

Heavy-flavour productions in the relativistic heavy ion collisions in LHC

Shingo Sakai^{1,a}

¹*Univ. of Tsukuba, 1-1-1 Tennoudai Tsukuba, Ibaraki, Japan*

Abstract. In the Large Hadron Collider (LHC), open heavy-flavour productions in the heavy-ion collisions (Pb–Pb) has studied by measuring D mesons, leptons from semi-leptonic decay of heavy-flavour hadrons and jets which are original from heavy quarks. In this proceedings, those results are shown together with the measurements with pp and p-Pb collisions and discussed with theoretical calculations to understand the properties of the QCD matter.

1 Introduction

The goal of the relativistic high-energy heavy-ion collisions is to create a hot and dense QCD matter, so called the quark-gluon plasma (QGP), and study the properties of the matter. Measurements of heavy-flavour productions in various collision systems and energies are important to understand the QGP. Heavy quarks, charm and beauty, are mainly produced by hard partonic interactions. Thus their production cross sections in pp collisions can be calculated using a perturbative QCD (pQCD) approach. In Pb-Pb collisions heavy-flavour production is of particular interest to probe and study the properties of the QGP. Because they are produced at the beginning of the heavy-ion collisions and propagate to the created hot and dense matter. Thus their measurements can be sensitive to the medium properties. One of the key measurements in the relativistic high-energy heavy-ion collisions is the nuclear modification factor (R_{AA}) which is defined as:

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T}, \quad (1)$$

where $\langle T_{AA} \rangle$ is the average of the nuclear overlap function. If there is no nuclear effects, R_{AA} is unity. However, R_{AA} is less than unity ($R_{AA} < 1$) represents particle productions in Pb–Pb collisions is suppressed with respect to the one in pp collisions. Such suppression of particle productions has been observed in heavy-ion collisions and it is thought to be due to energy loss of partons in the dense and hot QCD matter. Based on theoretical calculations, the energy loss ΔE in the hot and dense QCD matter (“jet quenching”) is expected to depend on the colour charge of the parton. Furthermore, the dead-cone effect, relevant for radiative energy loss, results in the prediction of a mass hierarchy in partonic energy loss, $\Delta E_g > \Delta E_{\text{light-q}} > \Delta E_c > \Delta E_b$ [1–4]. Therefore suppressions of D and B meson productions are smaller than π , and those R_{AA} are expected to be $R_{AA}^\pi < R_{AA}^D < R_{AA}^B$

^ae-mail: sakai.shingo.gw@u.tsukuba.ac.jp

in the experimental measurement. In addition the measurements of hadrons contain heavy quarks, jets originally from heavy flavours allow to address partonic level energy loss. Initial state effects (such as nuclear modification of the PDFs, k_T -broadening) on heavy-flavour productions in heavy-ion collisions can be investigated in pA collisions, which is considered as control measurements for heavy-ion collisions to disentangle initial from final state effects on the results. Further information for insight of the matter is provided by the azimuthal anisotropy of heavy-flavour observed in non-central heavy-ion collisions, which is sensitive to the transport properties of the medium. The anisotropy is quantified by the second Fourier coefficient v_2 of the particle transverse momentum spectra;

$$\frac{dN}{d\phi} = N_0 \left\{ 1 + \sum_n 2v_n \cos(n(\phi - \Psi_{R.P.})) \right\}, \quad (2)$$

where N_0 is a normalization constant, ϕ is the azimuthal angle of particles, and $\Psi_{R.P.}$ is the direction of the nuclear impact parameter ("reaction plane") in a given collision. The harmonic coefficients, v_n , indicate the strength of the n^{th} anisotropy. In hydro dynamical models, the azimuthal anisotropy is driven by pressure gradient in a thermalized medium with assuming very small viscosity.

In LHC, heavy flavours have been studied by measuring D and B mesons, leptons from semi-leptonic decay of D and B mesons, and jets contain heavy flavours. In these proceedings the heavy flavour measurements in ALICE, ATLAS, CMS and LHCb experiments at LHC are shown. Those results are based on pp collisions at $\sqrt{s} = 7$ and 13 TeV, Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

2 pp collisions

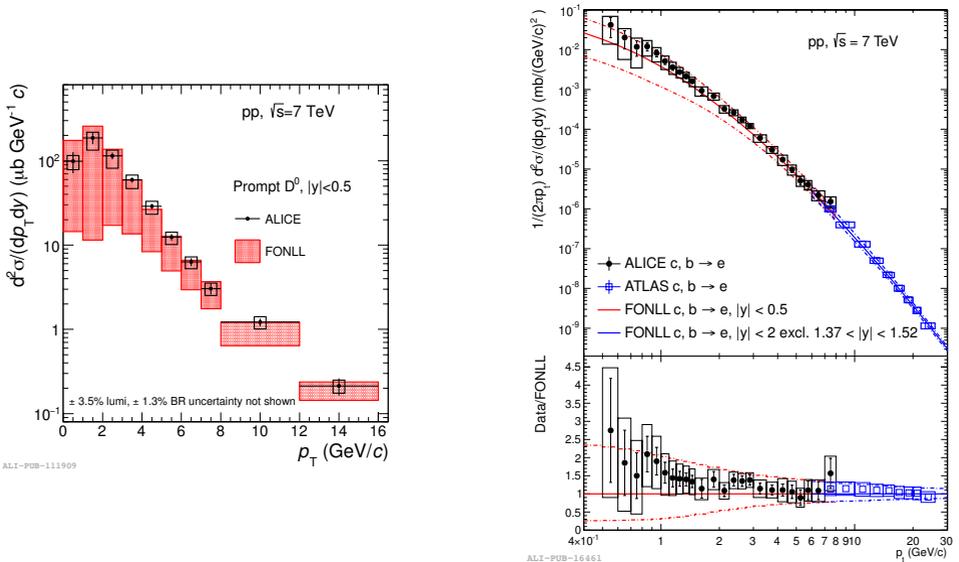


Figure 1. Transverse momentum differential production cross section of D mesons [5] and electrons from heavy-flavour decay hadrons [6] in pp collisions at $\sqrt{s} = 7$ TeV with pQCD calculations.

Heavy flavour production in pp collisions is an important baseline for understanding their productions in Pb–Pb collisions. And the measurements are used for a pp reference to calculate the nuclear modification in the heavy-ion collisions. Figure 1 (left) shows the production cross section of D^0 mesons ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 7$ TeV by ALICE [5]. The result is compared with a FONLL pQCD prediction for the D meson production, and they are in good agreement with in their uncertainties. In ALICE and ATLAS, electrons from semi-leptonic decay of D and B mesons also measure. In Fig. 1 (right), the result of the electrons from heavy flavour is shown [6]. The FONLL pQCD calculation is consistent up to 30 GeV/c with the measurement where electrons from beauty are dominant.

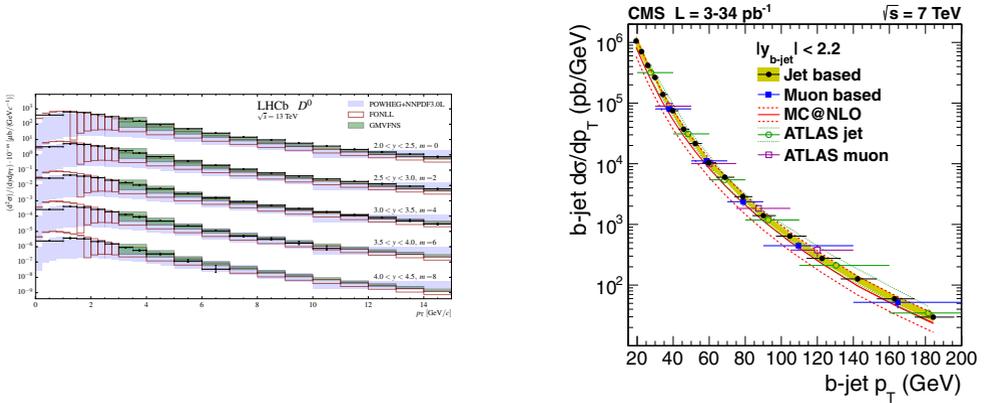


Figure 2. (left) Transverse momentum differential production cross section of D^0 mesons at forward rapidity in pp collisions at $\sqrt{s} = 13$ TeV by LHCb [7]. (right) Transverse momentum differential production cross section of b-jets in pp collisions at $\sqrt{s} = 7$ TeV by ATLAS and CMS [8].

In LHCb, D^0 production also measured at forward rapidity ($2.0 < y < 4.5$) in pp collisions at $\sqrt{s} = 13$ TeV [7]. The cross section was measured in several rapidity intervals and pQCD calculations represent the p_T -dependence in those rapidity selections (Fig. 2). Those results suggest that pQCD calculations well work on heavy flavour productions in LHC energies. For further test of pQCD calculation for heavy flavour productions, jets which originally from beauty were measured in ATLAS and CMS [8]. The beauty jets are compared with a theoretical calculation based on NLO (MC@NLO) in Fig 2. The MC@NLO calculation is in good agreement with the measurements from 20 to 200 GeV/c.

3 p–Pb collisions

Due to absence of the hot and dense matter in p–Pb collisions, the experiment is a control measurement for heavy-ion collisions to disentangle initial from final state effects. The initial state effects are such as nuclear modification of parton distribution functions (shadowing or gluon saturation), energy loss, k_T broadening and multiple collisions. The effects are studied by measuring the nuclear modification factor (R_{pPb}). Figure 3 shows the transverse momentum dependence of R_{pPb} for D mesons (left) and electrons from semi-leptonic decay of heavy-flavour hadrons (right) in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in ALICE [9]. Within the uncertainties, those results are consistent with unity ($R_{pPb} = 1$) over the whole p_T range and indicate there is no significant cold nuclear matter effects on heavy-flavour production. Theoretical calculations with the cold nuclear matter effects are compared with the measurements in those figures. The models based on NLO pQCD calculations with EPS09 nPDF

[11], CGC effective theory [12] and CNM energy loss with shadowing and k_T [13] are predicted that R_{pPb} for D mesons is unity within the uncertainty. However, they show a small suppression of D meson productions at low p_T , and which is also observed in the measurement. A possible effect from radial flow which modifies p_T spectrum at intermediate p_T was estimated with a blast-wave model [14]. It found the effect is small on heavy-flavour productions, and the calculation is consistent with the measurement as is shown in Fig. 3 (right).

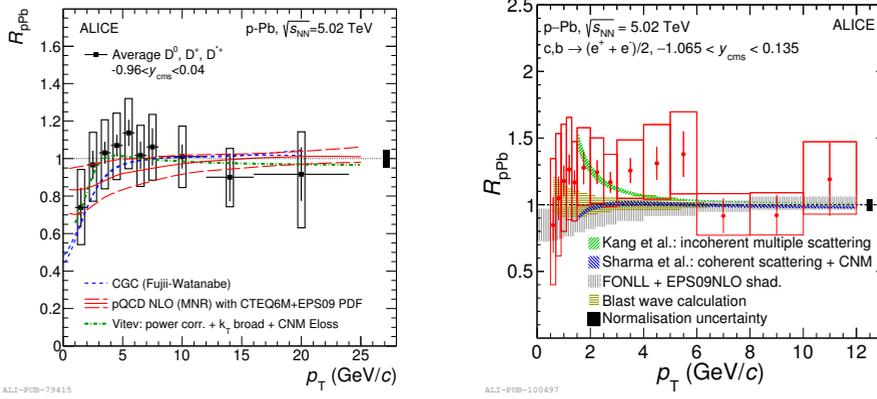


Figure 3. R_{pPb} of D mesons as a function of p_T [9](left) and electrons from heavy-flavour hadron decays [10] (right) in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in ALICE with theoretical calculations including cold nuclear matter effects.

The cold nuclear matter effects on beauty productions was studied by CMS measuring B mesons [15] and b-jets [16] in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The nuclear modification factor of B mesons as a function of p_T shows in Fig. 4 (left). The pp reference of the nuclear modification factor is based on FONLL pQCD calculations. The R_{pPb} is unity within the uncertainties, and the result suggests that there is no significant cold nuclear matter effects on B meson productions. In ALICE, R_{pPb} for electrons from B mesons is measured and the result also suggests that cold nuclear matter effects on beauty production is very small (Fig. 8(left)). The b-jets production in p-Pb collisions is also measured and the nuclear modification was calculated with PYTHIA simulations as the pp reference. Considering the uncertainty on the R_{pPb} and the normalization uncertainty from the PYTHIA calculations, the R_{pPb} is unity which is consistent with the electrons from B meson decays.

The cold nuclear matter effect from parton distribution functions can be studied by measuring heavy-flavour productions at forward- and backward-rapidity regions. Figure 5 shows non-prompt J/Ψ (J/Ψ from B) productions at $1.5 < \eta < 4.0$ (forward) and $-5 < \eta < -2.5$ (backward) measured in LHCb [17]. The left figure shows the forward-backward production ratio (R_{FB}) as a function of rapidity for J/Ψ from beauty. The R_{FB} shows that the backward yields is suppressed with respect to the yield at the forward yields. The asymmetry also predicts by a calculation with the EPS09 NLO nPDF which is shown in the figure. The transverse momentum dependence of R_{FB} for prompt and non-prompt J/Ψ is shown in right in Fig 5. The comparison indicates that CNM effect from parton distribution functions is less pronounced for J/Ψ from B mesons. The p_T dependences of R_{FB} are in good agreement with theoretical calculations [23] [24].

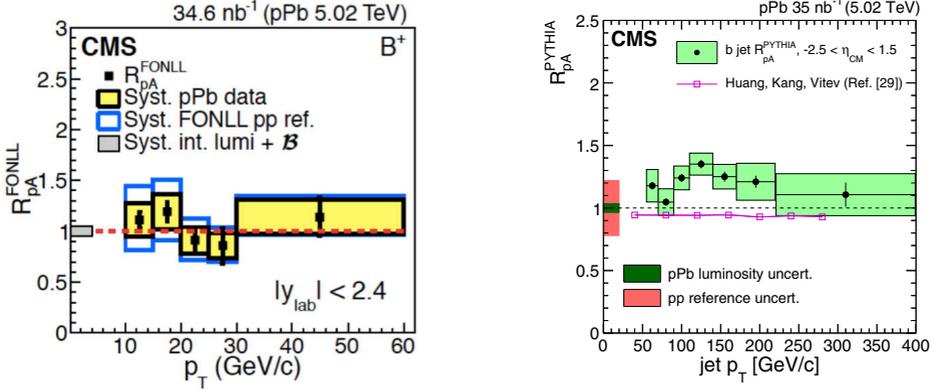


Figure 4. R_{pPb} for B mesons and b-jets as a function of p_T in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in CMS [15][16]. The pp references are obtained based on pQCD calculations.

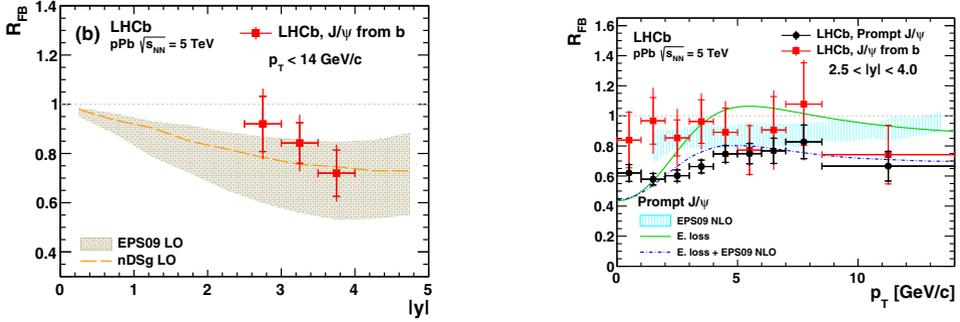


Figure 5. R_{FB} for non-prompt J/Ψ (J/Ψ from b) as a function of rapidity (left) and R_{FB} for non-prompt and prompt J/Ψ as a function of p_T (right) in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by LHCb [17].

4 Pb–Pb collisions

Heavy flavours play an important role to understand the property of hot and dense QCD matter made by Pb–Pb collisions at LHC. Since they are almost produced by hard-scattering processes at the early stage of the collisions and propagated to the medium. Thus they are sensitive probes to provide insight of the medium. Figure 6 shows the transverse momentum dependence of R_{AA} for D mesons in 0–20 % centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured in ALICE [18]. The R_{AA} is less than unity ($R_{AA} < 1$), and it suggests that D meson productions are significantly suppressed. Such the large suppression of D meson productions is not observed in p–Pb collisions (Fig. 3, left). Thus the result indicates a significant energy loss of charm quarks in the hot and dense matters. In ALICE, elliptic flow (v_2) of D mesons also measured [19]. In Fig. 6 (right), the transverse momentum dependence of D meson v_2 in 30–50 % centrality is shown. A positive v_2 is observed at low p_T . The magnitude of v_2 is similar to the one observed for charged particles [20], this suggesting that charm quarks take part in the collective motion of the system. Such strong suppression and elliptic flow are also observed in electrons from heavy-flavor hadron decays in 0-10% for R_{AA} [21] and 30-50% for v_2 [22] (Fig.

7). The suppression was observed up to 18 GeV/c where electrons from beauty are dominant. Thus the suppression at the high p_T suggests that not only charm quarks but also beauty quarks lose their energies in the hot and dense QCD matter. In the measurements of heavy flavours in Pb-Pb collisions, both a strong yields suppression and a non-zero v_2 are observed. Those results of D mesons and electrons from heavy-flavour hadron decays are compared with models, calculating both quantities simultaneously, Fig. 6 [2, 3, 25–28]. Theoretical calculations predict strong suppressions of D mesons and electrons from heavy-flavour hadron decays yield at high p_T in Pb-Pb collisions. However, there is a significant different strength of the v_2 in models especially at low p_T . The comparisons indicate that simultaneous description of R_{AA} and v_2 of heavy flavours are challenging for models.

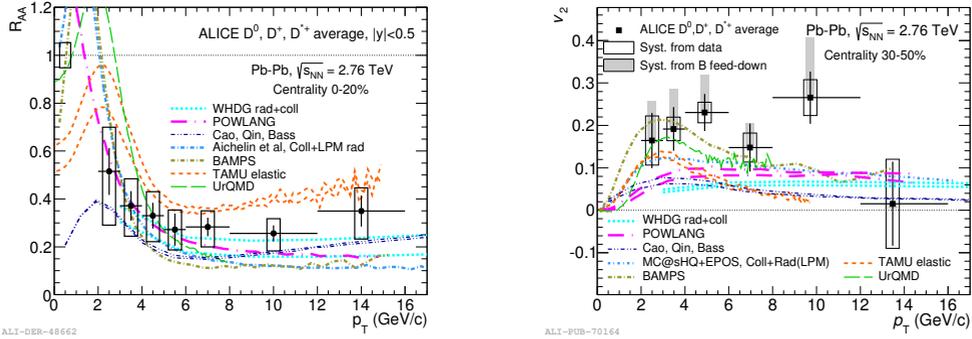


Figure 6. R_{AA} (left) and v_2 (right) for D mesons as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in ALICE [18] [19]

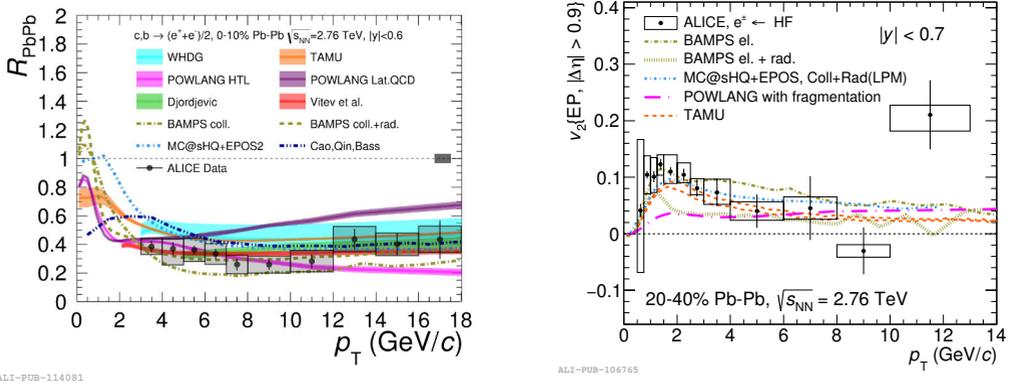


Figure 7. R_{AA} (left) and v_2 (right) for electrons from heavy-flavour hadron decays as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in ALICE [21],[22]

The suppression of beauty productions is also observed in Pb–Pb collisions. Figure 8 (left) shows R_{AA} for electrons from B hadron decays as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in ALICE [29]. At low p_T , the R_{AA} is consistent with unity in the uncertainties. However, the R_{AA} tends to be smaller than unity at high p_T , and it indicates that beauty production is suppressed. Further information of beauty productions in heavy-ion collisions can be obtained from b-jets measurements in the

Pb–Pb collisions, and the R_{AA} measured in CMS is shown in Fig. 8 (right) [30]. The result shows that b-jet productions in the Pb–Pb collisions is strongly suppressed ($R_{AA} < 0.4$) at $80 < p_T < 250$ GeV/c, indicating significant energy loss of beauty in the hot and dense matter. The order of suppression is similar to the inclusive jets [31], and this is because b-jets at high p_T are thought to be dominated by gluons (gluon splitting).

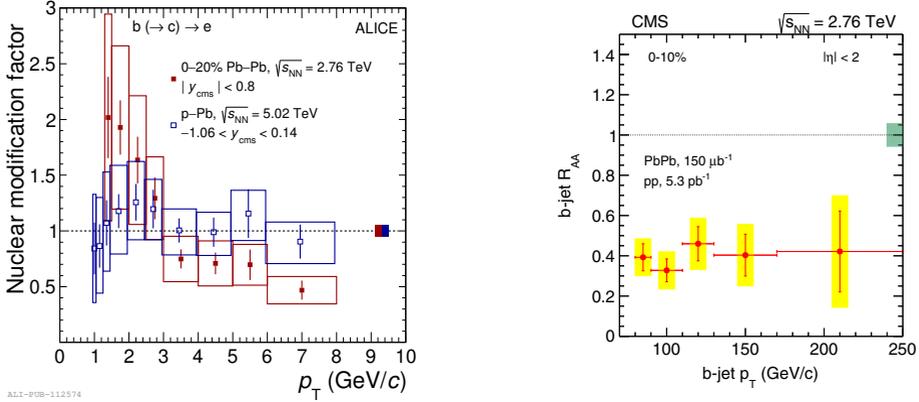


Figure 8. R_{AA} and R_{pPb} for electrons from B hadrons decays as a function of p_T in ALICE (left) [29]. R_{AA} for b-jets as a function of p_T in CMS [30].

Figure 9 shows centrality dependence of R_{AA} for charged pion ($8 < p_T$ (GeV/c) < 16) [32], D mesons ($8 < p_T$ (GeV/c) < 16) [33] and non-prompt J/Ψ ($6.5 < p_T$ (GeV/c) < 30) [34] in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The p_T range for non-prompt J/Ψ was chosen to have a large overlap with the p_T of parent B mesons and the D mesons. The R_{AA} for charged pions and D mesons are consistent with uncertainties in all centrality classes. Thus the measurement can not conclude on the expectation $R_{AA}^D > R_{AA}^\pi$. On the other hand, the comparison of R_{AA} for D mesons and non-prompt J/Ψ shows $R_{AA}^D < R_{AA}^{J/\Psi \leftarrow B}$, indicating B mesons are smaller suppression than D mesons. A theoretical calculation [35] for the centrality dependence of D mesons and non-prompt J/Ψ is shown in the right in Fig. 9. The calculation is based on radiative and collisional energy loss. Two masses, charm and beauty, are used for calculating non-prompt J/Ψ R_{AA} , and the result with beauty mass is well described the R_{AA} .

5 Summary

In the LHC, heavy-flavour productions have been measured in various systems (pp, p–Pb and Pb–Pb) and energies. In pp collisions, productions for D mesons, B mesons, leptons from heavy-flavour hadron decays and b-jets are well described by pQCD calculations. In p–Pb collisions which is a control measurement to investigate cold nuclear matter effects on heavy flavour productions, measurements for heavy flavours indicate that such cold nuclear matter effects is small. In Pb–Pb collisions, heavy flavour productions are strongly suppressed in most central collisions. The results suggest that significant energy loss of charm and beauty quarks in the hot and dense QCD matter made by Pb–Pb collisions at LHC because such suppressions are not observed in p–Pb collisions. R_{AA} for D mesons is smaller than R_{AA} for non-prompt J/Ψ indicating that charm lose larger energy than beauty quarks. However, the measurement can not conclude on the expectation that heavy flavours are less energy loss than light flavours in the matter. In addition to the suppression, a positive elliptic flow for D

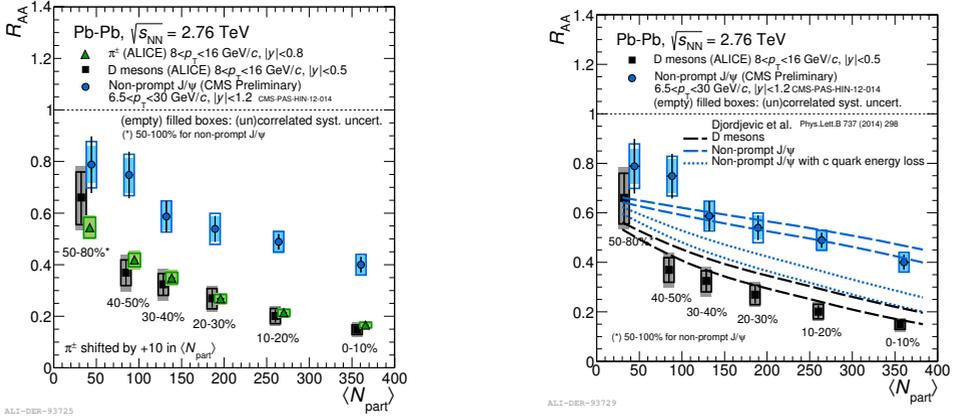


Figure 9. R_{AA} for charged pion, D mesons and non-prompt J/Ψ as a function of the average number of participant nucleons (left). R_{AA} for D mesons and non-prompt J/Ψ compare to model calculations including radiative and collisional energy loss [35](right).

mesons and electrons from heavy-flavour hadron decays was observed in semi-central collisions suggesting that charm quarks take part in the collective motion of the system. The strong suppression and positive v_2 indicate that heavy flavours are significantly affected by hot and dense QCD medium.

References

- [1] Yu. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B **519**, 199 (2001).
- [2] J. Uphoff, O. Fochler, Z. Xu and C. Greiner, J. Phys. G **38** 1241.
- [3] M. He, R. J. Fries and R. Rapp, Phys. Rev. C **86**, 014903 (2012).
- [4] M. Monteno, W. M. Alberico, A. Beraudo, A. De Pace, A. Molinari, M. Nardi and F. Prino, J. Phys. G **38** 124152.
- [5] B. Abelev *et al.*, [ALICE Coll.], 2012 JHEP 01 128.
- [6] B. Abelev *et al.*, [ALICE Coll.], Phys. Lett. B **721**, 13 (2013).
- [7] R. Aaij, [LHCb Coll.], JHEP03(2016)159
- [8] [CMS Coll.], S. Chatrchyan, JHEP04(2012)084
- [9] B. B. Abelev *et al.* [ALICE Coll.], Phys. Rev. Lett. **113**, 23 (232301)2014
- [10] J. Adam *et al.* [ALICE Coll.], Phys. Lett. B **754**, 81 (2014)
- [11] K. J. Eskola *et al.*, JHEP,0904 (2009) 65.
- [12] H. Fuji and K. Watanabe, NPA, 915, (2013), 1
- [13] I. Vitev, *et al.*, Phys. Rev. C **75**, 064906 (2007)
- [14] A. M. Sickles, Phys. Lett. B **731**, 51 (2014)
- [15] V. Khachatryan, *et al.*, Phys. Rev. Lett. **116**, 22 (032301)2014
- [16] V. Khachatryan, *et al.*, Phys. Lett. B **754**, 59 (2016)
- [17] R. Aaij, *et al.*, [LHCb collaboration], JHEP 02 (2014) 072
- [18] B. Abelev *et al.*, JHEP 09 (2012) 112
- [19] B. Abelev *et al.*, Phys. Rev. C **90**, 034904 (2014).
- [20] B. Abelev *et al.*, Phys. Lett. B **719**, 18 (2013).

- [21] J. Adam *et al.* [ALICE Coll.], arXiv:1609.07104
- [22] J. Adam *et al.* [ALICE Coll.], JHEP 09 (2016) 028
- [23] J. Albacete, *et al.*, Int. J. Mod. Phys. E 22 (2013) 047901
- [24] F. Arleo, *et al.*, JHEP 05 (2013) 155
- [25] W. A. Horowitz and M. Gyulassy, J. Phys. G 38 (2011) 124114.
- [26] W. M. Alberico *et al.*, Eur. Phys. J. C 71 (2011) 1666.
- [27] P. B. Gossiaux *et al.*, Phys. Rev. C **79**, 044906 (2009), J. Phys. G 37 (2010) 094019.
- [28] T. Lang *et al.*, arXiv:1211.6912, arXiv:1212.0696.
- [29] J. Adam *et al.* [ALICE Coll.], arXiv:1609.03898
- [30] S. Chatrchyan *et al.* [CMS Coll.], Phys. Rev. Lett. **13**, 132301 (2014)
- [31] G. Aad *et al.* [ATLAS Coll.], Phys. Lett. B **719**, 220 (2013)
- [32] J. Adam *et al.* [ALICE Coll.], Phys. Lett. B **736**, 196 (2014).
- [33] J. Adam *et al.* [ALICE Coll.], JHEP 11 (2015) 205
- [34] [CMS Coll.]CMS-PAS-HIN-12-014
- [35] M. Djordjevic *et al.*, Phys. Lett. B **737**, 298 (2014).