Quantum process tomography at particle colliders

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JAGIELLONIAN UNIVERSITY IN KRAKÓW

in collaboration with

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Outline

1. Motivation: *beyond* quantum theory

   [M.E., P. Horodecki, *Proc. R. Soc. A.* **478**:20210806 (2022), arXiv:2103.12000]

   - *Why* venturing beyond quantum theory?
   - *What* might be out there?
   - ***How*** to seek beyond-quantum effects?

2. Implementation: *quantum process tomography* in colliders

   [C. Altomonte, A. Barr, M.E., P. Horodecki, K. Sakurai, arXiv:2412.01892]

   - Quantum Field Theory and Standard Model *predictions*
   - Procedure for an empirical *test*

3. Example: polarised $e^+e^- \to t\bar{t}$ process

4. Summary and prospects

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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 (strings, loop etc.)
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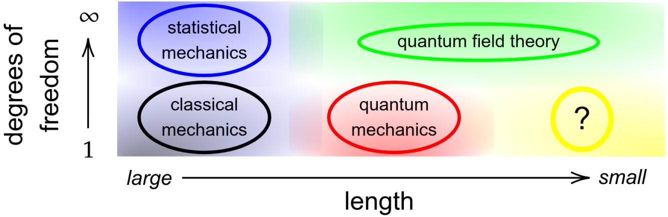

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- How to seek possible deviations from QM (*and* classicality)?

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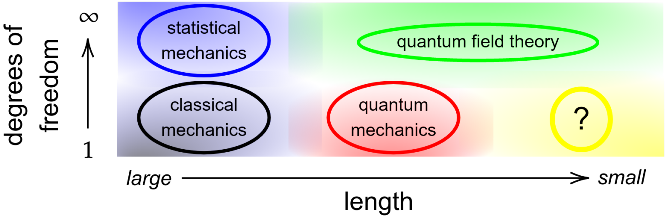

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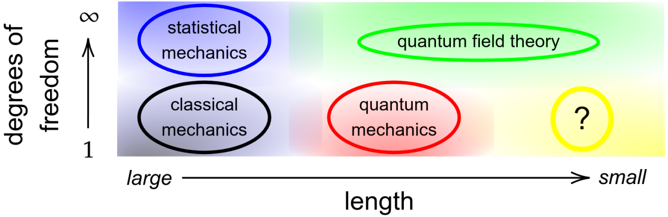

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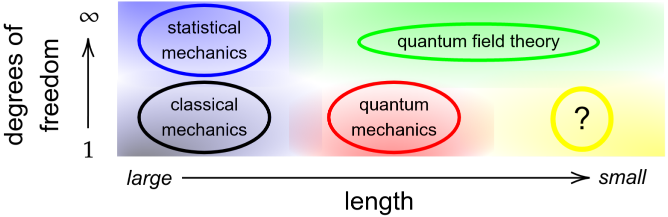

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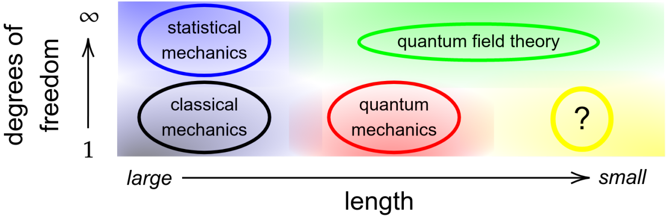

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The "theory independent" **black box** methodology

- Physical systems are treated as information-processing devices ("**black boxes**"), which can be 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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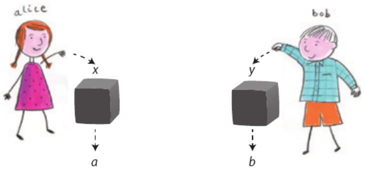

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[Sandu Popescu, *Nature Physics* **10**, 264 (2014)]

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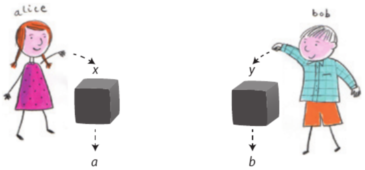

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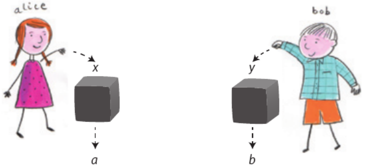

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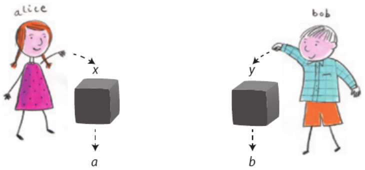

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Nonlocal correlations beyond quantum mechanics

Bell-CHSH inequality: 2 parties – 2 inputs – 2 outcomes

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

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

$$P(a,b\,|\,x,y) = \begin{cases} \frac{1}{2}, & \text{if } a \oplus b = xy, \\ 0, & \text{otherwise}, \end{cases} \qquad S_{\mathsf{PR}} = 4.$$

- No-signalling principle admits correlations that are **stronger than entanglement**.

Violation of the Tsirelson bound would refute all (local) quantum models!

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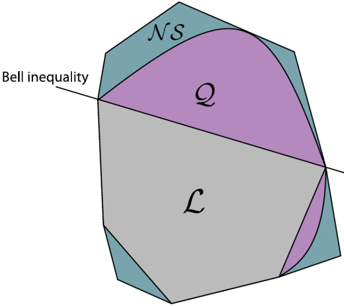

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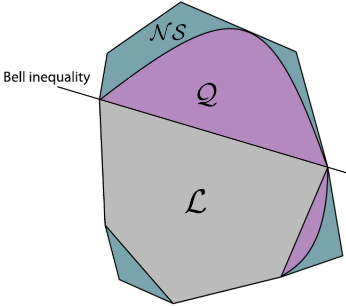

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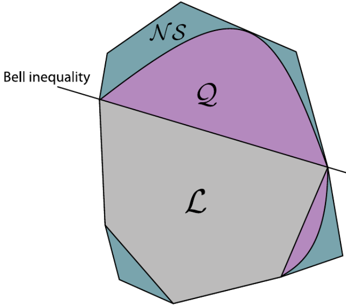

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Beyond linear quantum theory

Quantum mechanics is a **linear** theory.

- The Schrödinger equation is a *linear* PDE.
- The observables are *linear* operators and the states are *linear* functionals.

1. Wave function collapse models

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

   - Mostly aimed at explaining the 'quantum-to-classical' transition.
   - Spontaneous collapse and mixing [K. Simonov, *PRA* **102** 022226 (2020)]

2. Nonlinear Schrödinger equation

   - Schrödinger–Newton equation, aka the *Diósi – Penrose model*
   - DeBroglie (1960), Białynicki-Birula–Mycielski (1976), Weinberg (1989), Polchinski (1991), Czachor (1998/2002), Rembieliński–Caban (2019-21)
   - Nonlinear terms in QFT [Kaplan, Rajendran, *PRD* **105**, 055002 (2022)]

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How to seek beyond-quantum effects?

1. Motivation: *beyond* quantum theory

   [M.E., P. Horodecki, *Proc. R. Soc. A.* **478**:20210806 (2022), arXiv:2103.12000]

   - *Why* venturing beyond quantum theory?
   - *What* might be out there?
   - ***How*** to seek beyond-quantum effects?

2. Implementation: *quantum process tomography* in colliders

   [C. Altomonte, A. Barr, M.E., P. Horodecki, K. Sakurai, arXiv:2412.01892]

   - Quantum Field Theory and Standard Model *predictions*
   - Procedure for *experimental verification*

3. Example: polarised $e^+e^- \to t\bar{t}$ process

4. Summary and prospects

Quantum-data black box methodology

- We treat physical systems as **Q-data boxes**, i.e. *quantum-information* processing devices.
- A Q-data box is probed *locally* with quantum information.

- x are classical parameters (e.g. scattering kinematics)
- The *input state* is **prepared**.
- The *output state* is reconstructed from **quantum state tomography**.
- We assume that validity of QM *outside* the box, but not *inside* it.

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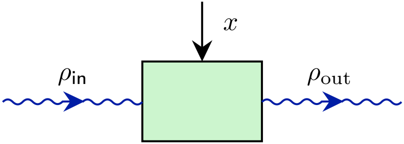

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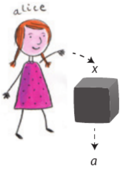
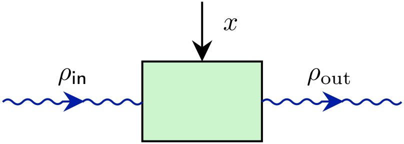


[Nat. Phys. **10**, 264 (2014)]



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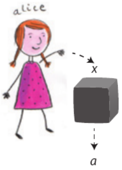

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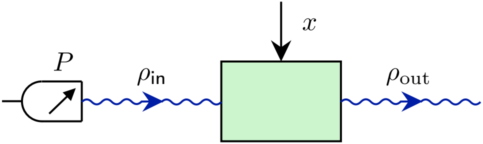

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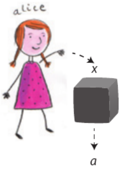

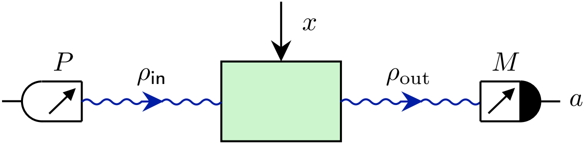

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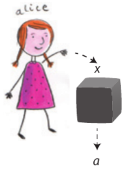

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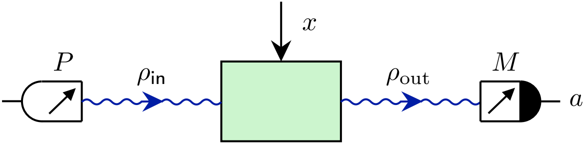

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Quantum state tomography:

- A (mixed) quantum state $\rho_{\text{out}} \in S(\mathcal{H})$ is an $n \times n$ matrix, $n = \dim \mathcal{H}$.
- Take a complete set of projectors $\{M_i\}_{i=1}^{n^2-1}$ (e.g. $\{\sigma_x, \sigma_y, \sigma_z\}$).
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Quantum-data tests

- Quantum mechanics predicts that every process is a quantum channel

$$\mathcal{E} : S(\mathcal{H}_{\text{in}}) \to S(\mathcal{H}_{\text{out}}), \qquad \rho_{\text{in}} \mapsto \rho_{\text{out}} = \mathcal{E}(\rho_{\text{in}}), \qquad \text{which is}$$

  - **linear**, $\mathcal{E}(\sum_k \lambda_k \rho_{\text{in}}^k) = \sum_k \lambda_k \rho_{\text{out}}^k$,
  - **completely positive**, i.e. $\mathcal{E} \otimes \mathbb{1}_N$ is positive for all N.

- A *selection* of the final states $\{\rho_{\text{out}}^{(k,x)}\}$ should yield a CP linear map

$$\mathcal{I}_x : S(\mathcal{H}_{\text{in}}) \to B_+(\mathcal{H}_{\text{out}}), \qquad \rho_{\text{in}} \mapsto \mathcal{I}_x(\rho_{\text{in}}) = P(x \,|\, \rho_{\text{in}}) \cdot \rho_{\text{out}}^x.$$

Choi–Jamiołkowski isomorphism (aka "channel–state duality")

A map $\mathcal{I}_x$ is completely positive if and only if its *Choi matrix*

$$\widetilde{\mathcal{I}}_x = \frac{1}{\dim \mathcal{H}_{\text{in}}} \sum_{i,j=1}^{\dim \mathcal{H}_{\text{in}}} |i\rangle\langle j| \otimes \mathcal{I}_x(|i\rangle\langle j|) \quad \text{is positive.}$$

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$$\mathcal{E} : S(\mathcal{H}_{\text{in}}) \to S(\mathcal{H}_{\text{out}}), \qquad \rho_{\text{in}} \mapsto \rho_{\text{out}} = \mathcal{E}(\rho_{\text{in}}), \quad \text{which is}$$

  - **linear**, $\mathcal{E}(\sum_k \lambda_k \rho_{\text{in}}^k) = \sum_k \lambda_k \rho_{\text{out}}^k$,
  - **completely positive**, i.e. $\mathcal{E} \otimes \mathbb{1}_N$ is positive for all N.

- A *selection* of the final states $\{\rho_{\text{out}}^{(k,x)}\}$ should yield a CP linear map

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Choi–Jamiołkowski isomorphism (aka "channel–state duality")

A map $\mathcal{I}_x$ is completely positive if and only if its *Choi matrix*

$$\widetilde{\mathcal{I}}_x = \frac{1}{\dim \mathcal{H}_{\text{in}}} \sum_{i,j=1}^{\dim \mathcal{H}_{\text{in}}} |i\rangle\langle j| \otimes \mathcal{I}_x(|i\rangle\langle j|) \quad \text{is positive.}$$

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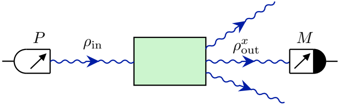

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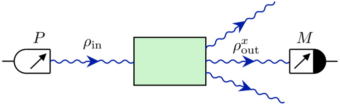

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Quantum process tomography as a foundational test

By performing the quantum tomography of a physical process we can reconstruct its Choi matrix and:

- compare it with theoretical predictions

  $\rightsquigarrow$ window for BSM physics

- reconstruct an *unknown* quantum dynamics

  $\rightsquigarrow$ low-energy QCD, gravity, ...

- study its properties
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Quantum process tomography at colliders

1. Motivation: *beyond* quantum theory

   [M.E., P. Horodecki, *Proc. R. Soc. A.* **478**:20210806 (2022), arXiv:2103.12000]

   - *Why* venturing beyond quantum theory?
   - *What* might be out there?
   - ***How*** to seek beyond-quantum effects?

2. Implementation: *quantum process tomography* at colliders

   [C. Altomonte, A. Barr, M.E., P. Horodecki, K. Sakurai, arXiv:2412.01892]

   - Quantum Field Theory prediction
   - Procedure for *experimental verification*

3. Example: polarised $e^+e^- \to t\bar{t}$ process

4. Summary and prospects

Quantum process tomography in particle colliders

- We consider $2 \to 2$ scattering process: $\alpha\beta \to \gamma\delta$.
- We consider finite-dimensional Hilbert spaces

$$\mathcal{H}_{\text{in}} = \mathcal{H}_\alpha \otimes \mathcal{H}_\beta, \qquad \mathcal{H}_{\text{out}} = \mathcal{H}_\gamma \otimes \mathcal{H}_\delta$$

corresponding to internal degrees of freedom (spin and/or flavour).

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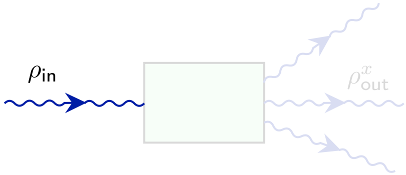

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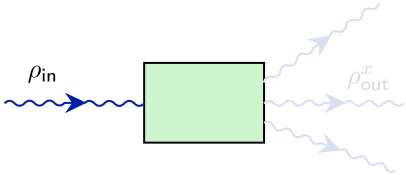

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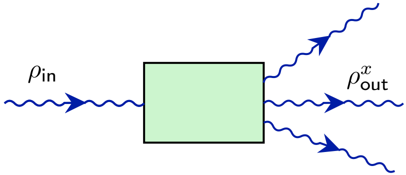

Initial state preparation and evolution

- The two beams of particles are initially uncorrelated $\rho_{\text{in}} = \rho_{\text{in}}^{\alpha} \otimes \rho_{\text{in}}^{\beta}$.
- A beam can be polarised in a direction $\mathbf{n}$ to a degree $q \cdot 100\%$

$$\rho_{\text{in}}^{\alpha} = q_{\alpha}|\mathbf{n}\rangle\langle\mathbf{n}| + \tfrac{1}{2}(1 - q_{\alpha})\mathbb{1}, \qquad \rho_{\text{in}}^{\beta} = q_{\beta}|\mathbf{n}\rangle\langle\mathbf{n}| + \tfrac{1}{2}(1 - q_{\beta})\mathbb{1}.$$

- In colliders we can assume that there is no initial correlations between momentum and spin, and that the momentum state is pure.

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3. We make a measurement of the final state **selecting** the $\gamma\delta$ final state **and**, possibly, their momenta in a restricted region x.

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$$\overline{\rho}_{\text{out}} \;\mapsto\; \varrho'_x = \mathrm{Tr}_P \left[\mathcal{P}_x \overline{\rho}_{\text{out}} \mathcal{P}_x\right].$$

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is the inclusive cross-section for unpolarised scattering.
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  where $\sigma_x(\alpha\beta[\rho_{\text{in}}] \to \gamma\delta)$ is the cross-section for polarised scattering with final-state momenta in x.

From S-matrix to quantum instruments

- In QFT we work with **cross-sections** rather than mere probabilities.
- We define the 'renormalised' output state

$$\varrho_x = \tfrac{V}{T}\tfrac{1}{2\sigma_{\mathcal{N}}}\varrho'_x, \quad \text{where} \quad \sigma_{\mathcal{N}} = \sigma(\alpha\beta[\rho_{\text{in}}^{\text{mix}}] \to \gamma\delta),$$

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The S-matrix calculations yield a map,

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for any choice x of final state momenta given by

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- the scattering amplitude $\mathcal{M}^{I,J}_{A,B} \propto \langle p_f; A,B|S|\tilde{p}_{\text{in}}; I,J\rangle$,
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- $d\Pi_{\text{LIPS}} = (2\pi)^4\delta^4\left(\sum p^\mu_{\text{in}} - \sum p^\mu_f\right)\prod_{j=\gamma,\delta}\frac{d^3p_j}{(2\pi)^3}\frac{1}{2E_j}$.

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Quantum process tomography at colliders

1. Motivation: *beyond* quantum theory

   [M.E., P. Horodecki, *Proc. R. Soc. A.* **478**:20210806 (2022), arXiv:2103.12000]

   - *Why* venturing beyond quantum theory?
   - *What* might be out there?
   - ***How*** to seek beyond-quantum effects?

2. Implementation: *quantum process tomography* at colliders

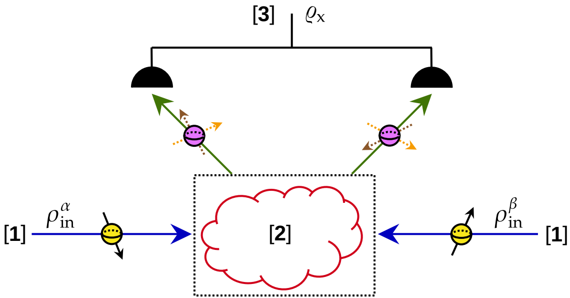
   [C. Altomonte, A. Barr, M.E., P. Horodecki, K. Sakurai, arXiv:2412.01892]

   - Quantum Field Theory prediction
   - Procedure for experimental verification

3. Example: polarised $e^+e^- \to t\bar{t}$ process

4. Summary and prospects

Experimental Choi matrix reconstruction



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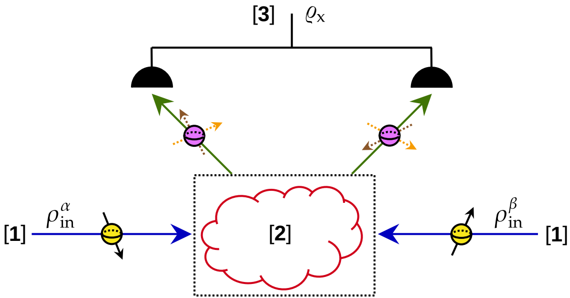

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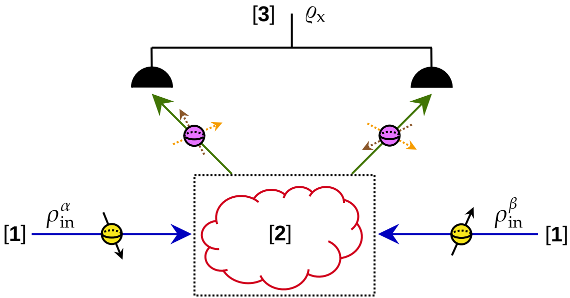

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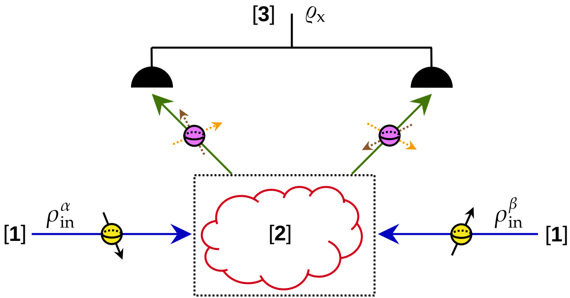

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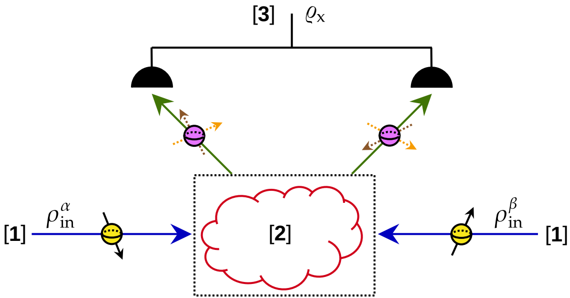

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Weakly decaying particles are "their own polarimeters".

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- The decay of the weak $W^{\pm}$ boson

$$W^+ \to \ell_R^+ + \nu_L, \qquad W^- \to \ell_L^- + \overline{\nu}_R$$

is formally equivalent to a projective (von Neumann) quantum measurement of its spin along the axis of the emitted lepton.

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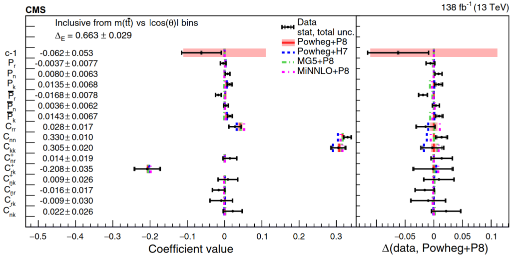

Reconstruction of the $t\bar{t}$ spin density matrix at CMS. [*PRD* **110**, 112016 (2024)]

Quantum process tomography at colliders

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- It would require 16 runs with 4 different polarisations of each beam.

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$$\mathcal{L} \ni \sum_i \frac{1}{\Lambda_i^2} [\bar{\psi}_e \gamma_\mu (c_L^i P_L + c_R^i P_R) \psi_e][\bar{\psi}_t \gamma^\mu (d_L^i P_L + d_R^i P_R) \psi_t],$$

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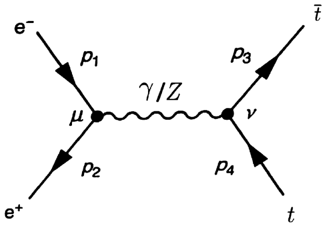

$$\mathcal{M}^{+-}_{AB} = \mathcal{M}^{-+}_{AB} = 0 \quad \Rightarrow \quad \widetilde{\mathcal{I}}_x = \frac{1}{4}\begin{pmatrix} \mathcal{I}_x(|++\rangle\langle++|) & 0 & 0 & \mathcal{I}_x(|++\rangle\langle--|) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \mathcal{I}_x(|--\rangle\langle++|) & 0 & 0 & \mathcal{I}_x(|--\rangle\langle--|) \end{pmatrix}$$

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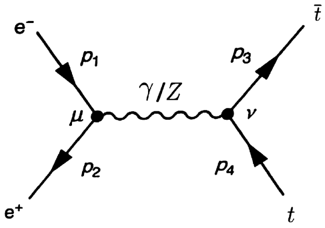

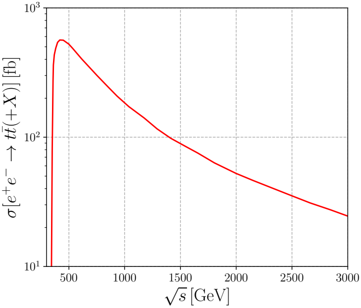

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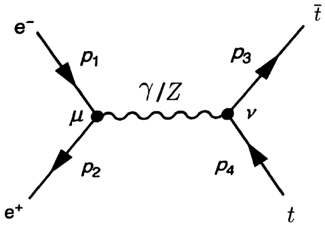

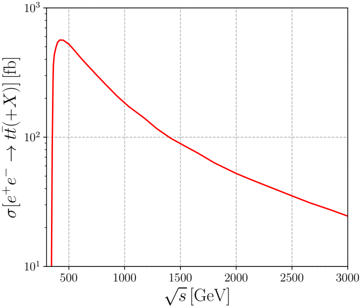

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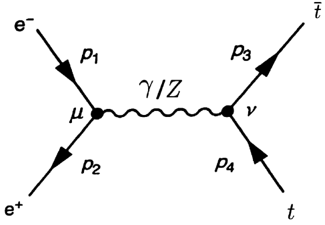

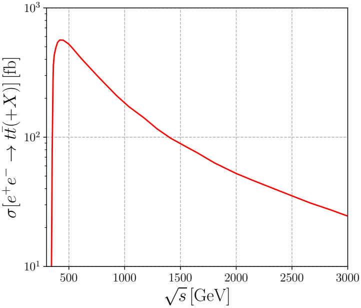

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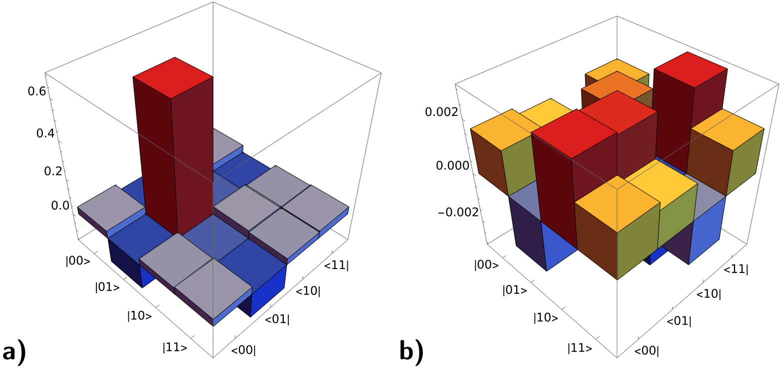

Block elements of the Choi matrix $\widetilde{\mathcal{I}}_x$ for $e^- e^+ \to t\bar{t}$ evaluated at tree level in the Standard Model at center of mass energy $\sqrt{s} = 370$ GeV.
a) $\mathcal{I}_x(|++\rangle\langle++|)$ for $x = \{\theta \subset [0,\pi], \phi \subset [-\pi,\pi]\}$
b) $\mathcal{I}_x(|++\rangle\langle--|)$ for $x = \{\theta \subset [2\pi/3,\pi], \phi \subset [-\pi/4,\pi/4]\}$

Quantum process tomography at colliders

1. Motivation: *beyond* quantum theory

   [M.E., P. Horodecki, *Proc. R. Soc. A.* **478**:20210806 (2022), arXiv:2103.12000]

   - *Why* venturing beyond quantum theory?
   - *What* might be out there?
   - ***How*** to seek beyond-quantum effects?

2. Implementation: *quantum process tomography* at colliders

   [C. Altomonte, A. Barr, M.E., P. Horodecki, K. Sakurai, arXiv:2412.01892]

   - Quantum Field Theory prediction
   - Procedure for experimental verification

3. Example: polarised $e^+e^- \to t\bar{t}$ process

4. Summary and prospects

Experimental prospects and opportunities

Search for new physics from quantum process tomography:

- Check the prediction of the Standard Model against BSM.
- Reconstruct quantum processes, which are *not* calculable perturbatively.
- Test the validity of quantum channel assumption (memory effects?)
- Foundational tests of QM: CP and linearity violations.

Experimental prospects:

- **Electron-Ion Collider**:
  electron and proton beams with 70% polarisation and CME 20–140 GeV
- **International Linear Collider**:
  e^-e^+ collider with 80% e^- and 30% e^+ polarisation and CME 500 GeV
- **Future Circular Collider**:
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Summary

Take-home messages:

- Quantum mechanics is great, but we should never stop questioning it.
- We should remain open to 'beyond-quantum' physics, ...
- ...whatever it might be: nonlinear?, supernonlocal?, beyond-spacetime?
- It is possible to make foundational tests of QM in near-future colliders.
- A paradigm shift in collider physics — from observations to experiments.

Thank you for your attention!

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