Experimental loophole-free violation of a Bell inequality using entangled electron spins separated by 1.3 km

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Adrian Hutter
Journal Club
September 15, 2015

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Gapped boundaries, group cohomology and fault-tolerant logical gates

Scite! 14 PDF

Beni Yoshida

Sep 14 2015 cond-mat.str-el quant-ph arXiv:1509.03626v1

This paper attempts to establish the connection among classifications of gapped boundaries in topological phases of matter, bosonic symmetry-protected topological (SPT) phases and fault-tolerantly implementable logical gates in quantum error-correcting codes. We begin by presenting constructions of gapped boundaries for the d-dimensional quantum double model by using d-cocycles functions ($d \geq 2$). We point out that the system supports m-dimensional excitations ($m < d$), which we shall call fluctuating charges, that are superpositions of point-like electric charges characterized by m-dimensional bosonic SPT wavefunctions. There exist gapped boundaries where electric charges or magnetic fluxes may not condense by themselves, but may condense only when accompanied by fluctuating charges. Magnetic fluxes and codimension-2 fluctuating charges exhibit non-trivial multi-excitation braiding statistics, involving more than two excitations. The statistical angle can be computed by taking slant products of underlying cocycle functions sequentially. We find that excitations that may condense into a gapped boundary can be characterized by trivial multi-excitation braiding statistics, generalizing the notion of the Lagrangian subgroup. As an application, we construct fault-tolerantly implementable logical gates for the d-dimensional quantum double model by using d-cocycle functions. Namely, corresponding logical gates belong to the dth level of the Clifford hierarchy, but are outside of the $(d-1)$th level, if cocycle functions have non-trivial sequences of slant products.

Classical Computation by Quantum Bits

Scite! 3 PDF

B. Antonio, J. Randall, W. K. Hensinger, G. W. Morley, S. Bose

Sep 14 2015 quant-ph arXiv:1509.03420v1

Atomic-scale logic and the minimization of heating (dissipation) are both very high on the agenda for future computation hardware. An approach to achieve these would be to replace networks of transistors directly by classical reversible logic gates built from the coherent dynamics of a few interacting atoms. As superpositions are unnecessary before and after each such gate (inputs and outputs are bits), the dephasing time only needs to exceed a single gate operation time, while fault tolerance should be achieved with low overhead, by classical

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Undecidability of the Spectral Gap (full version)

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Toby Cubitt, David Perez-Garcia, Michael M. Wolf

Feb 17 2015 quant-ph cond-mat.other hep-th math-ph math.MP

arXiv:1502.04573v2

We show that the spectral gap problem is undecidable. Specifically, we construct families of translationally-invariant, nearest-neighbour Hamiltonians on a 2D square lattice of d-level quantum systems (d constant), for which determining whether the system is gapped or gapless is an undecidable problem. This is true even with the promise that each Hamiltonian is either gapped or gapless in the strongest sense: it is promised to either have continuous spectrum above the ground state in the thermodynamic limit, or its spectral gap is lower-bounded by a constant in the thermodynamic limit. Moreover, this constant can be taken equal to the local interaction strength of the Hamiltonian. This implies that it is logically impossible to say in general whether a quantum many-body model is gapped or gapless. Our results imply that for any consistent, recursive axiomatisation of mathematics, there exist specific Hamiltonians for which the presence or absence of a spectral gap is independent of the axioms. These results have a number of important implications for condensed matter and many-body quantum theory.

Experimental loophole-free violation of a Bell inequality using entangled electron spins separated by 1.3 km

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B. Hensen, H. Bernien, A.E. Dréau, A. Reiserer, N. Kalb, M.S. Blok, J. Ruitenberg, R.F.L. Vermeulen, R.N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D.J. Twitchen, D. Elkouss, S. Wehner, T.H. Taminiau, R. Hanson

Aug 26 2015 quant-ph arXiv:1508.05949v1

For more than 80 years, the counterintuitive predictions of quantum theory have stimulated debate about the nature of reality. In his seminal work, John Bell proved that no theory of nature that obeys locality and realism can reproduce all the predictions of quantum theory. Bell showed that in any local realist theory the correlations between distant measurements satisfy an inequality and, moreover, that this inequality can be violated according to quantum theory. This provided a recipe for experimental tests of the fundamental principles

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Background

Einstein, Podolsky, and Rosen (1935):

Incompleteness of Quantum Mechanics

Assumptions:

- Locality (no instantaneous actions at a distance, i.e. faster-than-light)
- Realism (physical properties are defined prior to and independent of observation)

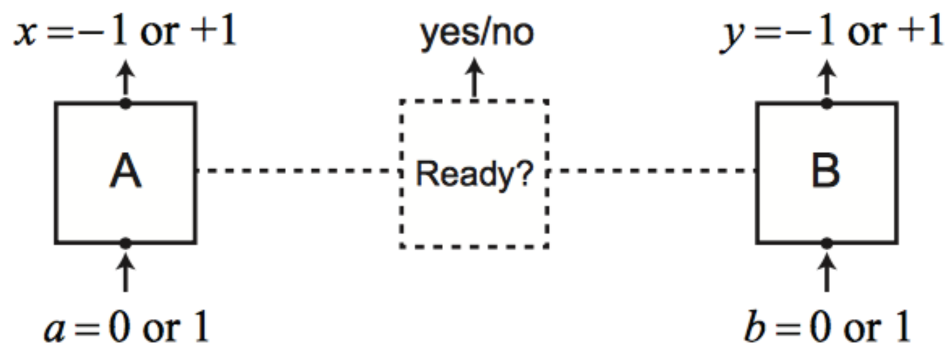
Bell (1964):

No theory satisfying these assumptions can reproduce the predictions of quantum mechanics

CHSH Inequality

Clauser, Horne, Shimony, and Holt (1969):

Proposal to experimentally detect a violation of local realism



If local realism holds:

$$S = \langle x \cdot y \rangle_{(0,0)} + \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} - \langle x \cdot y \rangle_{(1,1)} \leq 2$$

Violation of CHSH

Use a state $|\psi^-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

a=0: Measurement in A in Z direction

a=1: Measurement in A in X direction

b=0: Measurement in B in -Z+X direction

b=1: Measurement in B in -Z-X direction

➔ $S = 2\sqrt{2}$

Loopholes

- Locality loophole: exchange of information between the boxes
  - ➔ guarantee that no communication between the boxes is possible
  - ➔ space-like separation

- Detection loophole: if we disregard samples in which a box does not produce an output, the selected subset may show a violation even though the set of all trials may not
  - ➔ guarantee efficient measurements

Previous experiments

Close locality loophole with pairs of photons separated over large distances

➔ open the detection loophole due to imperfect detectors and inevitable photon loss during the spatial distribution of entanglement

PRL Milestone Free to Read

Experimental Test of Bell's Inequalities Using Time- Varying Analyzers

Alain Aspect, Jean Dalibard, and Gérard Roger

Phys. Rev. Lett. **49**, 1804 – Published 20 December 1982

ABSTRACT

Correlations of linear polarizations of pairs of photons have been measured with time-varying analyzers. The analyzer in each leg of the apparatus is an acousto-optical switch followed by two linear polarizers. The switches operate at incommensurate frequencies near 50 MHz. Each analyzer amounts to a polarizer which jumps between two orientations in a time short compared with the photon transit time. The results are in good agreement with quantum mechanical predictions but violate Bell's inequalities by 5 standard deviations.

Previous experiments

Close locality loophole with pairs of photons separated over large distances

➔ open the detection loophole due to imperfect detectors and inevitable photon loss during the spatial distribution of entanglement

Close detection loophole with massive entangled particles and high detection efficiency

➔ open locality loophole due to spatial proximity

Letters to Nature

Nature **409**, 791-794 (15 February 2001) | doi:10.1038/35057215; Received 25 October 2000; Accepted 30 November 2000

Experimental violation of a Bell's inequality with efficient detection

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2. Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA

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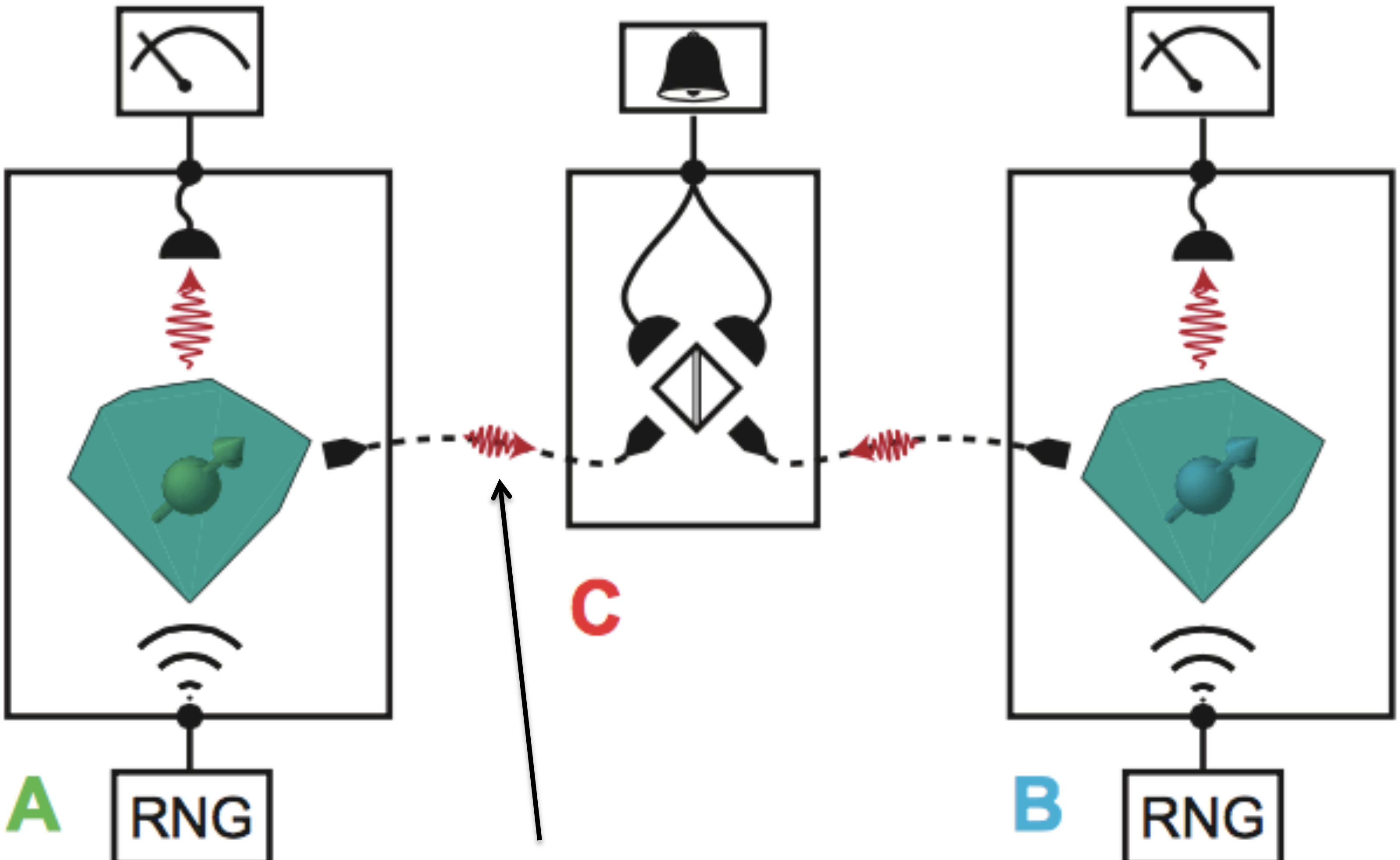
Local realism is the idea that objects have definite properties whether or not they are measured, and that measurements of these properties are not affected by events taking place sufficiently far away[1]. Einstein, Podolsky and Rosen[2] used these reasonable assumptions to conclude that quantum mechanics is incomplete. Starting in 1965, Bell and others constructed mathematical inequalities whereby experimental tests could distinguish between quantum mechanics and local realistic theories[1, 3, 4, 5]. Many experiments[1, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15] have since been done that are consistent with quantum mechanics and inconsistent with local realism. But these conclusions remain the subject of considerable interest and debate, and experiments are still being refined to overcome 'loopholes' that might allow a local realistic interpretation. Here we have measured correlations in the classical properties of massive entangled particles ($^{9}Be^{+}$ ions): these correlations violate a form of Bell's inequality. Our measured value of the appropriate Bell's 'signal' is 2.25 ± 0.03, whereas a value of 2 is the maximum allowed by local realistic theories of nature. In contrast to previous measurements with massive particles, this violation of Bell's inequality was obtained by use of a complete set of measurements. Moreover, the high detection efficiency of our apparatus eliminates the so-called 'detection' loophole.

Relevance

- So far: no experiment that closes both loopholes
- Here: perform a loop-hole free Bell test using an approach proposed by Bell himself
- Relevance:
  - foundational importance to the understanding of nature
  - critical component for device-independent quantum security protocols

Spin control

- Boxes employ the electron spin of a single NV defect centre in a diamond chip (T=4K)
- Control with microwave pulses
- Initialized through optical pumping and read out along Z axis
- Readout: resonant excitation of a spin-selective cycling transition
  - NV centre emits many photons if $m_s=0$ (+1 output)
  - NV centre remains dark if $m_s=\pm1$ (-1 output)



quantum random
number generator

photon whose arrival time
Is entangled with the spin state

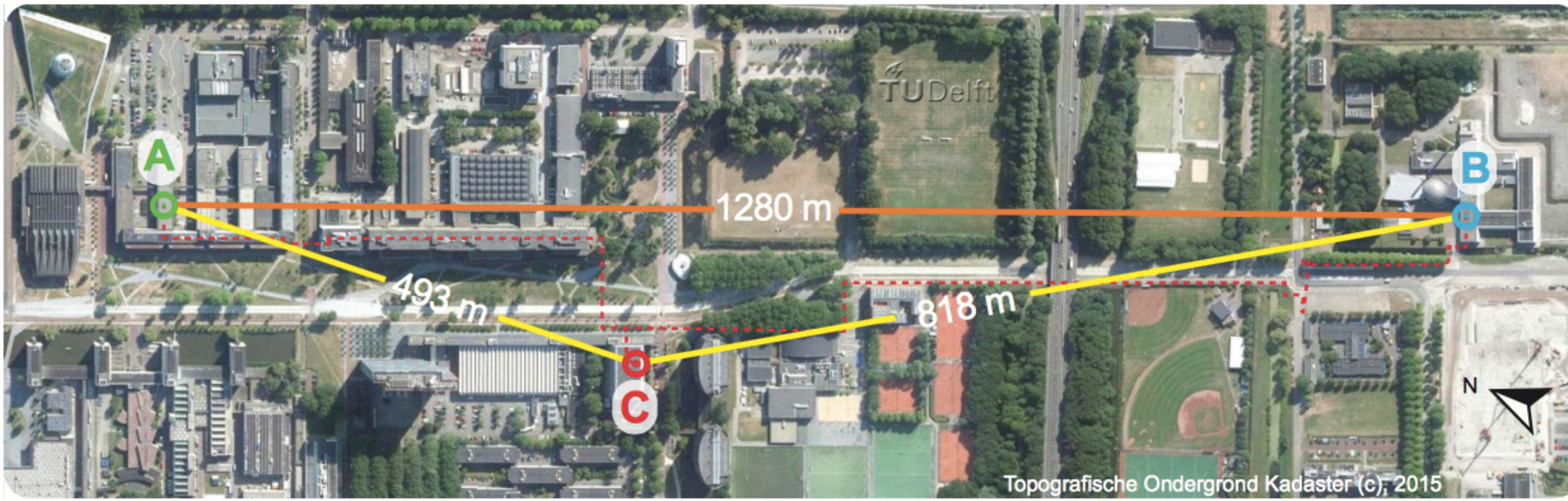
Entanglement generation

- At C, the photons are overlapped on a a beam-splitter and detected
- Arrival of one early and one late photon: successful preparation ➔ spins at A and B in a maximally entangled state

$$|\psi^-\rangle = \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

$$m_s = 0 \equiv |\uparrow\rangle \qquad m_s = -1 \equiv |\downarrow\rangle$$

- The distance between the entangled electrons is nearly two orders of magnitude larger than in any previous experiment


TU Delft
A
B
C
1280 m
493 m
818 m
N
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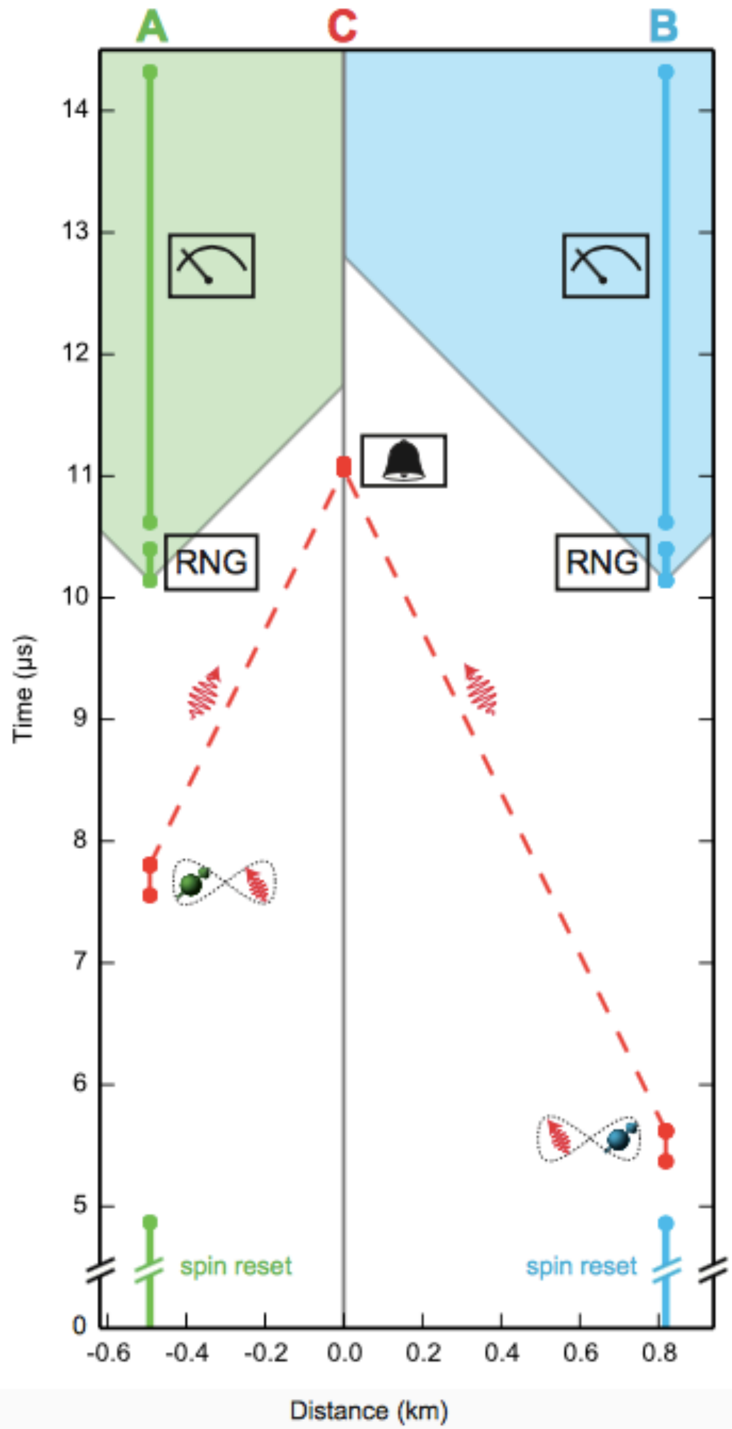
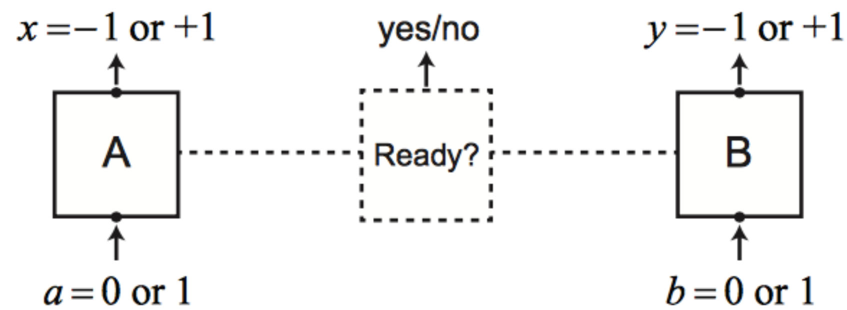
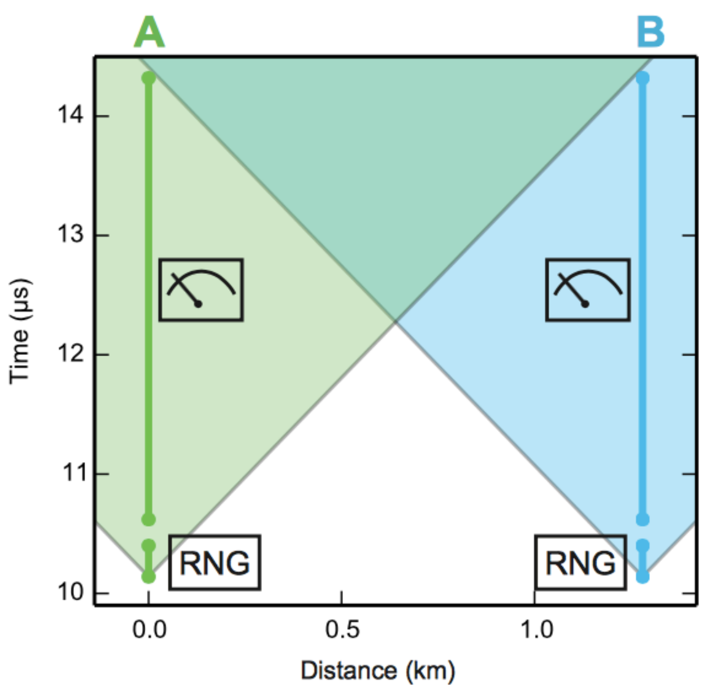


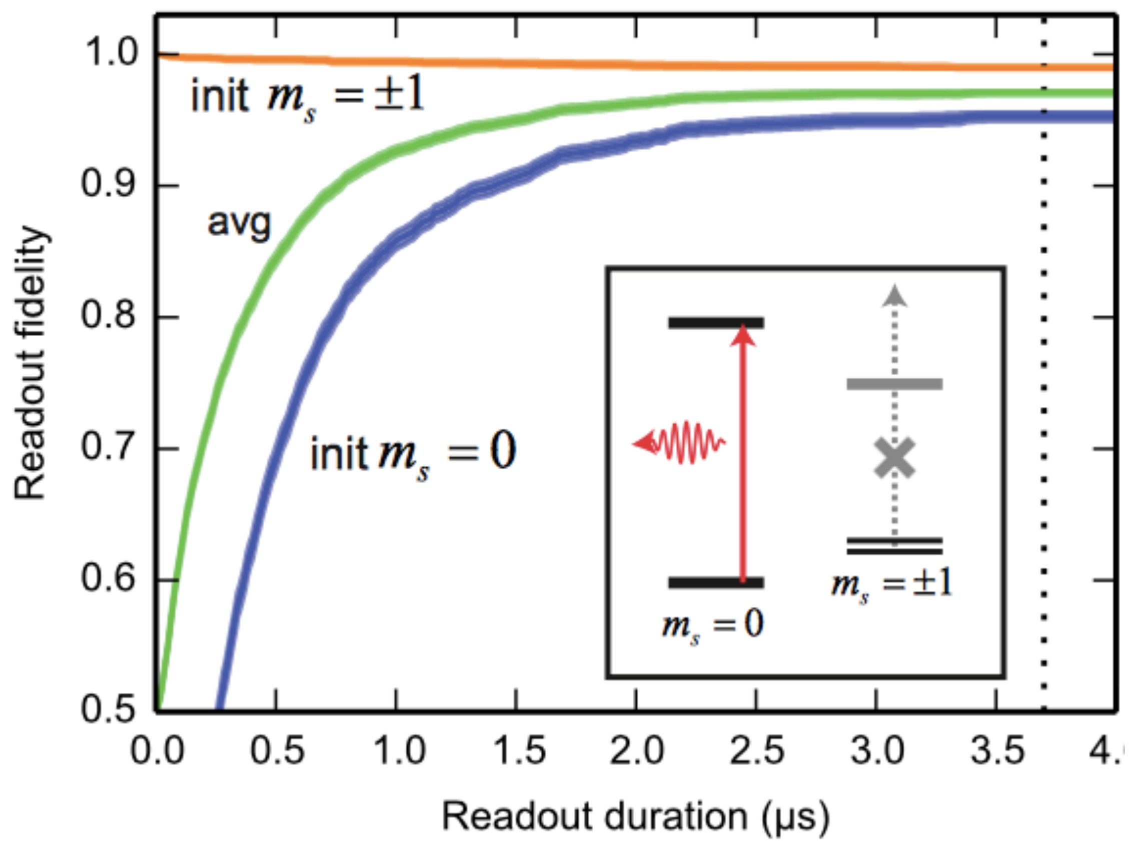


The event-ready signal is space-like separated from the random input bit generation at locations A and B.

Space-like separation

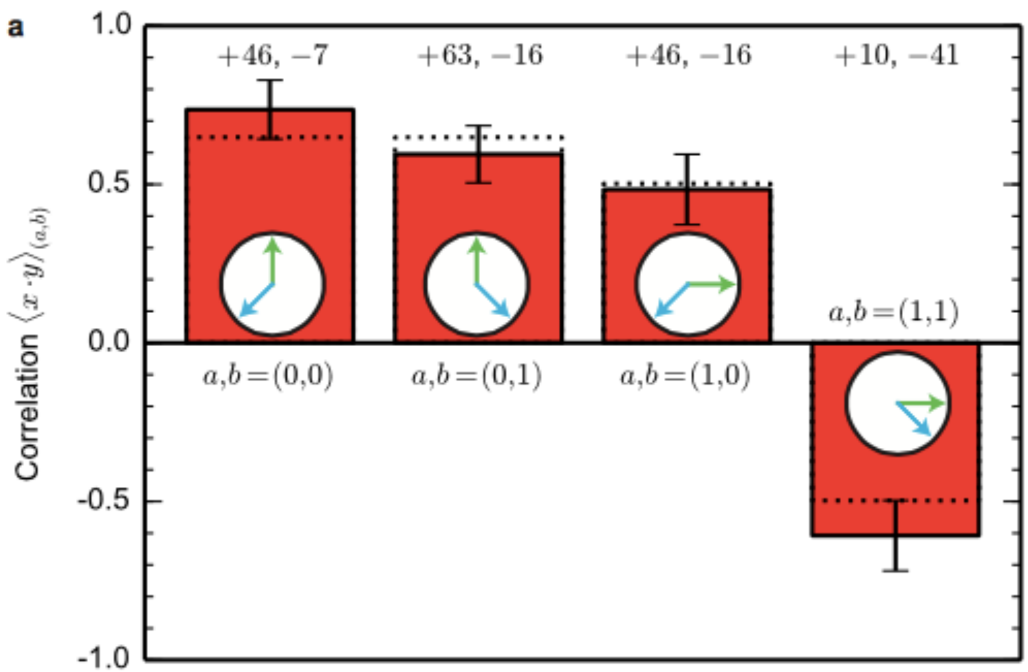
1280m separation ➔ 4.27μs time-window: choice of measurement basis and measurement of the spins





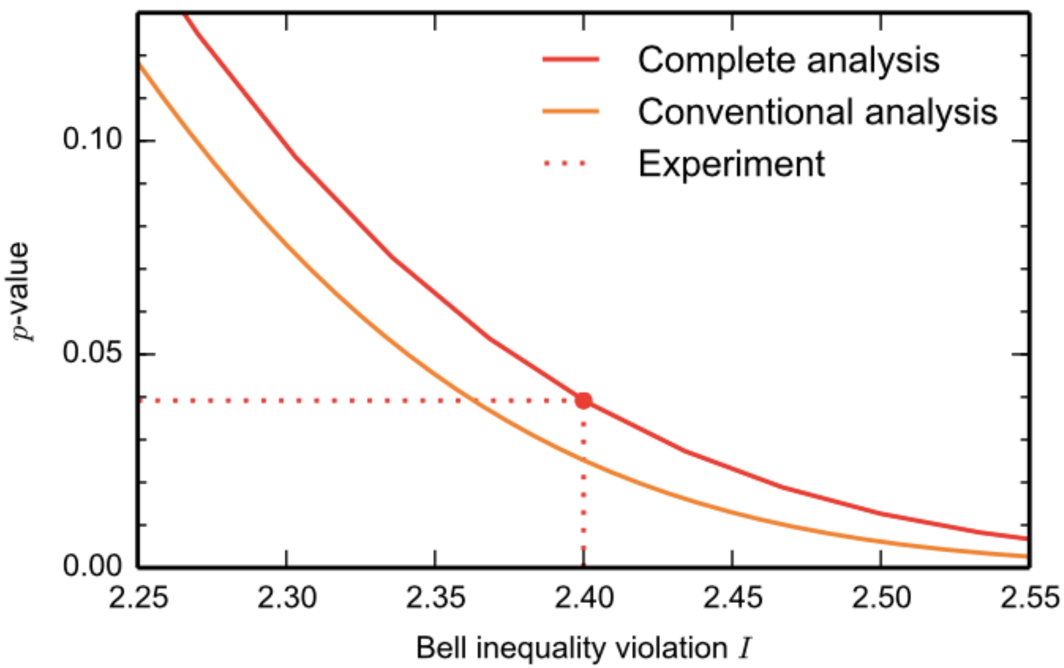
Results

- Success probability per entanglement generation attempt: 6×10^{-9} (photon loss over 1.7km optical fibre)
- n=245 trials in 220h of measurements



dotted: expected from characterization measurements

Results



Conventional:

- Bell trials indep. of each other
- Outcomes follow Gaussian distribution

Complete

- No such assumptions
- Independence only guaranteed for a *single* trial ➔ allow for *arbitrary* memory

Conclusions

- "Our experiment realizes the first Bell test that simultaneously addresses both the detection loophole and the locality loophole. (…) Our observation of a loophole-free Bell inequality violation thus rules out *all* local realist theories that accept that the number generators timely produce a free random bit and that the outputs are final once recorded in the electronics. This result places the strongest restrictions on local realistic theories of nature to date."

- The event-ready scheme has potential applications in device-independent QKD: safe, large-scale quantum networks