Probing the limits of quantum theory in high energy physics.

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JAGIELLONIAN UNIVERSITY IN KRAKÓW

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Kraków, 11 May 2023

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, ...)
   - quantum gravity
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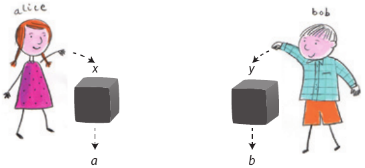
Bell nonlocality – the **black box** approach

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)]

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

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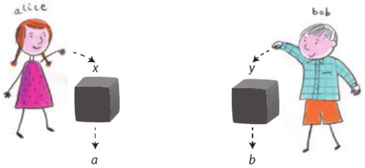

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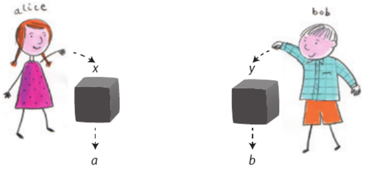

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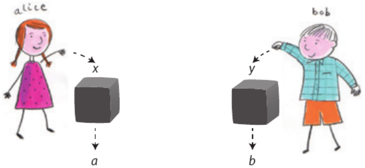

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Bell nonlocality — *beyond* quantum mechanics

$$S := C(x,y) + C(x,y') + C(x',y) - C(x',y')$$

Can we achieve $S = 4$?

- Alice and Bob can communicate,
- or their settings are pre-correlated.

But can we do it assuming:

- **no-signalling**: $\sum_b P(a,b\,|\,x,y) = \sum_b P(a,b\,|\,x,y')$, for all a,x,y,y',
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No-signalling boxes [Popescu, Rohrlich (1994)]

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   - No-signalling boxes
     [N. Brunner, D. Cavalcanti, S. Pironio, V. Scarani, S. Wehner, *Rev. Mod. Phys.* **86**, 419 (2014)]
   - 3-party monogamy violation
2. General Probabilistic Theories [G. Chiribella, R.W. Spekkens (Eds.), *Quantum Theory: Informational Foundations and Foils*, Springer, 2016]
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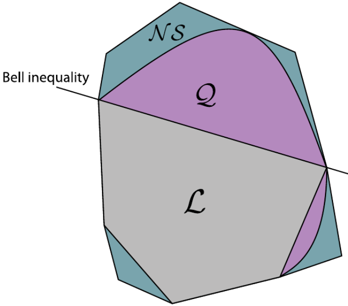

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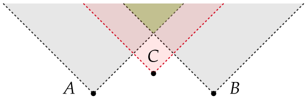
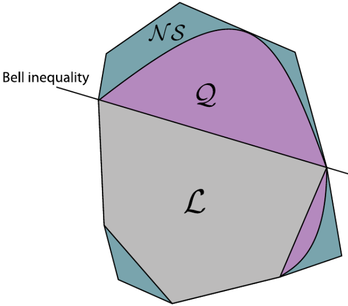


[P. Horodecki, R. Ramanathan, *Nat. Comm.* **10**, 1701 (2019)]



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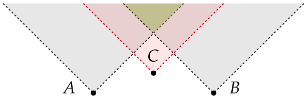

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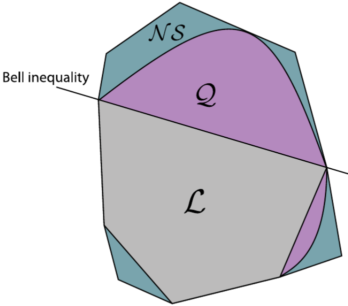

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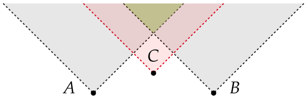

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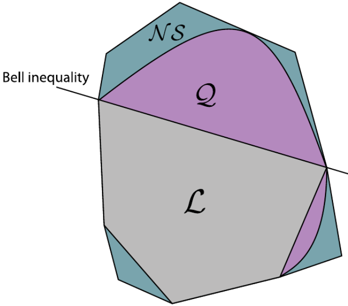

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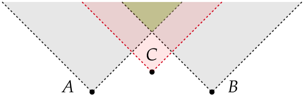

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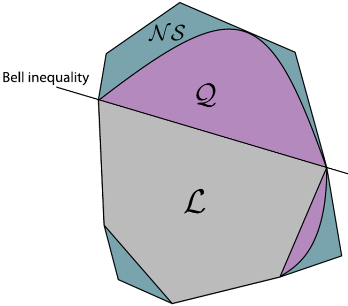

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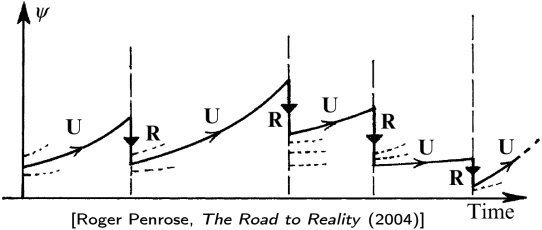
Purely operational 'theories' — model-independent approach

Objective collapse models



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

3. Wave function collapse models

   [A. Bassi, K. Lochan, S. Satin, T.P. Singh, H. Ulbricht, *Rev. Mod. Phys.* **85**, 471 (2013)]

   - Aimed at explaining the 'quantum-to-classical' transition.
   - **nonlinearity** — modified Schrödinger equation
   - **stochasticity** — 'collapse noise'

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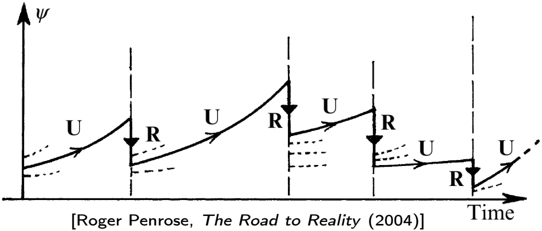

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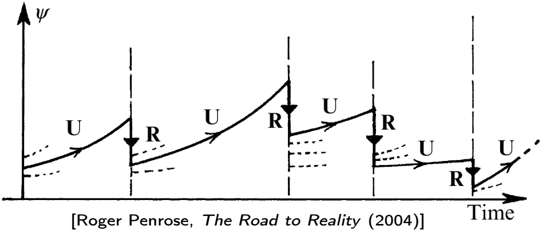

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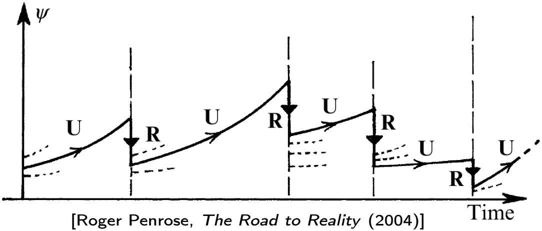

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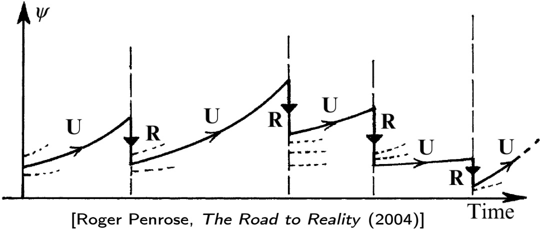

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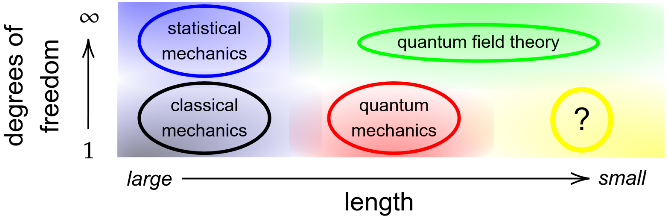
Objective collapse models involve deviations from unitarity and linearity.

Beyond-quantum physics?



- Is there a gap between QM and QFT?

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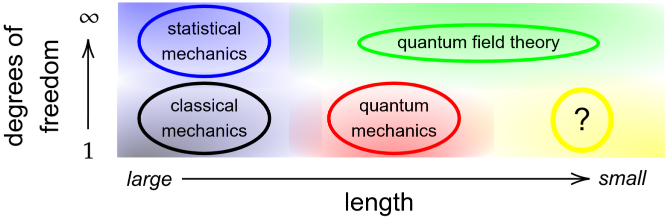

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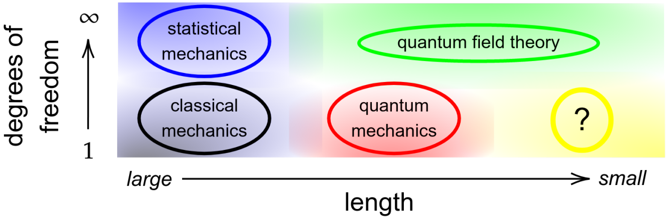

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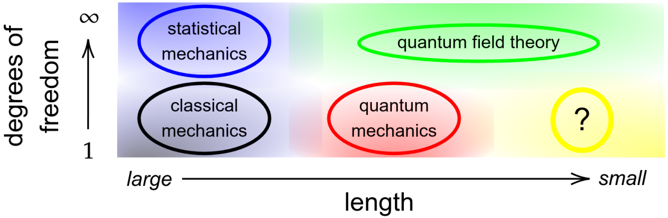

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Quantum-data boxes

- 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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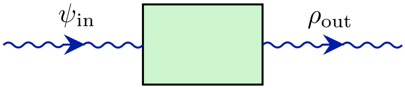

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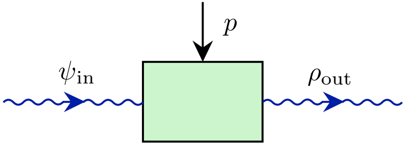

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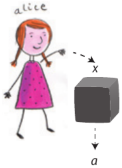
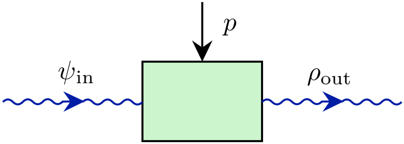


[Nat. Phys. **10**, 264 (2014)]



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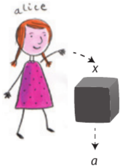

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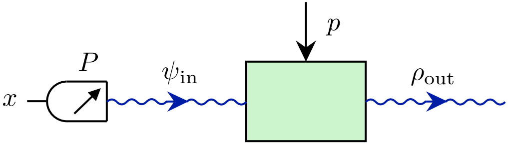

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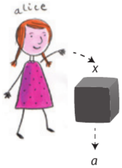

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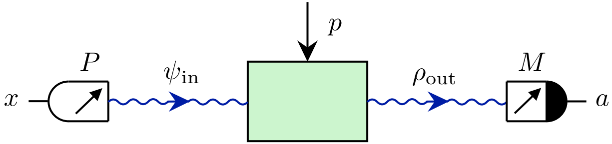

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Quantum preparation and tomography

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 $\mathrm{Tr}\left(M_i\, \rho_{\text{out}}\right) = \sum_j a_j P(a_j \,|\, M_i)$.

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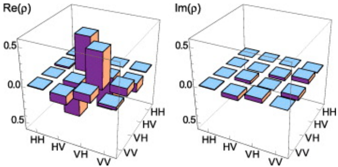
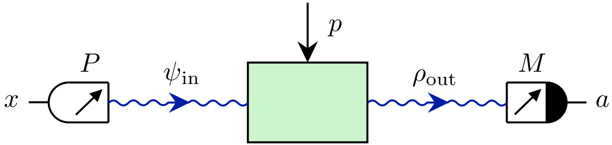


[J. Huwer et al., *New J. Phys.* 15, 025033 (2013)]

Quantum-data tests



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}.
- 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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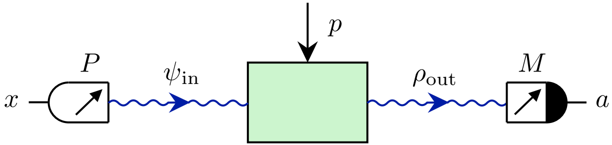

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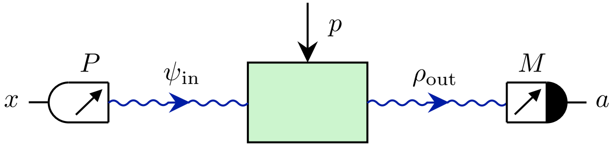

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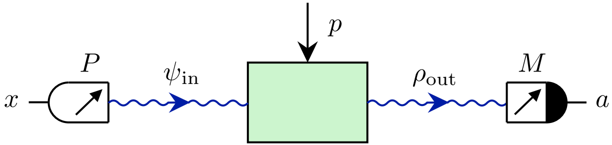

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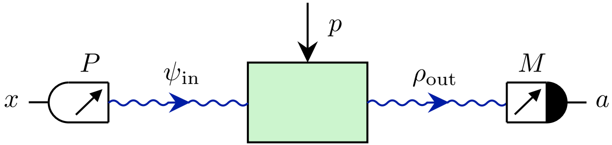

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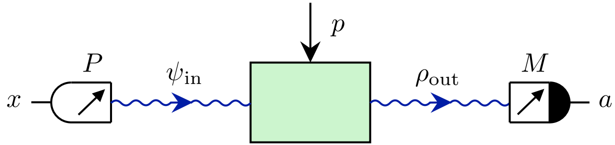

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An example — the Helstrom test

- 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**: $P_{\text{succ}}\big(\psi_{\text{in}}^{(1)}, \psi_{\text{in}}^{(2)}\big) := \frac{1}{2}\sum_{k=1}^{2} P\big(a = k \,|\, \psi_{\text{in}}^{(k)}\big)$.
- 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.
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- QM implies that any **quantum channel**, i.e. a map $\mathcal{E} : S(\mathcal{H}_{\text{in}}) \to S(\mathcal{H}_{\text{out}})$ is completely positive trace preserving (**CPTP**).

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For every CPTP map $\mathcal{E} : S(\mathcal{H}_{\text{in}}) \to S(\mathcal{H}_{\text{out}})$ there exists a (non-unique) set of operators $\{K_i\}_{i \leq mn}$, where $m = \dim \mathcal{H}_{\text{in}}, n = \dim \mathcal{H}_{\text{out}}$, such that

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$\mathcal{E}$ is CPTP if and only if $\widetilde{\mathcal{E}} = \frac{1}{m} \sum_{i,j=1}^{m} |i\rangle\langle j| \otimes \mathcal{E}(|i\rangle\langle j|) \in \mathbb{C}^{mn \times mn}$ is a state.

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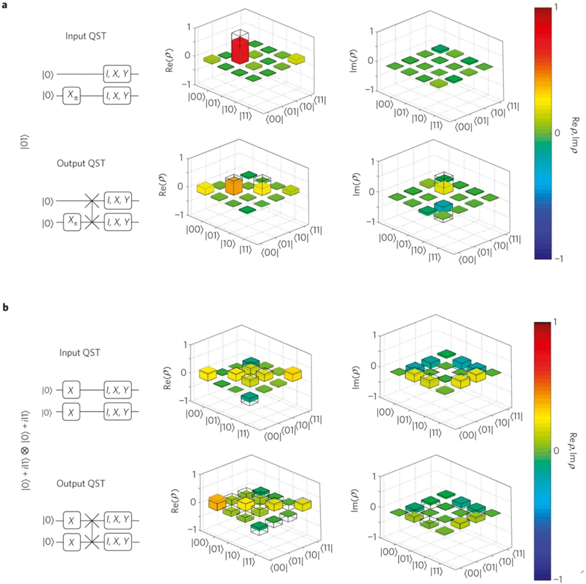
[R. Bialczak et al., *Nature Physics* **6**, 409 (2010)]



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1. Prepare a ‘quantum-programmed’ particle carrying ψ_{in}, e.g. electron’s spin or photon’s polarization.
2. Scatter it on a target.
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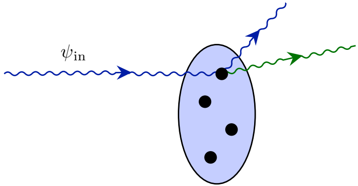

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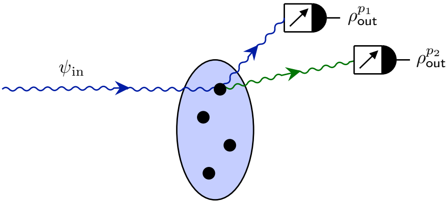

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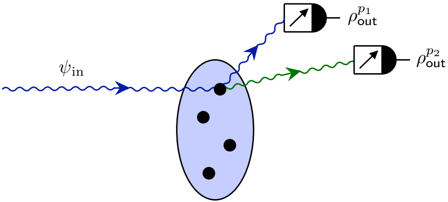

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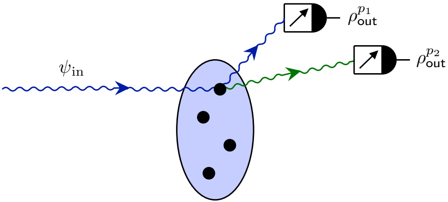

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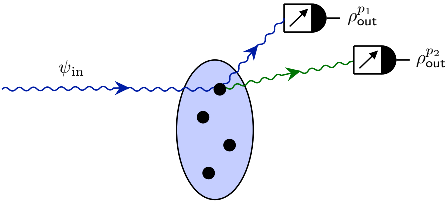

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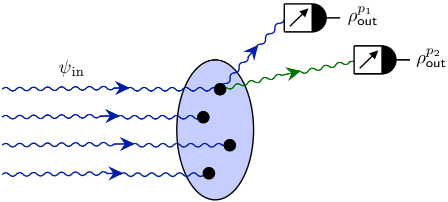

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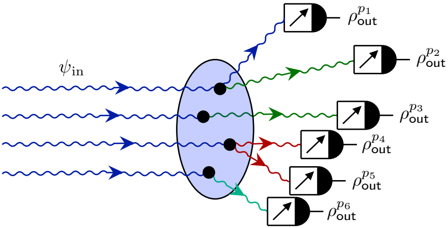

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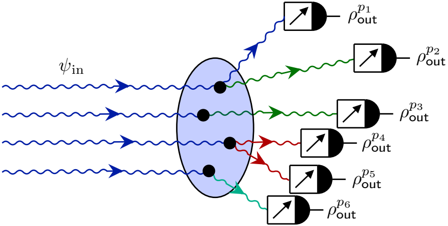

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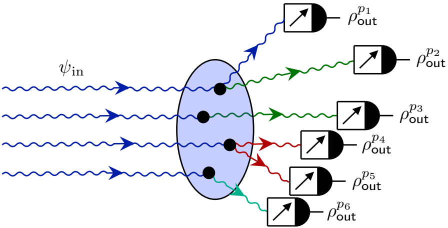

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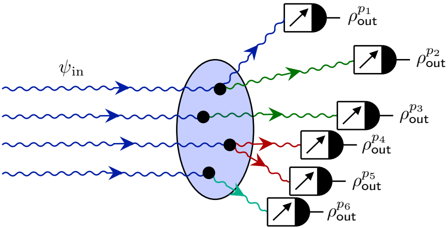

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Proc. R. Soc. A. **478**:20210806 (2022), arXiv:2103.12000

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Summary

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Take-home messages:

- Quantum mechanics can be probed from an **'outside' perspective**.
- Whenever we are doing a Bell-type test, we are testing QM against *both* local hidden variables and **beyond-quantum correlations**.
- Need for **quantum process tomography**:
  - Seeking deviations from unitarity and linearity.
  - Understanding quantum dynamics at subnuclear scales.

Thank you for your attention!