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# Study of Inclusive J/ψ Production Cross Section at Midrapidity in Proton-Proton Interactions at $\sqrt{s}$ = 13 TeV

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**ABSTRACT**

The primary objective of this study is to investigate J/ψ meson production in proton-proton (pp) collisions at a centre-of-mass energy of 13 TeV. Particular attention is given to the midrapidity region, defined by |y| < 0.9, while the transverse momentum (\(p_T\)) distribution is examined over the range of 0–40 GeV/c. Collision events are simulated using two versions of the EPOS event generator, namely EPOS-1.99 and EPOS-LHC. The resulting predictions are compared with experimental measurements reported by the ALICE experiment at CERN to evaluate the performance of these models in describing J/ψ production. The comparative analysis indicates that EPOS-LHC provides better agreement with the experimental data across several transverse momentum intervals, including 0–7, 0–10, 0–14, and 0–40 GeV/c. These findings demonstrate the improved capability of EPOS-LHC to reproduce the measured J/ψ production characteristics over the investigated momentum ranges. Furthermore, the variation in J/ψ production rates is investigated in two distinct rapidity regions of proton-proton collisions at a centre-of-mass energy of 13 TeV: the forward rapidity region (2.5 < y < 4) and the central rapidity region (|y| < 0.9). The comparison between model predictions and experimental measurements reveals that EPOS-LHC generally provides a closer description of the observed production distributions, particularly at lower transverse momentum. Although EPOS-1.99 demonstrates reasonable agreement within certain transverse momentum intervals, including 0–2, 0–3, 0–10, and 7–40 GeV/c, EPOS-LHC exhibits more consistent agreement across the soft and hard transverse momentum regions. Overall, the results suggest that EPOS-LHC offers a more reliable description of the differential J/ψ production characteristics in high-energy proton-proton collisions within the kinematic regions considered in this study.

**Keywords:** J/ψ Meson Production; EPOS-LHC; EPOS-1.99; Rapidity; Transverse Momentum; Large Hadron Collider (LHC); Quark-Gluon Plasma (Figure 1).

**Abbreviations:** HEP: High-Energy Physics; QCD: Quantum Chromodynamics; PP: Proton-Proton; LDMEs: Long-Distance Matrix Elements; NRQCD: Non-Relativistic Quantum Chromodynamics; CSM: Color Singlet Model; CEM: Color Evaporation Model; AI: Artificial Intelligence

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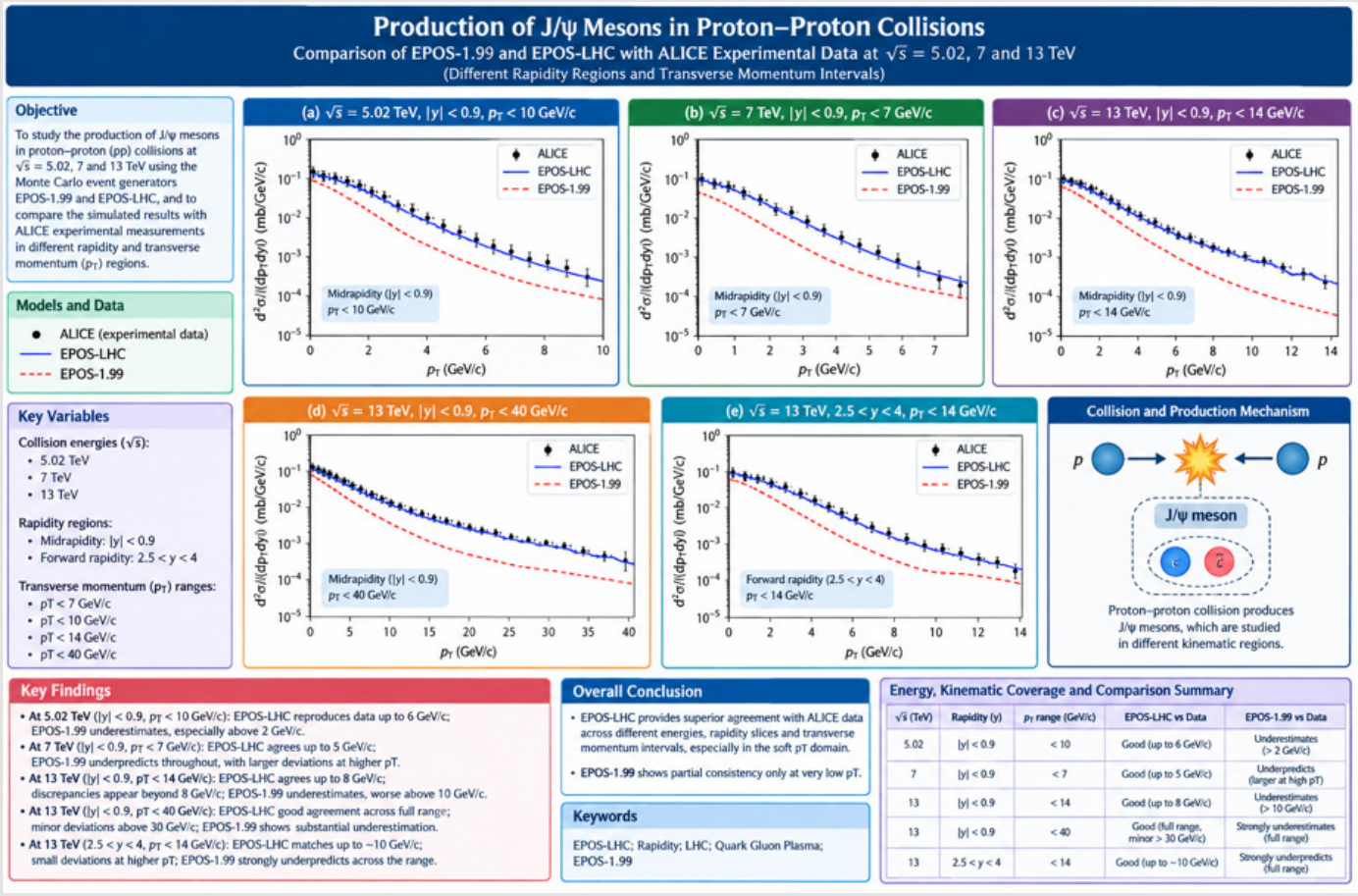



**Figure 1.**

## Introduction

Particle physics is concerned with identifying the fundamental constituents of matter and understanding the interactions that govern the universe. High-energy physics (HEP), commonly referred to as elementary particle physics, investigates the properties and interactions of subatomic particles. Protons and neutrons, which constitute atomic nuclei, are themselves composed of quarks. These quarks are held together by the strong interaction, which is mediated by gluons [1-3]. The study of high-energy nuclear collisions provides an important connection between nuclear physics and particle physics. In such collisions, heavy atomic nuclei are accelerated to relativistic velocities, allowing their constituent particles to interact under extreme energy and density conditions. These interactions provide an opportunity to investigate the properties of strongly interacting matter under conditions that cannot ordinarily be produced in laboratories. Quantum Chromodynamics (QCD) provides the theoretical framework for describing the strong interaction and the behaviour of quarks and gluons. According to QCD, sufficiently high temperatures or energy densities can lead to a transition from confined hadronic matter to a deconfined state known as the Quark-Gluon Plasma (QGP). In this state, quarks and gluons are no longer confined within individual hadrons and can interact over larger distances. Understanding the properties of this state requires the investigation of particle production and the kinematic characteristics of the resulting particles.

Among the important kinematic quantities used in high-energy collision studies is transverse momentum (\(p_T\)). It represents the component of a particle's momentum perpendicular to the direction of the colliding beams. Since transverse momentum remains invariant under Lorentz boosts along the beam direction, it is particularly useful for analysing particle production in high-energy interactions. The \(p_T\) distribution provides valuable information about the underlying production mechanisms, including both soft and hard scattering processes. In contrast, longitudinal momentum (\(p_z\)), which is directed along the beam axis, is affected by boosts along that direction and is therefore less convenient for certain comparative

analyses. Another essential kinematic variable is rapidity (\(y\)), which describes the longitudinal motion of a particle in relation to the beam direction. It is defined in terms of the particle's energy and longitudinal momentum. Owing to its additive transformation property under Lorentz boosts along the beam axis, rapidity provides a convenient means of comparing particle production in different reference frames [4-6]. The study of transverse momentum and rapidity distributions is therefore important for understanding particle production mechanisms and testing theoretical descriptions of high-energy interactions. The inclusive production cross-section of J/ψ mesons in proton-proton (pp) collisions at the Large Hadron Collider (LHC) provides an important opportunity to investigate the strong interaction within the framework of QCD.

The J/ψ meson is a charmonium state consisting of a charm quark and an anticharm quark (\(c\bar{c}\)). Its production is particularly useful for studying heavy-quark production mechanisms and the subsequent formation of bound states. Measurements performed at midrapidity provide valuable information about particle production in the central region of the collision and allow theoretical predictions to be tested against experimental observations. Such measurements also contribute to investigations of the energy dependence of charmonium production and the validity of different QCD-based approaches. For example, Sirunyan et al. reported measurements of double-differential production cross-sections for several quarkonium states in proton-proton collisions at a centre-of-mass energy of 13 TeV using the CMS detector. Their analysis extended the transverse momentum coverage and improved the statistical precision compared with earlier measurements at 7 TeV [7-10]. These experimental results provide an important basis for testing theoretical descriptions of quarkonium production, particularly the assumptions of Non-Relativistic Quantum Chromodynamics (NRQCD), the determination of Long-Distance Matrix Elements (LDMEs), and the energy dependence of charmonium production. The production of J/ψ mesons is generally associated with the creation of charm-anticharm quark pairs through initial partonic interactions, particularly gluon-gluon fusion. Perturbative QCD provides a theoretical description of the initial heavy-quark production process.

However, the subsequent formation of a physical charmonium state involves non-perturbative QCD dynamics, which cannot be calculated straightforwardly using perturbative methods alone. To describe this transition, several theoretical approaches have been developed, including NRQCD, the Color Singlet Model (CSM), and the Color Evaporation Model (CEM). These approaches provide different descriptions of the mechanisms through which a charm-anticharm pair evolves into a bound charmonium state [11-13]. The present study investigates the inclusive production cross-section of J/ψ mesons in proton-proton collisions at a centre-of-mass energy of 13 TeV. For this purpose, simulated collision events are generated using two Monte Carlo event generators, EPOS-1.99 and EPOS-LHC. A total of 500,000 pp interaction events are considered. The resulting simulation predictions are compared with experimental measurements to examine the ability of the two models to reproduce the observed J/ψ production behaviour. Particular attention is given to the transverse momentum and rapidity distributions, with the aim of evaluating the performance of these event generators in describing charmonium production at LHC energies.

## Method and Models

The inclusive production cross-section of J/ψ mesons in proton-proton collisions at a centre-of-mass energy of 13 TeV is investigated using two Monte Carlo event generators, EPOS-1.99 and EPOS-LHC. These computational models are employed to simulate particle production and examine the characteristics of the resulting collision events. Their predictions are subsequently compared with available experimental measurements to evaluate their ability to reproduce the observed J/ψ production distributions [14]. The EPOS framework incorporates several theoretical concepts, including parton ladders, off-shell remnants, and ladder-splitting mechanisms [15]. Within this approach, a proton-proton interaction can involve the exchange of parton ladders, which represent the underlying partonic interactions responsible for particle production [16]. An important characteristic of the EPOS framework is its treatment of energy conservation during particle production and cross-section calculations. This feature contributes to its description of hadronic interactions, particularly in situations involving multiple partonic interactions [17]. The EPOS event generator is based on a theoretical framework that has been developed and tested against a broad range of experimental data from hadronic interactions. Its applications extend beyond collider physics to the simulation of high-energy cosmic-ray interactions and the development of extensive air showers. In the present study, EPOS-1.99 is employed to investigate soft QCD interactions, whereas EPOS-LHC represents an updated version of the framework incorporating modifications intended to improve its description of particle production at LHC energies. Comparing the predictions of these two versions makes it possible to examine the effects of model developments on the simulated J/ψ production characteristics.

## Results and Discussion

In this study, simulated outcomes from high-energy collisions between protons were examined in order to investigate the behavior of the production patterns for J/ψ mesons. A thorough comparison of trends across several energy scales was made possible by segmenting the data into distinct intervals according to motion-related variables and spatial distribution features. For instance, the computed results at 5.02 TeV for $0 < pT < 10$ GeV/c and $|y| < 0.9$ are presented in Figure 4.1. Similar calculations were carried out at 7 TeV and 13 TeV, with $|y| < 0.9$ and $2.4 < y < 5$, covering broader pT ranges such as 0–7 GeV, 0–14 GeV,and 0–40 GeV/c.In the 5.02 TeV case, the EPOS-LHC model closely matches experimental findings, while EPOS 1.99 underestimates

cross-section values, especially in higher pT intervals. In contrast, at lower pT (<2 GeV/c), EPOS 1.99 predictions align more closely with the measurements. These differences grow with increasing transverse momentum. At 7 TeV, the trends remain consistent: EPOS-LHC delivers better predictions in the range 0–5 GeV/c, while deviations emerge at pT > 4 GeV/c. EPOS 1.99 performs moderately well at very low pT (below 3 GeV/c), but discrepancies increase with higher momentum. The 13 TeV analysis further strengthens these observations. For 0–14 GeV/c and |y| < 0.9, EPOS-LHC again exhibits strong agreement with data up to 8 GeV/c. Minor deviations appear at higher pT. EPOS 1.99's accuracy deteriorates beyond 10 GeV/c. The analysis of the full 0–40 GeV/c range in |y| < 0.9 and in 2.5 < y < 4 confirms EPOS-LHC's superior modeling across broader kinematic domains. In each case, ratio plots of experimental to Monte Carlo values are provided for visual comparison. The results consistently favor EPOS-LHC as the more reliable model for reproducing experimental J/ψ production data across different energies and rapidity slices (Figures 2-6).

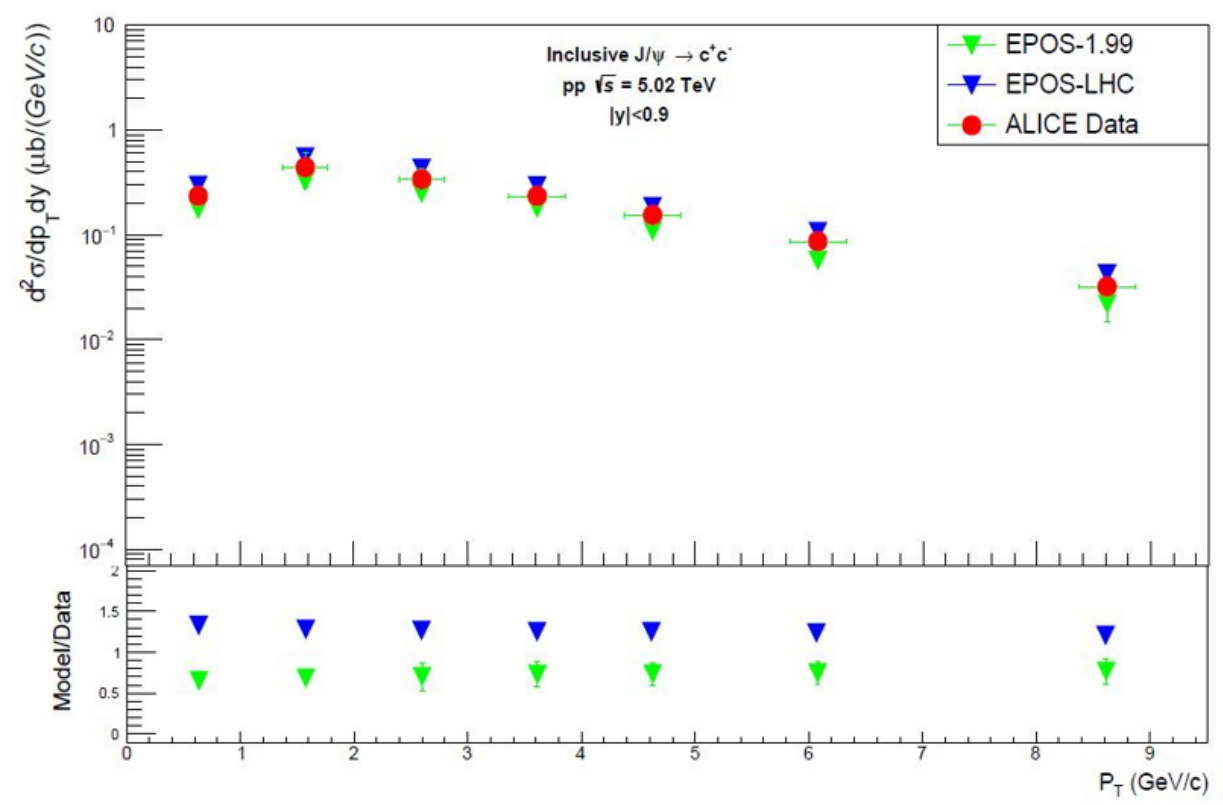



**Figure 2:** EPOS-LHC and EPOS-1.99 models for inclusive J/ψ generation cross section in proton-proton collisions at 5.02 TeV in the mid-rapidity, |y| < 0.9. The panel below also illustrates the ratio between models and ALICE data.

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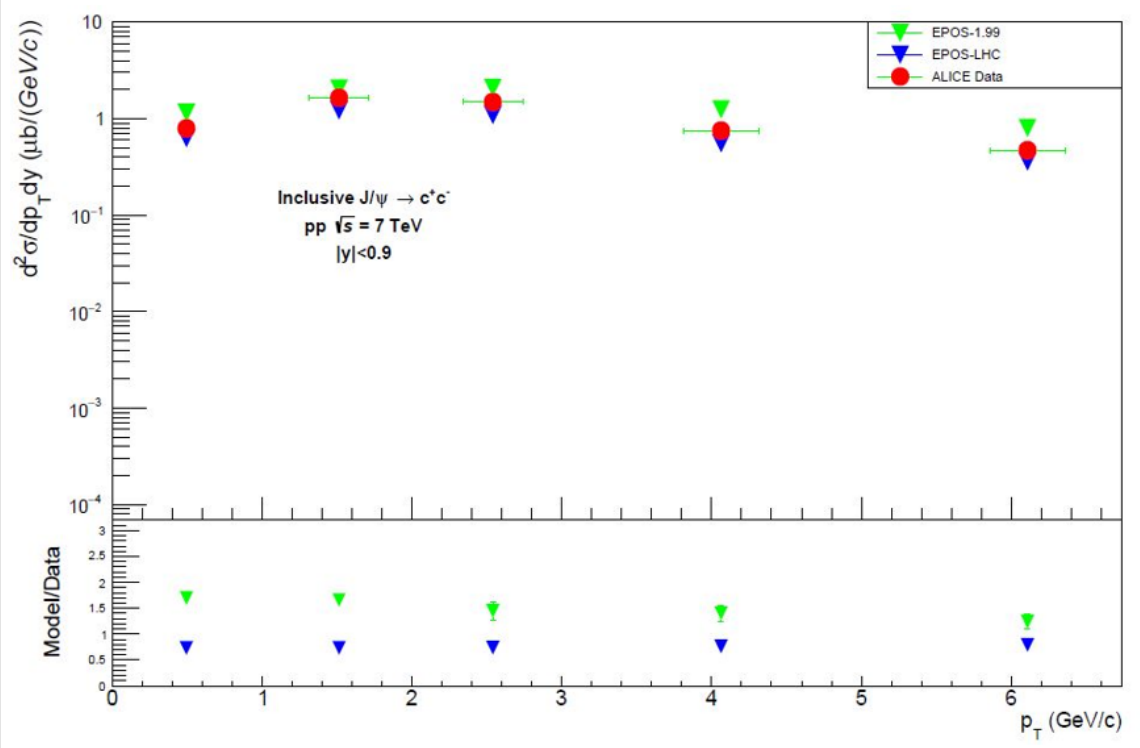



**Figure 3:** EPOS-LHC and EPOS-1.99 models for inclusive J/ψ generation cross section in proton-proton collisions at 7 TeV in the mid-rapidity, |y| < 0.9. The panel below also illustrates the ratio between models and ALICE data.

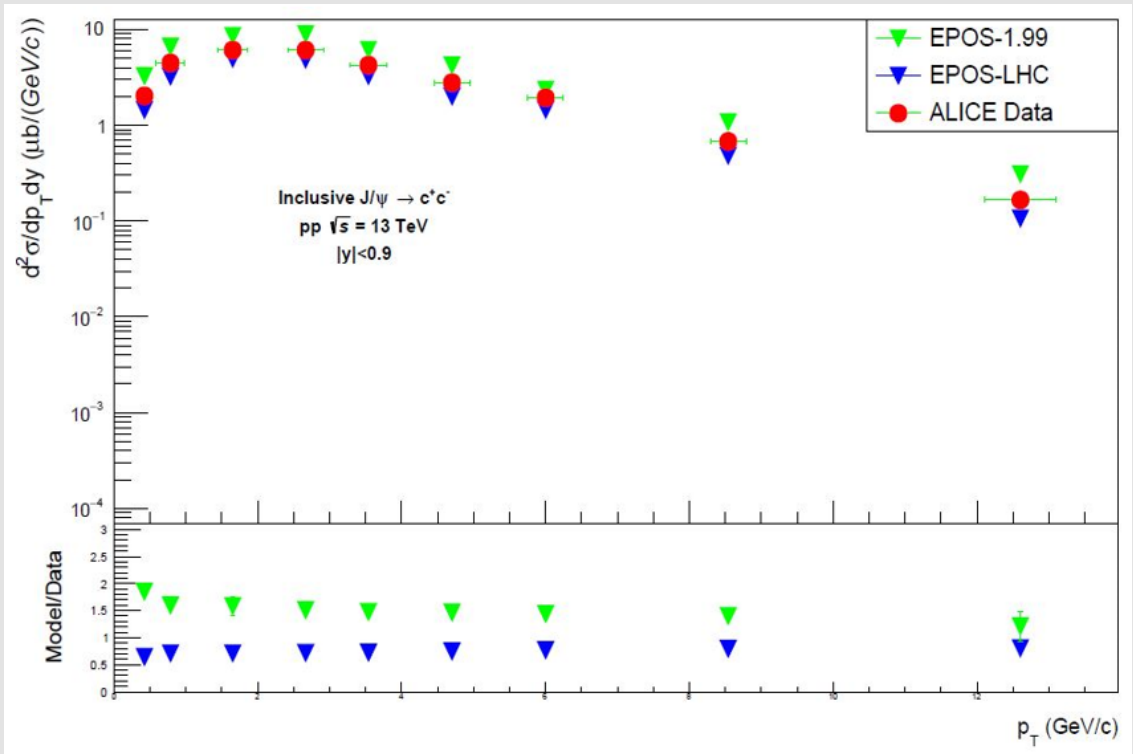



**Figure 4:** Cross section of inclusive J/ψ production in proton-proton collisions at 13 TeV in the transverse momentum interval 0 < pT > 14 and in the mid-rapidity, |y| < 0.9, using EPOS-LHC and EPOS-1.99 models. The panel below also illustrates the ratio between models and ALICE data.

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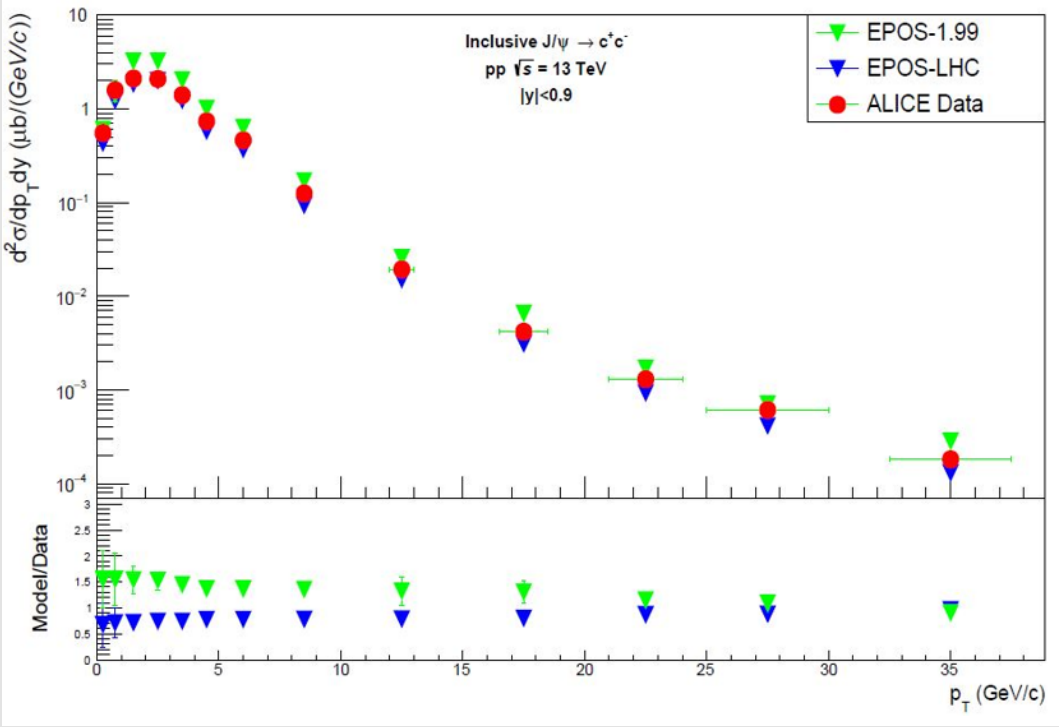



**Figure 5:** In the transverse momentum interval 0 < pT > 14 and in the mid-rapidity, |y| < 0.9, inclusive J/ψ production cross section in proton-proton collisions at 13 TeV using EPOS-LHC and EPOS-1.99 models. Additionally depicted in the panel below is the ratio between models and ALICE data.

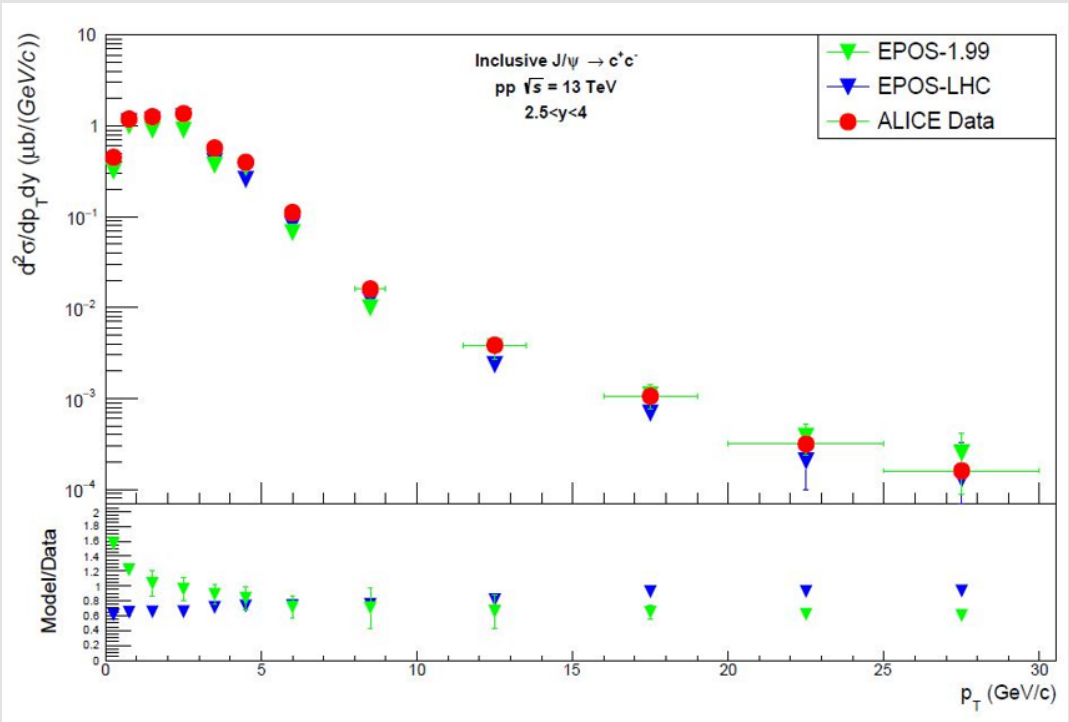



**Figure 6:** EPOS-LHC and EPOS-1.99 models for inclusive J/ψ production cross section in proton-proton collisions at 13 TeV in the transverse momentum interval 0 < pT > 40 and in the mid-rapidity, 2.5 < y < 4. The panel below also illustrates the ratio between models and ALICE data.

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## Author Contributions

Waqas Akbar: Conceptualization, methodology, formal analysis, and writing—original draft. Muhammad Zeeshan Khan: Data curation, investigation, and validation. Muhammad Faizan: Software, visualization, and data analysis. Hasnain Muhammad Shah: Literature review, interpretation of results, and manuscript editing. Omama Rahman: Supervision, validation, and critical revision of the manuscript. All authors reviewed and approved the final version of the manuscript.

## Conflicts of Interest

No conflicts of interest.

## Ethics Approval

Not applicable.

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The authors declare that generative artificial intelligence (AI) was used exclusively to create the graphical abstract and to correct grammatical errors and improve the English language of the manuscript. After completion of these AI-assisted tasks, all content was carefully reviewed and verified by the authors, who assume full responsibility for the accuracy, originality, and integrity of the final manuscript. AI tools are not authors and do not qualify for authorship or bear responsibility for the content of the manuscript. The use of AI in the graphical abstract, including the name of the tool, has been disclosed directly in the graphical abstract image.

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