Open heavy flavour production in heavy–ion collisions with ALICE

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Abstract. Heavy–flavour measurements give an important contribution to the understanding of the Quark–Gluon Plasma (QGP) produced in heavy–ion collisions. Heavy quarks are effective probes for the QGP and understanding their interaction with the medium can give insights into its transport properties. The ALICE Collaboration investigates heavy–flavour production by measuring leptons from heavy–flavour decays and by reconstructing hadronic decays of D mesons and charmed baryons. In this proceeding, recent results from ALICE as well as the direction of future heavy–flavour measurements are discussed.

1. Introduction
Heavy quarks – charm and beauty – are important tools to study the properties of the hot and dense matter produced in relativistic heavy–ion collisions. The study of their interaction with the medium can yield insight into its properties. Due to their large mass ($m_c/b \approx 1.5/4.5$ GeV/$c$), heavy quarks are produced almost exclusively in the initial hard scattering processes of the collision. Therefore, they witness the full evolution of the collision. Additionally, the large quark masses make perturbative calculations applicable even to a production at rest. In the vast majority of models, the interaction is modeled as discrete scatterings of the heavy quark off the medium constituents. In this framework, collisional ($2 \rightarrow 2$) and radiative ($2 \rightarrow 3$) processes can be distinguished. The relative contribution of these processes differs between models. It depends on the momentum and mass of the heavy quark. As a consequence, measurements over a large momentum range for both flavours are needed to disentangle the contributions.

After the initial hard scatterings, the number of heavy quarks in the system stays constant throughout the interaction. Thus, the effect of the medium is a redistribution of the produced particles in momentum space. Fast heavy quarks are slowed down, while slow ones may be accelerated due to the collective flow of the medium around them. The nuclear modification factor is frequently used to quantify the effects due to the formation of a medium. It compares the effect of a sample of heavy–ion collisions with an estimated mean value of binary (nucleon–nucleon) collisions of $\langle N_{\text{coll}} \rangle$ to a superposition of the same number of proton–proton (pp) collisions:

$$R_{AA}(p_T) = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{AA}}{dp_T} \frac{dN_{pp}}{dp_T} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}}{dp_T} \frac{d\sigma_{pp}}{dp_T},$$

where $T_{AA}$ is the nuclear overlap function. This approach assumes that the individual nucleon–nucleon collisions are well represented by proton–proton collisions in the vacuum. In reality,
the fact that the nucleons are part of a large nucleus may give rise to cold–nuclear–matter (CNM) effects which have to be estimated to interpret the measured nuclear modification factor. Additional measurements are performed in $p$–$Pb$ collisions to disentangle CNM effects from those due to the medium. Another important observable to quantify the interaction of heavy quarks with the medium is the elliptic flow coefficient $v_2$. It is defined as $v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle$, the second Fourier coefficient with respect to the second order symmetry plane of the azimuthal distribution. The $v_2$ quantifies the degree of participation in the collective motion of the surrounding medium.

Figure 1. Example of an invariant mass peak in the fully hadronic reconstruction of $\Lambda_c^+$.

Figure 2. Example of the transverse impact parameter template fit for extracting the beauty contribution to the electrons [1].

2. Experimental methods
The measurement at low transverse momenta and particle identification are particular strengths of the ALICE experiment. At mid–rapidity, open charm hadrons are measured via their hadronic decays (an example is shown in Figure 1). This includes $D^0 \rightarrow K^-\pi^+$ (branching ratio 3.93 ± 0.04%), $D^+ \rightarrow K^-\pi^+\pi^+$ (9.46 ± 0.24%), $D^{*+} \rightarrow D^0\pi^+$ (67.7 ± 0.5%), $D_s^+ \rightarrow \phi\pi^+$ (2.27 ± 0.08%). The $\Lambda_c^+$ is reconstructed via the $pK^-\pi^+$ and $pK^0_s$ channels and via the semi–leptonic $e^-\nu_e\Lambda$ channel. The $\Xi_c^0$ is reconstructed via the semi–leptonic $e^+\Xi^-\nu_e$ channel. The decay products can be identified using the signals of the Time Projection Chamber (TPC) and the Time Of Flight detector (TOF). For measurements at forward rapidity and to gain an access to beauty, semileptonic decays of heavy flavour hadrons are used. These are decays of the type $b \rightarrow l + X$, where only the lepton $l$ is measured. Such a measurement has the advantage that just by using particle identification, a large amount of the background can be removed. Due to the fairly large branching ratios and the softer $p_T$–distributions of electrons from background sources, electrons with transverse momenta above a few GeV/$c$ mostly come from heavy flavour sources. The branching ratios of charmed hadrons to a final state containing electrons is about 10%. For beauty hadrons, the ratio is about 20%, with about half of the contribution coming from decays with intermediate charmed states. At forward rapidity (2.5 $< \eta < 4$ for symmetric collisions), heavy flavour muons are measured by the Muon Spectrometer. The central barrel measurements ($|\eta| < 0.8$) are based on electrons identified using the TPC and TOF with additional PID information from the Inner Tracking System (ITS) at low $p_T$ and
the Electromagnetic Calorimeter (EMCal) at high $p_T$. To extract the contribution of heavy flavours, an estimate for the light–flavour contribution is subtracted from the measured leptons. To separate the beauty contribution, the impact parameter of the electron in the transverse plane is used as additional information. The different electron sources are then separated by a template fit of the transverse impact parameter distributions (example in Figure 2).
Figure 6. $R_{pA}$ of D mesons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Figure 7. Ratio of $R_{pA}$ of muons from heavy flavour hadron decays measured in p–Pb and Pb–p collisions

$R_{FB}$ has small uncertainties, because many contributions cancel out in the ratio. The $R_{FB}$ of muon from heavy–flavour hadron decays is shown in Figure 7. It deviates from unity and is consistent with the expectations from NLO calculations which include nPDFs [4].

Figure 8. $R_{pA}$ of electrons from beauty–hadron decays [1].

Figure 9. Elliptic flow of electrons from heavy–flavour hadron decays in p–Pb collisions.

Measuring electrons from beauty–hadron decays specifically, also yields an $R_{pA}$ consistent with unity as shown in Figure 8. All these results point towards pp and p–Pb collisions not showing large modifications of the heavy flavour production. As a consequence, strong deviations from the model of vacuum superpositions of nucleon–nucleon collisions in Pb–Pb could be interpreted as being medium induced. However, measurements of collective flow in small systems challenge this simple picture. Figure 9 shows a measured elliptic flow coefficient for electrons form heavy–flavour decays, which is significantly larger than zero. It is similar in magnitude to the measurement of light particles [5]. The measurement of collective behaviour
in the angular distributions, simultaneous with essentially unmodified $p_T$–distributions requires careful additional studies.

**Figure 10.** $R_{AA}$ of D mesons in central Pb–Pb collisions.

**Figure 11.** Elliptic flow of D mesons in Pb–Pb collisions.

### 4. Results in Pb–Pb collisions

The $p_T$–distributions of D mesons show a strong modification in central Pb–Pb collisions as shown in Figure 10. In addition, the elliptic flow of D mesons (Figure 11) shows a magnitude similar to that of light hadrons. This suggests a thermalization time for charm quarks of the order of the system lifetime. Careful comparison of the most successful models suggests $\tau_c = 3 - 14$ fm/c. The nuclear modification factor of $D^+_s$ was also measured. The result at low to intermediate $p_T$ hints at a larger $R_{AA}$ with respect to non–strange D mesons at the same $p_T$, consistent with an increased production of strange mesons expected by model predictions.

More differential quantities can be useful to further constrain models. In the case of the elliptic flow, events of the same centrality can produce a strong variation in the final state anisotropy. This can be quantified in by the reduced second–order flow vector $q^2_{TPC}$. It grows with event multiplicity and flow strength [6]. As shown in figure 12 it fluctuates strongly within centrality classes. Selecting $q^2_{TPC}$ as well as centrality classes of events gives a clear separation in the flow strength measured (Figure 13). Due to the fact that $q^2_{TPC}$ is measured in at mid–rapidity, where the D mesons are measured as well, some correlations can be present. As a result, the measured $v_2$ decreases when an $\eta$ gap is introduced between the measurement of the D mesons and the $q^2_{TPC}$ vector. This effect requires some additional careful analysis.

Even with the constraints from the nuclear modification factor and the elliptic flow, several diverse model calculations are able to describe the data reasonably. To complete the picture of heavy flavours in heavy ion collision, information about the mass dependence of the interaction is needed from the measurement of the beauty sector. Figure 14 shows the nuclear modification factor for electrons and muons from the decay of beauty hadrons. Towards higher $p_T$, the relative contribution of beauty increases, suggesting a suppression of beauty. This is further refined in the flavour–separated measurement shown in Figure 15. There is an indication for a suppression of electrons from beauty–hadron decays at the higher $p_T$ values measured, with the central points rising towards lower $p_T$. Several models can describe the measurement within uncertainties.
five. Summary

A comparison of the measurements of $p_T$-differential cross sections in pp and p–Pb collisions shows effects consistent with the expectations from cold nuclear matter effects, supporting the interpretation that the measured suppression and elliptic flow of heavy flavours in Pb–Pb collisions is a final state effect. This picture is complicated by the measurement of a significant elliptic flow for electrons from heavy–flavour decays even in p–Pb collisions. In addition, the measured production of charmed baryons in pp and p–Pb collisions is strongly underestimated by the model predictions. Future measurements may use more differential variables to constrain models further.
References
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