Search for SM deviations in top precision studies at CMS

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Abstract

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Search for the standard model deviations in top quark precision studies at CMS

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Precision studies of top quark properties provide a unique playground to test the predictions of the standard model and to search for new physics. Reviewed results from the CMS experiment done with the data collected at 8 TeV include studies of top quark Wtb anomalous and FCNC couplings, polarization, CP-violation, and spin correlation effects. No significant deviations from the SM predictions are observed.

The Large Hadron Collider (LHC) is a top quark factory that produces a large number of events containing top quarks. The top quark takes a special place in the standard model (SM) for numerous reasons. Top quarks can manifest themselves in distinctive experimental signatures as top quark almost exclusively decays to a W boson and a b quark with a very short lifetime escaping forming any bound states. This allows experimentalists to directly study the top quark properties by analyzing its decay products. The fact that this particle is the heaviest elementary particle ever discovered additionally suggests an enhanced sensitivity to various new particles and interactions proposed in beyond the SM (BSM) theories. New physics phenomena can be probed in the measurement of production rates of top quarks, in the study of the Wtb vertex structure and in the search for interactions that are heavily suppressed in SM.

A large number of top quark physics analyses have been done at CMS including the measurement of the production rates of single top quark, as well as top quark pair and top quark associative production with W, Z, Higgs bosons and photon. The Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|$ is directly extracted from the measured single top quark cross section. All these results are in remarkable agreement with theory predictions.

Events with single top quarks provide a unique playground to search for deviations from the SM by studying the Wtb vertex structure, as the single top production cross section is proportional to the strength of Wtb interaction. The general lagrangian that defines Wtb interaction includes several couplings that can be extracted from the measured kinematic distributions of top quarks and its decay products. The lagrangian includes two vector and two tensor couplings:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \bar{b} \gamma^{\mu}(f_L^V P_L + f_R^V P_R)t W_{\mu} - \frac{g}{\sqrt{2}} \sigma_{\mu \nu} \partial_\nu W^-_{\mu} (f_L^T P_L + f_R^T P_R)t,$$

where $P_{L,R} = (1 \mp \gamma_5)/2$, $\sigma_{\mu \nu} = i(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)$, $g$ is the coupling constant of the weak interaction, $f_L^V(f_R^V)$ represents the left-handed (right-handed) vector coupling and $f_L^T(f_R^T)$ is the left-handed (right-handed) tensor coupling. All couplings vanish at leading-order (LO) in SM but $f_L^V = V_{tb}$.

The analysis that probes anomalous Wtb couplings in t-channel production mode exploits Bayesian neural network (BNN) technique to define two neural networks: to suppress QCD background (Multijet BNN) and to extract t channel events from data (SM BNN). Additional anomalous Wtb BNNs are used to separate individual anomalous couplings contributions from the left-handed vector coupling component. In the limit setting procedure several strategies
are considered depending on the number of probed anomalous couplings. A multi-dimensional extraction of limits for anomalous couplings is possible because of negligible interference terms present for different types of couplings. One-dimensional limits at 95% CL on each of the couplings from the multi-dimensional fit after the integration over the rest of anomalous contributions yield $f_L^V > 0.98$, $f_R^V < 0.16$, $f_L^T < 0.057$ and $-0.049 < f_R^T < 0.048$. As expected in the SM, all but the left-handed vector coupling are consistent with zero.

The measurement of W helicity fractions in events with top quarks, where W helicity denotes the projection of W boson spin on its momentum, has a direct link to top quark properties and is sensitive to the real part of Wtb anomalous couplings. Each helicity fraction is defined as the relative top quark decay probability corresponding to a specific helicity of a W boson. Helicity fractions are extracted from the measurement of the $\cos(\theta^*)$ distribution. The definition of $\cos(\theta^*)$ corresponds to the angle between the W boson momentum in the top quark rest frame and the momentum of the down type decay fermion in the rest frame of the W boson.

The W boson helicity fractions can be measured in both single top and top quark pair events. The analysis that studies the single top production represents the first measurement of W boson helicity done in t-channel single top events. Single top events are accompanied by top quark pair events which are also considered in the analysis as signal. The $\cos(\theta^*)$ distribution from simulation is fitted to the distribution in data to extract the W boson helicity fractions. Left-handed and longitudinal polarizations of W boson are treated as free parameters in the fit, while the right-handed polarization is obtained from the constraint that the sum of all three polarizations must be equal to unity. The measured W helicities are used to set limits on the tensor terms of the Wtb anomalous couplings by fixing the vector terms to SM predicted values. The results are shown in Fig 1 and are consistent with the SM predictions.

![Figure 1 – Exclusion limits on Wtb anomalous tensor couplings. The Wtb vector couplings are fixed to SM values. $f_L^T \equiv -g_L$, $f_R^T \equiv -g_R$.](image)

The top quark polarization depends on the production mode and is very small in case of pair production, while it is expected to be very strong in case of singly produced top quarks. Deviations from SM can be probed in the measurement of top quark polarization as various new models can alter the spin of the top quark. In top quark pair events one can additionally study effects arising from spin correlations of top quarks.

The measurements of top quark polarization and spin correlations can be re-interpreted via the presence of anomalous ttg couplings that can significantly modify the shape of distributions of several kinematic variables. These anomalous interactions can be probed within the effective
model of chromo-electric ($\hat{d}_t$) and chromo-magnetic ($\hat{\mu}_t$) dipole moments. Spin correlations and top quark polarization are sensitive to $Re(\hat{\mu}_t)$ and $Im(\hat{d}_t)$, respectively. The value of $Re(\hat{\mu}_t)$ is determined from the measurement of normalized differential cross section which can be modified in the presence of new physics. SM and new physics contributions are parametrized by polynomial functions which are used in template fit to the measured normalized differential cross section. CP-violating component of top quark polarization is sensitive to $Im(\hat{d}_t)$. Upper limits of $-0.053 < Re(\hat{\mu}_t) < 0.026$ and $-0.068 < Re(\hat{d}_t) < 0.067$ are set at 95% CL.

In the SM, CP violation in production and decay of top quarks is predicted to be very small. However, in many BSM models a sizable CP violation effects can be observed to provide a possible explanation for the matter-antimatter asymmetry in the Universe. A first measurement of CP-violating asymmetries in production and decays of top quarks exploits T-odd, triple-product correlations. Several observables ($O_i$) are defined that represent a combination of a reconstructed object’s spin and momentum vectors. Asymmetry for each of these observables is defined as:

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)},$$

and is measured with and without applying corrections for detector effects as these additional corrections can also be affected by the BSM. Results of the actual measurement in data are shown in Fig 2. No deviations from the SM predictions are observed.

Flavour-changing neutral currents (FCNC) are highly suppressed at tree level in SM by the Glashow-Iliopoulos-Maiani (GIM) mechanism but can be significantly enhanced in various BSM. FCNC with top quarks can occur either in events with singly produced top quarks or in events with top quark pairs where one of the top quarks decays via FCNC.

Top-gluon FCNC is probed in the single top t channel production in association with an additional quark or gluon. This FCNC analysis is done by exploiting a similar BNN framework as is used in the analysis on the Wtb anomalous couplings. A difference with respect to the anomalous Wtb analysis is that here additional BNNs are trained sensitive to FCNC events. The observed (expected) limit at 95% CL on the FCNC branching ratio of top quark with up and charm-type quark is $B(t \to ug) < 2.0(2.8) \cdot 10^{-5}$ and $B(t \to cg) < 4.1(2.8) \cdot 10^{-4}$, respectively.

Top-Z FCNC is simultaneously probed in single top and top quark pair events with the final state of three leptons. Signal is extracted from a simultaneous fit to the transverse mass of the reconstructed W and to the final Boosted decision tree discriminant used to select signal events. Observed (expected) limit at 95% CL on the FCNC branching ratio of top quark with up and
charm-type quark is $B(t \rightarrow uZ) < 2.2 \cdot 10^{-4}(2.7 \cdot 10^{-4})$ and $B(t \rightarrow cZ) < 4.9 \cdot 10^{-4}(1.2 \cdot 10^{-3})$, respectively.

A summary of all FCNC searches at CMS is shown in Fig 3.10.

![Figure 3 – Summary of results on FCNC searches at CMS.](image)

A large number of experimental results with the high precision measurements of the top quark properties is available from 8 TeV analyses done with the CMS detector. Theoretical predictions stay in agreement with data observations and no significant deviations from the SM expectations are observed yet.

References

10. [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures).