Beyond quantum mechanics and where to find it

Michał Eckstein

Institute of Theoretical Physics, Jagiellonian University, Kraków, Poland
International Center for Theory of Quantum Technologies, University of Gdańsk

Oxford, 3 October 2024

Routes towards New Physics

Standard Model ⊂ QFT = Quantum Mechanics + Special Relativity

Routes towards New Physics:

1. Beyond Standard Model, but still in QFT
   - SUSY, composite Higgs, dark sector, inflation, ...
2. Beyond Special Relativity, but assuming QM
   - QFT in curved spacetimes – 'semi-classical' (Unruh effect, Hawking radiation ...)
   - quantum gravity
3. **Beyond Quantum Mechanics**, but assuming relativity

Routes towards New Physics

$$\text{Standard Model} \subset \text{QFT} = \text{Quantum Mechanics} + \text{Special Relativity}$$

Routes towards New Physics:

1. Beyond Standard Model, but still in QFT
   - SUSY, composite Higgs, dark sector, inflation, ...
2. Beyond Special Relativity, but assuming QM
   - QFT in curved spacetimes – 'semi-classical' (Unruh effect, Hawking radiation ...)
   - quantum gravity
3. **Beyond Quantum Mechanics**, but assuming relativity

Routes towards New Physics

Standard Model $\subset$ QFT = Quantum Mechanics + Special Relativity

Routes towards New Physics:

1. Beyond Standard Model, but still in QFT
   - SUSY, composite Higgs, dark sector, inflation, ...
2. Beyond Special Relativity, but assuming QM
   - QFT in curved spacetimes – 'semi-classical' (Unruh effect, Hawking radiation ...)
   - quantum gravity
3. **Beyond Quantum Mechanics**, but assuming relativity

Routes towards New Physics

Standard Model $\subset$ QFT = Quantum Mechanics + Special Relativity

Routes towards New Physics:

1. Beyond Standard Model, but still in QFT
   - SUSY, composite Higgs, dark sector, inflation, ...
2. Beyond Special Relativity, but assuming QM
   - QFT in curved spacetimes – 'semi-classical' (Unruh effect, Hawking radiation ...)
   - quantum gravity
3. **Beyond Quantum Mechanics**, but assuming relativity

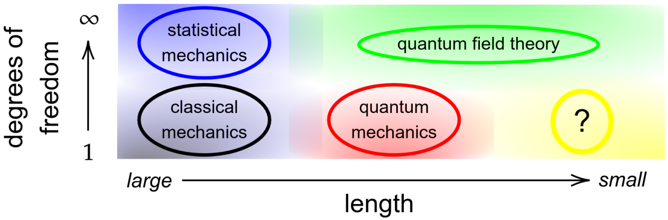
Routes towards New Physics

Standard Model $\subset$ QFT $=$ Quantum Mechanics $+$ Special Relativity

Routes towards New Physics:

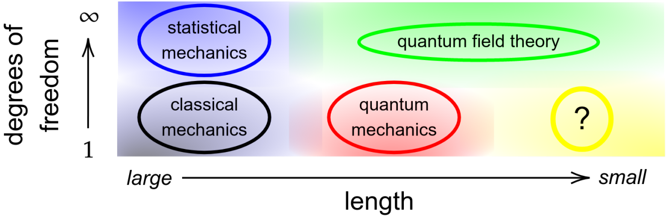
1. Beyond Standard Model, but still in QFT
   - SUSY, composite Higgs, dark sector, inflation, . . .
2. Beyond Special Relativity, but assuming QM
   - QFT in curved spacetimes – 'semi-classical' (Unruh effect, Hawking radiation . . .)
   - quantum gravity
3. **Beyond Quantum Mechanics**, but assuming relativity

Classical, quantum, . . . ?



- Where (when, how, . . .) does the measurement happen?
- Is there a gap between QM and QFT?
- Are QM & QFT only effective descriptions of Nature?
- How to seek possible deviations from QM (*and* classicality)?

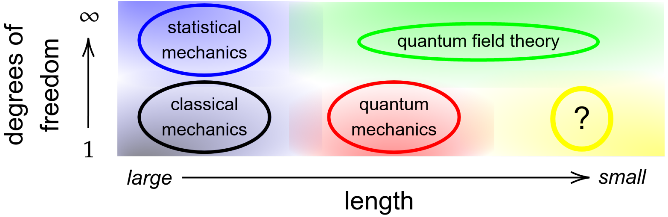
Classical, quantum, . . . ?



- Where (when, how, . . .) does the measurement happen?
- Is there a gap between QM and QFT?
- Are QM & QFT only effective descriptions of Nature?

- How to seek possible deviations from QM (*and* classicality)?

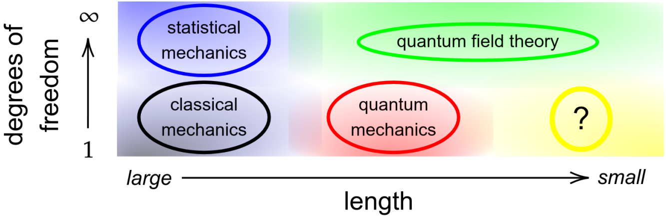
Classical, quantum, . . . ?



- Where (when, how, . . .) does the measurement happen?
- Is there a gap between QM and QFT?
- Are QM & QFT only effective descriptions of Nature?

- How to seek possible deviations from QM (*and* classicality)?

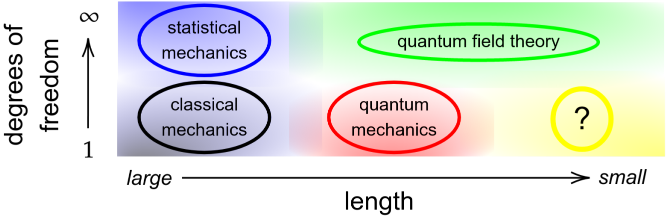
Classical, quantum, . . . ?



- Where (when, how, . . .) does the measurement happen?
- Is there a gap between QM and QFT?
- Are QM & QFT only effective descriptions of Nature?

- How to seek possible deviations from QM (*and* classicality)?

Classical, quantum, . . . ?



- Where (when, how, . . .) does the measurement happen?
- Is there a gap between QM and QFT?
- Are QM & QFT only effective descriptions of Nature?

- How to seek possible deviations from QM (*and* classicality)?

The "theory independent" **black box** methodology

- Physical systems are treated as information-processing devices ("**black boxes**") and probed by free agents.
- The conclusions are drawn from the **output–input correlations**.

$$P(\text{outputs} \,|\, \text{inputs})$$

Bell test: 2 agents (Alice and Bob) — 2 inputs (x, y) — 2 outputs (a, b)

The *experimental* (frequency) correlation function:

$$C_e(x, y) = P(a = b \,|\, x, y) - P(a \neq b \,|\, x, y)$$

The key assumption of *freedom of choice* ("measurement independence"):

$$P(x, y \,|\, \lambda) = P(x) \cdot P(y)$$

- No pre-correlations between the inputs (x, y) and the box (λ).

The "theory independent" **black box** methodology

- Physical systems are treated as information-processing devices ("**black boxes**") and probed by free agents.
- The conclusions are drawn from the **output–input correlations**.

$$P(\text{outputs} \,|\, \text{inputs})$$

Bell test: 2 agents (Alice and Bob) — 2 inputs (x, y) — 2 outputs (a, b)

The *experimental* (frequency) correlation function:

$$C_e(x, y) = P(a = b \,|\, x, y) - P(a \neq b \,|\, x, y)$$

The key assumption of *freedom of choice* ("measurement independence"):

$$P(x, y \,|\, \lambda) = P(x) \cdot P(y)$$

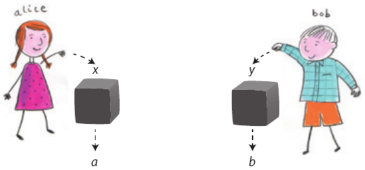
- No pre-correlations between the inputs (x, y) and the box (λ).

The "theory independent" **black box** methodology

- Physical systems are treated as information-processing devices ("**black boxes**") and probed by free agents.
- The conclusions are drawn from the **output–input correlations**.

$$P\big(\text{outputs}\,|\,\text{inputs}\big)$$

Bell test: 2 agents (Alice and Bob) — 2 inputs (x, y) — 2 outputs (a, b)



The *experimental* (frequency) correlation function:

$$C_e(x,y) = P(a = b\,|\,x,y) - P(a \neq b\,|\,x,y)$$

[Sandu Popescu, *Nature Physics* 10, 264 (2014)]

The key assumption of *freedom of choice* ("measurement independence"):

$$P(x, y\,|\,\lambda) = P(x) \cdot P(y)$$

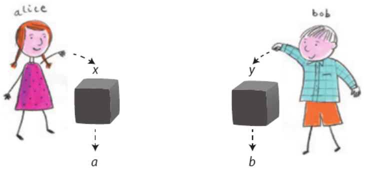
- No pre-correlations between the inputs (x, y) and the box (λ).

The "theory independent" **black box** methodology

- Physical systems are treated as information-processing devices ("**black boxes**") and probed by free agents.
- The conclusions are drawn from the **output–input correlations**.

$$P\big(\text{outputs}\,|\,\text{inputs}\big)$$

<u>Bell test</u>: 2 agents (Alice and Bob) — 2 inputs (x, y) — 2 outputs (a, b)



The *experimental* (frequency) correlation function:

$$C_e(x,y) = P(a = b\,|\,x,y) - P(a \neq b\,|\,x,y)$$

[Sandu Popescu, *Nature Physics* **10**, 264 (2014)]

The key assumption of *freedom of choice* ("measurement independence"):

$$P(x,y\,|\,\lambda) = P(x)\cdot P(y)$$

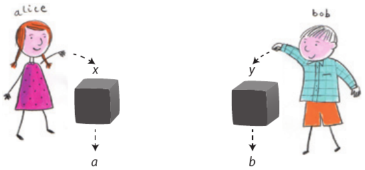
- No pre-correlations between the inputs (x, y) and the box (λ).

The "theory independent" **black box** methodology

- Physical systems are treated as information-processing devices ("**black boxes**") and probed by free agents.
- The conclusions are drawn from the **output–input correlations**.

$$P(\text{outputs} \,|\, \text{inputs})$$

Bell test: 2 agents (Alice and Bob) — 2 inputs (x, y) — 2 outputs (a, b)



The *experimental* (frequency) correlation function:

$$C_e(x,y) = P(a = b \,|\, x, y) - P(a \neq b \,|\, x, y)$$

[Sandu Popescu, *Nature Physics* **10**, 264 (2014)]

The key assumption of *freedom of choice* ("measurement independence"):

$$P(x, y \,|\, \lambda) = P(x) \cdot P(y)$$

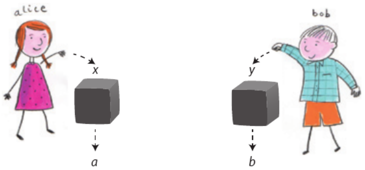
- No pre-correlations between the inputs (x, y) and the box (λ).

The "theory independent" **black box** methodology

- Physical systems are treated as information-processing devices ("**black boxes**") and probed by free agents.
- The conclusions are drawn from the **output–input correlations**.

$$P(\text{outputs} \,|\, \text{inputs})$$

<u>Bell test</u>: 2 agents (Alice and Bob) — 2 inputs (x, y) — 2 outputs (a, b)



The *experimental* (frequency) correlation function:

$$C_e(x, y) = P(a = b \,|\, x, y) - P(a \neq b \,|\, x, y)$$

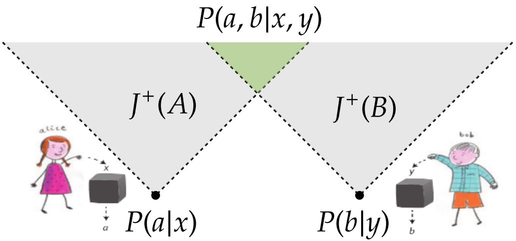
[Sandu Popescu, *Nature Physics* 10, 264 (2014)]

The key assumption of *freedom of choice* ("measurement independence"):

$$P(x, y \,|\, \lambda) = P(x) \cdot P(y)$$

- No pre-correlations between the inputs (x, y) and the box (λ).

Basic compatibility with relativity



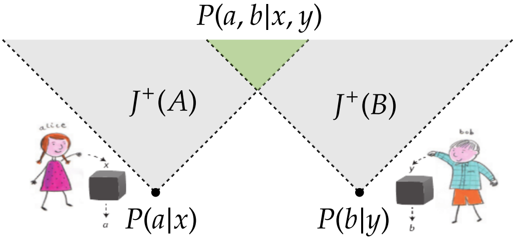
$\forall\, y \quad P(a|xy) = P(a|x)$ $\qquad$ $\forall\, x \quad P(b|xy) = P(b|y)$

The no-signalling principle

A *free* agent in spacetime region $\mathcal{K}$ cannot influence any detection statistics outside of $J^+(\mathcal{K})$.

- M.E., P. Horodecki, R. Horodecki, T. Miller, R. Ramanathan, arXiv:24xx.xxxxx.

Basic compatibility with relativity



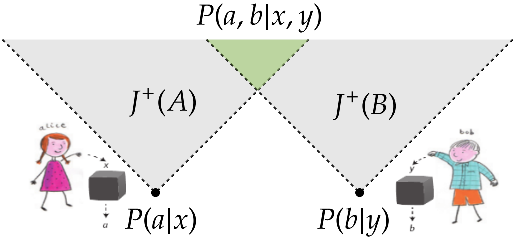
$\forall\, y \quad P(a|xy) = P(a|x)$ $\qquad \forall\, x \quad P(b|xy) = P(b|y)$

The no-signalling principle

A *free* agent in spacetime region $\mathcal{K}$ cannot influence any detection statistics outside of $J^+(\mathcal{K})$.

- M.E., P. Horodecki, R. Horodecki, T. Miller, R. Ramanathan, arXiv:24xx.xxxxx.

Basic compatibility with relativity



$\forall\, y \quad P(a|xy) = P(a|x) \qquad\qquad \forall\, x \quad P(b|xy) = P(b|y)$

The no-signalling principle

A *free* agent in spacetime region $\mathcal{K}$ cannot influence any detection statistics outside of $J^+(\mathcal{K})$.

- M.E., P. Horodecki, R. Horodecki, T. Miller, R. Ramanathan, arXiv:24xx.xxxxx.

Nonlocal correlations beyond quantum mechanics

Bell-CHSH inequality: 2 parties – 2 inputs – 2 outcomes

$$S := C_{\mathsf{LHV}}(x,y) + C_{\mathsf{LHV}}(x,y') + C_{\mathsf{LHV}}(x',y) - C_{\mathsf{LHV}}(x',y') \leq 2 < 2\sqrt{2}$$

Could we have $S = 4$ *assuming* free choice and no-signalling?

No-signalling boxes [Popescu, Rohrlich (1994)]

$$P(a,b\,|\,x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise,} \end{cases} \qquad S_{\mathsf{PR}} = 4.$$

- No-signalling principle admits correlations that are **stronger than entanglement**.

Nonlocal correlations beyond quantum mechanics

Bell-CHSH inequality: 2 parties – 2 inputs – 2 outcomes

$$S := C_{\mathsf{LHV}}(x,y) + C_{\mathsf{LHV}}(x,y') + C_{\mathsf{LHV}}(x',y) - C_{\mathsf{LHV}}(x',y') \leq 2 < 2\sqrt{2}$$

Could we have $S = 4$ *assuming* free choice and no-signalling?

No-signalling boxes [Popescu, Rohrlich (1994)]

$$P(a,b\,|\,x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise,} \end{cases} \qquad S_{\mathsf{PR}} = 4.$$

- No-signalling principle admits correlations that are **stronger than entanglement**.

Nonlocal correlations beyond quantum mechanics

Quantum bound on CHSH correlations [Tsirelson (1980)]

$$S = C_{\mathsf{QM}}(x,y) + C_{\mathsf{QM}}(x,y') + C_{\mathsf{QM}}(x',y) - C_{\mathsf{QM}}(x',y') \leq 2\sqrt{2} < 4$$

Could we have $S = 4$ *assuming* free choice and no-signalling?

No-signalling boxes [Popescu, Rohrlich (1994)]

$$P(a,b\,|\,x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise,} \end{cases} \qquad S_{\mathsf{PR}} = 4.$$

- No-signalling principle admits correlations that are **stronger than entanglement**.

Nonlocal correlations beyond quantum mechanics

Quantum bound on CHSH correlations [Tsirelson (1980)]

$$S = C_{\mathsf{QM}}(x,y) + C_{\mathsf{QM}}(x,y') + C_{\mathsf{QM}}(x',y) - C_{\mathsf{QM}}(x',y') \leq 2\sqrt{2} < 4$$

Could we have $S = 4$ *assuming* free choice and no-signalling?

No-signalling boxes [Popescu, Rohrlich (1994)]

$$P(a,b\,|\,x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise,} \end{cases} \qquad S_{\mathsf{PR}} = 4.$$

- No-signalling principle admits correlations that are **stronger than entanglement**.

Nonlocal correlations beyond quantum mechanics

Quantum bound on CHSH correlations [Tsirelson (1980)]

$$S = C_{\mathsf{QM}}(x,y) + C_{\mathsf{QM}}(x,y') + C_{\mathsf{QM}}(x',y) - C_{\mathsf{QM}}(x',y') \leq 2\sqrt{2} < 4$$

Could we have $S = 4$ *assuming* free choice and no-signalling?

No-signalling boxes [Popescu, Rohrlich (1994)]

$$P(a,b\,|\,x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise,} \end{cases} \qquad S_{\mathsf{PR}} = 4.$$

- No-signalling principle admits correlations that are **stronger than entanglement**.

Nonlocal correlations beyond quantum mechanics

Quantum bound on CHSH correlations [Tsirelson (1980)]

$$S = C_{\mathsf{QM}}(x,y) + C_{\mathsf{QM}}(x,y') + C_{\mathsf{QM}}(x',y) - C_{\mathsf{QM}}(x',y') \leq 2\sqrt{2} < 4$$

Could we have $S = 4$ *assuming* free choice and no-signalling? Yes, we can!

No-signalling boxes [Popescu, Rohrlich (1994)]

$$P(a,b\,|\,x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise,} \end{cases} \qquad S_{\mathsf{PR}} = 4.$$

- No-signalling principle admits correlations that are **stronger than entanglement**.

Nonlocal correlations beyond quantum mechanics

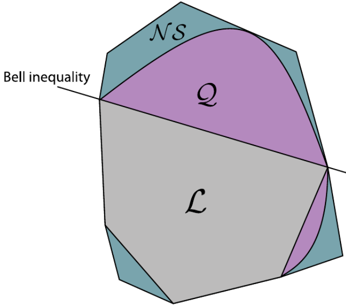
Quantum bound on CHSH correlations [Tsirelson (1980)]

$$S = C_{\mathrm{QM}}(x,y) + C_{\mathrm{QM}}(x,y') + C_{\mathrm{QM}}(x',y) - C_{\mathrm{QM}}(x',y') \le 2\sqrt{2} < 4$$

Could we have $S = 4$ *assuming* free choice and no-signalling? Yes, we can!

No-signalling boxes [Popescu, Rohrlich (1994)]

$$P(a,b\,|\,x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise,} \end{cases} \qquad S_{\mathrm{PR}} = 4.$$



- No-signalling principle admits correlations that are **stronger than entanglement**.

[N. Brunner, D. Cavalcanti, S. Pironio, V. Scarani, S. Wehner, *Rev. Mod. Phys.* **86**, 419 (2014)]

Nonlocal correlations beyond quantum mechanics

Quantum bound on CHSH correlations [Tsirelson (1980)]

$$S = C_{\mathsf{QM}}(x,y) + C_{\mathsf{QM}}(x,y') + C_{\mathsf{QM}}(x',y) - C_{\mathsf{QM}}(x',y') \leq 2\sqrt{2} < 4$$

Could we have $S = 4$ *assuming* free choice and no-signalling? Yes, we can!

No-signalling boxes [Popescu, Rohrlich (1994)]

$$P(a,b\,|\,x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise,} \end{cases} \qquad S_{\mathsf{PR}} = 4.$$


REVIEW ARTICLES | INSIGHT

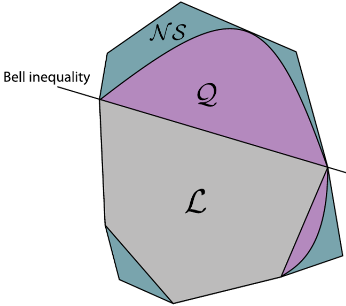
PUBLISHED ONLINE: 1 APRIL 2014 | DOI: 10.1038/NPHYS2916

nature physics

Nonlocality beyond quantum mechanics

Sandu Popescu

- No-signalling principle admits correlations that are **stronger than entanglement**.



[N. Brunner, D. Cavalcanti, S. Pironio, V. Scarani, S. Wehner, *Rev. Mod. Phys.* **86**, 419 (2014)]

Nonlocal correlations beyond quantum mechanics

Quantum bound on CHSH correlations [Tsirelson (1980)]

$$S = C_{\mathsf{QM}}(x,y) + C_{\mathsf{QM}}(x,y') + C_{\mathsf{QM}}(x',y) - C_{\mathsf{QM}}(x',y') \leq 2\sqrt{2} < 4$$

Could we have $S = 4$ *assuming* free choice and no-signalling? Yes, we can!

No-signalling boxes [Popescu, Rohrlich (1994)]

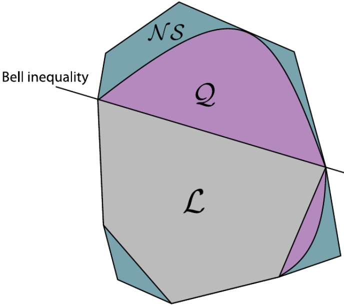
$$P(a,b\,|\,x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise}, \end{cases} \qquad S_{\mathsf{PR}} = 4.$$

REVIEW ARTICLES | INSIGHT
PUBLISHED ONLINE: 1 APRIL 2014 | DOI: 10.1038/NPHYS2916
nature physics

Nonlocality beyond quantum mechanics

Sandu Popescu

- No-signalling principle admits correlations that are **stronger than entanglement**.



[N. Brunner, D. Cavalcanti, S. Pironio, V. Scarani, S. Wehner, *Rev. Mod. Phys.* **86**, 419 (2014)]

Nonlocal jamming of correlations

- The standard 3-party 'no-signalling' conditions

$$P(a, b \,|\, x, y) = \sum_c P(a, b, c \,|\, x, y, z).$$

are sufficient, but not necessary for no-signalling!

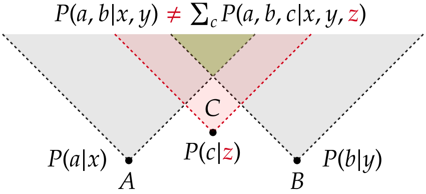
- Charlie changes '*at a distance*' the correlations between Alice and Bob, but he does not influence their local statistics.
- Alice and Bob can only check the correlations when they meet.

Nonlocal jamming of correlations

- The standard 3-party 'no-signalling' conditions

$$P(a, b \,|\, x, y) = \sum_c P(a, b, c \,|\, x, y, z).$$

are sufficient, but not necessary for no-signalling!



[P. Horodecki, R. Ramanathan, *Nat. Comm.* **10**, 1701 (2019)]

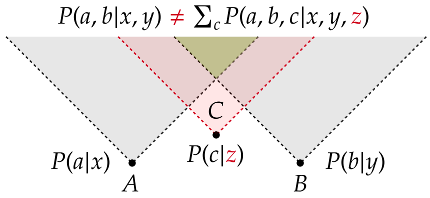
- Charlie changes '*at a distance*' the correlations between Alice and Bob, but he does not influence their local statistics.
- Alice and Bob can only check the correlations when they meet.

Nonlocal jamming of correlations

- The standard 3-party 'no-signalling' conditions

$$P(a, b \,|\, x, y) = \textstyle\sum_c P(a, b, c \,|\, x, y, z).$$

are sufficient, but not necessary for no-signalling!



[P. Horodecki, R. Ramanathan, *Nat. Comm.* **10**, 1701 (2019)]

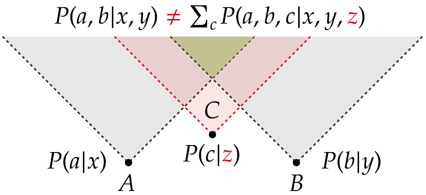
- Charlie changes '*at a distance*' the correlations between Alice and Bob, but he does not influence their local statistics.
- Alice and Bob can only check the correlations when they meet.

Nonlocal jamming of correlations

- The standard 3-party 'no-signalling' conditions

$$P(a, b \,|\, x, y) = \sum_c P(a, b, c \,|\, x, y, z).$$

are sufficient, but not necessary for no-signalling!



[P. Horodecki, R. Ramanathan, *Nat. Comm.* **10**, 1701 (2019)]

- Charlie changes '*at a distance*' the correlations between Alice and Bob, but he does not influence their local statistics.
- Alice and Bob can only check the correlations when they meet.

Commuting *versus* tensor correlations

- In QM we model spacelike separated measurements with a tensor product $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. *Local* observables have the form $A \otimes \mathbb{1}, \mathbb{1} \otimes B$.

$$P_\otimes(ab|xy) = \langle\psi|A_a^x \otimes B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B.$$

$C_\otimes := \overline{\{P_\otimes(ab|xy)\}}$ is the set of all tensor product correlations that can be approximated arbitrarily well by finite dimensional $\mathcal{H}$.

- In (A)QFT we model spacelike separated measurements by commuting observables, $A, B \in \mathcal{B}(\mathcal{H})$, $[A, B] = 0$. $\qquad C_{[\cdot,\cdot]} := \{P_{[\cdot,\cdot]}(ab|xy)\}$

$$P_{[\cdot,\cdot]}(ab|xy) = \langle\psi|A_a^x B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

The Tsirelson problem

We have $C_\otimes \subseteq C_{[\cdot,\cdot]}$, but do we have $C_\otimes = C_{[\cdot,\cdot]}$?

- Is the Tsirelson gap physical?

Commuting *versus* tensor correlations

- In QM we model spacelike separated measurements with a tensor product $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. *Local* observables have the form $A \otimes \mathbb{1}, \mathbb{1} \otimes B$.

$$P_\otimes(ab|xy) = \langle\psi| A_a^x \otimes B_b^y |\psi\rangle, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B.$$

$C_\otimes := \overline{\{P_\otimes(ab|xy)\}}$ is the set of all tensor product correlations that can be approximated arbitrarily well by finite dimensional $\mathcal{H}$.

- In (A)QFT we model spacelike separated measurements by commuting observables, $A, B \in \mathcal{B}(\mathcal{H})$, $[A, B] = 0$. $\quad C_{[\cdot,\cdot]} := \{P_{[\cdot,\cdot]}(ab|xy)\}$

$$P_{[\cdot,\cdot]}(ab|xy) = \langle\psi| A_a^x B_b^y |\psi\rangle, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

The Tsirelson problem

We have $C_\otimes \subseteq C_{[\cdot,\cdot]}$, but do we have $C_\otimes = C_{[\cdot,\cdot]}$?

- Is the Tsirelson gap physical?

Commuting *versus* tensor correlations

- In QM we model spacelike separated measurements with a tensor product $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. *Local* observables have the form $A \otimes \mathbb{1}, \mathbb{1} \otimes B$.

$$P_\otimes(ab|xy) = \langle\psi|A_a^x \otimes B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B.$$

$C_\otimes := \overline{\{P_\otimes(ab|xy)\}}$ is the set of all tensor product correlations that can be approximated arbitrarily well by finite dimensional $\mathcal{H}$.

- In (A)QFT we model spacelike separated measurements by commuting observables, $A, B \in \mathcal{B}(\mathcal{H})$, $[A, B] = 0$. $\quad C_{[\cdot,\cdot]} := \{P_{[\cdot,\cdot]}(ab|xy)\}$

$$P_{[\cdot,\cdot]}(ab|xy) = \langle\psi|A_a^x B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

The Tsirelson problem

We have $C_\otimes \subseteq C_{[\cdot,\cdot]}$, but do we have $C_\otimes = C_{[\cdot,\cdot]}$?

- Is the Tsirelson gap physical?

Commuting *versus* tensor correlations

- In QM we model spacelike separated measurements with a tensor product $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. *Local* observables have the form $A \otimes \mathbb{1}, \mathbb{1} \otimes B$.

$$P_\otimes(ab|xy) = \langle\psi|A_a^x \otimes B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B.$$

$C_\otimes := \overline{\{P_\otimes(ab|xy)\}}$ is the set of all tensor product correlations that can be approximated arbitrarily well by finite dimensional $\mathcal{H}$.

- In (A)QFT we model spacelike separated measurements by commuting observables, $A, B \in \mathcal{B}(\mathcal{H})$, $[A, B] = 0$. $C_{[\cdot,\cdot]} := \{P_{[\cdot,\cdot]}(ab|xy)\}$

$$P_{[\cdot,\cdot]}(ab|xy) = \langle\psi|A_a^x B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

The Tsirelson problem

We have $C_\otimes \subseteq C_{[\cdot,\cdot]}$, but do we have $C_\otimes = C_{[\cdot,\cdot]}$?

- Is the Tsirelson gap physical?

Commuting *versus* tensor correlations

- In QM we model spacelike separated measurements with a tensor product $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. *Local* observables have the form $A \otimes \mathbb{1}, \mathbb{1} \otimes B$.

$$P_\otimes(ab|xy) = \langle \psi | A_a^x \otimes B_b^y | \psi \rangle, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B.$$

$C_\otimes := \overline{\{P_\otimes(ab|xy)\}}$ is the set of all tensor product correlations that can be approximated arbitrarily well by finite dimensional $\mathcal{H}$.

- In (A)QFT we model spacelike separated measurements by commuting observables, $A, B \in \mathcal{B}(\mathcal{H})$, $[A, B] = 0$. $C_{[\cdot,\cdot]} := \{P_{[\cdot,\cdot]}(ab|xy)\}$

$$P_{[\cdot,\cdot]}(ab|xy) = \langle \psi | A_a^x B_b^y | \psi \rangle, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

The Tsirelson problem

We have $C_\otimes \subseteq C_{[\cdot,\cdot]}$, but do we have $C_\otimes = C_{[\cdot,\cdot]}$?

- Is the Tsirelson gap physical?

Commuting *versus* tensor correlations

- In QM we model spacelike separated measurements with a tensor product $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. *Local* observables have the form $A \otimes \mathbb{1}, \mathbb{1} \otimes B$.

$$P_\otimes(ab|xy) = \langle\psi|A_a^x \otimes B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B.$$

$C_\otimes := \overline{\{P_\otimes(ab|xy)\}}$ is the set of all tensor product correlations that can be approximated arbitrarily well by finite dimensional $\mathcal{H}$.

- In (A)QFT we model spacelike separated measurements by commuting observables, $A, B \in \mathcal{B}(\mathcal{H})$, $[A, B] = 0$. $\quad C_{[\cdot,\cdot]} := \{P_{[\cdot,\cdot]}(ab|xy)\}$

$$P_{[\cdot,\cdot]}(ab|xy) = \langle\psi|A_a^x B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

The Tsirelson problem

We have $C_\otimes \subseteq C_{[\cdot,\cdot]}$, but do we have $C_\otimes = C_{[\cdot,\cdot]}$?

- Is the Tsirelson gap physical?

Commuting *versus* tensor correlations

- In QM we model spacelike separated measurements with a tensor product $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. *Local* observables have the form $A \otimes \mathbb{1}, \mathbb{1} \otimes B$.

$$P_{\otimes}(ab|xy) = \langle\psi|A_a^x \otimes B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B.$$

  $C_{\otimes} := \overline{\{P_{\otimes}(ab|xy)\}}$ is the set of all tensor product correlations that can be approximated arbitrarily well by finite dimensional $\mathcal{H}$.

- In (A)QFT we model spacelike separated measurements by commuting observables, $A, B \in \mathcal{B}(\mathcal{H})$, $[A, B] = 0$. $\qquad C_{[\cdot,\cdot]} := \{P_{[\cdot,\cdot]}(ab|xy)\}$

$$P_{[\cdot,\cdot]}(ab|xy) = \langle\psi|A_a^x B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

The Tsirelson problem

We have $C_{\otimes} \subseteq C_{[\cdot,\cdot]}$, but do we have $C_{\otimes} = C_{[\cdot,\cdot]}$?

- Is the Tsirelson gap physical?

Commuting *versus* tensor correlations

- In QM we model spacelike separated measurements with a tensor product $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. *Local* observables have the form $A \otimes \mathbb{1}, \mathbb{1} \otimes B$.

$$P_\otimes(ab|xy) = \langle\psi|A_a^x \otimes B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B.$$

$C_\otimes := \overline{\{P_\otimes(ab|xy)\}}$ is the set of all tensor product correlations that can be approximated arbitrarily well by finite dimensional $\mathcal{H}$.

- In (A)QFT we model spacelike separated measurements by commuting observables, $A, B \in \mathcal{B}(\mathcal{H})$, $[A, B] = 0$. $\quad C_{[\cdot,\cdot]} := \{P_{[\cdot,\cdot]}(ab|xy)\}$

$$P_{[\cdot,\cdot]}(ab|xy) = \langle\psi|A_a^x B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

The Tsirelson gap

We have $C_\otimes \subseteq C_{[\cdot,\cdot]}$, but $C_\otimes \neq C_{[\cdot,\cdot]}$!

[Z. Ji, A. Natarajan, T. Vidick, J. Wright, H. Yuen, arXiv:2001.04383]

- Is the Tsirelson gap physical?

Commuting *versus* tensor correlations

- In QM we model spacelike separated measurements with a tensor product $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. *Local* observables have the form $A \otimes \mathbb{1}, \mathbb{1} \otimes B$.

$$P_\otimes(ab|xy) = \langle\psi|A_a^x \otimes B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B.$$

$C_\otimes := \overline{\{P_\otimes(ab|xy)\}}$ is the set of all tensor product correlations that can be approximated arbitrarily well by finite dimensional $\mathcal{H}$.

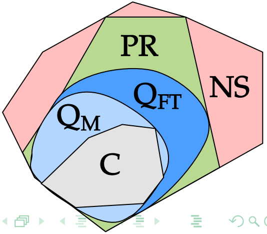
- In (A)QFT we model spacelike separated measurements by commuting observables, $A, B \in \mathcal{B}(\mathcal{H})$, $[A, B] = 0$. $\quad C_{[\cdot,\cdot]} := \{P_{[\cdot,\cdot]}(ab|xy)\}$

$$P_{[\cdot,\cdot]}(ab|xy) = \langle\psi|A_a^x B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

The Tsirelson gap

We have $C_\otimes \subseteq C_{[\cdot,\cdot]}$, but $C_\otimes \neq C_{[\cdot,\cdot]}$!

[Z. Ji, A. Natarajan, T. Vidick, J. Wright, H. Yuen, arXiv:2001.04383]



- Is the Tsirelson gap physical?

Commuting *versus* tensor correlations

- In QM we model spacelike separated measurements with a tensor product $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. *Local* observables have the form $A \otimes \mathbb{1}, \mathbb{1} \otimes B$.

$$P_\otimes(ab|xy) = \langle\psi|A_a^x \otimes B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B.$$

  $C_\otimes := \overline{\{P_\otimes(ab|xy)\}}$ is the set of all tensor product correlations that can be approximated arbitrarily well by finite dimensional $\mathcal{H}$.

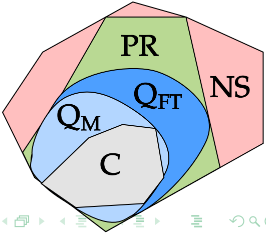
- In (A)QFT we model spacelike separated measurements by commuting observables, $A, B \in \mathcal{B}(\mathcal{H})$, $[A, B] = 0$. $\quad C_{[\cdot,\cdot]} := \{P_{[\cdot,\cdot]}(ab|xy)\}$

$$P_{[\cdot,\cdot]}(ab|xy) = \langle\psi|A_a^x B_b^y|\psi\rangle, \qquad |\psi\rangle \in \mathcal{H} \text{ and } [A_a^x, B_b^y] = 0.$$

The Tsirelson gap

We have $C_\otimes \subseteq C_{[\cdot,\cdot]}$, but $C_\otimes \neq C_{[\cdot,\cdot]}$!

[Z. Ji, A. Natarajan, T. Vidick, J. Wright, H. Yuen, arXiv:2001.04383]



- Is the Tsirelson gap physical?

How to seek possible deviations from QM in particle physics?

1. M.E., P. Horodecki,
   Probing the limits of quantum theory with quantum information at subnuclear scales,
   Proc. R. Soc. A. **478**:20210806 (2022), arXiv:2103.12000.

2. C. Altomonte, A. Barr, M.E., P. Horodecki, K. Sakurai,
   Prospects for quantum process tomography with polarized beams,
   arXiv:24xx.xxxxx.

Quantum-data boxes

- We treat physical systems as **Q-data boxes**, i.e. *quantum-information* processing devices.
- A Q-data box is probed *locally* with quantum information.

- p are classical parameters (e.g. scattering kinematics)
- The *pure input* state is **prepared**, $P : x \to \psi_{\text{in}}$.
- The *output state* is reconstructed from **quantum tomography**.
- We assume that validity of QM *outside* the box, but not *inside* it.

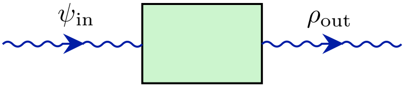
Quantum-data boxes

- We treat physical systems as **Q-data boxes**, i.e. *quantum-information* processing devices.
- A Q-data box is probed *locally* with quantum information.

- p are classical parameters (e.g. scattering kinematics)
- The *pure input* state is **prepared**, $P : x \to \psi_{\text{in}}$.
- The *output state* is reconstructed from **quantum tomography**.
- We assume that validity of QM *outside* the box, but not *inside* it.

Quantum-data boxes

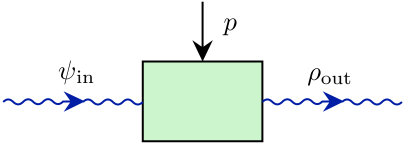
- We treat physical systems as **Q-data boxes**, i.e. *quantum-information* processing devices.
- A Q-data box is probed *locally* with quantum information.



- p are classical parameters (e.g. scattering kinematics)
- The *pure input* state is **prepared**, $P : x \to \psi_{\mathsf{in}}$.
- The *output state* is reconstructed from **quantum tomography**.
- We assume that validity of QM *outside* the box, but not *inside* it.

Quantum-data boxes

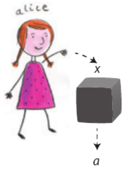
- We treat physical systems as **Q-data boxes**, i.e. *quantum-information* processing devices.
- A Q-data box is probed *locally* with quantum information.



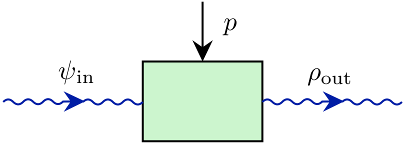
- p are classical parameters (e.g. scattering kinematics)
- The *pure input* state is **prepared**, $P : x \to \psi_{\text{in}}$.
- The *output state* is reconstructed from **quantum tomography**.
- We assume that validity of QM *outside* the box, but not *inside* it.

Quantum-data boxes

- We treat physical systems as **Q-data boxes**, i.e. *quantum-information* processing devices.
- A Q-data box is probed *locally* with quantum information.



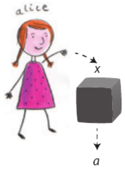
[Nat. Phys. **10**, 264 (2014)]



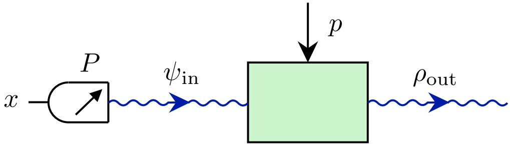
- p are classical parameters (e.g. scattering kinematics)
- The *pure input* state is **prepared**, $P : x \to \psi_{\text{in}}$.
- The *output state* is reconstructed from **quantum tomography**.
- We assume that validity of QM *outside* the box, but not *inside* it.

Quantum-data boxes

- We treat physical systems as **Q-data boxes**, i.e. *quantum-information* processing devices.
- A Q-data box is probed *locally* with quantum information.



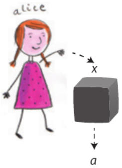
[Nat. Phys. **10**, 264 (2014)]



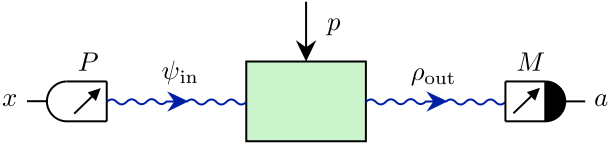
- p are classical parameters (e.g. scattering kinematics)
- The *pure input* state is **prepared**, $P : x \to \psi_{\text{in}}$.
- The *output state* is reconstructed from **quantum tomography**.
- We assume that validity of QM *outside* the box, but not *inside* it.

Quantum-data boxes

- We treat physical systems as **Q-data boxes**, i.e. *quantum-information* processing devices.
- A Q-data box is probed *locally* with quantum information.



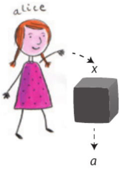
[Nat. Phys. **10**, 264 (2014)]



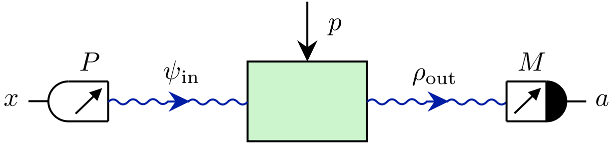
- p are classical parameters (e.g. scattering kinematics)
- The *pure input* state is **prepared**, $P : x \to \psi_{\text{in}}$.
- The *output state* is reconstructed from **quantum tomography**.
- We assume that validity of QM *outside* the box, but not *inside* it.

Quantum-data boxes

- We treat physical systems as **Q-data boxes**, i.e. *quantum-information* processing devices.
- A Q-data box is probed *locally* with quantum information.

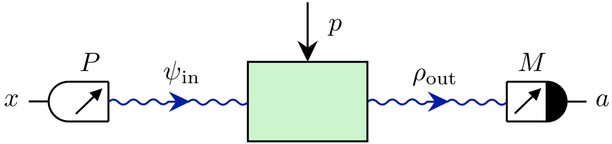


[Nat. Phys. **10**, 264 (2014)]



- p are classical parameters (e.g. scattering kinematics)
- The *pure input* state is **prepared**, $P : x \to \psi_{\mathsf{in}}$.
- The *output state* is reconstructed from **quantum tomography**.
- We assume that validity of QM *outside* the box, but not *inside* it.

Quantum-data tests

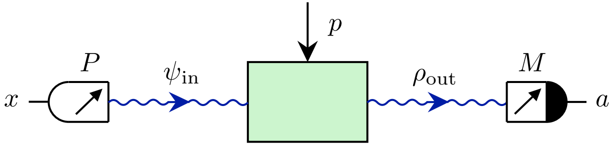


A **Q-data test** consists in probing a Q-data box with *prepared* input states.

- For every input state ψ_{in} one performs the full tomography of ρ_{out}.
- A Q-data test yields a dataset $\{\psi_{\text{in}}^{(k)}, p^{(\ell)}; \rho_{\text{out}}^{(k,\ell)}\}_{k,\ell}$.
- Compare against the SM predictions — quantum process tomography

- ψ_{in} is pure, **initially uncorrelated** with the box — freedom of choice
- We do not need to gather all outgoing quantum information.

Quantum-data tests

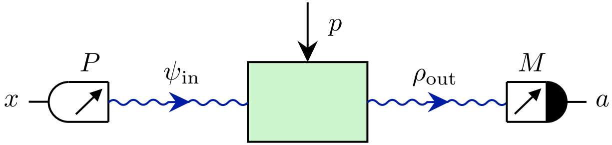


A **Q-data test** consists in probing a Q-data box with *prepared* input states.

- For every input state ψ_{in} one performs the full tomography of ρ_{out}.
- A Q-data test yields a dataset $\{\psi_{\text{in}}^{(k)}, p^{(\ell)}; \rho_{\text{out}}^{(k,\ell)}\}_{k,\ell}$.
- Compare against the SM predictions — quantum process tomography

- ψ_{in} is pure, **initially uncorrelated** with the box — freedom of choice
- We do not need to gather all outgoing quantum information.

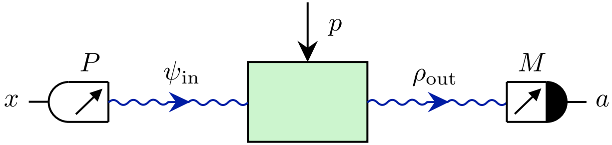
Quantum-data tests



A **Q-data test** consists in probing a Q-data box with *prepared* input states.

- For every input state ψ_{in} one performs the full tomography of ρ_{out}.
- A Q-data test yields a dataset $\{\psi_{\text{in}}^{(k)}, p^{(\ell)}; \rho_{\text{out}}^{(k,\ell)}\}_{k,\ell}$.
- Compare against the SM predictions — quantum process tomography
- ψ_{in} is pure, **initially uncorrelated** with the box — freedom of choice
- We do not need to gather all outgoing quantum information.

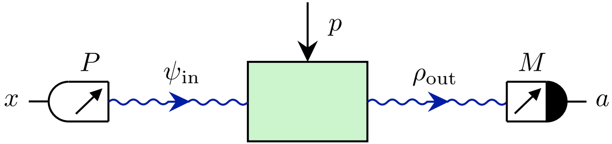
Quantum-data tests



A **Q-data test** consists in probing a Q-data box with *prepared* input states.

- For every input state ψ_{in} one performs the full tomography of ρ_{out}.
- A Q-data test yields a dataset $\{\psi_{\text{in}}^{(k)}, p^{(\ell)}; \rho_{\text{out}}^{(k,\ell)}\}_{k,\ell}$.
- Compare against the SM predictions — quantum process tomography
- ψ_{in} is pure, **initially uncorrelated** with the box — freedom of choice
- We do not need to gather all outgoing quantum information.

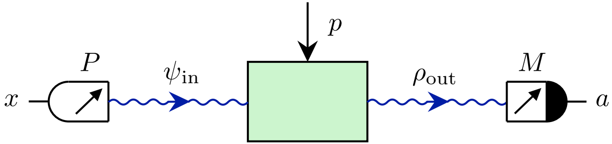
Quantum-data tests



A **Q-data test** consists in probing a Q-data box with *prepared* input states.

- For every input state ψ_{in} one performs the full tomography of ρ_{out}.
- A Q-data test yields a dataset $\{\psi_{\mathsf{in}}^{(k)}, p^{(\ell)}; \rho_{\mathsf{out}}^{(k,\ell)}\}_{k,\ell}$.
- Compare against the SM predictions — quantum process tomography
- ψ_{in} is pure, **initially uncorrelated** with the box — freedom of choice
- We do not need to gather all outgoing quantum information.

Quantum-data tests

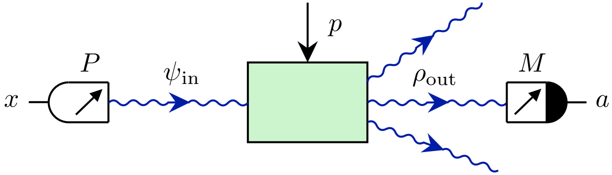


A **Q-data test** consists in probing a Q-data box with *prepared* input states.

- For every input state ψ_{in} one performs the full tomography of ρ_{out}.
- A Q-data test yields a dataset $\{\psi_{\text{in}}^{(k)}, p^{(\ell)}; \rho_{\text{out}}^{(k,\ell)}\}_{k,\ell}$.
- Compare against the SM predictions — quantum process tomography

- ψ_{in} is pure, **initially uncorrelated** with the box — freedom of choice
- We do not need to gather all outgoing quantum information.

Quantum-data tests



A **Q-data test** consists in probing a Q-data box with *prepared* input states.

- For every input state ψ_{in} one performs the full tomography of ρ_{out}.
- A Q-data test yields a dataset $\{\psi_{\text{in}}^{(k)}, p^{(\ell)}; \rho_{\text{out}}^{(k,\ell)}\}_{k,\ell}$.
- Compare against the SM predictions — quantum process tomography

- ψ_{in} is pure, **initially uncorrelated** with the box — freedom of choice
- We do not need to gather all outgoing quantum information.

An example — the Helstrom test

- Suppose that we have two available inputs $\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}$.
- We choose randomly the input (with probability 1/2).
- The task is to guess, which of the two states was input.
- Define the **success rate**: $P_{\text{succ}}(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}) := \frac{1}{2}\sum_{k=1}^{2} P(a = k \,|\, \psi_{\text{in}}^{(k)})$.
- In quantum theory P_{succ} cannot exceed the **Helstrom bound**

$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2}\left(1 + \sqrt{1 - \left|\langle \psi_{\text{in}}^{(1)} | \psi_{\text{in}}^{(2)} \rangle\right|^2}\right).$$

- Make a Q-data test with $\left\{\psi_{\text{in}}^{(k)}; \rho_{\text{out}}^{(k)}\right\}_{k=1,2}$.
- If $P_{\text{succ}}(\rho_{\text{out}}^{(1)}, \rho_{\text{out}}^{(2)}) > P_{\text{succ}}(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)})$ then the Q-data box is **not** quantum.
- Violation of the Helstrom bound occurs in nonlinear modifications of QM.

An example — the Helstrom test

- Suppose that we have two available inputs $\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}$.
- We choose randomly the input (with probability 1/2).
- The task is to guess, which of the two states was input.
- Define the **success rate**: $P_{\text{succ}}(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}) := \frac{1}{2}\sum_{k=1}^{2} P(a = k \mid \psi_{\text{in}}^{(k)})$.
- In quantum theory P_{succ} cannot exceed the **Helstrom bound**

$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2}\left(1 + \sqrt{1 - \left|\langle \psi_{\text{in}}^{(1)} | \psi_{\text{in}}^{(2)} \rangle\right|^2}\right).$$

- Make a Q-data test with $\left\{\psi_{\text{in}}^{(k)}; \rho_{\text{out}}^{(k)}\right\}_{k=1,2}$.
- If $P_{\text{succ}}(\rho_{\text{out}}^{(1)}, \rho_{\text{out}}^{(2)}) > P_{\text{succ}}(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)})$ then the Q-data box is **not** quantum.
- Violation of the Helstrom bound occurs in nonlinear modifications of QM.

An example — the Helstrom test

- Suppose that we have two available inputs $\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}$.
- We choose randomly the input (with probability 1/2).
- The task is to guess, which of the two states was input.
- Define the **success rate**: $P_{\text{succ}}(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}) := \frac{1}{2} \sum_{k=1}^{2} P(a = k \,|\, \psi_{\text{in}}^{(k)})$.
- In quantum theory P_{succ} cannot exceed the **Helstrom bound**

$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2} \left(1 + \sqrt{1 - \left| \langle \psi_{\text{in}}^{(1)} | \psi_{\text{in}}^{(2)} \rangle \right|^2} \right).$$

- Make a Q-data test with $\left\{ \psi_{\text{in}}^{(k)}; \rho_{\text{out}}^{(k)} \right\}_{k=1,2}$.
- If $P_{\text{succ}}(\rho_{\text{out}}^{(1)}, \rho_{\text{out}}^{(2)}) > P_{\text{succ}}(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)})$ then the Q-data box is **not** quantum.
- Violation of the Helstrom bound occurs in nonlinear modifications of QM.

An example — the Helstrom test

- Suppose that we have two available inputs $\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}$.
- We choose randomly the input (with probability 1/2).
- The task is to guess, which of the two states was input.
- Define the **success rate**: $P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big) := \frac{1}{2}\sum_{k=1}^{2} P\big(a = k \,|\, \psi_{\text{in}}^{(k)}\big)$.
- In quantum theory P_{succ} cannot exceed the **Helstrom bound**

$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2}\left(1 + \sqrt{1 - \left|\langle \psi_{\text{in}}^{(1)} | \psi_{\text{in}}^{(2)} \rangle\right|^2}\right).$$

- Make a Q-data test with $\big\{\psi_{\text{in}}^{(k)}; \rho_{\text{out}}^{(k)}\big\}_{k=1,2}$.
- If $P_{\text{succ}}\big(\rho_{\text{out}}^{(1)}, \rho_{\text{out}}^{(2)}\big) > P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big)$ then the Q-data box is **not** quantum.
- Violation of the Helstrom bound occurs in nonlinear modifications of QM.

An example — the Helstrom test

- Suppose that we have two available inputs $\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}$.
- We choose randomly the input (with probability 1/2).
- The task is to guess, which of the two states was input.
- Define the **success rate**: $P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big) := \frac{1}{2}\sum_{k=1}^{2} P\big(a = k \,|\, \psi_{\text{in}}^{(k)}\big)$.
- In quantum theory P_{succ} cannot exceed the **Helstrom bound**

$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2}\left(1 + \sqrt{1 - \left|\langle\psi_{\text{in}}^{(1)}|\psi_{\text{in}}^{(2)}\rangle\right|^2}\right) .$$

- Make a Q-data test with $\big\{\psi_{\text{in}}^{(k)}; \rho_{\text{out}}^{(k)}\big\}_{k=1,2}$.
- If $P_{\text{succ}}\big(\rho_{\text{out}}^{(1)}, \rho_{\text{out}}^{(2)}\big) > P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big)$ then the Q-data box is **not** quantum.
- Violation of the Helstrom bound occurs in nonlinear modifications of QM.

An example — the Helstrom test

- Suppose that we have two available inputs $\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}$.
- We choose randomly the input (with probability 1/2).
- The task is to guess, which of the two states was input.
- Define the **success rate**: $P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big) := \frac{1}{2}\sum_{k=1}^{2} P\big(a = k \,|\, \psi_{\text{in}}^{(k)}\big)$.
- In quantum theory P_{succ} cannot exceed the **Helstrom bound**

$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2}\left(1 + \sqrt{1 - \left|\langle\psi_{\text{in}}^{(1)}|\psi_{\text{in}}^{(2)}\rangle\right|^2}\right) .$$

- Make a Q-data test with $\big\{\psi_{\text{in}}^{(k)}; \rho_{\text{out}}^{(k)}\big\}_{k=1,2}$.
- If $P_{\text{succ}}\big(\rho_{\text{out}}^{(1)}, \rho_{\text{out}}^{(2)}\big) > P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big)$ then the Q-data box is **not** quantum.
- Violation of the Helstrom bound occurs in nonlinear modifications of QM.

An example — the Helstrom test

- Suppose that we have two available inputs $\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}$.
- We choose randomly the input (with probability 1/2).
- The task is to guess, which of the two states was input.
- Define the **success rate**: $P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big) := \frac{1}{2}\sum_{k=1}^{2} P\big(a = k \,|\, \psi_{\text{in}}^{(k)}\big)$.
- In quantum theory P_{succ} cannot exceed the **Helstrom bound**

$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2}\left(1 + \sqrt{1 - \left|\langle\psi_{\text{in}}^{(1)}|\psi_{\text{in}}^{(2)}\rangle\right|^2}\right).$$

- Make a Q-data test with $\big\{\psi_{\text{in}}^{(k)}; \rho_{\text{out}}^{(k)}\big\}_{k=1,2}$.
- If $P_{\text{succ}}\big(\rho_{\text{out}}^{(1)}, \rho_{\text{out}}^{(2)}\big) > P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big)$ then the Q-data box is **not** quantum.
- Violation of the Helstrom bound occurs in nonlinear modifications of QM.

An example — the Helstrom test

- Suppose that we have two available inputs $\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}$.
- We choose randomly the input (with probability 1/2).
- The task is to guess, which of the two states was input.
- Define the **success rate**: $P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big) := \frac{1}{2}\sum_{k=1}^{2} P\big(a = k \,|\, \psi_{\text{in}}^{(k)}\big)$.
- In quantum theory P_{succ} cannot exceed the **Helstrom bound**

$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2}\left(1 + \sqrt{1 - \left|\langle\psi_{\text{in}}^{(1)}|\psi_{\text{in}}^{(2)}\rangle\right|^2}\right) .$$

- Make a Q-data test with $\big\{\psi_{\text{in}}^{(k)}; \rho_{\text{out}}^{(k)}\big\}_{k=1,2}$.
- If $P_{\text{succ}}\big(\rho_{\text{out}}^{(1)}, \rho_{\text{out}}^{(2)}\big) > P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big)$ then the Q-data box is **not** quantum.
- Violation of the Helstrom bound occurs in nonlinear modifications of QM.

Summary

Take-home messages:

- The mathematical structure of QFT may hide surprises!
- Relativity allows for theories even weirder than quantum mechanics.
- We do not have beyond-quantum maths nor physics ...

  (..., with the exception of nonlinear QM and objective collapse models, ...)

  ..., but we can still test them!

- Whenever we make an honest Bell-type test we are testing QM against both LHV **and** beyond-quantum correlations.
- We can probe QM '*from the outside*' using polarized beams/targets.

Thank you for your attention!

Summary

Take-home messages:

- The mathematical structure of QFT may hide surprises!
- Relativity allows for theories even weirder than quantum mechanics.
- We do not have beyond-quantum maths nor physics . . .

  (. . . , with the exception of nonlinear QM and objective collapse models, . . .)

  . . . , but we can still test them!
- Whenever we make an honest Bell-type test we are testing QM against both LHV **and** beyond-quantum correlations.
- We can probe QM '*from the outside*' using polarized beams/targets.

Thank you for your attention!

Summary

Take-home messages:

- The mathematical structure of QFT may hide surprises!
- Relativity allows for theories even weirder than quantum mechanics.
- We do not have beyond-quantum maths nor physics . . .

  (. . . , with the exception of nonlinear QM and objective collapse models, . . .)

  . . . , but we can still test them!
- Whenever we make an honest Bell-type test we are testing QM against both LHV **and** beyond-quantum correlations.
- We can probe QM '*from the outside*' using polarized beams/targets.

Thank you for your attention!

Summary

Take-home messages:

- The mathematical structure of QFT may hide surprises!
- Relativity allows for theories even weirder than quantum mechanics.
- We do not have beyond-quantum maths nor physics . . .

  (. . . , with the exception of nonlinear QM and objective collapse models, . . .)

  . . . , but we can still test them!

- Whenever we make an honest Bell-type test we are testing QM against both LHV **and** beyond-quantum correlations.
- We can probe QM '*from the outside*' using polarized beams/targets.

Thank you for your attention!

Summary

Take-home messages:

- The mathematical structure of QFT may hide surprises!
- Relativity allows for theories even weirder than quantum mechanics.
- We do not have beyond-quantum maths nor physics . . .

  (. . . , with the exception of nonlinear QM and objective collapse models, . . .)

  . . . , but we can still test them!

- Whenever we make an honest Bell-type test we are testing QM against both LHV **and** beyond-quantum correlations.
- We can probe QM '*from the outside*' using polarized beams/targets.

Thank you for your attention!

Summary

Take-home messages:

- The mathematical structure of QFT may hide surprises!
- Relativity allows for theories even weirder than quantum mechanics.
- We do not have beyond-quantum maths nor physics . . .

  (. . . , with the exception of nonlinear QM and objective collapse models, . . .)

  . . . , but we can still test them!

- Whenever we make an honest Bell-type test we are testing QM against both LHV **and** beyond-quantum correlations.
- We can probe QM '*from the outside*' using polarized beams/targets.

Thank you for your attention!

Summary

Take-home messages:

- The mathematical structure of QFT may hide surprises!
- Relativity allows for theories even weirder than quantum mechanics.
- We do not have beyond-quantum maths nor physics . . .

  (. . . , with the exception of nonlinear QM and objective collapse models, . . .)

  . . . , but we can still test them!

- Whenever we make an honest Bell-type test we are testing QM against both LHV **and** beyond-quantum correlations.
- We can probe QM '*from the outside*' using polarized beams/targets.

Thank you for your attention!

Summary

Take-home messages:

- The mathematical structure of QFT may hide surprises!
- Relativity allows for theories even weirder than quantum mechanics.
- We do not have beyond-quantum maths nor physics . . .

  (. . . , with the exception of nonlinear QM and objective collapse models, . . .)

  . . . , but we can still test them!

- Whenever we make an honest Bell-type test we are testing QM against both LHV **and** beyond-quantum correlations.
- We can probe QM '*from the outside*' using polarized beams/targets.

Thank you for your attention!

Summary

Take-home messages:

- The mathematical structure of QFT may hide surprises!
- Relativity allows for theories even weirder than quantum mechanics.
- We do not have beyond-quantum maths nor physics . . .

  (. . . , with the exception of nonlinear QM and objective collapse models, . . .)

  . . . , but we can still test them!

- Whenever we make an honest Bell-type test we are testing QM against both LHV **and** beyond-quantum correlations.
- We can probe QM '*from the outside*' using polarized beams/targets.

Thank you for your attention!