, commonly referred to as cold nuclear matter (CNM) effects. These include modifications of the parton distribution functions in nuclei with respect to those in nucleons, in particular gluon shadowing described by phenomenological parameterizations [13] or in the Color Glass Condensate effective theory [14]. In general, these modifications lead to a depletion of nuclear parton densities at the Bjorken-x values relevant for low-$p_{\rm T}$ heavy-flavor production at the LHC and, to some extent, at RHIC. Also, $k_{\rm T}$ broadening, *i.e.* multiple soft parton scatterings in the initial state before the hard scattering process leading to heavy-flavor production takes place, can play a role. Finally, partonic energy loss both in the initial state and in the final state can not be neglected completely [15, 16].

Open heavy-flavor measurements in nuclear collisions were pioneered at RHIC, where heavy-flavor energy loss was discovered via the observation of the suppression of the yield of electrons from heavy-flavor hadron decays at high $p_{\rm T}$ in central Au-Au collisions with respect to *pp* collisions [17], and also elliptic flow was observed for the first time for such electrons in semi-central Au-Au collisions [18]. Measurements conducted during Run 1 at the LHC could take advantage of the much larger heavy-flavor production cross sections. Furthermore, the LHC experiments profited from the availability of high-resolution vertex spectrometers, which allow the decay topology of heavy-flavor hadrons to be exploited, from the first day of running. This important apparative feature was not available for the RHIC experiments during their first decade of operations, but recent upgrades have added high-resolution vertexing technology both to the PHENIX and STAR experiments.

2. Testing pQCD calculations in *pp* collisions

Heavy-flavor production cross sections have been measured in *pp* collisions at RHIC and at the LHC as a function of $p_{\rm T}$ and y in various channels [1, 2], *i.e.* via the full reconstruction of heavy-flavor hadrons through their hadronic decays, via single electrons or muons from the semileptonic decays of these hadrons, via lepton pairs, via non-prompt J/ψ from the decay of beauty hadrons, or via reconstructed beauty jets. The available extensive set of heavy-flavor production measurements in *pp* collisions keeps being extended into kinematic regions not accessible before, and the precision of the measured cross sections has improved considerably over the years. Therefore, the available data provide a crucial testing ground for perturbative