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J/Ψ Meson Production Pattern in PbPb Collisions at 5.02 TeV in HYDJET++ Model

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Keywords: *heavy ion collisions, quark-gluon plasma, heavy quarks.*

Introduction: Heavy quarks are primarily produced in hard scatterings on short time scales and traverse the surrounding medium, interacting with its constituents. Consequently, the production of hadrons containing heavy quark(s) serves as a particularly valuable probe for investigating the transport properties of the hot matter formed in ultrarelativistic heavy-ion collisions.

The contemporary understanding of multi-particle production in central heavy- ion collisions at RHIC and LHC energies suggests the formation of a hot, strongly- interacting matter with hydrodynamical properties often referred to as a “quark-gluon” fluid”. This medium absorbs energetic quarks and gluons through multiple scatterings and medium-induced energy loss (see, e.g., [1–5]).

This study continues a series of investigations into the thermalization of heavy quarks in quark-gluon plasma (QGP). In our previous works [6–11], we explored the interplay between thermal and non-thermal mechanisms of hidden and open charm production at RHIC and LHC energies (200 GeV and 2.76 TeV per nucleon pair respectively).

In this paper, we analyze and interpret LHC PbPb data on the momentum spectra of J/ψ mesons [12] in PbPb collisions at a center-of-mass energy of 5.02 TeV per nucleon pair, within the framework of the two-component HYDJET++ model [13]. Among various heavy-ion event generators, HYDJET++ is distinguished by its focus on simulating the jet-quenching effect, accounting for medium-induced radiative and collisional partonic energy loss (the “non-thermal” hard component), while also reproducing the main features of nuclear collective dynamics through the parametrization of relativistic hydrodynamics with preset freeze-out conditions (the “thermal” soft component). Previous studies have demonstrated that the HYDJET++ model successfully reproduces experimental

LHC data across a range of physical observables in PbPb collisions, including the centrality and pseudorapidity dependence of inclusive charged particle multiplicity, transverse momentum spectra of inclusive and identified hadrons (π, K, p), $\pi^{\pm}\pi^{\pm}$ femtoscopic correlation radii, momentum and centrality dependencies of elliptic and higher-order harmonic coefficients, dihadron angular correlations, and event-by-event fluctuations of anisotropic flow [14–17]. Our previous research revealed that, at RHIC energies, both light and heavy charmed hadrons are not in thermal equilibrium with the medium, undergoing thermal freeze-out earlier than light hadrons (those composed of light quarks). At LHC energies of 2.76 TeV per nucleon pair, light charmed hadrons (open charm hadrons containing a single *c* quark) appear to reach thermal equilibrium with the medium and are well-described by HYDJET++ parameters applicable to light hadrons. In contrast, J/ψ mesons still exhibit characteristics of an earlier kinetic freeze-out. This work aims to assess the situation at a higher energy of 5.02 TeV per nucleon pair.

1. Charm production in HYDJET++ model: HYDJET++ is a 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 multi-parton fragmentation ("non-thermal" component) [13]. The soft component corresponds to the hadronic state produced on the chemical and thermal freeze-out hypersurfaces, which are derived from the parametrization of relativistic hydrodynamics under predefined freeze-out conditions. This is achieved using the adapted event generator FAST MC [18, 19]). Hadron multiplicities are determined within the framework of the effective thermal volume approximation, employing a Poisson multiplicity distribution centered around its mean value. This mean is assumed to be proportional to the number of participating nucleons at a specified impact parameter of an AA collision. To simulate the elliptic flow effect, the hydro-inspired parametrization is implemented for the momentum and spatial anisotropy of a thermal hadron emission source.

The approach used for the hard component is based on the PYQUEN partonic energy loss model [20]. The simulation of a single hard NN sub-collision by PYQUEN is modeled as a modification of the jet event generated by PYTHIA 6.4 [21]. This approach integrates several key effects, including medium-induced rescattering, collisional and radiative energy loss of hard partons within the context of an expanding quark-gluon plasma, as well as considerations of realistic nuclear geometry and nuclear shadowing. The mean number of jets produced in an AA event is calculated by multiplying the number of binary NN sub-collisions at a specified impact parameter with the integral cross section of the hard process, determined by the minimum transverse momentum transfer, $p^{\min}$. Partons produced in hard processes with a momentum transfer lower than $p^{\min}$ are considered as being "thermalized". Consequently, their hadronization products are included "automatically" in the soft component of the event.

The input parameters of the model for both the soft and hard components have been tuned to fit heavy ion data on various observables for inclusive hadrons at RHIC [13] and LHC [14].

Charmed meson production in HYDJET++ includes both soft and hard components as well. Thermal production of D, J/ψ, and Λ_c hadrons is treated within the statistical hadronization approach [22, 23]. Momentum spectra of charm hadrons are computed according to thermal distributions, and the multiplicities N_c (where $C = D$, J/ψ, Λ_c) are calculated through the corresponding thermal numbers N_c^{th} as $N_c = \gamma_c^n N_c^{\text{th}}$, 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 based on the number of charm quark pairs obtained from PYTHIA and multiplied by the number of NN sub-collisions.

Non-thermal charmed hadrons are generated by PYQUEN, taking into account in- medium energy loss of heavy (b, c) quarks using the "dead-cone" generalization [24] of the BDMPS model [25, 26] for radiative loss and the high-momentum transfer limit [27, 28, 29] for collisional loss.

2. ***J/ψ-meson production in lead-lead collisions at $\sqrt{s_{NN}}$ = 5.02 TeV:*** The HYDJET++ model parameters for both the soft and hard components have been finely tuned to fit heavy ion data on various observables for inclusive hadrons. The chemical and thermal freeze-out temperatures, set at T_{ch} = 165 MeV and T_{th} = 105 MeV, respectively, for inclusive hadrons are of particular relevance. Earlier work [6] demonstrated that the HYDJET++ model could accurately reproduce p_T and y spectra of J/ψ mesons at RHIC energies ($\sqrt{s_{NN}}$ = 200 GeV) [30], under the assumption that the thermal freeze-out of J/ψ occurs at the same temperature as chemical freeze-out. This notion of early thermal freeze-out for J/ψ had been previously proposed to explain SPS data at 158 GeV/nucleon [31]. A similar trend was observed at LHC energies ($\sqrt{s_{NN}}$ = 2.76 TeV) [6, 7, 8, 9, 10, 11], and this pattern persists even at $\sqrt{s_{NN}}$ = 5.02 TeV.

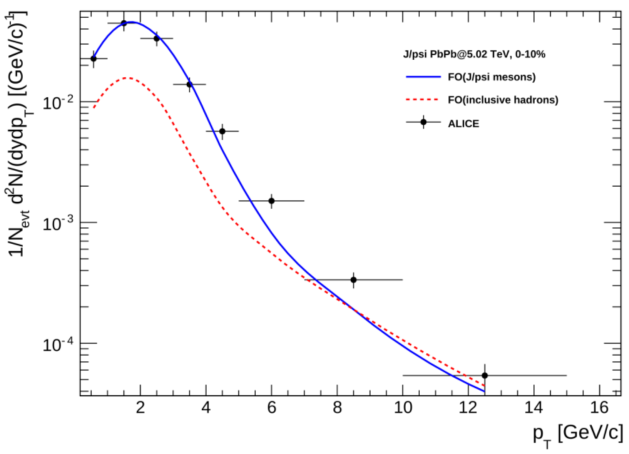

Fig. 1. Transverse momentum spectrum of inclusive J/ψ-mesons for rapidity |y| < 0.9 in 10% *of* most central PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The points denote ALICE data [12], histograms represent simulated HYDJET++ events (red dashed – freeze-out parameters as for inclusive hadrons, blue solid – early thermal freeze-out).

Figure 1 presents a comparison between HYDJET++ simulations and ALICE data [12] for the p_T spectrum of J/ψ mesons in the 10% most central PbPb collisions within the mid-rapidity region ($|y| < 0.9$) at $\sqrt{s_{NN}} = 5.02$ TeV. The results suggest that if J/ψ undergoes thermal freeze-out at the same temperature as chemical freeze- out (albeit with reduced collective velocities), the simulated spectrum aligns with the experimental data. A comparison in the forward rapidity region ($2.5 < |y| < 4$) for the 20% most central PbPb collisions is shown in Figure 2. It matches the data up to $p_T \approx 4$ GeV/c. However, an enhanced contribution from the hard component was required to better match the overall shape of the p_T spectrum. The observed discrepancy at high p_T might suggest the need to further tune the version of PYTHIA specifically for charmonium production.

It is important to note that HYDJET++ does not model final state effects for quarkonia, such as the melting of primordial quarkonia in the hot medium or dissociation by comovers. Therefore, it is not designed to accurately reproduce data at high transverse momenta for prompt (and consequently, inclusive) J/ψ mesons. Conversely, the production of non-prompt J/ψ mesons from B-meson decays is particularly interesting due to the potential to observe medium-induced bottom quark energy loss in this channel, which can be analyzed using our model.

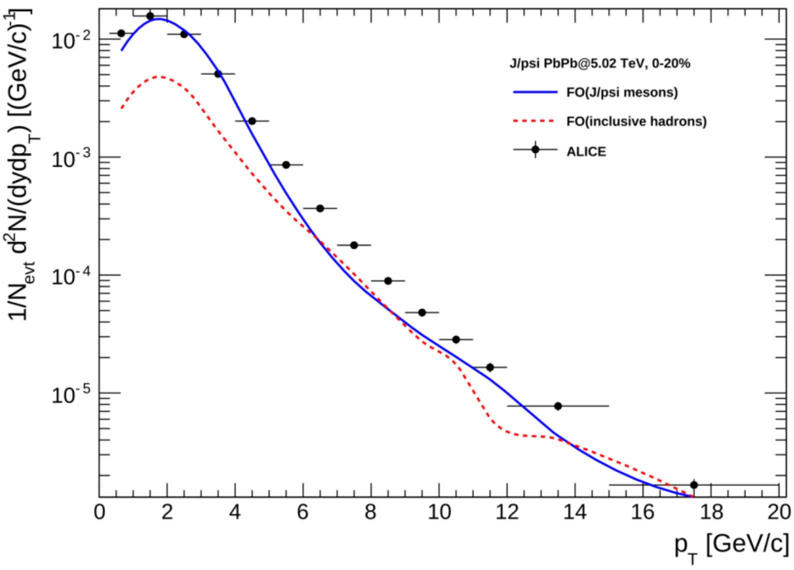

Fig. 2. Transverse momentum spectrum of inclusive J/ψ-mesons for rapidity $2.5 < |y| < 4$ in 20% of most central PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The points denote ALICE data [12], histograms represent simulated HYDJET++ events (red dashed – freeze-out parameters as for inclusive hadrons, blue solid – early thermal freeze-out).

Summary: The phenomenological analysis of charmed meson production in lead-lead collisions at a center-of-mass energy of 5.02 TeV per nucleon pair has been conducted using the two-component HYDJET++ model, which accounts for both thermal and non-thermal production mechanisms. The model successfully reproduces the momentum spectra of J/ψ mesons by assuming that the thermal freeze-out of J/ψ mesons occurs significantly earlier than that of light hadrons, likely during the phase of chemical freeze-out. This earlier freeze-out is associated with reduced radial and longitudinal collective velocities. As a result, a substantial fraction of J/ψ mesons, particularly those with transverse momenta up to $p_T \sim 4$ GeV/c, appears to be out of kinetic equilibrium with the hot hadronic matter created in PbPb collisions. This observation suggests that the interaction cross section of J/ψ mesons at this energy remains considerably smaller than that of light hadrons.

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J/Ψ Meson Production Pattern in PbPb Collisions at 5.02 TeV in HYDJET++ Model

The investigation of quarkonium production in heavy-ion collisions is essential for gaining insights into the properties of the quark-gluon plasma (QGP) and understanding the underlying mechanisms of particle production in high-energy physics. This paper provides a phenomenological analysis of the various properties of *J/ψ* mesons in PbPb collisions at a center-of-mass energy of 5.02 TeV per nucleon pair. The momentum spectra data of *J/ψ* mesons are accurately reproduced using the two-component model HYDJET++, which integrates both thermal and non-thermal production mechanisms. A substantial fraction of *J/ψ* mesons undergo earlier freeze- out compared to light hadrons, aligning with observations at an energy of 2.76 TeV. These results offer important insights into the dynamics of *J/ψ* meson production and their interactions within the quark-gluon plasma.

Ա.Վ. Բելյաև

J/Ψ մեզոնների առաջացման օրինաչափությունները 5.02 TeV PbPb-ի բախումների ժամանակ HYDJET++ մոդելում

Ծանր իոնների բախումների ժամանակ քվարկոնիումի առաջացման հետազոտությունը կարևոր է բարձր էներգիայի ֆիզիկայում՝ քվարկ-գլյուոնային պլազմայի հատկությունների և մասնիկների առաջացման հիմքում ընկած մեխանիզմների վերաբերյալ պատկերացումներ ձեռք բերելու համար։

Այս հոդվածում ներկայացված է զանգվածի կենտրոնում 5,02 TeV միջուկի էներգիայով PbPb-ի բախումներում J/ψ մեզոնների տարբեր հատկությունների ֆենոմենոլոգիական վերլուծություն:

J/ψ մեզոնների իմպուլսի սպեկտրային տվյալները ճշգրտորեն վերարտադրվում են՝ օգտագործելով երկբաղադրիչ մոդել HYDJET++, որը ներառում է ինչպես ջերմային, այնպես էլ ոչ ջերմային առաջացման մեխանիզմներ: J/ψ մեզոնների մի զգալի մասը ենթարկվում է ավելի վաղ սառեցման, համեմատած թեթև հադրոնների հետ, ինչը համընկնում է 2,76 TeV էներգիաների ժամանակ դիտարկումների հետ:

Այս արդյունքները կարևոր պատկերացում են տալիս J/ψ մեզոնների առաջացման դինամիկայի և քվարկ-գլյուոնային պլազմայում դրանց փոխազդեցությունների վերաբերյալ:

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Особенности рождения J/Ψ-мезонов в соударениях ионов свинца при энергии 5.02 ТэВ в модели HYDJET++

Исследование рождения кварькониев в столкновениях тяжелых ионов имеет ключевое значение для получения представлений о свойствах кварк-глюонной плазмы (QGP) и для понимания механизмов рождения частиц в физике высоких энергий. В данной работе проведен феноменологический анализ различных свойств J/ψ-мезонов в PbPb столкновениях при энергии 5,02 ТэВ на пару нуклонов в системе центра масс. Спектры импульсов J/ψ-мезонов были точно воспроизведены с использованием двухкомпонентной модели HYDJET++, которая включает как термальные, так и нетермальные механизмы рождения. Было показано, что существенная доля J/ψ-мезонов претерпевает более термическое вымораживание по сравнению с легкими адронами, что согласуется с наблюдениями для энергии 2,76 ТэВ. Эти результаты предоставляют важные сведения о динамике рождения J/ψ-мезонов и их взаимодействиях в кварк-глюонной плазме.

References

1. *Arsene I. et al.* (BRAHMS Collaboration) 2005 Nucl. Phys. A 757 1.
2. *Back B. B. et al.* (PHOBOS Collaboration) 2005 Nucl. Phys. A 757 28.
3. *Adams J. et al.* (STAR Collaboration) 2005 Nucl. Phys. A 757 102.
4. *Adcox K. et al.* (PHENIX Collaboration) 2005 Nucl. Phys. A 757 184.
5. *Armesto N. and Scomparin E.* 2016 Eur. Phys. J. Plus 131 52.
6. *Lokhtin I. P., Belyaev A. V., Malinina L. V., Petrushanko S. V., Snigirev A. M., Arsene I., Zabrodin E. E.* 2011 J. Phys.: Conf. Ser. 270 012060.
7. *Lokhtin I. P., Belyaev A. V., Eyyubova G. Kh., Ponimatkin G. and Pronina E. Yu.*2016 J. Phys.: Conf. Ser. 668 012068.

8. *Eyyubova G. Kh., Lokhtin I. P., Belyaev A. V., Ponimatkin G., Pronina E.Yu.* 2015 PoS EPS-HEP2015 214.
9. *Lokhtin I. P., Belyaev A. V., Eyyubova G. Kh., Ponimatkin G. and Pronina E. Yu.* 2016 J. Phys. G: Nucl. Phys. 43 125104.
10. *Lokhtin I. P., Belyaev A. V., Eyyubova G. Kh., Ponimatkin G. and Pronina E. Yu.* 2017 J. Exp. Theor. Phys. 124 244.
11. *Eyyubova G. Kh., Lokhtin I. P., Belyaev A. V., Ponimatkin G., Pronina E. Yu.* 2017 Phys. Part.Nucl. 48 938.
12. *S. Acharya et al.* [ALICE], Phys. Lett. B 849 (2024), 138451.
13. *Lokhtin I. P., Malinina L. V., Petrushanko S. V., Snigirev A. M., Arsene I. and Tywoniuk K.* 2009 Comput. Phys. Commun. 180 779.
14. *Lokhtin I. P., Belyaev A. V., Malinina L. V., Petrushanko S. V., Rogochnaya E. P. and Snigirev A. M* . 2012 Eur. Phys. J. C 72 2045.
15. *Bravina L. V., Brusheim Johansson B. H., Eyyubova G. Kh., Korotkikh V. L., Lokhtin I. P., Malinina L. V., Petrushanko S. V., Snigirev A. M. and Zabrodin E.E.* 2014 Eur. Phys. J. C 74 2807.
16. *Bravina L. V., Eyyubova G. Kh., Korotkikh V. L., Lokhtin I. P., Petrushanko S. V., Snigirev A. M. and Zabrodin E. E.* 2015 Phys. Rev. C 91 064907.
17. *Bravina L. V., Fotina E.S., Korotkikh V. L., Lokhtin I. P., Malinina L. V., Nazarova E. N., Petrushanko S. V., Snigirev A. M. and Zabrodin E. E.* 2015 Eur. Phys. J. C 75 588.
18. *Amelin N. S., Lednicky R., Pocheptsov T. A., Lokhtin I. P., Malinina L. V., Snigirev A. M., Karpenko Iu. A.and Sinyukov Yu. M.* 2006 Phys. Rev. C 74 064901.
19. *Amelin N. S., Lednicky R., Lokhtin I. P., Malinina L. V., Snigirev A. M., Karpenko Iu. A., Sinyukov Yu. M., Arsene I. and Bravina L.* 2008 Phys. Rev. C 77 014903.
20. *Lokhtin I. P. and Snigirev A. M.* 2006 Eur. Phys. J. C45 211.
21. *Sjostrand T., Mrenna S. and Skands P.* 2006 J. High Energy Phys. 0605 026.
22. *Andronic A., Braun-Munzinger P., Redlich K. and Stachel J.* 2003 Phys. Lett. B 571 36.
23. *Andronic A., Braun-Munzinger P., Redlich K. and Stachel J.* 2007 Nucl. Phys. A 789 334.
24. *Dokshitzer Yu. L. and Kharzeev D.* 2001 Phys. Lett. B 519 199.
25. *Baier R., Dokshitzer Yu. L., Mueller A. H., Peigne S. and Schiff D.* 1997 Nucl. Phys. B 483 291.
26. *Baier R., Dokshitzer Yu. L., Mueller A. H., Peigne S. and Schiff D.* 1999 Phys. Rev. C 60 064902.
27. *Bjorken J.D.* 1982 Fermilab Preprint Pub-82/29-THY.
28. *Braaten E. and Thoma M.* 1991 Phys. Rev. D 44 1298.
29. *Lokhtin I. P. and Snigirev A. M* . 2000 Eur. Phys. J. C 16 527.
30. *Adare A. et al.* (PHENIX Collaboration) 2007 Phys. Rev. Lett. 98 232301.
31. *Bugaev K. A., Gazdzicki M. and Gorenstein M. I.* 2001 Phys. Lett. B 523 255.