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Production and quenching studies of heavy flavour in pp, pA, AA collisions with ALICE, ATLAS, CMS

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The large interest in open heavy-flavour physics in heavy-ion collisions is proven by the flourishing results obtained at both RHIC and LHC energies. Heavy quarks are produced in the early stages of heavy-ion collisions and their abundance is not expected to change throughout the evolution of the system. Hence, they behave as self-generated probes that traverse the hot and dense medium losing energy via subsequent elastic scatterings and/or gluon radiation. The four LHC experiments provide complementary measurements of heavy-flavoured particles in different kinematical regions exploiting different experimental techniques. In these proceedings, the focus is given on the results obtained by ALICE, ATLAS and CMS in pp and AA collisions. The heavy-flavour measurements based on the exclusive reconstruction of charmed mesons, semi-leptonic decays of charm and beauty hadrons as well as beauty-tagged jets are discussed for pp and Pb-Pb collisions in different centrality ranges. In particular, the nuclear modification factor R_{AA} in the ALICE central barrel indicates a suppression of the yields of D mesons and electrons from heavy-flavour decays in Pb-Pb relative to binary-scaled pp collisions, in the measured momentum ranges 2-36 GeV/c and 3-18 GeV/c respectively. The same order of suppression is found for the muons from heavy-flavour decays from ATLAS at mid-rapidity and from ALICE at forward rapidities for $4<p_T<10$ GeV/c. The measurements of the suppression of beauty quarks is provided by CMS via semi-inclusive B meson decays in J/ψ at central and mid-rapidity in different centrality ranges and via b-tagged jets at high p_T. A comparison of the ALICE D-meson and CMS non-prompt J/ψ R_{AA} suggests a different suppression of charm and beauty in central collisions, predicted by mass dependent energy loss models. The measurements of the azimuthal anisotropies of heavy-flavour decay leptons and charmed mesons are also reported and they indicate a non-zero second Fourier harmonic v_2 with a dependence on the collision centrality. The results are compared to various energy loss models. Finally, the perspectives for the analysis of the p-Pb data set collected in 2013 are discussed.

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PoS(Beauty 2013)020

1. Introduction

Heavy quarks are produced via hard scatterings in the initial stages of the collision. At LHC energies, the heavy-flavour cross section is expected to be much higher than at RHIC (i.e. $\sigma_b^{LHC} \sim 50\sigma_b^{RHIC}$ for pp collisions), making the LHC the ideal place to test pQCD predictions at the highest energies ever reached. In addition, the study of heavy quarks in pp collisions provides a necessary reference for the results obtained in nuclear collisions, like pA and AA. The interest in studying heavy quarks in Pb-Pb collisions comes from their peculiarity to behave like initially-produced probes which are exposed to the medium evolution and, therefore, affected by the presence of the produced hot and dense medium, the so called "Quark-Gluon Plasma" (QGP). It is expected that heavy quarks traverse the medium losing energy via subsequent elastic scatterings and/or gluon radiation. Theoretical models of energy loss predict a hierarchical dependence on the colour charge and mass of the projectile parton. A larger energy loss is expected for partons with larger colour charge (gluons), as well as a suppression of gluon radiation at small angles for partons with larger mass ("dead-cone" effect [1]). There are unresolved questions regarding the mechanism of jet quenching in AA collisions, in particular concerning the colour-charge and mass dependence of energy loss and its dependence on the traversed path length. To answer to the above questions accurate measurements of heavy-flavour production in Pb-Pb collisions and a clear understanding of the reference system pp and p-Pb are required. The latter provides the control experiment needed to disentangle effects from "cold-nuclear" matter in absence of a QGP.

2. Heavy-flavour measurements at the LHC

The LHC experiments are well equipped with high-precision tracking detectors and calorimeters that provide complementary coverage. In particular, ALICE [2] has a unique low-momentum reach thanks to its tracking detectors and particle identification systems. ATLAS [3] and CMS [4] have a larger rapidity coverage and are able to explore a high-momentum phase-space. The low-momentum range is reachable in CMS at forward rapidity with secondary J/ψ. Heavy-flavour measurements are performed with various techniques, exploiting the long lifetime of charm and beauty quarks ($c\tau \sim 100-300\mu$m and $\sim 500\mu$m for c and b respectively). Electrons from decays of D and B mesons ($D/B \rightarrow e+X$) are identified in ALICE using the Time Projection Chamber, the Time of Flight detector, the Transition Radiation Detector and the electromagnetic calorimeter at central rapidity. The electron spectrum is obtained subtracting a cocktail of the non-heavy-flavour hadron sources from the inclusive electron spectrum. The main background sources are the Dalitz decays of light neutral mesons and photon conversions in the material. In addition, in Pb-Pb collision an analysis based on the measurement of e^+e^- invariant mass was also used to subtract the contributions from Dalitz decays and photon conversions. A similar analysis is performed by ATLAS in a higher momentum range. Muons are reconstructed by ATLAS in a large rapidity range ($|\eta| < 2.5$) by matching tracks from the inner tracker to the outer muon spectrometer. In ALICE, muons are reconstructed at forward rapidity ($-4.0 < \eta < -2.5$) with the muon tracking chambers and identified by requiring the tracks to traverse the muon iron filter and reach the muon trigger chambers. The background sources (i.e. muons from decays of kaons and pions, as well as Drell-Yan processes) are evaluated with discriminant selection variables and Monte Carlo simulations. Charmed mesons

PoS(Beauty 2013)020

are reconstructed in ALICE through their hadronic decays: $D^0 \rightarrow K\pi$, $D^+ \rightarrow K\pi\pi$, $D^{*+} \rightarrow D^0\pi$ and $D_s \rightarrow KK\pi$. The analysis strategy exploits the detector capability to reconstruct the secondary vertices of the D meson decays. The prompt charm spectrum was obtained after the subtraction of the feed-down contribution ($b \rightarrow D$) based on FONLL pQCD calculations [5]. Exclusive reconstruction of beauty hadrons is performed by ATLAS, CMS and LHCb in pp collisions [6, 7]. Results from semi-inclusive beauty decays are obtained by CMS in both pp and Pb-Pb collisions via the measurement of displaced J/ψ from B decays, which is based on a simultaneous fit to the $\mu^+\mu^-$ vertex mass and the pseudo-proper decay length. CMS has also measured for the first time b-tagged jets in Pb-Pb collisions, with a selection based on the search of secondary vertices and exploiting the long lifetime and large mass of beauty hadrons.

3. The pp reference

The heavy-flavour measurements were performed in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV. The results at both energies are well described by pQCD calculations. Fig. 1 (left) shows the p_T differential invariant cross section of electrons from heavy-flavour decays measured by ALICE and ATLAS in pp collisions at 7 TeV [8, 9]. The two experiments provide complementary measurements of the electrons from heavy-flavour decays in different momentum ranges and over the entire measured p_T range show a good agreement with pQCD [5]. The b-jet cross section for pp collisions at 7 TeV from CMS [10] is reported in Fig. 1 (right) for different rapidity intervals. Also for fully reconstructed jets containing beauty a reasonable agreement with pQCD calculations is observed. The overall agreement of the heavy-flavour pp results on both charm and beauty production with pQCD predictions in a wide kinematical range indicate that these pp measurements provide well calibrated references for measurements in Pb-Pb collisions. The limited integrated luminosity recorded for pp collisions at $\sqrt{s} = 2.76$ TeV prevents for the moment the use of this sample as reference for the Pb-Pb results at $\sqrt{s_{NN}} = 2.76$ TeV for the analyses of D mesons and electrons from heavy-flavour decays in ALICE. Therefore, the pp reference was obtained from a $\sqrt{s}$-scaling of the measurements at $\sqrt{s} = 7$ TeV via pQCD predictions. The procedure was validated by comparing the resulting pp reference to the measurement of prompt charmed mesons in pp collisions at 2.76 TeV and to CDF Tevatron data at 1.96 TeV. At high p_T, where the pp cross section is not available because of statistics limitations, the reference is obtained with a p_T-extrapolation of the corresponding cross sections.

4. Pb-Pb results

Two main experimental observables are utilized to characterize the medium created in high-energy heavy-ion collisions: the "nuclear modification factor" and the "elliptic flow". The nuclear modification factor R_{AA} is defined as:

$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{\langle T_{AA}\rangle \times \mathrm{d}\sigma_{pp}/\mathrm{d}p_T}$$

where dN_{AA}/dp_T is the yield of the hard probe in AA collisions, $d\sigma_{pp}/dp_T$ is the differential cross section for the same probe in pp collisions and $\langle T_{AA}\rangle$ is the average nuclear overlap function, which

PoS(Beauty 2013)020

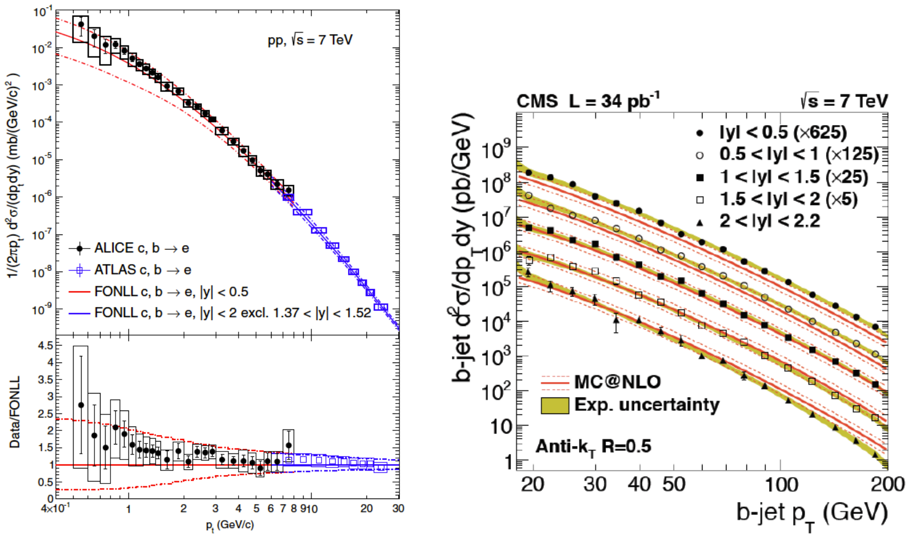

Figure 1: Left: p_T differential cross section of electrons from heavy-flavour decays (charm and beauty) measured by ALICE and ATLAS in pp collisions at 7 TeV [8, 9]. Right: p_T differential b-jet cross section measured by CMS in pp collisions at 7 TeV [10].

is the convolution of the nuclear density profiles of the colliding nuclei. In the absence of nuclear effects, the production of hard probes in AA collisions is expected to scale with the number of binary pp collisions, which would imply a R_{AA} value equal to unity. On the other hand, in central AA collisions, characterized by small collision impact parameter and a large number of participant nucleons, the nuclear effects are expected to be the largest, with R_{AA} less than unity. The collision centrality is estimated with scintillator arrays (ALICE) or electromagnetic calorimeters (ATLAS and CMS) located at forward rapidities. The R_{AA} of prompt D mesons was measured by ALICE in the $0-7.5\%$ centrality range (i.e. the most 7.5% central collisions) in a wide transverse momentum range ($2 < p_T < 36$ GeV/c) utilizing the central triggered events collected in 2011. As shown in Fig. 2 (left), the R_{AA} values for D^0, D^+ and D^{*+} agree within the uncertainties and show a strong suppression (factor of $4-5$ for $5 < p_T < 15$ GeV/c) of the D-meson yields in Pb-Pb collisions relative to the yields in pp collisions. The first measurement of the D_s meson in Pb-Pb collision is also reported. A suppression of the D_s is observed for $8 < p_T < 12$ GeV/c, in agreement within the uncertainties with the non-strange charmed mesons R_{AA} in this p_T range. At lower p_T, the yield of D_s mesons could be suppressed less. However, more data is needed to draw a conclusion. Theoretical models suggest an enhancement of low-p_T D_s mesons relative to non-strange D mesons due to c-quark recombination with the abundant strange quarks in the medium [11]. The R_{AA} of electrons (at mid-rapidity) and muons (at forward rapidity) from heavy-flavour decays also shows a strong suppression (factor of 1.5-3 for $3 < p_T < 10$ GeV/c), shown in Fig. 2 (right), together with the weighted average of D^0, D^+ and D^{*+} R_{AA}. The observed difference in the suppression between leptons from heavy-flavour decays and D mesons is expected to be due to the different decay kinematics. ATLAS also measured a suppression of muons from heavy-flavour decays in central Pb-Pb relative to peripheral Pb-Pb collisions [13] which is of the same order as the one observed in ALICE.

PoS(Beauty 2013)020

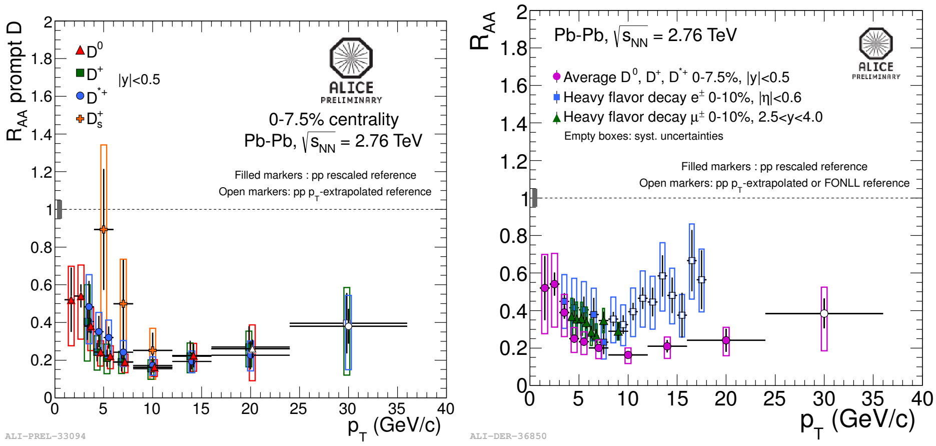

Figure 2: Left: R_{AA} as a function of p_T for prompt D^0, D^+, D^{*+} and D_s for $0-7.5\%$ most central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Right: R_{AA} as a function of p_T for combined prompt D mesons and electrons and muons from heavy-flavour decays [12].

The beauty frontier in Pb-Pb collisions has been explored by CMS, with the measurement of the R_{AA} of both secondary J/ψ from beauty decays and fully reconstructed jets containing b quarks. The R_{AA} for non-prompt J/ψ ($6.5 < p_T < 30$ GeV/c and $|\eta| < 1.2$) is reported in Fig. 3 (left) as a function of the number of participants in the collision [14]. The results are shown together with the D meson R_{AA} from ALICE ($6.0 < p_T < 12$ GeV/c and $|\eta| < 0.5$). It should be noted that the selected p_T ranges do not correspond to the same kinematical ranges for the b and c quarks, hence a quantitative conclusion cannot be drawn at the moment. However, a clear difference in the suppression of charm versus beauty can be observed in central collisions, consistent with the mass hierarchy expected from various energy-loss models. The b-jet fraction (defined as the number of tagged jets $\times$ purity / efficiency) is reported in Fig. 3 (right) as function of jet p_T for minimum bias 2.76 TeV Pb-Pb collisions [15]. The b-jet fraction is $\sim 3\%$ with no significant p_T dependence, consistent with both PYTHIA+HYDJET predictions and corresponding measurements in pp collisions at the same collision energy. The observation that the fraction of jets containing beauty does not change in Pb-Pb collisions relative to pp (i.e. their ratio is ~ 1 within the uncertainties), indicates that the b-jets in the p_T range $80-120$ GeV/c have a nuclear suppression factor similar to that of inclusive jets, i.e. about 0.5 in central Pb-Pb collisions.

The second experimental observable used to characterize the hot and dense medium is the "elliptic flow", which addresses the azimuthal anisotropy of particle emission in case of non-central A-A collisions. If the medium is characterized by a large collectivity of its particles, the typical almond-shaped initial geometry of a non-central collision is transformed into an anisotropy in momentum space which is experimentally quantified by a non-zero second harmonic coefficient v_2 of the following Fourier azimuthal expansion:

$$dN/d\phi = N_0/(2\pi)(1 + 2v_1\cos(\phi - \psi_1) + 2v_2 cos[2(\phi - \psi_2)] + \ldots)$$

where the expansion is performed relative to the event plane, defined by the beam direction and the collision impact parameter, ψ. This analysis was performed by ALICE with the 2011 data set. The v_2 of electrons from heavy-flavour decays was measured in the range $1.5 < p_T < 13$ GeV/c

PoS(Beauty 2013)020

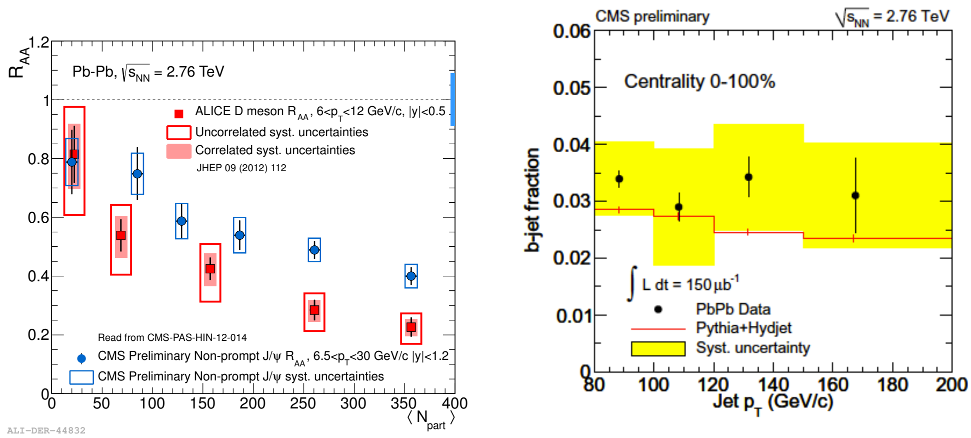

Figure 3: Left: R_{AA} as a function of the average number of participants for secondary J/ψ in $6.5 < p_T < 30$ GeV/c and $|\eta| < 1.2$ [14] compared to prompt D mesons in $6.0 < p_T < 12$ GeV/c and $|\eta| < 0.5$. Right: ratio of b-jet to inclusive jet in 0-100% Pb-Pb collisions as a function of the jet p_T [15].

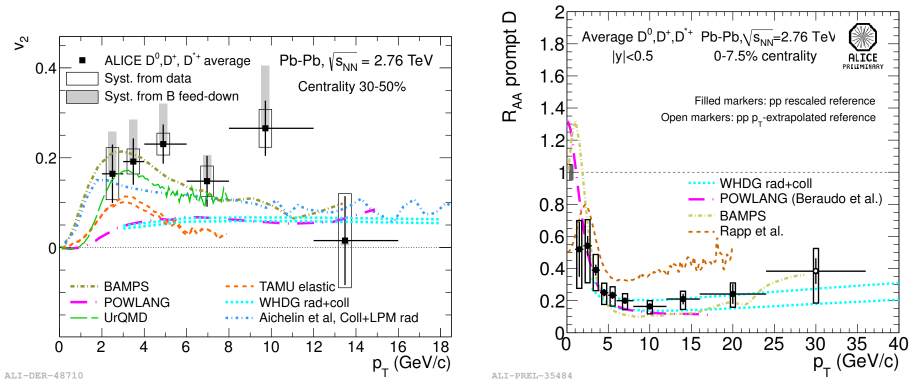

Figure 4: Left: v_2 for prompt D mesons (averaged for D^0, D^+ and D^{*+}) as a function of p_T. Right: prompt D meson R_{AA} (averaged for D^0, D^+ and D^{*+}) as a function of p_T. Theoretical predictions are also shown for v_2 and R_{AA} ([12] and references therein).

in the 20-40% centrality class [16]. The v_2 for prompt D mesons, reported in Fig. 4 (left) was measured for $2 < p_T < 18$ GeV/c in the 30-50% centrality class. ALICE measured a non-zero v_2 at low p_T, for both electrons from heavy-flavour decays ($2 < p_T < 3$ GeV/c) and prompt D mesons ($2 < p_T < 6$ GeV/c) . This result suggests a collective motion also for heavy-quarks in the low-p_T range, while at intermediate/high momentum an interplay with a path-length dependence of the in-medium energy loss is also expected given the different path lengths a parton propagates through the medium in the direction of the event plane and perpendicularly to it, respectively. A comparison with model calculations was done for the R_{AA} of electrons from heavy-flavour decays and prompt D mesons (shown in Fig. 4 (right) for prompt D mesons). The models calculating radiative energy loss with heavy-quark in-medium dissociation, or those based on both radiative and collisional energy loss, describe reasonably well heavy and light-flavour suppression. On the other hand, the models considering radiative energy loss without a hydrodynamical expansion of the medium underestimate the v_2. Currently a simultaneous description of the heavy-flavour suppression and

PoS(Beauty 2013)020

azimuthal anisotropy is challenging. From the experimental point of view, reducing the statistical and systematic uncertainties will help to disentangle among different models.

5. Conclusions

The cross sections in pp collisions at $\sqrt{s} = 7$ and 2.76 TeV were measured for D mesons, leptons from heavy-flavour hadron decays and J/ψ from B meson decays by ALICE, ATLAS and CMS. The results are well reproduced by pQCD calculations, indicating that the heavy-flavour measurements in pp collisions provide an unbiased reference for comparisons to other collisions systems, such as Pb-Pb and p-Pb. The various heavy-flavour Pb-Pb results at $\sqrt{s_{NN}} = 2.76$ TeV coming from different analyses clearly show evidence for a charm suppression in central Pb-Pb collisions and for charm azimuthal anisotropy in semi-peripheral Pb-Pb collisions. Theoretical models of in-medium energy loss reproduce reasonably well the measured heavy-flavour R_{AA}. Nevertheless, it is still challenging to have a simultaneous description of both R_{AA} and v_2.The comparison of D mesons and non-prompt J/ψ from B meson decays indicate a difference in the suppression of charm and beauty in central collisions. The upcoming results from the p-Pb run at the LHC will be crucial to assess the cold nuclear matter effects. Future measurements (Pb-Pb at $\sqrt{s_{NN}} = 5$ TeV from LHC Run 2 and the high-precision and the high-luminosity runs starting in 2018 with the LHC and detector upgrades) will be essential to further improve our understanding of the hot nuclear medium via heavy-flavour probes.

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PoS(Beauty 2013)020