Quantum Information at High-Energy Colliders

Matthew Low (University of Pittsburgh)

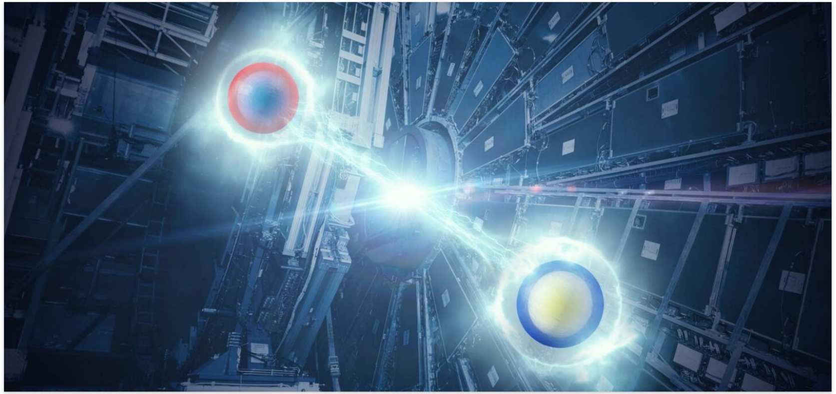
April 28, 2025
MIT LNS

In the Media

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



In the Media

LHC experiments at CERN observe

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The results o

18 SEPTEMBER,

ATLAS achieves highest-energy detection of quantum entanglement

28 September 2023 | By ATLAS Collaboration

Quantum entanglement is one of the most astonishing properties of quantum mechanics. If two particles are entangled, the state of one particle cannot be described independently from the other. This is a unique property of the quantum world and forms a crucial difference between classical and quantum theories of physics. It is so important, the 2022 Nobel Prize in Physics was awarded to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science".

In the Media

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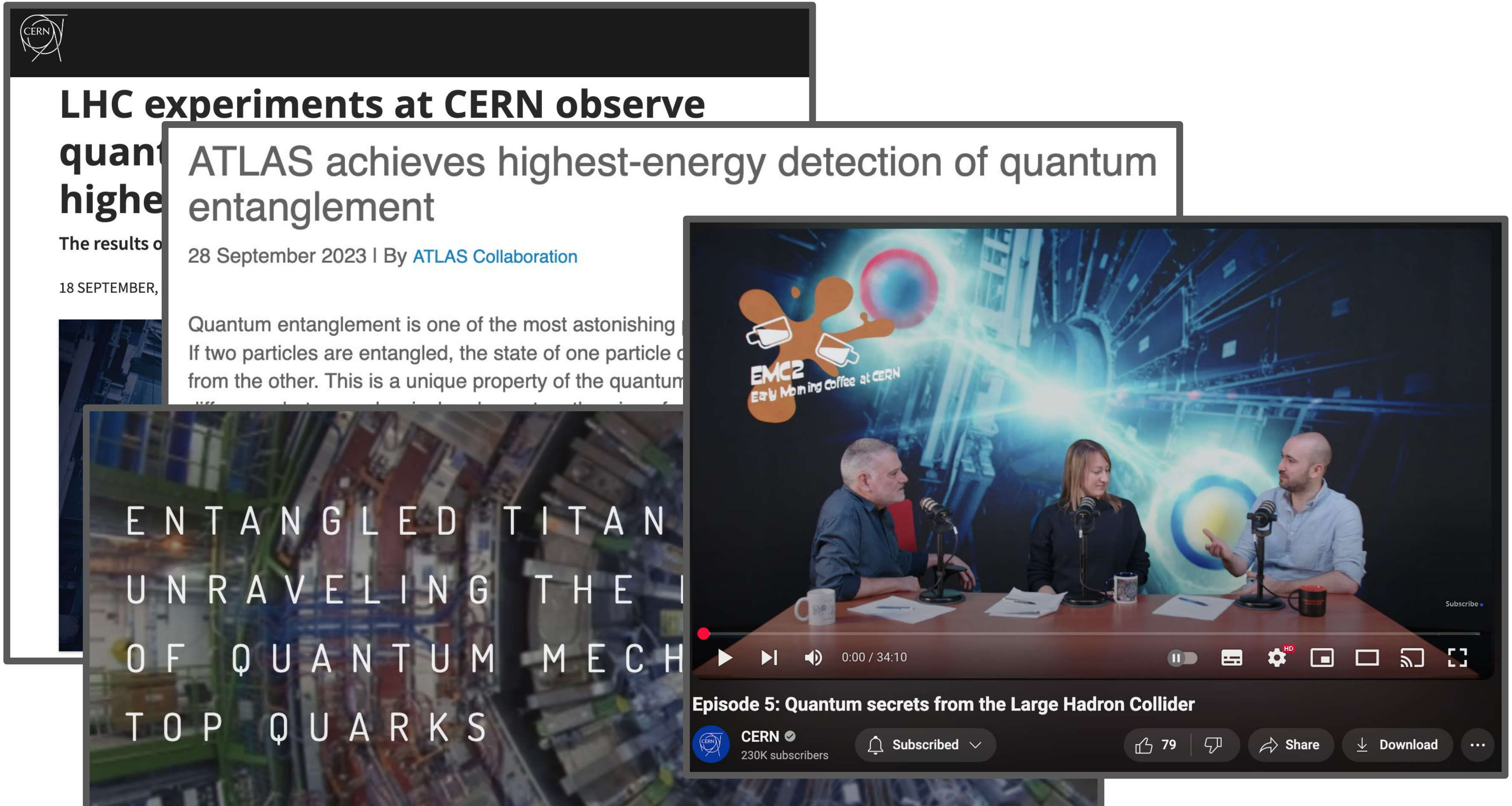

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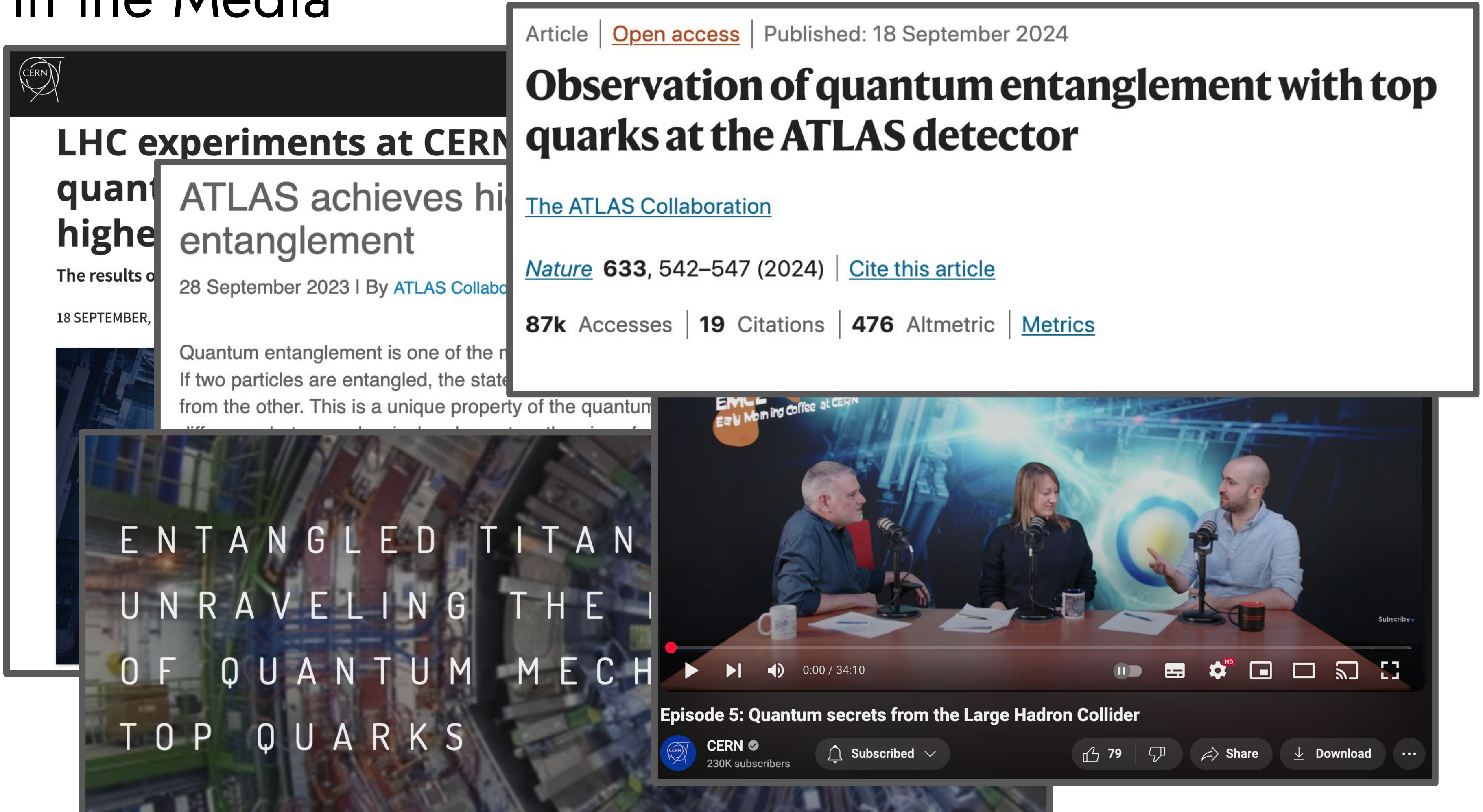
Article | Open access | Published: 18 September 2024
Observation of quantum entanglement with top quarks at the ATLAS detector
The ATLAS Collaboration
Nature 633, 542–547 (2024) | Cite this article
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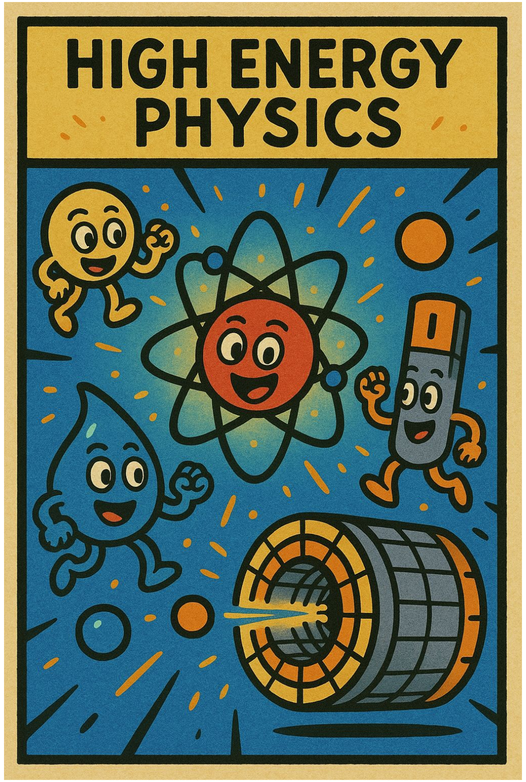
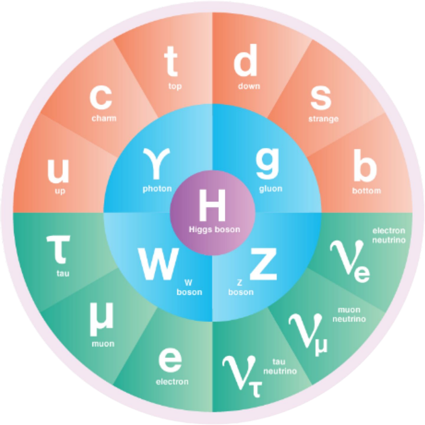
High-Energy Physics and Quantum Information Science

- Each of these are individually **interesting** and **vibrant** fields

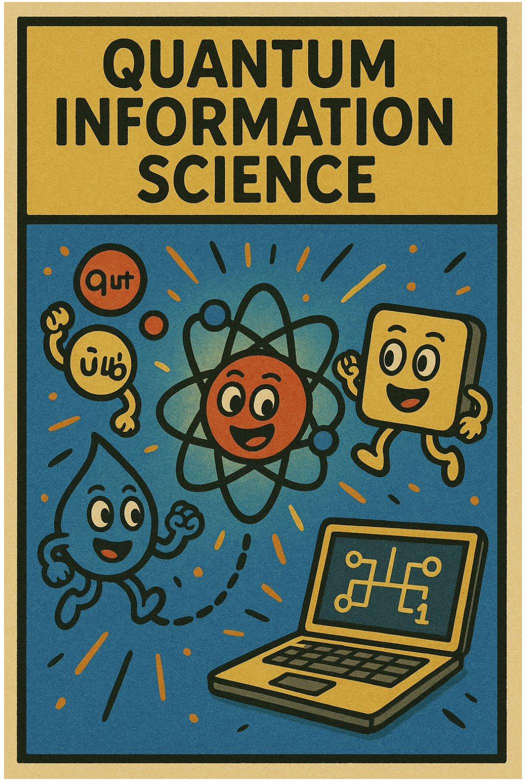


- Identify the **fundamental constituents** and laws of nature
- Test and refine the **Standard Model**
- Explore **symmetries** and conservation laws



High-Energy Physics and Quantum Information Science

- Each of these are individually **interesting** and **vibrant** fields



- Explore quantum systems as a resource for **information processing**
- Understand the **foundations** of quantum mechanics
- Build **quantum computers**

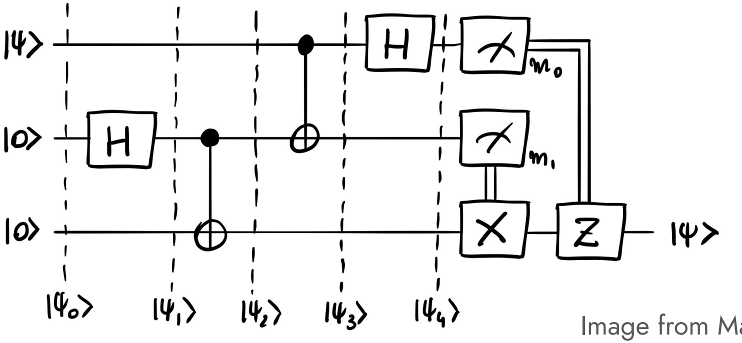


Image from Marek Narozniak

High-Energy Physics and Quantum Information Science

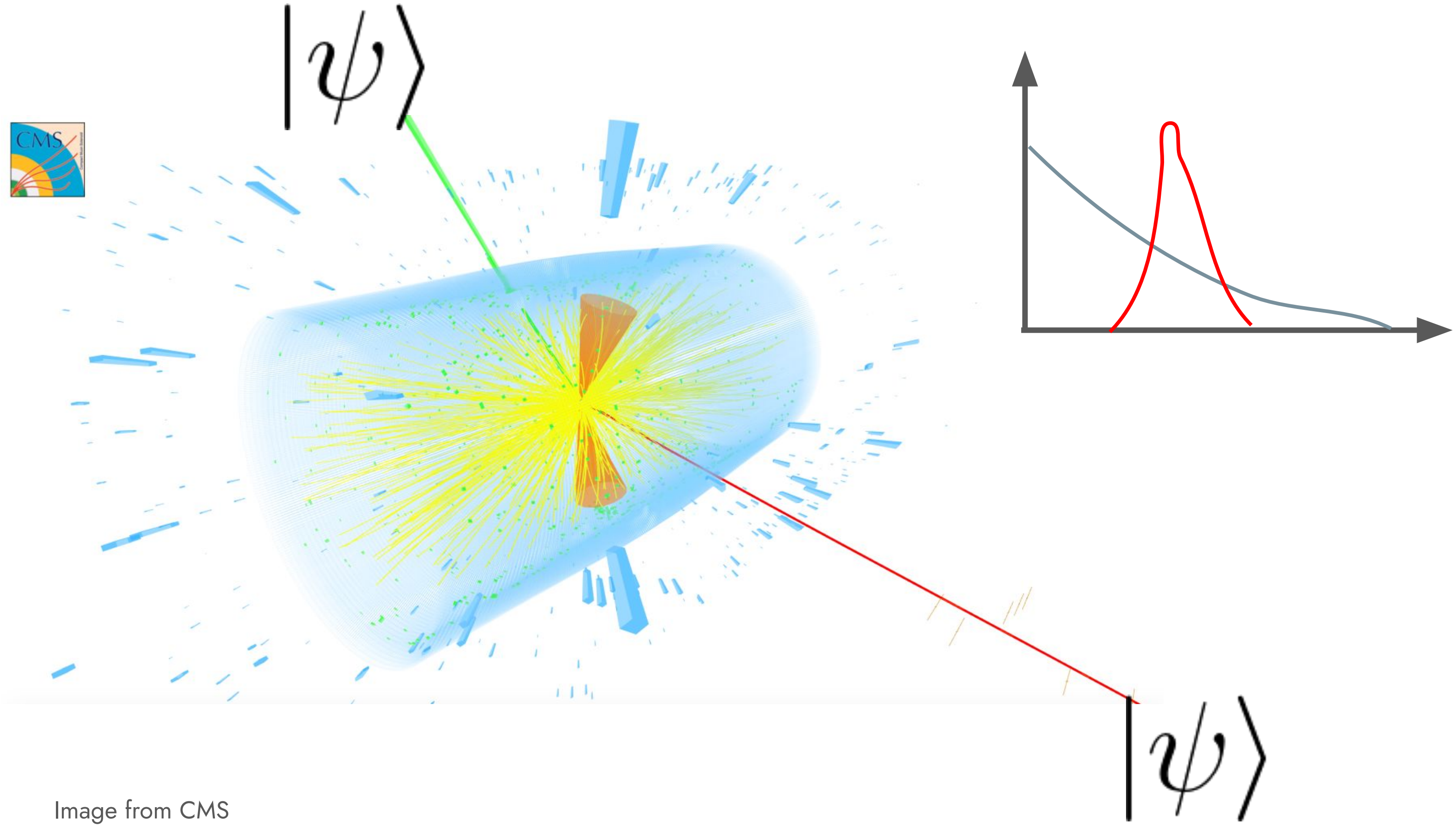


Image from CMS

High-Energy Physics and Quantum Information Science

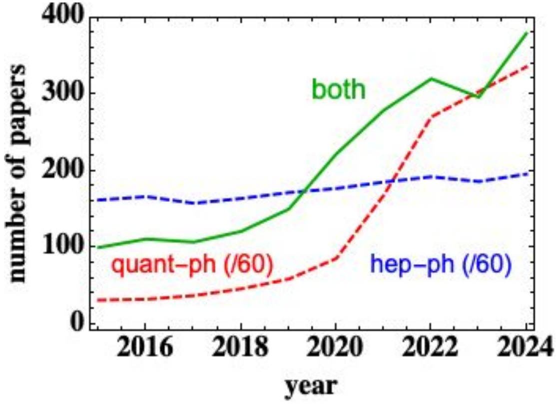
Afik, Fabbri, ML, Marzola, … [2504.00086]

New quantum systems: decaying particles

Fundamental massive particles as qudits

Enormous amounts of data

High-Energy Physics

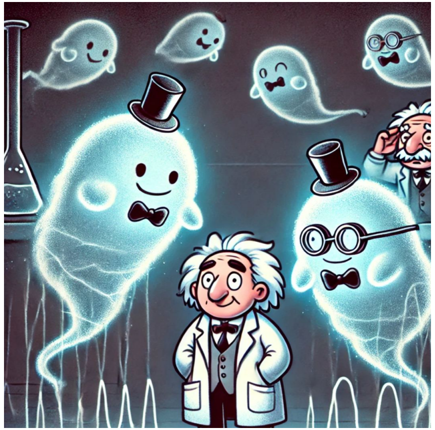


Quantum Information Science

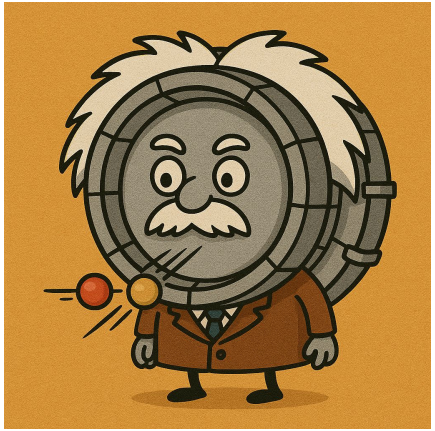
Quantum mechanics explicitly at work

New approaches to spin correlations

Highlight unique signal regions

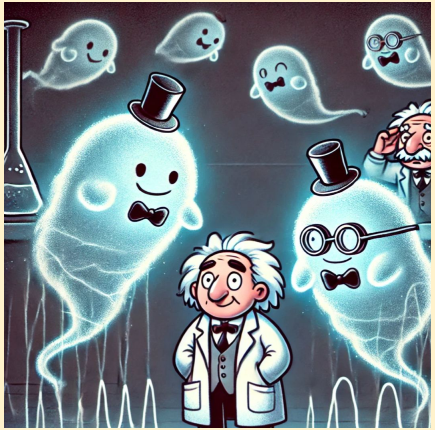


Features of QM

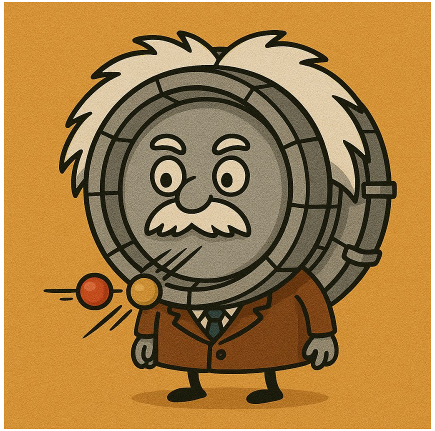


Colliders as a QM experiment

QI at Colliders



Features of QM



Colliders as a QM experiment

QI at Colliders

Features of Quantum Mechanics

- Consider a state with **two** values: 0 and 1

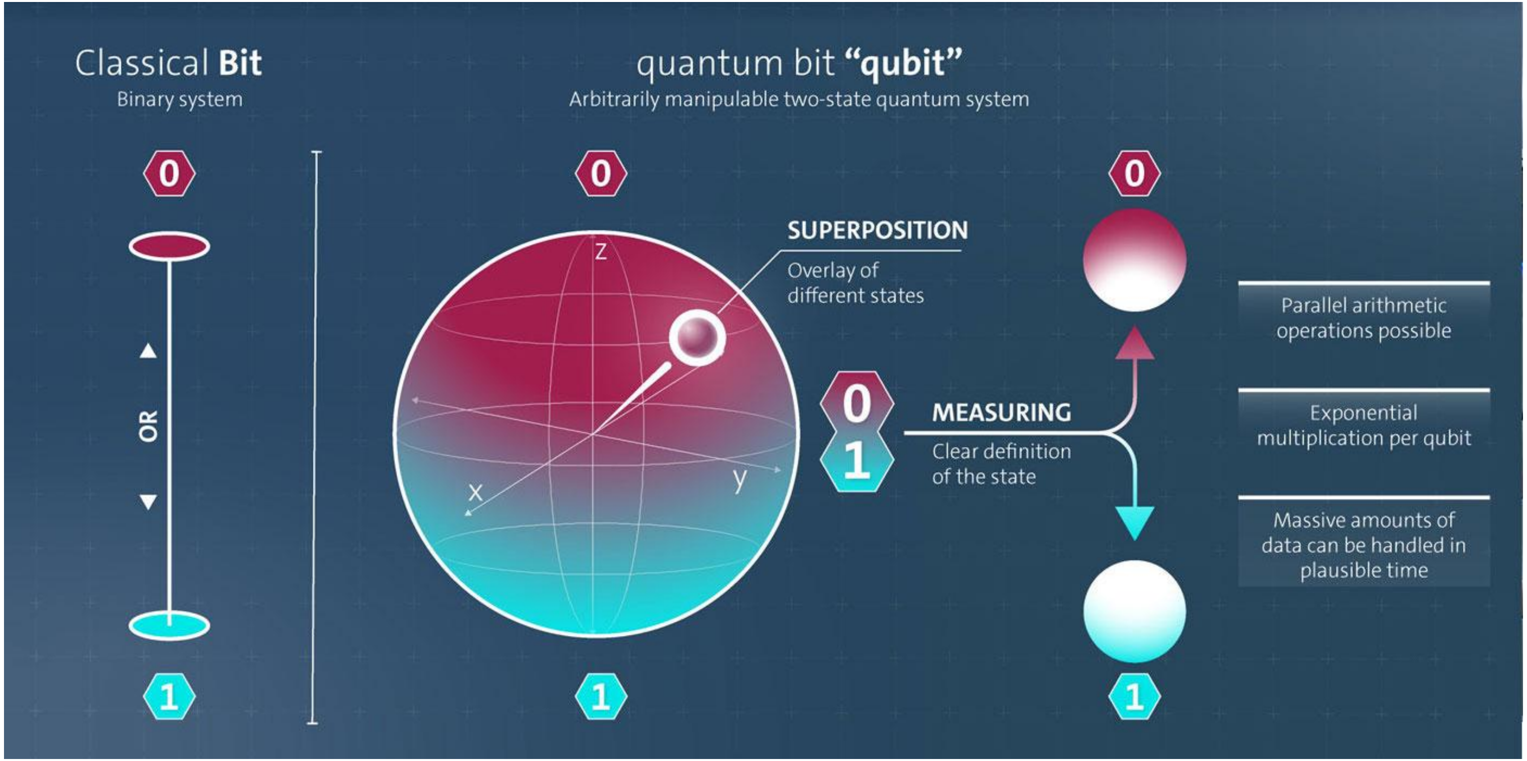


Image from Volkswagen

Features of Quantum Mechanics

- Single **qubit** $|\psi\rangle$ describes two-level state

$$|\uparrow\rangle, |\downarrow\rangle \qquad \text{or} \qquad |1\rangle, |0\rangle$$

- Generally have a **superposition**

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad \text{or} \qquad |\psi\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

- **Observables** represented by operators A
- **Measurement** of A given by $a = \langle\psi|A|\psi\rangle$

- **Example:** measure the spin along the z-direction

$$|\psi_1\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \langle\psi_1|\sigma_z|\psi_1\rangle = 1 \qquad\qquad |\psi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad \langle\psi_2|\sigma_z|\psi_2\rangle = 0$$

Features of Quantum Mechanics

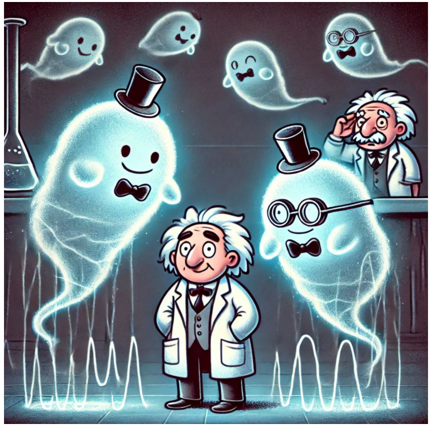
- **Two qubits** occupy the tensor space $\mathcal{H}_1 \otimes \mathcal{H}_2$
- Possible states are

$$|0\rangle \otimes |0\rangle \qquad |0\rangle \otimes |1\rangle \qquad |1\rangle \otimes |0\rangle \qquad |1\rangle \otimes |1\rangle$$

- Here's a **separable** state

$$|\psi\rangle = \frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$$

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \qquad |\psi_1\rangle = |\psi_2\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$



- Here's an **entangled** state

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

- First qubit cannot be **described independently** from second qubit

Features of Quantum Mechanics

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)

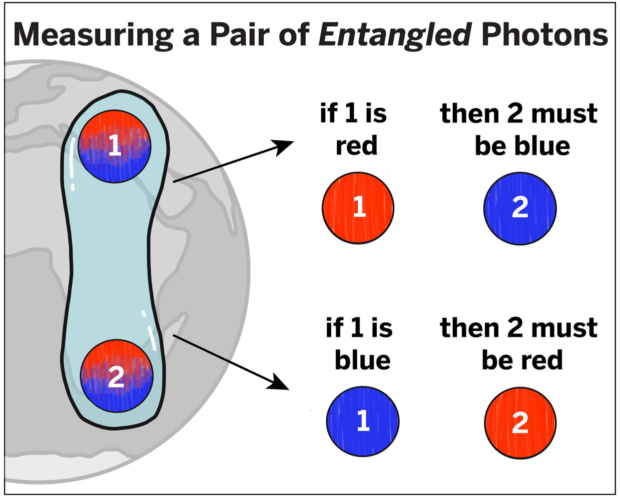


Image from UMD Quantum Atlas

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.

- Einstein-Podolsky-Rosen were famously uncomfortable with quantum entanglement and suggested Quantum Mechanics was **not a complete description**

Features of Quantum Mechanics

Bell 1964

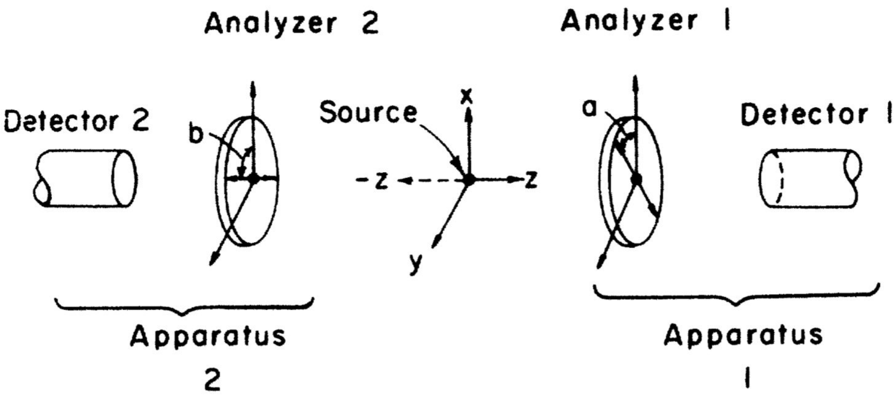
Clauser, Horne, Shimony, Holt 1969

Clauser, Horne 1974

- Another measure of *quantumness* is **Bell's inequality**

Detector settings:

b_1 and b_2



Detector settings:

a_1 and a_2

Measurements:

1	a_1	b_1	E_{11}
2	a_1	b_2	E_{12}
3	a_2	b_1	E_{21}
4	a_2	b_2	E_{22}

$$E = \frac{N^{++} + N^{--} - N^{+-} - N^{-+}}{N^{++} + N^{--} + N^{+-} - N^{-+}}$$

E=-1
Fully anti-correlated

E=0
Uncorrelated

E=+1
Fully correlated

Features of Quantum Mechanics

Bell 1964

Clauser, Horne, Shimony, Holt 1969

Clauser, Horne 1974

- Another measure of *quantumness* is **Bell's inequality**

Measurements:

1	a_1	b_1	E_{11}
2	a_1	b_2	E_{12}
3	a_2	b_1	E_{21}
4	a_2	b_2	E_{22}

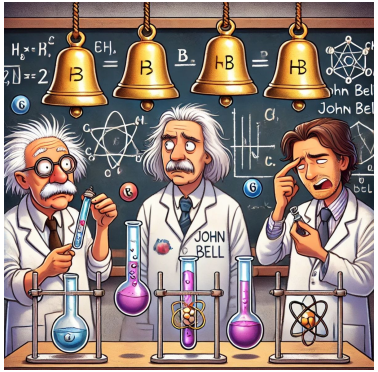
$$|E_{11} - E_{12} + E_{21} + E_{22}| \leq 2$$

- All *classical* theories satisfy this inequality
- *Quantum* theories can satisfy this inequality

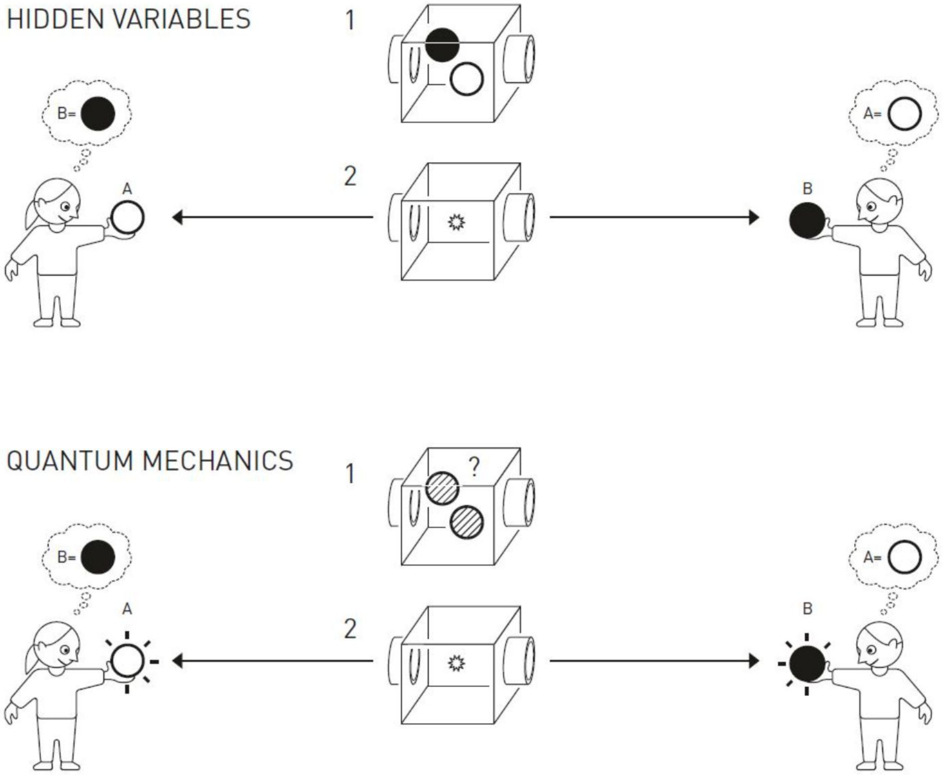
  Bell local state

- Or *quantum* theories can violate this inequality

  Bell nonlocal state



Features of Quantum Mechanics



nobelprize.org

Features of Quantum Mechanics

Aspect, Grangier, Roger 1981

Nobel Prize in Physics 2022

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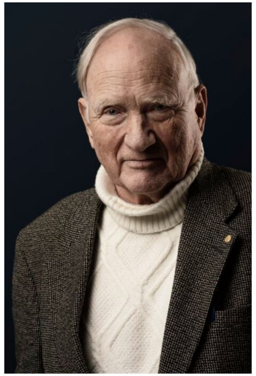
Alain Aspect

Prize share: 1/3



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John F. Clauser

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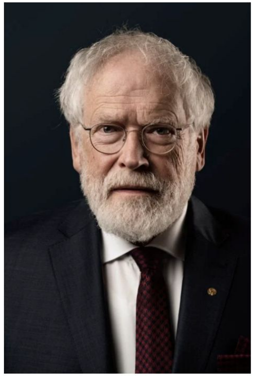

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Anton Zeilinger

Prize share: 1/3

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

$$S = E_{11} - E_{12} + E_{21} + E_{22}$$

$$S_{\text{expt}} = 2.697 \pm 0.015 .$$

$$S_{\text{QM}} = 2.70 \pm 0.05 .$$

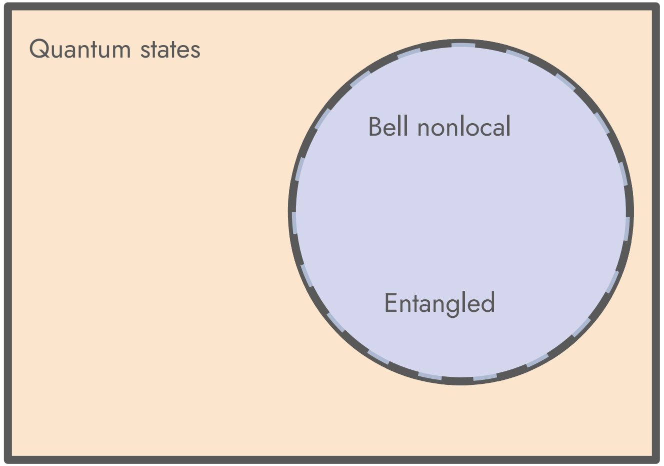
- Clear **violation** of Bell's inequality
- Excellent **agreement** with quantum mechanics prediction

Features of Quantum Mechanics

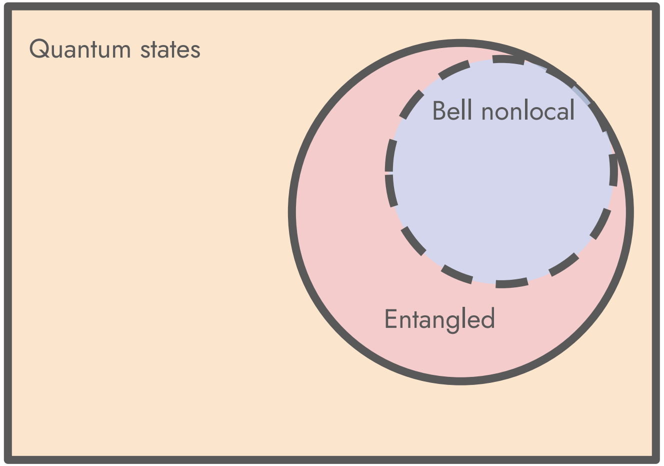
- For **pure** states, Bell's inequality and entanglement distinguish the same states
- For **mixed** states, there are more entangled states than Bell nonlocal

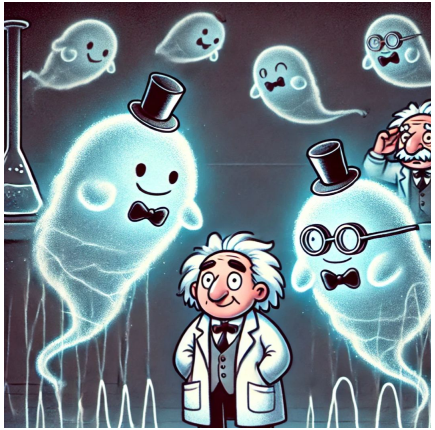
$$\rho = \sum_a p_a |\psi_a\rangle \otimes \langle\psi_a| \qquad \sum_a p_a = 1$$

pure $|\psi\rangle$

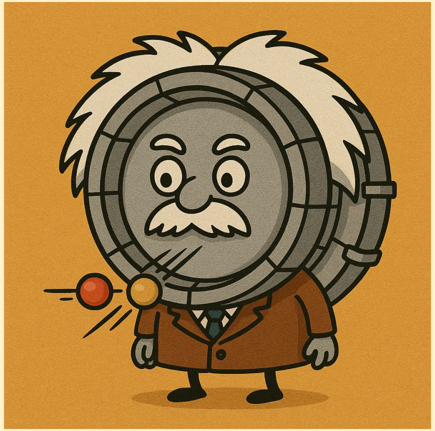


mixed ρ





Features of QM

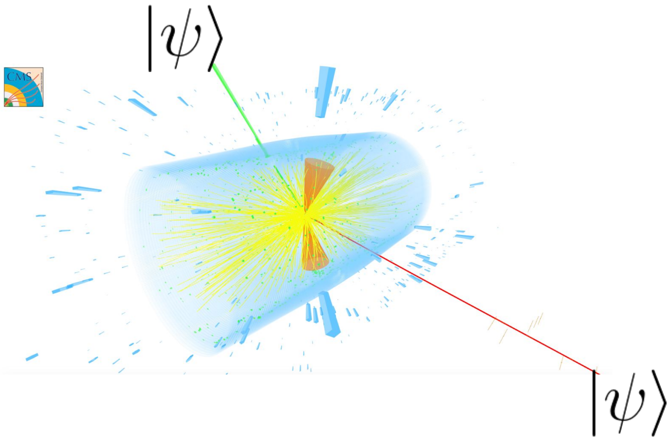


Colliders as a QM experiment

QI at Colliders

Colliders as a Quantum Mechanical System

- If a **collider** is our **source** of quantum particles, what are the qubits?
    - What are the **qubits**?
        - Color charge?
        - Electroweak charge?
        - Flavor?
        - Spin?



- Should be *conserved* and *observable*
    - **Spin**
    - Flavor

Colliders as a Quantum Mechanical System

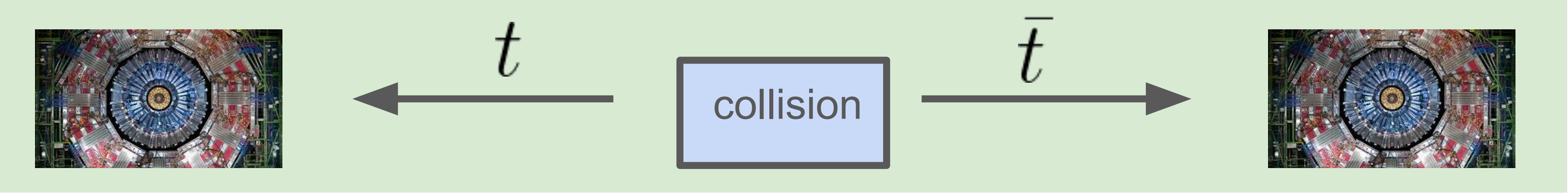
- Low-energy photon experiment

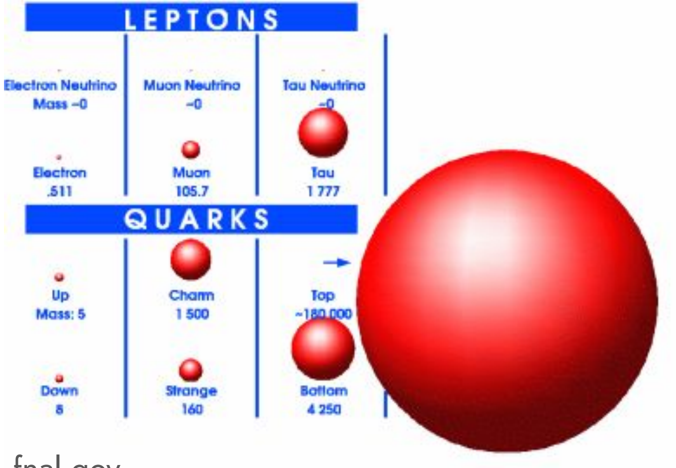
Alice $\xleftarrow{\gamma}$ source $\xrightarrow{\gamma}$ Bob

- At LHC, treat the spin of each particle as a qubit

 $\xleftarrow{t}$ collision $\xrightarrow{\bar{t}}$ 

Colliders as a Quantum Mechanical System





fnal.gov

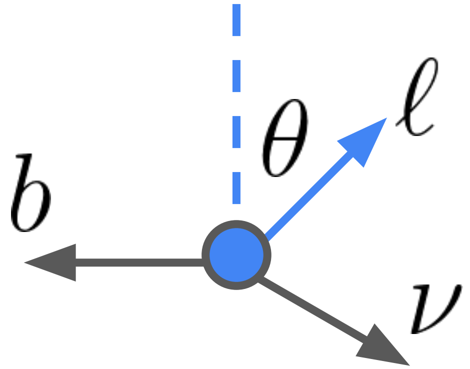
- Top quark is the heaviest fermion in the Standard Model (**172 GeV** or 1 Tungsten atom)
- Lifetime of **10^{-25} seconds** (decays before it hadronizes)
- Primarily decays to

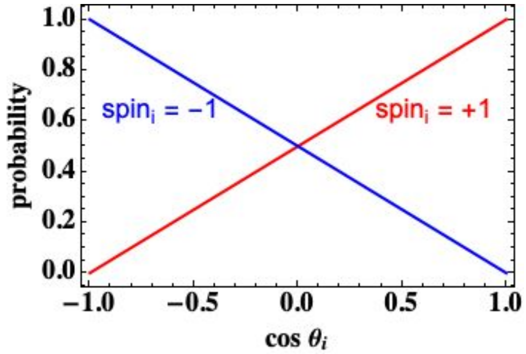
$$t \to Wb \to (qq')b$$
$$t \to Wb \to (\ell\nu)b$$

- Fully reconstructable

Colliders as a Quantum Mechanical System

- How to **measure** the **spin** of the top? $t \to \ell \nu b$





$$\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + B\kappa\cos\theta)$$

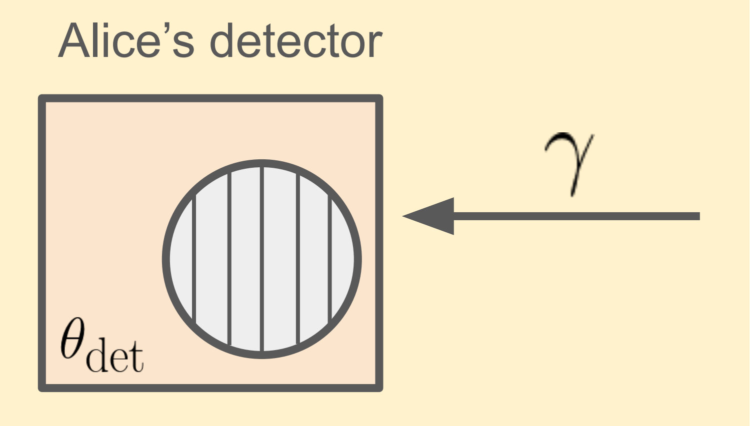
Θ = **angle** to one of the decay products

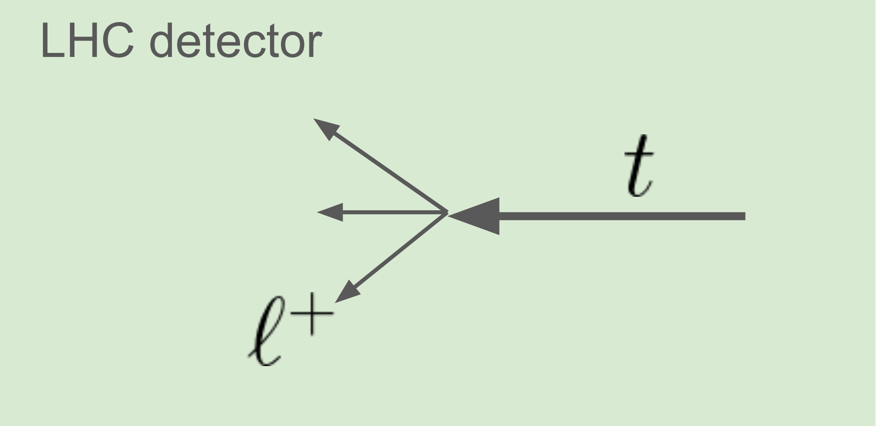
B = **polarization** of sample

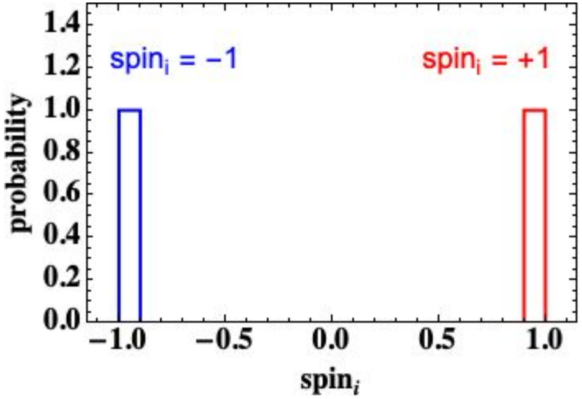
Κ = **spin analyzing power**

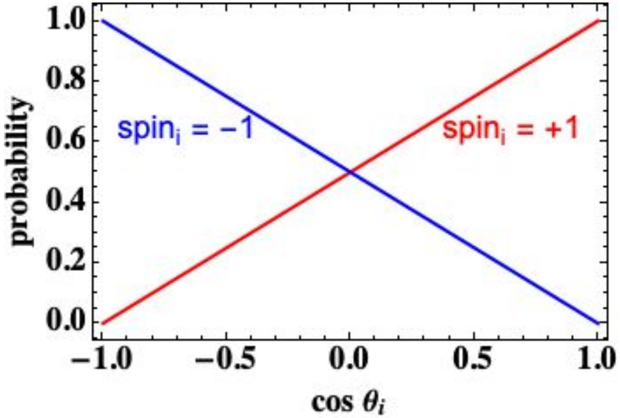
κ=-1	κ=0	κ=+1
Fully anti-correlated	Uncorrelated	Fully correlated

Colliders as a Quantum Mechanical System









Colliders as a Quantum Mechanical System

- **Top-antitop events** are measurements of a **two qubit quantum state ρ**
  - For one qubit, use **Pauli decomposition**

$$\rho = \frac{1}{2}\left(\mathbb{I}_2 + \sum_a B_a \sigma_a\right)$$

Qubit described by **3 parameters** B_a

  - For two qubits, use **Fano-Bloch decomposition**

$$\rho = \frac{1}{4}\left(\mathbb{I}_4 + \sum_i \underline{B_i^+ \sigma_i \otimes \mathbb{I}_2} + \sum_j \underline{B_j^- \mathbb{I}_2 \otimes \sigma_j} + \sum_{ij} \underline{C_{ij} \sigma_i \otimes \sigma_j}\right)$$

B_i^+ **Qubit 1 polarization** (3 parameters)

B_j^- **Qubit 2 polarization** (3 parameters)

C_{ij} **Spin correlations** (9 parameters)

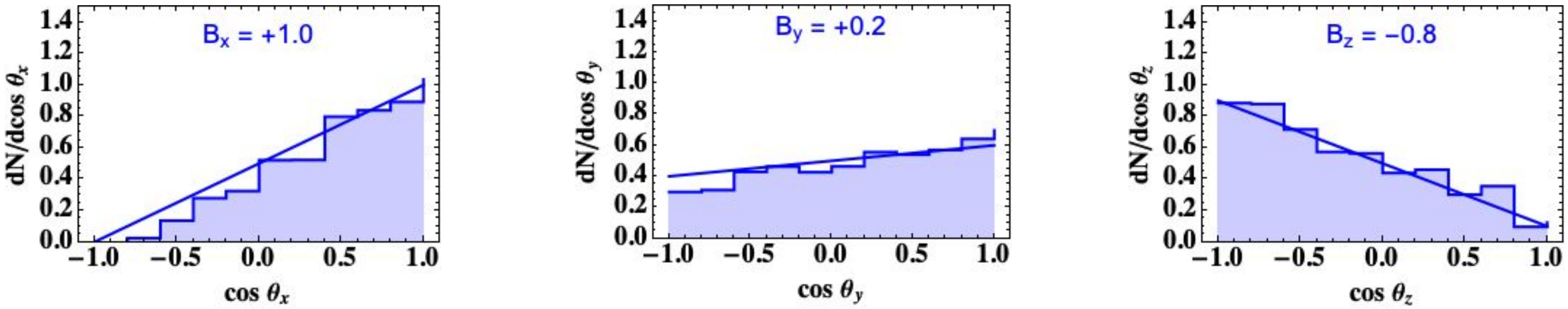
Colliders as a Quantum Mechanical System

- Can perform **quantum tomography** through angular distribution measurements

$$\rho = \frac{1}{4}\left(\mathbb{I}_4 + \sum_i B_i^+ \sigma_i \otimes \mathbb{I}_2 + \sum_j B_j^- \mathbb{I}_2 \otimes \sigma_j + \sum_{ij} C_{ij} \sigma_i \otimes \sigma_j\right)$$

B_i^+ **Qubit 1 polarization** (3 parameters)

- **Extract** density matrix parameters from data



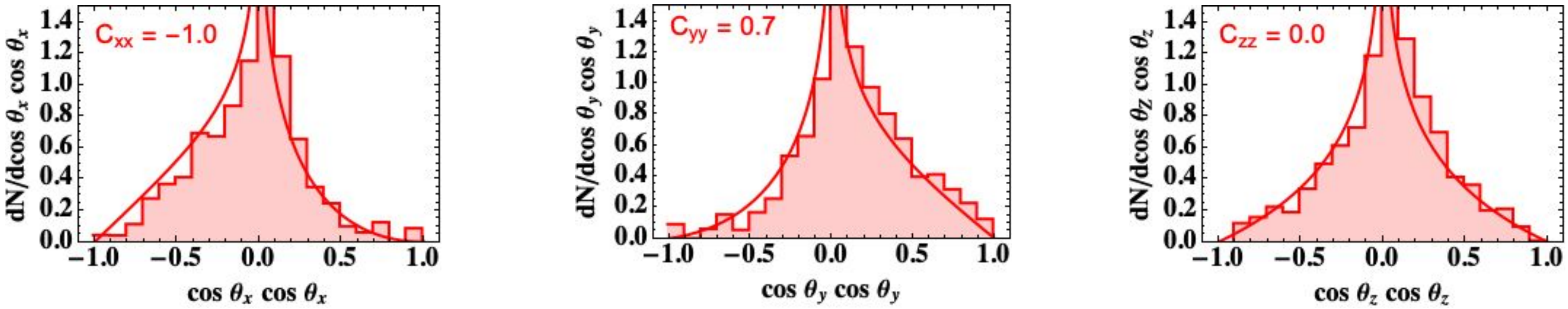
Colliders as a Quantum Mechanical System

- Can perform **quantum tomography** through angular distribution measurements

$$\rho = \frac{1}{4}\left(\mathbb{I}_4 + \sum_i B_i^+ \sigma_i \otimes \mathbb{I}_2 + \sum_j B_j^- \mathbb{I}_2 \otimes \sigma_j + \sum_{ij} C_{ij} \sigma_i \otimes \sigma_j\right)$$

C_{ij} **Spin correlations** (15 parameters)

- **Extract** density matrix parameters from data



Colliders as a Quantum Mechanical System

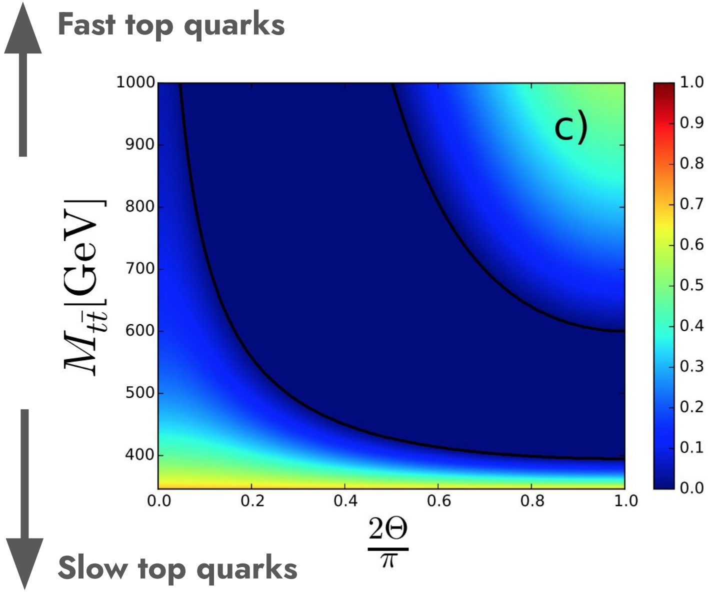
- Measure **spin correlations** and **polarizations** in given **signal region**

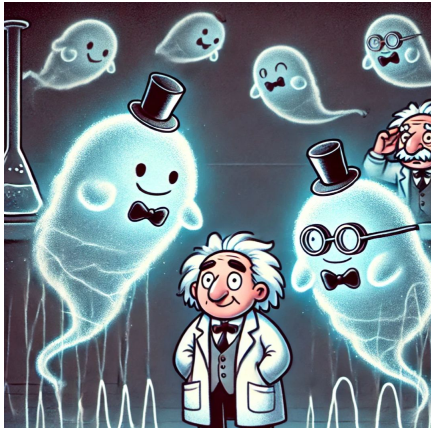
$$C_{ij} = \begin{pmatrix} 1.0 \pm 0.1 & 0.0 \pm 0.1 & 0.0 \pm 0.1 \\ 0.0 \pm 0.1 & -0.8 \pm 0.1 & 0.0 \pm 0.1 \\ 0.0 \pm 0.1 & 0.0 \pm 0.1 & -0.2 \pm 0.1 \end{pmatrix}$$

- Spin properties vary over **scattering angles** and **velocities**
  - For example:

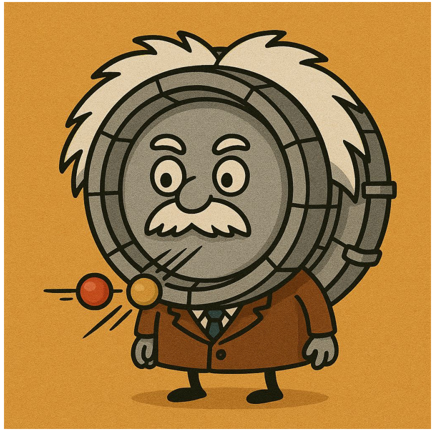
$$\frac{d\sigma}{d\Omega}(e^-_L e^+_R \to \mu^-_R \mu^+_L) = \frac{\alpha^2}{4E^2_{\rm cm}}(1-\cos\theta)^2;$$
$$\frac{d\sigma}{d\Omega}(e^-_L e^+_R \to \mu^-_L \mu^+_R) = \frac{\alpha^2}{4E^2_{\rm cm}}(1+\cos\theta)^2.$$

  - Entanglement varies over **kinematic space**





Features of QM



Colliders as a QM experiment

QI at Colliders

Quantum Information at Colliders

Afik, de Nova 2003.02280

- Given quantum density matrix ρ the **concurrence C** measures **entanglement**

$\mathcal{C} = 0$	separable
$0 < \mathcal{C} \leq 1$	entangled

- For *top-antitop* (at low velocities) this is related to the **spin correlations**

$$\mathcal{C} = -C_{11} - C_{22} - C_{33} - 1$$

- Experimentally it is preferred to do this using **1 measurement** rather than 3

$$D = -\frac{1+\mathcal{C}}{3}$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

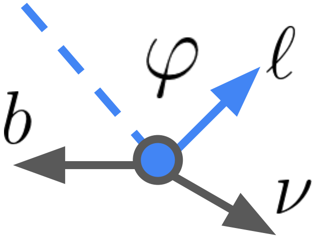
(angle between leptons)

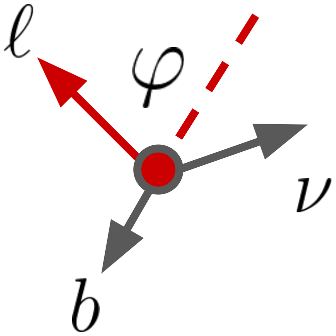
$D = -\frac{1}{3}$	separable
$-\frac{2}{3} \leq D < -\frac{1}{3}$	entangled

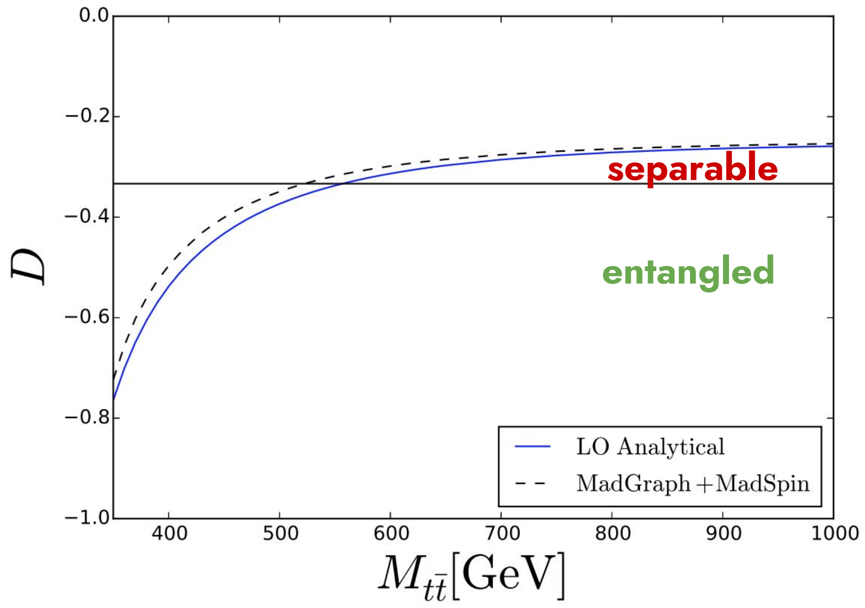
Quantum Information at Colliders

Afik, de Nova 2003.02280

- Quantity D was **already** measured! (but over the full phase space)
- Given quantum density matrix ρ the **concurrence C** measures **entanglement**







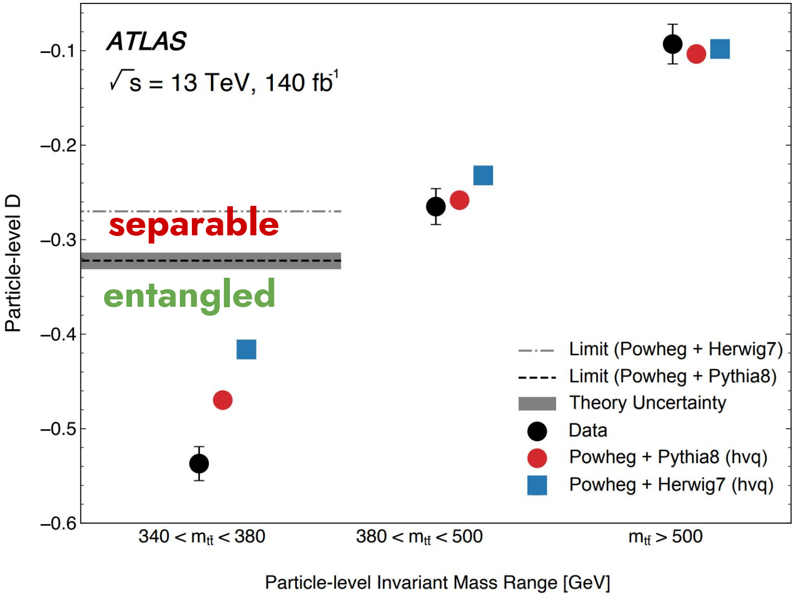
Slower top quarks

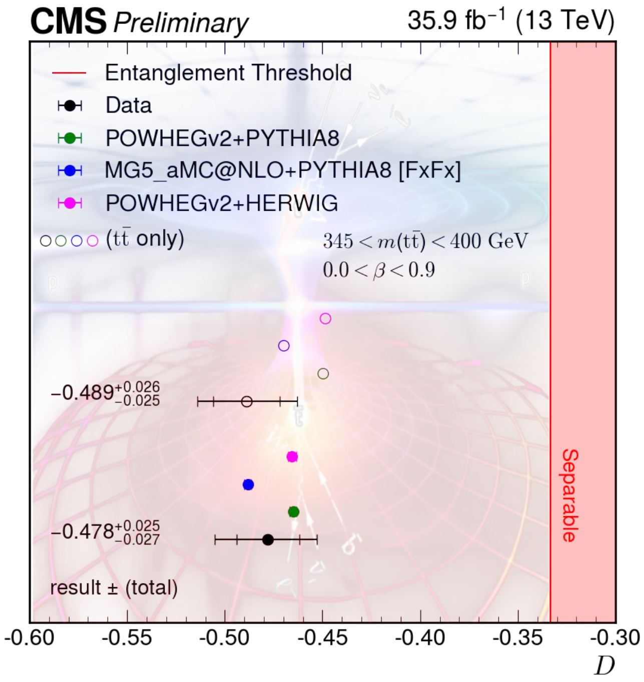
Faster top quarks

Quantum Information at Colliders

ATLAS 2311.07288
CMS 2406.03976

- **ATLAS** and **CMS** have measured entanglement *(in tt)*





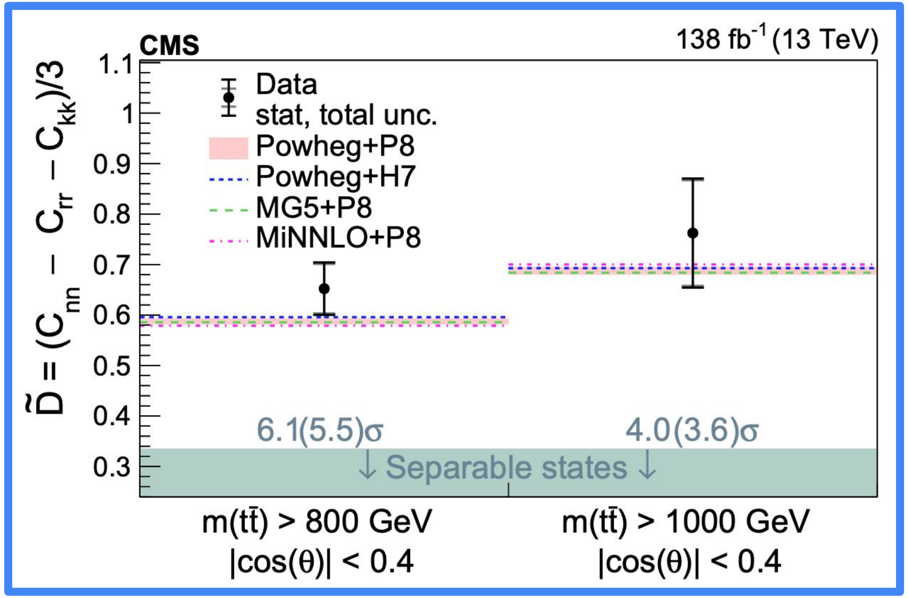
← Slower top quarks

Faster top quarks →

(Only slower top quarks)

Quantum Information at Colliders

- Other (upcoming) **entanglement** measurements:
  - $t\bar{t}$ with semi-leptonic decays   Han, ML, Wu 2310.17696
  - $H \to WW$ Aguilar-Saavedra 2209.14033
    Two qutrits
  - $H \to ZZ$ Aguilar-Saavedra 2209.13441
    Two qutrits
  - $Z \to \tau\tau$ Zhang, ML, et al. 2504.01496
  - $bb \to \Lambda_b \Lambda_b$ Afik, et al. 2406.04402



CMS 2409.11067

Quantum Information at Colliders

- **Bell nonlocality** can also be measured

Fabbrichesi, Floreanini, Panizzo 2102.11883

$$|E_{11} - E_{12} + E_{21} + E_{22}| \leq 2$$

- Each term calculable from **measured density matrix**

$$E_{11} = \underbrace{\vec{a}_1}_{} \cdot C \cdot \underbrace{\vec{b}_1}_{}$$

(9 measurements)

Detector 1 setting
Reference axis for top

Detector 2 setting
Reference axis for antitop

- **Optimal choice** of axes relates to **eigenvalues** of spin correlation matrix
- **Linear approximation** of the optimal choice is

Horodecki[3] 1995
Severi et al 2110.10112

$$\sqrt{2}|C_{ii} \pm C_{jj}| \leq 2$$

(2 measurements)

Quantum Information at Colliders

- Measuring **Bell nonlocality** using

$$\sqrt{2}|C_{ii} \pm C_{jj}| \leq 2$$

- Projections with the **current data**

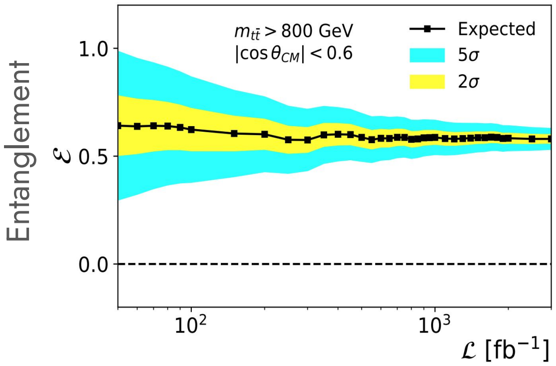
Aguilar-Saavedra, Casas 2205.00542

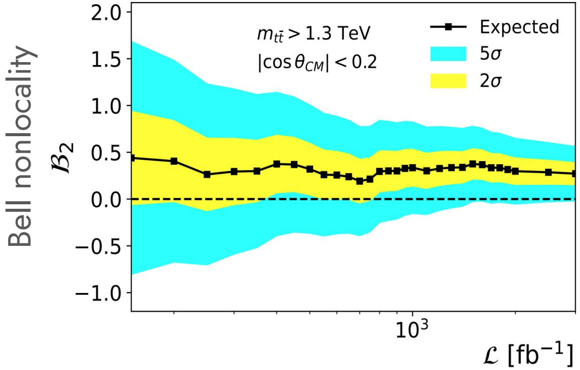
	Threshold	Boosted	
<1σ	0.027 ± 0.035	0.208 ± 0.125	**1.7σ**

- **Threshold**: Signal is too small
- **Boosted**: Cross section is too small

- Borderline even with **HL-LHC** (3000 /fb)

Dong et al. 2305.07075



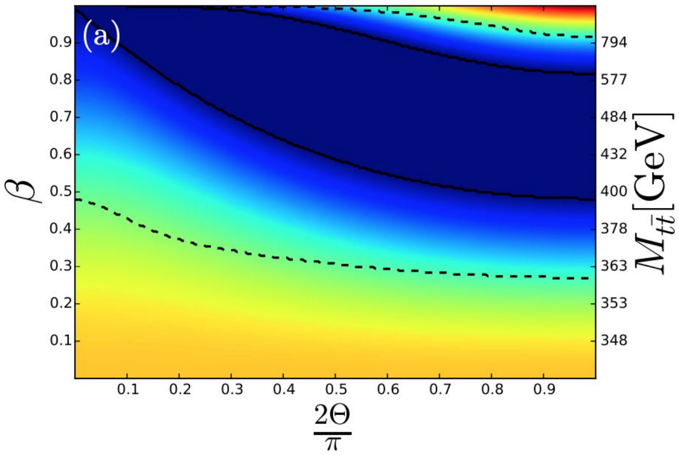


Quantum Information at Colliders

- Measuring **Bell nonlocality** is easier for ττ than for tt

$t\bar{t}$

Afik, de Nova 2203.05582

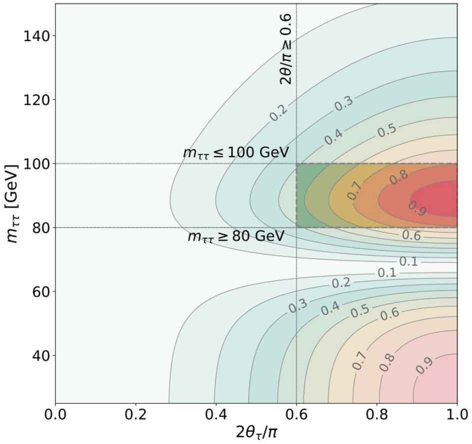


$\tau^+\tau^-$

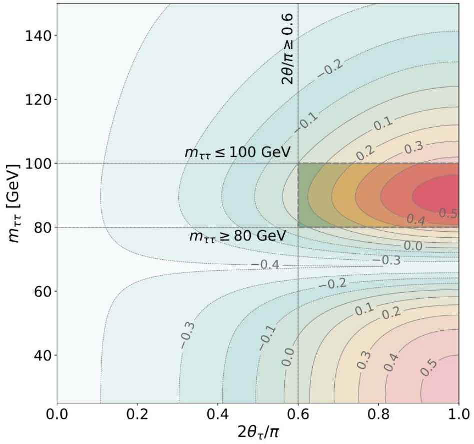
Zhang, ML, et al. 2504.01496

Fast taus

Slow taus



(a) The concurrence $\mathcal{C}$.



(b) The Bell variable $\mathcal{B}$.

Quantum Information at Colliders

Han, ML, McGinnis, Su 2412.21158

- Can measure the **entropy** of a qubit (amount of uncertainty about X)
  - In classical information theory, we use the **Shannon entropy**

$$H(X) = -\sum_{x\in X} p(x)\log_2(p(x))$$

- *Example*: X_1=0

$$H(X_1) = 0$$

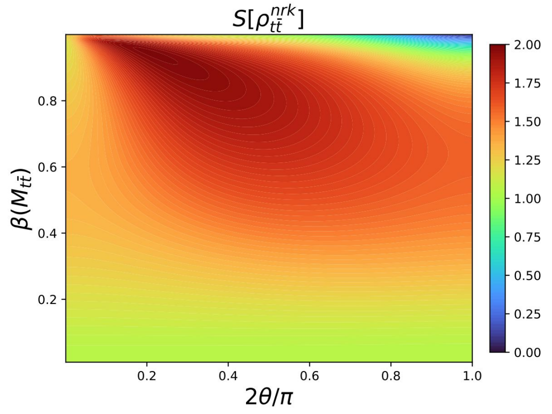
- *Example*: X_2=0 (50% of the time), 1 (50%)

$$H(X_2) = 1$$

- **Von Neumann entropy** (quantum information theory)

$$S(\rho) = -\mathrm{tr}(\rho\log_2(\rho))$$

  - S = 0 for pure states
  - S = N for maximally-mixed states



Quantum Information at Colliders

- **Classical Mutual Information**

$$I(X;Y) = H(X) - H(X|Y)$$
$$I(X;Y) = H(X) + H(Y) - H(X,Y)$$

- For two bits X and Y, mutual information is how much **information** you learn about one bit from **observing** the other bit

- *Example*: Alice flips two fair coins c_1 and c_2
  Bob flips two fair coins c_3 and c_4
  The results from Alice reveal **nothing** about Bob

$$I = 0$$

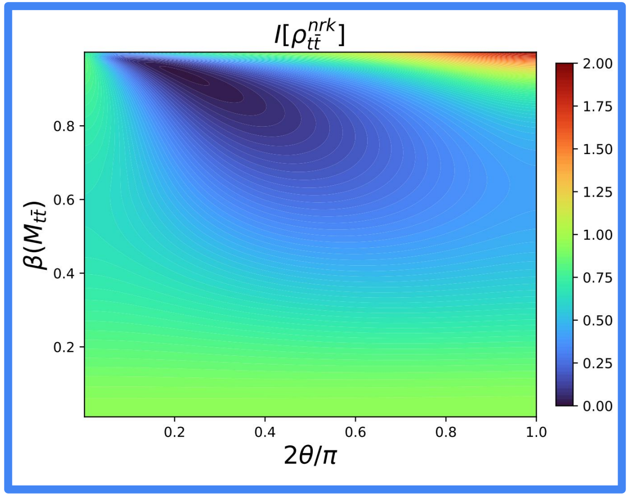
- *Example*: Alice flips two fair coins c_1 and c_2
  Bob flips two fair coins c_2 and c_3
  The results from Alice reveal **1 bit** of information about Bob

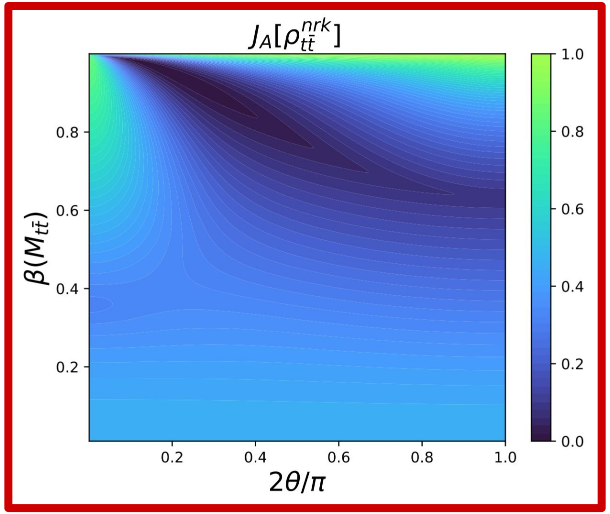
$$I = 1$$

Quantum Information at Colliders

Han, ML, McGinnis, Su 2412.21158

- Can measure **Mutual Information** between two qubits
  - The **amount of information** measuring one qubit tells you about the other
  - Quantum version generalizes to:
    - **Total mutual information** (sum of reduced entropies minus joint entropy)
    - **Classical mutual information** (difference of reduced entropy and conditional entropy)





Quantum Information at Colliders

Han, ML, McGinnis, Su 2412.21158

- Can measure **Quantum Discord** between two qubits

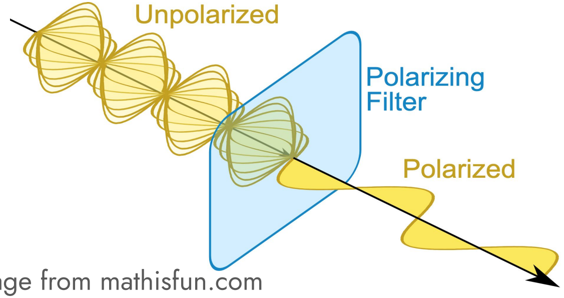
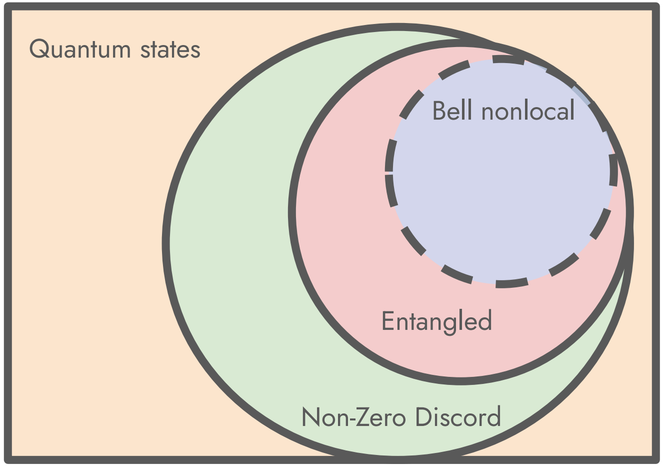
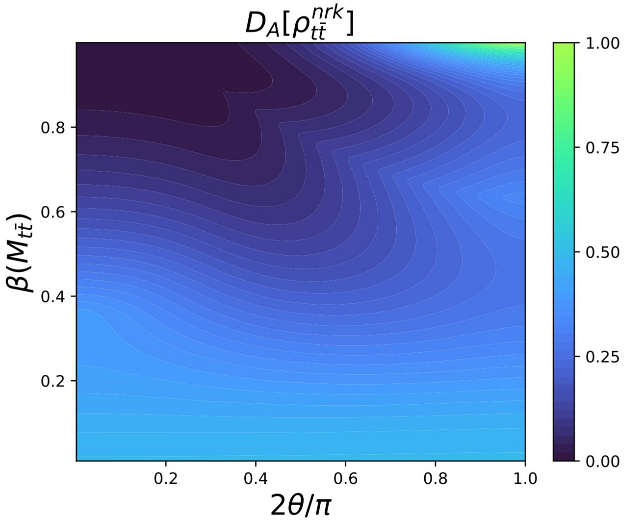


Image from mathisfun.com

- **Difference** between total and classical mutual information
- Quantifies impact of **measurements** in QM system
- Some **separable** states have quantum correlations

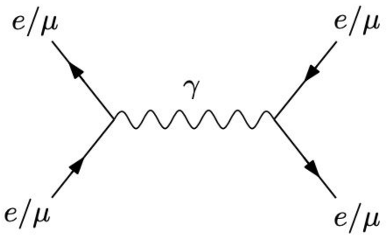


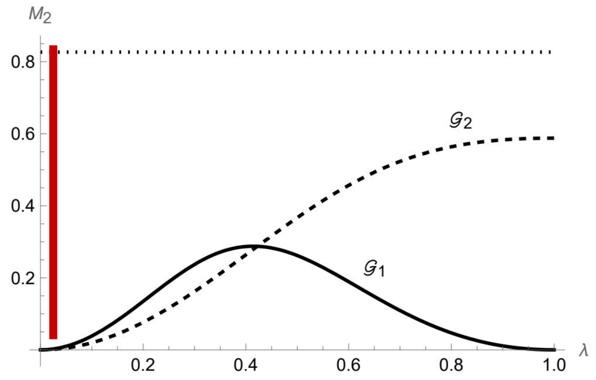


Quantum Information at Colliders

- ``**Magic**'' describes how much genuine **computational advantage** a quantum computer has over a classical computer
    - **Stabilizer states**/circuits can be efficiently simulated by a classical computer (Gottesman-Knill theorem)
    - Magic quantifies the **non-stabilizerness** of a state
    - The **scattering** of e^+e^- to $\mu^+\mu^-$ does not produce much magic

Liu, Low, Yin [2503.03098]



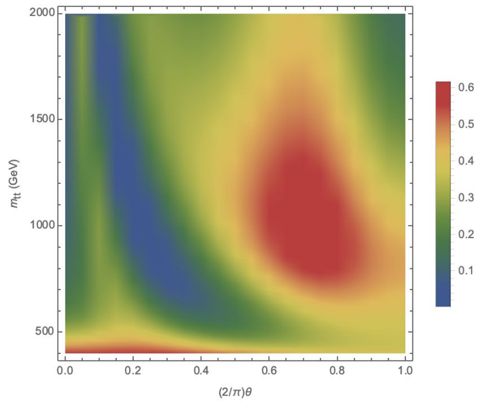


Quantum Information at Colliders

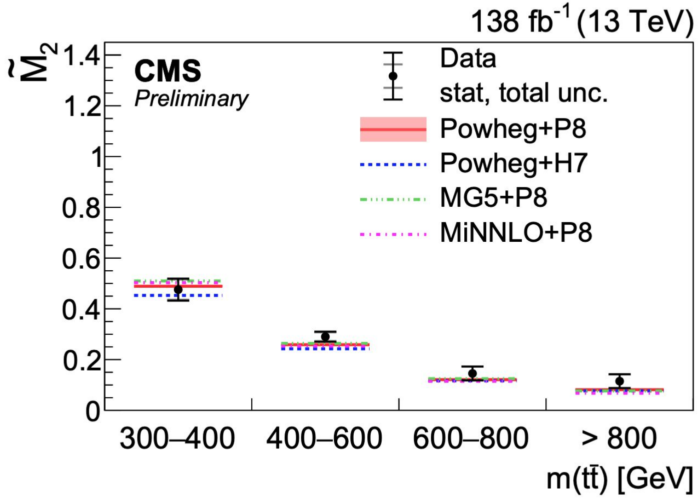
White, White 2406.07321
CMS TOP-25-001

- ``**Magic**'' describes how much genuine **computational advantage** a quantum computer has over a classical computer
    - The **top-antitop** state has measurable magic
    - Measurements have been made by **CMS**

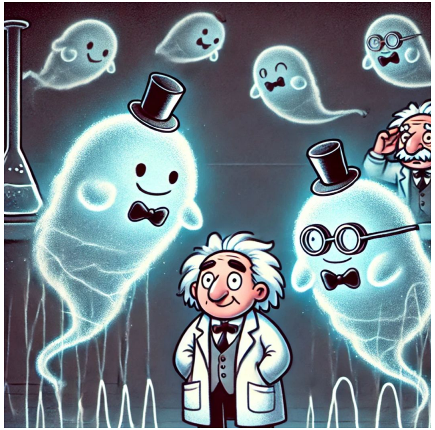
Fast top quarks



Slow top quarks

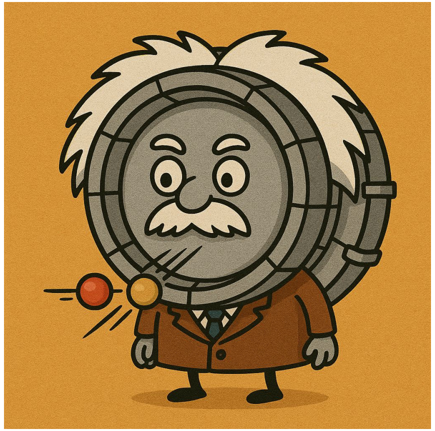


Summary



Features of QM

QM produces stronger correlations between particles than what is classically allowed



Colliders as a QM experiment

Spins of high-energy particles are used as a QM experiment by using decays to measure spins

QI at Colliders

Can measure entanglement, Bell nonlocality, quantum discord, magic, ...