

Quantum Tops: Quantum Information Meets High-Energy Physics

International Workshop on New Opportunities for Particle Physics 2026,
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

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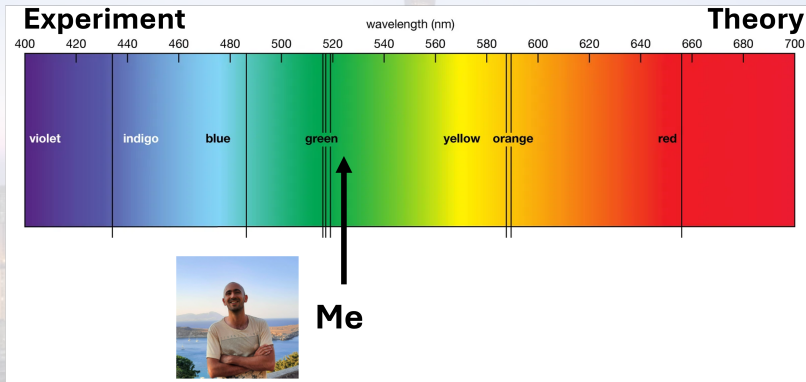
14.08.2026



Institute of High Energy Physics
Chinese Academy of Sciences

Disclaimer

I am not a theorist, but an experimentalist working as part of the ATLAS experiment at the LHC. However, on the spectrum between theory and experiment, I am relatively close to theory.



I am working closely with theorists, and typically **my experimental measurements are based on my theory papers.**

Overview

- There are three main parts to the story of Quantum Information (QI) and High-Energy Physics (HEP):
 - Theory: basic concepts. **See talk by Juan Ramón Muñoz de Nova.**
 - Phenomenology: implementation for top-quark pairs in hadron colliders. **This talk.**
 - Experiment: measurements. **This talk, and the talk by Didar Dobur.**



- This talk is based mostly (but not only) on:
 - YA, de Nova, EPJP (2021) (**Frontiers of Science Award 2026**).
 - YA, de Nova, Quantum (2022).
 - YA, de Nova, PRL (2023).

Overview

- 1 First part: Quantum Information in $t\bar{t}$
Basic Principles & Phenomenology.
- 2 Second part: Experiment
ATLAS & CMS $t\bar{t}$ entanglement results.
- 3 Third part: Future Outlook
Run 3 and Beyond.
- 4 Summary

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A Quantum Story...

Back in 2019, Juan and I were friends and office neighbors, working on completely different topics. One day, during a coffee break, we started discussing a rather ambitious question. Somehow, this is where it all started...



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**Hey, bro, do you think that
it's possible to measure
entanglement at the LHC?**



Juan

Hmmm... Good question!



Yoav

Our picture from back then



Our picture from back then



Our picture from back then



Well... approximately.

Top Quark

- **Top-quark:**

- The most massive particle in the SM.
- Lifetime: $\approx 5 \cdot 10^{-25}$ s.

- **General:**

- Hadronisation: $\approx 3 \cdot 10^{-24}$ s.
- Spin-decorrelation: $\approx 2 \cdot 10^{-21}$ s.
- Spin information $\rightarrow$ decay products.
- Spin-correlations between top-quark pairs can be measured.
- Considering di-leptonic decays.

**** A pair of $t\bar{t}$ is a two-qubit system. Their polarizations and spin-correlations can be measured.**

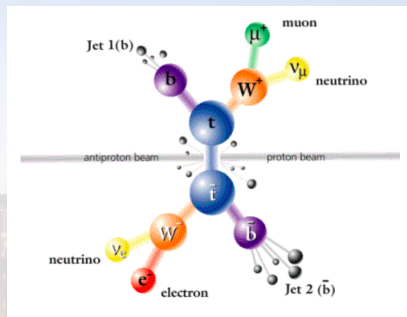
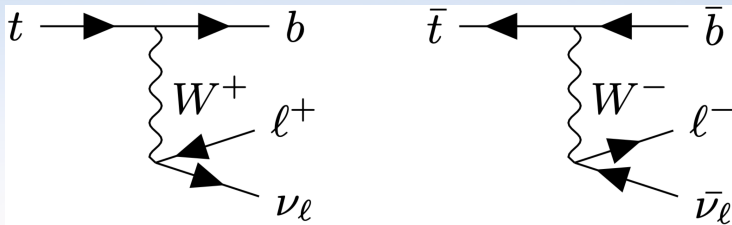


Figure: Di-leptonic decay of a $t\bar{t}$ pair.

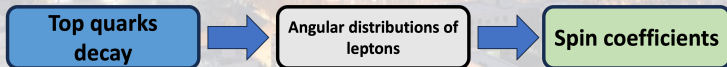
Quantum Tomography of the Spin Coefficients



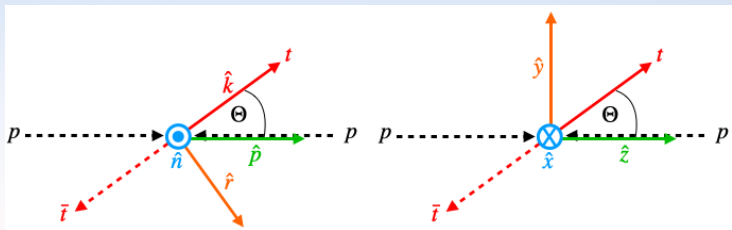
- Using the angular distributions of the decay products, the quantum tomography can be performed by measuring the spin coefficients.

$$\frac{1}{\sigma_{\ell^+\ell^-}} \frac{d\sigma_{\ell^+\ell^-}}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\ell}_+ - \mathbf{B}^- \cdot \hat{\ell}_- - \hat{\ell}_+ \cdot \mathbf{C} \cdot \hat{\ell}_-}{(4\pi)^2}$$

$$B_i^\pm = -3 \langle \cos \theta_i^\pm \rangle, \quad C_{ij} = -9 \langle \cos \theta_i^+ \cos \theta_j^- \rangle.$$



Basis Selection



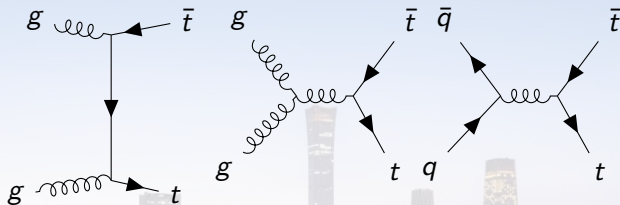
- Helicity basis: $\{\hat{k}, \hat{n}, \hat{r}\}$:

- $\hat{p}$: the proton-beam axis.
- $\hat{k}$: the direction of the top quark in the $t\bar{t}$ COM frame.
- $\hat{r} = (\hat{p} - \cos \Theta \hat{k}) / \sin \Theta$.
- $\hat{n} = \hat{r} \times \hat{k}$.
- $\cos \Theta = \hat{k} \cdot \hat{p}$.
- Describe each individual process with a **fixed direction**.

- Beam basis: $\{\hat{x}, \hat{y}, \hat{z}\}$:

- $\hat{z}$ along the beam axis.
- $\hat{x}, \hat{y}$ transverse directions to the beam.
- After averaging: $C_x = C_y = C_{\perp}$.
- Studying the **total quantum state**.

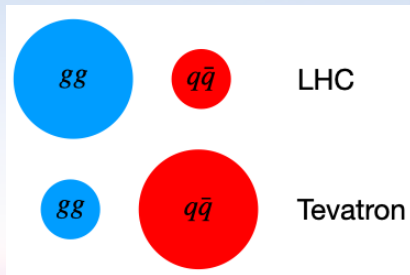
Leading-order Analytical Calculation



- Analytical calculation at leading-order. The system is defined by:
 - $\hat{k}$: the direction of the top with respect to the beam axis.
 - The invariant mass $M_{t\bar{t}}$, $\beta = \sqrt{1 - \frac{4 \cdot m_t^2}{M_{t\bar{t}}^2}}$.
- Each one $I = q\bar{q}, gg$ gives rise to $\rho^I(M_{t\bar{t}}, \hat{k})$ with probability $w_I(M_{t\bar{t}}, \hat{k})$, which is PDF dependent.
- The spin density matrix: $\rho(M_{t\bar{t}}, \hat{k}) = \sum_{I=q\bar{q}, gg} w_I(M_{t\bar{t}}, \hat{k}) \rho^I(M_{t\bar{t}}, \hat{k})$.
- The total quantum state:

$$\rho(M_{t\bar{t}}) \equiv \int_{2m_t}^{M_{t\bar{t}}} dM \int d\Omega \rho(M, \hat{k}) \rho(M, \hat{k}) = \int_{2m_t}^{M_{t\bar{t}}} dM \rho(M) \rho_\Omega(M)$$

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Collisions at the LHC



- At the LHC, protons are being collided at high energies.
- The proton is a complex creature!
- Proton: quarks and gluons (partons).
- Parton distribution function (PDF): the density of each parton in the proton.

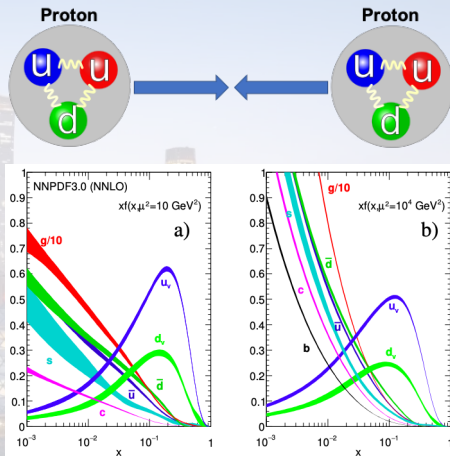
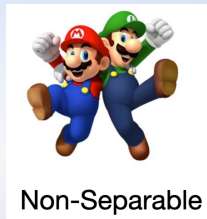


Figure: Parton density at the proton.
Figure is from [JHEP 2015, 40 \(2015\)](#).

Experimental Observables

Quantum Entanglement:

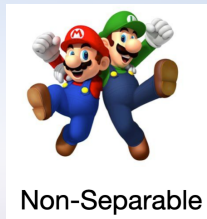
- **Concurrence** $\mathcal{C}[\rho]$: quantitative measurement of entanglement.
- $0 \leq \mathcal{C}[\rho] \leq 1$, $\mathcal{C}[\rho] \neq 0$ iff the state is entangled.
- Here, $\mathcal{C}[\rho] = \max(\Delta, 0)$; $\Delta = \frac{-C_{nn} + |C_{kk} + C_{rr}| - 1}{2}$.



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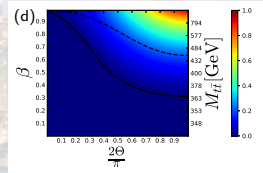
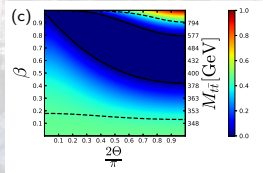
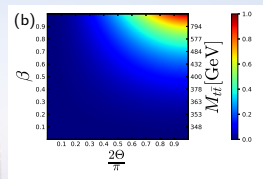
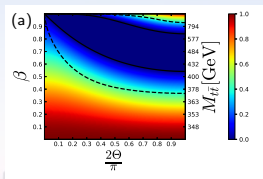
Bell Non-locality:

- A violation of the CHSH inequality:
 $|\mathbf{a}_1^T \mathbf{C} (\mathbf{b}_1 - \mathbf{b}_2) + \mathbf{a}_2^T \mathbf{C} (\mathbf{b}_1 + \mathbf{b}_2)| > 2$.
 - $\mathbf{C}$ - spin correlation matrix.
 - $\mathbf{a}_1, \mathbf{a}_2$ ($\mathbf{b}_1, \mathbf{b}_2$) - axes in which we measure the spin of the top (antitop).
- Maximization: $2\sqrt{\mu_1 + \mu_2} \leq 2\sqrt{2}$ where $0 \leq \mu_i \leq 1$ are the eigenvalues of $\mathbf{C}^T \mathbf{C}$.



Entanglement and Bell Correlation Before Integration

- a) $gg \rightarrow t\bar{t}$ Concurrence.
- b) $q\bar{q} \rightarrow t\bar{t}$ Concurrence.
- c) Full LHC $\rho(M_{t\bar{t}}, \hat{k})$ Concurrence.
- d) Full Tevatron $\rho(M_{t\bar{t}}, \hat{k})$ Concurrence.



- Solid line: entanglement limit; Dashed line: Bell correlation limit.
- Figures are from [YA, de Nova, Quantum \(2022\)](#).
- We have identified two regions of strong quantum correlations:
 - Close to the production threshold of $\sim 2 \cdot m_t$.
 - At high $M_{t\bar{t}}$ and high top- p_T .

Entanglement Observable

- Plots are shown with integration only for $[2m_t, M_{t\bar{t}}]$.
- Single observable:
$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D \cos\varphi),$$
$$D = \frac{\text{tr}[\mathbf{C}]}{3} = -3 \cdot \langle \cos\varphi \rangle,$$
 φ is the angle between the leptons measured in the parent top/antitop rest frame, and $\mathbf{C}$ is the spin correlation matrix.
- $D < -\frac{1}{3} \Rightarrow$ entanglement.
- Can be achieved by measuring D close to threshold at the LHC.
- Theory framework:
 - YA, de Nova, EPJP (2021) (**Frontiers of Science Award 2026**).
 - Severi et al., EPJC (2022).
 - YA, de Nova, Quantum (2022).

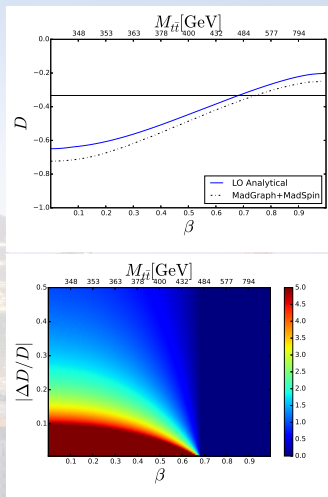


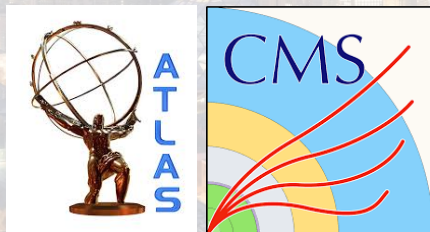
Figure: Up: the value of D ;
bottom: statistical deviation from
the null hypothesis ($D = -1/3$).

Outline

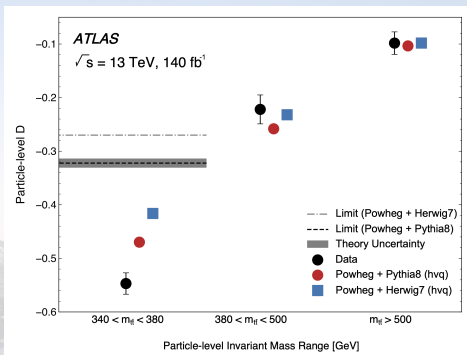
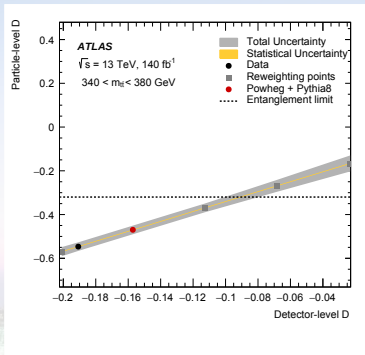
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Related Measurements

- Entanglement in $t\bar{t}$ pairs close to the production threshold:
 - ATLAS: [ATLAS, Nature \(2024\)](#).
 - CMS: [CMS, Rept. Prog. Phys. \(2024\)](#).
- Entanglement in $t\bar{t}$ pairs with boosted tops:
 - CMS: [PRD \(2024\)](#).
 - CMS: [PRD \(2026\)](#).
- Hierarchy of quantum correlations:
 - YA, Demina, Herrera, Hindrichs, de Nova, Ravina: [PRD \(2026\)](#).
- I'll discuss these results briefly. See also the talk by Didar Dobur.
- Many more are currently at work.

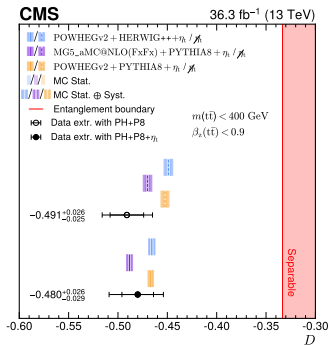
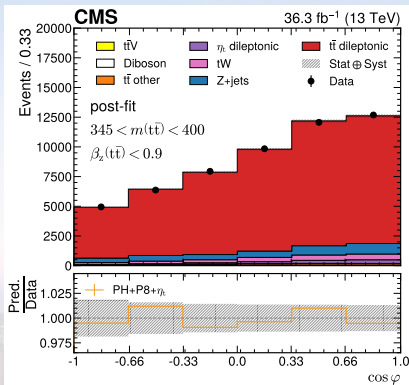


Threshold Region - ATLAS, Nature (2024)



- No clear preference of a specific MC prediction.
- The limit of $D = -1/3$ is folded from parton to particle level.
- **Entanglement is observed (expected) with well more than 5σ .**
Observed: $D = -0.537 \pm 0.002 \text{ [stat.]} \pm 0.019 \text{ [syst.]}$
Expected: $D = -0.470 \pm 0.002 \text{ [stat.]} \pm 0.017 \text{ [syst.]}$

Threshold Region - CMS, Rept. Prog. Phys. (2024)

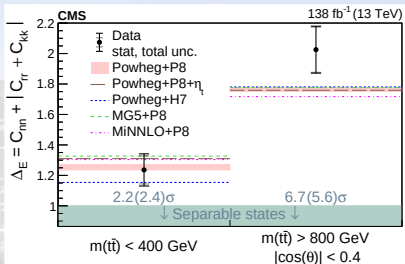
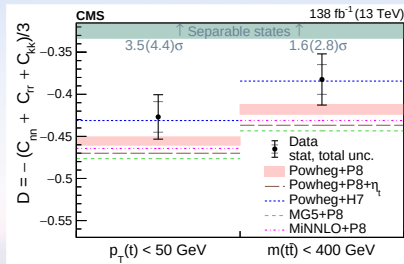


- Data seem to prefer Toponium.
- The limit of $D = -1/3$ is shown at parton-level.
- **Entanglement is observed (expected) with 5.1σ (4.7σ).**

Observed: $D = -0.480^{+0.016}_{-0.017}$ [stat.] $^{+0.020}_{-0.023}$ [syst.]

Expected: $D = -0.467^{+0.016}_{-0.017}$ [stat.] $^{+0.021}_{-0.024}$ [syst.]

Boosted Region - CMS, PRD (2024)



- Different final state: $t\bar{t} \rightarrow \ell^\pm + jets$.
- The limits of separability are shown at parton-level.
- **Entanglement is observed (expected) with 6.7 σ (5.6 σ).**
Observed: $\Delta_E = -2.03 \pm 0.15$.
- Sensitivity at the threshold region is lower.

QI Hierarchy - YA et al., PRD (2026)

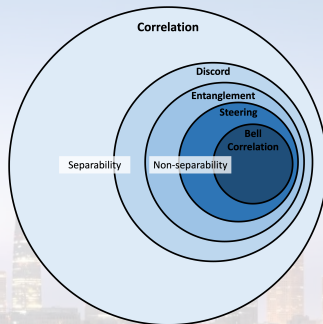
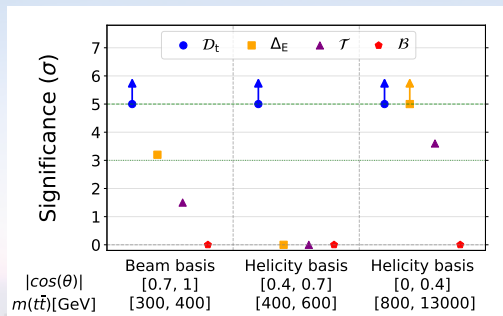


Figure: Significance in units of σ of the discord ($\mathcal{D}_t$), entanglement (Δ_E), steering ($\mathcal{T}$) and Bell correlation ($\mathcal{B}$) markers exceeding the threshold values.

- "Experimental characterization of the hierarchy of quantum correlations in top quark pairs" - YA, Demina, Herrera, Hindrichs, de Nova, Ravina, [PRD \(2026\)](#).
- We have used the recent CMS measurements ([PRD \(2024\)](#), [PRD \(2026\)](#)) to quantify the components of the QI Hierarchy in $t\bar{t}$.

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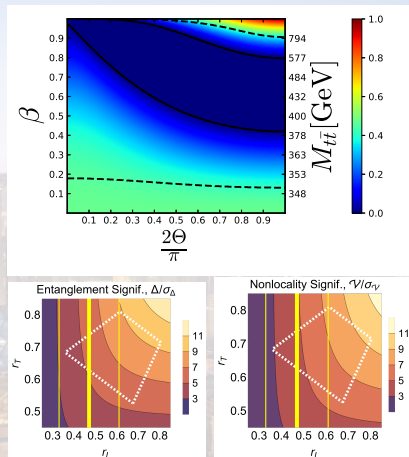
What should we measure next?

What is next? I will give a few prime examples.

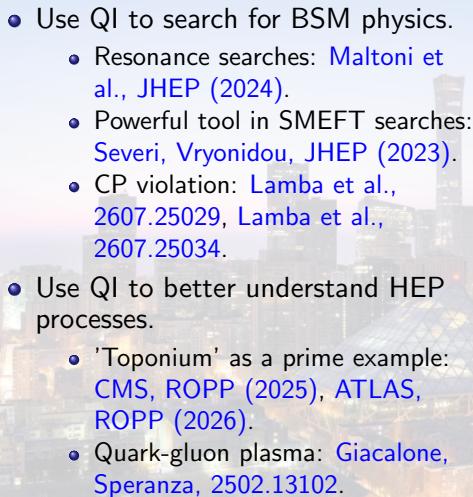


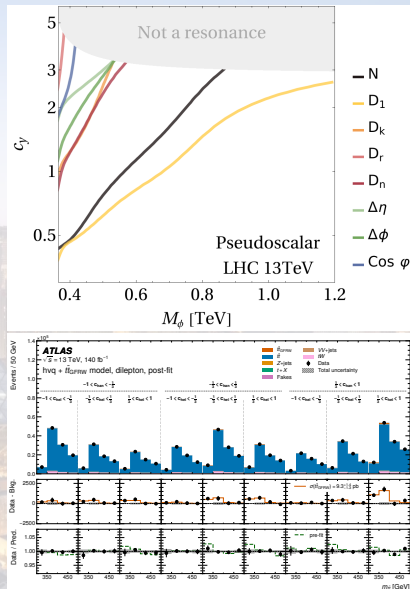
What should we measure next?

- Probe more QI concepts with $t\bar{t}$.
 - Evidence for Bell Correlation is expected with Run 3 data.
 - Discord and steering are measurable at the LHC.
 - Magic: the quantum resource that allows quantum computers beat classical ones.
- Probe QI with other systems.
 - $h \rightarrow ZZ^*$: [ATLAS, 2603.26463](#), [CMS-PAS-HIG-25-011](#).
 - $h \rightarrow WW^*$: [Barr, PLB \(2022\)](#).
 - $\tau^+\tau^-$ pairs: [Zhang et al., JHEP \(2026\)](#).
 - $pp \rightarrow b\bar{b}$: [YA et al., PRD \(2025\)](#).



What should we measure next?

- 
- Use QI to search for BSM physics.
 - Resonance searches: [Maltoni et al., JHEP \(2024\)](#).
 - Powerful tool in SMEFT searches: [Severi, Vryonidou, JHEP \(2023\)](#).
 - CP violation: [Lamba et al., 2607.25029](#), [Lamba et al., 2607.25034](#).
 - Use QI to better understand HEP processes.
 - 'Toponium' as a prime example: [CMS, ROPP \(2025\)](#), [ATLAS, ROPP \(2026\)](#).
 - Quark-gluon plasma: [Giacalone, Speranza, 2502.13102](#).



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Summary

- **Entanglement in top-quark pairs is observed with more than five standard deviations!**

Summary

- **Entanglement in top-quark pairs is observed with more than five standard deviations!**
- It constitutes as a proof of concept that QI measurements can be done in high-energy colliders.
- This is an exciting way to analyze collider data, and opens many new possibilities.
- This line of research is rapidly evolving, with many new ideas and dedicated workshops:
 - Oxford (March 2023): [link](#), Oxford (October 2024): [link](#).
 - GGI (November 2023): [link](#), GGI (April 2025): [link](#).
 - Pittsburgh (March 2024): [link](#).
 - Shanghai (July 2025): [link](#).
 - CERN (April 2026): [link](#).
- It all started during a coffee break at the Technion...

Consolidating as a Community

- Input to the update of the European Strategy for Particle Physics: [YA et al., EPJP \(2025\)](#).
- 71 authors:
 - Both theorists and experimentalists.
 - From HEP and QI backgrounds.

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

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New ATLAS Guidelines Document

- Provides general principles for analyses targeting QI observables: [ATL-PHYS-PUB-2026-006](#).
 - Introduces a common terminology based on the existing literature.
 - Particular attention to the interpretation, presentation, assumptions, and limitations.
 - Addresses common criticisms.



ATLAS PUB Note

ATL-PHYS-PUB-2026-006

21st May 2026



Probing Quantum Information observables with the ATLAS detector: some general principles

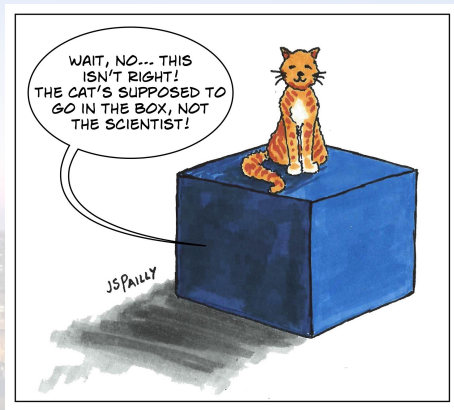
The ATLAS Collaboration

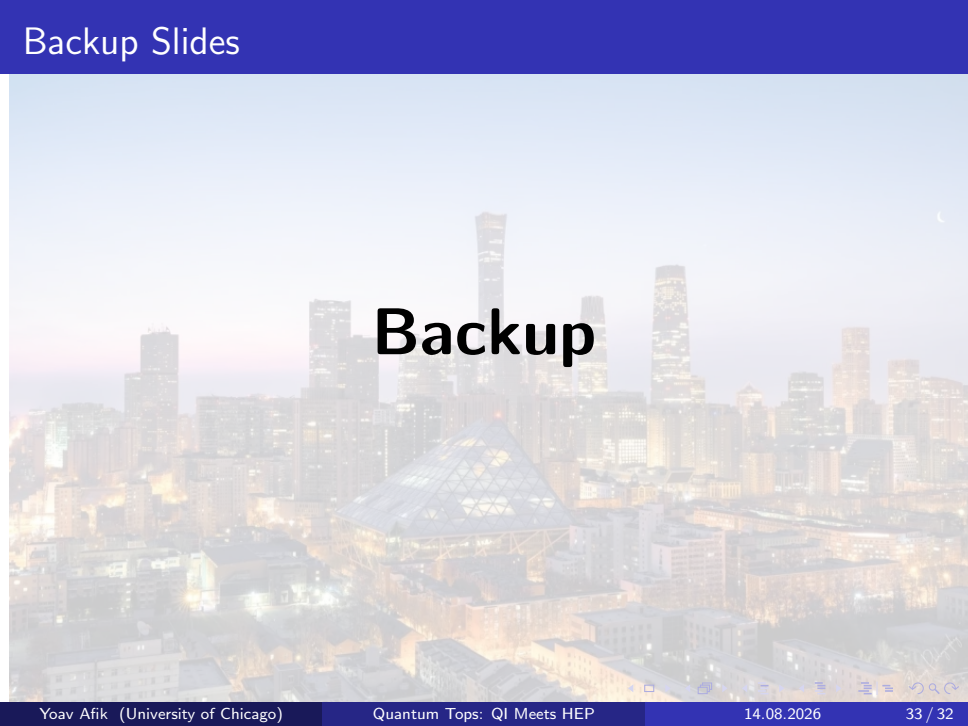
Next workshop



- Draft of a poster for the workshop of next year.
- Date to be confirmed.
- Venue - Northwestern University.
- Start of an annual event - QIHEP.
- International Advisory Committee has being established.

Thank You



An aerial night view of a city skyline, likely New York City, with numerous skyscrapers illuminated. The word "Backup" is overlaid in large, bold, black text in the center of the image.

Backup

Quantum State

- **Pure state:** can be described by wave-functions $\sum_i \alpha_i \cdot |\psi_i\rangle$.
- **Mixed state:** can be described by a density matrix: $\rho = \sum_i p_i \cdot |\psi_i\rangle \langle\psi_i|$.
 - Example: at the LHC we cannot control the internal d.o.f. of the initial state. The state is mixed and incoherent.
- **Quantum Tomography:** reconstruction of the quantum state from measurement of a set of expectation values.



Quantum Tomography: One Qubit

- Qubit: quantum system with two states (e.g., spin-1/2 particle).
- Most general density matrix for a qubit:

$$\rho = \frac{I_2 + \sum_i B_i \sigma^i \otimes I_2}{2}$$

- Only 3 parameters $B_i \rightarrow$ Quantum tomography is the measurement of spin polarization B_i :

$$B_i = \langle \sigma^i \otimes I_2 \rangle$$



Quantum Tomography: Two Qubits

- Most general density matrix for 2 qubits:

$$\rho = \frac{I_4 + \sum_i (B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j}{4}$$

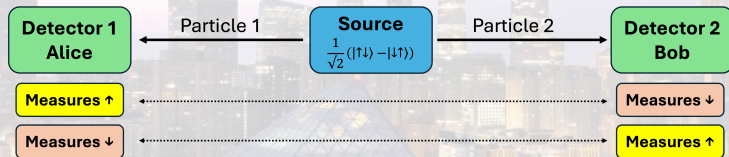
- 15 parameters $B_i^\pm, C_{ij} \rightarrow$ Quantum tomography=Measurement of individual spin polarizations $B_i^\pm$ and spin correlation matrix C_{ij} :

$$B_i^+ = \langle \sigma^i \otimes I_2 \rangle, \quad B_i^- = \langle I_2 \otimes \sigma^i \rangle, \quad C_{ij} = \langle \sigma^i \otimes \sigma^j \rangle$$



What is Quantum Entanglement?

- Quantum state of one particle cannot be described independently from another particle.
- $\Rightarrow$ **Correlations** of observed physical properties of both systems.
- $\Rightarrow$ **Measurement** performed on one subsystem seems to be influencing other subsystems entangled with it.



- Observed in photons, atoms, superconductors, mesons, analog Hawking radiation, nitrogen-vacancy centers in diamond and even macroscopic diamond. **Recently it has been observed in $t\bar{t}$ pairs.**

Quantum Entanglement Definition

- Two different systems A and B: $\mathcal{H} = \mathcal{H}_a \otimes \mathcal{H}_b$.
- Separable: $\rho = \sum_n p_n \rho_n^a \otimes \rho_n^b$.
- $\rho_n^{a,b}$ are quantum states in A, B, $\sum_n p_n = 1$, $p_n \geq 0$.
- Classically correlated state in $\mathcal{H} \rightarrow$ can be written in this form.
- Non-separable state is called **entangled** and hence, it is a non-classical state.



Separable

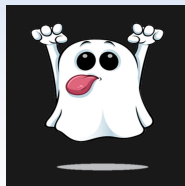


Non-Separable

- For two qubits:
 - Separability $\iff$ Classical probability distribution.
 - **Entanglement** $\iff$ No classical probability distribution description.

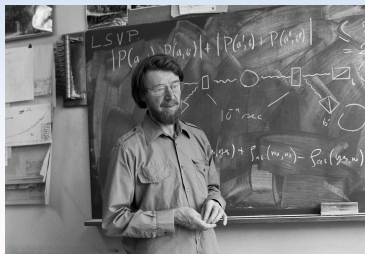
The EPR Paradox

- Entanglement: "Spooky action at a distance" (A. Einstein).



- Assuming two particles with spacial distance.
- When a measurement is done on one of the particles, the other one "knows" about it immediately.
- Information travel faster than light?
→ Contradicts the theory of relativity.
- **Conclusion:** the theory of QM is incomplete.
- By EPR, each particle "carries" variables that know the state before the measurement.
⇒ There are some hidden variables missing to have a full theory.
Such theories are called **Local Hidden Variable Theories (LHVTs)**.

Bell Inequality



- LHVTs must satisfy an inequality which QM can violate:

$$1 + C(b, c) \geq |C(a, b) - C(a, c)| ,$$

$C(x, y)$ are the **correlations between different measurements** at different detectors, a, b, c are different measurement directions.

- **This is not what was done with $t\bar{t}$, as we don't measure the spin per particle and don't change the detector setup.**
- Even if we cannot perform a Bell test, we can measure a **Bell-Correlated** state, using quantum state tomography.

The Nobel Prize in Physics 2022

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". ([link](#))



Figure: Alain Aspect, John F. Clauser and Anton Zeilinger.

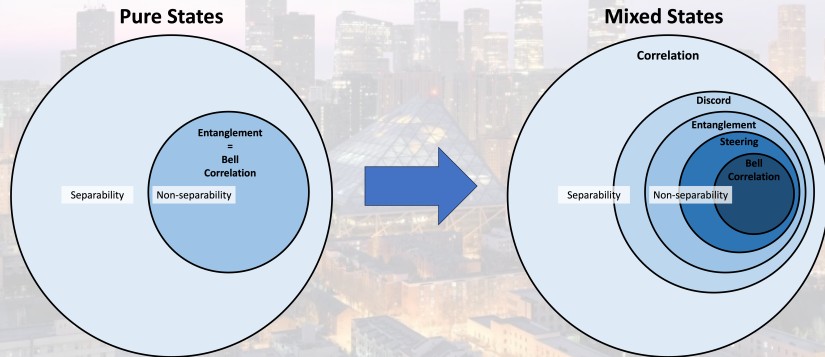
QI Hierarchy

- Both concepts coincide in pure states, but are separate in mixed states, see [Werner, PRA \(1989\)](#). In other words, for mixed states:

Bell Correlation $\neq$ Entanglement .

Therefore, **entanglement is not a probe of LHVTs.**

- In colliders, **we explore mixed states.**



QI Hierarchy - Mixed States

- Complete picture of quantum correlation hierarchy in top-quark pairs.
YA, de Nova, PRL (2023).
- Quantum Discord:
 - The most basic form of quantum correlations.
 - Asymmetric between different subsystems, natural test of CP .
- Quantum Steering:
 - Measurement of how one subsystem can be used to “steer” the other one.
 - A non-local feature that lies between entanglement and Bell correlation.

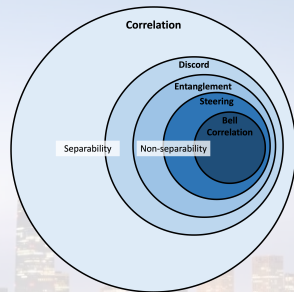


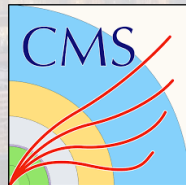
Figure: Schematic description of the relation between the different quantum correlations.

Some of these measurements are difficult to make in conventional labs, and are naturally accessible at the LHC due to the large statistics.

$\text{Bell Correlation} \subset \text{Steering} \subset \text{Entanglement} \subset \text{Discord} \subset \text{Correlation}$

Spin-Correlations between Top-Quark Pairs

- Studied extensively theoretically.
- Measured by the D0, CDF, ATLAS and CMS collaborations.
- No link between spin-correlations of top quarks and concepts of QI until recently.
- Spin-Correlations can be a classical property.
For example, **Spin-Correlations $\neq$ Quantum Entanglement!**
However, Quantum Entanglement $\subset$ Spin-Correlations.



Previous Spin Correlation Measurement

- D was measured inclusively, i.e. with no selection on $M_{t\bar{t}}$, by the CMS collaboration.
- Results:
 $D = -0.237 \pm 0.011 > -1/3$;
 $\Delta D/D = 4.6\%$.
- No evidence of quantum entanglement.
 $\Rightarrow$ **We need a dedicated analysis!**

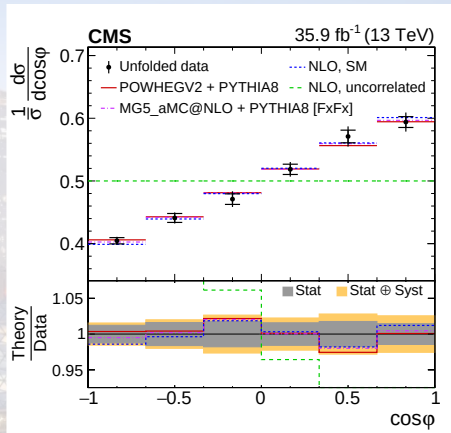
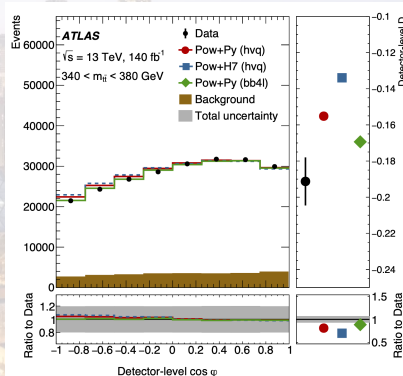
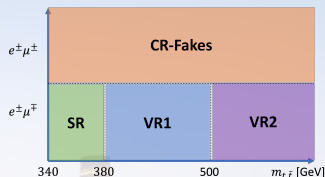


Figure: Distribution of $\cos\phi$. Figure is from [PRD \(2019\)](#).

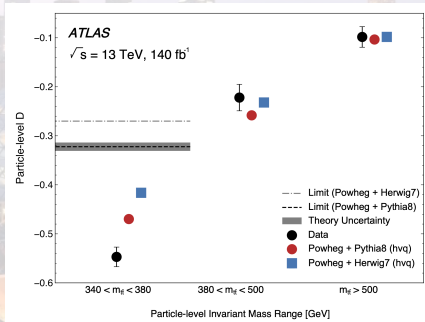
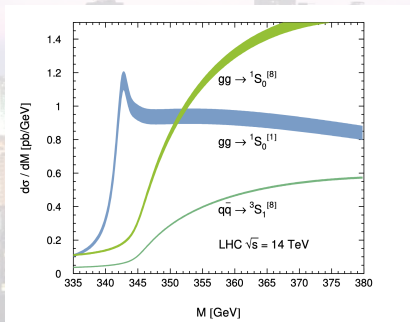
Analysis Strategy - ATLAS, Nature (2024)

- Analysis selection:
 - $1\mu, 1e$ with opposite charges.
 - Single lepton triggers.
 - Lepton $p_T > 25\text{--}28$ GeV.
 - $N_b \geq 1$ (85% b -tag efficiency).
- Backgrounds:
 - tW .
 - $t\bar{t} + X$ ($X = H, W, Z$).
 - VV ($V = W, Z$).
 - $Z \rightarrow \tau^+\tau^-$.
 - Fakes.
- Regions are categorized by $m_{t\bar{t}}$.
The $t\bar{t}$ purity is $> 90\%$ across the signal region (SR) and the validation regions (VR1, VR2).
- **Particle level fiducial regions are defined with similar selections.**



Toponium?

- Left: invariant mass distribution close to threshold including all partonic production channels. Figure is from [EPJC \(2009\)](#).
- Right: the recent ATLAS result.
- Toponium: higher cross-section next to threshold, more spin-singlet (maximally entangled). Not included in MC generators.



Top Reconstruction - ATLAS, Nature (2024)



- Three methods:
 - 85%: Ellipse Method. Calculates two ellipses for p_T^ν and finds the intersections.
 - 5%: Neutrino Weighting.
 - 10%: Rudimentary pairing.
- The solution with the smallest $m_{t\bar{t}}$ is taken.

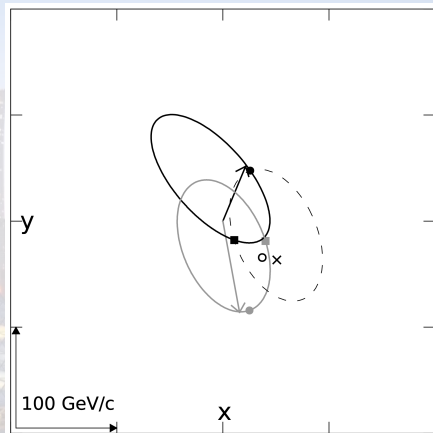
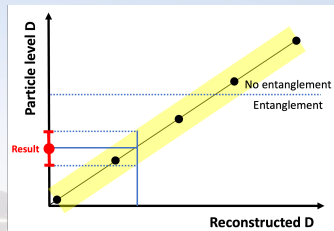


Figure: Constrain on neutrino momenta.
Figure is from [NIMA \(2014\)](#).

Calibrating the Observable - ATLAS, Nature (2024)

- Measure the particle level value of D using a calibration curve.
- The curve is built from alternative sets of **reconstructed** D and **particle level** D , with variations of the parton level D value: -60%, -40%, -20%, SM, +20%
- A first order polynomial is used to interpolate between the points.
- The data are corrected to the particle level value of D .
- One curve for each systematic. The difference w.r.t. the nominal curve is the uncertainty.



Systematic Uncertainties

- Three categories:
 - Signal ($t\bar{t}$) modeling.
 - Background modeling.
 - Detector uncertainties.

Systematic source	$\Delta D_{\text{expected}} (D = -0.470)$	ΔD (%)
Signal Modelling	0.015	3.2
Electron	0.002	0.4
Muon	0.001	0.1
Jets	0.004	0.8
b -tagging	0.002	0.4
Pileup	< 0.001	< 0.1
E_T^{miss}	0.002	0.4
Backgrounds	0.005	1.1
Stat.	0.002	0.4
Syst.	0.017	3.6
Total	0.017	3.6

Table: Systematic uncertainties for the **expected** D .

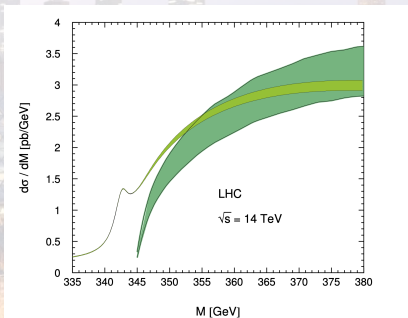
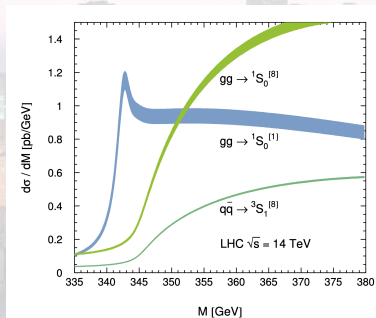
- Signal ($t\bar{t}$) modeling breakdown:
 - Top decay (MADSPIN): 1.6%
 - PDF (PDF4LHC): 1.2%
 - Recoil To Top: 1.1%
 - FSR: 1.1%
 - Scales (μ_R, μ_F): 1.1%
 - NNLO Reweighting: 1.1%
 - pThard (pThard = 1): 0.8%
 - m_t (172.5 ± 0.5 GeV): 0.7%
 - ISR: 0.2%
 - Parton Shower (HERWIG): 0.2%
 - h_{damp} : 0.1%
- Background modeling is dominated by $Z \rightarrow \tau^+ \tau^-$ uncertainty.
- For each systematic, we extract a curve. The difference w.r.t. the nominal curve is the uncertainty.

Systematic Uncertainties

Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.537)$	ΔD [%]	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.2	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b -tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
E_T^{miss}	0.002	0.4	0.002	0.4
Backgrounds	0.005	0.9	0.005	1.1
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.019	3.5	0.017	3.6
Total uncertainty	0.019	3.5	0.017	3.6

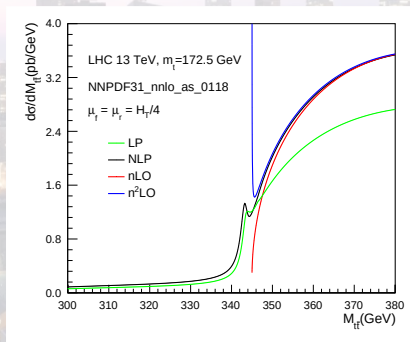
Differential Cross-Section - $m_{t\bar{t}}$ Dependence

- Left: Invariant mass distribution close to threshold including all partonic production channels.
- Right: Comparison of threshold re-summed results with fixed order QCD predictions.
- Figures are from [EPJC \(2009\)](#).



Differential Cross-Section - $m_{t\bar{t}}$ Dependence

- The comparison between the NLP resummed result and the LP resummed, nLO and nnLO ones.
 - NLP: next-to-leading power.
 - LP: leading power.
 - nLO: next-to-leading order.
 - nnLO: next-to-next-to-leading order.
- Figure is from [JHEP 06 \(2020\) 158](#).



Critical Values After Integration

- We focus on pp interactions.
- Clear motivation to restrict to selected regions of phase space.
- Plot is shown with integration only for $[2m_t, M_{t\bar{t}}]$.
- We focus on the region close to threshold. For high p_T see:
 - Fabbrichesi, Floreanini, Panizzo, PRL (2021).
 - Severi, Boschi, Maltoni, Sioli, EPJC (2022).

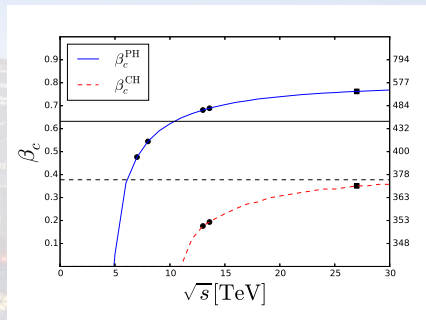


Figure: Critical values below which entanglement and CHSH violation can be observed, for different COM values.

Quantum Discord

- Classically: $I(A, B) = H(A) + H(B) - H(A, B) = H(A) - H(A|B)$, $H(X)$ is the Shannon entropy.
- QM “discord”: $\mathcal{D}(A, B) \equiv H(B) - H(A, B) + H(A|B) \neq 0$.
- The condition for discord in a two-qubit system is:
 $\mathcal{D}_A = S(\rho_B) - S(\rho) + \min_{\hat{n}} p_{\hat{n}} S(\rho_{\hat{n}}) + p_{-\hat{n}} S(\rho_{-\hat{n}}) \neq 0$.

with $S(\rho) = -\text{Tr} \rho \log_2 \rho$
the Von Neumann entropy.

- Can be asymmetric:
 $\mathcal{D}(A, B) \neq \mathcal{D}(B, A)$.
→ A test for *CP*-violation.

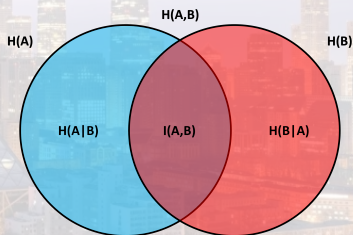


Figure: Schematic description of two subsystems with mutual information.

Steering

- Measurement of how Alice can “steer” the quantum state of Bob.
- Original conception of Schrödinger for the EPR paradox, only well-defined in 2007 ([Wiseman, Jones, Doherty, PRL \(2007\)](#)).
- Alice performs a spin measurement x and obtains the result $a = \pm$.
- Bob’s resulting state is the corresponding conditional states $\rho(a|x)$.
- Bob has to believe that Alice can influence his state, unless local hidden state holds.
- Can be asymmetric.
→ A test for CP -violation.

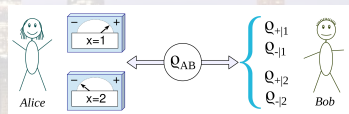
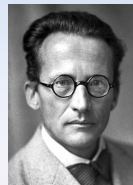
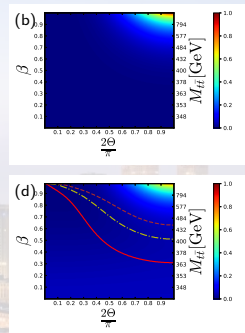
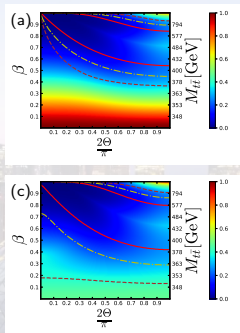


Figure: Schematic description of the steering phenomenon: Figure is from [Uola, Costa, Nguyen, Gühne, Rev. Mod. Phys. \(2020\)](#).

Discord and Steering Before Integration

- a) $gg \rightarrow t\bar{t}$ Discord.
- b) $q\bar{q} \rightarrow t\bar{t}$ Discord.
- c) Full LHC $\rho(M_{t\bar{t}}, \hat{k})$ Discord.
- d) Full Tevatron $\rho(M_{t\bar{t}}, \hat{k})$ Discord.

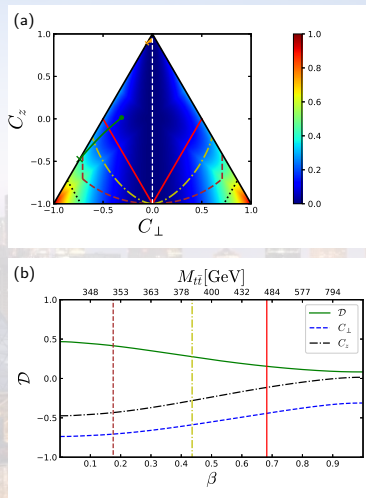
- Solid red, dashed-dotted yellow, and dashed brown lines are the critical boundaries of separability, steerability, and Bell locality, respectively.



Full picture of quantum correlations in $t\bar{t}$.

Discord and Steering After Integration

- Integration only for $[2m_t, M_{t\bar{t}}]$.
- a) Discord for $C_\perp, C_z$ (symmetry around the beam axis).
- **Green:** LHC trajectory;
 - **Orange:** Tevatron trajectory.
 - Cross: $\beta = 0$; Circle: $\beta = 1$.
 - Quantum discord: $C_\perp \neq 0$.
- Solid red, dashed-dotted yellow, dashed brown, and dotted black lines are the critical boundaries of separability, steerability, Bell locality, and NAQC, respectively.
- b) Detailed trajectory of green line in the upper panel.

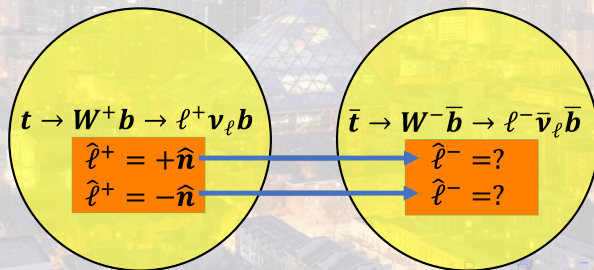


Experimental Measurement - Discord

- The tomography is required for $\rho_{A,B}$, ρ , $\rho_{\hat{n}}$, $\rho_{-\hat{n}}$:
 $\mathcal{D}_A = S(\rho_B) - S(\rho) + \min_{\hat{n}} p_{\hat{n}} S(\rho_{\hat{n}}) + p_{-\hat{n}} S(\rho_{-\hat{n}}) \neq 0$.
 $\rightarrow$ Can be done by measuring the differential cross-sections.
- One-qubit tomography of $\rho_{\hat{n}}$ from conditional Bloch vectors $\mathbf{B}_{\hat{n}}^{\pm}$:

$$p(\hat{\ell}_+, \hat{\ell}_-) = \frac{1 + \mathbf{B}^+ \cdot \hat{\ell}_+ - \mathbf{B}^- \cdot \hat{\ell}_- - \hat{\ell}_+ \cdot \mathbf{C} \cdot \hat{\ell}_-}{(4\pi)^2}$$

$$p(\hat{\ell}_{\pm} | \hat{\ell}_{\mp} = \mp \hat{n}) = \frac{p(\hat{\ell}_{\pm}, \hat{\ell}_{\mp} = \mp \hat{n})}{p(\hat{\ell}_{\mp} = \mp \hat{n})} = \frac{1 \pm \mathbf{B}_{\hat{n}}^{\pm} \cdot \hat{\ell}_{\pm}}{4\pi}.$$
- Actual discord is evaluated from minimization over $\hat{n}$.
 $\rightarrow$ Measuring discord according to its very definition.



Experimental Measurement - Steering

- Steering ellipsoid: the set of states to which Bob can steer Alice.
 - Forms an ellipsoid $\mathcal{E}_A$ in Alice's Bloch sphere, containing her Bloch vector $\mathbf{a}$.
 - Fundamental object in QI.
 - Contains most of the information about system's quantumness.
- Measurement of $\mathbf{B}_{\hat{n}}^{\pm}$ enables the reconstruction of $t, \bar{t}$ steering ellipsoids.
- Highly-challenging measurements in conventional setups.
 - Natural implementation in colliders.

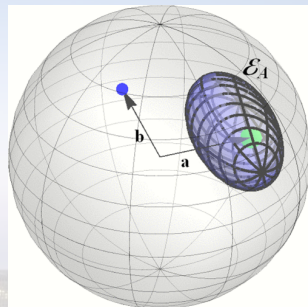
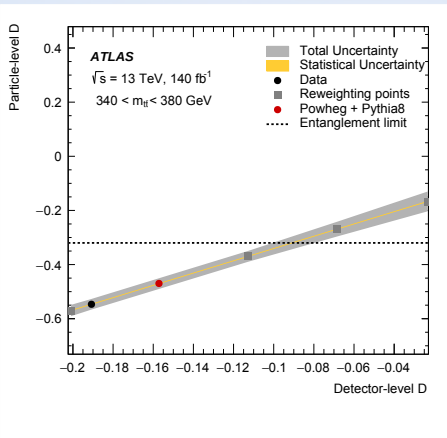


Figure: Ellipsoid representation of a two-qubit state. Figure is from [Jevtic, Pusey, Jennings, Rudolph, PRL \(2014\)](#).

Results



Systematic source	$\Delta D_{\text{observed}} (D = -0.537)$	$\Delta D (\%)$
Signal Modelling	0.017	3.2
Electron	0.002	0.4
Muon	0.001	0.2
Jets	0.004	0.7
b -tagging	0.002	0.4
Pileup	< 0.001	< 0.1
E_T^{miss}	0.002	0.4
Backgrounds	0.005	0.9
Stat.	0.002	0.3
Syst.	0.019	3.5
Total	0.019	3.5

Table: Systematic uncertainties for the observed D .

- The calibration curve for the SR and the uncertainties for the observed values are presented.

Summary of ATLAS Vs. CMS

Analysis Method	ATLAS	CMS
Dataset	Full Run 2 (140.0 fb ⁻¹)	2016 (35.9 fb ⁻¹)
$t\bar{t}$ decay	Di-lepton ($e\mu$)	Di-lepton ($e\mu/ee/\mu\mu$)
Main selections	$340 < M_{t\bar{t}} < 380$ GeV	$345 < M_{t\bar{t}} < 400$ GeV, $\beta_{t\bar{t}} < 0.9$
$t\bar{t}$ reconstruction	Ellipse method	Neutrino weighting
Corrected to	Particle-level	Parton-level
Fit type	No fit, calibration curve	Template fit
Alternative hypothesis D	Reweighting	Mixing samples with and without spin correlation
Threshold effects	Neglected	Considered
Dominant systematic	Top decay, PDF, Recoil, FSR, Scales, NNLO	JES, Toponium, ISR
Nominal MC	POWHEGBOX+PYTHIA	POWHEGBOX+PYTHIA
Alternative MC	POWHEGBOX+HERWIG, $bb4\ell$	POWHEGBOX+HERWIG, MG5_AMC@NLO [FxFx]
Expected D	-0.470 ± 0.002 [stat.] ± 0.017 [syst.]	$-0.467^{+0.016}_{-0.017}$ [stat.] $^{+0.021}_{-0.024}$ [syst.]
Observed D	-0.537 ± 0.002 [stat.] ± 0.019 [syst.]	$-0.480^{+0.016}_{-0.017}$ [stat.] $^{+0.020}_{-0.023}$ [syst.]
Significance	$>> 5\sigma$	$> 5\sigma$

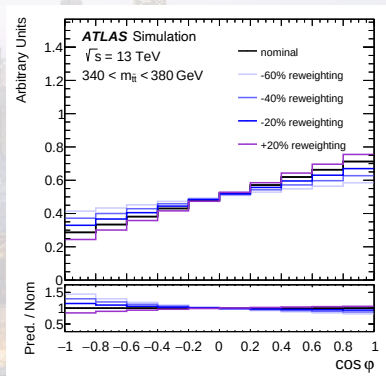
Table: Main differences between the ATLAS and CMS analyses.

Rewighting Method - ATLAS, Nature (2024)

- To test the alternative hypotheses we must change D .
- Inherent in particle generators.
- Alternative approach: each event is reweighted (at parton-level) taking into account $m_{t\bar{t}}$ to preserve linearity in $\cos \varphi$.
- $D(m_{t\bar{t}})$ is calculated for each modeling systematic.
- The reweighting is done for all systematic uncertainties.

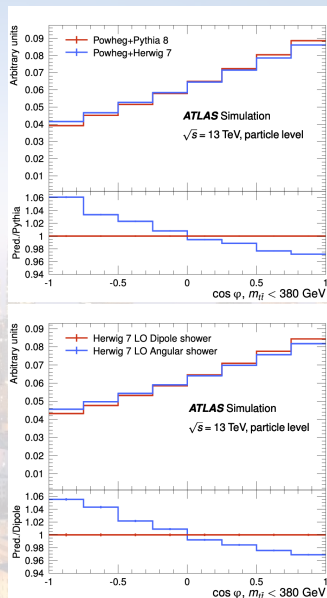
$$w = \frac{1 - D(m_{t\bar{t}}) \cdot \chi \cdot \cos \varphi}{1 - D(m_{t\bar{t}}) \cdot \cos \varphi}$$

$$\chi = 0.4, 0.6, 0.8, 1.2.$$



Parton Shower Modeling - ATLAS, Nature (2024)

- Large difference between POWHEGBOX+PYTHIA 8.230
POWHEGBOX+HERWIG 7.21, especially in the SR.
- A reason for an extensive scrutiny, to understand the difference.
- Comparison at particle-level.
- Main origin: the ordering of the shower.
- Observed both at detector and particle-level.
 - **Parton-level analysis: huge uncertainty.**
 - **Particle-level analysis: small uncertainty.**



Some Public Relations...

- In the background: nice image designed by CERN especially for the outreach of the analysis by ATLAS.
- CERN Courier: [link](#).
- ATLAS Briefing: [link](#).
- CERN Press Release: [link](#).
- Nature special article: [link](#).
- Nature reviews physics, research highlights, editors' picks 2023: [link](#).
- Articles in various magazines: Physics World, New Scientist, Symmetry, and many more.
- CERN Podcast: [link](#).
- 'Quantum entanglement' in Wikipedia: [link](#).

Entanglement of top quarks [edit]

In 2023 the LHC using techniques from [quantum tomography](#) measured entanglement at the highest energy so far,^{[119][120][121]} a rare intersection between quantum information and high energy physics based on theoretical work first proposed in 2021.^[122] The experiment was carried by the ATLAS detector measuring the spin of top-quark pair production and the effect was observed with more than 5 σ of level of significance, the top quark is the heaviest known particle and therefore has a very short lifetime ($\tau \sim 10^{-25}$ s) being the only quark that decays before undergoing [hadronization](#) ($\sim 10^{-23}$ s) and spin decorrelation ($\sim 10^{-21}$ s), so the spin information is transferred without much loss to the leptonic decays products that will be caught by the detector.^[123] The [spin polarization](#) and correlation of the particles was measured and tested for entanglement with [concurrence](#) as well as the [Peres–Horodecki criterion](#) and subsequently the effect has been confirmed too in the CMS detector.^{[124][125]}

Interpretation



- ✓ What have we measured?
 - ✓ The $t\bar{t}$ system is non-separable, i.e. entangled.
- ✓ What have we learned?
 - ✓ QI can be probed in high-energy systems. Entanglement is just one concept within many others.
 - ✓ This is a powerful tool, see e.g. 'toponium'.
 - ✓ QI can be used as a resource for HEP, see F. Maltoni's seminar ([link](#)).
- ✗ What we haven't measured (and haven't claim to measure)?
 - ✗ We did not perform a Bell test, therefore have not excluded LHVTs.

Spin Analyzing Power

- Spin analyzing power: the amount of spin info transferred from the top to its decay product: $\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_i^\pm} = \frac{1}{2}(1 + \alpha_{\ell^\pm} B_i^\pm \cos\theta_i^\pm)$.

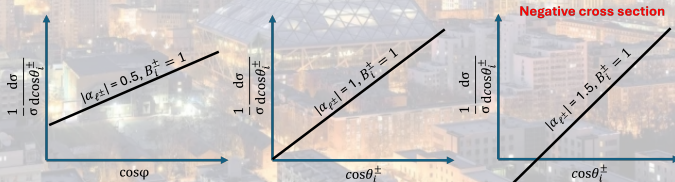
- Charged leptons: $|\alpha_{\ell^\pm}| \simeq 1$.
- Down-type quarks: $|\alpha_d| \simeq 0.97$.

- $|\alpha_\ell| > 1 \rightarrow$ more than 100% of the spin info is transferred to the decay product. **Not physical! Negative cross section.**

- We use dileptonic $t\bar{t}$ decays:

$$D^{\text{exp}}/|\alpha_{\ell^\pm}|^2 = -3 \cdot \langle \cos\varphi \rangle / |\alpha_{\ell^\pm}|^2 = D.$$

- Any value for $|\alpha_{\ell^\pm}|$ which is smaller than 1, only makes D to be more far from the null hypothesis of $D = -1/3$.



Null Hypothesis for Entanglement

- As shown in the previous slide, a **non-entangled state**, is by **definition a separable state**. This is, again by definition, the null hypothesis for entanglement.
- Entanglement is defined within QM. **Measuring entanglement is not, by any means, a test of a theory beyond QM**. Instead, it is a characterization of a **fundamental property of QM**.
- Obviously, this is not something we have invented, but a common QI notation, used daily by many people around the planet.
- There is really no ambiguity about this.

H_0 - separability

$$\rho = \sum_n p_n \rho_n^a \otimes \rho_n^b$$

H_1 - non-separability

~~$$\rho = \sum_n p_n \rho_n^a \otimes \rho_n^b$$~~