Tractable protocol for long distance detection-loophole-free Bell tests

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Photon loss is the main obstacle to distributing quantum correlations and performing loophole-free Bell tests over long distances, which are required for device-independent quantum communication. This loss opens the detection loophole and makes genuine nonlocality increasingly difficult to certify as the distance grows. We present an all-photonic, event-ready protocol that overcomes this limitation by heralding tunable photon-number entangled states using single-photon interference at a central station. Our approach combines two key advantages that have so far appeared separately in different schemes. First, it retains the favorable twin-field-like $\sqrt{\eta_c}$ scaling of single-photon interference, allowing entanglement to be distributed efficiently over long distances. Second, it reaches the Eberhard detection-efficiency limit of ~ 66.7%, which is the fundamental threshold for a detection-loophole-free Bell test with non-maximally entangled qubits. The enhanced robustness to loss originates from the coherent superposition involving the vacuum component in the heralded state, which allows the impact of photon loss to be suppressed by tuning the relative amplitudes of the state. We show that, under realistic detector efficiencies and interference visibilities, our protocol yields stronger Bell violations than existing all-photonic schemes based on polarization or single-photon path entanglement. The scheme relies only on standard SPDC sources, weak coherent states, and photon counting, making it compatible with current experimental technology. This provides a practical route toward long-distance loophole-free Bell tests and device-independent quantum key distribution in near-term quantum networks.

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References

[1] Alwehaibi, Y. K., Mer, E., Machado, G. J., Yu, S., Walmsley, I. A., & Patel, R. B. (2025). Tractable protocol for detection-loophole-free Bell tests over long distances. *Physical Review Research*, *7*(4), 043198.