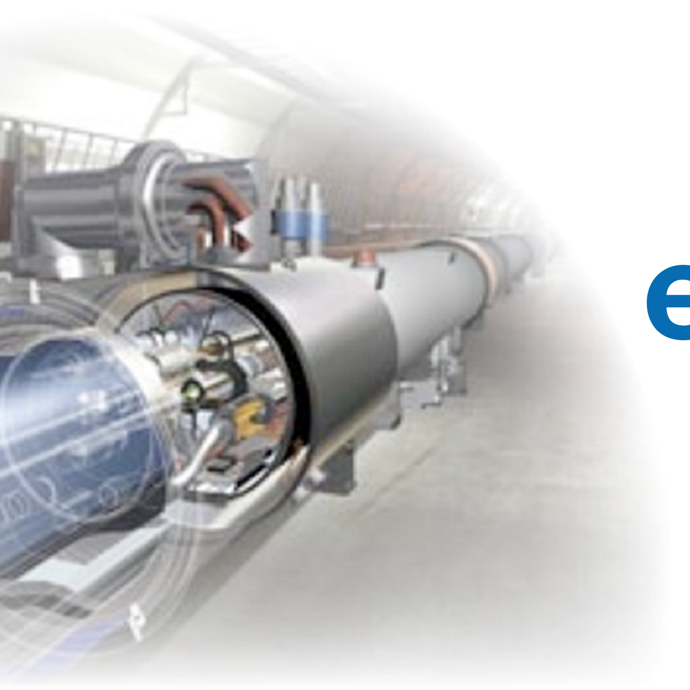

Measuring quantum entanglement in $t\bar{t}$ events at the LHC

7th RedLHC workshop - May 11, 2023

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CSIC Consejo Superior de Investigaciones Científicas

Vniversitat de València

Ministerio de Ciencia e Innovación

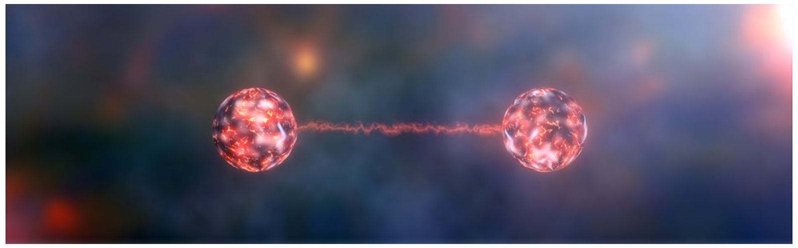
Agencia Estatal de Investigación

The **Standard Model** is a **Quantum Field Theory**: Special Relativity + Quantum Mechanics

Standard Model measurements → **Test fundamental properties of Quantum Mechanics**

Entanglement is perhaps the most genuine and essential feature of Quantum Mechanics

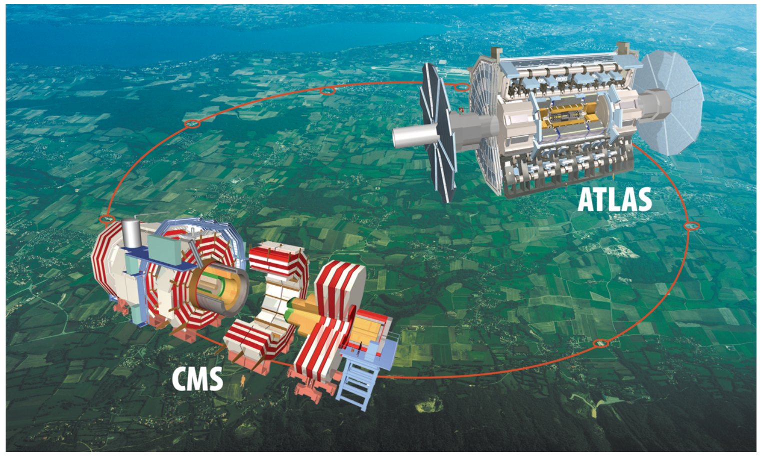
- If two (or more) particles become entangled, they remain connected even when separated by vast distances
- In other words, the quantum state of one particle cannot be described independently of the quantum state(s) of the other(s)



$$|\psi\rangle = |a_1\rangle_A \otimes |b_1\rangle_B + |a_2\rangle_A \otimes |b_2\rangle_B$$

The **LHC** has the potential to explore fundamental properties of Quantum Mechanics such as **Entanglement**!

- It can be measured with data already recorded at the LHC → Run 2 dataset
- Measuring experimentally this fundamental property requires a **very precise understanding of our detectors**



Spin correlations

The LHC is a top-quark factory… and the top quark is the ideal candidate for measuring spin correlations:

- **Lifetime (~10^{-25} s) ≪ hadronization (~10^{-23} s) ≪ depolarization (~10^{-21} s)**
  - Decays before forming bound states
  - **Spin information preserved in the angular distribution of its decay products**

In SM, tt̄ production:

- General form:

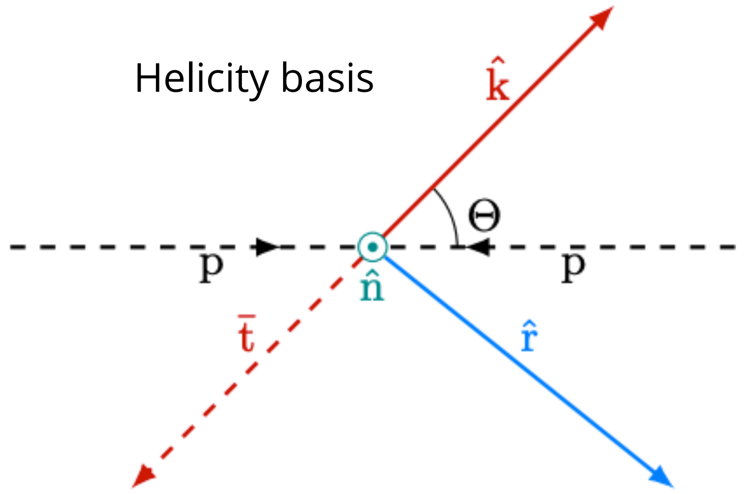
$$\rho = \frac{I_4 + \sum_i \left(B_i^+ \sigma^i + B_i^- \bar{\sigma}^i\right) + \sum_{i,j} C_{ij} \sigma^i \bar{\sigma}^j}{4}$$

- $\sigma^i/2, \bar{\sigma}^i/2$ - spin operators of the top, antitop.
- B_i^+, B_i^- characterize the spin polarizations, $B_i^+ = \langle \sigma^i \rangle$, $B_i^- = \langle \bar{\sigma}^i \rangle$.
- At LO $B_i^\pm = 0$.
- C_{ij} the $t\bar{t}$ spin correlations, $C_{ij} = \langle \sigma^i \bar{\sigma}^j \rangle$.

- **Top-quark not polarised (at LO) in tt̄ production in SM (parity invariant)**
- **But spins of t and t̄ strongly correlated (rich structure of spin correlations)**

- Top-quark spins cannot be measured directly!
- This is done by measuring the **angle between spin axis and lepton** in parent top-quark rest frame

- Helicity basis: $\{\hat{k}, \hat{r}, \hat{n}\}$:
  - $\hat{k}$ - direction of the top in the $t\bar{t}$ CM frame.
  - $\hat{p}$ - direction of the beam.
  - $\cos\Theta = \hat{k} \cdot \hat{p}$.
  - $\hat{r} = (\hat{p} - \cos\Theta\hat{k})/\sin\Theta$.
  - $\hat{n} = \hat{r} \times \hat{k}$.
  - 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.

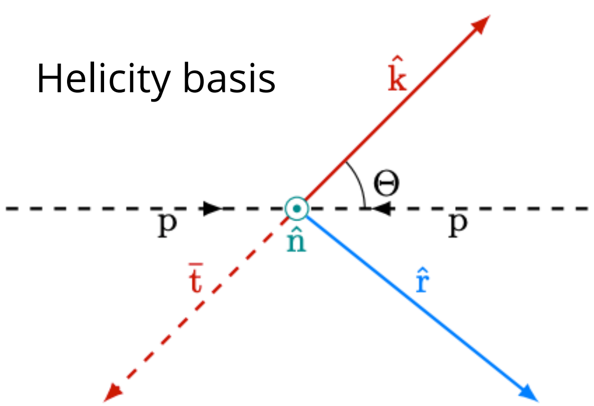


Spin correlations

- Coefficients measured by CMS and ATLAS from diff. cross-section:

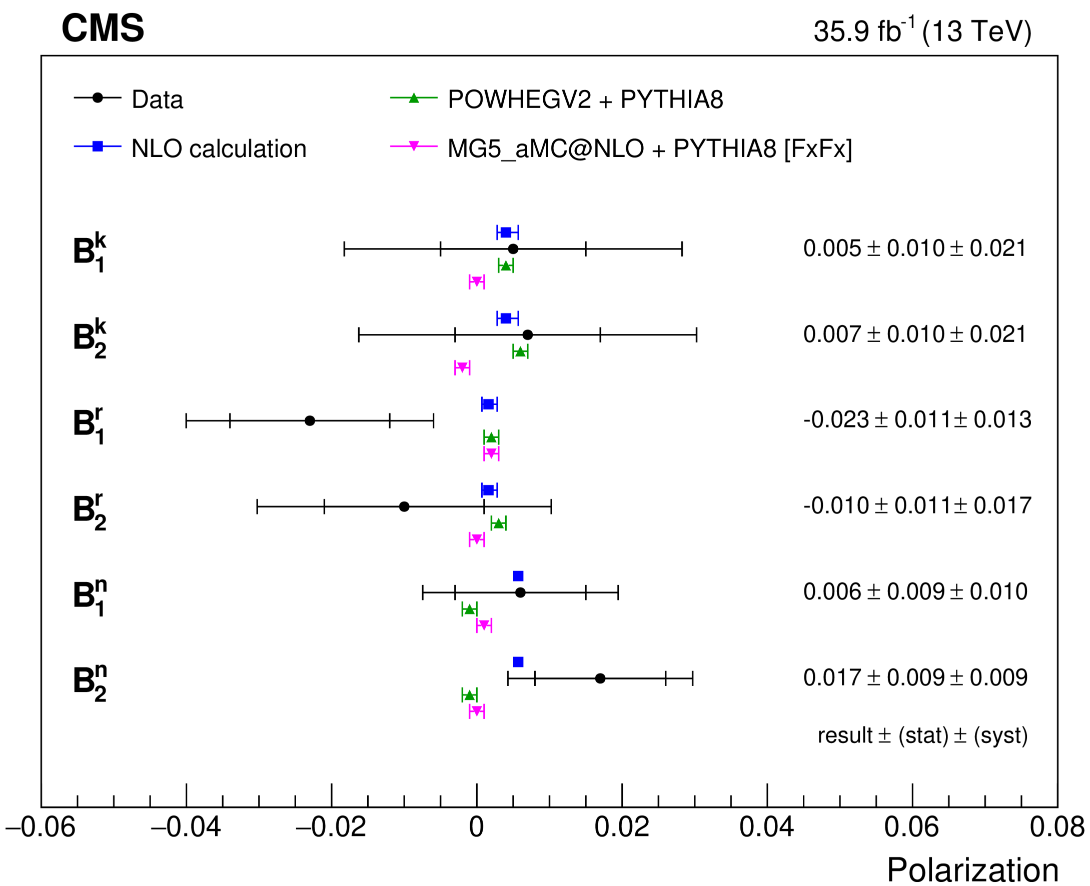
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + B_1 \cos\theta_+ + B_2 \cos\theta_- - C \cos\theta_+ \cos\theta_-\right)$$

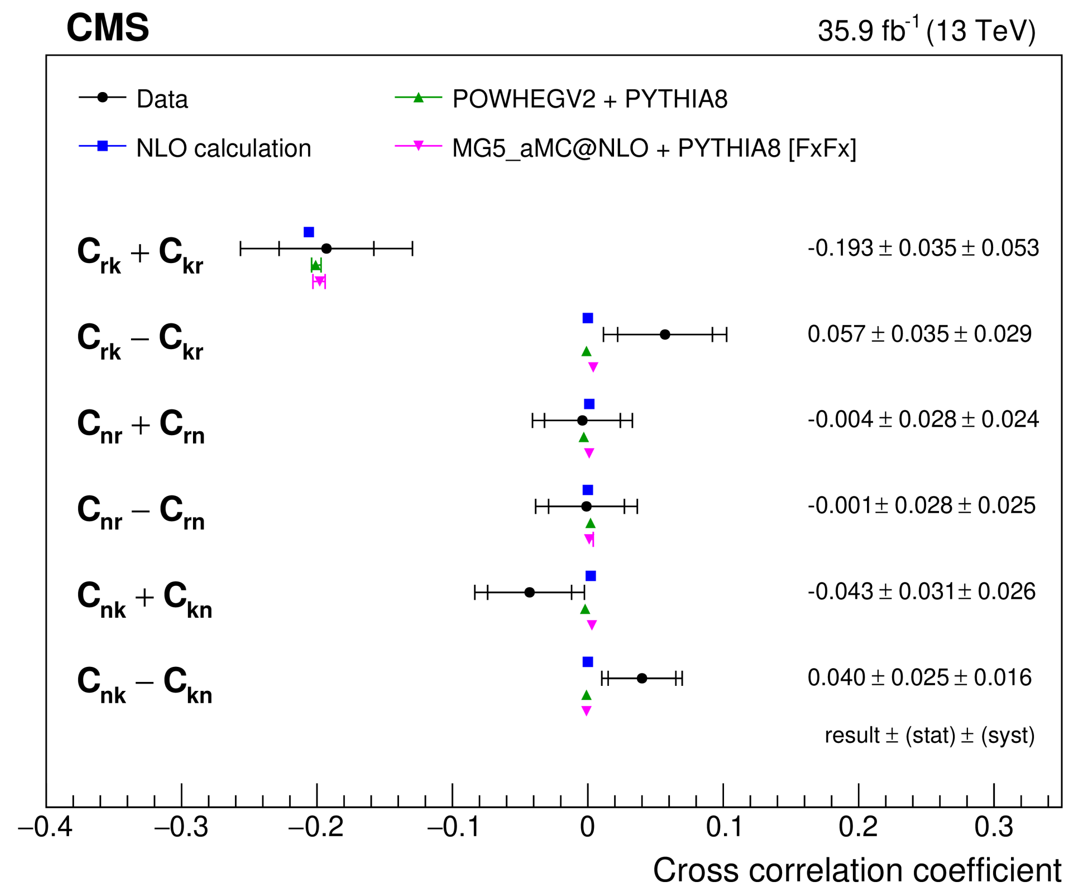
Helicity basis



Observable	Measured coefficient	Coefficient function	Symmetries
$\cos\theta_1^k$	B_1^k	b_k^+	P-odd, CP-even
$\cos\theta_2^k$	B_2^k	b_k^-	P-odd, CP-even
$\cos\theta_1^r$	B_1^r	b_r^+	P-odd, CP-even
$\cos\theta_2^r$	B_2^r	b_r^-	P-odd, CP-even
$\cos\theta_1^n$	B_1^n	b_n^+	P-even, CP-even
$\cos\theta_2^n$	B_2^n	b_n^-	P-even, CP-even
$\cos\theta_1^{k*}$	B_1^{k*}	b_k^+	P-odd, CP-even
$\cos\theta_2^{k*}$	B_2^{k*}	b_k^-	P-odd, CP-even
$\cos\theta_1^{r*}$	B_1^{r*}	b_r^+	P-odd, CP-even
$\cos\theta_2^{r*}$	B_2^{r*}	b_r^-	P-odd, CP-even
$\cos\theta_1^k \cos\theta_2^k$	C_{kk}	c_{kk}	P-even, CP-even
$\cos\theta_1^r \cos\theta_2^r$	C_{rr}	c_{rr}	P-even, CP-even
$\cos\theta_1^n \cos\theta_2^n$	C_{nn}	c_{nn}	P-even, CP-even
$\cos\theta_1^r \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^r$	$C_{rk} + C_{kr}$	c_{rk}	P-even, CP-even
$\cos\theta_1^r \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^r$	$C_{rk} - C_{kr}$	c_n	P-even, CP-odd
$\cos\theta_1^n \cos\theta_2^r + \cos\theta_1^r \cos\theta_2^n$	$C_{nr} + C_{rn}$	c_{nr}	P-odd, CP-even
$\cos\theta_1^n \cos\theta_2^r - \cos\theta_1^r \cos\theta_2^n$	$C_{nr} - C_{rn}$	c_k	P-odd, CP-odd
$\cos\theta_1^n \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^n$	$C_{nk} + C_{kn}$	c_{kn}	P-odd, CP-even
$\cos\theta_1^n \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^n$	$C_{nk} - C_{kn}$	$-c_r$	P-odd, CP-odd
$\cos\varphi$	D	$-(c_{kk} + c_{rr} + c_{nn})/3$	P-even, CP-even
$\cos\varphi_{\mathrm{lab}}$	$A_{\cos\varphi}^{\mathrm{lab}}$	—	—
$\lvert\Delta\phi_{\ell\ell}\rvert$	$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$	—	—

Spin correlations





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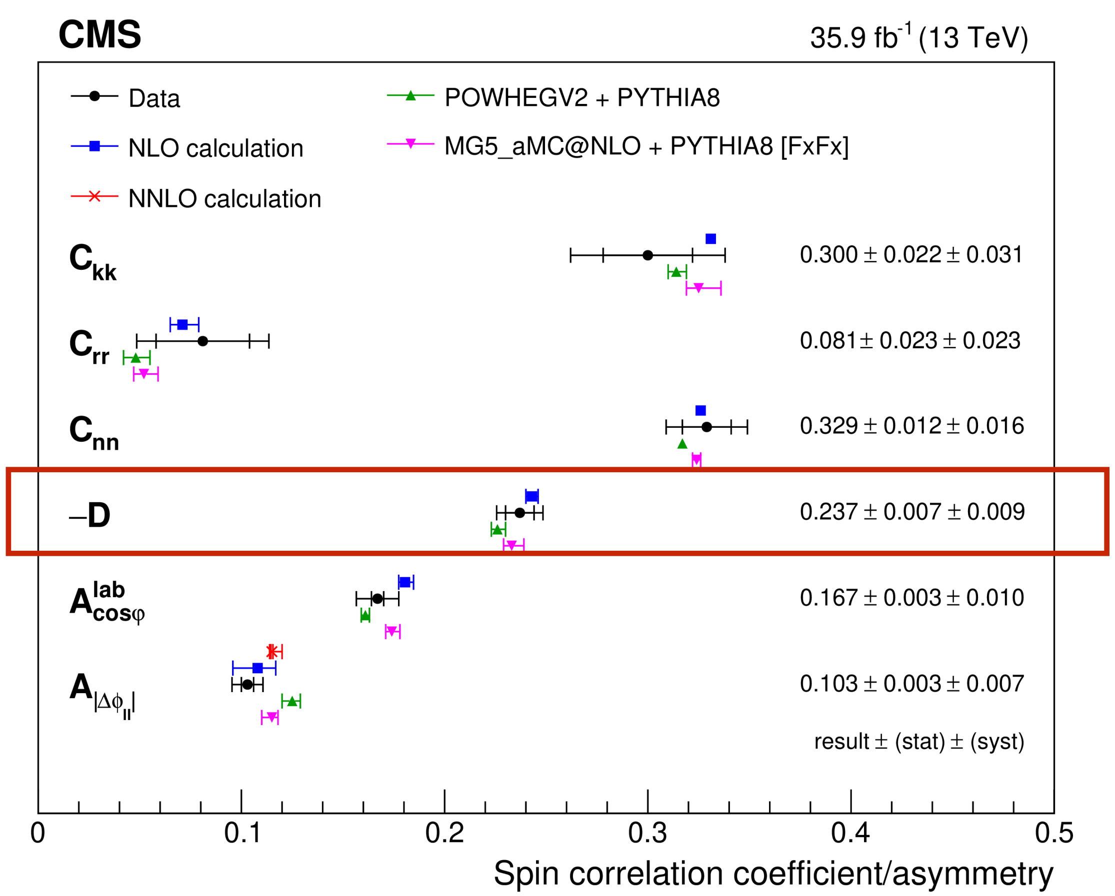


Entanglement criterion

- Spin Correlations can be a classical property
  - **Spin Correlations ≠ Quantum Entanglement!**
  - However, **Quantum Entanglement** ⊂ **Spin-Correlations**
- Indeed, the link between spin correlations of top quarks and Quantum Information is recent (Eur. Phys. J. Plus 136 (2021) 9, 907...)
  - $t\bar{t}$ process represents a simple entangled system composed by two qubits
  - $t\bar{t}$ events → good candidates to test entanglement and Bell inequalities at high energy!

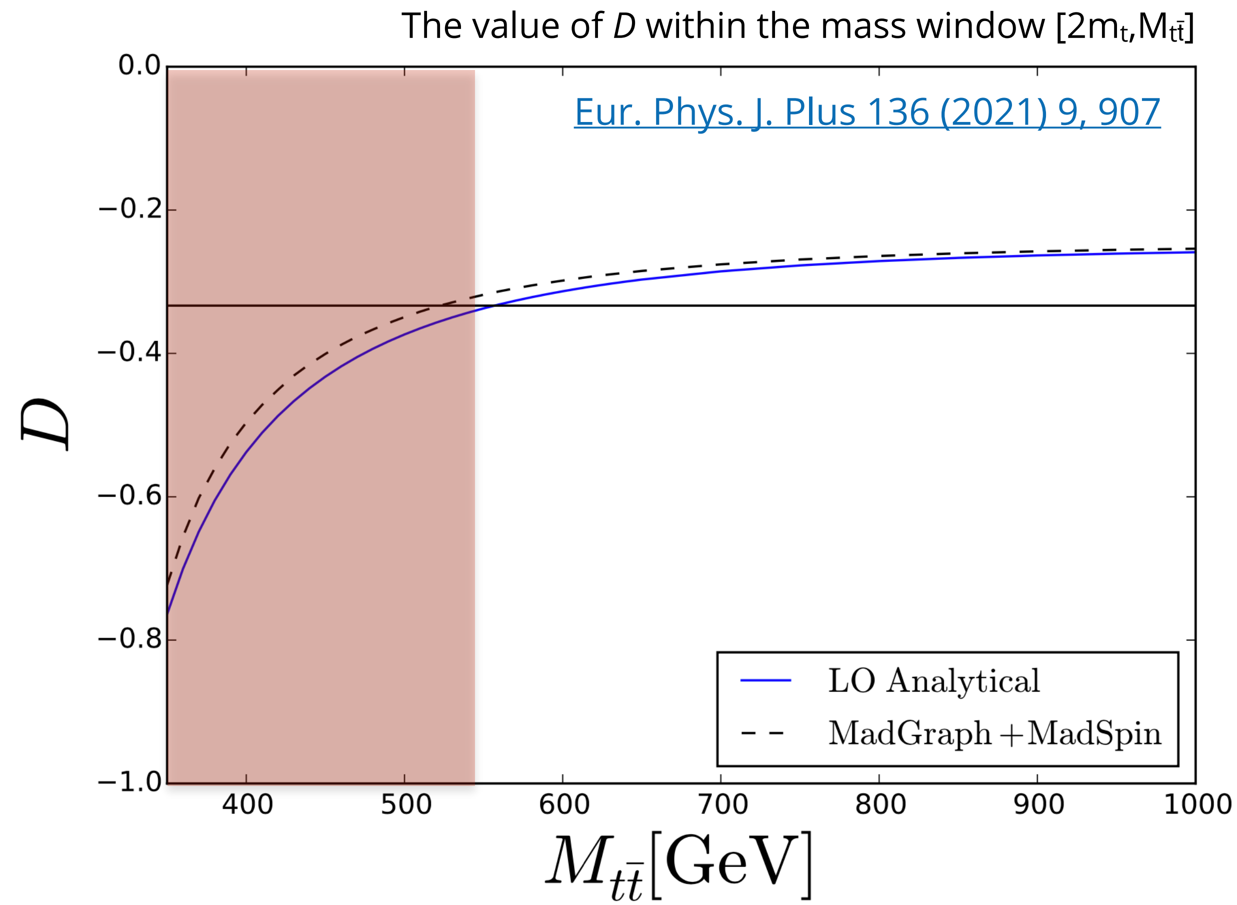
Entanglement criterion: $D = \frac{\mathrm{tr}[C]}{3}$

where $\mathrm{tr}[C] = 2C_{\perp} + C_z = C_{rr} + C_{nn} + C_{kk}$

No requirement to measure the spin density matrix!

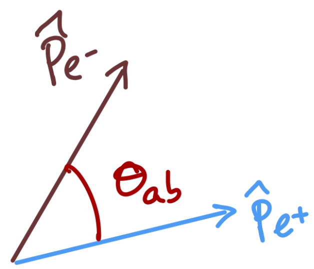
Entanglement condition

Upper bound on trace of spin density matrix: $$D = \frac{\mathrm{tr}[C]}{3} < -\frac{1}{3}$$



- **Theory: simple observable** from single differential normalized cross-section:

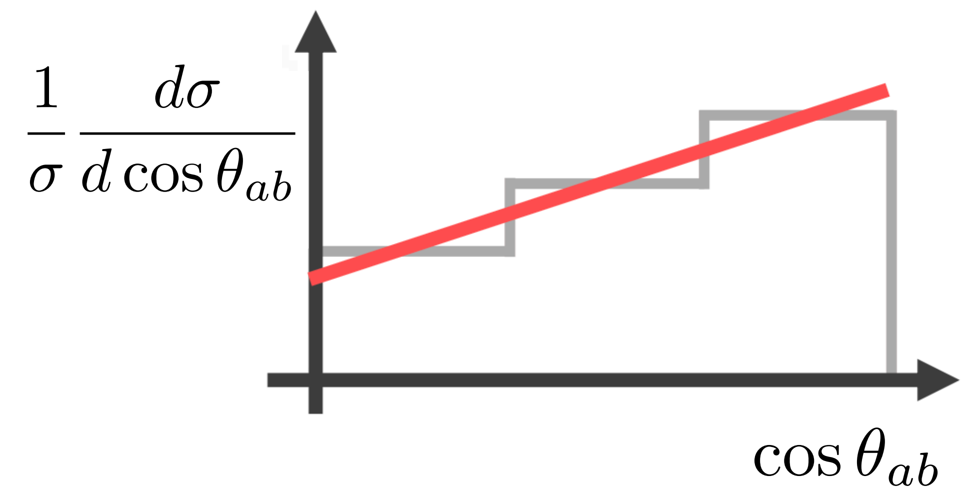
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{ab}} = \frac{1}{2}\left(1 - \alpha_a\alpha_b D\cos\theta_{ab}\right)$$

where 

is the angle between the two leptons in their respective top-quark parent rest-frame

- **Theory: "just" measure cos(θ_{ab}) in a low M($t\bar{t}$) region**

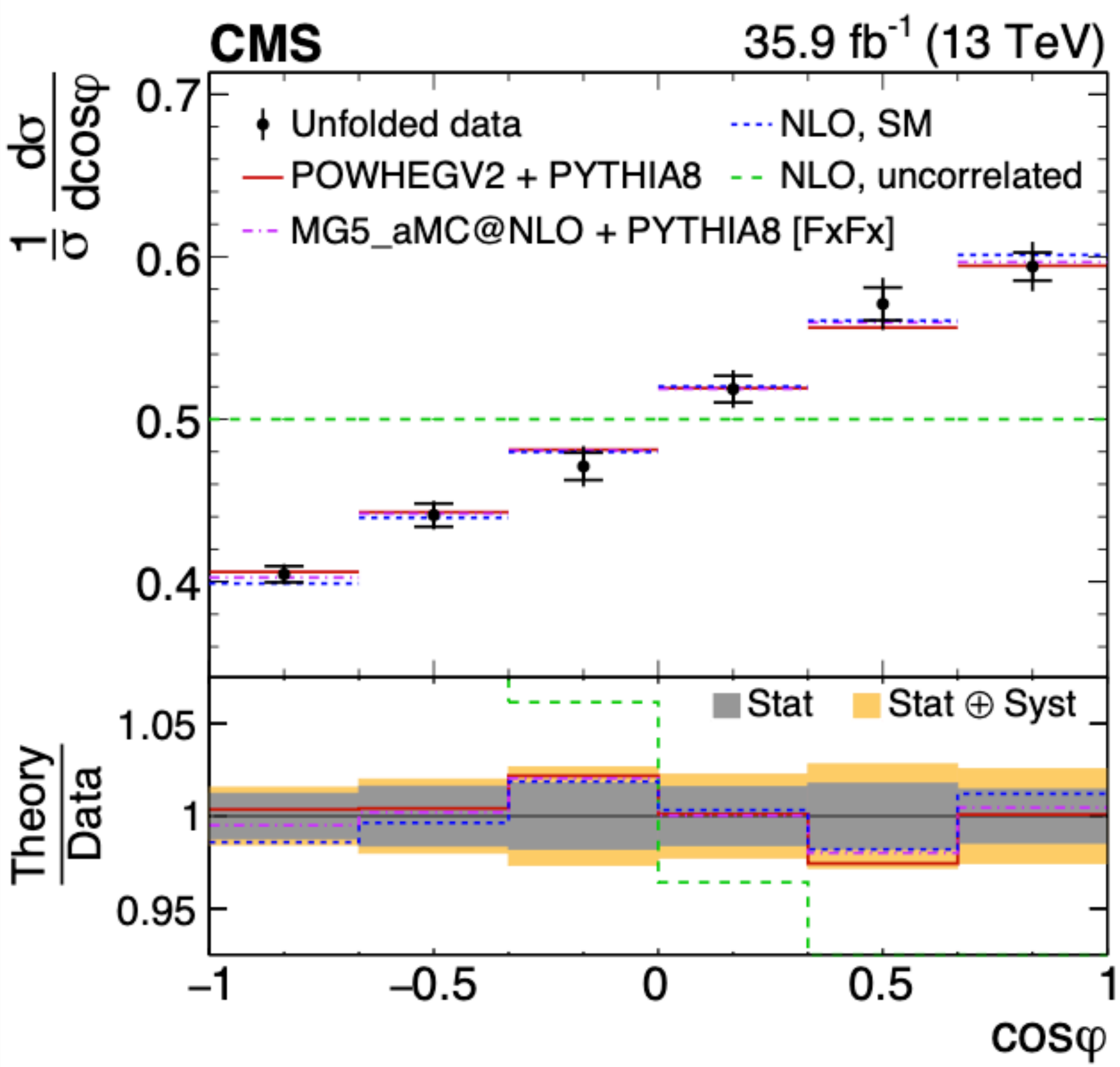
$$\left.\frac{1}{\sigma}\,\frac{d\sigma}{d\cos\theta_{ab}}\right|_{m_{t\bar{t}}<M} = \frac{1}{2}\left(1 - D\cos\theta_{ab}\right)$$



D already measured though inclusively

Recently, D was measured inclusively on $M(t\bar{t})$ by CMS:

- $D = -0.237 \pm 0.011 > -1/3$
- $\Delta D/D = 4.6\%$



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- Spin Correlations ≠ Quantum Entanglement!

No public results yet neither from ATLAS nor CMS

- I cannot show you any result (though they exist) 😤
- Good news: many people currently working on this topic!

ATLAS and CMS are working on two $t\bar{t}$ final states:

Dileptonic

2 opposite-sign leptons

≥ 2 jets (b-tagged)

≥ 1 b-tagged jets

Exclude Z-mass window

$M_{t\bar{t}}$ < ~400 GeV

↓

Challenge: reconstruct the neutrinos

↓

Several techniques are available:

- Roots of quartic polynomial
- NeutrinoWeighter
- Sonnenschein method
- Ellipse method
- Use ML (new): Transformers (SPANet)

Lepton+jets

- 1 lepton
- >= 4 jets
- 2 jets must be b-tagged
- MET > 20 GeV
- $M_{t\bar{t}}$ < ~400 GeV

↓

Challenge: tagging the correct jet(s)

- High-multiplicity jet final state

↓

Use ML for multi-jet final state:

- Transformers (SPANet)

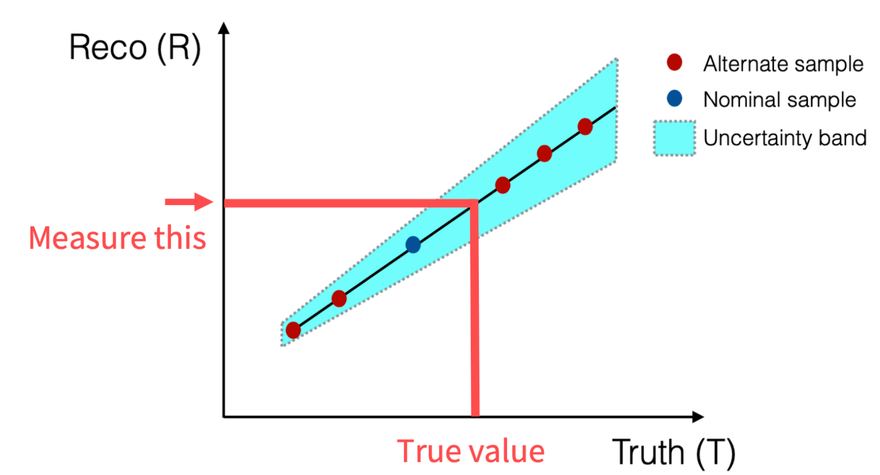
How we are trying to measure entanglement in $t\bar{t}$:

Unfold $\cos(\theta_{ab})$, then extract D

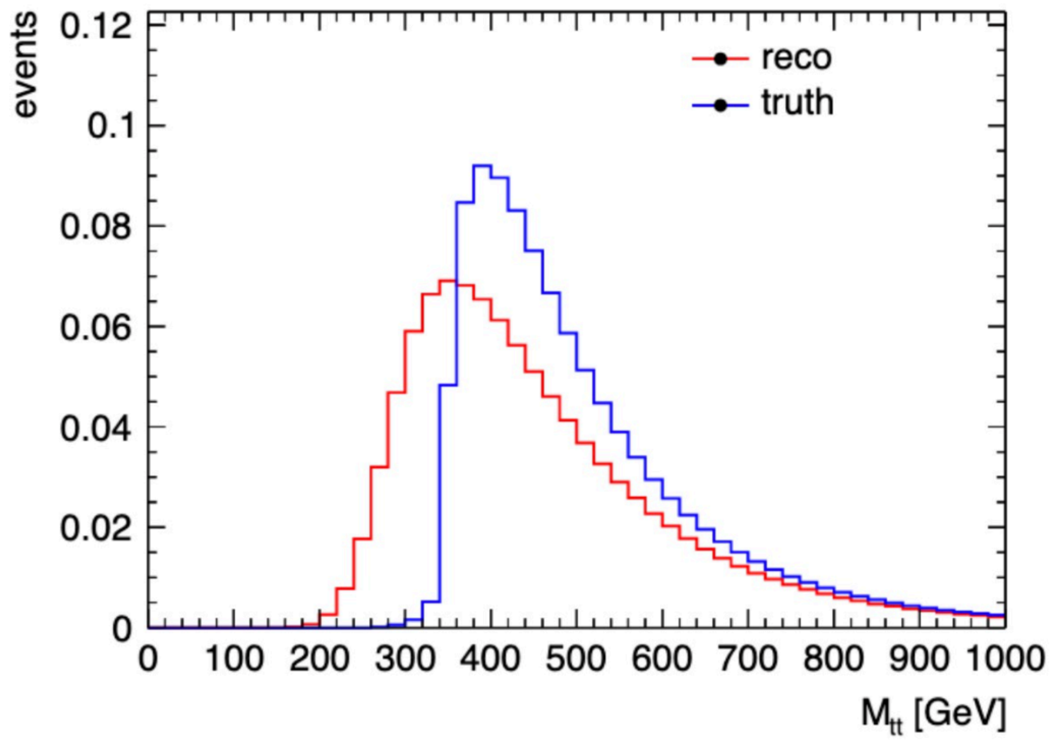
- Correction of the detector effects is needed since efficiency decreases when the leptons approach collinearity
- Many unfolding techniques exist:
  - Iterative Bayesian unfolding
  - Profile likelihood unfolding
  - SVD unfolding
- Stress tests (SM bias) needed → **Issues appear!**

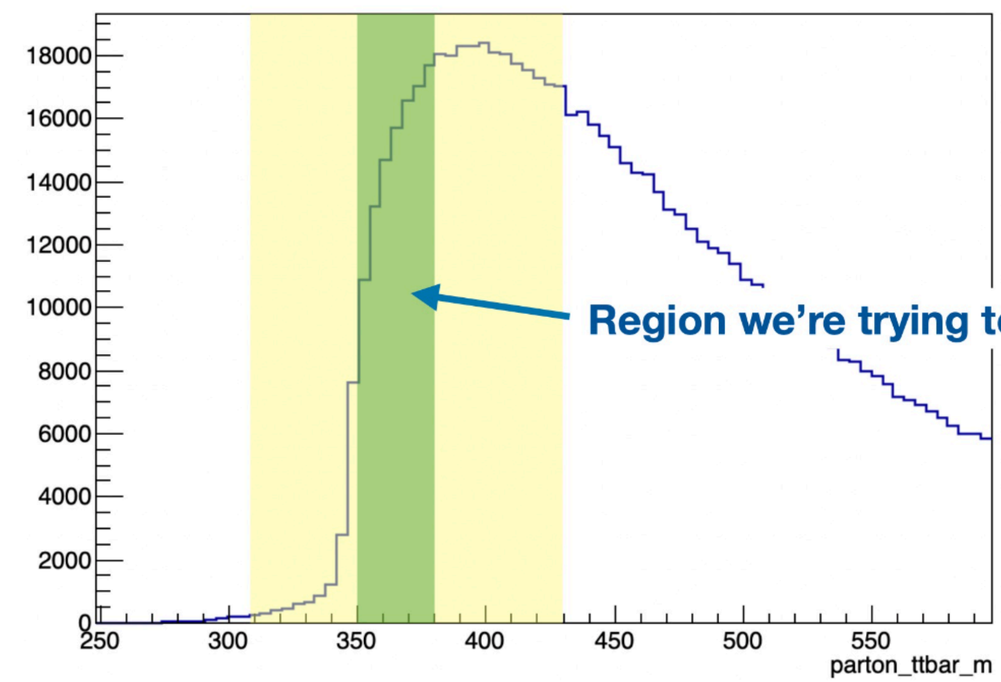
Extract D from reconstructed events, then extract D

- Calibration Curve
- Problem how to produce alternate samples
  - This is not a free parameter in the SM
  - In MC event generators, not an input parameter which we can alter
  - Reweighting? → **Issues appear!**
    - Alter slope of $\cos(\theta_{ab})$ artificially
    - Did not preserve linearity
    - Preserved inclusive value of *D*



The problem is the resolution of $M_{t\bar{t}}$





- **Measuring the entanglement in $t\bar{t}$ events requires better (great) top-quark reconstruction when considering such narrow phase-space**
- **Modelling effects affect systematics estimation**

Theory: "just" measure $\cos(\theta_{ab})$ in a low $M(t\bar{t})$ region

→

Experiment: wait, this is not so easy

Conclusions

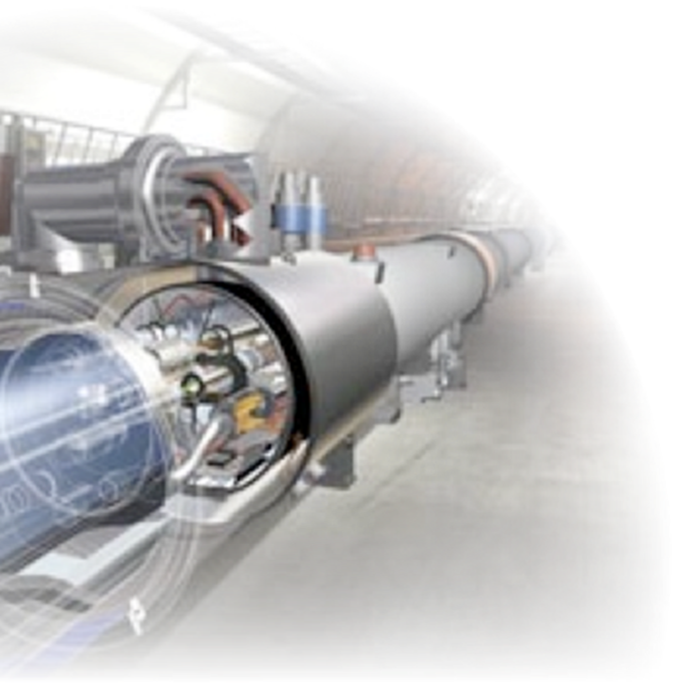
- First studies of the measurement of entanglement between quarks
- Can be detected at the LHC with current recorded data (Run2)
- Simple observable from single differential cross-section:

$$D = \frac{\mathrm{tr}[C]}{3} < -\frac{1}{3} \quad \longrightarrow \quad \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{ab}}\bigg|_{m_{t\bar{t}}<M} = \frac{1}{2}(1 - D\cos\theta_{ab})$$

- Several $t\bar{t}$ final states being studied
- Several techniques being explored to extract *D*
- Real requirement for superior top-quark reconstruction
- Narrow phase-space is problematic

"Quantum entanglement is theoretically clean, but experimentally quite nasty" — Alan Barr —

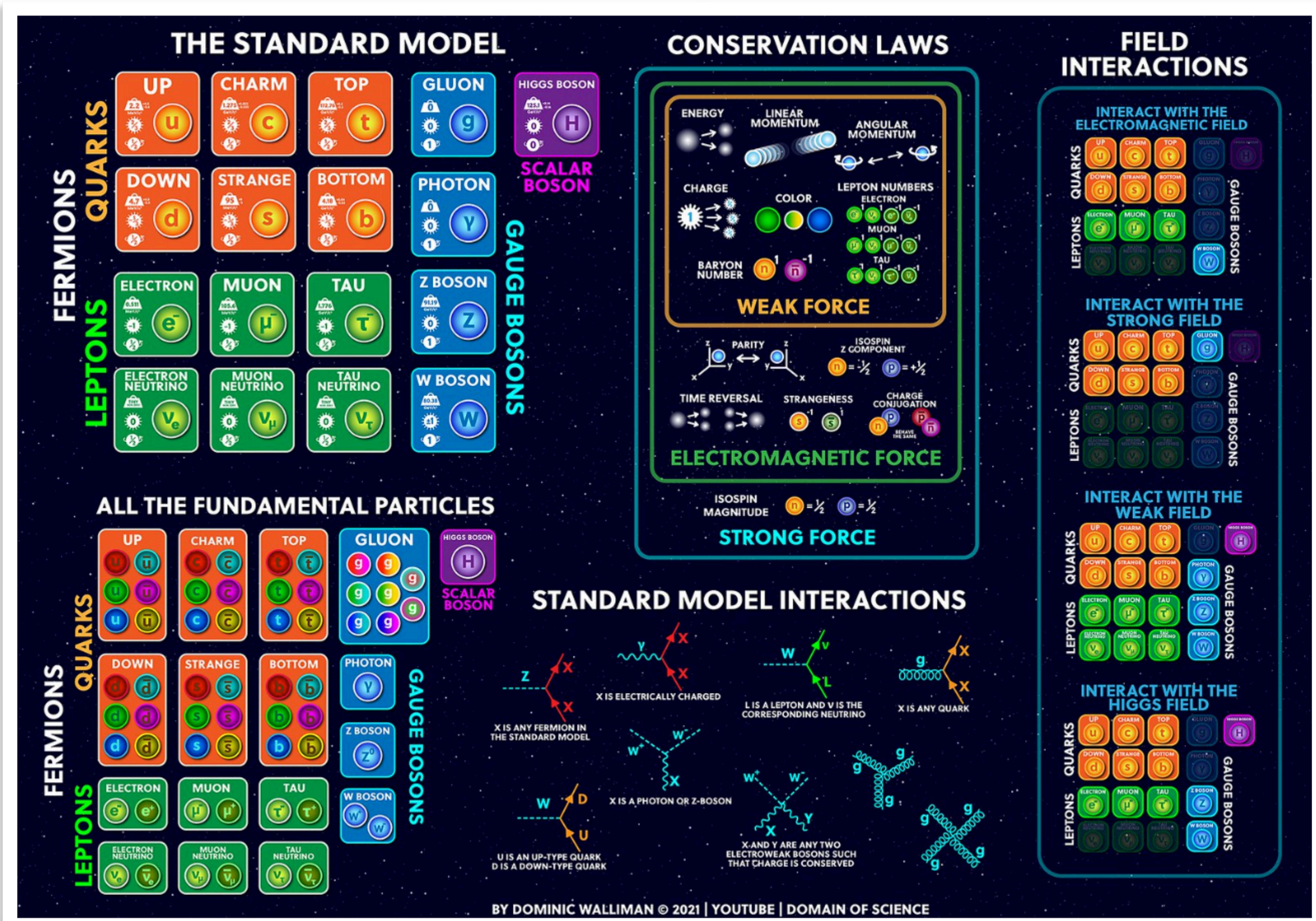
- **ATLAS and CMS: work in progress, please stay tuned!**



BACKUP

The **Standard Model** is a **Quantum Field Theory**:

- Special Relativity
- Quantum Mechanics



The **Standard Model** is a **Quantum Field Theory**:
- Special Relativity
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Fundamental properties of Quantum Mechanics can be tested via the Standard Model

Standard Model measurements → **Test features of Quantum Mechanics**

Entanglement is perhaps the most genuine and essential feature of Quantum Mechanics

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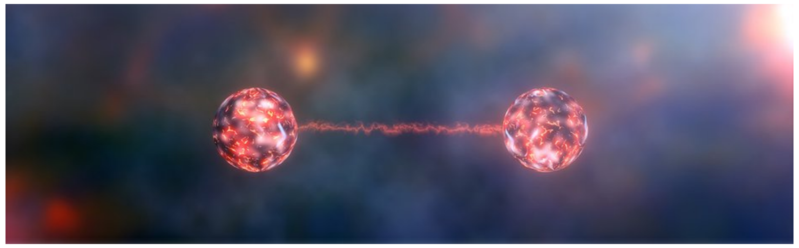
- In other words, the quantum state of one particle cannot be described independently of the quantum state(s) of the other(s)



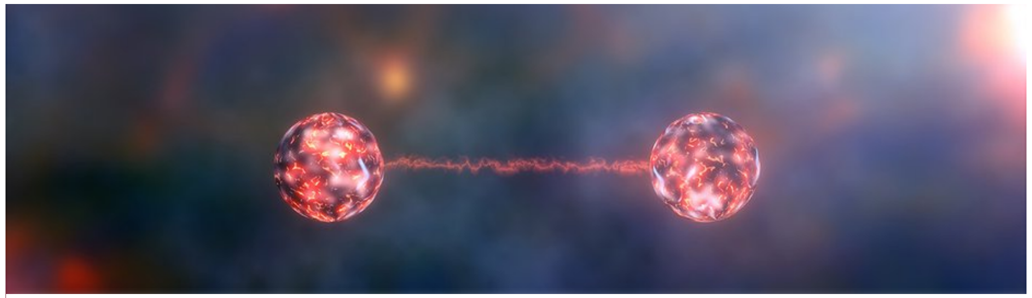
$$|\psi\rangle = |a_1\rangle_A \otimes |b_1\rangle_B + |a_2\rangle_A \otimes |b_2\rangle_B$$

Fundamental properties of Quantum Mechanics can be tested via the Standard Model

Standard Model measurements → **Test features of Quantum Mechanics**

Entanglement is perhaps the most genuine and essential feature of Quantum Mechanics

- In other words, the quantum state of one particle cannot be described independently of the quantum state(s) of the other(s)
- EPR paradox → Information travel faster than light?
  - Contradicts the theory of relativity
  - Conclusion: the theory of Quantum Mechanics is incomplete



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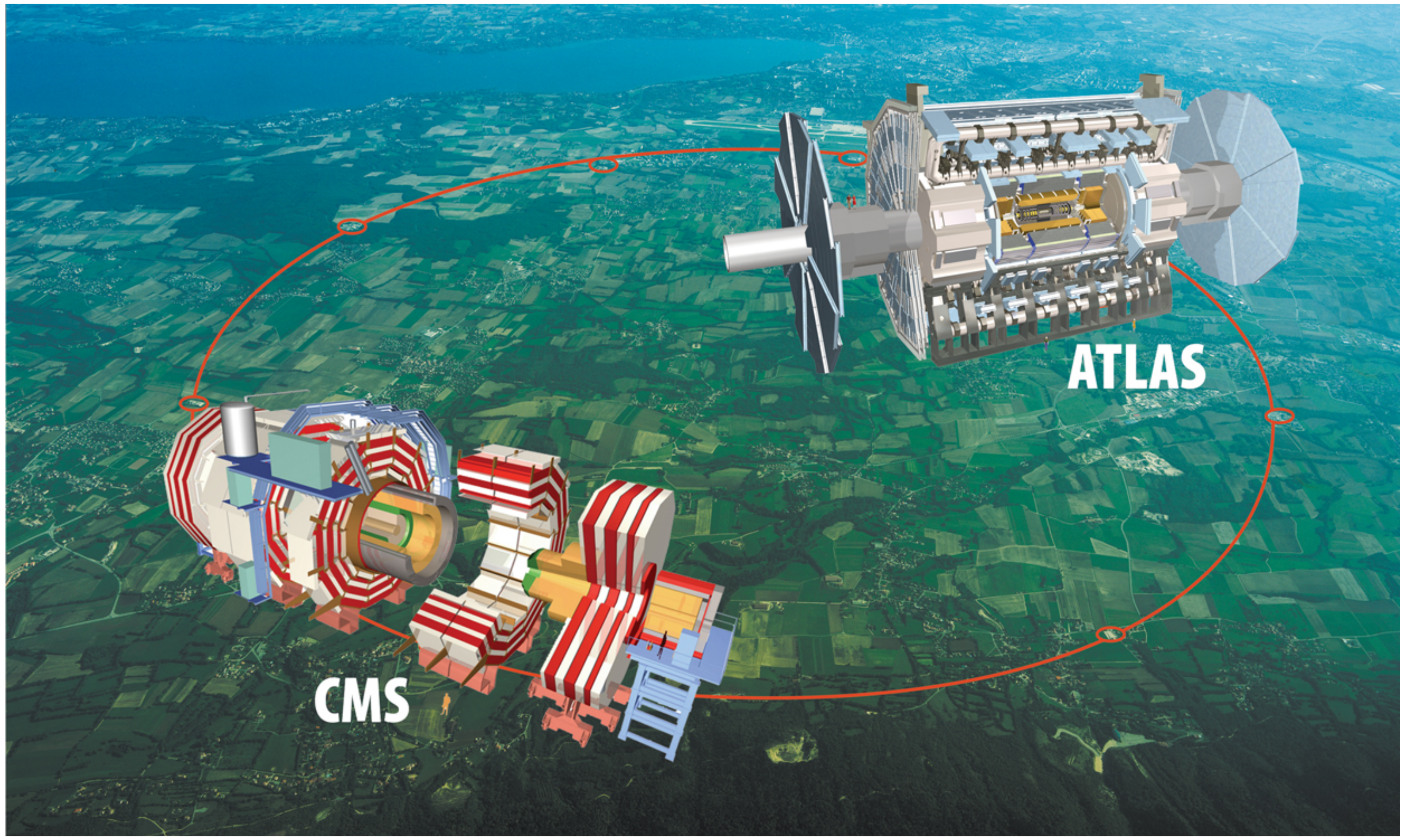
The **LHC** has the potential to explore fundamental properties of Quantum Mechanics such as **Entanglement**!

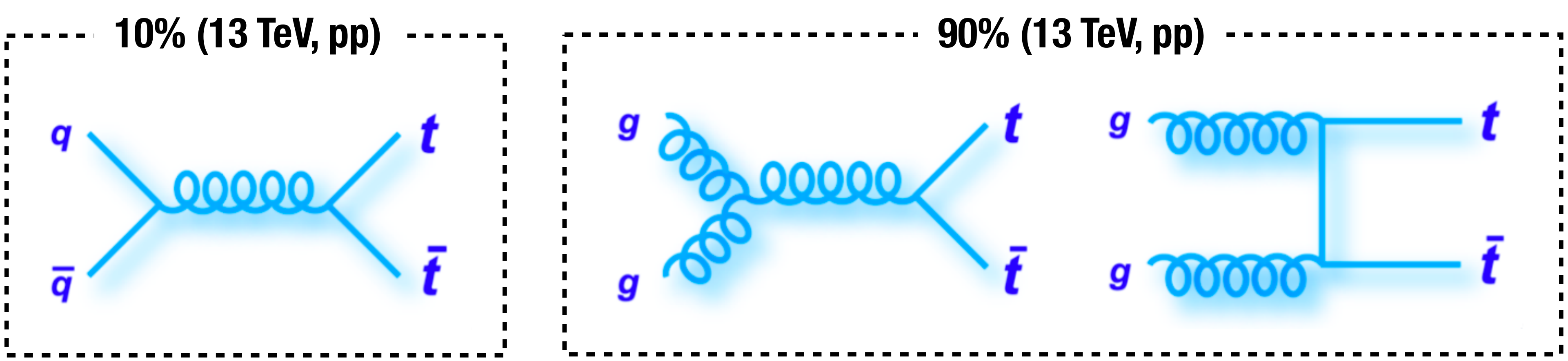
- It can be measured with data already recorded at the LHC → Run 2 dataset
- Measuring experimentally this fundamental property requires a **very precise understanding of our detectors**



Introduction

The **LHC** is a **top-quark factory**:

- Top quarks are abundantly produced at the LHC
  - At low luminosity (i.e. 10^{32} cm^{-2} s^{-1} @ 7 TeV): ~60 $t\bar{t}$ every hour
  - At design luminosity (i.e. 10^{34} cm^{-2} s^{-1} @ 14 TeV): ~8 $t\bar{t}$ every second



Unique properties of the top quark:

- Heaviest known elementary particle
- Strongest Yukawa coupling (almost unity)
- Smallest cross-section of all of the SM particles
- **Lifetime (~10^{-25} s) ≪ hadronization (~10^{-23} s) ≪ depolarization (~10^{-21} s)**
  - **The decay products preserve the spin information of the top quark**
  - Only quark whose most of its properties can be directly measured!
- The top quark decays almost exclusively (>99%, i.e. $|V_{tb}| \approx 0.999$) to $t \rightarrow Wb$ (@LO)
- New physics: a key player in most solutions to the problems of the SM

Hidden variables

By EPR, each particle ”carries” variables that knows the state before the measurement
⇒ There are some hidden variables that are missing in order to have a full theory

The Copenhagen Interpretation: superposition of states until a measurement is done

Bell’s Inequality

- If local hidden variables holds, they should satisfy some inequality
- $C(x,y)$ are the correlations between different measurements at different detectors
- The parameters a,b,c are different directions for the measurement
- Original form: $1+C(b,c) \geq |C(a,b)-C(a,c)|$

Spin correlations

Top quark is the ideal candidate for measuring spin correlations:

- extremely short lifetime → decays before forming bound states
- spin information preserved in the angular distribution of its decay products
- top-quark spin observables (expected to be) well predicted by perturbative QCD

In SM, $t\bar{t}$ production:

- General form:

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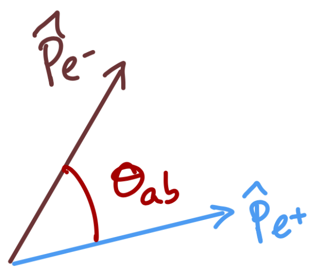
where 

is the angle between the two leptons in their respective top-quark parent rest-frame

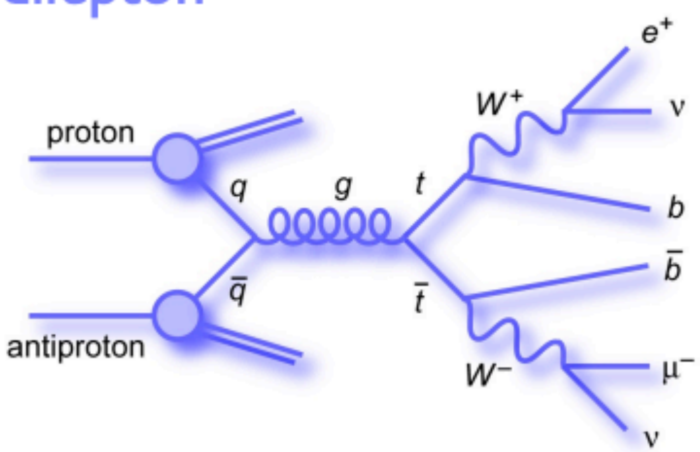
	b-quark	W^+	l^+	$\bar{d}$-quark or $\bar{s}$-quark	u-quark or c-quark
α_i (LO)	-0.41	0.41	1	1	-0.31
α_i (NLO)	-0.39	0.39	0.998	0.97	-0.32

No public results yet neither from ATLAS nor CMS

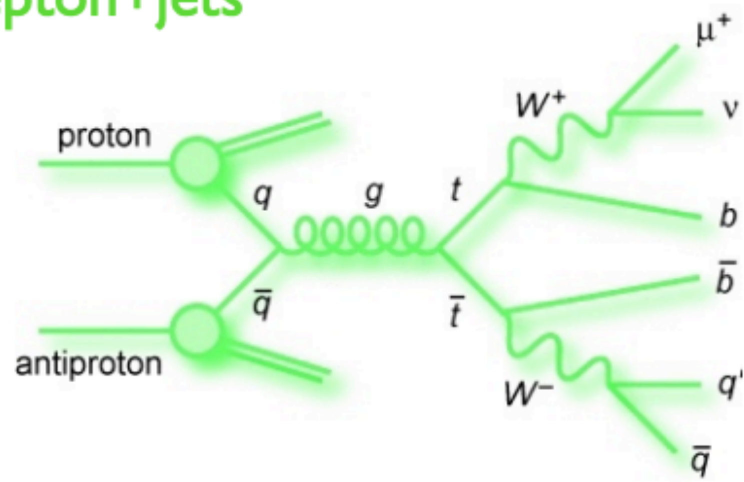
- I cannot show you any result (though they exist) 😤
- Good news: many people currently working on this topic!

From the experimental point of view, we have three options:

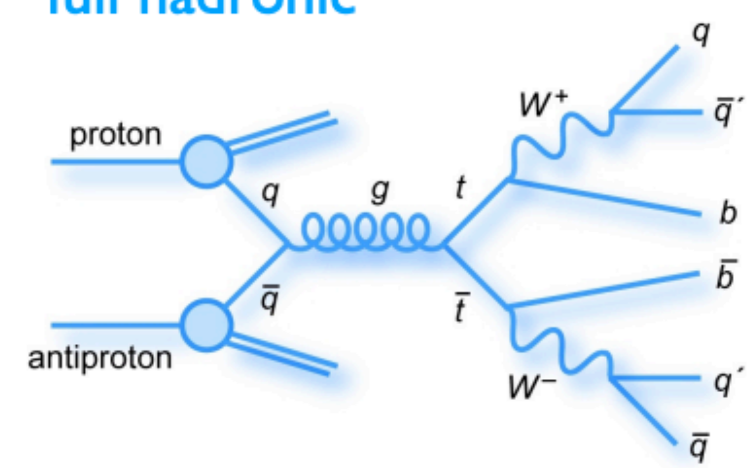
dilepton



lepton+jets



full hadronic



BR increases.... but background too!

Challenge: reconstruct the neutrinos

Challenge: tagging the correct jet(s)
- High-multiplicity jet final state