New foundational experiments with quantum process tomography

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JAGIELLONIAN UNIVERSITY IN KRAKÓW
University of Gdańsk
GDAŃSK UNIVERSITY OF TECHNOLOGY

West Lafayette, IN, Oct 2, 2023

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, Hawking radiation ...)
   - quantum gravity
3. **Beyond Quantum Mechanics**, but assuming relativity
   - Super-quantum correlations, ...
   - Deviations from linearity in QM and/or QFT
   - Objective wave function collapse models

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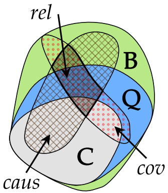

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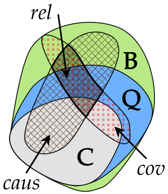

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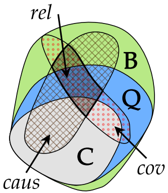

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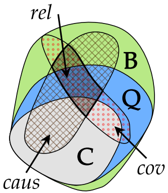

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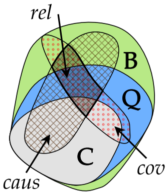

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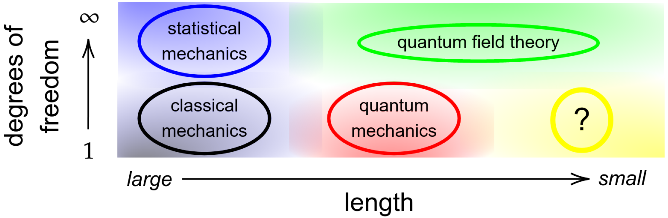

- Is there an 'objective collapse' in a decay process?
- Are correlations in QFT stronger than in QM?
- Are QM & QFT only effective descriptions of Nature?
- How to look for possible deviations from QM?

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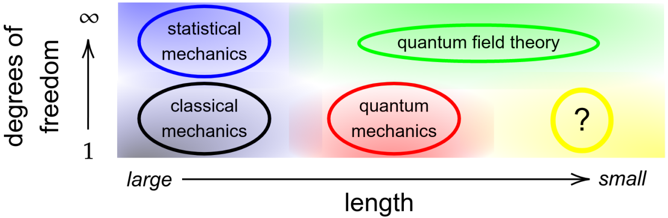

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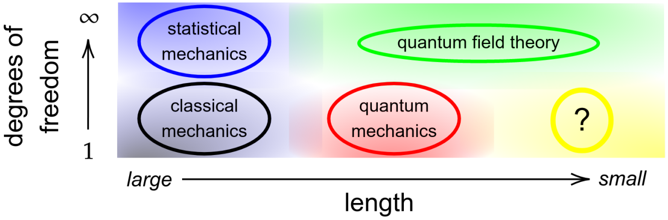

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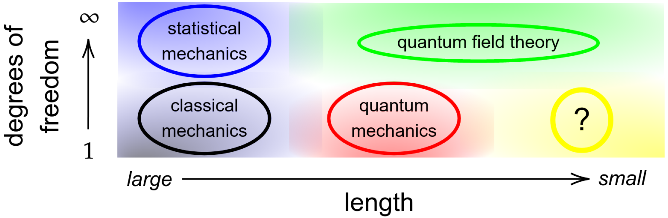

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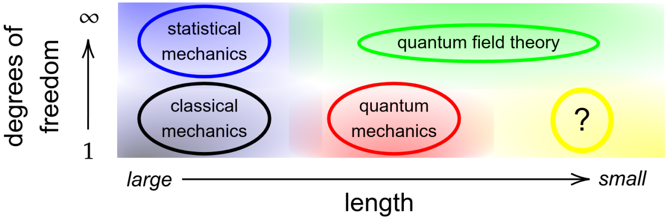

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The theory independent **black box** methodology

- Physical systems are treated (merely!) as information-processing devices ("**black boxes**") and probed by free agents.
- The conclusions are drawn from the **output–input correlations**.

$$P(\text{outputs} \,|\, \text{inputs})$$

Bell test: 2 agents (Alice and Bob) — 2 inputs (x, y) — 2 outputs (a, b)

The *experimental* (frequency) correlation function:

$$C_e(x, y) = P(a = b \,|\, x, y) - P(a \neq b \,|\, x, y)$$

The key assumption of *freedom of choice* ("measurement independence"):

$$P(x, y \,|\, \lambda) = P(x) \cdot P(y)$$

- No pre-correlations between the inputs (x, y) and the box (λ).

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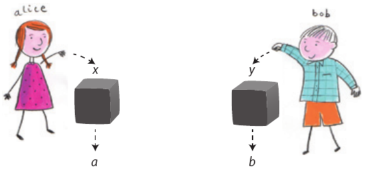

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[Sandu Popescu, *Nature Physics* 10, 264 (2014)]

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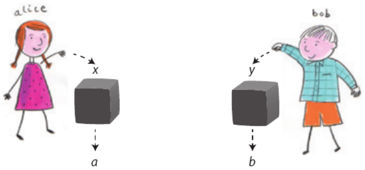

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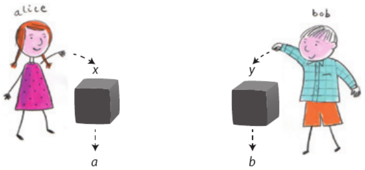

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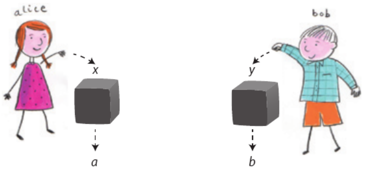

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Quantum-data boxes

- We treat physical systems 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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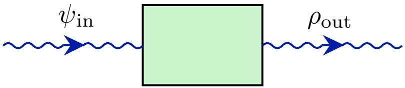

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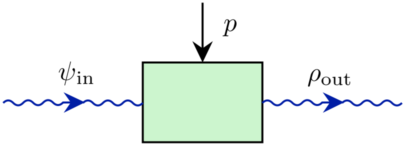

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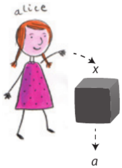

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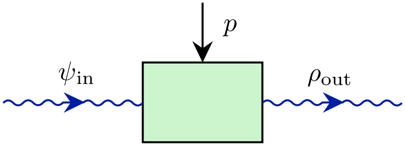

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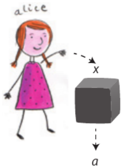

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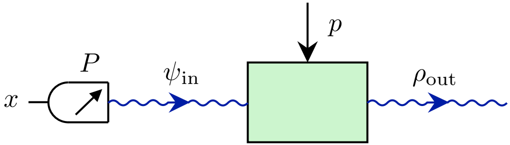

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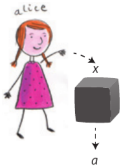

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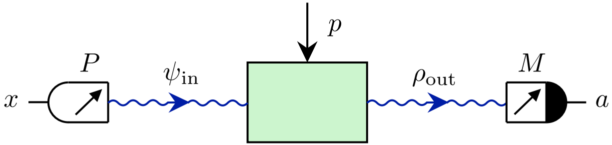

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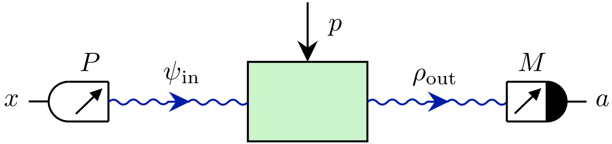

A **Q-data test** consists in probing a Q-data box with *prepared* input states.

- For every input state ψ_{in} one performs the full tomography of ρ_{out}.
  - 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 $\{P(a_j \mid M_i)\}_{i,j}$.
  - The state ρ_{out} is estimated from $\mathrm{Tr}\,(M_i\,\rho_{\text{out}}) = \sum_j a_j P(a_j \mid M_i)$.
- A Q-data test yields a dataset $\{\psi_{\text{in}}^{(k)}, p^{(\ell)}; \rho_{\text{out}}^{(k,\ell)}\}_{k,\ell}$.
- ψ_{in} is pure, initially **uncorrelated** with the box — freedom of choice.
- ρ_{out} is in general *mixed*, i.e. entangled with the box.

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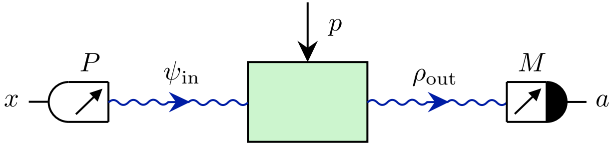

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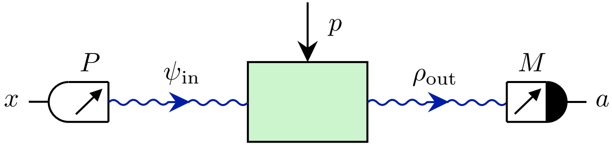

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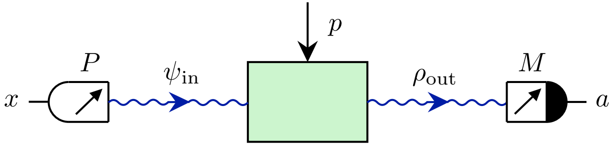
Quantum-data tests



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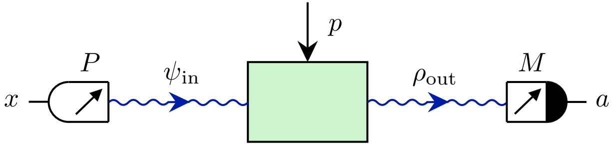

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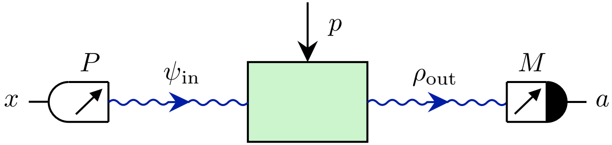

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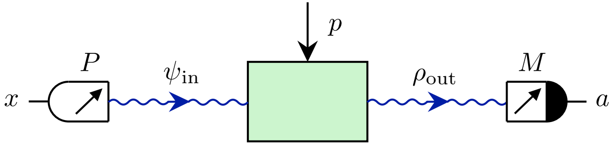

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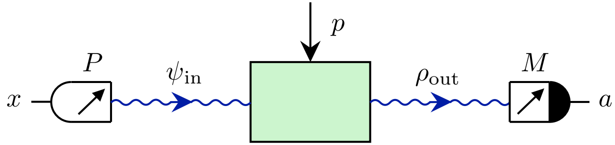

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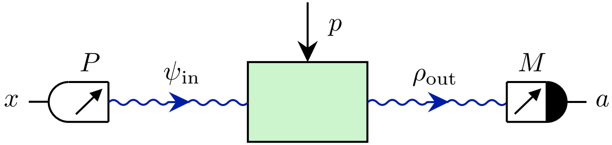

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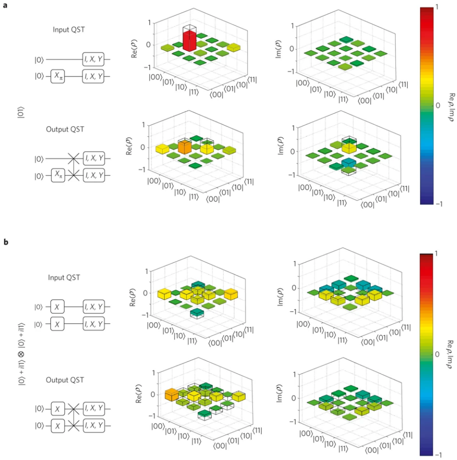

[R. Bialczak et al., *Nat. Phys.* **6**, 409 (2010)]

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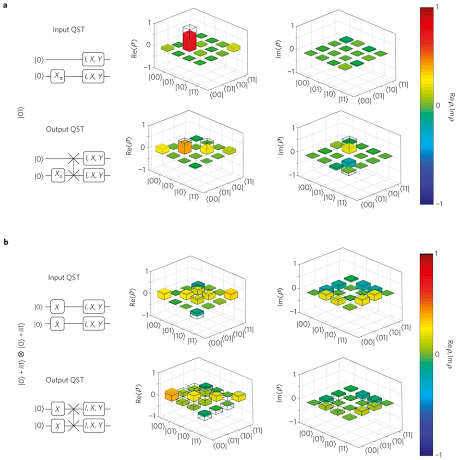

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Prospects for quantum process tomography in colliders

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3. Measure projectively the outgoing projectiles.
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Proc. R. Soc. A. **478**:20210806 (2022), arXiv:2103.12000

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