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Կվարկոնիումի և բարձր էներգիայի հադրոնների ծնման մեխանիզմները պրոտոն-պրոտոնային և միջուկ-միջուկային բախումներում Մեծ հադրոնային կոլայդերի էներգիաներում

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ՍԵՂՄԱԳԻՐ

ԵՐԵՎԱՆ - 2025

A. I. ALIKHANYAN NATIONAL SCIENCE LABORATORY
(YEREVAN PHYSICS INSTITUTE)

Andrey Belyaev

Mechanisms of the birth of quarkonium and high-energy hadrons in proton-proton and nucleus-nuclear collisions at the energies of the Large Hadron Collider

SYNOPSIS

of Dissertation in 01.04.16 -- "Nuclear, elementary particles and cosmic ray physics" presented for the degree of candidate in physical and mathematical sciences

YEREVAN - 2025

Ատենախոսության թեման հաստատվել է Ա. Ի. Ալիխանյանի անվան Ազգային Գիտական Լաբորատորիայի (ԵրՖԻ) գիտական խորհուրդում:

Գիտական ղեկավար՝
Ֆիզ. մաթ. գիտ. թեկնածու — Իոաննիսյան Արա Նիկոլայի (ԱԱԳԼ)

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Ֆիզ. մաթ. գիտ. թեկնածու — Շահոյան Ռուբեն Միքայելի (ՑԵՌՆ)

Առաջատար կազմակերպություն՝ — Երևանի պետական համալսարան (ԵՊՀ)

Ատենախոսության պաշտպանությունը կայանալու է 2025 թ. փետրվարի 17-ին, ժամը 14:00-ին, ԱԱԳԼ-ում գործող ԲԿԳԿ-ի 024 «Ֆիզիկայի» մասնագիտական խորհուրդում (Երևան, 0036, Ալիխանյան Եղբայրների փ. 2):

Ատենախոսությանը կարելի է ծանոթանալ ԱԱԳԼ-ի գրադարանում:
Սեղմագիրն առաքված է 2025 թ. հունվարի 17-ին:

Մասնագիտական խորհրդի գիտական քարտուղար՝
Ֆիզ. մաթ. գիտ. դոկտոր — Հրաչյա Մարուքյան

The subject of the dissertation is approved by the scientific council of the A.I. Alikhanyan National Science Laboratory (YerPhI).

Scientific Supervisor:
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Official Opponents:
Doctor of ph-math. sciences — Anahit Balabekyan (YSU)
Candidate of ph-math. sciences — Ruben Shahoyan (CERN)

Leading Organization: — Yerevan State University (YSU)

The defense will take place on the 17^{th} of February, 2025, at 14:00 during the "Physics" professional council's session of HESC 024 acting within AANL (2 Alikhanyan Brothers str., 0036, Yerevan).

The dissertation is available at the AANL library.
The synopsis is sent out on the 17^{th} of January, 2025.

Scientific Secretary of the Special Council:
Doctor of ph-math. sciences — Hrachya Marukyan

General characteristics of the dissertation

This dissertation focuses on the comprehensive study of heavy quarkonium production in proton-proton (pp) and nucleus-nucleus (PbPb) collisions at the Large Hadron Collider (LHC) energies. The research presented here employs a combination of phenomenological modeling and experimental analysis to investigate quarkonium production mechanisms and their suppression in a Quark-Gluon Plasma (QGP) environment.

The dissertation is divided into two major parts: the first part involves a phenomenological analysis using the HYDJET++ Monte Carlo model, which incorporates both thermal and non-thermal components of particle production. This part of the research focuses on the reproduction of experimental data related to charmonium production in PbPb collisions, including nuclear modification factors, transverse momentum spectra, and elliptic flow coefficients. The study provides significant insights into the thermal and kinetic properties of J/ψ mesons, revealing their earlier freeze-out compared to light hadrons, and highlights the role of both thermal and non-thermal production mechanisms in different energy regimes.

The second part of the dissertation presents an experimental analysis of heavy quarkonium production based on data collected by the CMS detector at the LHC. This analysis focuses on the suppression of prompt and non-prompt J/ψ mesons, as well as Υ mesons in PbPb collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV. The experimental findings provide evidence of quarkonium suppression as a key signature of QGP formation and offer a detailed comparison between different quarkonium states, contributing to the understanding of in-medium quarkonium behavior in high-energy heavy-ion collisions.

The findings of this dissertation contribute to the advancement of high-energy nuclear physics by offering a detailed understanding of quarkonium production mechanisms and their interaction with the QGP. The work also opens pathways for future research, aiming to refine phenomenological models and enhance experimental measurements in heavy-ion physics.

Keywords: Quarkonium production, Quark-gluon plasma, Heavy-ion collisions, LHC, HYDJET++ model, CMS experiment, Charmonium, Bottomonium, Nuclear modification factor, Transverse momentum spectra.

Theme Actuality

The study of quarkonium production in high-energy collisions remains one of the most significant areas in nuclear and particle physics. Heavy quarkonium, composed of heavy quark-antiquark pairs (such as charmonium and bottomonium), serves as a crucial probe for understanding the properties of the quark-gluon plasma (QGP), a state of matter that is thought to have existed in the early universe. The unique interaction of quarkonium states with the hot and dense medium created in nucleus-nucleus (A-A) collisions allows researchers to investigate the characteristics of the QGP and its role in color screening and quark confinement.

The Large Hadron Collider (LHC) provides a unique environment for studying quarkonium production and suppression mechanisms in both proton-proton (pp) and nucleus-nucleus (PbPb) collisions at unprecedented energy scales. The accurate modeling and experimental investigation of quarkonium production in these collisions are essential for advancing our understanding of QGP formation and evolution, as well as for improving theoretical models of quantum chromodynamics (QCD), particularly in the non-perturbative regime.

Despite significant progress over the past five decades, many aspects of quarkonium production remain unresolved. This includes the complex interplay between thermal and non-thermal production mechanisms, the role of initial and final state effects, and the dynamics of quarkonium suppression in heavy-ion collisions. Additionally, there is a need for further experimental verification of theoretical predictions, especially regarding the differences between charmonium and bottomonium states under extreme conditions.

Given the relevance of these open questions and the growing availability of high-precision experimental data from the LHC, the current study of quarkonium production mechanisms and their suppression in the QGP was highly timely. This dissertation contributes to these efforts by employing both phenomenological modeling, using the HYDJET++ Monte Carlo model, and experimental analysis with the CMS detector, thereby providing a comprehensive approach to advancing the field of heavy-ion physics.

The Purpose of the Work

The primary purpose of this dissertation is to investigate the mechanisms of quarkonium production in high-energy proton-proton (pp) and nucleus-nucleus (PbPb) collisions at the Large Hadron Collider (LHC). Specifically, the study aims to provide both, a detailed phenomenological and experimental analysis of the production and suppression of heavy quarkonia, with a focus on the dynamics of charmonium and bottomonium states in the quark-gluon plasma (QGP). The work is divided into two main objectives:

- **Phenomenological Modeling:** The dissertation aims to apply the HYDJET++ Monte Carlo model to describe both thermal and non-thermal quarkonium production mechanisms. This includes reproducing transverse momentum spectra, nuclear modification factors, and elliptic flow of charmed mesons in PbPb collisions at LHC energies.
- **Experimental Analysis:** Another key objective is to analyze the suppression of J/ψ and Υ mesons in PbPb collisions using data collected by the CMS detector at the LHC. The analysis focuses on extracting key experimental observables, including production rates, suppression patterns, and momentum spectra, to enhance the understanding of quarkonium behavior in a hot, dense QGP environment.

Ultimately, this dissertation seeks to bridge the gap between theoretical predictions and experimental observations by providing both a comprehensive modeling approach and precise experimental measurements. The results will contribute to advancing knowledge of heavy quarkonium production mechanisms, QGP properties, and high-energy QCD processes in high-energy collisions.

Scientific Novelty and Practical Value

Scientific Novelty: The dissertation presents several novel contributions to the study of heavy quarkonium production in high-energy collisions:

J/ψ meson production and suppression patterns across different transverse momentum ranges and centrality classes in HYDJET++ model.

- The dissertation provides new insights into the early thermal freeze-out of J/ψ mesons, demonstrating that these mesons freeze-out earlier than light hadrons in PbPb collisions, an observation that holds across multiple energy scales. This result significantly advances our understanding of the interplay between quarkonium production mechanisms and the dynamics of the quark-gluon plasma (QGP).
- The experimental component of the dissertation is the first to systematically measure the suppression of prompt and non-prompt J/ψ, as well as Υ mesons, in PbPb collisions at a center-of-mass energy of 2.76 TeV. The analysis provides detailed measurements of the nuclear modification factors for quarkonia states, contributing important empirical data to the ongoing study of QGP properties.

Practical Value: The practical value of this dissertation lies in its potential to improve the accuracy of theoretical models used to describe heavy quarkonium production and suppression in high-energy nuclear collisions. The results and methodologies presented in this work have several practical applications:

- The findings can be applied to refine Monte Carlo event generators such as HYDJET++, which are widely used in the high-energy physics community for simulating hadron production and QGP effects in heavy-ion collisions.
- The experimental measurements of quarkonium suppression in PbPb collisions provide valuable reference data for future studies at the LHC, as well as for other experiments investigating quarkonium production in extreme conditions, such as at the Relativistic Heavy Ion Collider (RHIC) and future colliders.
- The results offer critical insights into the mechanisms underlying QGP formation and the interaction of heavy quarks with the medium, which may have broader implications for understanding fundamental QCD processes and developing new methods for probing the properties of QGP in future experiments.

Personal Commitment

The presented dissertation is the culmination of extensive personal contributions across both phenomenological and experimental domains, demonstrating a comprehensive approach to the study of quarkonium production mechanisms.

Phenomenological Contributions

- Conducted a full analysis of J/ψ production using the HYDJET++ model for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, focusing on the transverse momentum and $dN/d\eta$ spectra observables.
- Investigated the nuclear modification factor for J/ψ mesons in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV within the HYDJET++ framework, providing insights into quarkonium suppression mechanisms.
- Performed reference analyses for J/ψ production in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV using HYDJET++, enabling comparisons across different collision energies and collision systems.

Experimental Contributions

- Calculated acceptance values for Υ and prompt J/ψ mesons in the CMS analysis of quarkonium suppression at $\sqrt{s_{NN}} = 2.76$ TeV in PbPb collisions.
- Measured the polarization of J/ψ and Υ mesons in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.
- Conducted a subanalysis to determine the dependence of acceptance on the polarization of J/ψ and Υ mesons, highlighting the impact of polarization effects on experimental observables.

These contributions reflect a significant personal effort in advancing the understanding of heavy quarkonium production mechanisms, both through theoretical modeling and experimental analysis.

The main points for defense

The author defends the following key scientific contributions based on the findings of the dissertation:

1. A detailed phenomenological analysis of J/ψ mesons production in PbPb collisions at LHC energies $\sqrt{s_{NN}} = 2.76$ and $\sqrt{s_{NN}} = 5.02$ TeV, utilizing the HYDJET++ Monte Carlo model.
2. The first observation that J/ψ mesons experience an earlier thermal freeze-out compared to lighter hadrons at the energies $\sqrt{s_{NN}} = 2.76$ and $\sqrt{s_{NN}} = 5.02$ TeV.
3. The first experimental evidence of non-prompt J/ψ suppression in PbPb collisions, attributed to the in-medium energy loss of b-hadrons. The suppression of non-prompt J/ψ mesons is comparable to that of charged hadrons, offering new insights into heavy-flavor energy loss mechanisms.
4. New experimental results on the suppression of Υ mesons in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, including the first precise measurement of the nuclear modification factors for quarkonia states.
5. The part of softwere, developed to preform this analysis. Espeacially for the phenomenological analysis, experimental pollarization mesurement and acceptance calculation.

Approbation of the Work

The results of this dissertation have been presented and discussed at numerous international conferences, workshops, and seminars dedicated to high-energy physics and heavy-ion collisions, including:

- Lomonosov Readings 2011, M.V. Lomonosov Moscow State University, Moscow, Russia,
- Quark Matter 2011, Annecy, France,
- The 15h International Conference on Strangeness in Quark Matter, Dubna, Russia
- The European Physical Society Conference on High Energy Physics (EPS-HEP 2015), Vienna, Austria
- The XXV International Conference on Ultrarelativistic Nucleus-Nucleus Collisions "Quark Matter 2015", Kobe, Japan

- The 15h International Conference on Strangeness in Quark Matter, Dubna, Russia
- The European Physical Society Conference on High Energy Physics (EPS-HEP 2015), Vienna, Austria
- The XXV International Conference on Ultrarelativistic Nucleus-Nucleus Collisions "Quark Matter 2015", Kobe, Japan
- Session of Nuclear Physics of the Department of Physical Sciences of the Russian Academy of Sciences, Moscow, Russia,
- Lomonosov Readings, M.V. Lomonosov Moscow State University, Moscow, Russia,
- The CMS Collaboration meetings.

Key findings from the phenomenological analysis of J/ψ meson production, as well as the experimental results on J/ψ and Υ suppression in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, have been peer-reviewed and published in 10 articles, the list of which is given at the end of the synopsis.

The experemental work has also been subjected to internal review processes within the CMS Collaboration, where it has been validated by experts in heavy-ion physics. These presentations and publications have allowed for valuable feedback, contributing to the robustness and scientific impact of the research findings.

Structure of the dissertation

The dissertation is 150 pages long and include an introduction, three chapters, a conclusion, 244 references, 85 figures, and 6 tables.The structure of the dissertation is as follows.

The **Introduction** provides an overview of the history and background of quarkonia studies over the past fifty years. It examines the key challenges encountered during this period and highlights the current state of research in the field. The final section reviews recent publications and addresses the most pressing and challenging questions facing the field today.

Chapter 1 discusses the methods used for investigating quarkonia production, including both phenomenological approaches and the experimental techniques employed at the LHC.

Chapter 2, presents a detailed phenomenological analysis of charmonium production in heavy-ion collisions, utilizing the HYDJET++ Monte Carlo model. This model incorporates both thermal and non-thermal mechanisms to simulate the production of J/ψ mesons. The chapter focuses on reproducing experimental data and analyzing production rates, transverse momentum spectra, nuclear modification factors, and the elliptic flow of J/ψ mesons in PbPb collisions. Comparisons between the model's predictions and empirical data provide valuable insights into quarkonium suppression and production mechanisms within the quark-gluon plasma.

Chapter 3 presents an experimental investigation into the suppression of heavy quarkonia in PbPb collisions at a center-of-mass energy of 2.76 TeV, using data collected by the CMS experiment. The study focuses on charmonium (J/ψ) and bottomonium (Υ) states, analyzing their suppression as a key signature of quark-gluon plasma (QGP) formation and the differences in the formation of heavy quarkonia in the presence of a hot colored medium. The experimental analysis includes detailed procedures for event selection, muon reconstruction, and the use of Monte Carlo simulations to account for detector responses.

Finally, the **Conclusion** summarizes the key findings, discusses their implications for the field, and outlines prospects for future research.

Outline of the dissertation

Introduction

The study of heavy quarkonium production in high-energy hadron collisions plays a fundamental role in advancing our understanding of Quantum Chromodynamics (QCD), particularly in its non-perturbative regime. Heavy quarkonia, such as charmonium and bottomonium, are bound states of heavy quarks and antiquarks (charm and bottom), and their production mechanisms offer unique insights into the quark-gluon plasma (QGP) formed in nucleus-nucleus collisions. These studies are essential for probing the properties of hot and dense color matter, believed to have existed microseconds after the Big Bang.

The Large Hadron Collider (LHC) at CERN provides a unique opportunity to explore quarkonium production at unprecedented energies. Quarkonium states produced in proton-proton (pp) and nucleus-nucleus (PbPb) collisions serve as a sensitive probe for studying the QGP and testing the limits of perturbative and non-perturbative QCD processes. While considerable progress has been made over the last fifty years in understanding quarkonium production, several fundamental questions remain unanswered, particularly regarding the non-perturbative aspects of QCD.

Despite substantial theoretical and experimental efforts, key challenges persist in describing heavy quarkonia production in high-energy collisions. The complex interplay between color singlet and color octet states, the suppression mechanisms in heavy-ion environments, and the impact of parton energy loss in QGP are areas of active research. The production and suppression of J/ψ and Υ mesons in the hot QGP medium remain one of the most critical observables for understanding the behavior of strongly interacting matter.

This dissertation examines the mechanisms of quarkonium and high-energy hadron production in proton-proton and nucleus-nucleus collisions at LHC energies. The work integrates experimental and phenomenological analyses conducted over the period from 2011 to 2024. The first part of the dissertation presents a comprehensive phenomenological analysis using the HYDJET++ Monte Carlo model, which accounts for both thermal and non-thermal components of particle production. The findings offer new insights into the dynamics of quarkonium production, including their interaction with the quark-gluon plasma (QGP) and behavior across different energy scales. The second part of the dissertation presents an experimental measurement of heavy quarkonium suppression in PbPb collisions at 2.76 TeV, based on data collected by the CMS experiment. This experimental analysis provides valuable empirical data that complements the phenomenological findings, contributing to a more comprehensive understanding of quarkonium suppression and production mechanisms in heavy-ion collisions.

In addition to the above discussion, the Introduction chapter provides an overview of the historical development of heavy quarkonia studies, tracing discoveries such as the J/ψ and Υ mesons, which marked milestones in particle physics. It discusses foundational theoretical models for quarkonium production, including the Color Singlet Model (CSM), Color Evaporation Model (CEM), and Non-Relativistic Quantum Chromodynamics (NRQCD). The chapter also highlights unresolved challenges in the field, emphasizing the significance of polarization studies and exotic quarkonium states in advancing our understanding of QCD.

1 Methods of Investigation of Heavy Quarkonium Production

Chapter 1 of this dissertation provides a comprehensive overview of the methodologies used to investigate heavy quarkonium production in both proton-proton (pp) and nucleus-nucleus (AA) collisions at the Large Hadron Collider (LHC). The chapter is structured around two main investigative approaches: phenomenological approaches and the experimental techniques employed at the LHC.

The chapter begins by introducing the role of Monte Carlo (MC) simulations in High-Energy Physics (HEP). These stochastic methods are essential for simulating the complex processes in high-energy particle collisions, including event generation, cross-section calculations, and the propagation of particles through detector material. Several widely-used MC event generators are discussed, including HYDJET++, PYTHIA, HERWIG, and EPOS. Each of these models has distinct advantages depending on the type of collision (pp or AA) and the physics processes under study.

In the context of this dissertation, a particular focus is placed on the HYDJET++ Monte Carlo model, which is tailored for heavy-ion collisions. HYDJET++ integrates two components to simulate the full event: a thermal (soft) component that models the collective behavior of particles in a thermalized quark-gluon plasma, and a non-thermal (hard) component that models high-momentum jets and hard scatterings. This two-component model is ideal for investigating quarkonium production, as it accounts for both the initial production mechanisms and the suppression phenomena in the QGP.

The core of this chapter is devoted to the application of the HYDJET++ model to simulate heavy quarkonium production in AA collisions. The model incorporates relativistic hydrodynamics to describe the expansion and freeze-out of the QGP, where quarkonia are either produced or dissociated. This modeling approach allows for a detailed investigation of how quarkonium states (such as J/ψ) interact with the hot and dense medium created in ultrarelativistic heavy-ion collisions. The chapter explains the two-component structure of HYDJET++, where the soft component is based on parameterization of equations of relativistic hydrodynamics and the hard component - models parton energy loss through the PYQUEN subroutine, which modifies parton showers generated by PYTHIA to include medium-induced energy loss effects.

The thesis further explores how the model reproduces key experimental observables such as transverse momentum spectra, nuclear modification factors (R_{AA}), and elliptic flow coefficients (v_2). These observables are crucial for understanding the mechanisms of quarkonium suppression, particularly in the context of the color-screening effect in QGP, which leads to the dissociation of bound quarkonium states. The role of recombination models in explaining the regeneration of J/ψ mesons at lower energies is also discussed, with a focus on the temperature and energy density dependence of the suppression.

In addition to MC simulations, the chapter reviews the experimental techniques used to study quarkonia at the LHC and the Relativistic Heavy Ion Collider (RHIC). The CMS detector, a general-purpose detector at the LHC, is introduced as the primary experimental tool for the data analyzed in this dissertation. The discussion covers the detector's capabilities for quarkonium detection, emphasizing its high-resolution muon system, which is critical for reconstructing quarkonium states decaying into muon pairs.

The CMS muon system (Fig. 1) incorporates three technologies—Drift Tubes (DT), Cathode Strip Chambers (CSC), and Gas Electron Multipliers (GEM)—all operating on the principle of gas ionization. These detectors are organized into chambers that function independently. DTs are placed in the cylindrical region of the detector, CSCs in the endcaps, and GEMs in both regions. Muon chambers track particles at multiple points along their trajectories, allowing precise measurement of their deflection in

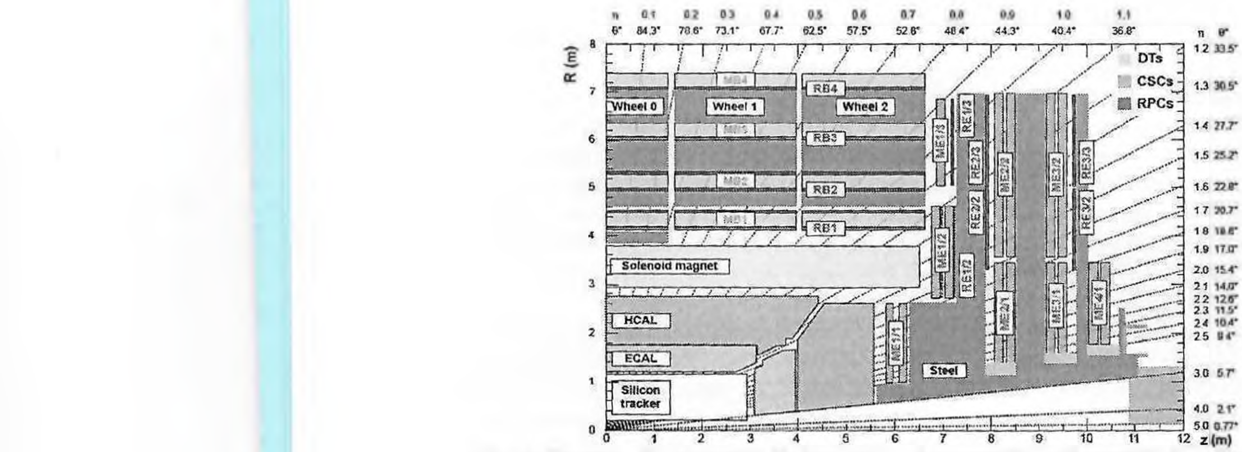

Figure 1: The cross-section of the CMS detector in the R-z plane features the z-axis oriented horizontally and the R-axis vertically. The interaction point is located in the lower left corner. This layout illustrates the positioning of various muon stations and steel disks (dark gray areas). The four Drift Tube stations (light orange) are labeled MB ("muon barrel"), while the Cathode Strip Chambers (green) are denoted ME ("muon endcap"). Gas Electron Multiplier detectors (blue) are situated in both the cylindrical and endcap parts of CMS and are marked as RB and RE, respectively.

the magnetic field. Chambers are arranged in layers at different radial distances (RR) in the cylindrical region and along the z-axis in the endcaps. Four muon stations, designated MB1–MB4 and ME1–ME4, are positioned in each region. In the cylindrical part, DTs and GEMs are distributed across five wheels along the z-axis, with W0 at z=0, W+1 and W+2 at positive z, and W-1 and W-2 at negative z. In the endcaps, CSCs and GEMs are arranged in concentric rings, labeled ME1/n to ME4/n, where n increases with radius.

The chapter highlights the advantages of the CMS detector, particularly its ability to measure quarkonia over a wide range of transverse momentum and rapidity, making it an ideal instrument for probing the hot and dense medium created in AA collisions.

The chapter also explains how quarkonia, specifically the J/ψ and Υ families, serve as sensitive probes of QGP formation. The suppression of these states due to color screening in the QGP is one of the most direct signatures of QGP formation, and thus their measurement is of paramount importance. The use of dimuon decay vertex information in the CMS detector, allows for precise measurements of both prompt and non-prompt J/ψ production, where the non-prompt component arises from decays of b-hadrons.

The Chapter 1 concludes by summarizing the methodological approaches used in this dissertation. The combination of MC simulations, particularly the HYDJET++ model, and experimental data from the CMS detector allows for a detailed investigation of quarkonium production and suppression mechanisms. The chapter sets the stage for the detailed phenomenological analysis presented in Chapter 2, where the HYDJET++ model is applied to reproduce experimental observables in PbPb collisions, and Chapter 3, which presents an experimental investigation of heavy quarkonium suppression at CMS experiment.

Overall, the methods described in this chapter provide a robust framework for the investigation of heavy quarkonia in both theoretical and experimental contexts, offering new insights into the behavior of these states in the presence of a quark-gluon plasma.

2 Charmonium Production in Heavy Ion Collisions with the HYDJET++ Model

This chapter focuses on the study of charmonium production in relativistic heavy-ion collisions, specifically analyzing the production and dynamics of J/ψ mesons within the context of the HYDJET++ Monte Carlo model. The phenomenological approach adopted integrates both thermal and non-thermal components of hadron production, providing a comprehensive framework to simulate the underlying processes of J/ψ meson formation in a Quark-Gluon Plasma (QGP) environment.

The production of quarkonia, such as J/ψ mesons, in heavy-ion collisions serves as a critical probe for studying the properties of the QGP. The suppression of quarkonia, due to the color screening effect in a deconfined medium, is one of the key signatures of QGP formation. This chapter utilizes the HYDJET++ model, which includes a hydrodynamic description of the thermal component, complemented by a jet quenching model for the non-thermal component. Together, these components simulate the full event structure of nucleus-nuclear collisions, allowing the model to reproduce key observables related to charmonium production.

A key focus of this study is the analysis of charmonia and charmed meson production in PbPb collisions at energies of $\sqrt{s_{NN}} = 2.76$ TeV, $\sqrt{s_{NN}} = 5.02$ TeV (LHC) and, as a reference, its production in AuAu collisions at energies of $\sqrt{s_{NN}} = 200$ GeV (RHIC). The HYDJET++ model were tuned to reproduce the transverse momentum (p_T) spectra, nuclear modification factor (R_{AA}), and elliptic flow (v_2) of J/ψ and D mesons (full set of the plots in the thesis).

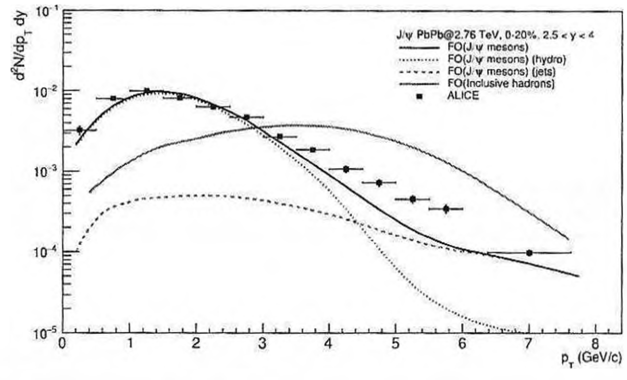

Figure 2: Transverse momentum spectrum of inclusive J/ψ-mesons for rapidity $2.5 < y < 4$ in 20% of most central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The points denote ALICE data (reference in the thesis),histograms represent simulated HYDJET++ events (magenta solid – freeze-out parameters as for inclusive hadrons, black solid – early thermal freeze-out, blue dotted and red dashed – soft and hard components respectively for the latter case).

In particular, the results for $\sqrt{s_{NN}} = 2.76$ TeV shows (Fig. 2) that J/ψ mesons exhibit early thermal freeze-out compared to lighter hadrons. This finding aligns with previous studies for RHIC energies (see reference in the thesis) and suggests that J/ψ mesons, due to their larger mass and smaller interaction cross-sections, decouple from the medium earlier than lighter particles.

Thus Figure 2 shows the comparison of HYDJET++ simulations with the ALICE data for the p_T-spectrum of inclusive J/ψ mesons in the 20% most central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Two sets of input parameters were used:

- As for inclusive hadrons ($T^{ch} = 165$ MeV, $T^{th} = 105$ MeV, $Y_L^{\max} = 4.5$, $Y_T^{\max} = 1.265$, $p_T^{\min} = 8.2$ GeV/c)
- For early thermal freeze-out ($T^{th} = T^{ch} = 165$ 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.

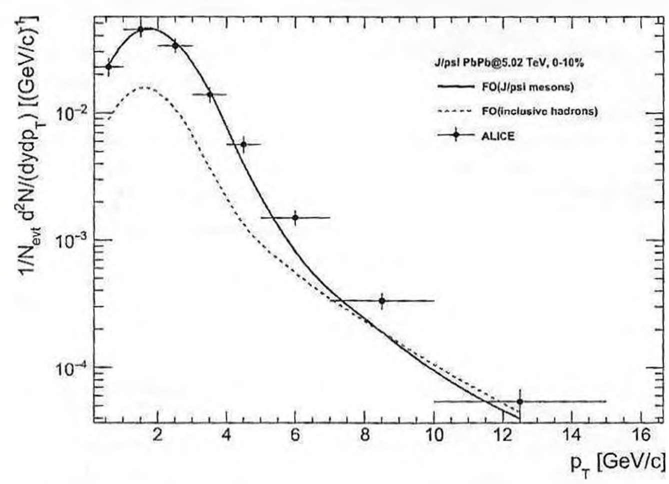

Figure 3: Transverse momentum spectrum of inclusive J/ψ-mesons for rapidity $|y| < 0.9$ in 10% of most central PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The points denote ALICE data (see reference in the thesis) , histograms represent simulated HYDJET++ events (red dashed - freeze-out parameters as for inclusive hadrons, blue solid – early thermal freeze-out).

The simulation results for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, indicate (Figure 3) that the p_T spectra of J/ψ mesons in the central rapidity region ($|y| < 0.9$) match experimental observations, with a significant portion of J/ψ mesons showing an earlier freeze-out temperature ($T^{th}_{J/\psi} = T^{ch} = 165$ MeV, blue solid line) than that of inclusive hadrons ($T^{th}_{hadrons} = 105$ MeV, red dashed line). This early freeze-out behavior is similar to one observed at $\sqrt{s_{NN}} = 2.76$ TeV, and crucial for understanding the interactions of charmonium states with the QGP and their dissociation and recombination processes. The comparizon for other observables, like elliptic flow and nuclear modification factor is also presented in the dissertation.

Additionally, the study explores the production of D mesons in PbPb collisions. The thermal freeze-out temperature for D mesons at $\sqrt{s_{NN}} = 2.76$ TeV is observed to align with that of light hadrons (Figure 4). This result implies that D mesons, unlike J/ψ mesons, achieve kinetic equilibrium with the

QGP at this energy. This observation contrasts with findings from $\sqrt{s_{NN}} = 200$ GeV AuAu collisions (Figure 5), where D mesons exhibited behavior similar to that of J/ψ mesons.This observation further underscores the importance of thermal and non-thermal components in the charmonium production mechanism.

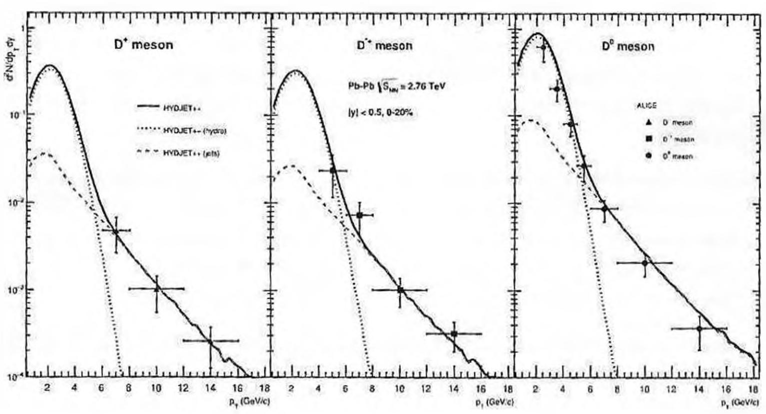

Figure 4: Transverse momentum spectra of $D^{\mp}$ (left panel), $D^{*}\pm$ (middle panel) and D^0 (right panel) for rapidity $|y| < 0.5$ in 20% of most central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The points denote ALICE data (see reference in the thesis) , histograms represent simulated HYDJET++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

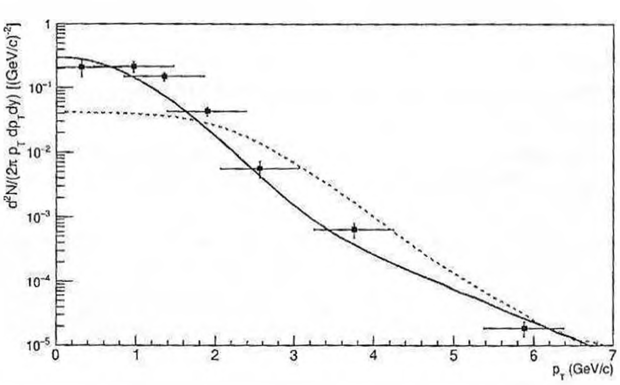

Figure 5: Transverse-momentum distribution of D^0 mesons in 10% of the most central Au–Au collisions at the energy $\sqrt{s_{NN}} = 200$ GeV for the rapidity range $|y| < 1$. The points are STAR data from (see reference in the thesis) and the lines are the results of the HYDJET++ simulation with the freeze-out parameters for inclusive hadrons (red dashed line) and "early" thermal freeze-out (solid blue line).

Summarizing, the results presented in Chapter 2 of the dissertation highlight the ability of the HYDJET++ model to describe the production and suppression of J/ψ mesons in PbPb collisions at the LHC. Within the framework of HYDJET++, the momentum spectra and elliptic flow (presented in the thesis) of D and J/ψ mesons are simultaneously reproduced, based on specific assumptions about their thermal behaviors:

- **Thermal Freeze-Out of D-mesons at the LHC energies:** It is assumed that the thermal freeze-out of D-mesons occurs simultaneously with that of light hadrons. This suggests that a significant part of D-mesons, particularly those up to a transverse momentum (p_T) of approximately 4 GeV/c, achieve kinetic equilibrium with the hot hadronic matter created in the collisions. This equilibrium implies that the interaction cross section of D-mesons at LHC energies becomes comparable to that of light hadrons.
- **Thermal Freeze-Out of J/ψ Mesons at the LHC energies:** In contrast, the thermal freeze-out of J/ψ mesons is assumed to occur appreciably earlier, presumably at the phase of chemical freeze-out, with reduced radial and longitudinal collective velocities. This earlier freeze-out suggests that J/ψ mesons do not reach kinetic equilibrium with the surrounding medium, and their interaction cross section remains significantly smaller than that of light hadrons.

This phenomenological study elucidates the nuanced interaction dynamics of charmed mesons and charmonium in heavy ion collisions, providing significant insights into their production mechanism, in such extreme environments as QGP. By delineating the conditions under which charmed mesons and charmonium achieve or fail to achieve kinetic equilibrium, this study contributes significantly to our knowledge of high-energy physics and the complex interplay of forces within a quark-gluon plasma.

3 Heavy Quarkonia Suppression in PbPb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

This chapter explores the suppression of heavy quarkonia in PbPb collisions, focusing on both charmonium (J/ψ) and bottomonium (Υ) states. The suppression of these states serves as a significant signature of quark-gluon plasma (QGP) formation and the interaction of quarkonia with the hot, deconfined medium. The analysis relies on data collected by the CMS experiment during collisions at a center-of-mass energy of 2.76 TeV per nucleon pair.

The investigation into quarkonium suppression reveals a number of key observations. For J/ψ, the study identifies a marked reduction in yield, with a pronounced centrality dependence (see Fig. 6, left plot). The suppression is quantified by the nuclear modification factor, R_{AA}, which indicates an approximately fivefold suppression for prompt J/ψ mesons in the most central collisions compared to proton-proton (pp) results (Fig. 6, black cross on the right plot). No significant transverse momentum (p_T) dependence is observed in the R_{AA} (Fig. 7), but suppression is found to be more pronounced at mid-rapidity than at forward rapidity (Fig. 8). This suggests complex dynamics in how quarkonia interact with the QGP.

Non-prompt J/ψ, originating from b-hadron decays, exhibit less suppression compared to prompt states, although the suppression factor still reaches approximately two in central collisions (Fig. 9). The non-prompt component provides important insights into b-quark energy loss in the medium, as these mesons are less affected by color screening but more by the medium's energy dissipation mechanisms.

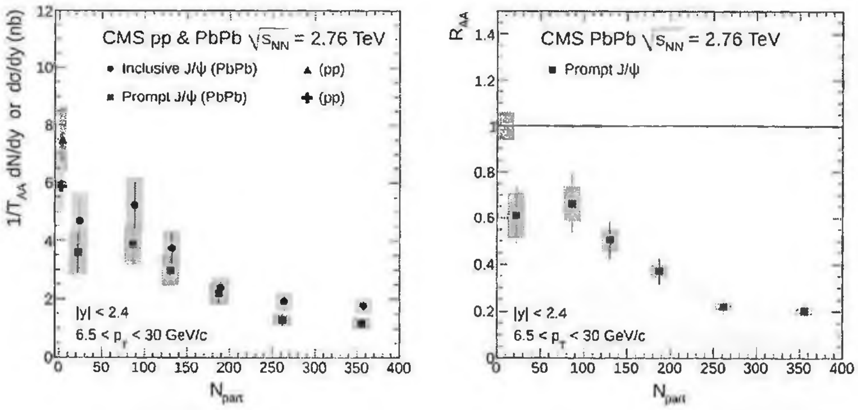

Figure 6: Left: yield of inclusive J/ψ (blue circles) and prompt J/ψ (red squares) divided by T_{AA} as a function of N_{part}. The results are compared to the cross sections of inclusive J/ψ (black triangle) and prompt J/ψ (black cross) measured in pp. The inclusive J/ψ points are shifted by $\Delta N_{part} = 2$ for better visibility. Right: nuclear modification factor R_{AA} of prompt J/ψ as a function of N_{part}. A global uncertainty of 6%, from the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Statistical (systematic) uncertainties are shown as bars (boxes).

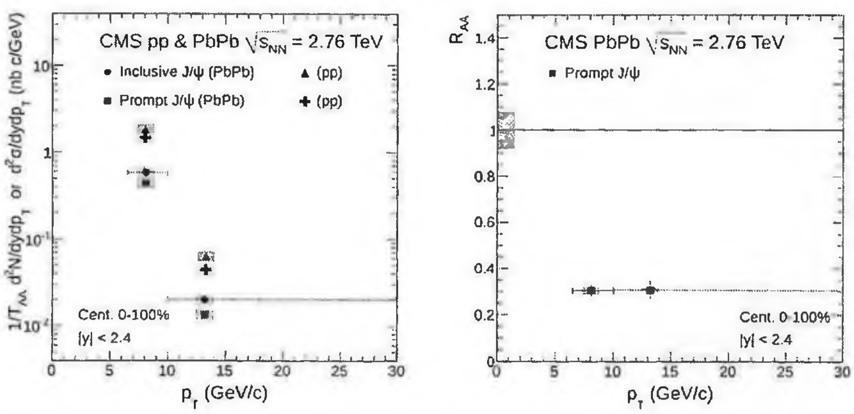

Figure 7: Left: yield of inclusive J/ψ (blue circles) and prompt J/ψ (red squares) divided by T_{AA} as a function of p_T. The results are compared to the cross sections of inclusive J/ψ (black triangles) and prompt J/ψ (black crosses) measured in pp. The global scale uncertainties on the PbPb data due to T_{AA} (5.7%) and the pp integrated luminosity (6.0%) are not shown. Right: nuclear modification factor R_{AA} of prompt J/ψ as a function of p_T. A global uncertainty of 8.3%, from T_{AA} and the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Points are plotted at their measured average p_T. Statistical (systematic) uncertainties are shown as bars (boxes). Horizontal bars indicate the bin width.

The study extends to the bottomonium family, specifically $\Upsilon(1S)$, where a similar suppression pattern is noted. The R_{AA} for $\Upsilon(1S)$ shows a suppression by a factor of two, largely at low p_T (Fig. 10, right), with minimal variation across rapidity(Fig. 10, left) and centrality (Fig. 11, left). The results hint at

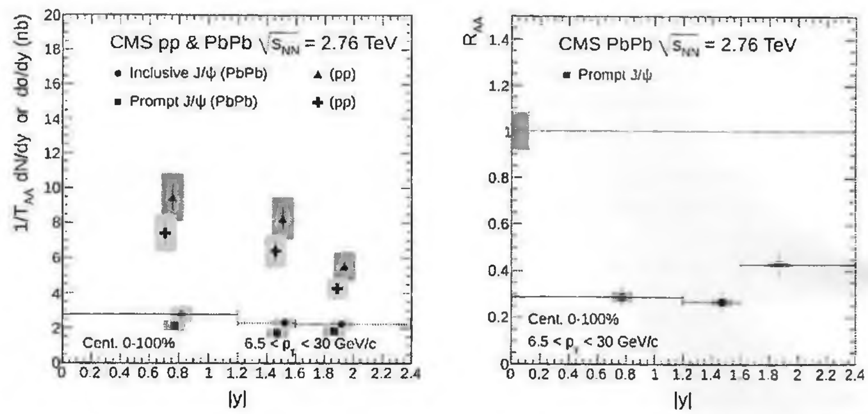

Figure 8: Left: yield of inclusive J/ψ (blue circles) and prompt J/ψ (red squares) divided by T_{AA} as a function of rapidity. The results are compared to the cross sections of inclusive J/ψ (black triangles) and prompt J/ψ (black crosses) measured in pp. The inclusive J/ψ points are shifted by $\Delta y = 0.05$ for better visibility. The global scale uncertainties on the PbPb data due to T_{AA} (5.7%) and the pp integrated luminosity (6.0%) are not shown. Right: nuclear modification factor R_{AA} of prompt J/ψ as a function of rapidity. A global uncertainty of 8.3%, from T_{AA} and the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Points are plotted at their measured average $|y|$. Statistical (systematic) uncertainties are shown as bars (boxes). Horizontal bars indicate the bin width.

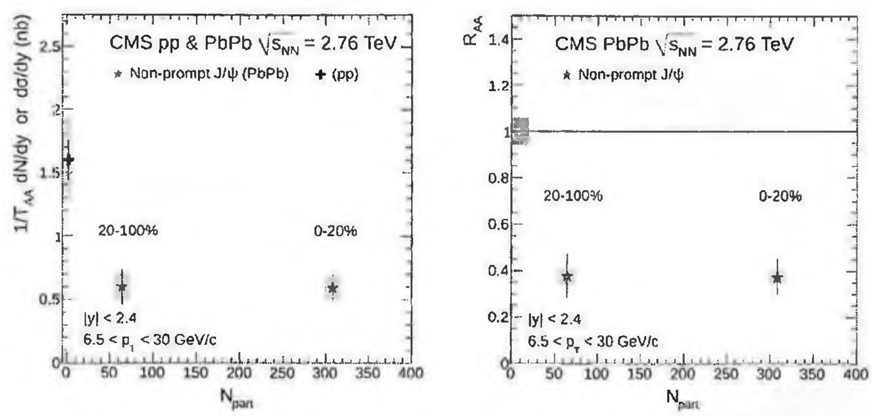

Figure 9: Left: Non-prompt J/ψ yield in PbPb collisions divided by T_{AA} compared to the pp cross-section. Right: Nuclear modification factor R_{AA} of non-prompt J/ψ as a function of N_{part}. A global uncertainty of 6%, from the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$.

the survival of the ground state $\Upsilon(1S)$, while the higher excited states such as $\Upsilon(2S)$ experience more significant suppression (Fig. 11, right), which may be connected to their lower binding energies.

Overall, the chapter offers a comprehensive experimental analysis of heavy quarkonium suppression in PbPb collisions. The findings provide empirical evidence that supports theoretical models of QGP formation and quarkonium behavior within such extreme conditions. This work enriches the understanding

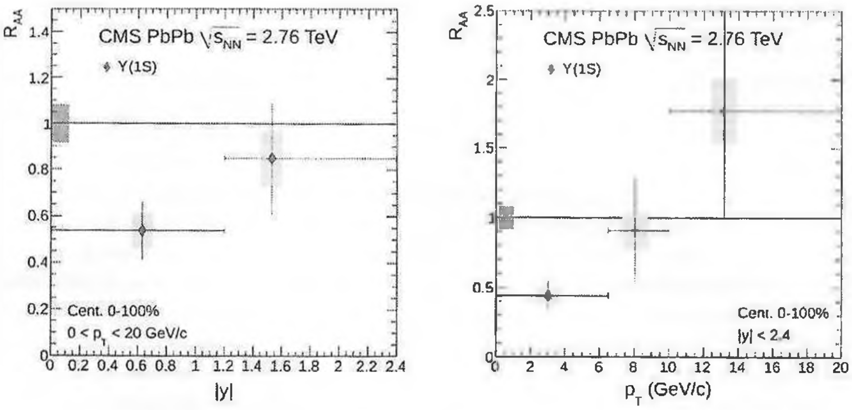

Figure 10: Nuclear modification factor R_{AA} of $\Upsilon(1S)$ as a function of rapidity (left) and p_T (right). A global uncertainty of 8.3%, from T_{AA} and the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Points are plotted at their measured average p_T. Statistical (systematic) uncertainties are shown as bars (boxes). Horizontal bars indicate the bin width.

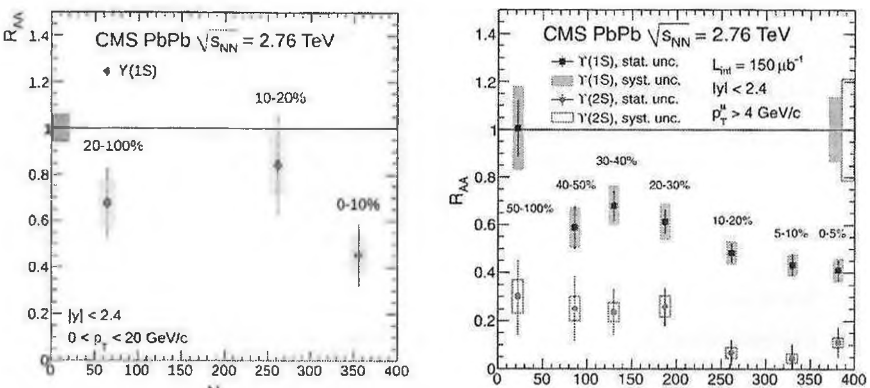

Figure 11: Nuclear modification factor R_{AA} of $\Upsilon(1S)$ (left) and both 1S+2S (right) states as a function of N_{part}. A global uncertainty of 6%, from the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Statistical (systematic) uncertainties are shown as bars (boxes).

of quarkonium suppression mechanisms and contributes to ongoing efforts to disentangle the complex interplay between quarkonium production and the deconfined QGP phase in heavy-ion collisions.

4 Conclusion

4.1 Discussion

The discussion chapter critically synthesizes the findings from both phenomenological and experimental analyses regarding heavy quarkonium production in heavy-ion collisions. The phenomenological analysis leverages the HYDJET++ model to replicate key observables such as the spectra, nuclear modification factors and elliptic flow coefficients for J/ψ and D-mesons, employing both thermal and non-thermal mechanisms. This analysis highlights that J/ψ mesons demonstrate earlier freeze-out behavior compared to D-mesons, contributing to a deeper understanding of their interactions with the quark-gluon plasma (QGP).

In parallel, the experimental data obtained from the CMS detector reinforces the suppression effects observed for quarkonium states in PbPb collisions, particularly in measurements of prompt and non-prompt J/ψ and Υ mesons. Significant suppression in central collisions is evident, as is empirical evidence of b-hadron suppression, offering further insights into the impact of QGP on quarkonium production.

This chapter emphasizes the importance of these findings for advancing the understanding of quarkonium suppression mechanisms. The study not only refines the two-component model for quarkonium production in the QGP but also provides a solid foundation for future experimental and theoretical efforts in the field of high-energy heavy-ion physics.

The results presented in this discussion pave the way for future research aimed at deepening our knowledge of QGP dynamics and quarkonium behavior, underlining the value of integrated phenomenological and experimental approaches in high-energy physics.

4.2 Main Results

This dissertation presents both a comprehensive phenomenological and experemental analysis of charmed meson, charmonium and bottomonium production in lead-lead collisions at a center-of-mass energy of 2.76 and 5.02 TeV per nucleon pair, elucidating several key aspects:

- The phenomenological analysis utilizes the HYDJET++ model, which integrates both thermal and non-thermal production mechanisms, to successfully reproduce the momentum spectra and elliptic flow of D and J/ψ mesons.
- It is demonstrated that D-mesons achieve kinetic equilibrium with the hot hadronic matter created in PbPb collisions at LHC, indicative of their interaction cross-section becoming comparable to that of light hadrons. Conversely, J/ψ mesons undergo thermal freeze-out earlier, presumably at the chemical freeze-out phase, suggesting significantly smaller interaction cross-sections.
- The experemental study on CMS, presents the first measurements of suppression in prompt J/ψ, non-prompt J/ψ, and Υ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Notably, this includes the first direct observation of b-hadron suppression.
- The impact of J/ψ and $\Upsilon(1S)$ polarization on detection acceptance is quantified for the most extreme polarization scenarios in both the Collins–Soper and helicity frames, illustrating significant effects on the measured yields in heavy-ion collisions.

These findings collectively advance our understanding of quarkonium behavior in the quark-gluon plasma, significantly contributing to the field of heavy-ion physics at the Large Hadron Collider.

4.3 Actuality and Future Works

Despite over fifty years of investigation into heavy quarkonia, many questions remain (see the literature review in the thesis), particularly regarding the non-perturbative aspects of its production mechanism, which are still under intense study. This dissertation contributes to the body of knowledge by presenting a series of studies on heavy quarkonia production mechanisms. The author has continued to develop this topic further, focusing on disentangling the contributions from the Color Singlet and Color Octet processes within the Non-Relativistic Quantum Chromodynamics (NRQCD) framework for heavy quarkonia production in proton-proton (pp) collisions at LHC energies. Articles detailing these findings are currently being prepared. Furthermore, the author plans to extend these studies to heavy ion collisions, aiming to provide deeper insights into the complexities of Heavy Quarkonium production in such environments and direct comparison with results achieved in proton-proton collisions.

Complete **Bibliography** is presented in the thesis.

Publication list

1. I. P. Lokhtin, A. V. Belyaev, G. Kh. Eyyubova, G. Ponimatkin, and E. Yu Pronina. Thermal and non-thermal charmed meson production in heavy ions collisions at the LHC. J. Phys. Conf. Ser., 668(1):012068, 2016.

2. Gyulnara Eyyubova, I. P. Lokhtin, A. V. Belyaev, G. Ponimatkin, and E. Yu. Pronina. Spectra and elliptic flow of charmed hadrons in HYDJET++ model. PoS, EPS-HEP2015:214, 2015.

3. I. P. Lokhtin, A. V. Belyaev, G. Kh. Eyyubova, G. Ponimatkin, and E. Yu. Pronina. Charmed meson and charmonium production in PbPb collisions at the LHC. J. Phys. G, 43(12):125104, 2016.

4. I. P. Lokhtin, A. V. Belyaev, G. Ponimatkin, E. Yu. Pronina, and G. Kh. Eiyubova. On the possibility of thermalization of heavy mesons in ultrarelativistic nuclear collisions. J. Exp. Theor. Phys., 124(2):244–250, 2017.

5. G. Kh. Eyyubova, I. P. Lokhtin, A. V. Belyaev, G. Ponimatkin, and E. Yu. Pronina. Charm meson production in Pb-Pb collisions at the LHC in HYDJET++ model. Phys. Part. Nucl., 48(6):938–940, 2017.

6. I. P. Lokhtin, A. V. Belyaev, L. V. Malinina, S. V. Petrushanko, A. M. Snigirev, I. Arsene, and E. E. Zabrodin. Modeling the jet quenching, thermal resonance production and hydrodynamical flow in relativistic heavy ion collisions. J. Phys. Conf. Ser., 270:012060, 2011.

7. CMS collaboration (... A.Belyaev... et al.). Indications of suppression of excited Υ states in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys. Rev. Lett., 107:052302, 2011.

8. CMS collaboration (... A.Belyaev... et al.). Suppression of Non-Prompt J/ψ, Prompt J/ψ, and $\Upsilon(1S)$ in PbPb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV. JHEP, 05:063, 2012.

9. CMS collaboration (... A.Belyaev... et al.). Observation of Sequential Upsilon Suppression in PbPb Collisions. Phys. Rev. Lett., 109:222301, 2012. [Erratum: Phys.Rev.Lett. 120, 199903 (2018)].

10. A. Belyaev. J/ψ Meson Production Pattern in PbPb Collisions at 5.02 TeV in HYDJET++ Model. RNAS RA., 124(3-4):13–19, 2024.

Բեկյան Անդրեյ Վլադիսլավովիչ

Կվարկոնիումի և բարձր էներգիայի հադրոնների ծնման մեխանիզմները պրոտոն-պրոտոնային և միջուկ-միջուկային բախումներում Մեծ հադրոնային կոլայդերի էներգիաներում

Ամփոփագիր

Այս դիսերտացիան ներկայացնում է չարմոնիումի, բոթտոմոնիումի և չարմավորված մեզոնների ծննդի համապարփակ ֆենոմենոլոգիական և փորձարարական վերլուծություն՝ կատարված միջուկ-միջուկ բախումների ընթացքում $\sqrt{s_{NN}}$ = 2.76 և 5.02 ՏէՎ էներգիաների պայմաններում՝ բացահայտելով քվարկոնիումների դինամիկայի և դրանց փոխազդեցության հիմնական ասպեկտները կվարկ-գլյուոնային պլազմայում (ԿԳՊ):

Ֆենոմենոլոգիական վերլուծության արդյունքում ձեռք է բերվել D- և J/ψ-մեզոնների իմպուլսային սպեկտրների և էլիպտիկական հոսքերի նկարագրությունը՝ հիմնված HYDJET++ երկբաղադրիչ մոդելի վրա, որը միավորում է մասնիկների ծննդի թերմիկ և ոչ թերմիկ մեխանիզմները:

Ցուցադրվել է, որ D-մեզոնները հասնում են թերմիկական հավասարակշռության այն տաք միջավայրի հետ, որը ձևավորվում է կապար իոնների բախումների ընթացքում LHC էներգիաների պայմաններում: Միևնույն ժամանակ, J/ψ-մեզոնները բնութագրվում են ավելի վաղ թերմիկական "սառեցմամբ", ինչը վկայում է դրանց թույլ փոխազդեցության մասին կվարկ-գլյուոնային պլազմայի հետ:

Չափվել է ուղղակի և երկրորդային J/ψ-մեզոնների, ինչպես նաև Υ-պայմանների ճնշումը PbPb բախումների ընթացքում $\sqrt{s_{NN}} = 2.76$ ՏէՎ էներգիայով: Ուղղակի J/ψ-մեզոնների համար միջուկային փոփոխության գործակիցը կազմել է $R_{AA} = 0.20 \pm 0.03 \pm 0.01$ առավել կենտրոնական բախումների դեպքում և աճել է մինչև $0.61 \pm 0.12 \pm 0.12$ ծայրամասային բախումների ժամանակ:

Առաջին անգամ, անուղղակիորեն (երկրորդային J/ψ-մեզոնների ճնշման չափման միջոցով), չափվել է b-հադրոնների ճնշումը ԿԳՊ-ում, ինչը հաստատում է ծանր քվարկների էներգիայի կորուստը կվարկ-գլյուոնային պլազմայում: Երկրորդային J/ψ-մեզոնների ճնշումը, որոնք ծագում են b-հադրոնների տրոհումներից, բնութագրվել է $R_{AA} = 0.37 \pm 0.08 \pm 0.02$ գործակցով առավել կենտրոնական բախումների 20

Հաստատվել է, որ J/ψ և $\Upsilon(1S)$-մեզոնների բևեռացումը զգալի ազդեցություն է ունենում դետեկտորի գեոմետրիկ ընդունման չափման վրա: Առավելագույն ազդեցությունը դիտվել է լրիվ երկայնական բևեռացման դեպքում J/ψ-ի համար (մինչև 40

Բացի այդ, ցույց է տրվել, որ $\Upsilon(2S)$ գրգռված վիճակները ենթարկվում են ավելի ուժեղ ճնշման՝ համեմատած հիմնական $\Upsilon(1S)$ վիճակի հետ, ինչը կապված է գրգռված վիճակների ավելի փոքր կապման էներգիայի հետ:

Ստացված արդյունքները լրացնում են քվարկոնիումի ծննդի մեխանիզմների, ծանր քվարկների տաք միջավայրի հետ փոխազդեցությունների և ծանր իոնների բախումների ընթացքում դիսոցիացիոն գործընթացների ժամանակակից ըմբռնումը:

Беляев Андрей Владиславович

Механизмы рождения кварկониев и высокоэнергетических адронов в протон-протонных и ядро-ядерных столкновениях при энергиях Большого адронного коллайдера

Резюме

Данная диссертация представляет всесторонний феноменологический и экспериментальный анализ рождения чармония, боттомония и чармированных мезонов в ядро-ядерных столкновениях при энергиях $\sqrt{s_{NN}} = 2.76$ и 5.02 ТэВ на пару нуклонов, раскрывая ключевые аспекты динамики кварькониев и их взаимодействия в среде кварко-глюонной плазмы (КГП).

В результате феноменологического анализа, было достигнуто описание спектров импульсов и эллиптических потоков D- и J/ψ-мезонов в тяжелоионных столкновениях на основе двухкомпонентной модели HYDJET++, объединяющей термические и нетермические механизмы рождения частиц.

Было показано, что D-мезоны достигают термического равновесия с горячей средой, сформированной в столкновениях ионов свинца при энергиях LHC. В то же время J/ψ-мезоны характеризуются более ранним термическим вымораживанием, что указывает на их слабое взаимодействие с кварко-глюонной плазмой.

Было измерено подавление прямых и вторичных J/ψ-мезонов, а также Υ-состояний в столкновениях PbPb при $\sqrt{s_{NN}} = 2.76$ ТэВ. Фактор ядерной модификации R_{AA} для прямых J/ψ-мезонов составил $0.20 \pm 0.03 \pm 0.01$ в наиболее центральных столкновениях и увеличивался до $0.61 \pm 0.12 \pm 0.12$ в периферийных.

Впервые было косвенно (через измерение подавления вторичных J/ψ-мезонов) измерено подавление b-адронов в КГП, что подтверждает энергетические потери тяжелых кварков в кварко-глюонной плазме. Подавление вторичных J/ψ-мезонов, происходящих из распада b-адронов, характеризовалось фактором $R_{AA} = 0.37 \pm 0.08 \pm 0.02$ в 20% наиболее центральных соударений.

Также было установлено, что поляризация J/ψ и $\Upsilon(1S)$-мезонов оказывает существенное влияние на измерение геометрического аксептанса детектора. Максимальное влияние наблюдалось для полностью продольной поляризации J/ψ (до 40%) и поперечной поляризации $\Upsilon(1S)$. Однако измеренные в эксперименте значения поляризации были близки к нулю.

Помимо этого, было продемонстрировано, что возбужденные состояния $\Upsilon(2S)$ испытывают более сильное подавление по сравнению с основным состоянием $\Upsilon(1S)$, что связано с меньшей энергией связи возбужденных состояний.

Полученные результаты дополняют современное понимание механизмов рождения кваркониума, взаимодействий тяжелых кварков с горячей средой и процессов диссоциации в условиях соударений тяжелых ионов при высоких энергиях.