

# Exploring the limits of quantum theory inside nucleons

*Proc. R. Soc. A.* **478**:20210806 (2022), arXiv:2103.12000

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Humboldt Kolleg, Kitzbühel, 30 June 2022

# Routes towards New Physics

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

Routes towards New Physics:

- 1 Beyond Standard Model, but still in QFT
- 2 Beyond Special Relativity, but assuming QM (QFT on curved bg, QG)
  - Quantum Gravity
  - String Theory (Green, Schwarz, Witten 1987)
  - Loop Quantum Gravity (Rovelli 2004)
  - Causal Dynamical Triangulations (Ambjørn, Jurkiewicz, Loll 2000)
  - Asymptotically Safe Gravity (Lautrup, Litllewood, Marziani, Reuter 2019)
- 3 Beyond Quantum Mechanics, but assuming (Special) Relativity
  - nonlinear quantum mechanics
    - de Broglie-Bohm Model – Pusey (PNS 05), Pusey, Barrett, Rudolph (2012)
    - Bohmian Mechanics (Bohm 1952, Dürr, Goldstein, Zanghì 1989)
  - Generalised Probability Theories
    - Quantum Theory as a Special Case (Barrett, Kent 2004)
    - Generalised Probabilities (Speiser 1962)
    - Generalised Probabilities and Quantum Theory (Barrett 2007)
    - Quantum Theory as a Special Case (Barrett, Pagonis (PRA 2010/2012))
  - beyond-quantum correlations – a theory-independent approach

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  - Generalised Probability Theories
  - Quantum Bayesianism (see e.g. Barrett 2007, Barrett et al. 2011)
  - Quantum Reference Frames (see e.g. Ahluwalia 2007, Ahluwalia and Percacci 2008, Ahluwalia 2010, Ahluwalia 2011)
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    - Dirac's Galilean relativity: Pashen (PNS 60), Pauli (61, 62), Weinberg (1962)
    - and even for Double SL, Weinberg (1989)
  - Generalised Probability Theories
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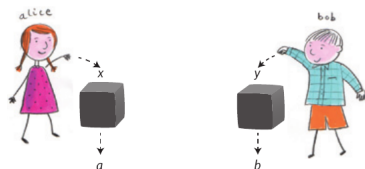
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# The black box methodology



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

The *experimental* (frequency) correlation function:

$$C_e(x, y) = \frac{N_{++} + N_{--} - N_{+-} - N_{-+}}{N_{++} + N_{--} + N_{+-} + N_{-+}}$$

Local hidden variables [Bell (1964) / Clauser, Horne, Shimony, Holt (1969)]

$$S_{\text{LHV}} := C_{\text{LHV}}(x, y) + C_{\text{LHV}}(x, y') + C_{\text{LHV}}(x', y) - C_{\text{LHV}}(x', y') \leq 2$$

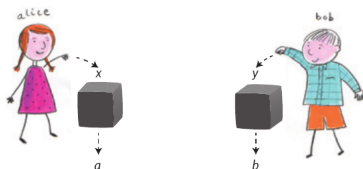
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No-signalling boxes [Popescu, Rohrlich (1994)]

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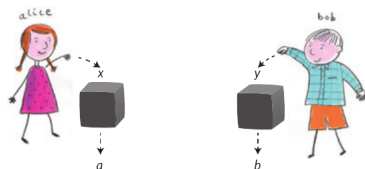
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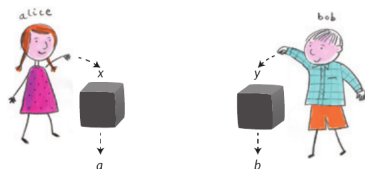
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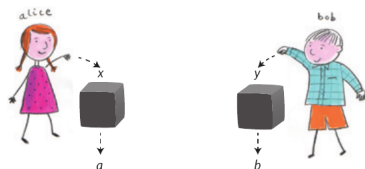
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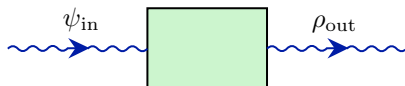
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# Quantum-data boxes

- We regard a chosen physical system as a **Q-data box**, which can be probed with quantum information.
- Quantum mechanics is valid *outside* the box, but not necessarily *inside*.



- The *pure input* state is **prepared**,  $P : x \rightarrow \psi_{\text{in}}$ .
- The *output state* is reconstructed via **quantum tomography** from the outcomes of projective measurements  $M : \rho_{\text{out}} \rightarrow a$ .
- $p$  are classical parameters (e.g. scattering kinematics)

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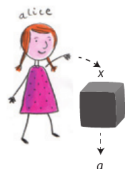
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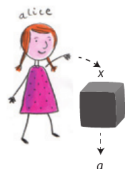


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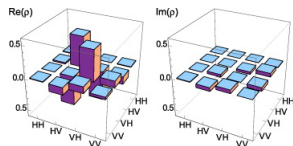
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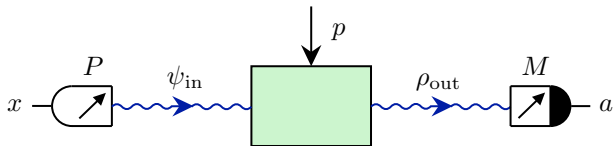
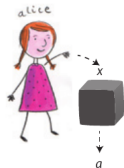
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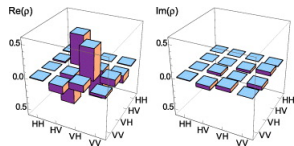
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## Example: the Helstrom test

- Suppose that we have two available inputs  $\psi^1, \psi^2$ .
- 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  $P_{\text{succ}}$  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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- 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  $P_{\text{succ}}$  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.
- Violation of the Helstrom bound occurs in non-linear modifications of QM.

# Quantum information at subnuclear scales

- The framework of Q-data boxes is *universal* and theory-independent.
- It can be applied in any physical context — gravity, particle physics ...
- In particular, one can regard **nucleons as Q-data boxes**.

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- 1 QCD (and QFT in general) perfectly describes all *available* data
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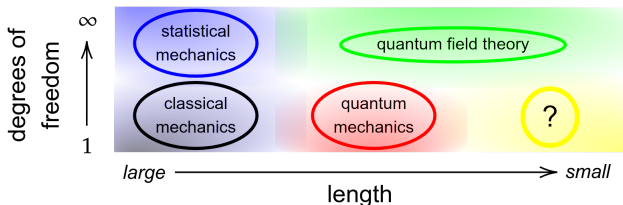
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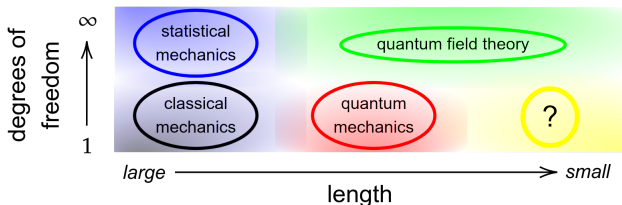


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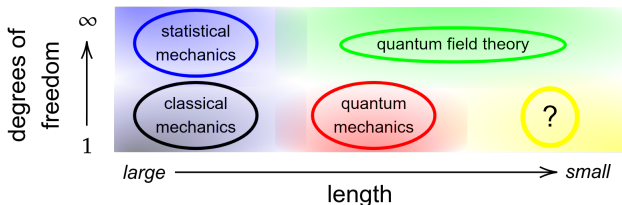


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## Main idea:

- 1 Prepare a 'quantum-programmed' particle carrying  $\psi_{\text{in}}$ , e.g. electron's spin or photon's polarization.
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- 4 Reconstruct the output state  $\rho_{\text{out}}$ .

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- Need to prepare the quantum state of GeV particles  $\rightsquigarrow$  polarized beams
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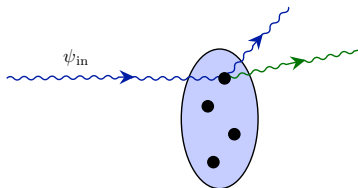
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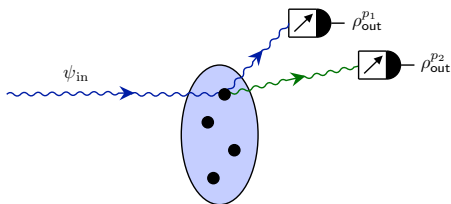
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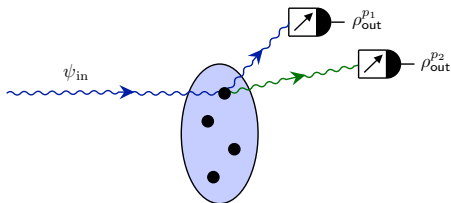
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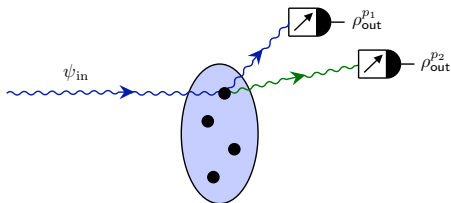
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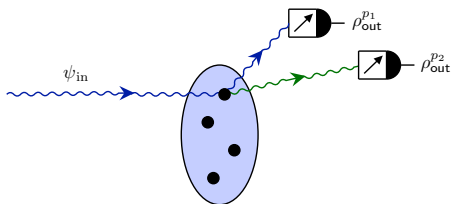
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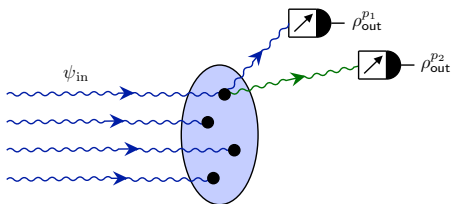
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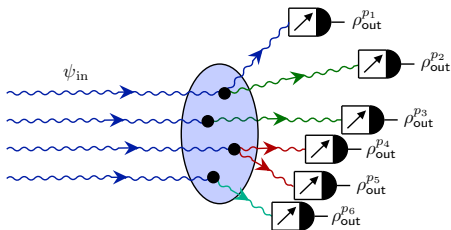
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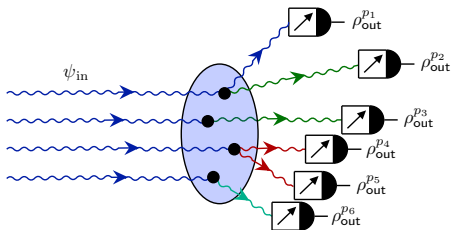
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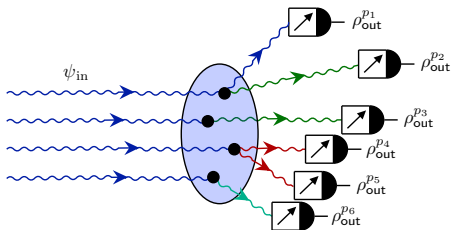
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*Proc. R. Soc. A.* **478**:20210806 (2022), arXiv:2103.12000

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