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Heavy flavour production in heavy-ion collisions

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Abstract

The study of heavy-flavour (HF) production at the RHIC and the LHC have provided in last years new insights into the properties of the Quark Gluon Plasma (QGP) created in ultra-relativistic heavy-ion collisions. Charm and beauty quarks are indeed mostly produced in hard scatterings in the early stages of heavy-ion collisions. Once the QGP is formed, they traverse the medium and interact with its constituents via collisional and radiative processes. As a consequence of these interactions, low momentum heavy-quarks can thermalize in the QGP and eventually take part in the expansion and hadronization of the QGP. Measurements of charmed and beauty hadrons can therefore provide information on all the stages of the QGP evolution.

Heavy-flavour production mechanisms in p+p, e^{+}+e^{-}, and e+p/A collisions: Measurements of the production cross-section of charm and beauty hadrons provide a unique opportunity to test pQCD predictions from low to high transverse momenta within the QCD factorization approach. NLO calculations coupled with fragmentation functions information from e^{+}+e^{-} data [1, 2] have been shown to describe LHC and RHIC p_T-differential cross-sections in pp collisions with good accuracy for both charmed and beauty mesons. However, theoretical calculations still struggle to describe more differential observables, such as the HF particle angular correlations [3, 4, 5, 6, 7], calling for a more accurate description and understanding of NLO production mechanisms. Future measurements of D–$\bar{D}$, B–$\bar{B}$ correlations from high to low transverse momenta together with high accuracy measurement of the in-jet production of D and B hadrons (e.g. R-shape production of HF hadrons) will provide important experimental constraints to improve the description of the p+p production mechanisms in calculations [8]. The future electron-ion collider [9, 10] will also open the opportunity for studying the HF production mechanism via the e+p collisions and clean access to the cold nuclear matter effects via the e+A collisions. These data would provide a foundation to interpret the HF measurements in the heavy-ion collisions, including the heavy quark (HQ) production, their interaction with QGP, hadronization, and the testing the factorization for these processes.

Heavy-flavour energy loss and collectivity: Measurements of nuclear modification factors (R_{AA}) have been performed with good accuracy both at the RHIC and LHC [11]. The nuclear modification factor at low p_T is expected to be sensitive to the mechanisms of collisional energy loss and to modifications of the hadronization mechanisms, while at intermediate-high p_T the medium-induced radiative energy loss mechanisms are expected to be more important. At the intermediate p_T, the comparison between the measured nuclear modification factors of light hadrons, D, and B mesons have shown significant differences, which are consistent with the hypothesis of different energy loss for gluon, light, and heavy quarks as predicted by QCD in presence of a deconfined medium [12]. To obtain a microscopic understanding of the energy loss phenomena, and in particular to quantify the collisional and radiative processes, more accurate measurement of the nuclear modification factors for the various charmed and beauty hadrons are envisioned over a broad kinematics range at both RHIC and LHC [8, 13]. Furthermore, differential measurement of HF energy loss phenomena through HF jet substructures and correlations will highlight the dynamic properties of energy loss mechanisms and parton shower development, which provide further discrimination power for theoretical models [14, 15].

On the other hand, the evidence of the positive elliptic flow of charm and beauty hadrons have been observed [11, 16, 17, 18]. Although these experimental observations support that heavy quarks participate in the collective expansion of the medium, a quantitative understanding of the interaction, such as the temperature dependence of the diffusion coefficient, is still lacking. To have a complete picture of the interaction of HQ with the medium, high precision dataset covering a wide kinematics region in multiple collision systems is needed, and quantitative global model fits that simultaneously describing these datasets are desired.

Heavy-flavour hadronization from small to large systems: The hadronization mechanisms are not well understood for both light and heavy flavours. The study of charm dynamics in heavy-ion collisions suggests the hadronization process has a large effect on the observable R_{AA} and v_n [19, 11, 20]. There are two main hadronization mechanisms for the production of heavy-flavour hadrons: fragmentation and recombination. Fragmentation has been widely applied at describing the production of light hadrons from high-momentum partons in p+p collisions. In heavy-ion collisions, in addition to the fragmentation process, hadron production can also occur via recombination, which is expected to dominate in the hadron production at the low-momentum regime. According to the recent measurements in LHC, fragmentation cannot describe charm hadron production at low p_{T} in p+p collisions [21, 22], and additional processes are needed to be implemented.

Recombination leads to enhancement of baryon-to-meson ratio and strange-to-nonstrange meson ratio, and therefore high precision measurements of $\Lambda_{\mathrm{c}}/\mathrm{D}^0$ and $\Lambda_{\mathrm{b}}/\mathrm{B}^+$ ratio and $\mathrm{D_s}/\mathrm{D}^0$ and $\mathrm{B_s}/\mathrm{B}^+$ ratio would apply strong constraints on the hadronization mechanisms. In addition, heavy charm baryon production (Ξ_{c}) is sensitive to the hadronization process with a strange quark in the constituent quarks. Also, the production of the tetra-quark state is more affected by the underlying hadronization process compared to baryons. Therefore, the measurements of multi-quark and heavy charm baryon production provide a new approach to study heavy flavour hadronization mechanisms. In addition to the baryon-to-meson ratio, the measurements of absolute cross-sections of open heavy flavour hadrons are critical to constrain the fragmentation functions and fragmentation fractions.

Heavy-flavour collectivity in small systems: Traditionally, the deconfined medium produced in heavy-ion collisions is expected to be absent in smaller collision systems, for instant, proton-proton and proton-nucleus collisions. However, signals traditionally attributed to the formation of a hot deconfined medium have been observed in high-multiplicity p+p and p+Pb collisions. Non-vanishing flow harmonics v_2 of prompt D^0 and prompt J/ψ in p+Pb collisions and muons from charm hadron decay in pp collisions have been observed [23, 24, 25]. One interpretation of these observations is the presence of a hot medium in smaller systems, and hydrodynamics provides a consistent framework with heavy-ion collisions. On the other hand, no significant suppression of high-momentum particle production has been observed, which should be taken into account in the same framework. Another explanation of the collective behaviors observed in small systems is in terms of initial-state effect (Color-Glass-Condensate [26]). So far, what causes the collective behaviors observed in small systems is still under debate.

To resolve the question, the measurements of heavy quarks in small systems are of great interest. Because of their large mass, heavy quarks are expected to have weaker collective behavior in the medium, while being more affected by the initial-state effect. These characteristics make heavy quarks unique probes to distinguish hot nuclear matter effects from cold matter effects. To connect small and large systems, the future measurements of heavy-flavour flow harmonics in high-multiplicity p+p and p+A collisions, in the most peripheral nucleus-nucleus collisions, and in the intermediate ion collisions (e.g. O+O collisions) will provide insights into the origins of collective behaviors in small systems and the onset of the deconfined medium.

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