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Charmed meson production pattern in PbPb collisions at the LHC

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The phenomenological analysis of various characteristics of J/ψ and D mesons in PbPb collisions at the center-of-mass energy 2.76 TeV per nucleon pair is presented. The data on charmed meson momentum spectra and elliptic flow are reproduced by two-component model HYDJET++ including thermal and non-thermal production mechanisms. The significant part of D-mesons is found to be in a kinetic equilibrium with the created medium, while J/ψ-mesons are characterized by earlier (as compared to light hadrons) freeze-out.

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I. INTRODUCTION

Heavy quarks are predominantly produced in hard scatterings on a short time-scale and traverse the surrounding medium interacting with its constituents. Thus the production of hadrons containing heavy quark(s) is a particularly useful tool to probe transport properties of hot and dense matter formed in ultrarelativistic heavy ion collisions. The modern pattern of multiparticle production in (most central) heavy ion collisions at RHIC and LHC agrees with the formation of hot strongly-interacting matter with hydrodynamical properties (so called "quark-gluon fluid"), which absorbs energetic quarks and gluons due to their multiple scattering and medium-induced energy loss (see, e.g., [1–5]). Within such paradigm, a number of questions related to heavy flavor production is definitely of interest. Are heavy quarks thermalized in quark-gluon plasma? What is the mass dependence of medium-induced quark energy loss? Are charmed hadrons in a kinetic equilibrium with the created medium? What is the interplay between thermal and non-thermal mechanisms of hidden and open charm production?

The interesting measurements at the LHC involving momentum and centrality dependencies of charmed meson production and its azimuthal anisotropy in PbPb collisions at center-of-mass energy 2.76 TeV per nucleon pair have been done by ALICE [6–17] ATLAS [18] and CMS [19, 20] Collaborations. At that a number of theoretical calculations and Monte-Carlo simulations in different approaches were attempted to reproduce these data [21–31]. Note that the simultaneous description of momentum spectra (nuclear modification factors) and elliptic flow coefficients of charmed mesons is currently the challenging problem for most theoretical models. In this paper, the LHC PbPb data on momentum spectra and elliptic flow of charmed hadrons ($D^{\pm}$, $D^{*\pm}$, D^0 and J/ψ mesons) are analyzed and interpreted within two-component HYDJET++ model [32]. Among other heavy ion event generators, HYDJET++ focuses on the detailed simulation of jet quenching effect taking into account medium-induced radiative and collisional partonic energy loss (hard "non-thermal" component), and reproducing the main features of nuclear collective dynamics by the parametrization of relativistic hydrodynamics with preset freeze-out conditions (soft "thermal" component). It has been shown in the previous papers [33–36] that the model is able to reproduce the experimental LHC data on various physical observables measured in PbPb collisions, such as centrality and pseudorapidity dependence of inclusive charged particle multiplicity, transverse momentum spectra of inclusive and identified (π, K, p) hadrons, $\pi^{\pm}\pi^{\pm}$ correlation radii, momentum and centrality dependencies of elliptic and higher-order harmonic coefficients, dihadron angular correlations and event-by-event fluctuations of anisotropic flow. The next step is to apply this model for phenomenological analysis of LHC data on charmed hadron production.

II. SIMULATION OF CHARM PRODUCTION IN HYDJET++ MODEL

HYDJET++ is the model of relativistic heavy ion collisions, which includes two independent components: the soft hydro-type state ("thermal" component) and the hard state resulting from the medium-modified multiparton fragmentation ("non-thermal" component). The details of this model can be found in the HYDJET++ manual [32]. Main features of the model are just sketched below.

The soft component represents the hadronic state generated on the chemical and thermal freeze-out hypersurfaces obtained from the parametrization of relativistic hydrodynamics with preset freeze-out conditions (the adapted event generator FAST MC [37, 38]). Hadron multiplicities are calculated using the effective thermal volume approximation and Poisson multiplicity distribution around its mean value, which is supposed to be proportional to a number of participating nucleons for a given impact parameter of a heavy ion collision. To simulate the elliptic flow effect, the hydro-inspired paramet-

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rization is implemented for the momentum and spatial anisotropy of a thermal hadron emission source [32, 39]. Thermal production of D, J/ψ and Λ_c hadrons is treated within the statistical hadronization approach [40, 41]. Momentum spectra of charmed hadrons are computed according to the thermal distribution, and the multiplicities N_c ($C = D, J/\psi, \Lambda_c$) are calculated through the corresponding thermal numbers $N_c^{\rm th}$

$$N_{\rm c} = \gamma_c^{\rm n_c} N_{\rm c}^{\rm th} \ , \qquad (1)$$

where γ_c is the charm enhancement factor (or charm fugacity), and n_c is the number of charm quarks in a hadron C. The fugacity γ_c can be treated as a free parameter of the model, or calculated through the number of charm quark pairs obtained from perturbative QCD (PYTHIA) and multiplied by the number of nucleon-nucleon subcollisions.

The approach used for the hard component is based on the PYQUEN partonic energy loss model [42]. The simulation of single hard nucleon-nucleon sub-collision by PYQUEN is constructed as a modification of the jet event obtained with PYTHIA_6.4 generator [43]. It takes into account medium-induced rescattering, collisional and radiative energy loss of hard partons in the expanding quark-gluon fluid with realistic nuclear geometry. The radiative energy loss is computed within BDMPS model [44–46], the simple 'dead-cone" generalization to a radiative energy loss of massive quark [47] being used. The collisional energy loss due to elastic scatterings is calculated in the high-momentum transfer limit [48–50]. The number of PYQUEN jets is generated according to the binomial distribution. The mean number of jets produced in an nucleus-nucleus interaction is computed as a product of the number of binary nucleon-nucleon sub-collisions at a given impact parameter per the integral cross section of the hard process with the minimum transverse momentum transfer $p_{\rm T}^{\rm min}$. The partons produced in (semi)hard processes with the momentum transfer lower than $p_{\rm T}^{\rm min}$, are considered as being "thermalized". So, their hadronization products are included "automatically" in the soft component of the event. The impact parameter dependent parametrization[51] obtained in the framework of Glauber-Gribov theory is applied to treat the effect of nuclear shadowing on parton distribution functions.

The input parameters of HYDJET++ for soft and hard components have been tuned from fitting to heavy ion data on various observables for inclusive hadrons at RHIC [32] and LHC [33].

Previously it was shown in [52] that if J/ψ-mesons are produced in HYDJET++ at the same freeze-out parameters as for inclusive (light) hadrons, then simulated $p_{\rm T}$- and y-spectra in central AuAu collisions at RHIC energy $\sqrt{s_{\rm NN}} = 200$ GeV are much wider than ones measured by PHENIX Collaboration [53]. However the assumption that the thermal freeze-out for J/ψ-mesons happens at the same temperature as chemical freeze-out with reduced radial and longitudinal collective velocities allows HYDJET++ to match the data. Note that the early thermal freeze-out of J/ψ-mesons was already suggested some years ago to describe SPS PbPb data at beam energy 158 GeV/nucleon [54]. Recently we also have checked [55] that $p_{\rm T}$-spectrum of D-mesons measured by STAR Collaboration [56] in central AuAu collisions at $\sqrt{s_{\rm NN}} = 200$ GeV is reproduced by HYDJET++ simulation with the same freeze-out parameters as for J/ψ-mesons, but not for inclusive hadrons. It means that D-mesons like J/ψ-mesons are not in a kinetic equilibrium with the created medium at RHIC. Then let us get a look at the LHC situation.

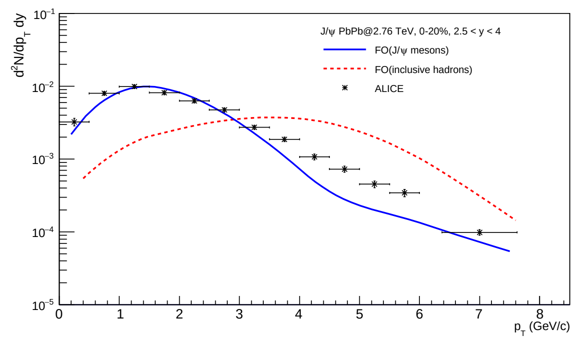

FIG. 1: Transverse momentum spectrum of inclusive J/ψ-mesons for rapidity $2.5 < y < 4$ in 20% of most central PbPb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The points denote ALICE data [14], histograms represent simulated HYDJET++ events (red dashed – freeze-out parameters as for inclusive hadrons, blue solid – early thermal freeze-out).

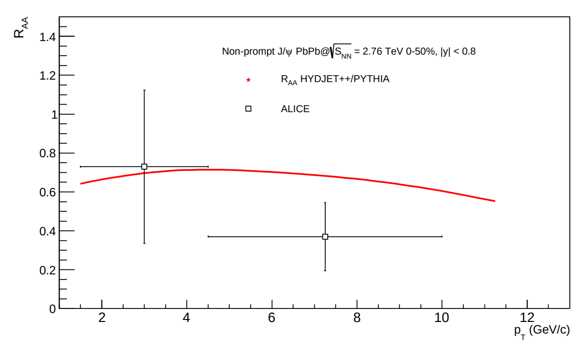

FIG. 2: Nuclear modification factor $R_{\rm AA}(p_{\rm T})$ of non-prompt J/ψ-mesons for rapidity $\mid y \mid < 0.8$ in 50% of most central PbPb collisions at $\sqrt{s}_{\rm NN} = 2.76$ TeV. The open squares denote ALICE data [12], the histogram represents simulated HYDJET++ events.

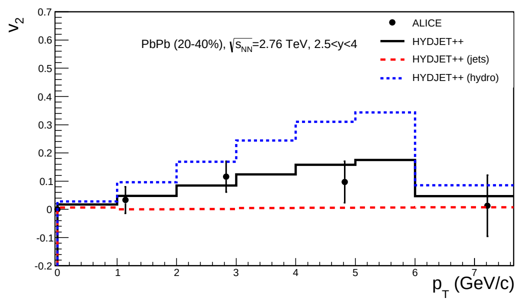

FIG. 3: Elliptic flow coefficient $v_2(p_T)$ of inclusive J/ψ-mesons for rapidity $2.5 < y < 4$ in the 20–40% centrality class of PbPb collisions at $\sqrt{s}_{NN} = 2.76$ TeV. The points denote ALICE data [9], histograms represent simulated HYDJET++ events (blue dotted – soft component, red dashed – hard component, black solid - both components).

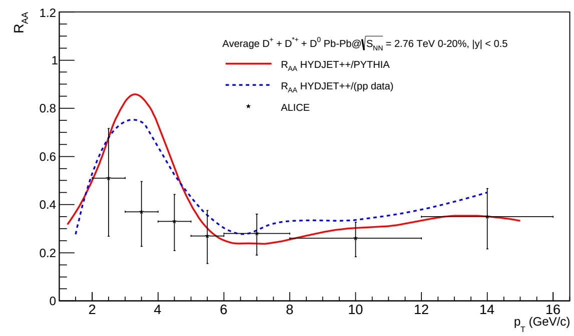

FIG. 5: Average of the three D-meson species nuclear modification factor $R_{AA}(p_T)$ for rapidity $| y |< 0.5$ in 20% of most central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The points denote ALICE data [7], histograms represent simulated HYDJET++ events for two pp references (blue dashed – extrapolated pp data, red solid – PYTHIA).

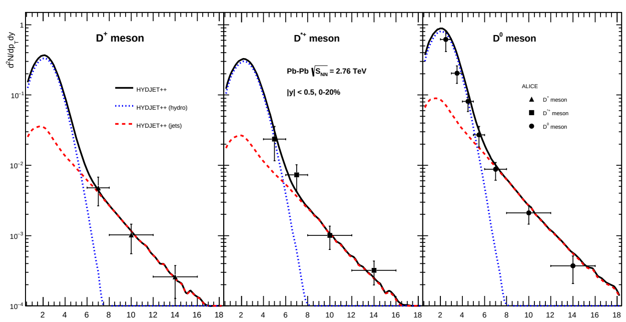

FIG. 4: Transverse momentum spectra of $D^{\pm}$ (left panel), $D^{*\pm}$ (middle panel) and D^0 (right panel) for rapidity $| y |< 0.5$ in 20% of most central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The points denote ALICE data [7], histograms represent simulated HYDJET++ events (blue dotted – soft component, red dashed – hard component, black solid - both components).

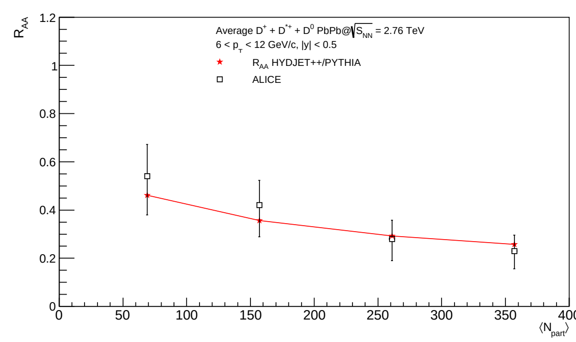

FIG. 6: Centrality dependence of average of the three D-meson species nuclear modification factor R_{AA} for rapidity $| y |< 0.5$ and $6 < p_T < 12$ GeV/c in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The open squares denote ALICE data [7], asterisks represent simulated HYDJET++ events. The line is drawn to guide the eye.

III. J/ψ-MESON PRODUCTION IN LEAD-LEAD COLLISIONS AT $\sqrt{s_{NN}} = 2.76$ TEV

As it was already mentioned in previous section, the input parameters of HYDJET++ have been tuned from fitting to PbPb data at $\sqrt{s_{NN}} = 2.76$ TeV for inclusive hadrons [33]. The most important parameters for our current consideration are the chemical and thermal freeze-out temperatures, $T_{ch} = 165$ MeV and $T_{th} = 105$ MeV, maximal longitudinal and transverse flow rapidities, $Y_L^{max} = 4.5$ and $Y_T^{max} = 1.265$, and the minimal transverse momentum transfer of parton-parton scatterings $p_T^{min} = 8.2$ GeV/c. Figure 1 shows the comparison of HYDJET++ simulations with the ALICE data [14] for p_T-spectrum of inclusive J/ψ-mesons in 20% of most central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with two sets of input parameters: *1)* as for inclusive hadrons (as listed above), and *2)* for early thermal freeze-out ($T_{ch} = T_{th} = 165$ MeV, $Y_L^{max} = 2.3$, $Y_T^{max} = 0.6$, $p_T^{min} = 3.0$ GeV/c). The fugacity value $\gamma_c = 11.5$ was fixed from absolute J/ψ yields. One can see that the situation is similar to RHIC: simulated spectra match the data (up to $p_T \sim 3$ GeV/c) only assuming early thermal freeze-out, which happens presumably at the phase of chemical freeze-out (with reduced collective velocities, and enhanced contribution of non-thermal component). The discrepancy at high p_T may indicate on the necessity to tune used version of PYTHIA for charmonium production in this non-thermal kinematic domain. However, since HYDJET++ does not include modeling of melting of primordial quarkonia in hot matter, anyway it cannot pretend to reproduce the data at high transverse momenta for prompt and inclusive J/ψ's. On the other hand, the production of non-prompt J/ψ's from B-meson decays is of particular interest due to a manifestation of medium-induced bottom quark energy loss in this channel, and may be analyzed within our model.

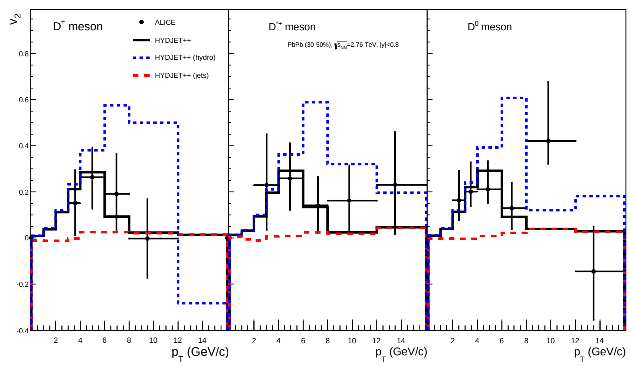

FIG. 7: Elliptic flow coefficient $v_2(p_{\rm T})$ of $D^{\pm}$ (left panel), $D^{*\pm}$ (middle panel) and D^0 (right panel) mesons at rapidity $\mid y \mid< 0.8$ in the 30–50% centrality class of PbPb collisions at $\sqrt{s}_{\rm NN}$ = 2.76 TeV. The points denote ALICE data [8], histograms represent simulated HYDJET++ events (blue dotted – soft component, red dashed – hard component, black solid - both components).

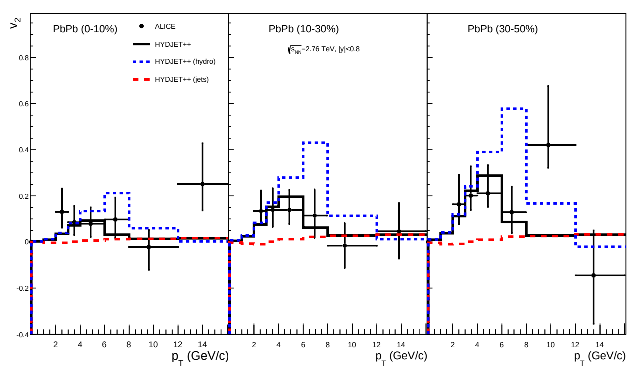

FIG. 8: Elliptic flow coefficient $v_2(p_{\rm T})$ of D^0-mesons at rapidity $\mid y \mid< 0.8$ in the 0–10% (left panel), 10–30% (middle panel) and 30–50% (right panel) centrality classes of PbPb collisions at $\sqrt{s}_{\rm NN}$ = 2.76 TeV. The points denote ALICE data [11], histograms represent simulated HYDJET++ events (blue dotted – soft component, red dashed – hard component, black solid - both components).

Figure 2 shows the nuclear modification factor $R_{\rm AA}$ (the ratio of particle yields in AA and pp collisions normalized to the number of nucleon-nucleon sub-collisions at given event centrality) for non-prompt J/ψ-mesons as a function of $p_{\rm T}$ in 50% of most central PbPb collisions. Good model description of the ALICE data [12] is achieved up to $p_{\rm T} \sim 5$ GeV/c. Some discrepancy at higher $p_{\rm T}$ may indicate again on the necessity to tune used version of PYTHIA for the process under consideration.

In addition, we have found that the $p_{\rm T}$-dependence of the elliptic flow coefficient v_2 measured by ALICE for inclusive J/ψ's [9] is reproduced by HYDJET++ simulations in the case of early freeze-out (figure 3). A key role of non-thermal component at high $p_{\rm T}$ is clearly seen.

Thus we conclude that the significant part of J/ψ-mesons (up to $p_{\rm T} \sim 3$ GeV) produced in PbPb collisions at the LHC is thermalized, but without being in kinetic equilibrium with the medium.

IV. D-MESON PRODUCTION IN LEAD-LEAD COLLISIONS AT $\sqrt{s_{\rm NN}} = 2.76$ TEV

At first, we have simulated D-meson production with the same freeze-out parameters as for inclusive hadrons. The fugacity value $\gamma_c = 11.5$ was fixed from J/ψ yield. Figure 4 shows the comparison of HYDJET++ simulations with the ALICE data [7] for $p_{\rm T}$-spectra of $D^{\pm}$, $D^{*\pm}$ and D^0 mesons in 20% of most central PbPb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The simulated results are close to the data within the experimental uncertainties. Thus in contrast to RHIC, thermal freeze-out of D-mesons at the LHC happens simultaneously with thermal freeze-out of light hadrons. The $p_{\rm T}$-dependence of average of the three D-meson species nuclear modification factor $R_{\rm AA}$ is presented on figure 5. The simulated results are closed to the data up to highest $p_{\rm T} = 16$ GeV. To estimate the uncertainties related to choice of pp reference, two cases were considered: PYTHIA predictions and FONLL-based extrapolation of pp data from $\sqrt{s} = 7$ TeV [7]. One can see that the results obtained with two pp references are similar. The measured centrality dependence of nuclear modification factor for high-$p_{\rm T}$ D-mesons [7] is described well by HYDJET++ simulations. This is demonstrated in figure 6, where the events are divided by four centrality classes (0–10%, 10–20%, 20–40% and 40–60%), and characterized by the average number of participating nucleons $\langle N_{\rm part}\rangle$. For this plot, PYTHIA pp reference was used.

Finally, HYDJET++ is able to reproduce the ALICE data [8, 11] on $p_{\rm T}$-dependence of the elliptic flow coefficient v_2 (figures 7,8).

Therefore we conclude that the significant part of D-mesons (up to $p_{\rm T} \sim 4$ GeV/c) produced in PbPb collisions at the LHC seems to be in a kinetic equilibrium with the medium. The momentum and centrality dependencies of nuclear modification factors $D^{\pm}$, $D^{*\pm}$ and D^0 mesons at high-$p_{\rm T}$ is reproduced by HYDJET++ modeling (including the treatment of medium-induced charm quark energy loss).

V. SUMMARY

The phenomenological analysis of charmed meson production in lead-lead collisions at the center-of-mass energy 2.76 TeV per nucleon pair has been performed within the two-component HYDJET++ model including thermal (soft) and non-thermal (hard) components. Momentum spectra and elliptic flow of D and J/ψ mesons may be reproduced by the two-component model assuming that thermal freeze-out of D-mesons happens simultaneously with thermal freeze-out of light hadrons, while thermal freeze-out of J/ψ-mesons happens appreciably before, presumably at the phase of chemical freeze-out (with reduced radial and longitudinal collective velocities). Thus the significant part of D-mesons (up to transverse momenta $p_{\rm T} \sim 4$ GeV/c), unlike J/ψ mesons, seems to be in a kinetic equilibrium with the created in PbPb collisions hot hadronic matter.

Non-thermal charm production mechanism is important at high transverse momenta. A tolerable agreement of the simulated results with the data for D and non-prompt J/ψ meson nuclear modification factors testifies in favor of successful treatment of medium-induced heavy quark rescattering and energy loss within the framework of the HYDJET++ model.

VI. ACKNOWLEDGMENTS

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