

**Title:** Quantum non-classicality in the simplest causal network

**Speakers:** Pedro Lauand

**Collection/Series:** Causalworlds

**Subject:** Quantum Foundations, Quantum Information

**Date:** September 20, 2024 - 3:45 PM

**URL:** <https://pirsa.org/24090113>

# A minimal example of quantum non-classicality without inputs

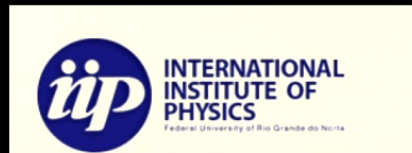
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Sabrina Zani  
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Sidiney Montanhano  
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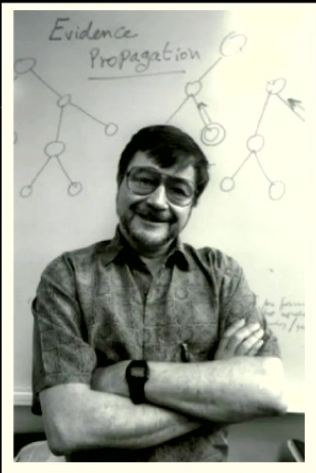
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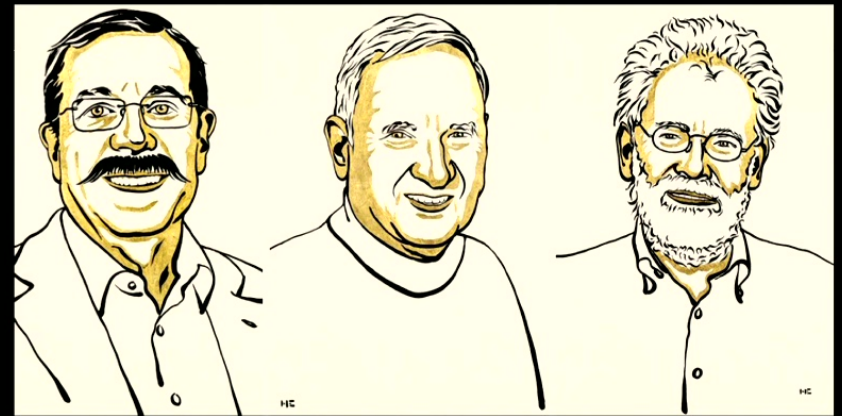
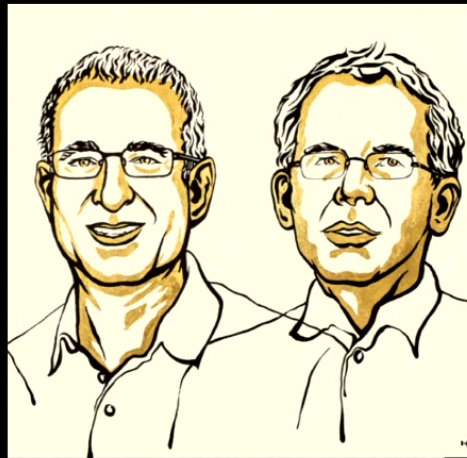
# Introduction

## Causality is a central concept in science



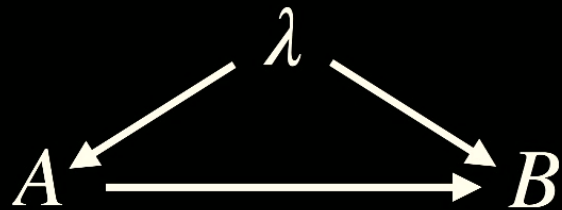
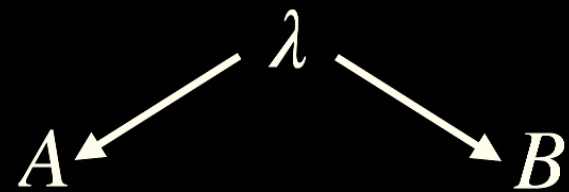
Judea Pearl

Joshua D. Angrist & Guido W. Imbens

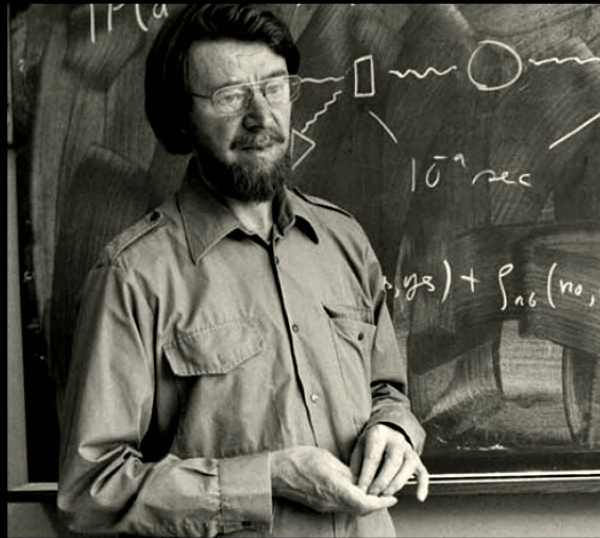


Alain Aspect, John F. Clauser & Anton Zeilinger

"Correlations cry out for explanations"- John S. Bell



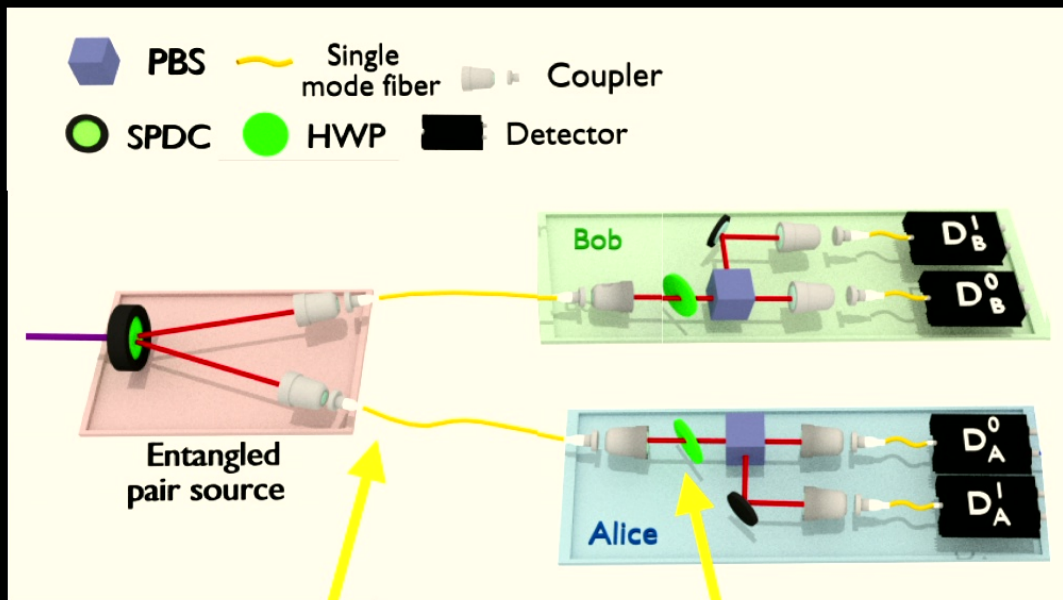
## Causal Inference is very much in the job description of a physicist



"I am a Quantum Engineer, but on Sundays I have principles." - John S. Bell



**What do our experiments look like ?**

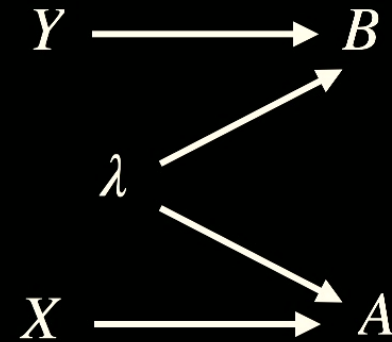
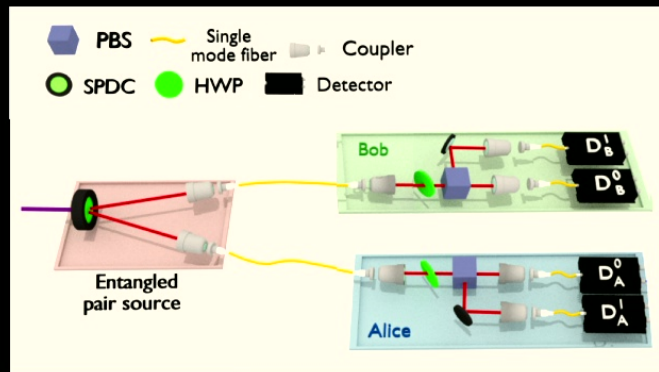


We actually measure the path of the photons

We know the source of correlation between the path of the photons must be due to the source.

We can choose the orientation of the HWP in our lab

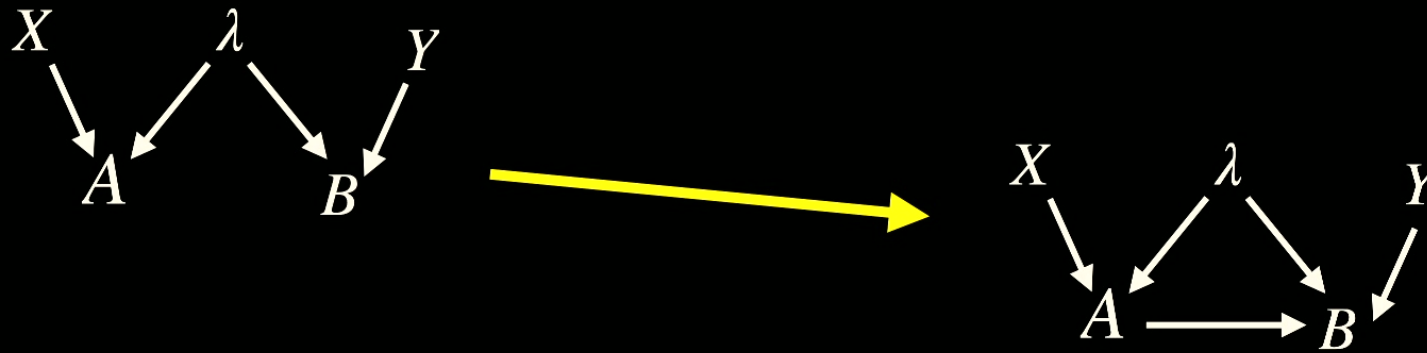
# Bell's theorem



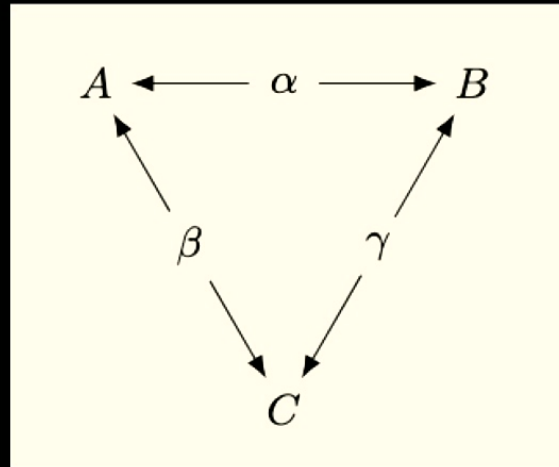
$$p_Q(a, b | x, y) \neq \sum_{\lambda} p(\lambda) p(a | \lambda, x) p(b | \lambda, y)$$

# Bell non-classicality in networks

# 1) Communication



## 2) Independent sources



Featured in Physics

Editors' Suggestion

## Genuine Quantum Nonlocality in the Triangle Network

Marc-Olivier Renou, Elisa Bäumer, Sadra Boreiri, Nicolas Brunner, Nicolas Gisin, and Salman Beigi  
Phys. Rev. Lett. **123**, 140401 – Published 30 September 2019

Editors' Suggestion

## Proofs of Network Quantum Nonlocality in Continuous Families of Distributions

Alejandro Pozas-Kerstjens, Nicolas Gisin, and Marc-Olivier Renou  
Phys. Rev. Lett. **130**, 090201 – Published 28 February 2023

PAPER • OPEN ACCESS

## Beyond Bell's theorem: correlation scenarios

Tobias Fritz<sup>1</sup>

Published 1 October 2012 • © IOP Publishing and Deutsche Physikalische Gesellschaft

[New Journal of Physics, Volume 14, October 2012](#)

Citation Tobias Fritz 2012 *New J. Phys.* **14** 103001

DOI 10.1088/1367-2630/14/10/103001

## Partial Self-Testing and Randomness Certification in the Triangle Network

Pavel Sekatski, Sadra Boreiri, and Nicolas Brunner  
Phys. Rev. Lett. **131**, 100201 – Published 5 September 2023

[Submitted on 13 Jun 2024]

## Topologically Robust Quantum Network Nonlocality

Sadra Boreiri, Tamas Krivachy, Pavel Sekatski, Antoine Girardin, Nicolas Brunner

## Constraints on nonlocality in networks from no-signaling and independence

[Nicolas Gisin](#) , [Jean-Daniel Bancal](#) , [Yu Cai](#) , [Patrick Remy](#), [Armin Tavakoli](#), [Emmanuel Zambrini](#)  
[Cruzeiro](#), [Sandu Popescu](#) & [Nicolas Brunner](#)

*Nature Communications* **11**, Article number: 2378 (2020) | [Cite this article](#)

## Causal compatibility inequalities admitting quantum violations in the triangle structure

Thomas C. Fraser and Elie Wolfe

Phys. Rev. A **98**, 022113 – Published 8 August 2018; Erratum *Phys. Rev. A* **102**, 029901 (2020)

## Limits on Correlations in Networks for Quantum and No-Signaling Resources

Marc-Olivier Renou, Yuyi Wang, Sadra Boreiri, Salman Beigi, Nicolas Gisin, and Nicolas Brunner  
Phys. Rev. Lett. **123**, 070403 – Published 15 August 2019

## Violation of the Finner inequality in the four-output triangle network

Antoine Girardin and Nicolas Gisin

Phys. Rev. A **108**, 042213 – Published 18 October 2023

Article | [Open access](#) | Published: 17 February 2023

## Experimental nonclassicality in a causal network without assuming freedom of choice

[Emanuele Polino](#), [Davide Poderini](#), [Giovanni Rodari](#), [Iris Agresti](#), [Alessia Suprano](#), [Gonzalo Carvacho](#), [Elie Wolfe](#) , [Askery Canabarro](#), [George Moreno](#), [Giorgio Milani](#), [Robert W. Spekkens](#), [Rafael Chaves](#)  & [Fabio Sciarrino](#) 

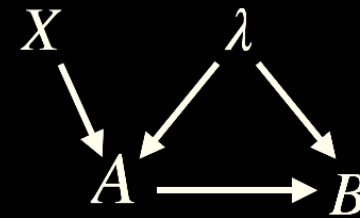
*Nature Communications* **14**, Article number: 909 (2023) | [Cite this article](#)

**What would be the minimal scenario  
for quantum non-classicality in  
networks?**



# Quantum violations in the Instrumental scenario and their relations to the Bell scenario






Thomas Van Himbeeck<sup>1,2</sup>, Jonatan Bohr Brask<sup>3</sup>, Stefano Pironio<sup>1</sup>,  
Ravishankar Ramanathan<sup>1</sup>, Ana Belén Sainz<sup>4,5</sup>, and Elie Wolfe<sup>4</sup>



## Towards a minimal example of quantum nonlocality without inputs

Sadra Boreiri, Antoine Girardin, Bora Ulu, Patryk Lipka-Bartosik, Nicolas Brunner, and Pavel Sekatski  
Phys. Rev. A **107**, 062413 – Published 13 June 2023

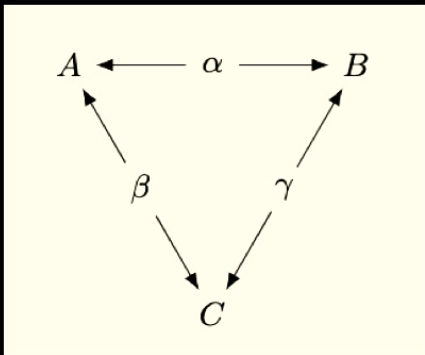
## Post-quantum nonlocality in the minimal triangle scenario

Alejandro Pozas-Kerstjens<sup>6,1,2,3</sup> , Antoine Girardin<sup>2</sup> , Tamás Kriváchy<sup>4</sup> , Armin Tavakoli<sup>5</sup>   
and Nicolas Gisin<sup>2,3</sup> 

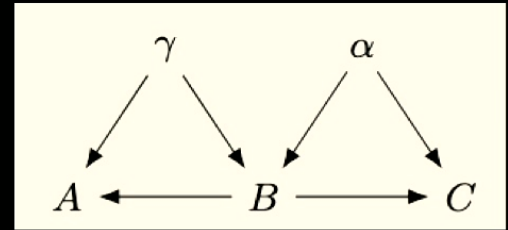
Published 22 November 2023 • © 2023 The Author(s). Published by IOP Publishing Ltd on behalf of the Institute of Physics and Deutsche Physikalische Gesellschaft

[New Journal of Physics](#), [Volume 25](#), [November 2023](#)

**Citation** Alejandro Pozas-Kerstjens *et al* 2023 *New J. Phys.* **25** 113037



# Entanglement swapping experiment



$$1/\sqrt{2}(|01\rangle + |10\rangle)$$

$$1/\sqrt{2}(|01\rangle + |10\rangle)$$

$$\parallel$$

$$|\psi^+\rangle$$

$$\parallel$$

$$|\psi^+\rangle$$



**X** if  $b = 0$

**X** if  $b = 0$

**Z** if  $b = 1$

**Z** if  $b = 1$



$B$

$$|\psi_{\theta}^{+}\rangle\langle\psi_{\theta}^{+}|, \quad 1 - |\psi_{\theta}^{+}\rangle\langle\psi_{\theta}^{+}|$$

for  $b = 0$

for  $b = 1$

$$|\psi_{\theta}^{+}\rangle = \sin(\theta) |01\rangle + \cos(\theta) |10\rangle$$

$$\theta \in [0, \frac{\pi}{4}]$$

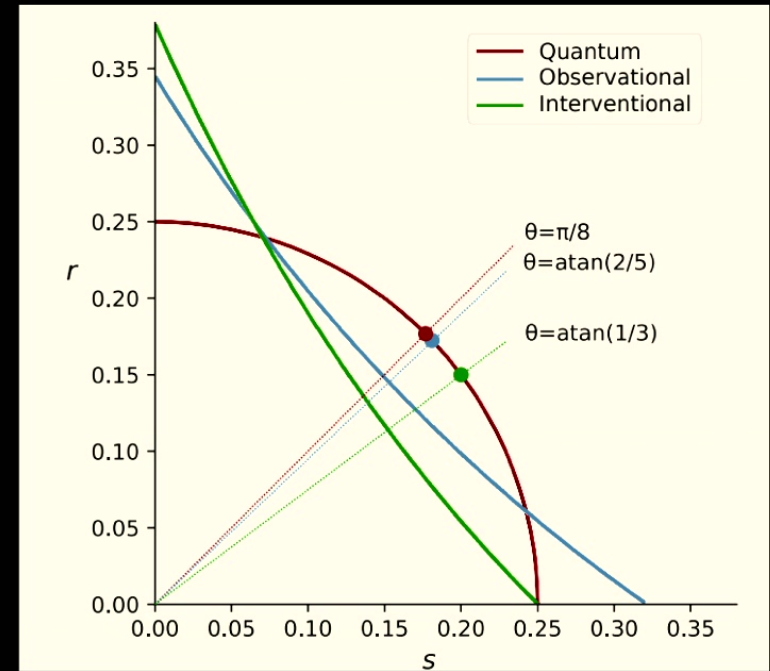
# Non-linear Bell inequalities

$$I = 2 \sum_{a=c} \sqrt{P(a, b=0, c)} + 3\sqrt{P(1,1,0)}$$

$$-18 \left| P(b=0) - \frac{1}{4} \right| - 18 \left| \sum_{a \neq c} P(a, b=1, c) - \frac{1}{4} \right| - 4 \sum_{a=c} \left| P(a, b=1, c) - \frac{1}{4} \right|$$

$$-4 \left| \langle AC \rangle_1 - \frac{1}{4} \right| - |\langle A \rangle_1 + \langle C \rangle_1| - |\langle A \rangle_0| - |\langle C \rangle_0| \leq \frac{3}{\sqrt{2}} + \frac{\sqrt{7}}{6}$$

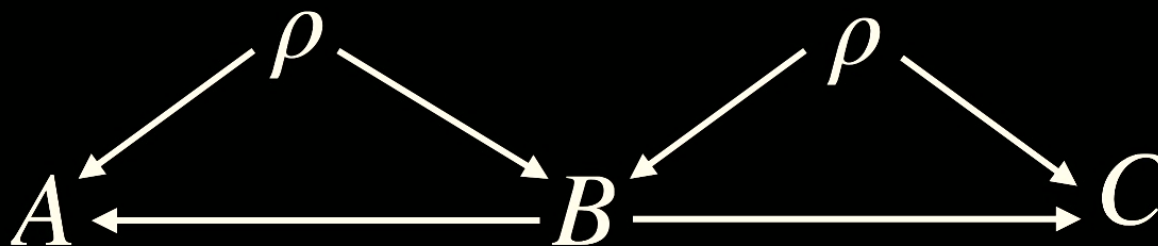
$$I_Q\left(\frac{\pi}{8}\right) = \sqrt{2 + \sqrt{2}} \left( \frac{3\sqrt{2} + 4}{4\sqrt{2}} \right) \approx 2.69238 > \frac{3}{\sqrt{2}} + \frac{\sqrt{7}}{6} \approx 2.562278895$$



arXiv preprint arXiv:2404.1279

Is this protocol resistant to noise?

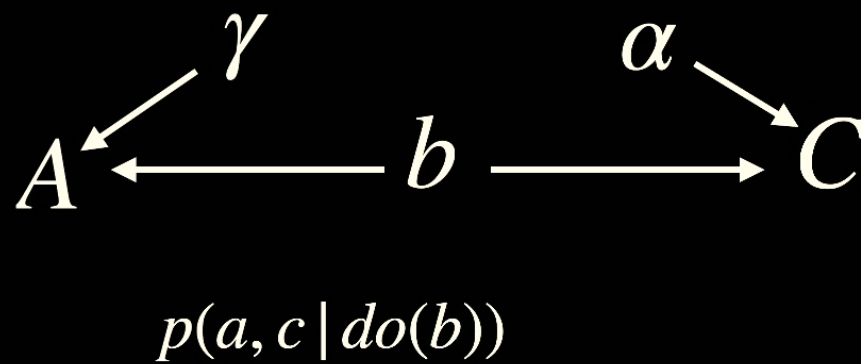
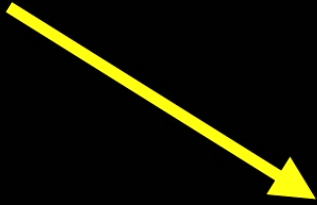
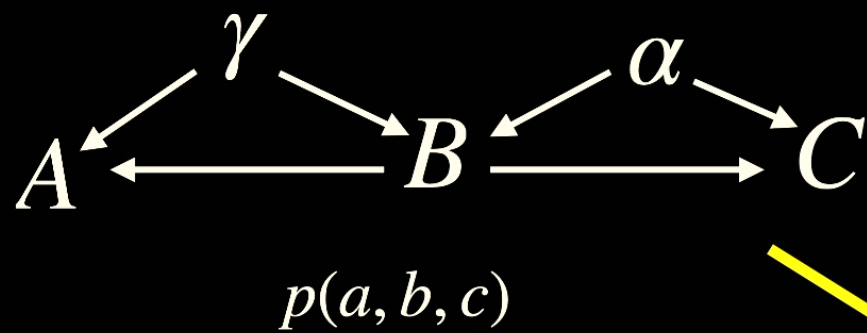
$$|\psi^+\rangle \longrightarrow \rho = v |\psi^+\rangle\langle\psi^+| + (1 - v)\frac{I}{4}$$



$$v_{min} \approx 0.98$$

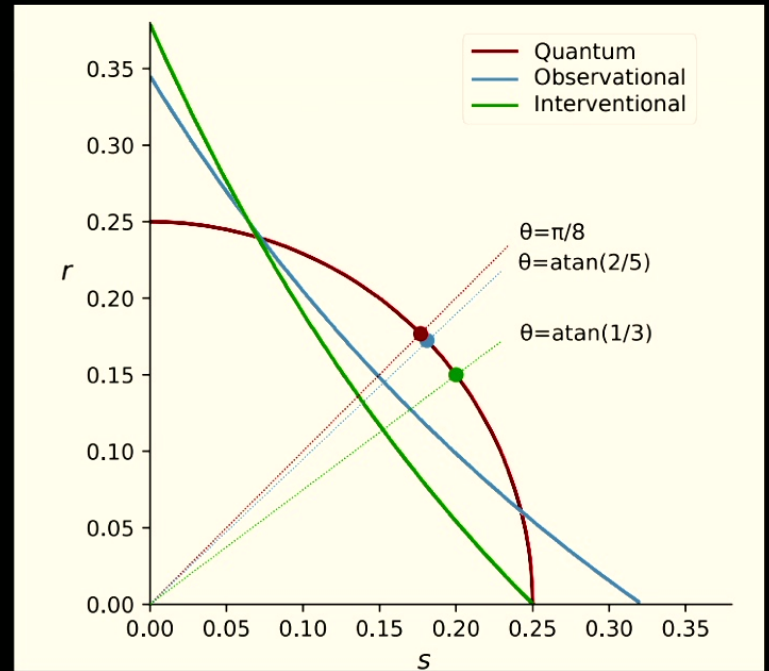
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# How can we increase our power of detection of non-classicality ?





# Incorporating interventions



arXiv preprint arXiv:2404.1279

# Incorporating interventions

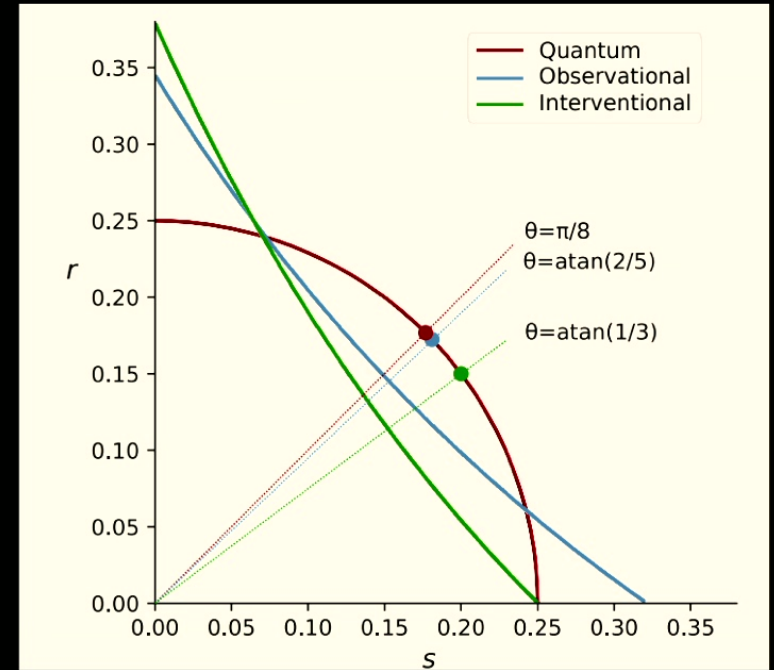
$$F = 2 \sum_{a=c} \sqrt{P(a, b = 0, c)} + 4\sqrt{P(1, 1, 0)}$$

$$- \sum_{a=c} \left| P(a, b = 1, c) - \frac{1}{4} \right| - \left| \langle AC \rangle_1 - \frac{1}{4} \right| - 18 \left| P(b = 0) - \frac{1}{4} \right|$$

$$- \left| \sum_{a \neq c} P(a, b = 1, c) - \frac{1}{4} \right| - |\langle A \rangle_1 + \langle C \rangle_1| - |\langle A \rangle_0| - |\langle C \rangle_0|$$

$$- \sum_b \left( |\langle A \rangle_{do(b)}| + |\langle C \rangle_{do(b)}| \right) \leq \frac{9}{7} + \frac{7}{10} \sqrt{6}$$

$$F_Q = \frac{1}{2} (2 + \sqrt{2})^{\frac{3}{2}} \approx 3.15432 > \frac{9}{7} + \frac{7}{10} \sqrt{6} \approx 3.000357$$



arXiv preprint arXiv:2404.1279

- The Evans scenario exhibits quantum non-classicality without inputs in the minimal scenario
- We can solve **some** non-convex programming problems
- We can incorporate interventions (or counterfactuals) to Bell's theorem

# Advertisement

## Non-trivial Topological Complexity as a precondition for Contextuality

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<sup>1</sup>*Instituto de Matemática, Estatística e Computação Científica,*

*Universidade Estadual de Campinas, 13083-859, Campinas, São Paulo, Brazil*

<sup>2</sup>*Instituto de Física “Gleb Wataghin”, Universidade Estadual de Campinas, 130830-859, Campinas, Brazil*

<sup>3</sup>*Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada, N2L 2Y5*