Measurement of the D-meson Nuclear Modification Factor and Elliptic Flow in Pb–Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE at the LHC

Syaefudin Jaelani (for the ALICE Collaboration)
*Physics Department, Utrecht University, Princetonplein 1
Utrecht, 3584 CC, Netherlands
syaefudin.jaelani@cern.ch*

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Heavy-flavour hadrons are effective probes to study the Quark-Gluon Plasma (QGP) formed in ultra-relativistic heavy-ion collisions. The ALICE Collaboration measured the D-mesons (D^0 , D^+ , D^{*+} and D_s^+) production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The in-medium energy loss can be studied by means of the nuclear modification factor (R_{AA}). The comparison between the D_s^+ and the non-strange D-meson R_{AA} can help to study the hadronisation mechanism of the charm quark in the QGP. In semi-central collisions the measurement of the D-meson elliptic flow, v_2 , at low p_T allows to investigate the participation of the heavy quarks in the collective expansion of the system while at high p_T it constrains the path-length dependence of the energy loss. Furthermore the Event-Shape Engineering (ESE) technique is used to measure D-meson elliptic flow in order to study the coupling of the charm quarks to the light quarks of the underlying medium.

Keywords: Heavy-flavour; nuclear modification factor; elliptic flow; Event-Shape Engineering.

1. Introduction

Heavy flavours are effective probes to study the Quark-Gluon Plasma (QGP) which is formed in ultra-relativistic heavy-ion collisions. Due to their large masses, heavy quarks are produced in hard scattering processes in the early stages of the collisions before the QGP formation time, which is about 0.3–1.5 fm/c at Large Hadron Collider (LHC) energies¹. Thus, they experience the full evolution of the medium and lose part of their energy interacting with its constituents via inelastic (gluon radiation)^{2,3} or elastic scatterings (collisional processes)^{4–6}. The in-medium energy loss can be studied by measuring the nuclear modification factor

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(R_{AA}), which compares the p_T -differential yield in Pb–Pb collisions with that in pp collisions, $R_{AA}(p_T) = (dN_{AA}/dp_T)/(\langle T_{AA} \rangle \cdot d\sigma_{pp}/dp_T)$. The comparison of the non-strange and strange D mesons can provide information about the mechanism of charm hadron formation ⁷. In addition, the information on the transport properties of the medium is obtained by the measurement of the azimuthal anisotropy in the momentum distribution of heavy-flavour hadrons, by the elliptic flow $v_2 = \langle \cos(2(\varphi - \Psi_2)) \rangle$. The measurement of the elliptic flow v_2 of D-meson production in semi-central collisions allows to investigate, at low p_T , the participation of the heavy quarks in the collective expansion of the system and their thermalization in the medium. In addition at high p_T , the measurement of v_2 can provide information on the path length dependence of parton energy loss ^{8,9}.

2. D-meson reconstruction

In ALICE D mesons are reconstructed in the hadronic decay channels $D^0 \rightarrow K^-\pi^+$ (with branching ratio, BR, of $3.93 \pm 0.04\%$), $D^+ \rightarrow K^-\pi^+\pi^+$ (BR of $9.46 \pm 0.24\%$), $D^{*+} \rightarrow D^0\pi^+$ (BR of $67.7 \pm 0.5\%$) and $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$ (BR of $2.27 \pm 0.08\%$) ¹⁰, and their charge conjugates. The decay topologies are resolved via secondary vertex-reconstruction thanks to the excellent performance of the Inner Tracking System. Background is reduced by applying topological selections in order to maximize the signal-to-background ratio. In addition, particle identification is carried out for charged pions and kaons, with the Time Projection Chamber and the Time Of Flight detector. Finally, an invariant mass analysis is used to extract the D-meson yields. The efficiency and acceptance corrections are obtained from MC simulations based on HIJING ¹¹ and PYTHIA 6 ¹² event generators. The prompt yield of D mesons is obtained by subtracting from the inclusive yield the secondary yield from beauty hadrons as estimated based on FONLL calculations ^{13,14}. The V0 scintillators, that cover the pseudorapidity region $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$, provide centrality and event plane angle (estimator of Ψ_2).

3. Prompt D-meson nuclear modification factor and elliptic flow

The R_{AA} of prompt D^0 , D^+ , D^{*+} and D_s^+ is measured in three different centrality classes (central 0–10%, semi central 30–50% and peripheral 60–80%) in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV ¹⁵. The proton-proton reference was obtained by scaling the measurement cross section at $\sqrt{s_{NN}} = 7$ TeV ¹⁶ to $\sqrt{s_{NN}} = 5.02$ TeV using the FONLL prediction. Fig. 1, in the left panel, shows the increasing suppression of the average non-strange D-meson R_{AA} from peripheral to central collisions up to a factor about 5 for $p_T > 5$ GeV/c. These results are compatible within uncertainties with Run 1 data at $\sqrt{s_{NN}} = 2.76$ TeV ¹⁵, showing at the same time an improvement in terms of precision and p_T reach. The central value of the prompt D_s^+ R_{AA} is higher relative to non-strange D-meson for all centralities, however, due to the large statistical and systematic uncertainties, additional data are needed to conclude. Fig. 1, on the right panel, shows the comparison of non-strange D-meson and D_s^+ R_{AA}

Fig. 1. Left: average R_{AA} of prompt D^0 , D^+ and D^{*+} in central 0–10% (red), semi-central 30–50% (blue) and peripheral 60–80% (black) in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV¹⁵. Right: R_{AA} of prompt D_s^+ compared with the average non-strange D-meson R_{AA} in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in 0–10% centrality class¹⁵. The D_s^+ model predictions includes hadronisation mechanism of charm hadrons via coalescence in the QGP^{17,18}.

Fig. 2. Left: average non-strange D-meson elliptic flow v_2 as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in 30–50% centrality class (black), compared with the same measurement of v_2 (blue) and with the $\pi^\pm$ v_2 at $\sqrt{s_{NN}} = 2.76$ TeV¹⁹. Right: average D^0 and D^+ v_2 in semi-central 30–50% Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the 60% of events with smallest q_2 and the 20% of events with largest q_2 compared to the unbiased result.

in the 0–10% centrality class with model predictions that include hadronisation mechanism of charm via coalescence^{25,26}.

The measurement of prompt D-meson elliptic flow v_2 in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the 30–50% centrality class¹⁹ is reported in Fig. 2, on the right panel. The elliptic flow coefficients, v_2 , of prompt D^0 , D^+ and D^{*+} are compatible with each other within uncertainties and confirm a non-zero D-meson v_2 for $2 < p_T < 10$ GeV/c, indicating that charm quarks participate in the collective expansion dynamics. The measurement of the D-meson v_2 at $\sqrt{s_{NN}} = 5.02$ TeV is compatible with the same measurement at $\sqrt{s_{NN}} = 2.76$ TeV and with the charged pion v_2 measured in the same centrality class (see Fig. 2, left panel). The D_s^+ v_2 hints a

Fig. 3. Average non-strange D-meson R_{AA} in the 0-10% centrality class (left)¹⁵ and elliptic flow v_2 in 30-50% centrality class (right)¹⁹ measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared with some of the available models.

non-zero value in $2 < p_T < 8$ GeV/c with significance of about 2.6σ and it is also compatible within uncertainties to that of non-strange D mesons. The Event-Shape Engineering technique was used for the first time to investigate the D^0 and D^+ v_2 in 30-50% centrality class. The second-harmonic reduced flow vector, $q_2 = |Q_2|/\sqrt{M}$, can be used to quantify the eccentricity (average v_2) of the events, where M is the multiplicity and Q_2 is the second-harmonic flow vector. The events were divided into two groups, namely 60% of events with smallest q_2 and 20% of events with largest q_2 . The average D-meson v_2 for the two q_2 values compared to the unbiased are presented on the right panel of Fig. 2. The separation between the D-meson v_2 in the large q_2 and small q_2 hints to sensitivity of charm quarks to the light quarks collectivity and to the event-by-event fluctuations in the initial state. Though, the effect can be increased by autocorrelations and non-flow correlations between q_2 and D-meson v_2 , since they are measured in the same pseudorapidity region $|\eta| < 0.8$.

The average R_{AA} of the three non-strange D-meson (D^0 , D^+ and D^{*+}) in the 0-10% centrality class (left) and v_2 in the 30-50% centrality class (right) are compared with theoretical models in Fig. 3. Models based on perturbative QCD calculation of parton energy loss²⁰⁻²⁴ provide a fair description of the R_{AA} for $p_T > 10$ GeV/c. All models (except of BAMPs and CUJET3.0) include a nuclear modification of the parton distribution functions as one of their ingredients. Models that rely on heavy-quark transport provide a fair description of the R_{AA} at low p_T and the D-meson v_2 as well.

4. Conclusion

The ALICE Collaboration measured the D mesons (D^0 , D^+ , D^{*+} and D_s^+) R_{AA} and the elliptic flow v_2 in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The comparison between the non-strange D-meson and D_s^+ gives a hint of charm hadronisation via coalescence. The results of the D meson elliptic flow v_2 show non-zero value for $2 < p_T < 10$ GeV/c in 30-50% centrality class, which provide information of the

collective expansion of the system. The first measurement of the $D_s^+ v_2$ at the LHC has been reported. Event-Shape Engineering technique for the non-strange D-meson elliptic flow was applied.

References

1. F. M Liu and S. X. Liu, *Phys. Rev. C* **89**, 034906 (2014).
2. M. Gyulassy and M. Plumer, *Phys. Lett. B* **234**, 432 (1990).
3. R. Baier et. al, *Nucl. Phys. B* **484**, 265 (1997).
4. M. H. Thoma and M. Gyulassy, *Nucl. Phys. B* **351**, 491 (1991).
5. E. Braaten and M. H. Thoma, *Phys. Rev. D* **44**, 1298 (1991).
6. E. Braaten and M. H. Thoma, *Phys. Rev. D* **44**, 2625 (1991).
7. Kuznetsova and Rafelski, *Eur. Phys. J. C* **51**, 113 (2007).
8. S. Batsouli et. al, *Phys. Lett. B* **557**, 26 (2003).
9. M. Gyulassy et. al, *Phys. Rev. Lett.* **86**, 2537 (2001).
10. Particle Data Group Collab. (C. Patrignani *et al.*), *Chin. Phys. C* **40**, 100001 (2016).
11. X. N. Wang and M. Gyulassy, *Phys. Rev. D* **44**, 3501 (1991).
12. T. Sjostrand et. al, *JHEP.* **05**, 026 (2006).
13. M. Cacciari et. al, *JHEP.* **05**, 007 (1998).
14. ALICE Collab. (S. Acharya *et al.*), *JHEP.* **11**, 205 (2015).
15. ALICE Collab., *ALICE-PUBLIC-2017-003*, <https://cds.cern.ch/record/2265109>.
16. ALICE Collab. (S. Acharya *et al.*), *Eur. Phys. J. C* **77**, 550 (2017).
17. M. He et. al, *Phys. Lett. B* **735**, 445 (2014).
18. T. Song et. al, *Phys. Rev. C* **92**, 014910 (2015).
19. ALICE Collab. (S. Acharya *et al.*), (2017), 1707.01005.
20. A. M. Poskanzer and S. A. Voloshin, *Phys. Rev. C* **58**, 1671 (1998).
21. M. Djordjevic and M. Djordjevic, *Phys. Rev. C* **92**, 024918 (2015).
22. Z.B. Kang et. al, *JHEP.* **03**, 146 (2017).
23. M. Nahrgang et. al, *Phys. Rev. C* **03**, 014905 (2014).
24. J. Xu et. al, *JHEP.* **02**, 169 (2016).
25. M. He et. al, *Phys. Lett. B* **735**, 445 (2014).
26. T. Song et. al, *Phys. Rev. C* **92**, 014910 (2015).
27. A. Beraudo et. al, *Eur. Phys. J. C* **75**, 121 (2015).
28. J. Uphoff et. al, *J. Phys. G* **42**, 115106 (2015).