Experimental overview on heavy-flavor production

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Alessandro Grelli

Princetonplein 1, Oornestein laboratory, Utrecht, NL

E-mail: `a.grelli@uu.nl`

Abstract. Hadrons containing heavy-flavors are unique probes of the properties of the hot and dense QCD medium produced in heavy-ion collisions. Due to their large masses, heavy quarks are produced at the initial stage of the collision, almost exclusively via hard partonic scattering processes. Therefore, they are expected to experience the full collision history propagating through and interacting with the QCD medium. The parton energy loss, which is sensitive to the transport coefficients of the produced medium, can be studied experimentally by measuring the nuclear modification factor which accounts for the modification of the heavy– flavored hadron yield in Pb–Pb collisions with respect to pp collisions. In semi-central Pb–Pb collisions, the degree of thermalization of charm quarks in the QCD medium can be accessed via the measurement of the heavy flavor elliptic flow v_2 at low p_T. Furthermore, the measurement of heavy-flavors production in pp collisions allows testing the perturbative QCD calculations.
The PHENIX and STAR Collaborations at the Relativistic Heavy-Ion Collider and ALICE, CMS and ATLAS Collaborations at the Large Hadron Collider have measured the production of charmonium and bottonium states as well as open heavy flavor hadrons via their hadronic and semi-leptonic decays at mid-rapidity and in the semi-muonic decay channel at forward rapidity in pp, p-A and A–A collisions in an energy domain that ranges from $\sqrt{s} = 0.2$ TeV to $\sqrt{s} = 13$ TeV in pp collisions and from $\sqrt{s_{NN}} = 0.2$ TeV to $\sqrt{s_{NN}} = 5.02$ TeV in A–A collisions. In this contribution the latest experimental results will be reviewed.

1. Introduction

The lattice QCD calculations predict for the strongly-interacting matter, in conditions of high density and temperature such as the one produced in high-energy ultra relativistic heavy-ion collisions, quark de-confinement and the formation of the so called Quark-Gluon Plasma (QGP) [1]. Heavy-flavor hadrons are qualitatively and quantitatively unique probes for the investigation of the QGP. Open charm and beauty hadrons are expected to be sensitive to the energy density through the in-medium energy loss of their heavy quark constituents. In particular, charm and beauty quarks, due to the large masses, are produced at the early stage of the collision [2] and expected to loose less energy than light quarks and gluons while traversing the QGP due to dead-cone and color-charge effects [3, 4]. Furthermore, the in-medium thermal production is expected to be negligible [5]. In addition, if in-medium hadronization is the dominant mechanism of charm hadron formation at low-p_T then strange charm hadrons (i.e D_s^+) should be enhanced relatively to non-strange charm hadrons (i.e D^0) [6]. The aforementioned properties make heavy quarks a clean and effective probe for the QGP properties.
In addition quarkonium states (i.e Charmonium and Bottonium) are expected to be sensitive to the initial temperature of the system via their dissociation due to color screening. At Large Hadron Collider (LHC) energy scale the recombination effects, that can be pictured as in-medium recombination and statistical recombination at the freeze-out, are expected to become

competitive with the dissociation producing a visible effect on the nuclear modification factor once compared with the same observable at lower collision energy (i.e. Relativistic Heavy-Ion Collider (RHIC)).

The nuclear modification factor R_{AA} of particles is well-established as a sensitive observable for the study of the interaction of hard partons with the medium. This factor is defined as the ratio of the p_T-differential yield measured in nucleus-nucleus (AA) collisions in a given centrality class to the yield calculated from the proton-proton cross-section scaled by the nuclear overlap function $< T_{AA} >$ for that centrality class, obtained from Glauber model calculations of the collision geometry [7],

$$R_{AA}(p_T) = \frac{1}{< T_{AA} >} \cdot \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{\mathrm{d}\sigma_{pp}/\mathrm{d}p_T} \tag{1}$$

A strong suppression of the yield of charged particles was observed in A–A collisions at intermediate-high p_T relative to scaled pp collisions both at RHIC [8, 9] and LHC [10].

Further insight in the medium properties is provided by the measurement of anisotropy in the azimuthal distribution of particle momenta characterized by the Fourier coefficients $v_n = < cos[n(\phi - \psi n)] >$, where n is the order of the harmonic, ϕ is the azimuthal angle of the particles momentum, and ψn is the azimuthal angle of the initial state symmetry plane for the n-th harmonic. At low-intermediate ($< 6~GeV$/c) transverse momentum a non zero v_2 reflects the collective expansion, while high transverse momentum a positive v_2 is expected as a consequence of the path-length dependence of the in-medium parton energy loss.

In this paper we review the results on heavy flavor production in pp collisions in a range of energies from $\sqrt{s} = 0.2$ TeV to $\sqrt{s} = 13$ TeV and in A–A collisions in a range of energies from $\sqrt{s_{NN}} = 0.2$ TeV to $\sqrt{s_{NN}} = 5.02$ TeV. The proton-proton results provide the baseline for the study of medium-induced effects in nucleus–nucleus collisions. Moreover they offer the possibility to test pQCD. Perturbative QCD predictions extracted using FONLL [25] (FixedOrder-plus-Next-to-Leading-Log) describe well the beauty production cross section measured in pp collisions at $\sqrt{s} = 1.96$ TeV by CDF at the Tevatron [26]. Additionally, the CMS experiment found that at the LHC energy scale the beauty production is well described by the theory [27]. In the case of charm, FONLL prediction agrees with data within errors. Nevertheless, the data points are systematically on the upper edge of the theory error band suggesting that charm production could be underestimated in the calculation as also seen at RHIC energies ($\sqrt{s}= 0.2$ and 0.5 TeV) [28].

2. Open heavy-flavor production in nucleon–nucleon collisions

At the RHIC and LHC the production of open heavy flavor hadrons has been measured via their hadronic and semi-leptonic decays at mid-rapidity in pp collisions in an energy domain that rages from $\sqrt{s} = 0.2$ TeV to $\sqrt{s} = 13$ TeV and in the semi-muonic decay channel at forward rapidity at $\sqrt{s} = 7$ TeV. The D meson production, as well as the total charm production cross-section, are discussed in section 2.1 while a review of heavy-flavor measurement via heavy-flavor hadron semi-leptonic decays can be found at [14, 15, 16, 17].

2.1. D meson production cross-section at central and forward rapidity

The study of open charm production via D meson hadronic decays is performed in a fairly similar way at RHIC and LHC. It is based either on displaced vertex reconstruction or on background simulation [18] (i.e event mixing, like-sign or rotational background). The displaced vertex reconstruction, is achieved thanks to the excellent tracking systems of the modern high-energy experiments that allow selection of decay vertices of open charm mesons ($c\tau \sim 120$ – 310 μm). In a second step an invariant mass analysis is performed. On the left panel of Fig. 1 the $D^0 \to K^- \pi^+$ production cross-section is shown in the transverse momentum region
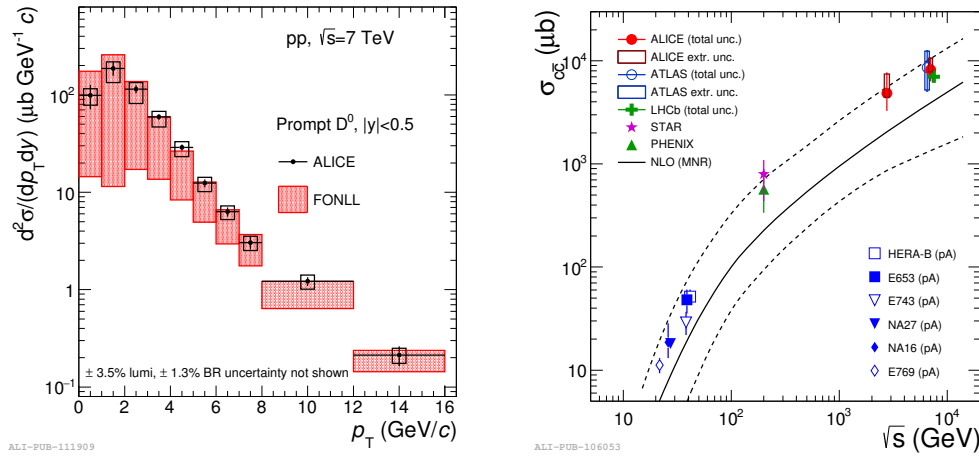
Figure 1. Left panel: D^0 p_T-differential production cross-section as measure by ALICE Collaboration super-imposed with FONLL pQCD calculation (solid red boxes). Right panel: total charm production cross-section versus $\sqrt{s}$ [18].
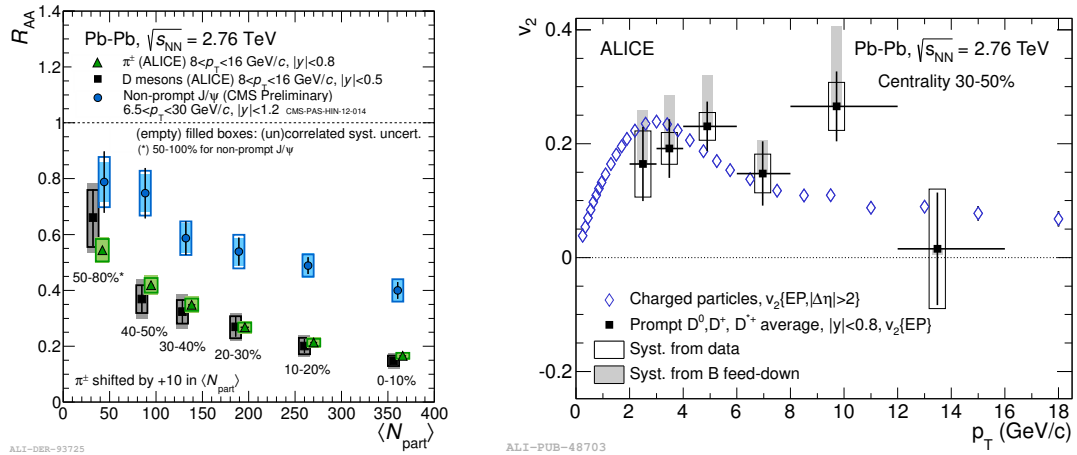
$0 < p_T < 16$ GeV/c as measured by ALICE Collaboration in pp collisions at $\sqrt{s} = 7$ TeV at mid-rapidity ($|y| < 0.5$) [18]. The measured cross-section sits on the upper-side of the FONLL pQCD calculation error band. The result, qualitatively similar to the measurements performed at $\sqrt{s} = 0.2, 0.5$ TeV and $\sqrt{s} = 1.96$ TeV by STAR [28] and CDF [26] collaborations, respectively, suggests an underestimation of the charm production by the calculation. The right side of Fig. 1 shows the evolution of the total charm production cross-section versus the collision energy as measured by several collaborations [18]. The experimental results are compared with NLO MNR [19] calculations. The model is compatible with the measured data within uncertainties. It is noticeable the agreement of the ALICE, ATLAS [20] mid-rapidity measurements with the LHCb [21] forward rapidity measurement at $\sqrt{s} = 7$ TeV.

3. Open heavy-flavors in nucleus–nucleus collisions

Due to the QCD nature of parton energy loss discussed in the introduction, hierarchy in the R_{AA} is expected to be observed when comparing the mostly gluon-originated light-flavor hadrons to D and to B mesons [11, 12]: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$. Clearly there are caveats to be taken into account while interpreting the results, like the different parton p_T spectra that can modify this picture.

The production of D^0, D^{*+} and D^+ was measured [13, 12, 22, 23] in A–A collisions at mid-rapidity via the exclusive reconstruction of the decays $D^0 \to K^-\pi^+$, $D^{*+} \to D^0\pi^+$ and $D^+ \to K^-\pi^+\pi^+$.

ALICE measured the R_{AA} of prompt D mesons in 10% wide centrality bins from 0 to 80% and in the $8 < p_T < 16$ GeV/c region [33]. The measurement was compared with the R_{AA} of non-prompt J/ψ (from B-mesons decays) measured by the CMS Collaboration [35]. As shown in the left panel of Fig. 2, the comparison of the two results, in a similar kinematic range, shows clear indication for a mass hierarchy in the suppression pattern being the non-prompt J/ψ less suppressed than D mesons, as expected from a larger energy loss of charm quark with respect to beauty quark. A comparison of the p_T-differential D meson R_{AA} measured at $\sqrt{s_{NN}} = 0.2$ TeV by STAR Collaboration [34] and the one measured by ALICE Collaboration [24] at $\sqrt{s_{NN}} = 2.76$ TeV hints a different trend at low-p_T. Namely the STAR result show an enhancement at about 1.5 GeV/c while in the ALICE case a suppression is found. The difference

Figure 2. Left panel: D meson R_{AA} versus N_{part} measured by ALICE Collaboration [33] compared with the non-prompt J/ψ measured by CMS Collaboration [35]. Right panel: D meson elliptic flow compared with charged hadrons as measured by ALICE Collaboration [30].

may be related to initial state effects and elliptic flow but the relatively large uncertainties of the two measurements suggest the need for additional statistics before drawing any conclusion. In addition to the D mesons measurements, the R_{AA} of heavy-flavor hadron decay electrons was measured by ALICE, STAR and PHENIX [15, 16, 17]. Furthermore, ALICE measured the D-meson elliptic flow (v_2) as a function of transverse momentum in the Pb–Pb centrality interval $30 - 50\%$ [30]. As shown in the right panel of Fig. 2 the D meson v_2 shows a similar trend of the charged particle v_2, within the rather large systematic and statistical uncertainties. The measurement indicates, at 5σ confidence level, a positive v_2 for $2 < p_T < 6\ GeV/c$. More recent results from CMS (at LHC) [23] and STAR (at RHIC) [31] confirm the observation. The D meson results, supported by recent measurements in the semi-leptonic sector [32], suggests that charm quarks participate in the collective flow of the expanding medium.

4. Quarkonium measurements in nucleus-nucleus collisions

Quarkonium is considered one of the main probes of the investigation of QGP. Its production in A–A collisions is expected to be significantly suppressed with respect to the pp yield, scaled by the number of binary nucleon-nucleon collisions. The origin of such a suppression is thought to be the colour screening [36]. According to it the suppression should occur sequentially, following the binding energy of each meson. Strongly bound states, such as the $\Upsilon(1S)$ or the J/ψ, should melt at higher temperatures with respect to the more loosely bound states such as $\Upsilon(2S)$, or $\Upsilon(3S)$. The simple picture of color screening needs to be complemented by recombination effects at LHC energies.

On this regard, the centrality dependence of the inclusive J/ψ production at low-p_T in A–A collisions [38, 39, 40] has been measured by ALICE and PHENIX Collaborations. In Fig. 3 the inclusive J/ψ nuclear modification factor, as a function of the number of participant nucleons (N_{part}), is compared to the one measured by the PHENIX [38] in a similar kinematic range. It is evident a smaller J/ψ suppression at LHC energies, with respect to RHIC. The smaller suppression at the LHC is assumed to be due to the larger $c\bar{c}$ pair multiplicity which allows a larger recombination, resulting in a compensation of the suppression from color screening. The measured behavior is expected by the statistical model [29], where the J/ψ yield is completely determined by the chemical freeze–out conditions and by the abundance of $c\bar{c}$ pairs. A precise
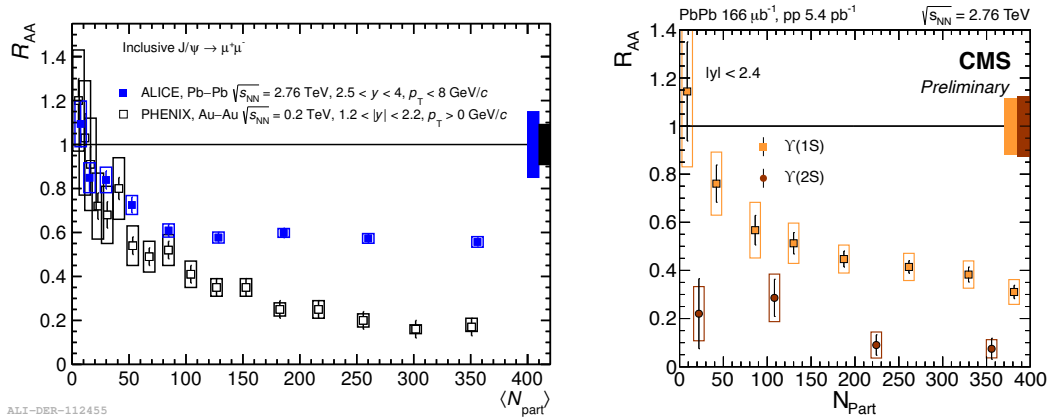
Figure 3. Left panel: ALICE [39] and PHENIX [38] inclusive low-p_T J/ψ nuclear modification factor versus the number of participant nucleons at forward rapidity. Right panel: R_{AA} of Υ states as a function of centrality, as measured by CMS Collaboration [45].

comparison between the experimental result and the theory predictions will benefit from the improvements in the experimental measurement of the charm production cross-section. Due to kinamatical reasons the (re)combination process is expected to be dominant in central collisions and at low-p_T, becoming negligible as the $J/\psi p_T$ increases. This observation is confirmed by the mid-rapidity R_{AA} measured by CMS [41] and STAR [42] for high-p_T J/ψ. Further insight on charmonium production in Pb-Pb collisions can be achieved comparing the production yields of a higher mass resonance, as the $\psi(2S)$, to the J/ψ ones. The double ratio of the $\psi(2S)$ to J/ψ yields in Pb–Pb and in pp collisions as a function of centrality, can be found in CMS [43] and for ALICE [40, 44]. CMS observes values of the double ratio higher than one in the region $1.6 < |y| < 2.4$, $3 < p_T < 30 \, GeV/c$, implying a $\psi(2S)$ R_{AA} larger than the J/ψ one. Results obtained in the range $|y| < 1.6$ and $6.5 < p_T < 30 \, GeV/c$ show a decreasing pattern towards most central collisions, i.e. the $\psi(2S)$ R_{AA} is, smaller than the corresponding J/ψ value, as expected by sequential suppression scenario. However, the large statistics and systematic uncertainties associated to the $\psi(2S)$ measurement preclude any strong conclusion.

Finally, the LHC energies allow the study of the resonances of the bottomonium family. CMS results [45], confirm the observation of sequential suppression for $\Upsilon(1S)$ ($R_{AA} = 0.43 \pm 0.03 \pm 0.07$), $\Upsilon(2S)(R_{AA} = 0.13 \pm 0.03 \pm 0.02)$ shown in Fig. 3 (right) and $\Upsilon(3S)(R_{AA} = 0.14$ at 95% CL.). A comprehensive overview on quarkonium production can be found at [37].

5. Conclusions

In the last ten years the experimental investigation of heavy-flavor physics in heavy ion collisions had a boost with the start of the LHC operations at CERN and with the upgrade of the RHIC at BNL. A considerable amount of new measurements become available both in pp and A–A.

In pp collisions the limit of $\sim 0 \, p_T$ was reached, both at mid- and forward rapidity, allowing on one side a clear test of pQCD and on the other side the definition of a solid experimental reference for A–A studies. In A–A collisions the study of charm and beauty nuclear modification factors become available via hadronic and semi-leptonic decays of open heavy-flavor hadrons at mid-rapidity and in their semi-muonic decay channel at forward rapidity. In addition elliptic flow measurements proved that charm take part in the collective motion of the system. Quarkonium studies proved that at high collisional energy the simple picture of dissociation via color screening needs to be complemented with the concept of in-medium and statistical regeneration.

In this frame of new measurements and theoretical developments the run II of the LHC and the RHIC operations of the next few years will open the possibility of precision measurements in the charm sector. The run III of the LHC starting in 2019 will open the era of precision measurements in the beauty sector.

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