Do we have the freedom of choice in high-energy experiments and why should we care?

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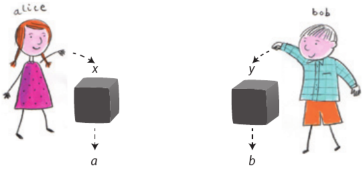
Bell nonlocality – the **black box** approach

2 parties (Alice and Bob) — 2 **inputs** (x, y) — 2 **outputs** (a, b)

$$P(a, b \,|\, x, y)$$



[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)]

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

Quantum Mechanics [Cirelson (1980)]

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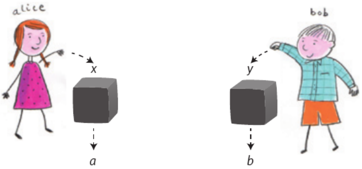

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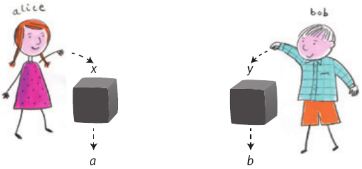

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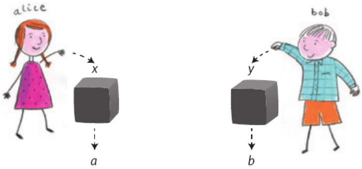

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Assumptions – "**loopholes**" in the Bell test

- *locality* (i.e. '*no-signalling*'): Alice and Bob cannot communicate
- *fair sampling*: need to register $\geq 83\%$ events
- *freedom of choice*: (aka 'setting independence'):
  - Alice's and Bob's **settings** are independent from each other
    $$P(x, y) = P(x) \cdot P(y)$$
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- *freedom of choice* (aka 'measurement independence'):
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   - No-signalling boxes
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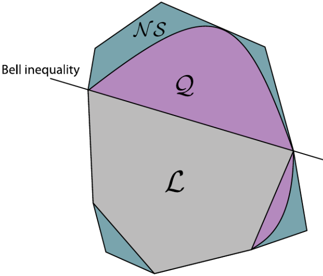

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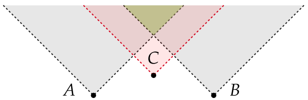

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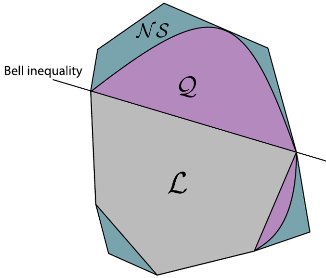

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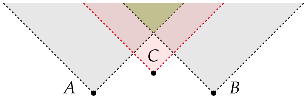

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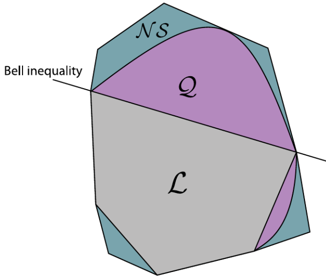

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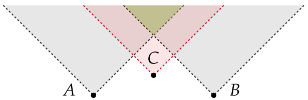

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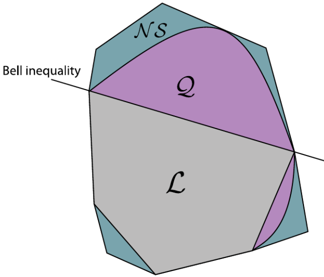

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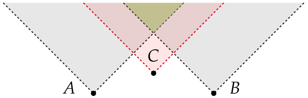

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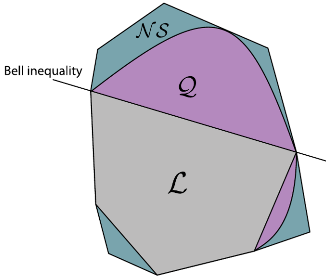

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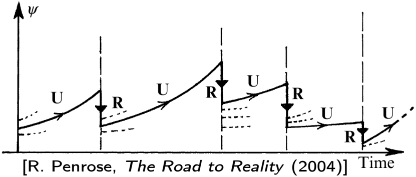
Purely operational 'theories' — model-independent approach

Objective collapse models — nonlinear QM



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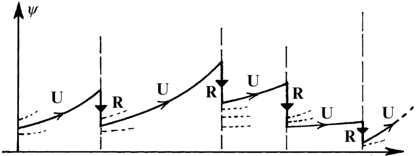

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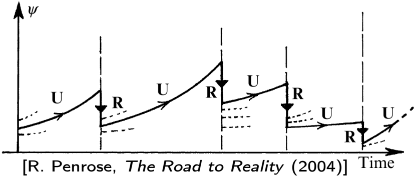

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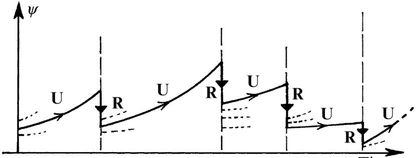

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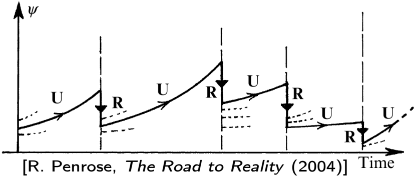

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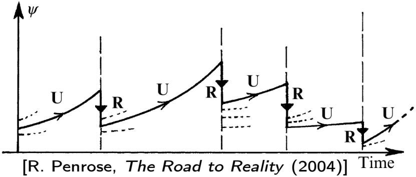

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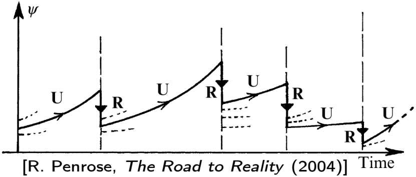

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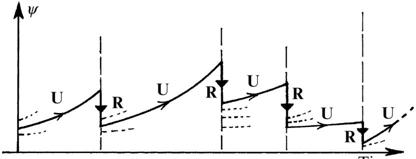

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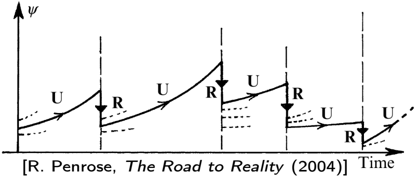
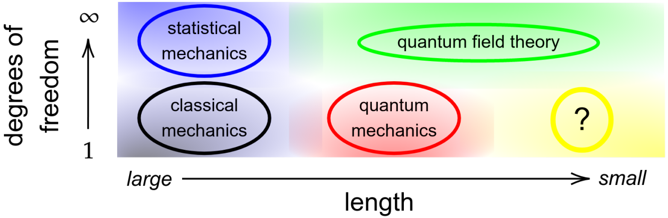


[R. Penrose, *The Road to Reality* (2004)]

3. Wave function collapse models — 'quantum-to-classical' transition
   [A. Bassi, K. Lochan, S. Satin, T.P. Singh, H. Ulbricht, *RMP* **85**, 471 (2013)]
   - **nonlinearity** — modified Schrödinger equation
   - **stochasticity** — 'collapse noise'
4. Nonlinear terms in QM/QFT
   - Nonlinear Schrödinger eq. [Penrose, Weinberg, ...]
   - **Problems with relativistic causality** [N. Gisin, (1989)]
   - NL QFT — D.E. Kaplan, S. Rajendran, *PRD* **105**, 055002
   - M. Bielińska, M.E., P. Horodecki — work in progress ...

Beyond-quantum physics?



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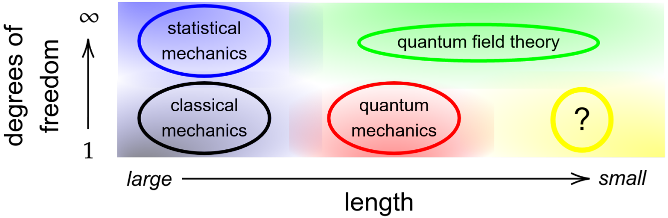

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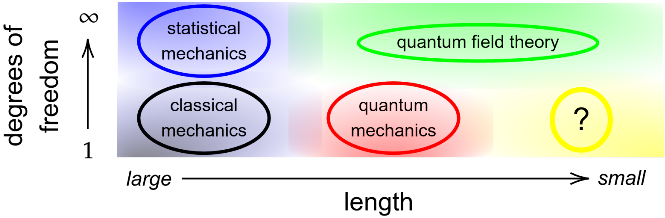

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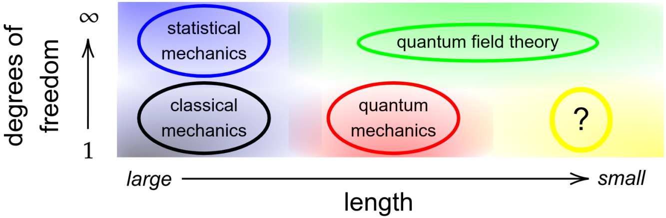

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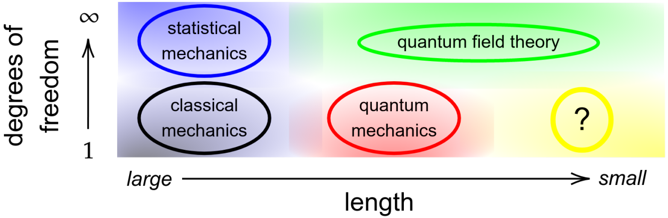

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Quantum-data boxes

- We regard 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)
- 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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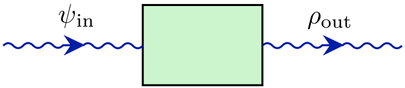

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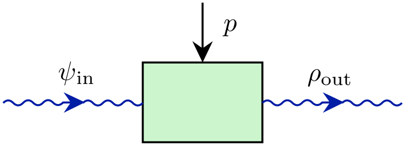

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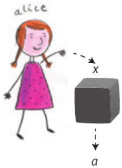
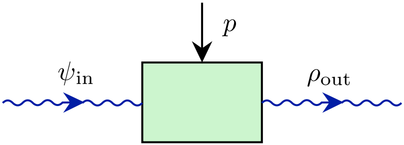


[Nat. Phys. 10, 264 (2014)]



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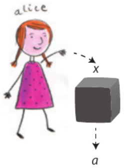

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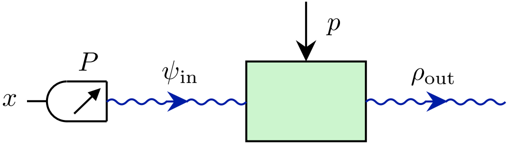

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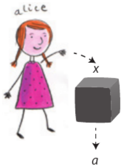

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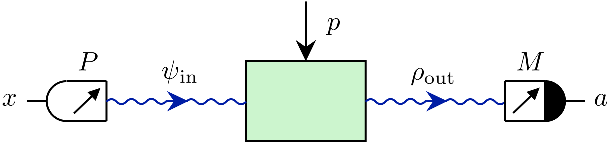

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Quantum state preparation and tomography

Quantum state preparation:

- In principle, any quantum state can be prepared via proj. measurements.
- ψ_{in} is pure, **uncorrelated** with the box — freedom of choice.

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 $\{M_i\}_{i=1}^{n^2-1}$ (e.g. $\{\sigma_x, \sigma_y, \sigma_z\}$).
- 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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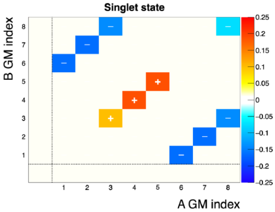
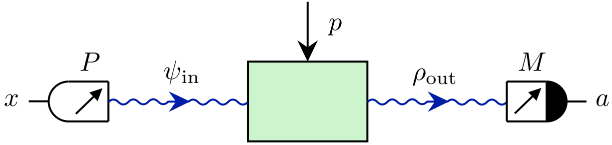


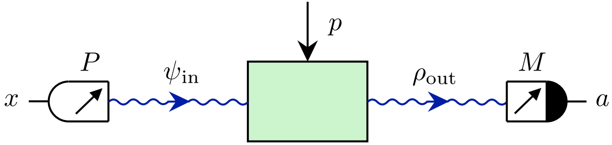
[R. Ashby-Pickering, A.J. Barr, A. Wierzchucka, arXiv:2209.13990]

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 $\{\psi_{\text{in}}^{(k)}, p^{(\ell)}; \rho_{\text{out}}^{(k,\ell)}\}_{k,\ell}$.
- The more tomographic measurements, the more reliable the test.
- The input ψ_{in} is pure, but the output ρ_{out} is *mixed*.



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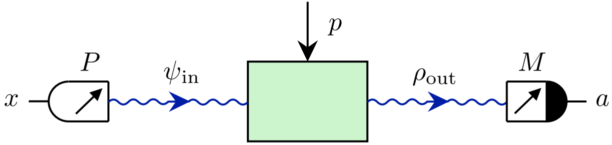

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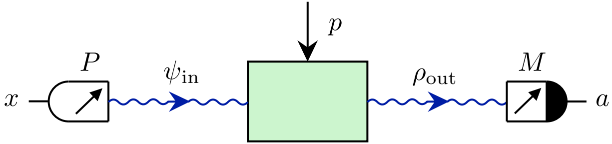

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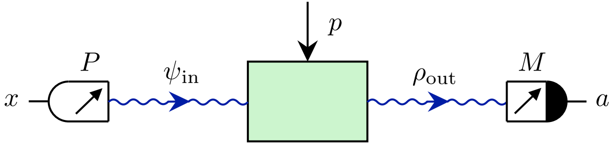

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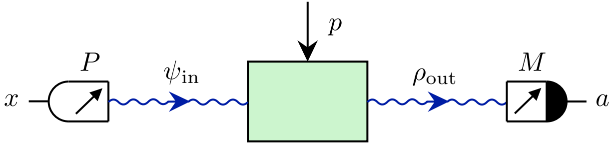

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An example — the Helstrom test

- 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 $\{\psi_{\text{in}}^{(k)}; \rho_{\text{out}}^{(k)}\}_{k=1,2}$.
- 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.
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- In QM *any* dynamics $\mathcal{E} : \mathcal{H}_{\text{in}} \to S(\mathcal{H}_{\text{out}})$ must be a **CPTP map**.
- $\mathcal{E}$ is completely characterised by $m^2(n^2 - 1)$ real parameters, with $m = \dim \mathcal{H}_{\text{in}}$, $n = \dim \mathcal{H}_{\text{out}}$.
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- Q-data tests $\{\psi_{\text{in}}^{(k)}\}$ with $k > m^2$ can show deviations from CPTP!

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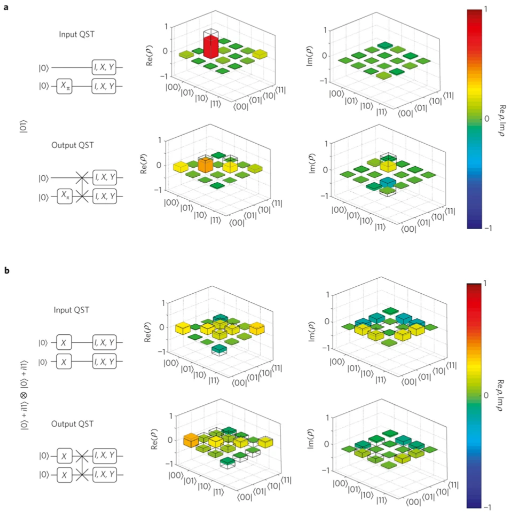

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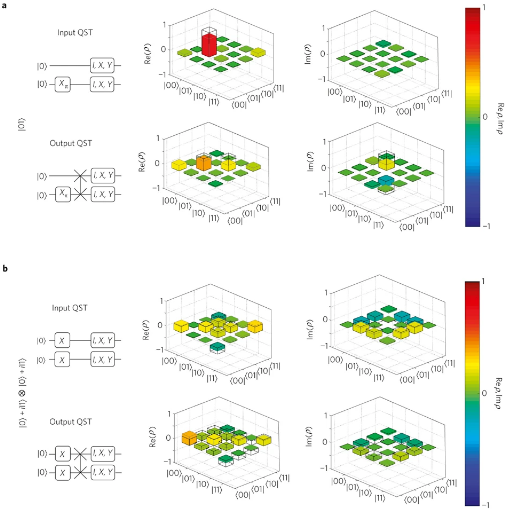

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Towards experimental quantum process tomography

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

Main challenges:

- Need to prepare the quantum state of GeV particles $\rightsquigarrow$ polarized beams
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  For example, in $W \to \ell\nu$ process the direction of ℓ strongly depends on the W's spin state. [A. Barr, *Phys. Lett. B* **825** 136866 (2022)]

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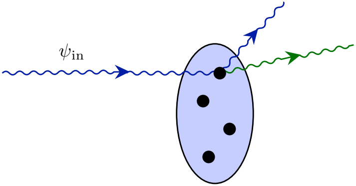

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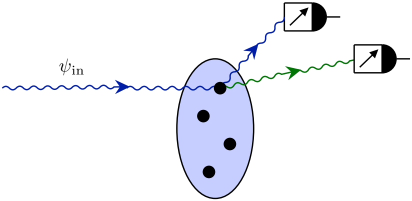

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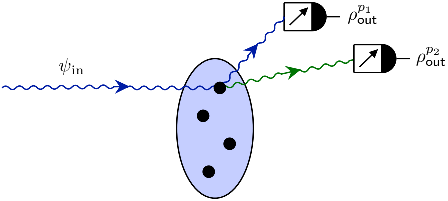

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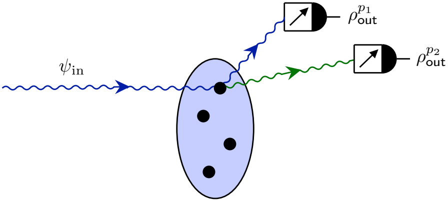

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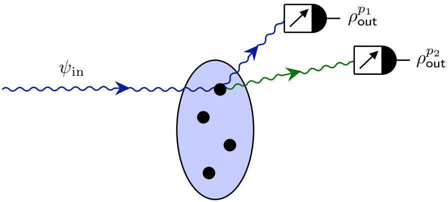

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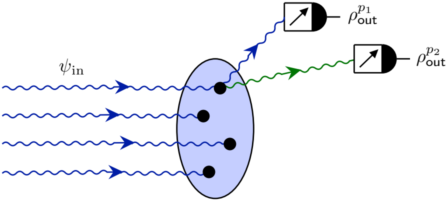

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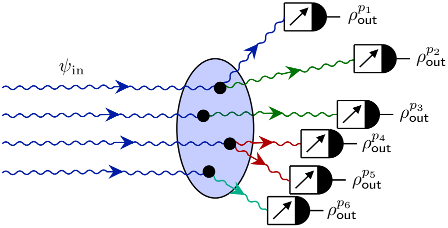

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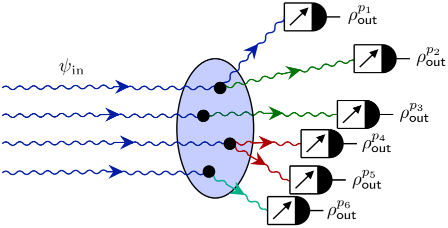

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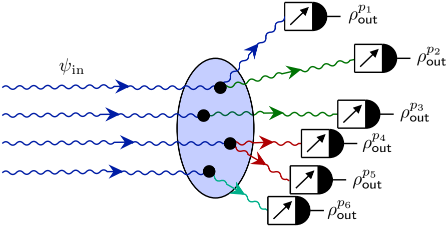

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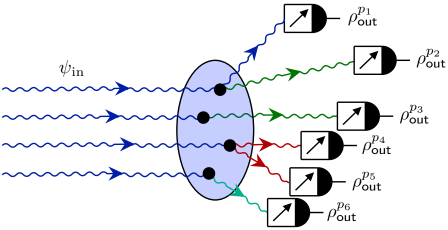

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Proc. R. Soc. A. **478**:20210806 (2022), arXiv:2103.12000

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