New foundational experiments with quantum process tomography

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JAGIELLONIAN UNIVERSITY IN KRAKÓW

University of Gdańsk

GDAŃSK UNIVERSITY OF TECHNOLOGY

Firenze, 6 November 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, Hawking radiation ...)
   - quantum gravity
3. **Beyond Quantum Mechanics**, but assuming relativity
   - Super-quantum correlations, GPTs, ...
   - Deviations from linearity in QM and/or QFT
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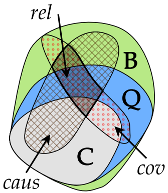

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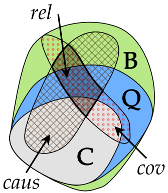

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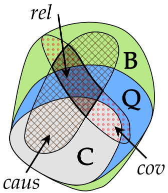

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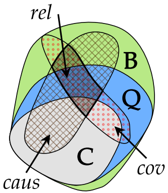

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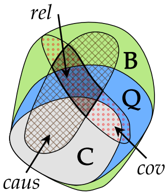

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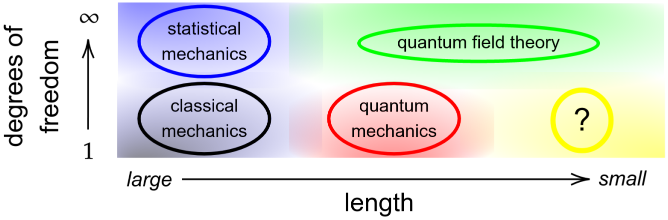

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- Are QM & QFT only effective descriptions of Nature?

- How to look for possible deviations from QM?

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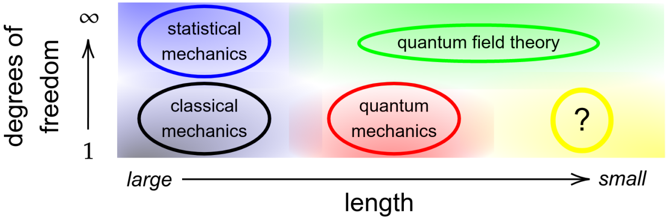

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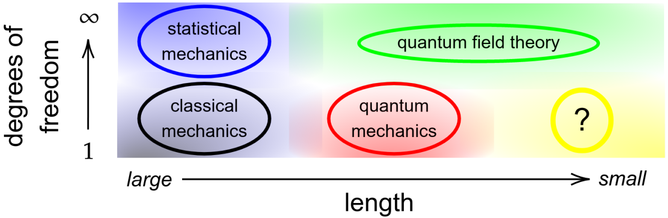

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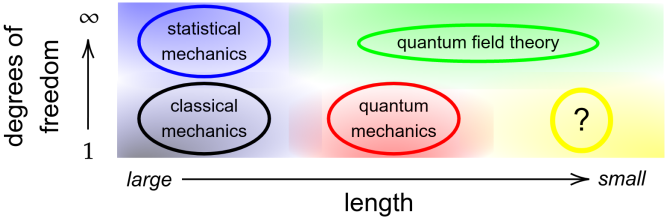

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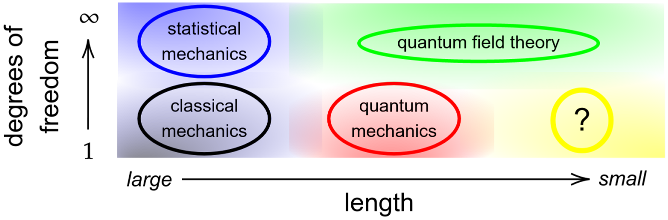

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The theory independent **black box** methodology

- 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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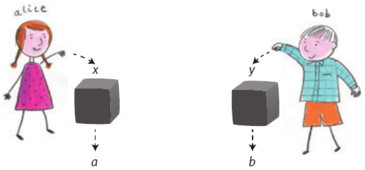

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[Sandu Popescu, *Nature Physics* **10**, 264 (2014)]

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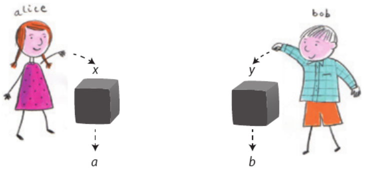

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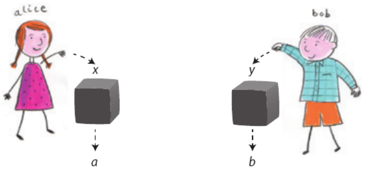

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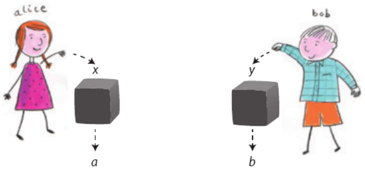

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Quantum-data boxes

- 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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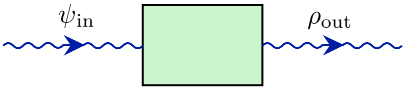

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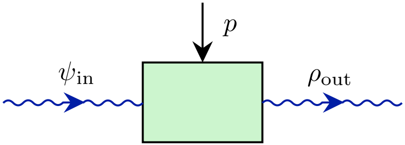

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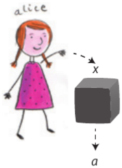

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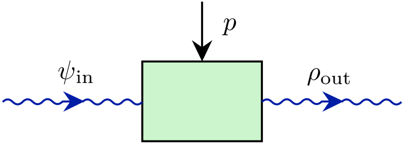

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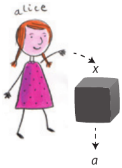

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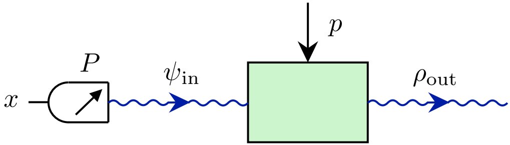

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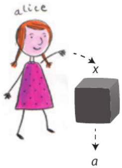

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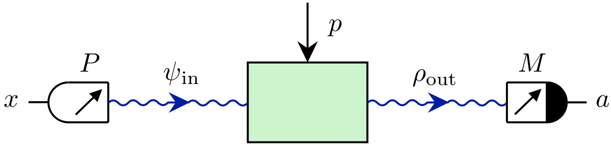

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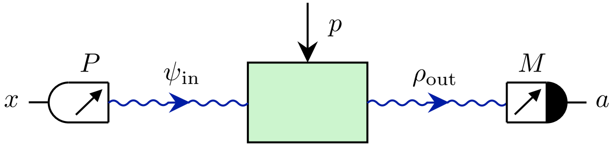

A **Q-data test** consists in probing a Q-data box with *prepared* input states.

- For every input state ψ_{in} one performs the full tomography of ρ_{out}.
- 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 'environment'.
- Don't need to gather all outgoing quantum information.

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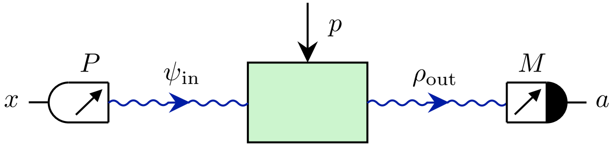

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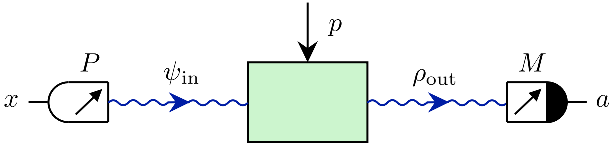

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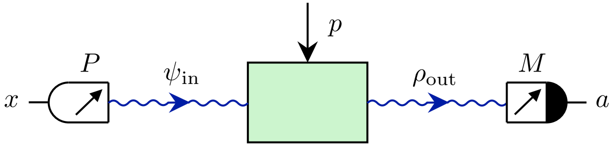

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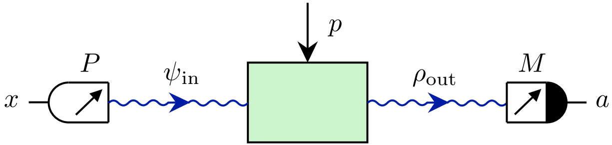

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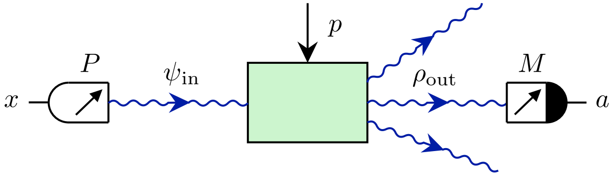

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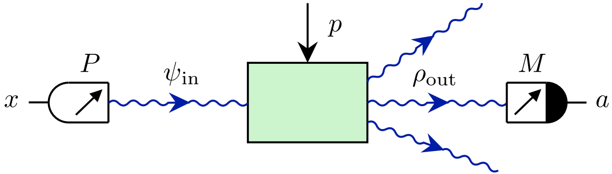

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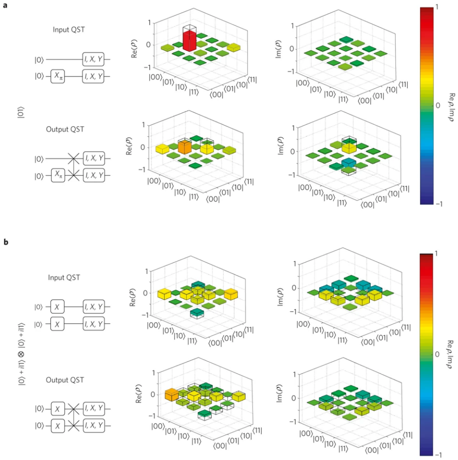

[R. Bialczak et al., *Nat. Phys.* **6**, 409 (2010)]

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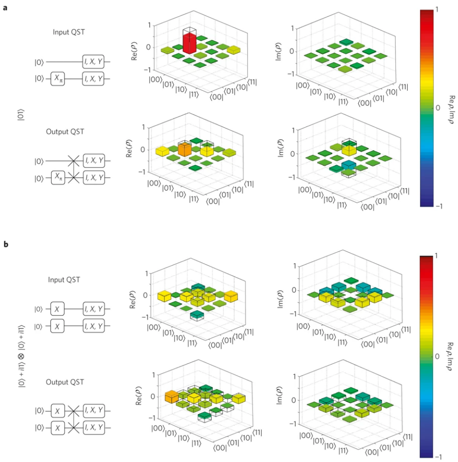

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3. Reconstruct the output states ρ_{out}. $\rightsquigarrow$ weak decays

- Experimental prospects:
  - Explore the spin dynamics with polarised beams, $\mathcal{H}_{\text{in}} = \mathbb{C}^2 \otimes \mathbb{C}^2$, $\mathcal{H}_{\text{out}} = \mathbb{C}^2 \otimes \mathbb{C}^2$ or $\mathcal{H}_{\text{out}} = \mathbb{C}^3 \otimes \mathbb{C}^3$
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  - Indirect processes, e.g. $e^-p^+ \to \gamma g + X \to t\bar{t} + Y$

    Such an operation $\mathcal{E} : \mathbb{C}^2_p \otimes \mathbb{C}^2_{e^-} \to S\big(\mathbb{C}^2_{t^+} \otimes \mathbb{C}^2_{t^-}\big)$ is *not* unitary, but it must be CP *if* quantum mechanics is valid.

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

Take-home messages:

- To make a proper Bell-type test you need the **freedom of choice**!
  - Entanglement detection is not a Bell test!
  - Could we make **direct** projective measurements of spin??
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  - Seek deviations from QM (unitarity, CP, linearity, ...)
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