Exploring the potential of quantum observables to search for new physics, in boosted top-pair production

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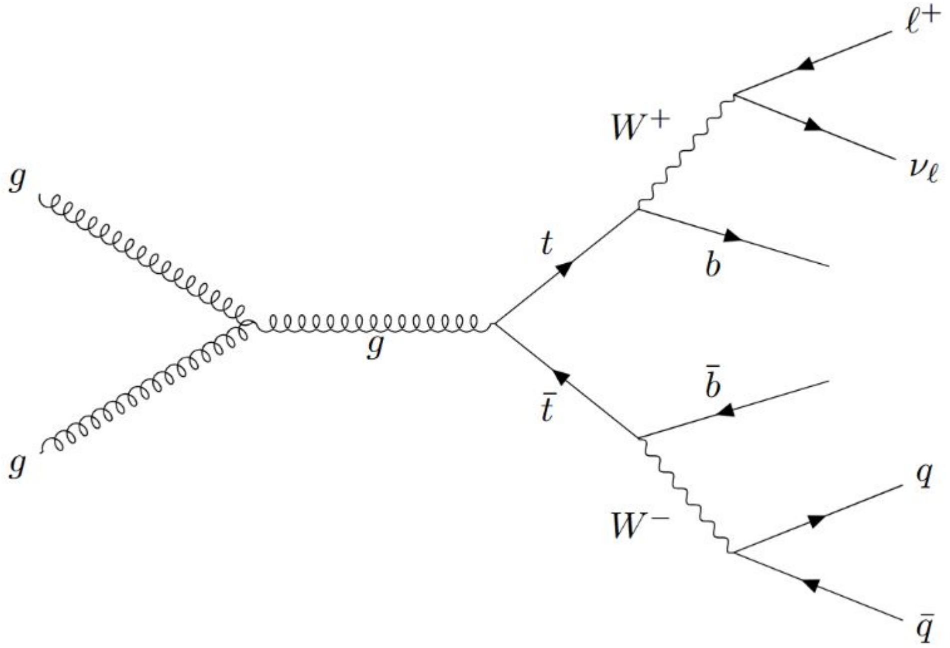
Motivation

- ➔ The top quark:
    - Largest mass among Standard Model (SM) particles
    - Strongest coupling to the Higgs boson
    - Top decays before ***hadronization*** and before ***spin-decorrelation***
- ➔ The Standard Model (SM) is incomplete:
    - Dark Matter
    - Baryon asymmetry
    - Gravity outside the framework
- ➔ SM is valid up to ~ 13.6 TeV

Goal

- ➔ GOAL: Use quantum information principles to study new physics effects in top-pair production
- ➔ FOCUS: **Semileptonic** channel



Spin in top quark

- Spin is an intrinsic form of angular momentum carried by elementary particles
- Spin ½ Fermion
- Top quark spin can be represented as a qubit with a 2×2 density matrix ρ

$$\rho = \frac{1}{2}\left(\mathbb{1} + \sum_{i=1}^{3} B_i \sigma_i\right)$$

Spin in $t\bar{t}$ system

- The density matrix of a top-antitop pair system is given by

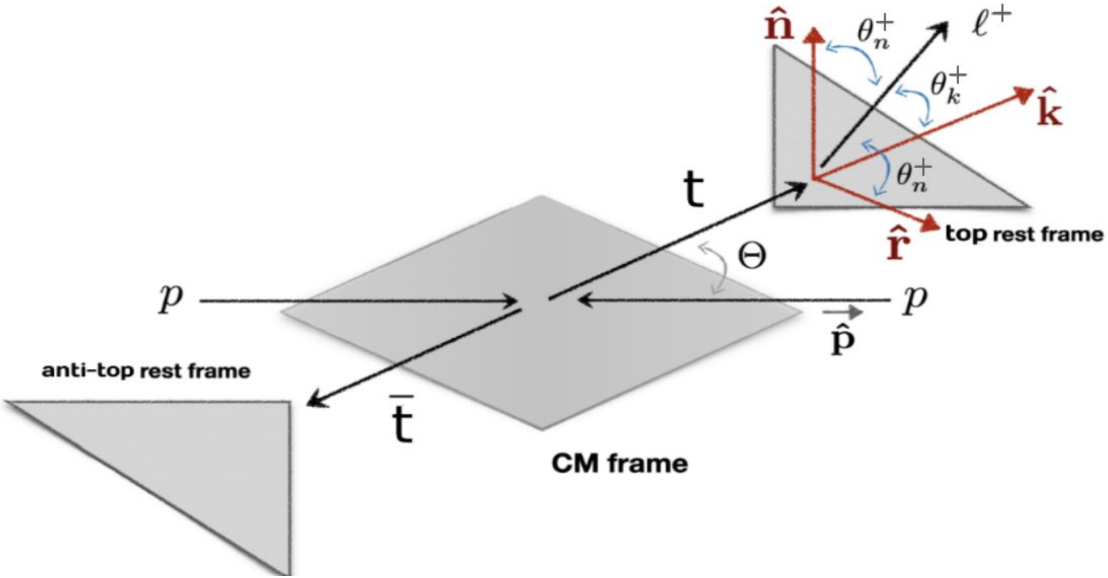
$$\rho = \frac{1}{4}\Big(\mathbb{1}\otimes\mathbb{1} + \underbrace{\sum_{i=1}^{3} B_i\sigma_i\otimes\mathbb{1}}_{\text{Polarization of top}} + \underbrace{\sum_{j=1}^{3} \bar{B}_j\mathbb{1}\otimes\sigma_j}_{\text{Polarization of anti-top}} + \underbrace{\sum_{i=1}^{3}\sum_{j=1}^{3} C_{ij}\sigma_i\otimes\sigma_j}_{C_{ij}:\ \text{Spin correlation matrix}}\Big)$$

❖ C_{ij} : encodes how the spins of the top and anti–top are correlated along different axes.

- ➢ **Entanglement**: these correlations cannot be explained by treating top and anti–top as having independent states.

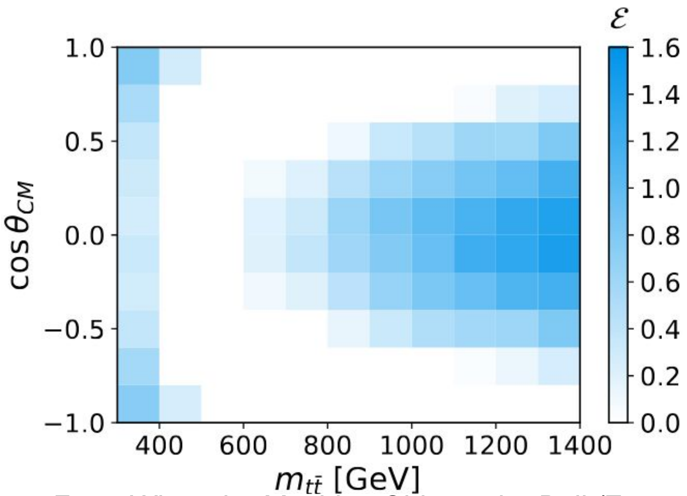
Spin Correlation Matrix Reconstruction

- Weak interactions are chiral
  - Top quark **spin reconstruction** is possible with the **angles** of its decay products
  - Variables defined before hadronization
  - Lepton and down-type quark as **spin analyzers**



Spin Correlation and Entanglement in $t\bar{t}$

- Spin Correlations:
  - Present in **all** phase space
  - Expected to be strong in threshold and high momentum ttbar events



From When the Machine Chimes the Bell (Z. Dong, D. Gonçalves, K. Kong, A. Navarro).

- Entanglement:
  - Expected in central region.
  - Verified by criteria involving observable D_3.

$$D_3 = -\frac{1}{3}(C_{kk} + C_{rr} - C_{nn})$$

  - Criteria for entanglement

$$D_3 > \frac{1}{3} \quad \Rightarrow \quad \text{entangled state.}$$

SM as an Effective Field Theory (SMEFT)

- Powerful tool to search for new physics beyond the LHC energy scale
- **Modifies** couplings
- New physics may appear as small deviations in known observables

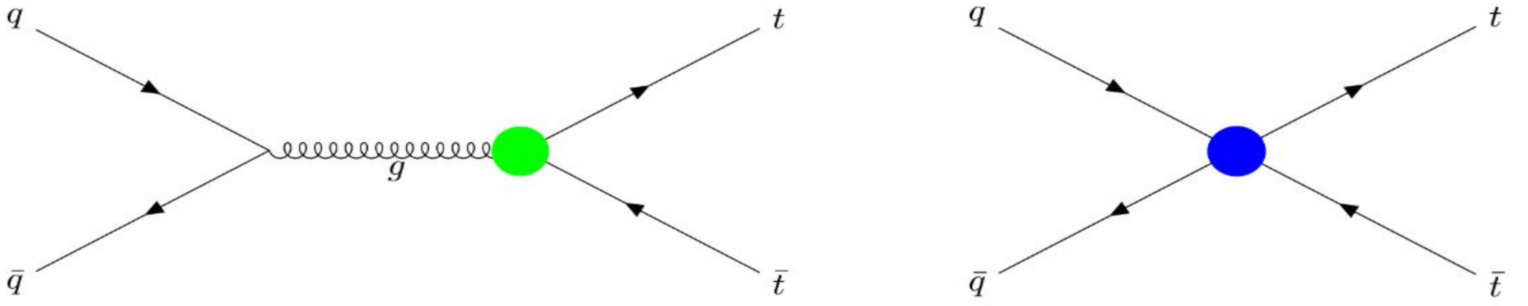
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d\geq 5} \sum_{k} \frac{c_k^{(d)}}{\Lambda^{d-4}} O_k^{(d)}$$

- $\mathcal{L}_{\mathrm{SM}}$: SM Lagrangian.
- Λ: new physics scale (cutoff).
- $O_k^{(d)}$: operators of dimension $d > 4$.
- $c_k^{(d)}$: Wilson coefficient.

Dimension-6 SMEFT Operators

❖ The list of relevant operators is

$$\{\mathcal{O}_{tG}, \mathcal{O}_{tu}, \mathcal{O}_{td}, \mathcal{O}_{tq}, \mathcal{O}_{Qu}, \mathcal{O}_{Qd}, \mathcal{O}_{Qq}^{(1)}, \mathcal{O}_{Qq}^{(3)}\}$$



(a) gluon–$t\bar{t}$ vertex (b) four-quark vertex

❖ The effects of dimension-six operators on spin correlations can be parametrized as follows

$$\sigma(c_i) = \sigma_{\mathrm{SM}} + \frac{1}{\Lambda^2}\sigma_{\mathrm{SM}\times\mathrm{EFT}} + \frac{1}{\Lambda^4}\sigma_{\mathrm{EFT}}$$

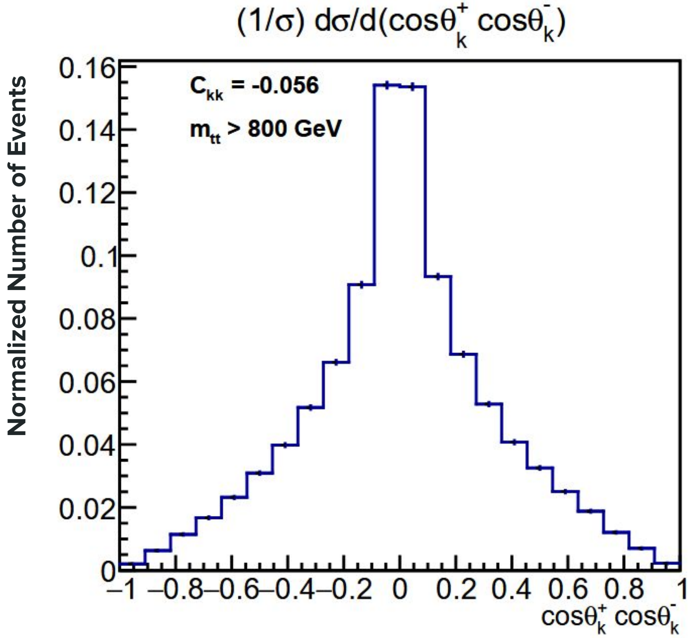
Reconstruction of Observables

- Reconstruction of normalized angular distributions
- Angular distributions to extract different observables
  - Spin Correlations: C_{kk}, C_{rr}, C_{nn}
  - Entanglement Marker: D_3
  - Number of events: $N_{\mathrm{EFT}} \propto \sum w_{\mathrm{EFT}}$

$$C_{ij} = -9 \left\langle \cos\theta_i^+ \cos\theta_j^- \right\rangle$$

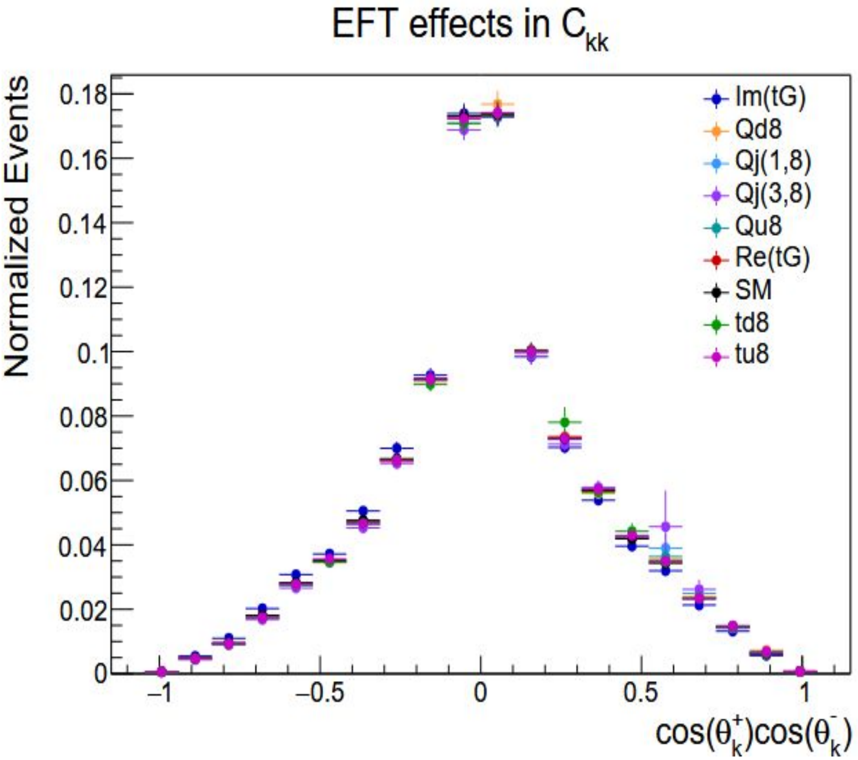
- Different regions have different sensitivity

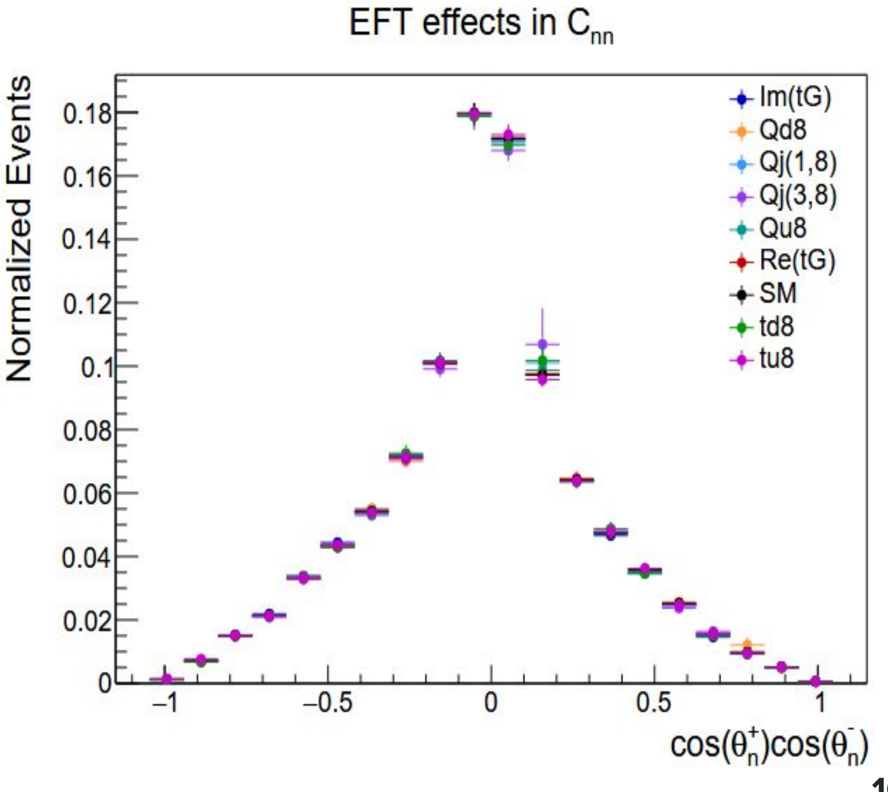
Region	Cut Applied
Threshold	$m_{t\bar{t}} < 400$ GeV
Boosted	$m_{t\bar{t}} > 800$ GeV
Central Boosted	$m_{t\bar{t}} > 800$ GeV, $\lvert\cos\theta\rvert < 0.4$
Central Highly-Boosted	$m_{t\bar{t}} > 1500$ GeV, $\lvert\cos\theta\rvert < 0.2$



Effect of dim-6 Operators

- ❖ SMEFT effects introduced via event weights

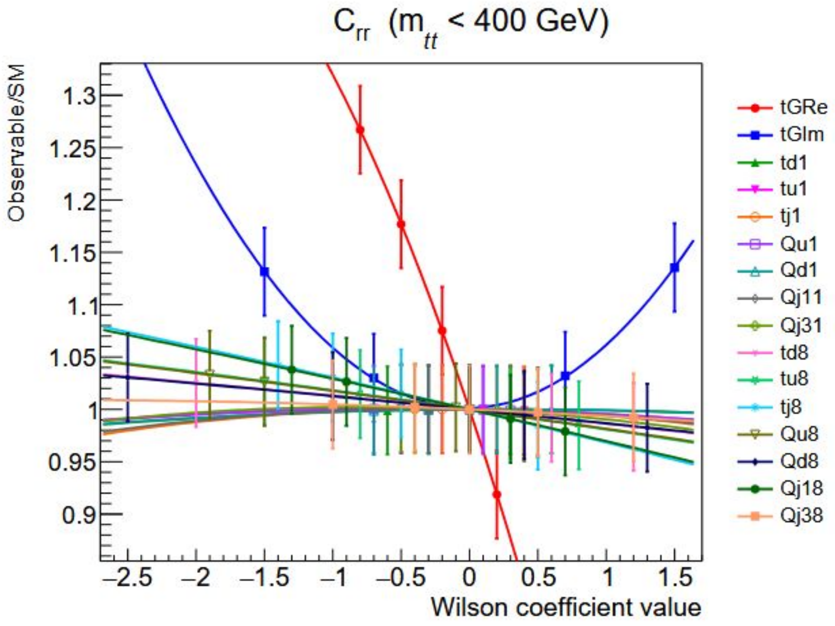




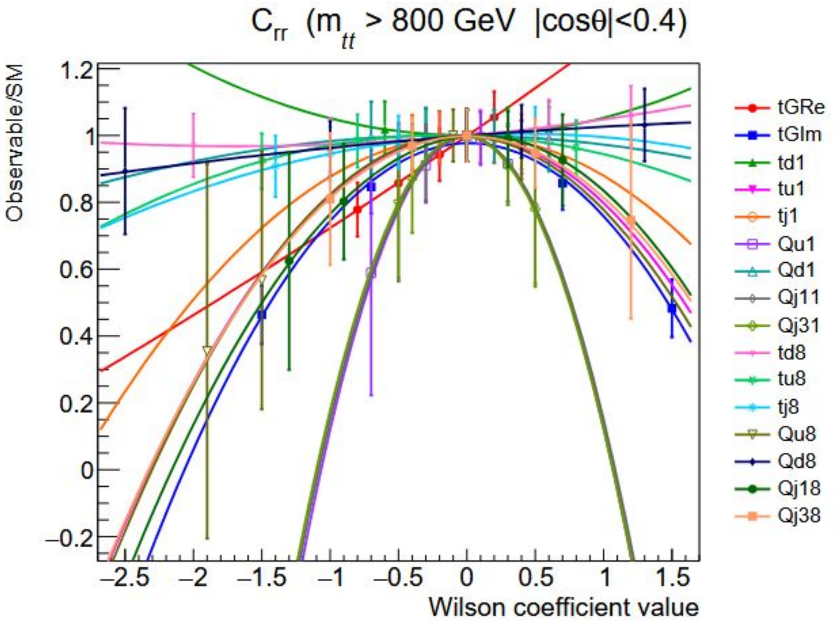
Parametrization of SMEFT effects

- EFT predictions for observables are modeled as polynomial functions of Wilson Coefficients (WCs)

$$O_{EFT}(c) = \alpha_0 + \alpha_1 c + \alpha_2 c^2$$



Threshold region

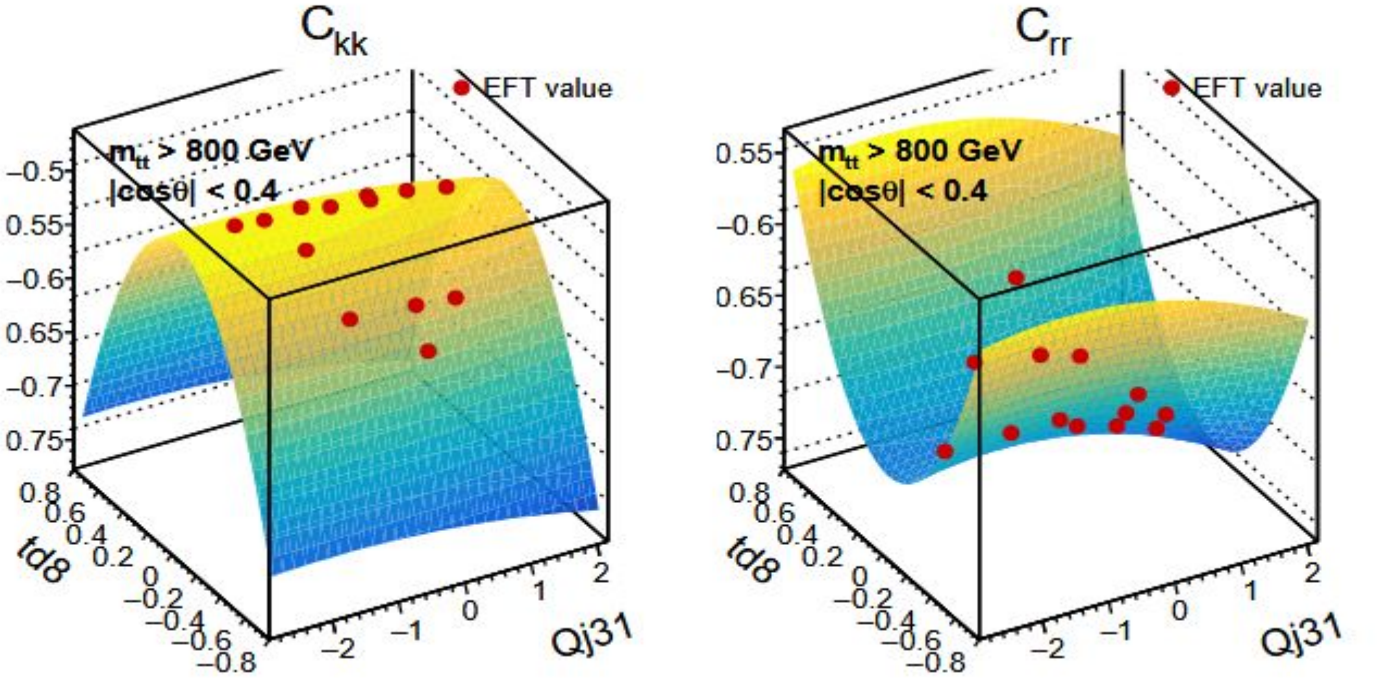


Boosted region

Parametrization of SMEFT effects on 2 WCs

❖ Case of two operators effects simultaneously

$$O_{EFT}(c_1, c_2) = \alpha_1 + \alpha_2 c_1 + \alpha_3 c_2 + \alpha_4 c_1^2 + \alpha_5 c_2^2 + \alpha_6 c_1 c_2$$



Deriving Limits on Wilson Coefficients

- **Method**: Bayesian inference using EFTfitter* tool
- **Parameters** : Pairs of WCs
- **Observables**: Polynomial deppendance previously obtained

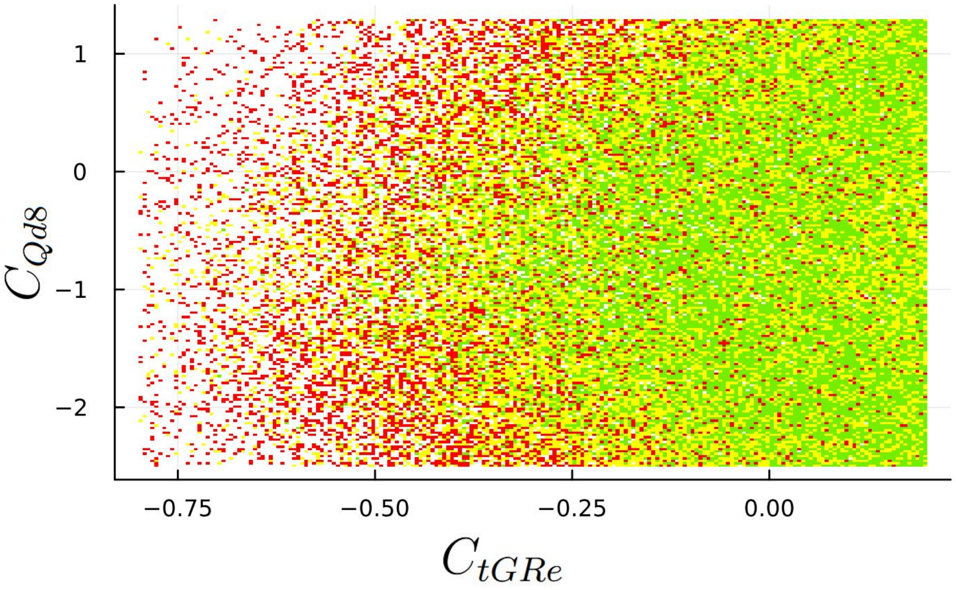
❖ Case 1: Toy Study for Ranking of Observables
- ➢ **Measurements:**
  - SM predictions
  - 10% sys. uncertainty assumed
- ➢ **No correlations between observables assumed.**

❖ Case 2: Using CMS data (TOP-23-007)
- ➢ **Measurements:**
  - C_{kk}, C_{rr}, C_{nn} measurements
  - Covariance matrices from CMS (TOP-23-007) included : Statistical + Sys. uncertainties

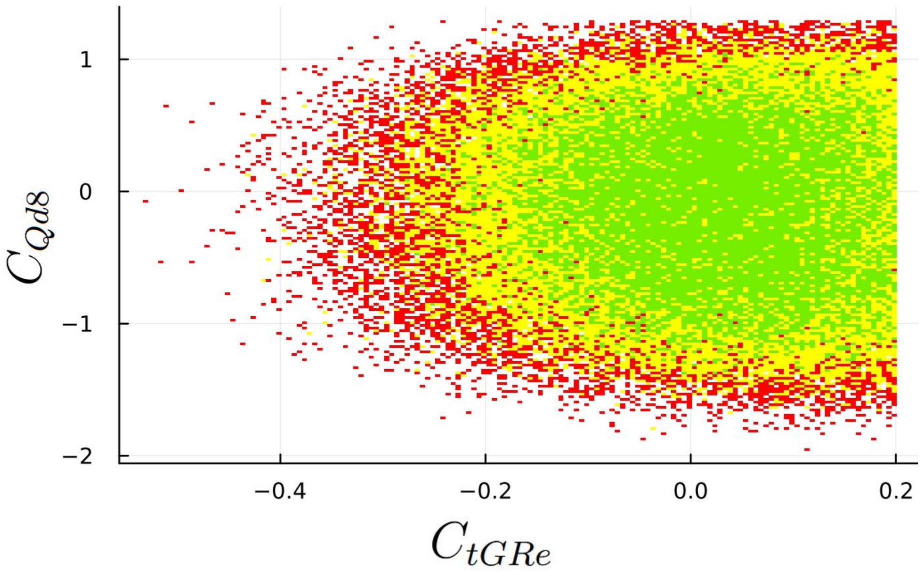
*N. Castro et al., *Eur. Phys. J. C* 76, 432 (2016). doi:10.1140/epjc/s10052-016-4273-4

Limits Obtained in Case 1

- Posterior distribution for a pair of WCs in the central boosted region
- Posterior distribution with 68%, 95% and 99% credible intervals.



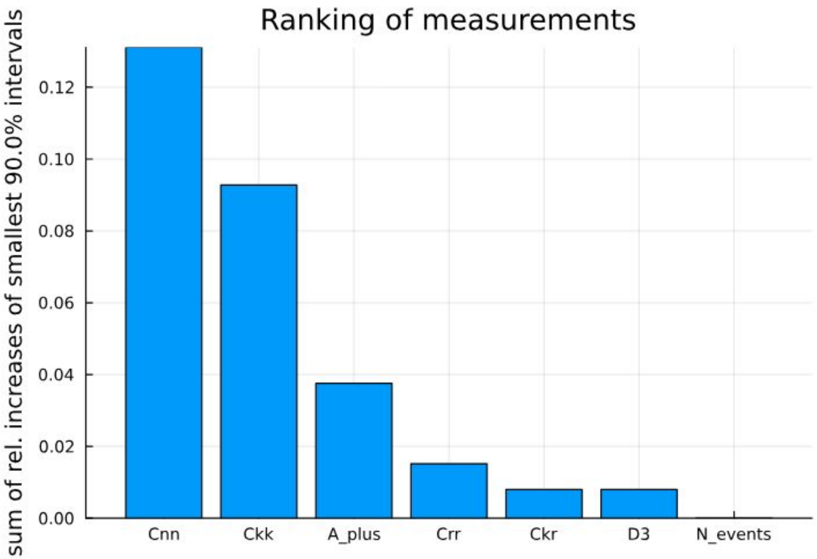
Only N_{events}



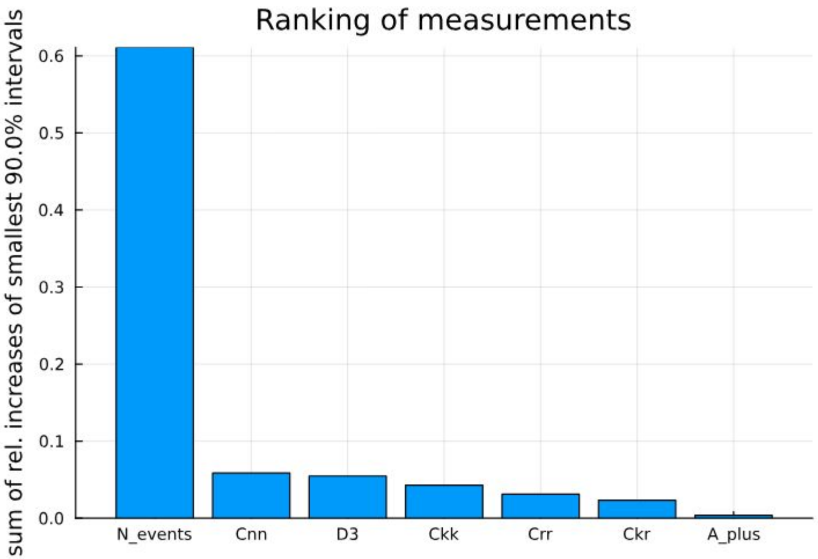
Including Quantum Observables

Ranking Result

- **Ranking of results** evaluates the importance of each observable
- A **larger increase** means the observable provides stronger constraints



(a) Boosted region

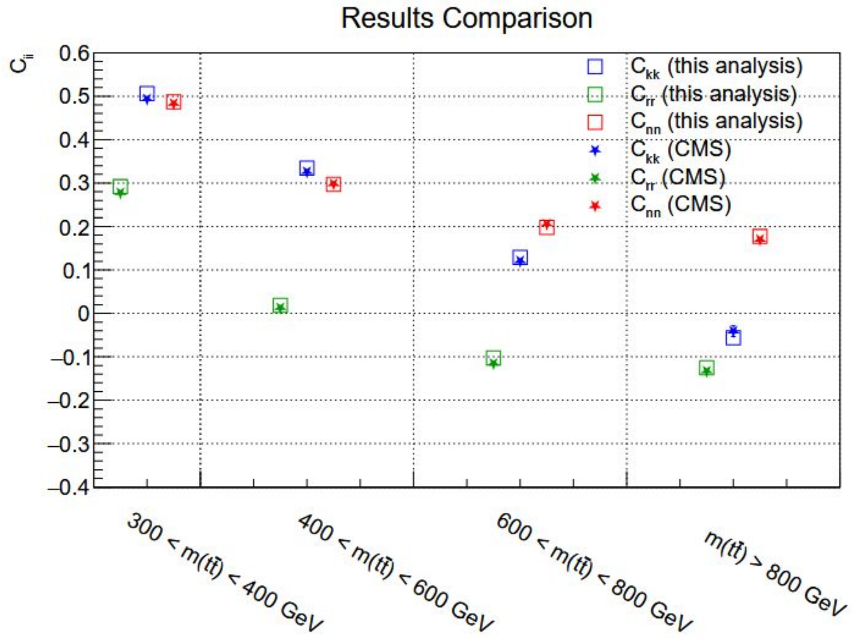


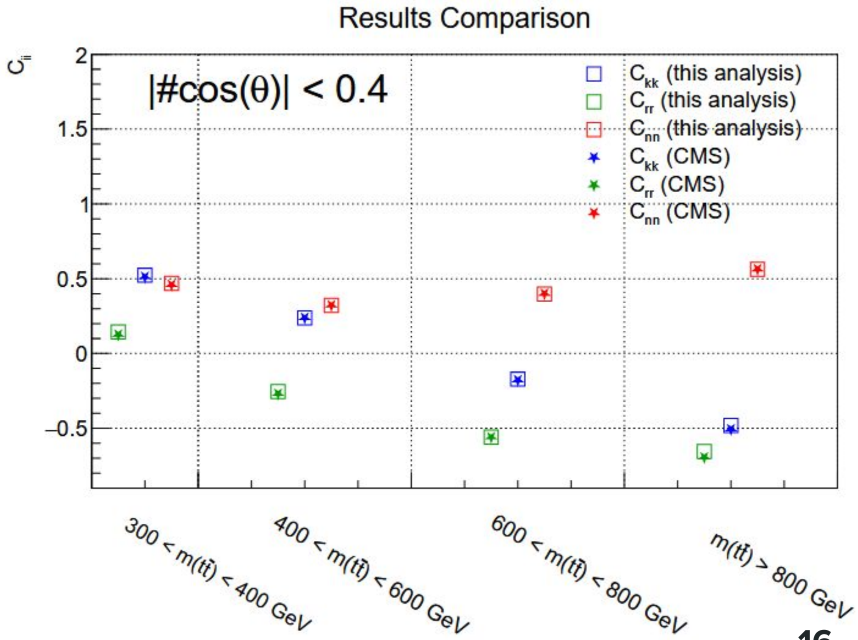
(b) Central high-boosted region

- **Summary**: Spin observables are the main drivers of sensitivity overall, while Number of events gains importance only in the central high-boosted regime.

Validation using CMS data

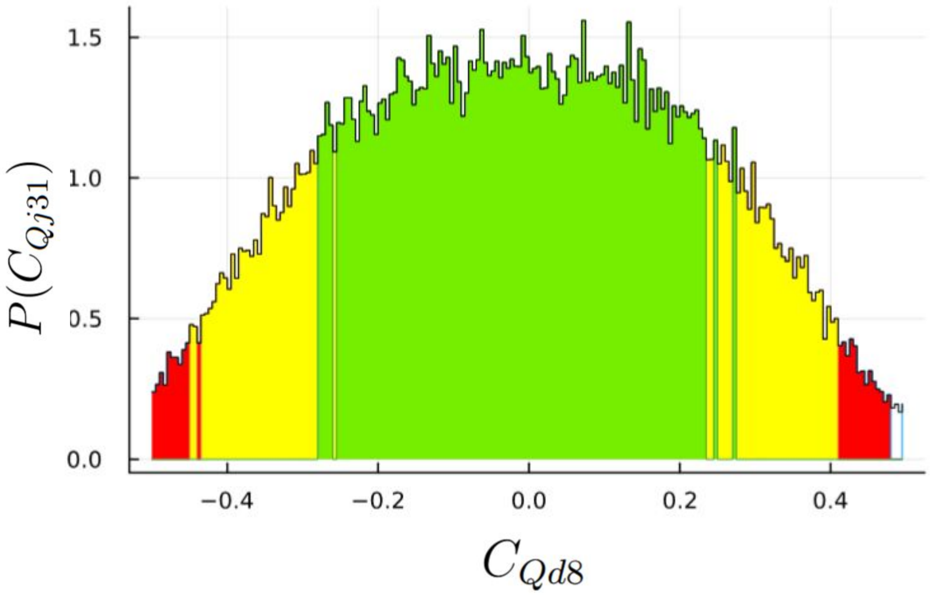
- Validation of the simulation is performed by comparison of C_{kk}, C_{rr}, C_{nn}
- CMS data comparison at different $m_{t\bar{t}}$ regions and with and without $|\cos(\theta)| < 0.4$
- Good agreement is found in both cases.

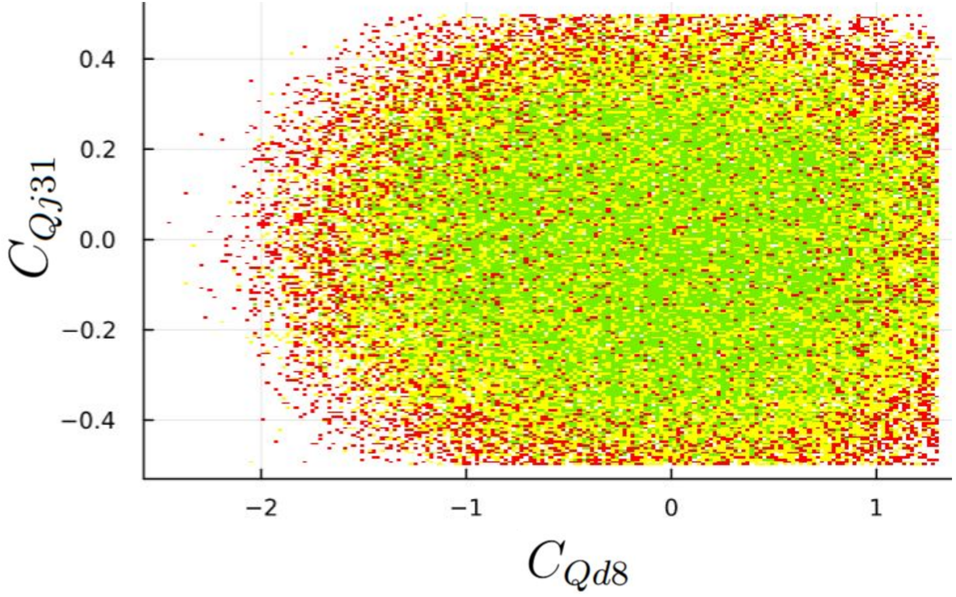




Analysis Results using CMS data: Posteriors

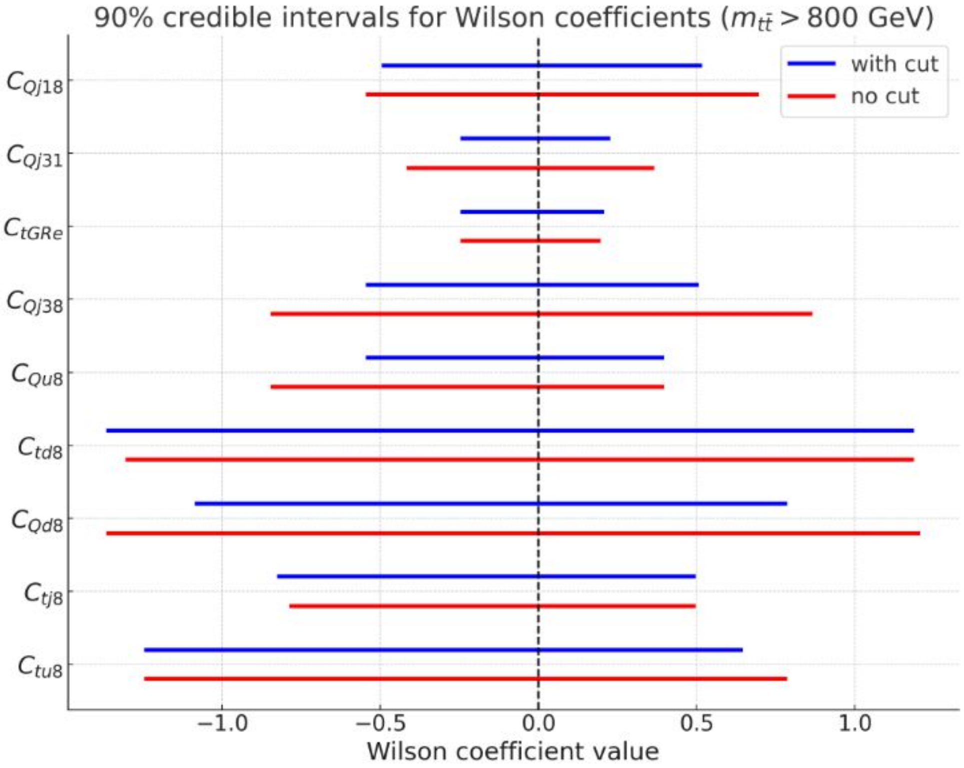
❖ Posterior distribution with 68%, 95% and 99% credible intervals.





Credible Intervals extracted

- ❖ Results are shown with (blue) and without (red) the angular cut | cos θ| < 0.4 in the boosted region



Summary Results

- ❖ Posterior distributions are consistent with the SM (0) and set EFT limits from spin–correlation data.

- ❖ Central boosted region provides the strongest sensitivity:
  - ➢ C_{rr} dominates for many operator pairs.
  - ➢ C_{nn} leads in other cases, while Nevents matter in highly boosted scenarios.

- ❖ Strongest bounds for WCs: C_{tGRe} and C_{Qj31} (~ ±0.3).

- ❖ Weakest bounds for WCs: C_{Qd8}, C_{td8}, C_{tj8}, especially C_{tu8} (> 2).

- ❖ Angular cut | cos θ| < 0.4 improves constraints (up to ~ 30% for C_{Qj31}, C_{Qu8}).

Conclusion

- Quantum observables in tt-bar production were studied as probes of new physics.

- Spin density matrix coefficients and entanglement marker are reconstructed from $t\bar{t}$ final states in the semileptonic channel.

- SMEFT analysis with dimension–six operators:
  - Identified operator effects on spin and entanglement observables.
  - EFT transform observables into WC bounds.

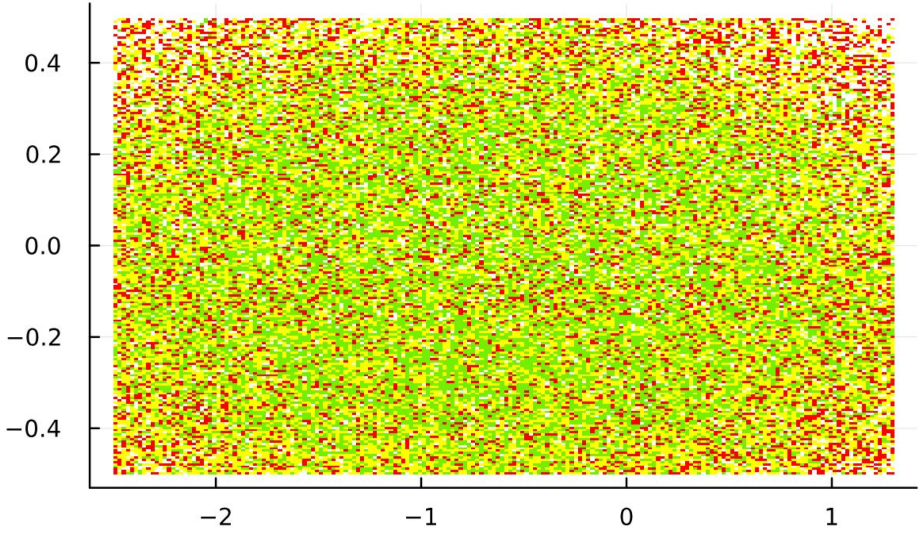
- Test using SM values as pseudo-data
  - **Central boosted regime** most sensitive regime

- Use CMS data to derive real limits WCs for dim-6 operators

Thank you for your attention

Limits Obtained in Case 1

❖ Posterior distributions for Qj31 WCs in the central boosted region



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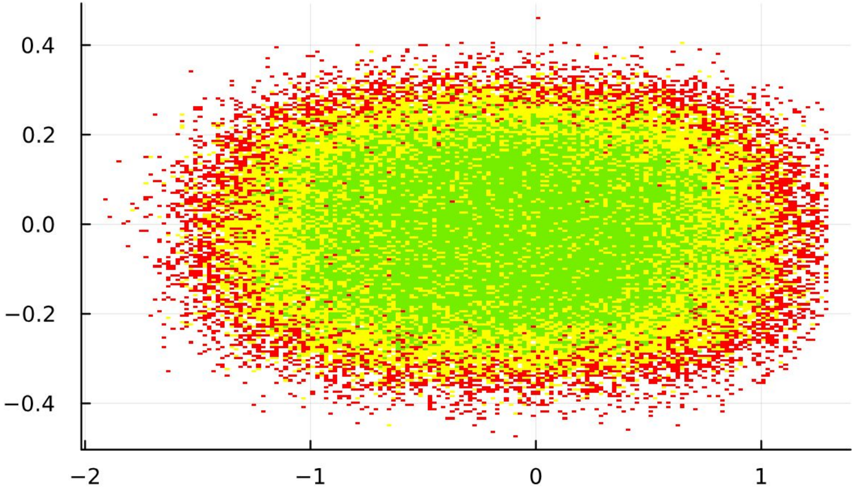

Including Quantum Observables