Exploring J/ψ and $\psi(2S)$ polarization dynamics in pp collisions at the LHC energies with PYTHIA8

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Introduction

While significant progress has been made in the past three decades towards understanding the deconfined medium generated in ultra-relativistic heavy-ion collisions, the production and polarization of quarkonia in both hadronic and nucleus-nucleus collisions remain subjects of intense debate within both experimental and theoretical communities. To date, no single theoretical framework has successfully accounted for both quarkonia production and its polarization. The color-octet model of non-relativistic quantum chromodynamics (NRQCD) explains the quarkonia production cross-section well, but it fails to account for its polarization. It predicts a fully transverse polarization at high $p_{\rm T}$, while the color-singlet model predicts a high longitudinal polarization. However, the current measurement of the experimental data of ALICE indicate nearly zero polarization for J/ψ, while LHCb predicts a small longitudinal polarization in minimum bias pp collisions within uncertainity. This disparity between theory and experiment is commonly referred to as the 'J/ψ polarization puzzle'. In this work, we endeavor to elucidate the polarization of J/ψ and $\psi(2S)$ in pp collisions at the LHC energies using PYTHIA8. We studied the λ polarization parameters (λ_θ, λ_ϕ, $\lambda_{\theta\phi}$) as functions of transverse momentum $p_{\rm T}$ in the helicity and Collins-Soper reference frames.

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Formalism and Results

The polarization of the charmonium states can be measured by studying the angular distribution, W(θ, ϕ), in the dimuon decay channel. It can be parameterized as follows:

$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta} \left(1+\lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi\right) \quad (1)$$

where, θ and ϕ are the polar and azimuthal angles of the μ^+ with respect to the quantization axis of the chosen polarization frames and λ_θ, λ_ϕ, $\lambda_{\theta\phi}$ are the polarization parameters. In particular, the cases (λ_θ = 1, λ_ϕ =0 , $\lambda_{\theta\phi}$ = 0), (λ_θ = -1, λ_ϕ =0, $\lambda_{\theta\phi}$ = 0), and (λ_θ = 0, λ_ϕ =0, $\lambda_{\theta\phi}$ = 0) correspond to the transverse and longitudinal polarization, and zero polarization, respectively.

We use an alternative approach over the multiparameter fit of Eq. (1) to the dimuon angular distribution to obtain the polarization parameter [1]

$< \cos^2\theta >= \frac{1+\frac{3}{5}\lambda_\theta}{3+\lambda_\theta}$, $< \cos 2\phi >= \frac{\lambda_\phi}{3+\lambda_\theta}$, $< \sin 2\theta \cos\phi >= \frac{4}{5}\frac{\lambda_{\theta\phi}}{3+\lambda_\theta}$.

The polarization parameters λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$ are obtained for helicity and Collins-Soper frames by taking the average over $\cos^2\theta$, $\cos 2\phi$, and $\sin 2\theta \cos\phi$. The details regarding the event generation in PYTHIA8 and definition of quantization-axis in helicity and Collins-Soper reference frames are discussed in Ref. [1].

Figure 1 shows the polarization parameters of J/ψ and ψ(2S) as a function of $p_{\rm T}$ at $\sqrt{s}$

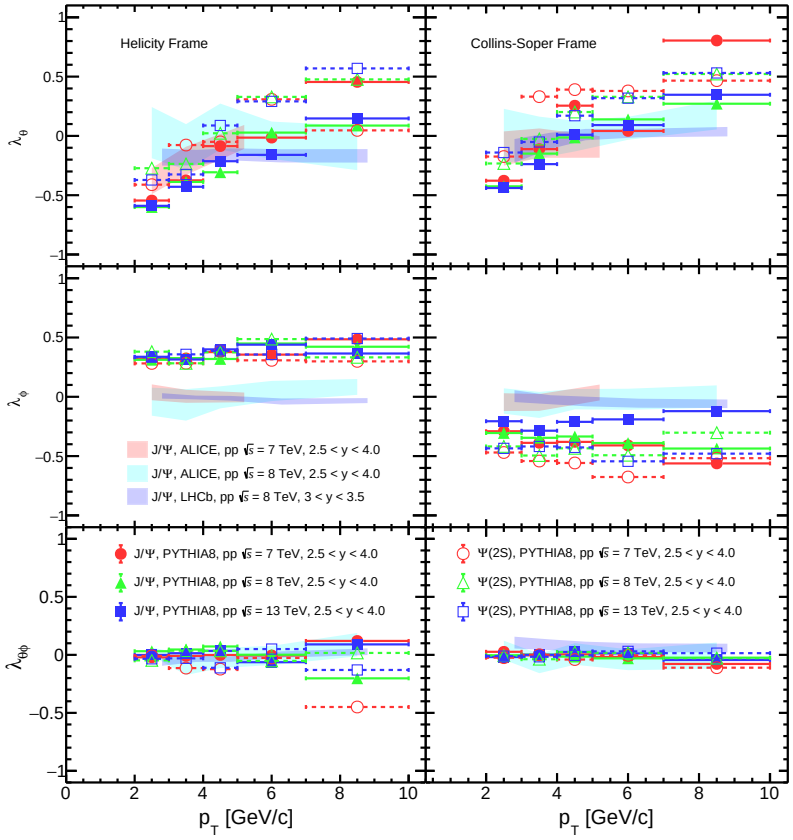

FIG. 1: (Color online) The J/ψ and ψ(2S) polarization parameters as a function of transverse momentum for pp collisions at $\sqrt{s}$ = 7, 8, and 13 TeV using PYTHIA8 compared with the J/ψ polarization measurement in pp collisions from ALICE at $\sqrt{s}$ = 7, 8 TeV and LHCb at $\sqrt{s}$ = 7 TeV in both helicity (left column) and Collins-Soper (right column) reference frames [1].

= 7, 8, and 13 TeV in pp collisions. The $p_{\rm T}$-interval in PYTHIA8 is chosen in accordance with the ALICE measurement of J/ψ at $\sqrt{s}$ = 8 TeV in both reference frames for all energies.

Summary

It is observed that the λ_θ parameter shows J/ψ and ψ(2S) are longitudinally polarized at low-$p_{\rm T}$ and transversely polarized at high-$p_{\rm T}$ in both the reference frames. The λ_ϕ parameter indicates the longitudinal polarization in helicity and transverse polarization in the Collins-Soper frame for J/ψ and ψ(2S) across all energies.The $\lambda_{\theta\phi}$ parameter values are close to zero as a function of $p_{\rm T}$. The finite value of λ_θ and λ_ϕ parameters indicates that the probability of finding the J/ψ (or ψ(2S)) vector mesons in the three spin states are not equal.

References

[1] B. Sahoo, D. Sahu, S. Deb, C. R. Singh and R. Sahoo, [arXiv:2308.15151 [hep-ph]].