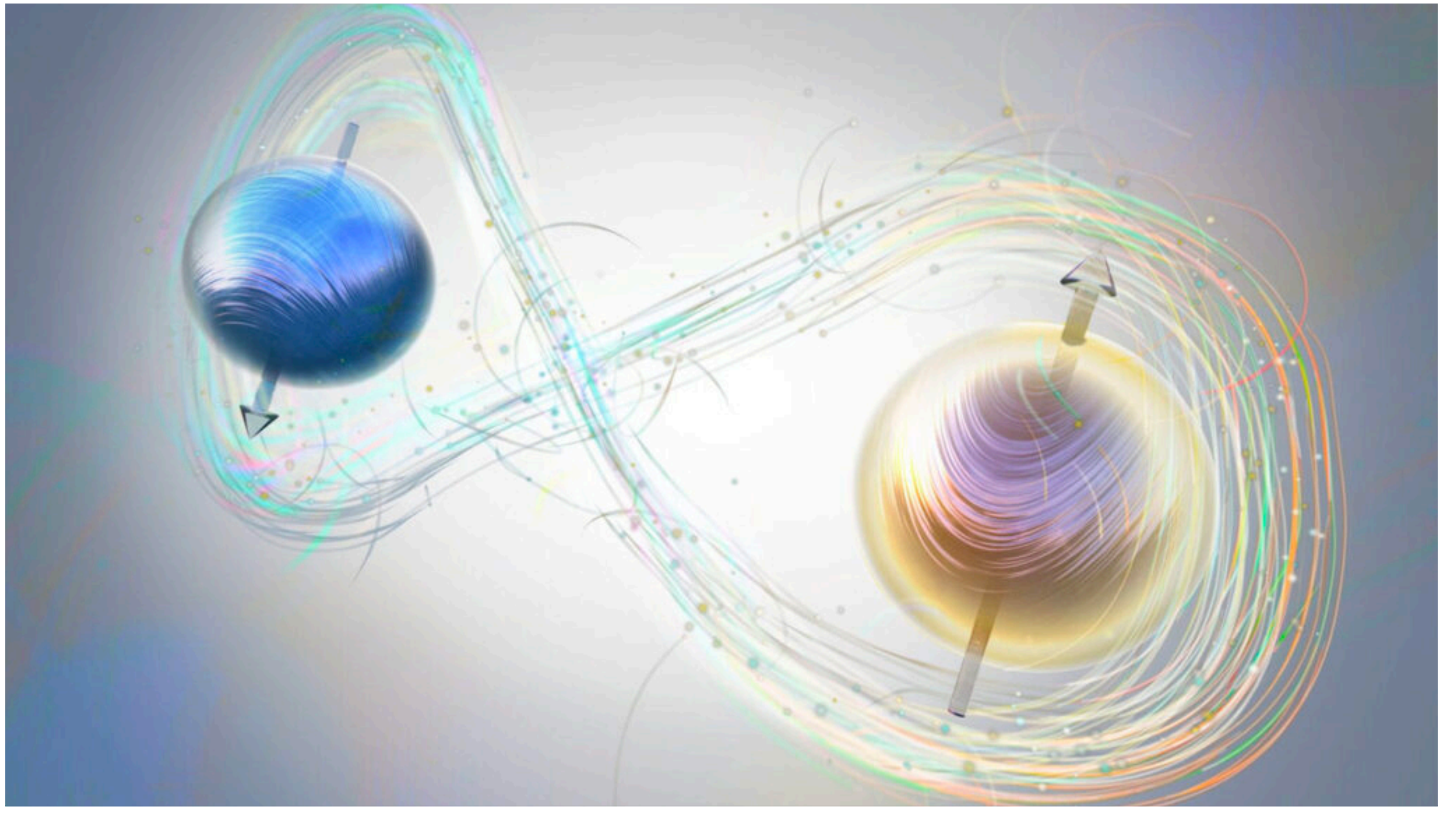
Entanglement and Bell inequalities with boosted top quarks

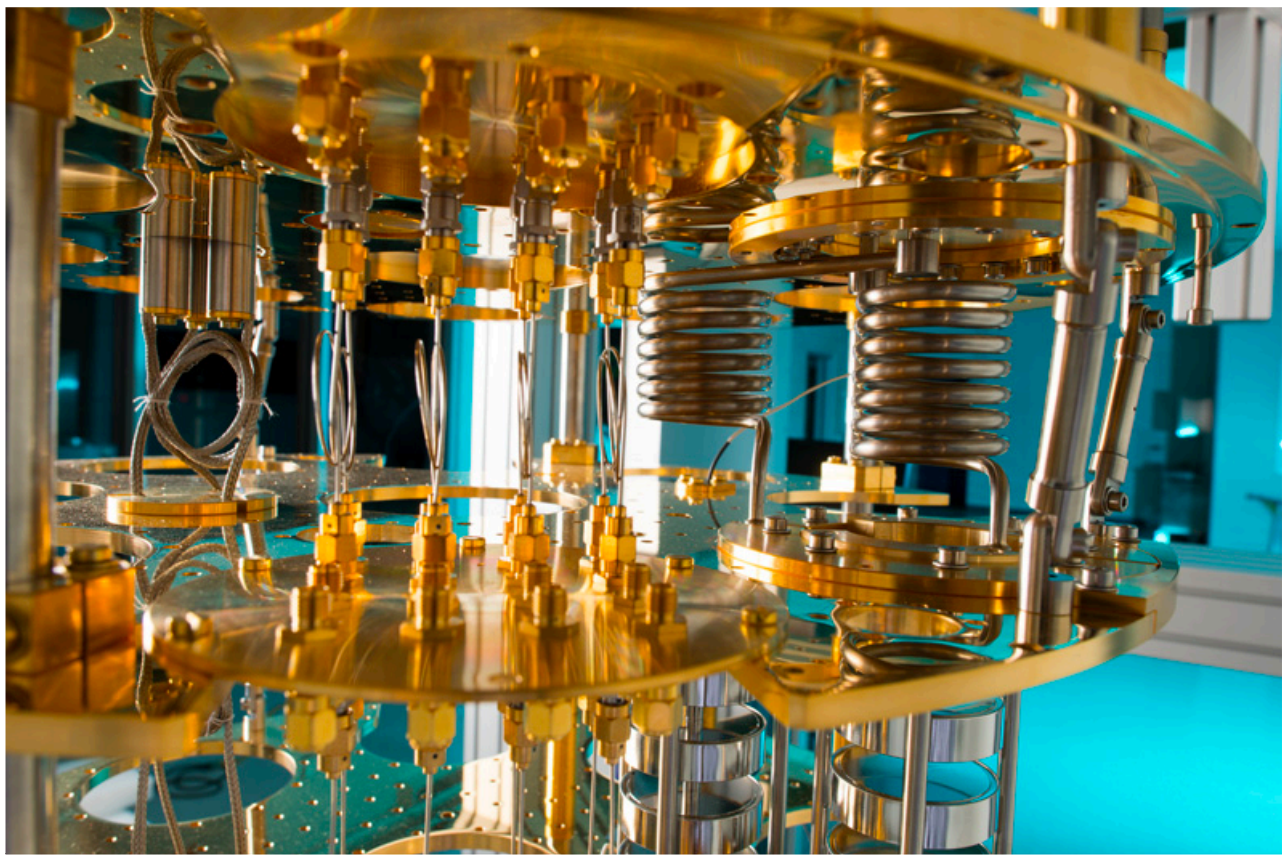
LPC EFT Workshop at Notre Dame - April 25, 2024

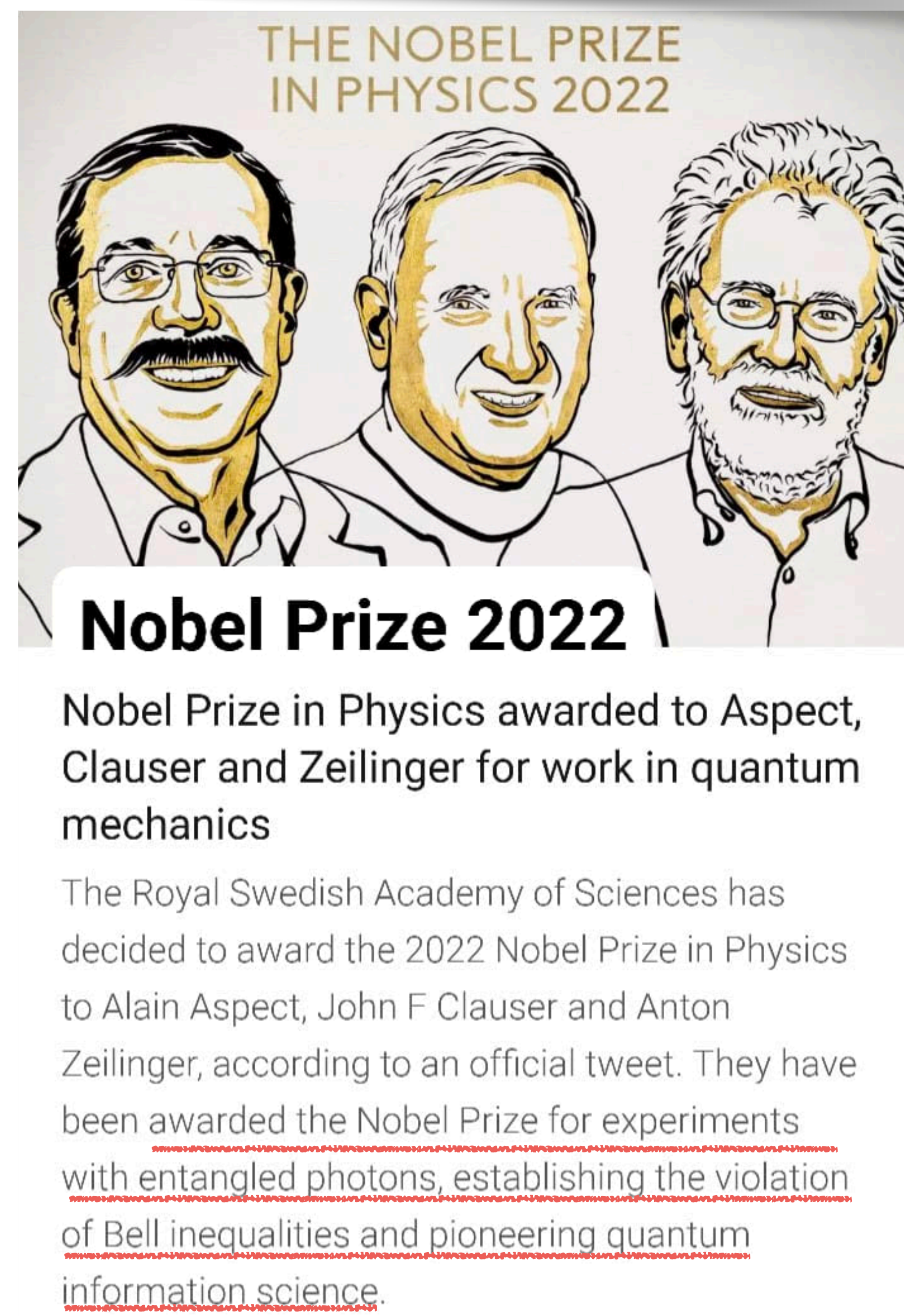
Dorival Gonçalves



arXiv:2305.07075: Z. Dong, DG, KC Kong, A. Navarro

Entanglement and Bell's Inequalities with Boosted Top Quarks

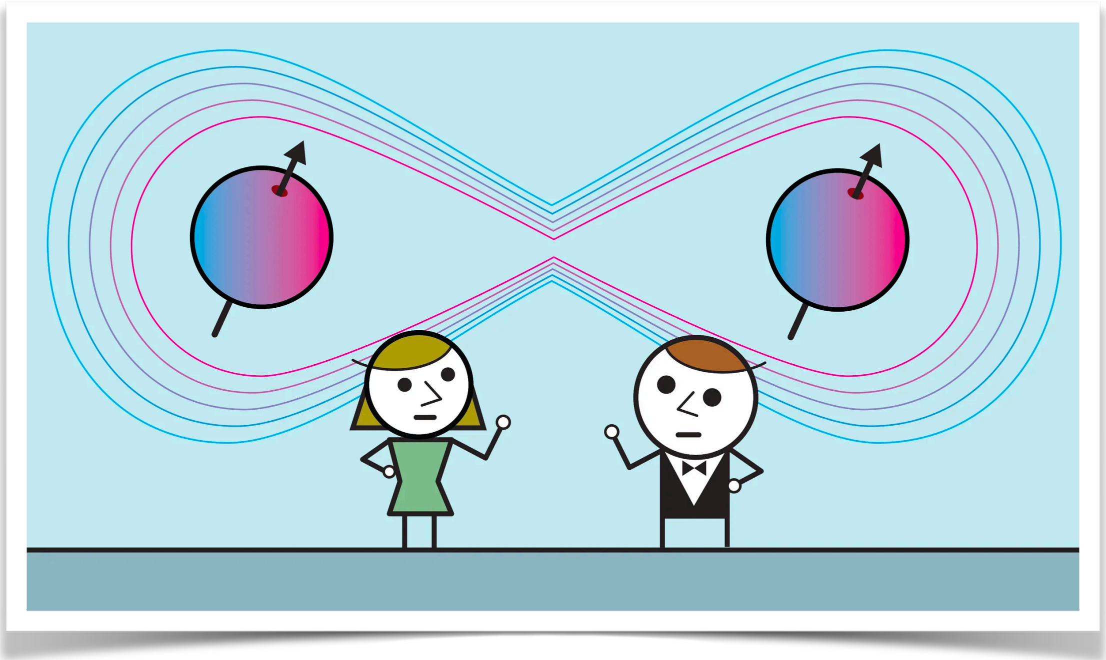


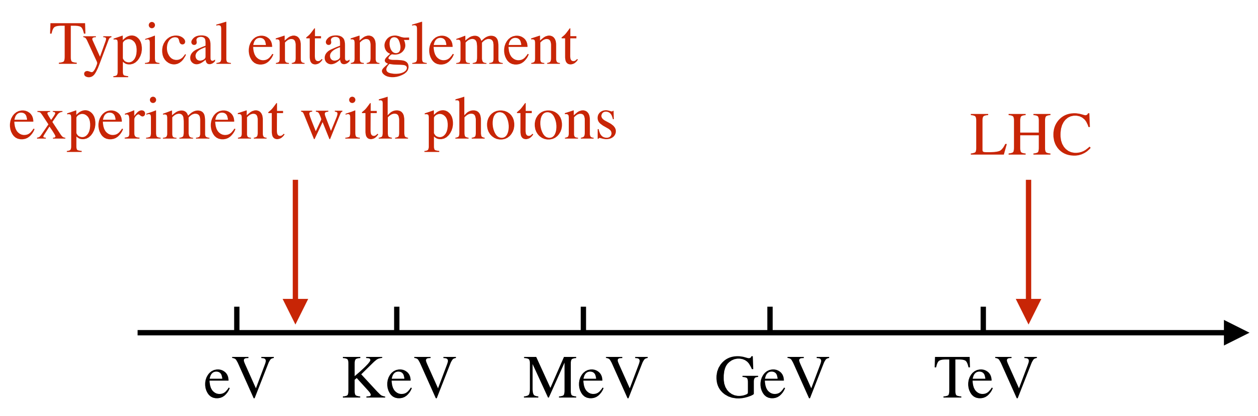


- QI theory provides a set of tools designed to probe the inner behavior of QM. While these phenomena have been widely tested at low energies, their study at higher energy scales has not be undertaken

Entanglement and Bell's Inequalities with Boosted Top Quarks

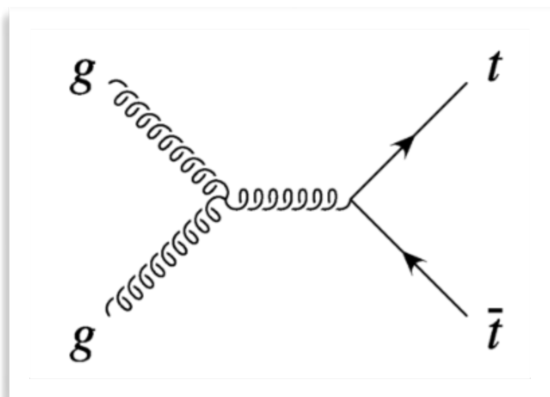
- LHC can provide a unique environment to study entanglement and violation of Bell's inequalities at the highest energy available today





- Top quark pair production is an optimal candidate for these studies

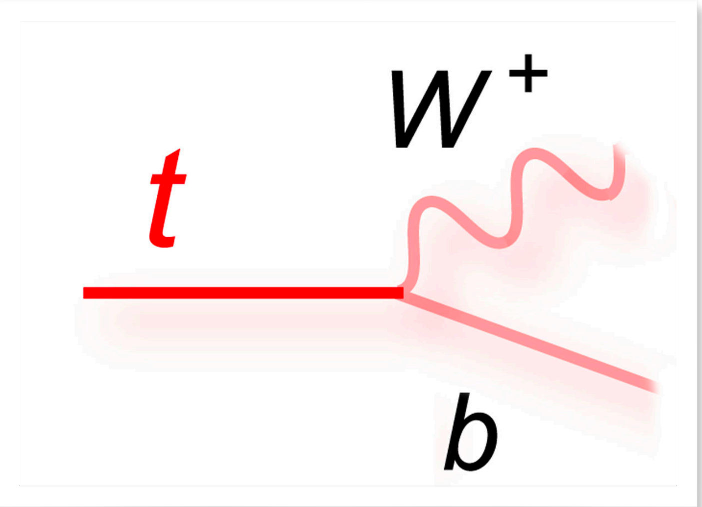
Afik, Nova '20; Fabbrichesi, Floreanini, Panizzo '21; Severi, Boschi, Maltoni, Sioli '21
Saavedra, Casas '22; Severi, Vryonidou 22
Dong, DG, Kong, Navarro '23



Top quark as a one qubit system

- As a spin-1/2 particle, the most general spin density matrix for the top quark is

$$\rho = \frac{\mathbb{I} + B_i \sigma_i}{2}$$



- Characterized by three parameters: $B_i = \langle \sigma_i \rangle = tr(\sigma_i \rho)$

→ However, the top quark decays. In general, spin information could be lost by hadronization or spin decorrelation effects

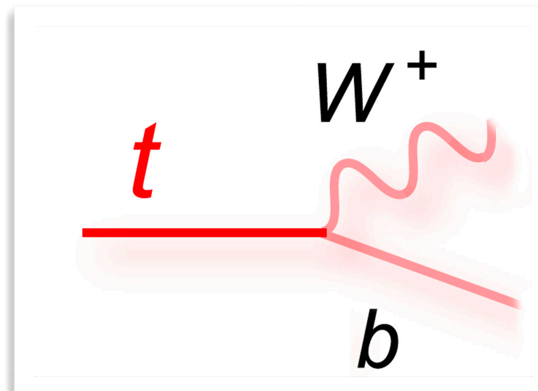
Top Quark is Unique

- Decays before it hadronizes or its spin flips

$$\tau_{top} \approx 5 \times 10^{-25} s$$

$$\tau_{had} \sim 1/\Lambda_{QCD} \sim 10^{-24} s$$

$$\tau_{flip} \sim m_t/\Lambda_{QCD}^2 \sim 10^{-21} s$$



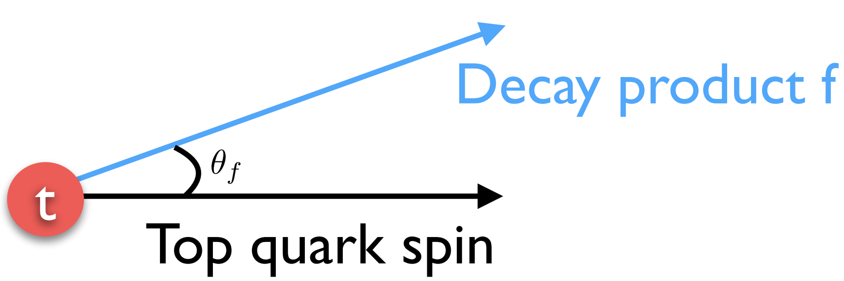
Bottom quark is several orders of magnitude behind $\tau_b \approx 10^{-12} s$

- Top polarization directly observable via angular distributions of its decay products

$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \omega_f \cos\theta_f)$$

	$l^+, \bar{d}$	b	$\bar{\nu}, u$
ω_f	1	-0.4	-0.3

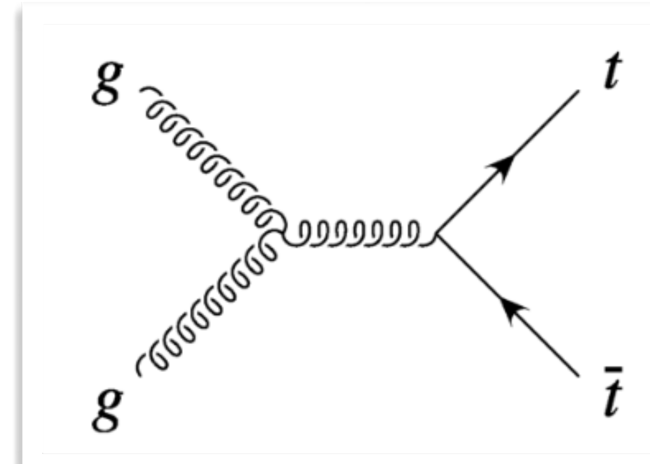
Spin analyzing power: maximum for charged leptons



Top quark pair production as a two qubit system

- The most general two-qubit system can be represented by

$$\rho = \frac{\mathbb{I}\otimes\mathbb{I}+\left(B_i\sigma_i\otimes\mathbb{I}+\bar{B}_i\mathbb{I}\otimes\sigma_i\right)+C_{ij}\sigma_i\otimes\sigma_j}{4}$$



- Characterized by 15 parameters parameters: B_i, $\bar{B}_i$, and C_{ij}

$B_i = \langle\sigma_i \otimes \mathbb{I}\rangle$ → Polarizations

$\bar{B}_i = \langle\mathbb{I} \otimes \sigma_i\rangle$ → Polarizations

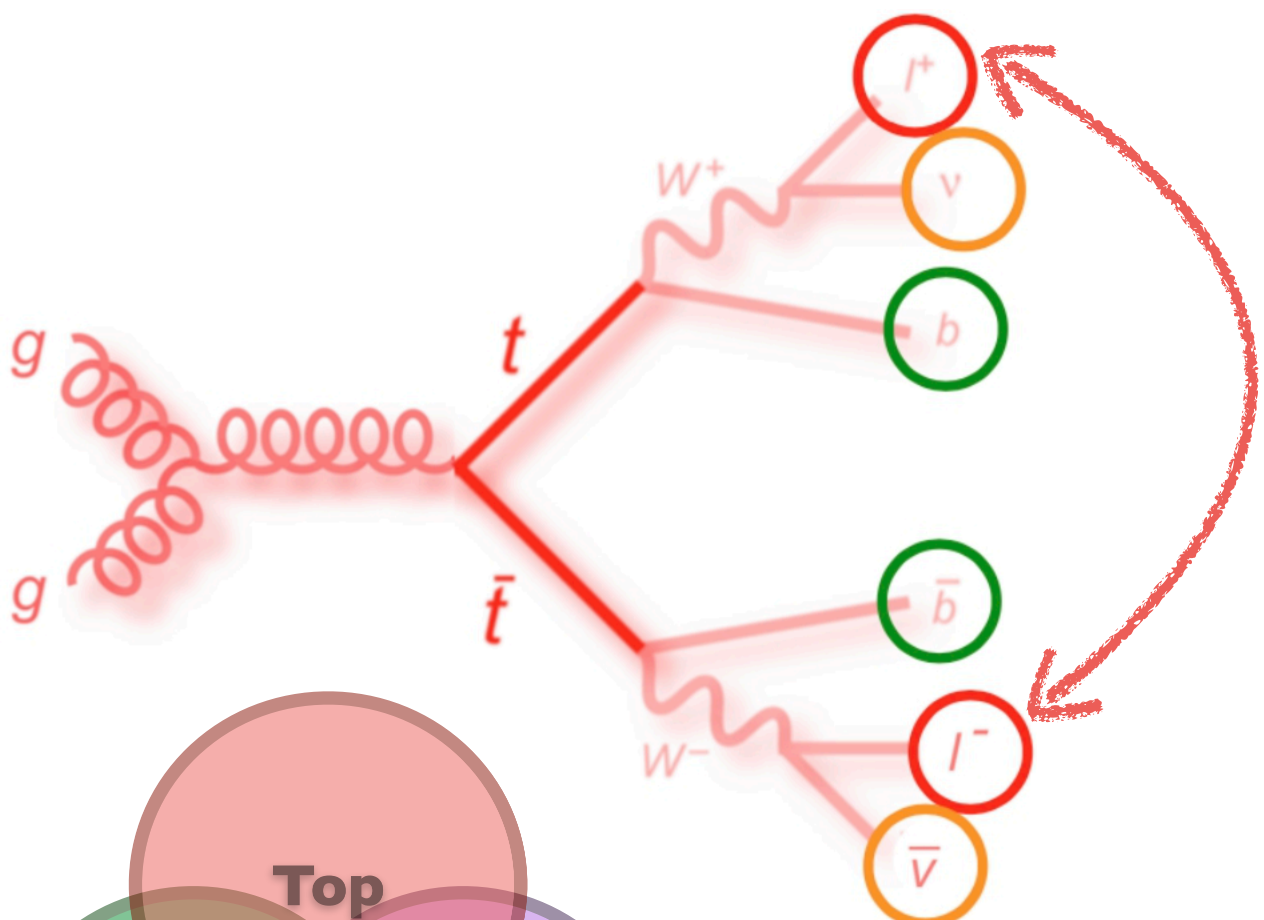
$C_{ij} = \langle\sigma_i \otimes \sigma_j\rangle$ ⟶ Spin correlations

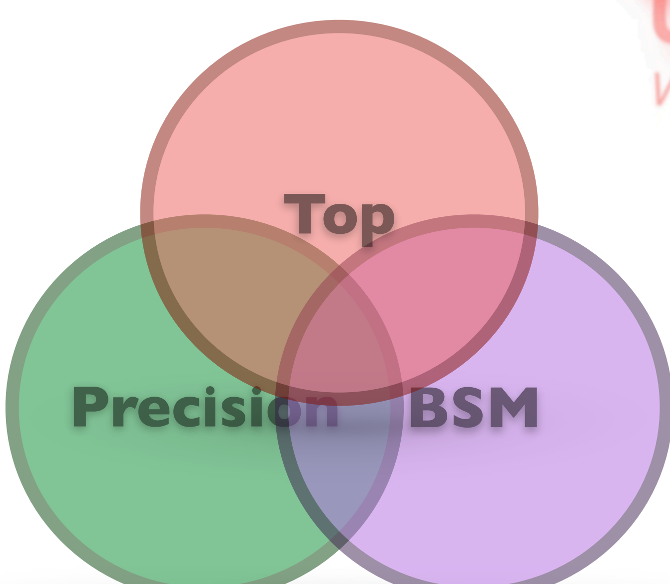
- P and CP invariance under $t\bar{t}$ production $\rightarrow B_i = \bar{B}_i = 0$ and $C_{ij} = C_{ji}$
- Things further simplify in the helicity basis: only non-vanishing parameters are the diagonal terms C_{ii} and one off-diagonal term $C_{12} \simeq C_{21}$

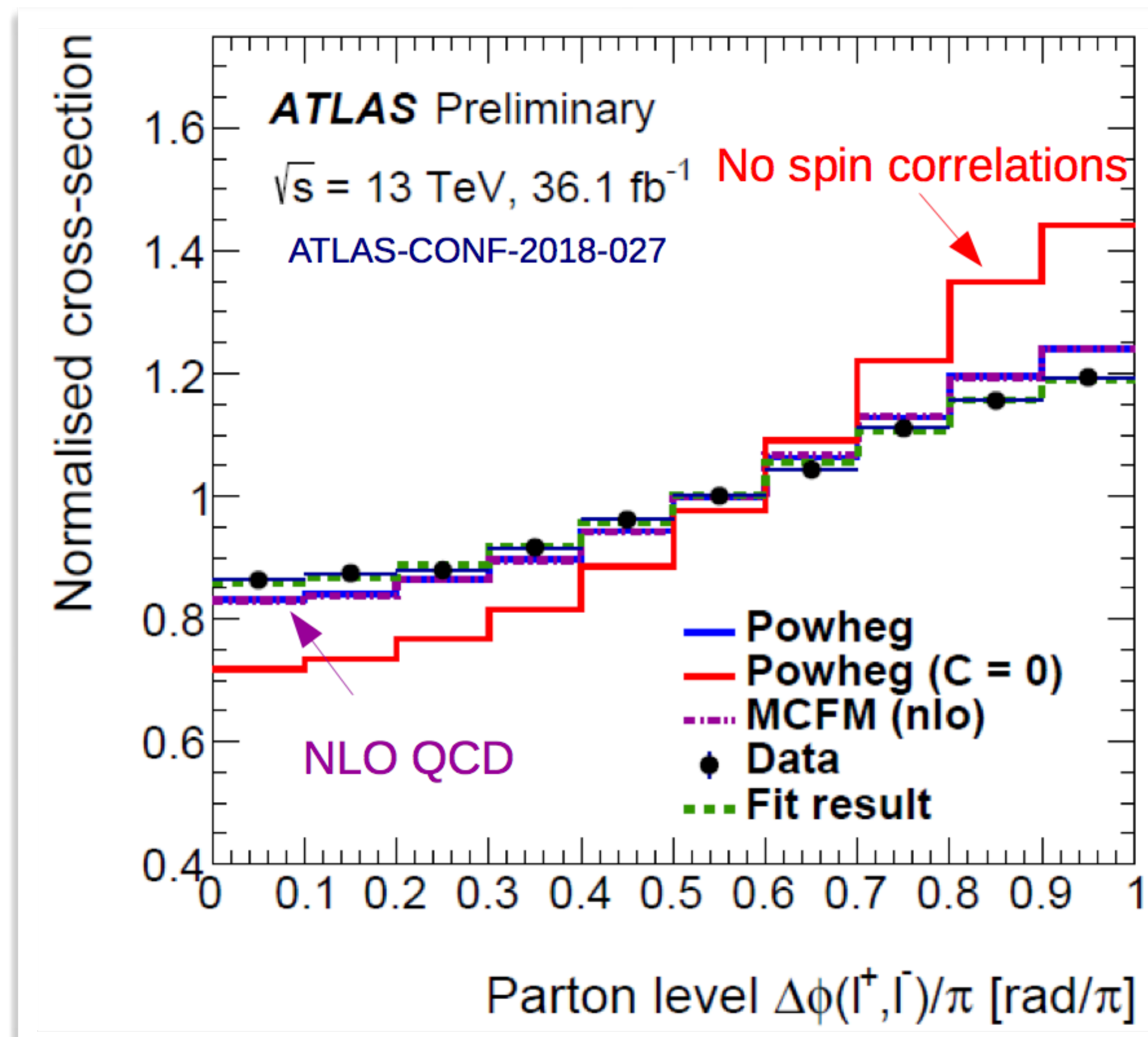
Bernreuther, Heisler, Si '15
Frederix, Tsinikos, Vitos '21

Top quark pair production as a two qubit system

- We are probing the spin correlations of top and anti-top since the Tevatron era and continue to study them at the LHC in different forms: relevant precision observable







Parke, Mahlon '95

Top quark pair production as a two qubit system

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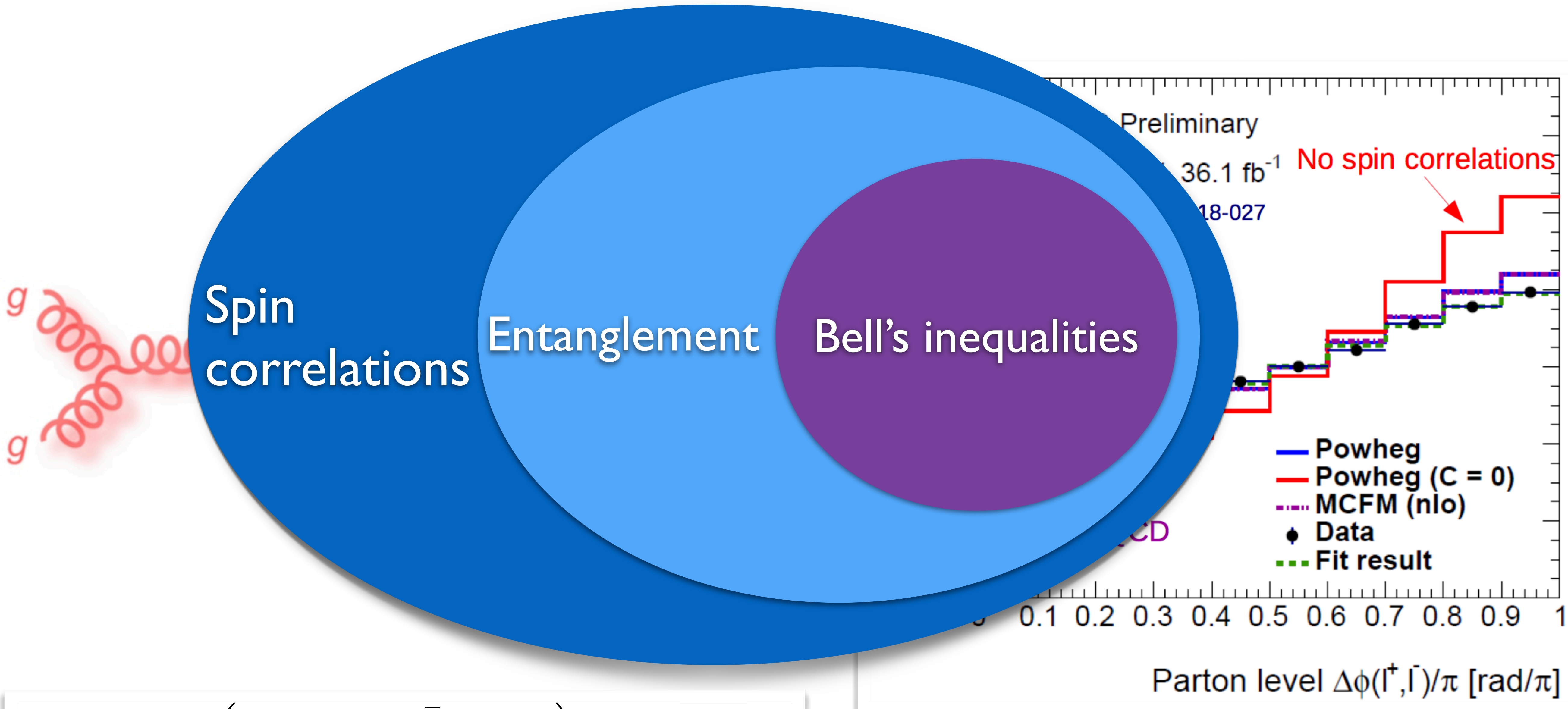


Parke, Mahlon '95

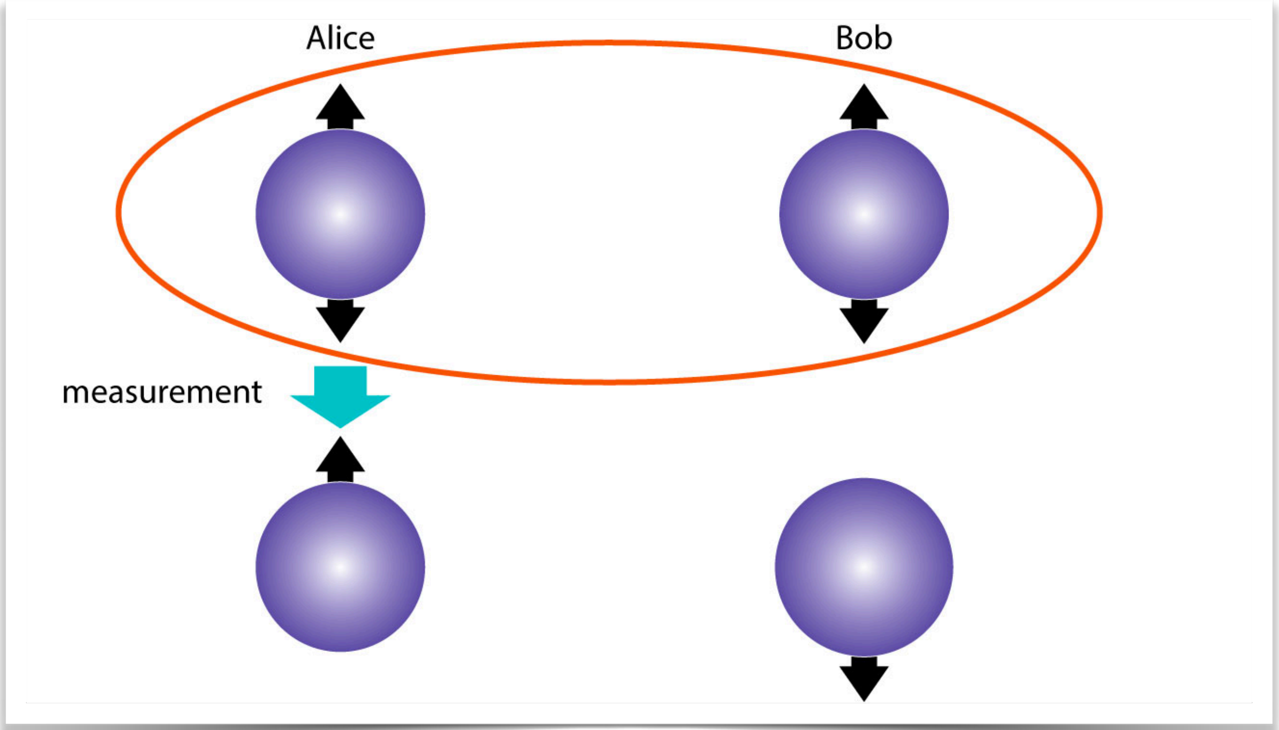
$$\rho = \frac{\mathbb{I}\otimes\mathbb{I} + \left(B_i\sigma_i\otimes\mathbb{I} + \bar{B}_i\mathbb{I}\otimes\sigma_i\right) + C_{ij}\sigma_i\otimes\sigma_j}{4}$$

Quantum Entanglement

- A quantum state of two subsystems A and B is separable when its density matrix ρ can be expressed as a convex sum

$$\rho = \sum_i p_i \rho_A^i \otimes \rho_B^i$$

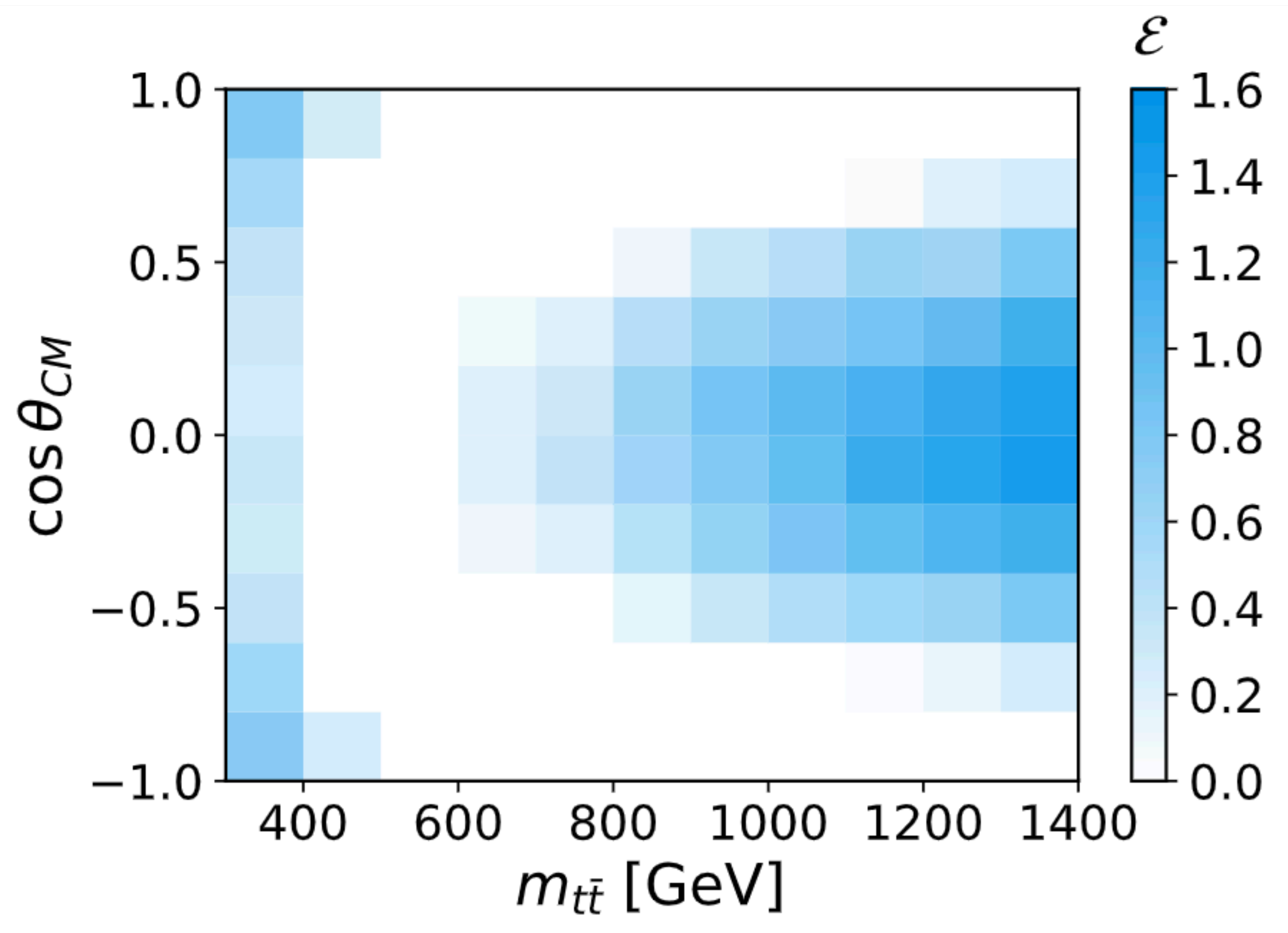
→ If the state is not separable, it is named *entangled*



Measurement in one subsystem immediately affect the other, even if they are causally disconnected

Quantum Entanglement

$$\mathcal{E} \equiv |C_{kk} + C_{rr}| - C_{nn} - 1 > 0$$

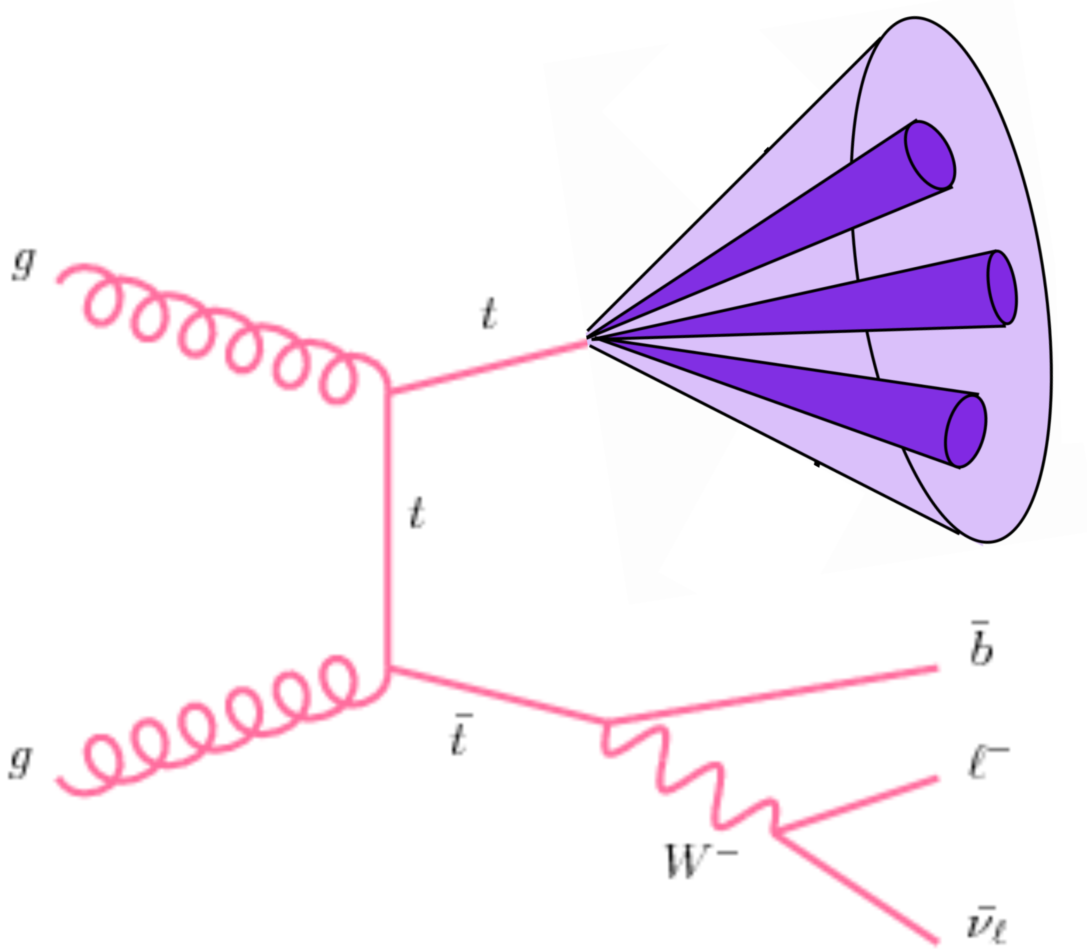


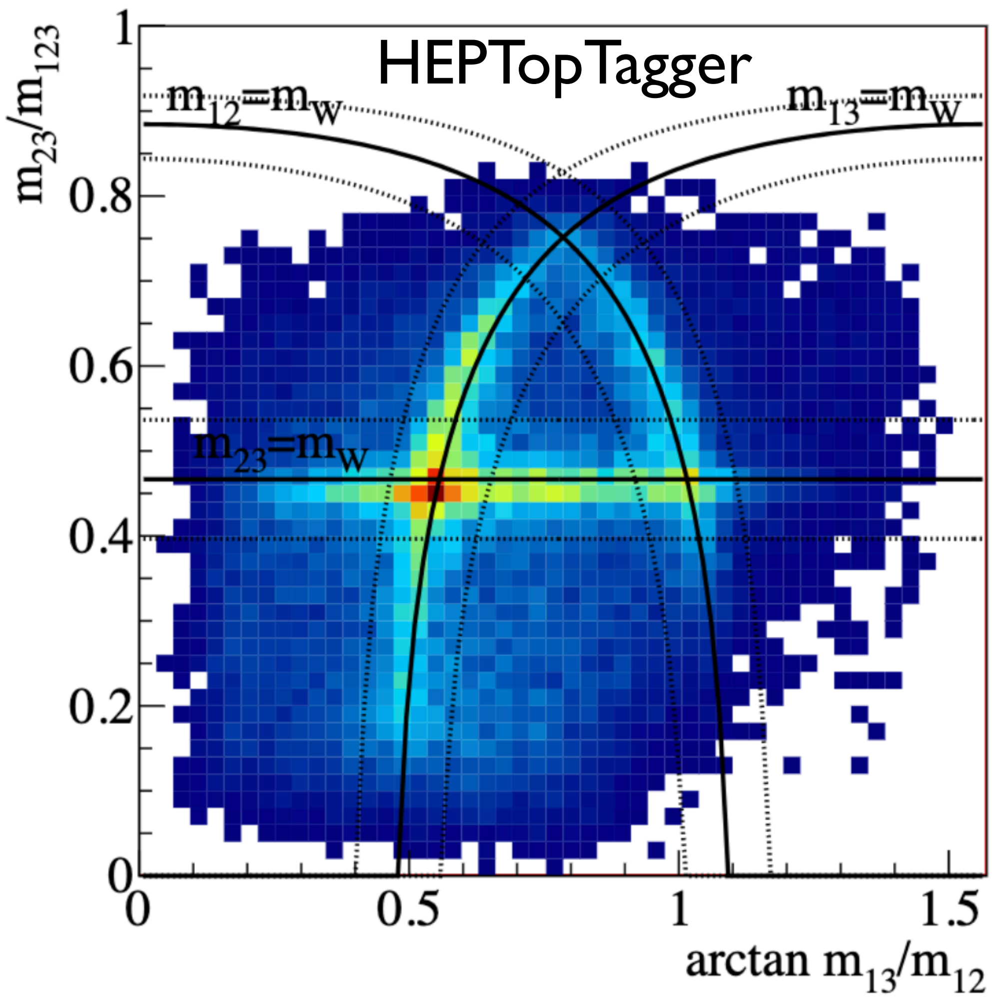
Dong, DG, Kong, Navarro '23

➡ Top pair displays entanglement in two disconnected regimes: **threshold** and **boosted** regions

Analysis

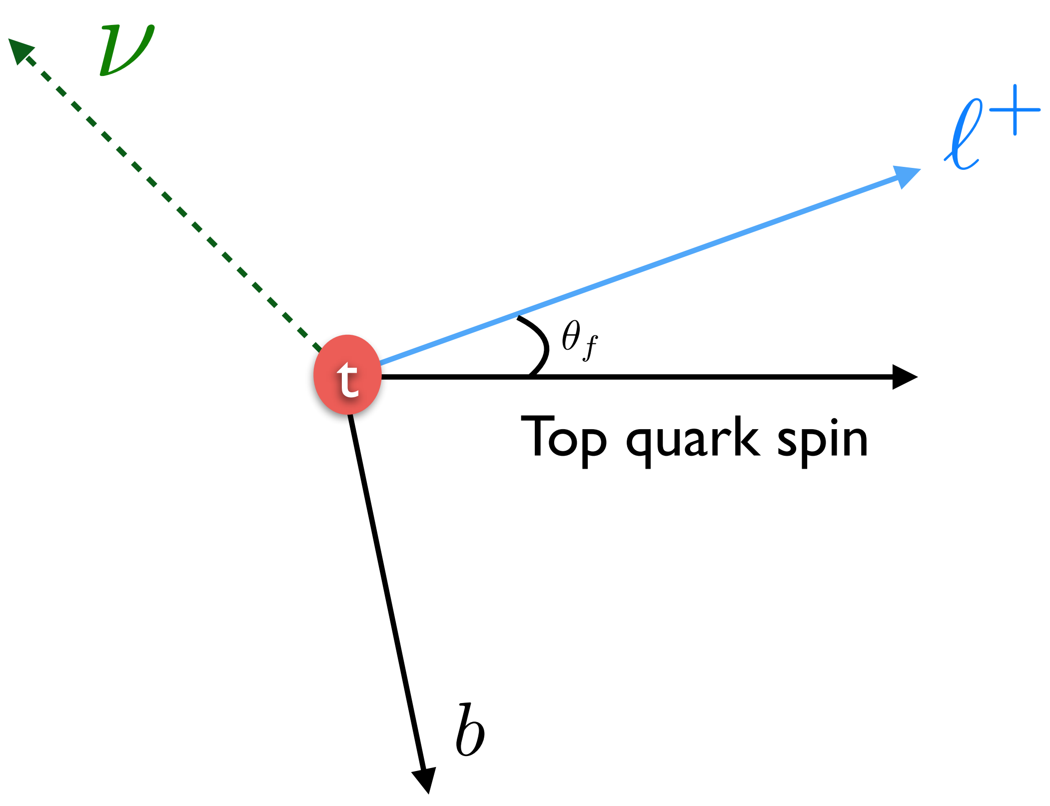
- Semi-leptonic top pair
  - High event rate: ~6 times higher than dileptonic case
  - Easier reconstruction
  - Boosted top tagging aid subject and light quark matching
  - Proxy for down-quark: optimal hadronic polarimeter





Hadronic top quark polarimetry

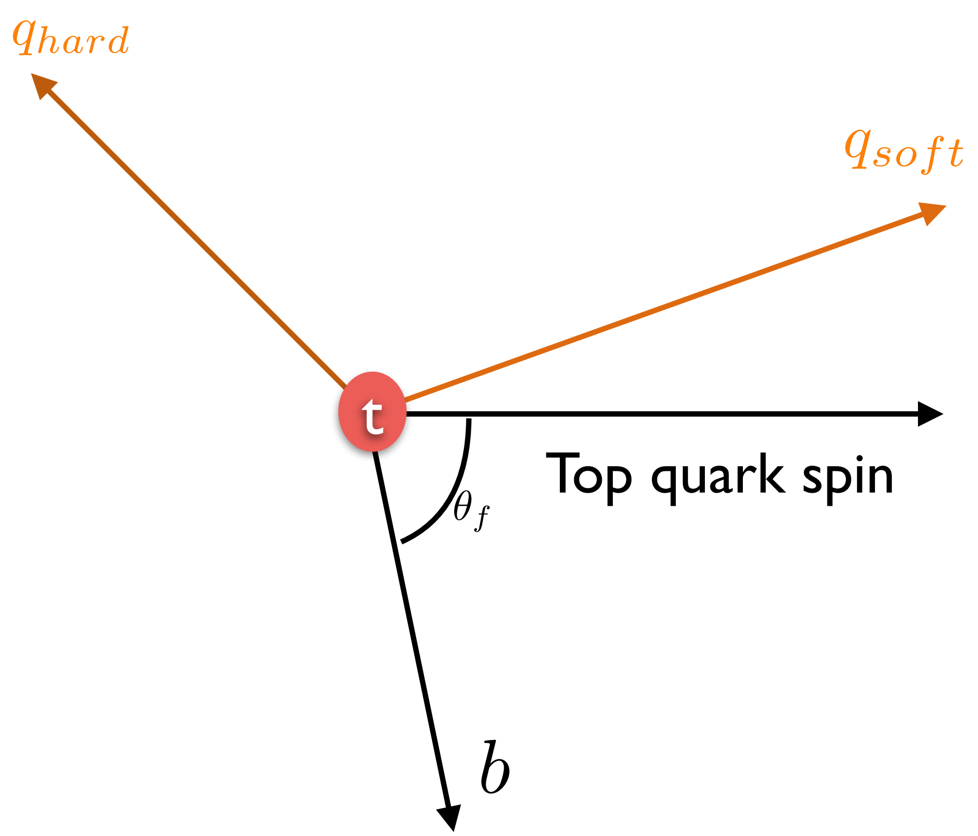
- In the high-energy regime, boosted techniques can be employed to tag the hadronic top and efficiently identify the optimal hadronic direction



$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \mathbf{1.0}\ \cos\theta_f)$$

Hadronic top quark polarimetry

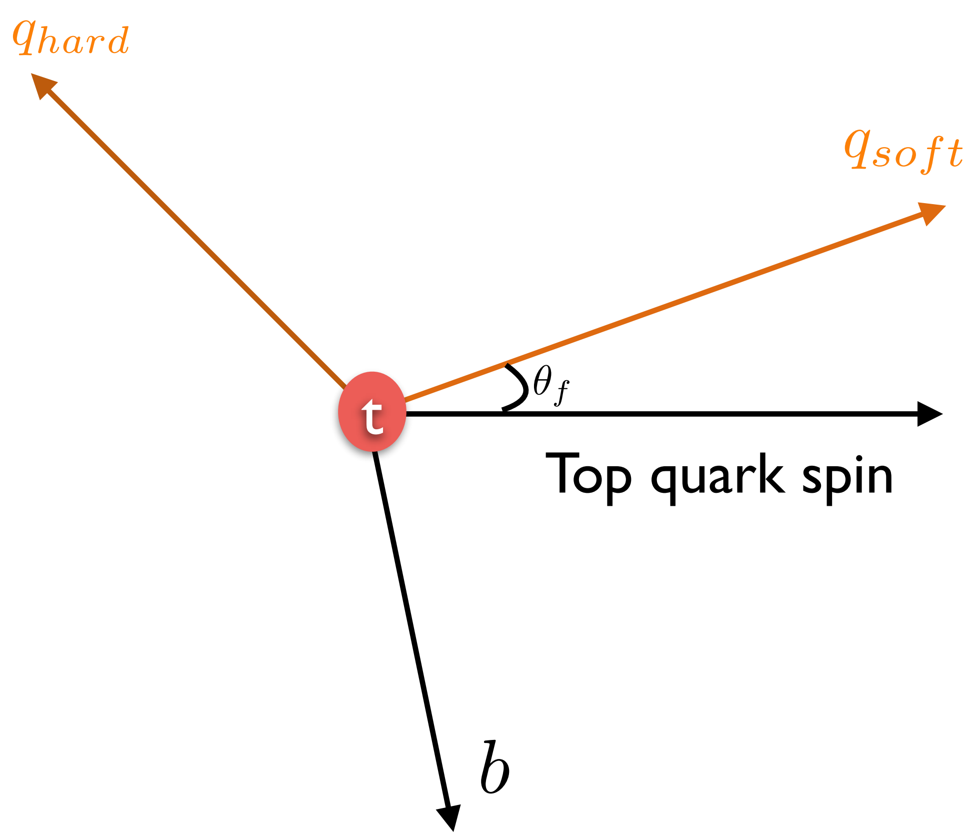
- In the high-energy regime, boosted techniques can be employed to tag the hadronic top and efficiently identify the optimal hadronic direction



$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 \;\; \mathbf{-0.4} \;\; \cos\theta_f)$$

Hadronic top quark polarimetry

- In the high-energy regime, boosted techniques can be employed to tag the hadronic top and efficiently identify the optimal hadronic direction



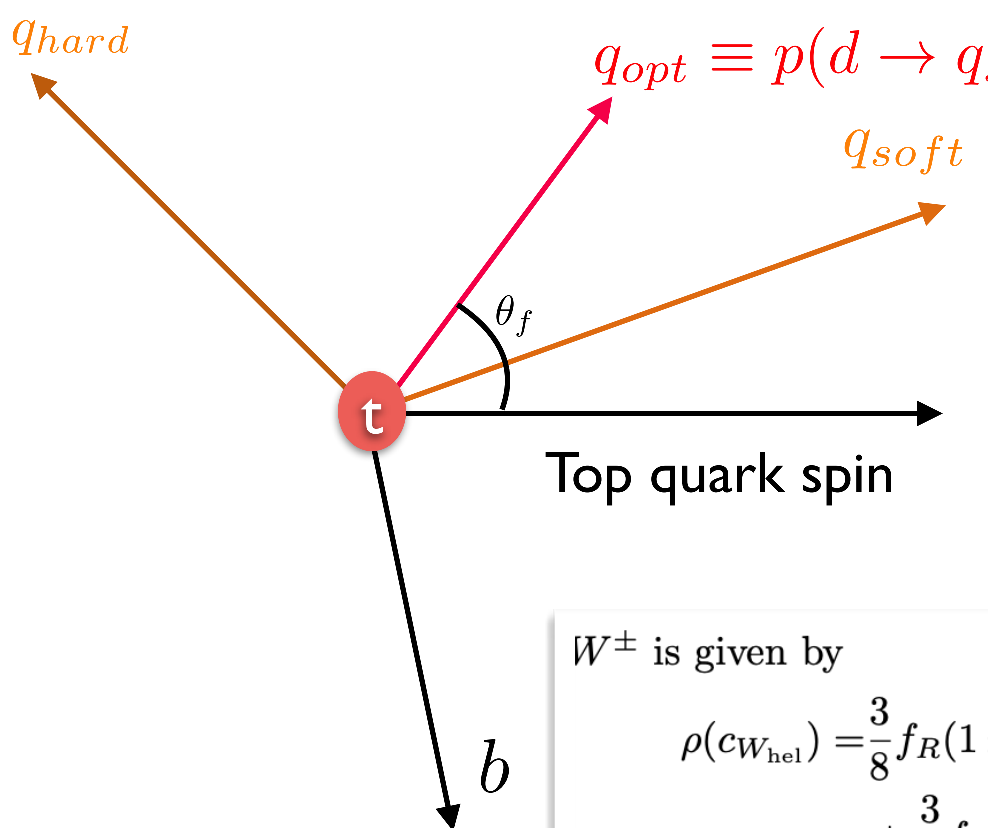
$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \mathbf{0.5}\,\cos\theta_f)$$

Jezabek '94

Hadronic top quark polarimetry

- In the high-energy regime, boosted techniques can be employed to tag the hadronic top and efficiently identify the optimal hadronic direction

$$q_{opt} \equiv p(d \to q_{soft})\hat{q}_{soft} + p(d \to q_{hard})\hat{q}_{hard}$$



$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \mathbf{0.64}\cos\theta_f)$$

$W^{\pm}$ is given by

$$\rho(c_{W_{\rm hel}}) = \frac{3}{8} f_R (1 \pm c_{W_{\rm hel}})^2 + \frac{3}{4} f_0 (1 - c^2_{W_{\rm hel}}) + \frac{3}{8} f_L (1 \mp c_{W_{\rm hel}})^2 .$$

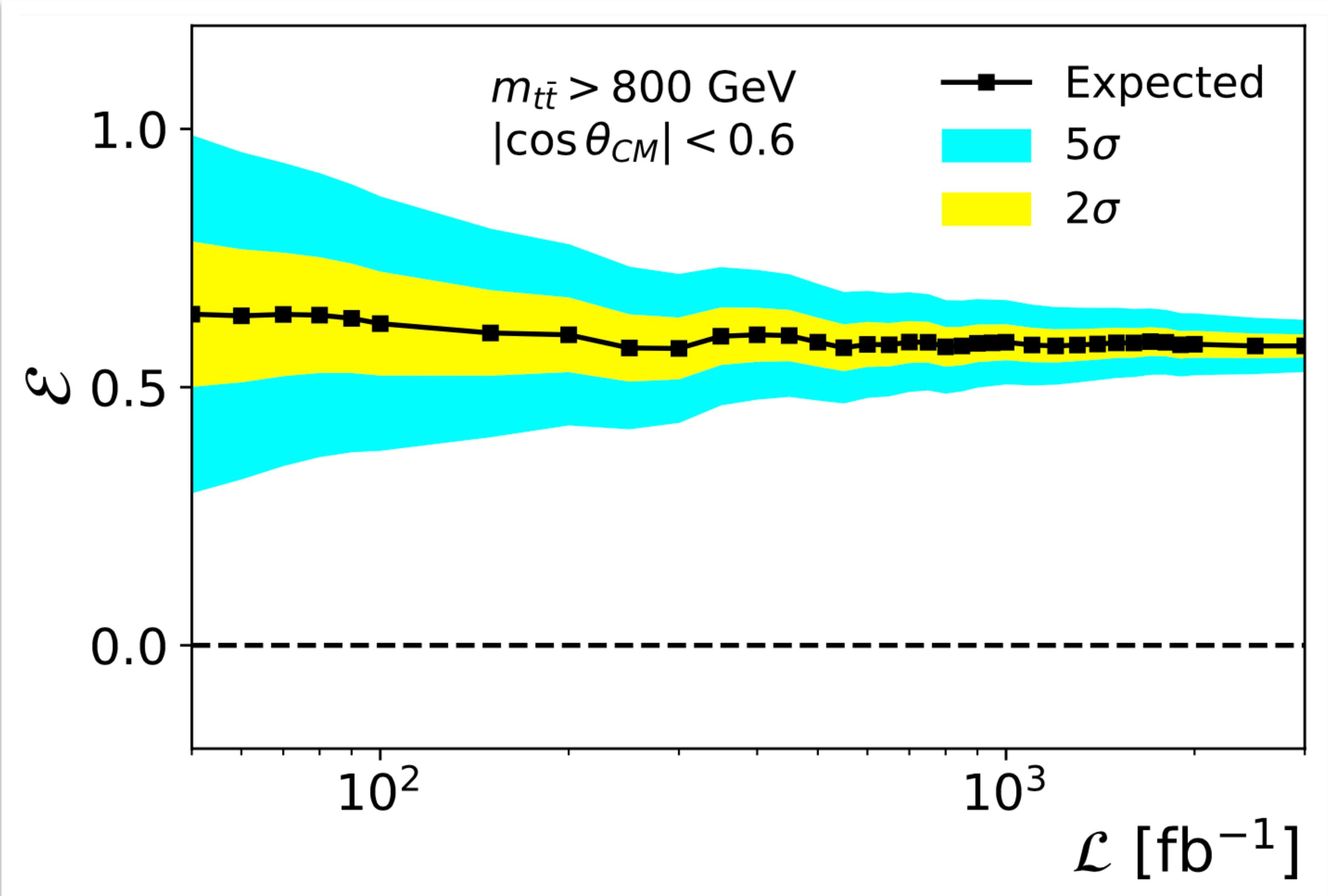
$$p(d \to q_{\rm hard}) = \frac{\rho(|c_{W_{\rm hel}}|)}{\rho(|c_{W_{\rm hel}}|) + \rho(-|c_{W_{\rm hel}}|)}$$

$$p(d \to q_{\rm soft}) = \frac{\rho(-|c_{W_{\rm hel}}|)}{\rho(|c_{W_{\rm hel}}|) + \rho(-|c_{W_{\rm hel}}|)}$$

Tweedie '14

LHC Projections

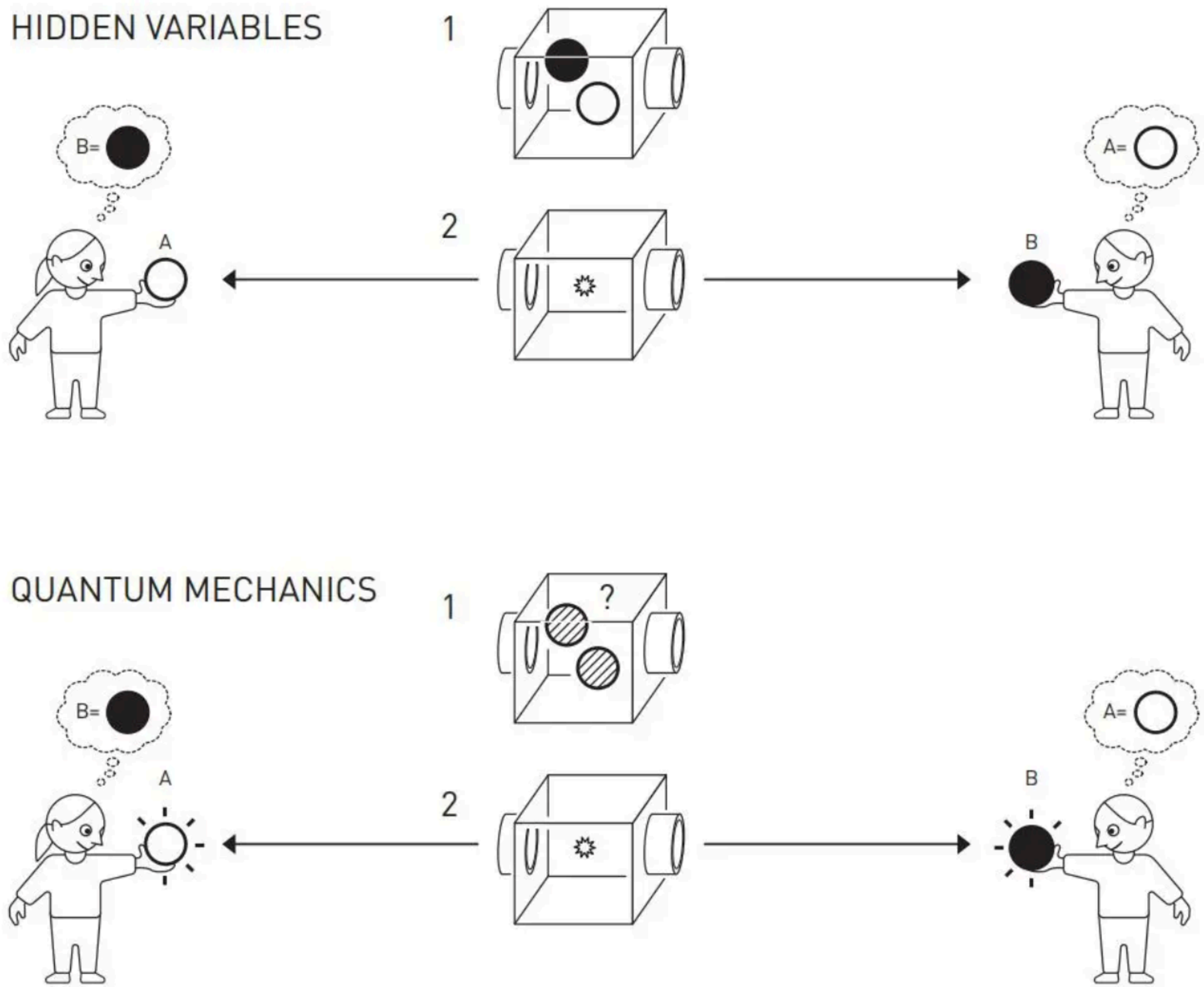
- Entanglement: $\mathcal{E} \equiv |C_{kk} + C_{rr}| - C_{nn} - 1 > 0$



Dong, DG, Kong, Navarro '23

➡ Current dataset can probe entanglement at 5-sigma level!

Bell’s Inequalities



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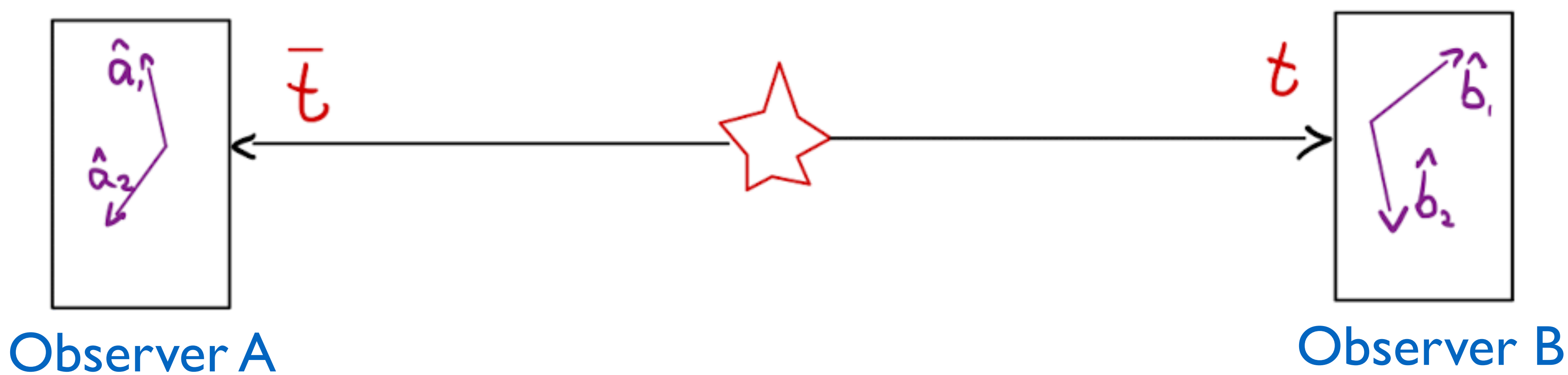
Bell's Inequalities

- Violation of Bell-type inequalities demonstrates that there is no hidden variable theory capable of encoding the generated entanglement. QM cannot be explained by classical laws

- Bell's inequality can be distilled in a simpler form: CHSH inequality

Clauser, Horne, Shimony, Holt '69

$$|\langle A_1 B_1 \rangle + \langle A_2 B_1 \rangle + \langle A_1 B_2 \rangle - \langle A_2 B_2 \rangle| \leq 2$$

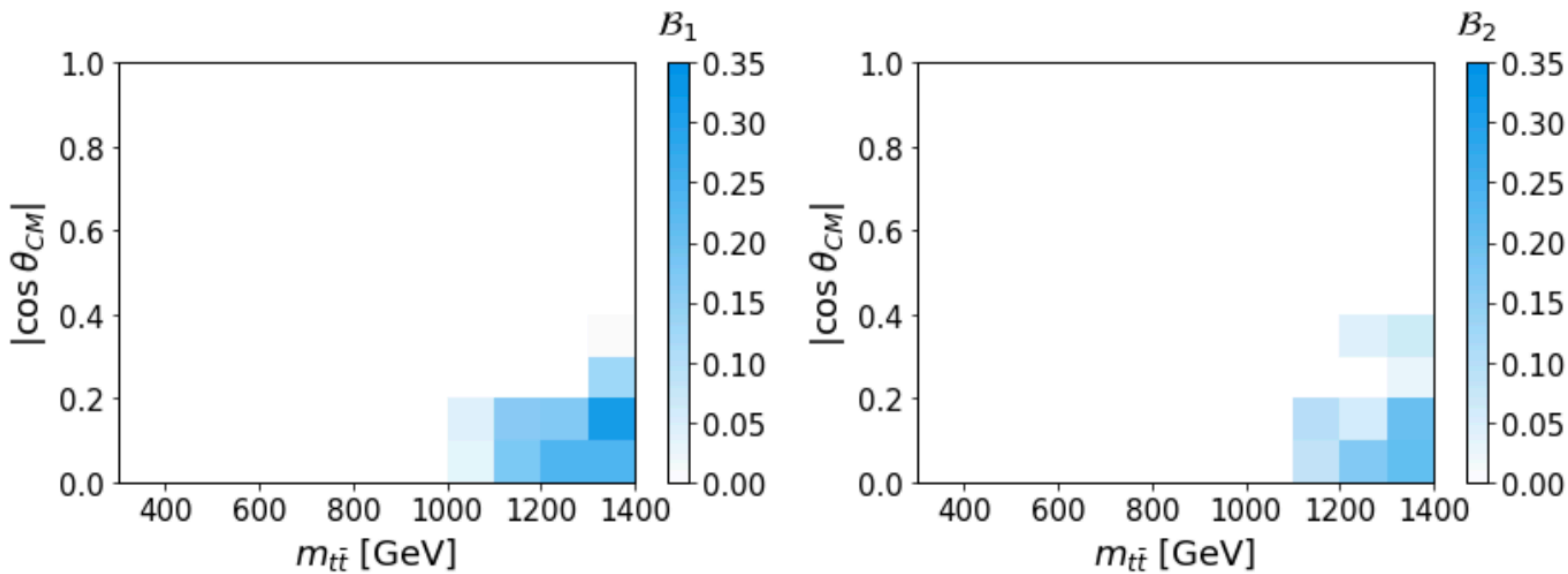


Bell's Inequalities

- Bell/CHSH inequalities:

$$\mathcal{B}_1 \equiv |C_{rr} - C_{nn}| - \sqrt{2} > 0$$
$$\mathcal{B}_2 \equiv |C_{kk} + C_{rr}| - \sqrt{2} > 0,$$

Afik, Nova '20
Severi, Boschi, Maltoni, Sioli '21
Saavedra, Casas '22



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→ Bell/CHSH violation studies well match **boosted** top pair searches

LHC Projections

- Bell/CHSH inequalities: $\mathcal{B}_1 \equiv |C_{rr} - C_{nn}| - \sqrt{2} > 0$
  $\mathcal{B}_2 \equiv |C_{kk} + C_{rr}| - \sqrt{2} > 0,$

Afik, Nova '20
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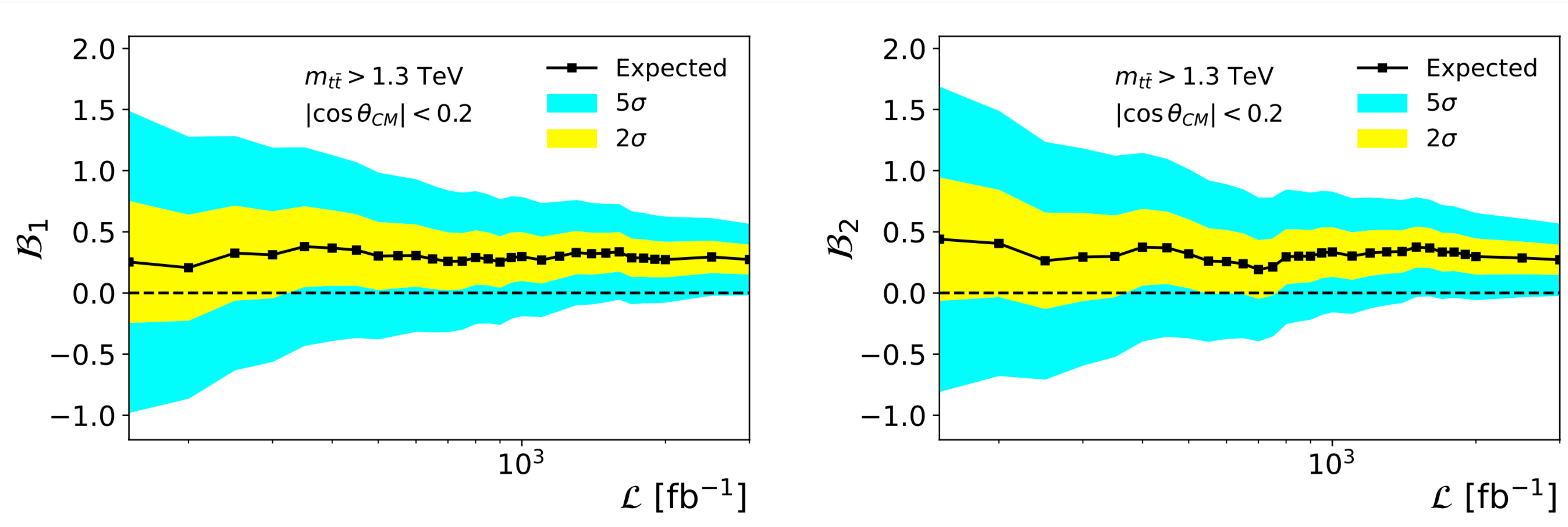


Indicator	Parton-level	Unfolded	Significance ($\mathcal{L} = 3$ ab^{-1})
$\mathcal{B}_1$	0.267 ± 0.023	0.274 ± 0.057	4.8
$\mathcal{B}_2$	0.204 ± 0.023	0.272 ± 0.058	4.7

Dong, DG, Kong, Navarro '23

We are just at the beginning

Observation of quantum entanglement in top-quark pair production using pp collisions of $\sqrt{s} = 13$ TeV with the ATLAS detector

28th September 2023

The ATLAS Collaboration

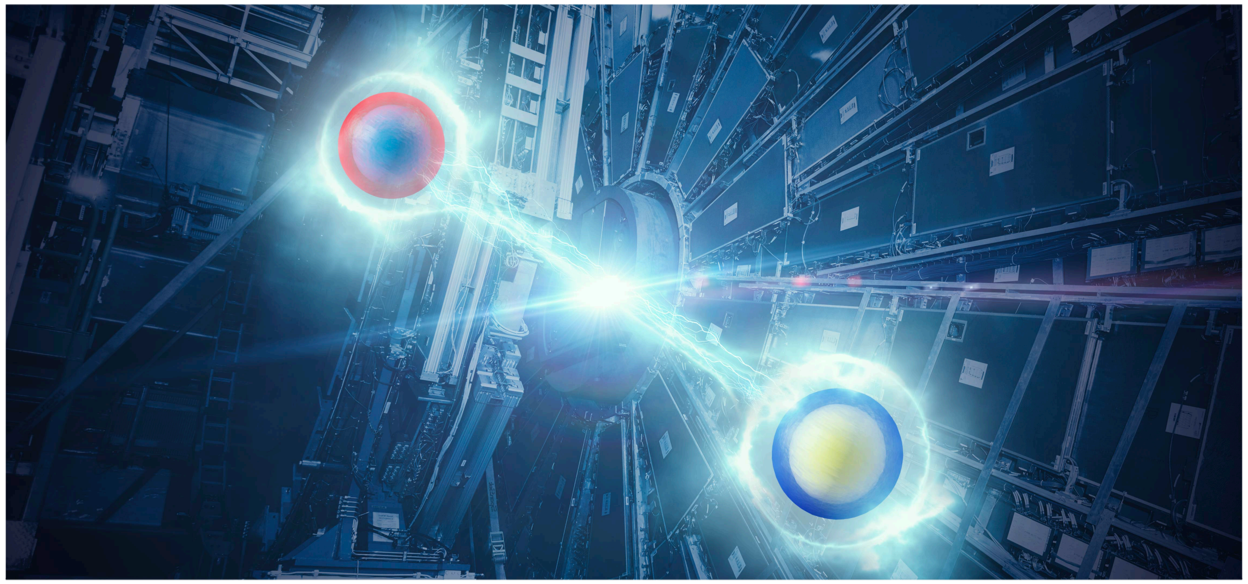
We report the highest-energy observation of entanglement so far in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision data set with a centre-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 fb^{-1}. Spin entanglement is detected from the measurement of a single observable D, inferred by the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured on a narrow interval around the top-quark–antitop-quark production threshold, where the entanglement detection is expected to be significant. The entanglement observable is measured in a fiducial phase-space with stable particles. The entanglement witness is measured to be $D = -0.547 \pm 0.002$ (stat.) ± 0.021 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The large spread in predictions from several mainstream event generators indicates that modelling this property is challenging. The predictions depend in particular on the parton-shower algorithm used. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks, and the observation of entanglement at the highest energy to date.

Summary

- LHC provides a unique opportunity to study quantum correlations, such as entanglement and violation of Bell's inequalities, at high energy scales: quantum tomography

- Boosted semileptonic top pair searches well match entanglement and CHSH studies:
  - High event rate
  - Boosted top tagging aid subject and light quark matching
  - Optimal hadronic polarimeter

- We are just at the beginning:
  - ATLAS announced few months ago the first measurement of entanglement @LHC. We are looking forward to the CMS results
  - Bell/CHSH violation may be probed at 4-5 sigma level at the HL-LHC
  - Many new channels can be analogously studied in the SM and beyond



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