PROCEEDINGS OF SCIENCE

Measurement of top polarization and top pair spin correlations at CMS at $\sqrt{s} = 13$ TeV

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Measurements of the properties of the top quark can serve as stringent tests of the standard model (SM). To date, all the measurements of its pair and single production cross sections and properties indicate that it is indeed the top quark as predicted by the SM. However, moderate deviations from this expectation still cannot be ruled out. The spin density matrix of top quark pair production consists of coefficients which are affected by various discrete symmetry properties, making it a rich trove of information to search for effects beyond the SM. This talk describes the first measurement of top polarization and $\mathrm{t\bar{t}}$ spin correlations at $\sqrt{s} = 13$ TeV that are encoded in a systematic way into the spin density matrix, using data recorded by the CMS experiment in 2016. The measurements are found to be consistent with the SM prediction derived from Monte Carlo generators and analytic calculations at next to leading order QCD (+weak) accuracy. They are also used to derive the best constraint on the anomalous chromomagnetic moment of the top quark to date.

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1. Introduction

Due to its extremely short lifetime, the top quark is special in that it is the only quark whose spin structure can be studied. Furthermore, the tWb vertex involved in the decay means that the down-type fermion from the W decay is always emitted along the spin of its parent top quark, making it a perfect spin analyzer of the latter [1]. As charged leptons, in particular electrons and muons, are measurable with excellent resolution, events containing leptonic decays of top quarks are of particular interest.

Pair production of top quarks occur primarily through the strong interaction. Due to the parity invariance of Quantum Chromodynamics (QCD), the top quark pair ($\mathrm{t\bar{t}}$) is largely unpolarized. However, the top and antitop quark spins are correlated in a particular way. In addition, new $\mathrm{t\bar{t}}$ production mechanisms such as decays of a heavy scalar particle can modify this structure. Therefore, the measurement of top polarization and $\mathrm{t\bar{t}}$ spin correlation is at once a stringent test of the standard model (SM) and a powerful probe for the physics beyond. This document discusses such a measurement using 36 fb^{-1} proton-proton collision data at 13 TeV recorded by the CMS experiment in 2016 [2]. Events containing two isolated and oppositely charged leptons and at least two jets are analyzed, where at least one of the jets is required to be b-tagged.

2. The top pair spin density matrix

The normalized $\mathrm{t\bar{t}}$ differential cross section, in terms of all spin-dependent parts of the production density matrix, is given by:

$$\frac{1}{\sigma}\frac{\mathrm{d}^4\sigma}{\mathrm{d}\Omega_1\mathrm{d}\Omega_2} = \frac{1}{(4\pi)^2}\left(1+\vec{\mathrm{B}}_1\cdot\hat{\ell}^1+\vec{\mathrm{B}}_2\cdot\hat{\ell}^2-\hat{\ell}^1\cdot\mathrm{C}\cdot\hat{\ell}^2\right) \tag{2.1}$$

where $\vec{\mathrm{B}}_a$ are polarization vectors with indices $a = 1,2$ representing the top and antitop quarks respectively, and $\hat{\ell}^a$ are the directions of the spin analyzers. C is a 3×3 matrix that encodes the spin correlation between the top and antitop quarks. In specifying both $\vec{\mathrm{B}}_a$ and C, a basis has to be specified. The basis that is used here is called the $\{\mathrm{k},\mathrm{r},\mathrm{n}\}$ basis, chosen such that elements of $\vec{\mathrm{B}}_a$ and C have definite properties with respect to discrete symmetries [3], and is illustrated in Fig. 1.

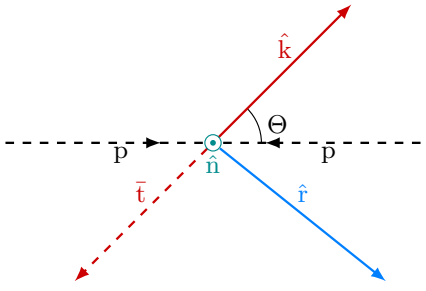

Figure 1: Visualization of the $\{\mathrm{k},\mathrm{r},\mathrm{n}\}$ basis used in this measurement. The basis is evaluated in the zero momentum frame of the $\mathrm{t\bar{t}}$ system, and Θ is the top quark scattering angle within this frame.

3. Results

The first set of results of this measurement is the top and antitop polarization coefficients i.e. elements of $\vec{B}_a$. They are shown in Fig. 2 (left). As indicated by Fig. 2 (left), the measured polarization coefficients are all consistent with 0, and the current precision is not sufficient to test the prediction of the SM. Next are the cross-correlation coefficients i.e. the off-diagonal elements of C. They are shown in Fig. 2 (right). Except for the $C_{rk} + C_{kr}$ coefficient, all are predicted to be zero in the SM. All measured cross-correlation coefficients are found to be compatible with the SM, and this measurement establishes that $C_{rk} + C_{kr}$ is different from zero at the 3σ level. The observables corresponding to the diagonal elements of C are the products of the cosines of the angles of top and antitop quark spin analyzer along a given axis. One of the measured distributions of these observables is shown in Fig. 3 (left). As suggested by the distribution, agreement with the SM is observed here as well.

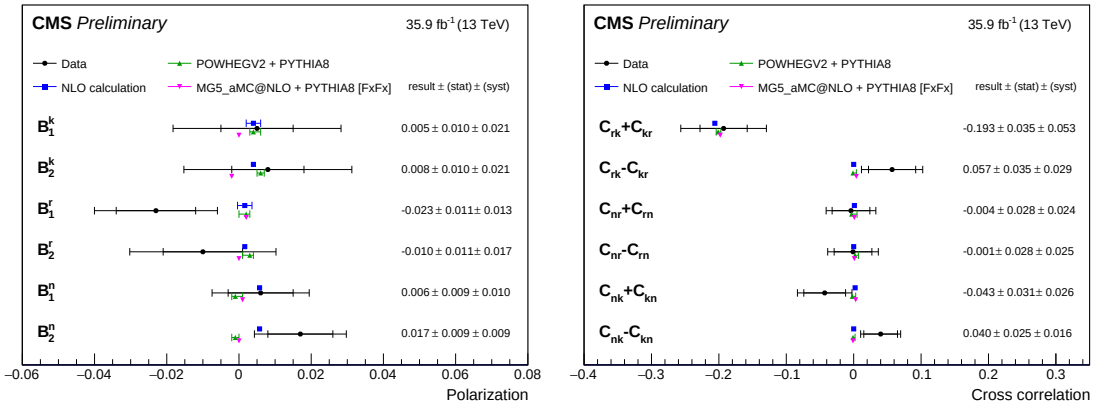

Figure 2: Left: measured values of top and antitop polarization coefficients. Right: measured values of the off-diagonal elements of C. In both cases the SM predictions from Monte-Carlo generators and fixed-order calculations are shown together for comparison. Figures are taken from Ref. [2].

In addition, the cosine of opening angle between the charged leptons in the $\{k, r, n\}$ basis ($\cos\varphi$) and the azimuthal gap between them in the laboratory frame ($|\Delta\phi_{\ell\ell}|$) are also measured. The slope of the $\cos\varphi$ distribution is proportional to the trace of C, this is the most precisely measured spin correlation coefficient so far. $|\Delta\phi_{\ell\ell}|$ on the other hand is only indirectly sensitive to the $t\bar{t}$ spin correlation, it however has the advantage of being measurable excellent experimental resolution. There appears to be some tension between the measured distribution and the SM predictions, and an improved theoretical calculation is necessary to resolve this discrepancy.

4. Constraints on top chromomagnetic dipole moment

The measurement is used to constrain the top chromomagnetic dipole moment (CMDM), represented by the Effective Field Operator $\mathcal{O}_{tG}$ and its associated Wilson coefficient C_{tG}. Using the

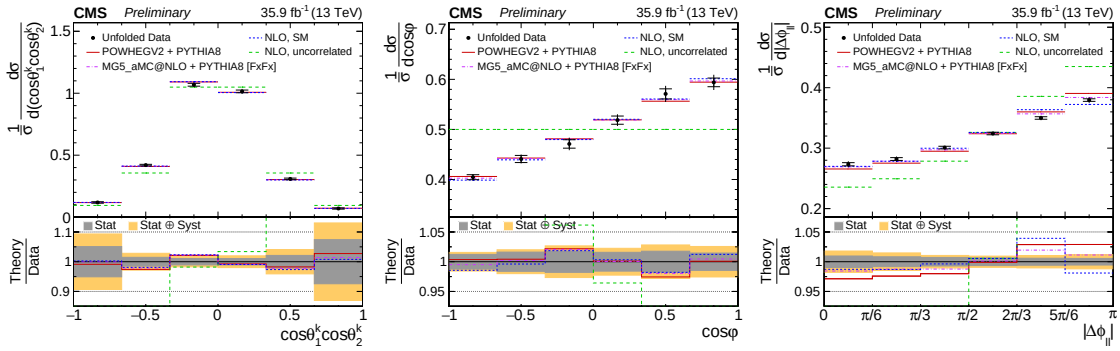

Figure 3: Left: measured distribution of $\cos\theta_1^k \cos\theta_2^k$. Middle: measured distribution of $\cos\varphi$. Right: measured distribution of $|\Delta\phi_{\ell\ell}|$. Figures are taken from Ref. [2].

predictions from Ref. [4] and 20 of the measured distributions and their covariance matrices, a constraint of $-0.07 < C_{tG}/\Lambda^2 < 0.16$ TeV^{-2} is obtained.

5. Summary

Measurement of top quark polarization and spin correlation is at once a stringest test of QCD and a powerful probe for physics beyond. It has the advantage that, with a properly chosen basis, its coefficients have definite properties with respect to C and P symmetries. As such, deviations with respect to the SM in any measured coefficients can be used to deduce the form of new physical effects that induce them. The CMS Collaboration has performed such a measurement using 36 fb^{-1} of data recorded in 2016, which has been used to constrain the top CMDM. The resulting constraint of $-0.07 < C_{tG}/\Lambda^2 < 0.16$ TeV^{-2} is the tightest direct constraint to date.

Disclaimer: Between the conference and the publication of these proceedings, the results presented here have been superseded by Ref. [5].

References

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