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Entanglement and Bell Nonlocality in τ+τ- at the LHC using Machine Learning for Neutrino Reconstruction

Experiments at the CERN Large Hadron Collider (LHC) have accumulated an unprecedented amount of data corresponding to a large variety of quantum states. Although searching for new particles beyond the Standard Model of particle physics remains a high priority for the LHC program, precision measurements of the physical processes predicted in the Standard Model continue to lead us to a deeper understanding of nature at high energies. We carry out detailed simulations for the process $pp \to \tau^+\tau^-$ to perform quantum tomography and to measure the quantum entanglement and the Bell nonlocality of the $\tau^+\tau^-$ two-qubit state, including both statistical and systematic uncertainties. By using advanced machine learning techniques for neutrino momentum reconstruction, we achieve precise measurements of the full spin density matrix, a critical advantage over previous studies limited by reconstruction challenges for missing momenta. Our analysis reveals a clear observation of Bell nonlocality with high statistical significance, surpassing 5σ, establishing $\tau^+\tau^-$ as an ideal system for quantum information studies in high-energy collisions. Given its experimental feasibility and the high expected sensitivity for Bell nonlocality, we propose that $\tau^+\tau^-$ should be regarded as the new benchmark system for quantum information studies at the LHC, complementing and extending the insights gained from the $t\bar{t}$ system.

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