Photo taken 8th Nov 2023

Alan Barr, University of Oxford

GGI, Florence, 7th April 2025

CERN Accelerating science

CERN website: September 2024

ABOUT NEWS

News › Press release › Topic: Physics

*Voir en français*

# 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

Artist's impression of a quantum-entangled pair of top quarks. (Image: CERN)

Quantum entanglement is a fascinating feature of quantum physics – the theory of the very small. If two particles are quantum-entangled, the state of one particle is tied to that of the other, no matter how far apart the particles are. This mind-bending phenomenon, which has no analogue in classical physics, has been observed in a wide variety of systems and has found several important applications, such as quantum cryptography and quantum computing. In 2022, the Nobel Prize in Physics was awarded to Alain Aspect, John F.

symmetry topics follow +

A joint Fermilab/SLAC publication

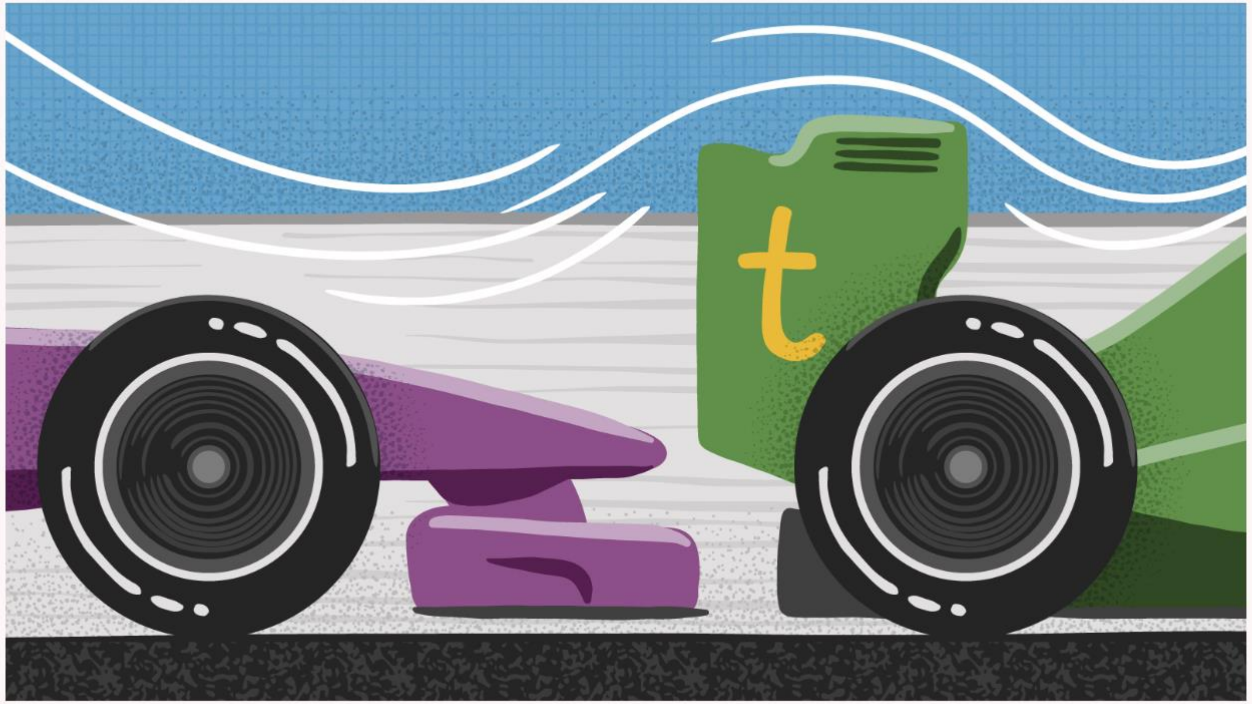



Illustration by Sandbox Studio, Chicago with Steve Shanabruch

# The quantum chase

11/26/24 | By Laura Dattaro

Some friendly competition led up to the first discovery of entanglement at the Large Hadron Collider.

Symmetry magazine, November 2024


GIZMODO

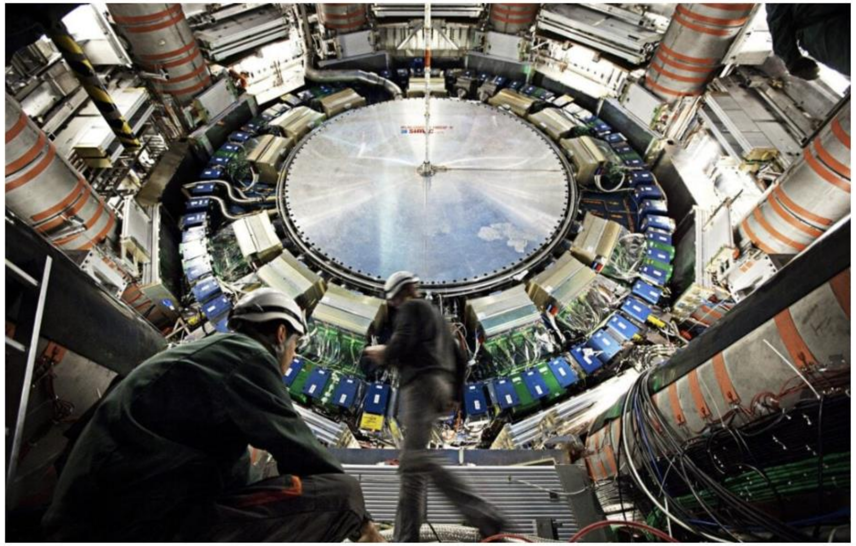
BIOLOGY

## Twin Brothers Find ‘Magic’ in Quarks at Large Hadron Collider

A unique property of quantum systems is on display in one of the LHC's standard particle production methods.

By Isaac Schultz

Published December 20, 2024 | Comments (24) |

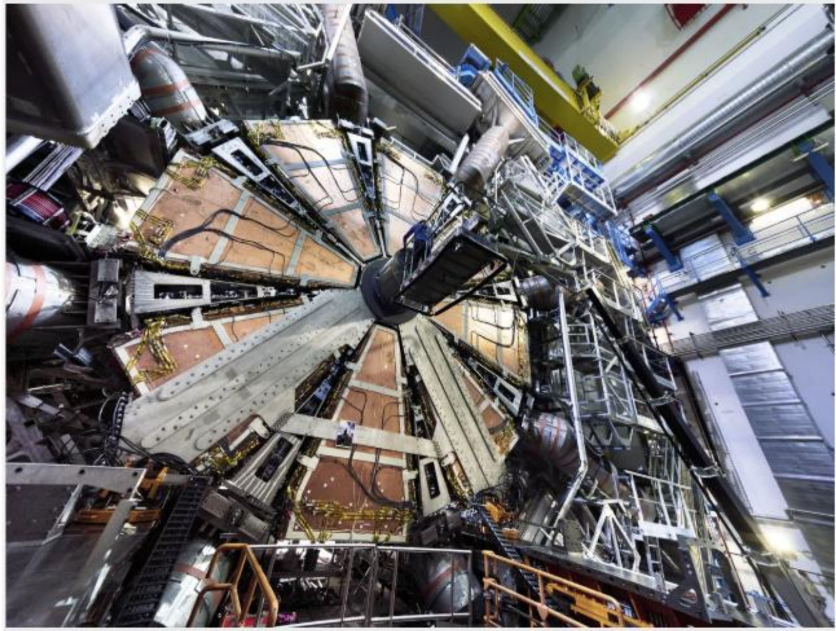


SEPTEMBER 25, 2024 | 4 MIN READ

## ‘Spooky Action at a Distance’ Observed in Quarks for the First Time

Physicists report the first observations of quantum entanglement in top and anti-top quarks, the heaviest known fundamental particles and their antimatter counterparts, inside the Large Hadron Collider

BY DAN GARISTO & NATURE MAGAZINE

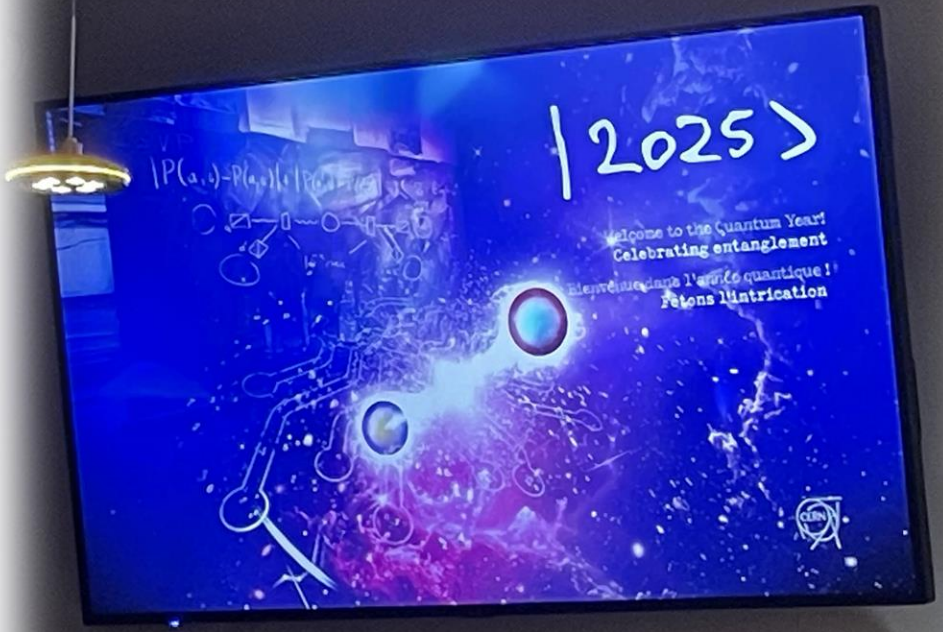


The ATLAS detector, part of the Large Hadron Collider, sits 100 meters below ground, where it measures various properties of high-energy particles. Maximilien Brice/CERN

New Scientist April 2024

Gizmodo December 2024

Scientific American September 2024




# CERN, Restaurant 1

## January |2025>

## “Celebrating entanglement”

CERN

News › News › Topic: At CERN

April 1st 2025

*Voir en* [français]

# CERN scientists find evidence of quantum entanglement in sheep

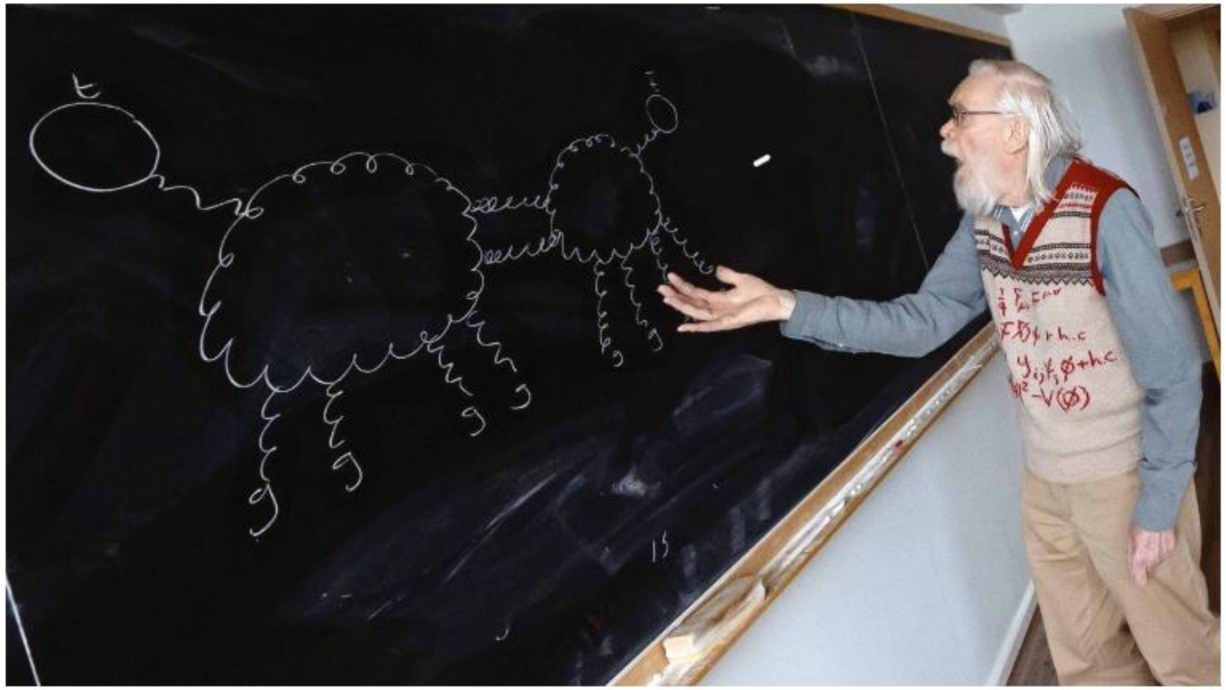
**The findings could help to explain the species' fascinating flocking behaviour**

1 APRIL, 2025 | By Naomi Dinmore

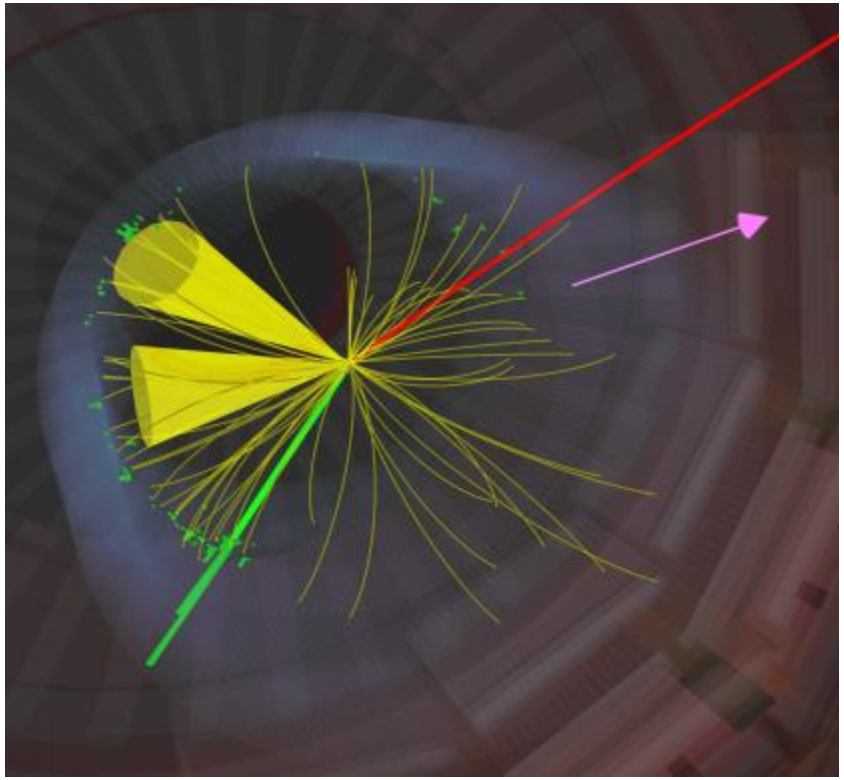

The CERN flock of sheep on site in 2017. (Image: CERN)

entanglement or a statistical fluctuation," says Ewen Woolly, spokesperson for the HERD collaboration. "This may be difficult, as we have found that the research makes physicists become inexplicably drowsy."

"While entanglement is now the leading theory for this phenomenon, we have to take everything into account," adds Dolly Shepherd, a CERN theorist. "Who knows, maybe further variables are hidden beneath their fleeces. Wolves, for example."



Theoretical physicist John Ellis, pioneer of the penguin diagram, with its updated sheep version. Scientists at CERN find evidence of quantum entanglement in sheep in 2025, the year declared by the United Nations as the International Year of Quantum Science and Technology. (Image: CERN)



# First LHC entanglement papers published

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
Published online: 18 September 2024
Open access
Check for updates

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 $(\text{fb})^{-1}$ 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.

OPEN ACCESS
IOP Publishing
Reports on Progress in Physics
Rep. Prog. Phys. 87 (2024) 117801 (33pp)
https://doi.org/10.1088/1361-6633/ad7e4d

## Observation of quantum entanglement in top quark pair production in proton–proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

CERN, Geneva, Switzerland

E-mail: cms-publication-committee-cha

Received 6 June 2024, revised 18 Septe
Accepted for publication 23 September
Published 23 October 2024

Corresponding editor: Dr Lorna Bri

**Abstract**
Entanglement is an intrinsic proper
the particles produced at the Large
entanglement in top quark-antiquar
center-of-mass energy of 13 TeV is
the CERN LHC in 2016, and corres
are selected based on the presence
momentum. An entanglement-sensi
spin-dependent parts of the $t\bar{t}$ produ
production threshold. Values of $D$ <
(expected) to be $-0.480^{+0.026}_{-0.029}$ (−0.
of 5.1 standard deviations with resp
observation of quantum mechanical
measurement provides a new probe

Keywords: CMS, top quark, entang

### 1. Introduction

Entanglement is a fundamental co
anics that describes a strong corre
such that the state of one particle
described without considering the
less of the distance between them [1–3]. Quantum entangle-
ment has been extensively studied in the context of photons
and electrons [4–6]. In these measurements, entanglement is

typically refers to each particle as a quantum bit (qubit) of
information. An entangled state for two qubits is a superpos-
ition of their joint states that cannot be factorized into indi-
vidual states. A common example is the Bell state, $|\psi^-\rangle =$

PHYSICAL REVIEW D 110, 112016 (2024)

## Measurements of polarization and spin correlation and observation of entanglement in top quark pairs using lepton + jets events from proton-proton collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.**
(CMS Collaboration)

(Received 17 September 2024; accepted 13 November 2024; published 30 December 2024)

Measurements of the polarization and spin correlation in top quark pairs ($t\bar{t}$) are presented using events with a single electron or muon and jets in the final state. The measurements are based on proton-proton collision data from the LHC at $\sqrt{s} = 13$ TeV collected by the CMS experiment, corresponding to an integrated luminosity of 138 $\text{fb}^{-1}$. All coefficients of the polarization vectors and the spin correlation matrix are extracted simultaneously by performing a binned likelihood fit to the data. The measurement is performed inclusively and in bins of additional observables, such as the mass of the $t\bar{t}$ system and the top quark scattering angle in the $t\bar{t}$ rest frame. The measured polarization and spin correlation are in agreement with the standard model. From the measured spin correlation, conclusions on the $t\bar{t}$ spin entanglement are drawn by applying the Peres-Horodecki criterion. The standard model predicts entangled spins for $t\bar{t}$ states at the production threshold and at high masses of the $t\bar{t}$ system. Entanglement is observed for the first time in events at high $t\bar{t}$ mass, where a large fraction of the $t\bar{t}$ decays are spacelike separated, with an expected and observed significance of above 5 standard deviations.

DOI: 10.1103/PhysRevD.110.112016

### I. INTRODUCTION

The top quark is the most massive known fundamental particle with a lifetime of the order of $10^{-25}$ s. This is shorter than the quantum chromodynamics (QCD) hadronization time scale $1/\Lambda_{QCD} \approx 10^{-24}$ s, and the spin decorrelation timescale $m_t/\Lambda^2_{QCD} \approx 10^{-21}$ s, where $m_t$ is the top quark mass [1,2]. Consequently, the top quark usually decays before hadronization, thus preserving its spin information in the angular distribution of the decay products. This makes top quark and antiquark ($t\bar{t}$) pairs excellent candidates for studying polarization and spin correlation.

charged lepton and a neutrino. In this analysis, we focus on the final state with two $b$ jets, two jets from one $W$ boson, and an electron or muon paired with a neutrino from the other $W$ boson. This decay channel is referred to as the $e/\mu$ + jets channel. Events with tau leptons are treated as $t\bar{t}$ background and not included in the $e/\mu$ + jets category.

At the LHC $t\bar{t}$ pairs are produced through gluon-gluon ($gg$) fusion and quark-antiquark ($q\bar{q}$) annihilation. The top quarks and antiquarks are unpolarized at leading order (LO). However, their spins are expected to be strongly correlated [3]. The complete spin correlation is encoded in a $3 \times 3$ matrix that depends on the $t\bar{t}$ production mechanism, the

Snapshot of 2 April 2025

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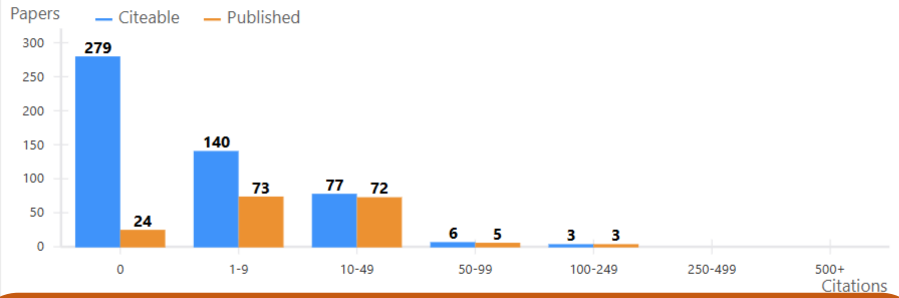
| Citations/paper (avg) | 5.4 | 13.5 |




**Observation of four-top-quark production in the multilepton final state with the ATLAS detector** #1
ATLAS Collaboration • Georges Aad (Marseille, CPPM) et al. (Mar 27, 2023)
Published in: *Eur.Phys.J.C* 83 (2023) 6, 496, *Eur.Phys.J.C* 84 (2024) 156 (erratum) • e-Print: 2303.15061 [hep-ex]
pdf DOI cite datasets claim reference search 111 citations

**Observation of quantum entanglement with top quarks at the ATLAS detector** #2
ATLAS Collaboration • Georges Aad (Marseille, CPPM) et al. (Nov 13, 2023)
Published in: *Nature* 633 (2024) 8030, 542-547 • e-Print: 2311.07288 [hep-ex]
pdf links DOI cite claim reference search 108 citations

**Software and computing for Run 3 of the ATLAS experiment at the LHC** #3
ATLAS Collaboration • Georges Aad (Marseille, CPPM) et al. (Apr 9, 2024)
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**The ATLAS experiment at the CERN Large Hadron Collider: a description of the detector configuration for Run 3** #4
ATLAS Collaboration • Georges Aad (Marseille, CPPM) et al. (May 26, 2023)
Published in: *JINST* 19 (2024) 05, P05063 • e-Print: 2305.16623 [physics.ins-det]
pdf DOI cite claim reference search 86 citations

**Development of the CMS detector for the CERN LHC Run 3** #1
CMS Collaboration • Aram Hayrapetyan (Yerevan Phys. Inst.) et al. (Sep 11, 2023)
Published in: *JINST* 19 (2024) 05, P05064 • e-Print: 2309.05466 [physics.ins-det]
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**New Structures in the $J/\psi J/\psi$ Mass Spectrum in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV** #2
CMS Collaboration • Aram Hayrapetyan (Yerevan Phys. Inst.) et al. (Jun 12, 2023)
Published in: *Phys.Rev.Lett.* 132 (2024) 11, 111901 • e-Print: 2306.07164 [hep-ex]
pdf links DOI cite datasets claim reference search 125 citations

**The CMS Statistical Analysis and Combination Tool: Combine** #3
CMS Collaboration • Aram Hayrapetyan (Yerevan Phys. Inst.) et al. (Apr 9, 2024)
Published in: *Comput.Softw.Big Sci.* 8 (2024) 1, 19 • e-Print: 2404.06614 [physics.data-an]
pdf DOI cite claim reference search 124 citations

**Evidence for the Higgs Boson Decay to a $Z$ Boson and a Photon at the LHC** #4
ATLAS and CMS Collaborations • Georges Aad (Marseille, CPPM) et al. (Sep 7, 2023)
Published in: *Phys.Rev.Lett.* 132 (2024) 2, 021803 • e-Print: 2309.03501 [hep-ex]
pdf links DOI cite datasets claim reference search 75 citations

**Measurement of Energy Correlators inside Jets and Determination of the Strong Coupling $\alpha_S(m_Z)$** #5
CMS Collaboration • Aram Hayrapetyan (Yerevan Phys. Inst.) et al. (Feb 21, 2024)
Published in: *Phys.Rev.Lett.* 133 (2024) 7, 071903 • e-Print: 2402.13864 [hep-ex]
pdf DOI cite datasets claim reference search 58 citations

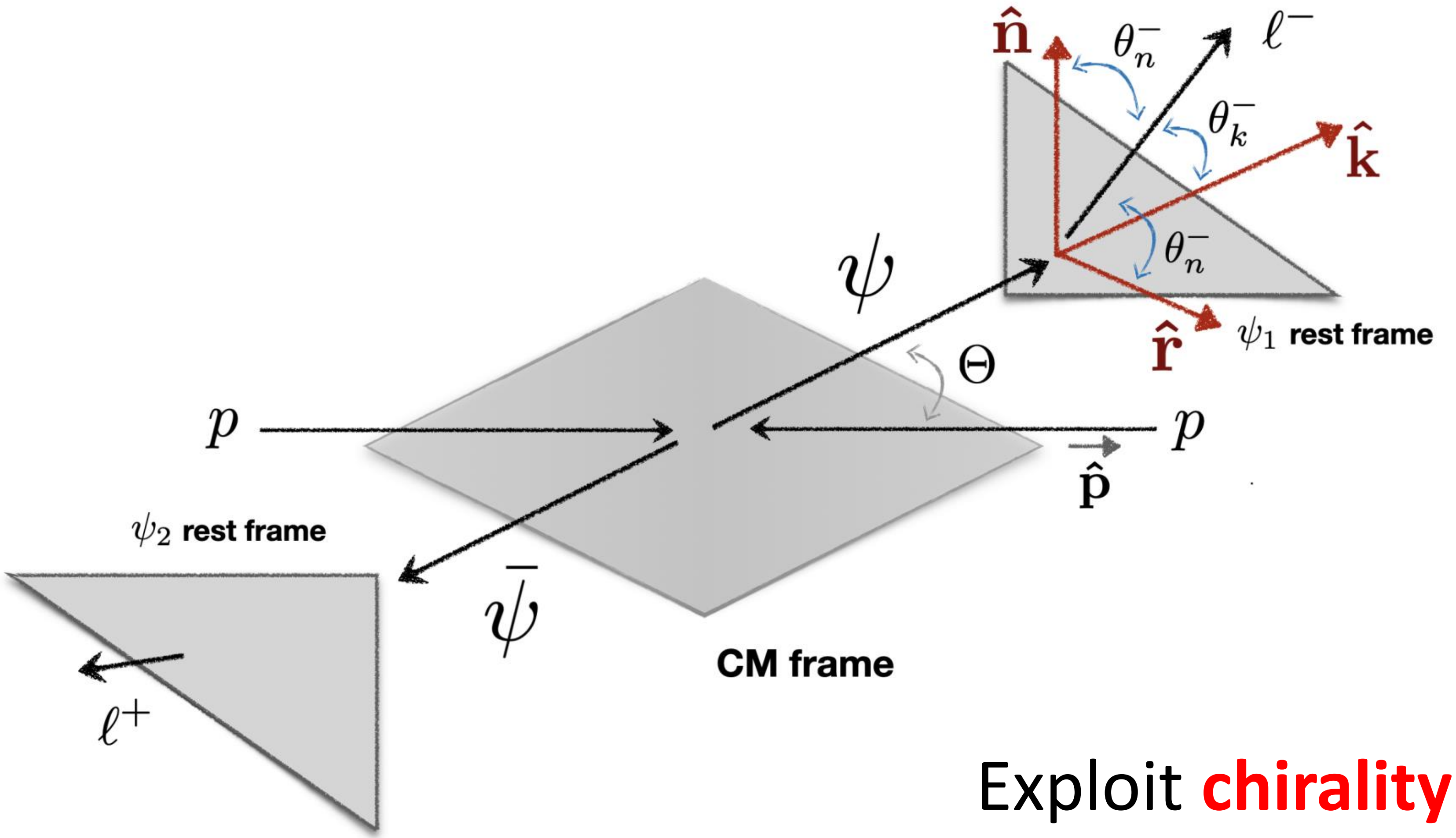
**Observation of quantum entanglement in top quark pair production in proton–proton collisions at $\sqrt{s} = 13$ TeV** #6
CMS Collaboration • Aram Hayrapetyan (Yerevan Phys. Inst.) et al. (Jun 6, 2024)
Published in: *Rept.Prog.Phys.* 87 (2024) 11, 117801, *Rept.Prog.Phys.* 87 (2024) 117801 • e-Print: 2406.03976 [hep-ex]
pdf DOI cite datasets claim reference search 50 citations

**Test of lepton flavor universality in $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$ and $B^{\pm} \to K^{\pm}e^{+}e^{-}$ decays in proton-proton collisions at $\sqrt{s} = 13$ TeV** #7
CMS Collaboration • Aram Hayrapetyan (Yerevan Phys. Inst.) et al. (Jan 13, 2024)

ATLAS top-cited papers of 2024

CMS top-cited papers of 2024

# Momentum measurement → infer spin of parent particle




Exploit **chirality** of the weak decay
Momentum <-> Spin

# Entanglement

**For some density matrix**

$$\rho = \sum_i p_i \left|\psi_i\right\rangle \left\langle\psi_i\right|$$

$p_i$ is a classical probability

**Q: Can we write:**

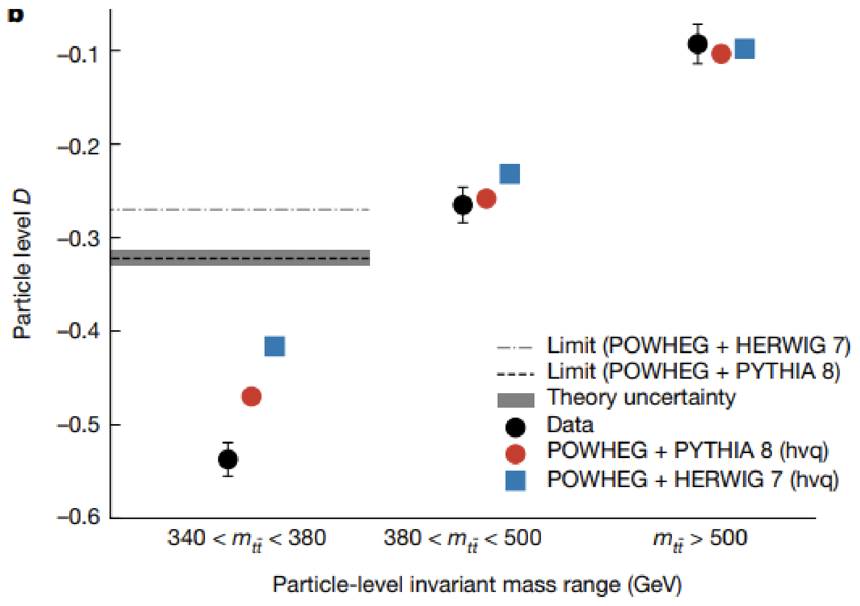
$$\rho \stackrel{?}{=} \sum_i p_i \, \rho_A \otimes \rho_B \qquad p_i \geq 0, \sum p_i = 1$$

i.e. as a convex sum of product states?

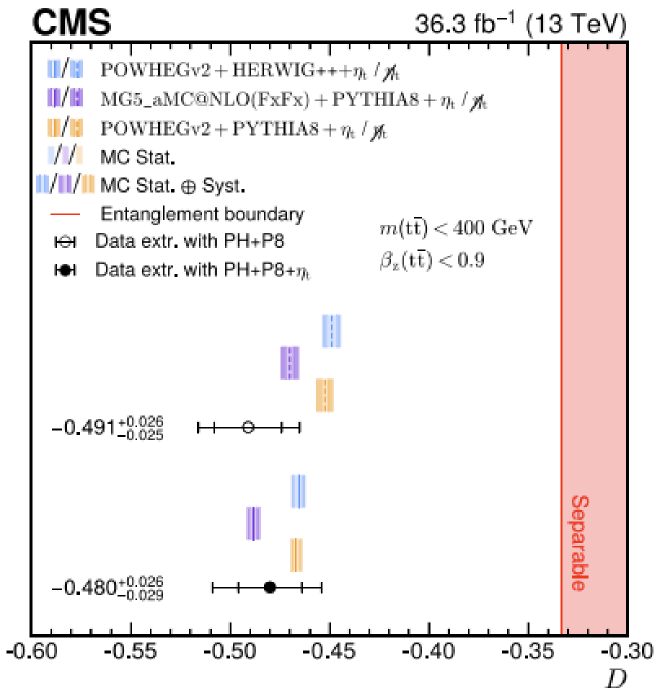
- Yes $\implies$ separable
- No $\implies$ entangled

For general $\rho$ (i.e. not pure states) this is a very different statement from just being correlated

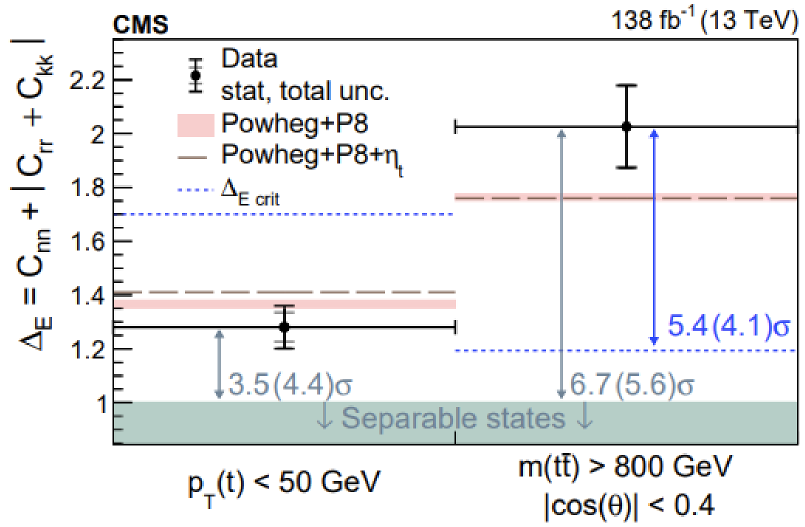
# Experimental observation of entanglement in top quark systems




ATLAS dileptonic, threshold




CMS dileptonic, threshold




CMS semi-leptonic, threshold & high mmtm

https://arxiv.org/abs/2311.07288

https://arxiv.org/abs/2406.03976

https://arxiv.org/abs/2409.11067

Talks by Alexander Grohsjean, Ethan Simpson

# Quantum state tomography

## Parameterise $\rho$ – bipartite system of qubits

in terms of the Pauli matrices $\sigma_i$

### Single qubit

$$\rho = \frac{1}{2} I_2 + \sum_{i=1}^{3} a_i \sigma_i,$$

$a_i$ : 3 real parameters $(2^2 - 1)$

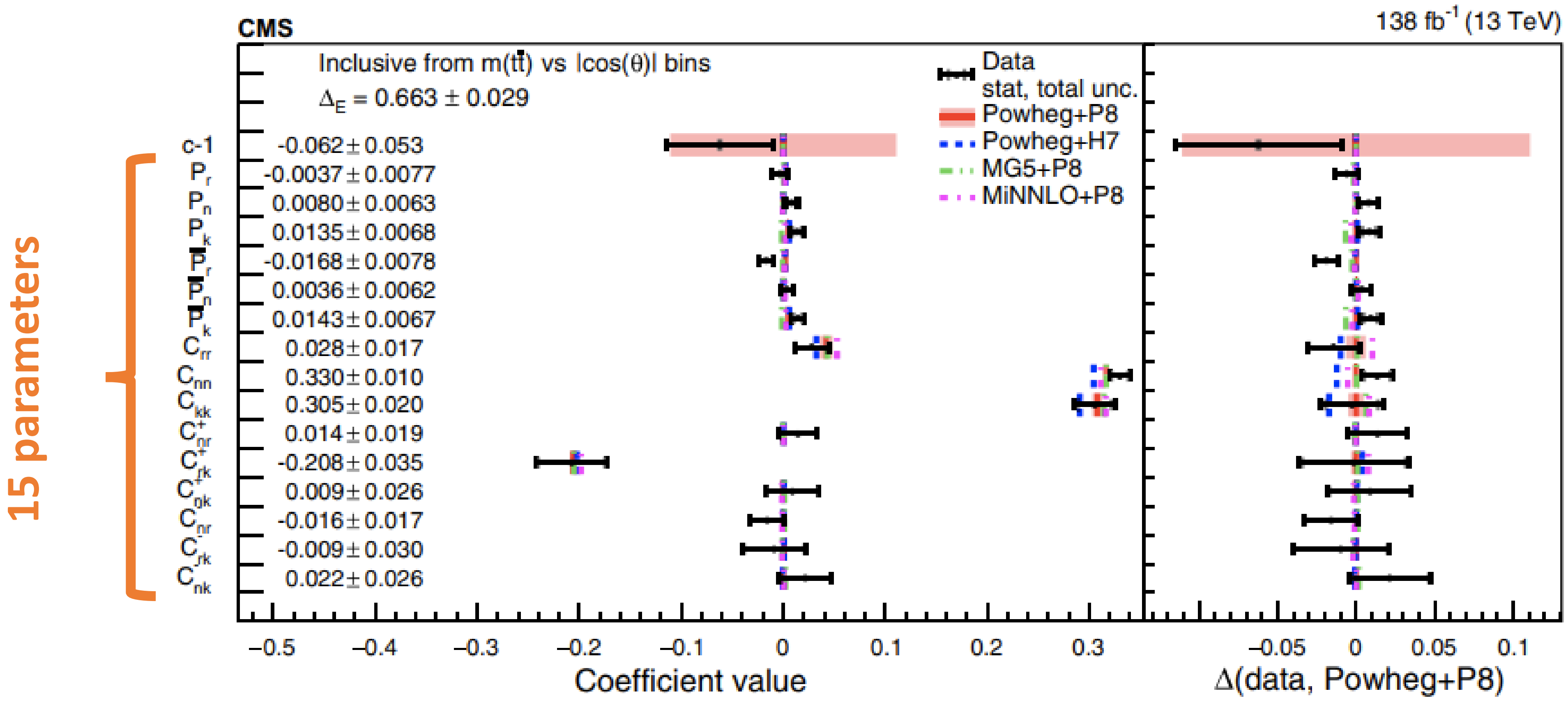
### Two qubits

$$\rho = \frac{1}{4} I_2 \otimes I_2 + \sum_{i=1}^{3} a_i\, \sigma_i \otimes \frac{1}{2} I_2 + \sum_{j=1}^{3} b_j\, \frac{1}{2} I_2 \otimes \sigma_j + \sum_{i,j=1}^{3} c_{ij}\, \sigma_i \otimes \sigma_j,$$

3+3+9 = 15 real parameters $(4^2 - 1)$

Measure the parameters $(a_i\ b_j, c_{ij})$ and test properties of bipartite $\rho$

# Quantum state tomography - measurement

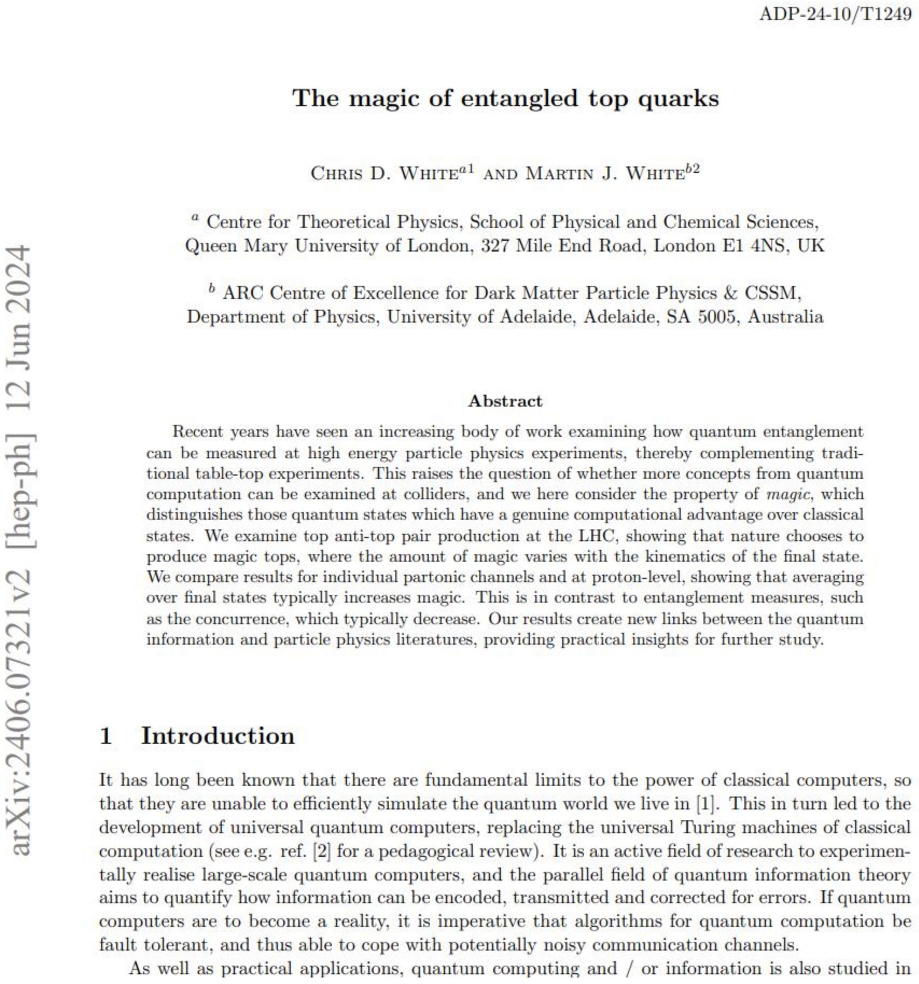



$$\Sigma_{\text{tot}}(\phi_{p(\bar{p})}, \theta_{p(\bar{p})}) = \frac{d^4\sigma}{d\phi_p \, d\cos(\theta_p) \, d\phi_{\bar{p}} \, d\cos(\theta_{\bar{p}})}$$
$$= \sigma_{\text{norm}}\left(1 + \kappa \mathbf{P} \cdot \mathbf{\Omega} + \bar{\kappa} \bar{\mathbf{P}} \cdot \bar{\mathbf{\Omega}} - \kappa\bar{\kappa} \mathbf{\Omega} \cdot (\mathrm{C}\bar{\mathbf{\Omega}})\right),$$



https://arxiv.org/abs/2409.11067

# Measurement of Magic


ADP-24-10/T1249

arXiv:2406.07321v2 [hep-ph] 12 Jun 2024

**The magic of entangled top quarks**


Chris D. White[a1] and Martin J. White[b2]

[a] Centre for Theoretical Physics, School of Physical and Chemical Sciences, Queen Mary University of London, 327 Mile End Road, London E1 4NS, UK

[b] ARC Centre of Excellence for Dark Matter Particle Physics & CSSM, Department of Physics, University of Adelaide, Adelaide, SA 5005, Australia



**Abstract**

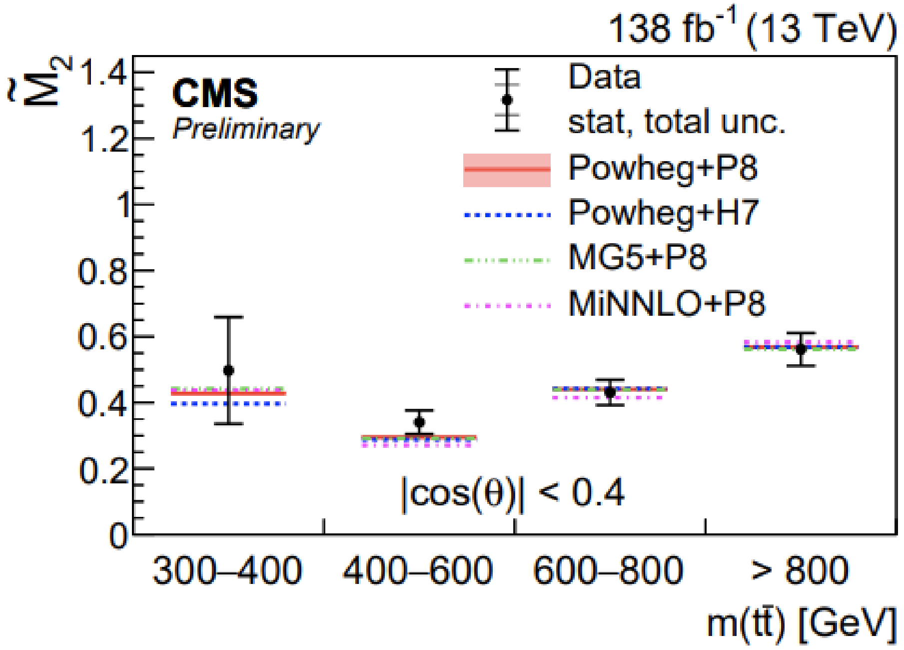
Recent years have seen an increasing body of work examining how quantum entanglement can be measured at high energy particle physics experiments, thereby complementing traditional table-top experiments. This raises the question of whether more concepts from quantum computation can be examined at colliders, and we here consider the property of *magic*, which distinguishes those quantum states which have a genuine computational advantage over classical states. We examine top anti-top pair production at the LHC, showing that nature chooses to produce magic tops, where the amount of magic varies with the kinematics of the final state. We compare results for individual partonic channels and at proton-level, showing that averaging over final states typically increases magic. This is in contrast to entanglement measures, such as the concurrence, which typically decrease. Our results create new links between the quantum information and particle physics literatures, providing practical insights for further study.


**1 Introduction**

It has long been known that there are fundamental limits to the power of classical computers, so that they are unable to efficiently simulate the quantum world we live in [1]. This in turn led to the development of universal quantum computers, replacing the universal Turing machines of classical computation (see e.g. ref. [2] for a pedagogical review). It is an active field of research to experimentally realise large-scale quantum computers, and the parallel field of quantum information theory aims to quantify how information can be encoded, transmitted and corrected for errors. If quantum computers are to become a reality, it is imperative that algorithms for quantum computation be fault tolerant, and thus able to cope with potentially noisy communication channels.

As well as practical applications, quantum computing and / or information is also studied in

$$\tilde{M}_2 = -\log_2\left(\frac{1+\sum_{i\in n,k,r}[(P_i^4+\bar{P}_i^4)]+\sum_{i,j\in n,k,r}C_{ij}^4}{1+\sum_{i\in n,k,r}[(P_i^2+\bar{P}_i^2)]+\sum_{i,j\in n,k,r}C_{ij}^2}\right).$$




https://arxiv.org/abs/2406.07321

https://arxiv.org/abs/2503.03098

CMS PAS TOP-25-001 (March 2025)

See also talks by Ian Low, Yin Zhewei

# Inspired by the quantum entanglement measurements…

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS-TOP-24-007

CERN-EP-2025-061
2025/03/31

## Observation of a pseudoscalar excess at the top quark pair production threshold

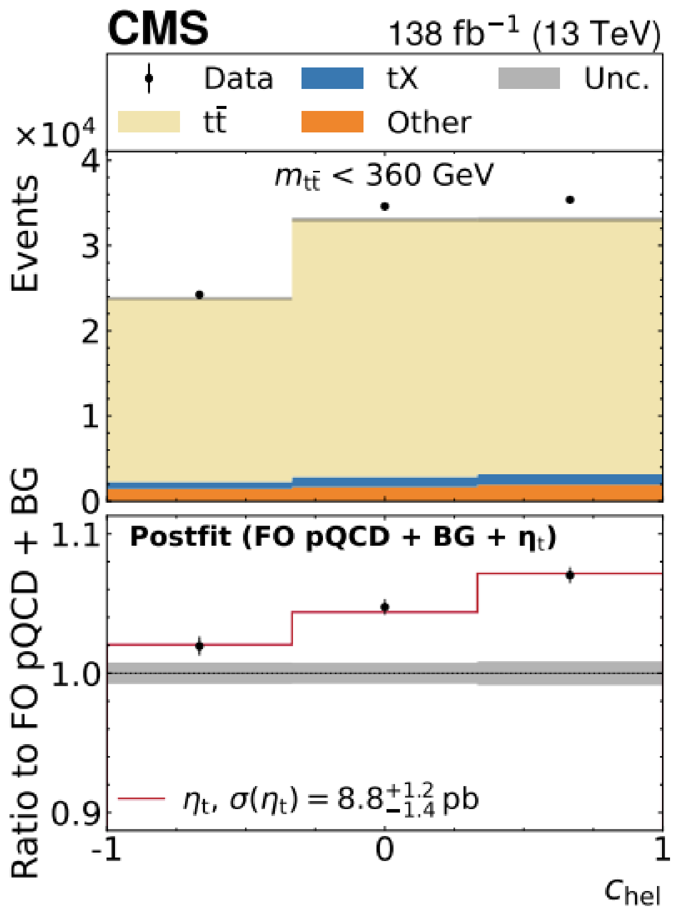
The CMS Collaboration*

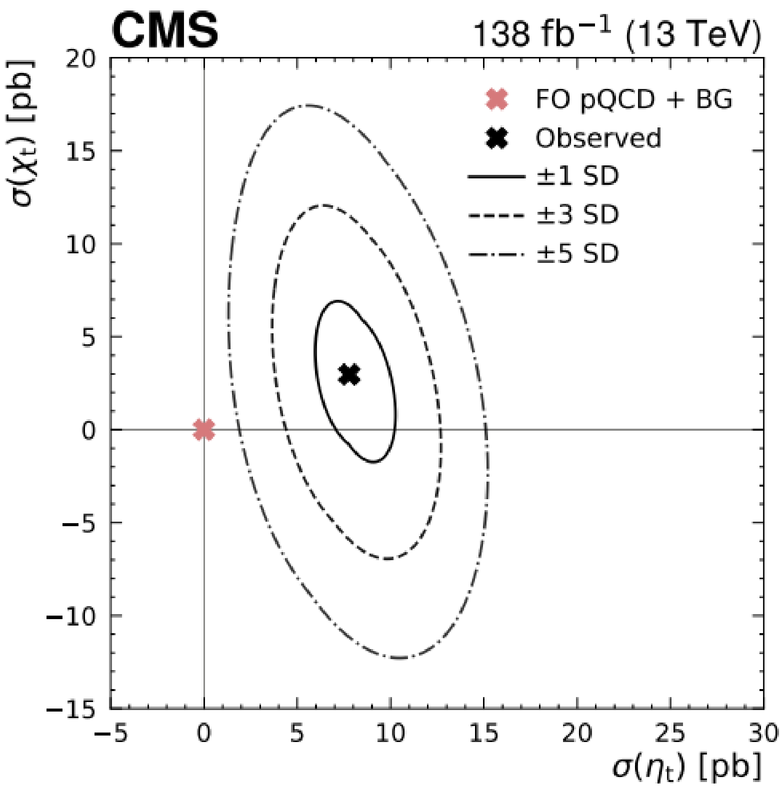

### Abstract

A search for resonances in top quark pair ($t\bar{t}$) production in final states with two charged leptons and multiple jets is presented, based on proton-proton collision data collected by the CMS experiment at the CERN LHC at $\sqrt{s} = 13\,\text{TeV}$, corresponding to $138\,\text{fb}^{-1}$. The analysis explores the invariant mass of the $t\bar{t}$ system and two angular observables that provide direct access to the correlation of top quark and antiquark spins. A significant excess of events is observed near the kinematic $t\bar{t}$ threshold compared to the nonresonant production predicted by fixed-order perturbative quantum chromodynamics (pQCD). The observed enhancement is consistent with the production of a color-singlet pseudoscalar (${}^1S_0^{[1]}$) quasi-bound toponium state, as predicted by nonrelativistic quantum chromodynamics. Using a simplified model for ${}^1S_0^{[1]}$ toponium, the cross section of the excess above the pQCD prediction is measured to be $8.8^{+1.2}_{-1.4}$ pb.


Submitted to Reports on Progress in Physics

arXiv:2503.22382v1 [hep-ex] 28 Mar 2025




https://arxiv.org/pdf/2503.22382

Talks by Ben Fuks, Alexander Grohsjean, Ethan Simpson

28th March 2025


SEIKO
SEIKO

# Review

## Quantum entanglement and Bell inequality violation at colliders

Alan J. Barr [a,b], Marco Fabbrichesi [c], Roberto Floreanini [c], Emidio Gabrielli [d,c,e,*], Luca Marzola [e]

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[c] INFN, Sezione di Trieste, Via Valerio 2, I-34127 Trieste, Italy
[d] Physics Department, University of Trieste, Strada Costiera 11, I-34151 Trieste, Italy
[e] Laboratory of High-Energy and Computational Physics, NICPB, Rävala pst. 10, 10143 Tallinn, Estonia

**Abstract**

The study of entanglement in particle physics has been gathering pace in the past few years. It is a new field that is providing important results about the possibility of detecting entanglement and testing Bell inequality at colliders for final states as diverse as top-quark, $\tau$-lepton pairs and $\Lambda$-baryons, massive gauge bosons and vector mesons. In this review, after presenting definitions, tools and basic results that are necessary for understanding these developments, we summarize the main findings—as published by the beginning of year 2024—including analyses of experimental data in $B$ meson decays and top-quark pair production. We include a detailed discussion of the results for both qubit and qutrits systems, that is, final states containing spin one-half and spin one particles. Entanglement has also been proposed as a new tool to constrain new particles and fields beyond the Standard Model and we introduce the reader to this promising feature as well.

*Keywords:* Quantum entanglement, Bell locality, Collider physics, Particle polarizations, Standard Model and beyond

https://arxiv.org/abs/2402.07972

**December 2024**

# Submission to the European Strategy for Particle Physics

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


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Abstract: Some of the most **astonishing** and **prominent** properties of Quantum Mechanics, such as **entanglement** and **Bell nonlocality**, have only been studied extensively in dedicated low-energy laboratory setups. The feasibility of these studies in the high-energy regime explored by particle colliders was only recently shown, and has gathered the attention of the scientific community. For the range of particles and fundamental interactions involved, particle colliders provide a **novel environment** where quantum information theory can be probed, with energies exceeding, by about **12 orders of magnitude**, the laboratory setups typically used in the field. Furthermore, collider detectors have inherent **advantages** in performing certain quantum information measurements, and allow for the reconstruction the state of the system under consideration via **quantum state tomography**. Here, we elaborate on the potential, challenges, and goals of this **innovative** and **rapidly evolving** line of research, and discuss its expected impact on both quantum information theory and high-energy physics


https://arxiv.org/abs/2504.00086

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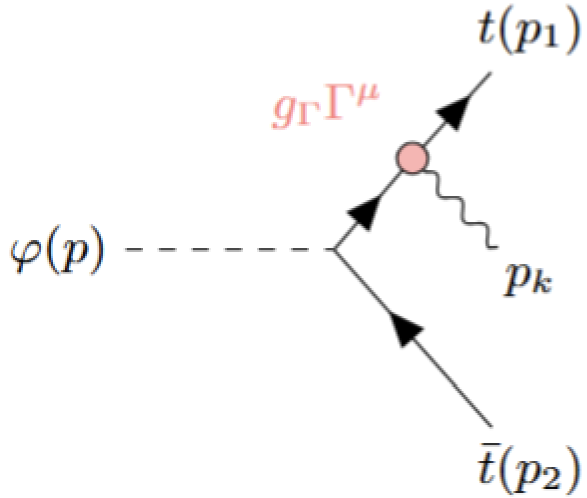
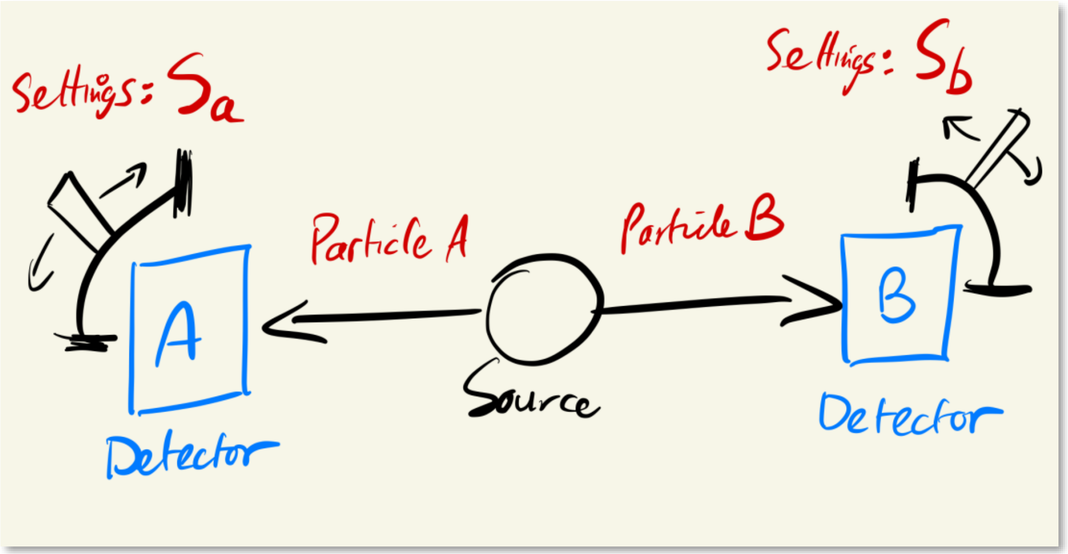
# Uncertainties, NLO effects, QFT effects…




Fields are not particles. Interpretation beyond particle-particle picture…

Talks by Baptiste Ravina, Rafael Aoude, Pawel Caban

# Unmeasured quantum effects

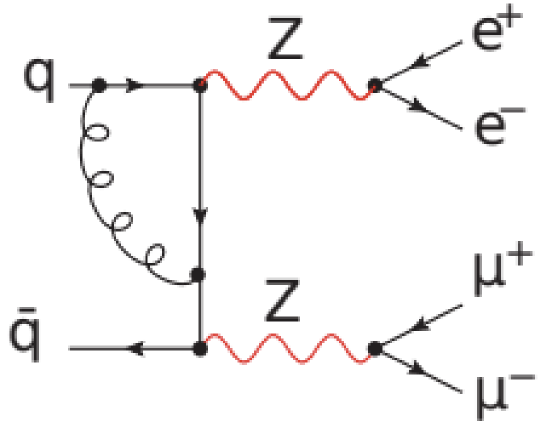


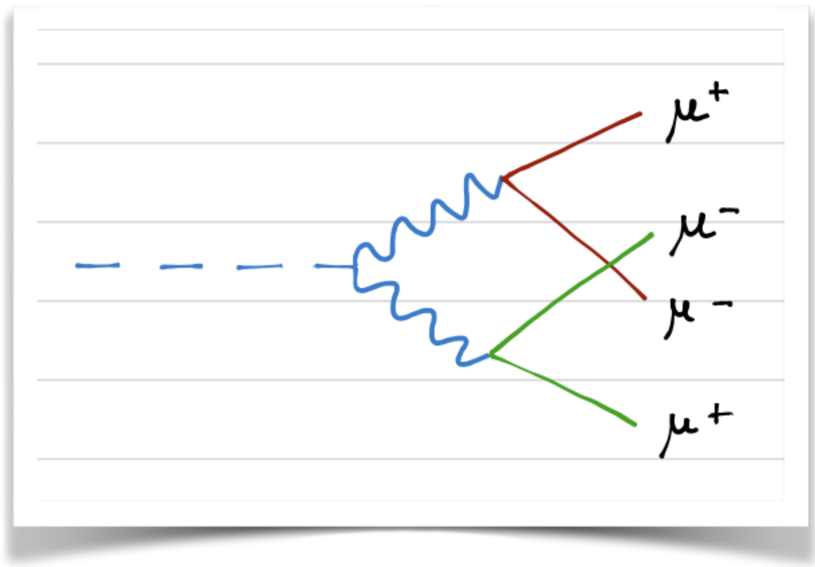

$$D_A(\rho_{AB}) = S(\rho_B) - S(\rho_{AB}) + \min_{\hat{n}} \left(p_{+\hat{n}} S(\rho_{+\hat{n}}) + p_{-\hat{n}} S(\rho_{-\hat{n}})\right) .$$

Discord, Bell Violation, non-locality, …

Talks by Matthew Low, David Uzan, Navin McGinnis, Alexander Bernal

# qtrits and qdits rather than qbits

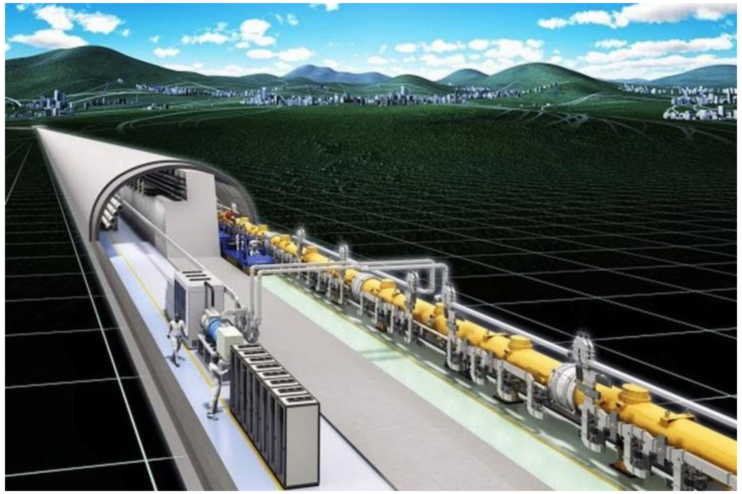



Identical particle effects, off-shell effects, NLO, larger spin-density matrices,…

Talks by Juan Antonio Saavedra, Giovanni Pellicciolo, Priyanka Lambda

# Measurements at future colliders



e+ e-

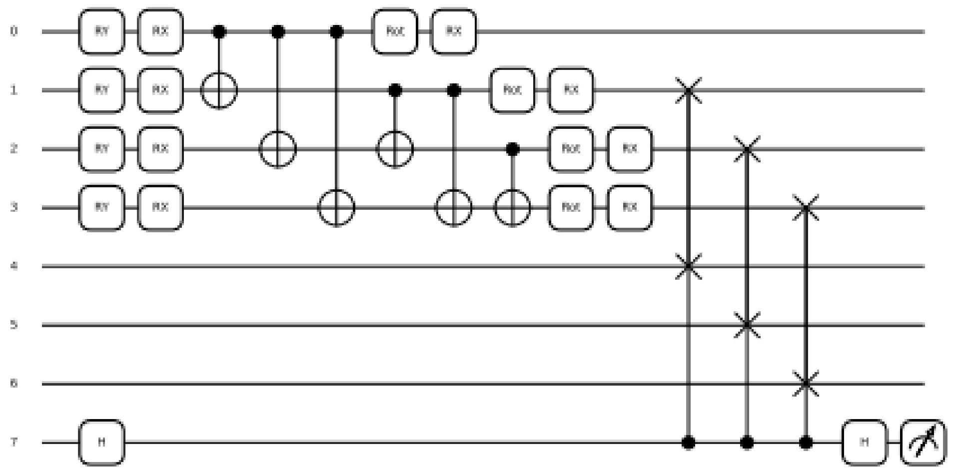
EIC


Muon colliders

**Clean initial states, high energies, polarised beams, …**

Talks by Kazuki Sakurai, Eleni Vryonidou, Alim Ruzi, Luca Marzola

# Relation with quantum computers

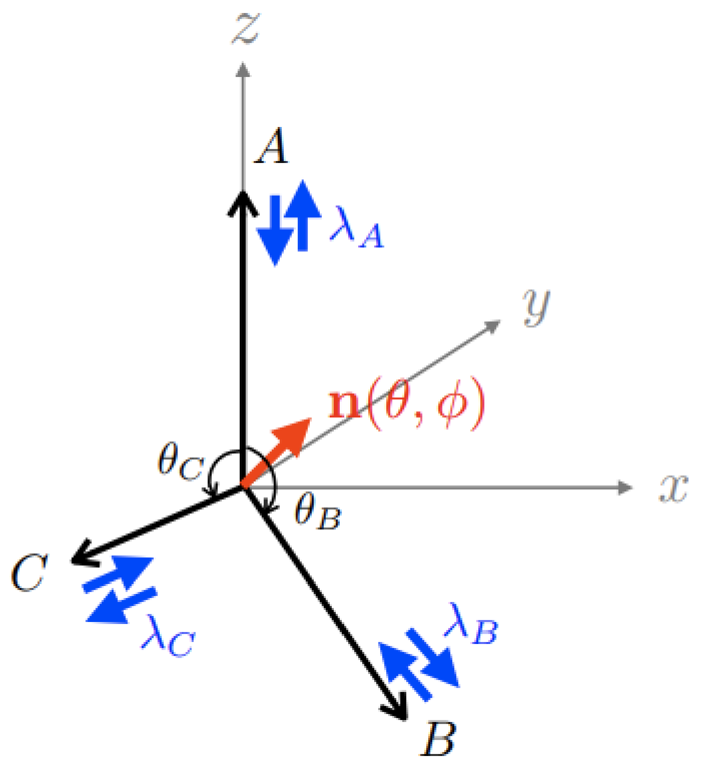


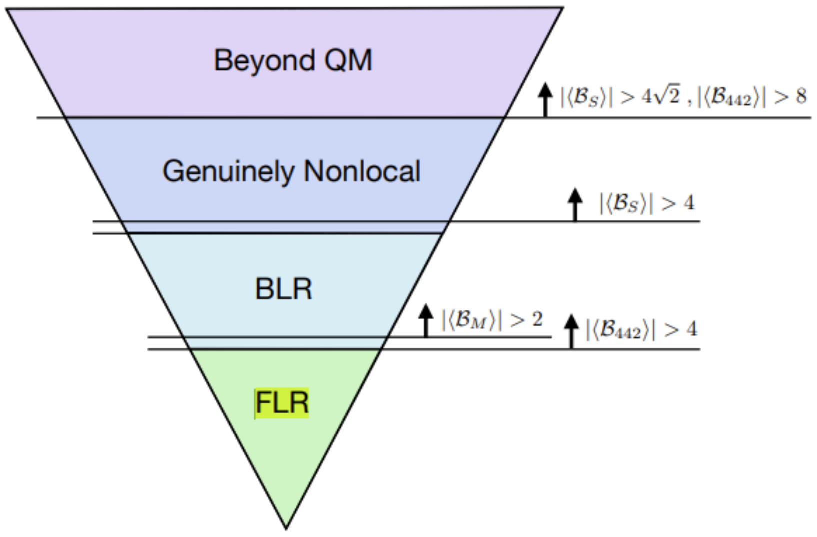
$$\rho_{\text{out}} = \sum_k E_k \rho_{\text{in}} E_k^\dagger \,.$$

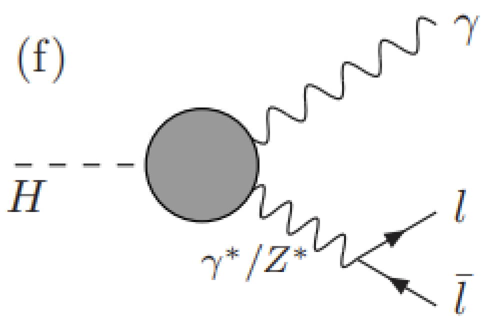
Quantum process tomography. Encoding particles for quantum learning

Talks by Michal Spannowsky, Kazuki Sakurai

# Multi-particle entanglement & non-locality




Talks by Pawel Horodecki, Roberto Morales

# … and much more…