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## Decoding charmonia polarization in pp collisions at LHC energies: PYTHIA8 analysis and future trajectories

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In this study, we investigate the polarization parameters of  $J/\psi$  and  $\psi(2S)$  in proton-proton (pp) collisions at LHC energies, utilizing PYTHIA8 to analyze dimuon angular distributions. Our findings reveal intriguing insights: at low transverse momentum ( $p_T$ ), both particles exhibit longitudinal polarization, transitioning to transverse polarization at higher  $p_T$  in both helicity and Collins-Soper reference frames. Moreover, longitudinal polarization is evident across all energies, while transverse polarization is prominent in the Collins-Soper frame. Notably, the degree of longitudinal polarization of  $\psi(2S)$  increases with charged particle multiplicity, contrasting the relatively constant polarization observed for  $J/\psi$ . Although we find no clear dependence of polarization parameters on rapidity, future studies with wider kinematics acceptance, such as the ALICE 3 setup, could shed light on this aspect. Our results, based on pQCD-based PYTHIA8 simulation, suggest the necessity for comprehensive studies utilizing theoretical models in conjunction with experimental data to fully understand charmonia polarization in ultra-relativistic pp collisions.

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