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Heavy flavour and quarkonia

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Being produced in the very early stages of heavy-ion collisions, open heavy flavour and quarkonia have always been considered among the most valuable tools to investigate the formation and the properties of the plasma of quarks and gluons. The high precision data now available from RHIC and LHC experiments confirm the central role of these observables, on one side allowing their study over a wide kinematic range and on the other opening up searches for new particles or new measurements previously not yet within reach.

In these proceedings, I'll present an overview of the most recent experimental results on open heavy-flavour and quarkonium production presented at the "10^{th} International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions" and I'll discuss the comparison of these measurements with state-of-the art theory calculations.

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1. Introduction

A phase transition between the hadronic matter and a state, named quark gluon plasma (QGP), where quarks and gluons are no more confined into hadrons, is predicted by quantum chromodynamics (QCD) when high temperatures and/or baryonic densities are reached. Since almost thirty years, the production and the properties of such a state of matter are experimentally investigated in ultrarelativistic heavy-ions collisions. The first measurements were carried on, still in the eighties, at CERN SPS at $\sqrt{s_{\rm NN}}$ = 17 GeV. Higher centre-of-mass energies were then obtained at RHIC ($\sqrt{s_{\rm NN}}$ = 200 GeV) from year 2000 and, ten years later, at LHC (up to $\sqrt{s_{\rm NN}}$ = 5.02 TeV) allowing the exploration of a system in which even higher temperatures and energy densities are reached. Open and closed heavy-flavour particles are produced in the early stages of the collisions in the initial high-Q^2 scatterings and then they probe the entire medium evolution, being affected by the presence of the QGP. Hence, since the beginning of this field of research, these particles are considered powerful tools to characterize the created medium and their crucial role is confirmed, nowadays, by the large number of experimental and theory presentations on this topic at this conference.

Heavy-ions experiments usually study the production of open and closed heavy flavours in three colliding systems, namely in pp, p-A and A-A interactions. While A-A collisions allow the study of the modifications induced by the hot QGP medium on the probes, the elementary collisions are interesting for QCD studies and represent a reference for the particle production in nuclear systems. These studies are complemented by proton-nucleus collisions which open up the investigation of effects not related to the creation of a hot medium, i.e. the so called “cold nuclear matter” (CNM) effects, as the nuclear modification of parton functions inside nuclei or the initial/final state energy loss of the parton/particle while crossing the medium. The separation between the expected properties of the medium created in these three colliding systems is, in reality, not so sharp. Recent results obtained at LHC energies indicate that behaviours observed in the so-called small systems, i.e. pp and p-A interactions, in particular when high multiplicities are reached, are reminescent of observations done in A-A (see for example [1]). This observation has recently opened a new and interesting line of research on the role of small systems in heavy-ion physics.

At RHIC, the heavy-ion program focussed on the investigation of QGP probes by varying the colliding ions (Cu, Au or U) and the energy of the collisions, from $\sqrt{s_{\rm NN}}$ = 39 GeV to 200 GeV. At LHC, the peculiarity is not only that top A-A collision energies are reached ($\sqrt{s_{\rm NN}}$ = 5.02 TeV for Pb-Pb and $\sqrt{s_{\rm NN}}$ = 8.16 TeV for p-Pb), but also the fact that all of the four main LHC experiments (ALICE, ATLAS, LHCb and CMS) take part to the heavy-ion program. These experiments, being characterised by very different, but complementary, kinematic coverages, provide an unique way to investigate heavy-flavour probes over very broad transverse momentum ($p_{\rm T}$) and rapidity (y) ranges. All the experiments both at RHIC and LHC usually evaluate the modification of the open and closed heavy-flavour production yields, induced by either hot or cold-matter effects, through the nuclear modification factor ($R_{\rm AA}$). $R_{\rm AA}$ is defined as the ratio of the particle yields in A-A or p-A collisions and the expected value obtained by scaling the pp yield by the average number of nucleon-nucleon collisions evaluated through a Glauber model calculation. $R_{\rm AA}$ is expected to be equal to unity if the particle yield in A-A scales with $N_{\rm coll}$, while values different from unity imply that the particle production is affected by the medium, through hot or cold-matter effects.

Another observable which plays a crucial role in understanding the properties of the system produced in the heavy-ion collisions is the azimuthal distribution of open and closed heavy-flavour particles, which is sensitive to the geometry and dynamics of the early stages of the interactions. The initial spatial anisotropy, due to the almond-shaped overlap region of the colliding nuclei in non-central collisions, is converted into an anisotropic momentum distribution due to multiple collisions in a dense system. The second coefficient of the Fourier expansion of the azimuthal distribution, with respect to the event plane, is the so called "elliptic flow" (v_2) and quantifies the participation of the particle under study to the collective motion of the system.

At this conference, many new results on heavy flavours and quarkonia have been presented. In the following a personal, and certainly limited, selection of some of these results will be discussed.

2. Open heavy flavours

Being produced in high-Q^2 hard-scattering, in the early collision stages, heavy-flavour particles probe the entire medium evolution in their path out of the colliding zone. They interact strongly with the medium constituents, through parton energy loss processes (either of radiative or collisional origin) and through the partecipation to the collective flow. The amount of energy which is lost depends on several factors, as the path length of the particle inside the medium and the density of the medium itself. Furthermore, the loss of energy is influenced by the color charge, being more important for gluons than for quarks, and by the mass of the quark (m_q), since the emission of the gluon radiation is expected to be suppressed in a cone of aperture angle proportional to m_q (i.e. the so-called dead cone effect). In this scenario, a hierarchy in the amount of lost energy is expected, being larger for open-charm and smaller for the heavier open-beauty mesons. This hierarchy, visible in the intermediate p_T range, can be observed in Fig. 1 (left), where a compilation of open charm and open beauty R_{AA}, at LHC energies, is shown over a very broad p_T range. Similar conclusions can also be drawn by the results obtained at RHIC energies [2, 3]. For a review of theory and experimental results presented in this conference see [4, 5].

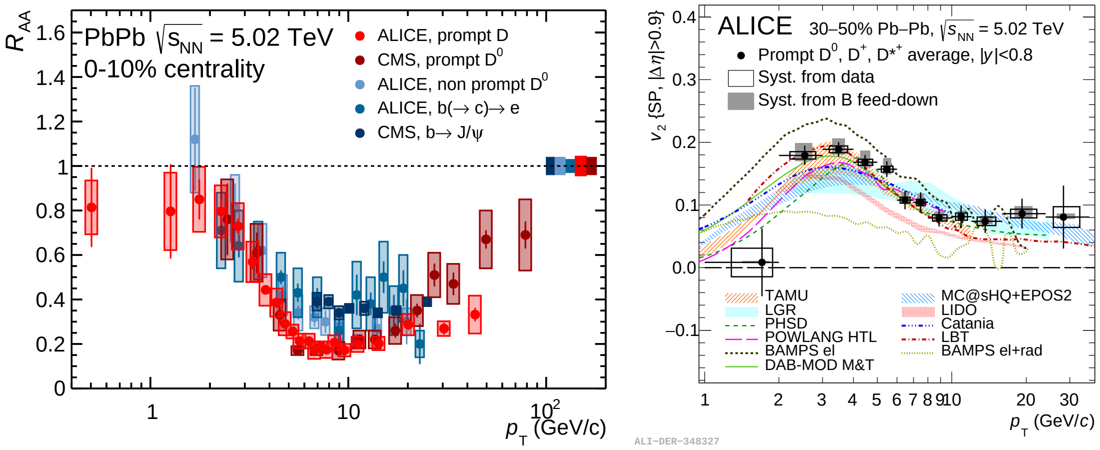

Figure 1: Left: open charm and open beauty R_{AA} as a function of p_T (data from [6–9]). Right: v_2 of open charm mesons vs. p_T , compared with several theory calculations (see [10] and references therein)

LHC experiments have presented at this conference new and precise open-charm and open-beauty mesons v_2 measurements which, coupled with the R_{AA} results, confirms the strong coupling of charm and beauty quarks to the collectively expanding fireball [8, 9, 11]. It can also be noted that a significant v_2 for open-charm mesons is already visible in pp and p-Pb collisions, while this is not the case for the heavier open beauty [11, 12].

For all theory models, the simultaneous description of the R_{AA} and v_2 measurements clearly represent a challenge [13–16]. New theory developments have been presented in this conference, aiming to improve the description of the various components at play. In fact, as it can be seen in Fig. 1 (right), (almost) all models describe the main features of the data, but the differences in the details of the approaches are still rather large.

The large statistics now available at LHC allows to extend the study of heavy-flavour particles to charmed or multi-charmed baryons. The ratio of Λ_c/D^0 yields, evaluated in pp and A-A systems, shows a strong p_{T} dependence, with a striking enhancement with respect to the e^+e^- measurement, suggesting a baryon-to-meson ratio sensitive to the in-medium hadronization of charm quarks [9, 17, 18]. New ALICE measurements indicates that such enhancement is even more important in high multiplicity pp collisions with respect to the low multiplicity ones. This multiplicity dependence can be reproduced by PYTHIA8 calculations including color reconnection.

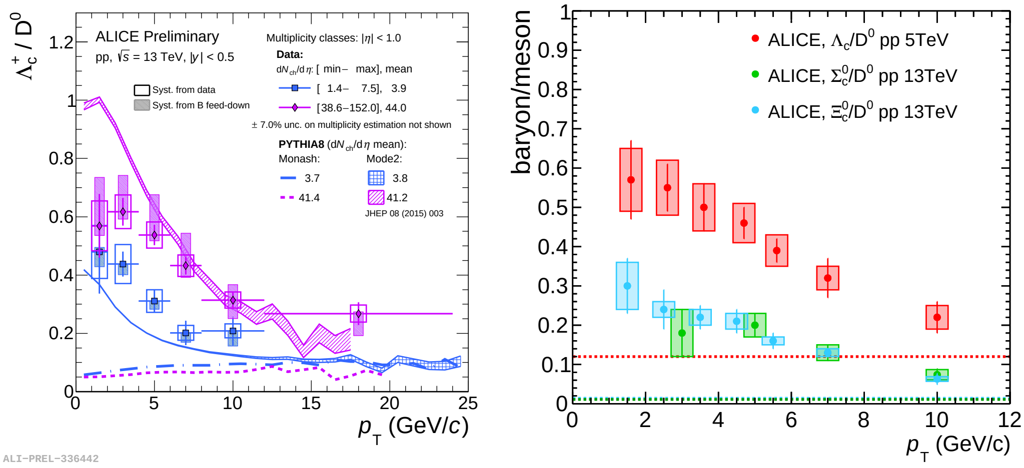

Figure 2: Left: p_{T} dependence of Λ_c/D^0 yields in two multiplicity classes, compared to PYTHIA8 calculations, with (Mode 2) or without (Monash) color reconnection. Right: multi-charmed baryon-to-meson ratio (data from [9, 17]). The dashed lines correspond to the e^+e^- measurements.

ALICE has now extended such a study to multi-charmed baryons, as $\Sigma_c^{0,+,++}$ and $\Xi_c^{0,+}$: all of them, when compared to the D^0 production, show an enhancement with respect to the e^+e^- expectations [9, 17]. On one side these results might provide further insight on the Λ_c/D^0 enhancement, due to the contribution to the Λ_c from higher mass baryons. On the other side, the measurements of heavier charmed baryons are crucial to evaluate the total charm cross section, an important ingredient for all theory models.

3. Quarkonia

In a hot and dense medium, the production of quarkonium, i.e. the bound state of a Q and a $\bar{Q}$ pair, is significantly suppressed with respect to the corresponding pp yield scaled by the number of nucleon-nucleon collisions. The mechanism driving this suppression is the color screening of the force which binds the two quarks together [19]. In this scenario, quarkonium suppression should happen in a sequential way, according to the binding energy of the various resonances, with weakly bound charmonium states as the $\psi(2S)$ melting at lower temperature and strongly bound states as the J/ψ, melting at higher temperatures. Similar ordering is expected also in the bottomonium sector [20]. However, several competing mechanisms, as the feed-down contributions from higher-mass resonances and the B-hadron decay into charmonium, can affect the sequential suppression pattern. Furthermore, also CNM effects, as the modification of the parton distributions into nuclei (i.e. the shadowing), energy loss processes or the formation of a color glass condensate, can induce a modification of the quarkonium yields, masking the pure hot-matter effects. At the high centre-of-mass energies reached in A-A collisions at LHC, the abundance of Q and $\bar{Q}$ quarks leads to the formation of quarkonia via recombination processes [21–23]. For a review of theory and experimental results presented in this conference see [24, 25].

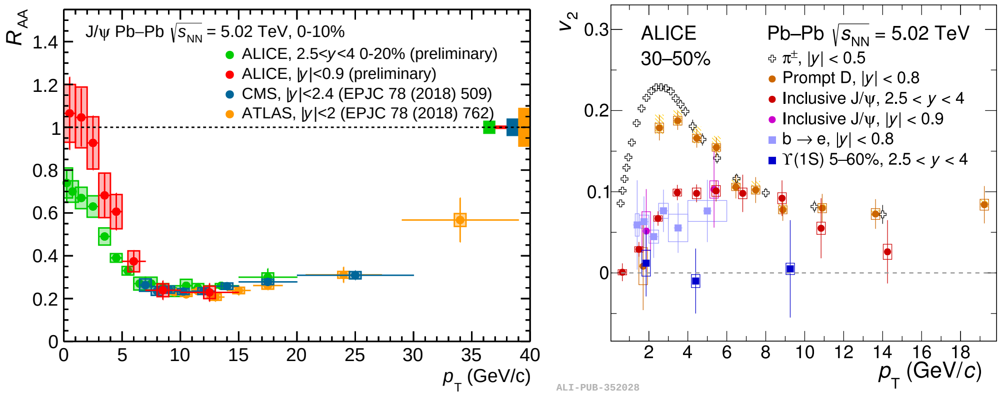

Figure 3: Left: compilation of J/ψ R_{AA} as a function of p_T (data from [7, 26–28]). Right: compilation of v_2 measurements as a function of p_T for J/ψ , $\Upsilon(1S)$, open charm, open beauty mesons and π [29].

A compilation of the J/ψ R_{AA}, at LHC, energies, is shown in Fig. 3 (left). The R_{AA} has a strong p_T dependence, with a significant suppression at intermediate and high p_T, and a rise towards the low p_T region [27, 28]. The rise at low p_T is even more significant at midrapidity with respect to forward rapidity. Theory models including suppression mechanisms, dominant at high p_T, and recombination processes, relevant in the low p_T region and at midrapidity, where the abundance of charm quarks is higher, provide a fair description of the data. A quantitative comparison between theory calculations and experimental results still requires a precise measurement of the total charm cross section, which drives the size of recombination effects, and a precise knowledge of the CNM effects, mainly dominated by shadowing. A significant suppression is also observed in the bottomonium sector. In this case, recombination mechanisms are less important, given the lower abundance of b quarks, even if the precise size of these effects is still at the center of theory debates [30]. The role played by recombination in the charmonium production is confirmed by the significant v_2 measured in semi-central Pb-Pb collisions at LHC, as shown in Fig. 3 (right). At low p_T, a hierarchy in the v_2 values is observed, going from the larger v_2 of charged hadrons, to the one of open charm mesons and eventually to the smaller J/ψ one. It can also be noted that, on the contrary, the v_2 of $\Upsilon(1S)$ is compatible with zero, suggesting a limited participation of the resonance to the medium collectivity and/or an earlier dissociation of the $\Upsilon(1S)$ in the fireball evolution [31].

The high statistics collected by LHC experiments allow the study of observables previously not accessible, as the J/ψ polarization measurement in Pb-Pb collisions, presented in HP2020 [32]. The J/ψ polarization in Pb-Pb might differ with respect to the one measured in pp, being influenced by recombination mechanisms or by the feed-down fractions. The ALICE measurement indicates a polarization in Pb-Pb collisions compatible with zero, with a 2σ indication for transverse polarization at low p_{T}. Also J/ψ production studies in jets, previously performed in pp collisions, have now been extended to Pb-Pb interactions. New CMS results show that J/ψ produced with a large degree of jet activity are more suppressed than those produced in isolation [33].

4. Exotic states

The production of exotic states is investigated at LHC energies, now extending the pp studies to the heavy-ions. Particular interest is reserved to the X(3872), since the nature of this state (molecule composed by two open-charm mesons or a tetraquark) is not yet understood. The investigation of its production in heavy-ion collisions might provide a new way to get insight on its inner structure. LHCb has observed a significant decrease of the ratio of prompt $X(3872)/\psi(2S)$ as a function of the event activity, as shown in Fig. 4 (left) [34]. The comparison of the LHCb results to a theory model based on comoving hadrons suggests that the X(3872) behaves as a tetraquark [35]. CMS has now extended the study of the X(3872) from pp to Pb-Pb collisions [36, 37]. In this case, the ratio of prompt $X(3872)/\psi(2S)$, shown in Fig. 4 (right) has a value closer to unity, much larger than the corresponding pp result. Even if from the experimental point of view this interesting measurement is still limited by the large statistical uncertainty, it is now triggering many theoretical studies [38].

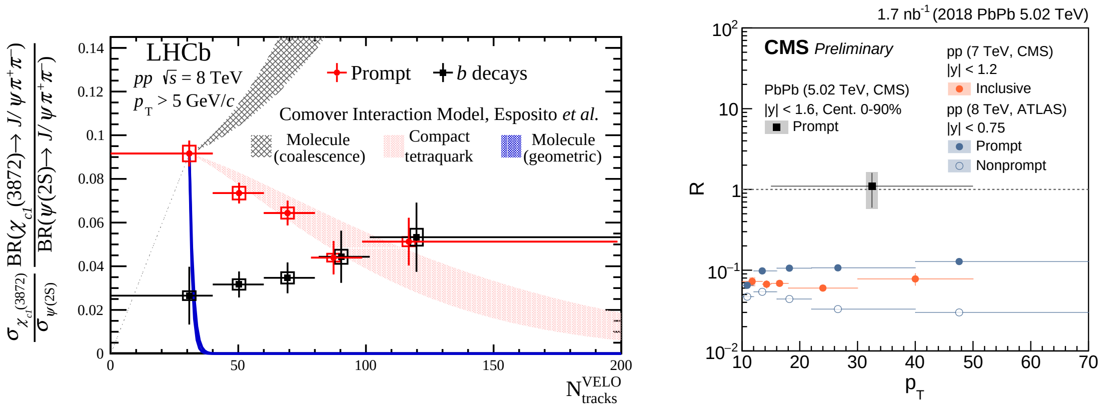

Figure 4: Left: LHC measurement of the prompt $X(3872)/\psi(2S)$ ratio as a function of event activity in pp at $\sqrt{s}$ = 8 TeV [35]. Right: CMS prompt $X(3872)/\psi(2S)$ ratio evaluated in Pb-Pb and pp collisions [36].

5. Conclusions

Many new interesting results on quarkonia and heavy flavours have been released at Hard Probes 2020. The remarkable improvements in the precision of the most traditional observables, as R_{AA}

and v_2, the new observables, as the exotic states production, and the recent theory developments, aiming to extract the medium properties from heavy-flavour results, have triggered very lively discussions in spite of the "virtual" format of the conference! These results and their comparison to theory models certainly represent a step further in our knowledge of the QGP properties.

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