Towards probing quantum foundations at subnuclear scales

Michał Eckstein & Paweł Horodecki

arXiv:2103.12000

UNIWERSYTET GDAŃSKI

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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, ...)
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Why to go beyond quantum mechanics?

Motivations:

1. *Phenomenological*
   - Hypothesis: The resolution to some of the fundamental puzzles (e.g. dark matter, dark energy etc.) requires a new paradigm.
2. *Theoretical*
   - We don't know any interacting non-perturbative QFT in 3+1 dim (!)
   - Problems with the quantisation of gravity.
3. *Information-theoretic*
   - How is the information processed in Nature?
   - Is there a more fundamental theory behind QM?

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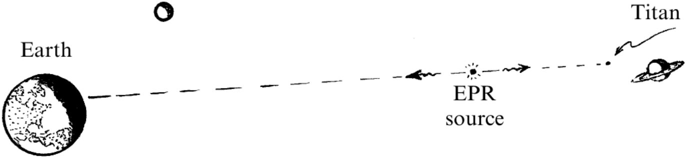

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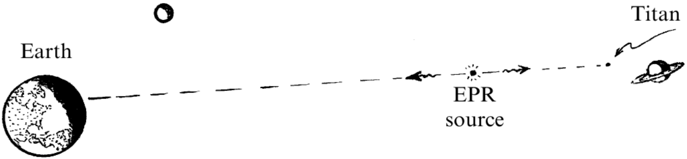

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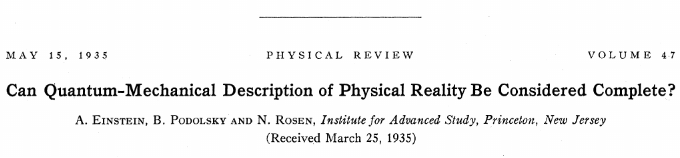
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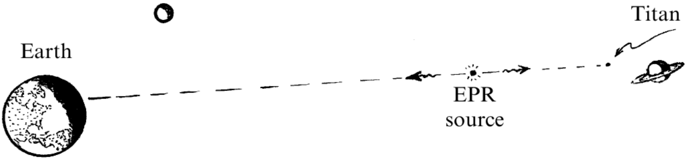

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Bell's theorem

- Consider a *hidden variable* λ from a probability space (Λ, μ).
- Alice and Bob are making measurement on a composite system:
  - measurement **settings** $x, y \in \{-1, 1\}$
  - measurement **outcomes** $a, b : \{-1, 1\} \times \Lambda \to \{-1, 1\}$
- **Correlation** function $C_c(x, y) := \int_\Lambda a(x, \lambda) b(y, \lambda) d\mu(\lambda)$

Bell / Clauser + Horne + Shimony + Holt Theorem (1964/1969)

$$S_c := C_c(x, y) + C_c(x, y') + C_c(x', y) - C_c(x', y') \leq 2$$

Quantum Mechanics

$$S_q := C_q(x, y) + C_q(x, y') + C_q(x', y) - C_q(x', y') \leq 2\sqrt{2}$$

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The **black box** approach

The *experimental* (frequency) correlation function:

$$C_e = \frac{N_{++} + N_{--} - N_{+-} - N_{-+}}{N_{++} + N_{--} + N_{+-} + N_{-+}} \in [-1, +1]$$

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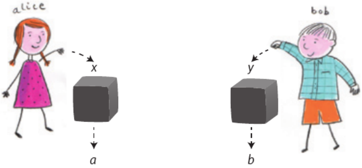

[Sandu Popescu, *Nature Physics* 10, 264 (2014)]

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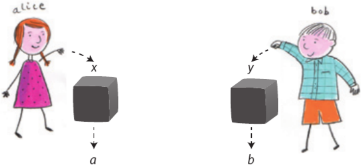

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VIEWPOINT

Closing the Door on Einstein and Bohr's Quantum Debate

Some remarks about Bell's theorem and tests

- Bell–CHSH inequality is **violated** in Nature.
- Bell's theorem is **theory-independent**.
  - It holds in *any* classical theory.
  - It *does not* require quantum mechanics.
- In 1964 there was no reason question the validity of QM and QFT!
- Bell's theorem promotes a **new type of questions**.
- This gave birth to the idea of **quantum information** processing.
  - new experiments
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Our goal: *Ask questions, which cannot be asked within QFT paradigm.*

- How is the information processed within the nucleon?

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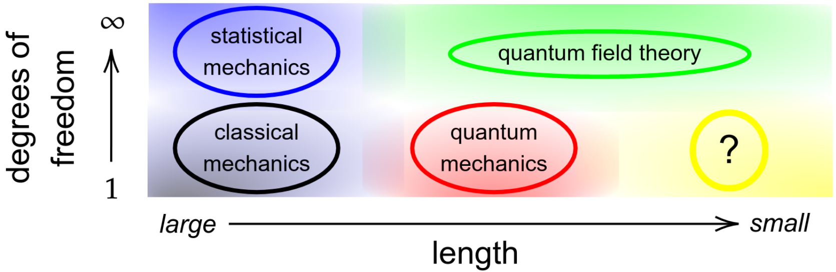

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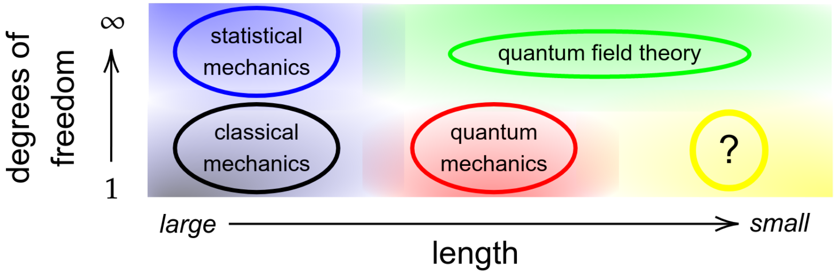

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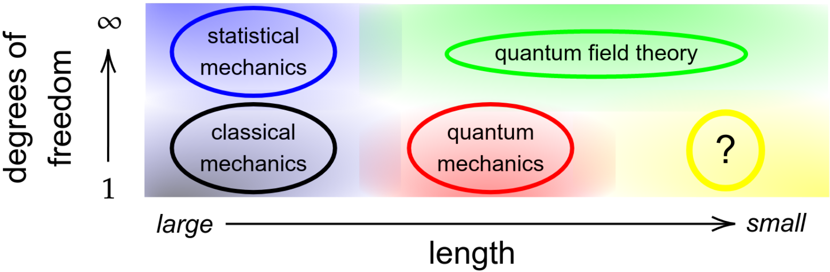

- How is the quantum information processed within the nucleon?

Quantum information

- Classical information – collection of **bits**
  - inputs x
  - outputs a
  - experiments $P(a\,|\,x)$
- Quantum information – states on a Hilbert space $\mathcal{H}$
  - **pure** states $\psi \in \mathcal{H}$
  - **mixed** states $\rho = \sum_i p_i \psi_i$, with $0 \leq p_i \leq 1$ and $\sum_i p_i = 1$
  - Pure states correspond to *maximal information* about the system.
  - Classical mixed states are *probability distributions* $\sum_i p_i x_i$.
- Quantum information can be **non-local**

$$\rho^{AB} = \sum_i \lambda_i \, \psi_i^A \otimes \chi_i^B$$

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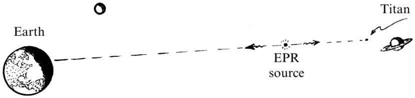

[Roger Penrose, *Road to Reality* (2004)]

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Quantum-data boxes

- We regard physical systems (e.g. a single nucleon) 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)
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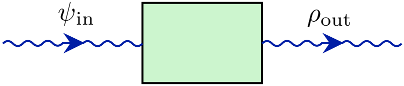

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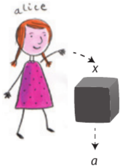
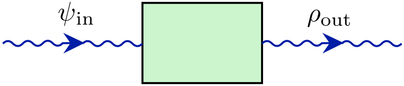


[Nat. Phys. **10**, 264 (2014)]



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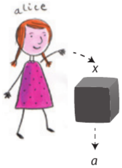

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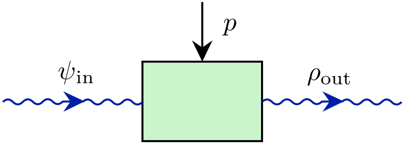

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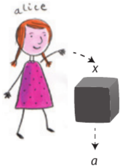

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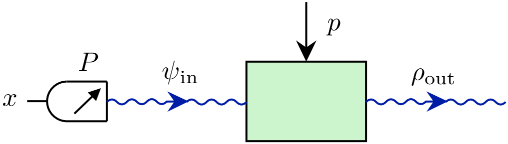

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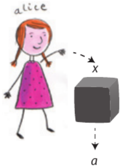

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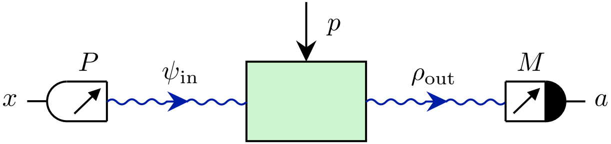

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Quantum preparation and tomography

Quantum state preparation:

- In principle, any quantum state can be prepared via proj. measurements.
- Single polarized photons are routinely prepared.

Quantum state tomography:

- A mixed state ρ_{out} on $\mathcal{H}$ is an $n \times n$ matrix, with $n = \dim \mathcal{H}$.
- Take a complete set of projectors $\{M_i\}_{i=1}^{n^2}$ (e.g. $\{\mathbb{1}, \sigma_x, \sigma_y, \sigma_z\}$).
- Make *multiple* measurements and register $\{P(a_j \,|\, M_i)\}_{i,j}$
- The state ρ_{out} is estimated from $\operatorname{Tr}\left(M_i \, \rho_{\text{out}}\right) = \sum_j a_j P(a_j \,|\, M_i)$.

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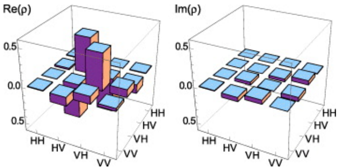
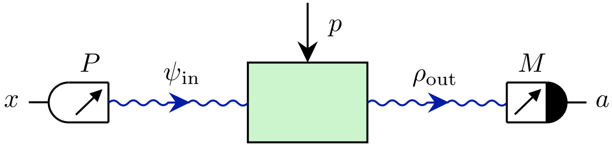


[J. Huwer et al., *New J. Phys.* 15, 025033 (2013)]

Quantum-data test



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

- For every input state ψ_{in} one needs to perform the full tomography of ρ_{out}.
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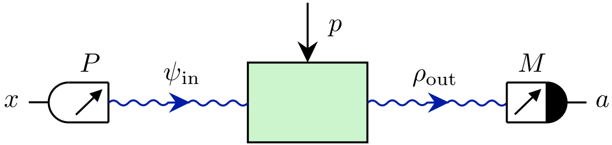

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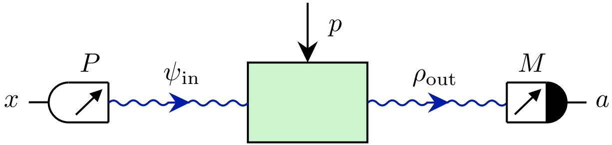

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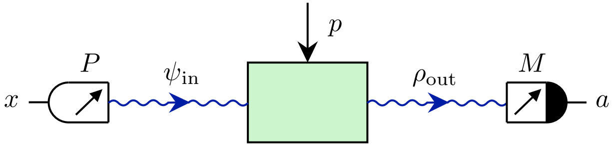

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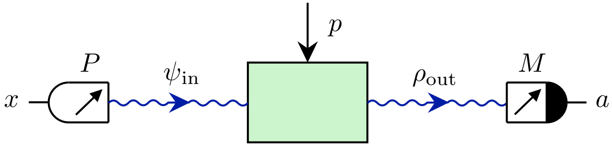

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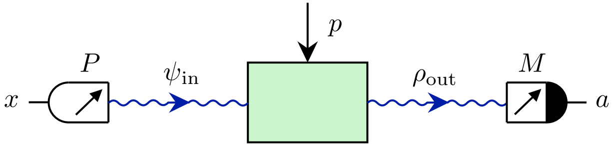

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- Suppose that we have two available inputs ψ^1, ψ^2.
- We choose randomly the input (with probability 1/2).
- The task is to *guess*, which of the two states was input.
- Define the **success rate**:

$$P_{\text{succ}}(\psi^1, \psi^2) := \frac{1}{2} \sum_{i=1}^{2} P(a = i \,|\, \psi^i),$$

- In quantum theory P_{succ} cannot exceed the **Helstrom bound**

$$P_{\text{succ}} \leq P_{\text{succ}}^{\text{QM}} := \frac{1}{2} \left(1 + \sqrt{1 - |\langle \psi_1 | \psi_2 \rangle|^2} \right)$$

- If $P_{\text{succ}}(\rho_{\text{out}}^1, \rho_{\text{out}}^2) > P_{\text{succ}}(\psi^1, \psi^2)$ then the Q-data box is **not** quantum.
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- If $P_{\mathsf{succ}}(\rho^1_{\mathsf{out}}, \rho^2_{\mathsf{out}}) > P_{\mathsf{succ}}(\psi^1, \psi^2)$ then the Q-data box is **not** quantum.
- Violation of the Helstrom bound occurs in non-linear modifications of QM.

Example: Helstrom test

- Suppose that we have two available inputs ψ^1, ψ^2.
- We choose randomly the input (with probability 1/2).
- The task is to *guess*, which of the two states was input.
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Towards an experiment

Main idea:

1. Prepare a 'quantum-programmed' particle carrying ψ_{in}, e.g. electron's spin or photon's polarization.
2. Scatter it on a nucleonic target.
3. Perform projective measurements on the outgoing projectiles.
4. Reconstruct the output state ρ_{out}.

Challenges:

- Need to prepare the quantum state of GeV particles.
- Abundance of projectiles in high-energy collisions.
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- Measure projectively as many projectiles as possible.
- Post-select the data wrt particle types and kinematic parameters.
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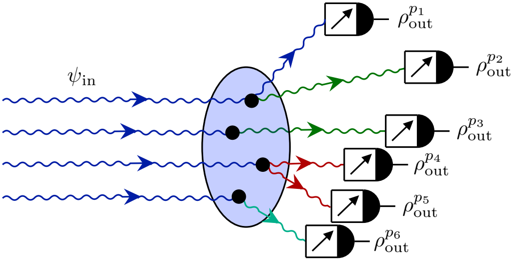

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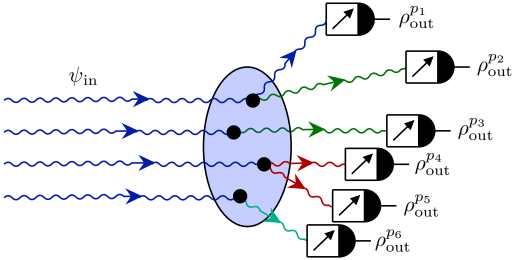

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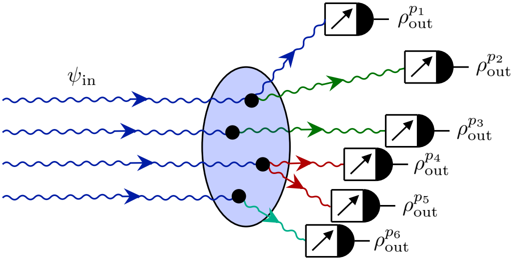

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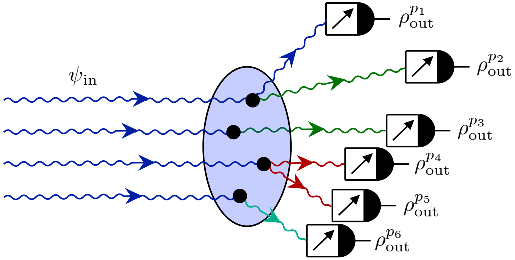

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arXiv:2103.12000

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- The framework is **theory-independent**.
- Implementation through scattering of highly polarized beams.
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