

Overview on Heavy-Flavour at RHIC and LHC †

Andrea Dubla ^{1,2} ¹ Physikalisches Institut, Universität Heidelberg, 69120 Heidelberg, Germany; andrea.dubla@cern.ch² GSI Helmholtzzentrum für Schwerionenforschung, 64248 Darmstadt, Germany

† Presented at Hot Quarks 2018 - Workshop for Young Scientists on the Physics of Ultrarelativistic Nucleus-Nucleus Collisions, Texel, The Netherlands, 7–14 September 2018.

Published: 16 April 2019



Abstract: The PHENIX and STAR Collaborations at the Relativistic Heavy-Ion Collider and ALICE, CMS, ATLAS and LHCb Collaborations at the Large Hadron Collider have measured the production of charmonium and bottonium states as well as open heavy flavor hadrons via their hadronic and semi-leptonic decays at mid-rapidity and in the semi-muonic decay channel at forward rapidity in pp, p–A and A–A collisions in an energy domain that ranges from $\sqrt{s} = 0.2$ TeV to $\sqrt{s} = 13$ TeV in pp collisions and from $\sqrt{s_{NN}} = 0.2$ TeV to $\sqrt{s_{NN}} = 5.02$ TeV in A–A collisions. In this contribution the latest experimental results will be reviewed.

Keywords: heavy-flavour; Large Hadron Collider; Relativistic Heavy Ion Collider

1. Introduction

The lattice QCD calculations have shown that, in case the temperature exceeds a critical value [1], the nuclear matter undergoes a phase transition from colourless hadronic matter (baryons and mesons) to the so-called Quark Gluon Plasma (QGP), a de-confined system of quarks and gluons. Heavy-flavour hadrons are unique probes for the investigation of the QGP. Open charm and beauty hadrons are expected to be sensitive to the energy density through the in-medium energy loss of their heavy quark constituents. In particular, charm and beauty quarks, due to the large masses, are produced at the early stage of the collision [2] and expected to lose less energy than light quarks and gluons while traversing the QGP due to dead-cone and colour-charge effects [3,4]. In addition quarkonium states are expected to be sensitive to the initial temperature of the system via their dissociation due to color screening. At Large Hadron Collider (LHC) energy scale the recombination effects, that can be pictured as in-medium recombination and statistical recombination at the freeze-out, are expected to become competitive with the dissociation producing a visible effect on the nuclear modification factor once compared with the same observable at lower collision energy (i.e., Relativistic Heavy-Ion Collider (RHIC)). In order to exploit the sensitivity of heavy-flavour observables to medium effects a precise reference, where such effects are not expected, is needed and it is provided by pp collisions. The modification of the p_T -differential yield in heavy-ion collisions with respect to pp collisions at the same centre-of-mass energy is quantified by the nuclear modification factor R_{AA} . Further insight into the transport properties of the medium is provided by the measurement of the elliptic flow v_2 of heavy-flavour particle. At low p_T , the v_2 of heavy-flavour particle is sensitive to the degree of thermalization of charm and beauty quarks in the de-confined medium and to different hadronisation mechanisms, namely the fragmentation in the vacuum and the coalescence in the medium. At higher p_T , the measurement of v_2 carries information on the path-length dependence of in-medium parton energy loss.

2. Open hHeavy-Flavour Production in Nucleon–Nucleon Collisions

The production of open heavy-flavour hadrons has been measured via their hadronic and semi-leptonic decays at mid- and forward-rapidity in pp collisions in an energy domain that ranges from $\sqrt{s} = 0.2$ TeV to $\sqrt{s} = 13$ TeV at the RHIC and LHC. The D^0 meson measurements and FONLL [5] pQCD calculations in pp collisions at 5 TeV [6] are shown in the left panel of Figure 1. The D^0 , D^+ and D^{*+} $d\sigma/dp_T$ are reproduced by the theoretical calculations within uncertainties [7]. Yet, FONLL and POWHEG [8] predictions tend to underestimate the data, whereas GM-VFNS [9] calculations tend to overestimate the data. The LHCb collaboration recently reported results on the p_T -differential production cross section of D mesons at $\sqrt{s} = 13$ TeV [10] and found them to be in agreement with NLO predictions. Studies of open-beauty production have also been performed in hadronic [11,12] and semi-leptonic decays [13,14] channels. The differential cross section of B^+ mesons [11,12] and FONLL predictions in pp collisions at $\sqrt{s} = 7$ TeV are shown in the right panel of Figure 1. FONLL provides a good description of the experimental data. A similar agreement with FONLL is observed for the recent measurements of non-prompt J/Ψ cross section at $\sqrt{s} = 13$ TeV [15].

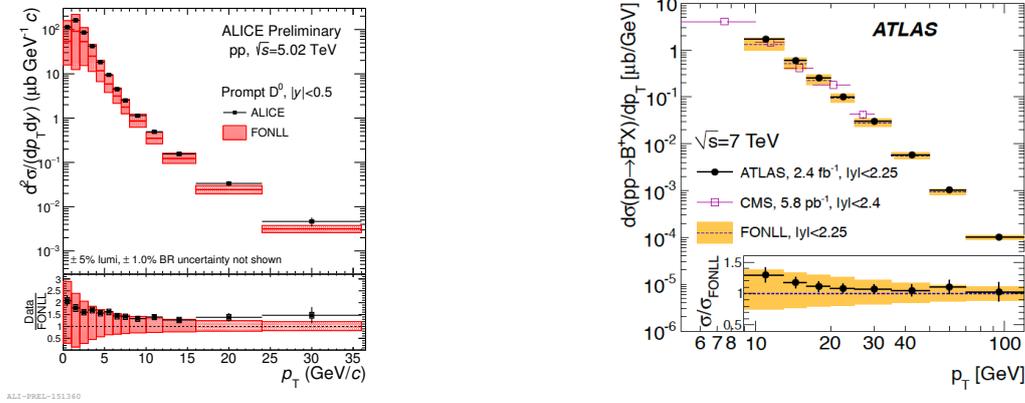


Figure 1. Left: The p_T -differential production cross sections for prompt D^0 mesons in pp collisions at $\sqrt{s} = 5.02$ TeV compared to FONLL calculations. Right: The differential cross-section of B^+ production as a function of p_T . The solid (open) circle points correspond to the measurement of ATLAS (CMS). Predictions of the FONLL calculation are compared to the experimental data.

3. Open Heavy-Flavour Production in Nucleus–Nucleus Collisions

Due to the QCD nature of parton energy loss discussed in the introduction, hierarchy in the R_{AA} is expected to be observed when comparing the mostly gluon-originated light-flavor hadrons to D and B mesons: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$. However, there are caveats that need to be taken into account while interpreting the results, like the different shape of the parton p_T spectra. The left panel of Figure 2 shows the R_{AA} of prompt Λ_c^+ baryons measured in the 0–80% centrality class (that is dominated by the 0–10% production given the scaling of the yields with $N_{coll} \cdot R_{AA}$) compared with the average nuclear modification factors of non-strange D mesons, D_s^+ mesons, and charged particles measured in the 0–10% centrality class [16–19]. The R_{AA} of charged particles is smaller than that of D mesons by more than 2σ of the combined statistical and systematic uncertainties up to $p_T = 8$ GeV/c, while they are compatible within 1σ for $p_T > 10$ GeV/c. The R_{AA} values of D_s^+ mesons are larger than those of non-strange D mesons, but the two measurements are compatible within one standard deviation of the combined uncertainties. A hint of a larger Λ_c^+ R_{AA} with respect to non-strange D mesons is observed, although the results are compared for different centrality classes. The STAR and ALICE Collaborations also have studied the Λ_c^+/D^0 ratio, which is essential to understand charm hadronisation [17,20]. The experimental results are described by the model calculation including coalescence [21,22]. However, models obtained by modelling charm hadronisation via vacuum fragmentation plus coalescence, which describes the Λ_c^+/D^0 ratio measured in Au–Au collisions at RHIC energy, significantly underestimates the measurement in Pb–Pb collisions at the LHC. The CMS

$D^0 R_{AA}$ measured in the centrality range 0–100% is compared in the right panel of Figure 2 to the CMS measurements of the R_{AA} of charged particles [23], B^+ mesons [24] and non-prompt J/Ψ mesons [25] performed at the same energy and in the same centrality range. The $D^0 R_{AA}$ is compatible with the B^+ R_{AA} in the intermediate p_T region. The R_{AA} of non-prompt J/Ψ appears to be independent of rapidity and higher than the $D^0 R_{AA}$ in almost the entire p_T range.

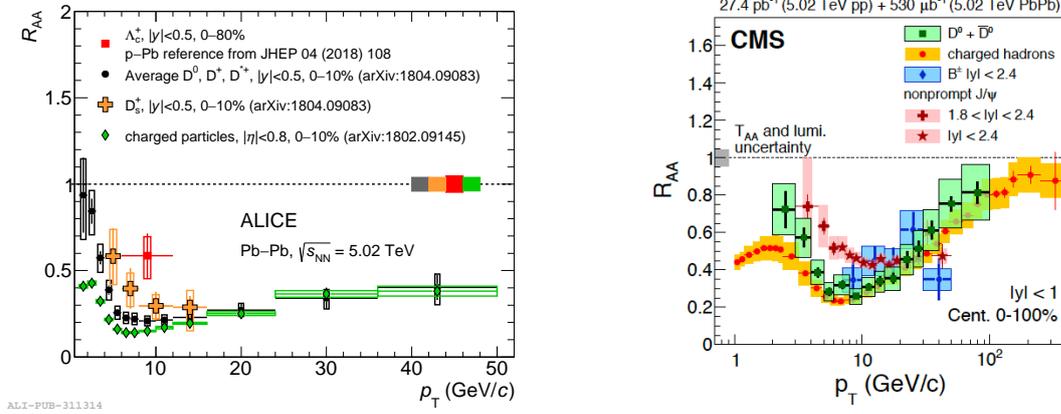


Figure 2. Left: R_{AA} of prompt Λ_c^+ (red marker) compared with the non-strange D mesons (black markers), D_s^+ (orange markers), and charged particle (green markers). Right: D^0 meson R_{AA} as a function of p_T (green markers) compared to the R_{AA} of charged particles (red circles), B^+ mesons (blue markers), non-prompt J/Ψ meson (purple markers) and charged particles (red markers).

4. Quarkonium Measurements in Nucleus-Nucleus Collisions

Quarkonium is considered to be one of the main probes that could be used to investigate the QGP properties. Its production in A–A collisions is expected to be significantly suppressed with respect to the pp yield, scaled by the number of binary nucleon-nucleon collisions. The origin of such a suppression is thought to be the colour screening [26]. However, the simple picture of colour screening needs to be complemented by recombination effects. In this regard, the centrality dependence of the inclusive J/Ψ production at low- p_T in A–A collisions has been measured at both RHIC and LHC [25,27–29]. In the left panel of Figure 3 the inclusive J/Ψ nuclear modification factor, as a function of the number of participant nucleons (N_{part}), is compared to the one measured by the PHENIX in a similar kinematic range. A smaller J/Ψ suppression at LHC energies with respect to RHIC is observed. The smaller suppression at the LHC could be due to the larger $c\bar{c}$ multiplicity allowing a larger recombination, resulting in a compensation of the suppression from colour screening. This measured behaviour is expected by the statistical model [30], where the J/Ψ yield is completely determined by the chemical freeze-out conditions and by the abundance of $c\bar{c}$ pairs. In the right panel of Figure 3 the elliptic flow of inclusive J/Ψ mesons as a function of p_T from the ALICE experiment [31] and prompt J/Ψ from the CMS [32] and ATLAS [33] experiments are shown. Despite different rapidity selections, the magnitudes of the elliptic flow coefficients are compatible with each other. Two features can be observed: first, the hydrodynamic peak is around 7 GeV/c, a value that is significantly higher than what is observed for charged particles where the peak is around 3 to 4 GeV/c. This effect can be described qualitatively by thermalisation of charm quarks in the quark gluon plasma medium with J/Ψ regeneration playing a dominant role during the flow formation. The second feature is that v_2 has a substantial magnitude at high p_T . This can be connected with the suppression of J/Ψ production due to mechanisms involving interactions with the medium such as energy loss [33].

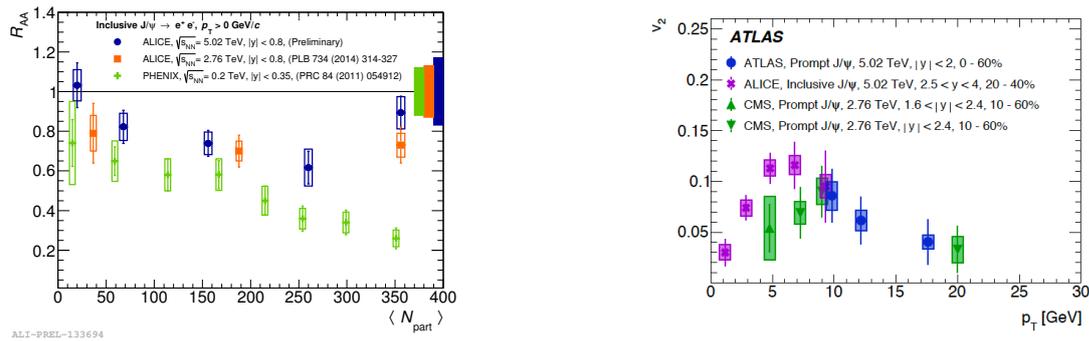


Figure 3. Left: Inclusive J/Ψ R_{AA} at mid-rapidity as a function of centrality as measured by PHENIX and ALICE. Right: Results for v_2 as a function of p_T of prompt J/Ψ as measured by ATLAS and CMS compared with inclusive J/Ψ as measured by ALICE.

References

- Petreczky, P. Review of recent highlights in lattice calculations at finite temperature and finite density. In Proceedings of the Xth Quark Confinement and the Hadron Spectrum Conference, Garching, Munich, Germany, 8–12 October 2012.
- Liu, F.-M.; Liu, S.-X. Heavy-flavor electron-muon correlations in $p + p$ and $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev. C* **2014**, *89*, 034906.
- Baier, R.; Yu, L.; Dokshitzer, A.H.; Mueller, S.; Peign, D. Schiff Radiative energy loss and p_{\perp} -broadening of high energy partons in nuclei. *Nucl. Phys. B* **1997**, *484*, 265–282.
- Gyulassy, M.; Plumer, M. Jet Quenching in Dense Matter. *Phys. Lett. B* **1990**, *243*, 432–438.
- Cacciari, M.; Greco, M.; Nason, P. The p_T Spectrum in Heavy-Flavour Hadroproduction. *J. High Energy Phys.* **1998**, *9805*, 7. doi:10.1088/1126-6708/1998/05/007.
- Acharya, S.; et al. [ALICE Collaboration]. Preliminary Physics Summary: Measurement of D^0 , D^+ , D^{*+} and D_s^+ production in pp collisions at $\sqrt{s} = 5.02$ TeV with ALICE; ALICE-PUBLIC-2018-006; ALICE Publications: 2018.
- Acharya, S.; et al. [ALICE Collaboration]. Measurement of D-meson production at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV. *Eur. Phys. J. C* **2017**, *77*, 550.
- Frixione, S.; Nason, P.; Ridolfi, G. A Positive-Weight Next-to-Leading-Order Monte Carlo for Heavy Flavour Hadroproduction. *J. High Energy Phys.* **2007**, *0709*, 126. doi:10.1088/1126-6708/2007/09/126.
- Kniehl, B.A.; Kramer, G.; Schienbein, I.; Spiesberger, H. Collinear Subtractions in Hadroproduction of Heavy Quarks. *Eur. Phys. J. C* **2005**, *41*, 199–212.
- Aaij, R.; et al. [LHCb Collaboration]. Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV. *J. High Energy Phys.* **2016**, *3*, 159.
- Khachatryan, V.; et al. [CMS Collaboration]. Measurement of the B^+ Production Cross Section in pp Collisions at $\sqrt{s} = 7$ TeV. *Phys. Rev. Lett.* **2011**, *106*, 112001.
- Aad, G.; et al. [ATLAS Collaboration]. Measurement of the differential cross-section of B^+ meson production in pp collisions at $\sqrt{s} = 7$ TeV at ATLAS. *J. High Energy Phys.* **2013**, *1310*, 42.
- Abelev, B.B.; et al. [ALICE Collaboration]. Measurement of electrons from beauty hadron decays in pp collisions at $\sqrt{s} = 7$ TeV. *Phys. Lett. B* **2013**, *721*, 13–23.
- Abelev, B.B.; et al. [ALICE Collaboration]. Beauty production in pp collisions at $\sqrt{s} = 2.76$ TeV measured via semi-electronic decays. *Phys. Lett. B* **2014**, *738*, 97–108.
- Aaij, R.; et al. [LHCb Collaboration]. Measurement of forward J/ψ production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV. *J. High Energy Phys.* **2015**, *1510*, 172.
- Acharya, S.; et al. [ALICE Collaboration]. Transverse momentum spectra and nuclear modification factors of charged particles in pp , p -Pb and Pb-Pb collisions at the LHC. *arXiv* **2018**, arXiv:1802.09145 [nucl-ex].
- Acharya, S.; et al. [ALICE Collaboration]. Λ_c^+ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *arXiv* **2018**, arXiv:1809.10922 [nucl-ex].
- Acharya, S.; et al. [ALICE Collaboration]. Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions. *arXiv* **2015**, arXiv:1804.09083 [nucl-ex].

19. Khachatryan, V.; et al. [CMS Collaboration]. Nuclear modification factor of D0 mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Lett. B* **2018**, *782*, 474.
20. Xie, G. [STAR Collaboration]. Λ_c Production in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV measured by the STAR experiment. *Nucl. Phys. A* **2017**, *967*, 928–931.
21. Plumari, S.; Minissale, V.; Das, S.K.; Coci, G.; Greco, V. Charmed hadrons from coalescence plus fragmentation in relativistic nucleus-nucleus collisions at RHIC and LHC. *Eur. Phys. J. C* **2018**, *78*, 348.
22. Song, J.; Li, H.-H.; Shao, F.-L. New feature of low p_T charm quark hadronization in pp collisions at $\sqrt{s} = 7$ TeV. *Eur. Phys. J. C* **2018**, *78*, 344.
23. Khachatryan, V.; et al. [CMS Collaboration]. Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *J. High Energy Phys.* **2017**, *4*, 39.
24. Khachatryan, V.; et al. [CMS Collaboration]. Measurement of the B^\pm Meson Nuclear Modification Factor in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Rev. Lett.* **2017**, *119*, 152301.
25. Khachatryan, V.; et al. [CMS Collaboration]. Measurement of prompt and nonprompt charmonium suppression in PbPb collisions at 5.02 TeV. *Eur. Phys. J. C* **2018**, *78*, 509.
26. Matsui, T.; Satz, H. J/ψ Suppression by Quark-Gluon Plasma Formation. *Phys. Lett. B* **1986**, *178*, 416–422.
27. Adare, A.; et al. [PHENIX Collaboration]. J/ψ suppression at forward rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev. C* **2011**, *84*, 054912.
28. Abelev, B.B.; et al. [ALICE Collaboration]. Centrality, rapidity and transverse momentum dependence of J/ψ suppression in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Lett. B* **2014**, *734*, 314–327.
29. Aabou, M.; et al. [ATLAS Collaboration]. Prompt and non-prompt J/ψ and $\psi(2S)$ suppression at high transverse momentum in 5.02 TeV Pb+Pb collisions with the ATLAS experiment. *Eur. Phys. J. C* **2018**, *78*, 762.
30. Andronic, A.; Braun-Munzinger, P.; Redlich, K.; Stachel, J. The thermal model on the verge of the ultimate test: particle production in Pb-Pb collisions at the LHC. *J. Phys. G* **2011**, *38*, 124081.
31. Acharya, S.; et al. [ALICE Collaboration]. J/ψ Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Rev. Lett.* **2017**, *119*, 242301.
32. Khachatryan, V.; et al. [CMS Collaboration]. Suppression and azimuthal anisotropy of prompt and nonprompt J/ψ production in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Eur. Phys. J. C* **2017**, *77*, 252.
33. Aabou, M.; et al. [ATLAS Collaboration]. Prompt and non-prompt J/ψ elliptic flow in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector. *Eur. Phys. J. C* **2018**, *78*, 784.

