Exploring the limits of quantum theory inside nucleons

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Humboldt Kolleg, Kitzbühel, 30 June 2022

Routes towards New Physics

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

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1. Beyond Standard Model, but still in QFT
2. Beyond Special Relativity, but assuming QM (QFT on curved bg, QG)
3. **Beyond Quantum Mechanics**, but assuming (Special) Relativity
   - nonlinear quantum mechanics
     - Objective Collapse Models – Penrose (GRG 96), PMP 28, 581 (2014)
     - and more (de Broglie 60, Weinberg 89, ...)
   - Generalised Probability Theories
     - Inspired by Information-theoretic axiomatisation of QM (Hardy 2001)
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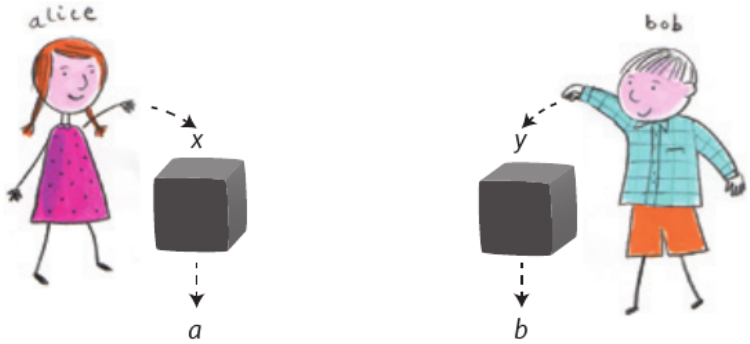

[Sandu Popescu, *Nature Physics* **10**, 264 (2014)]

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)]

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

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

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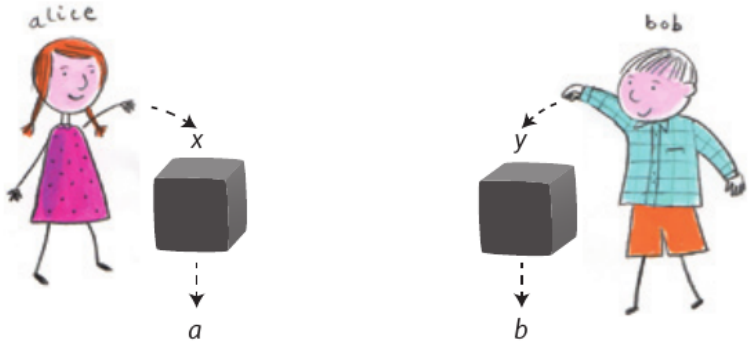

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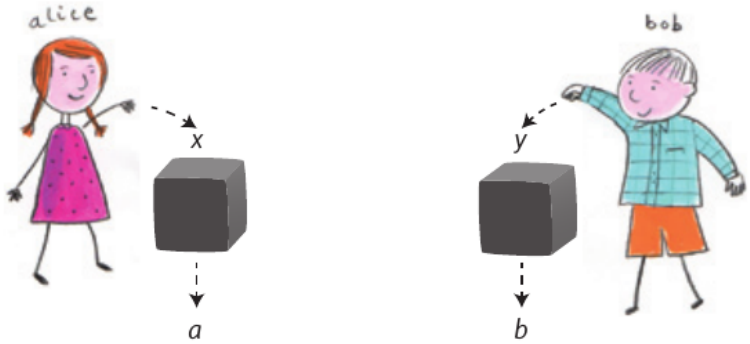

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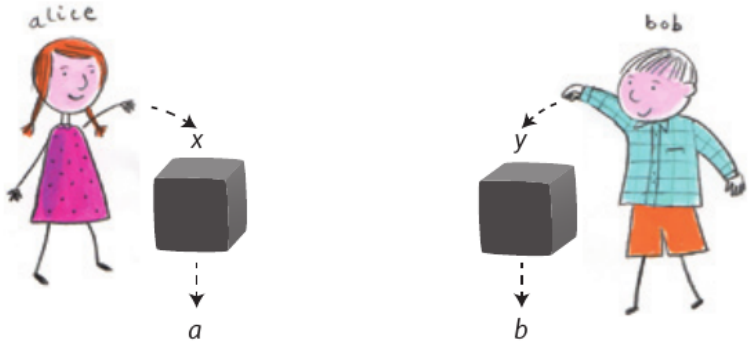

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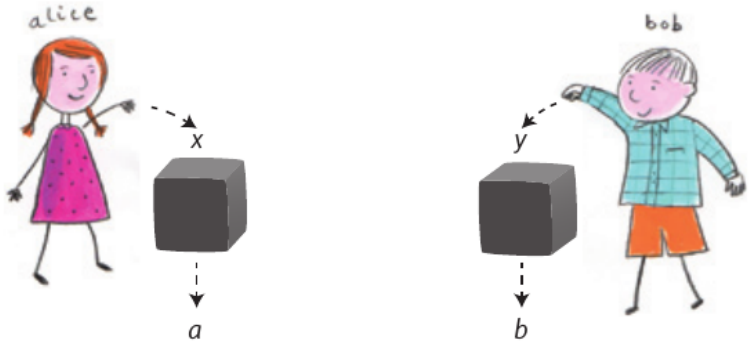

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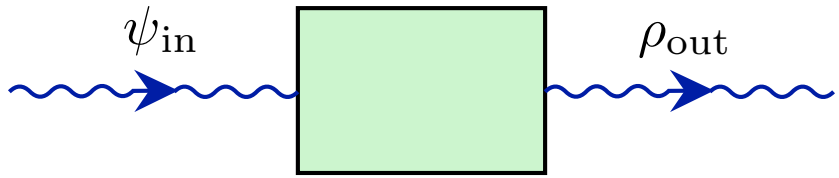
Quantum-data boxes

- 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**, $P : x \to \psi_{\text{in}}$.
- The *output state* is reconstructed via **quantum tomography** from the outcomes of projective measurements $M : \rho_{\text{out}} \to a$.
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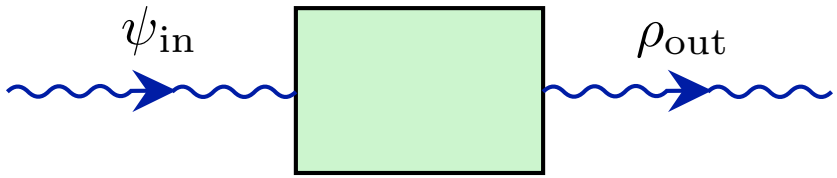

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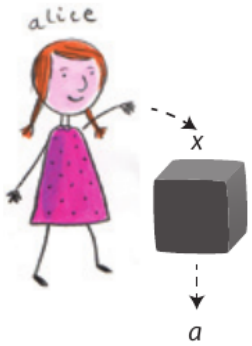

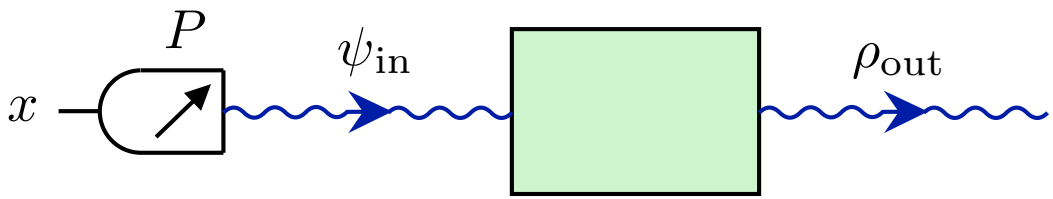

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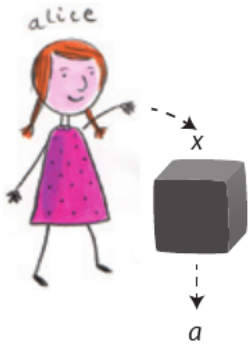

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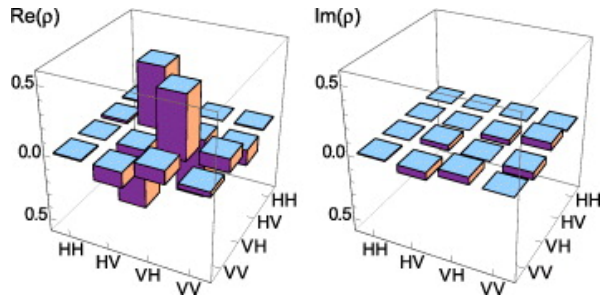

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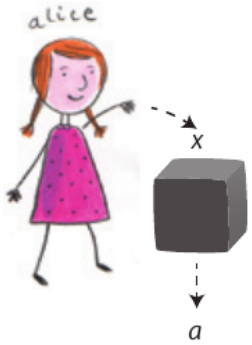

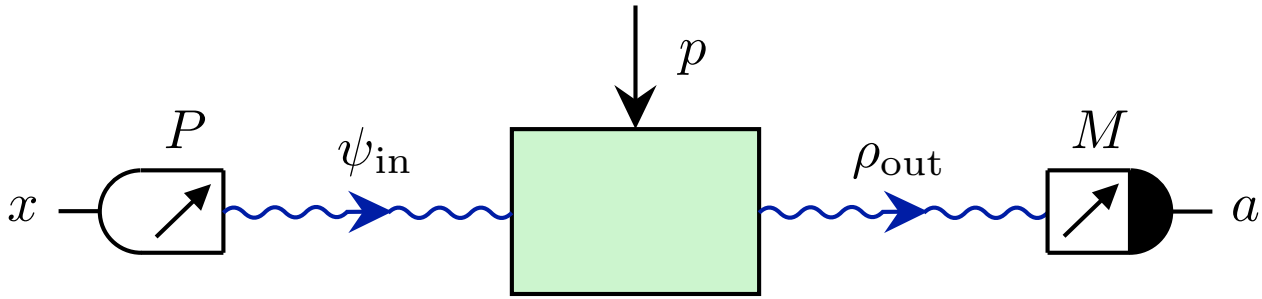

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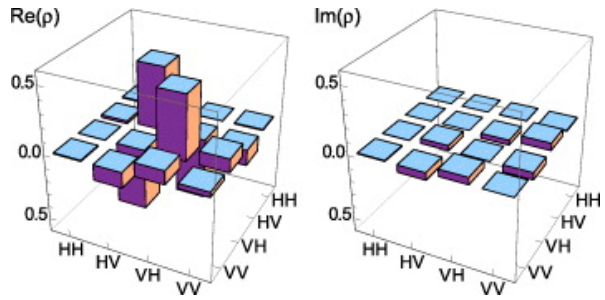

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Example: the Helstrom test

- 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.
- Define the **success rate**:

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

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

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

- If $P_{\text{succ}}(\rho^1_{\text{out}}, \rho^2_{\text{out}}) > P_{\text{succ}}(\psi^1, \psi^2)$ then the Q-data box is **not** quantum.
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- Suppose that we have two available inputs ψ^1, ψ^2.
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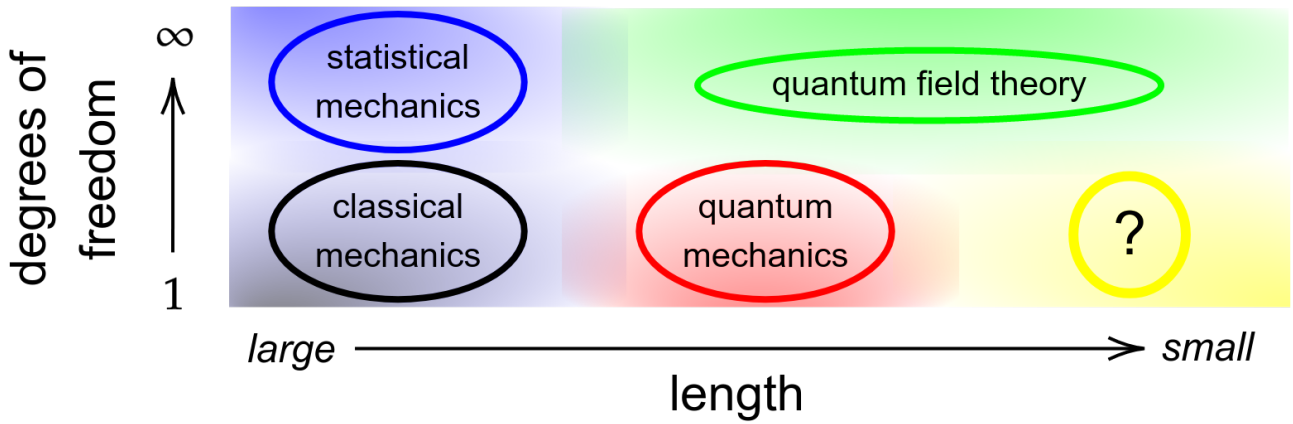

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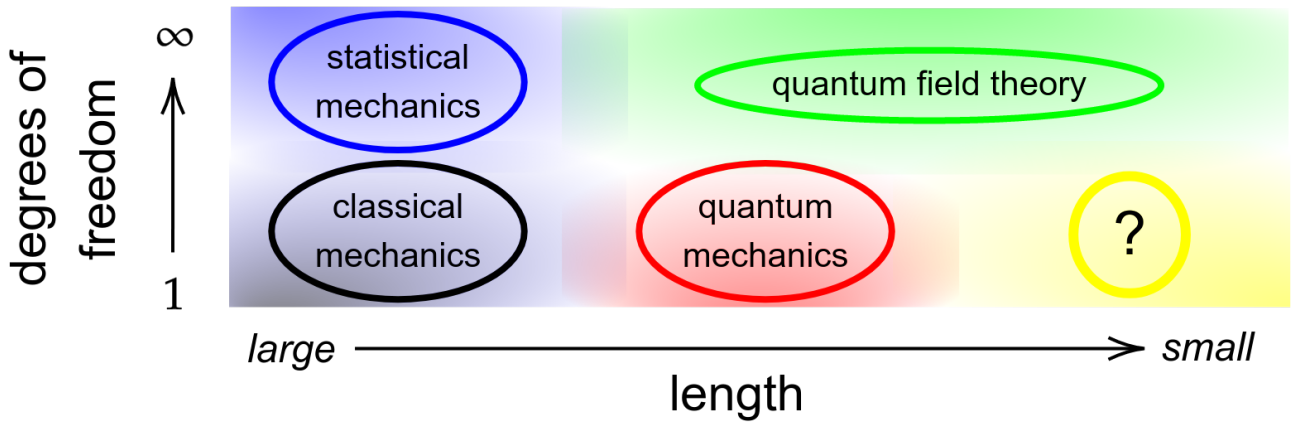

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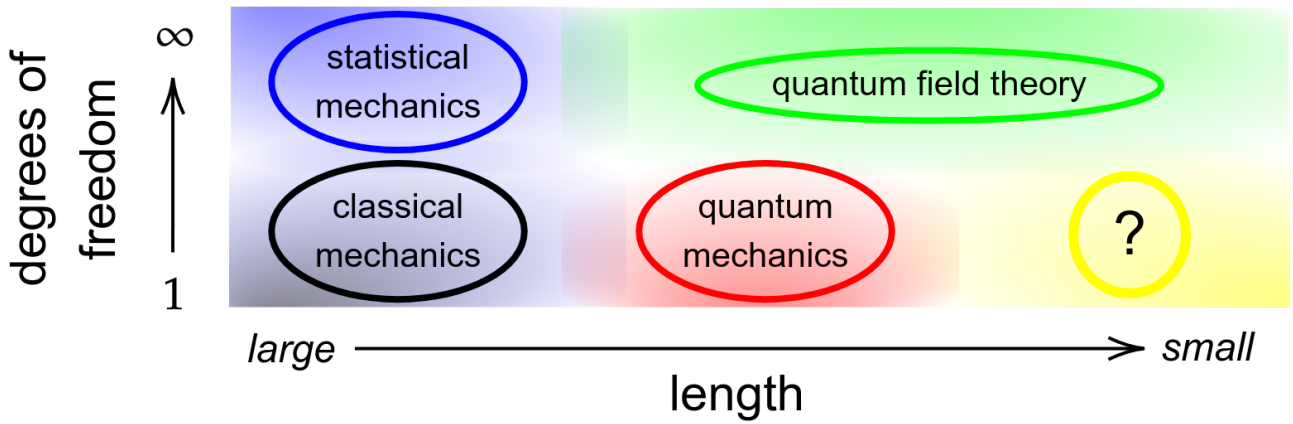

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Main idea:

1. Prepare a 'quantum-programmed' particle carrying 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 $\rightsquigarrow$ polarized beams
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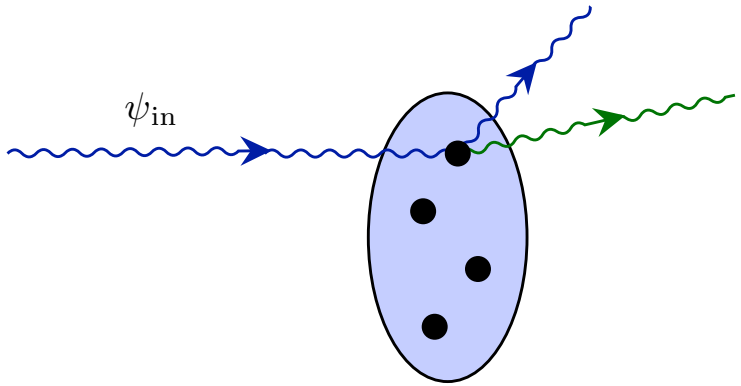

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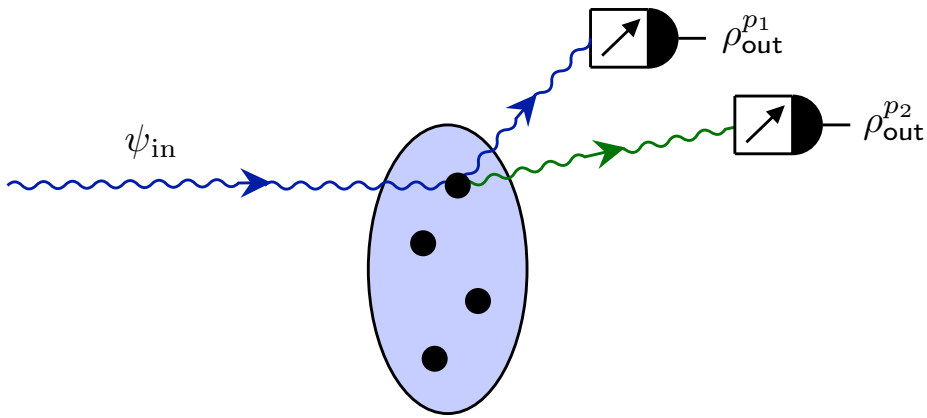

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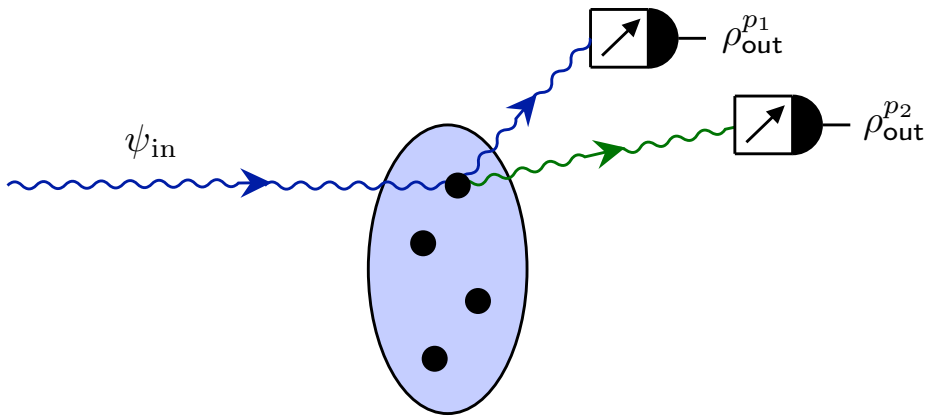

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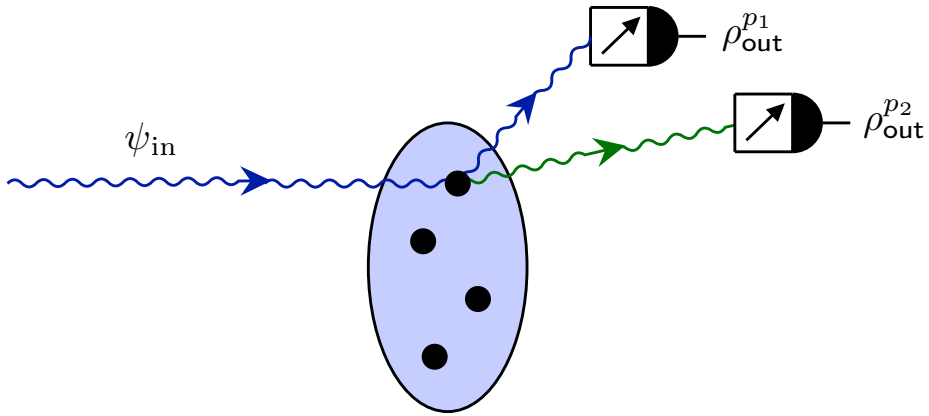

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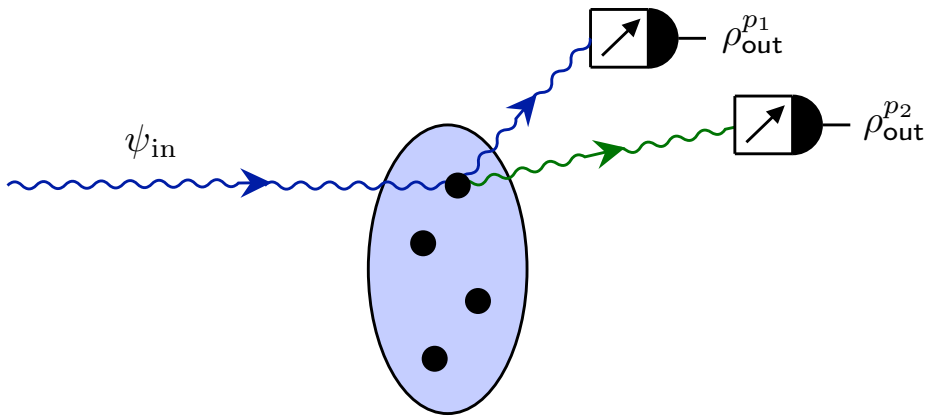

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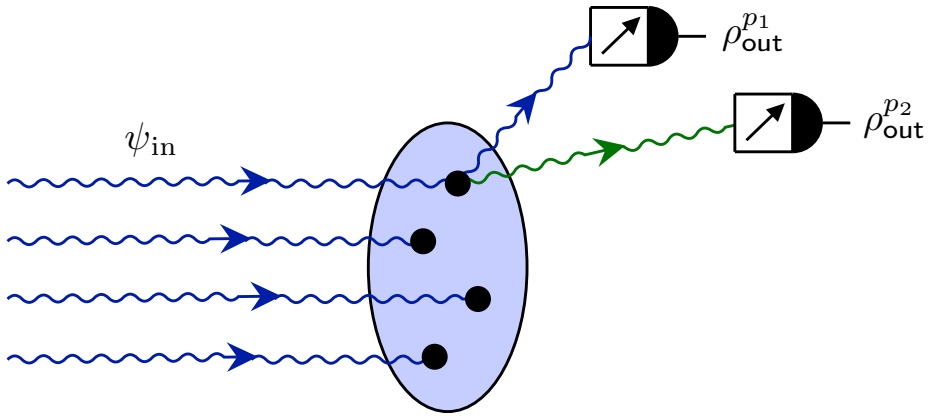

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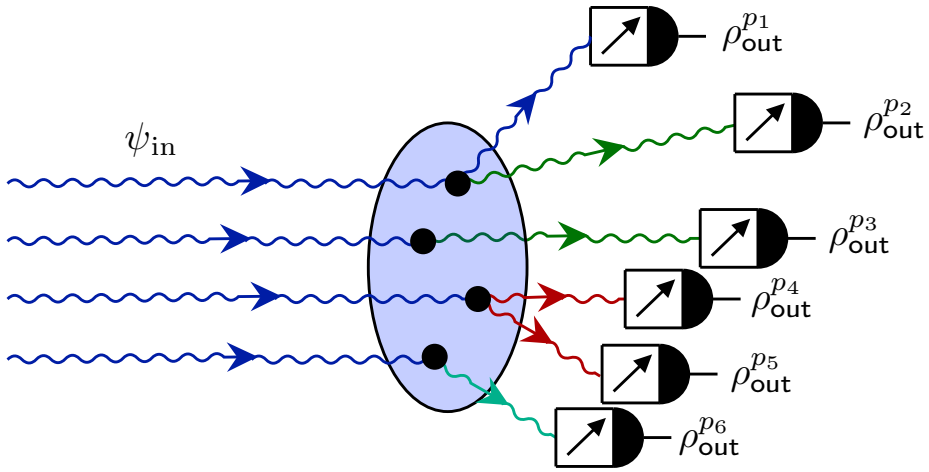

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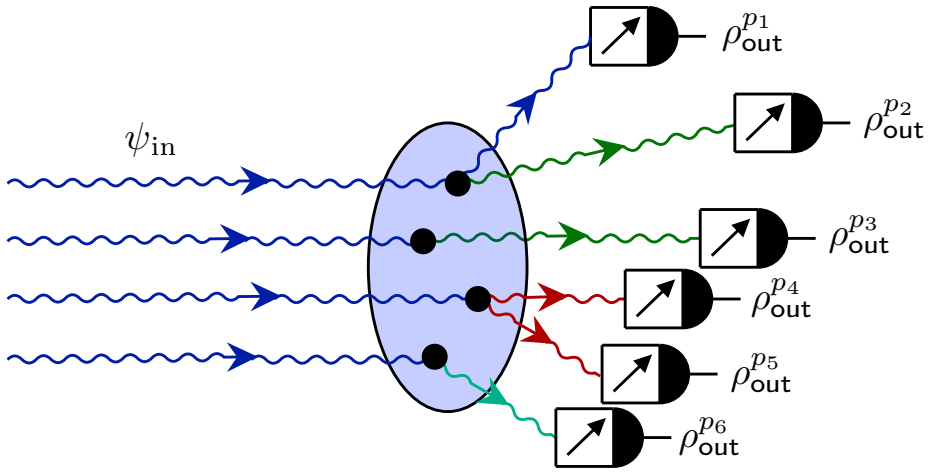

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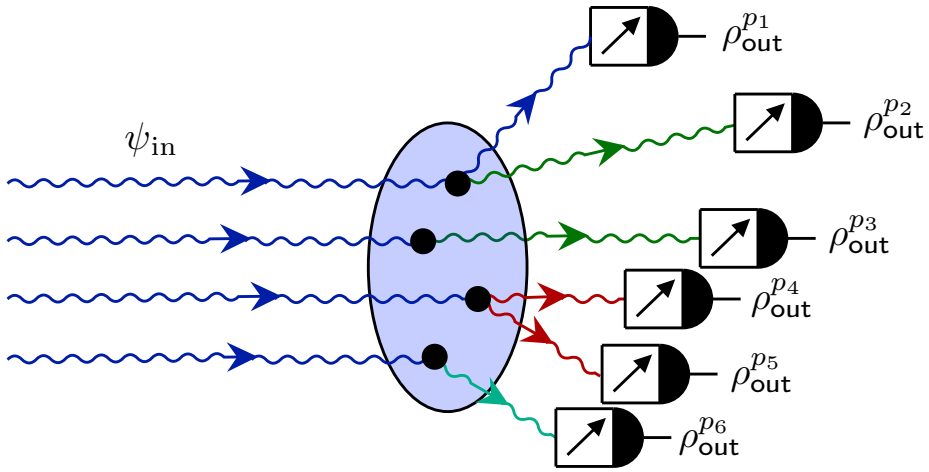

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Proc. R. Soc. A. **478**:20210806 (2022), arXiv:2103.12000

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