

*'Causality in the Quantum World', Templeton Workshop,  
Anacapri, Italy, Sep 17th 2019*

# EXPERIMENTAL ENTANGLEMENT OF TEMPORAL ORDERS

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G. Rubino, L. A. Rozema, F. Massa, M. Araújo,  
M. Zych, C. Brukner and P. Walther

Preprint at [arXiv:1712.06884 \[quant-ph\]](https://arxiv.org/abs/1712.06884)

# OUTLOOK

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- Introduction
- Causally unordered processes
- A theory independent approach
- Experimental implementation
- Results
- Conclusion and Outlook

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## Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky, and N. Rosen

Phys. Rev. **47**, 777 – Published 15 May 1935



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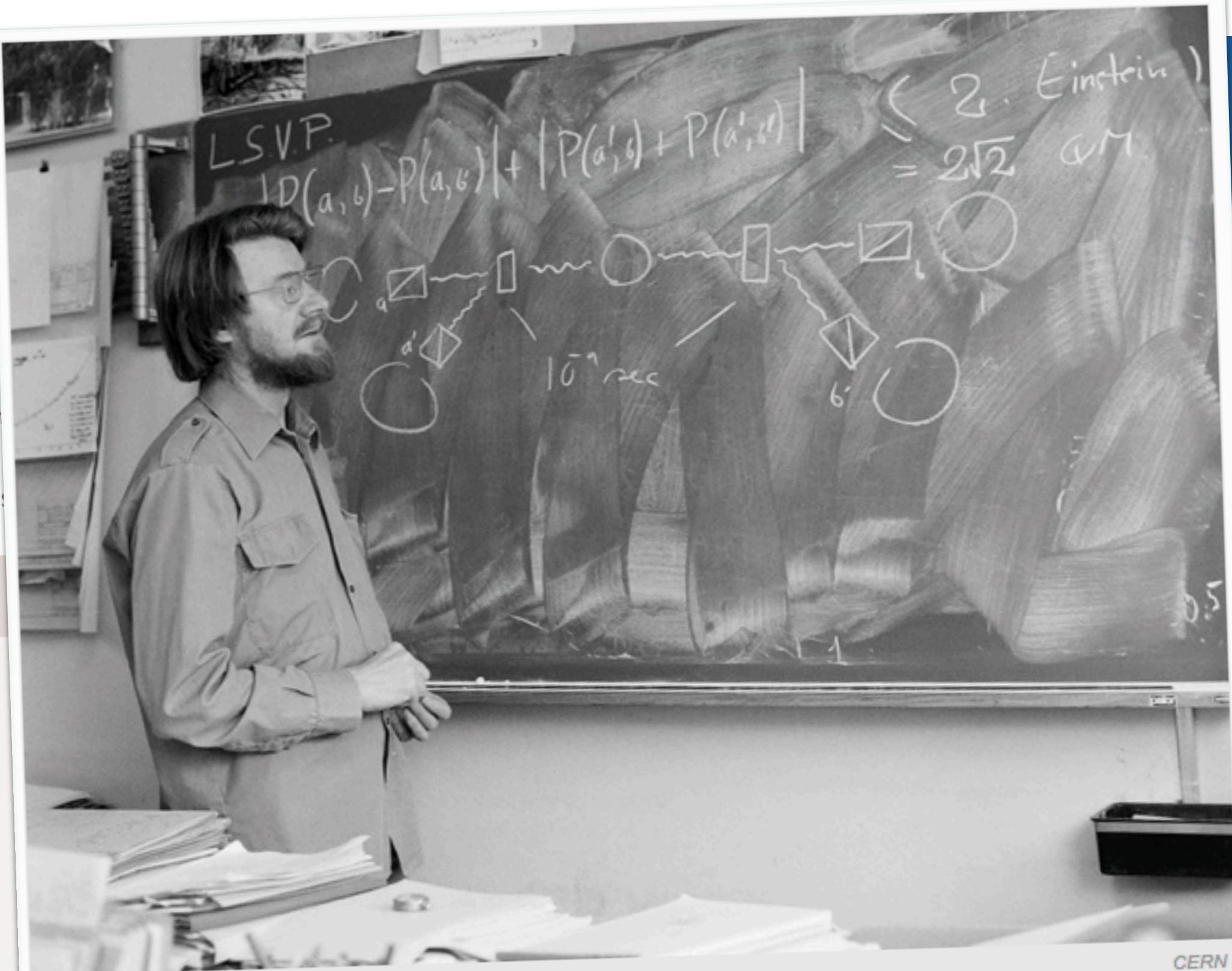
### ABSTRACT

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

### Issue

Vol. 47, Iss. 10 — May 1935

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CERN

Physicist John Bell at CERN, Europe's particle-physics lab near Geneva, Switzerland, in 1982.



May 1935

sessions

# Quantum mechanics and hidden variables: A test of Bell's inequality by the measurement of the spin correlation in low-energy proton-proton scattering

M. Lamehi-Rachti and W. Mittig  
Phys. Rev. D **14**, 2543 – Published 15 November 1976

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## ABSTRACT

The inequality of Bell has been tested by the measurement of the spin correlation in proton-proton scattering. Measurements were made at  $E_p = 13.2$  and 13.7 MeV using carbon analyzers of 18.6 and 29 mg/cm<sup>2</sup>, respectively, accumulating a total of  $10^4$  coincidences. The experimental analyzing power, geometric correlation coefficients, and energy spectra are compared to the result of a Monte Carlo simulation of the apparatus. The results are in good agreement with quantum mechanics and in disagreement with the inequality of Bell if the same additional assumptions are made. The conditions

## PHYSICAL REVIEW LETTERS

### Experimental Test of Local Hidden-Variable Theories

Stuart J. Freedman and John F. Clauser  
Phys. Rev. Lett. **28**, 938 – Published 3 April 1972

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## ABSTRACT

## PHYSICAL REVIEW LETTERS

We have performed an experiment to test local hidden-variable theories. We have calculated the spin correlation function for two different spin components and found it to vary with the angle between the directions of the two spin components. The results are in agreement with quantum mechanics and in disagreement with the inequality of Bell if the same additional assumptions are made. The conditions

Realization of the Einstein-Podolsky-Rosen Paradox Using Momentum- and Position-Entangled Photons from Spontaneous Parametric Down Conversion

John C. Howell, Ryan S. Bennink, Sean J. Bentley, and R. W. Boyd  
Phys. Rev. Lett. **92**, 210403 – Published 28 May 2004

## PHYSICAL REVIEW LETTERS

### Experimental violation of Bell's inequality based on phase and momentum

J. G. Rarity and P. R. Tapster  
Phys. Rev. Lett. **64**, 2495 – Published 21 May 1990

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## Abstract

## References

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# Experimental violation of a Bell's inequality with efficient detection

M. A. Rowe D. Kielpinski, V. Meyer, C. A. Sackett, W. M. Itano, C. Monroe & D. J. Wineland

Nature **409**, 791–794 (15 February 2001)

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Giulio Chiribella

Phys. Rev. A **86**, 040301(R) – Published 10 October 2012

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## Quantum correlations with no causal order

Ognyan Oreshkov , Fabio Costa &amp; Časlav Brukner

Nature Communications **3**,  
Article number: 1092 (2012)  
doi:10.1038/ncomms2076

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Quantum mechanics Theoretical physics

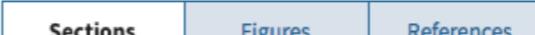
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Abstract

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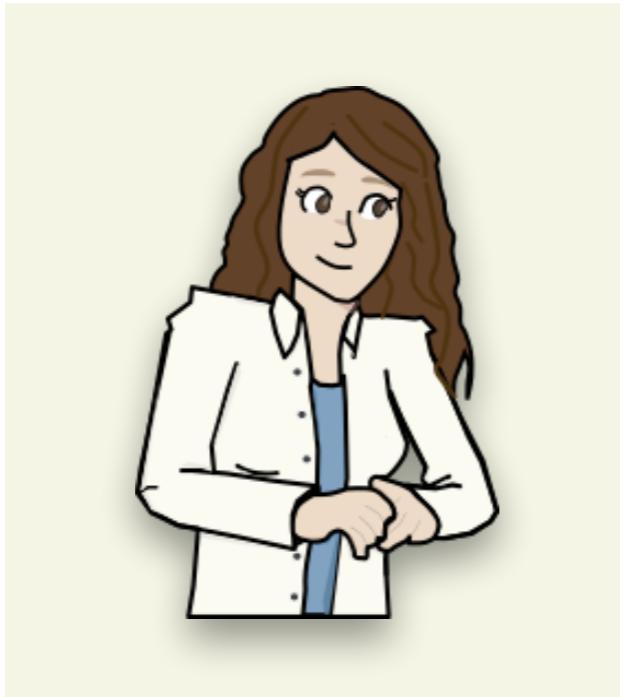
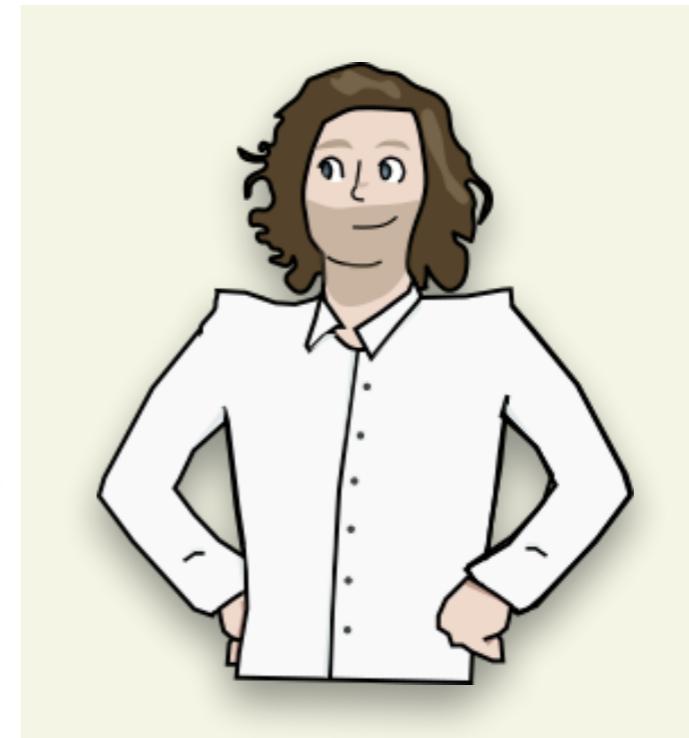


Quantum mechanics predicts the existence of processes that are neither *causally ordered* nor a *probabilistic mixture of causally ordered processes*

# CAUSALLY UNORDERED PROCESSES

## Local Laboratories:

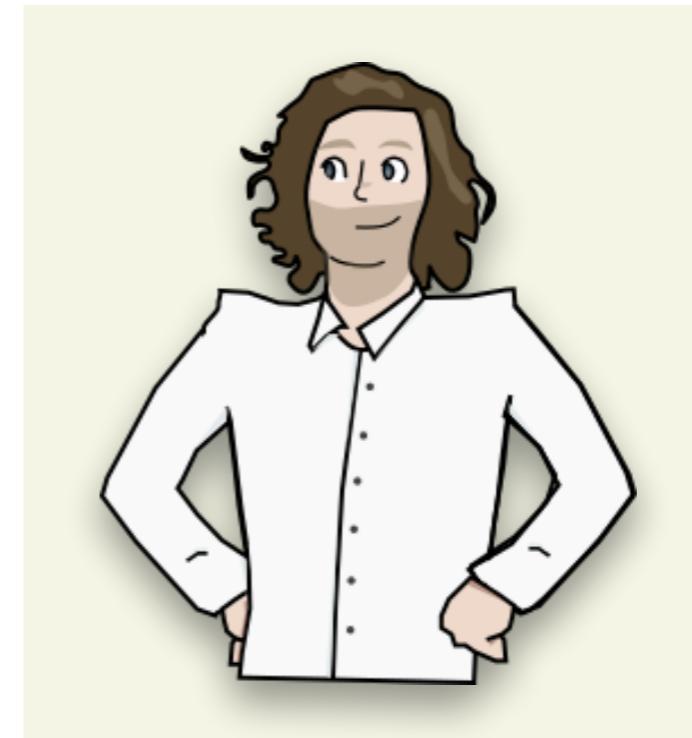
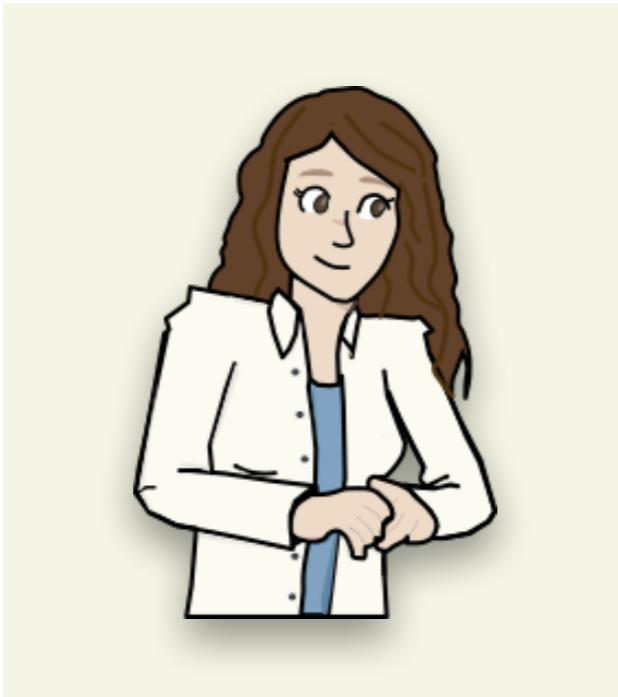
A and B can receive and send a signal, but their laboratories are isolated from the rest of the world between these two events


$$\mathcal{A}(\psi)$$

$$\mathcal{B}(\psi)$$

# CAUSALLY UNORDERED PROCESSES

## Local Laboratories:

A and B can receive and send a signal, but their laboratories are isolated from the rest of the world between these two events



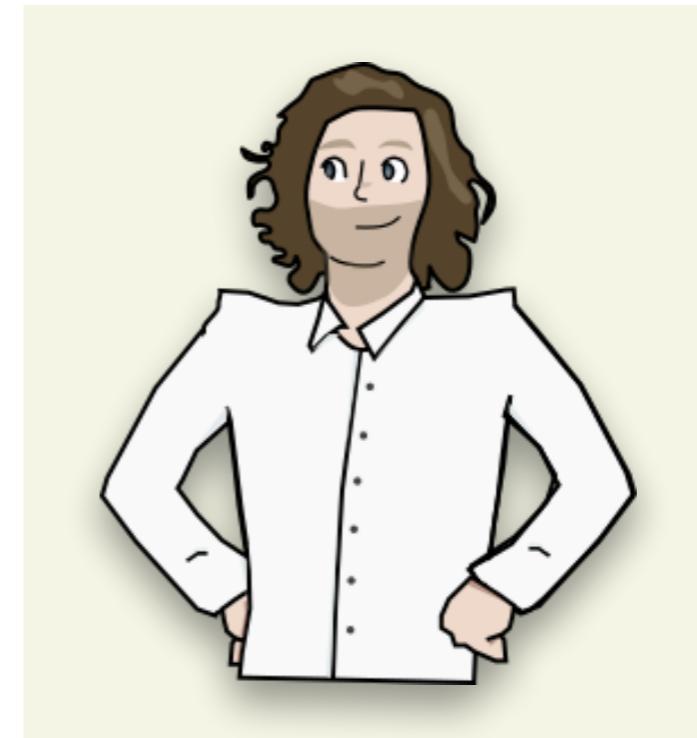
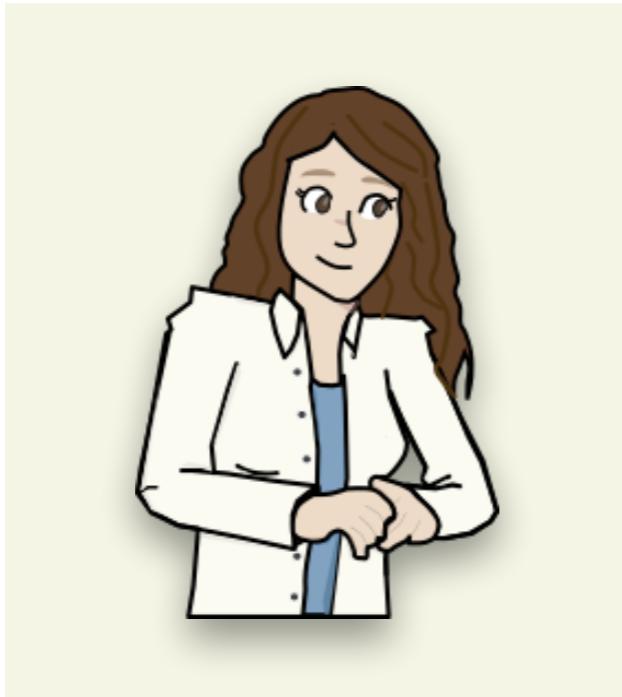
$$\Omega(\psi) = \zeta \cdot \mathcal{B}(\mathcal{A}(\psi)) + (1 - \zeta) \cdot \mathcal{A}(\mathcal{B}(\psi))$$

*causally ordered*

# CAUSALLY UNORDERED PROCESSES

## Local Laboratories:

A and B can receive and send a signal, but their laboratories are isolated from the rest of the world between these two events

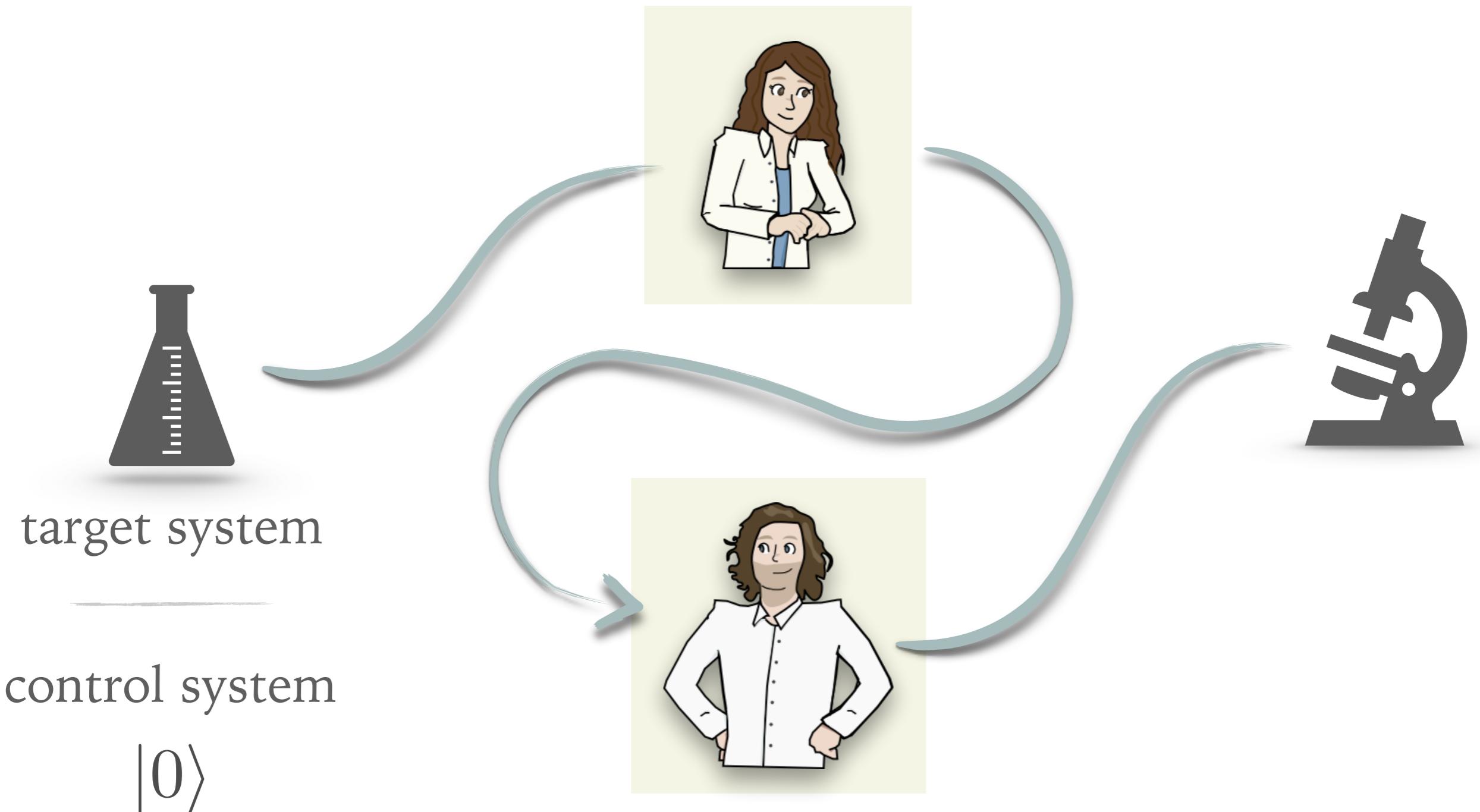


$$\Omega(\psi) = \zeta \cdot \mathcal{B}(\mathcal{A}(\psi)) + (1 - \zeta) \cdot \mathcal{A}(\mathcal{B}(\psi))$$

*probabilistic mixture of causally ordered processes*

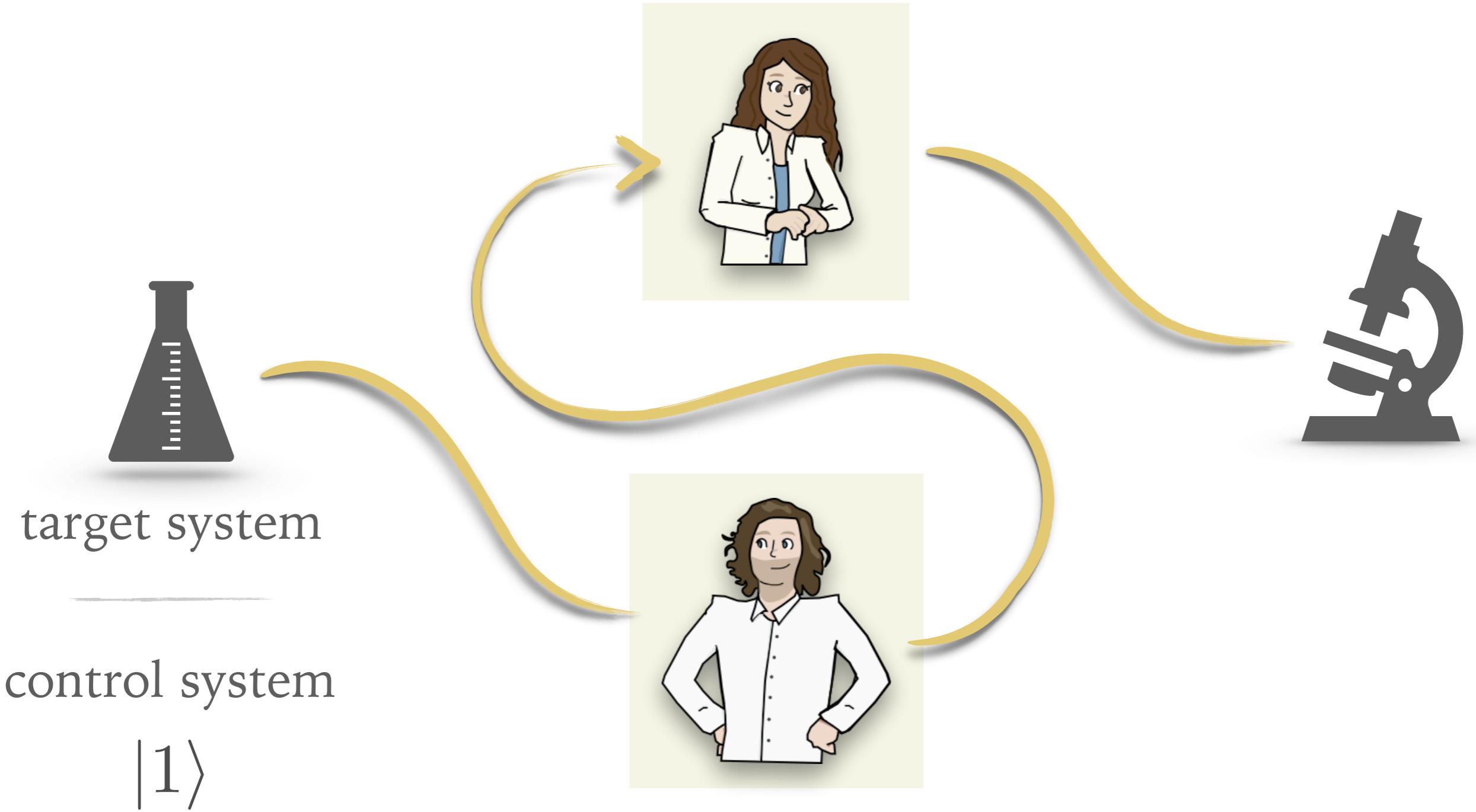
# CAUSALLY UNORDERED PROCESSES

What is a quantum SWITCH?



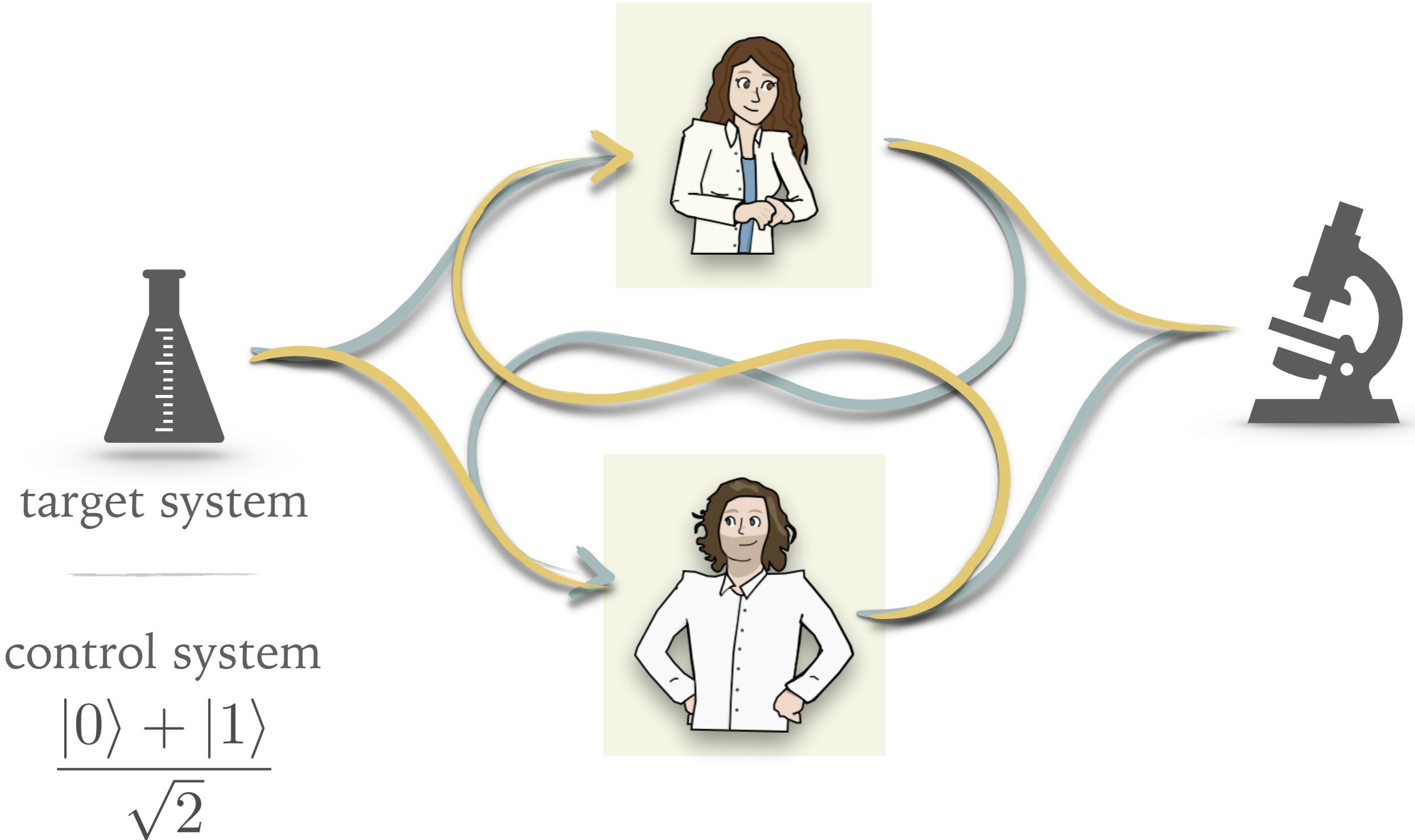
# CAUSALLY UNORDERED PROCESSES

What is a quantum SWITCH?



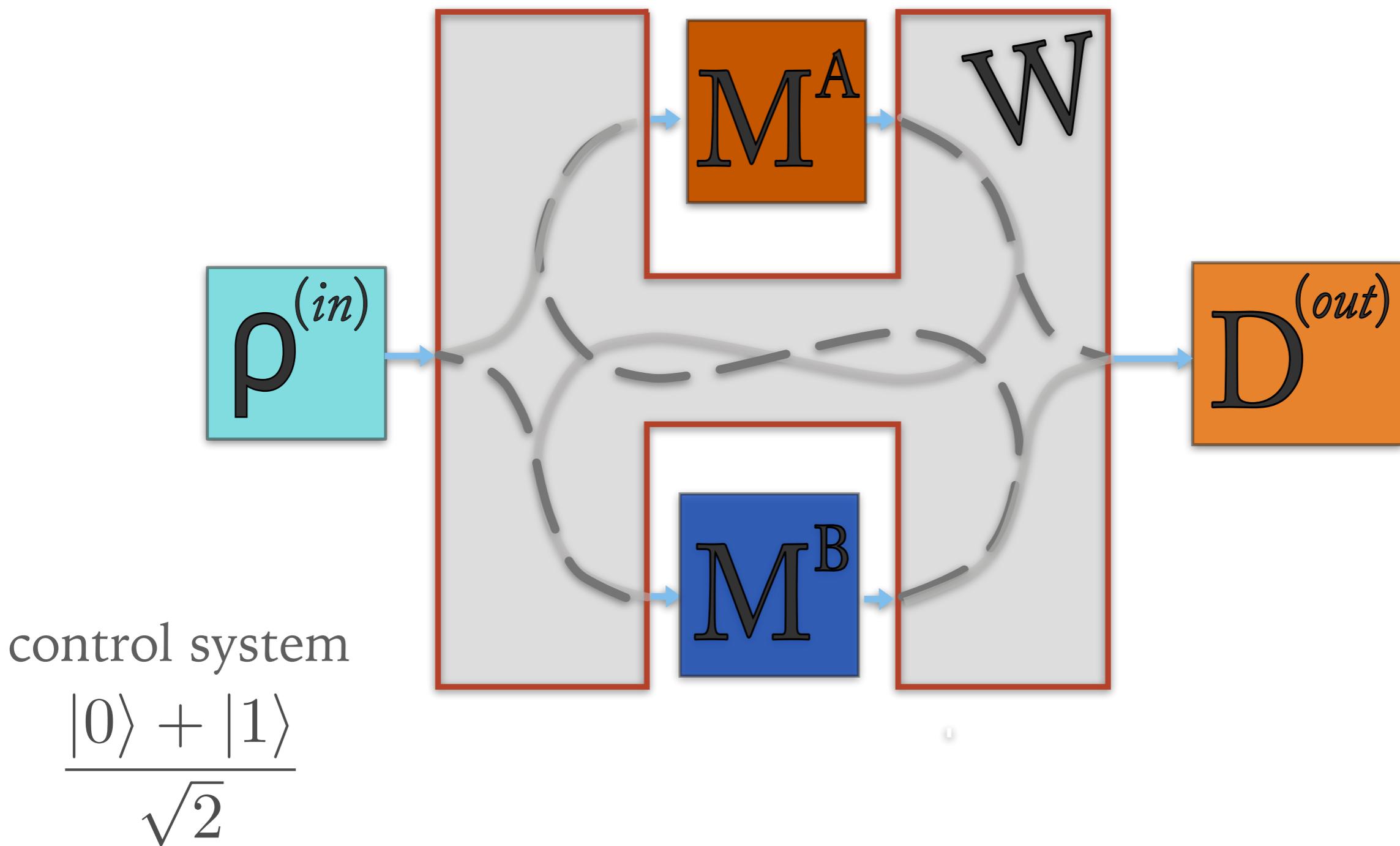
# CAUSALLY UNORDERED PROCESSES

What is a quantum SWITCH?



# CAUSALLY UNORDERED PROCESSES

What is a process matrix?



# CAUSALLY UNORDERED PROCESSES

Process Matrices:

Probability of obtaining the outcomes  $a$  and  $b$

$$p(a, b, d|x, y, z) = \text{Tr}[(\rho_z^{(\text{in})} \otimes M_{a,x}^A \otimes M_{b,y}^B \otimes D_d^{(\text{out})}) \cdot W]$$

where

$$\sum_{a,b,d} p(a, b, d|x, y, z) = 1$$

\* O. Oreshkov, F. Costa, and Č. Brukner, Nat. Comm. 3 (2012)

# CAUSALLY UNORDERED PROCESSES

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*Causally Separable Process Matrices:*

A bipartite  $W$  is separable if it is writable as

$$W^{sep} := \zeta W^{A \rightarrow B} + (1 - \zeta) W^{B \rightarrow A}$$

- \* M. Araújo, C. Branciard, F. Costa, A. Feix, C. Giarmatzi, and Č. Brukner,  
New Jour. of Phys. 17, 102001 (2015)

## CAUSALLY UNORDERED PROCESSES

*Causally Separable Process Matrices:*

For all causally-separable  $W^{sep}$  there exists a Hermitian operator  $S$  s. t.

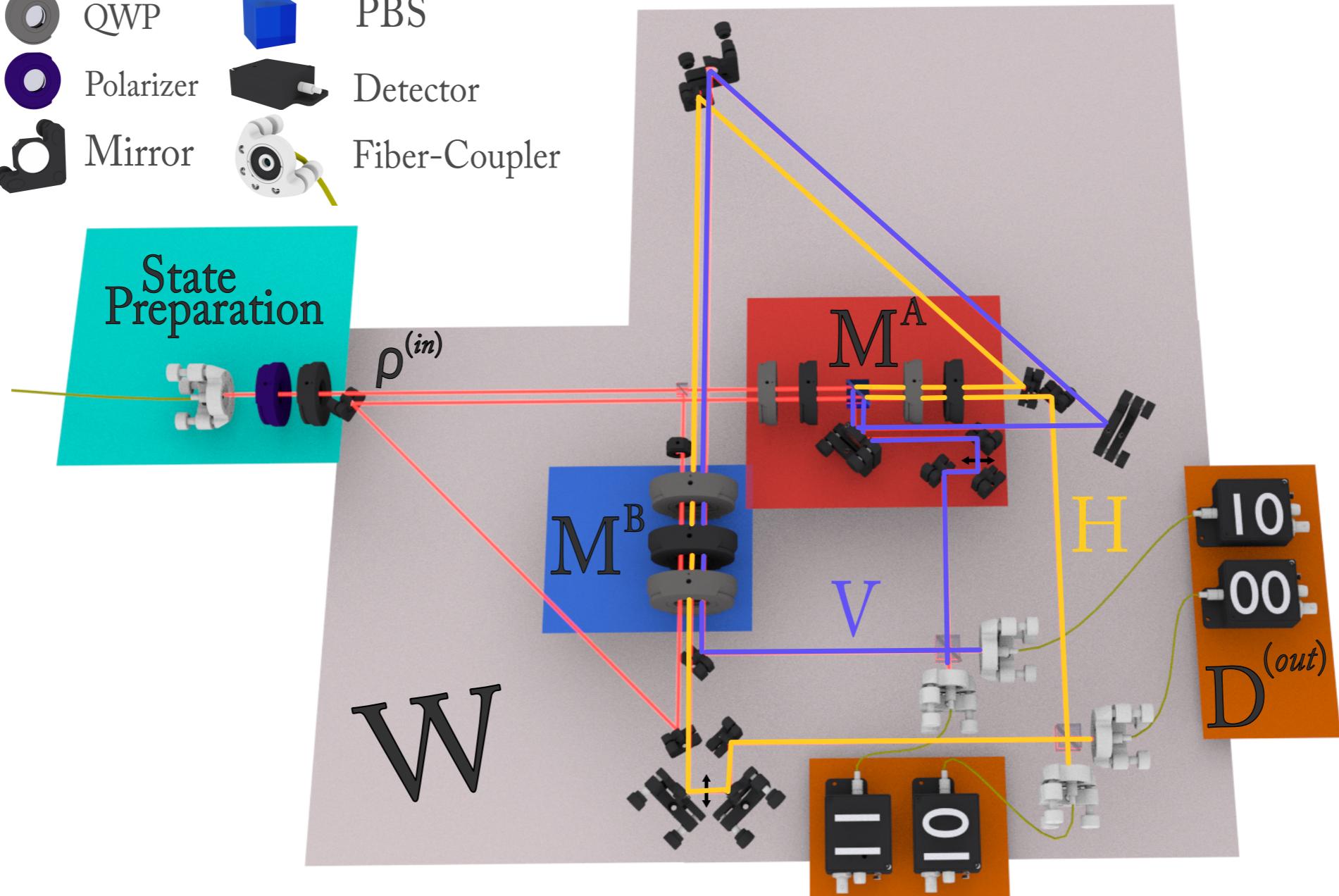
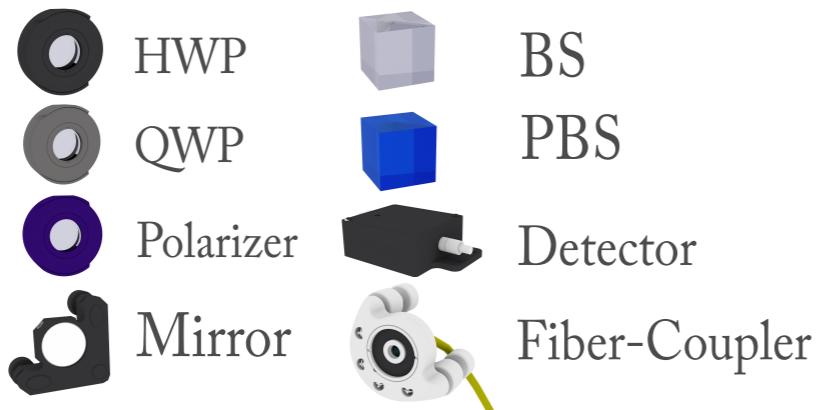
$$\text{Tr}(SW^{sep}) \geq 0 \text{ and } \text{Tr}(SW^{n\text{-}sep}) < 0$$

for all causally non-separable  $W^{n\text{-}sep}$ .

$$\text{CNS} = -\text{Tr}(SW_{\text{SWITCH}})$$

- \* M. Araújo, C. Braciard, F. Costa, A. Feix, C. Giarmatzi, and Č. Brukner, New Jour. of Phys. 17, 102001 (2015)
- \* G. Rubino, L. A. Rozema, A. Feix, M. Araújo, J. M. Zeuner, L. M. Procopio, Č. Brukner, and P. Walther, Preprint at arXiv:1608.01683[quant-ph]

# CAUSALLY UNORDERED PROCESSES



$$\text{CNS} = 0.202 \pm 0.029$$

# A THEORY INDEPENDENT APPROACH

It was shown that superposition of massive objects can effectively lead to ‘entanglement’ in the temporal order between local operations

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Bell's theorem for temporal order

Magdalena Zych , Fabio Costa, Igor Pirovski & Časlav Brukner

Nature Communications 10, Article number: 3772 (2019) | [Download Citation](#) 

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Abstract

Time has a fundamentally different character in quantum mechanics and in general relativity. In quantum theory events unfold in a fixed order while in general relativity temporal order is influenced by the distribution of matter. When matter requires a quantum description, temporal order

Introduction

Results

Discussion

Methods

Data availability

# A THEORY INDEPENDENT APPROACH

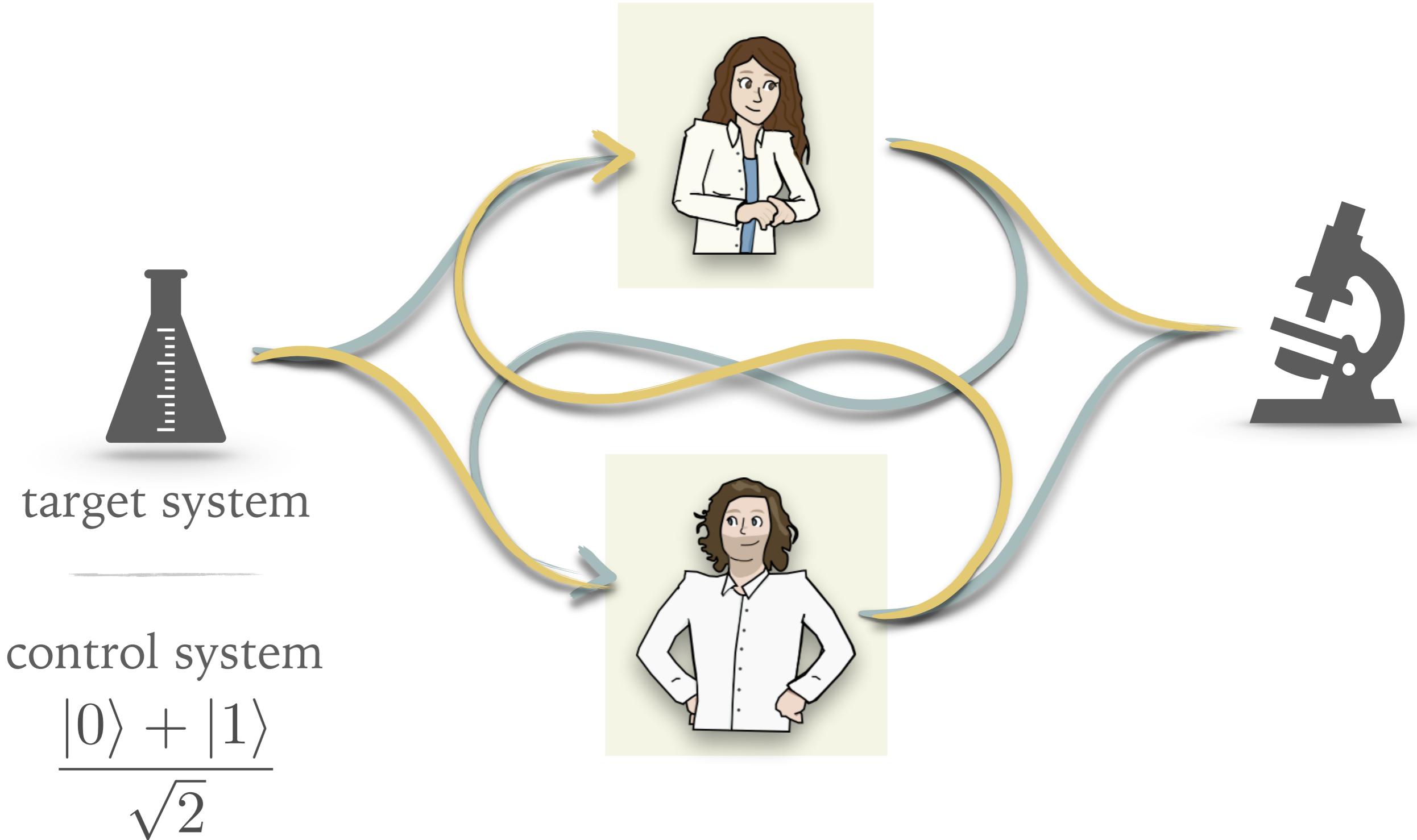
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1. The initial joint state of the target system is *local* (i.e., it does not violate a Bell inequality).
2. The laboratory operations are *local transformations* of the target systems (i.e., they do not increase the amount of a violation of Bell inequalities between the two target systems).
3. The order of operations is pre-defined.

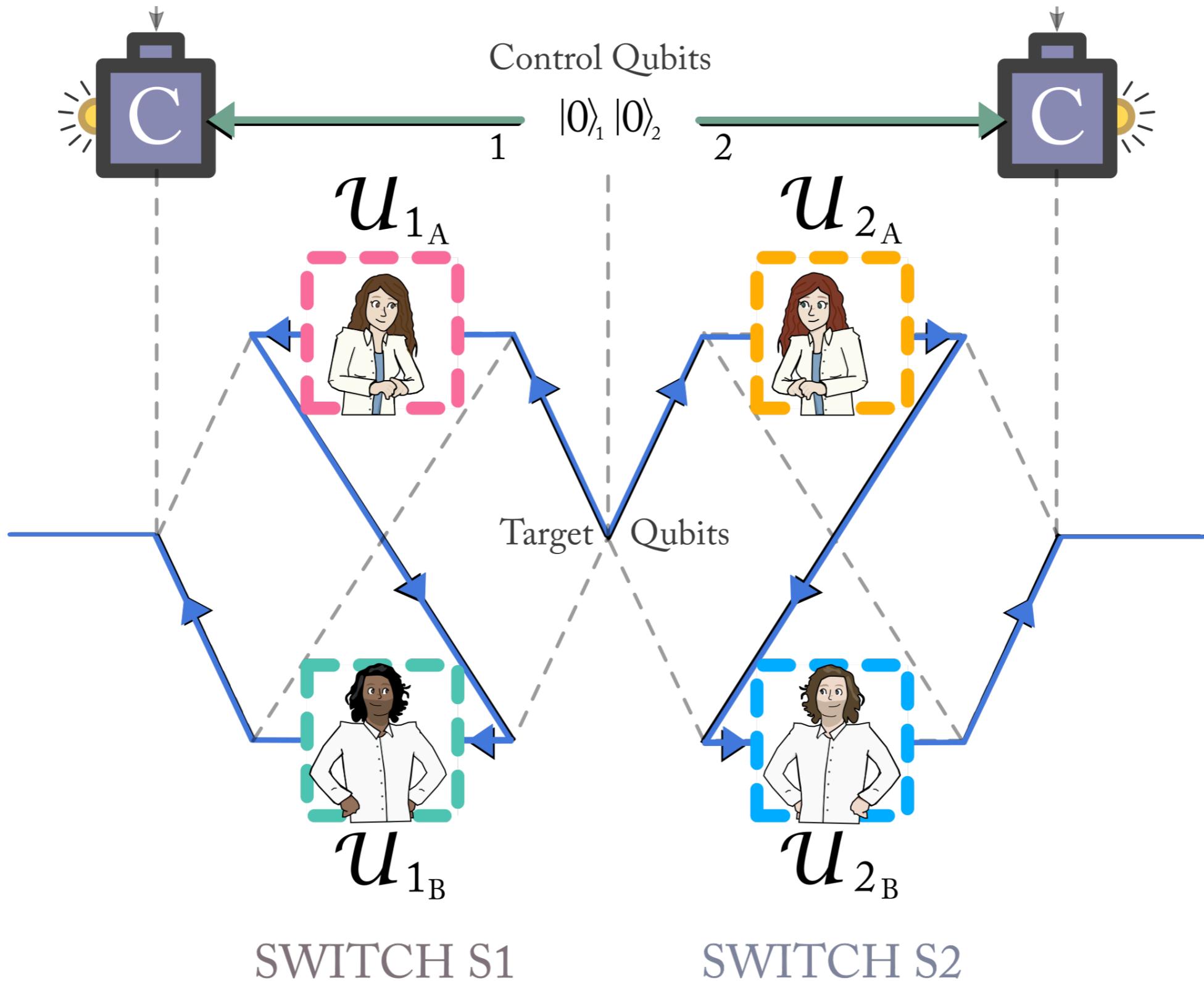
*Theorem.* No states, set of transformations and measurements which obey assumptions 1.-3. can result in violation of Bell's inequalities

# A THEORY INDEPENDENT APPROACH

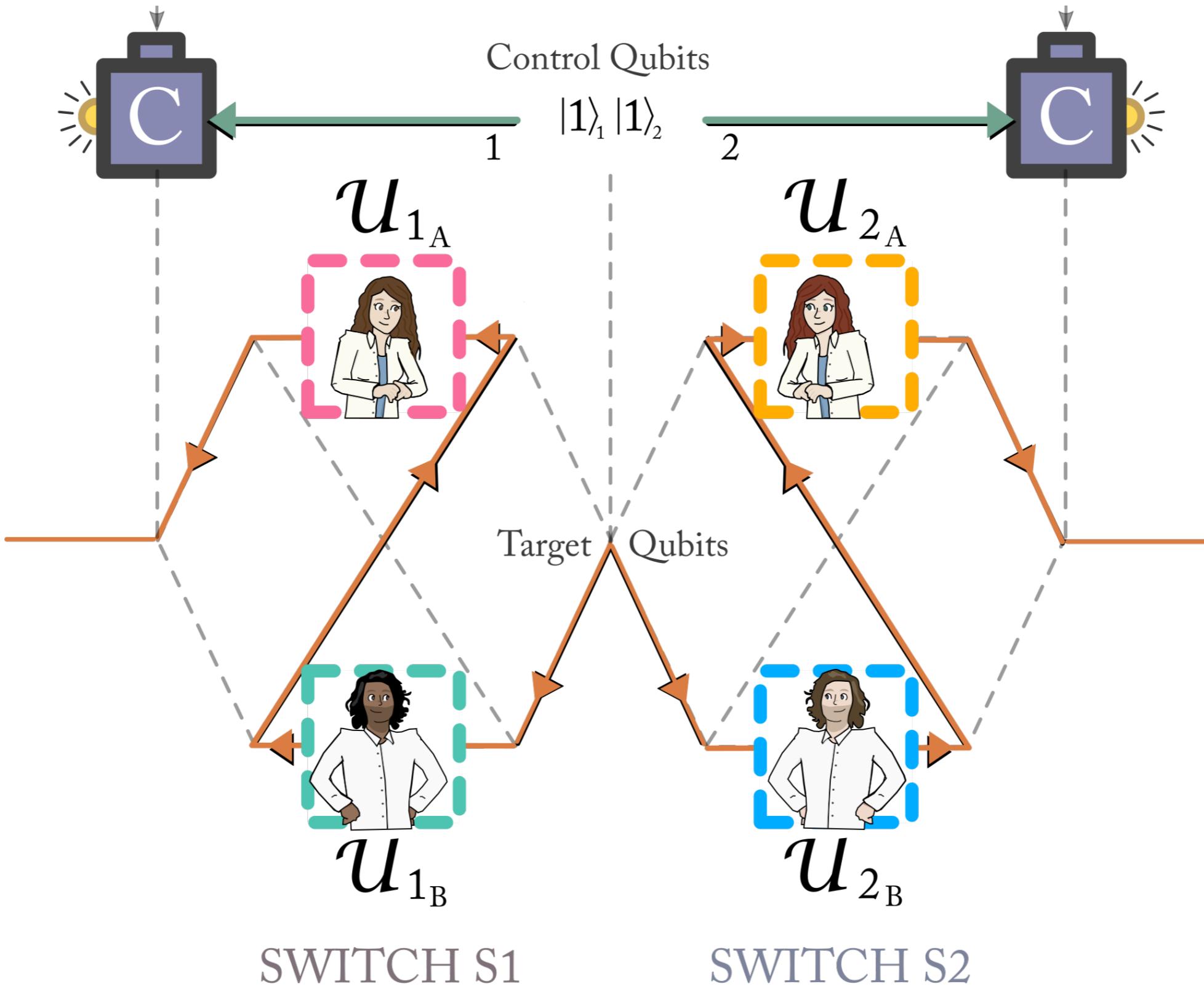
What is a quantum SWITCH?



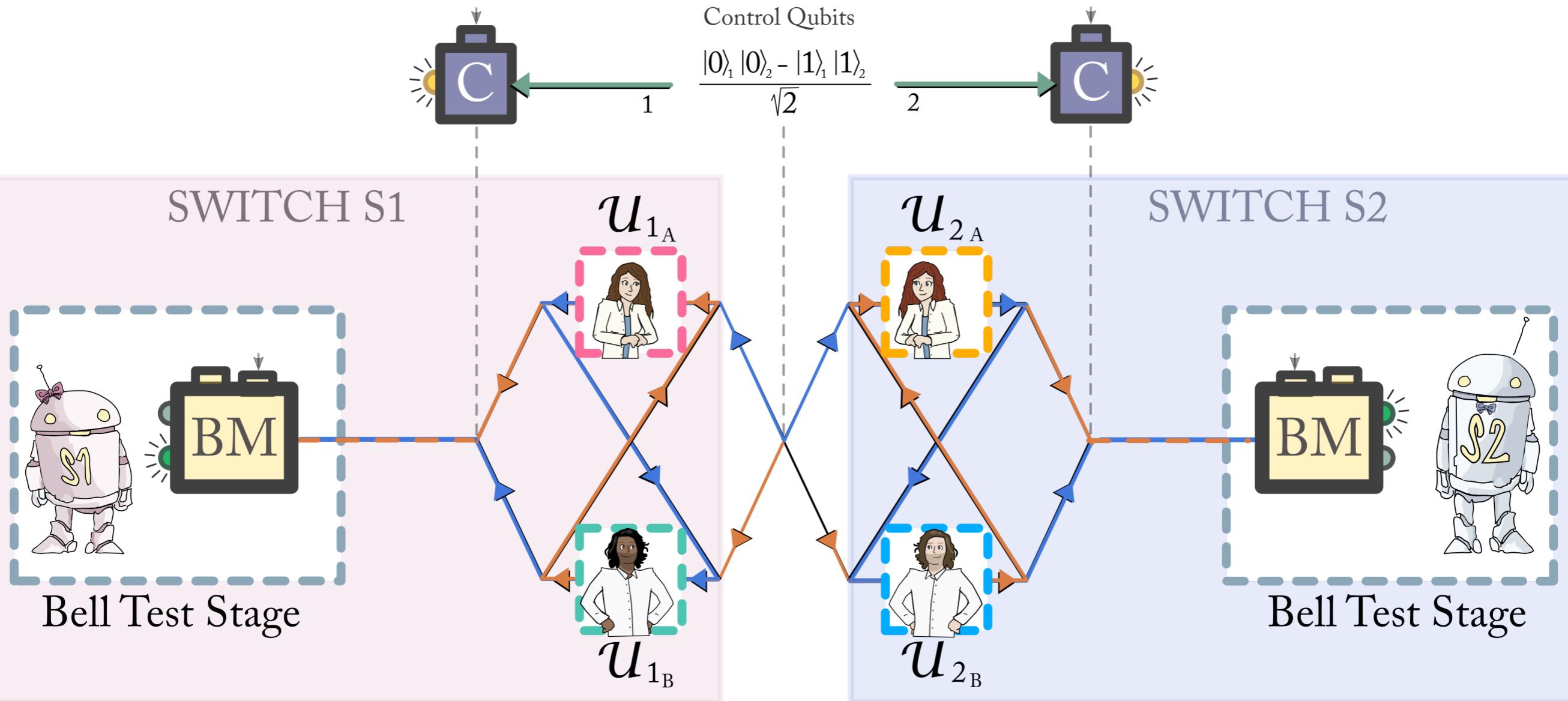
# A THEORY INDEPENDENT APPROACH



# A THEORY INDEPENDENT APPROACH

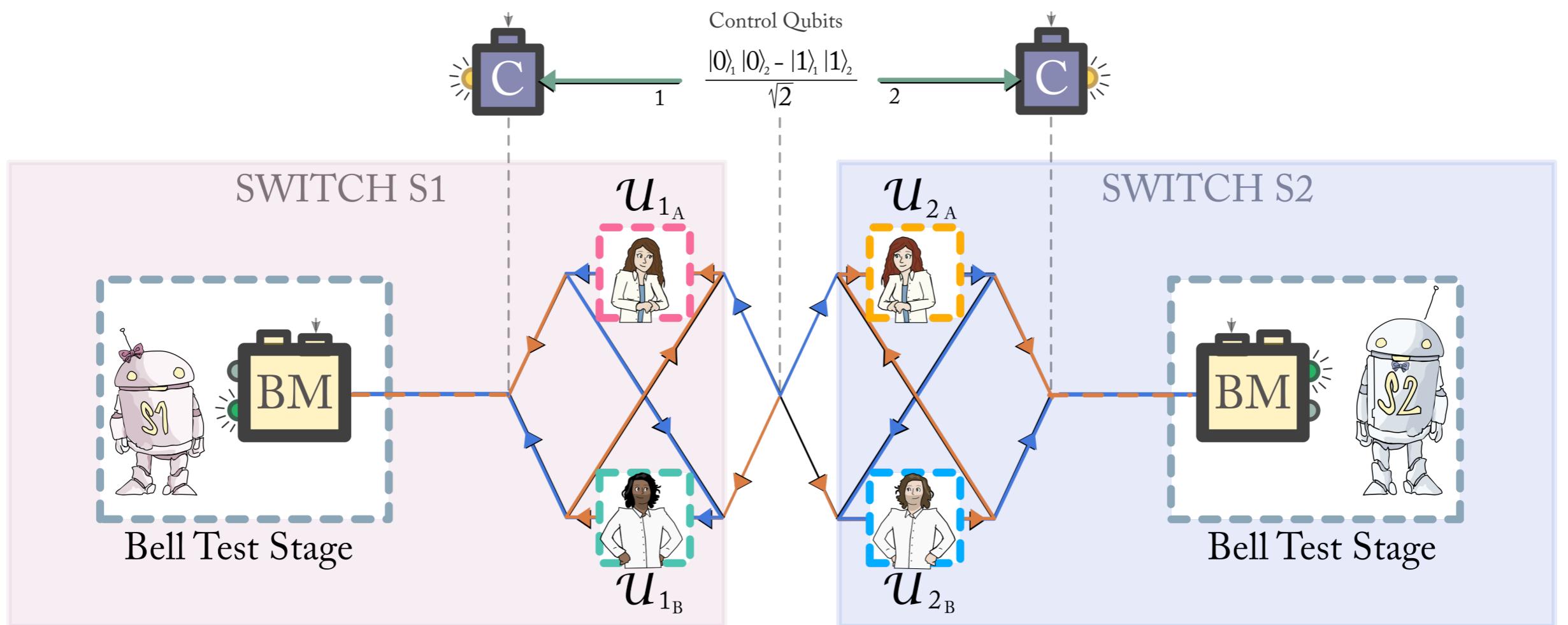


# A THEORY INDEPENDENT APPROACH



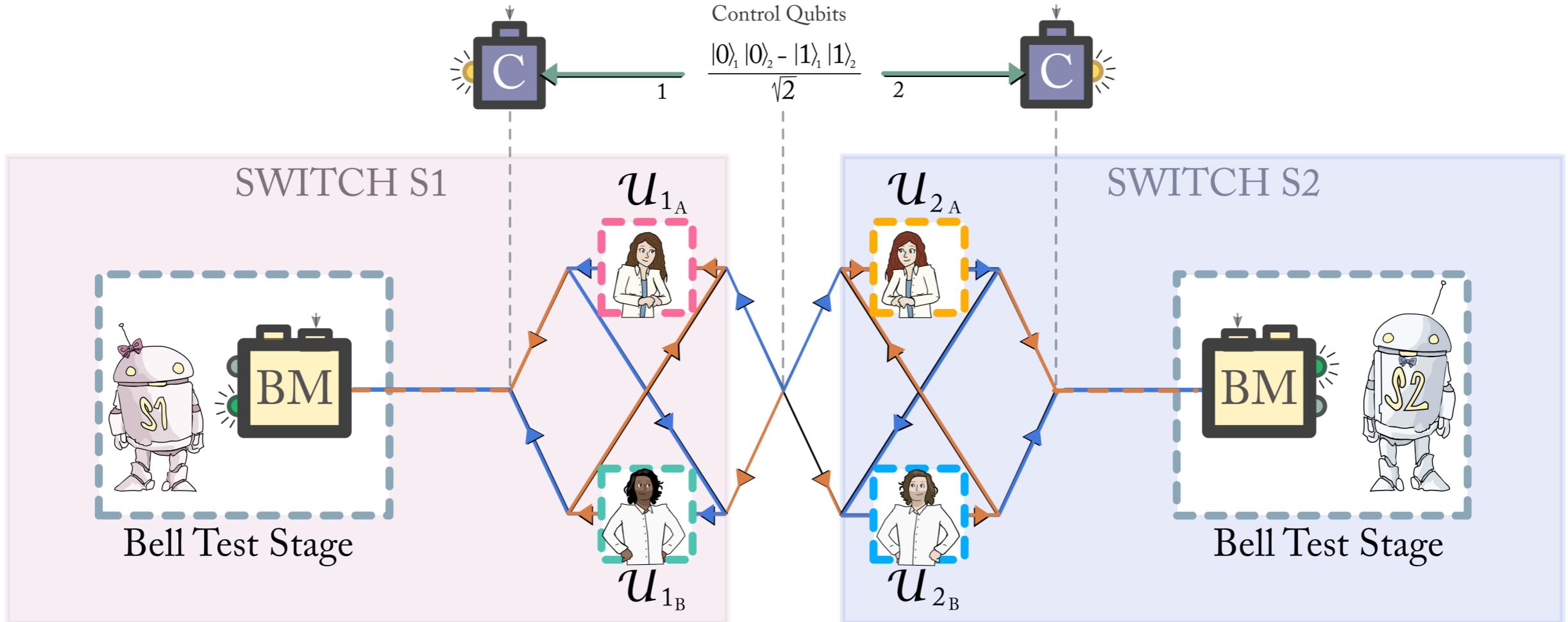
The order in which the target qubit in SWITCH 1 passes through  $\mathcal{U}_{1A}$  and  $\mathcal{U}_{1B}$  is entangled with the order in which the target qubit in SWITCH 2 passes through  $\mathcal{U}_{2A}$  and  $\mathcal{U}_{2B}$ .

# A THEORY INDEPENDENT APPROACH



1) Initial state:  $|0\rangle_1^T \otimes |0\rangle_2^T \otimes \left( \frac{|0\rangle_1^C \otimes |0\rangle_2^C - |1\rangle_1^C \otimes |1\rangle_2^C}{\sqrt{2}} \right)$

# A THEORY INDEPENDENT APPROACH

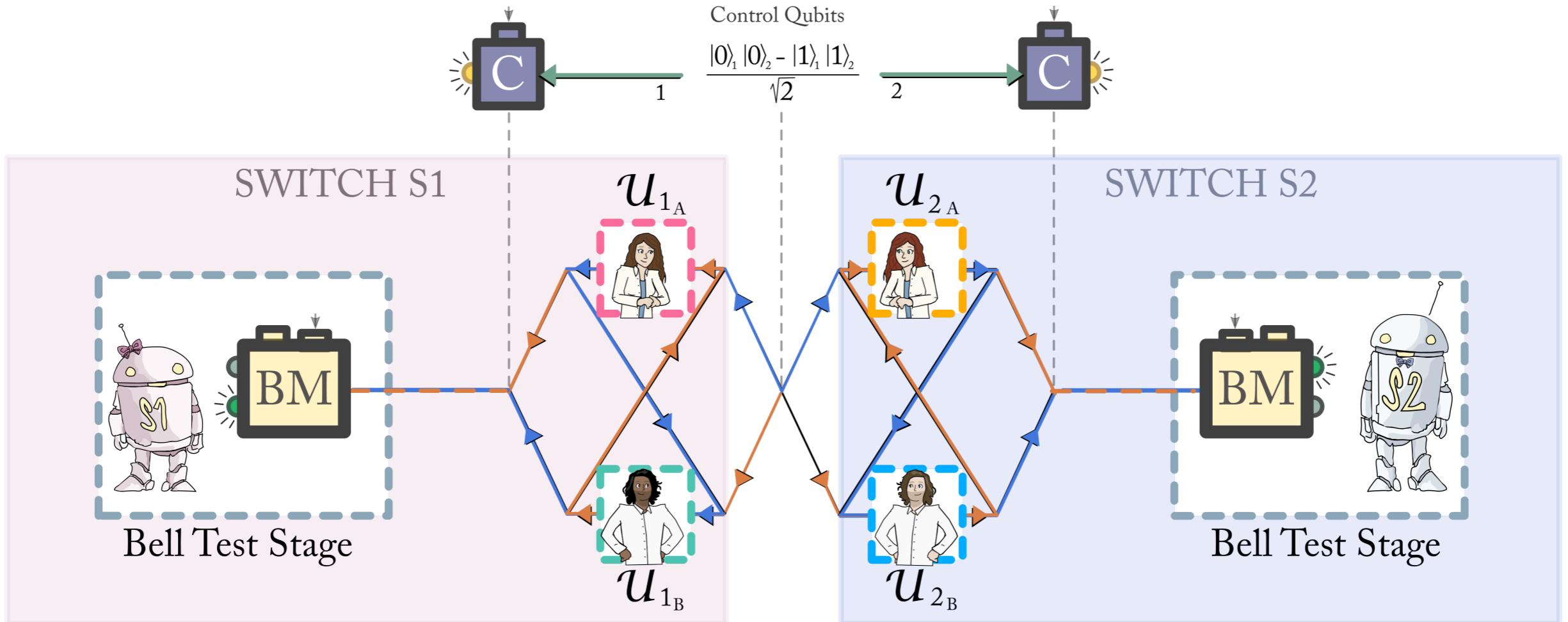


2) Application of the gates:

$$\frac{1}{\sqrt{2}} \left( U_{1B} \circ U_{1A} |0\rangle_1^T \right) \otimes |0\rangle_1^C \otimes \left( U_{2B} \circ U_{2A} |0\rangle_2^T \right) \otimes |0\rangle_2^C$$

$$- \frac{1}{\sqrt{2}} \left( U_{1A} \circ U_{1B} |0\rangle_1^T \right) \otimes |1\rangle_1^C \otimes \left( U_{2A} \circ U_{2B} |0\rangle_2^T \right) \otimes |1\rangle_2^C$$

# A THEORY INDEPENDENT APPROACH

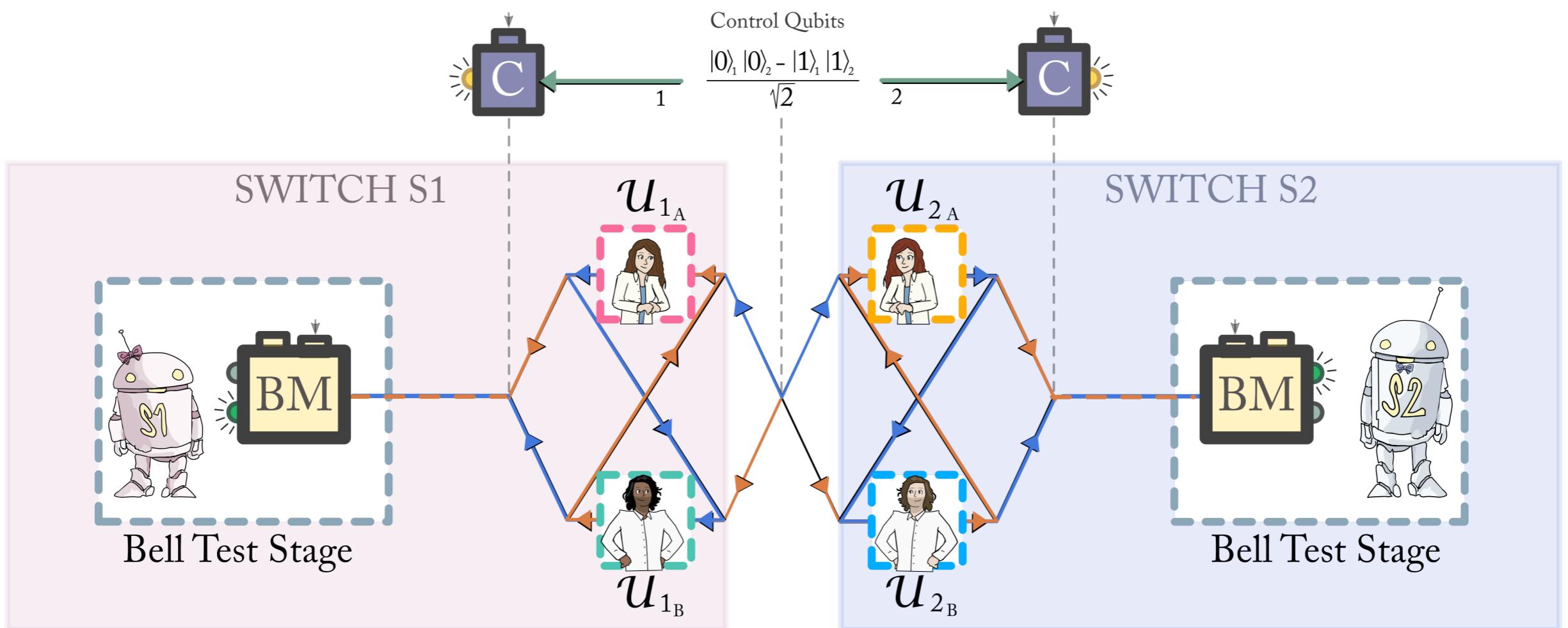


3) Projection of the control qubit on  $|+\rangle^C, |-\rangle^C$

$$\frac{1}{\sqrt{2}} (\mathcal{U}_{1_B} \circ \mathcal{U}_{1_A} |0\rangle_1^T \otimes \mathcal{U}_{2_B} \circ \mathcal{U}_{2_A} |0\rangle_2^T$$

$$- \mathcal{U}_{1_A} \circ \mathcal{U}_{1_B} |0\rangle_1^T \otimes \mathcal{U}_{2_A} \circ \mathcal{U}_{2_B} |0\rangle_2^T)$$

# A THEORY INDEPENDENT APPROACH

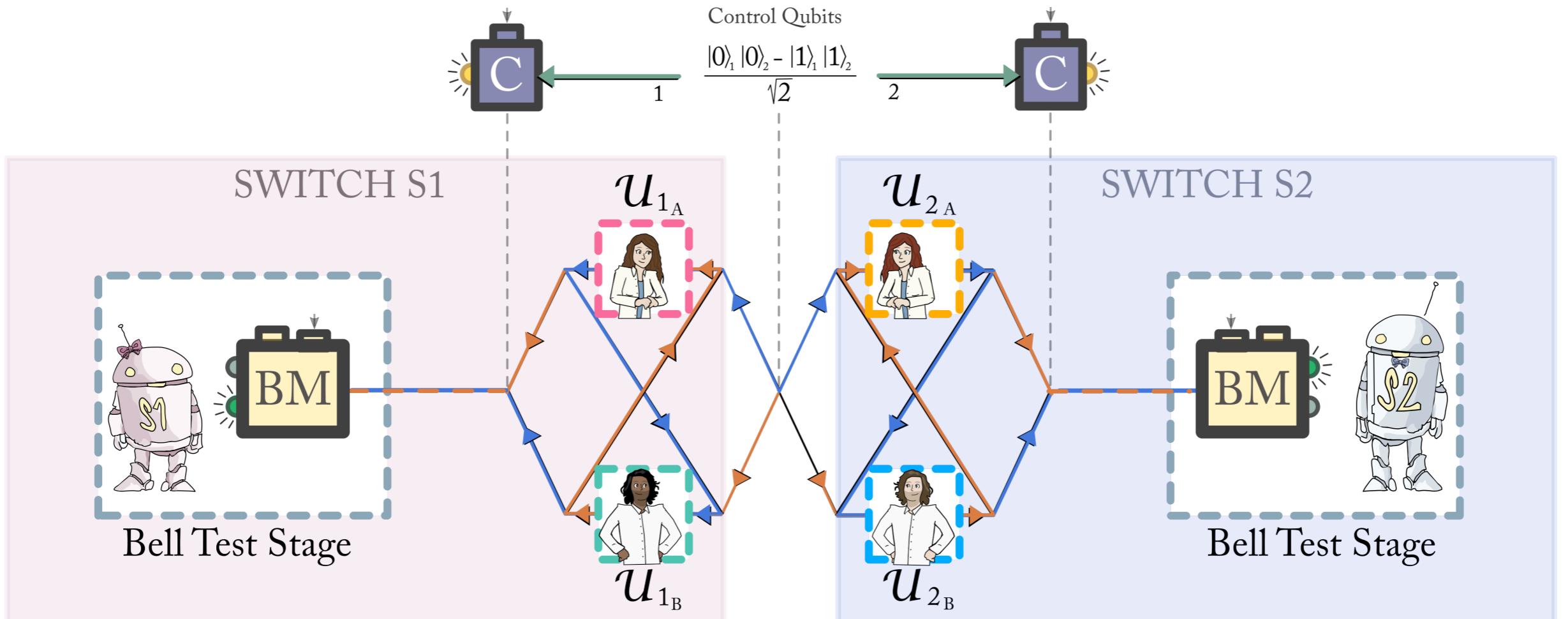


4) Applied Unitaries:

$$\mathcal{U}_{1A} = \mathcal{U}_{2A} = \sigma_z$$

$$\mathcal{U}_{1B} = \mathcal{U}_{2B} = \frac{\mathcal{I} + i\sigma_x}{\sqrt{2}}$$

# A THEORY INDEPENDENT APPROACH

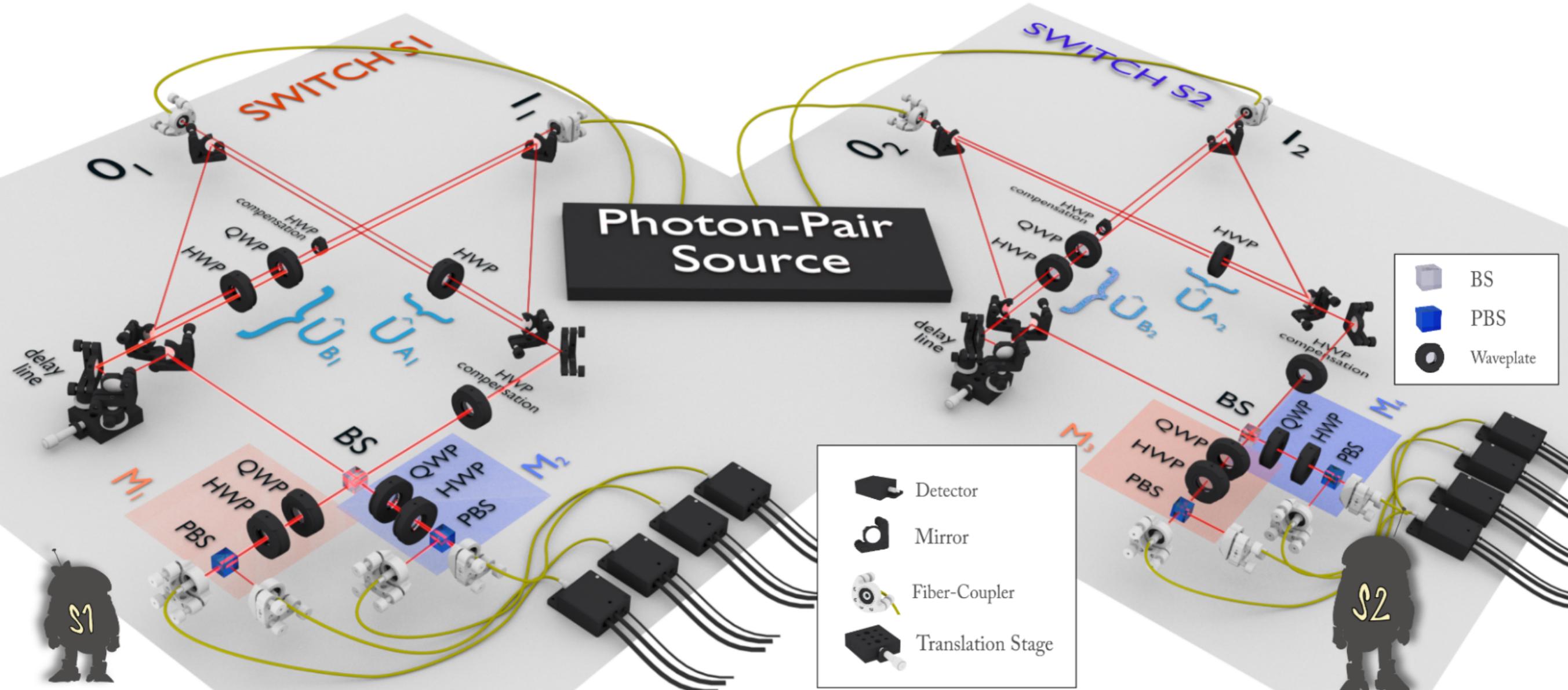


⇒ Final state:

$$\frac{1}{\sqrt{2}}(|L\rangle_1^T |L\rangle_2^T - |R\rangle_1^T |R\rangle_2^T)$$

which *violates Bell inequalities*

# EXPERIMENTAL IMPLEMENTATION



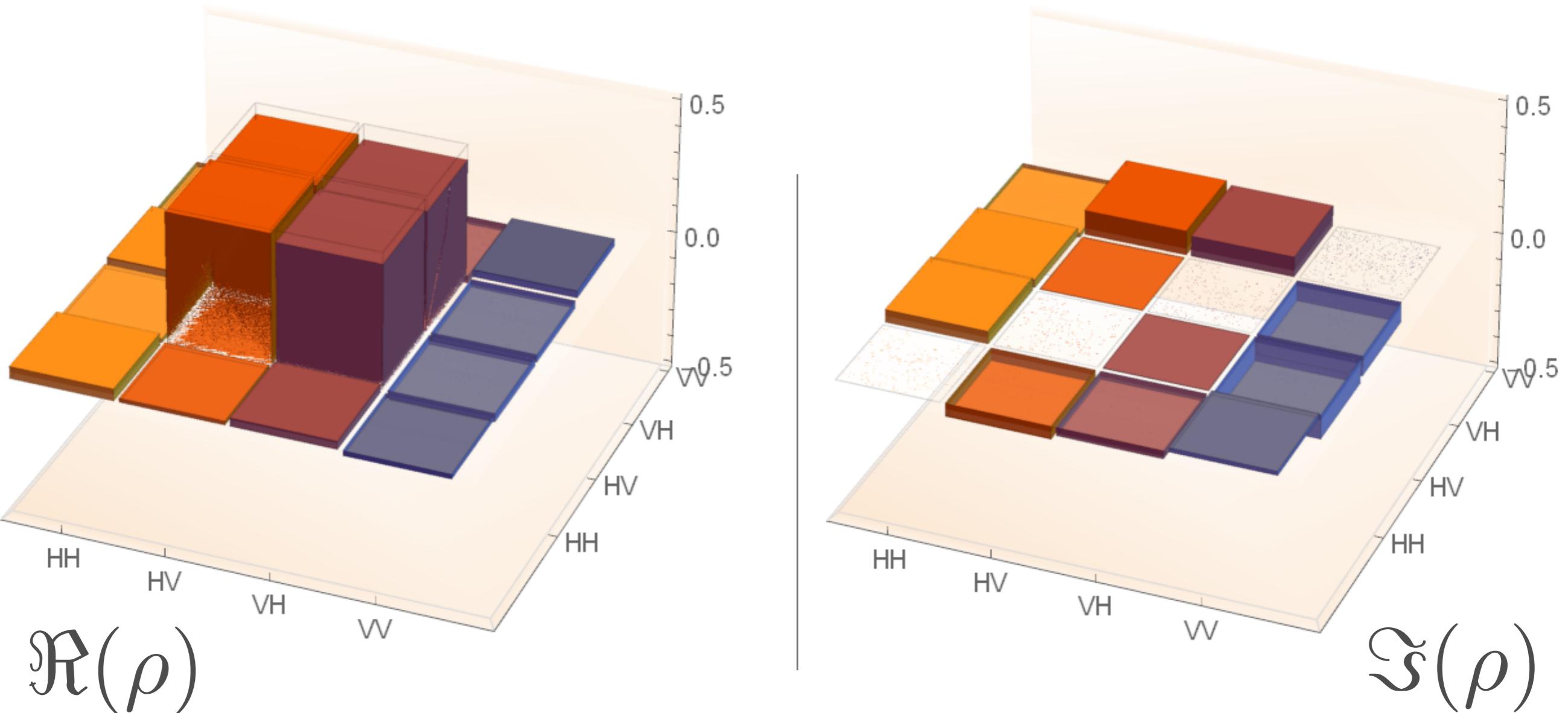
# A THEORY INDEPENDENT APPROACH

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1. The initial joint state of the target system is *local* (i.e., it does not violate a Bell inequality).
2. The laboratory operations are *local transformations* of the target systems (i.e., they do not increase the amount of a violation of Bell inequalities between the two target systems).
3. The order of operations is pre-defined.

*Theorem.* No states, set of transformations and measurements which obey assumptions 1.-3. can result in violation of Bell's inequalities

## RESULTS - VIOLATION OF NO-GO THEOREM



$$S_{\text{target}} = 2.55 \pm 0.08$$

Fidelity =  $0.922 \pm 0.005$

Concurrence =  $0.95 \pm 0.01$

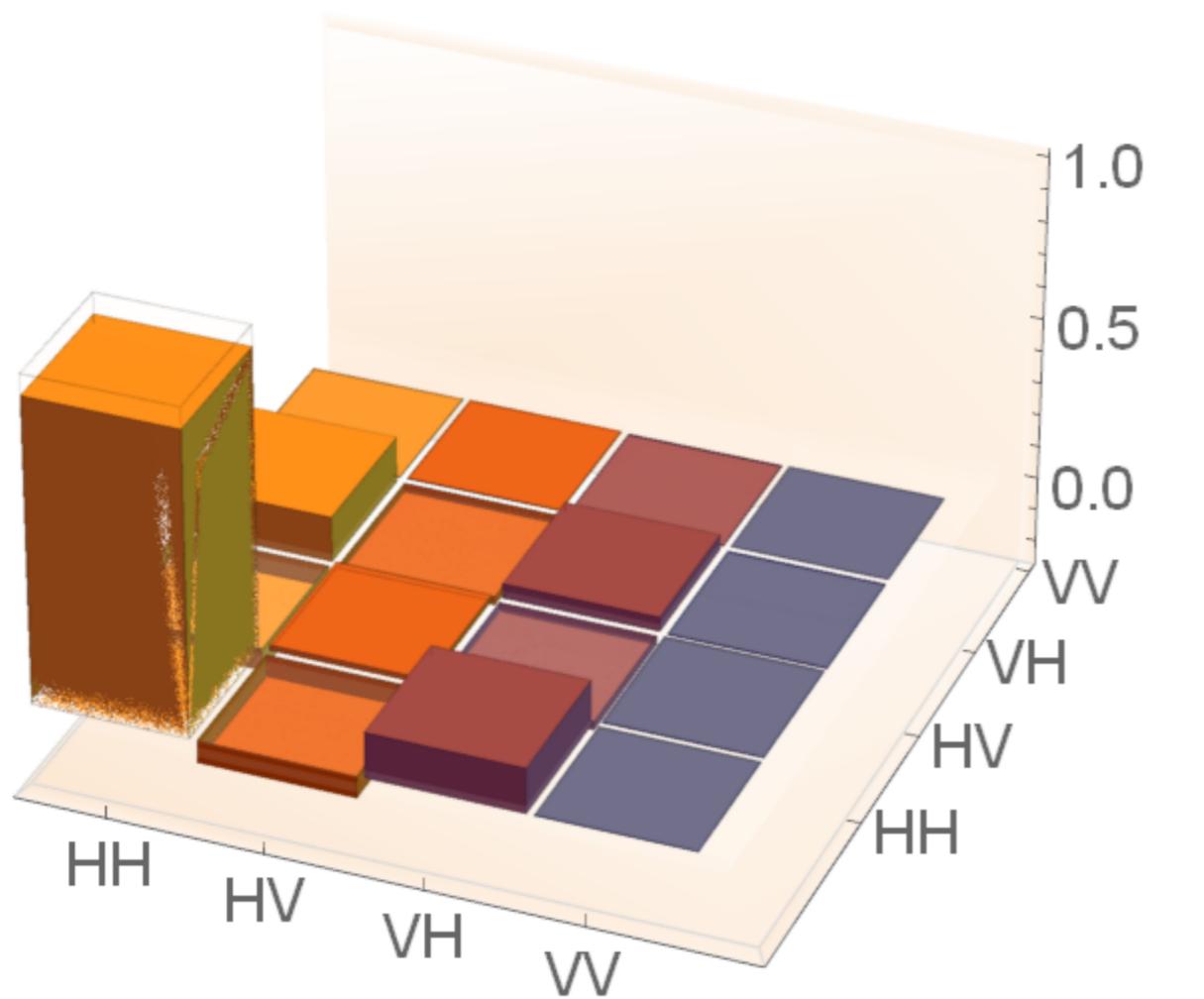
# A THEORY INDEPENDENT APPROACH

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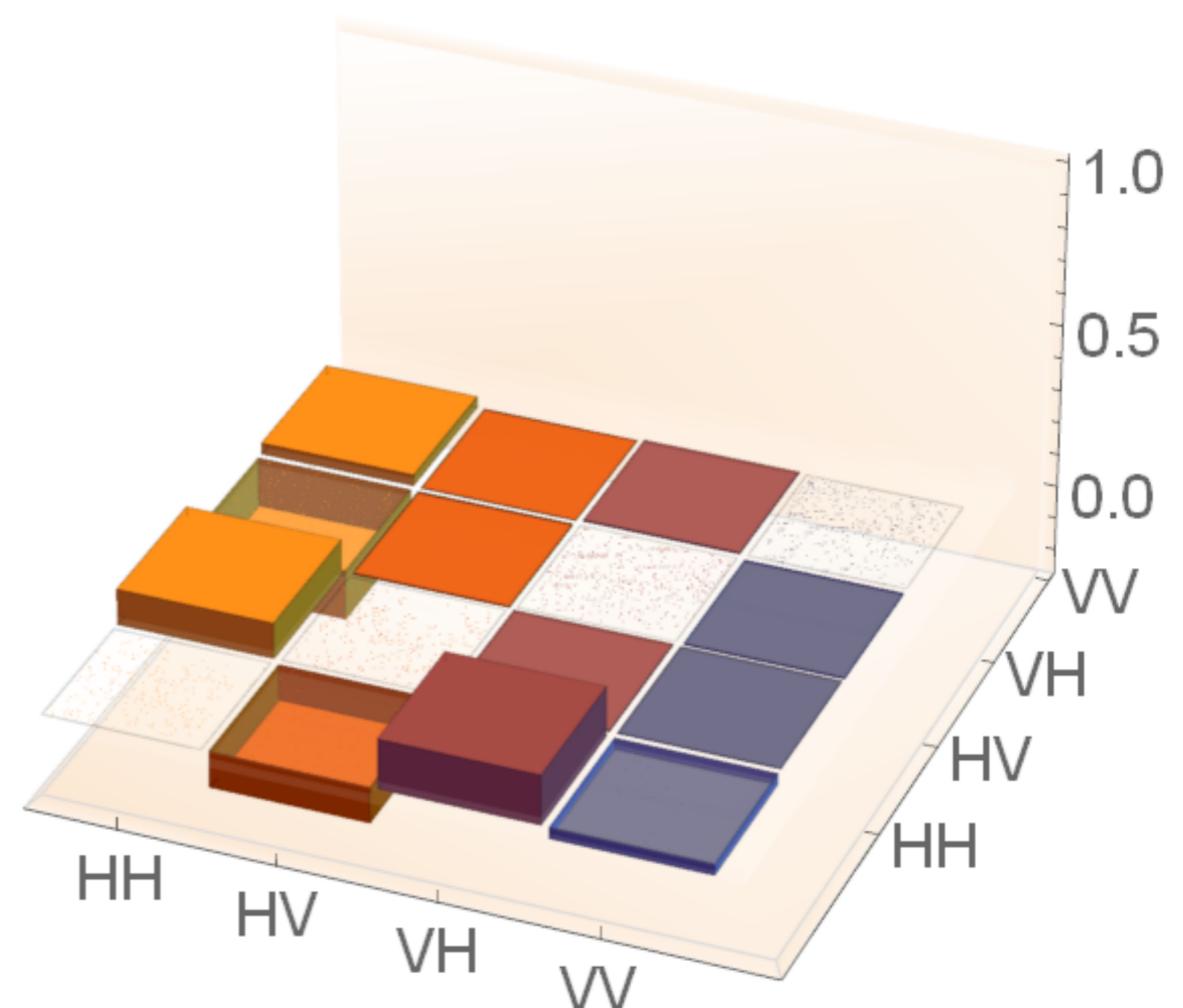
*Theorem.* No states, set of transformations and measurements which obey assumptions 1.-3. can result in violation of Bell's inequalities

## RESULTS - VERIFICATION OF ASSUMPTION 1.



$$\Re(\rho)$$

Fidelity =  $0.935 \pm 0.004$



$$\Im(\rho)$$

Concurrence =  $0.001 \pm 0.010$

## RESULTS - VERIFICATION OF ASSUMPTION 1.

---

Probabilities for measurement outcomes as measured on reduced states of target system of S1 and S2

$$p(o_1, o_2 | m_1, m_2, \omega_{1,2}^T) = p(o_1 | m_1, \omega_1^T) \cdot p(o_2 | m_2, \omega_2^T)$$

The probability for joint outcomes on the composite system of the two targets  $\omega_{1,2}^T$  in the initial state is *factorisable*

# RESULTS - VERIFICATION OF ASSUMPTION 1.

The distance between these two sets of probabilities is  $3.2 \cdot 10^{-2}$

Measur. Basis	$p(\omega_{1,2}^T)$	$p(\omega_{1,2^\perp}^T)$	$p(\omega_{1^\perp,2}^T)$	$p(\omega_{1^\perp,2^\perp}^T)$	$p(\omega_1^T)$ $\cdot p(\omega_2^T)$	$p(\omega_1^T)$ $\cdot p(\omega_{2^\perp}^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_2^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_{2^\perp}^T)$
H, H	0.99	0.03	0.00	0.00	1.00	0.03	0.00	0.00
H, V	0.01	0.97	0.00	0.00	0.01	0.95	0.00	0.00
H, A	0.56	0.41	0.00	0.00	0.55	0.39	0.00	0.00
H, D	0.43	0.59	0.00	0.00	0.45	0.61	0.00	0.00
H, R	0.39	0.62	0.00	0.00	0.40	0.63	0.00	0.00
H, L	0.60	0.38	0.00	0.00	0.59	0.37	0.00	0.00
V, H	0.00	0.00	0.97	0.04	0.00	0.00	0.98	0.04
V, V	0.00	0.00	0.03	0.96	0.00	0.00	0.03	0.95
V, A	0.00	0.00	0.63	0.39	0.00	0.00	0.64	0.40
V, D	0.00	0.00	0.37	0.61	0.00	0.00	0.37	0.59
V, R	0.00	0.00	0.34	0.63	0.00	0.00	0.33	0.62
V, L	0.00	0.00	0.66	0.37	0.00	0.00	0.68	0.38
A, H	0.33	0.01	0.48	0.02	0.27	0.01	0.40	0.01
A, V	0.01	0.30	0.02	0.47	0.01	0.24	0.01	0.38
Total	0.55	0.44	0.24	0.25	0.47	0.44	0.24	0.47

# RESULTS - VERIFICATION OF ASSUMPTION 1.

The distance between these two sets of probabilities is 0.13

Measur. Basis	$p(\omega_{1,2}^T)$	$p(\omega_{1,2^\perp}^T)$	$p(\omega_{1^\perp,2}^T)$	$p(\omega_{1^\perp,2^\perp}^T)$	$p(\omega_1^T)$ $\cdot p(\omega_2^T)$	$p(\omega_1^T)$ $\cdot p(\omega_{2^\perp}^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_2^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_{2^\perp}^T)$
H, H	0.02	0.50	0.44	0.04	0.24	0.28	0.22	0.26
H, V	0.43	0.04	0.04	0.49	0.23	0.25	0.24	0.28
V, V	0.02	0.47	0.48	0.04	0.24	0.24	0.26	0.26
V, H	0.41	0.03	0.04	0.52	0.19	0.25	0.25	0.31
R, H	0.24	0.38	0.22	0.17	0.28	0.33	0.18	0.21
R, V	0.32	0.30	0.17	0.21	0.30	0.32	0.18	0.19
D, V	0.18	0.33	0.30	0.19	0.24	0.26	0.24	0.26
D, H	0.24	0.28	0.23	0.25	0.24	0.28	0.22	0.25
D, R	0.31	0.21	0.30	0.18	0.32	0.20	0.30	0.19
D, D	0.47	0.03	0.03	0.47	0.25	0.25	0.25	0.25
R, D	0.30	0.32	0.20	0.18	0.31	0.31	0.19	0.19
H, D	0.28	0.24	0.24	0.24	0.27	0.25	0.25	0.23
V, D	0.20	0.26	0.31	0.23	0.24	0.23	0.27	0.26
V, L	0.16	0.31	0.20	0.33	0.17	0.30	0.19	0.34
H, L	0.20	0.30	0.16	0.35	0.18	0.32	0.18	0.33

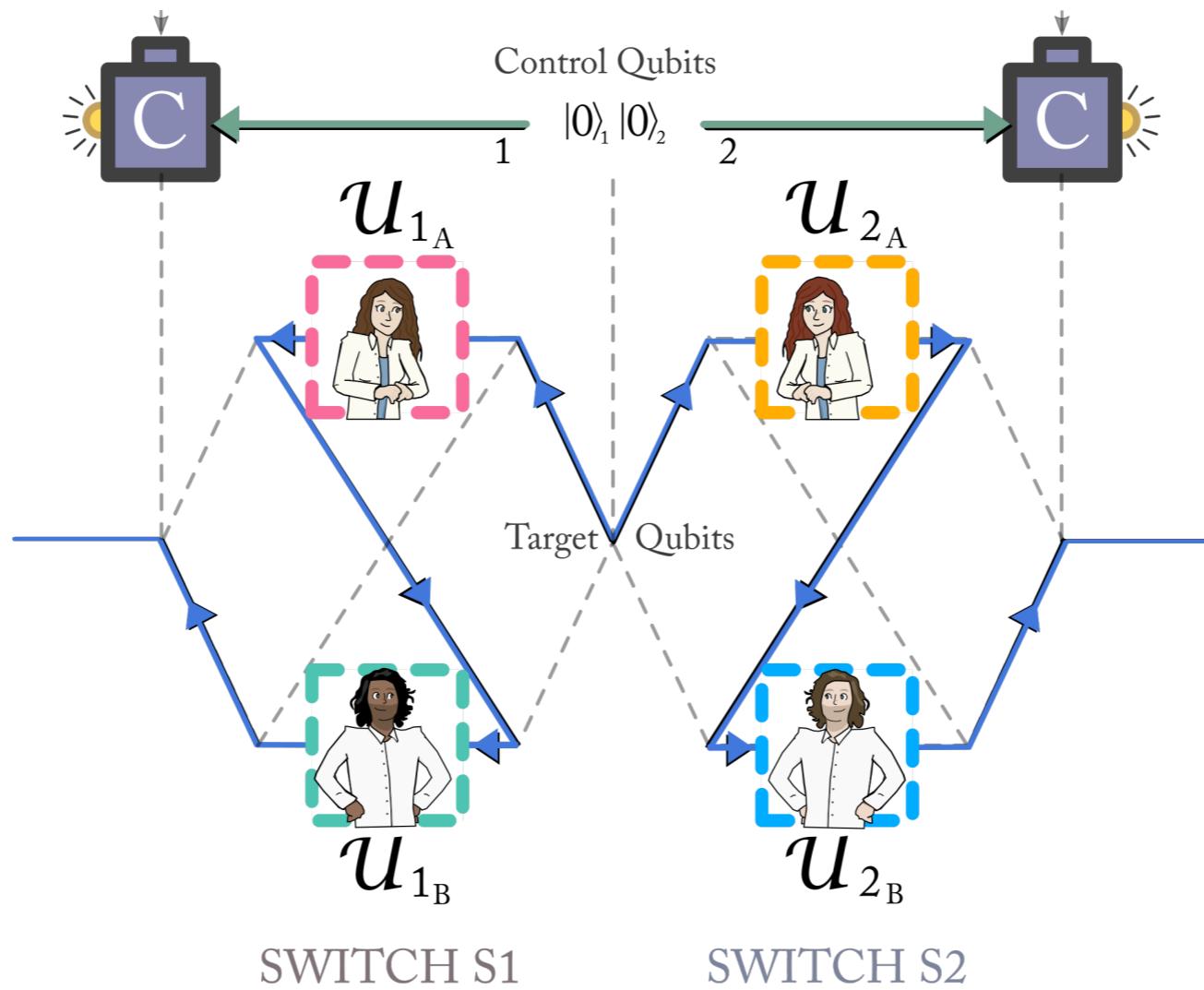
## RESULTS - VERIFICATION OF ASSUMPTION 2.

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1. The initial joint state of the target system is *local* (i.e., it does not violate a Bell inequality).
  
2. The laboratory operations are represented as *local transformations* of the target systems in the GPTs (i.e., they do not increase the “amount of a violation” of Bell inequalities between the target systems).
  
3. The order of operations is pre-defined.

*Theorem.* No states, set of transformations and measurements which obey assumptions 1.-3. can result in violation of Bell’s inequalities

# RESULTS - VERIFICATION OF ASSUMPTION 2.



⇒ Final state:

$$\frac{1}{\sqrt{2}} \left( \cancel{|L\rangle_1^T |L\rangle_2^T} - |R\rangle_1^T |R\rangle_2^T \right)$$

# RESULTS – VERIFICATION OF ASSUMPTION 2.

Measur. Basis	$p(\omega_{1,2}^T)$	$p(\omega_{1,2^\perp}^T)$	$p(\omega_{1^\perp,2}^T)$	$p(\omega_{1^\perp,2^\perp}^T)$	$p(\omega_1^T)$ $\cdot p(\omega_2^T)$	$p(\omega_1^T)$ $\cdot p(\omega_{2^\perp}^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_2^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_{2^\perp}^T)$
H, H	0.23	0.24	0.25	0.27	0.23	0.25	0.25	0.27
H, V	0.25	0.23	0.28	0.25	0.25	0.23	0.27	0.25
V, V	0.24	0.23	0.28	0.26	0.24	0.22	0.28	0.26
V, H	0.21	0.23	0.27	0.29	0.21	0.23	0.27	0.29
R, H	0.48	0.50	0.01	0.01	0.48	0.50	0.01	0.01
R, V	0.51	0.47	0.01	0.01	0.51	0.47	0.01	0.01
D, V	0.25	0.23	0.27	0.25	0.25	0.23	0.27	0.25
D, H	0.24	0.24	0.25	0.27	0.24	0.25	0.25	0.26
D, R	0.47	0.02	0.50	0.02	0.47	0.02	0.50	0.02
D, D	0.25	0.23	0.27	0.25	0.25	0.23	0.27	0.25
R, D	0.51	0.46	0.01	0.01	0.51	0.46	0.01	0.01
H, D	0.24	0.23	0.27	0.26	0.24	0.23	0.27	0.26
V, D	0.24	0.21	0.29	0.26	0.24	0.22	0.29	0.26
V, L	0.01	0.44	0.01	0.54	0.01	0.44	0.01	0.54
H, L	0.01	0.47	0.01	0.51	0.01	0.47	0.01	0.51
R, L	0.02	0.96	0.00	0.02	0.02	0.96	0.00	0.02

# RESULTS - VERIFICATION OF ASSUMPTION 2.

The distance between these two sets of probabilities is  $1.6 \cdot 10^{-2}$

Measur. Basis	$p(\omega_{1,2}^T)$	$p(\omega_{1,2^\perp}^T)$	$p(\omega_{1^\perp,2}^T)$	$p(\omega_{1^\perp,2^\perp}^T)$	$p(\omega_1^T)$ $\cdot p(\omega_2^T)$	$p(\omega_1^T)$ $\cdot p(\omega_{2^\perp}^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_2^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_{2^\perp}^T)$
H, H	0.23	0.24	0.25	0.27	0.23	0.25	0.25	0.27
H, V	0.25	0.23	0.28	0.25	0.25	0.23	0.27	0.25
V, V	0.24	0.23	0.28	0.26	0.24	0.22	0.28	0.26
V, H	0.21	0.23	0.27	0.29	0.21	0.23	0.27	0.29
R, H	0.48	0.50	0.01	0.01	0.48	0.50	0.01	0.01
R, V	0.51	0.47	0.01	0.01	0.51	0.47	0.01	0.01
D, V	0.25	0.23	0.27	0.25	0.25	0.23	0.27	0.25
D, H	0.24	0.24	0.25	0.27	0.24	0.25	0.25	0.26
D, R	0.47	0.02	0.50	0.02	0.47	0.02	0.50	0.02
D, D	0.25	0.23	0.27	0.25	0.25	0.23	0.27	0.25
R, D	0.51	0.46	0.01	0.01	0.51	0.46	0.01	0.01
H, D	0.24	0.23	0.27	0.26	0.24	0.23	0.27	0.26
V, D	0.24	0.21	0.29	0.26	0.24	0.22	0.29	0.26
V, L	0.01	0.44	0.01	0.54	0.01	0.44	0.01	0.54
H, L	0.01	0.47	0.01	0.51	0.01	0.47	0.01	0.51

# RESULTS - VERIFICATION OF ASSUMPTION 2.

Measur. Basis	$p(\omega_{1,2}^T)$	$p(\omega_{1,2^\perp}^T)$	$p(\omega_{1^\perp,2}^T)$	$p(\omega_{1^\perp,2^\perp}^T)$	$p(\omega_1^T)$ $\cdot p(\omega_2^T)$	$p(\omega_1^T)$ $\cdot p(\omega_{2^\perp}^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_2^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_{2^\perp}^T)$
H, H	0.31	0.23	0.26	0.20	0.31	0.23	0.26	0.20
H, V	0.27	0.27	0.23	0.23	0.26	0.27	0.23	0.23
V, V	0.23	0.24	0.26	0.27	0.23	0.24	0.26	0.27
V, H	0.28	0.21	0.29	0.22	0.28	0.21	0.29	0.22
R, H	0.02	0.01	0.54	0.44	0.02	0.01	0.54	0.43
R, V	0.01	0.01	0.49	0.49	0.01	0.01	0.49	0.49
D, V	0.26	0.27	0.23	0.24	0.26	0.27	0.23	0.24
D, H	0.31	0.23	0.26	0.20	0.30	0.24	0.26	0.20
D, R	0.02	0.50	0.02	0.46	0.02	0.51	0.02	0.45
D, D	0.28	0.24	0.26	0.21	0.29	0.24	0.26	0.22
R, D	0.01	0.01	0.54	0.44	0.01	0.01	0.54	0.44
H, D	0.31	0.24	0.24	0.21	0.31	0.24	0.25	0.20
V, D	0.28	0.21	0.28	0.23	0.27	0.22	0.28	0.23
V, L	0.47	0.02	0.50	0.02	0.47	0.02	0.50	0.02
H, L	0.52	0.02	0.44	0.02	0.52	0.02	0.44	0.02
R, L	0.03	0.00	0.93	0.04	0.03	0.00	0.93	0.04

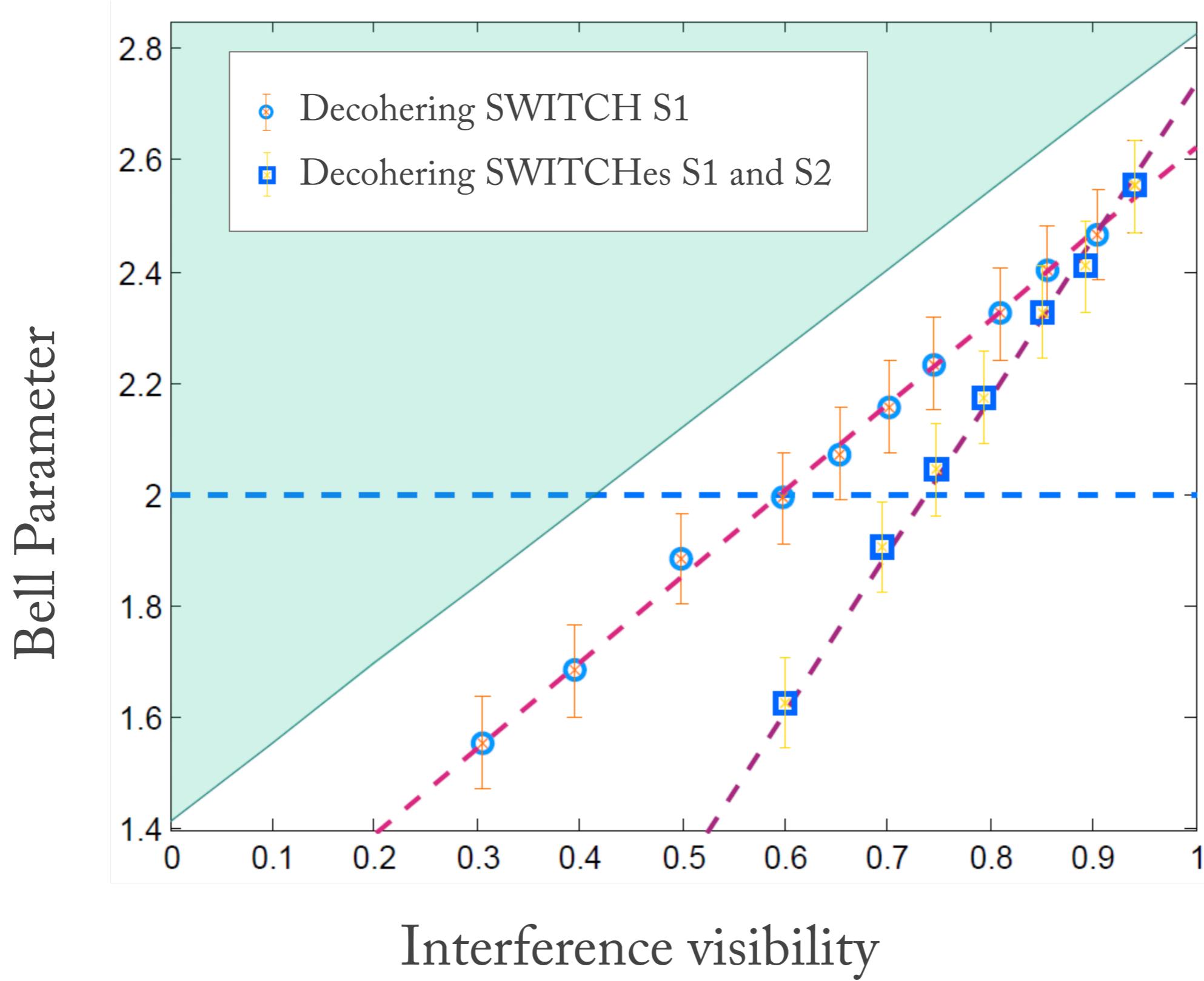
# RESULTS - VERIFICATION OF ASSUMPTION 2.

The distance between these two sets of probabilities is  $3.0 \cdot 10^{-2}$

Measur. Basis	$p(\omega_{1,2}^T)$	$p(\omega_{1,2^\perp}^T)$	$p(\omega_{1^\perp,2}^T)$	$p(\omega_{1^\perp,2^\perp}^T)$	$p(\omega_1^T)$ $\cdot p(\omega_2^T)$	$p(\omega_1^T)$ $\cdot p(\omega_{2^\perp}^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_2^T)$	$p(\omega_{1^\perp}^T)$ $\cdot p(\omega_{2^\perp}^T)$
H, H	0.31	0.23	0.26	0.20	0.31	0.23	0.26	0.20
H, V	0.27	0.27	0.23	0.23	0.26	0.27	0.23	0.23
V, V	0.23	0.24	0.26	0.27	0.23	0.24	0.26	0.27
V, H	0.28	0.21	0.29	0.22	0.28	0.21	0.29	0.22
R, H	0.02	0.01	0.54	0.44	0.02	0.01	0.54	0.43
R, V	0.01	0.01	0.49	0.49	0.01	0.01	0.49	0.49
D, V	0.26	0.27	0.23	0.24	0.26	0.27	0.23	0.24
D, H	0.31	0.23	0.26	0.20	0.30	0.24	0.26	0.20
D, R	0.02	0.50	0.02	0.46	0.02	0.51	0.02	0.45
D, D	0.28	0.24	0.26	0.21	0.29	0.24	0.26	0.22
R, D	0.01	0.01	0.54	0.44	0.01	0.01	0.54	0.44
H, D	0.31	0.24	0.24	0.21	0.31	0.24	0.25	0.20
V, D	0.28	0.21	0.28	0.23	0.27	0.22	0.28	0.23
V, L	0.47	0.02	0.50	0.02	0.47	0.02	0.50	0.02
H, L	0.52	0.02	0.44	0.02	0.52	0.02	0.44	0.02

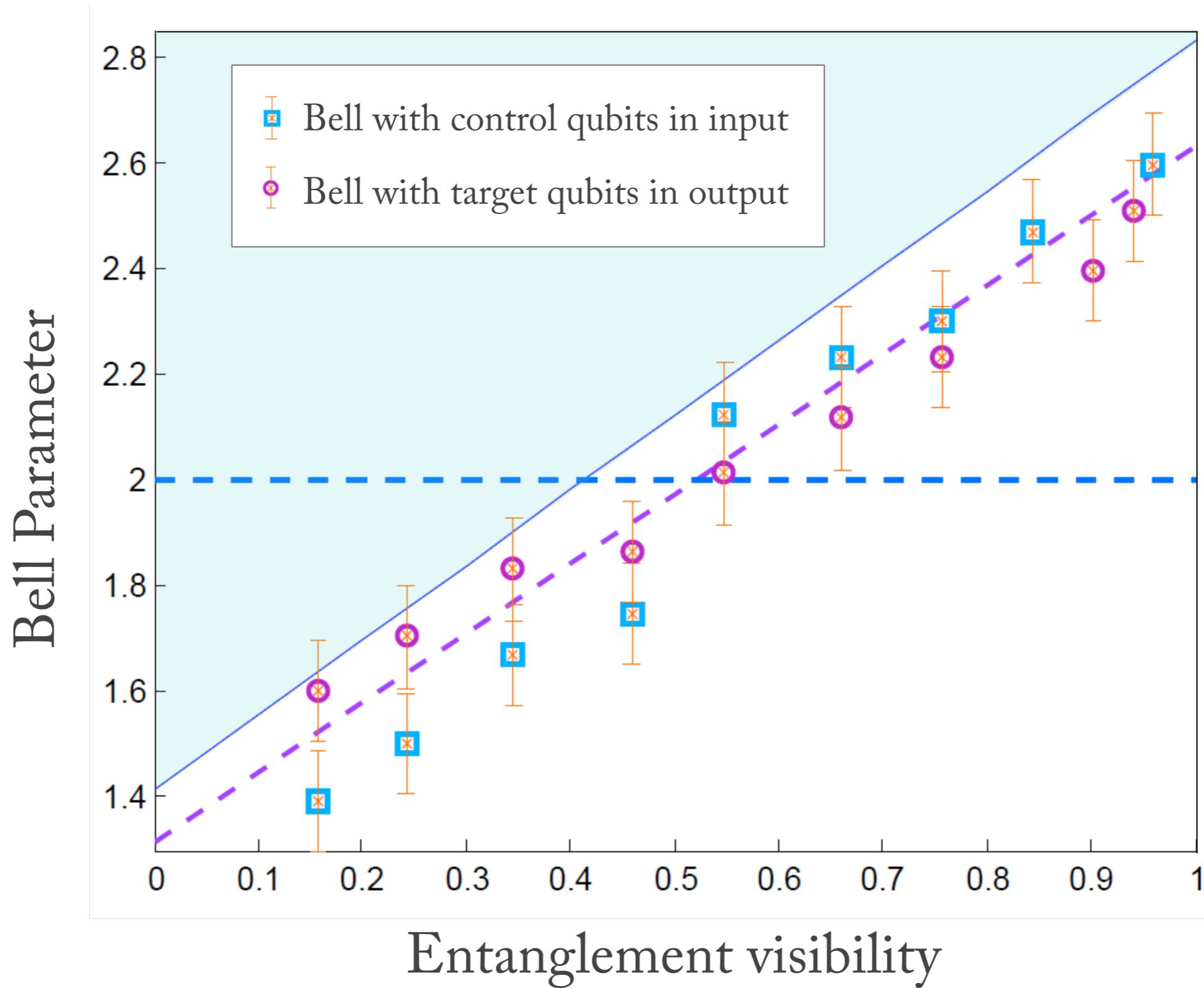
# RESULTS - PRESENCE OF NOISE IN THE SWITCH

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# RESULTS - PRESENCE OF NOISE IN THE SOURCE



## CONCLUSION AND OUTLOOK

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First demonstration of a process that is incompatible with a large class of theories which are *local* and have a *definite temporal order*



*Entangled quantum SWITCH*

What's next?

- Scaling up the number of parties
- Perform more complex operations on the control qubit

# **THANKS FOR YOUR ATTENTION**

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