Title: PSI 2016/2017 Quantum Information (Review) - Lecture 8 (Kevin Resch)

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Abstract:

Outline

LETTERS
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nature photonics

Experimental three-photon quantum nonlocality under strict locality conditions

C. Erven[1,2]*, E. Meyer-Scott[1], K. Fisher[1], J. Lavoie[1], B. L. Higgins[1], Z. Yan[1,3], C. J. Pugh[1], J.-P. Bourgoin[1], R. Prevedel[1,4], L. K. Shalm[1,5], L. Richards[1], N. Gigov[1], R. Laflamme[1], G. Weihs[1,6], T. Jennewein[1] and K. J. Resch[1]*

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GHZ, Mermin's Inequality, and Experimental Test

Quantum correlations

- Correlations exhibited by quantum systems are very strange
- Sometimes the strangeness is described through EPR paradox, Bell's inequalities, or discussions of local hidden variable theories
- Here we'll try a different approach…

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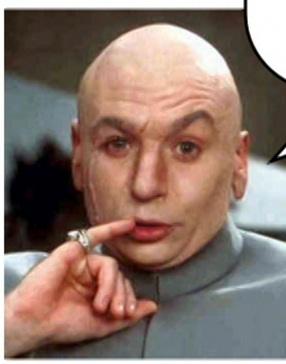
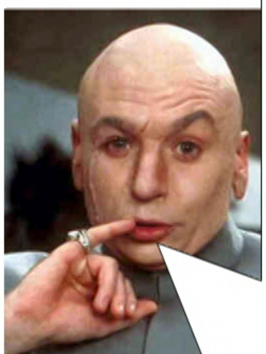
A problem

I've caught you now Schroedinger, Pauli, and Einstein! The only way out of my trap is if you can beat my game. Tomorrow morning, I'm going to place you all in different rooms with no means of communicating.



A problem



Once separated, you will either:

i) All be asked “What is Y?”

OR

ii) One of you will be asked “What is Y?” and the other two will be asked, “What is X?”

The only answers allowed are +1 or -1.

You will be freed if in case: i) the product of your answers is +1, ii) the product of your answers is -1. Otherwise…

What strategy should they use?

S

P

E

They want:

$$
\begin{array}{cccccc}
Y & Y & Y & = & +1 \\
X & X & Y & = & -1 \\
X & Y & X & = & -1 \\
Y & X & X & = & -1
\end{array}
$$

What strategy should they use?

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P

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One possible strategy:
S, P, E always answer -1

They want:

$$
\begin{array}{cccc}
Y & Y & Y & = +1 \\
X & X & Y & = -1 \\
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They want:

$$\begin{array}{ccccc} Y & Y & Y & = & +1 \\ X & X & Y & = & -1 \\ X & Y & X & = & -1 \\ Y & X & X & = & -1 \end{array}$$

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X & X & Y & = & -1 \\
X & Y & X & = & -1 \\
Y & X & X & = & -1
\end{array}
$$

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What strategy should they use?

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Another possible strategy:
P, E always answer -1
S answers +1 if asked Y or -1 if asked X

They want:

$$\begin{array}{ccccc} Y & Y & Y & = & +1 \\ X & X & Y & = & -1 \\ X & Y & X & = & -1 \\ Y & X & X & = & -1 \end{array}$$

What strategy should they use?

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P

E

Another possible strategy:
P, E always answer -1
S answers +1 if asked Y or -1 if asked X

i) Each asked "What is Y?"
S*P*E = (+1)*(-1)*(-1) = +1
(Win)

ii) One asked "What is Y?", two asked "What is X?"
XXY: S*P*E=(-1)*(-1)*(-1)=-1
(Win)

They want:

$$\begin{array}{ccccc} Y & Y & Y & = & +1 \\ X & X & Y & = & -1 \\ X & Y & X & = & -1 \\ Y & X & X & = & -1 \end{array}$$

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$$X \quad X \quad Y \quad = \quad -1$$
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$$Y \quad X \quad X \quad = \quad -1$$

What strategy should they use?

S


P


E


Another possible strategy:
P, E always answer -1
S answers +1 if asked Y or -1 if asked X

i) Each asked "What is Y?"
S*P*E = (+1)*(-1)*(-1) = +1
(Win)

ii) One asked "What is Y?", two asked "What is X?"
XXY: S*P*E=(-1)*(-1)*(-1)=-1
(Win)
XYX: S*P*E=(-1)*(-1)*(-1)=-1
(Win)
YXX: S*P*E=(+1)*(-1)*(-1)=+1
(Lose)

They want:

$$Y \quad Y \quad Y = +1$$
$$X \quad X \quad Y = -1$$
$$X \quad Y \quad X = -1$$
$$Y \quad X \quad X = -1$$

Any such strategy will fail...

- Cases where S,P, and E pre-decide their answers to *X* or *Y* are examples of a **Local-Realistic model**.
- They require the relations

$$
\begin{aligned}
Y \quad Y \quad Y &= +1 \\
X \quad X \quad Y &= -1 \\
X \quad Y \quad X &= -1 \\
Y \quad X \quad X &= -1
\end{aligned}
$$

- Since X and Y are +1 or -1, $X^2=1$ & $Y^2=1$
- Compare the products of the left side and right side

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Y\;X\;X &= -1
\end{aligned}
$$

$X^2Y^2=1$ $\quad X^2Y^2=1 \quad$ $X^2Y^2=1$

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\hline
\end{array}
$$

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- Since X and Y are +1 or -1, $X^2=1$ & $Y^2=1$
- Compare the products of the left side and right side
- To always win, they need coordinated decisions **without** communicating

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GHZ solution

$$|\text{GHZ}_{-i}\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\uparrow\rangle - i|\downarrow\downarrow\downarrow\rangle)$$

$$\begin{aligned} YYY|\text{GHZ}_{-i}\rangle &= +1|\text{GHZ}_{-i}\rangle \\ YXX|\text{GHZ}_{-i}\rangle &= -1|\text{GHZ}_{-i}\rangle \\ XYX|\text{GHZ}_{-i}\rangle &= -1|\text{GHZ}_{-i}\rangle \\ XXY|\text{GHZ}_{-i}\rangle &= -1|\text{GHZ}_{-i}\rangle \end{aligned}$$

Greenberger-Horne-Zeilinger

- ‘All-or-nothing’ test against local hidden variable description

GHZ, *Bells Theorem, Quantum Theory and Conceptions of the Universe* p 73 (1989)

Mermin's inequality

- GHZ argument is based on perfect correlations
- Mermin converted the argument, and test of local realism, into an inequality which allows for imperfection

$$\left| E(\mathrm{a},\mathrm{b},\mathrm{c}) - E(\mathrm{a},\mathrm{b}',\mathrm{c}') - E(\mathrm{a}',\mathrm{b},\mathrm{c}') - E(\mathrm{a}',\mathrm{b}',\mathrm{c}) \right| \leq 2$$

where *E*(***a***,***b***,***c***)=<abc> is the *correlation*.

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N.D. Mermin, PRL 65, 1838 (1990).

GHZ solution

$$|\mathsf{GHZ}_{-i}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\uparrow\rangle - i|\downarrow\downarrow\downarrow\rangle\right)$$

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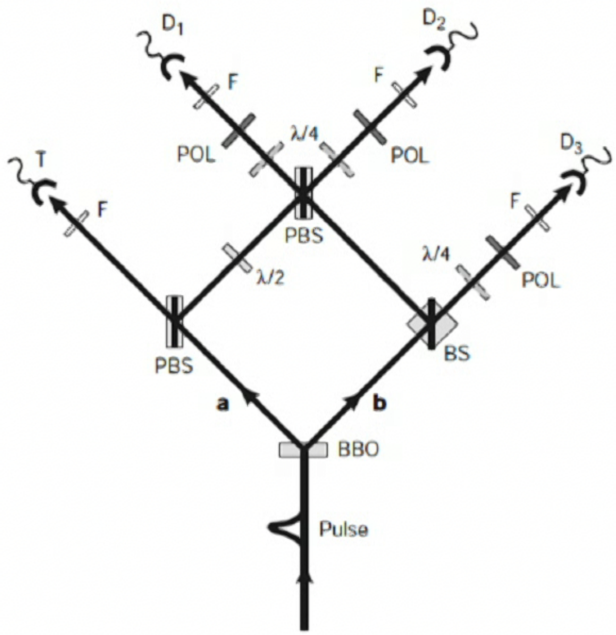
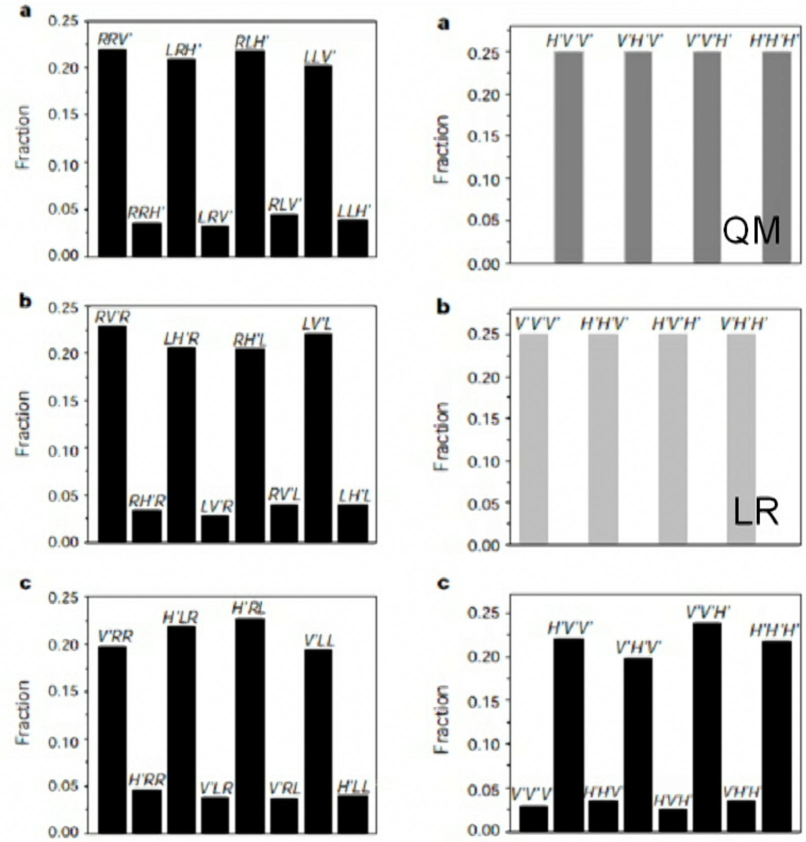
Maximum eigenvalue, product of spin outcomes is **certain** and **+1** even though each individual spin outcome is random

Experimental test

Spin-1/2 → Photon polarization





Pan et al, Nature 403, 515 (2000)

Loopholes

- Experimental limitations which allow nature to appear nonlocal it isn't
- **Detection**: low detection efficiency preferentially measures high correlations (violates "fair sampling")
- **Locality**: measurement settings at the various stations are not causally disconnected
- **Freedom-of-choice**: measurement settings not causally disconnected from the source

Loopholes

- Experimental limitations which allow nature to appear nonlocal it isn't
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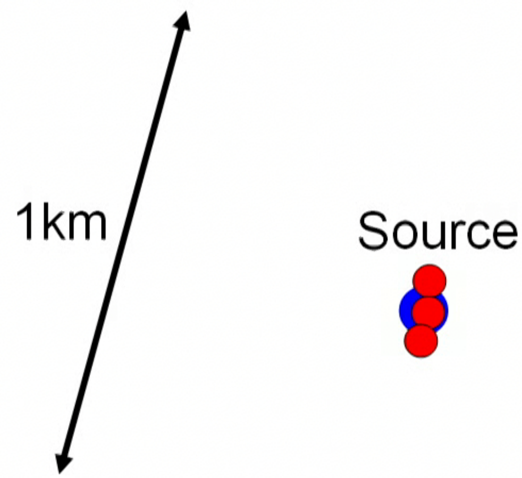
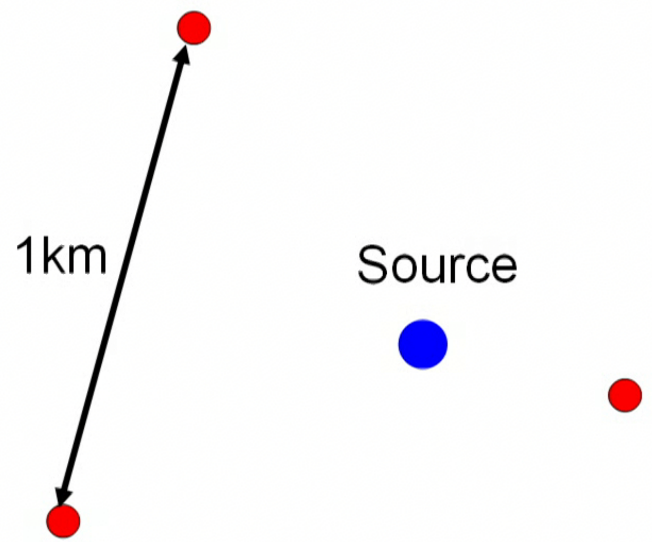
Closing locality & FOC loopholes



Closing locality & FOC loopholes



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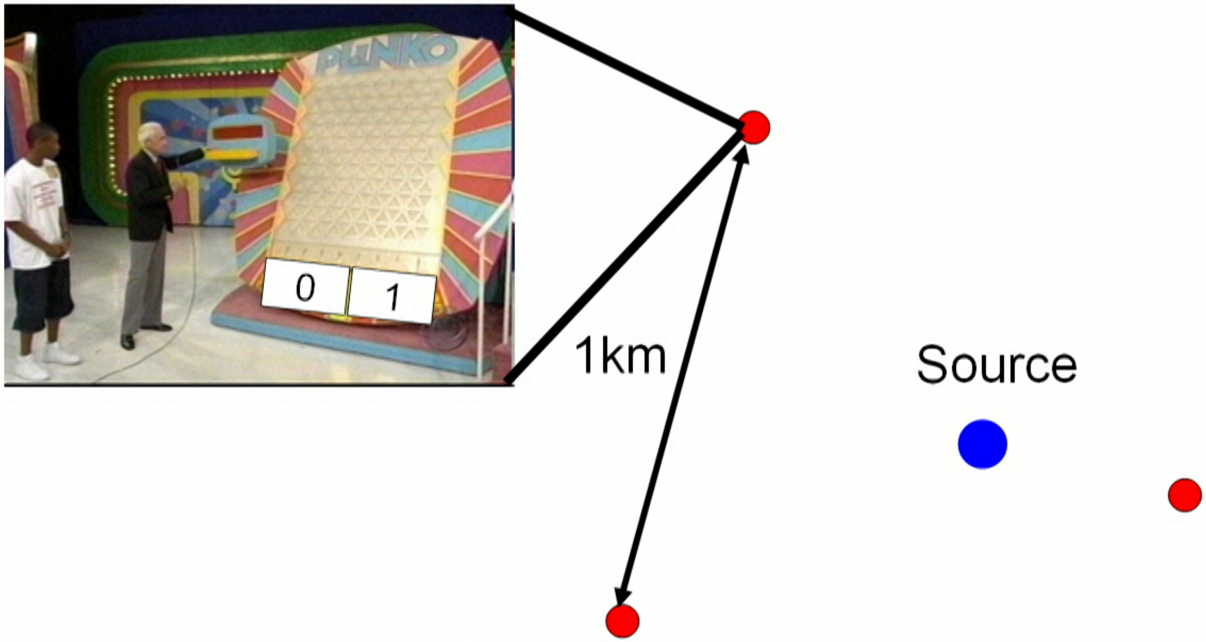
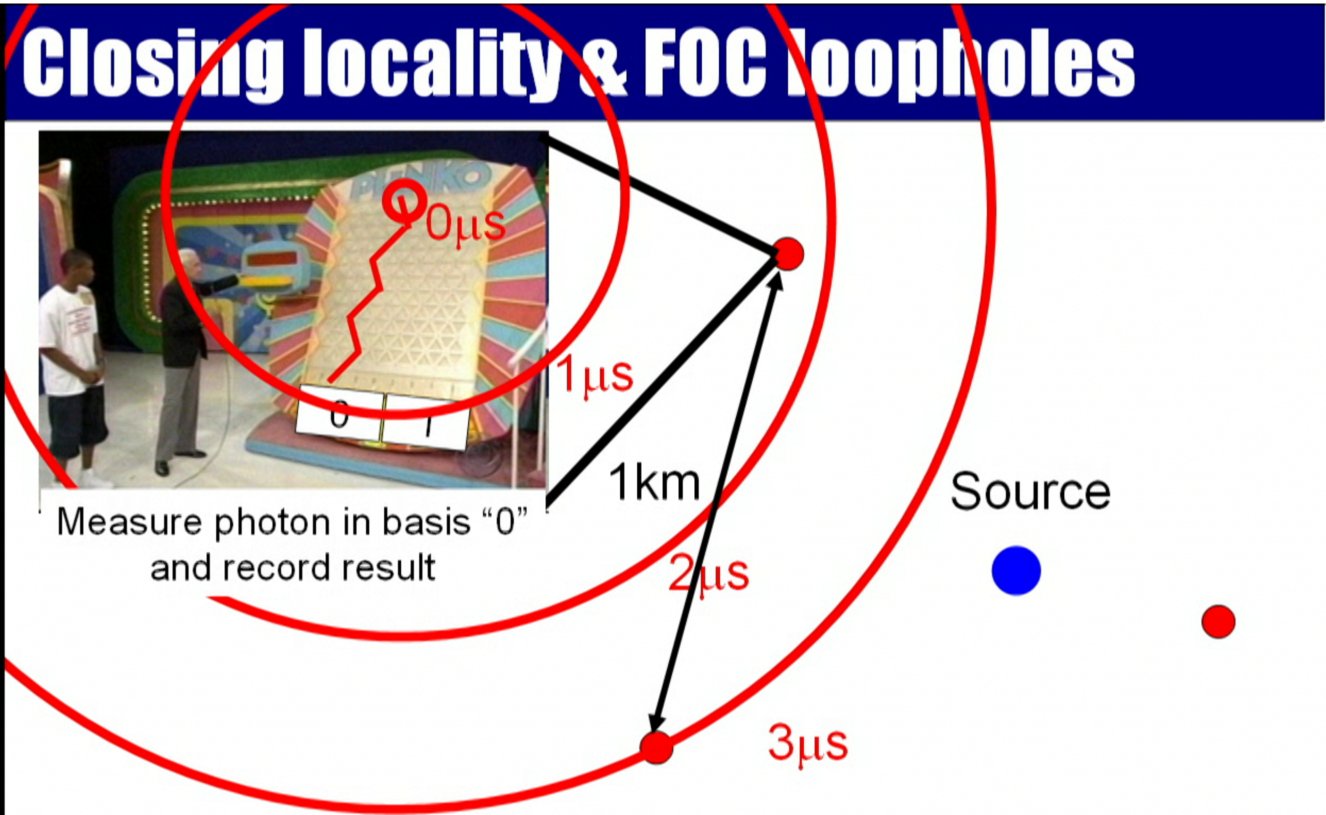
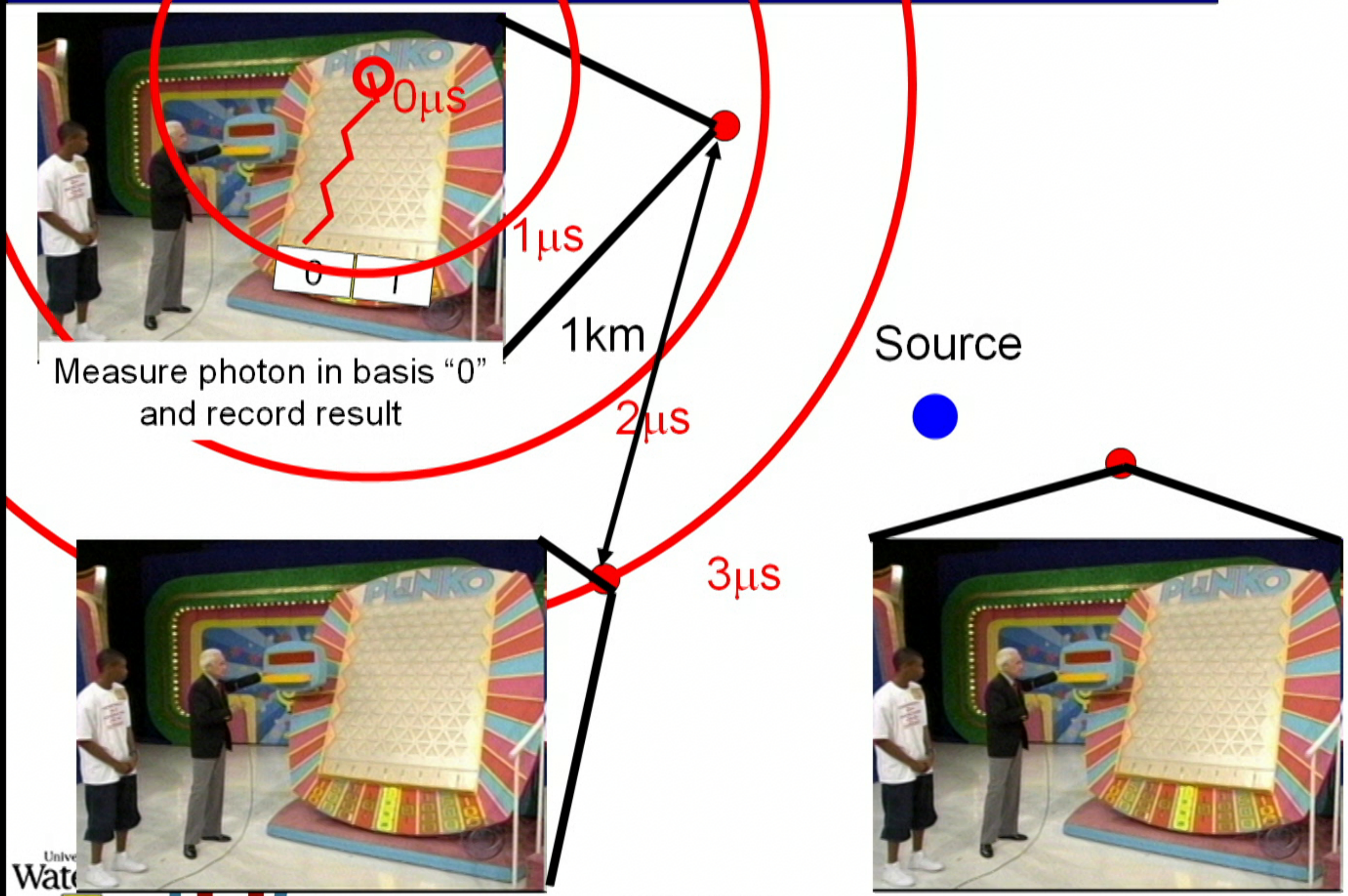


Closing locality & FOC loopholes



Closing locality & FOC loopholes



Locality loopholes

- Locality/FoC loopholes have been closed in experiments with ***pairs*** of photons
- Three-particle challenges:
  - Rate: entangled pairs at a rate of 1MHz, but triples at a rate of ~Hz
  - Loss: sensitive to loss cubed vs. loss squared
  - Noise: lots of background light due to probabilistic nature of the source
  - Complexity: space-time arrangement/people/parts
  - Weather…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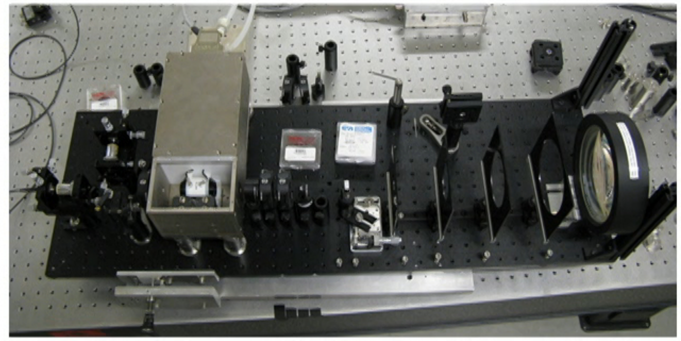
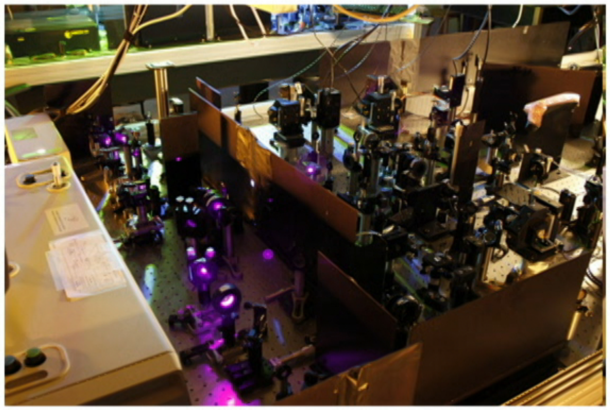
IQC collaboration

Laflamme/Weihs





Resch

Jennewein

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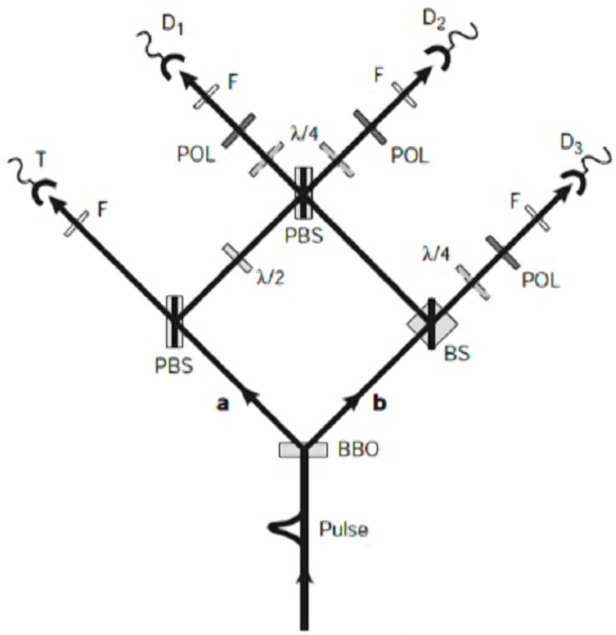
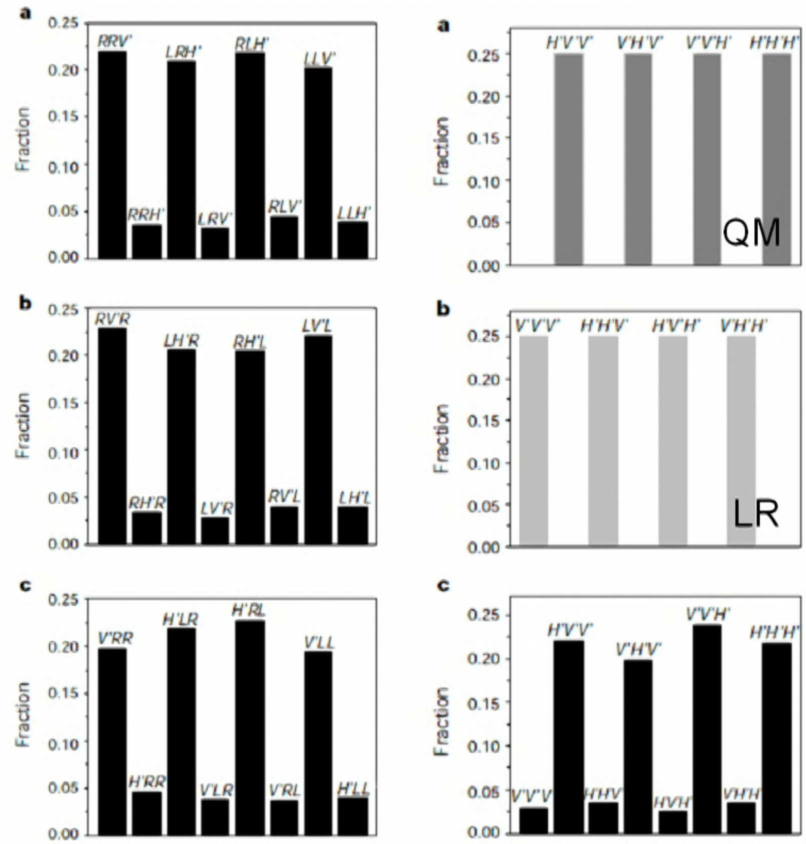
Experimental test

Spin-1/2 → Photon polarization





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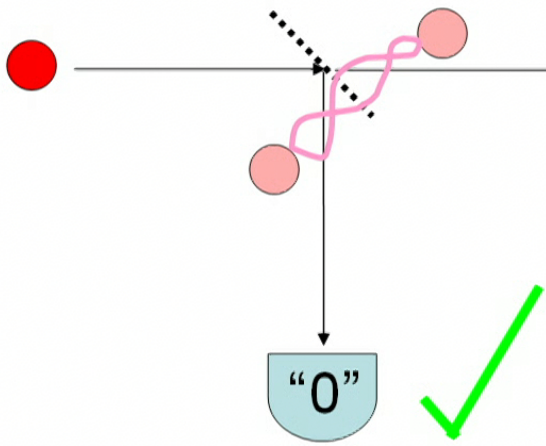
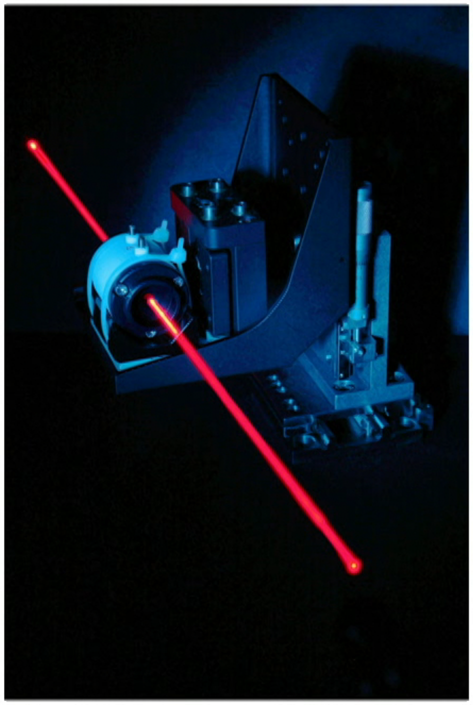
Pan et al, Nature 403, 515 (2000)

Locality loophole

- Requires fast truly random measurements (not pseudo random)





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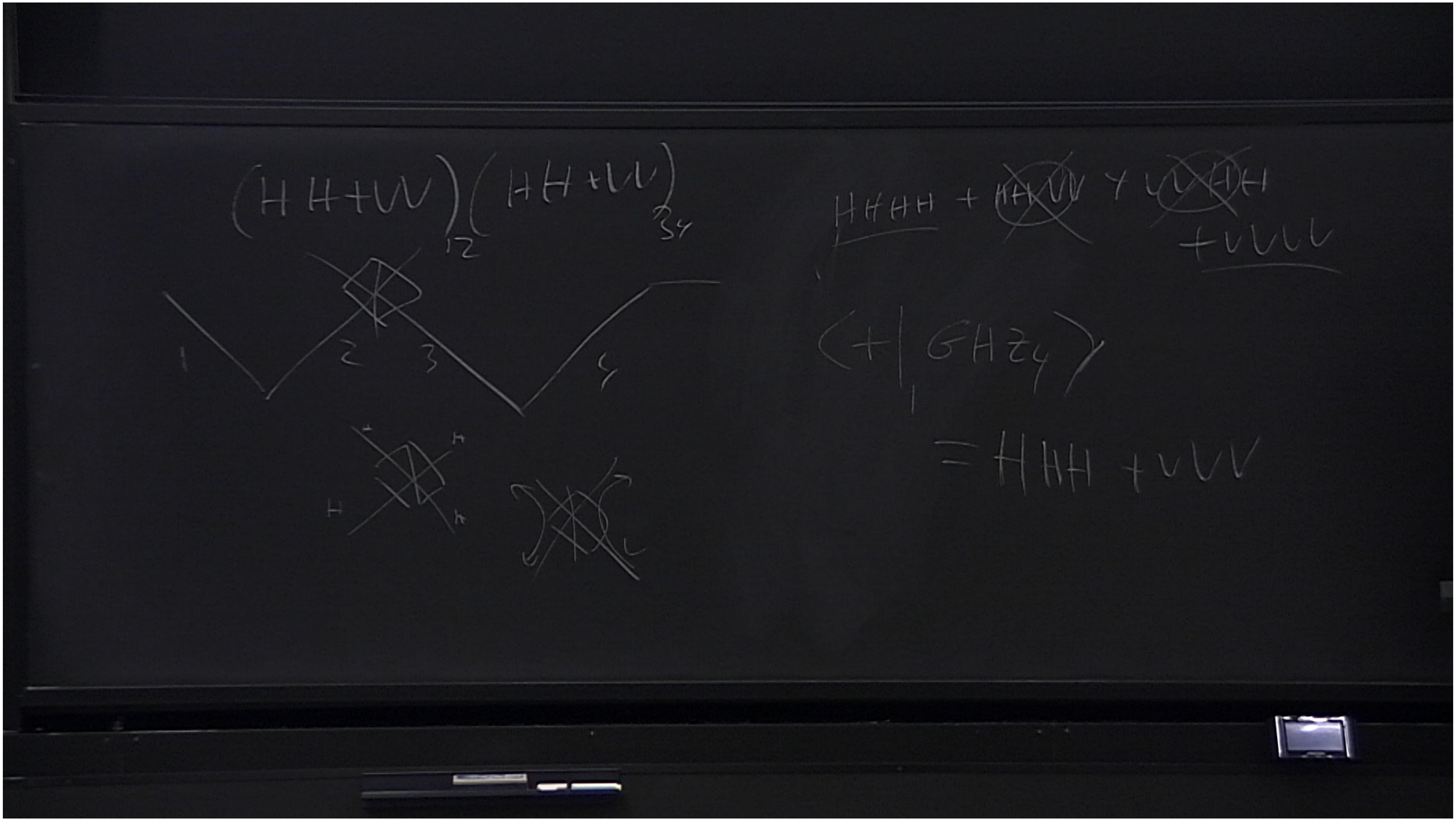
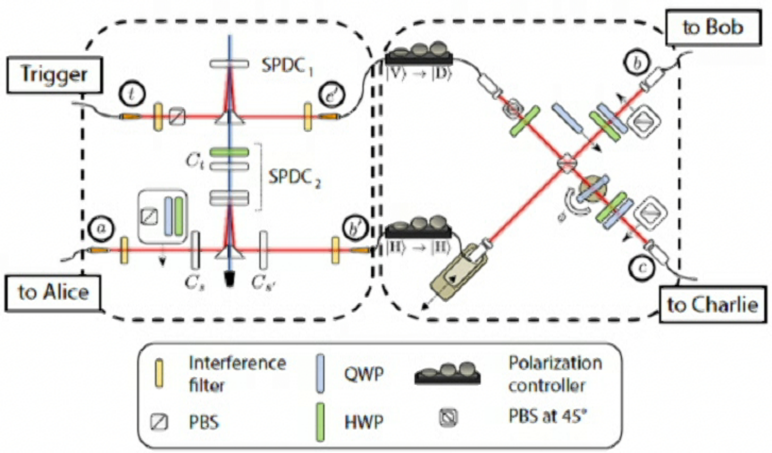
T. Jennewein et al., Rev Sci Inst. 71, 1675 (2000).


(HH+VV)12 (HH+VV)34
HHHH + HHVV + VVHH
+VVVV
⟨+|1 GHZ4⟩
= HHH + VVV

GHZ source



in modes a, b, and c. With no analyzers in place we directly measured the singles rates of 576 kHz, 386 kHz, 417 kHz, and 476 kHz for modes a, b, c, and t respectively, and a four-fold coincidence rate of 39 Hz.

cf. 130 counts in 3h, 0.01Hz in Pan et al.

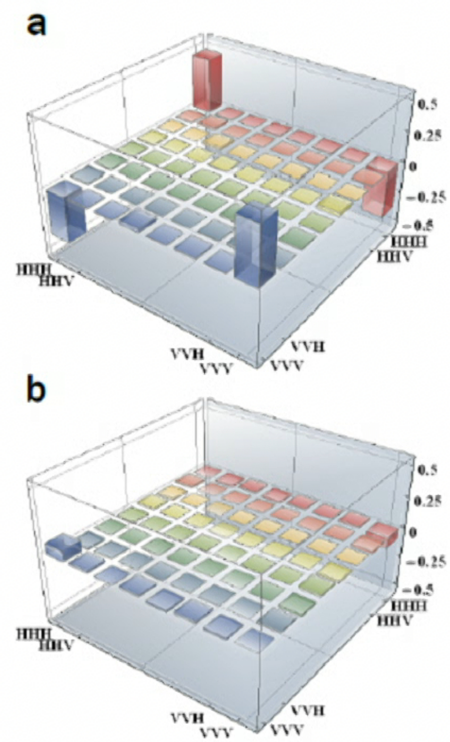


FIG. 5. Quantum state tomography. Real (a) and imaginary (b) parts of the reconstructed density matrix of our GHZ state as measured directly in the laboratory. The fidelity of our state at the source with the desired state $|\mathrm{GHZ}_\pi\rangle$ was $(82.9 \pm 0.3)\%$.

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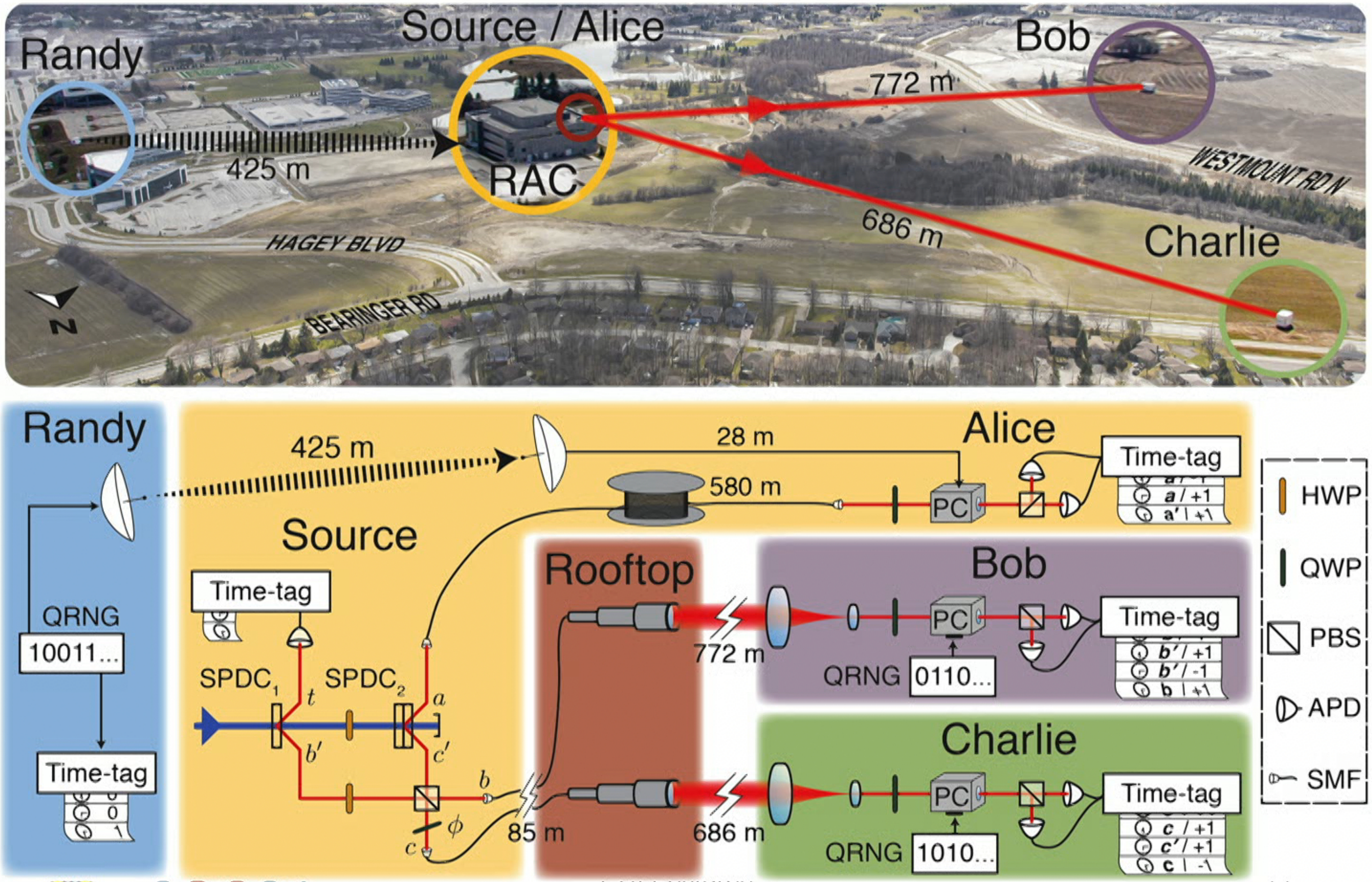
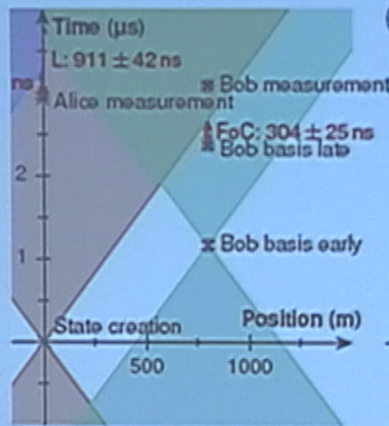
Marley

Experimental setup



Space-time analysis



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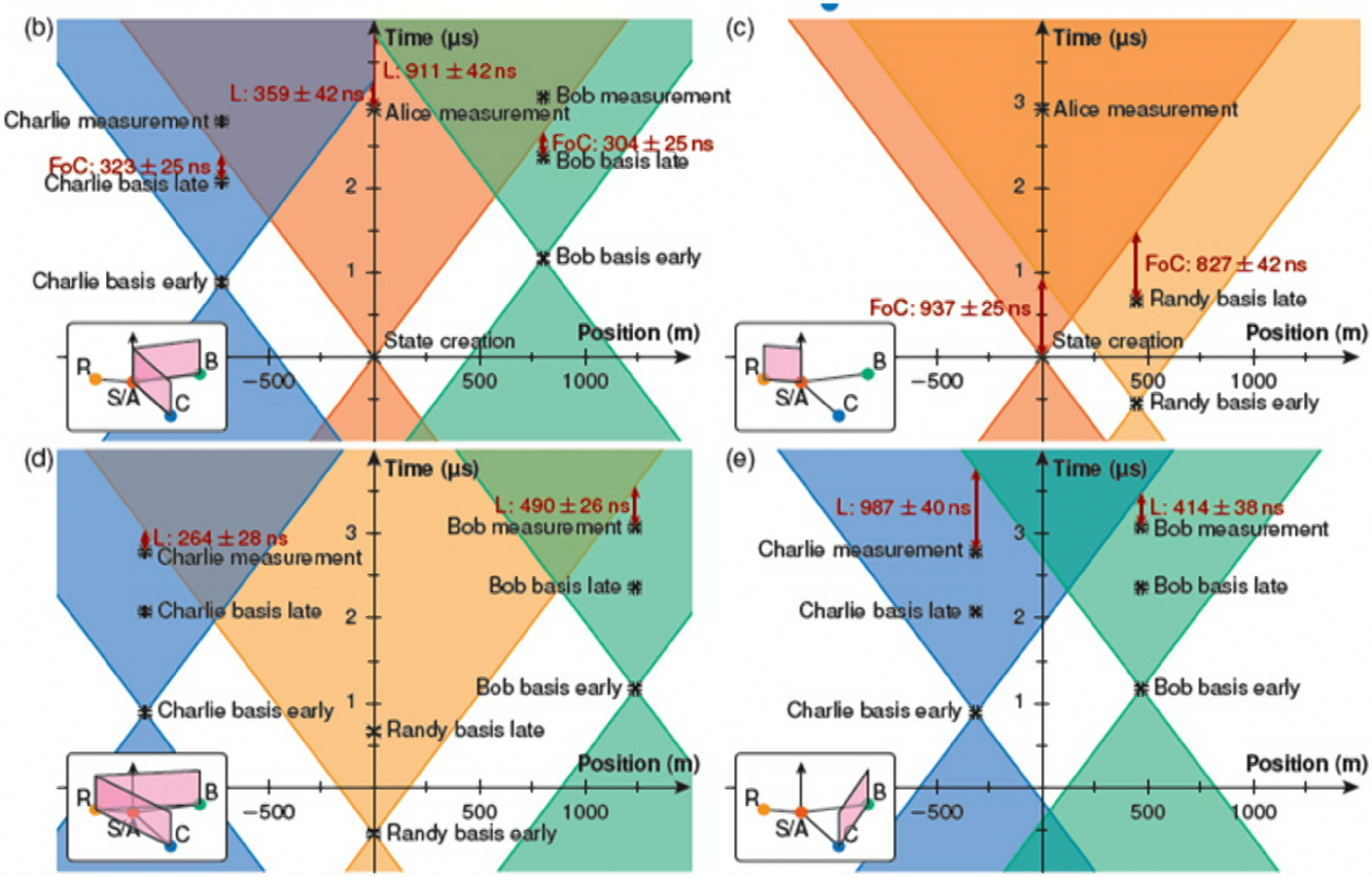

Correlation results

Counts (Alice,Bob,Charlie)							
RRR	**RRL**	**RLR**	**RLL**	**LRR**	**LRL**	**LLR**	**LLL**
55	9	18	92	9	53	77	15
RRD	**RRA**	**RLD**	**RLA**	**LRD**	**LRA**	**LLD**	**LLA**
14	49	55	40	32	30	35	60
RDR	**RDL**	**RAR**	**RAL**	**LDR**	**LDL**	**LAR**	**LAL**
21	46	72	43	34	30	23	50
RDD	**RDA**	**RAD**	**RAA**	**LDD**	**LDA**	**LAD**	**LAA**
3	53	68	15	43	9	13	72
DRR	**DRL**	**DLR**	**DLL**	**ARR**	**ARL**	**ALR**	**ALL**
21	39	56	55	37	26	28	59
DRD	**DRA**	**DLD**	**DLA**	**ARD**	**ARA**	**ALD**	**ALA**
3	61	80	15	51	16	14	100
DDR	**DDL**	**DAR**	**DAL**	**ADR**	**ADL**	**AAR**	**AAL**
8	56	69	18	34	8	14	81
DDD	**DDA**	**DAD**	**DAA**	**ADD**	**ADA**	**AAD**	**AAA**
30	28	32	59	16	34	30	56
M				M'			
2.7720 ± 0.0824				0.7746 ± 0.1108			

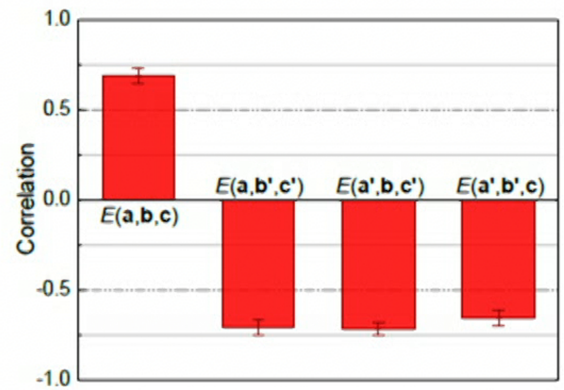

FIG. 2. Experimentally measured three-photon polarization correlations. The analyzers were set to the *R/L* basis for settings a, b, and c and the *D/A* basis for settings a′, b′, and c′. During a 1 hr 19 min experiment, we measured 2,472 four-fold coincidence events of which 1,232 were used to extract correlations for a test of Mermin's inequality. The measured correlations were $E(\mathrm{a},\mathrm{b},\mathrm{c}) = 0.689 \pm 0.040$, $E(\mathrm{a},\mathrm{b}',\mathrm{c}') = -0.710 \pm 0.042$, $E(\mathrm{a}',\mathrm{b},\mathrm{c}') = -0.718 \pm 0.038$, and $E(\mathrm{a}',\mathrm{b}',\mathrm{c}) = -0.655 \pm 0.044$ yielding a Mermin parameter of 2.77 ± 0.08 violating the local hidden variable bound of 2 by over 9σ. Error bars represent one standard deviation based on Poisson statistics.

Summary

- Quantum information with optics
- Polarization transformations, measurements, and entanglement
- Experimental teleportation
- Three-particle nonlocality test closing locality and freedom-of-choice loopholes