# Quantum relay diagnostics

## using collective entanglement witnesses

Karel Lemr, Antonín Černoch
and Karol Bartkiewicz

Joint laboratory of Optics,
Palacký University Olomouc

Faculty of Physics, Adam Mickiewicz University

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# Transmission of quantum information is fragile

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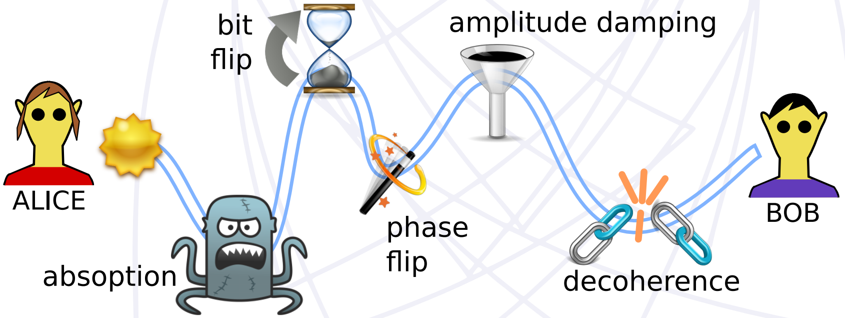
**What could possibly go wrong?**



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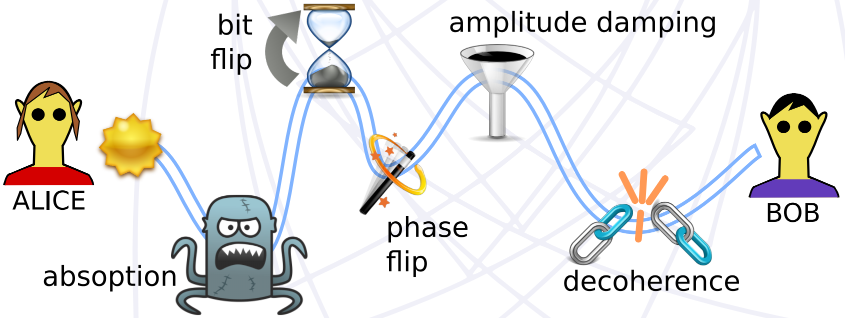


*"For the night is dark and full of (t)errors"*, R. R. Martin

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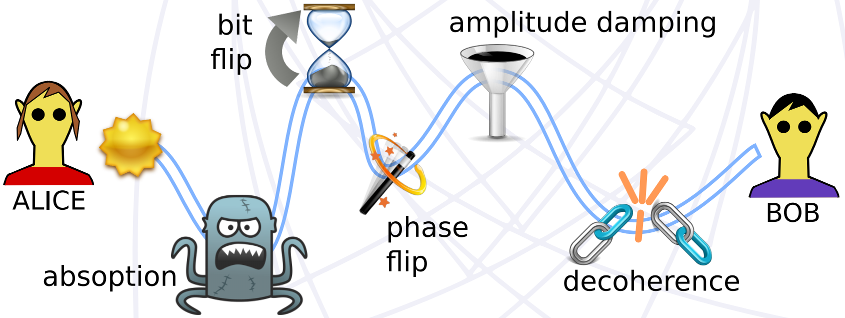


**The longer the channel, the bigger the problem.**

# Quantum repeaters and relays

solution for long-distance quantum communications

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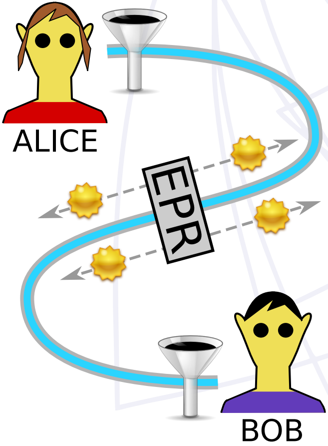
solution for long-distance quantum communications

**Quantum repeater**

*[Briegel et al., PRL* **81***, 5932 (1998)]*



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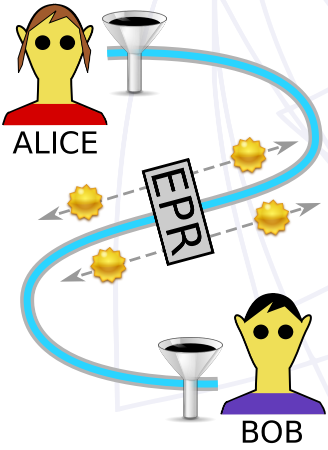
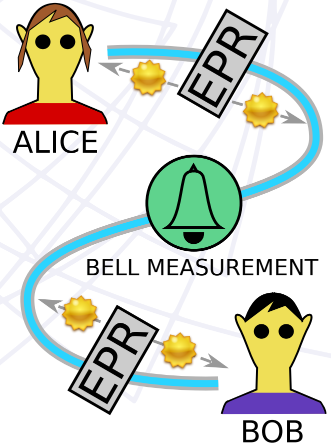



**Quantum relay**

*[Jacobs et al., PRA* ***66****, 052307 (2002)]*



# Entanglement swapping

core protocol in repeaters and relays

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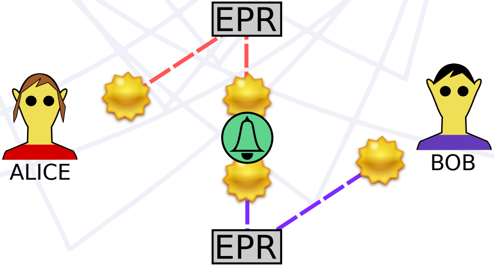

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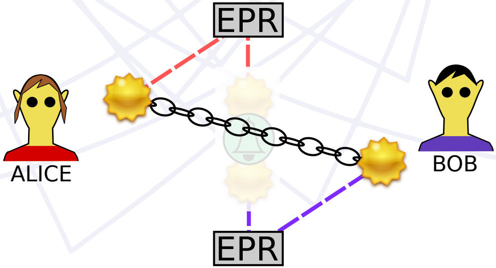

**Experimental Entanglement Swapping: Entangling Photons That Never Interacted**


Jian-Wei Pan, Dik Bouwmeester, Harald Weinfurter, and Anton Zeilinger

*Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria*



(Received 6 February 1998)



We experimentally entangle freely propagating particles that never physically interacted with one another or which have never been dynamically coupled by any other means. This demonstrates that quantum entanglement requires the entangled particles neither to come from a common source nor to have interacted in the past. In our experiment we take two pairs of polarization entangled photons and subject one photon from each pair to a Bell-state measurement. This results in projecting the other two outgoing photons into an entangled state. [S0031-9007(98)05913-4]



PACS numbers: 03.65.Bz, 03.67.–a, 42.50.Ar


- 1998: first experimental implementation

# Entanglement swapping

previous experiments

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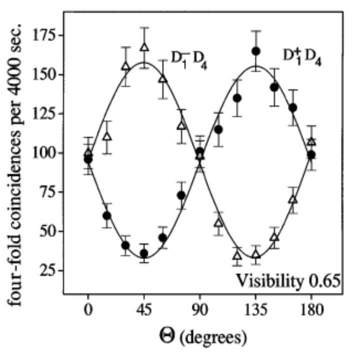



- 1998: first experimental implementation
- verification: correlation fringes (many measurements + fit)

# Entanglement swapping

previous experiments

**Experimental Nonlocality Proof of Quantum Teleportation and Entanglement Swapping**

Thomas Jennewein, Gregor Weihs, Jian-Wei Pan, and Anton Zeilinger

*Institut für Experimentalphysik, Universität Wien Boltzmanngasse 5, 1090 Wien, Austria*

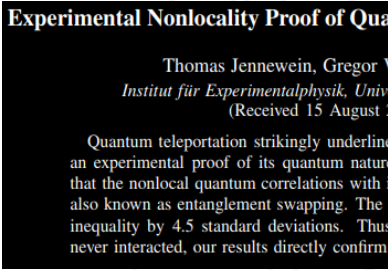
(Received 15 August 2001; published 18 December 2001)

Quantum teleportation strikingly underlines the peculiar features of the quantum world. We present an experimental proof of its quantum nature, teleporting an entangled photon with such high quality that the nonlocal quantum correlations with its original partner photon are preserved. This procedure is also known as entanglement swapping. The nonlocality is confirmed by observing a violation of Bell's inequality by 4.5 standard deviations. Thus, by demonstrating quantum nonlocality for photons that never interacted, our results directly confirm the quantum nature of teleportation.

- 2001: subsequent experimental implementation

# Entanglement swapping

## previous experiments



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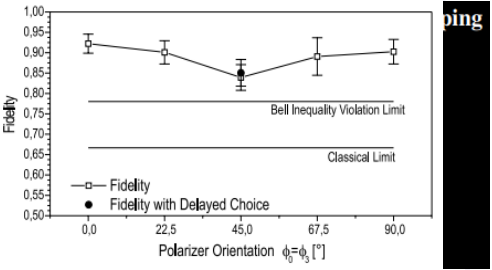
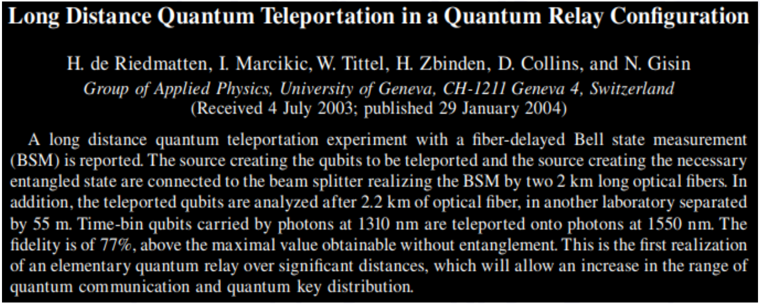



- 2001: subsequent experimental implementation
- verification: CHSH inequalities (16 measurements)

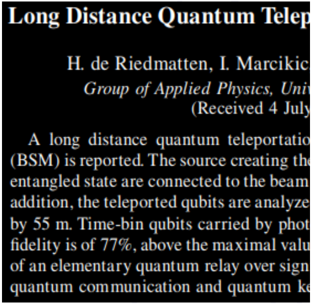


**Long Distance Quantum Teleportation in a Quantum Relay Configuration**

H. de Riedmatten, I. Marcikic, W. Tittel, H. Zbinden, D. Collins, and N. Gisin
*Group of Applied Physics, University of Geneva, CH-1211 Geneva 4, Switzerland*
(Received 4 July 2003; published 29 January 2004)

A long distance quantum teleportation experiment with a fiber-delayed Bell state measurement (BSM) is reported. The source creating the qubits to be teleported and the source creating the necessary entangled state are connected to the beam splitter realizing the BSM by two 2 km long optical fibers. In addition, the teleported qubits are analyzed after 2.2 km of optical fiber, in another laboratory separated by 55 m. Time-bin qubits carried by photons at 1310 nm are teleported onto photons at 1550 nm. The fidelity is of 77%, above the maximal value obtainable without entanglement. This is the first realization of an elementary quantum relay over significant distances, which will allow an increase in the range of quantum communication and quantum key distribution.

- 2004: teleportation in relay configuration



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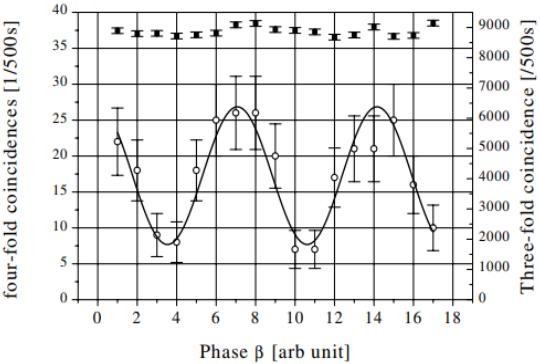



- 2004: teleportation in relay configuration
- verification: correlation fringes (many measurements + fit)

# Entanglement swapping

## previous experiments

**Long-distance entanglement swapping with photons from separated sources**

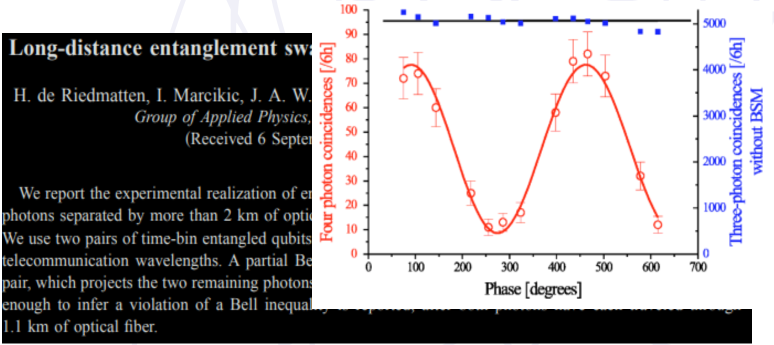
H. de Riedmatten, I. Marcikic, J. A. W. van Houwelingen, W. Tittel, H. Zbinden, and N. Gisin
*Group of Applied Physics, University of Geneva, Geneva, Switzerland*
(Received 6 September 2004; published 31 May 2005)

We report the experimental realization of entanglement swapping over long distances in optical fibers. Two photons separated by more than 2 km of optical fibers are entangled, although they never directly interacted. We use two pairs of time-bin entangled qubits created in spatially separated sources and carried by photons at telecommunication wavelengths. A partial Bell-state measurement is performed with one photon from each pair, which projects the two remaining photons, formerly independent onto an entangled state. A visibility high enough to infer a violation of a Bell inequality is reported, after both photons have each traveled through 1.1 km of optical fiber.

- 2005: swapping over 1.1 km

# Entanglement swapping

## previous experiments




- 2005: swapping over 1.1 km
- verification: correlation fringes (many measurements + fit)

**Experimental Synchronization of Independent Entangled Photon Sources**


Tao Yang,[1] Qiang Zhang,[1] Teng-Yun Chen,[1] Shan Lu,[1] Juan Yin,[1] Jian-Wei Pan,[1,*] Zhi-Yi Wei,[2,†] Jing-Rong Tian,[2] and Jie Zhang[2]

[1]*Department of Modern Physics and Hefei National Laboratory for Physical Sciences at Microscale, University of Science and Technology of China, Hefei, Anhui 230026, China*

[2]*Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China*

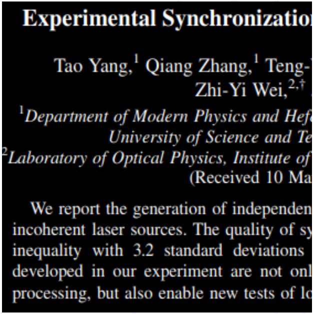


(Received 10 March 2005; published 20 March 2006)



We report the generation of independent entangled photon pairs from two synchronized but mutually incoherent laser sources. The quality of synchronization is confirmed by observing a violation of Bell's inequality with 3.2 standard deviations in an entanglement swapping experiment. The techniques developed in our experiment are not only important for realistic linear optical quantum-information processing, but also enable new tests of local realism.


- 2006: swapping with independent sources



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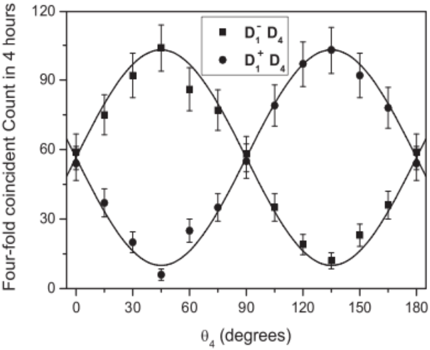



- 2006: swapping with independent sources
- verification: correlation fringes (many measurements + fit)

# Entanglement swapping

previous experiments

## Entangling independent photons by time measurement

MATTHÄUS HALDER*, ALEXIOS BEVERATOS, NICOLAS GISIN, VALERIO SCARANI, CHRISTOPH SIMON AND HUGO ZBINDEN

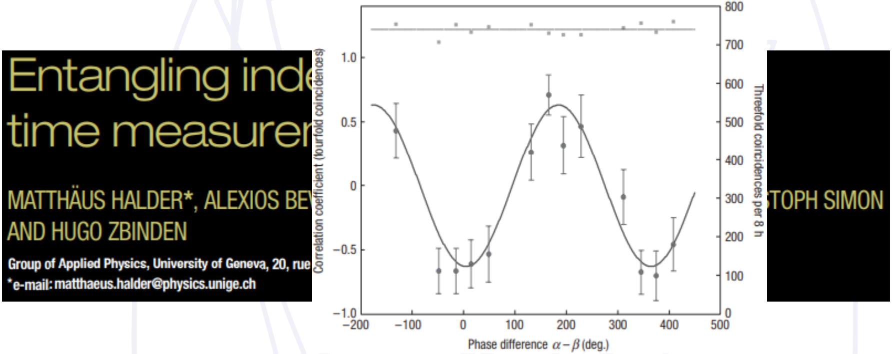
Group of Applied Physics, University of Geneva, 20, rue de l'Ecole-de-Médecine, 1211 Geneva 4, Switzerland

*e-mail: matthaeus.halder@physics.unige.ch

- 2007: swapping with independent CW sources

# Entanglement swapping

## previous experiments

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**And now for something (not completely) different...**

# Collective entanglement witness

detecting entanglement with multiple copies of tested state

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## detecting entanglement with multiple copies of tested state

PRL **107,** 150502 (2011) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2011

**Collective Uncertainty Entanglement Test**

Łukasz Rudnicki,[1,*] Paweł Horodecki,[2,3] and Karol Życzkowski[1,4]

[1]*Center for Theoretical Physics, Polish Academy of Sciences, Aleja Lotników 32/46, PL-02-668 Warsaw, Poland*
[2]*Faculty of Applied Physics and Mathematics, Technical University of Gdańsk, PL-80-952 Gdańsk, Poland*
[3]*National Quantum Information Centre of Gdańsk, PL-81-824 Sopot, Poland*
[4]*Smoluchowski Institute of Physics, Jagiellonian University, ul. Reymonta 4, PL-30-059 Kraków, Poland*
(Received 17 June 2011; published 3 October 2011)

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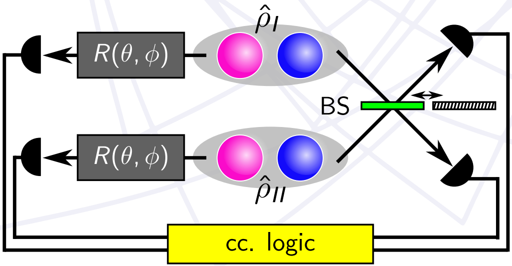

# Collective entanglement witness

## experimental implementation

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PHYSICAL REVIEW A **94**, 052334 (2016)

**Experimental measurement of collective nonlinear entanglement witness for two qubits**

Karel Lemr,[1,*] Karol Bartkiewicz,[1,2,†] and Antonín Černoch[3,‡]

[1]*RCPTM, Joint Laboratory of Optics of Palacký University and Institute of Physics of Czech Academy of Sciences, 17 listopadu 12, 771 46 Olomouc, Czech Republic*

[2]*Faculty of Physics, Adam Mickiewicz University, PL-61-614 Poznań, Poland*

[3]*Institute of Physics of the Czech Academy of Sciences, Joint Laboratory of Optics of PU and IP AS CR, 17 listopadu 50A, 772 07 Olomouc, Czech Republic*

(Received 5 August 2016; published 28 November 2016)

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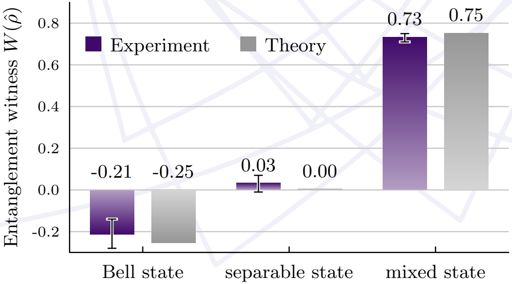

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- ✓ **collectibility**: requires only 4 measurement configurations (local projections: $|00\rangle$, $|01\rangle$, $|11\rangle$, $|++\rangle$)

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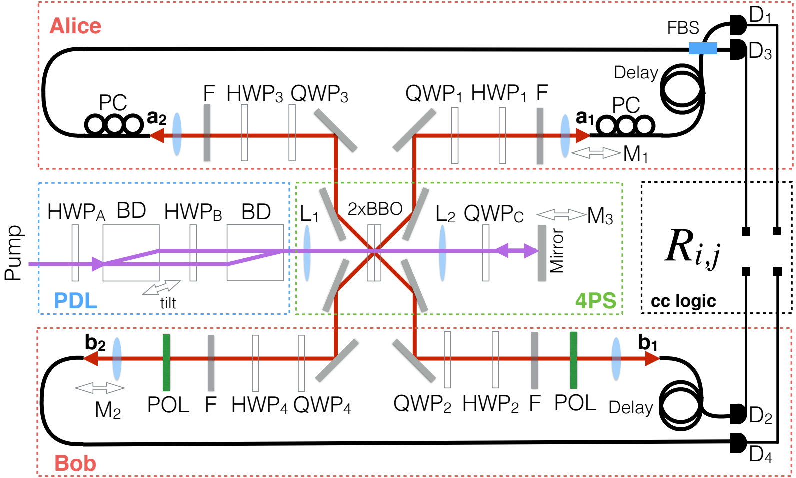
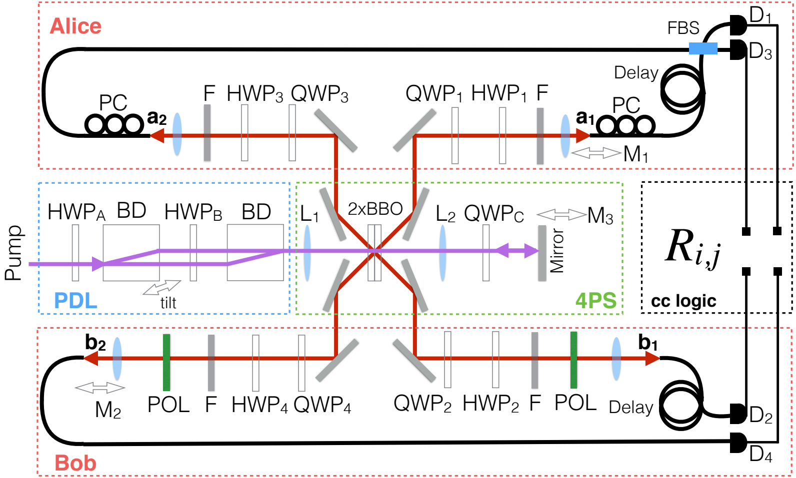
**Why not use collectibility for relay diagnostics?**

# Experimental implementation




- constructed a quantum relay using linear optics

# Experimental implementation




- constructed a quantum relay using linear optics
- used QWP and HWP to simulate errors

# Experimental implementation

measurement procedure

- four-fold coincidence acquisition was split into 60 segments (each about 10 minutes long)

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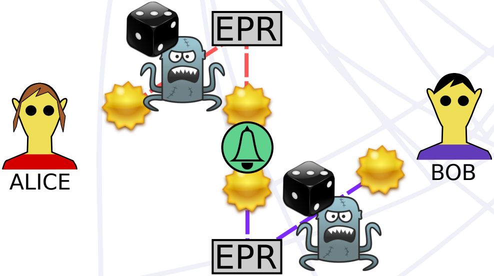
- for each segment: randomly introduce error (a) between EPR and Alice, (b) between EPR and Bob



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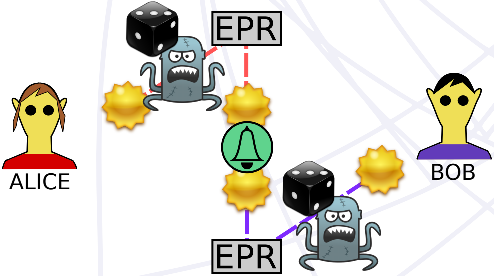


- the error corresponds to one of three tested damping channels

# Phase-damping channel

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- Kraus operators:

$$M_0 = \sqrt{1 - \frac{p}{2}}\hat{1}, M_1\sqrt{\frac{p}{2}}\hat{\sigma}_z$$

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QWP at: 45 degrees $(1-p)$, $-45$ degrees $(p/2)$

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- Experimental implementation:

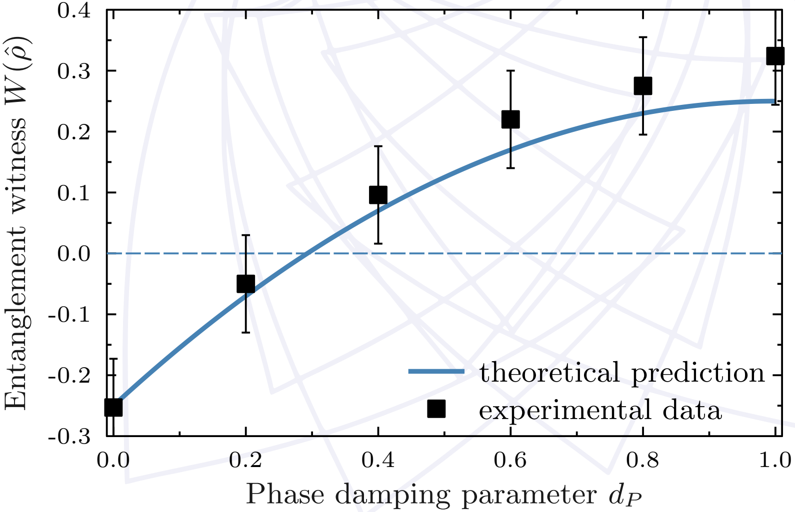
QWP at: 45 degrees $(1-p)$, $-45$ degrees $(p/2)$

- Effect:

Transition: $|\Phi^+\rangle\langle\Phi^+| \rightarrow \frac{1}{2}\left(|HH\rangle\langle HH| + |VV\rangle\langle VV|\right)$

# Phase-damping channel

results



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- Experimental implementation:

| | | | | |
|---|---|---|---|---|
| Probability: | (1-p) | p/3 | p/3 | p/3 |
| QWP at: | +45 | -45 | +45 | -45 degrees |
| HWP at: | 0 | 0 | 45 | 45 degrees |

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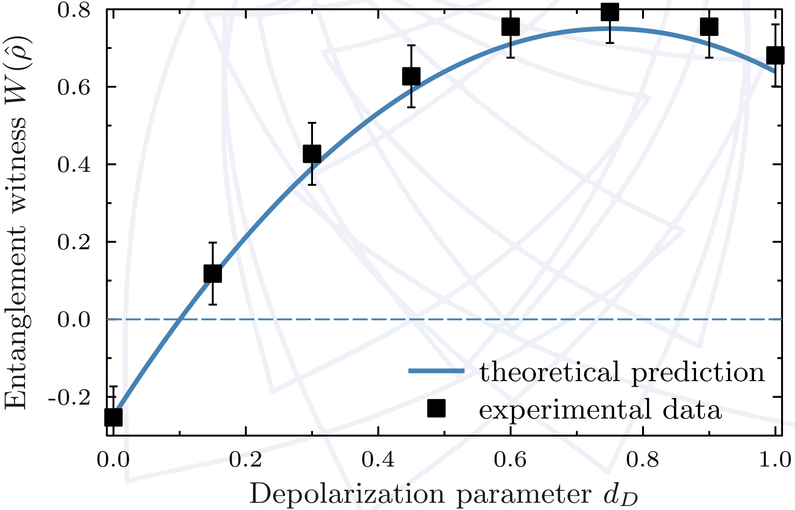
| | | | | |
|---|---|---|---|---|
| Probability: | (1-p) | p/3 | p/3 | p/3 |
| QWP at: | +45 | -45 | +45 | -45 degrees |
| HWP at: | 0 | 0 | 45 | 45 degrees |

- Effect:

$$|\Phi^+\rangle\langle\Phi^+| \rightarrow \frac{1}{4}\left(|HV\rangle\langle HV| + |VH\rangle\langle VH| + |HH\rangle\langle HH| + |VV\rangle\langle VV|\right)$$

# Depolarizing channel

results



# Amplitude-damping channel

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- Non-unitary transformation:

$$\hat{\rho} \to \begin{pmatrix} 1 & 0 \\ 0 & \sqrt{1-p} \end{pmatrix} \hat{\rho} \begin{pmatrix} 1 & 0 \\ 0 & \sqrt{1-p} \end{pmatrix}$$

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- Experimental implementation:

Single-shot measurement + post-selection (accept randomly vertical polarization results)

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- Experimental implementation:

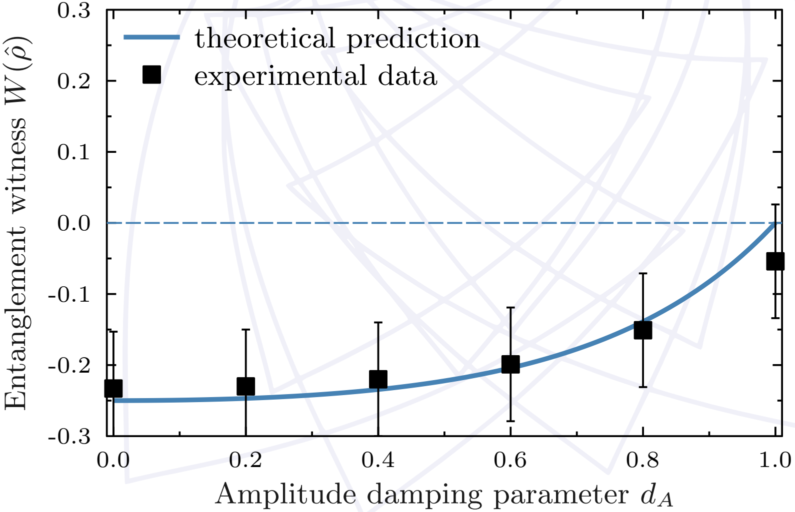
Single-shot measurement + post-selection (accept randomly vertical polarization results)

- Effect:

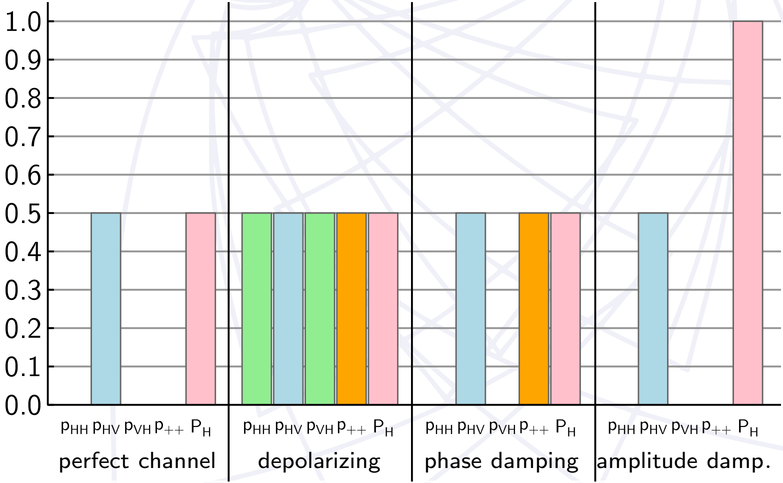
$|\Phi^+\rangle \to |HH\rangle$ (remains pure)

# Amplitude-damping channel

results

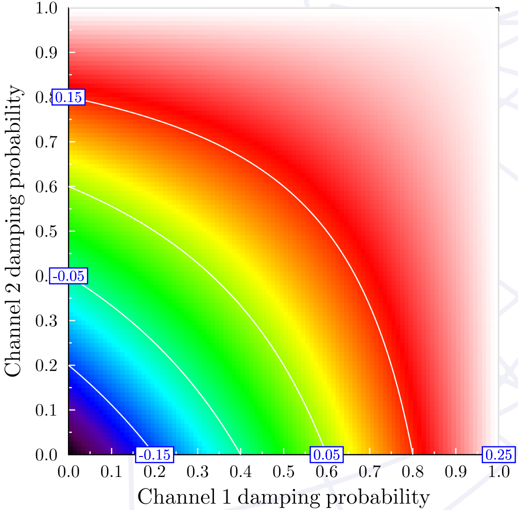


# Characteristic signatures




- each channel type introduces characteristic errors

# Asymmetric channels




- the method behaves quite well if the channel errors on Alice's and Bob's side are asymmetric

**Thank You for your attention!**