Closing the Locality and Detection Loopholes in Multiparticle Entanglement Self-Testing

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First proposed by Mayers and Yao, self-testing provides a certification method to infer the underlying physics of quantum experiments in a black-box scenario. Numerous demonstrations have been reported to self-test various types of entangled states. However, all the multiparticle self-testing experiments reported so far suffer from both detection and locality loopholes. Here, we report the first experimental realization of multiparticle entanglement self-testing closing the locality loophole in a photonic system, and the detection loophole in a superconducting system, respectively. We certify three-party and four-party GHZ states with at least 0.84(1) and 0.86(3) fidelities in a device-independent way. These results can be viewed as a meaningful advance in multiparticle loophole-free self-testing, and also significant progress on the foundations of quantum entanglement certification.

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In 1964, John Bell showed that the correlations of measurement outcomes on distant particles cannot be reproduced by locality and realism theory, and thereby certify the existence of entanglement [1]. Since then, the field of Bell nonlocality has grown considerably [2]. Apart from manifesting the existence of nonlocality and entanglement in the separated black boxes, as the maximal quantum violation of the Bell inequality is further observed, new physics and phenomena appear such that one could also certify the inner working of the devices, e.g., what states are prepared and what operations are performed in these black boxes [3,4]. This certification is referred to as self-testing [3,4], which can be applied to device-independent quantum cryptography, entanglement detection, and delegated quantum computing [5]. However, for these high-level security device-independent tasks, some theoretical conditions might be compromised in the implementations, leading to different kinds of loopholes in Bell inequalities. If one does not close these loopholes, a malicious adversary could take advantage of them to fake the Bell violation; then the corresponding cryptographic tasks would not be secure anymore.

In Bell inequalities, each party receives a random classical input and is required to output classical data. In the implementation, inputs and outputs correspond to the measurement setting choices and measurement outcomes, respectively. Bell's proof requires the no-signaling condition, that is, the measurement choice at one party cannot influence the outcomes at other parties. Otherwise, leveraged by signaling, local hidden variable strategies could spoof and thus violate the Bell inequalities even without entanglement. If a compact experiment setup lacks the spacelike separation which is generally employed to guarantee the no-signaling condition, an additional assumption should be made—local hidden variables cannot signal one another, leading to the "locality" loophole.

In addition, due to unavoidable imperfections in state preparation and detection, not all the experimental trials can be correctly detected. By discarding the no-detection trials or performing postselection, one has to assume that the statistics of the detected trials can faithfully reflect that of all the trials. Otherwise, a malicious adversary may assign some rounds to be no-detection events and fake the violation without entanglement, which opens the "detection" loophole [6].

Compared with nonlocality tests that only rely on the violation of Bell inequalities, self-testing further requires near-maximal violation, thus dramatically increasing the

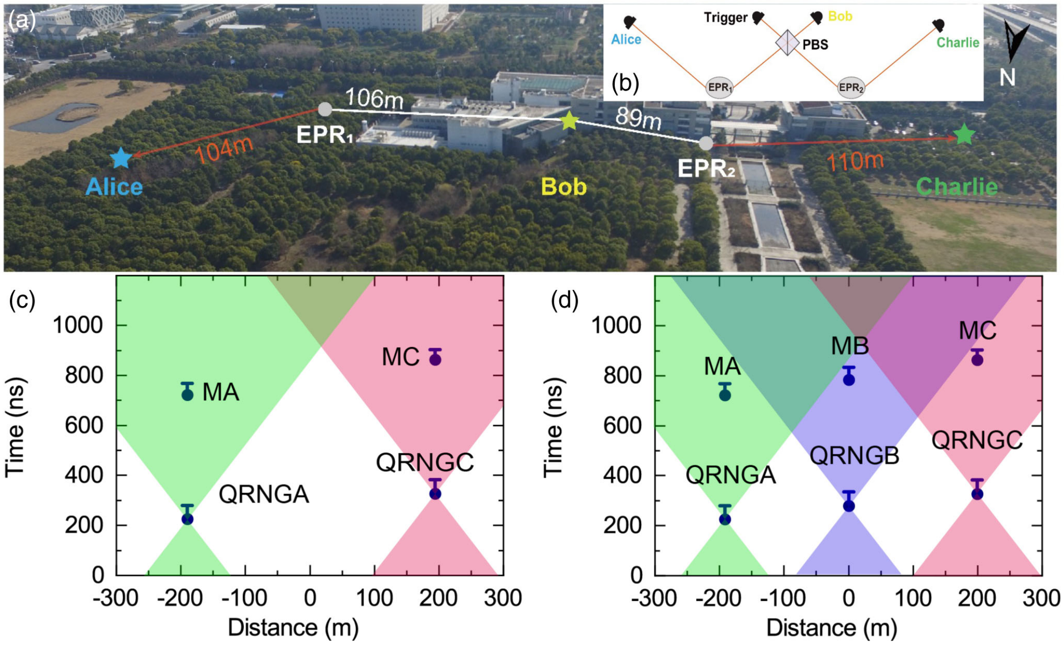

FIG. 1. Field implementation and space-time diagram of the experiment. (a) Bird's-eye view of the nonlocal game with three players (Alice, Bob, and Charlie) and two independent sources EPR1 and EPR2. The relative distances between Alice-EPR1, EPR1-Bob, Bob-EPR2, and EPR2-Charlie are 104 m, 106 m, 89 m, and 110 m, respectively. The length of the corresponding connecting fiber links is 112.63 m, 124.9 m, 109.6 m, and 125.48 m. (b) A brief figure of three-photon GHZ state preparation. (c) Spacelike separation between quantum random number generation events of Alice (QRNGA) and Charlie (QRNGC), and spacelike separation between setting choice event QRNGA(QRNGC) and measurement event MC(MA). Origins of the axes are displaced to reflect the relative space and time difference between them. (d) Similar to (c), QRNGB is the quantum random number generation event of Bob and the measurement event is MB, spacelike separation between QRNGB and two other QRNGs (QRNGA,QRNGC), and spacelike separation between QRNGB and two other measurement events (MA, MC), spacelike separation between MB and two other QRNGs (QRNGA, QRNGC). (c) and (d) illustrate spacelike separation of each other between MA, MB, and MC.

difficulty of the experimental demonstrations. However, a series of self-testing experiments have been implemented principally including two-party entangled states [7–13], and multipartite graph states [14–16]. Except for the two-particle demonstration in Ref. [7], all the previous self-testing demonstrations suffer from both the locality and detection loopholes. Even with the state-of-the-art experimental techniques, how to achieve nearly perfect state preparations with a high detection efficiency in a multipartite spacelike separate setup is still an open problem.

Recent theoretical works have proposed families of Bell inequalities to robustly self-test graph states [17,18], which make the demonstration of multiparticle self-testing more feasible. In order to pave the way for this important milestone—loophole-free multiparticle self-testing—in this Letter, we adopt the advantages of different physical systems, and demonstrate the multiparticle self-testing free of locality and detection loophole individually. In the photonic system, we create space-likely separated three-photon polarization-entangled GHZ states. We test three different Bell inequalities, including the Mermin inequality and the newly proposed inequalities in Refs. [17,18]. With the values of the Bell inequalities, we self-test three-photon GHZ states without the locality loophole and certify the state with at least 0.843(7) fidelity. In the superconducting system, we generate four-party GHZ states and keep all the events in Bell inequalities without postselection. We test three different Bell inequalities without the detection loophole and certify the fidelity with at least 0.86. Moreover, applying our proposed Bell inequalities, we also test the entanglement structure of prepared states. Our demonstration takes a vital step toward the loophole-free multiparticle Bell nonlocality and self-testing. Our results also lay the foundation for future large-scale quantum entanglement states' verification and related applications.

Theoretical schemes.—In Bell nonlocal inequalities, without the help of entanglement, local hidden variable strategies could at most obtain the value β_C, referred to as the classical bound, whereas quantum strategies using entanglement could reach at most a quantum bound $\beta_Q > \beta_C$. As one observes a Bell value $\langle\mathcal{B}\rangle$ close to the quantum bound, $\langle\mathcal{B}\rangle = \beta_Q - \varepsilon$, the self-testing analysis [17–19] could certify that the underlying state at least has the fidelity $1 - f(\varepsilon)$ to the target state up to local isometries. Much effort has been devoted to optimizing the robustness performance, i.e., the derivation of function f, in self-testing tasks. Here we apply the Bell inequalities proposed in Refs. [17,18]. Focusing on N-party GHZ states, $N-1$ different Bell inequalities $\{\mathcal{B}_s\}_{s=1}^{N-1}$ can be constructed as

$$\mathcal{B}_s:\ s\langle(A_1+B_1)\prod_{i=2}^{N}B_i\rangle+\sum_{j=2}^{s+1}\langle(A_1-B_1)A_j\rangle + \delta(s\le N-2)\sum_{k=s+2}^{N}\langle A_2A_k\rangle\le N+s-1, \quad (1)$$

where $s=1,2,\ldots,N-1$ and $\delta(s\le N-2)$ is an indicator function which equals to 1 when $s\le N-2$ and equals to 0 otherwise. The classical bounds and quantum bounds are $\beta_{C,s}=N+s-1$ and $\beta_{Q,s}=2\sqrt{2}s+N-s-1$, respectively. The optimal quantum bounds are saturated by taking $A_1=[(X+Z)/\sqrt{2}]$, $B_1=[(X-Z)/\sqrt{2}]$, and $A_i=Z$, $B_i=X$ when $i\neq 1$. Besides these families of Bell inequalities, for three-party GHZ states, we also apply the Mermin inequality [20],

$$\mathcal{B}_M:\langle A_1A_2B_3\rangle+\langle A_1B_2A_3\rangle+\langle B_1A_2A_3\rangle-\langle B_1B_2B_3\rangle\le 2. \quad (2)$$

Its quantum bound $\beta_{Q,M}=4$ can be reached via $A=X$, $B=-Y$ for particle 1 and 2, and $A_3=Y$, $B_3=X$. In Refs. [17,18], the fidelity between the underlying measured state ρ and the target graph state ψ_G (under local isometry Λ), $F=\max_\Lambda\langle\psi_G|\Lambda(\rho)|\psi_G\rangle$, can be lower bounded via a linear function $F\ge 1-k_i(\beta_{Q,s}-\langle\mathcal{B}_s\rangle)$. We show more detail of the exact values and the calculation of the slopes k_i in Ref. [21]. Furthermore, based on Eq. (1), we also propose a family of Bell inequalities which could detect the entanglement structure of the underlying states. The theoretical details are shown in Ref. [21].

Photonic system without the locality loophole.— The bird's-eye view of the experimental setup is shown in Fig. 1(a); two entanglement sources, Einstein–Podolsky–Rosen pairs, EPR1 and EPR2 and the three nodes are located in the Shanghai Research Institute of the University of Science and Technology of China.

Three mutually spacelike separated 250 MHz quantum random number generators are located at Alice, Bob, and Charlie respectively. In free space, the distance between Alice and Bob, Alice and Charlie, and Bob and Charlie are 191.8 m, 384.2 m, and 199 m, respectively. We use optical fiber to send photons to these three sites for measurement. From the time-space diagram shown in Figs. 1(c) and 1(d), the quantum random numbers generated at these three sites and the final basis vector measurement all satisfy strict spacelike separate conditions (for more details, see Ref. [21]). Hence, the locality loophole in the experimental multiparty self-testing is closed within our settings. Note that our experimental setup is quite different from the ones in previous multipartite self-testing [14–16] where all the

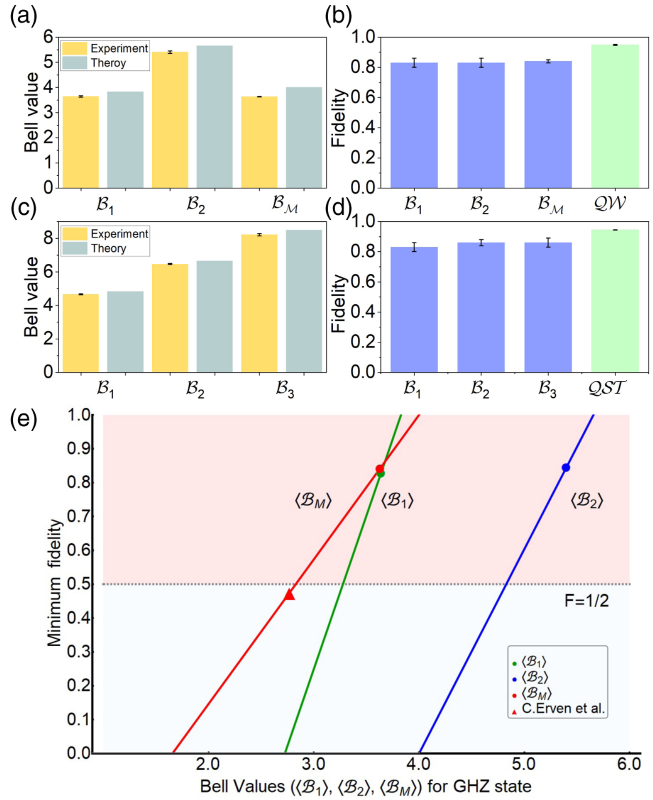

FIG. 2. The results from three-party and four-party GHZ states demonstrated in the photonic system and superconducting system. (a),(b),(e) and (c),(d) show the results obtained in the photonic system without the locality loophole, and the superconducting system without the detection loophole, respectively. (a),(c) The experimental observed Bell inequality values and the maximal quantum values for $\mathcal{B}_1$, $\mathcal{B}_2$, and $\mathcal{B}_M$ ($\mathcal{B}_3$). (b),(d) The estimated fidelity from the Bell values $\langle\mathcal{B}_1\rangle$, $\langle\mathcal{B}_2\rangle$, $\langle\mathcal{B}_M\rangle$ ($\langle\mathcal{B}_3\rangle$). The light green bar shows the traditional device-dependent fidelity estimation of the prepared states using quantum witness (QW) [28] or QST [29]. (e) The comparison between our results and the previous best-known results without the locality loophole in Ref. [30]. For Mermin inequality, we obtain the Bell value 3.63(1), and the result in Ref. [30] is 2.77(8), represented by the triangle. According to the fidelity estimation curve for Mermin inequality in Ref. [19], we could certify that the fidelities are 0.84(1) and 0.475(3) with the results obtained in our work and Ref. [30], respectively. The fidelity $F>1/2$ implies the existence of genuine entanglement. Here, all error bars indicate 1 standard deviation deduced from propagated Poissonian counting statistics of the raw detection events.

sites are on the same compact platform without random measurement choices.

In our experiment, we utilize the 779 nm laser to pump the periodically poled MgO doped lithium niobate crystal in a Sagnac loop to produce a pair of entangled photons $|\Phi\rangle=(|HH\rangle+|VV\rangle)/\sqrt{2}$ with wavelengths 1560 nm (signal) and 1556 nm (idler), where $|H\rangle$ and $|V\rangle$ represent the horizontal and vertical polarization of single photons, respectively [26]. In order to ensure the high fidelity of the

TABLE I. Summary of the multipartite device-independent demonstrations. This work (*P*) and (*S*) denotes our results using the photonic system and superconducting system, respectively. In the Locality and Detection columns, the check mark indicates the corresponding loophole is closed. In the Self-Testing column, the check mark indicates the existence of the nontrivial self-testing results. The Fidelity column shows the fidelity estimation in the corresponding demonstrations. For those with more than one kind of multipartite entangled states demonstration, we list the best fidelity estimation in this column. There have been numerous demonstrations of multipartite Bell inequalities without the self-testing results. Thus, here we only list the ones closing at least one loophole.

Scheme	Locality	Detection	Self-Testing	Fidelity
Ref. [31]	✗	✓	✗	···
Ref. [30]	✓	✗	✗	···
Ref. [11]	✗	✗	✓	0.98
Ref. [15]	✗	✗	✓	0.96
Ref. [16]	✗	✗	✓	0.92
This work (P)	✓	✗	✓	0.84
This work (S)	✗	✓	✓	0.86

entanglement source, we upgraded the original electro-optic modulator (EOM) loop and raised the transmittance from 0.25 to 0.5. Therefore, although we add one more measured EOM loop in our experiment, we do not need to increase the power which would introduce extra noise to improve the count rate.

In Fig. 1(b), for preparing a three-photon GHZ state, we pump periodically poled MgO doped lithium niobate to produce two-photon pairs in the state $|\Phi\rangle = (|HH\rangle + |VV\rangle)/\sqrt{2}$ from EPR1 and EPR2. After the interference and postselection with a polarizing beam splitter (PBS) at Bob, one of the photons is used as the trigger to $|+\rangle = (|H\rangle + |V\rangle)/\sqrt{2}$, and the remaining three photons are the prepared GHZ entangled state $|\psi\rangle = (|HHH\rangle + |VVV\rangle)/\sqrt{2}$ [27].

For the measurement settings, we use the superconducting nanowire single-photon detectors with an average efficiency of 0.82 to collect 9688, 11 675, and 16 763 fourfold coincidences and improve the minimal measurement fidelity from 0.984 in Ref. [26] to 0.991. Consequently, we obtain the Bell values for the Bell inequalities $\langle \mathcal{B}_1\rangle = 3.64(3)$, $\langle \mathcal{B}_2\rangle = 5.40(5)$, $\langle \mathcal{B}_M\rangle = 3.63(1)$. From the obtained results, we can predict that the state fidelity is 0.83(3), 0.84(3), and 0.84(1) in Fig. 2(b), respectively. Meanwhile, using the device dependent entanglement witness [28], the fidelity of the three-photon GHZ state is 0.950(3), as shown in Fig. 2(b). Moreover, we compare the estimated fidelities obtained from different experimental Mermin inequality values without the locality loophole in the self-testing criterion with results shown in Fig. 2(e). For clarity, we list a few multiparticle nonlocality demonstrations with or without closing the loopholes, and self-testing phenomenon in Table I.

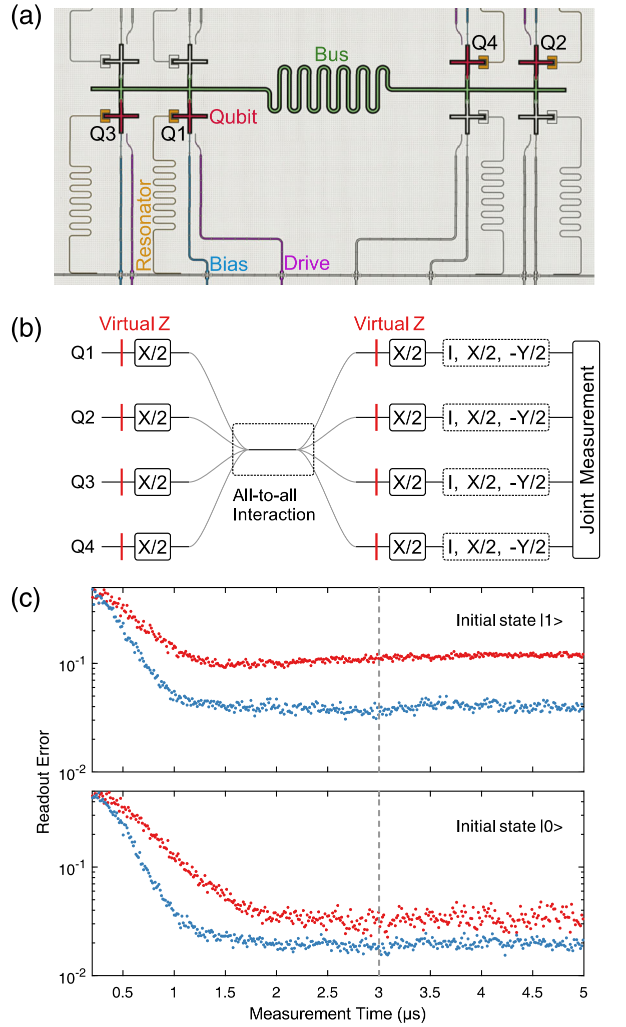

FIG. 3. (a) False-colored optical micrograph of the superconducting quantum processor. Eight X-mon qubits are capacitively coupled to a common central bus (green). Four qubits with the best performance (red) are used in our experiment. Each qubit has a microwave drive line (purple), a flux bias line (blue), and a readout resonator (yellow). (b) Circuit implementation. (c) The readout error of dispersive measurement as a function of the measurement time. Upper (lower) panel, the probability of incorrectly identifying the qubit state when prepared in the first excited state $|1\rangle$ (the ground state $|0\rangle$). Red dots, conventional dispersive measurement; blue dots, dispersive measurement exploiting the second excited state $|2\rangle$, where the decay error is strongly suppressed; gray dashed line, measurement time used (3 μs).

Superconducting system without the detection loophole.—This experiment is carried out on a superconducting quantum processor consisting of 8 Xmon qubits [32] simultaneously coupled to a central bus, as shown in Fig. 3(a). For each item in the Bell inequalities, we implement 10 000 trials and keep all the events to collect the outputs according to the read-out results without postselection. We assign $+1$ to the output if we detect the ground state $|0\rangle$ and -1 otherwise. The average readout fidelities reach 0.981 for the $+1$ result and 0.964 for the -1 result.

Figure 3(b) illustrates our quantum circuit to generate the 4-qubit GHZ state. We first idle 200 μs to relax $Q1 \sim Q4$ into their ground states. Then, we apply $X/2$ gate to each qubit and rotate them to the $|-i\rangle^{\otimes 4}$ state. After that, 4 qubits are tuned to resonance and undergo an all-to-all interaction assisted by the central bus [33]. Finally, we apply $X/2$ gate to each qubit again and obtain a 4-qubit GHZ state. The tuning of the qubits' transition frequencies introduces unwanted phases. To cancel them, we rotate the frame by applying virtual Z gates at each qubit before two groups of $X/2$ gates. The virtual Z gate is realized by adding a phase offset to the microwave drive line for all subsequent pulses. To improve the readout fidelity, we apply an additional gate before each measurement pulse, which excite the qubit from the first excited state $|1\rangle$ to the second excited state $|2\rangle$ and suppress decay error during the readout [34,35]. Compared with the conventional dispersive measurement [36,37], the readout error is greatly reduced [see Fig. 3(c)]. As a result, we generate a 4-qubit GHZ state with the fidelity of 0.944(1), measured from quantum state tomography (QST) and obtain the Bell values $\langle \mathcal{B}_1 \rangle = 4.66(3)$, $\langle \mathcal{B}_2 \rangle = 6.46(4)$, $\langle \mathcal{B}_3 \rangle = 8.21(7)$, with the estimated state fidelities 0.83(3), 0.86(2), and 0.86(3), respectively. Moreover, we also device independently test the entanglement structure of other 4-qubit prepared states based on our proposed Bell inequalities shown in Ref. [21].

Conclusion and outlook.—Our experiment has realized the first multiparticle self-testing while closing the locality loophole and the detection loophole individually via the photonic and superconducting experimental systems, respectively. By preparing the high-quality GHZ entanglement sources, we have certified the genuine entanglement and obtained the fidelity 0.84(1) and 0.86(3) for three-party and four-party GHZ states, respectively.

Compared with the two-party nonlocality, multipartity nonlocality could not only reveal different new physics which is theoretically interesting but also possess practical applications, for instance, multiuser quantum cryptography tasks. Therefore, multiparticle loophole-free Bell violation is one of the ultimate goals in device-independent quantum information. Our results pave two independent steps to this goal. A remaining problem is how to close the other loophole in these two platforms. For the photonic system, relying on eliminating the postselection by directly preparing the GHZ state [38] and improving the efficiency of collection, it is possible to close the detection loophole. For the superconducting system, by extending the length of cryogenic wave guides [39], qubits could be entangled over longer distances, and the locality loophole could be overcome. On the other hand, an alternative way of self-testing [40] in a single device that does not require spacelike separations but is based on computational assumptions was proposed. For the practical implementation of this type of protocols, our superconducting system is also one of the most promising candidates.

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D. W., Q. Z., and C. W. contributed equally to this work.

[1] J. S. Bell, Physics **1**, 195 (1964).
[2] N. Brunner, D. Cavalcanti, S. Pironio, V. Scarani, and S. Wehner, Rev. Mod. Phys. **86**, 419 (2014).
[3] D. Mayers and A. Yao, in *Proceedings 39th Annual Symposium on Foundations of Computer Science (Cat. No. 98CB36280)* (IEEE, 1998), pp. 503–509.
[4] D. Mayers and A. Yao, Quantum Inf. Comput. **4**, 273 (2004).
[5] I. Šupić and J. Bowles, Quantum **4**, 337 (2020).
[6] P. M. Pearle, Phys. Rev. D **2**, 1418 (1970).
[7] J.-D. Bancal, K. Redeker, P. Sekatski, W. Rosenfeld, and N. Sangouard, Quantum **5**, 401 (2021).
[8] W.-H. Zhang, G. Chen, P. Yin, X.-X. Peng, X.-M. Hu, Z.-B. Hou, Z.-Y. Zhou, S. Yu, X.-J. Ye, Z.-Q. Zhou *et al.*, npj Quantum Inf. **5**, 4 (2019).
[9] S. Gómez, A. Mattar, I. Machuca, E. S. Gómez, D. Cavalcanti, O. J. Farías, A. Acín, and G. Lima, Phys. Rev. A **99**, 032108 (2019).
[10] K. T. Goh, C. Perumangatt, Z. X. Lee, A. Ling, and V. Scarani, Phys. Rev. A **100**, 022305 (2019).
[11] W.-H. Zhang, G. Chen, X.-X. Peng, X.-J. Ye, P. Yin, Y. Xiao, Z.-B. Hou, Z.-D. Cheng, Y.-C. Wu, J.-S. Xu, C.-F. Li, and G.-C. Guo, Phys. Rev. Lett. **121**, 240402 (2018).
[12] J. Wang, S. Paesani, Y. Ding, R. Santagati, P. Skrzypczyk, A. Salavrakos, J. Tura, R. Augusiak, L. Mančinska, D. Bacco *et al.*, Science **360**, 285 (2018).
[13] I. Agresti, B. Polacchi, D. Poderini, E. Polino, A. Suprano, I. Šupić, J. Bowles, G. Carvacho, D. Cavalcanti, and F. Sciarrino, PRX Quantum **2**, 020346 (2021).
[14] J. Li, T.-J. Liu, S. Wang, C. Jebarathinam, and Q. Wang, Opt. Express **27**, 13559 (2019).
[15] D. Wu, Q. Zhao, X.-M. Gu, H.-S. Zhong, Y. Zhou, L.-C. Peng, J. Qin, Y.-H. Luo, K. Chen, L. Li, N.-L. Liu, C.-Y. Lu, and J.-W. Pan, Phys. Rev. Lett. **127**, 230503 (2021).
[16] J.-M. Xu, Q. Zhou, Y.-X. Yang, Z.-M. Cheng, X.-Y. Xu, Z.-C. Ren, X.-L. Wang, and H.-T. Wang, Opt. Express **30**, 101 (2022).
[17] F. Baccari, R. Augusiak, I. Šupić, J. Tura, and A. Acín, Phys. Rev. Lett. **124**, 020402 (2020).
[18] Q. Zhao and Y. Zhou, arXiv:2002.01843.

[19] J. Kaniewski, Phys. Rev. Lett. **117**, 070402 (2016).
[20] N. D. Mermin, Phys. Rev. Lett. **65**, 1838 (1990).
[21] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.128.250401 for theoretical details and experimental details including Refs. [22–25].
[22] D. Wu, Y.-F. Jiang, X.-M. Gu, L. Huang, B. Bai, Q.-C. Sun, S.-Q. Gong, Y. Mao, H.-S. Zhong, M.-C. Chen, J. Zhang, Q. Zhang, C.-Y. Lu, and J.-W. Pan, arXiv:2201.04177.
[23] F. B. Maciejewski, Z. Zimborás, and M. Oszmaniec, Quantum **4**, 257 (2020).
[24] C. Ryan, M. Laforest, and R. Laflamme, New J. Phys. **11**, 013034 (2009).
[25] E. Lucero, J. Kelly, R. C. Bialczak, M. Lenander, M. Mariantoni, M. Neeley, A. D. O'Connell, D. Sank, H. Wang, M. Weides, J. Wenner, T. Yamamoto, A. N. Cleland, and J. M. Martinis, Phys. Rev. A **82**, 042339 (2010).
[26] Q.-C. Sun, Y.-F. Jiang, B. Bai, W. Zhang, H. Li, X. Jiang, J. Zhang, L. You, X. Chen, Z. Wang, Q. Zhang, J. Fan, and J.-W. Pan, Nat. Photonics **13**, 687 (2019).
[27] D. Bouwmeester, J.-W. Pan, M. Daniell, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. **82**, 1345 (1999).
[28] O. Gühne, C.-Y. Lu, W.-B. Gao, and J.-W. Pan, Phys. Rev. A **76**, 030305(R) (2007).
[29] K. J. Resch, P. Walther, and A. Zeilinger, Phys. Rev. Lett. **94**, 070402 (2005).
[30] C. Erven, E. Meyer-Scott, K. Fisher, J. Lavoie, B. Higgins, Z. Yan, C. Pugh, J.-P. Bourgoin, R. Prevedel, L. Shalm *et al.*, Nat. Photonics **8**, 292 (2014).
[31] J. T. Barreiro, J.-D. Bancal, P. Schindler, D. Nigg, M. Hennrich, T. Monz, N. Gisin, and R. Blatt, Nat. Phys. **9**, 559 (2013).
[32] R. Barends, J. Kelly, A. Megrant, A. Veitia, D. Sank, E. Jeffrey, T. White, J. Mutus, A. Fowler, B. Campbell *et al.*, Nature (London) **508**, 500 (2014).
[33] C. Song, K. Xu, H. Li, Y.-R. Zhang, X. Zhang, W. Liu, Q. Guo, Z. Wang, W. Ren, J. Hao *et al.*, Science **365**, 574 (2019).
[34] F. Mallet, F. R. Ong, A. Palacios-Laloy, F. Nguyen, P. Bertet, D. Vion, and D. Esteve, Nat. Phys. **5**, 791 (2009).
[35] S. S. Elder, C. S. Wang, P. Reinhold, C. T. Hann, K. S. Chou, B. J. Lester, S. Rosenblum, L. Frunzio, L. Jiang, and R. J. Schoelkopf, Phys. Rev. X **10**, 011001 (2020).
[36] A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, Phys. Rev. A **69**, 062320 (2004).
[37] A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, J. Majer, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, Phys. Rev. Lett. **95**, 060501 (2005).
[38] D. R. Hamel, L. K. Shalm, H. Hübel, A. J. Miller, F. Marsili, V. B. Verma, R. P. Mirin, S. W. Nam, K. J. Resch, and T. Jennewein, Nat. Photonics **8**, 801 (2014).
[39] P. Magnard, S. Storz, P. Kurpiers, J. Schär, F. Marxer, J. Lütolf, T. Walter, J.-C. Besse, M. Gabureac, K. Reuer, A. Akin, B. Royer, A. Blais, and A. Wallraff, Phys. Rev. Lett. **125**, 260502 (2020).
[40] T. Metger and T. Vidick, Quantum **5**, 544 (2021).