Probing Foundational Aspects of Quantum Mechanics using Light

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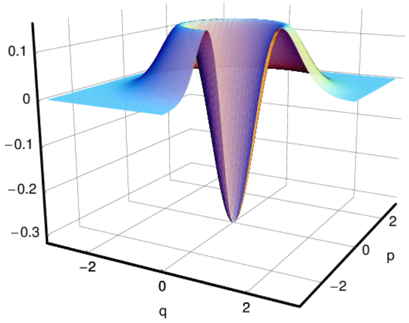
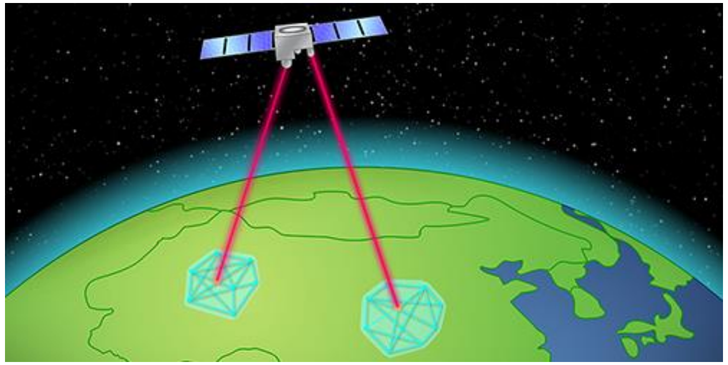
Observing a Century of Quantum Mechanics
Indian Institute of Science Education & Research Kolkata
December 20, 2024

Why do Quantum Foundations with Photons?

Photons are a natural platform to demonstrate quantum effects and probe fundamental questions.



only **weak interaction** with environment (good coherence)



high-speed (c), low-loss transmission (‘flying qubits”)

good **single-qubit control** with standard optical components

Quantum photonics is an incredibly flexible platform

Many things to talk about

Bell's Test Experiments!

nature reviews physics
https://doi.org/10.1038/s42254-023-00589-w

Review article
Check for updates

Applications of single photons in quantum metrology, biology and the foundations of quantum physics

Christophe Couteau[1], Stefanie Barz[2,3], Thomas Durt[4], Thomas Gerrits[5], Jan Huwer[6], Robert Prevedel[7], John Rarity[8], Andrew Shields[6] & Gregor Weihs[9]

- Sorkin interference experiments
- Superposition of causal order
- Hypercomplex quantum mechanics
- Tunnelling time
- Berry phase
- Weak Measurement of single-photon trajectories, spin Hall effect of light, and violation of Heisenberg's measurement-disturbance relationship

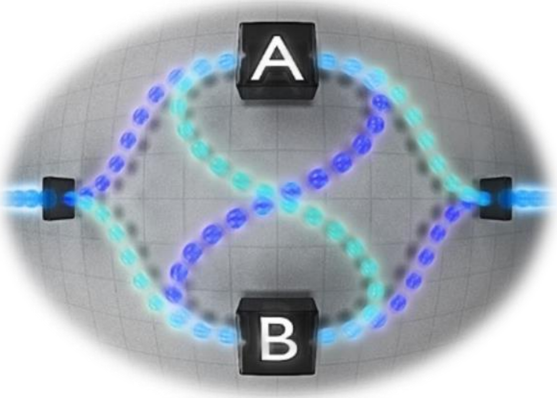
But also:

- Induced coherence
- Weak measurements for:
  - Amplification, three-box problem, Hardy's paradox, Cheshire Cat…
- Hong-Ou-Mandel interference (Boson sampling, etc.)
- Quantum eraser, Elitzur-Vaidman bomb scenarios
- Counterfactual communication
- …

This talk

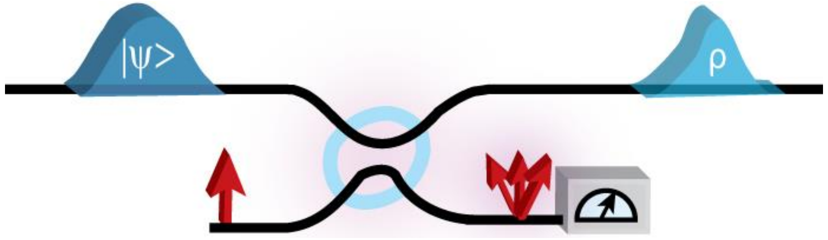
Indefinite Causal Orders

- What is indefinite causal order
- The quantum switch and two implementations
- Limitations of current experiments



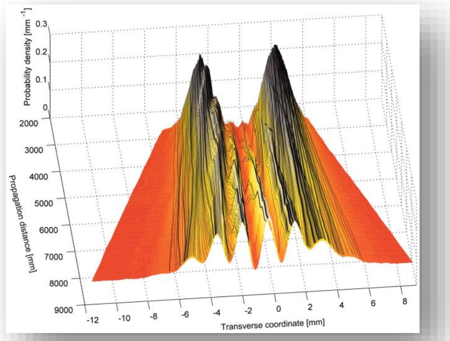
Weak Measurement

- Weak measurements with pre- and post-selection in a quantum circuit
- Anomalous weak values (amplification)

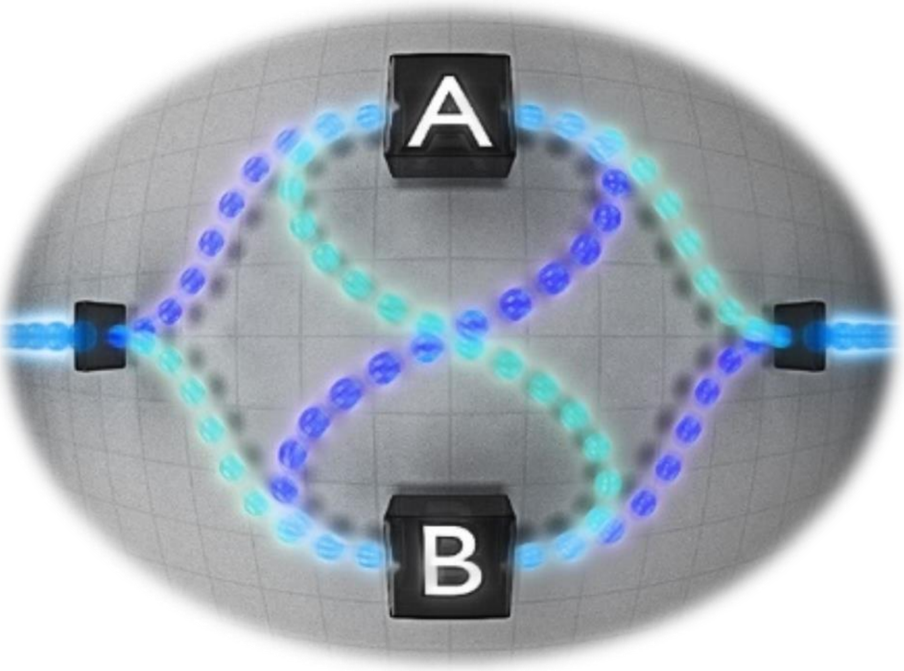


Measuring Photon Trajectories

- Measuring photon trajectories
- Weak trajectories are Bohmian trajectories
- Surreal Trajectories



Using photons to superpose the order of events



Quantum correlations with no causal order

a = 

guess: x

b = 

guess: y

Alice and Bob each flip a coin, and simultaneously each guesses the other's result.

Then a referee flips another coin, b':

b'=1   Bob must guess Alice's result

b'=0   Alice must guess Bob's result

Their goal is to maximize: $p_{\text{succ}} := \frac{1}{2}\left[P(x = b \,|\, b' = 0) + P(y = a \,|\, b' = 1)\right].$

If Alice acts before Bob, she can send him her result, but he can't send her his result (and vice versa).

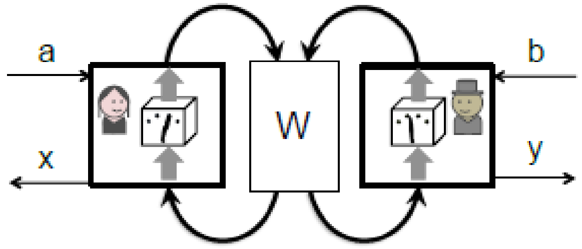
Thus $p_{\text{succ}} \leq 3/4$

Quantum processes can beat this!

Oreshkov, Costa, Brukner, Nat. Comm. 3, 1092 (2012)

Quantum correlations with no causal order

Quantum mechanical processes can violate this inequality.



Impossible to say who acted first

OCB showed that a valid process matrix exists, but we still have no physical implementation

Led to the notion of "Causal Separability"

Causally separable process: $W^{sep} := pW^{A \to B} + (1-p)W^{B \to A}$

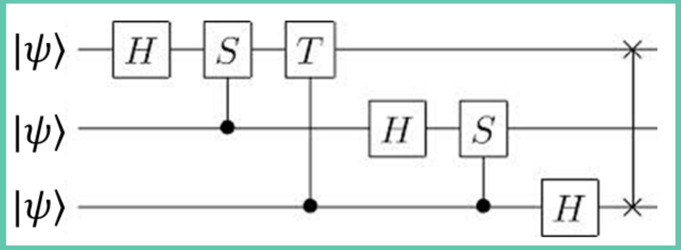
Causally non-separable process: Cannot be written in this form

M. Araújo, et. Al., New Jour. of Phys. 17, 102001 (2015)

O. Oreshkov, F. Costa & Č. Brukner, Nat. Comm. 3, 1092 (2012)

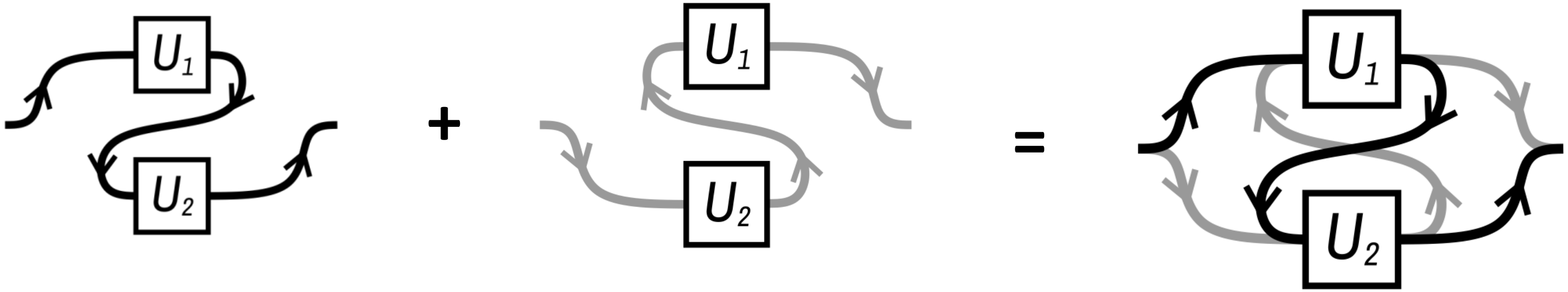
Causally non-separable processes go beyond the circuit model

Quantum Computers Process Qubits using gates:



Quantum wires connect different quantum gates

Imagine we have 2 gates U1 and U2



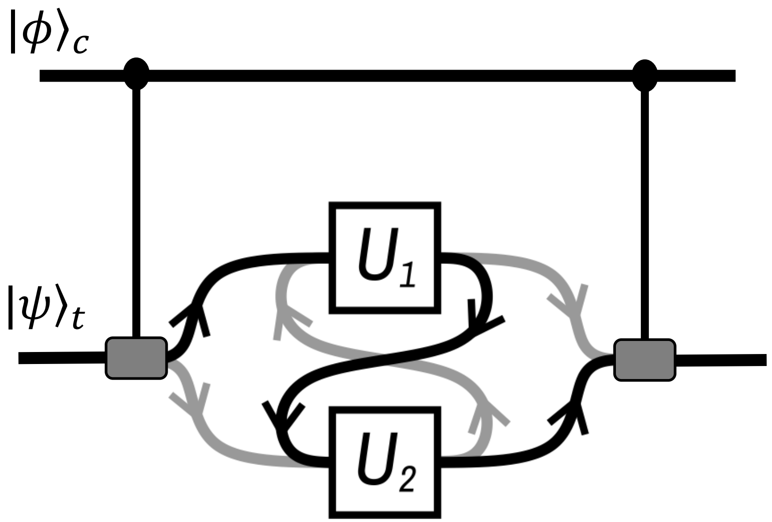
This cannot be described by a quantum circuit

The quantum Switch

For the quantum SWITCH we add a control qubit

$|\phi\rangle_c = |0\rangle_c \rightarrow |0\rangle_c\, U_2 U_1 |\psi\rangle$

$|\phi\rangle_c = |1\rangle_c \rightarrow |1\rangle_c\, U_1 U_2 |\psi\rangle$



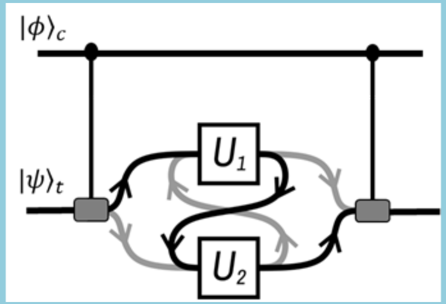
The switch is causally nonseparable, but it CANNOT violate a causal inequality!

Chiribella et al, PRA 88, 022318 (2013)

Araújo, et al, Quantum 1, 10 (2017).

First Application of the Switch

Can we tell if a pair of gates *commute or anti-commute WITH ONLY ONE USE?*



With a quantum circuit this is not possible

Consider the action of the SWITCH:

$$|0\rangle|\psi\rangle \rightarrow |0\rangle\, U_1 U_2|\psi\rangle \qquad |1\rangle|\psi\rangle \rightarrow |1\rangle\, U_2 U_1|\psi\rangle$$

If the control is |+>:

$$|+\rangle|\psi\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle\, U_1 U_2|\psi\rangle + |1\rangle\, U_2 U_1|\psi\rangle)$$

Change basis:

Commute Anti-commute

$$|+\rangle|\psi\rangle \rightarrow \frac{1}{\sqrt{2}}(|+\rangle\, \{U_1, U_2\}|\psi\rangle + |-\rangle\, [U_1, U_2]|\psi\rangle)$$

Chiribella *et al*, PRA 88, 022318 (2013)

More Applications

Quantum tasks

- promise problems[1]
- channel discrimination[2]
- Communication complexity[3]

Quantum communication

- Communication through noisy channels[4,5]
- QKD[6],entanglement generation[7], entanglement distillation[8], entanglement distribution[9]

Quantum thermodynamics[10]

Quantum metrology[11,12]

Other applications

- Measuring Incompatibility[13]
- Reversing unknown operations[14]
- Teleportation of causal structures[15]

1. Computational Advantage from Quantum-Controlled Ordering of Gates. PRL 113, 250402 (2014)
2. Strict Hierarchy between Parallel, Sequential, and Indefinite-Causal-Order Strategies for Channel Discrimination. PRL 127, 200504 (2021)
3. Exponential communication complexity advantage from quantum superposition of the direction of communication. Phys. Rev. Lett. 117, 100502 (2016)
4. Enhanced Communication with the Assistance of Indefinite Causal Order. PRL 120, 120502, (2018)
5. Experimental quantum communication enhancement by superposing trajectories. PRR. 3 013093, (2021)
6. Indefinite causal key distribution. arXiv:2303.03893, (2023).
7. Deterministic generation of multipartite entanglement via causal activation in the quantum internet. IEEE Access 11, 73863–73878 (2023)
8. Coherent Control of Causal Order of Entanglement Distillation. arXiv:2302.13990, (2023).
9. Entanglement Distribution and Quantum Teleportation in Higher Dimension over the Superposition of Causal Orders of Quantum Channels. arXiv:2303 (2023).
10. Quantum Refrigeration with Indefinite Causal Order. PRL 125, 070603, (2020).
11. Quantum Metrology with Indefinite Causal Order. PRL 124, 190503, (2020).
12. Experimental super-heisenberg quantum metrology with indefinite gate order. Nat. Phys. 1-6 (2023).
13. Measuring Incompatibility and Clustering Quantum Observables with a Quantum Switch. PRL 130, 170201, (2023).
14. Reversing Unknown Quantum Transformations: Universal Quantum Circuit for Inverting General Unitary Operations. PRL 123, 210502, (2019).
15. Quantum teleportation of quantum causal structures. arXiv:2203.00433, (2022).

Photonic implementation

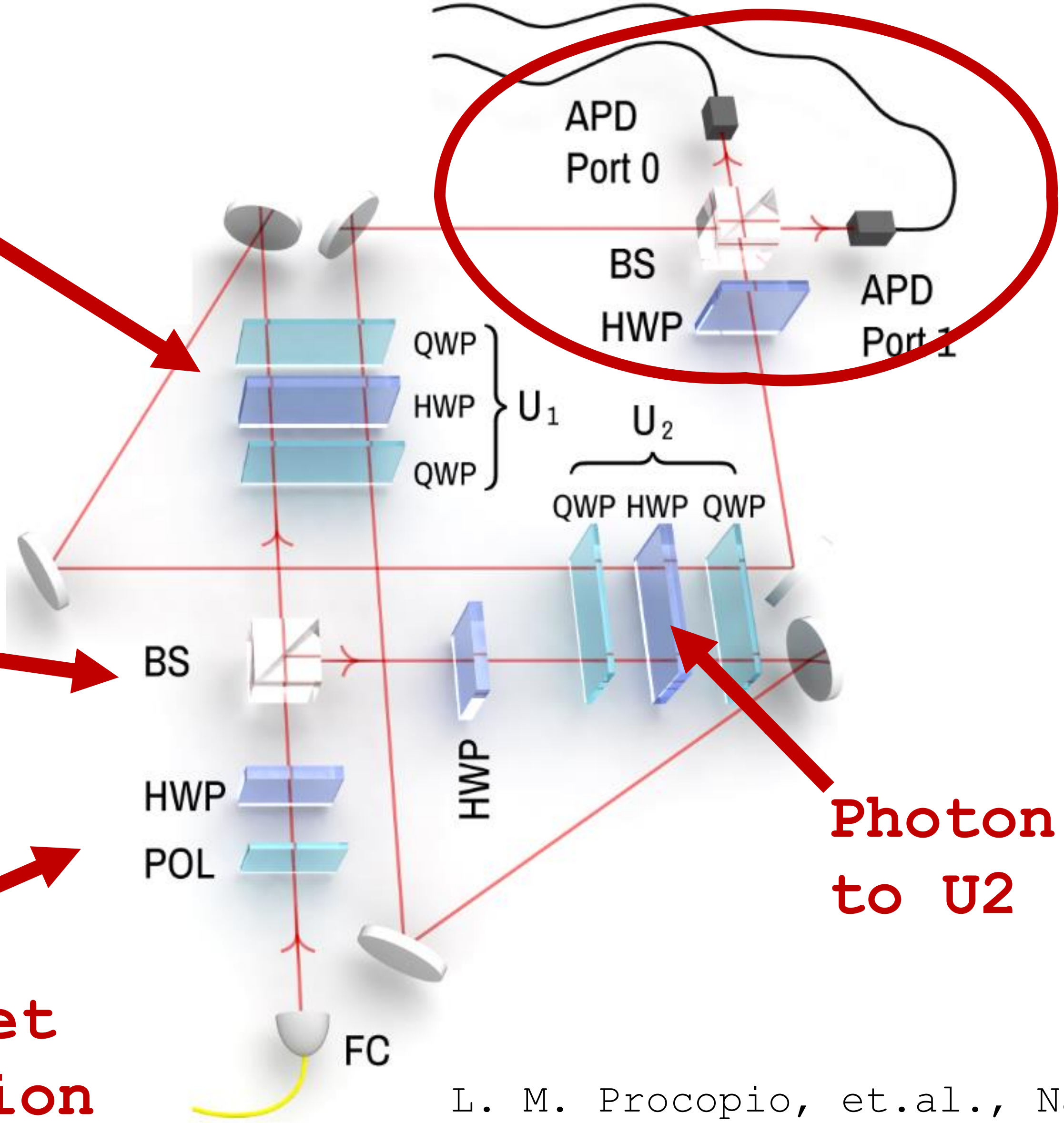
Photon goes to U1

BS adds path qubit in |+>

Prepare target in polarization

Measure control qubit

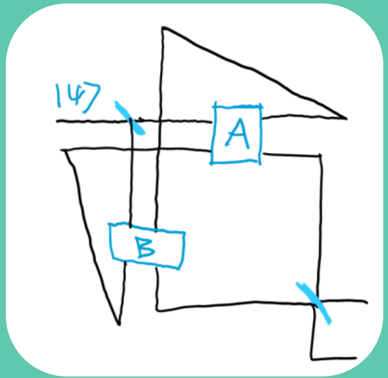
Photon goes to U2

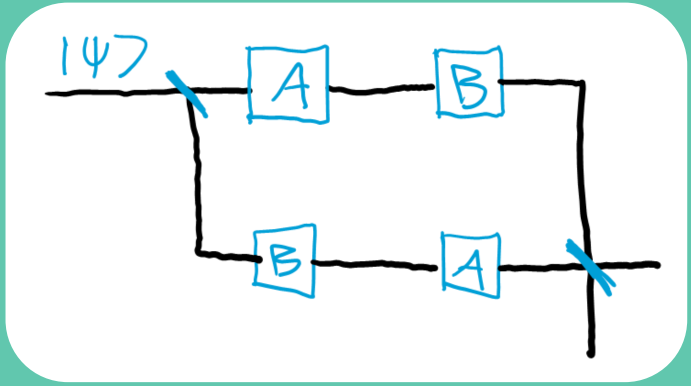


L. M. Procopio, et.al., Nat. Comm. 6, 7913 (2015)

Loopholes/Criticisms

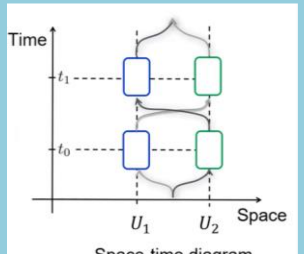
Multiple uses





In all experiments to date, gates act on multiple modes (path, polarization, time, etc.)

Multiple events



Space-time diagram of the switch

Can draw 4 space-time event

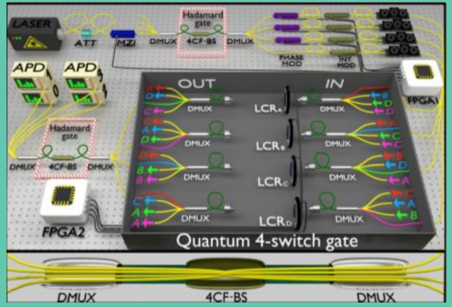
- photon at gate 1 at t_0
- photon at gate 2 at t_0
- photon at gate 1 at t_1
- photon at gate 2 at t_1

But the events are superposed, how should we think about time-delocalized events?

Experiments are not scalable

PRX Quantum **2**, 010320 (2021)

- Each order requires one path of the interferometer
- N-gate Quantum SWITCH has N! orders



4 gate experiment, but only 4 orders

Many Single-Photon Experiments

- **Path Control**
  - Experimental superposition of orders of quantum gates, Nature Communications 6, 7913 (2015)
  - Experimental verification of an indefinite causal order, Science Advances 3, e1602589 (2017).
  - Experimental Transmission of Quantum Information Using a Superposition of Causal Orders, PRL 124, 030502 (2020)
  - Experimental quantum communication enhancement by superposing trajectories Physical Review Research 3 (1), 013093 (2021)
  - Quantum simulation of indefinite causal order induced quantum refrigeration, PRR 4, L032029 (2022)
  - Experimental entanglement of temporal order, Quantum 6, 621 (2022)
  - Experimental semi-device-independent certification of indefinite causal order, Optica 10, 561 (2023)
- **Polarization Control**
  - Indefinite Causal Order in a Quantum Switch, PRL 121, 090503 (2018)
  - Increasing communication capacity via superposition of order, PRR 2, 033292 (2020)
  - Experimental super-Heisenberg quantum metrology with indefinite gate order. Nat. Phys. 19, 1 (2023)
- **Propagation direction control**
  - Experimental quantum switching for exponentially superior quantum communication complexity. Phys. Rev. Lett. 122, 120504 (2019).
  - Demonstration of a quantum switch in a Sagnac configuration. Phys. Rev. Lett. 131, 060803 (2023).
  - Demonstration of universal time-reversal for qubit processes. Optica 10, 200 (2023).
  - Experimentally demonstrating indefinite causal order algorithms to solve the generalized Deutsch's problem. arxiv: 2305.05416 (2023).
- **Time-Bin control**
  - Higher-order process matrix tomography of a passively-stable quantum switch. PRX Quantum 5, 010325 (2024).

nature reviews physics https://doi.org/10.1038/s42254-024-00739-8

Review article Check for updates

Experimental aspects of indefinite causal order in quantum mechanics

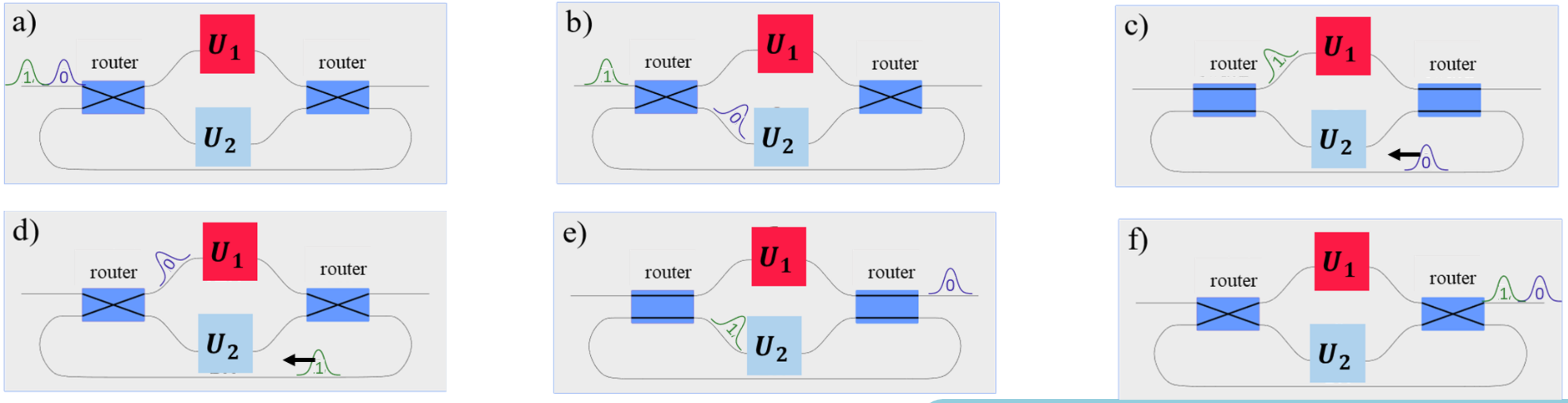
Lee A. Rozema[1,2,8], Teodor Strömberg[1,2,8], Huan Cao[1,2,8], Yu Guo[3,4,8], Bi-Heng Liu[3,4,5] & Philip Walther[1,2,6,7]

Time-Bin quantum switch

$$\frac{1}{\sqrt{2}}\left(|0\rangle_c\,|\psi\rangle_t + |1\rangle_c\,|\psi\rangle_t\right)$$

$$\frac{1}{\sqrt{2}}\left(|0\rangle_c\,U_2|\psi\rangle_t + |1\rangle_c\,|\psi\rangle_t\right)$$

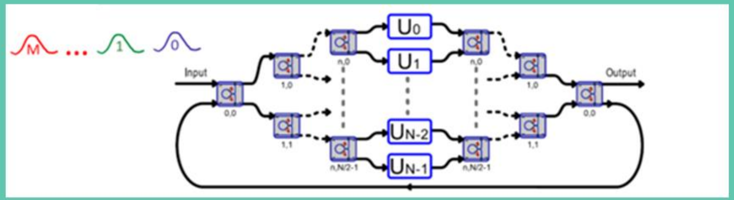
$$\frac{1}{\sqrt{2}}\left(|0\rangle_c\,U_2|\psi\rangle_t + |1\rangle_c\,U_1|\psi\rangle_t\right)$$



$$\frac{1}{\sqrt{2}}\left(|0\rangle_c\,U_1U_2|\psi\rangle_t + |1\rangle_c\,U_1|\psi\rangle_t\right)$$

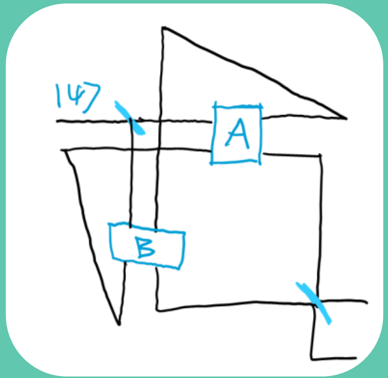
$$|\phi_{out}\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_c\,U_1U_2|\psi\rangle_t + |1\rangle_c\,U_2U_1|\psi\rangle_t\right)$$

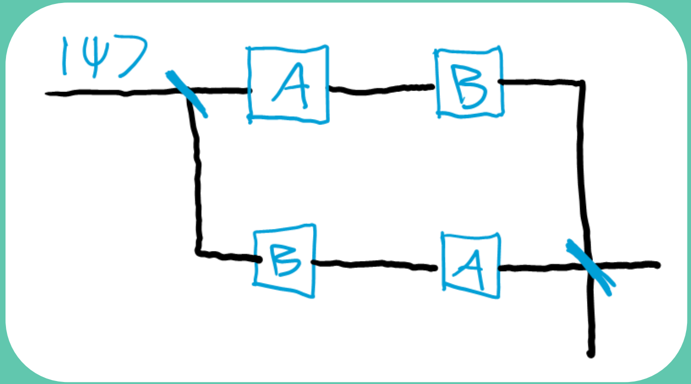
- Only one spatial mode per gate
- Can be generalized to N-switch



Doesn't solve anything

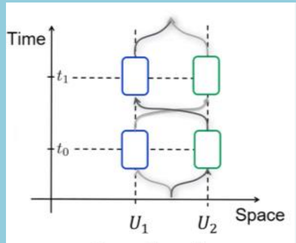
Multiple uses





Instead of acting on many spatial modes N! spatial modes, it acts on N! time bins

Multiple events



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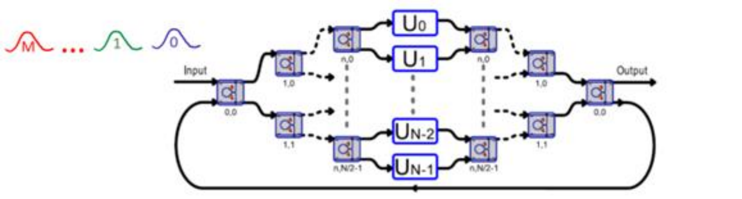
But the events are superposed, how should we think about time-delocalized events?

Scalability

Experiments are not scalable

- Each order requires one path of the interferometer
- N-gate Quantum SWITCH has N! orders

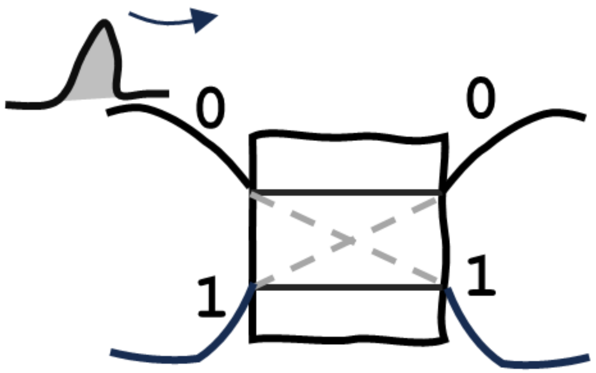


Time bin approach can be generalized, but still needs N! dimensional control.

Replace optical switch with a "quantum router"

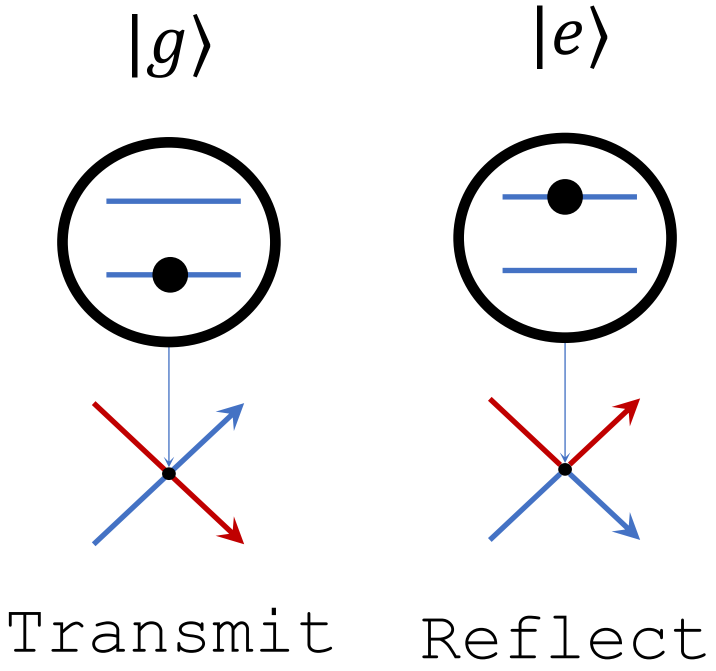
Place our optical routers in superposition:

$$|\psi\rangle_0(|=\rangle + |\times\rangle)$$



$$|\psi\rangle_0|=\rangle + |\psi\rangle_1|\times\rangle$$

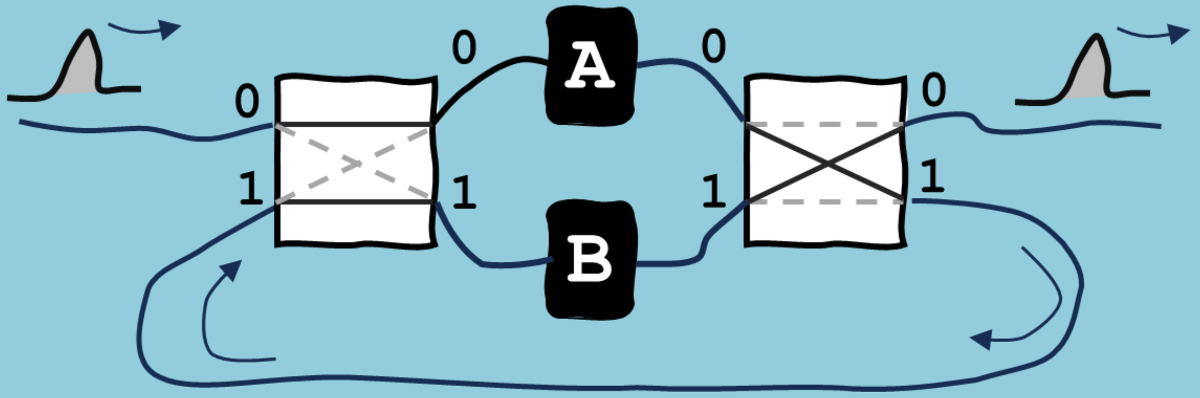
Photon mode becomes entangled with router



"All-optical routing of single photons by a one-atom switch controlled by a single photon" *Science* **345**, 903 (2014).

Replace optical switch with a “quantum router”

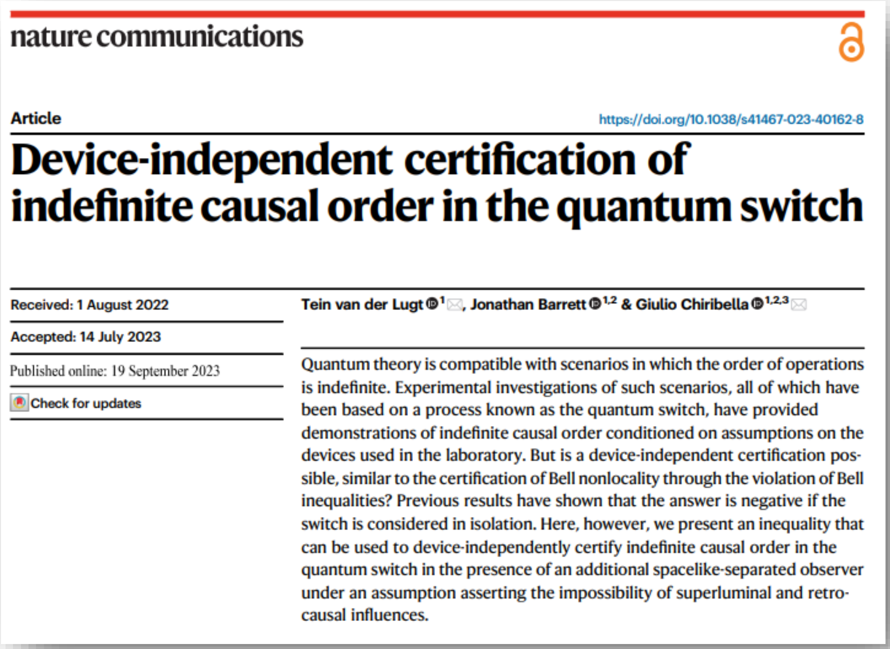
Two entangled quantum routers can implement the switch for two gates



$$|\psi\rangle_0(|{=},\times\rangle + |\times,{=}\rangle) \rightarrow \boldsymbol{BA}|\psi\rangle|{=},\times\rangle + \boldsymbol{AB}|\psi\rangle|\times,{=}\rangle$$

- Now only **one optical mode per gate**
- We have a construction using one router
- N-switch needs **o(N log(N))** 2x2 routers

Can a scalable photonic switch close these loopholes?



nature communications

Article

https://doi.org/10.1038/s41467-023-40162-8

Device-independent certification of indefinite causal order in the quantum switch

Received: 1 August 2022

Accepted: 14 July 2023

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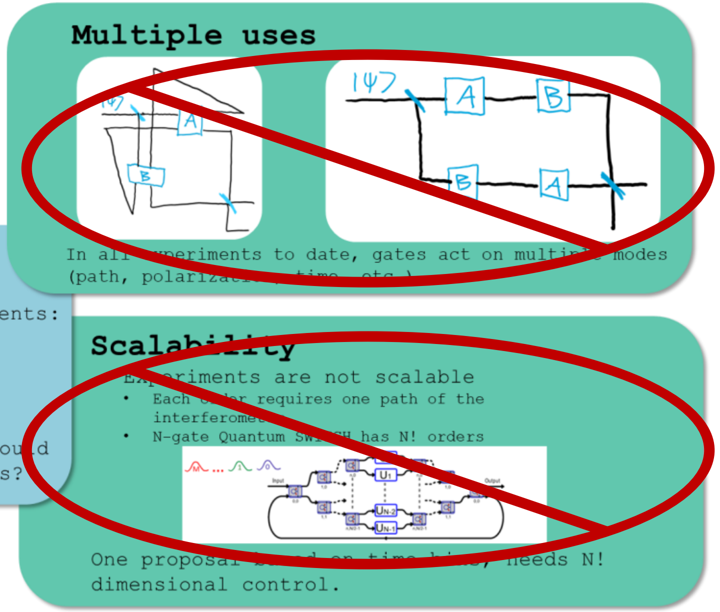
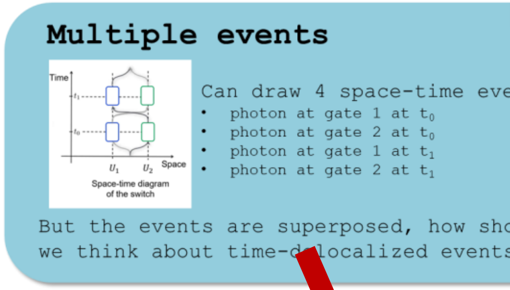
Check for updates

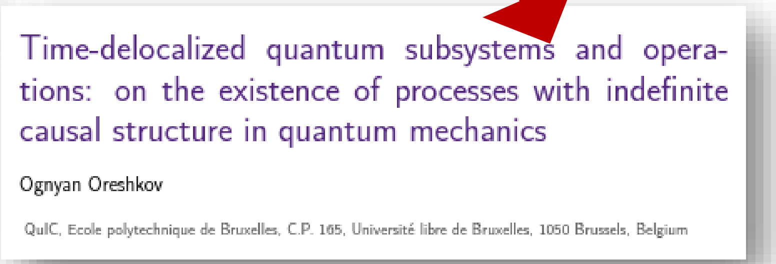
Tein van der Lugt[1], Jonathan Barrett[1,2] & Giulio Chiribella[1,2,3]

Quantum theory is compatible with scenarios in which the order of operations is indefinite. Experimental investigations of such scenarios, all of which have been based on a process known as the quantum switch, have provided demonstrations of indefinite causal order conditioned on assumptions on the devices used in the laboratory. But is a device-independent certification possible, similar to the certification of Bell nonlocality through the violation of Bell inequalities? Previous results have shown that the answer is negative if the switch is considered in isolation. Here, however, we present an inequality that can be used to device-independently certify indefinite causal order in the quantum switch in the presence of an additional spacelike-separated observer under an assumption asserting the impossibility of superluminal and retro-causal influences.

Loopholes/Criticisms







Time-delocalized quantum subsystems and operations: on the existence of processes with indefinite causal structure in quantum mechanics

Ognyan Oreshkov

QuIC, Ecole polytechnique de Bruxelles, C.P. 165, Université libre de Bruxelles, 1050 Brussels, Belgium

Photons with long coherence times?

Final remarks on the quantum switch

- **Some argue the exhibit indefinite causal order**
  - de la Hamette, Kabel, Christodoulou, and Brukner, *"Quantum diffeomorphisms cannot make indefinite causal order definite"* arXiv:2211.15685 (2022)
  - Fellous-Asiani, M. et al. "Comparing the quantum switch and its simulations with energetically constrained operations." Phys. Rev. Res. 5, 023111 (2023).
- **Some argue they are simulations**
  - Vilisani and Renner, "Embedding cyclic information-theoretic structures in acyclic space-times: No-go results for indefinite causality" Phys. Rev. A 110, 022227 (2024)
  - Ormrod, N., Vanrietvelde, A. & Barrett, J. Causal structure in the presence of sectorial constraints, with application to the quantum switch. Quantum 7, 1028 (2023).
- **Should we consider the criticisms as loopholes, or something more serious?**
- **Would a scalable switch provide truly useful advantages over quantum circuits?**
- **Can processes violating causal inequalities be realized?**

Weak Measurements

VOLUME 60, NUMBER 14 PHYSICAL REVIEW LETTERS 4 APRIL 1988

How the Result of a Measurement of a Component of the Spin of a Spin-$\frac{1}{2}$ Particle Can Turn Out to be 100

Yakir Aharonov, David Z. Albert, and Lev Vaidman

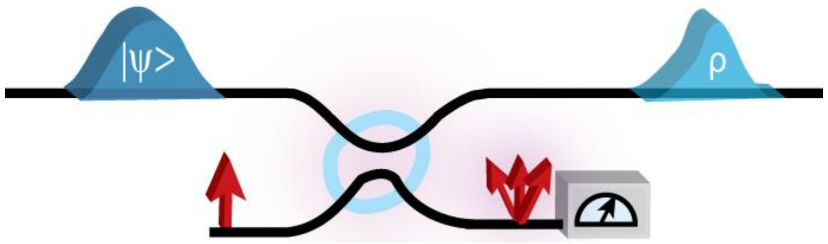
Physics Department, University of South Carolina, Columbia, South Carolina 29208, and School of Physics and Astronomy, Tel-Aviv University, Ramat Aviv 69978, Israel

(Received 30 June 1987)

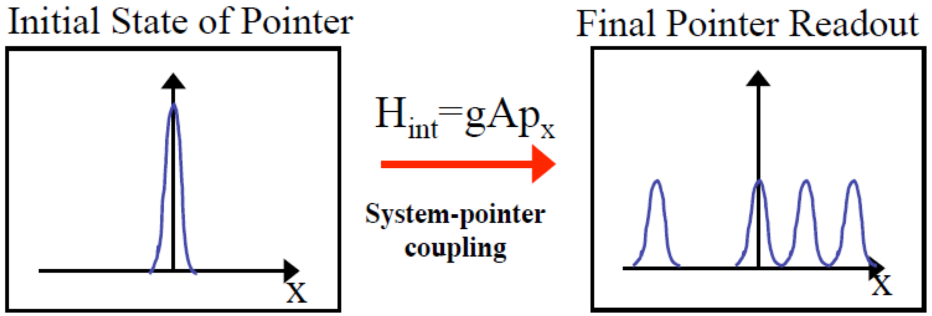
We have found that the usual measuring procedure for preselected and postselected ensembles of quantum systems gives unusual results. Under some natural conditions of weakness of the measurement, its result consistently defines a new kind of value for a quantum variable, which we call the weak value. A description of the measurement of the weak value of a component of a spin for an ensemble of preselected and postselected spin-$\frac{1}{2}$ particles is presented.

PACS numbers: 03.65.Bz

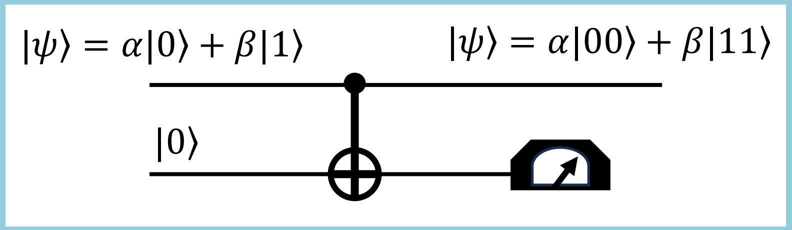
Von Neuman Measurement



Couple system to auxiliary probe



C-NOT couples Z to probe qubit



Measuring probe qubit in Z basis:

$$p_0 = |\alpha|^2$$
$$p_1 = |\beta|^2$$

$$\langle Z\rangle = \frac{p_0 - p_1}{p_0 + p_1}$$

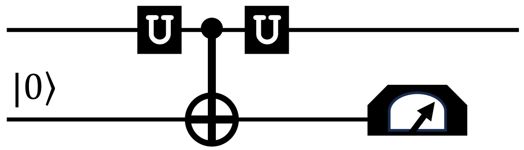
Can read out system information from probe

System is collapsed

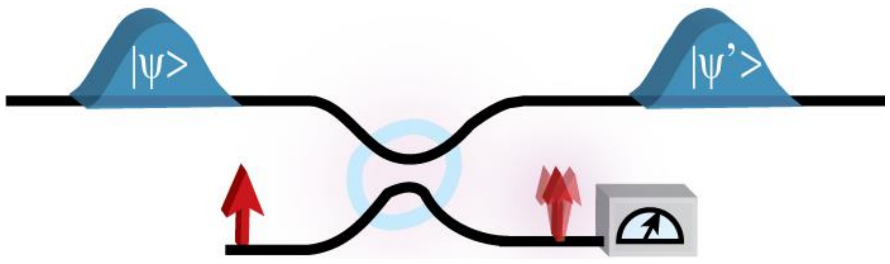
$$\rho_{sys} = \begin{pmatrix} |\alpha|^2 & 0 \\ 0 & |\beta|^2 \end{pmatrix}$$

- Well resolved pointer states, strong interaction disturbs |ψ>
- On a given shot, |ψ> is left in an eigenstate of the measurement.

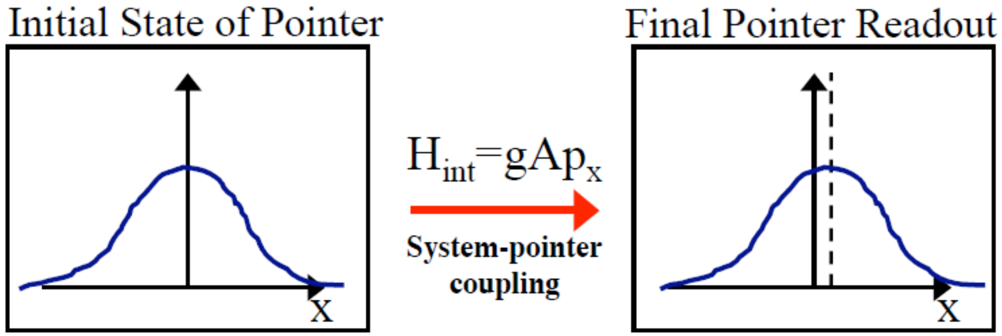
Can couple other observables to probe



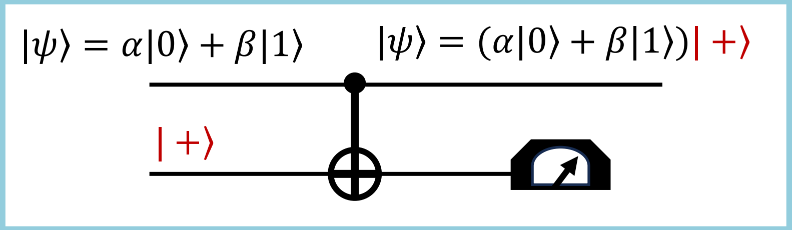
WEAK Von Neuman Measurement



Make interaction weak



Change state of target



Now probe measurements reveal nothing $p_0 = p_1 = 1/2$

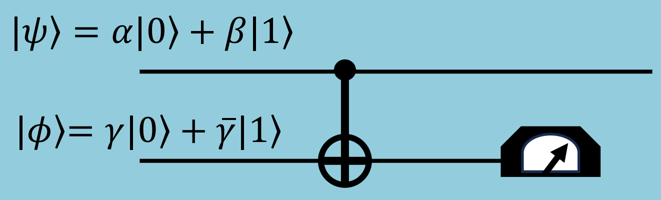
System is undisturbed

$$\rho_{sys} = |\psi\rangle\langle\psi|$$

No information is gained

Useful Weak Measurement

Change state of target



$\alpha|0\rangle|\phi\rangle + \beta|1\rangle|\phi'\rangle \qquad |\phi'\rangle = \gamma|1\rangle + \bar{\gamma}|0\rangle$

Some entanglement is generated

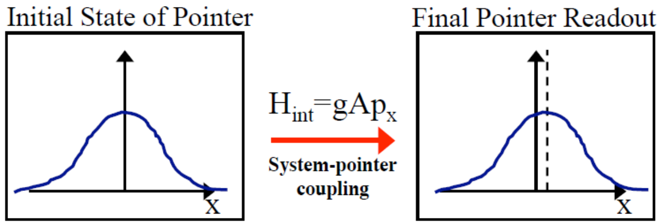
$$p_0 = |\alpha|^2|\gamma|^2 + |\beta|^2|\bar{\gamma}|^2$$
$$p_1 = |\beta|^2|\gamma|^2 + |\alpha|^2|\bar{\gamma}|^2$$

Gain some information

$$\langle Z\rangle = \frac{p_0 - p_1}{p_0 + p_1} = |\alpha|^2 - |\beta|^2$$

Can reconstruct expectation values on system

Pointer moves, but moves less than its width:



System is partially disturbed

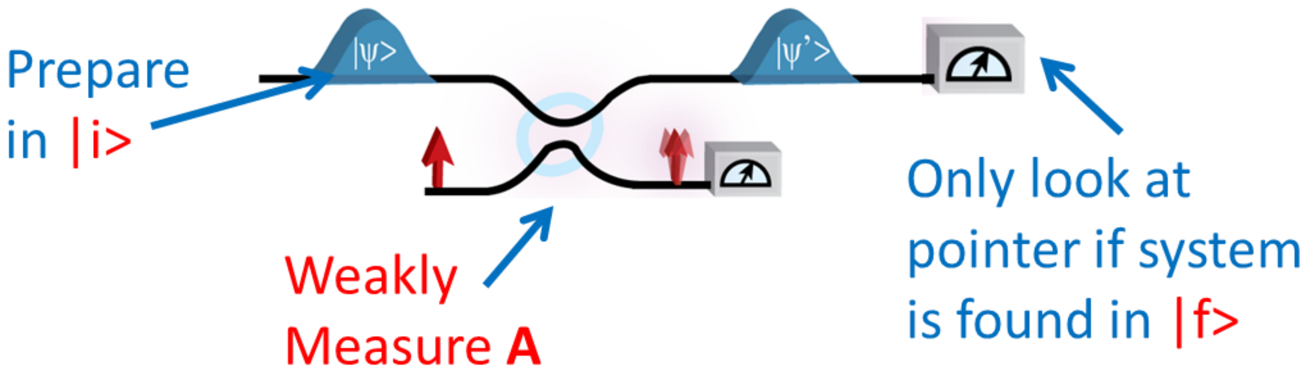
$$\rho_{sys} = \begin{pmatrix} |\alpha|^2 & \alpha^*\beta\,(1-S^2) \\ \alpha\beta^*(1-S^2) & |\beta|^2 \end{pmatrix}$$

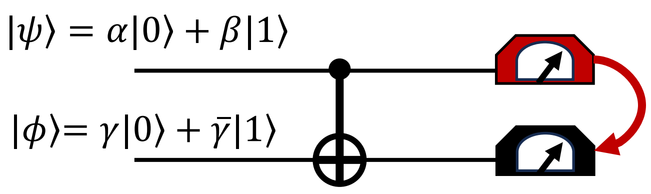
Measurement strength: $S = 2\gamma^2 - 1$

$S = 0$: no decoherence
$S = 1$: maximal decoherence

- Poor resolution: repeat many times to average
- Negligible disturbance
- Can perform subsequent measurements

Weak Values





Use weak measurement to ask about conditional values

If we start in |i> and end in |f>, what was the value of **A**?

Y. Aharonov, D. Albert and L. Vaidman, *PRL 60, 1355 (1988)*

Weird Weak Values

Prepare system in superposition of x eigenstates.

$$|i\rangle = \cos(\frac{\alpha}{2})|+\rangle + \sin(\frac{\alpha}{2})\,|-\rangle$$

Post-select on $|f\rangle = |+\rangle$

What value of <Z> does the probe read out?

Using same formalism as before, and taking $\gamma \to {}^{1}/_{\sqrt{2}}$

$$\langle Z\rangle = \tan(\frac{\alpha}{2})$$

As $\alpha \to \pi$ we see $\langle Z\rangle \to \infty$

But post-selection rarely succeeds, since $|i\rangle \to |-\rangle$, and we only keep data when we find it in $|+\rangle$

VOLUME 60, NUMBER 14 PHYSICAL REVIEW LETTERS 4 APRIL 1988

How the Result of a Measurement of a Component of the Spin of a Spin-$\frac{1}{2}$ Particle Can Turn Out to be 100

Yakir Aharonov, David Z. Albert, and Lev Vaidman

Physics Department, University of South Carolina, Columbia, South Carolina 29208, and School of Physics and Astronomy, Tel-Aviv University, Ramat Aviv 69978, Israel

(Received 30 June 1987)

We have found that the usual measuring procedure for preselected and postselected ensembles of quantum systems gives unusual results. Under some natural conditions of weakness of the measurement, its result consistently defines a new kind of value for a quantum variable, which we call the weak value. A description of the measurement of the weak value of a component of a spin for an ensemble of preselected and postselected spin-$\frac{1}{2}$ particles is presented.

PACS numbers: 03.65.Bz

In general, this procedure yields the weak value

$$A_w = \frac{\langle f|A|i\rangle}{\langle f|i\rangle}$$

Weak Value Amplification

Another striking aspect of this experiment becomes evident when we consider it as a device for measuring a small gradient of the magnetic field $\partial B_z/\partial z$. Our choosing α close to π yields a tremendous amplification.

$$A_w = \frac{\langle f|A|i\rangle}{\langle f|i\rangle}$$

Observation of the Spin Hall Effect of Light via Weak Measurements

Onur Hosten* and Paul Kwiat

SCIENCE, 319, 787-790 (2008)

Selected for a Viewpoint in *Physics*
PRL **102,** 173601 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Ultrasensitive Beam Deflection Measurement via Interferometric Weak Value Amplification

P. Ben Dixon, David J. Starling, Andrew N. Jordan, and John C. Howell
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA
(Received 12 January 2009; published 27 April 2009)

November 1, 2014 / Vol. 39, No. 21 / OPTICS LETTERS 6229

Simultaneous weak value amplification of angular Goos–Hänchen and Imbert–Fedorov shifts in partial reflection

S. Goswami,† M. Pal,† A. Nandi, P. K. Panigrahi, and N. Ghosh*
Department of Physical Sciences, Indian Institute of Science Education and Research-Kolkata, Mohanpur Campus, Mohanpur 741 252, India
*Corresponding author: nghosh@iiserkol.ac.in

nature physics LETTERS
PUBLISHED ONLINE: 27 FEBRUARY 2017 | DOI: 10.1038/NPHYS4040

Weak-value amplification of the nonlinear effect of a single photon

arXiv > quant-ph > arXiv:1612.04920

Quantum Physics

[Submitted on 15 Dec 2016]

How the Result of Counting One Photon Can Turn Out to Be a Value of 8

Matin Hallaji, Amir Feizpour, Greg Dmochowski, Josiah Sinclair, Aephraim M. Steinberg

Requires you to throw out a lot of data!

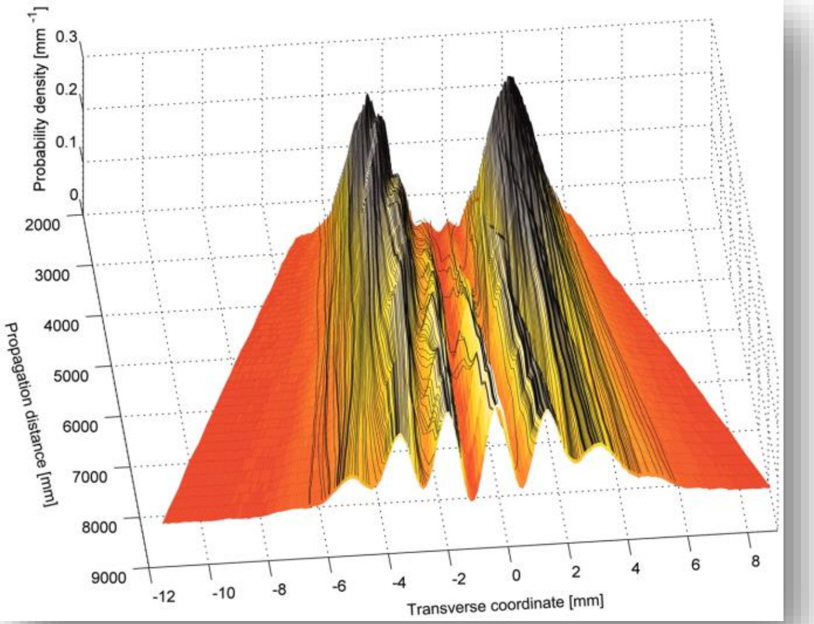
Weakly Measured Trajectories

New Journal of Physics
The open access journal at the forefront of physics

OPEN ACCESS

Grounding Bohmian mechanics in weak values and bayesianism

To cite this article: H M Wiseman 2007 *New J. Phys.* **9** 165



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19 November 2001

PHYSICS LETTERS A

Physics Letters A 290 (2001) 205–213

www.elsevier.com/locate/pla

Bohmian trajectories for photons

Partha Ghose [a], A.S. Majumdar [a,*], S. Guha [b], J. Sau [b]

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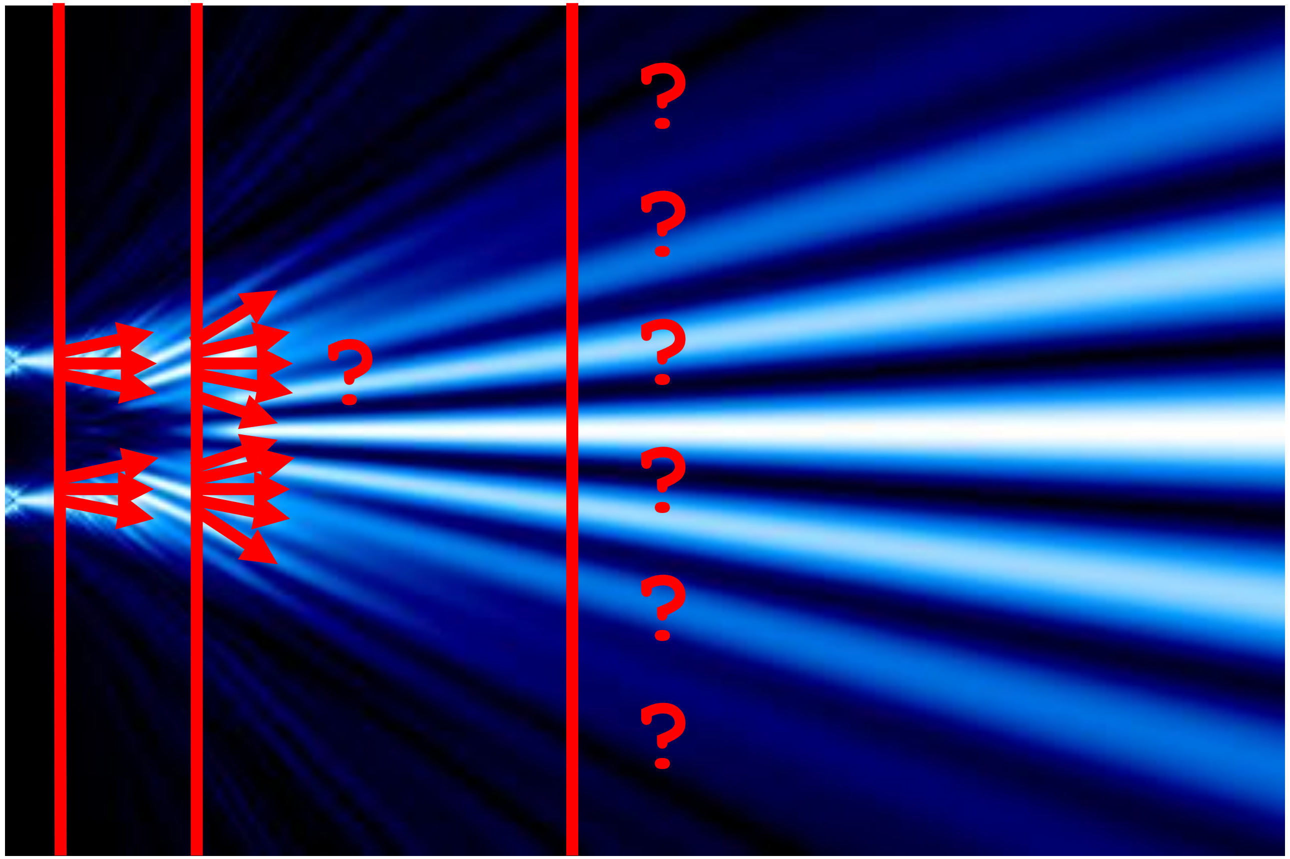
[b] *Department of Electrical Engineering, Indian Institute of Technology, Kanpur 208 016, India*

Received 20 February 2001; received in revised form 2 October 2001; accepted 11 October 2001
Communicated by P.R. Holland

Given that assumption, the naive experimentalist with a large enough ensemble could reconstruct the possible paths of Bohmian particles directly from experimental data. For example, the set of Bohmian paths in the twin-slit experiment first calculated in [30] are naively observable in this way.

Can we measure the trajectories of an interfering quantum particle?



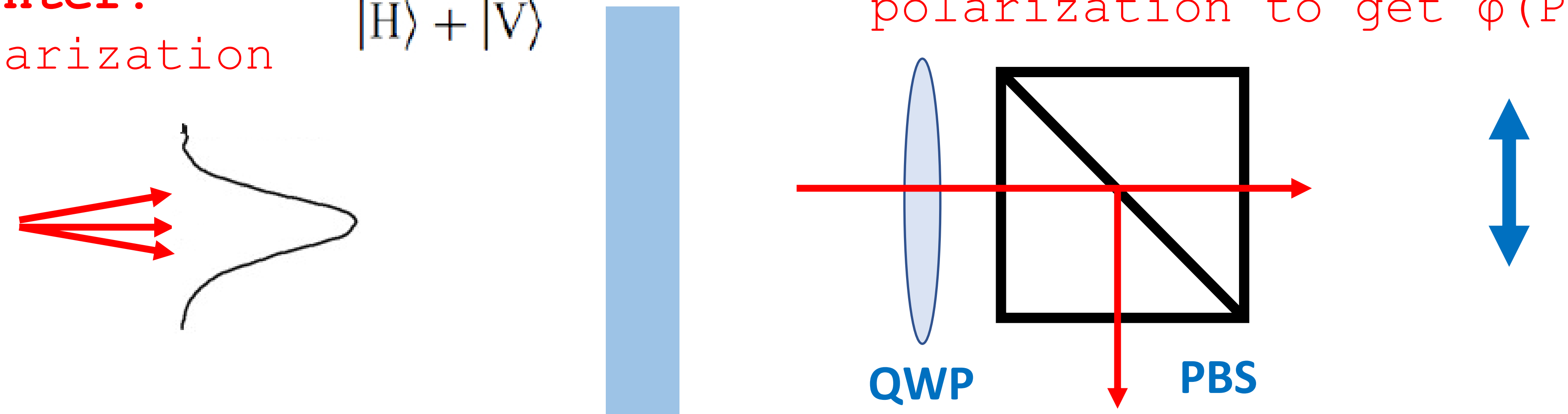
QM doesn't let us simultaneously measure x & p. Moreover, doing so collapses the system & destroys interference

How to Weakly Measure a Photon's momentum

Pointer: polarization

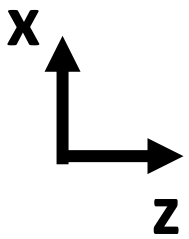
$|\mathrm{H}\rangle + |\mathrm{V}\rangle$

At each x we can measure polarization to get $\varphi(P_x)$



System: $|\psi\rangle$
transverse profile

Birefringent crystal



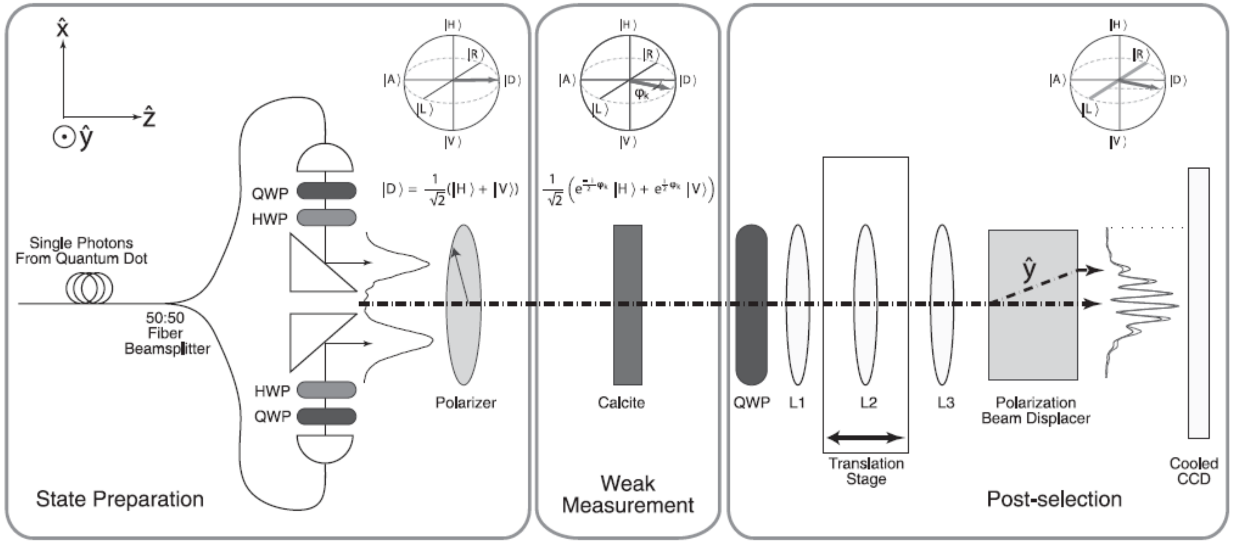
Rotates polarization dependent on P_x

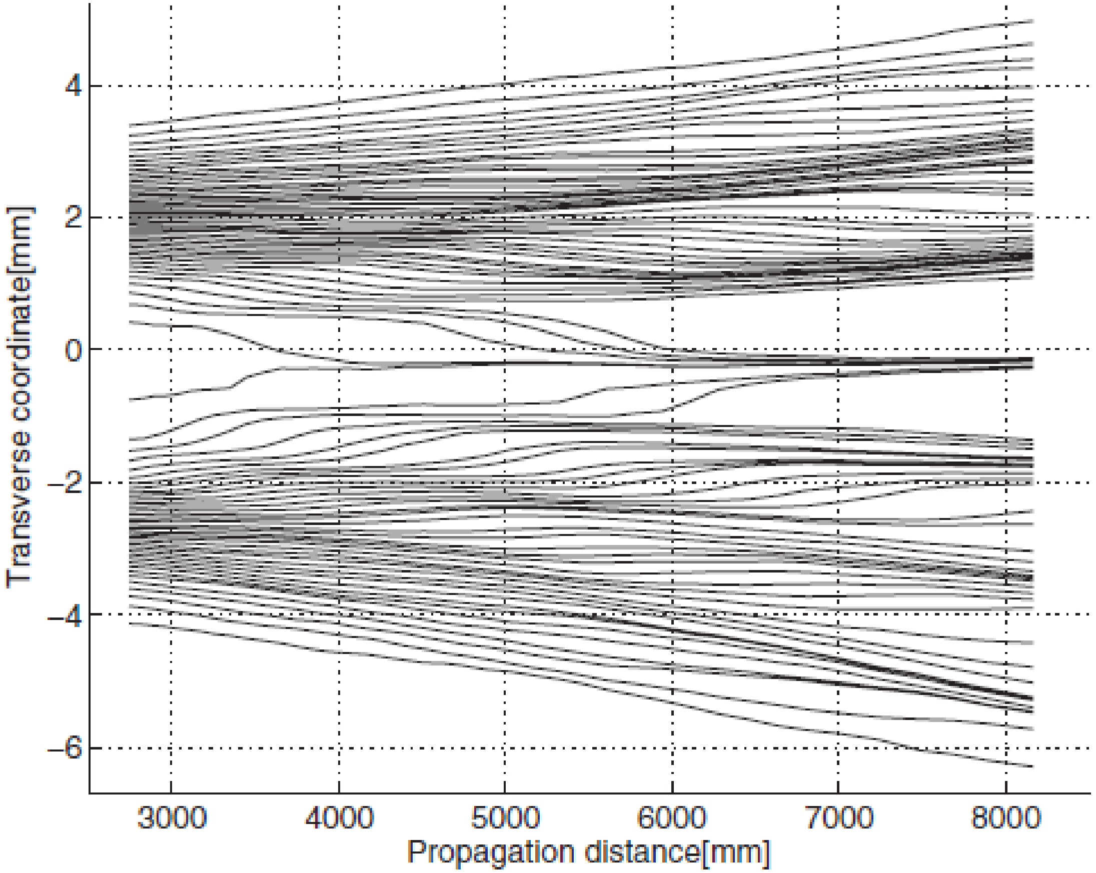
$$e^{i\phi(P_x)}\,|\mathrm{H}\rangle + |\mathrm{V}\rangle$$

$$\left\langle \hat{P}_x \right\rangle_w = \frac{\langle x_f | \hat{P}_x | \psi \rangle}{\langle x_f | \psi \rangle}$$

H. Wiseman, *Grounding Bohmian mechanics in weak values and bayesianism. NJP. 9, 165 (2007)*

Result: Reconstructed Trajectories

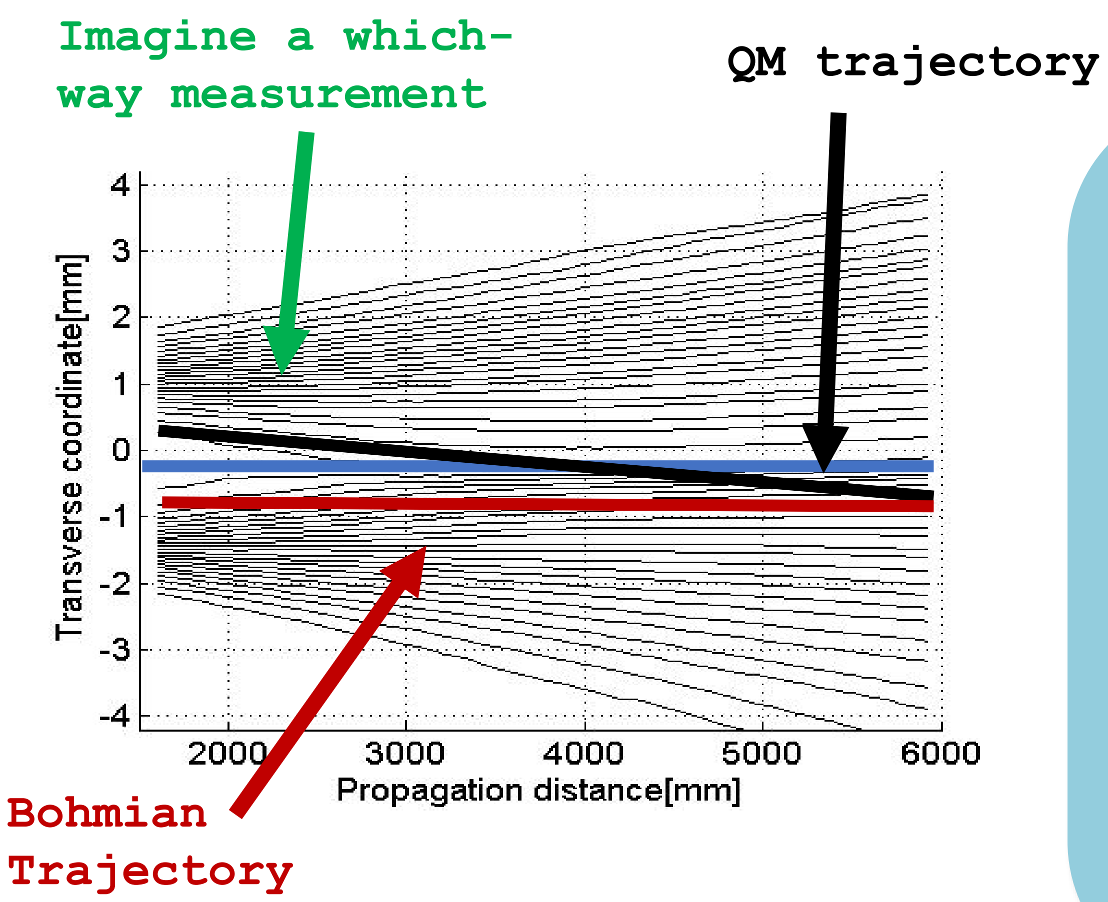




Trajectories never cross. So a particle starting in the upper slit hits the upper part of the screen! (more later)

S. Kocsis, et. al, *Science* ***332,*** *1170 (2011)*

Non-crossing Trajectories



QM says there are times when the WWM says “Upper Slit” and we find particles below the blue line

Bohmian trajectory says the photon came from the bottom slit:
Such trajectories are SURREAL

Englert, Scully, Süssmann, and Walther "Surrealistic Bohm Trajectories". *Zeitschrift für Naturforschung A.* **47** 1175 (1992).

What does Bohm say?

Bohmian mechanics is inherently non-local

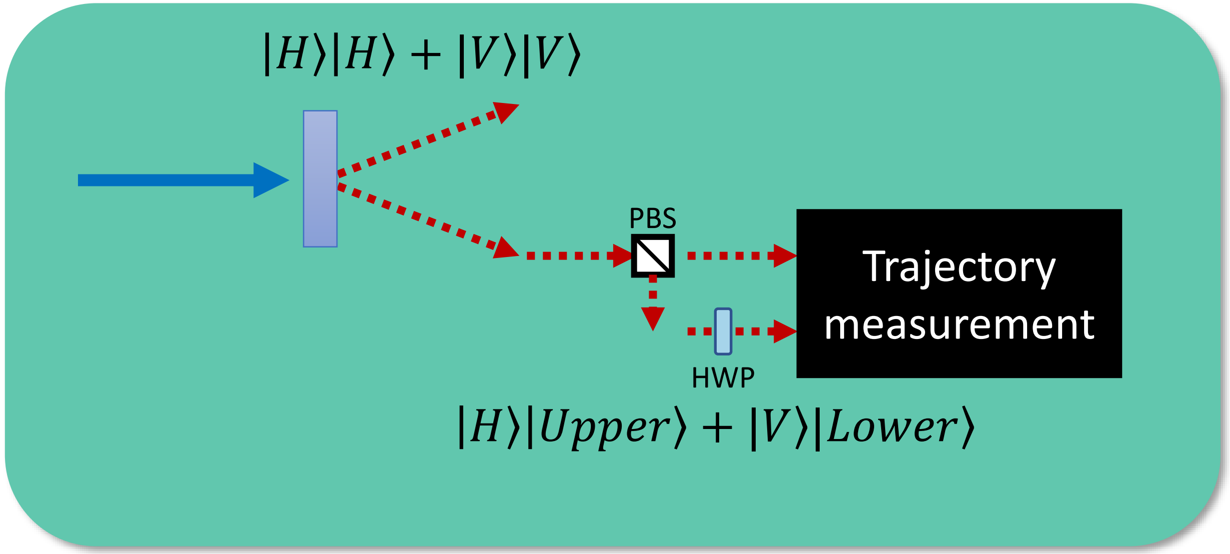
The state of one particle can depend non-locally on another.

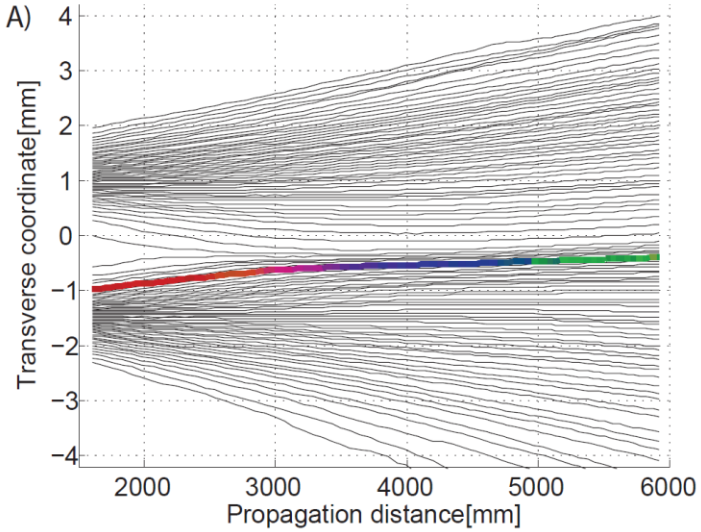
Resolution

Bohmian mechanics predicts that the state of the measuring device depends on the position of the photon in the interferometer.

A which "slit" measurement with photons

- Create an entangled polarization state
- Photon 2's slit depends on its polarization
  - polarization then erased
- Photon 1's polarization tells us which slit the other photon takes

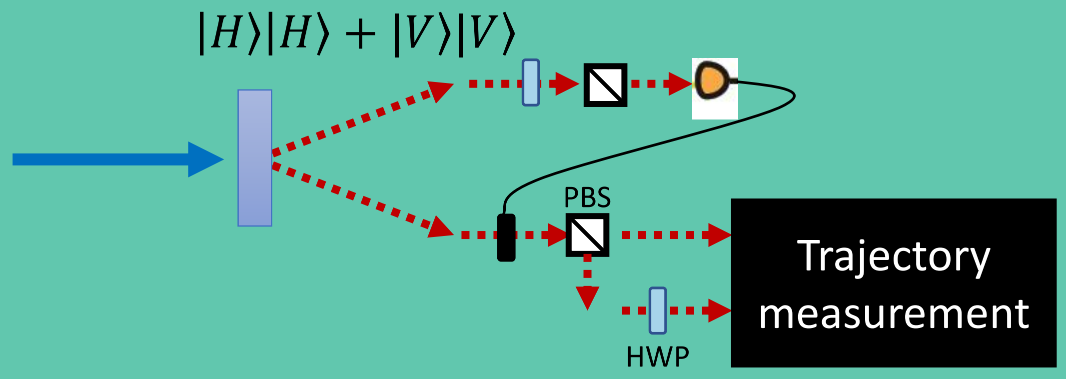




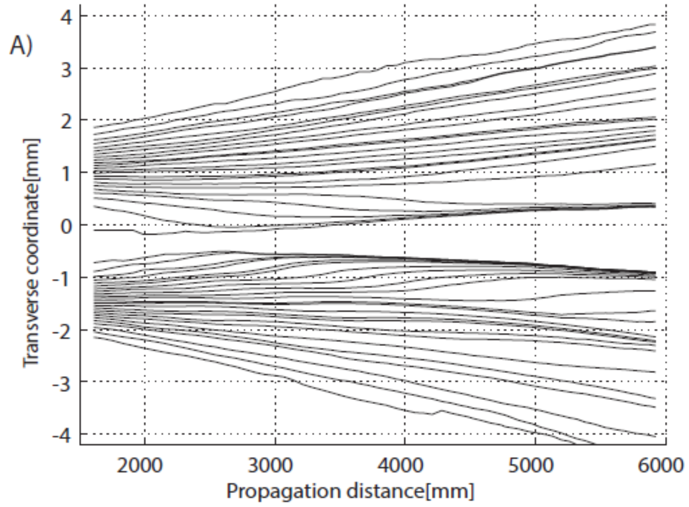
This destroys the interference

Science Advances **2**, e1501466 (2016)

Bringing the inference back



Projecting measurement photon in superposition basis restores interference



$$|H\rangle|Upper\rangle + |V\rangle|Lower\rangle$$

$$|H\rangle = |D\rangle + |A\rangle$$
$$|V\rangle = |D\rangle - |A\rangle$$

$$= (|D\rangle + |A\rangle)|Upper\rangle + (|D\rangle - |A\rangle)|Lower\rangle$$
$$= |D\rangle(|Upper\rangle + |Lower\rangle) + |A\rangle(|Upper\rangle - |Lower\rangle)$$

quantum eraser!

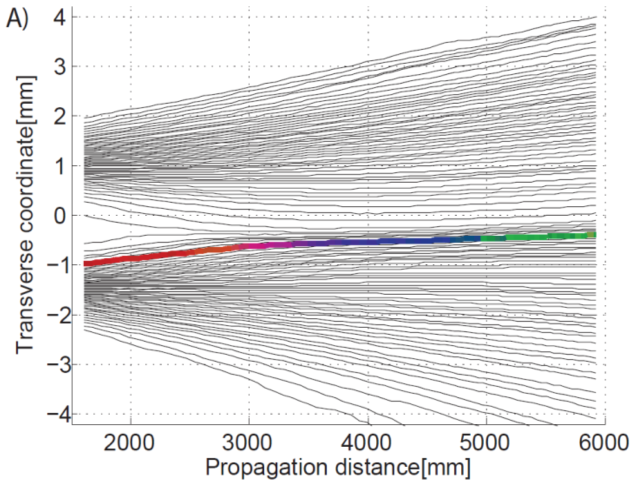
Scully and Kai *PRA* **25** 2208 (1982).

Science Advances **2**, e1501466 (2016)

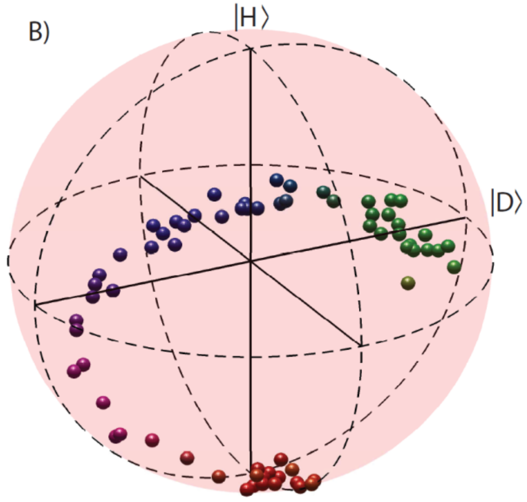
Project the Slit Photon

Focus on one trajectory:
Measure WWM photon as a function of slit photon's position

Double slit Photon



WWM photon



- In Bohmian mechanics one particle's state depends on a guiding equation, which depends NON-LOCALLY on the configuration of the entire universe

- Weak measurements require averaging: cannot follow a given pair of photons, thus cannot verify Bohm's nonlocal predictions

What do these trajectories tell us?

These trajectories are mathematically equivalent to the trajectories of predicted by **Bohmian mechanics**.

Bohmian interpretation: position is hidden variable. A particle’s position dictates its trajectory

Proof for Bohmian Mechanics?

- These are **average** trajectories. We cannot follow an individual photon
- Bohmian trajectories are consistent with the trajectories a naïve experimentalist measures

H. Wiseman, *Grounding Bohmian mechanics in weak values and bayesianism. NJP. 9, 165 (2007)*

Conclusions

Photonics allows us to study many different aspects of quantum theory (and build useful technology)

Indefinite causal order has been probed with photonics, should we think of current experiments as simulations, loopholes or real?

Will building a scalable photonic switch address these issues?

Weak measurement is not magic. It is a well-defined measurement procedure.

- They can lead to surprising results (expectation values outside of eigenvalue range)
- Weak-value amplification can be used for applications
- Sometimes weak measurements (without anomalous values) can be related to deeper phenomena

Thanks for listening!

Indefinite Causal Order

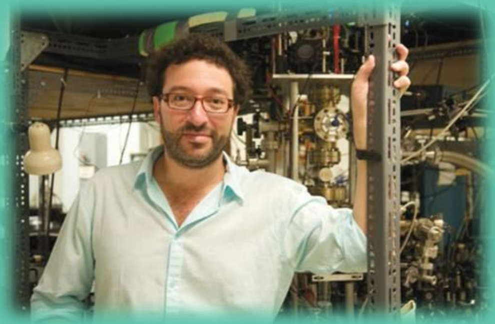
Philip Walther

Vienna Foundations Team

Daniel Kun, Mariana Schmid, Carla Richter, **Micheal Antesberger**, Huan Cao, Marti Cladera Rossello

\+ **Giulia Rubino**, **Lorenzo Procopio**, Caslav Brukner, **Fabio Costa**

Trajectory experiments



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Toronto: Boris Braverman, Sacha Kocsis, Krister Shalm, Dylan Mahler, **Aephraim Steinberg**

IQC: Kent Fisher, Kevin Resch

Brisbane: Howard Wiseman