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Quantum Information Lab
Dipartimento di Fisica, Università di Roma La Sapienza

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Quantum causality: Violation of bilocality and instrumental test

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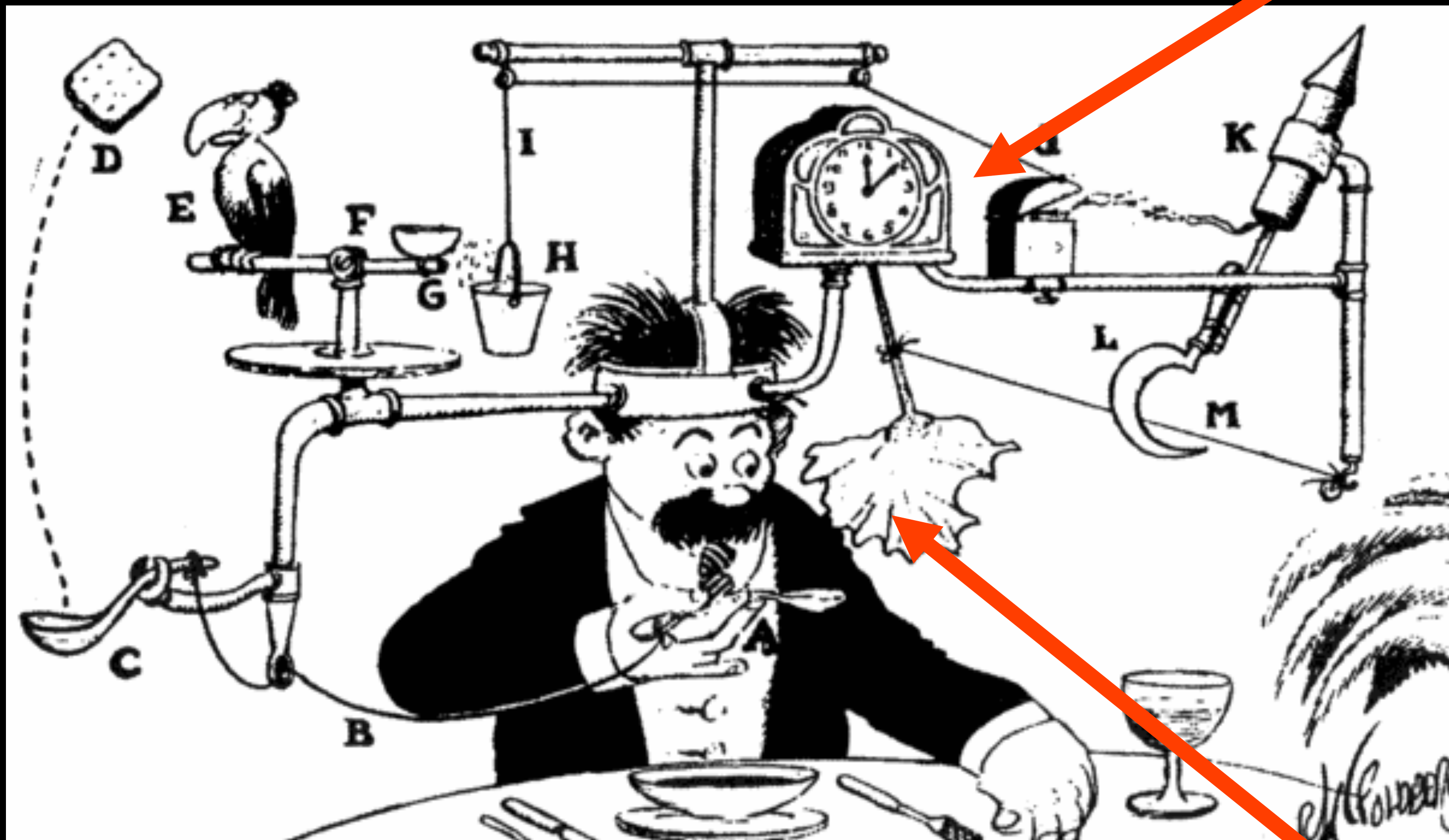
Quantum Information Lab
Sapienza, Università di Roma
www.quantumlab.it

3D-QUEST

Causal inference

Causal explanation

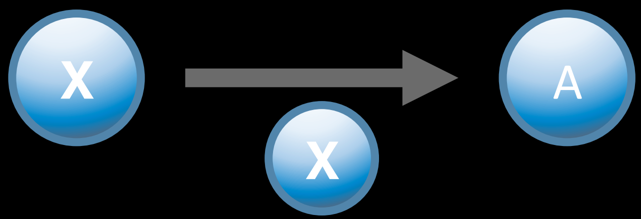


Observed data

Quantum Nonlocality from a Causal Inference Perspective

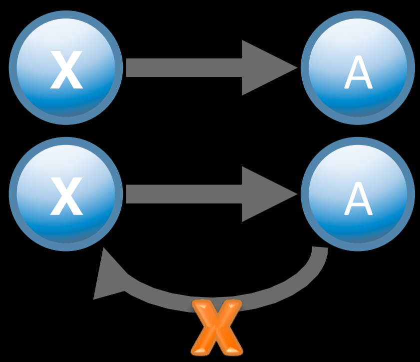
Classical Causal Structures

- For n variables $X_1, \ldots, X_n$, the causal relationships are encoded in a causal structure, represented by a directed acyclic graph (**DAG**).



Nodes of graph

- event: random variable X (A) acquires a precise value



Directed graph

- arrow: causal relation between two variables

Acyclic graph

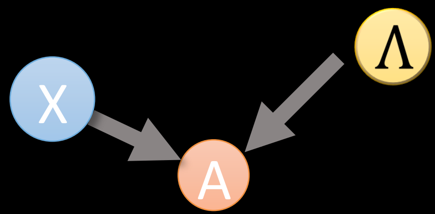
- closed cycle are not allowed (relativistic causality)

Quantum Nonlocality from a Causal Inference Perspective

Classical Causal Structures

- For n variables $X_1, \ldots, X_n$, the causal relationships are encoded in a causal structure, represented by a directed acyclic graph (<u>**DAG**</u>).

- Causal relationships are encoded in the conditional independencies implied by the DAG:

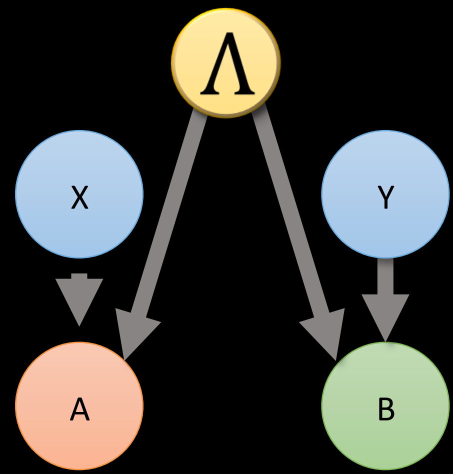


$$p(a|b,x,y,\lambda) = \boxed{p(a|x,\lambda)}$$
$$p(b|a,x,y,\lambda) = p(b|y,\lambda)$$

GOAL: to disregard some classical causal structures from observational (statistical) data.

…more in general: to infer causal relationships

Directed Acyclic Graph associated to Bell inequalities



Nodes: ***relevant random variables in the network***

Arrows: ***causal relations***

Directed Acyclic Graph associated to Bell inequalities

- Alice and Bob measure two possible observables each: A_0, A_1, B_0, B_1

- After sufficiently many repetitions they can estimate statistical quantities. The experiment can be described in terms of $p(a,b|x,y)$

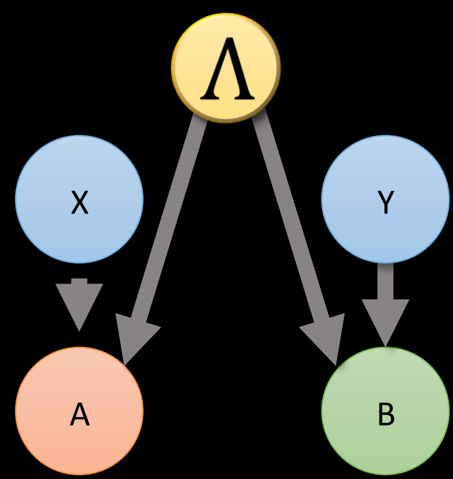
- There are two causal assumptions.

Measurement Independence:

$$p(x,y,\lambda) = p(x)p(y)p(\lambda)$$

Locality:

$$p(b|a,x,y,\lambda) = p(b|y,\lambda)$$

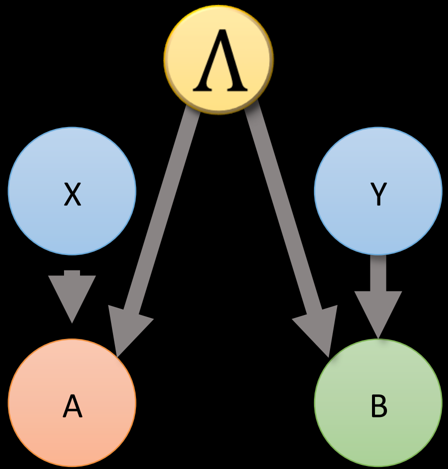


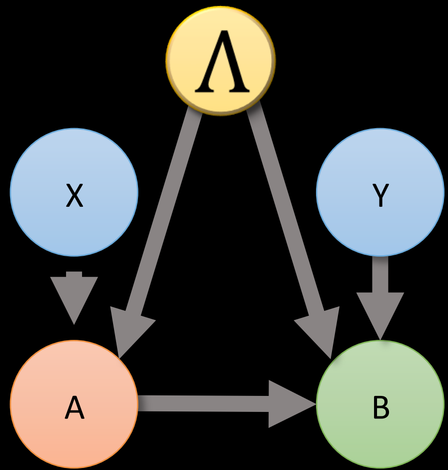
Nodes: ***relevant random variables in the network***

Arrows: ***causal relations***

Quantum Non-locality from a Causal Inference Perspective

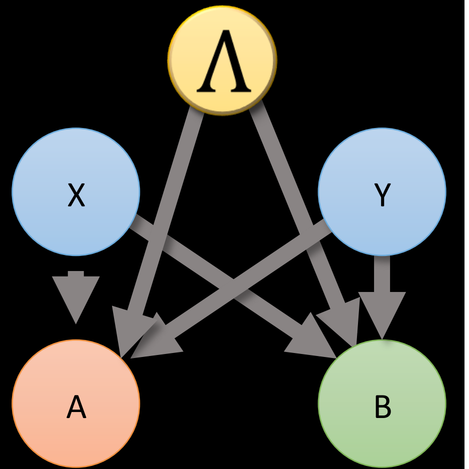
- Alternative causal structures can easily be represented with the graphical notation of directed acyclic graph





$$p(a|b,x,y,\lambda) = p(a|x,\lambda)$$

$$p(b|a,x,y,\lambda) = p(b|a,y,\lambda)$$

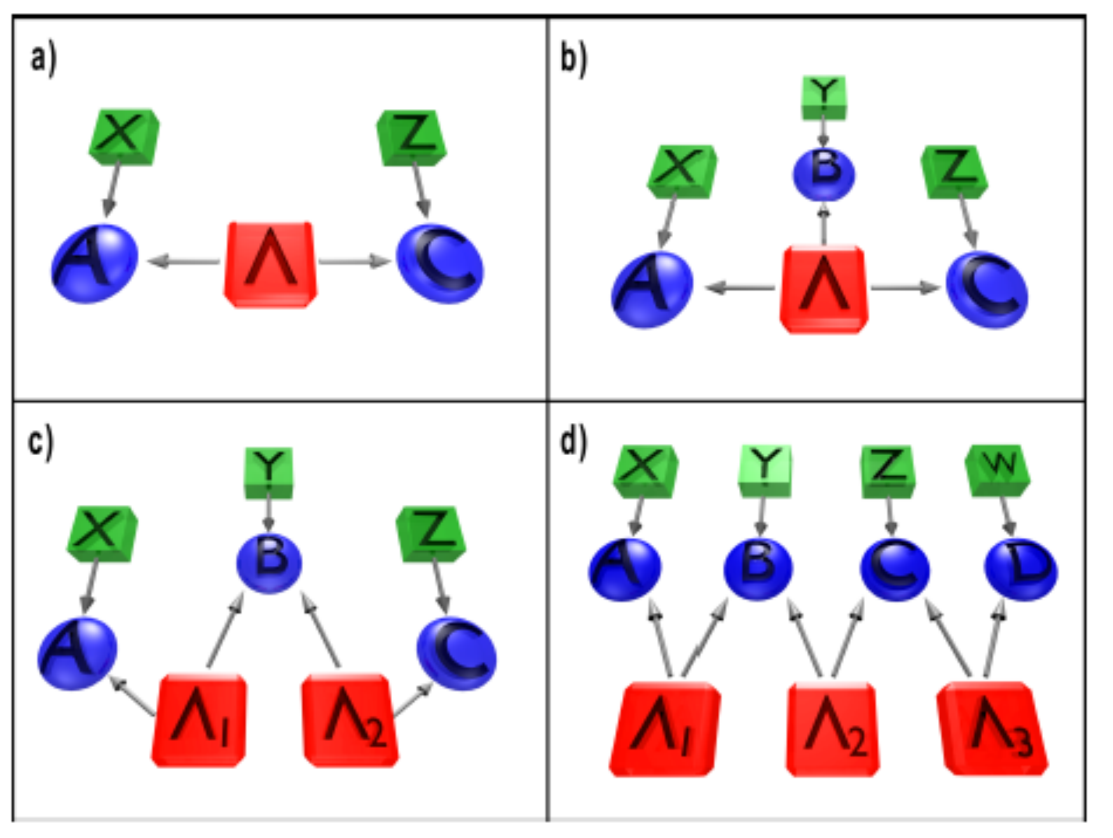


$$p(a|b,x,y,\lambda) = p(a|x,y,\lambda)$$

$$p(b|a,x,y,\lambda) = p(b|x,y,\lambda)$$

M.Ringbauer, C. Giarmatzi, R. Chaves, F. Costa, A-G. White, and A. Fedrizzi, *Science Advances* **2**, e1600162 (2016)

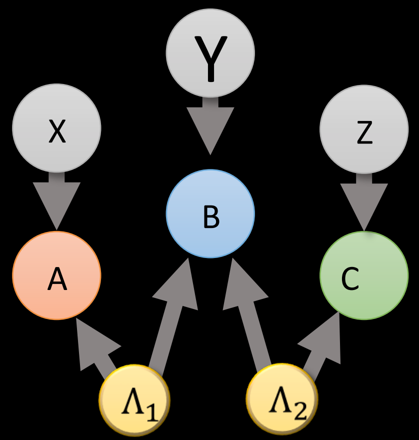
Representation of the causal structures underlying the networks as directed acyclic graphs



To generalize Bell's theorem to more complex networks

C. Branciard, D. Rosset, N. Gisin, and S. Pironio, *Phys. Rev. A*,85:032119 (2012)
Branciard, C., Gisin, N. & Pironio, S. *Phys. Rev. Lett.* 104, 170401 (2010).
Chaves, R., Kueng, R., Brask, J. B. & Gross, D. *Phys. Rev. Lett.* **114**, 140403 (2015).

Non-localiy in a tripartite scenario with two independent sources



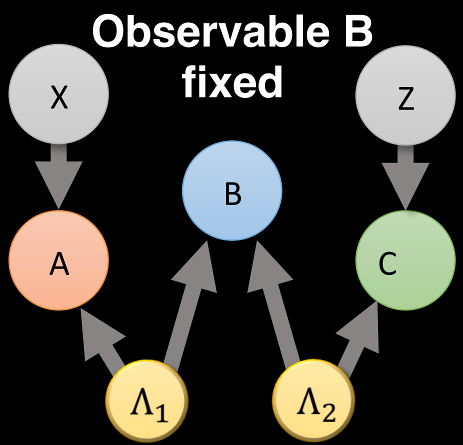
Correlation between distant parties mediated by two independent sources

Bilocal Hidden Variable (BLHV) Model

$$p(a,b,c|x,y,z) = \int d\lambda_1 d\lambda_2 \; \boxed{\rho_1(\lambda_1)\rho_2(\lambda_2)} p(a|x,\lambda_1)p(b|y,\lambda_1,\lambda_2)p(c|z,\lambda_2)$$

C. Branciard, D. Rosset, N. Gisin, and S. Pironio, *Phys. Rev. A*,85:032119 (2012)
Branciard, C., Gisin, N. & Pironio, S. Phys. Rev. Lett. 104, 170401 (2010).
Tavakoli, A., Skrzypczyk, P., Cavalcanti, D. & Acín, A. Phys. Rev. A 90, 062109 (2014).
Chaves, R., Kueng, R., Brask, J. B. & Gross, D. Phys. Rev. Lett. 114, 140403 (2015).
Chaves, R. Phys. Rev. Lett. 116, 010402 (2016).
Rosset, D. et al. Phys. Rev. Lett. 116, 010403 (2016).

Bilocality inequality



$b = b_0 b_1 \qquad b_0, b_1 = 0{,}1$

$x, z = 0{,}1 \quad$ e $\quad a, b = 0{,}1$

$\longrightarrow$ $p(a, b_0 b_1, c|x, z)$

$$\langle A_x B_y C_z \rangle = \sum_{a,b,c} (-1)^{a+b_y+c} p(a, b_0 b_1, c|x, z)$$

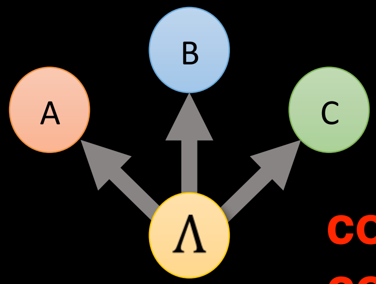
$$I = \frac{1}{4} \sum_{x,z=0,1} \langle A_x B_0 C_z \rangle \qquad J = \frac{1}{4} \sum_{x,z=0,1} (-1)^{x+z} \langle A_x B_1 C_z \rangle$$

Polynomial Bell inequality

$$\mathfrak{B} \equiv \sqrt{|I|} + \sqrt{|J|} \leq \mathbf{1}$$

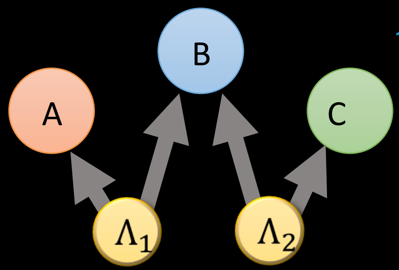
C. Branciard, D. Rosset, N. Gisin, and S. Pironio, *Phys. Rev. A* 85:032119 (2012)

Locality versus bilocality



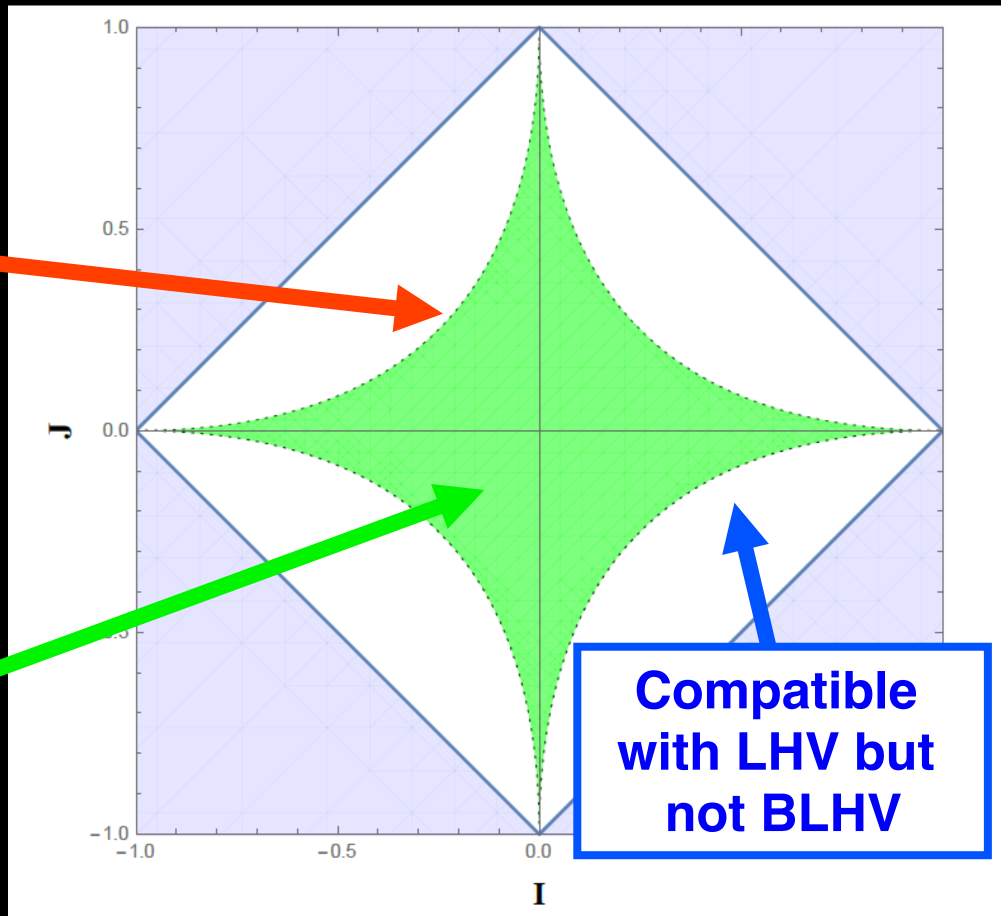
$$|I| + |J| \leq 1$$

convex set of correlations

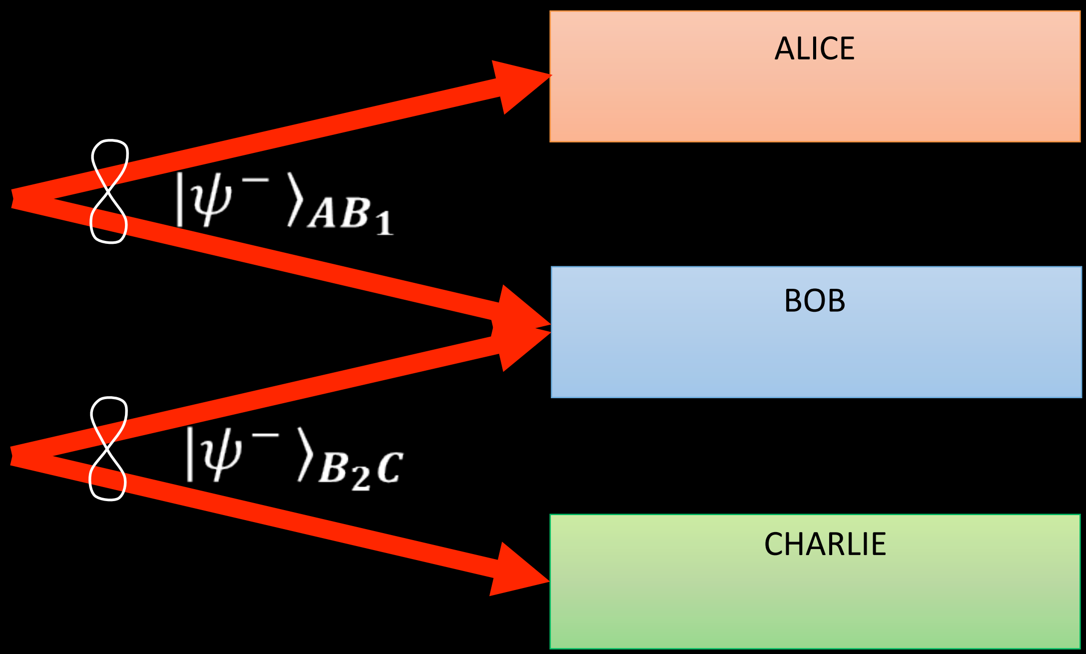


$$\sqrt{|I|} + \sqrt{|J|} \leq 1$$

non-convex set of correlations



How to violate bilocality?
Entanglement swapping scenario



A_0 $(\sigma_z + \sigma_x)/\sqrt{2}$

A_1 $(\sigma_z - \sigma_x)/\sqrt{2}$

$a = 0, 1$

Fixed measurement: Bell states

$b = b_0 b_1$

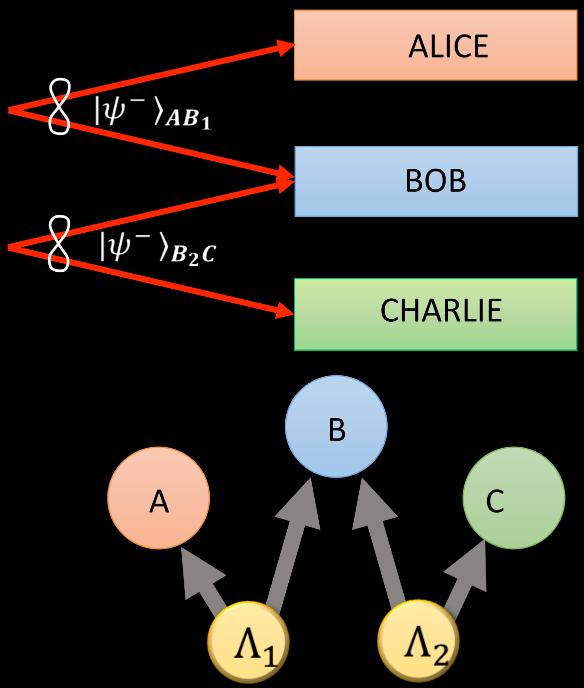
$b_0, b_1 = 0,1$

C_0 $(\sigma_z + \sigma_x)/\sqrt{2}$

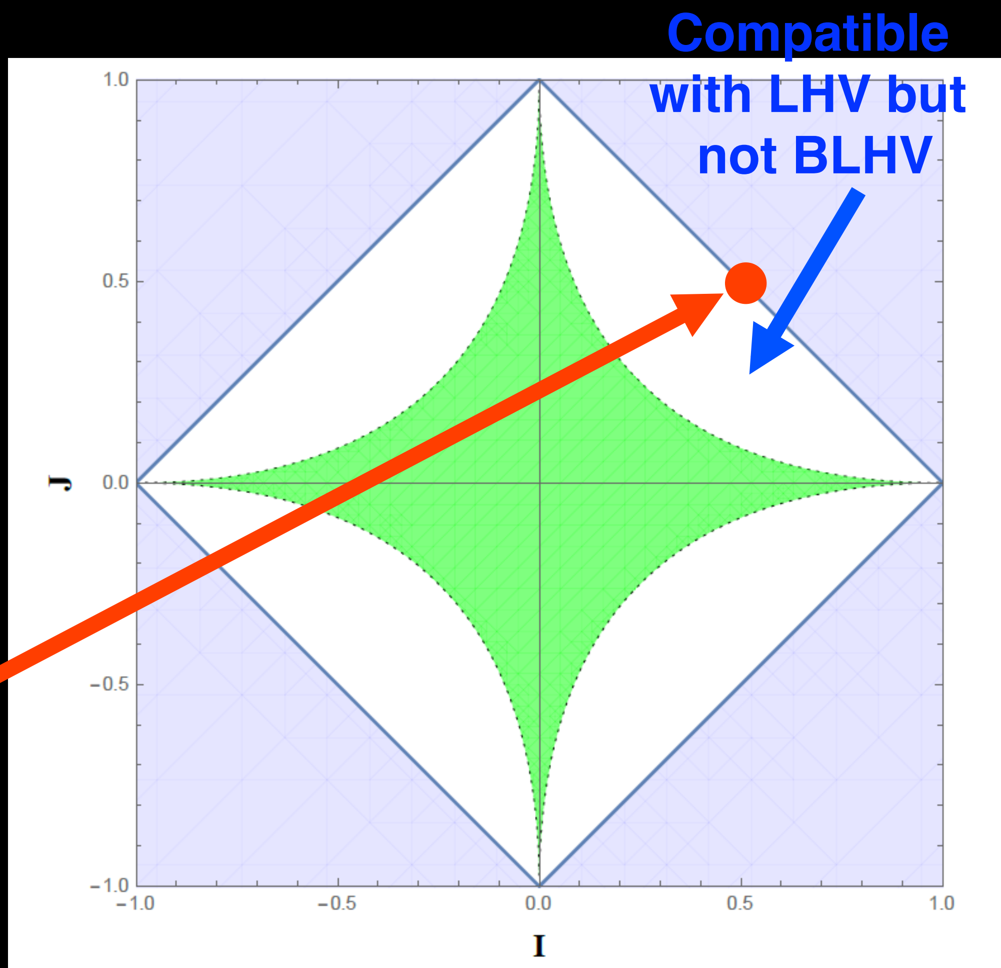
C_1 $(\sigma_z - \sigma_x)/\sqrt{2}$

$b = 0, 1$

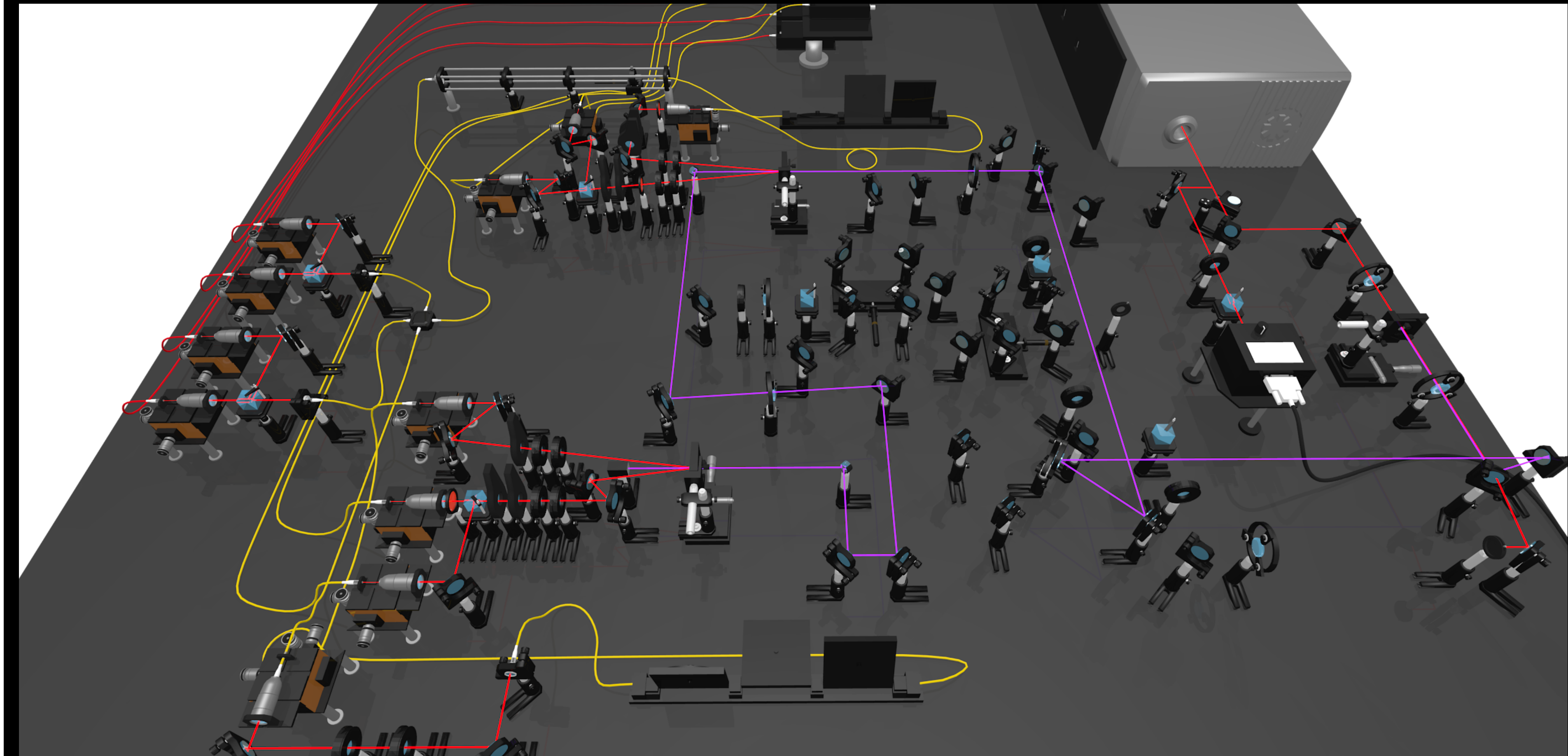
Violation of bilocality via entanglement swapping

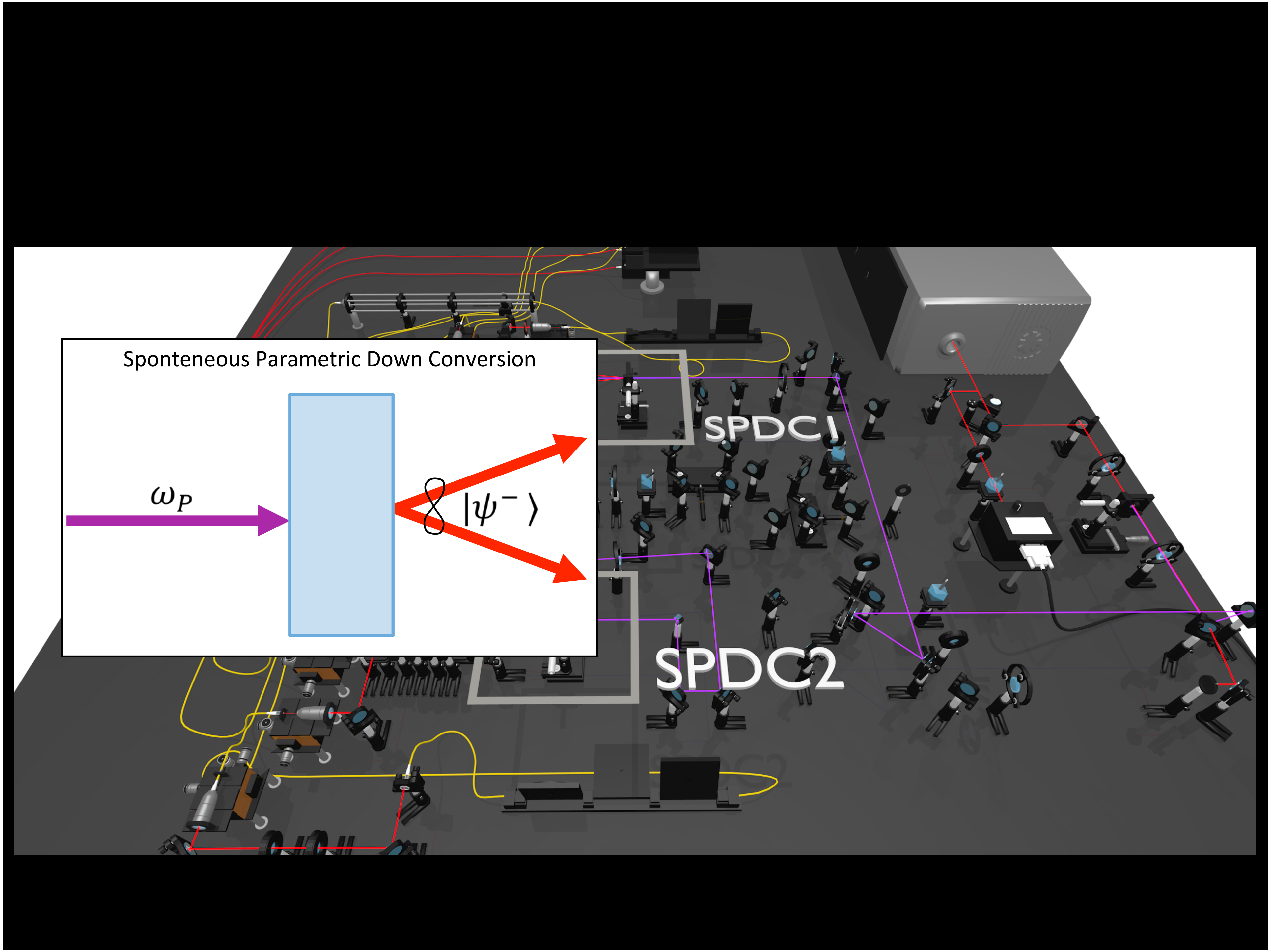


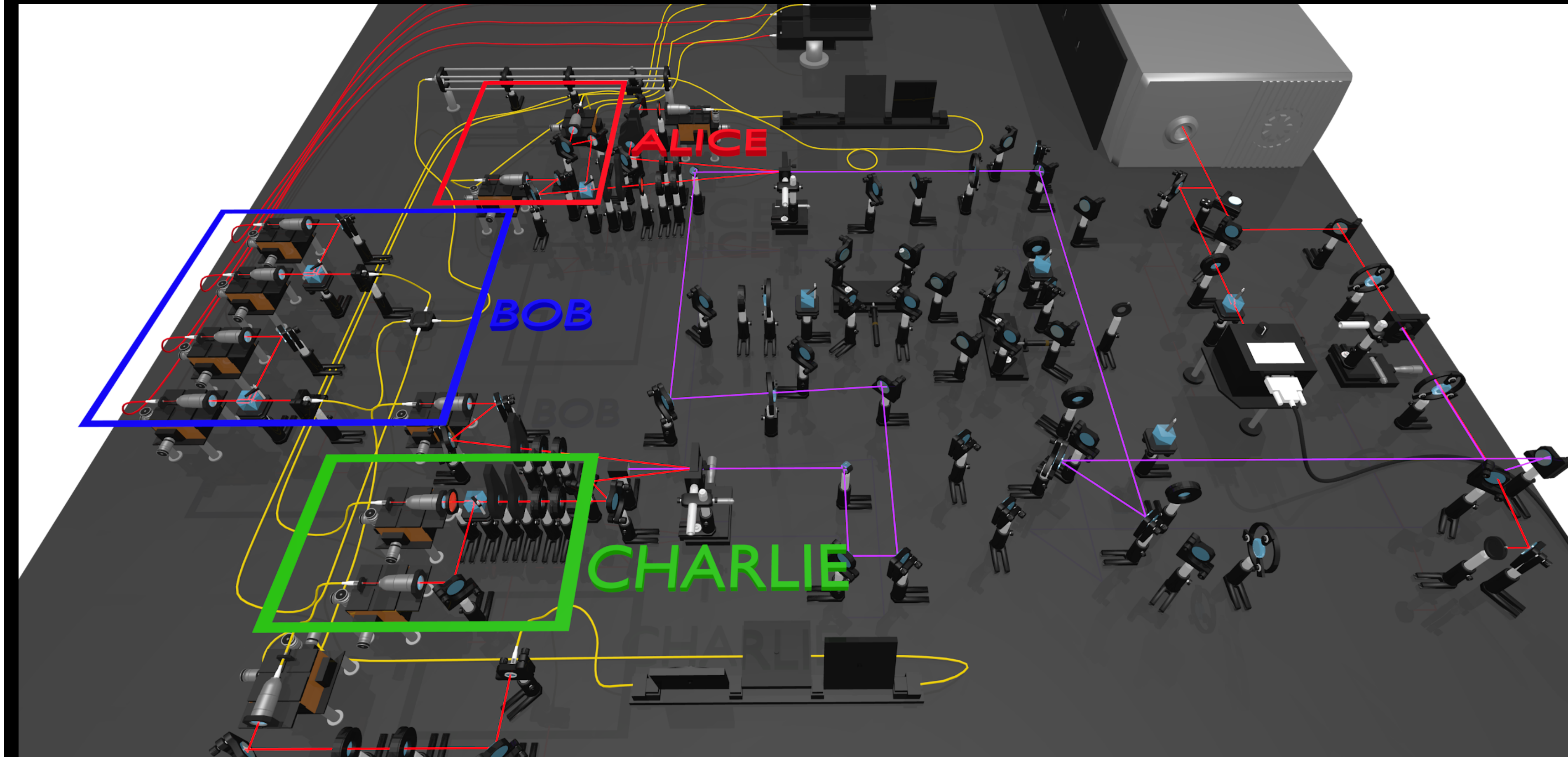
$$\mathfrak{B}_{QM} = 1.41 > 1$$



Our goal: to experimentally observe non-locality in a quantum network

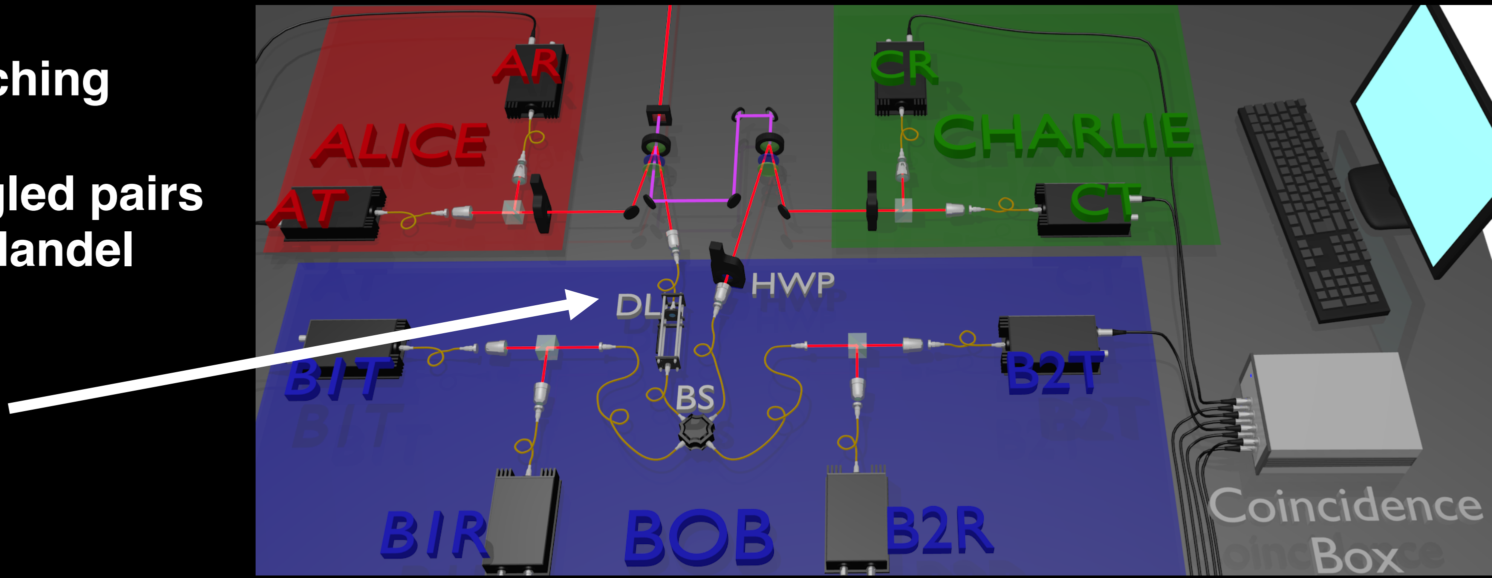



Sponteneous Parametric Down Conversion
ω_P
$|\psi^-\rangle$
SPDC1
SPDC2


ALICE
BOB
CHARLIE

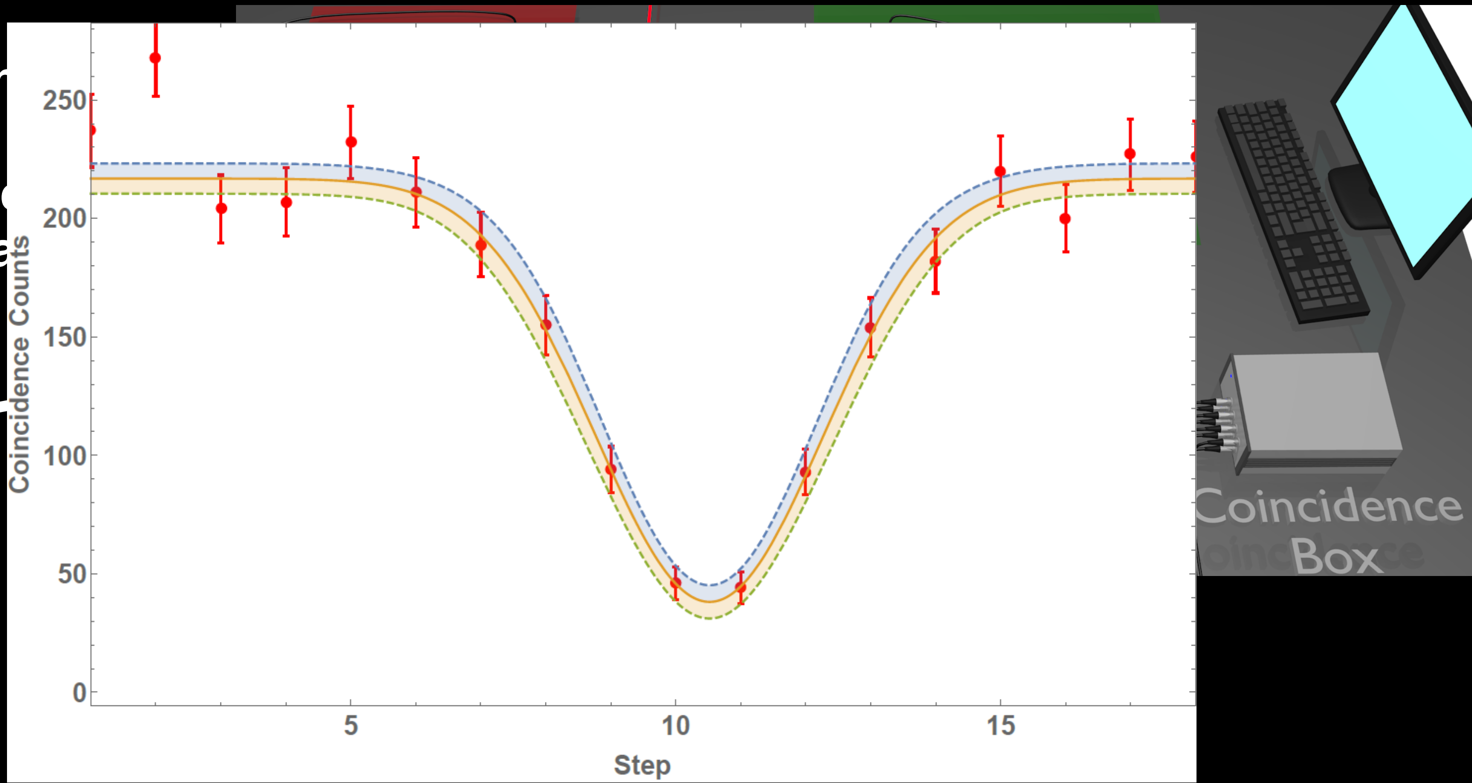
Optimization of the setup

Temporal matching between
the two entangled pairs
via Hong-Ou-Mandel effect

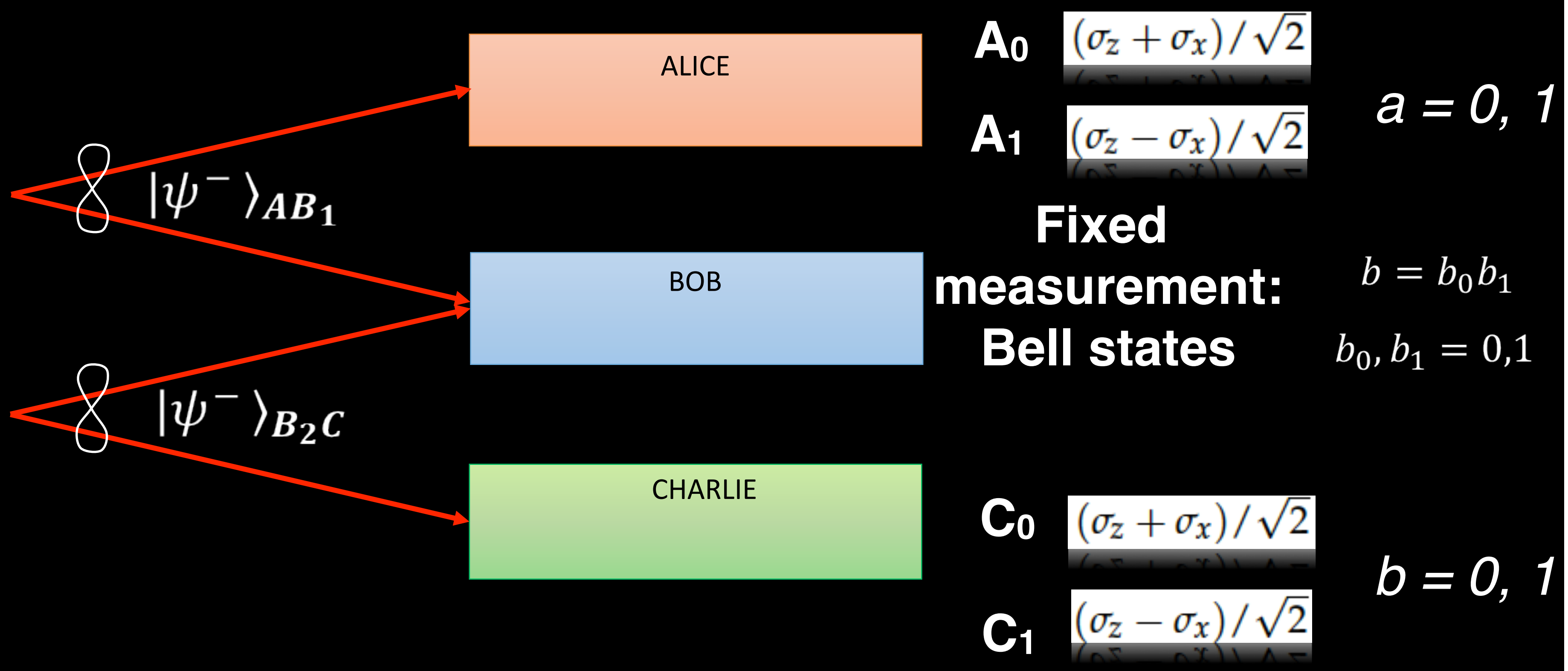


Optimization of the setup

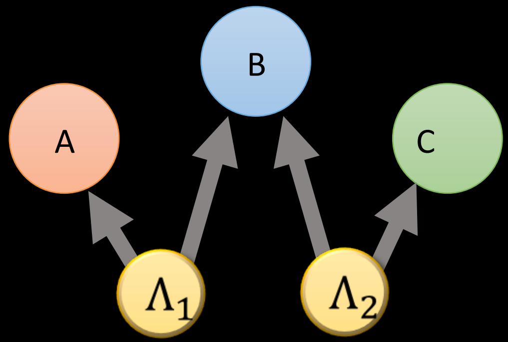
Temporal match
between
the two entangl
via Hong-Ou-Ma
effect



Experimental bilocality violation in an entanglement swapping scenario

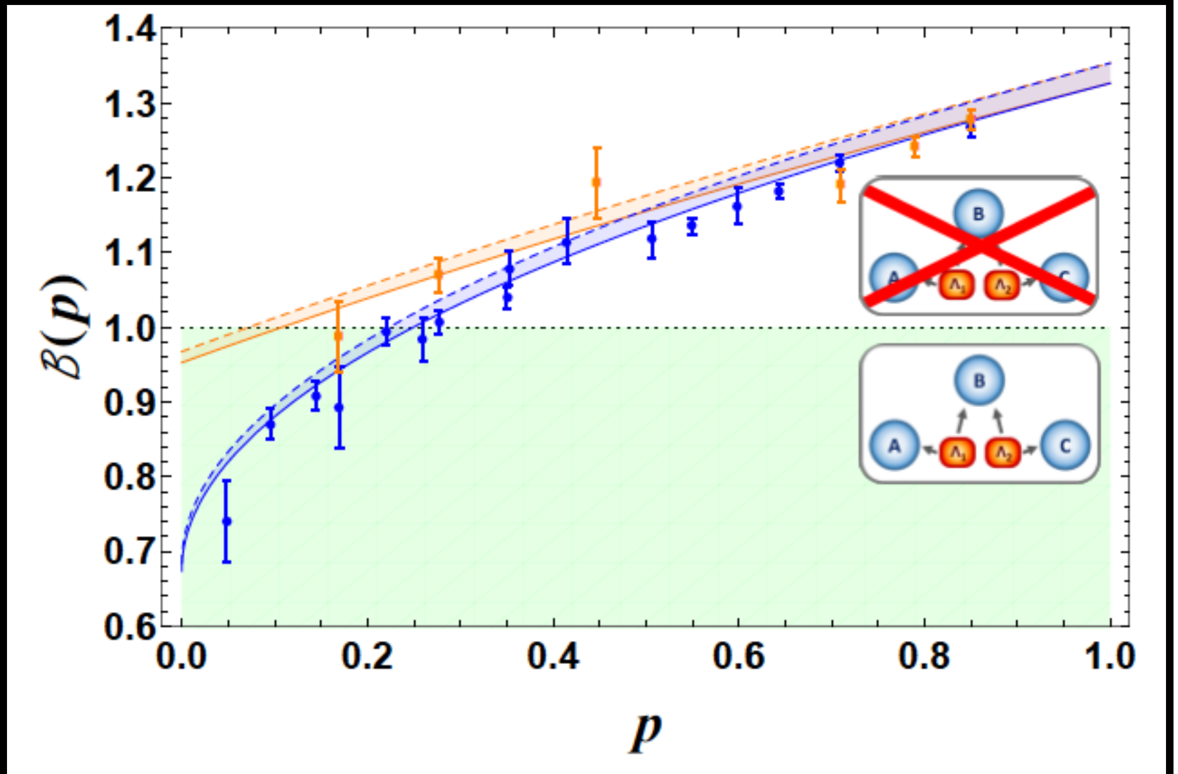


Violation of bilocality inequality versus the noise of Bell measurement



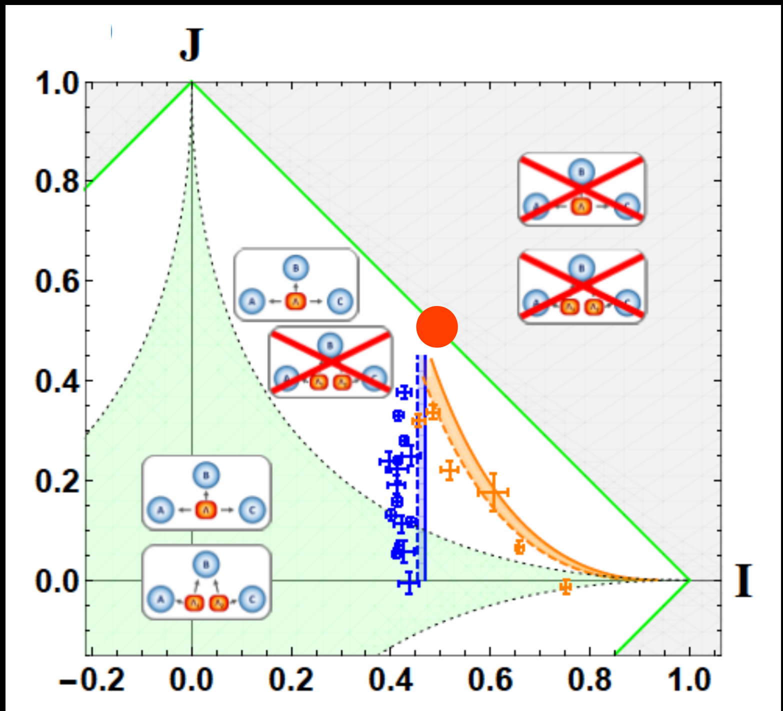
$$\mathfrak{B} = 1.268 \pm 0.014$$

Noise in Bell measurement
=
Distinguishability p between photons
(increase of temporal delay)

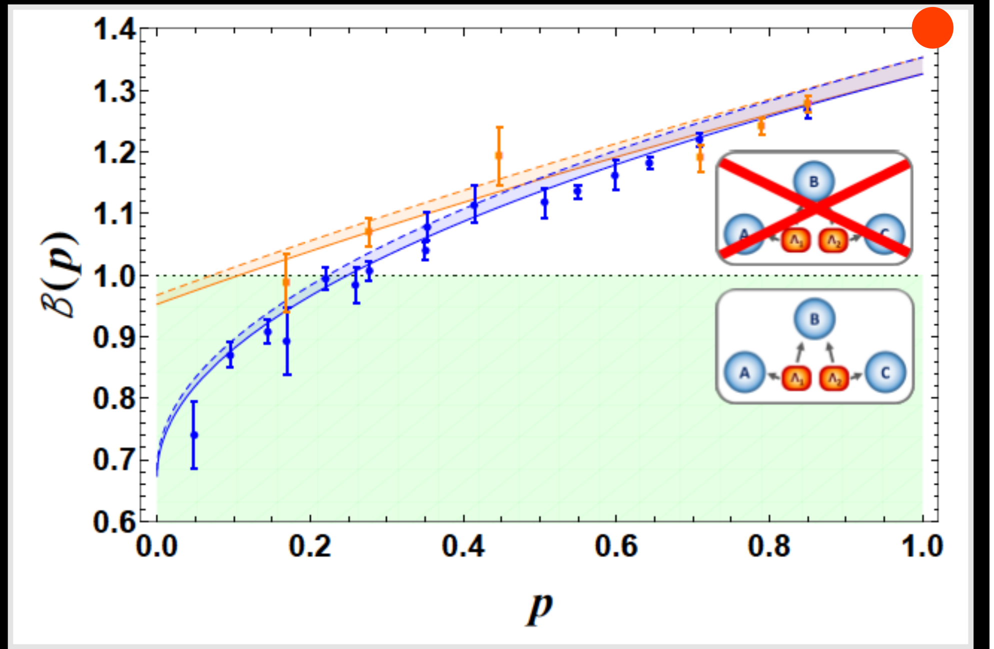


G. Carvacho, F. Andreoli, L. Santodonato, M. Bentivegna, R. Chaves, F. Sciarrino, *Nature Communications* 8, 14775 (2017)

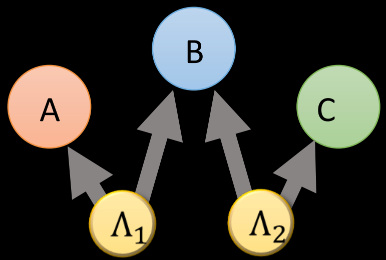
Experimental locality versus bilocality

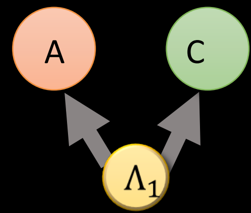


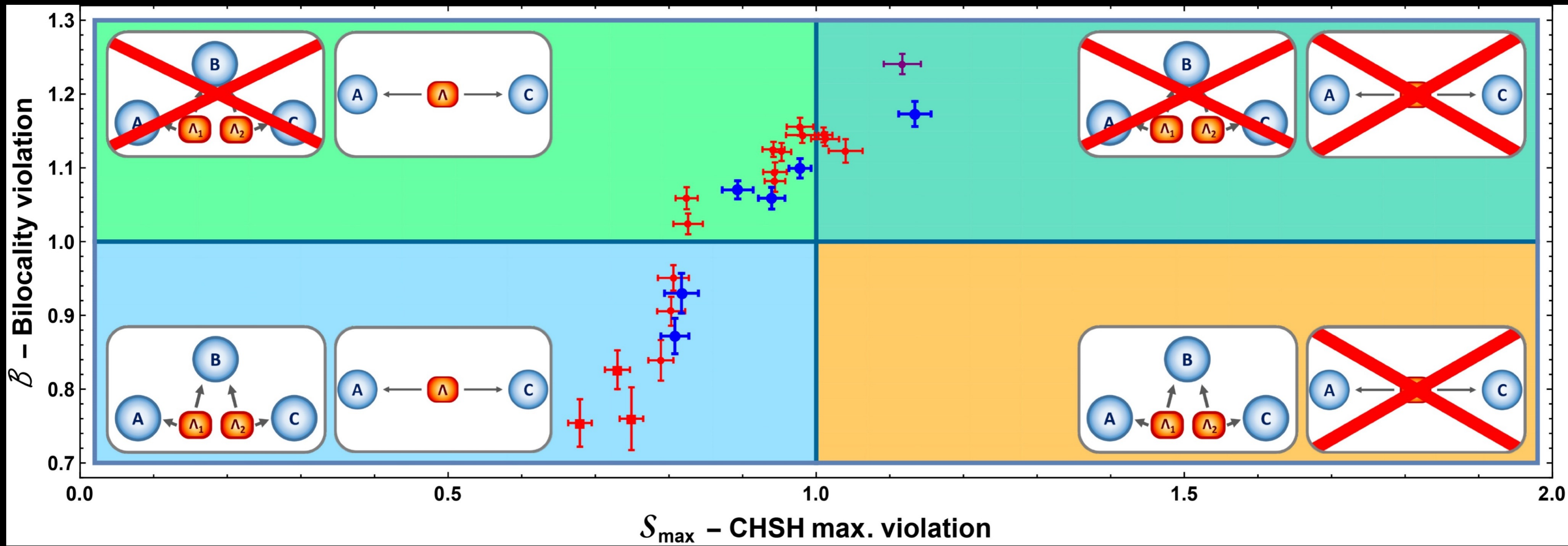
Specific LHV inequality



Experimental bilocality violation versus optimal CHSH violation on the swapped pair

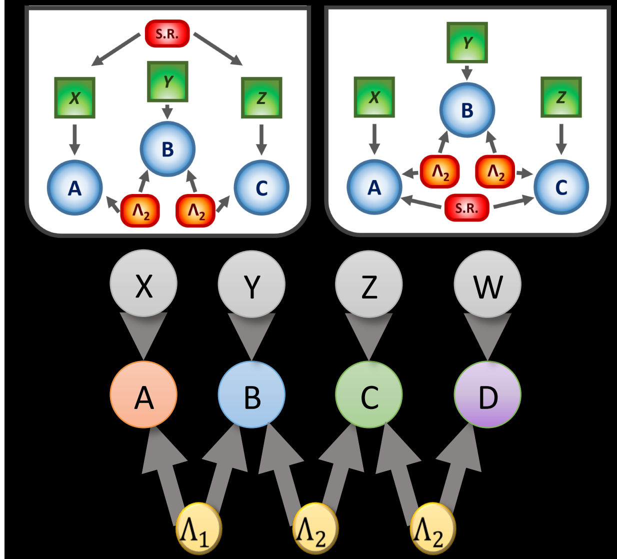






R. Horodecki, P. Horodecki, M. Horodecki, *Physics Letters A*, 200(5):340 – 344, 19

Conclusion - part I



Experimental violation of bilocality based on entanglement Swapping.

Next steps.. to experimentally address

Bilocality without shared reference frames

Other causal structures

Application for quantum information processing

More complex scenarios

Experimental demonstration of non-bilocal quantum correlations

Dylan J. Saunders[†,1,2] Adam J. Bennet,[1] Cyril Branciard,[3] and Geoff J. Pryde[1]

[1]*Centre for Quantum Dynamics and Centre for Quantum Computation and Communication Technology, Griffith University, Brisbane, 4111, Australia*

[2]*Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK*

[3]*Institut Néel, CNRS and Université Grenoble Alpes, 38042 Grenoble Cedex 9, France*

(Dated: October 28, 2016)

arXiv: 1610.08154

nature COMMUNICATIONS

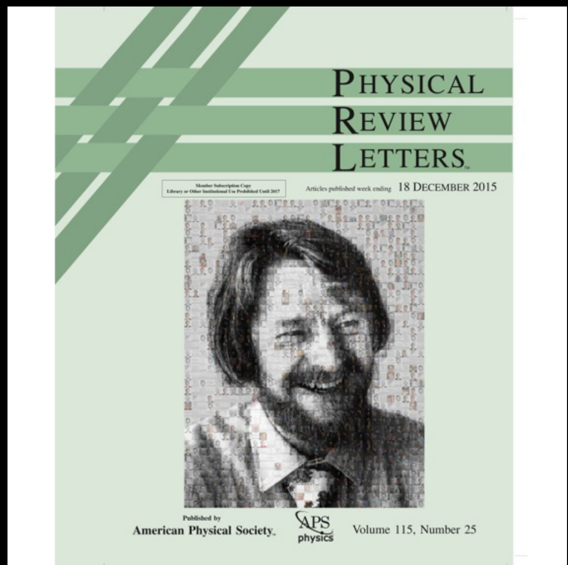
ARTICLE

Received 1 Aug 2016 | Accepted 1 Feb 2017 | Published 16 Mar 2017 DOI: 10.1038/ncomms14775 OPEN

Experimental violation of local causality in a quantum network

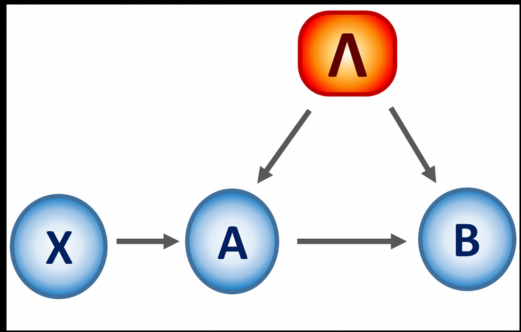
Gonzalo Carvacho[1], Francesco Andreoli[1], Luca Santodonato[1], Marco Bentivegna[1], Rafael Chaves[2,3] & Fabio Sciarrino[1]

What is the simplest causal structure that admits a gap between classical and quantum causal models?



Instrumental inequalities

Instrumental causal models:



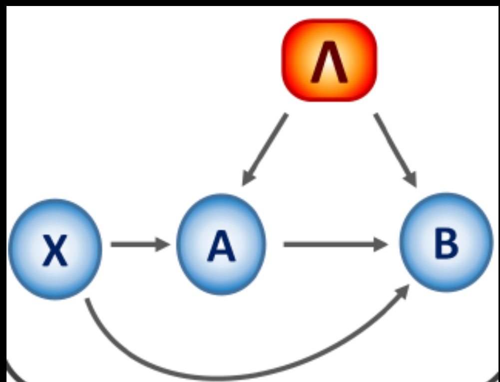
$$p(a,b|x) = \sum_{\lambda} p(\lambda)\, p(a|x,\lambda)\, p(b|a,\lambda)$$

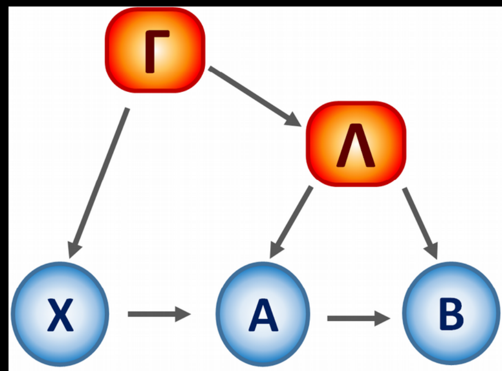
… they all satisfy:

$$\max_{a} \sum_{b} \max_{x} p(a,b|x) \leq 1$$

J. Pearl, UAI (1995).

- ***Classical*** instrumental-inequality ***violations possible only by non-instrumental** causal **models***





- Quantum mechanically ***no violation by quantum instrumental causal models.***

J. Henson, R. Lal, and M. Pussey, New J. Phys. **16**, 113043 (2014) .

Violation of a classical instrumental test with quantum instrumental causal models

If X is trichotomic, another instrumental inequality appears:

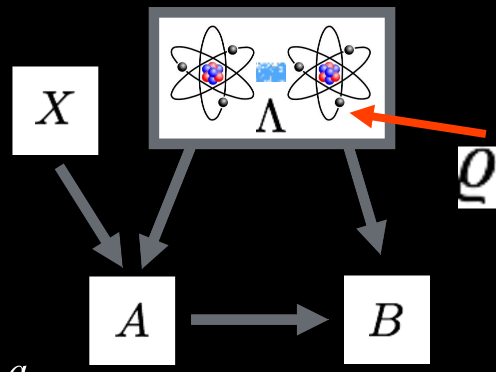
$$I_{\text{inst}} := -\langle B\rangle_{x=1} + 2\langle B\rangle_{x=2} + \langle A\rangle_{x=1} - \langle A\,B\rangle_{x=1} + 2\langle A\,B\rangle_{x=3} \leq 3$$

B. Bonet, UAI (2001).

Quantum instrumental causal models:

$$p_Q(a,b|x) := \text{Tr}\left[M_x^{(a)} \otimes M_a^{(b)} \varrho_\Lambda\right]$$

(measurement setting x, measurement outcome a) (measurement setting a, measurement outcome b)

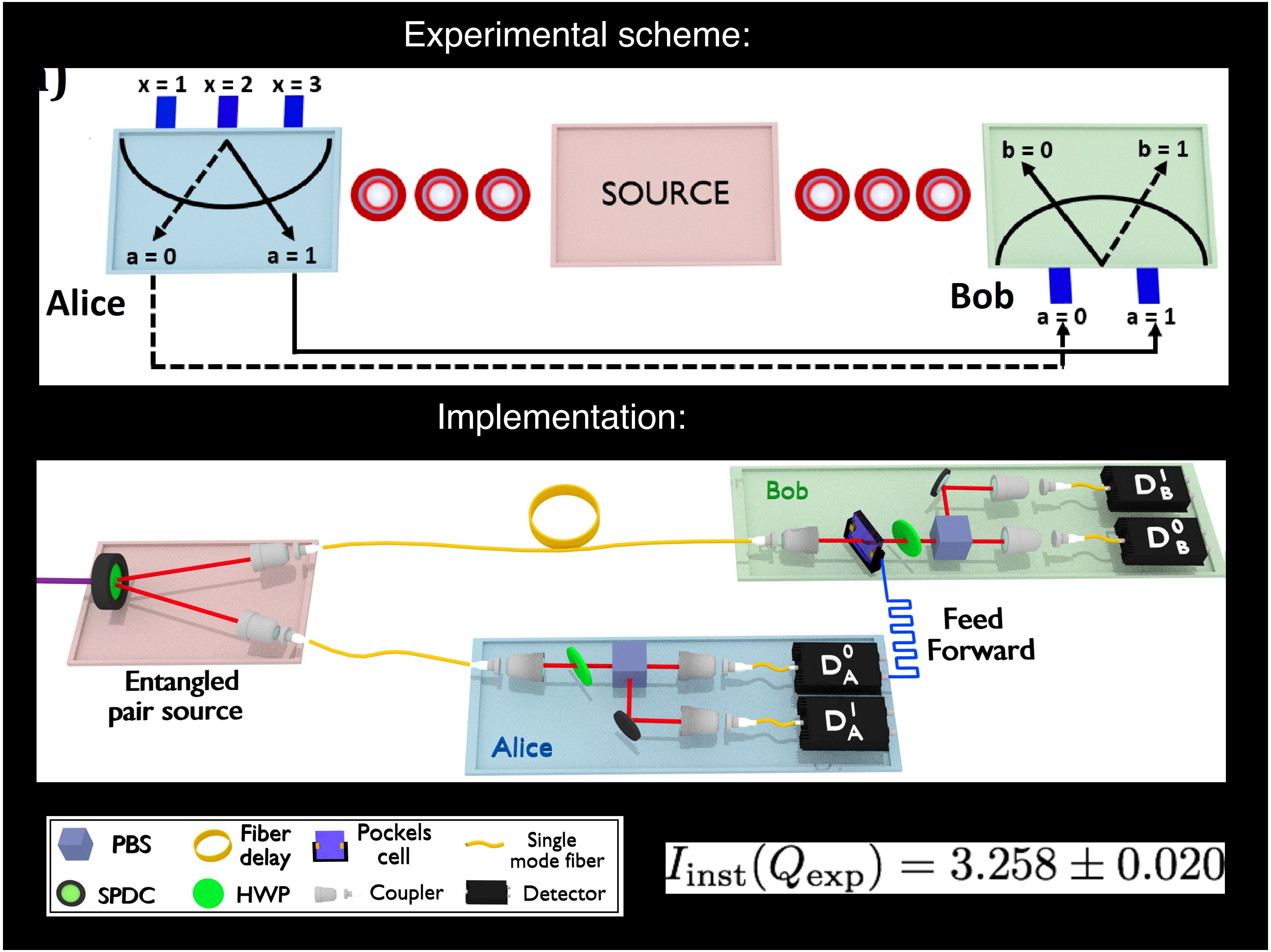


$$\varrho_\Lambda = \varrho_{\Lambda_A \Lambda_B}$$

A quantum common cause

$$\varrho_\Lambda = |\Phi^+\rangle := \frac{1}{\sqrt{2}}\Big(|0_{\Lambda_A}\, 0_{\Lambda_A}\rangle + |1_{\Lambda_A}\, 1_{\Lambda_A}\rangle\Big) \Rightarrow I_{\text{inst}}(Q) = 1 + 2\sqrt{2} \approx 3.82 \text{ !!!}$$

R. Chaves, G. Carvacho, I. Agresti, V. Di Giulio, L. Aolita, S. Giacomini, and F. Sciarrino, Nature Physics (2017).


Experimental scheme:
x = 1
x = 2
x = 3
a = 0
a = 1
Alice
SOURCE
b = 0
b = 1
Bob
a = 0
a = 1
Implementation:
Bob
D_B^1
D_B^0
Feed
Forward
Entangled
pair source
D_A^0
D_A^1
Alice
PBS
Fiber
delay
Pockels
cell
Single
mode fiber
SPDC
HWP
Coupler
Detector
$I_{\mathrm{inst}}(Q_{\mathrm{exp}}) = 3.258 \pm 0.020$

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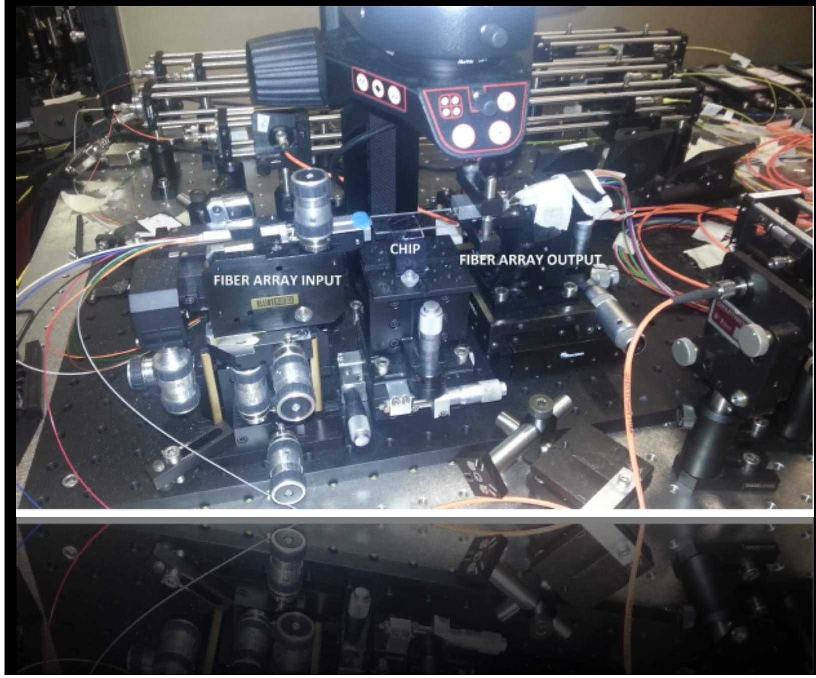

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