Spin correlation and entanglement with the ATLAS experiment

TOP2023, Traverse City, Michigan, USA

Yoav Afik[1]
On behalf of the ATLAS collaboration

[1]University of Chicago, Enrico Fermi Institute

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Overview

- The Standard Model is a Quantum Field Theory:
  - Special Relativity.
  - Quantum Mechanics.
- Recently, it was shown that fundamental properties of Quantum Mechanics can be tested via processes of the Standard Model.
- An opportunity to study concepts of Quantum Information at High-Energy Colliders, like the LHC.
- In this talk, the result of a measurement of spin entanglement in top quark pair production is presented.
  - **ATLAS-CONF-2023-069**.

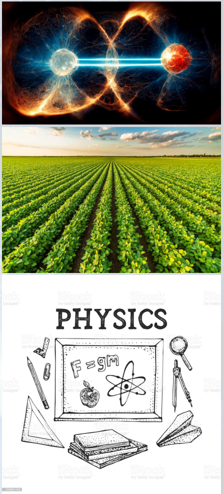

Figure: Quantum + Field + Theory.

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

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- **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 $\mathbf{B}$:

$$B_i = \langle \sigma^i \rangle = \mathrm{tr}(\sigma^i \rho)$$

Quantum Tomography: Two Qubits

- Most general density matrix for 2 qubits:

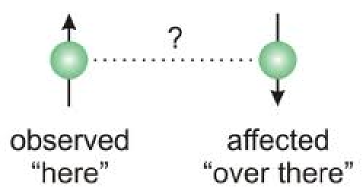
$$\rho = \frac{I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i \right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j}{4}$$

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

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

What is Quantum Entanglement?

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



- Observed in photons, atoms, superconductors, mesons, analog Hawking radiation, nitrogen-vacancy centers in diamond and even macroscopic diamond.

Quantum Entanglement

- 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, $\sum_n p_n = 1,\ p_n \geq 0$
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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 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.

Top-Quark

- **Top-quark:**
  - The most massive particle in the Standard Model.
  - Lifetime: $\sim 10^{-25}$ s.
- **General:**
  - Hadronisation: $\sim 10^{-23}$ s.
  - Spin-decorrelation: $\sim 10^{-21}$ s.
- Spin information → decay products.
- Spin-correlations between a pair of top-quarks can be measured.
- Considering di-leptonic decays.

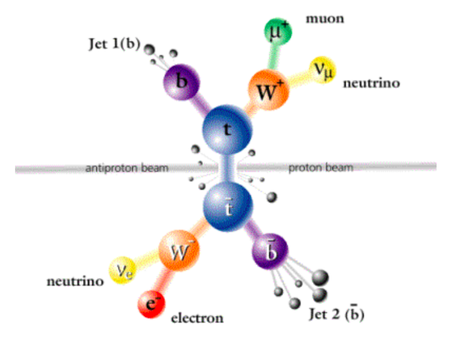


Figure: Di-leptonic decay of a $t\bar{t}$ pair.

Entanglement Observable

- 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, due to gg dominance at the LHC.
- Theory framework:
  - YA, de Nova: EPJP (2021), Quantum (2022).
  - Severi et al.: EPJC (2022).

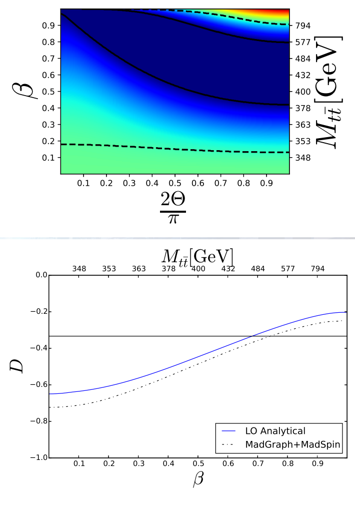
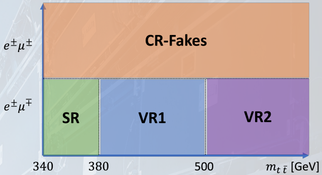
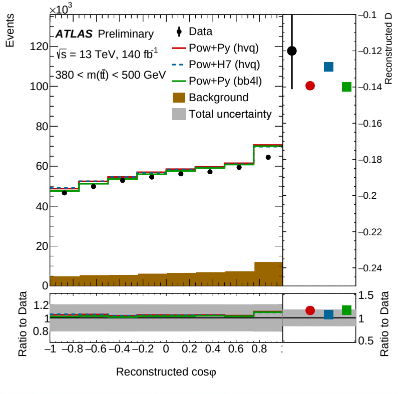


Figure: Up: entanglement before integration; bottom: D after integration in $[2m_t, M_{t\bar{t}}]$.

Analysis Strategy

- 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.**





Top Reconstruction

- 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.

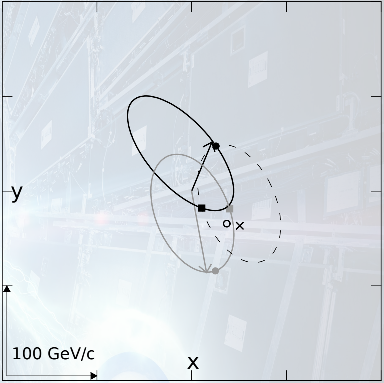
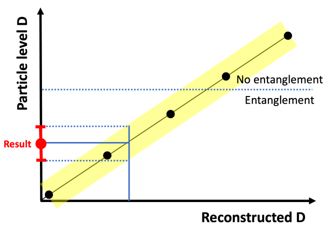


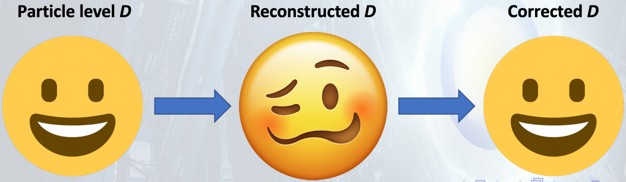
Figure: Constrain on neutrino momenta. Figure is from Nucl.Instrum.Meth.A 736 (2014) 169-178.

Calibrating the Observable

- 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.



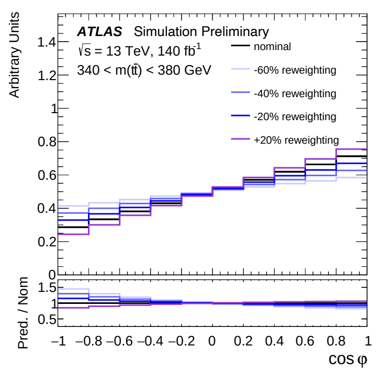
Reweighting Method

- 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.

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

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



Systematic Uncertainties

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

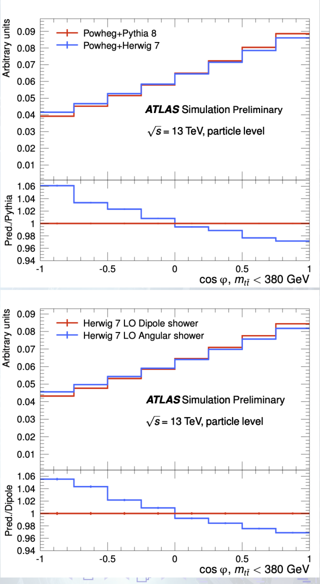
Systematic source	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD (%)
Signal Modelling	0.015	3.2
Electron	0.002	0.4
Muon	0.001	0.1
Jets	0.004	0.8
b-tagging	0.002	0.4
Pileup	< 0.001	< 0.1
E_T^{miss}	0.002	0.4
Backgrounds	0.009	1.8
Stat.	0.002	0.4
Syst.	0.018	3.9
Total	0.018	3.9

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

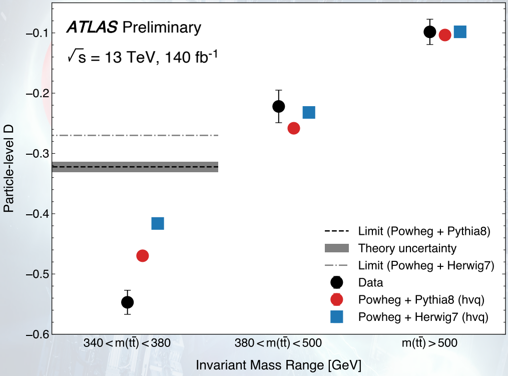
- Signal ($t\bar{t}$) modeling breakdown:
  - Top decay (MADSPIN): 1.6%
  - PDF (PDF4LHC): 1.2%
  - Recoil To Top: 1.1%
  - FSR: 1.1%
  - Scales (μ_R, μ_F): 1.1%
  - NNLO Reweighting: 1.1
  - pThard1 (`pThard = 1`): 0.8%
  - m_t (172.5 ± 0.5 GeV): 0.7%
  - ISR: 0.2%
  - Parton Shower (HERWIG): 0.2%
  - 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.

Parton Shower Modeling

- 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. Not a source of a large uncertainty if we are doing the measurement at particle level.



Results



- No clear preference of a specific MC prediction.
- The limit of $D = -1/3$ is folded from parton to particle level.
- **Entanglement is observed with a significance of more than** 5σ**.**
  Observed: $D = -0.547 \pm 0.002$ [stat.] $\pm\, 0.021$ [syst.]
  Expected: $D = -0.470 \pm 0.002$ [stat.] $\pm\, 0.018$ [syst.]

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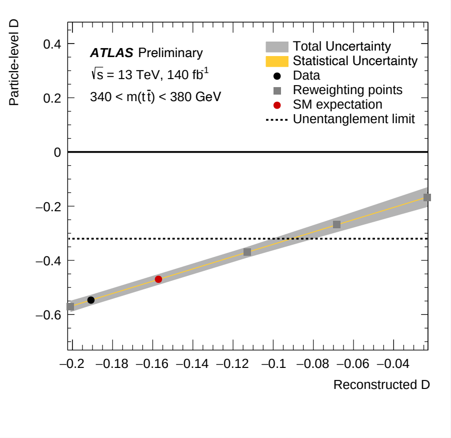

Systematic source	$\Delta D_{\text{observed}}(D = -0.547)$	ΔD (%)
Signal Modelling	0.017	3.2
Electron	0.002	0.4
Muon	0.001	0.1
Jets	0.004	0.7
b-tagging	0.002	0.4
Pileup	< 0.001	< 0.1
E_T^{miss}	0.002	0.3
Backgrounds	0.010	1.8
Stat.	0.002	0.3
Syst.	0.021	3.8
Total	0.021	3.8

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

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

Summary

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- **Entanglement in top quark pairs is observed with more than five standard deviations!**
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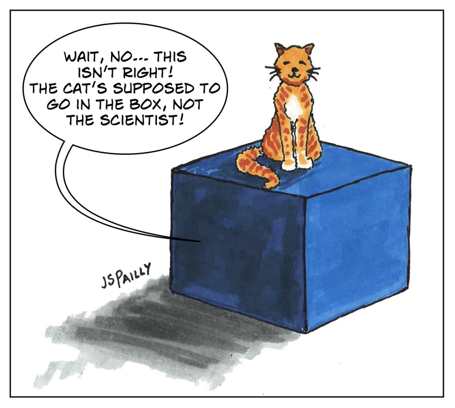
- **Entanglement in top quark pairs is observed with more than five standard deviations!**
  - **ATLAS-CONF-2023-069**.
- This is the first measurement of entanglement between a pair of quarks ever made, and the highest-energy-scale observation of entanglement.
- This measurement tests quantum entanglement in a new environment, and paves the way to use the LHC as a laboratory to study quantum information and other foundational problems in quantum mechanics.
- The observable under study is sensitive to modeling of the parton shower; more work required to validate mainstream generators for precision measurements.

Thank You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JSPAILLY

Backup Slides

Backup

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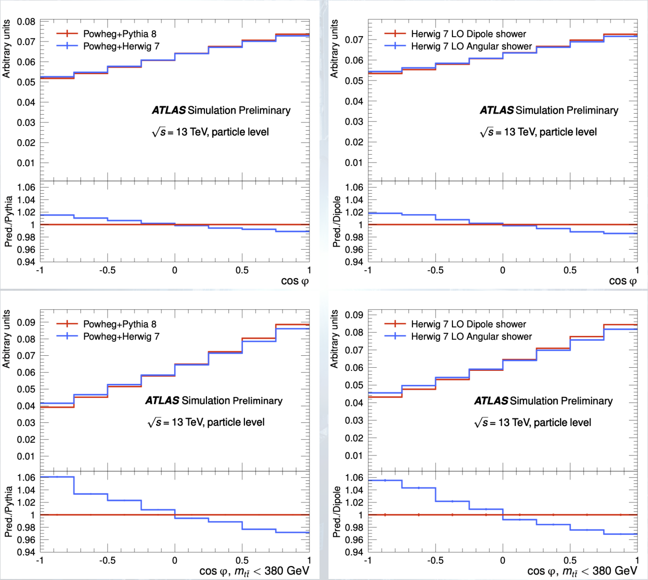
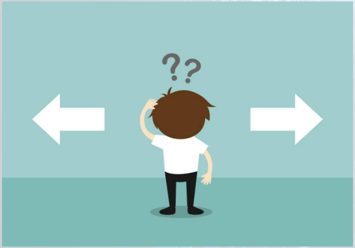
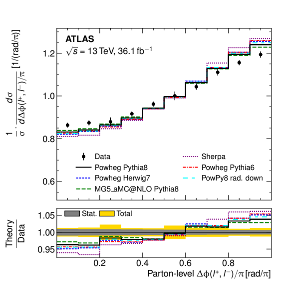
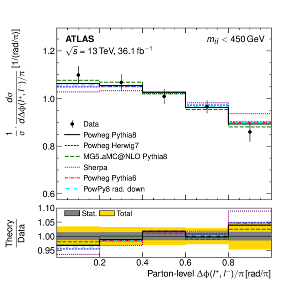


Parton Shower Modeling

- Similar behavior already spotted at Eur.Phys.J.C 80 (2020) 8, 754.
- The plots show the unfolded $\Delta\phi$ distribution at parton level inclusively (top) and with $m_{t\bar{t}} < 450$ GeV (bottom).
- There is no preference of one specific model.







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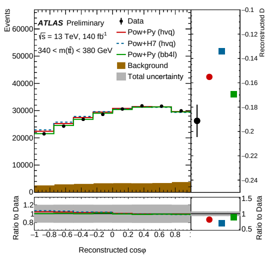
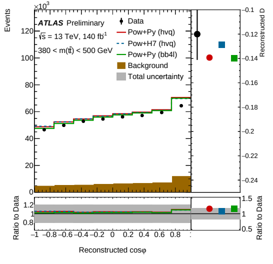

ATLAS Preliminary
√s = 13 TeV, 140 fb⁻¹
340 < m(tt̄) < 380 GeV
Data
Pow+Py (hvq)
Pow+H7 (hvq)
Pow+Py (bb4l)
Background
Total uncertainty
Events
Ratio to Data
Reconstructed cosφ
Reconstructed D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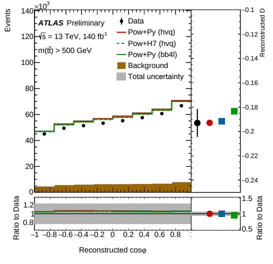
ATLAS Preliminary
√s = 13 TeV, 140 fb⁻¹
m(tt̄) > 500 GeV
Data
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Total uncertainty
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Quantum Information Hierarchy

- Completing the puzzle of quantum information in high-energy physics.
- Quantum Discord:
  - The most basic form of quantum correlations.
  - Asymmetric between different subsystems.
- Quantum Steering:
  - Measurements on one subsystem can be used to “steer” the other one.
  - A non-local feature that lies between entanglement and Bell non-locality.

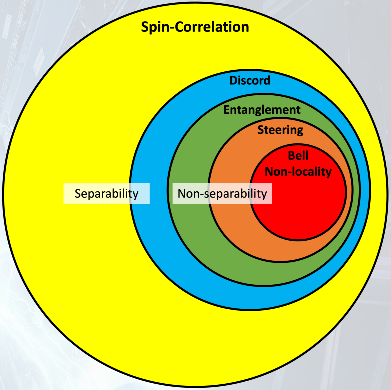

Figure: Schematic description of the relation between the different concepts discussed in the talk.

Bell Non-locality $\subset$ *Steering* $\subset$ *Entanglement* $\subset$ *Discord* $\subset$ *Spin-Correlation*