Quantum correlations: Where, how and why

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SCIENCE WITHOUT BORDERS

FQXi FOUNDATIONAL QUESTIONS INSTITUTE

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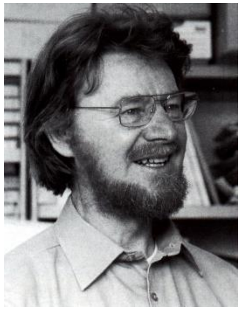
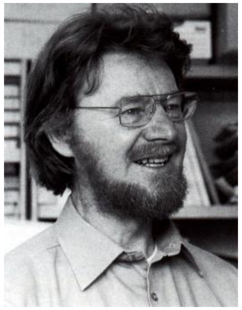
Bell's inequality

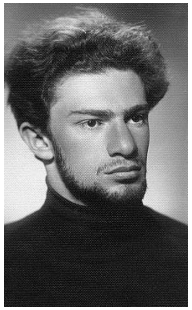


$$S_{\mathrm{CHSH}} \overset{\mathrm{LR}}{\leq} 3$$

J. S. Bell, Physics **1**, 195 (1964).

Tsirelson's bound

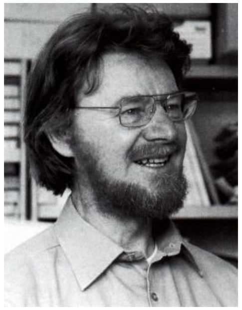


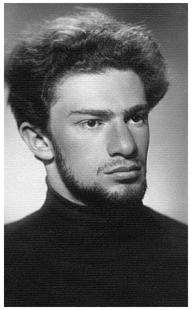


$$S_{\mathrm{CHSH}} \overset{\mathrm{LR}}{\leq} 3 \overset{\mathrm{Q}}{\leq} 2+\sqrt{2}$$

B. S. Cirel'son [Tsirelson], Lett. Math. Phys. **4**, 93 (1980).

Popescu-Rohrlich non-local non-signalling boxes

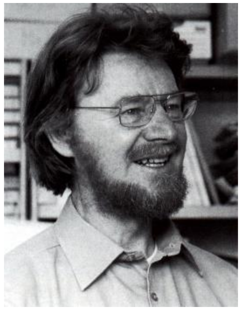


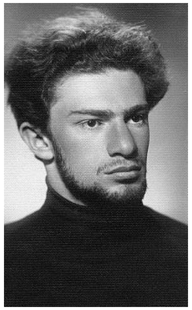


$$S_{\mathrm{CHSH}} \overset{\mathrm{LR}}{\leq} 3 \overset{\mathrm{Q}}{\leq} 2+\sqrt{2} \overset{\mathrm{NS}}{\leq} 4$$

S. Popescu and D. Rohrlich, Found. Phys. **24**, 379 (1994).

Why?





$$S_{\mathrm{CHSH}} \overset{\mathrm{LR}}{\leq} 3 \overset{\mathrm{Q}}{\leq} 2+\sqrt{2} \overset{\mathrm{NS}}{\leq} 4$$

Quantum correlations

- *"Quantum correlations"*: Correlations between outcomes of joint measurements of sharp quantum observables (i.e., von Neumann's "quantum observables") predicted by quantum theory.

NC inequalities

- *"Non-contextuality (NC) inequality"*: Bound satisfied by non-contextual hidden variable (NCHV) theories for a linear combination of correlations between the outcomes of compatible observables.
- *"NCHV theories"*: Those in which outcomes are determined and are independent of which other compatible measurements are performed.
- Every Bell inequality is a NC inequality, but most NC inequalities cannot be expressed as Bell inequalities, since they require compatible observables that cannot be decomposed into observables on different subsystems.

Purpose of this talk

- Explain quantum correlations
  - **Where?** = Which Bell and NC inequalities are violated?
  - **How?** = Which are the limits of the quantum violations?
  - **Why?** = Which principle enforces these limits?

NC inequalities and exclusivity graphs

- Every **NC inequality** can be associated to a **graph**.
- Each **vertex** represents an **event** (e.g., "*A* and *B* have been measured with results 0 and 1, respectively").
- There is an **edge** iff the events are **mutually exclusive** (e.g., "*A* and *B* have been measured with results 0 and 1" and "*A* and *B'* have been measured with results 1 and 1" are mutually exclusive).

A. Cabello, S. Severini, and A. Winter, arXiv:1010.2163.

A. Cabello, S. Severini, and A. Winter, Phys. Rev. Lett. **112**, 040401 (2014).

Exclusivity graph of the CHSH Bell inequality

$$\beta = \langle A_0 B_0 \rangle + \langle A_0 B_1 \rangle + \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle \overset{\text{LR}}{\leq} 2$$

$$\pm \langle A_i B_j \rangle = 2[P(1, \pm 1 \,|\, i, j) + P(-1, \mp 1 \,|\, i, j)] - 1$$

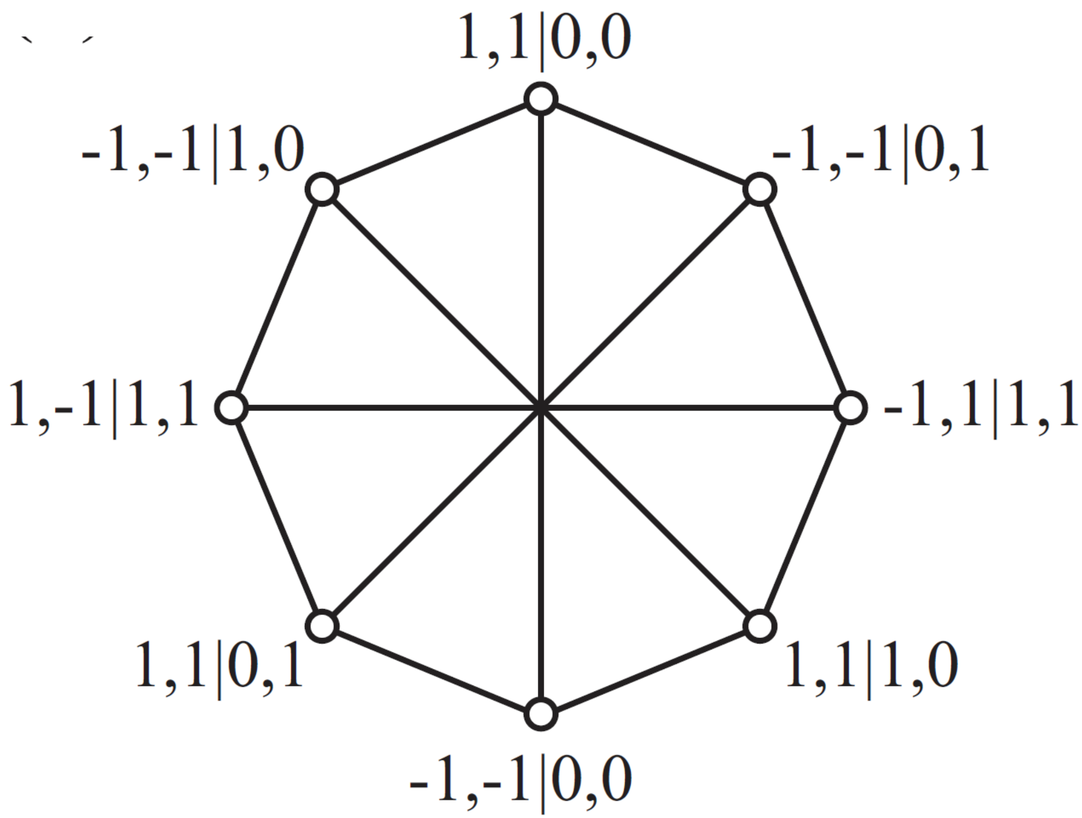
$$S = P(1,1\,|\,0,0) + P(-1,-1\,|\,0,0) + P(1,1\,|\,0,1) + P(-1,-1\,|\,0,1) \\ + P(1,1\,|\,1,0) + P(-1,-1\,|\,1,0) + P(1,-1\,|\,1,1) + P(-1,1\,|\,1,1)$$

$$S \overset{\text{LR}}{\leq} 3$$

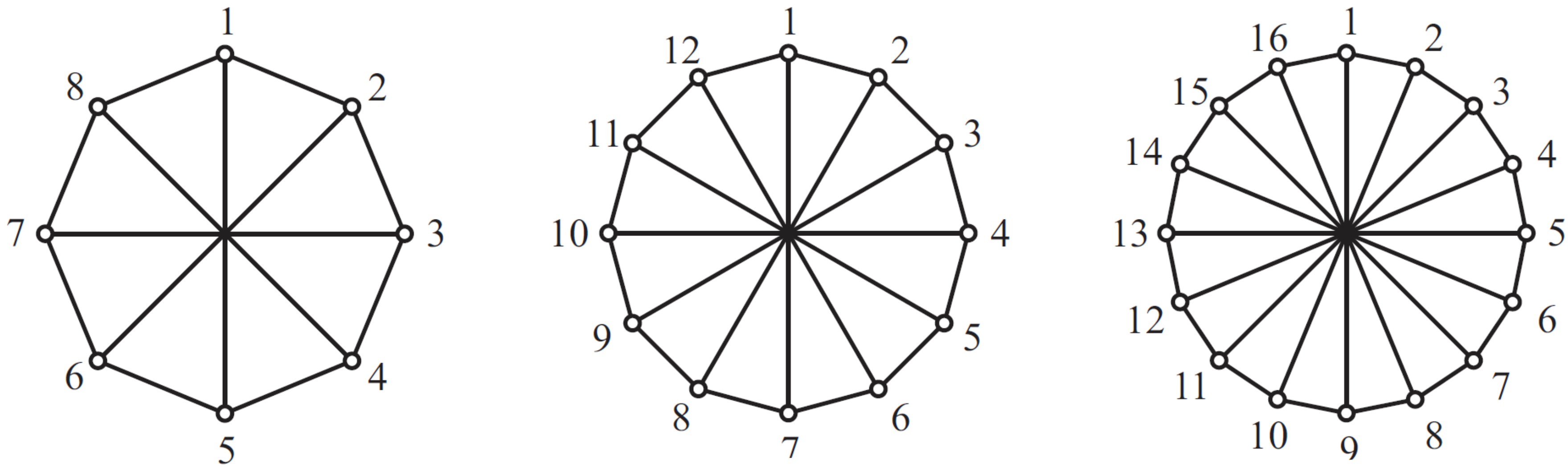
$$S = \frac{\beta}{2} + 2$$

Exclusivity graph of the CHSH Bell inequality

$$S = P(1,1\,|\,0,0) + P(-1,-1\,|\,0,0) + P(1,1\,|\,0,1) + P(-1,-1\,|\,0,1) \\ + P(1,1\,|\,1,0) + P(-1,-1\,|\,1,0) + P(1,-1\,|\,1,1) + P(-1,1\,|\,1,1)$$



Exclusivity graphs of the chained Bell inequalities

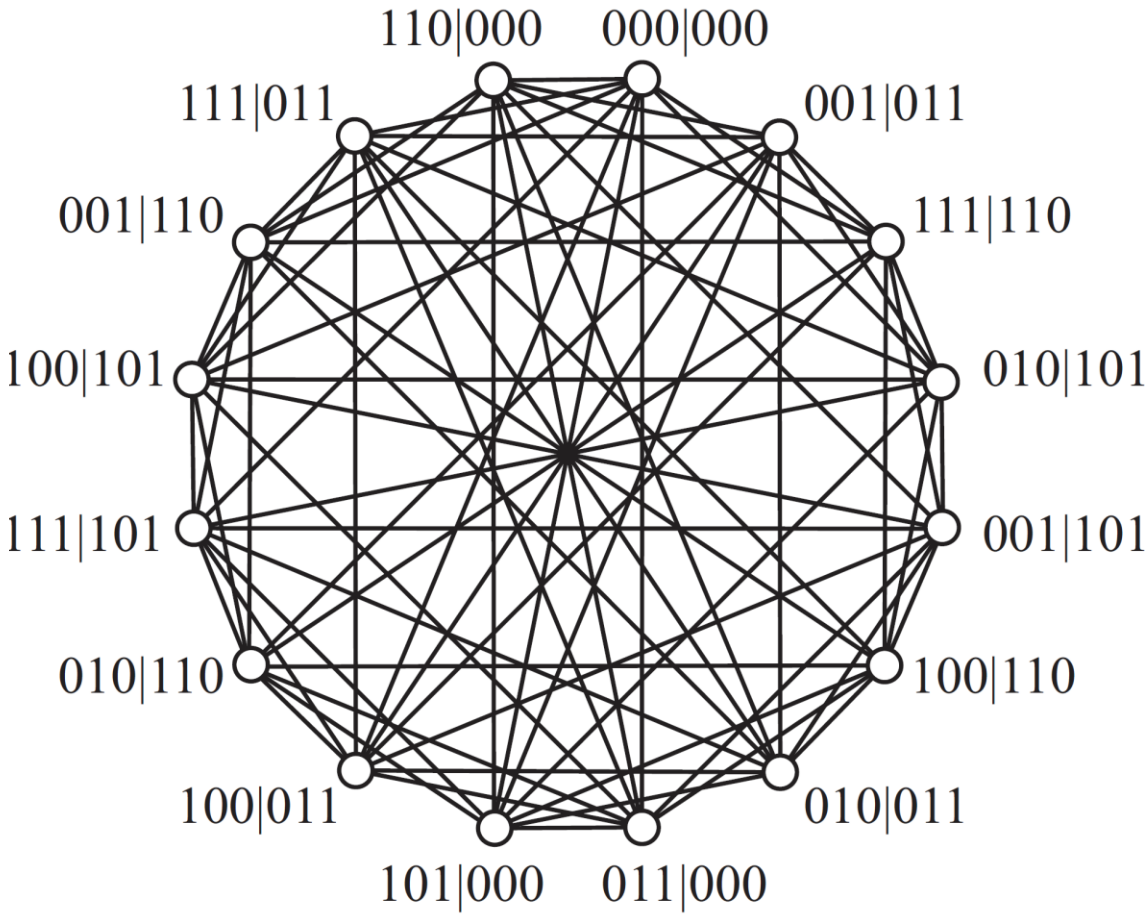


circulant graphs $Ci_{2n}(1, n)$

$$|\langle a_1 b_2\rangle + \langle b_2 a_3\rangle + \cdots + \langle a_{2n-1} b_{2n}\rangle - \langle b_{2n} a_1\rangle| \leq 2n - 2$$

P. M. Pearle, Phys. Rev. D **2**, 1418 (1970).
S. L. Braunstein and C. M. Caves, Nucl. Phys. B, Proc. Suppl. **6**, 211 (1989).

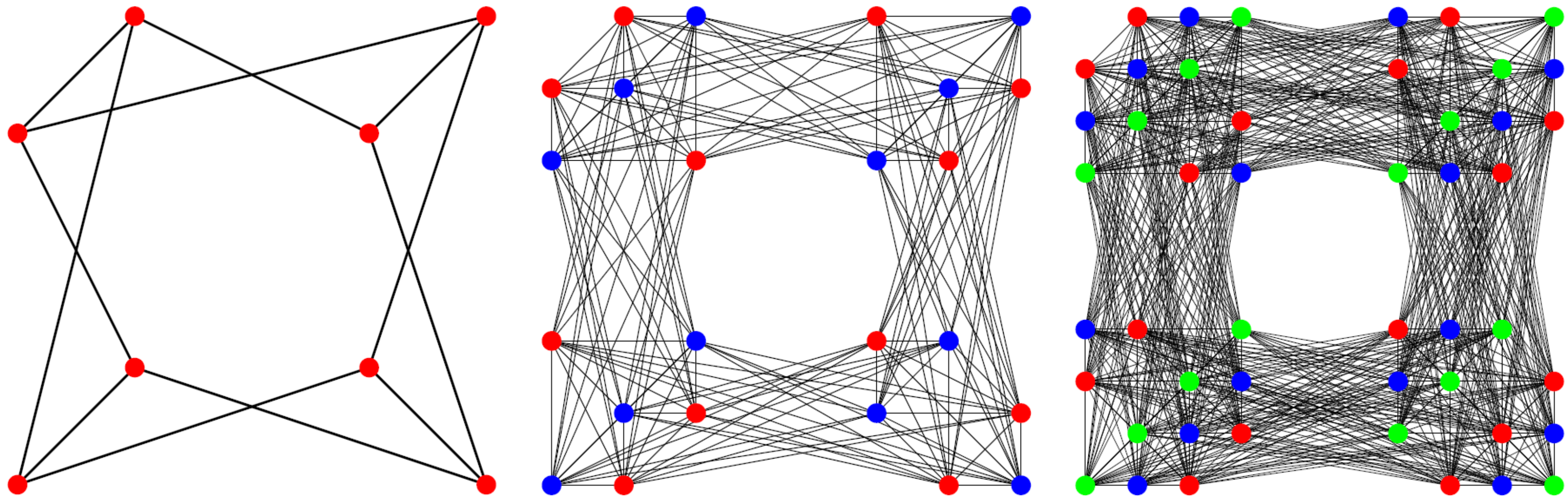
Exclusivity graph of the Mermin Bell inequality



Complement of the Shrikhande graph

N. D. Mermin, Phys. Rev. Lett. **65**, 1838 (1990).

Exclusivity graphs of the CGLMP Bell inequalities



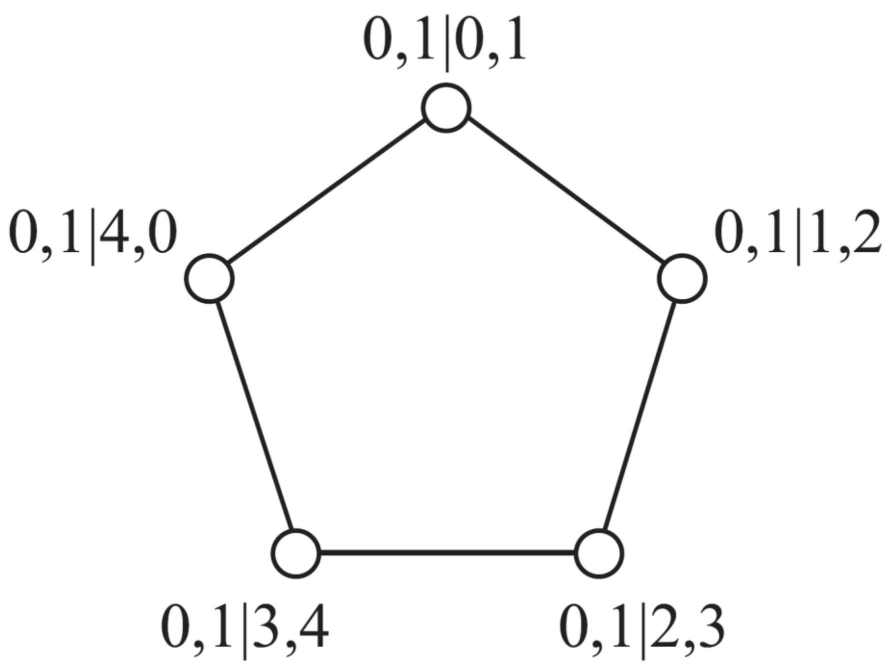
$G(I_2)$ $G(I_3)$ $G(I_4)$

Chen J L et al 2014 (in preparation)

D. Collins, N. Gisin, N. Linden, S. Massar, and S. Popescu, Phys. Rev. Lett. **88**, 040404 (2002).

Exclusivity graph of the KCBS NC inequality

$$S_{\mathrm{KCBS}} = \sum_{i=0}^{4} P(0,1\,|\,i,i+1) \overset{\mathrm{NCHV}}{\leq} 2$$



A. A. Klyachko, M. A. Can, S. Binicioğlu, and A. S. Shumovsky, Phys. Rev. Lett. **101**, 020403 (2008).

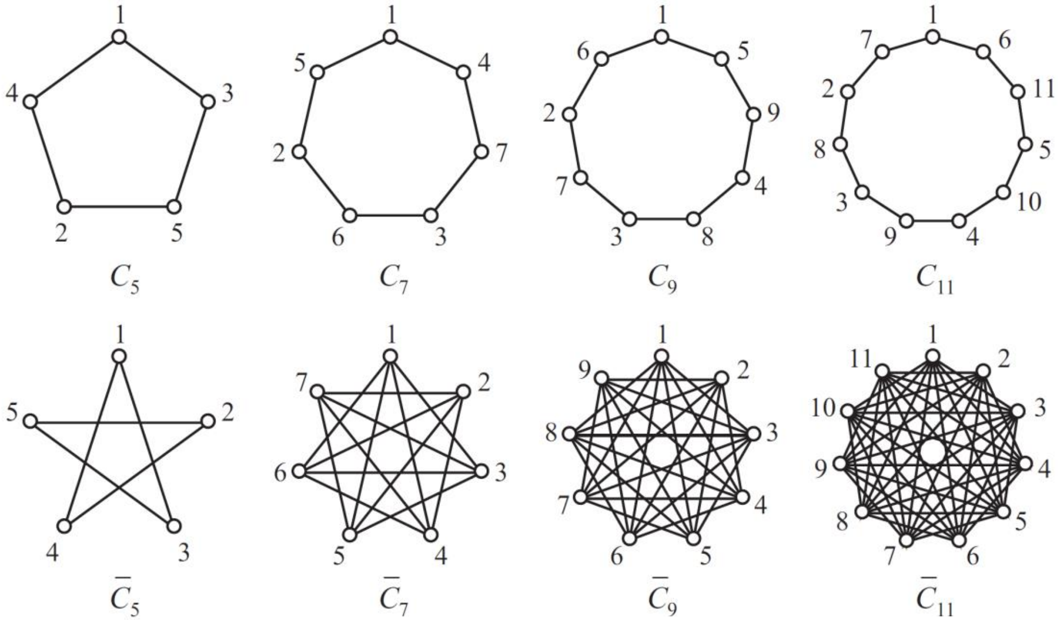
Where?

Quantum correlations. Where?

- Which NC inequalities are violated?

Quantum correlations. Where?

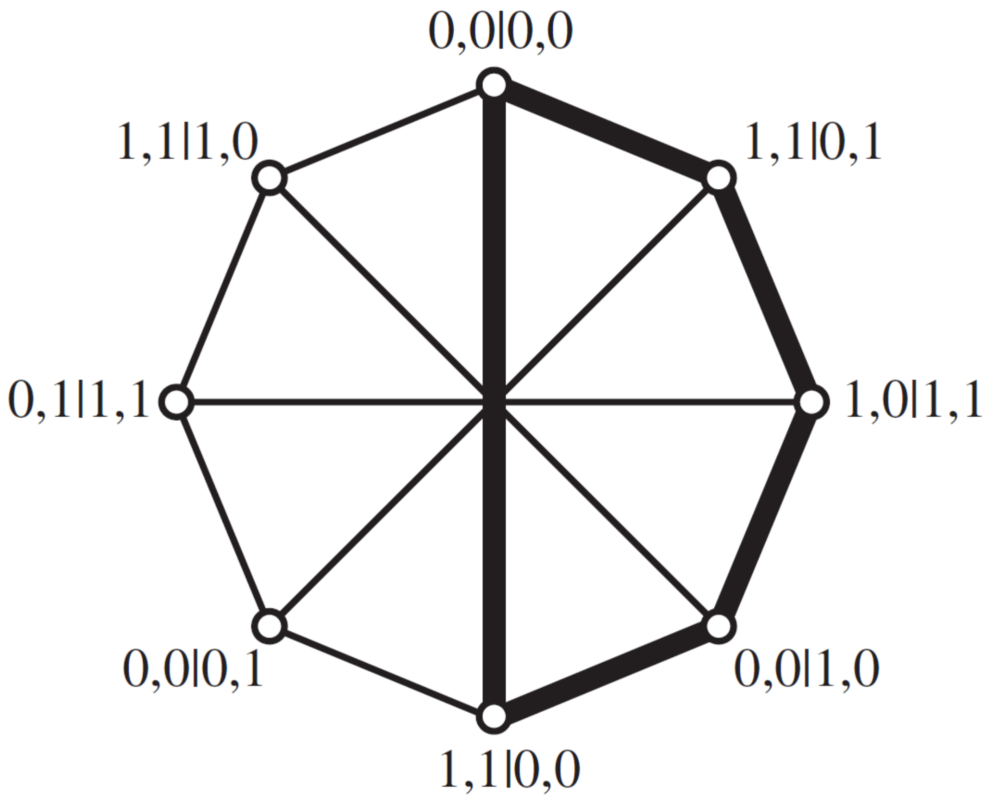
- QT violates a given NC inequality *iff* the exclusivity graph contains at least one induced pentagon, or heptagon, or nonagon, etc. (i.e., a "hole") or their complements (i.e., an "antihole")



A. Cabello, S. Severini, and A. Winter, arXiv:1010.2163.

A. Cabello, S. Severini, and A. Winter, Phys. Rev. Lett. **112**, 040401 (2014).

Example: CHSH Bell inequality



A. Cabello, Phys. Rev. Lett. **110**, 060402 (2013).

How?

Quantum correlations. How?

- **1.** Which is the **non-contextual (local) limit**?
- **2.** Which is the **quantum limit**?

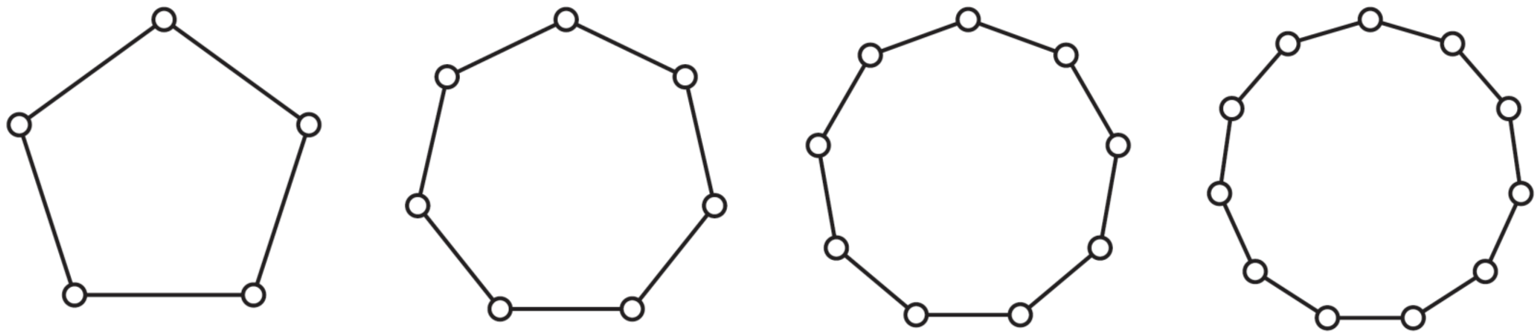
Quantum correlations. How?

- **1.** Which is the **non-contextual (local) limit**?
- **2.** Which is the **quantum limit**?
- Answer to **1:** The **independence number** of the exclusivity graph.
- Answer to **2:** The **Lovász number** of the exclusivity graph.

A. Cabello, S. Severini, and A. Winter, arXiv:1010.2163.

A. Cabello, S. Severini, and A. Winter, Phys. Rev. Lett. **112**, 040401 (2014).

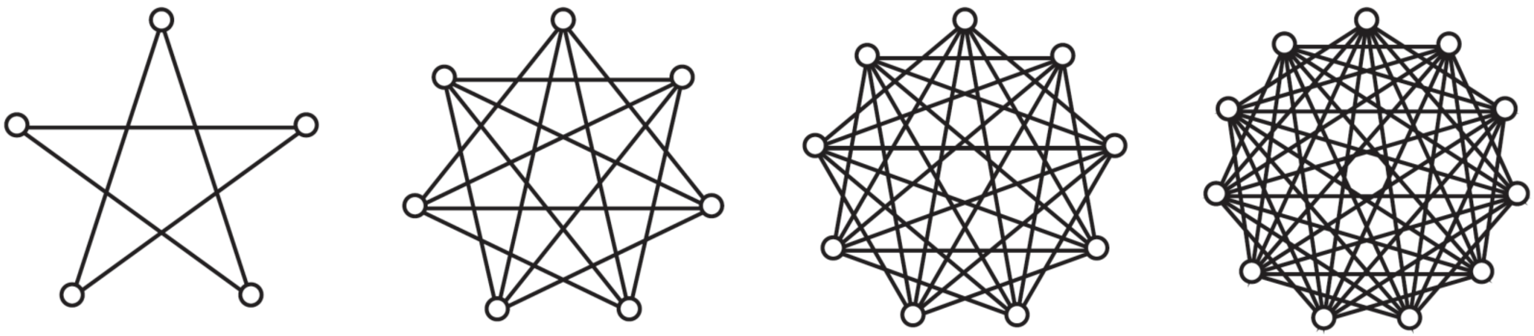
Basic NC inequalities (1)



$$\sum_{i=1}^{n} P(1,0|i,i+[\frac{n}{2}]) \overset{\text{NCHV}}{\leq} \frac{n-1}{2} \overset{\text{Q}}{\leq} \frac{n\cos\left(\frac{\pi}{n}\right)}{1+\cos\left(\frac{\pi}{n}\right)}$$

Y.-C. Liang, R. W. Spekkens, and H. M. Wiseman, Phys. Rep. **506**, 1 (2011).
A. Cabello, S. Severini, and A. Winter, arXiv:1010.2163.
A. Cabello, S. Severini, and A. Winter, Phys. Rev. Lett. **112**, 040401 (2014).

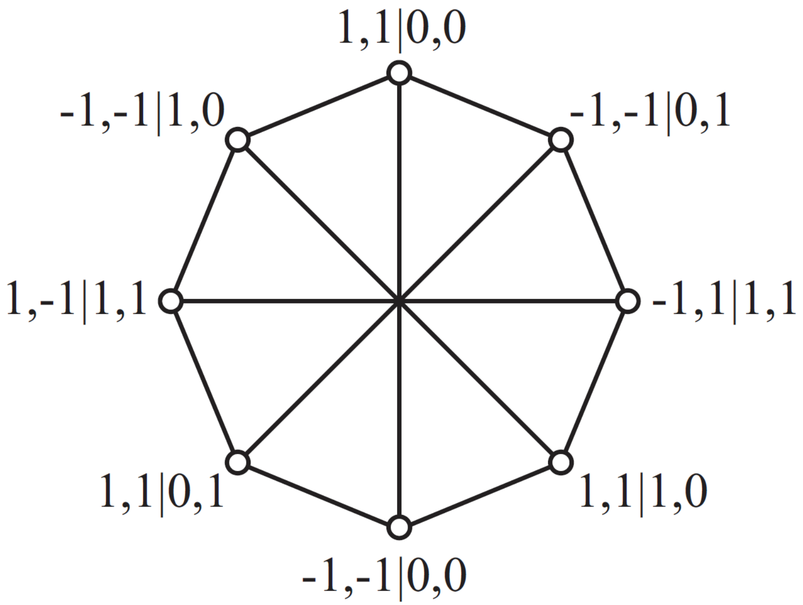
Basic NC inequalities (2)



$$\sum_{i=1}^{n} P(1,0,\ldots,0|i,i+2,\ldots,i+n-3) \overset{\text{NCHV}}{\leq} 2 \overset{\text{Q}}{\leq} \frac{1+\cos\left(\frac{\pi}{n}\right)}{\cos\left(\frac{\pi}{n}\right)}$$

A. Cabello, L. E. Danielsen, A. J. López-Tarrida, and J. R. Portillo, Phys. Rev. A **88**, 032104 (2013).

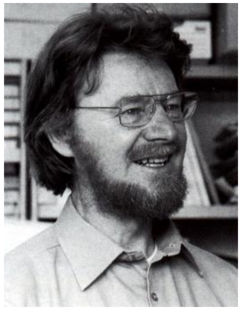
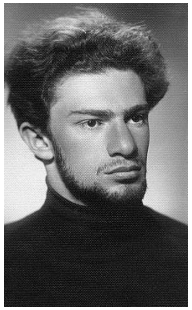
CHSH Bell inequality



$$S \overset{\mathrm{LR}}{\leq} 3 \overset{\mathrm{Q}}{\leq} 2 + \sqrt{2}$$

Why?

Why?

$$S_{\mathrm{CHSH}} \overset{\mathrm{LR}}{\leq} 3 \overset{\mathrm{Q}}{\leq} 2+\sqrt{2} \overset{\mathrm{NS}}{\leq} 4$$

Why?

$$S_{\mathrm{CHSH}} \overset{\mathrm{LR}}{\leq} 3 \overset{\mathrm{Q}}{\leq} 2+\sqrt{2} \overset{\mathrm{NS}}{\leq} 4$$

$$S_{\mathrm{KCBS}} \overset{\mathrm{NCHV}}{\leq} 2 \overset{\mathrm{Q}}{\leq} \sqrt{5} \overset{\mathrm{GPT}}{\leq} \frac{5}{2}$$

Forgot all you know about QT

Let’s try to understand QT

- **Let’s try to understand the limits of quantum correlations without knowing QT**

3-box game

- Maximize $S=P(1,0|1,2)+P(1,0|2,3)+P(1,0|3,1)$

3-box game

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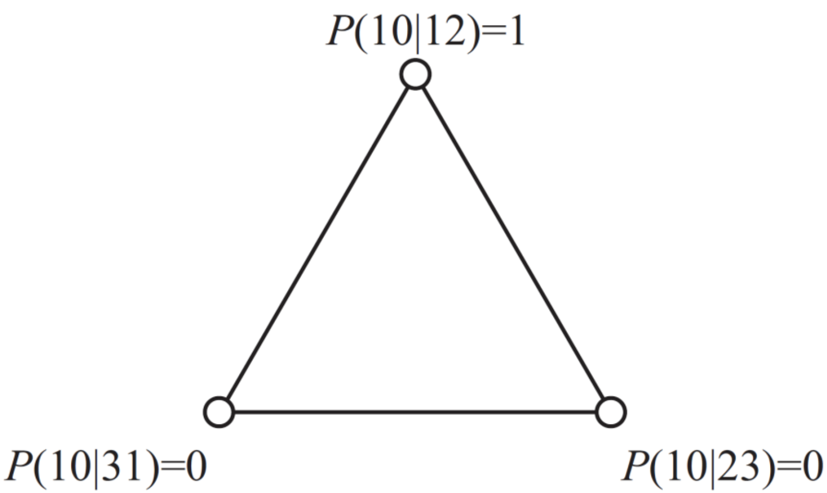
- Classical state: 3 boxes, one ball in one of them (the other 2 boxes empty). S=1.

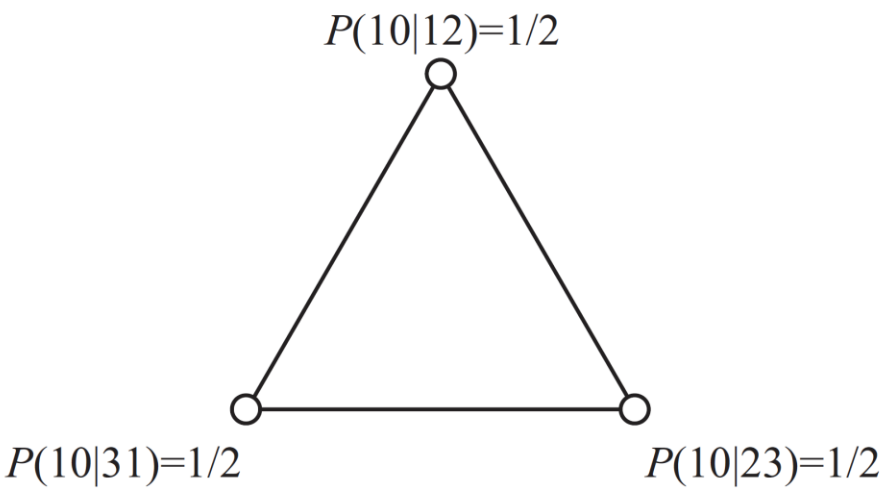
3-box game

- Maximize $S=P(1,0|1,2)+P(1,0|2,3)+P(1,0|3,1)$

- Classical state: 3 boxes, one ball in one of them (the other 2 boxes empty). $S=1$.
- Specker's triangle state: Each of the probabilities is ½, $S=3/2$.

Classical and Specker triangle states





Classical state: S=1

Specker triangle state: S=3/2

E. P. Specker, Dialectica **14**, 239 (1960). English translation: arXiv:1103.4537.

Where is quantum theory?

Where is quantum theory?

- Not in the classical world (we know that).
- Not in Specker's world.

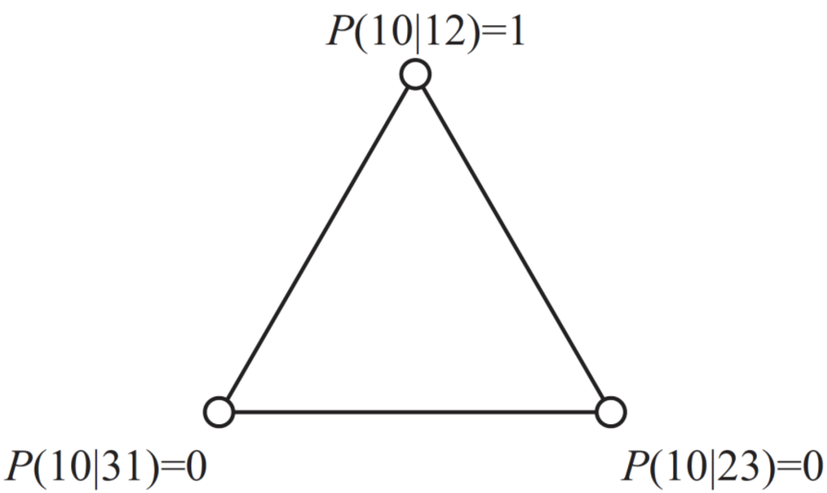
Where is quantum theory?

- Not in the classical world (we know that).
- Not in Specker's world.
- Observation: In Specker's world the E principle is not satisfied.

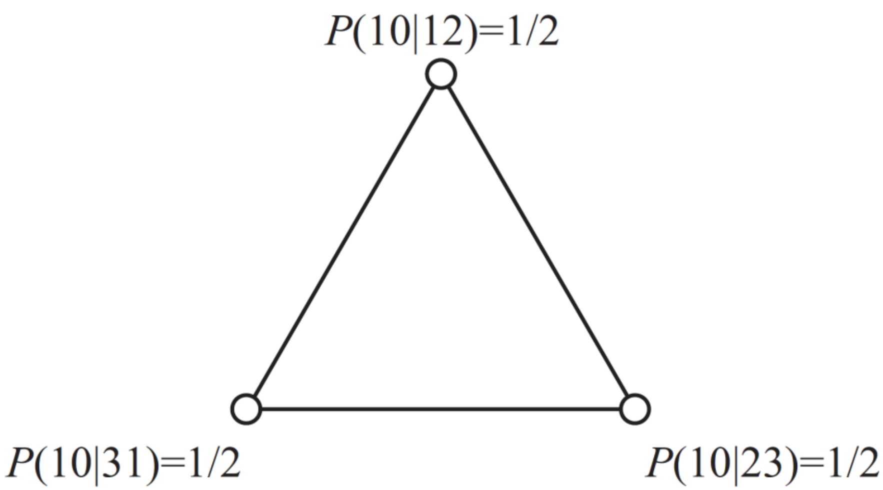
The E principle

- A theory satisfies the **E principle** when *any set of <u>pairwise</u> mutually exclusive events is jointly (i.e., n-wise mutually) exclusive*.
- Therefore, from Kolmogorov’s axioms of probability, *the sum of the probabilities of any set of pairwise mutually exclusive events cannot be higher than 1*.
- Important: The E principle cannot be derived from Kolmogorov’s axioms of probability.

Classical (Specker) triangle states satisfy (do not) E



Classical state: S=1



Specker triangle state: S=3/2

Where is quantum theory?

5-box game

- Maximize
  $S=P(1,0|1,2)+P(1,0|2,3)+P(1,0|3,4)+P(1,0|4,5)+P(1,0|5,1)$

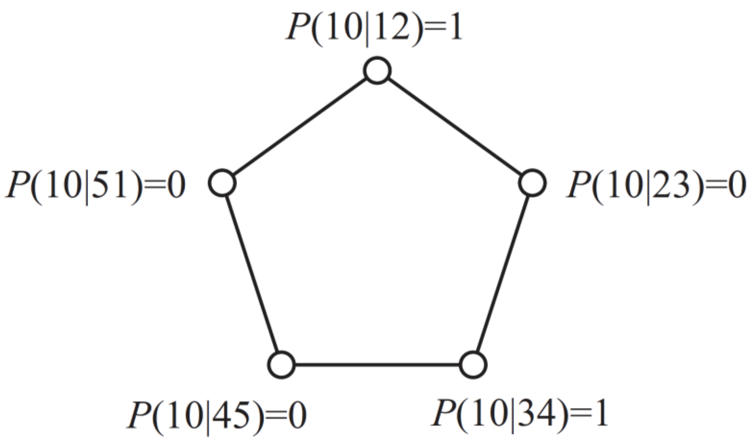
5-box game

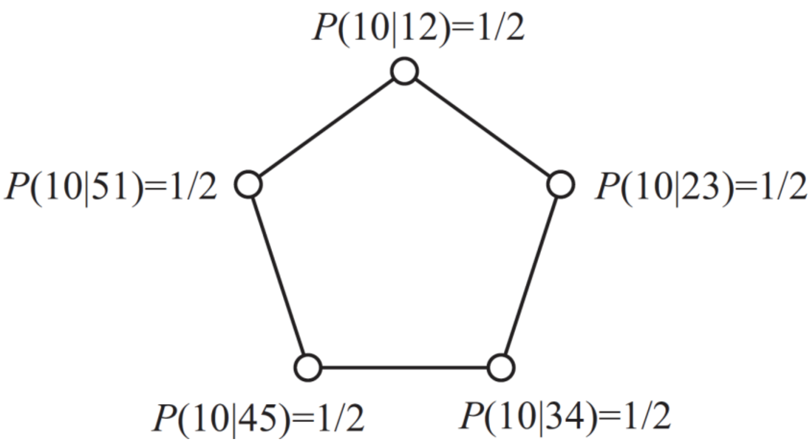
- Maximize
  $S=P(1,0|1,2)+P(1,0|2,3)+P(1,0|3,4)+P(1,0|4,5)$
  $+P(1,0|5,1)$

- Classical state: 5 boxes, two balls in non adjacent boxes (the other 3 boxes empty). $S=2$.
- Wright's pentagon state: Each of the probabilities is ½, $S=5/2$.

R. Wright, in *Mathematical Foundations of Quantum Mechanics*, edited by A. R. Marlow (Academic, San Diego, 1978), p. 255.

Classical and Wright's pentagon states

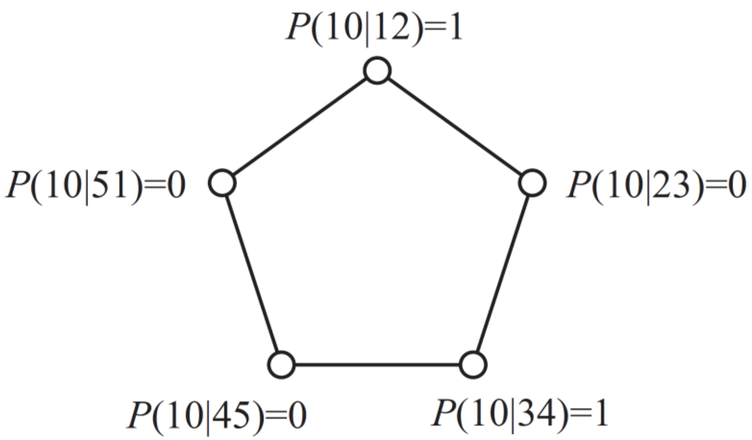


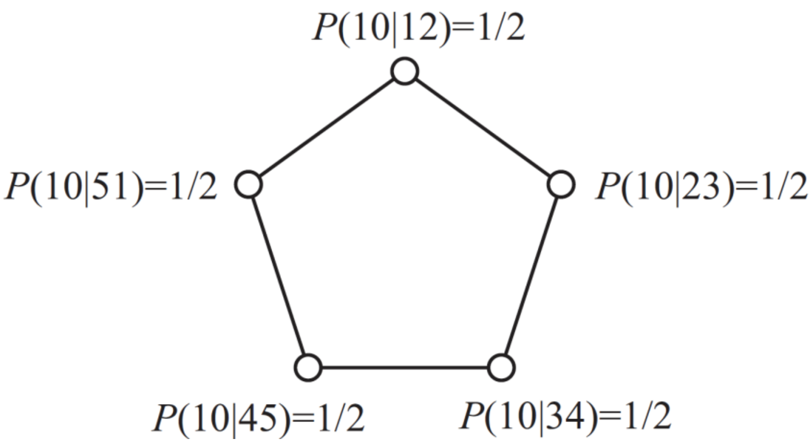


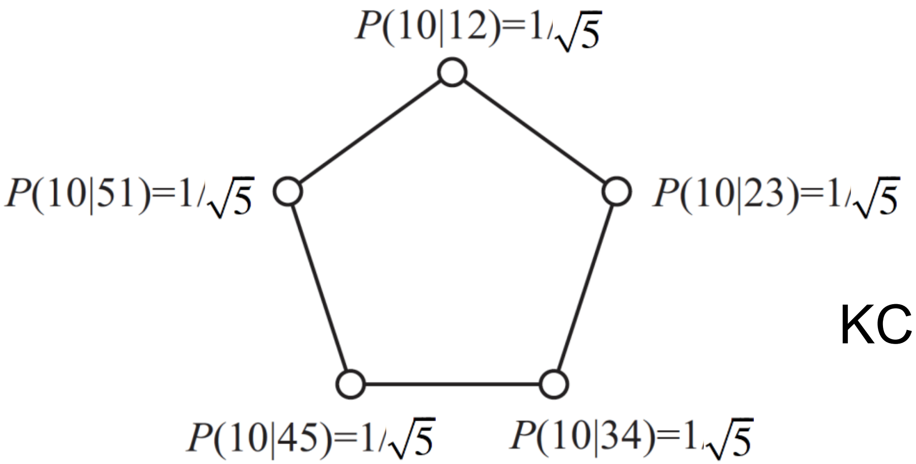
Classical state: S=2

Wright's pentagon state: S=5/2

Classical, quantum (KCBS's) and Wright's states







KCBS's state: *S*=Sqrt[5]

The KCBS NC inequality

$$S_{\mathrm{KCBS}} \overset{\mathrm{NCHV}}{\leq} 2 \overset{\mathrm{Q}}{\leq} \sqrt{5} \overset{\mathrm{GPT}}{\leq} \frac{5}{2}$$

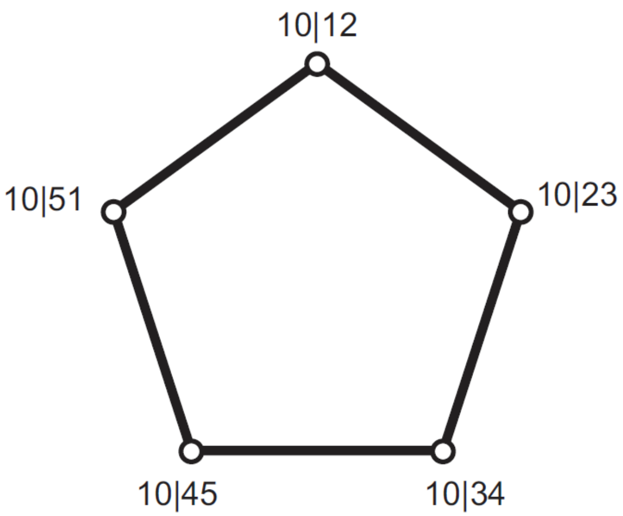
A. A. Klyachko, M. A. Can, S. Binicioğlu, and A. S. Shumovsky, Phys. Rev. Lett. **101**, 020403 (2008).

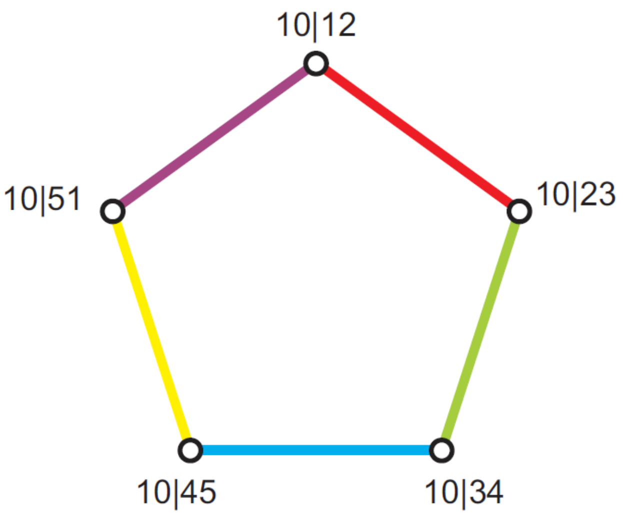
Why?

$$S_{\mathrm{KCBS}} \overset{\mathrm{NCHV}}{\leq} 2 \overset{\mathrm{Q}}{\leq} \sqrt{5} \overset{\mathrm{GPT}}{\leq} \frac{5}{2}$$

A. A. Klyachko, M. A. Can, S. Binicioğlu, and A. S. Shumovsky, Phys. Rev. Lett. **101**, 020403 (2008).

Consider two copies





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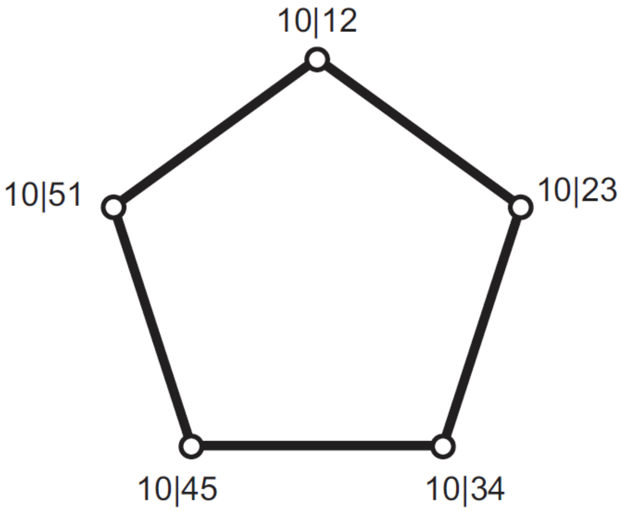

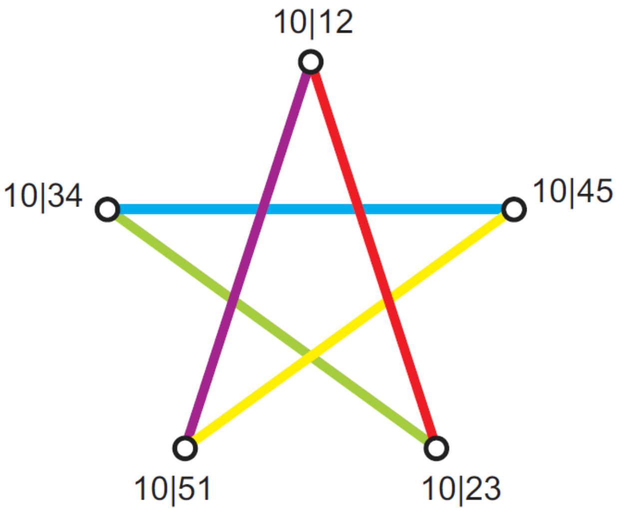

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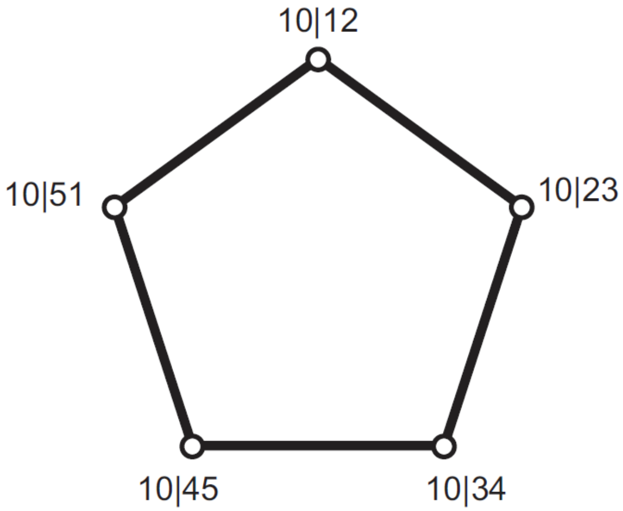

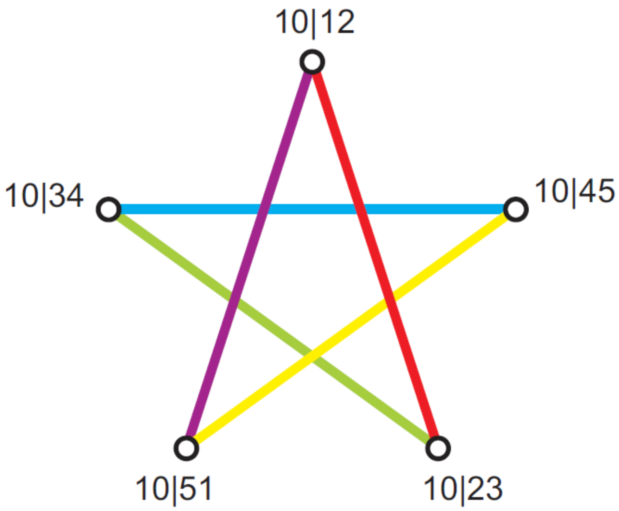

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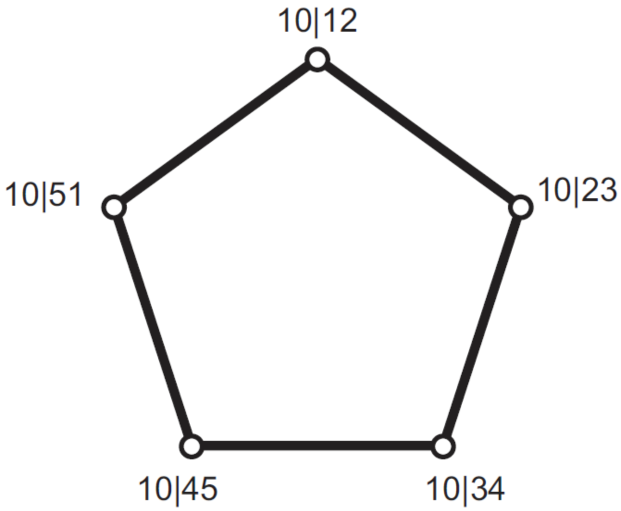
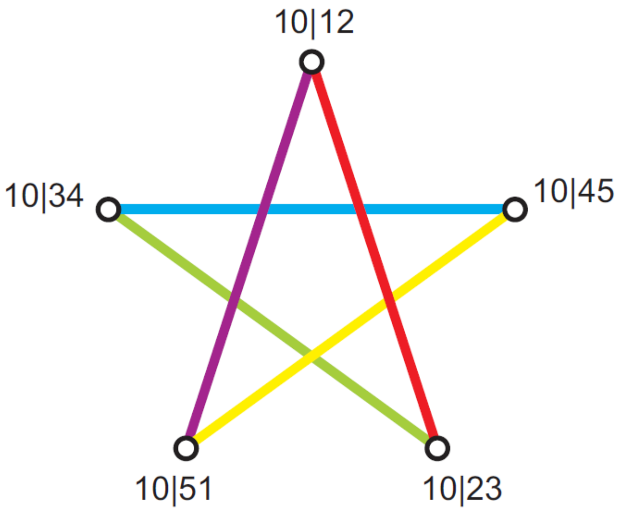
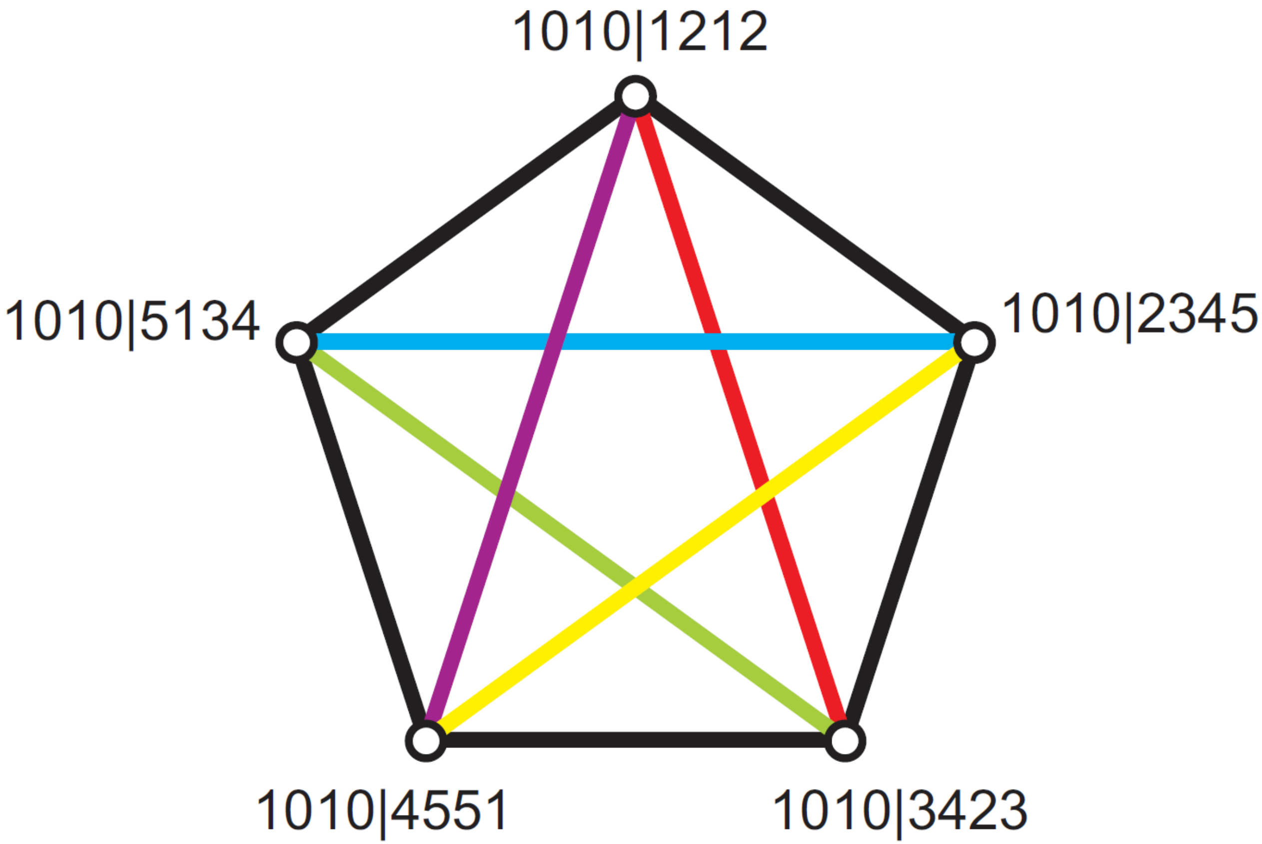




Vienna-Stockholm events

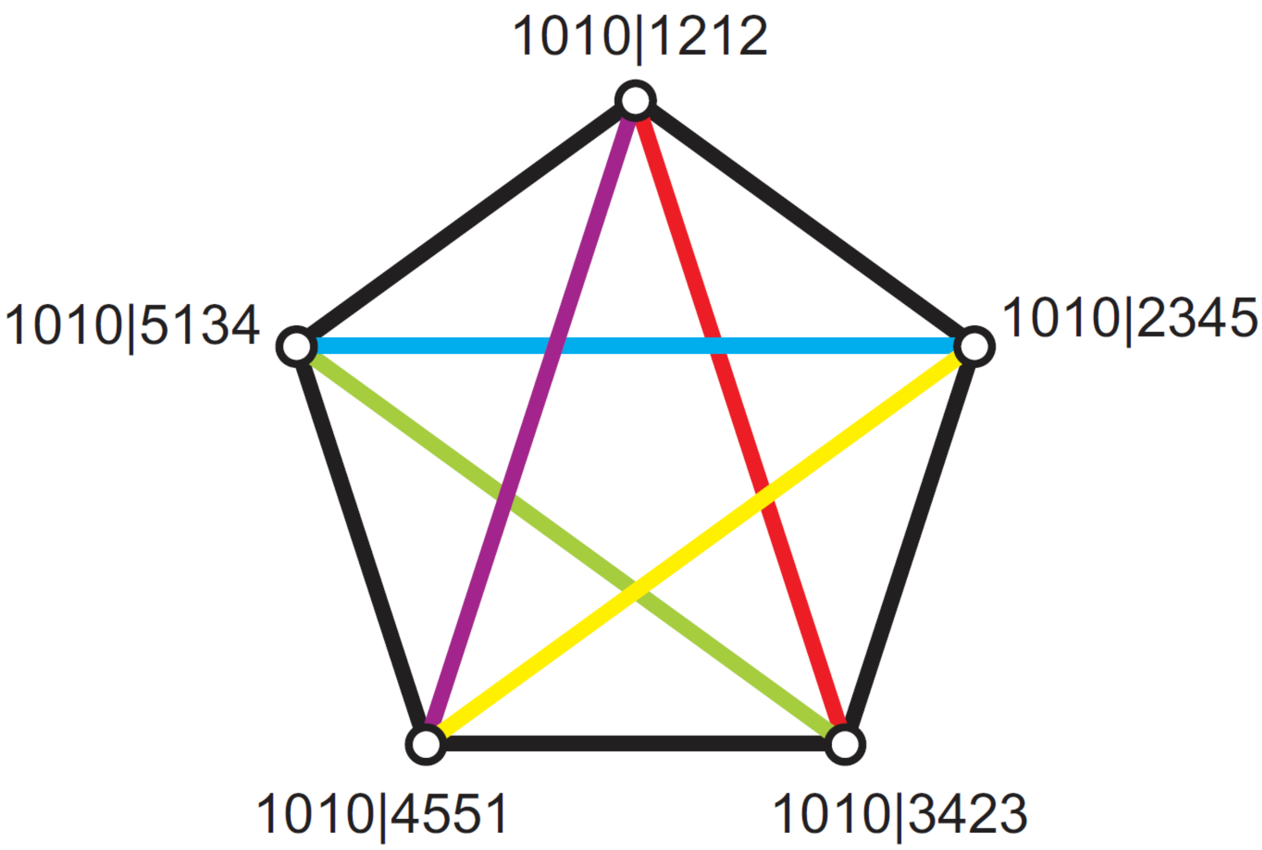


Since the V and S experiments are independent

Joint probability of two independent events:

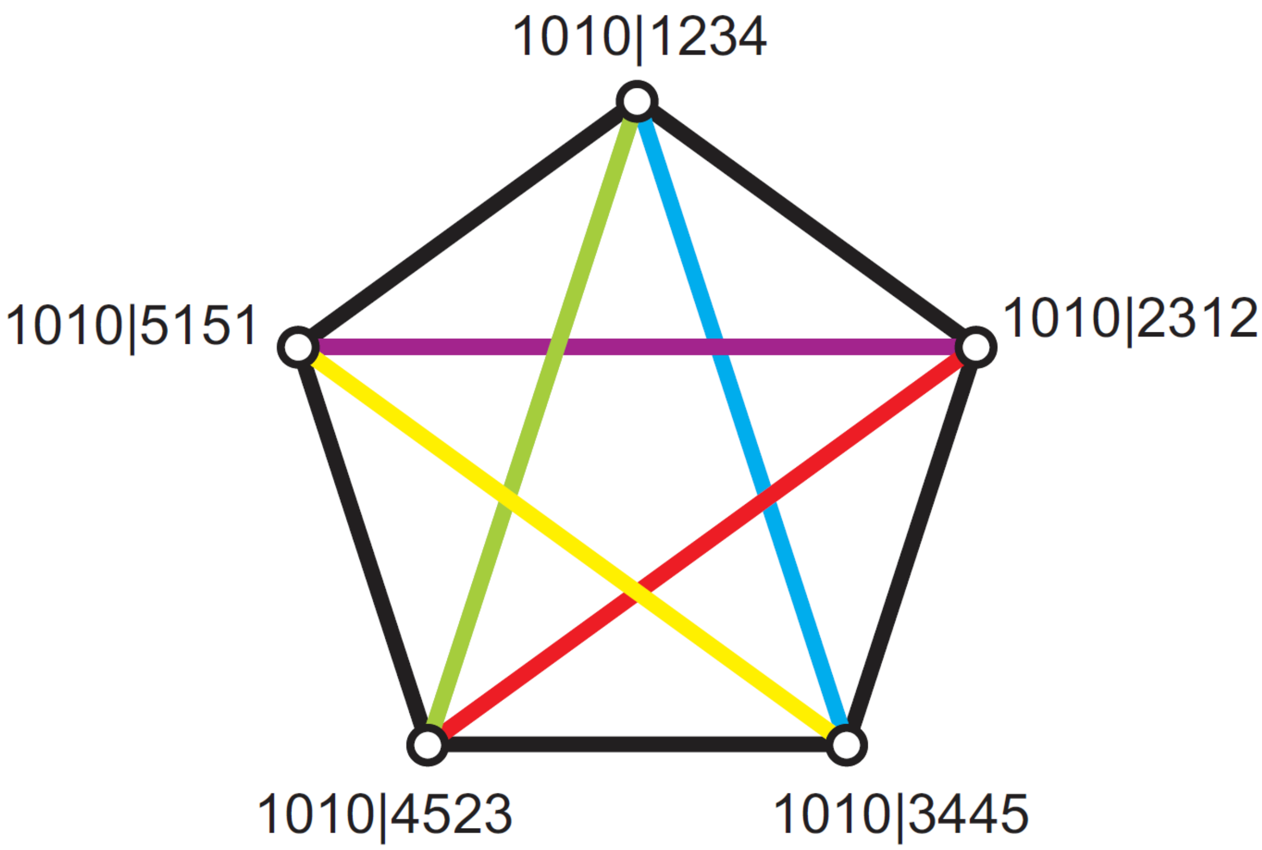
$$P(a, b, c, d | i_V, i{+}1_V, j_S, j{+}1_S) = P(a, b | i_V, i{+}1_V) P(c, d | j_S, j{+}1_S)$$

E inequality #1



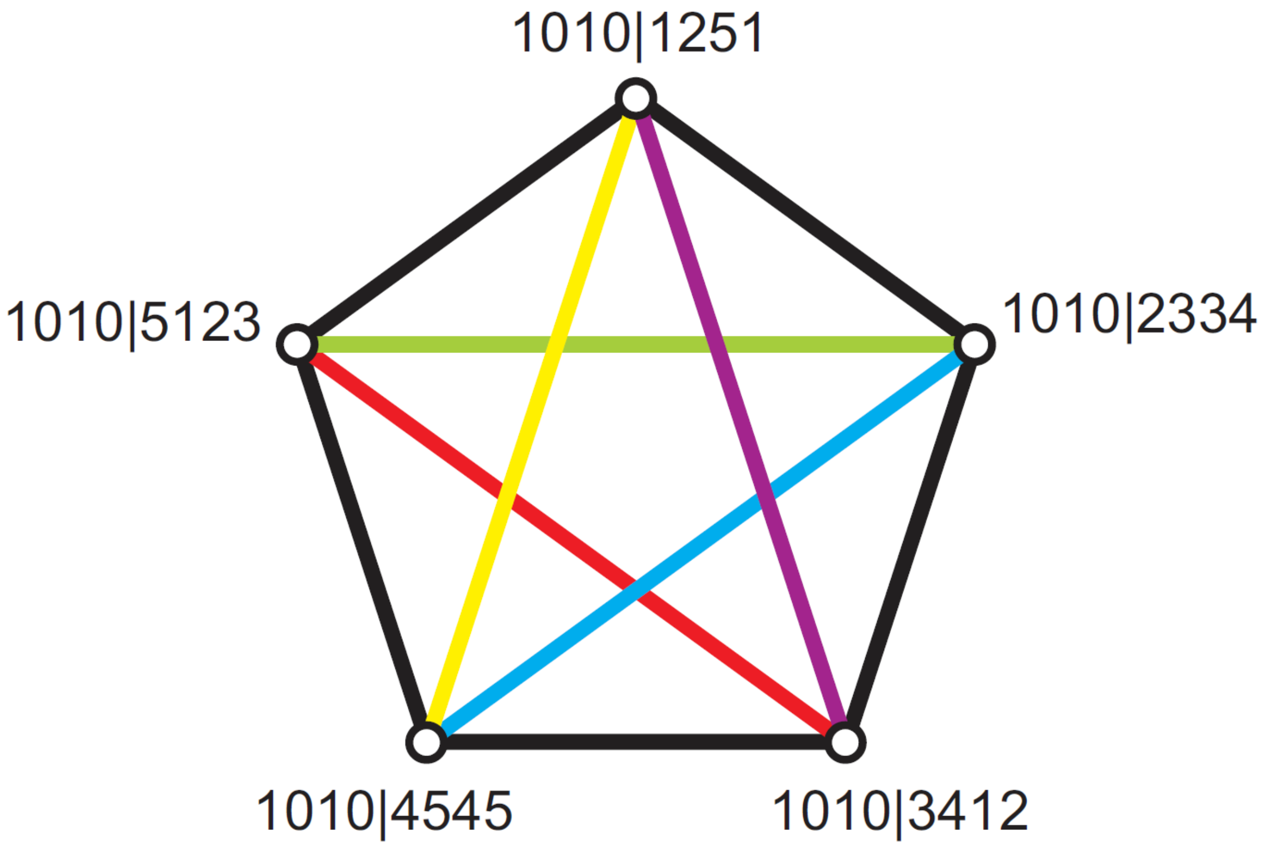
$$\boxed{P(10|12)P(10|12) + P(10|23)P(10|45) + P(10|34)P(10|23) + P(10|45)P(10|51) + P(10|51)P(10|34) \overset{\mathrm{E}}{\leq} 1}$$

E inequality #2



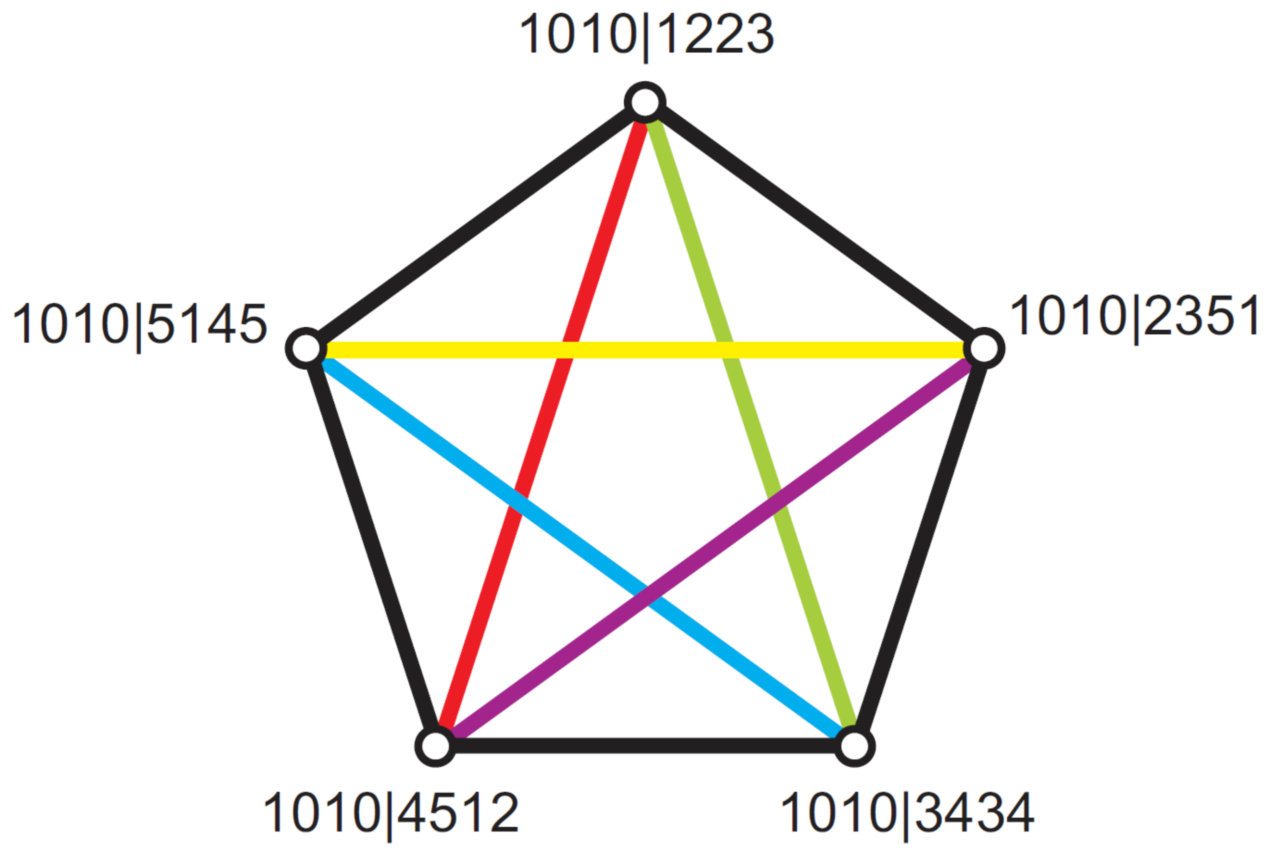
$$\boxed{P(10|12)P(10|34) + P(10|23)P(10|12) + P(10|34)P(10|45) + P(10|45)P(10|23) + P(10|51)P(10|51) \overset{\mathrm{E}}{\leq} 1}$$

E inequality #3



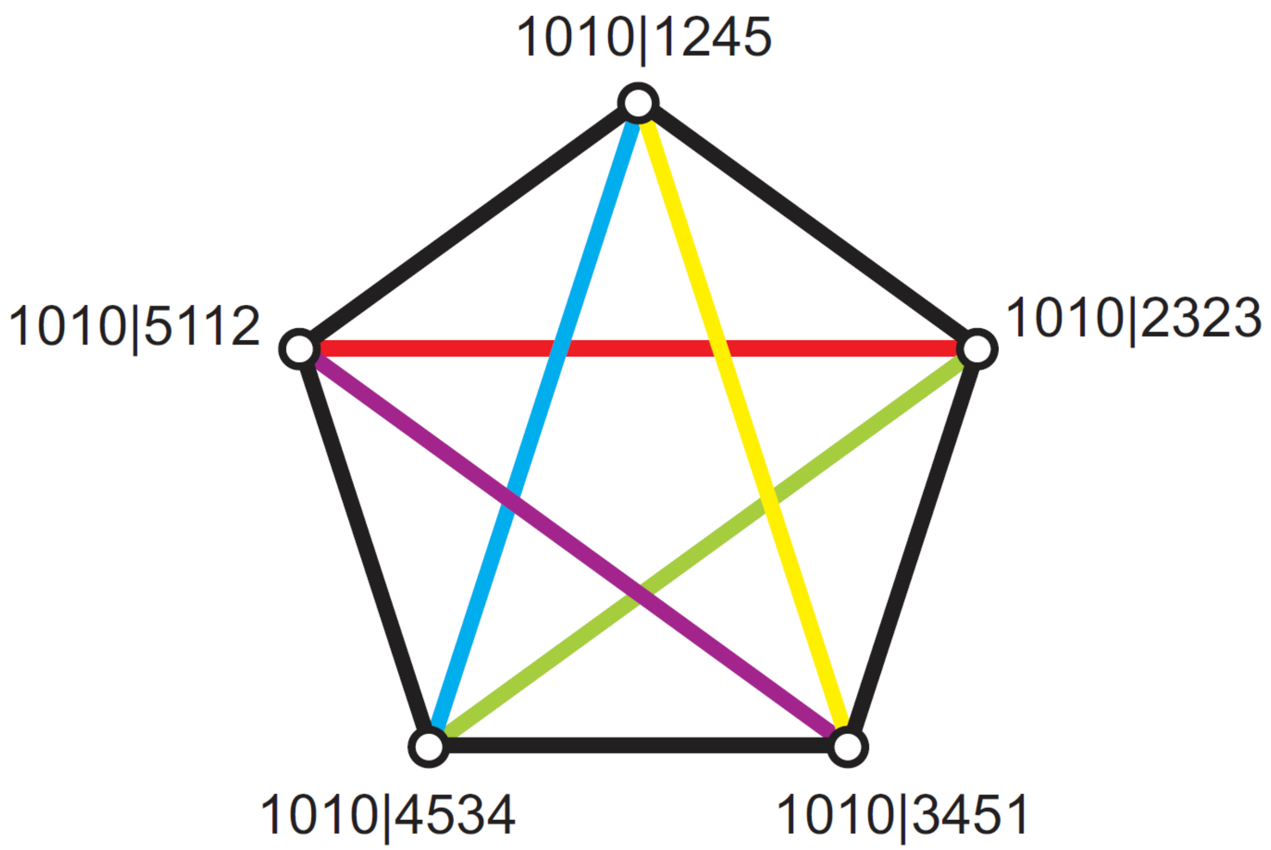
$$\boxed{P(10|12)P(10|51) + P(10|23)P(10|34) + P(10|34)P(10|12) + P(10|45)P(10|45) + P(10|51)P(10|23) \overset{\mathrm{E}}{\leq} 1}$$

E inequality #4



$$P(10|12)P(10|23) + P(10|23)P(10|51) + P(10|34)P(10|34) + P(10|45)P(10|12) + P(10|51)P(10|45) \overset{\mathrm{E}}{\leq} 1$$

E inequality #5



$$P(10|12)P(10|45) + P(10|23)P(10|23) + P(10|34)P(10|51) + P(10|45)P(10|34) + P(10|51)P(10|12) \overset{\mathrm{E}}{\leq} 1$$

Summing the 5 E inequalities

$$P(10|12)P(10|12) + P(10|23)P(10|45) + P(10|34)P(10|23) + P(10|45)P(10|51) + P(10|51)P(10|34) \overset{\text{E}}{\leq} 1$$
$$P(10|12)P(10|34) + P(10|23)P(10|12) + P(10|34)P(10|45) + P(10|45)P(10|23) + P(10|51)P(10|51) \overset{\text{E}}{\leq} 1$$
$$P(10|12)P(10|51) + P(10|23)P(10|34) + P(10|34)P(10|12) + P(10|45)P(10|45) + P(10|51)P(10|23) \overset{\text{E}}{\leq} 1$$
$$P(10|12)P(10|23) + P(10|23)P(10|51) + P(10|34)P(10|34) + P(10|45)P(10|12) + P(10|51)P(10|45) \overset{\text{E}}{\leq} 1$$
$$P(10|12)P(10|45) + P(10|23)P(10|23) + P(10|34)P(10|51) + P(10|45)P(10|34) + P(10|51)P(10|12) \overset{\text{E}}{\leq} 1$$

$$S^2 \overset{\text{E}}{\leq} 5$$

$$S \overset{\text{E}}{\leq} \sqrt{5}$$

$$S_{\text{KCBS}} \overset{\text{NCHV}}{\leq} 2 \overset{\text{Q}}{\leq} \sqrt{5} \overset{\text{GPT}}{\leq} \frac{5}{2}$$

A. Cabello, Phys. Rev. Lett. **110**, 060402 (2013).

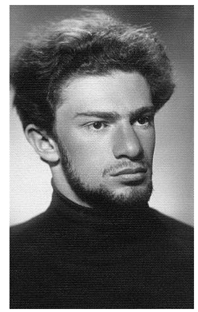
E explains the whole Q set for the pentagon

Result 2: If G is a self-complementary graph, the E principle, without any further assumptions, excludes any set of probability distributions strictly larger than the quantum set.

B. Amaral, M. Terra Cunha, and A. Cabello, Phys. Rev. A **89**, 030101(R) (2014).
A. B. Sainz, T. Fritz, R. Augusiak, J. Bohr Brask, R. Chaves, A. Leverrier, and A. Acín, Phys. Rev. A **89**, 032117 (2014).

Quantum physicists obsessed by Tsirelson's bound

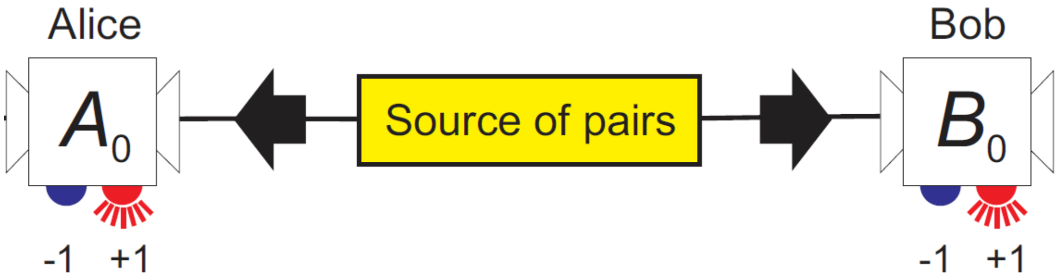
Why?

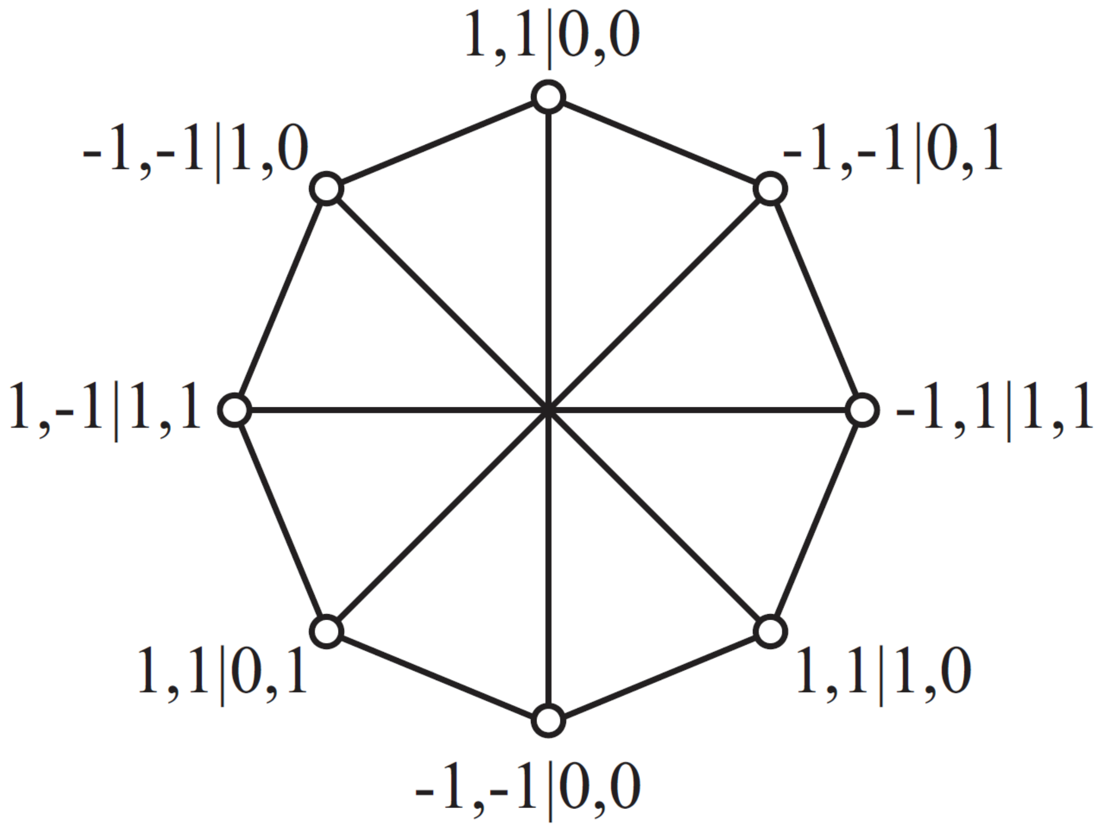
$$S_{\text{CHSH}} \overset{\text{LR}}{\leq} 3 \overset{\text{Q}}{\leq} 2+\sqrt{2} \overset{\text{NS}}{\leq} 4$$

$$\begin{aligned} S = {} & P(1,1\,|\,0,0) + P(-1,-1\,|\,0,0) + P(1,1\,|\,0,1) + P(-1,-1\,|\,0,1) \\ & + P(1,1\,|\,1,0) + P(-1,-1\,|\,1,0) + P(1,-1\,|\,1,1) + P(-1,1\,|\,1,1) \end{aligned}$$

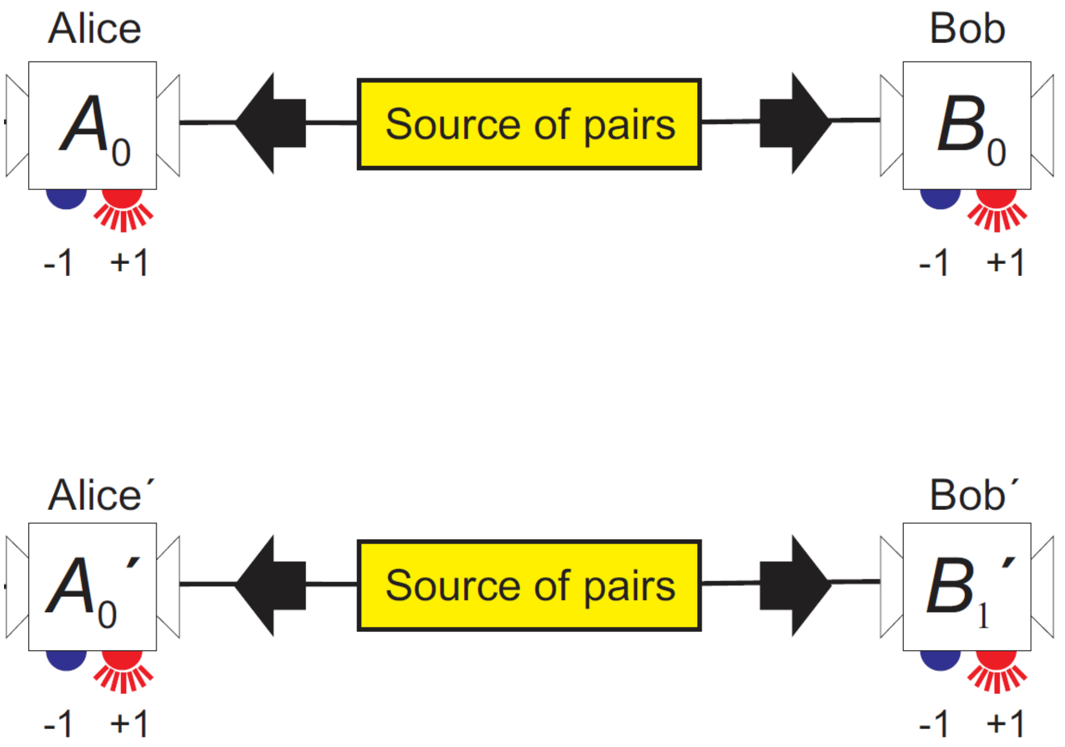
Why Tsirelson's bound?



Let's assume that each of the 8 events has prob. *p*



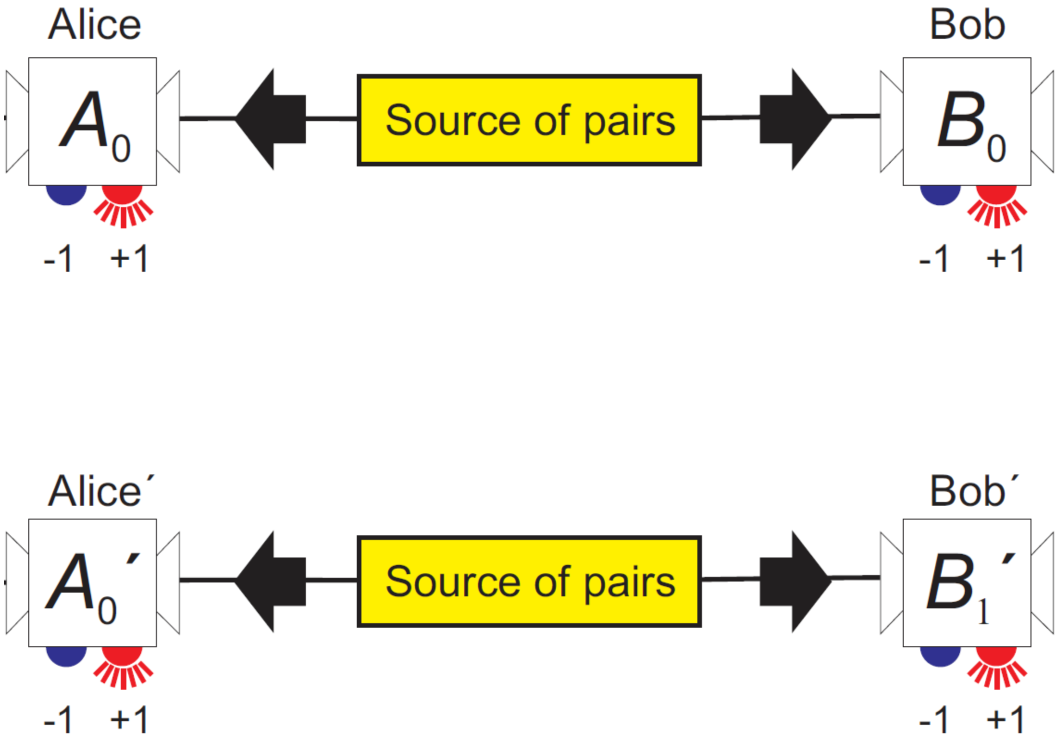
Consider a second copy



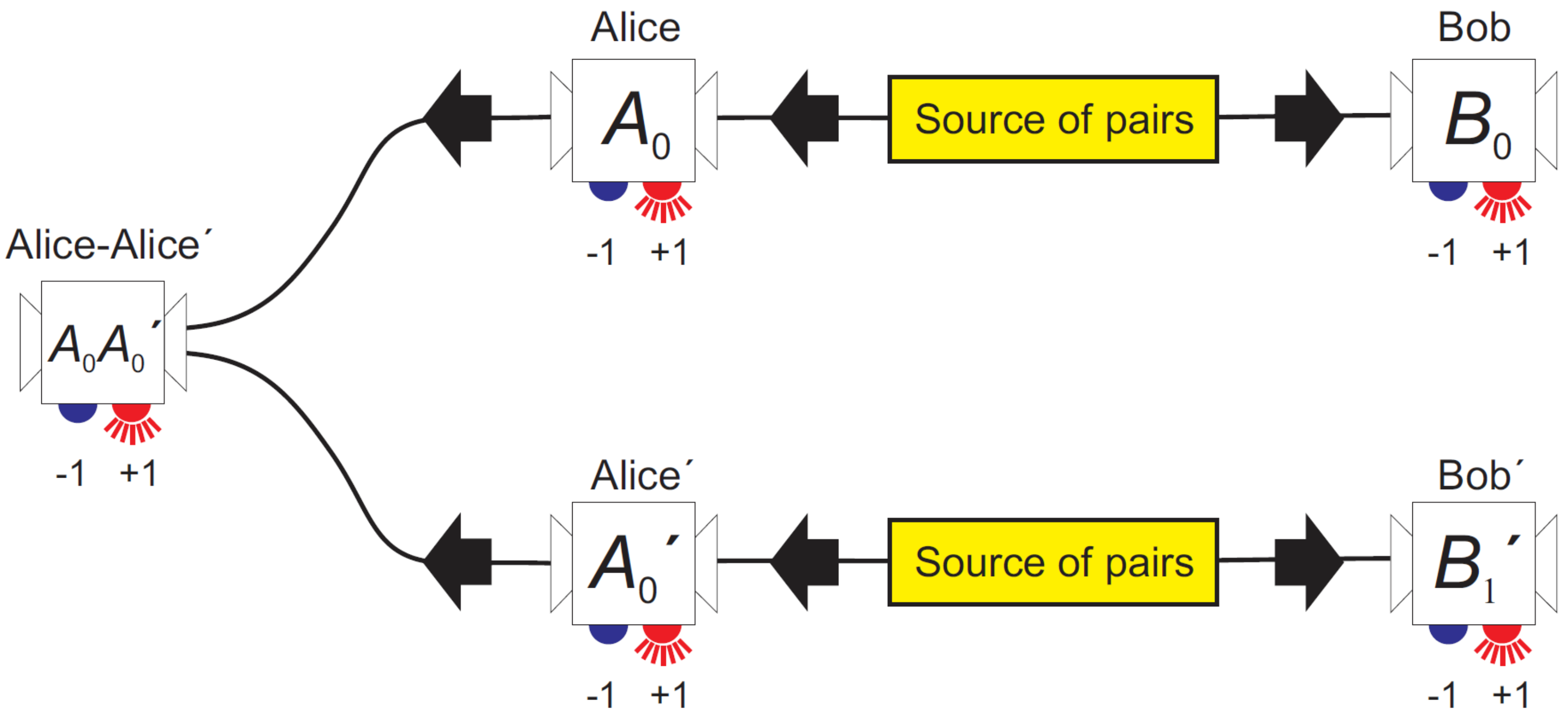
Then

Event	Probability
$e_1 = (A_0+, B_0+, A'_0+, B'_1+$	p^2
$e_3 = (A_0+, B_0-, A'_0+, B'_1-$	$\left(\frac{1}{2} - p\right)^2$

Now, in addition to the Bell-inequality measurements



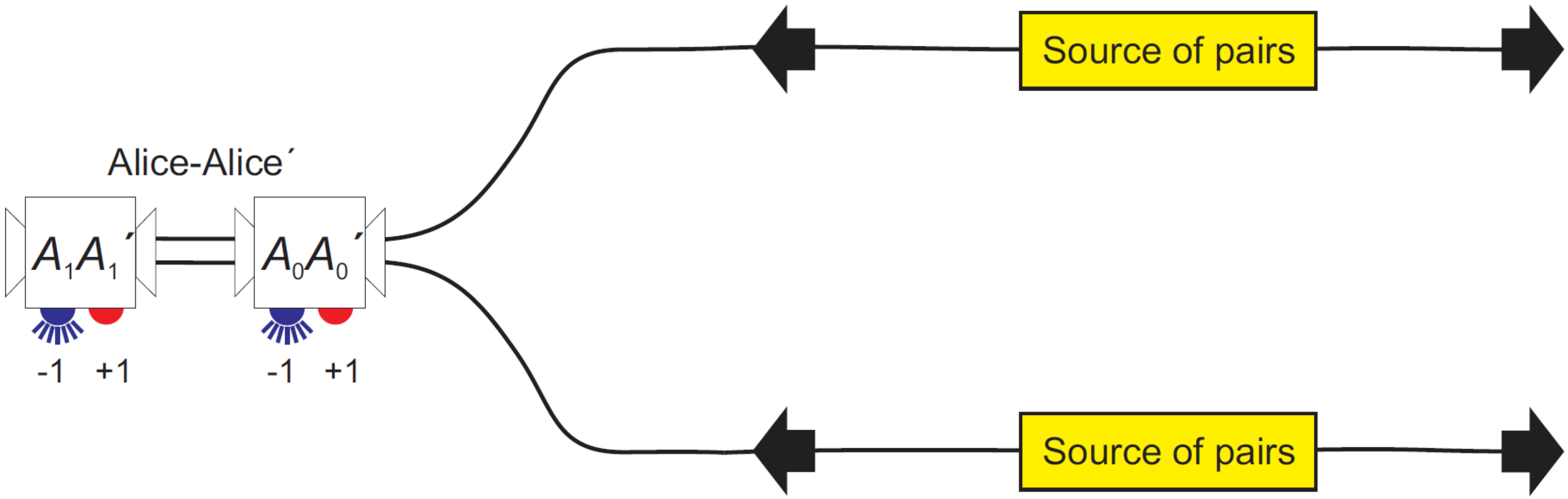
One can measure



So one can re-label the events as

Event	Probability
$e_1 = (A_0+, B_0+, A'_0+, B'_1+, A_0A'_0+)$	p^2
$e_3 = (A_0+, B_0-, A'_0+, B'_1-, A_0A'_0+)$	$\left(\frac{1}{2} - p\right)^2$

Alternatively



So one also has other type of events

Event	Probability
$e_1 = (A_0+, B_0+, A'_0+, B'_1+, A_0A'_0+)$	p^2
$e_3 = (A_0+, B_0-, A'_0+, B'_1-, A_0A'_0+)$	$\left(\frac{1}{2} - p\right)^2$
$e_9 = (A_0A'_0-, A_1A'_1-)$	$P(e_9)$

Consider the following 9 pairwise exclusive events

Event	Probability
$e_1 = (A_0+, B_0+, A'_0+, B'_1+, A_0A'_0+)$	p^2
$e_2 = (A_0-, B_0-, A'_0-, B'_1-, A_0A'_0+)$	p^2
$e_3 = (A_0+, B_0-, A'_0+, B'_1-, A_0A'_0+)$	$\left(\frac{1}{2} - p\right)^2$
$e_4 = (A_0-, B_0+, A'_0-, B'_1+, A_0A'_0+)$	$\left(\frac{1}{2} - p\right)^2$
$e_5 = (A_1+, B_0+, A'_1+, B'_1-, A_1A'_1+)$	p^2
$e_6 = (A_1-, B_0-, A'_1-, B'_1+, A_1A'_1+)$	p^2
$e_7 = (A_1+, B_0-, A'_1+, B'_1+, A_1A'_1+)$	$\left(\frac{1}{2} - p\right)^2$
$e_8 = (A_1-, B_0+, A'_1-, B'_1-, A_1A'_1+)$	$\left(\frac{1}{2} - p\right)^2$
$e_9 = (A_0A'_0-, A_1A'_1-)$	$P(e_9)$

$$\sum_{i=1}^{9} P(e_i) \overset{\text{E}}{\leq} 1$$

Similarly

Event	Probability	Event	Probability
$e_1 = (A_0+, B_0+, A'_0+, B'_1+, A_0A'_0+)$	p^2	$f_1 = (A_0+, B_0+, A'_0+, B'_0+, A_0A'_0+)$	p^2
$e_2 = (A_0-, B_0-, A'_0-, B'_1-, A_0A'_0+)$	p^2	$f_2 = (A_0-, B_0-, A'_0-, B'_0-, A_0A'_0+)$	p^2
$e_3 = (A_0+, B_0-, A'_0+, B'_1-, A_0A'_0+)$	$\left(\frac{1}{2}-p\right)^2$	$f_3 = (A_0+, B_0-, A'_0+, B'_0-, A_0A'_0+)$	$\left(\frac{1}{2}-p\right)^2$
$e_4 = (A_0-, B_0+, A'_0-, B'_1+, A_0A'_0+)$	$\left(\frac{1}{2}-p\right)^2$	$f_4 = (A_0-, B_0+, A'_0-, B'_0+, A_0A'_0+)$	$\left(\frac{1}{2}-p\right)^2$
$e_5 = (A_1+, B_0+, A'_1+, B'_1-, A_1A'_1+)$	p^2	$f_5 = (A_1+, B_0+, A'_1-, B'_0-, A_1A'_1-)$	p^2
$e_6 = (A_1-, B_0-, A'_1-, B'_1+, A_1A'_1+)$	p^2	$f_6 = (A_1-, B_0-, A'_1+, B'_0+, A_1A'_1-)$	p^2
$e_7 = (A_1+, B_0-, A'_1+, B'_1+, A_1A'_1+)$	$\left(\frac{1}{2}-p\right)^2$	$f_7 = (A_1+, B_0-, A'_1-, B'_0+, A_1A'_1-)$	$\left(\frac{1}{2}-p\right)^2$
$e_8 = (A_1-, B_0+, A'_1-, B'_1-, A_1A'_1+)$	$\left(\frac{1}{2}-p\right)^2$	$f_8 = (A_1-, B_0+, A'_1+, B'_0-, A_1A'_1-)$	$\left(\frac{1}{2}-p\right)^2$
$e_9 = (A_0A'_0-, A_1A'_1-)$	$P(e_9)$	$f_9 = (A_0A'_0-, A_1A'_1+)$	$\frac{1}{2} - P(e_9)$

$$\sum_{i=1}^{9} P(e_i) \overset{\mathrm{E}}{\leq} 1 \qquad \sum_{i=1}^{9} P(f_i) \overset{\mathrm{E}}{\leq} 1$$

Summing the 2 E inequalities

$$\sum_{i=1}^{9} P(e_i) + P(f_i) \overset{\mathrm{E}}{\leq} 2$$

$$p \overset{\mathrm{E}}{\leq} \frac{2+\sqrt{2}}{8}$$

$$S \overset{\mathrm{E}}{\leq} 2+\sqrt{2}$$

Assuming arbitrary probabilities for the 8 vertices

- There are 16 tables. Summing them all, we get

$$S^2 + (4 - S)^2 + 4 \overset{\mathrm{E}}{\leq} 16$$

$$S \overset{\mathrm{E}}{\leq} 2 + \sqrt{2}.$$

A. Cabello, arXiv:1406.5656.

Principles (2009)

	Information causality	Macroscopic locality	Local orthogonality	E
Q maximum of KCBS	No	No	No	Yes (the whole Q set!)
Q maximum of the basic NC inequalities	No	No	No	"Strong evidence" that yes
Q maximum of Bell CHSH	Yes	Yes	?	Yes
Lack of extremal tripartite correlations	No	No	Yes	Yes
Lack of irreducible third-order interference implies...	?	?	Yes	Yes

M. Pawłowski, T. Paterek, D. Kaszlikowski, V. Scarani, A. Winter, and M. Żukowski, Nature (London) **461**, 1101 (2009).

M. Navascués and H. Wunderlich, Proc. Royal Soc. A **466**, 881 (2009).

Principles (2013)

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T. Fritz, A. B. Sainz, R. Augusiak, J. Bohr Brask, R. Chaves, A. Leverrier, and A. Acín, Nat. Comm. **4**, 2263 (2013).

A. Cabello, Phys. Rev. Lett. **110**, 060402 (2013).

What the principles explain

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A. Cabello, Phys. Rev. Lett. **110**, 060402 (2013).

B. Amaral, M. Terra Cunha, and A. Cabello, Phys. Rev. A **89**, 030101(R) (2014).

A. B. Sainz, T. Fritz, R. Augusiak, J. Bohr Brask, R. Chaves, A. Leverrier, and A. Acín, Phys. Rev. A **89**, 032117 (2014).

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A. Cabello, L. E. Danielsen, A. J. López-Tarrida, and J. R. Portillo, Phys. Rev. A **88**, 032104 (2013).

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R. Gallego, L. E. Würflinger, A. Acín, and N. Navascués, Phys. Rev. Lett. **107**, 210403 (2011).
T. H. Yang, D. Cavalcanti, M. L. Almeida, C. Teo, and V. Scarani, New J. Phys. **14**, 013061 (2012).

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Q maximum of Bell CHSH	Yes	Yes	?	Yes
Lack of extremal tripartite correlations	No	No	Yes	Yes
Lack of irreducible third-order interference implies. . .	?	?	Yes	Yes

J. Henson, arXiv:1406.3281.

What the principles explain

	Information causality	Macroscopic locality	Local orthogonality	E
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Q maximum of the basic NC inequalities	No	No	No	"Strong evidence" that yes
Q maximum of Bell CHSH	Yes	Yes	?	Yes
Lack of extremal tripartite correlations	No	No	Yes	Yes
Lack of irreducible third-order interference implies...	?	?	Yes	Yes

Conclusions and open question

- The E principle explains more about quantum correlations than any other proposed principle.
- The E principle is not an “information principle”, but a “logic principle”.
- Is the E principle “the” principle of quantum correlations and therefore a key principle of QT?