Efficient Adaptive Entanglement Witnessing

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Introduction

Quantum cryptography uses quantum entanglement to secure data against the threat of quantum computing. Verifying entanglement distribution to end users is necessary for secure long-distance quantum communication but can be time-consuming, especially for low qubit rates in current implementations [1]. Entanglement witnessing can be used to efficiently detect entanglement without requiring full state tomography. We consider entanglement witnessing, as in Figure 1, that involves correlated local measurements on many copies of a two-qubit state but does not rely on prior knowledge of the specific entangled state.

Entanglement witnesses are observables in a bipartite or multipartite quantum state that have negative expectation value only if the state is entangled. Previous work [2] developed 6 two-qubit witnesses, $\{W^3\}$, that use the measured probabilities of 12 polarization pairs. Our group has expanded this set with three groups of witnesses, $\{W^5\}$, doubling the number of detected entangled states with an additional 8 measurements. We experimentally demonstrate the use of $\{W^5\}$ to witness partially entangled states.

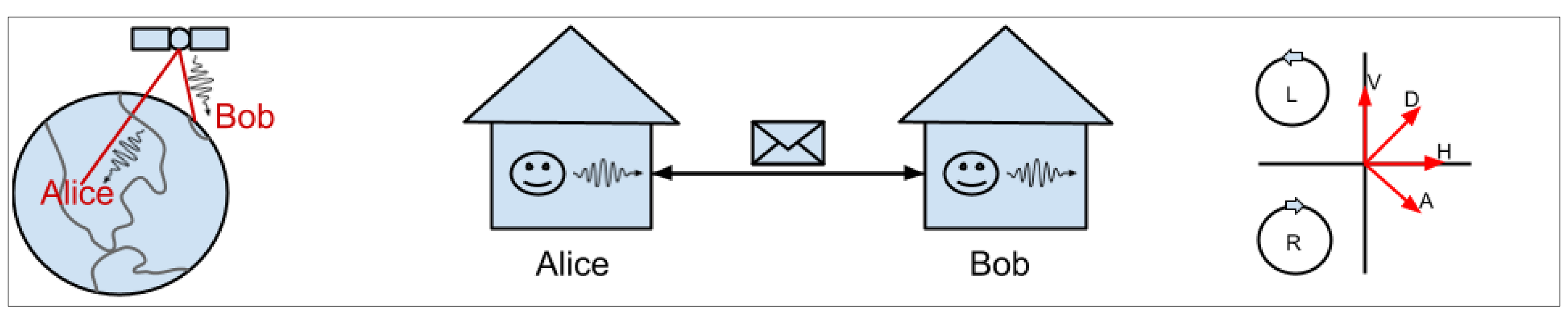


Figure 1: Alice and Bob each receive photons distributed from a source, in this case, a satellite. They separately measure their photons in polarizations of their choice: H,V,D,A,L,R. By classically communicating the measurement results on many copies of the two-photon state, Alice and Bob can verify that the source provides entangled photons.

Adaptive Witnessing Procedure

Figure 2A shows the flow of our adaptive witnessing procedure. See Exhibit Hall A Poster 312 for more background on the adaptive choice.

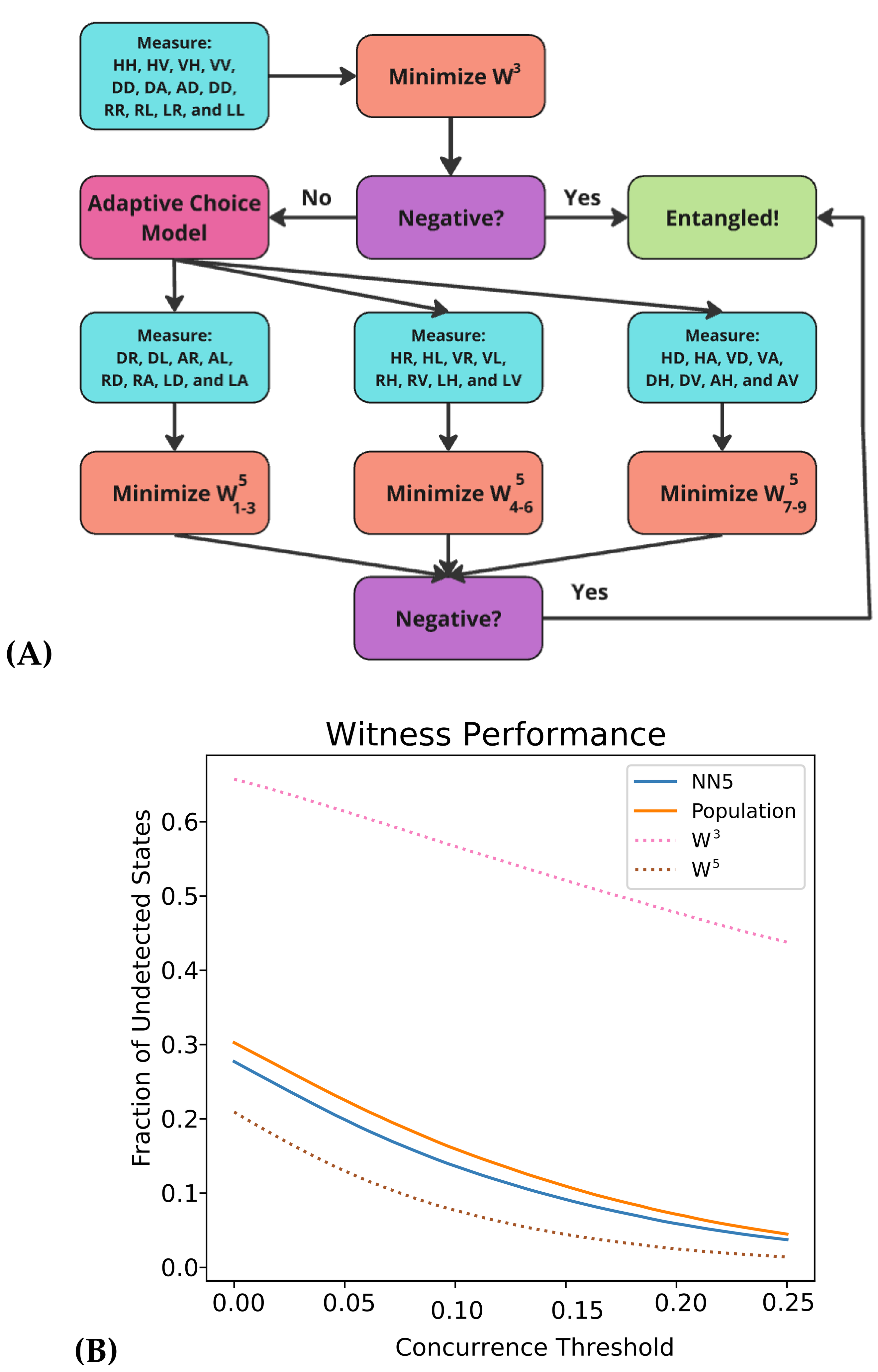


Figure 2: (A) Flow chart of the adaptive witnessing procedure beginning with $\{W^3\}$ then selecting a $\{W^5\}$ if entanglement is not detected. **(B)** Fraction of computationally generated random entangled states witnessed by $\{W^3\}$, all $\{W^5\}$, and the $\{W^5\}$ triplet chosen by each adaptive method. $\{W^3\}$ witnesses 34.27% of all the entangled states and $\{W^5\}$ detects 79.07%. Adaptive choice of a $\{W^5\}$ triplet detects 72.28% of the states using the five-layer neural network (NN5) or 69.74% using the population model. Detected fractions are shown as a function of minimum concurrence (degree of entanglement) in the states considered.

Experimental Implementation

Our experiment uses polarization-entangled photon pairs created from Type-I Spontaneous Parametric Down Conversion (SPDC) to construct and detect entangled states of the form given in Eq. 1, and probabilistic mixtures of these states.

$$|\varphi\rangle = \cos\left(\frac{\chi}{2}\right)|H\rangle_A|\alpha\rangle_B + e^{i\eta}\sin\left(\frac{\chi}{2}\right)|V\rangle_A|\alpha_\perp\rangle_B \tag{1}$$

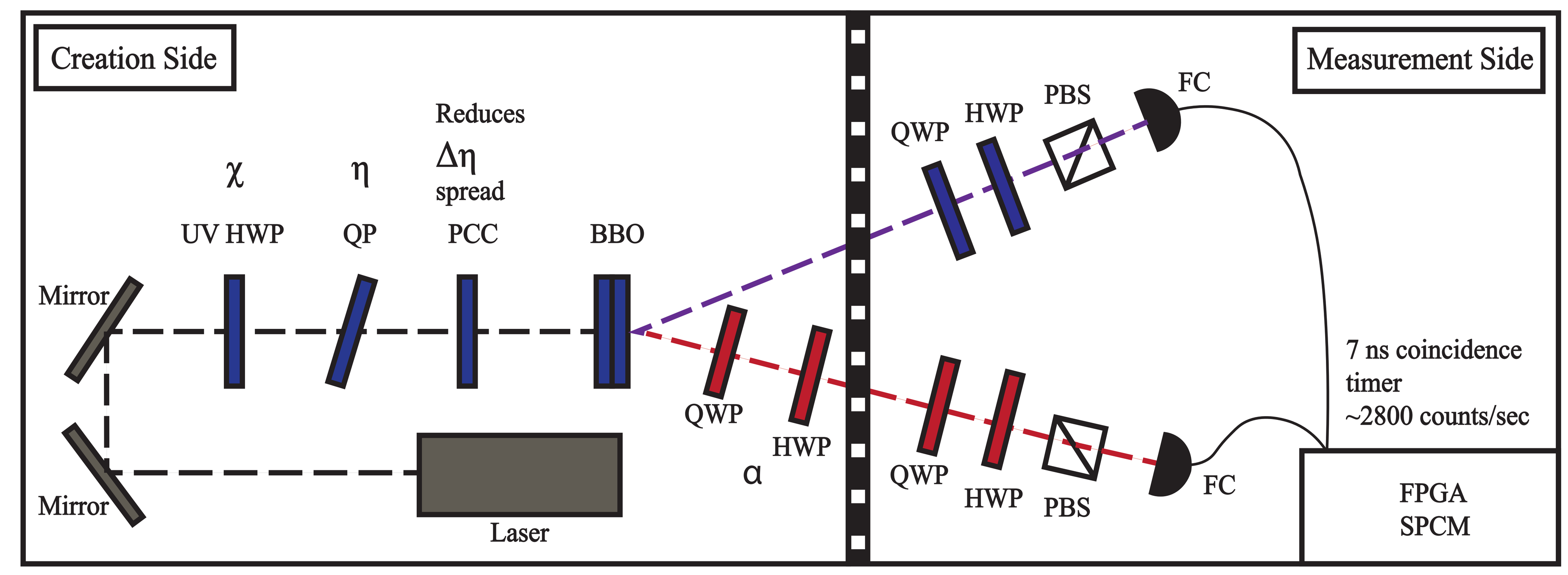
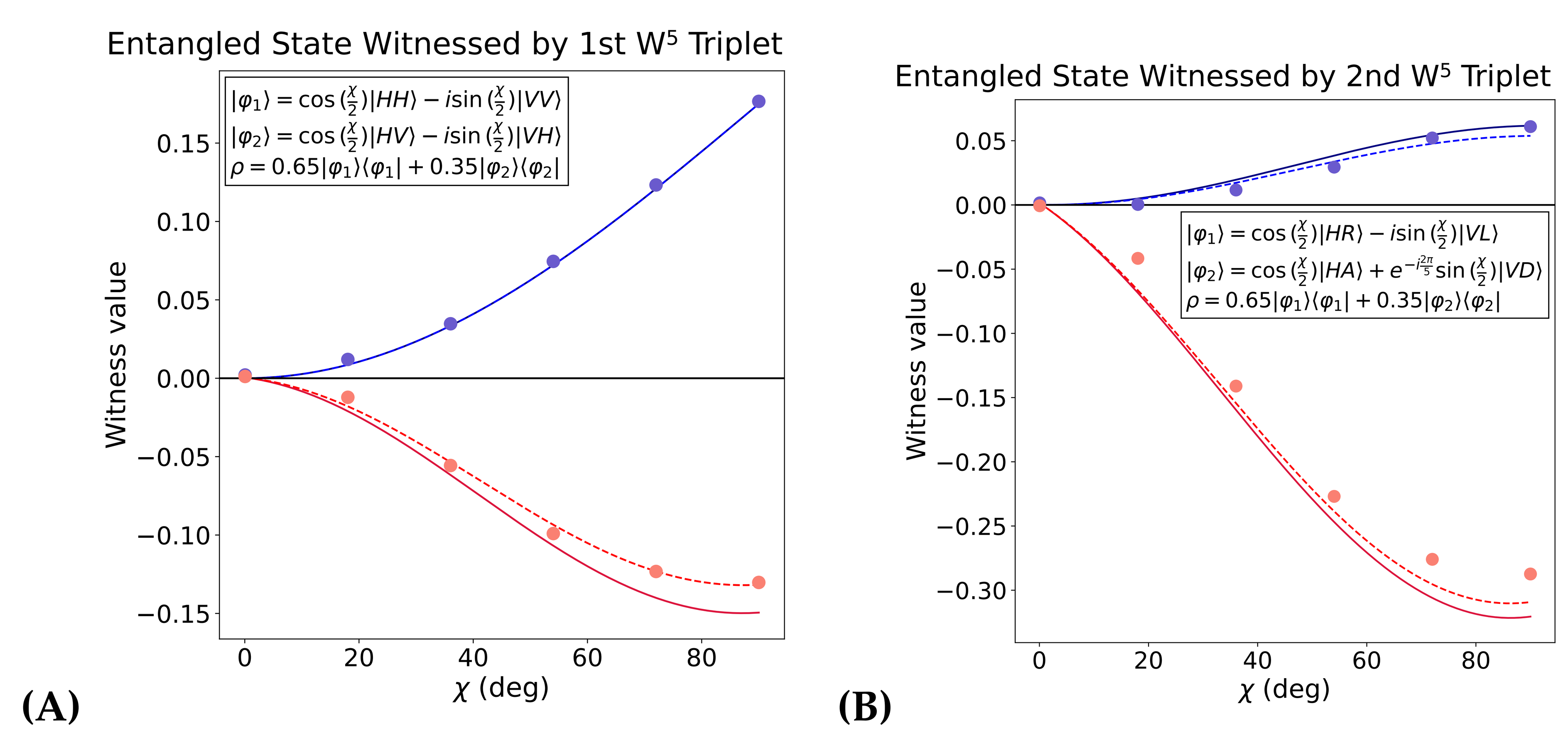


Figure 3: Entangled state creation occurs to the left of the vertical dashed line, while measurement occurs to the right. Measurement occurs in separate channels: Alice (top) and Bob (bottom). Creation components: 403 nm Diode Laser (laser), UVHWP (ultraviolet half wave plate), QP (quartz plate), PCC (precompensation crystal), BBO (β-barium borate crystal), QWP (quarter wave plate), HWP (half wave plate). Measurement components: QWP, HWP, PBS (polarizing beam splitter), FC (optical fiber coupler), SPCM + FPGA: (single-photon counting module).



In Fig. 4 the solid lines correspond to witness values for theoretical density matrices and points to experimental data. The remaining spread in $\Delta\eta$ from Fig. 3 results in a state that is 95% $|\varphi\rangle$, 5% $\cos^2(\frac{\chi}{2})\,|H\rangle_A|\alpha\rangle_B$, and 5% $\sin^2(\frac{\chi}{2})\,|V\rangle_A|\alpha_\perp\rangle_B$. The adjusted theory accounts for this and is shown as dashed lines in Fig. 4.

Experimental detection of these states by each $\{W^5\}$ triplet when they are missed by $\{W^3\}$ illustrates that our adaptive procedure improves the success of entanglement detection. The adaptive choice methods correctly predict which $\{W^5\}$ witness triplet to measure in each case shown.

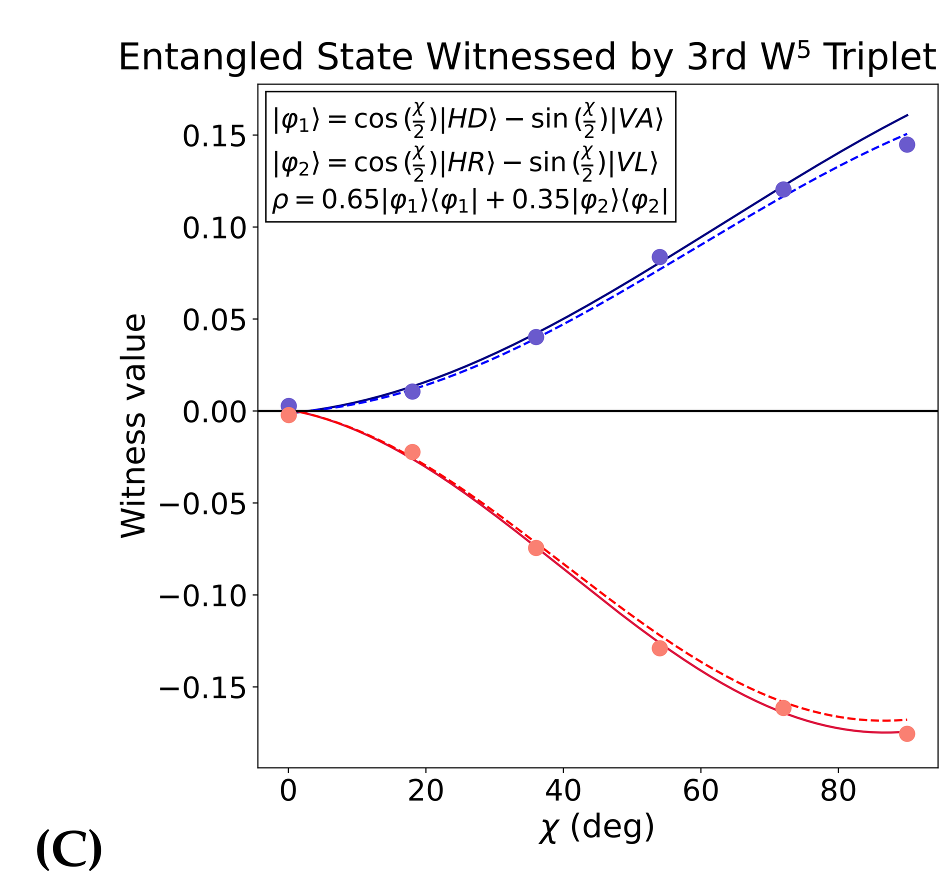


Figure 4: Demonstration of entanglement witnessing by each $\{W^5\}$ triplet (min values in red) on states not witnessed by $\{W^3\}$ (min values in blue). [3]

References

[1] Yin, Juan et al., *Nature* 582.7813 (2020): 501-505.
[2] A. Riccardi, D. Chruściński, and C. Macchiavello, *Phys. Rev. A* **101**, 062319 (2020).
[3] L. Gruber, B. Hartley, S. Kerr, P. Navarro, A. Roberson, O. Scholin, R. Verghese, Q. Yang, and T. W. Lynn, "Adaptive Two-Qubit Entanglement Witnessing", in preparation.

Acknowledgments

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