When Theory Becomes Reality: Measuring Quantum Information Concepts with Heavy-Flavor Quarks

WQC Workshop on Quantum Entanglement of High Energy Particles, Wilczek Quantum Center, Shanghai, China

Yoav Afik[1]

[1]University of Chicago, Enrico Fermi Institute

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Outline

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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 and High-Energy Physics:
  - Theory: basic concepts. **See talk by Juan Ramón Muñoz de Nova**.
  - Phenomenology: implementation for heavy-flavor quarks in hadron colliders. **This talk**.
  - Experiment: measurements. **See talks by Regina Demina, Vasiliki Mitsou, Andy Jung, Baptiste Ravina, Steffen Korn, Eleanor Jones**. Some results will be mentioned briefly in this talk.

- This talk is based on:
  - YA, de Nova, EPJP (2021).
  - YA, de Nova, Quantum (2022).
  - YA, de Nova, PRL (2023).
  - YA, Kats, de Nova, Soffer, Uzan, PRD (2025).

Outline

Back then at 2019...

Juan and me were friends and also office neighbors, working on completely different topics, and used to have coffee breaks together.

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

Me: "Hmmm... Good question!"

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Top-Quark

- **Top-quark:**
  - Has spin of $1/2$.
  - 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 $\rightarrow$ decay products.
- Spin-correlations between a pair of top-quarks can be measured.
- Considering di-leptonic decays.

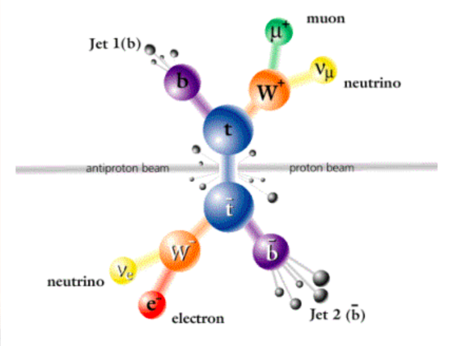
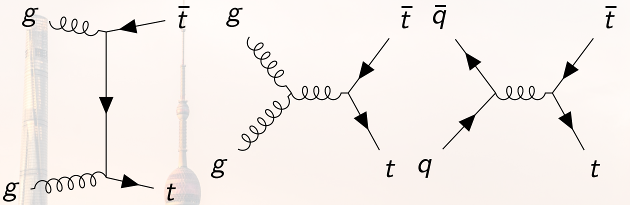


Figure: Di-leptonic decay of a $t\bar{t}$ pair.

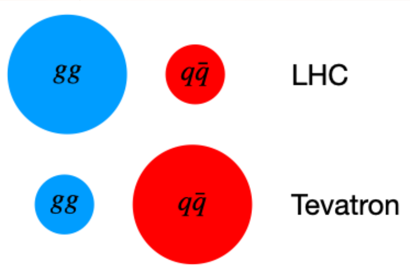
** **A pair of $t\bar{t}$ is a two-qubit system. Their polarizations and spin-correlations can be measured.**

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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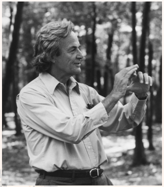
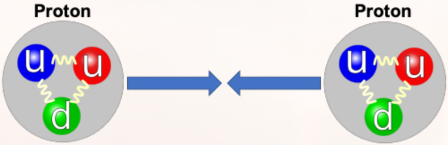
Collisions at the LHC





- 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.

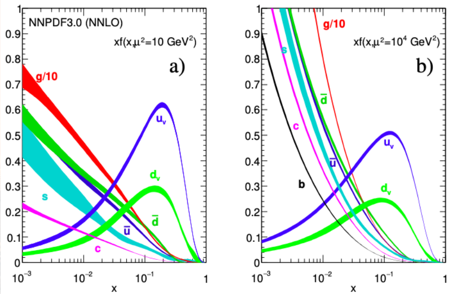
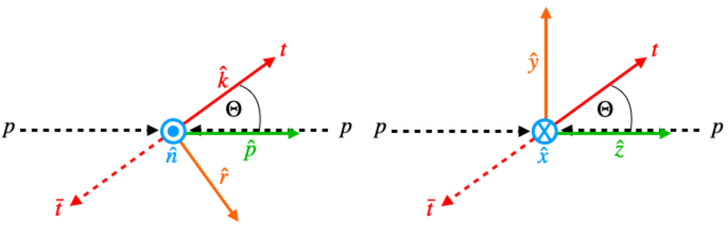


Figure: Parton density at the proton. Figure is from JHEP 2015, 40 (2015).

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**.

Experimental Observables

<u>Quantum Entanglement:</u>

- **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, $\mathcal{C}[\rho] = \max(\Delta, 0)$; $\Delta = \frac{-C_{nn} + |C_{kk} + C_{rr}| - 1}{2}$.

Non-Separable

Experimental Observables

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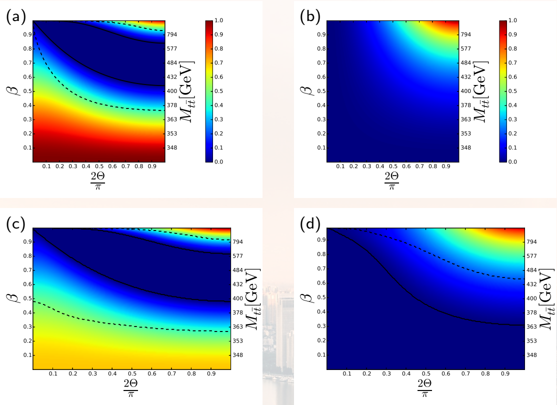
Bell Non-locality:

- A violation of the CHSH inequality: $|\mathbf{a}_1^{\mathrm{T}}\mathbf{C}\,(\mathbf{b}_1 - \mathbf{b}_2) + \mathbf{a}_2^{\mathrm{T}}\mathbf{C}\,(\mathbf{b}_1 + \mathbf{b}_2)\,| > 2$.
  - $\mathbf{C}$ - 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: $2\sqrt{\mu_1 + \mu_2} \le 2\sqrt{2}$ where $0 \le \mu_i \le 1$ are the eigenvalues of $\mathbf{C}^{\mathrm{T}}\mathbf{C}$.

Entanglement and Bell Non-locality 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.

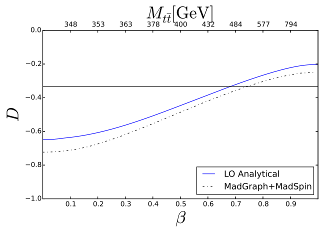
- Solid line: entanglement limit; Dashed line: Bell inequality limit.
- Figures are from YA, de Nova, Quantum (2022).



- 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.
- Theory framework:
  - YA, de Nova, EPJP (2021).
  - YA, de Nova, Quantum (2022).
  - Severi, Boschi, Maltoni, Sioli, EPJC (2022).



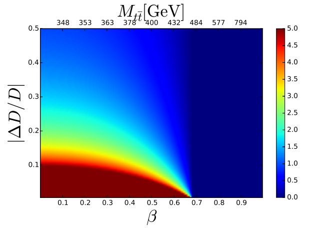
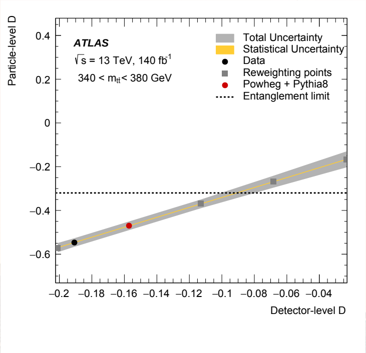
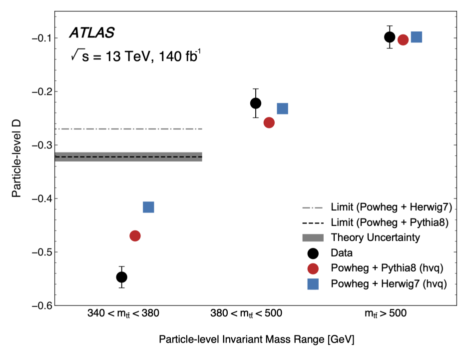


Figure: Up: the value of D; bottom: statistical deviation from the null hypothesis ($D = -1/3$).

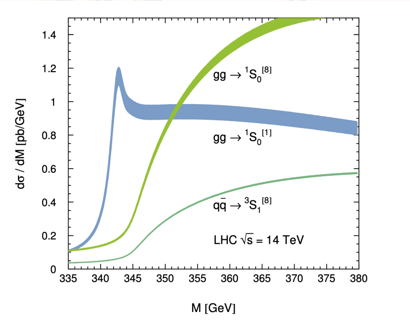


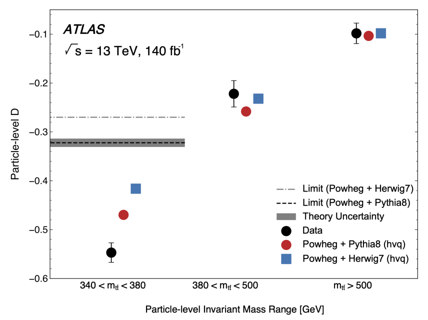


- The limit of $D = -1/3$ is folded from parton to particle level.
- **Entanglement is observed (expected) with well more than 5σ.**
  Observed: $D = -0.537 \pm 0.002$ [stat.] ± 0.019 [syst.]
  Expected: $D = -0.470 \pm 0.002$ [stat.] ± 0.017 [syst.]
- **More details are in the talk by Vasiliki Mitsou.**

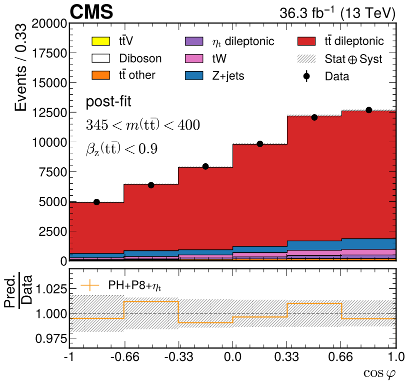
Toponium?

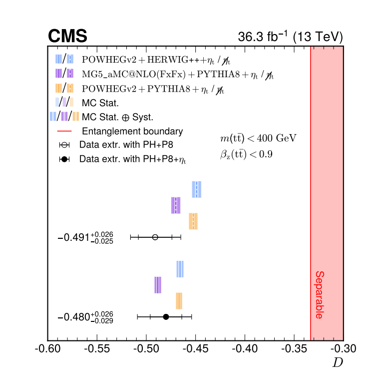
- Left: invariant mass distribution close to threshold including all partonic production channels. Figure is from EPJC (2009).
- Right: the recent ATLAS result.
- Toponium: higher cross-section next to threshold, more spin-singlet (maximally entangled). Not included in MC generators.





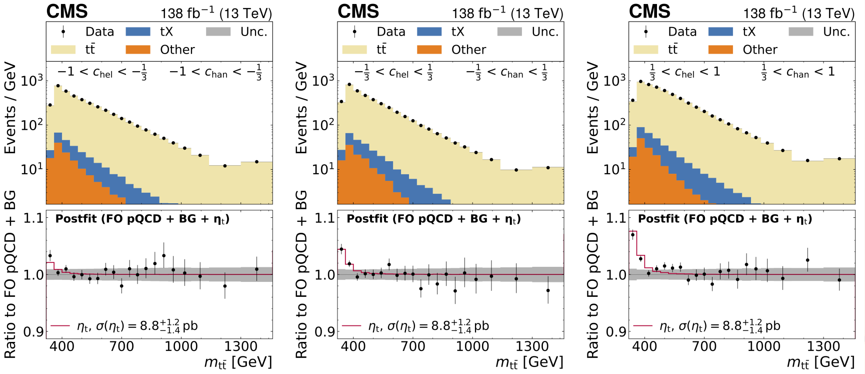
Threshold Region - CMS, Rept. Prog. Phys. (2024)



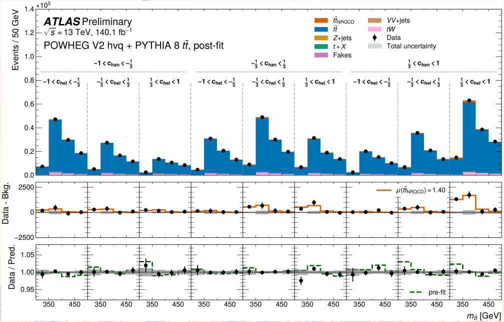


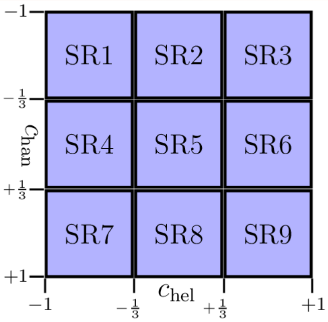
- Data seem to prefer Toponium.
- The limit of $D = -1/3$ is shown at parton-level.
- **Entanglement is observed (expected) with** 5.1σ **(**4.7σ**).**
  Observed: $D = -0.480^{+0.016}_{-0.017}$ [stat.]$^{+0.020}_{-0.023}$ [syst.]
  Expected: $D = -0.467^{+0.016}_{-0.017}$ [stat.]$^{+0.021}_{-0.024}$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

Toponium? - CMS, 2503.22382



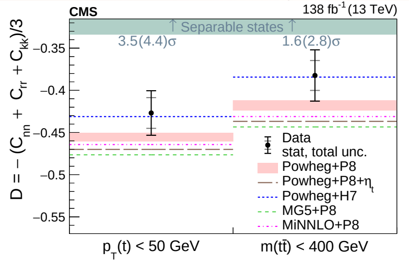
- Using spin correlation observables.
- Excess of more than 5σ.
- Data seem to prefer toponium.
  - Using a toy model for toponium: $\sigma(\eta_t) = 8.8^{+1.2}_{-1.4}$ pb.

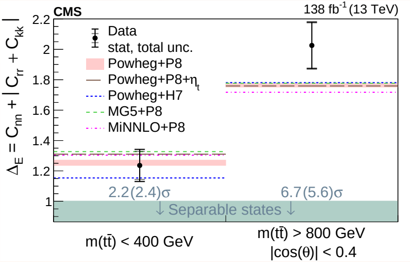




- Confirms the excess by CMS.
- Modeling matters! Using different models for toponium:
  - An improved model, including non-relativistic QCD: $\sigma(t\bar{t}_{NRQCD}) = 9.0 \pm 1.3$ pb.
  - The toy model used by CMS: $\sigma(\eta_t) = 13.4 \pm 1.9$ pb.

Boosted Region - CMS, PRD (2024)

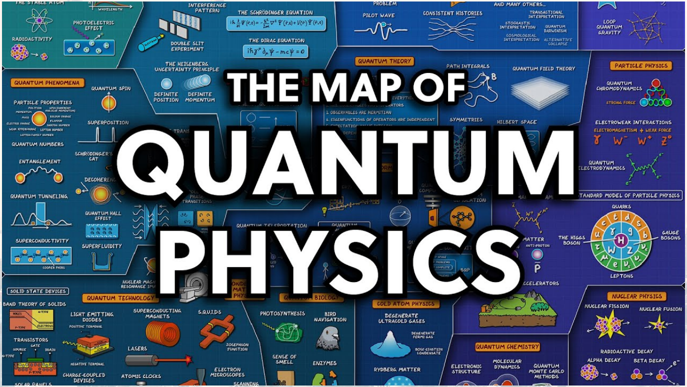




- Different final state: $t\bar{t} \to \ell^{\pm} + jets$.
- The limits of separability are shown at parton-level.
- **Entanglement is observed (expected) with 6.7σ (5.6σ).** Observed: $\Delta_E = -2.03 \pm 0.15$.
- Sensitivity at the threshold region is lower.
- **More details are in the talk by Regina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

What else?

Entanglement and Bell non-locality are both well known concepts, but **what else is out there**?



Quantum Information Hierarchy

- Full puzzle of quantum information in high-energy physics.
  YA, de Nova, PRL (2023).
- Quantum Discord:
  - The most basic form of quantum correlations.
  - Asymmetric between different subsystems.
  - Further studied in Han, Low, McGinnis, Su, JHEP (2025).
- 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.

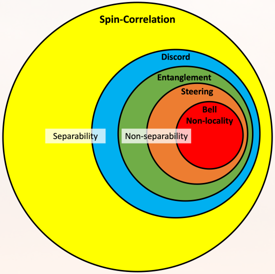


Figure: Schematic description of the relation between the different concepts discussed in the talk.

Bell Non-locality ⊂ Steering ⊂ Entanglement ⊂ Discord ⊂ Spin-Correlation

** Other concepts, like **magic and contextuality**, are not mentioned here.

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.

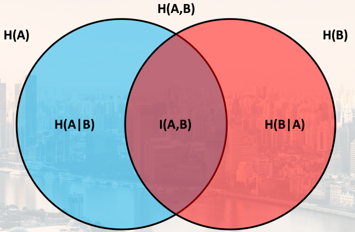


Figure: Schematic description of two subsystems with mutual information.

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.

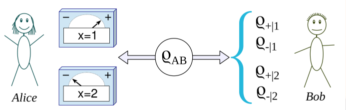


Figure: Schematic description of the steering phenomenon: Figure is from Uola, Costa, Nguyen, Gühne, Rev. Mod. Phys. (2020).

Discord and Steering Before Integration

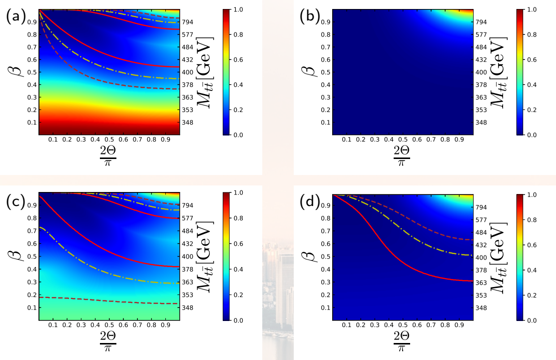
a) $gg \to t\bar{t}$ Discord.

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 $t\bar{t}$.

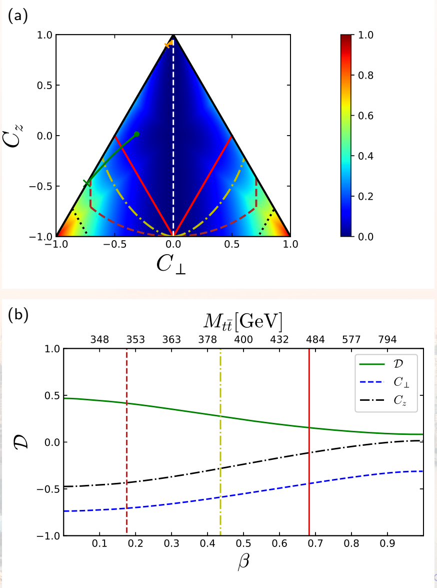
Discord and Steering After Integration

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

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

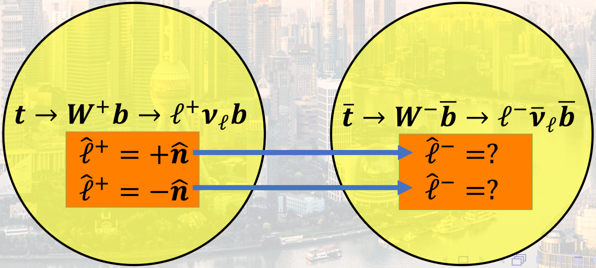
- Green: LHC trajectory; Orange: Tevatron trajectory.
- Cross: $\beta = 0$; Circle: $\beta = 1$.
- Quantum discord: $C_\perp \neq 0$. Solid red, dashed-dotted yellow, dashed brown, and dotted black lines are the critical boundaries of separability, steerability, Bell locality, and NAQC, respectively.

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 Quantum Information.
  - 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.

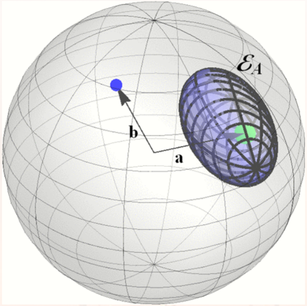
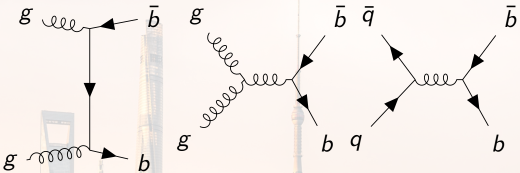
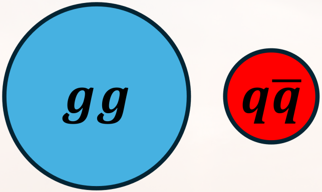


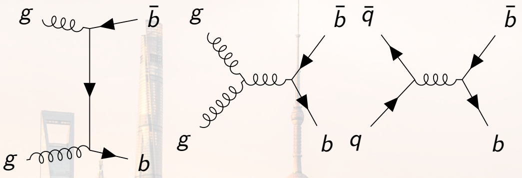
Figure: Ellipsoid representation of a two-qubit state. Figure is from Jevtic, Pusey, Jennings, Rudolph, PRL (2014).

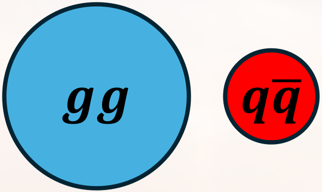
Outline

Production of $b\bar{b}$ at the LHC



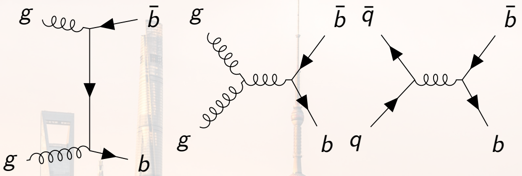


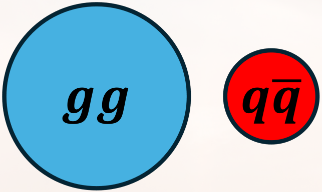




- Similar production mechanism as $t\bar{t}$, gg fusion is dominant at the LHC.
- Lower mass $\rightarrow$ more boosted ($m_b \sim 5$ GeV Vs. $m_t \sim 173$ GeV), i.e. typically $M_{b\bar{b}} \gg m_b$.
- Large cross-section.
- Jets typically contain b-hadrons, which allow efficient tagging of b-jets.

Production of $b\bar{b}$ at the LHC





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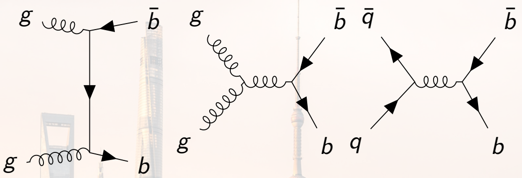

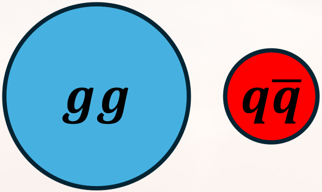

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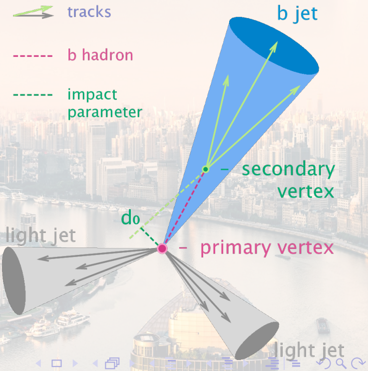
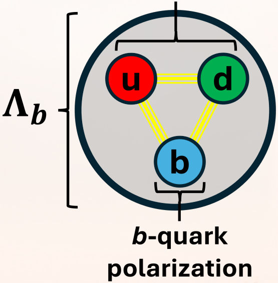


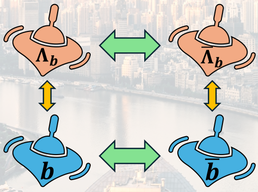
Reaching the $b\bar{b}$ Polarizations and Spin Correlations

- Spin-correlation measurements can be performed with Λ_b and $\overline{\Lambda}_b$.
  - The lightest, most commonly produced b-baryon.
  - ud-quarks: spin-singlet, isospin-singlet.
  - b-quark: carries the baryon spin.
  - Since $m_b \gg \Lambda_{\mathrm{QCD}}$, Λ_b baryons are expected to carry a large fraction of the original b-quark polarization.



- The retention factors r_L and r_T:

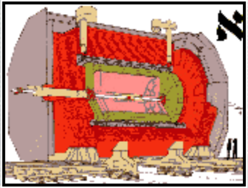
$$r_{\hat{\mathcal{P}}} = \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)}\,, \hat{\mathcal{P}} = L, T\,.$$



Determine how much of the polarization is transferred $b \to \Lambda_b$.

The Retention Factors

- In order to perform the measurement, we have to extract r_L, r_T.
  - Their values are expected to be roughly in the ranges $0.4 \lesssim r_L \lesssim 0.8$, $0.5 \lesssim r_T \lesssim 0.8$.
  - One possibility is to use dedicated control regions where significant entanglement is not expected while some of the elements C_{ij} are sizable.
- The polarizations have been measured in Z-boson decays at LEP, by ALEPH, OPAL, DELPHI.
  - An approximate combination gives $r_L = 0.47 \pm 0.14$.



OPAL

DELPHI

Spin Measurement with $b\bar{b}$

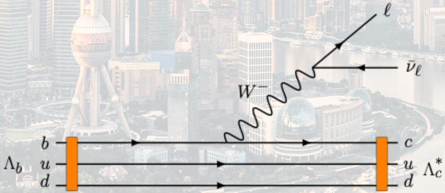
- We use $\Lambda_b \to X_c \ell^- \bar{\nu}_\ell$, where X_c denotes a charmed state containing a baryon, usually the Λ_c^+.
- Neutrinos as spin analyzers ($\alpha \simeq 1$):

$$\frac{1}{\sigma}\frac{d\sigma}{dx_{ij}} = \frac{1}{2}\left(1 - c_{ij}x_{ij}\right)\ln\left(\frac{1}{|x_{ij}|}\right),$$

where $x_{ij} = \cos\theta_i^+ \cos\theta_j^-$, and

$$c_{ij} = \alpha^2 r_i r_j C_{ij}\,.$$

- The retention factors: r_T goes for $i, j = n, r$ and r_L for $i, j = k$ indices.



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:

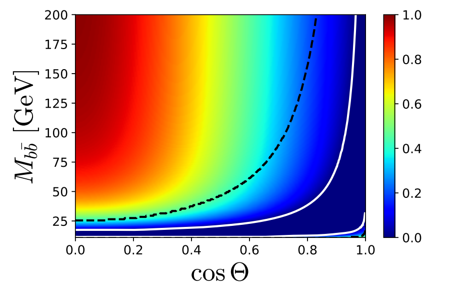
- A violation of the CHSH inequality: $\sqrt{\mu_1 + \mu_2} \geq 1$, where $0 \leq \mu_i \leq 1$ are the eigenvalues of $\mathbf{C}^{\mathrm{T}}\mathbf{C}$. A sufficient criterion:

$$\mathcal{V} \equiv C_{kk}^2 + C_{rr}^2 - 1 \leq \mu_1 + \mu_2 - 1\,.$$

$\mathcal{V} > 0$ is expected to accurately capture the Bell non-locality in the ultrarelativistic regime, in which $\mathbf{C}$ is diagonal, and $C_{kk}^2, C_{rr}^2 > C_{nn}^2$.

Entanglement and Bell Non-locality Before Integration

- Full LHC $\rho(M_{b\bar{b}}, \hat{k})$ Concurrence.
- Solid white line: entanglement limit; Dashed black line: Bell non-locality limit.
- Regions with strong quantum correlations:
  - $M_{b\bar{b}} \simeq 2m_b$: maximally entangled spin singlet.
  - Ultra-relativistic regime: maximally entangled spin-triplet state for transverse production ($\cos\Theta \simeq 0$).
- In practice, most events are boosted.



$$|\psi\rangle_{singlet} = \frac{1}{\sqrt{2}}(|\uparrow_{\hat{n}}\downarrow_{\hat{n}}\rangle - |\downarrow_{\hat{n}}\uparrow_{\hat{n}}\rangle)$$

$$|\psi\rangle_{triplet} = \frac{1}{\sqrt{2}}(|\uparrow_{\hat{n}}\downarrow\rangle_{\hat{n}} + |\downarrow_{\hat{n}}\uparrow_{\hat{n}}\rangle)$$

Experimental Setups

- ATLAS:
  - Large data size.
  - High trigger thresholds.
- CMS *B*-parking data:
  - Storing a large amount of raw detector data, with low trigger thresholds.
  - Processed when sufficient computational power is available to handle such data.
  - High statistics thanks to the low p_T thresholds.
- LHC*b*:
  - Smaller data size.
  - Low trigger thresholds and better reconstruction.

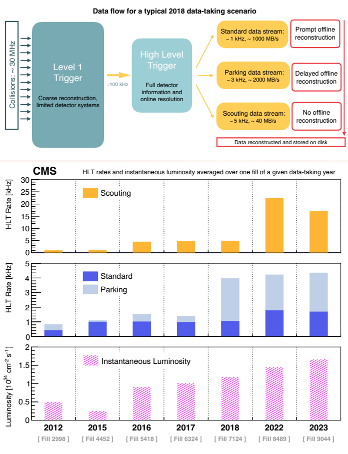


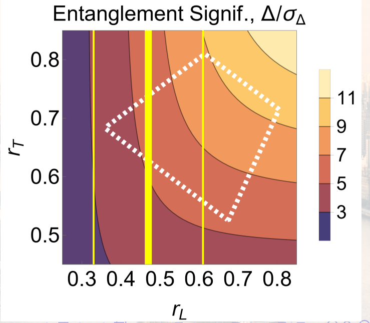
Figure: A schematic view of the typical Run 2 data flow (up) and comparison of the typical HLT rates (down) in the CMS experiment (CMS, 2403.16134).

Feasibility Study - A Glimpse to the Present

	$\sigma\epsilon_{\mu\mu}$ [pb]	$\mathcal{L}$ [fb^{-1}]	N	C_{kk}	C_{rr}	C_{nn}	Δ	$\mathcal{V}$	r_L	$\sigma_\Delta^{\text{stat}}$	$\sigma_\mathcal{V}^{\text{stat}}$	$\frac{\Delta}{\sigma_\Delta^{\text{stat}}}$	$\frac{\mathcal{V}}{\sigma_\mathcal{V}^{\text{stat}}}$	$\frac{\Delta}{\sigma_\Delta^{\text{tot}}}$	$\frac{\mathcal{V}}{\sigma_\mathcal{V}^{\text{tot}}}$
Run 2, $\sqrt{s} = 13$ TeV															
ATLAS	1.9×10^4	140	2.7×10^4	0.94	0.57	-0.56	0.54	0.21	0.75	0.14	0.33	3.9	0.6	3.1	0.6
									0.45	0.23	0.78	2.3	0.3	2.1	0.3
LHCb, $\Delta > 0.2$	3.9×10^6	5.7	1.8×10^4	0.55	0.67	-0.56	0.39	-0.24	0.75	0.17	0.34	2.2	-0.7	2.0	-0.7
									0.45	0.29	0.62	1.3	-0.4	1.3	-0.4
CMS B parking, $\Delta > 0.2$	7.9×10^5	41.6	1.8×10^5	0.76	0.63	-0.59	0.49	-0.03	0.75	0.055	0.120	8.9	-0.3	4.4	-0.3
									0.45	0.092	0.256	5.3	-0.1	3.6	-0.1

Table: Sensitivity studies: $r_T = 0.7$, systematic uncertainty of 20%.

- The expected significance of entanglement with CMS B-parking Run 2 data.
- Scanning the unknown r_L, r_T.
- White dotted polygon: plausible values for r_L and r_T.
- Vertical yellow lines: central value of r_L (thick line) and its $\pm 1\sigma$ uncertainties from LEP measurements.

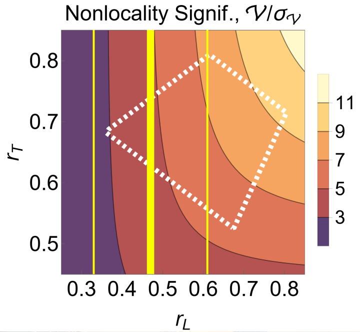


Feasibility Study - A Glimpse to the Future

ATLAS, $\mathcal{V} > 0.3$	9.9×10^4	3000	1.0×10^6	0.91	0.85	-0.83	0.79	0.55	0.75 0.45	0.02 0.04	0.06 0.13	> 10 > 10	8.7 4.3	4.9 4.9	4.3 3.3
LHCb, $\mathcal{V} > 0.3$	4.3×10^6	300	8.2×10^4	0.79	0.88	-0.81	0.74	0.43	0.75 0.45	0.080 0.135	0.215 0.406	9.2 5.5	2.0 1.0	4.4 3.7	1.8 1.0
CMS B parking, $\mathcal{V} > 0.2$	8.4×10^5	800	1.2×10^6	0.83	0.82	-0.78	0.71	0.35	0.75 0.45	0.021 0.036	0.055 0.110	> 10 > 10	6.4 3.2	4.9 4.9	3.9 2.7

Table: Sensitivity studies: $r_T = 0.7$, systematic uncertainty of 20%.

- The expected significance of Bell non-locality with HL-LHC ATLAS expected data.
- Scanning the unknown r_L, r_T.
- White dotted polygon: plausible values for r_L and r_T.
- Vertical yellow lines: central value of r_L (thick line) and its $\pm 1\sigma$ uncertainties from LEP measurements.



Outline

Summary

- Top-quark and bottom-quark pairs production have a rich phenomenology (also) when it comes to quantum information.
- It is amazing how much we can do with these two-qubit systems at colliders.
- **We are only at the beginning of the story!**

Summary

- Top-quark and bottom-quark pairs production have a rich phenomenology (also) when it comes to quantum information.
- It is amazing how much we can do with these two-qubit systems at colliders.
- **We are only at the beginning of the story!**
- **The collaboration between the theory and experimental communities is a key for the success of this rapidly evolving new line of research.**

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

Consolidating as a Community

- Input to the update of the European Strategy for Particle Physics: YA et al., 2504.00086.
- 71 authors:
  - Both theorists and experimentalists.
  - From high-energy physics and quantum information 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]

A Message to the Young Generation

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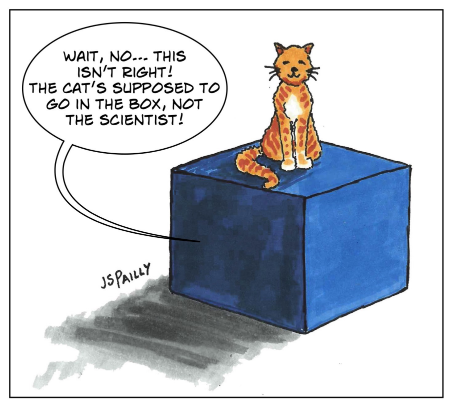
- Of course it doesn't mean that it is a good paper...

A Message to the Young Generation

- If your paper has been rejected by a journal, it doesn't mean that it is a bad paper.
- Of course it doesn't mean that it is a good paper...
- It could be that it is just not within the mainstream of the field.
- Our initial paper which established this line of research has been rejected a few times. But we insisted!
  Chronological order:
  - YA, de Nova, **EPJP** (2021).
  - YA, de Nova, **Quantum** (2022).
  - YA, de Nova, **PRL** (2023).
  - The ATLAS Collaboration, **Nature** (2024).
- Many other papers followed our ideas and further developed this field.
- Workshops took place to discuss quantum information observables in high-energy colliders.
- If you are confident that you have a good idea, don't give up.

Thank You


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

Backup

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).

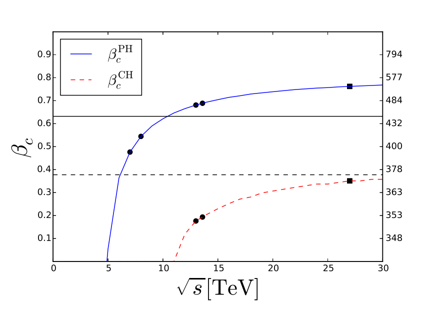


Figure: Critical values below which entanglement and CHSH violation can be observed, for different COM values.

Recent Related Measurement

- Recently, 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! See talk by James Howarth.**

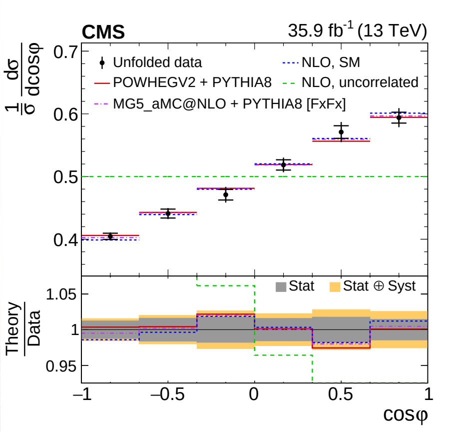


Figure: Distribution of $\cos\varphi$. Figure is from Phys. Rev. D 100, 072002.

Analysis Selection

- We apply similar selections to the ones applied in the experiments.
- Selections with Run 2 data:

	ATLAS	CMS B-parking	LHCb
Trigger	$2\mu^{\pm}$	displaced $1\mu^{\pm}$	$1\mu^{\pm}$
p_{T} (μ_1)	> 15 GeV	$> 7 - 12$ GeV	> 1.8 GeV
η (μ_1)	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 1.5$	$2 < \eta < 5$
p_{T} (μ_2)	> 15 GeV	> 5 GeV	> 0.5 GeV
η (μ_2)	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$2 < \eta < 5$
$N_{b-tagged}$	≥ 1	-	≥ 1
$M_{b\bar{b}}$	-	-	> 20 GeV
$p_{\mathrm{T}}^{\mu}/p_{\mathrm{T}}^{\mathrm{jet}}$	> 0.2 for at least 1μ	-	-
Tracks	-	-	2-4, displaced
Additional	-	-	$p_{\mathrm{T}}(X^{\pm}) > 1.6$ GeV, displaced
Λ_c^+ reco	Full reco on one of the sides		

- For HL-LHC the selections are the same, besides the ATLAS $2\mu^{\pm}$ muon threshold: p_{T} $(\mu_{1,2}) > 10$ GeV, $\lvert\eta(\mu_{1,2})\rvert < 2.5$.

Feasibility Study - Determine the Statistics

- For ATLAS and LHC*b*, we use:

$$N = 2\,\sigma\epsilon_{\mu\mu}\,\mathcal{L}\,f^2(b \to \Lambda_b)\,\mathrm{BR}^2(\Lambda_b \to X_c \mu^- \bar{\nu}_\mu) \\ \times \mathrm{BR}(\Lambda_c^+ \to \mathrm{reco.})\,\epsilon_{\mathrm{reco.}}\,\epsilon_{b,2}\,,$$

  - $\sigma\epsilon_{\mu\mu}$: the $b\bar{b}$ production cross section with muon cuts efficiency.
  - $\mathcal{L}$: integrated luminosity.
  - $f(b \to \Lambda_b) \approx 7\%$: fragmentation fraction for Λ_b.
  - $\mathrm{BR}(\Lambda_b \to X_c \mu^- \bar{\nu}_\mu) \approx 11\%$ and $\mathrm{BR}(\Lambda_c^+ \to \mathrm{reco.}) \approx 18\%$.
  - $\epsilon_{\mathrm{reco.}} \approx 50\%$: estimate for the average Λ_c^+ decay reconstruction efficiency.
  - $\epsilon_{b,2}$: the efficiency for at least one of the two jets to pass the *b*-tagging condition.

Feasibility Study - Determine the Statistics

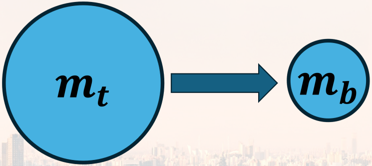
- For the CMS *B*-parking data, we use:

$$N = 2f^2(b \to \Lambda_b)\,\mathrm{BR}(\Lambda_b \to X_c \mu^- \bar{\nu}_\mu)\,\epsilon_{\mu_2} \times \mathrm{BR}(\Lambda_c^+ \to \mathrm{reco.})\,\epsilon_{\mathrm{reco}}\,N_0\ ,$$

  - $N_0 \approx 10^{10}$: the number of $b\bar{b}$ events in the CMS B parking dataset.
  - $\epsilon_{\mu_2} \approx 38\%$: the efficiency of selecting the muon on the non-triggering side of the event.

Spin Correlations with $b\bar{b}$ - Calculations

- Spin correlations of $b\bar{b}$ are not included in MC generators.
  - Calculated analytically.
  - Cross section and efficiency are calculated from simulation.
- How can we calculate the spin correlations analytically?
  - Same calculation as for $t\bar{t}$, with $m_t \rightarrow m_b$.



The Retention Factors

- In the heavy-quark limit:

$$r_L \approx \frac{1 + A\,(0.23 + 0.38w_1)}{1 + A}\,, \quad r_T \approx \frac{1 + A\,(0.62 - 0.19w_1)}{1 + A}\,.$$

The above expressions describe the dominant polarization loss effect, due to the contribution to the Λ_b sample from $\Sigma_b^{(*)} \to \Lambda_b \pi$ decays.

$$1 \leq A \leq 5\,, \qquad 0 \leq w_1 \leq 1\,.$$

where the chosen range for A reflects a large systematic uncertainty.

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 → Quantum tomography is the measurement of spin polarization **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 $\mathbf{C}$:

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