Quantum Tops: Quantum Information Meets High-Energy Physics

Top LHC France 2026, Paris, France

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Overview

- The Standard Model is a Quantum Field Theory, based on:
  - Special Relativity.
  - Quantum Mechanics (QM).
- Recently, it was shown that fundamental properties of QM can be probed via processes of the Standard Model.
- An opportunity to study concepts of Quantum Information Science (QIS) at High-Energy Physics (HEP) colliders, like the LHC.
  - Using the LHC as the largest QIS laboratory in the world.
  - Energies that are about 12 orders of magnitude larger than laboratory setups.
  - Fundamental particles and interactions.

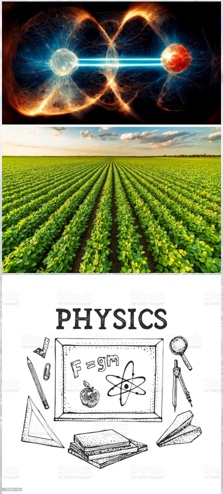

Figure: Quantum + Field + Theory.

Overview

1. First part: Quantum Information in $t\bar{t}$
   Basic Concepts & 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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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:

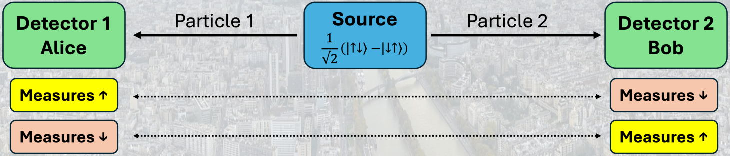
$$\rho = \frac{I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i \right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j}{4}$$

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

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


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.

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- 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.

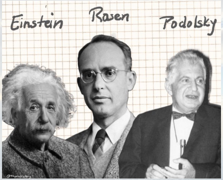
Separable

Non-Separable

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

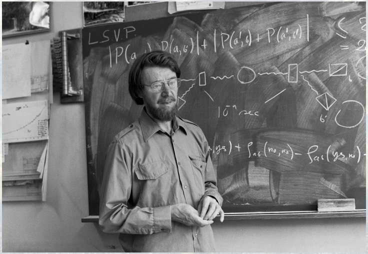
The EPR Paradox

- 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?
  $\rightarrow$ 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.
  $\Rightarrow$ 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.

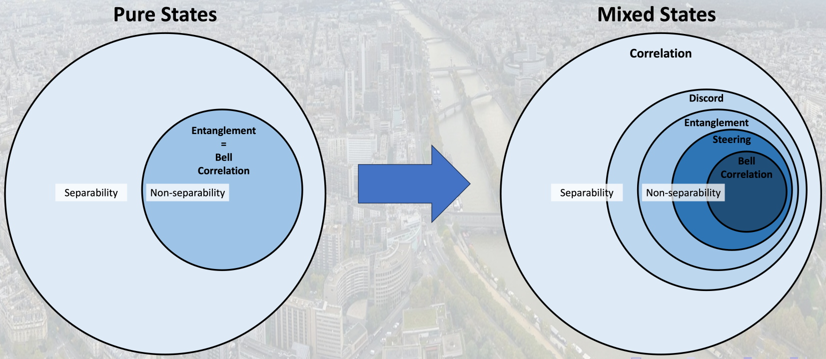
QIS Hierarchy

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

$$\text{Bell Correlation} \neq \text{Entanglement}\ .$$

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

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



QIS 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.

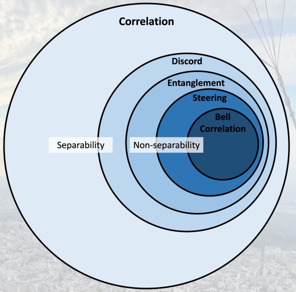


Figure: Schematic description of the relation between the different quantum correlations.

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

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

Top Quark

- **Top-quark:**
  - The most massive particle in the Standard Model.
  - 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.

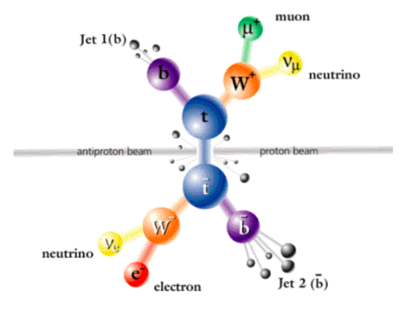
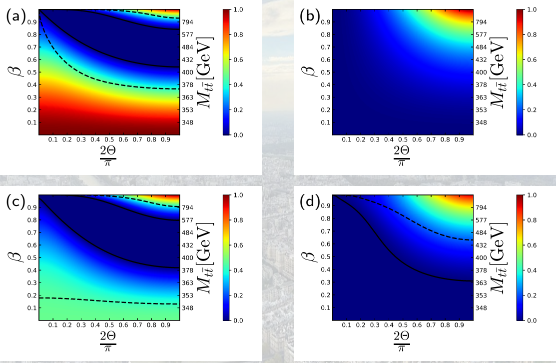


Figure: Di-leptonic decay of a $t\bar{t}$ pair.

Entanglement and Bell Correlation Before Integration

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

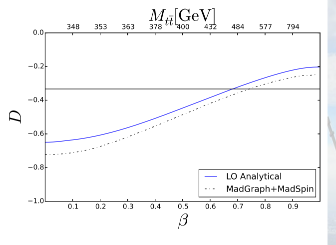
- Solid line: entanglement limit; Dashed line: Bell correlation limit.
- Figures are from YA, de Nova, Quantum (2022).



- 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:
  $\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$,
  $D = \frac{\mathrm{tr}[\mathbf{C}]}{3} = -3 \cdot \langle\cos\varphi\rangle$, φ is the angle between the leptons measured in the parent top/antitop rest frame, and **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**).
  - Severiet al., EPJC (2022).
  - YA, de Nova, Quantum (2022).



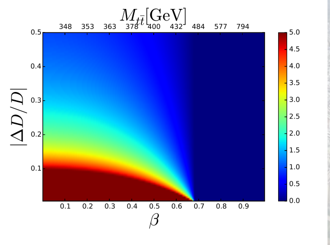


Figure: Up: the value of D; bottom: statistical deviation from the null hypothesis ($D = -1/3$).

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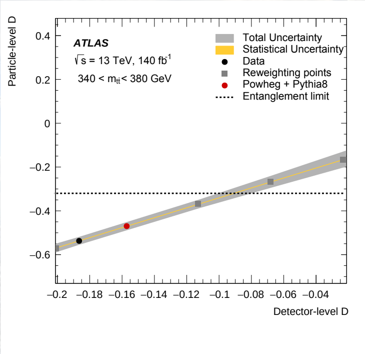
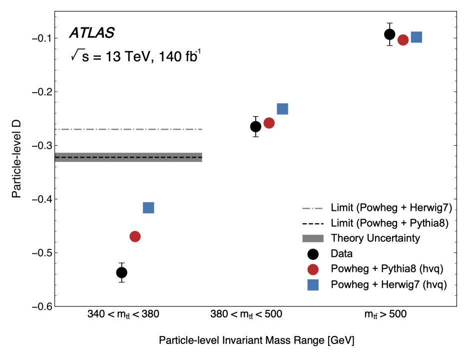
Recent Measurements

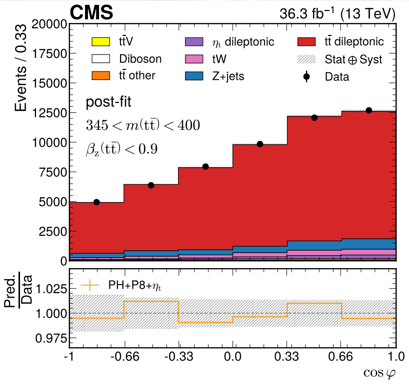
- Entanglement in $t\bar{t}$ pairs close to the production threshold:
  - ATLAS: ATLAS, Nature (2024).
  - CMS: CMS, Rept. Prog. Phys. (2024).
- Entanglement in $t\bar{t}$ pairs with boosted tops:
  - CMS: PRD (2024).
  - CMS: PRD (2026).
- Many more are currently at work.

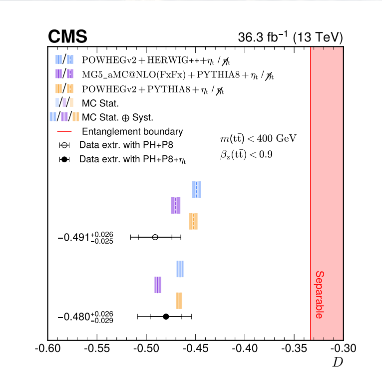




- No clear preference of a specific MC prediction.
- The limit of $D = -1/3$ is folded from parton to particle level.
- **Entanglement is observed (expected) with well more than 5σ.**
  Observed: $D = -0.537 \pm 0.002$ [stat.] $\pm\, 0.019$ [syst.]
  Expected: $D = -0.470 \pm 0.002$ [stat.] $\pm\, 0.017$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

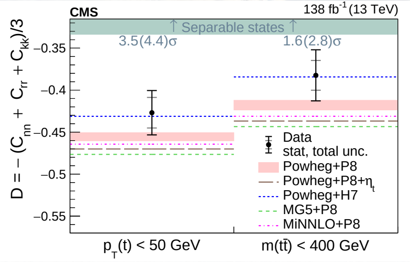
Threshold Region - CMS, Rept. Prog. Phys. (2024)

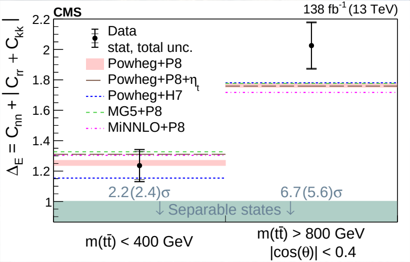




- Data seem to prefer Toponium.
- The limit of $D = -1/3$ is shown at parton-level.
- **Entanglement is observed (expected) with** 5.1σ **(**4.7σ**).**
  Observed: $D = -0.480^{+0.016}_{-0.017}$ [stat.]$^{+0.020}_{-0.023}$ [syst.]
  Expected: $D = -0.467^{+0.016}_{-0.017}$ [stat.]$^{+0.021}_{-0.024}$ [syst.]

Boosted Region - CMS, PRD (2024)





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

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

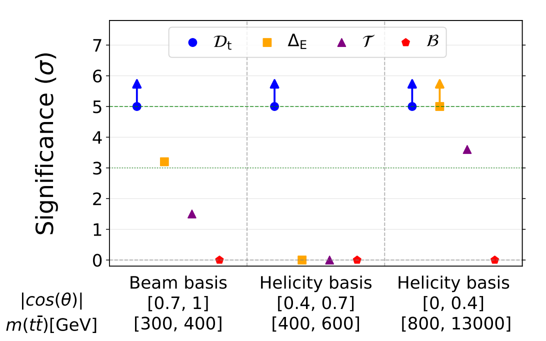


Figure: Significance in units of σ of the discord ($\mathcal{D}_t$), entanglement (Δ_E), steering ($\mathcal{T}$) and Bell correlation ($\mathcal{B}$) markers exceeding the threshold values.

- "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 QIS Hierarchy in $t\bar{t}$.

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What should we measure next?

What is next?

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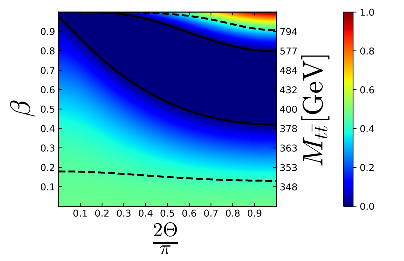
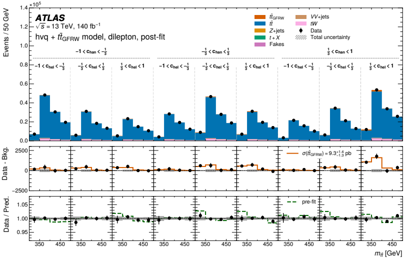
"Theory will only take you so far", from the movie Oppenheimer.

- I will give a few prime examples.

What should we measure next?

- Probe more QIS 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 QIS with other systems.
  - $h \to ZZ^*$: ATLAS, 2603.26463, CMS-PAS-HIG-25-011.
  - $pp \to b\bar{b}$: YA et al., PRD (2025).
- Use QIS to search for BSM physics.
- Use QIS to better understand high-energy physics processes.
  - 'Toponium' as a prime example: CMS, ROPP (2025), ATLAS, ROPP (2026) (talk by Léandre).





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

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- **Entanglement in top-quark pairs is observed with more than five standard deviations!**
- It constitutes as a proof of concept that QIS measurements can be done in high-energy colliders.
- This is a new and 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 (talk by Eleanor).
- 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 QIS background.

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

Contact Persons: Yoav Afik *[1], **Federica Fabbri** †[2,3], **Matthew Low** ‡[4], **Luca Marzola** §[5,6],
Juan Antonio Aguilar-Saavedra[7], Mohammad Mahdi Altakach[8], Nedaa Alexandra Asbah[9], Yang Bai[10,11], Hannah Banks[12], Alan J. Barr[13], Alexander Bernal[7], Thomas E. Browder[14], Paweł Caban[15], J. Alberto Casas[7], Kun Cheng[4], Frédéric Déliot[16], Regina Demina[17], Antonio Di Domenico[18,19], Michał Eckstein[20], Marco Fabbrichesi[21], Benjamin Fuks[22], Emidio Gabrielli[5,21,23], Dorival Gonçalves[24], Radosław Grabarczyk[25], Michele Grossi[9], Tao Han[4], Timothy J. Hobbs[11], Paweł Horodecki[26,27], James Howarth[28], Shih-Chieh Hsu[29], Stephen Jiggins[30], Eleanor Jones[30], Andreas W. Jung[31], Andrea Helen Knue[32], Steffen Korn[33], Theodota Lagouri[34], Priyanka Lamba[2,3], Gabriel T. Landi[17], Haifeng Li[35], Qiang Li[36], Ian Low[11,37], Fabio Maltoni[2,3,38], Josh McFayden[39], Navin McGinnis[40], Roberto A. Morales[41], Jesús M. Moreno[7], Juan Ramón Muñoz de Nova[42], Giulia Negro[31], Davide Pagani[3], Giovanni Pelliccioli[43,44], Michele Pinamonti[45,46], Laura Pintucci[45,46], Baptiste Ravina[9], Alim Ruzi[36], Kazuki Sakurai[47], Ethan Simpson[48], Maximiliano Sioli[2,3], Shufang Su[40], Sokratis Trifinopoulos[49], Sven E. Vahsen[14], Sofia Vallecorsa[9], Alessandro Vicini[50,51], Marcel Vos[52], Eleni Vryonidou[48], Chris D. White[53], Martin J. White[54], Andrew J. Wildridge[31], Tong Arthur Wu[4], Laura Zani[55], Yulei Zhang[29], and Knut Zoch[56]

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

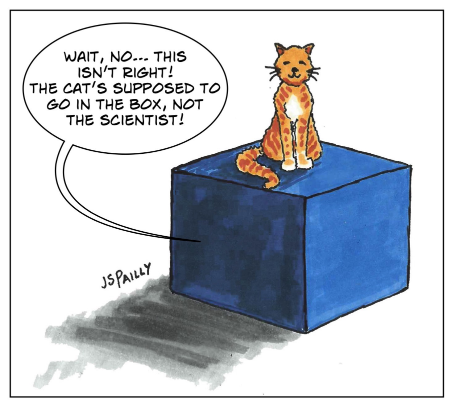
Probing Quantum Information observables with the ATLAS detector: some general principles

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


WAIT, NO... THIS ISN'T RIGHT! THE CAT'S SUPPOSED TO GO IN THE BOX, NOT THE SCIENTIST!
JSPAILLY


Backup

Quantum State

- **Pure state:** can be described by wave-functions $\sum_i \alpha_i \cdot |\psi_i\rangle$.

- **Pure state:** can be described by wave-functions $\sum_i \alpha_i \cdot |\psi_i\rangle$.

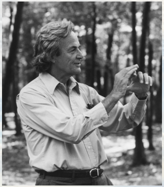
- **Mixed state:** can be described by a density matrix: $\rho = \sum_i p_i \cdot |\psi_i\rangle \langle\psi_i|$.
    - Example: at the LHC we cannot control the internal d.o.f. of the initial state. The state is mixed and incoherent.

- **Quantum Tomography**: reconstruction of the quantum state from measurement of a set of expectation values.

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 QIS until recently.
- Spin-Correlations can be a classical property.
  For example, **Spin-Correlations $\neq$ Quantum Entanglement!**
  However, Quantum Entanglement $\subset$ Spin-Correlations.

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.

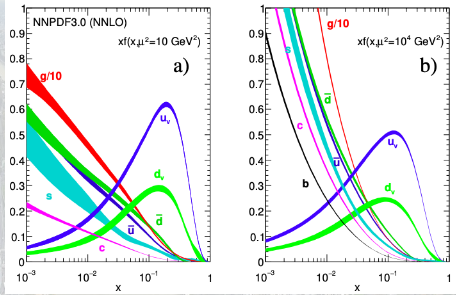
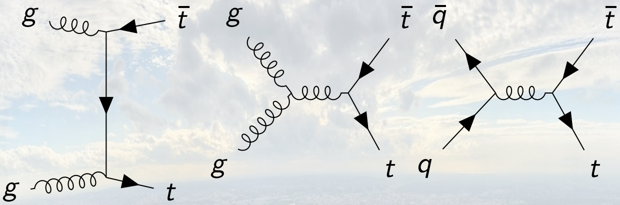


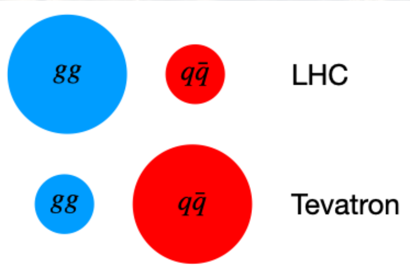
Figure: Parton density at the proton. Figure is from JHEP 2015, 40 (2015).

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

Leading-order Analytical Calculation



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- 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:

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

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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Non-Separable

Bell Correlation:

- A violation of the CHSH inequality: $\left|\mathbf{a}_1^{\mathrm{T}}\mathbf{C}\left(\mathbf{b}_1 - \mathbf{b}_2\right) + \mathbf{a}_2^{\mathrm{T}}\mathbf{C}\left(\mathbf{b}_1 + \mathbf{b}_2\right)\right| > 2$.
  - $\mathbf{C}$ - 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 $\mathbf{C}^{\mathrm{T}}\mathbf{C}$.

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!**

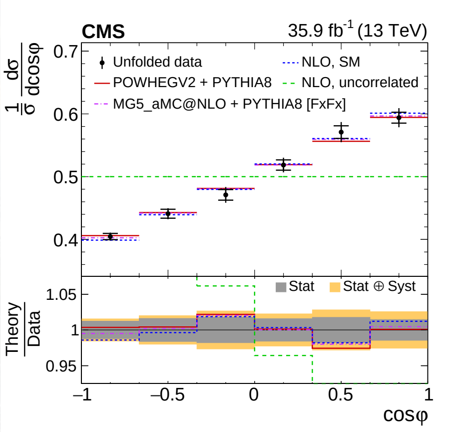
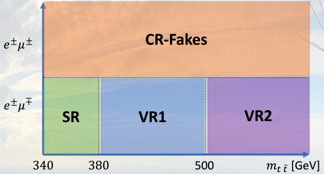
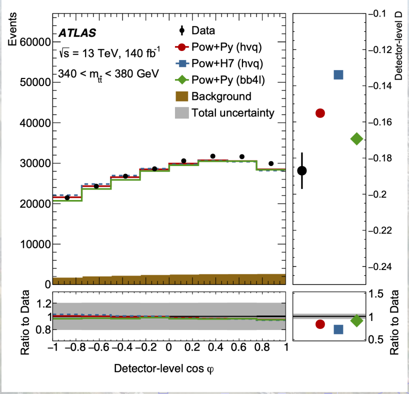


Figure: Distribution of $\cos\varphi$. Figure is from PRD (2019).

Analysis Strategy - ATLAS, Nature (2024)

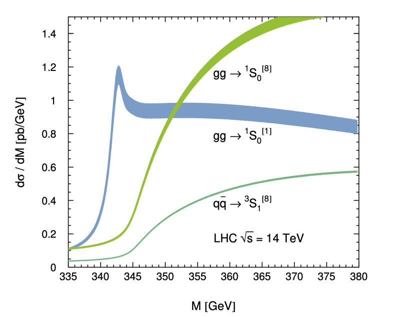
- Analysis selection:
  - $1\mu, 1e$ with opposite charges.
  - Single lepton triggers.
  - Lepton $p_{\mathrm{T}} > 25$–28 GeV.
  - $N_b \geq 1$ (85% b-tag efficiency).
- Backgrounds:
  - tW.
  - $t\bar{t} + X (X = H, W, Z)$.
  - $VV (V = W, Z)$.
  - $Z \to \tau^+\tau^-$.
  - Fakes.
- Regions are categorized 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.**

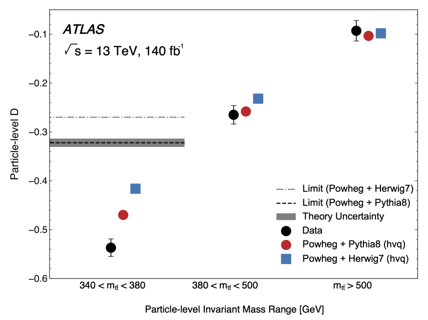




Toponium?

- 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.

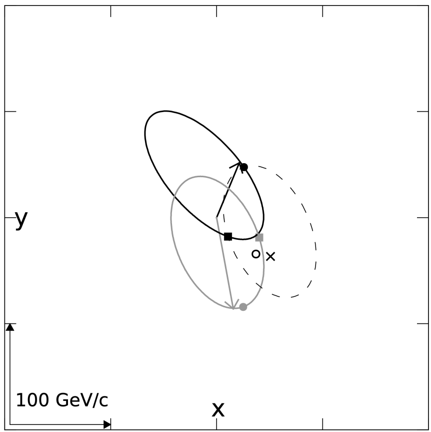
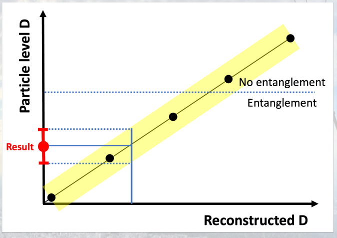


Figure: Constrain on neutrino momenta. Figure is from NIMA (2014).

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.

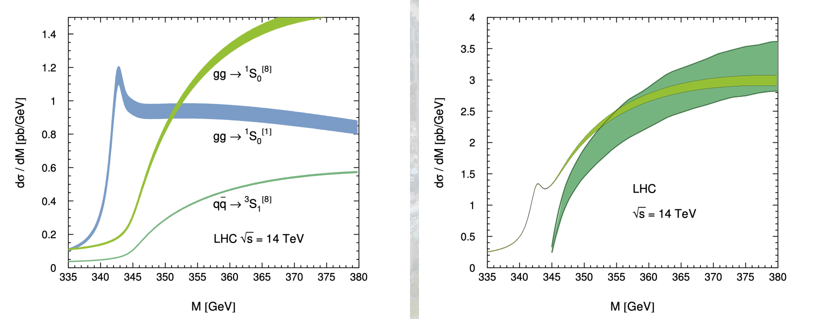
- Signal ($t\bar{t}$) modeling breakdown:
  - Top decay (MadSpin): 1.6%
  - PDF (PDF4LHC): 1.2%
  - Recoil To Top: 1.1%
  - FSR: 1.1%
  - Scales (μ_R, μ_F): 1.1%
  - NNLO Reweighting: 1.1%
  - pThard (`pThard = 1`): 0.8%
  - m_t (172.5 ± 0.5 GeV): 0.7%
  - ISR: 0.2%
  - Parton Shower (Herwig): 0.2%
  - h_{damp}: 0.1%
- Background modeling is dominated by $Z \to \tau^+\tau^-$ 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

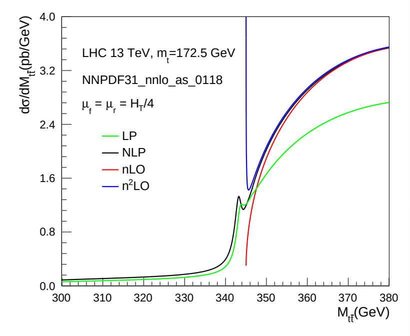
Differential Cross-Section - $m_{t\bar{t}}$ Dependence

- 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).

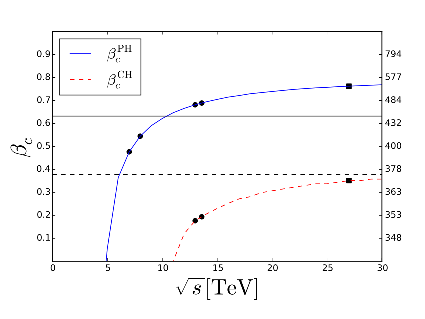


Figure: Critical values below which entanglement and CHSH violation can be observed, for different COM values.

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: $\mathcal{D}_A = S(\rho_B) - S(\rho) + \min_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}} S(\rho_{\hat{\mathbf{n}}}) + p_{-\hat{\mathbf{n}}} S(\rho_{-\hat{\mathbf{n}}}) \neq 0$.

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

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

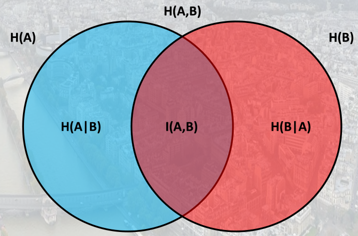


Figure: Schematic description of two subsystems with mutual information.

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)).

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- 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.
  $\rightarrow$ A test for CP-violation.

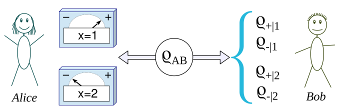
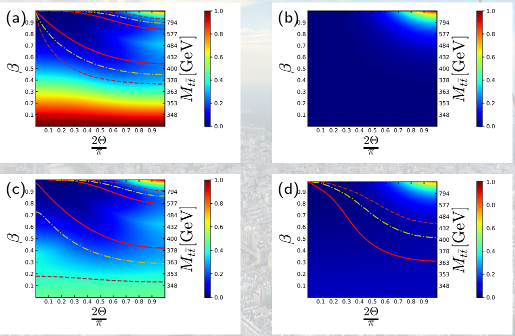


Figure: Schematic description of the steering phenomenon: Figure is from Uola, Costa, Nguyen, Gühne, Rev. Mod. Phys. (2020).

a) $gg \to t\bar{t}$ Discord.
b) $q\bar{q} \to t\bar{t}$ 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 $t\bar{t}$.

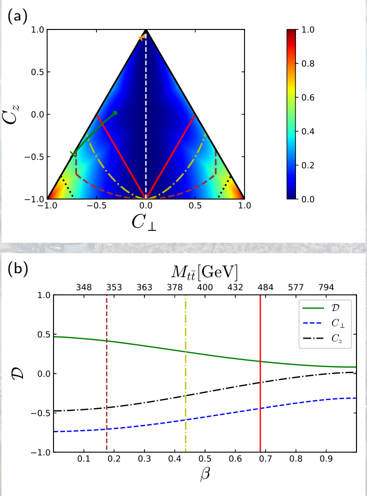
Discord and Steering After Integration

- Integration only for $[2m_t, M_{t\bar{t}}]$.

a) Discord for $C_\perp, C_z$ (symmetry around the beam axis).

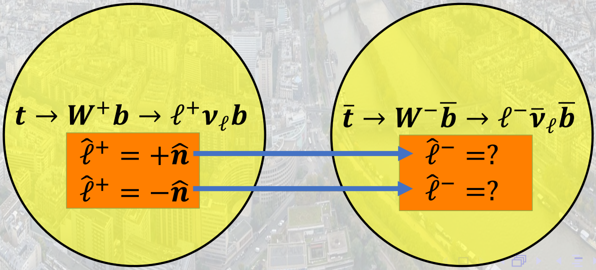
- Green: LHC trajectory; Orange: Tevatron trajectory.
- Cross: $\beta = 0$; Circle: $\beta = 1$.
- Quantum discord: $C_\perp \neq 0$. Solid red, dashed-dotted yellow, dashed brown, and dotted black lines are the critical boundaries of separability, steerability, Bell locality, and NAQC, respectively.

b) Detailed trajectory of green line in the upper panel.



Experimental Measurement - Discord

- The tomography is required for $\rho_{A,B}$, ρ, $\rho_{\hat{\mathbf{n}}}$, $\rho_{-\hat{\mathbf{n}}}$:
  $\mathcal{D}_A = S(\rho_B) - S(\rho) + \min_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}} S(\rho_{\hat{\mathbf{n}}}) + p_{-\hat{\mathbf{n}}} S(\rho_{-\hat{\mathbf{n}}}) \neq 0.$
  $\rightarrow$ Can be done by measuring the differential cross-sections.
- One-qubit tomography of $\rho_{\hat{\mathbf{n}}}$ from conditional Bloch vectors $\mathbf{B}^{\pm}_{\hat{\mathbf{n}}}$:
  $$p(\hat{\ell}_+, \hat{\ell}_-) = \frac{1+\mathbf{B}^+\cdot\hat{\ell}_+ - \mathbf{B}^-\cdot\hat{\ell}_- - \hat{\ell}_+\cdot\mathbf{C}\cdot\hat{\ell}_-}{(4\pi)^2}$$
  $$p(\hat{\ell}_\pm|\hat{\ell}_\mp = \mp\hat{\mathbf{n}}) = \frac{p(\hat{\ell}_\pm, \hat{\ell}_\mp = \mp\hat{\mathbf{n}})}{p(\hat{\ell}_\mp = \mp\hat{\mathbf{n}})} = \frac{1 \pm \mathbf{B}^\pm_{\hat{\mathbf{n}}}\cdot\hat{\ell}_\pm}{4\pi}.$$
- Actual discord is evaluated from minimization over $\hat{\mathbf{n}}$.
  $\rightarrow$ 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 **a**.
  - Fundamental object in QIS.
  - Contains most of the information about system's quantumness.
- Measurement of $\mathbf{B}^{\pm}_{\hat{\mathbf{n}}}$ enables the reconstruction of $t, \bar{t}$ steering ellipsoids.
- Highly-challenging measurements in conventional setups.
  $\rightarrow$ Natural implementation in colliders.

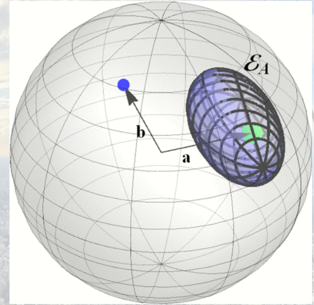
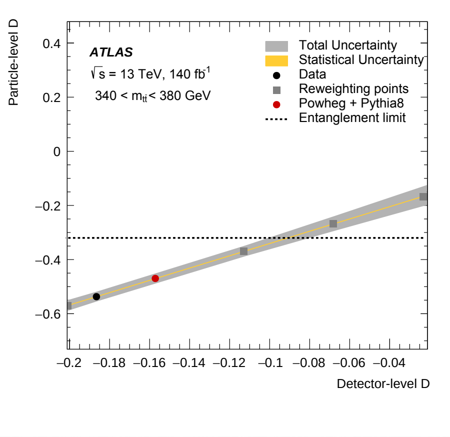


Figure: Ellipsoid representation of a two-qubit state. Figure is from Jevtic, Pusey, Jennings, Rudolph, PRL (2014).

Results



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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	Reweighing	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, *bb4ℓ*	PowhegBox+Herwig, MG5_aMC@NLO [FxFx]
Expected D	-0.470 ± 0.002 [stat.] $\pm\ 0.017$ [syst.]	$-0.467^{+0.016}_{-0.017}$ [stat.]$^{+0.021}_{-0.024}$ [syst.]
Observed D	$-0.537\ \pm 0.002$ [stat.] $\pm\ 0.019$ [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.

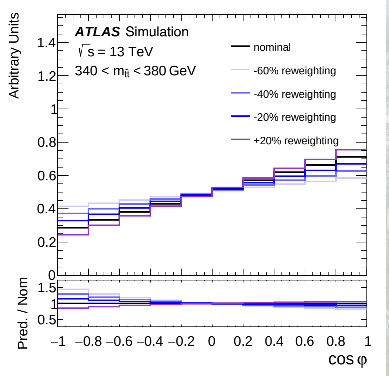
Reweighting Method - ATLAS, Nature (2024)

- 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.

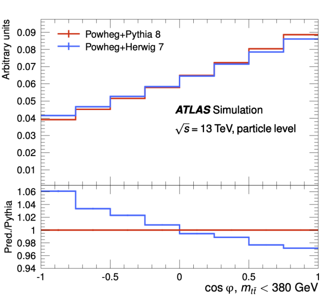
$$w = \frac{1 - D(m_{t\bar{t}}) \cdot \chi \cdot \cos\varphi}{1 - D(m_{t\bar{t}}) \cdot \cos\varphi}$$

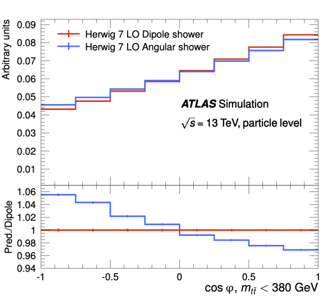
$$\chi = 0.4, 0.6, 0.8, 1.2.$$



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.
  $\rightarrow$ **Parton-level analysis: huge uncertainty.**
  $\rightarrow$ **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**.
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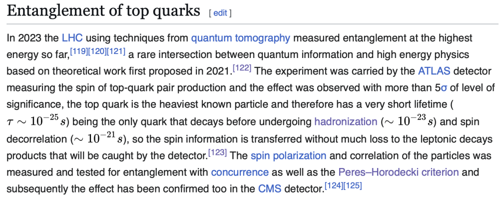
- 'Quantum entanglement' in Wikipedia: **link**.



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 5σ 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]

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  - ✓ QIS can be used as a resource for HEP, see F. Maltoni's seminar (link).

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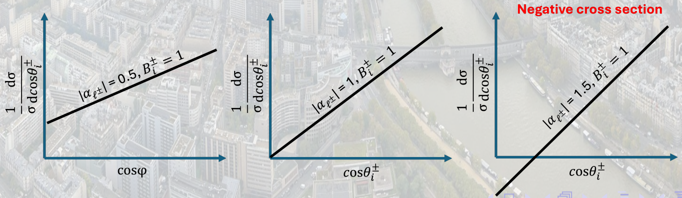
  - ✓ This is a powerful tool, see e.g. 'toponium'.
  - ✓ QIS can be used as a resource for HEP, see F. Maltoni's seminar (link).
- × What we haven't measured (and haven't claim to measure)?
  - × We did not perform a Bell test, therefore have not excluded LHVTs.

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:

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

- 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 QIS notation, used daily by many people around the planet.
- There is really no ambiguity about this.

H_0 - separability
$\rho = \Sigma_n p_n \rho_n^a \otimes \rho_n^b$

H_1 - non-separability
~~$\rho = \Sigma_n p_n \rho_n^a \otimes \rho_n^b$~~