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Open heavy-flavour production in heavy-ion collisions at the LHC

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Abstract. This work presents the latest results on open heavy-flavour production in proton–proton, proton–lead, lead–lead and xenon–xenon collisions from the ALICE, ATLAS, CMS and LHCb Collaborations at the LHC.

1. Physics Motivation

The production of heavy-flavour hadrons (those containing charm or beauty quarks) is one of the key probes of the colour-deconfined and strongly interacting state of matter, the Quark–Gluon Plasma (QGP) that is formed in ultrarelativistic heavy-ion collisions [1]. Due to their large masses with respect to the QCD energy scale ($m_{c,b} \gg \Lambda_{QCD}$), they are formed at early times in hard (high-Q^2) partonic scatterings. This means that they experience the full evolution of the system before decaying, and so studying their behaviour in heavy-ion collisions gives a unique handle on the transport coefficients of the medium.

In the context of heavy-ion physics, it is necessary to study multiple different collision systems to fully understand the observed effects. Proton–proton collisions are used as a baseline for cross-section measurements in the absence of a medium, and can also be used to test predictions made by perturbative QCD (pQCD) calculation frameworks. Minimum-bias proton–lead collisions can also be compared with lead–lead collisions in order to disentangle the role of cold nuclear matter (CNM) effects that arise simply from the presence of a nucleus in the initial state, such as nuclear shadowing, from those occurring due to the presence of a deconfined medium. Lead–lead and, more recently, xenon–xenon collisions at the LHC, form the basis of the QGP studies among the LHC experiments, and comparisons between the two systems at similar numbers of binary nucleon–nucleon collisions (N_{coll}) can provide an insight into the path length dependence of energy loss in the medium.

Charmed baryon production has also recently become an important topic in heavy-ion physics. Previous studies in the strangeness sector have shown an enhancement in the baryon-to-meson ratio of Λ baryons compared with kaons due to the effect of recombination of strange quarks with light quarks in the medium. Similar studies in the charm and beauty sectors will shed light on the fragmentation and hadronisation mechanisms of heavy quarks.

Heavy flavours are measured in the four LHC experiments using a variety of techniques: the reconstruction of electrons and muons from the semileptonic decays of open heavy-flavour hadrons (ALICE, ATLAS), where it is possible to separate the beauty contribution from

that of charm; direct reconstruction of charmed mesons and baryons (ALICE, ATLAS, CMS, and LHCb), which retains the full kinematic information of the original particle; and the reconstruction of non-prompt J/ψ mesons which originate from the decay of beauty particles.

The main observables used in the context of heavy-ion collisions are the nuclear modification factor, R_{AA}, and the Fourier coefficients v_n of the azimuthal distribution of particle momenta. The R_{AA} is the ratio of the production rate in nuclear collisions to that in proton–proton collisions at the same $\sqrt{s}$, scaled by the number of binary nucleon–nucleon collisions. A similar quantity, R_{pA}, is defined for proton–nucleus collisions, and is the ratio of the p–A and pp cross sections scaled by the mass number of the nucleus. If the R_{pA} is equal to unity then this implies that there are no CNM effects present; an R_{AA} of less than 1 is evidence of suppression, which at intermediate p_T is typically a sign of partonic energy loss in the medium. The energy loss in the medium is expected to be dependent on the mass and colour charge of particles due to the so-called 'dead cone effect', leading to an expected hierarchy of $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b)$, and so $R_{AA}(g) < R_{AA}(u,d,s) < R_{AA}(c) < R_{AA}(b)$.

The v_n coefficients can be expressed from a Fourier decomposition of the angular distribution of particles, with each v_n representing the coefficient for the nth harmonic. The main notable v_n parameters are v_1 ("direct flow"), which gives insight into magnetic field behaviour in the medium; v_2 ("elliptic flow"), which shows the degree to which a spatial asymmetry and resulting pressure gradient in the initial state translates to a momentum asymmetry in the final state, thus revealing the degree of collective behaviour in the expansion; and v_3 ("triangular flow"), which arises mainly due to fluctuations in the nuclear overlap and provides further information on the collective behaviour of particles in the medium.

2. Measurements in small collision systems

Proton–proton collisions are the main baseline for heavy-ion measurements. Figure 1 shows the cross section measurements for D^0 mesons in pp collisions from ALICE [2] and CMS [3], and for inclusive heavy-flavour decay muons from ATLAS [4]. In each case the measurements are described within uncertainties by perturbative QCD models such as the Fixed Order plus Nearest Leading Logarithm approach (FONLL) [5]; however, the D mesons measured by CMS and ALICE tend to populate the upper region of the theoretical uncertainty band.
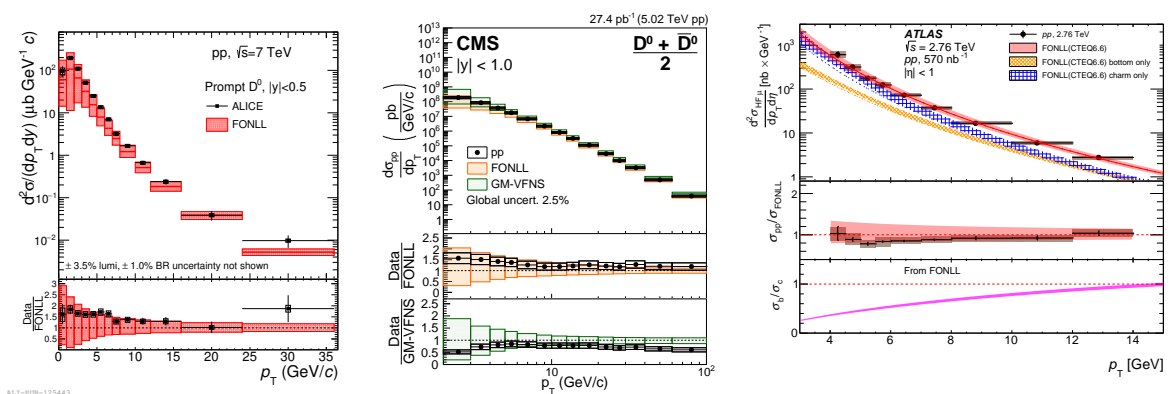

Figure 1: (colour online) Left: ALICE measurement of the D^0-meson production cross section in pp collisions at $\sqrt{s} = 7$ TeV, compared with FONLL pQCD calculations [2]. Middle: CMS measurement of the D^0-meson production cross section in pp collisions at $\sqrt{s} = 5.02$ TeV, compared with FONLL and GM-VFNS calculations [3, 5, 6, 7, 8]. Right: ATLAS measurement of the inclusive heavy-flavour decay muon production cross section [4].

Figure 2 illustrates measurements from ALICE and ATLAS for D-meson production in proton–nucleus collisions. The ALICE measurement shows the R_{pPb} of non-strange D mesons

at mid-rapidity, which is compatible with both unity and models within uncertainties, thus implying that any modification seen in nucleus–nucleus collisions is not significantly due to CNM effects. The plot from ATLAS shows the R_{FB}, the ratio of forward to backward production, at mid-rapidity for p–Pb collisions. Here, the ratio is equal to unity, implying that there is no significant rapidity dependence of charm-quark production in this kinematic region. The LHCb Collaboration has also measured the D^0-meson production cross section in its fixed target p–Ar campaign, finding that the p–Ar cross section is similar to that in pp collisions at low p_{T}. The results in both collision systems are described well by theoretical model calculations.
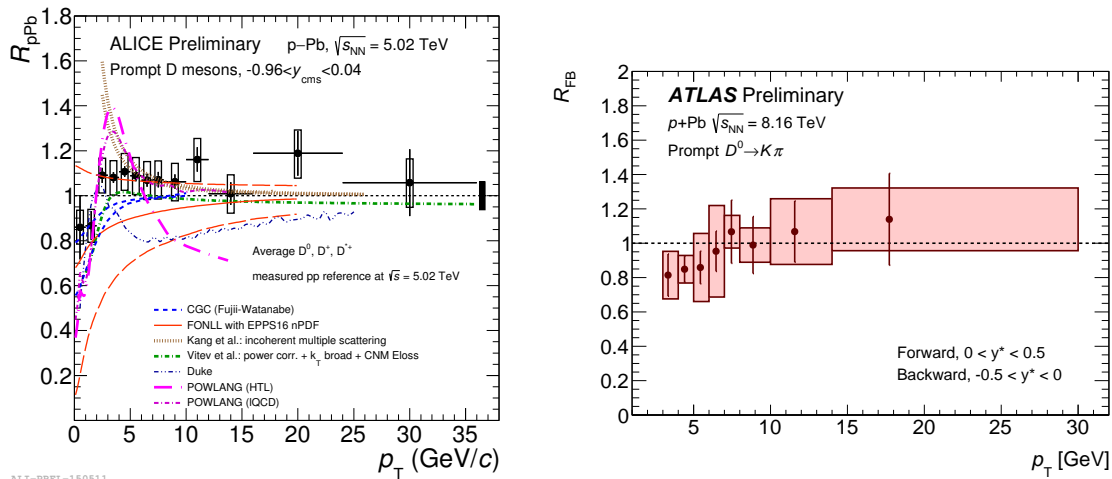

Figure 2: Left: ALICE preliminary measurement of R_{pPb} of D mesons at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ using Run-2 data. Right: ATLAS preliminary meaurement of forward-to-backward production ratio of D^0 mesons in p–Pb collisions at mid-rapidity.

Further measurements are made in small systems to determine the multiplicity dependence of particle production, allowing the role of multi-parton interactions (MPI) to be studied. Figure 3 depicts the ALICE measurements for the multiplicity dependence of D mesons and heavy-flavour decay muons in pp collisions and for D mesons and heavy-flavour decay electrons in p–Pb collisions. In each case, the 'self-normalised yield' is plotted, where the yield per event in a given multiplicity class is divided by the yield per event averaged over all multiplicities. The x-axis shows the equivalent value for overall charged particle production; a linear rise (indicated by the black dashed $y = x$ lines) would therefore indicate a simple correlation between hard and soft particle production processes. In fact, a slightly faster-than-linear trend is seen at higher multiplicities in both collision systems and at all rapidities, implying that the presence of multiple hard interactions is more relevant at high multiplicity. The results are better described by the EPOS model in p–Pb collisions when viscous hydrodynamic effects are considered in the calculations than when they are not, potentially implying that some degree of collectivity is present here.

This can be further demonstrated by considering the elliptic flow, which is studied through the means of long-ranged angular correlations in p–Pb collisions. The results for CMS, ALICE and ATLAS are shown in Fig. 4, where a significant positive flow parameter is seen by all three experiments. The CMS measurement shows a smaller v_2 parameter for D^0 mesons than for strange mesons and baryons; a similar effect is seen when comparing the ALICE results for heavy-flavour decay leptons with overall charged particle production. The heavy-flavour decay muons and electrons from ALICE are measured in three separate rapidity classes; no significant dependence on rapidity is seen for the v_2 coefficient in these kinematical ranges.
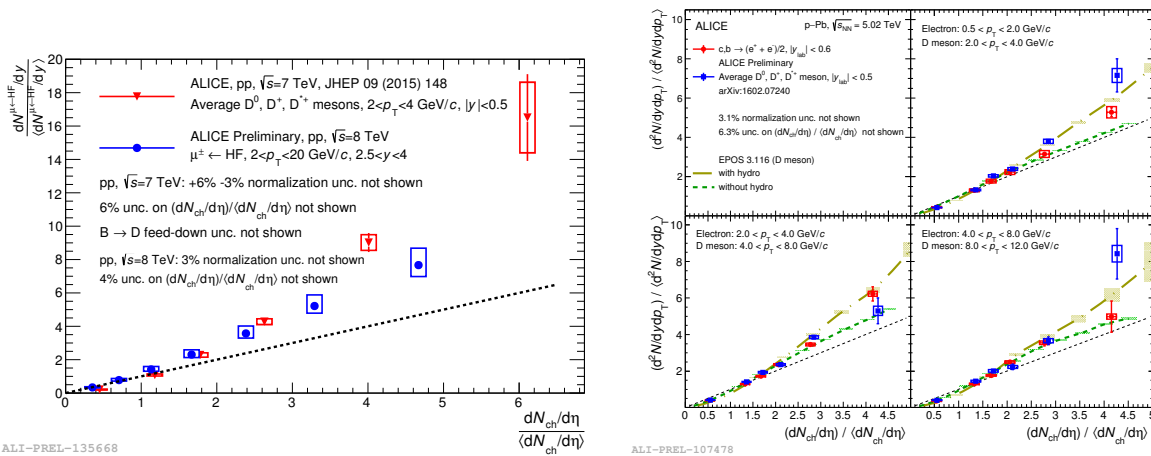
Figure 3: (colour online) Multiplicity dependence of heavy-flavour particle production in pp and p–Pb collisions measured by the ALICE Collaboration. Left: D-meson and inclusive heavy-flavour decay muon production in proton–proton collisions. Right: D-meson and inclusive heavy-flavour decay electron production in p–Pb collisions.
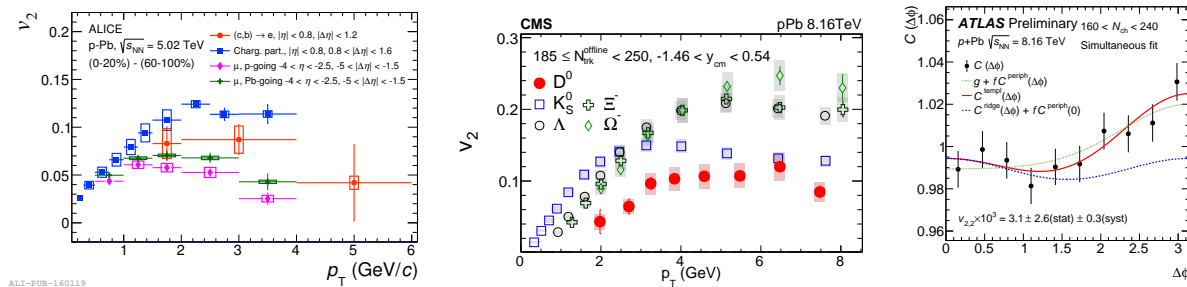

Figure 4: (colour online) Left: ALICE measurement of the v_2 coefficient of inclusive heavy-flavour decay electrons and muons, compared with charged particles [9]. Middle: CMS measurement of D^0-meson v_2 coefficient compared with strange mesons and baryons [10]. Right: ATLAS measurement of two-particle correlation function for D mesons, showing the extracted $v_{2,2}$ coefficient.

3. Measurements in Pb–Pb and Xe–Xe collisions

The R_{AA} of non-strange heavy-flavour hadrons is shown in Fig. 5. The left plot shows the ATLAS measurement of inclusive heavy-flavour decay muons in three centrality classes [4]. Here, it can be seen that there is a significant suppression of heavy-flavour particle production at intermediate p_T, and that the degree of suppression increases (R_{AA} decreases) when considering more central collisions. The middle plot shows the ALICE measurement of non-strange D mesons at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ and $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$ for 0–10% central collisions, compared with energy loss models [11]. A hint of a difference in the R_{AA} based on the collision energy can be seen at low p_T; however, this is not significant with the current measurement uncertainties. The p_T distribution at high p_T is well described by the models. The right plot shows the equivalent measurement by CMS for D^0 mesons, compared with the R_{AA} of charged hadrons, which are dominated by light-flavour particles [3]. While there is no difference seen between D mesons and lighter particles at intermediate to high p_T, a significantly lesser degree of suppression is seen for D mesons at $p_T < 5\,\mathrm{GeV}/c$.

The beauty R_{AA} sheds further light on the mass dependence of partonic energy loss. This is shown in Fig. 6: on the left, for electrons from beauty-hadron decays in ALICE, compared with inclusive heavy-flavour decay electrons; and on the right for both non-prompt J/ψ (which originate from B decays) and B^+ mesons in CMS. In each case, it can be seen that the
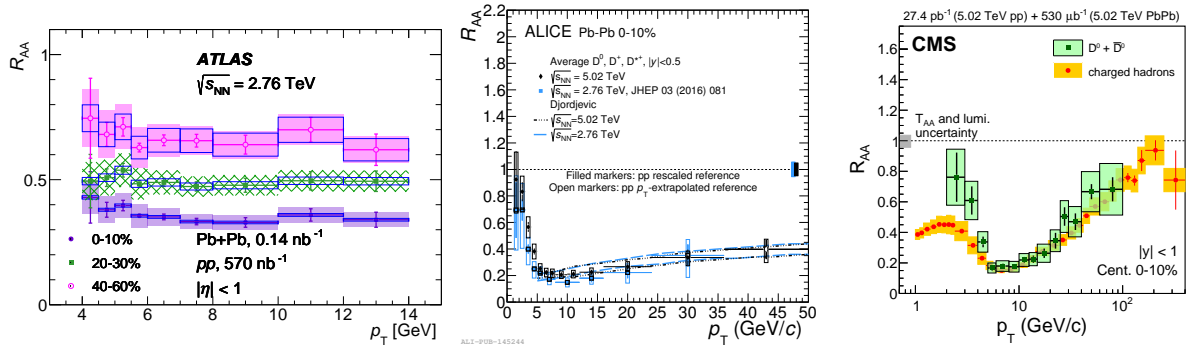
Figure 5: (colour online) Measurements of the R_{AA} of non-strange heavy hadrons in Pb–Pb collisions at the LHC. Left: ATLAS measurement of inclusive heavy-flavour decay muons in three centrality classes [4]. Middle: ALICE measurement of non-strange D-meson R_{AA} at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ and $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ [11]. Right: CMS measurement of D^0 mesons compared with charged hadrons [3].

contribution to the inclusive spectra by beauty hadrons is still suppressed, but to a lesser degree than for charmed hadrons, partially confirming the prediction that beauty hadrons suffer less energy loss than charmed hadrons.
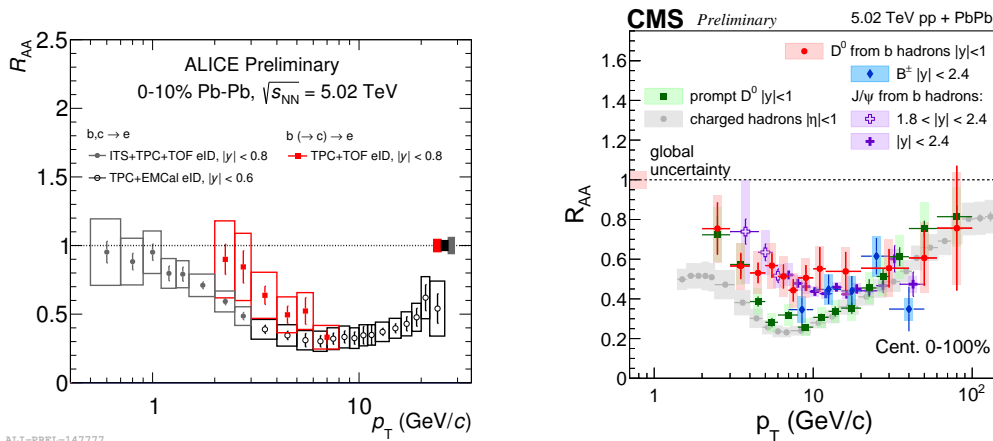

Figure 6: (colour online) Measurements of the R_{AA} of beauty hadrons. Left: ALICE measurement of beauty-decay electrons compared with inclusive heavy-flavour decay electrons. Right: CMS measurement of non-prompt J/ψ and of B^+ mesons compared with D^0 mesons and charged hadrons.

It is also instructive to consider the production of strange heavy mesons in heavy-ion collisions. The enhancement of strangeness production is considered to be a potential signature of QGP formation, and therefore a modification of D_s^+-meson and B_s^0-meson production with respect to non-strange D and B mesons could be a sign of recombination of charm quarks with strange quarks in the medium. The ALICE measurement of the R_{AA} of non-strange and strange D mesons [11], and the CMS measurement of B_s^0 and B^+ mesons, are shown in Fig. 7. In both cases, the heavy mesons containing a strange quark appear to be less suppressed than those without, although the measurement uncertainties are still large enough that it is difficult to draw a firm conclusion. The TAMU model [12], which considers only elastic energy loss processes, describes the D_s^+ R_{AA} better than the PHSD model [13], which also includes gluon radiation.

Measurements of the flow parameters of charmed hadrons in Pb–Pb collisions are shown in Fig. 8. The left plot displays the elliptic flow (v_2) measurements for D mesons and charged pions by the ALICE Collaboration in 30–50% central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ and $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ [14]; the right plot shows the elliptic and triangular (v_3) flow parameters for
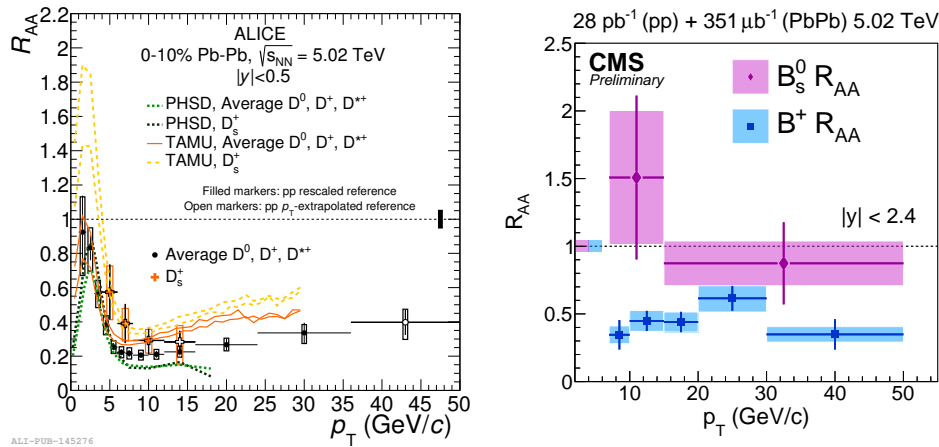
Figure 7: (colour online) Measurements of strange heavy-meson production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Left: ALICE measurement of the R_{AA} of D_s^+-meson production compared with non-strange D mesons and models [11]. Right: CMS preliminary measurement of the R_{AA} of B_s^0 mesons compared with B^+ mesons.

D^0 mesons measured by the CMS Collaboration at $\sqrt{s_{NN}} = 5.02$ TeV [15]. The v_2 of D mesons is largely consistent with that of charged pions, suggesting that they participate in the collective expansion in the medium to a similar degree, and there appears to be no significant dependence on the collision energy based on the current measurement uncertainties. However, as expected due to the effect of the anisotropy of the collision region, peripheral collisions display a much higher v_2 than central collisions. Conversely, the triangular flow, which is driven predominantly by geometrical fluctuations in the overlap region, shows no significant centrality dependence.
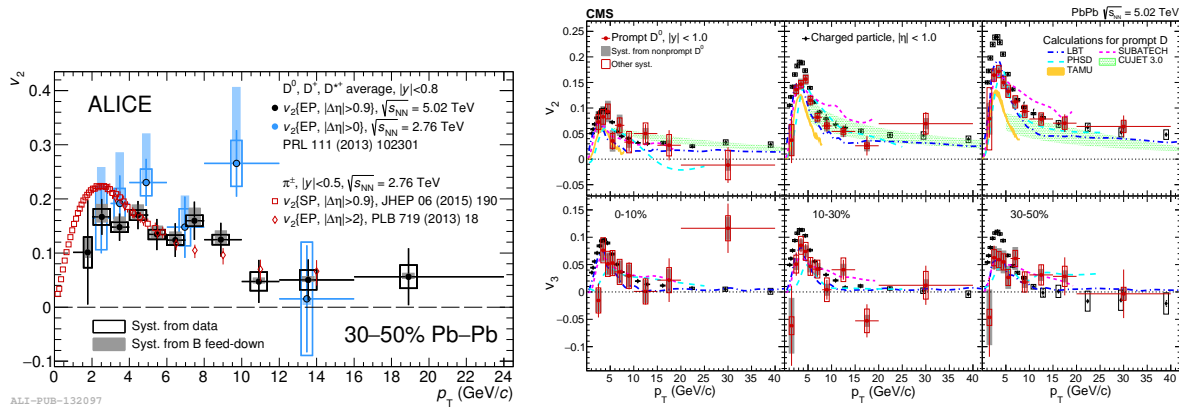

Figure 8: (colour online) Left: elliptic flow of D mesons measured by the ALICE Collaboration at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV, compared with charged particles [14]. Right: elliptic (v_2) and triangular (v_3) flow of D^0 mesons measured by the CMS Collaboration compared with charged particles and models in three centrality intervals [15].

In 2017, a brief run was made of Xe–Xe collisions at the LHC. Due to the difference in system size, comparisons between Xe–Xe and Pb–Pb collisions allow the path length dependence of energy loss in the medium to be studied. This system has been studied by the ALICE Collaboration for inclusive heavy-flavour decay electrons at mid-rapidity and muons at forward rapidity. These results are shown in Fig. 9. The heavy-flavour decay electrons show a mild centrality dependence, with an R_{AA} that increases when going from central (0–20%) to more peripheral (20–40%) collisions. The results are described well by multiple theoretical models.

The heavy-flavour decay muons are shown in one centrality class (0–10%) and compared with Pb–Pb collisions in 10–20% centrality; the centralities for the comparison are chosen such that the charged-particle multiplicity in the collisions is similar. It can be seen that, although a difference in the R_{AA} is predicted by the PHSD model for the two collision systems, this prediction is not borne out by the data, where a clear agreement between R_{XeXe} and R_{PbPb} is observed. This result potentially implies that it is the particle multiplicity and not necessarily the system size itself that determines the degree of nuclear modification.
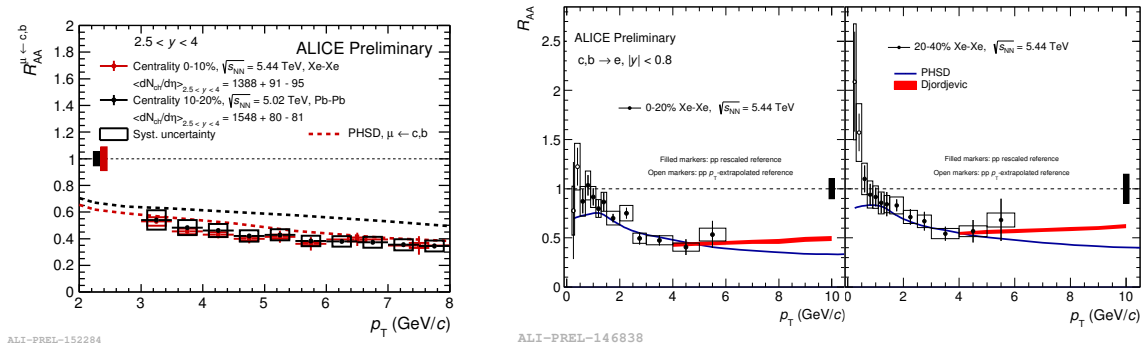

Figure 9: (colour online) Measurements of open heavy-flavour production in Xe–Xe and Pb–Pb collisions by the ALICE Collaboration, compared with theoretical model calculations. Left: Inclusive heavy-flavour decay muons in Xe–Xe and Pb–Pb collisions. Right: Inclusive heavy-flavour decay electrons in Xe–Xe collisions in two centrality classes.

4. Charmed baryon production

Charmed baryons have currently been measured by both the ALICE and LHCb Collaborations at the LHC. The measurements of the Λ_c^+/D^0 baryon-to-meson ratio in pp and p–Pb collisions at mid-rapidity by ALICE and LHCb are shown in Fig. 10. The ALICE measurements show a consistent behaviour as a function of p_{T} for Λ_c^+ baryons at mid-rapidity in both pp and p–Pb collisions. The recent preliminary results from the Run 2 p–Pb data show a noticeable p_{T} dependence, with a decreasing ratio at high p_{T}. The results are compared with the equivalent quantities from the light-flavour sector, namely the p/π and $\Lambda/\mathrm{K}_{\mathrm{S}}^0$ ratios. Qualitatively, the p_{T} distributions of the baryon-to-meson ratios have a similar shape, and the magnitude of the Λ_c^+/D^0 ratio is similar to that of the $\Lambda/\mathrm{K}_{\mathrm{S}}^0$ ratio, potentially meaning that the hadronisation of strange and charmed baryons is due to similar processes in small systems. Meanwhile, the LHCb results from p–Pb collisions at forward rapidity [16] show a lower Λ_c^+/D^0 ratio than the ALICE results, and a flat p_{T} distribution, implying a possible rapidity-dependent effect on charm baryon fragmentation in the absence of a medium. The data are described well by Monte Carlo models tuned to the existing LHCb results in proton–proton collisions.

Figure 11 shows the R_{AA} of Λ_c^+ baryons measured by ALICE, compared with strange D mesons, non-strange D mesons, and light-flavour charmed hadrons. A hint of a hierarchy in the R_{AA} is apparent in the p_{T} region where all particle species are measured; this seems to imply that Λ_c^+ baryons are less suppressed than strange D mesons, which are in turn less suppressed than non-strange D mesons and lighter hadrons. The Λ_c^+/D^0 ratio in Pb–Pb collisions is also increased above unity, implying a difference in the hadronisation mechanisms. A possible explanation for this is that quark recombination may play a significant role for charmed baryons in the medium. A similar effect is also seen by the STAR experiment at RHIC, where an increasing Λ_c^+/D^0 ratio is found in Au–Au collisions as a function of the collision centrality. The STAR results are described relatively well by models including quark coalescence, while currently the available models at LHC energies vastly underpredict the ALICE results.
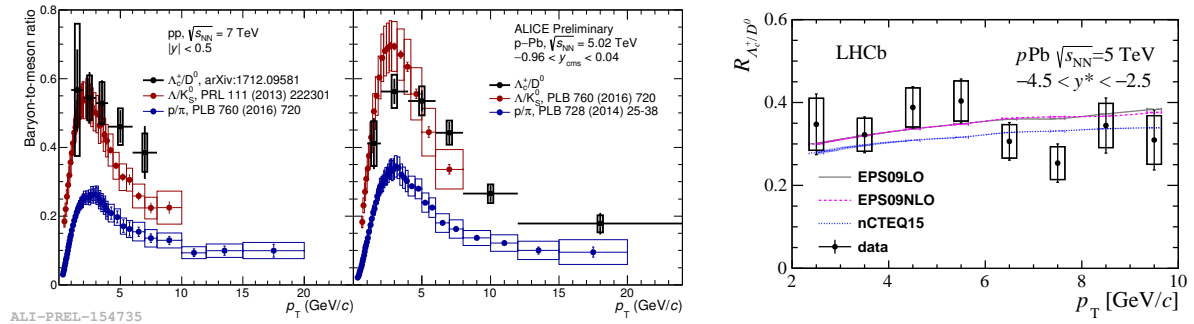
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Figure 10: (colour online) Measurements of Λ_c^+ production in small systems at the LHC. Left: Λ_c^+/D^0 production ratio in pp and p–Pb collisions in ALICE, compared with light-flavour particles. Right: Λ_c^+/D^0 production ratio in LHCb, compared with theoretical model calculations [16].
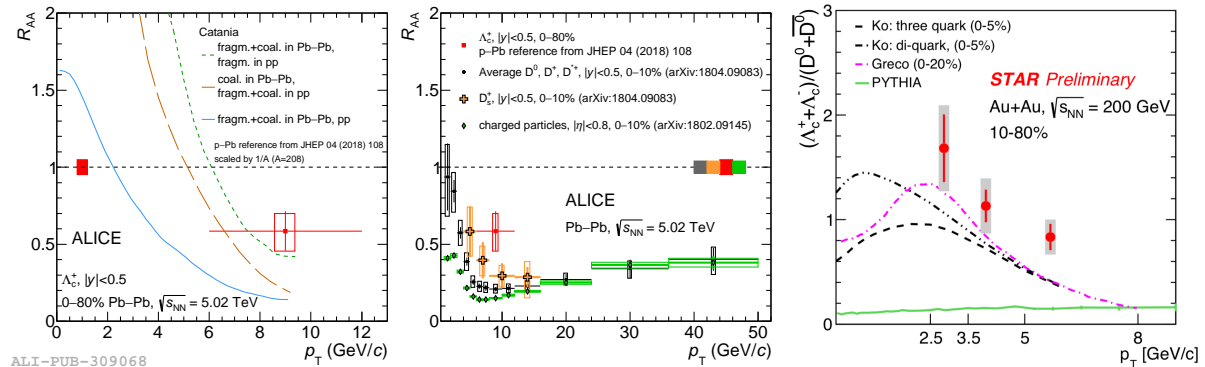

Figure 11: (colour online) Measurements of Λ_c^+ production in heavy-ion collisions. Left: R_{AA} of Λ_c^+ baryons, measured by ALICE in Pb–Pb collisions, compared with models [17]. Middle: ALICE Λ_c^+ measurement compared with strange and non-strange D mesons, and light charged particles, measured by ALICE in Pb–Pb collisions [17]. Right: STAR measurement of Λ_c^+/D^0 ratio in Au–Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$.

5. Summary & Outlook

Many interesting properties of the production of heavy-flavour particles have been studied so far in heavy-ion collisions. The suppression of D and B mesons follows the hierarchy expected due to the mass dependence of quark energy loss. The v_2 of heavy particles in p–Pb collisions hints at possible effects of collectivity in smaller systems at higher multiplicities, which was previously unexpected. Path length dependences of the energy loss have been studied by considering Xe–Xe and Pb–Pb collisions together, finding no significant dependence of the suppression of heavy-flavour particles on the system size. And the reduced suppression of D_s^+, B_s^0 and Λ_c^+ compared with non-strange D and B mesons in heavy-ion collisions suggests the presence of unforeseen hadronisation mechanisms, for example the recombination of heavy quarks with lighter quarks within the medium.

Run 3 of the LHC will begin in 2021; over the course of the second Long Shutdown, significant upgrades will be made both to the experiments and the accelerator itself, allowing a factor $\sim$10 increase in the recorded luminosity. This will lead to vast improvements in the precision of measurements for these rare particles, further constraining models, and will potentially allow new channels to be studied: for instance, the upgraded Inner Tracking System in the ALICE detector will allow the ALICE Collaboration to fully reconstruct B mesons in the central barrel, and increased statistics may make it possible to measure even rarer probes such as the Σ_c and Λ_b baryons in Pb–Pb collisions with high precision.

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