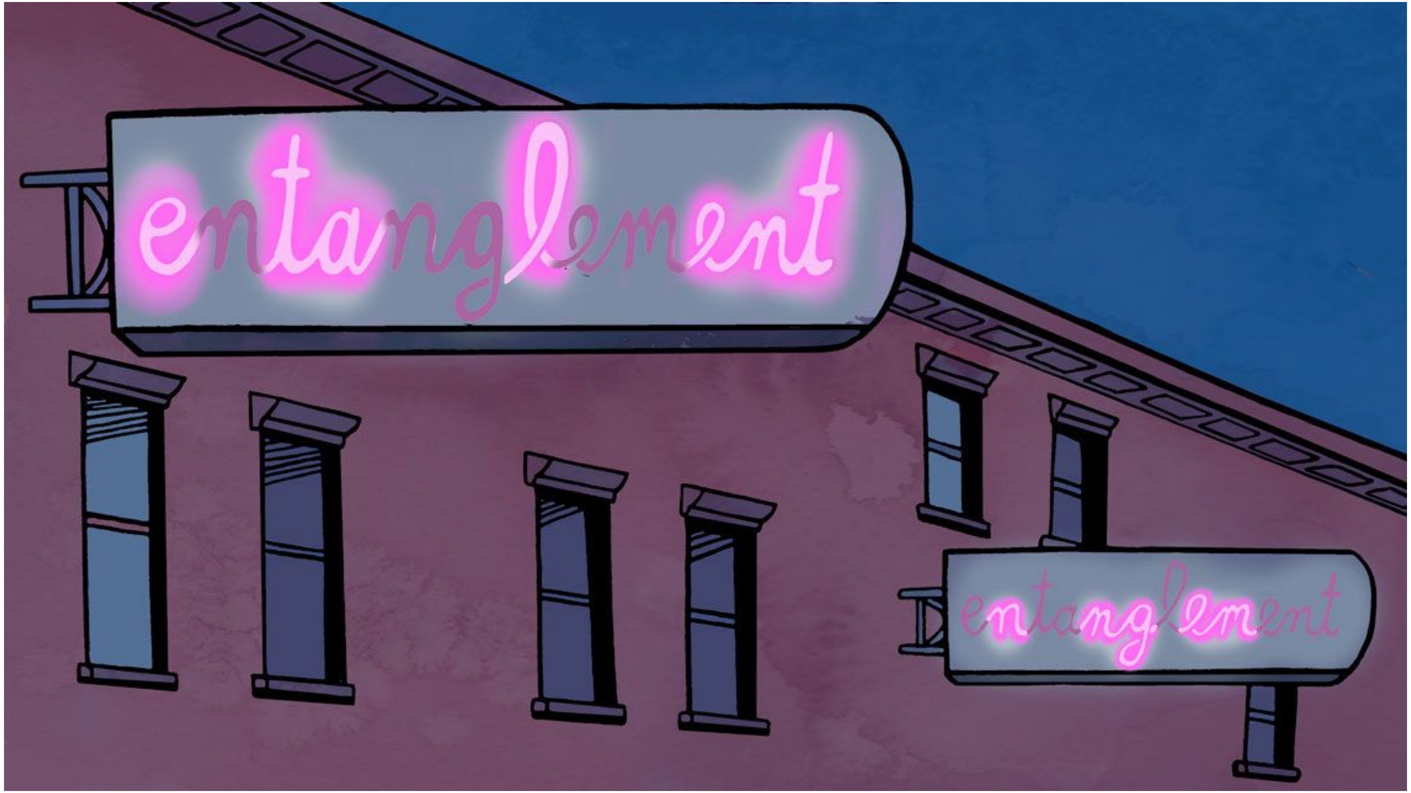
$|2025, \text{Beijing}\rangle \quad \langle 2026, \text{XXYYZZ}|$



Peking University

- **Founded in 1898, a comprehensive and national top university**
- More than 50,000 students
  - Sciences
  - Information & Engineering
  - Humanities
  - Social Sciences
  - Economic & Management
  - Schools of Medical Sciences and interdisciplinary
- Playing an essential pioneering role in the course of Chinese modernization

PKU HEP-CMS Group

7 faculties: Yong Ban, Ya-Jun Mao, Qiang Li, Da-Yong Wang, Si-Guang Wang, Chen Zhou, Xiaohu Sun

2 engineers: Qite Li, Z.H.Xue

5 postdocs: Andrew Levin, Antonios Agapitos, Zhiyuan Li, Qianying Guo, …

30 students
+ One large theo. group focusing on QCD and TeV Physics
In CMS since 1996, Stable support from Government
RPC and GEM ; VBS; B→Kμμ; Boosted Jet


Visit from CMS Spokesperson Dr. Joe Butler, June/2016

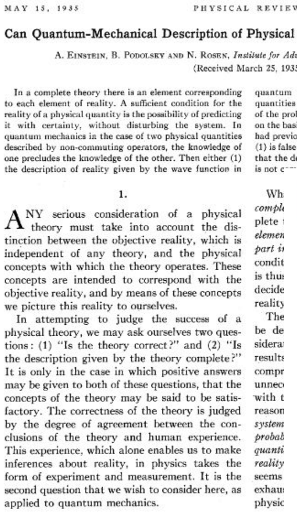
Spooky action at a distance!

ref

"Can Quantum Mechanical Description of Physical Reality Be Considered Complete?"

Physical reality must be local! - Podolsky

EPR Paradox



MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

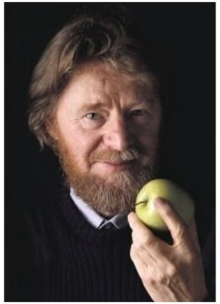
In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not c

1.

ANY serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves.

In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) "Is the theory correct?" and (2) "Is the description given by the theory complete?" It is only in the case in which positive answers may be given to both of these questions, that the concepts of the theory may be said to be satisfactory. The correctness of the theory is judged by the degree of agreement between the conclusions of the theory and human experience. This experience, which alone enables us to make inferences about reality, in physics takes the form of experiment and measurement. It is the second question that we wish to consider here, as applied to quantum mechanics.

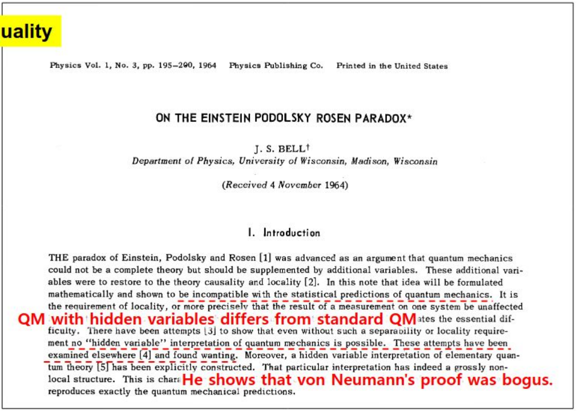
1964 QM with hidden variables differs from QM



1928~1990
John Stewart Bell

In the 1980s, he was always mentioned as a candidate for the Nobel Prize.

Bell's Inequality



Physics Vol. 1, No. 3, pp. 195–200, 1964 Physics Publishing Co. Printed in the United States

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

J. S. BELL†
Department of Physics, University of Wisconsin, Madison, Wisconsin

(*Received* 4 *November* 1964)

I. Introduction

THE paradox of Einstein, Podolsky and Rosen [1] was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality [2]. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected ates the essential difficulty. There have been attempts [3] to show that even without such a separability or locality requirement no "hidden variable" interpretation of quantum mechanics is possible. These attempts have been examined elsewhere [4] and found wanting. Moreover, a hidden variable interpretation of elementary quantum theory [5] has been explicitly constructed. That particular interpretation has indeed a grossly nonlocal structure. This is chara reproduces exactly the quantum mechanical predictions.

QM with hidden variables differs from standard QM

He shows that von Neumann's proof was bogus.

Upon observation, the cat was found to be alive.

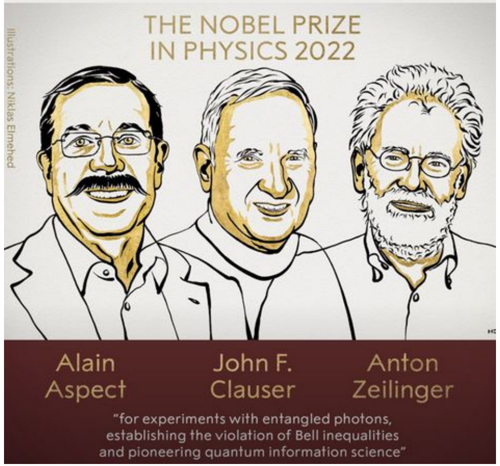
Huh? The cat suddenly died.

Quantum mechanics is nonlocal

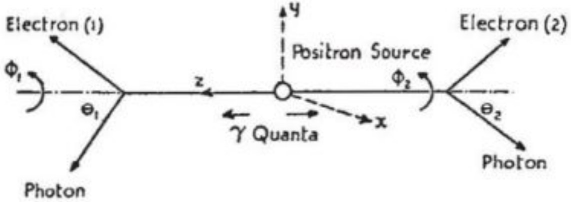
However, it still takes 1 light year for A and B to exchange answers.

Quantum entanglement tests

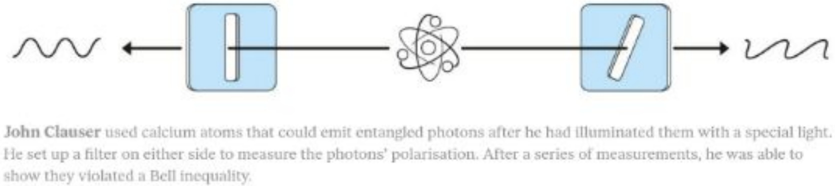
- As reviewed by C. N. Yang, the first experiment on quantum entanglement is the Wu-Shaknov Experiment published in 1950 in which the angular correlation of two Compton scattered photons arising from e^+e^- annihilation are measured.
- The violation of Bell inequality was demonstrated in 1970s using entangled photons, confirming the non-locality of our universe.
- Alain Aspect, John Clauser and Anton Zeilinger won Nobel Prize in Physics in 2022 for demonstrating the potential to investigate and control particles (photons) that are in entangled states



"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"



Wu-Shaknov Experiment



John Clauser used calcium atoms that could emit entangled photons after he had illuminated them with a special light. He set up a filter on either side to measure the photons' polarisation. After a series of measurements, he was able to show they violated a Bell inequality.

Clauser's photon entanglement experiment

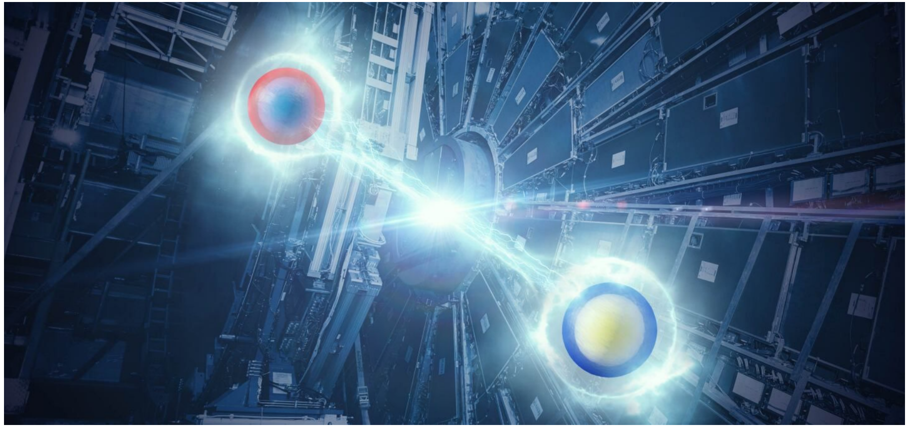
Quantum entanglement at high energy

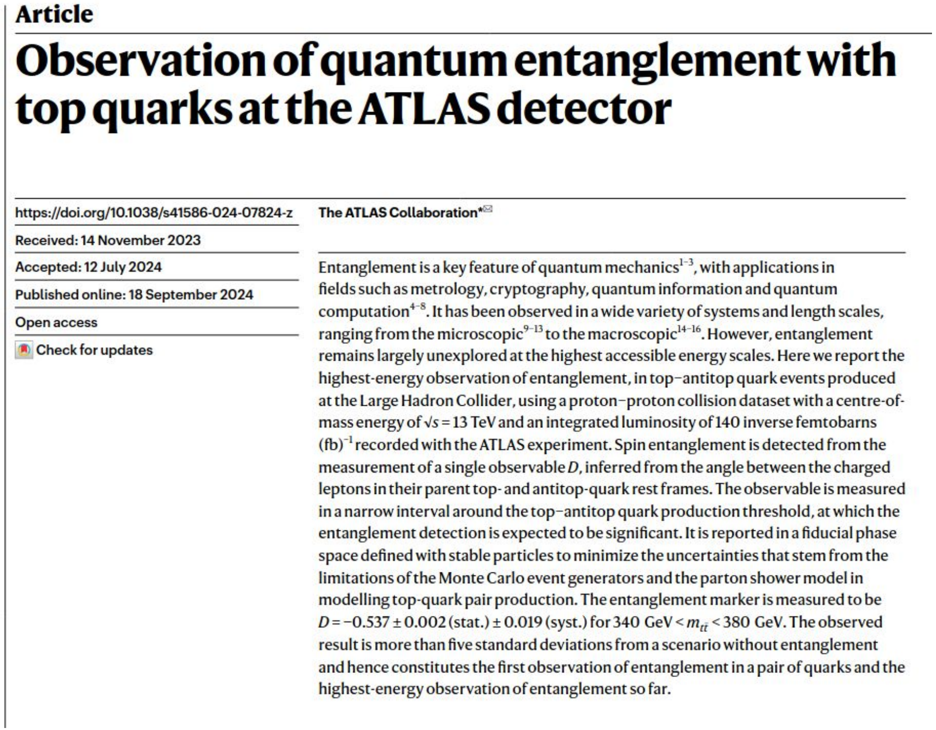
Nature volume 633, pages 542–547 (2024)

LHC experiments at CERN observe quantum entanglement at the highest energy yet

The results open up a new perspective on the complex world of quantum physics

18 SEPTEMBER, 2024





Article

Observation of quantum entanglement with top quarks at the ATLAS detector

https://doi.org/10.1038/s41586-024-07824-z

Received: 14 November 2023

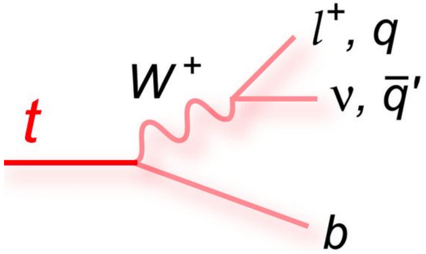
Accepted: 12 July 2024

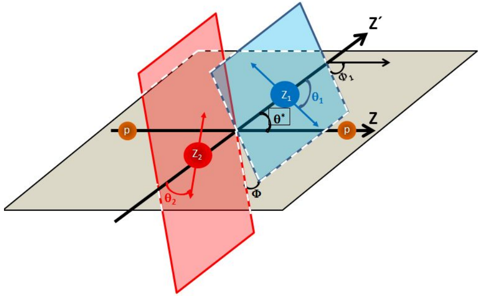
The ATLAS Collaboration*

Entanglement is a key feature of quantum mechanics[1–3], with applications in fields such as metrology, cryptography, quantum information and quantum computation[4–8]. It has been observed in a wide variety of systems and length scales, ranging from the microscopic[9–13] to the macroscopic[14–16]. However, entanglement remains largely unexplored at the highest accessible energy scales. Here we report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision dataset with a centre-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 inverse femtobarns (fb)$^{-1}$ recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, at which the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from the limitations of the Monte Carlo event generators and the parton shower model in modelling top-quark pair production. The entanglement marker is measured to be $D = -0.537 \pm 0.002$ (stat.) $\pm$ 0.019 (syst.) for 340 GeV $< m_{t\bar{t}} <$ 380 GeV. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement so far.

Why QE at high energy? (ref)

- **Understand quantum nature & seek for BSM effects.**
- Particle scattering/decay of unstable particles provide **a natural laboratory**
  - the momenta of observed particles are essentially commuting observables. Therefore, there is always some hidden variable theory that can explain the observed momentum data
  - However, one can focus on **spin correlation** emerges in different phase-space region
- It is plausible that **quantum mechanics undergoes modifications** (ref) **at some short distance scales** to achieve compatibility with gravity. Such modifications could, in principle, **be (only) detected by measuring Bell-type observables** or through quantum process tomography (ref)
- offers the potential to uncover **new insights into quantum field theory**.





https://scipost.org/10.21468/SciPostPhys.3.5.036

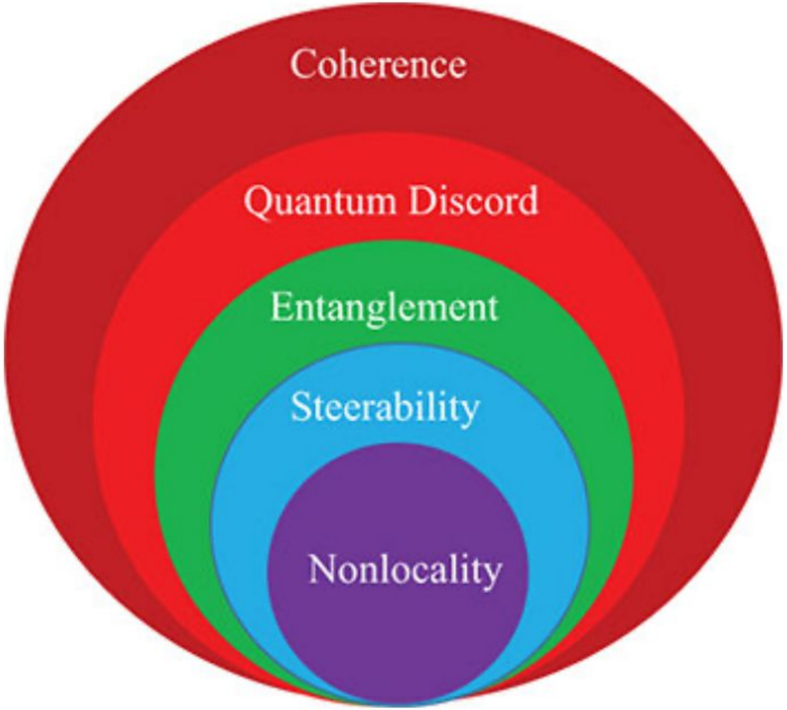

SciPost

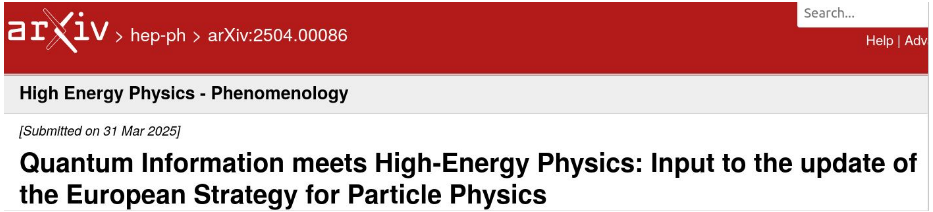
SciPost Phys. 3, 036 (2017)

Maximal entanglement in high energy physics

Alba Cervera-Lierta[1], José I. Latorre[1,2], Juan Rojo[3] and Luca Rottoli[4]

Quantum Collisions: a rich hierarchy of information to explore





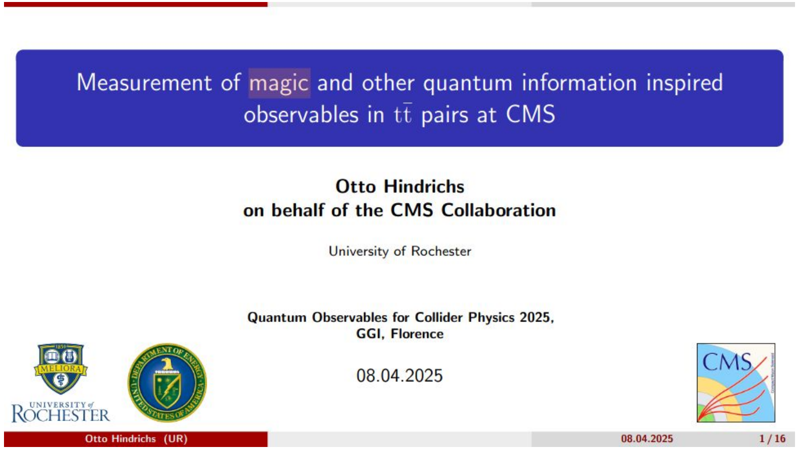
arXiv > hep-ph > arXiv:2504.00086

High Energy Physics - Phenomenology

[Submitted on 31 Mar 2025]

Quantum Information meets High-Energy Physics: Input to the update of the European Strategy for Particle Physics

“ It is important to note that there is **a whole hierarchy of quantum correlations that can be studied**. For instance, discord is a measure of non-classical correlations that can interconnect the components of a system even if they are not entangled”



Measurement of magic and other quantum information inspired observables in $t\bar{t}$ pairs at CMS

Otto Hindrichs
on behalf of the CMS Collaboration

University of Rochester

Quantum Observables for Collider Physics 2025,
GGI, Florence

08.04.2025

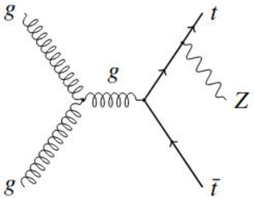
Otto Hindrichs (UR) 08.04.2025 1 / 16

https://www.youtube.com/watch?v=HAgiLO-CFxQ

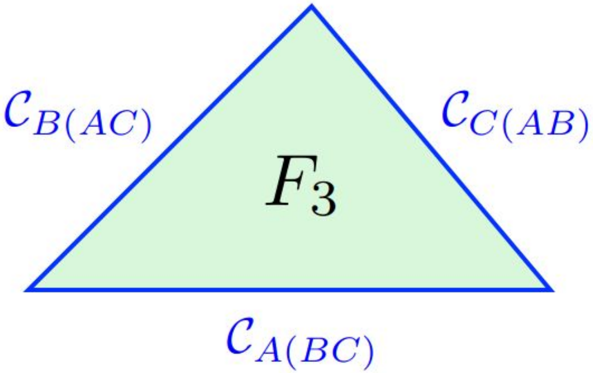
Conclusions

- Quantum information and computing is hyped up. It promises a quantum advantage that, while not yet proven, could bring to transformative applications.
- The current status builds upon a number of theoretical and experimental advances in the last 30 years that have changed the way we think about quantum mechanics.
- Our current description of fundamental interactions, based on QFT, has QM at its core. Theoretically, it is embedded in our formalism so deeply that (sometimes) we do not even notice. Experimentally, however, most of our measurements are not correlations, but just counting experiments.
- A novel interest in looking at fundamental interactions at TeV scale with QI glasses has started since two/three years ago and has quickly lead to a variety of studies and interesting results, …

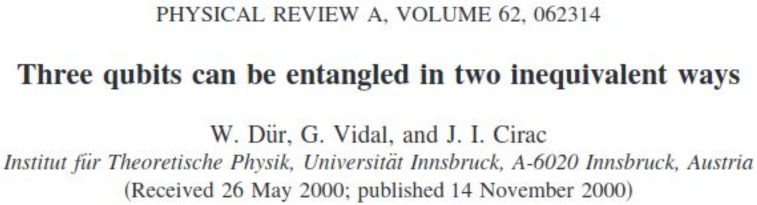
Quantum Collisions: more funs



- **Three-partite entanglement**
  - 3-body Decay: *Phys.Rev.Lett.* 132 (2024) 15, 151602; arXiv:2502.19470
  - 2 to 3 process (ttZ): arXiv:2404.03292
- **Quantum Process Tomography** (operating initial particles’ flavor and spin)
  - arXiv:2412.01892



concurrence triangle



PHYSICAL REVIEW A, VOLUME 62, 062314

Three qubits can be entangled in two inequivalent ways

W. Dür, G. Vidal, and J. I. Cirac
Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria
(Received 26 May 2000; published 14 November 2000)

PHYSICAL REVIEW A, VOLUME 65, 052112

Four qubits can be entangled in nine different ways

F. Verstraete,[1,2] J. Dehaene,[2] B. De Moor,[2] and H. Verschelde[1]
[1]*Department of Mathematical Physics and Astronomy, Ghent University, Krijgslaan 281 (S9), B-9000 Gent, Belgium*
[2]*Department of Electrical Engineering, Katholieke Universiteit Leuven, Research Group SISTA Kasteelpark Arenberg 10, B-3001 Leuven, Belgium*
(Received 29 November 2001; published 25 April 2002)

Quantum Process Tomography: one further step

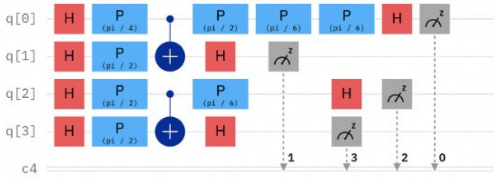
- **Spin and flavour measurements** in collider experiments as a **quantum instrument**
- **Choi matrix**, which completely determines input-output transitions, can be both **theoretically computed** and **experimentally reconstructed**
- **Polarized Beam collisions, or,**

ref **lepton scattering on polarized target experiments (see next)**

Particle Collider = Quantum Computer

=

C. Altomonte, A.Barr [2312.02242]



$|\psi\rangle_{\rm in} \longrightarrow$ Unitary Evolution $\longrightarrow$ Measurements

Reconstruction of Choi matrix $\boxed{e^-e^+ \to t\bar{t}}$

- Reconstruction of the diagonal part:

$$\widetilde{\mathcal{I}}_x = \frac{1}{4}\begin{pmatrix} \mathcal{I}_x(|++\rangle\langle++|) & \mathcal{I}_x(|++\rangle\langle+-|) & \mathcal{I}_x(|++\rangle\langle-+|) & \mathcal{I}_x(|++\rangle\langle--|) \\ \mathcal{I}_x(|+-\rangle\langle++|) & \mathcal{I}_x(|+-\rangle\langle+-|) & \mathcal{I}_x(|+-\rangle\langle-+|) & \mathcal{I}_x(|+-\rangle\langle--|) \\ \mathcal{I}_x(|-+\rangle\langle++|) & \mathcal{I}_x(|-+\rangle\langle+-|) & \mathcal{I}_x(|-+\rangle\langle-+|) & \mathcal{I}_x(|-+\rangle\langle--|) \\ \mathcal{I}_x(|--\rangle\langle++|) & \mathcal{I}_x(|--\rangle\langle+-|) & \mathcal{I}_x(|--\rangle\langle-+|) & \mathcal{I}_x(|--\rangle\langle--|) \end{pmatrix}$$

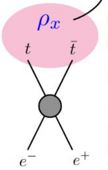
- Consider 4 purely polarised beam settings:

$$\{|i\rangle\} = \{|++\rangle, |+-\rangle, |-+\rangle, |--\rangle\} \qquad \rho_0^i = |i\rangle\langle i|$$

$$\mathcal{I}_x(|i\rangle\langle i|) = \varrho_x^i = \mathrm{Tr}\varrho_x^i \cdot \frac{\varrho_x^i}{\mathrm{Tr}\varrho_x^i}$$

measurable

$$\frac{\sigma_x[e^-e^+(\rho_0^i) \to t\bar{t}]}{\sigma[e^-e^+(\rho_0^{\rm mix}) \to t\bar{t}]}$$



Reconstruction of spin-density matrix is possible

Quantum State Tomography

Y.Afik, J.Nova [2003.02280], Ashby-Pickering, Barr, Wierzchucka [2209.13990]