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Probing global symmetries with top quarks and Higgs bosons at CMS

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Several global symmetries of the Standard Model – Lorentz invariance, CPT and CP symmetries – are tested with top quarks and Higgs bosons using LHC data collected with the CMS detector. Top-antitop ($t\bar{t}$) production is used to probe CPT symmetry and Lorentz invariance. The top-boson coupling is employed to test the CP symmetry, in the top quark coupling to the gluon with the $t\bar{t}$ process, in the top quark coupling to the Z boson with $t\bar{t}\gamma/Z$ processes, and in the top quark coupling to the Higgs boson with the $t\bar{t}H$ process.

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1. Introduction

A Lagrangian respecting a global symmetry remains invariant by a transformation applied simultaneously at all points of spacetime. In these proceedings, we focus on Lorentz invariance, CPT and CP symmetries. The baryon asymmetry observed in the Universe is 17 orders of magnitude larger than that predicted by the Standard Model (SM) electroweak baryogenesis. Electroweak baryogenesis beyond the SM usually requires a new source of CP violation, and extends the scalar sector to ensure a first order phase transition. As an alternative, CPT baryogenesis includes a new CPT-violation source, which induces a baryon number violation at thermal equilibrium. Since the violation of CPT symmetry implies the violation of Lorentz invariance [1], both symmetries are tightly connected. In these proceedings, we will present results obtained with CMS [2, 3], relative to the tests of CPT symmetry and Lorentz invariance in top-antitop ($t\bar{t}$) production, and tests of CP symmetry in the couplings between the top quark and the SM bosons.

2. Tests of CPT and Lorentz invariance with $t\bar{t}$ production

Possible violation of Lorentz invariance and of CPT symmetry is predicted in models of strings [4] or loop quantum gravity [5]. The $t\bar{t}$ production can be employed to search for a violation of Lorentz invariance or of CPT symmetry.

2.1 A measurement of the top-antitop mass difference

The mass difference between top quark and antiquark was measured with the 8 TeV dataset provided by the LHC Run 1 and collected with CMS [6, 7], in the $t\bar{t}$ semi-leptonic decay channels. The top quarks and antiquarks are reconstructed with a kinematic fit. Many systematic uncertainties cancel out in the mass difference, which is measured to be: $\Delta m_t = 0.15 \pm 0.19$ (stat) ± 0.09 (syst), compatible with the SM predictions. The measurement was recently interpreted in term of constraint on the b_μ CPT-violating parameter [8], impacting the differently the top quark and antiquark propagators (while the masses remain the same), within the framework of a Lorentz-violating Effective Field Theory called the Standard Model Extension [9, 10] (SME).

2.2 Searches for violation of Lorentz invariance with $t\bar{t}$

The analysis presented here [11] is searching for a modulation of $t\bar{t}$ cross section in the dilepton decay channel as a function of the sidereal time, using the 13 TeV dataset of the LHC Run 2 at CMS. While one rotation period of the Earth is equal to approximately 23 h 56 min UTC (Universal Time Coordinated), one rotation period is defined as being equal to 24 sidereal hours. The CMS detector moves around the Earth's rotation axis during a sidereal day, and so does the beam line direction at the interaction point, or the average direction of top quarks produced in the collisions, resulting in cross sections for top quark production modulating with sidereal time. The signal extraction is using the distribution in the number of b jets to discriminate $t\bar{t}$ from the main background, tW process, in each sidereal hour. A direct fit of $t\bar{t}$ differential normalized cross section as a function of sidereal time yields an uncertainty of 2.2% per time bin, where 0.9% is due to statistical uncertainties, as shown in Fig. 1 (left). The integrated luminosity, pileup distribution, and trigger efficiencies, with their uncertainties, are computed as a function of sidereal time. Dominant systematic uncertainties are arising from experimental sources and treated as uncorrelated in time, while other experimental uncertainties (luminosity, pileup and trigger) were treated as correlated and are as negligible as SM theory uncertainties. A set of 16 coefficients of the SME are measured at the 0.1 – 0.8% level and presented in Fig. 1 (right), showing no deviation larger than 1σ relative to the SM. These results represent an improvement up to a factor 100 relative to a previous such analysis at D0 experiment [12]. The result is the first test of spacetime anisotropy in special relativity with top quarks at the LHC.

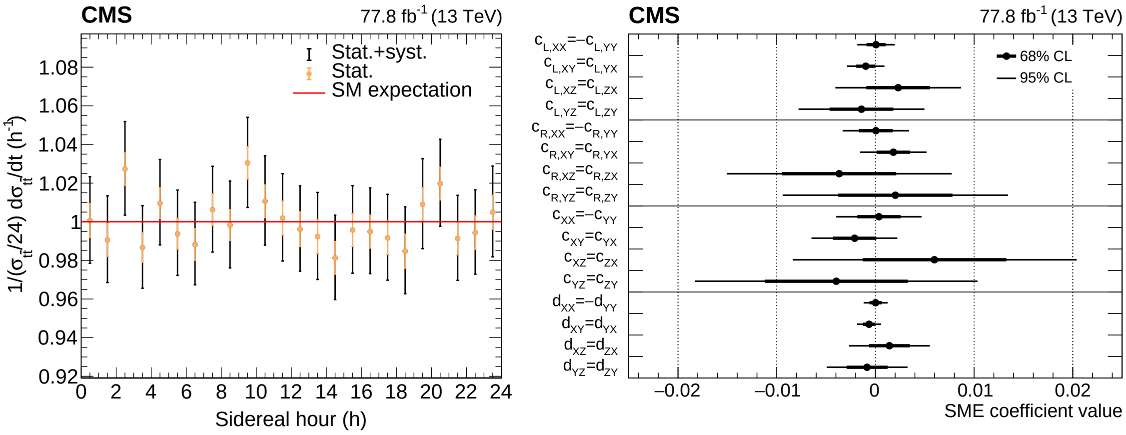

Figure 1: Normalized differential $t\bar{t}$ cross section as a function of sidereal time (left); and measured Lorentz-violating coefficients (right) [11].

3. Probing CP symmetry in top quark - boson couplings

The searches for CP violation presented here employ the framework of the Standard Model Effective Field Theory [13] (SMEFT), where several dimension 6 operators that are impacting the top quark can have an imaginary component and violate CP symmetry.

3.1 Search for CP violation in top quark - gluon coupling using $t\bar{t}$ production

CP-violation in the coupling between the top quark and the gluon would induce a chromoelectric dipole moment, which can be searched for with several methods. Employing the $t\bar{t}$ process in the dilepton final state allows to measure angular distributions, connected with top quark polarization and spin correlation observables, that are sensitive to CP-violation. From a simultaneous fit to several of these distributions, the result $-0.33 < Im(c_{tG}) < 0.2$ TeV^{-2} is obtained [14]. A similar sensitivity is obtained by measuring instead asymmetries of triple product of lepton or jet momenta, designed to be CP-odd [15, 16].

3.2 Search for CP violation in top quark - Z boson coupling using $t\bar{t}\gamma/Z$ production

The measurement of the coupling between the top quark and the Z boson employing $t\bar{t}Z$ final state [17] has recently been complemented with the use of the $t\bar{t}\gamma$ final state [18, 19]. The idea relies on choosing the appropriate EFT basis. Before electroweak symmetry breaking (EWSB) the

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relevant EFT operators are c_{tB} and c_{tW} (where B and W refer to the electroweak field strength tensors), while after EWSB they are $c_{t\gamma}$ and c_{tZ} (where γ and Z are the electromagnetic and Z boson tensor fields). In the analyses of the $t\bar{t}\gamma$ final state, the EFT basis employed is (c_{tW}, c_{tZ}), which allows indeed to constrain c_{tZ}.

The discriminant observable employed to measure $Im(c_{tZ})$ in the $t\bar{t}Z$ final state is the Z boson p_T in bins of the $cos\theta^*$ distribution, while in the $t\bar{t}\gamma$ final state the photon p_T is employed, both in the semileptonic [18] and in the dilepton [19] decay channels. It is to be noted that this latter variable is CP-even, which means that the sensitivity to $Im(c_{tZ})$ cannot be distinguished from that to $Re(c_{tZ})$. In the future, CP-conservation and CP-violation could be disentangled by utilizing a CP-odd observable (Fig. 2 (left)). The best precision on $Im(c_{tZ})$ is obtained from the combination of $t\bar{t}\gamma$ final state in the single lepton and in the dilepton channels [19], with a result compatible with SM predictions within a precision of ≈ 0.4 TeV^{-2}, as shown in Fig. 2 (right).

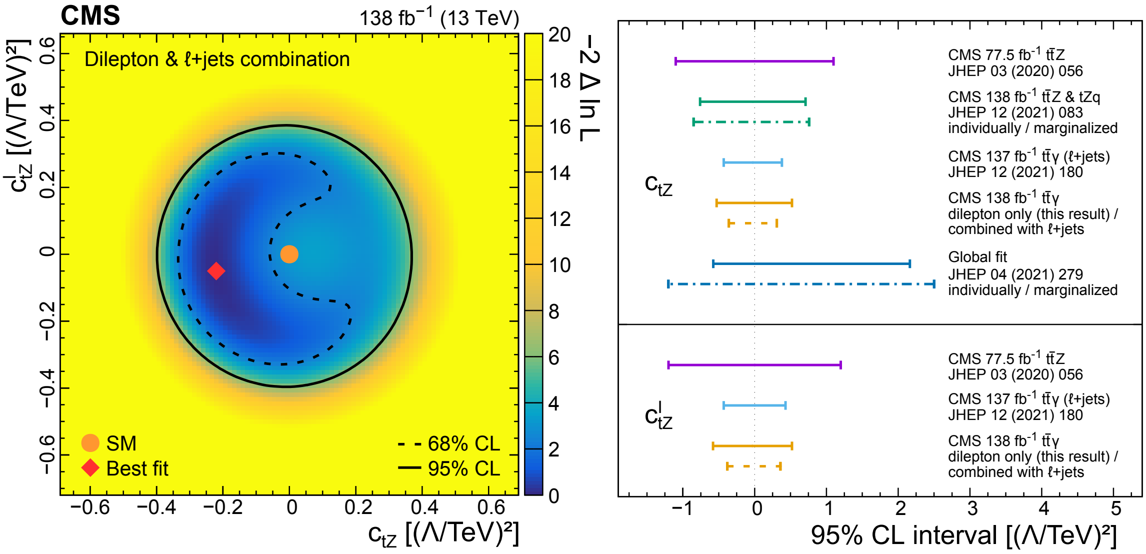

Figure 2: Two-dimensional scan of the Wilson coefficients $Re(c_{tZ})$ and $Im(c_{tZ})$ using the photon p_T distribution from the combination of the $t\bar{t}\gamma$ analyses in the dilepton and lepton+jets channels [19] (left); and measured values of $Re(c_{tZ})$ and $Im(c_{tZ})$ with their uncertainty in past CMS analyses [19] (right).

3.3 Search for CP violation in top quark - Higgs boson coupling using $t\bar{t}H$ production

It was shown that the SM electroweak baryogenesis, extended with EFT operators among which a CP-violating component to the top quark - Higgs boson coupling, can actually reproduce the observed baryon density [20]. At CMS, possible CP-violation in this coupling is primarily searched for in $t\bar{t}H + tH$ production using the $H \to \gamma\gamma$ [21] and the multilepton [22] final states, which have the best sensitivity, with the recent addition of the $H \to b\bar{b}$ [23] final state. The lagrangian is parametrized as following:

$$L(Ht\bar{t}) = -\frac{m_t}{v}\bar{t}(\kappa_t + i\tilde{\kappa}_t)tH \qquad (1)$$

The fraction of CP-violating top-Higgs coupling is:

$$f_{CP}^{Ht\bar{t}} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} sign(\tilde{\kappa}_t/\kappa_t) \qquad (2)$$

In the $H \to \gamma\gamma$ channel [21], a boosted decision tree (BDT) is used in several $t\bar{t}H$ and tH event classes to discriminate the Higgs boson signal from the SM backgrounds. A dedicated discriminant is built aiming at enhancing sensitivity to CP violation. The multilepton analysis [22] is targeting mainly the $H \to W^+W^-$ and $H \to \tau^+\tau^-$ final states, through event classes with two same-sign leptons (where lepton is electron or muon), three leptons, and two leptons with a hadronic tau. The $t\bar{t}H$ process is discriminated from the SM backgrounds with a deep neural network, while a BDT is targeting the CP-violating signal. The 2D likelihood scan for κ_t and $\tilde{\kappa}_t$ is shown in Fig. 3 (left). The $H \to b\bar{b}$ channel [23] uses neural networks in 0, 1, and 2 lepton event classes with various number of jets and b-jets. The measured Higgs boson signal strength is $\mu_{t\bar{t}H} = 0.33 \pm 0.26$. The $H \to b\bar{b}$ channel, when combined with the other channels, improves the expected result. However, the low measured signal strength weakens the observed sensitivity to CP-violation, as shown in Fig. 3 (right).

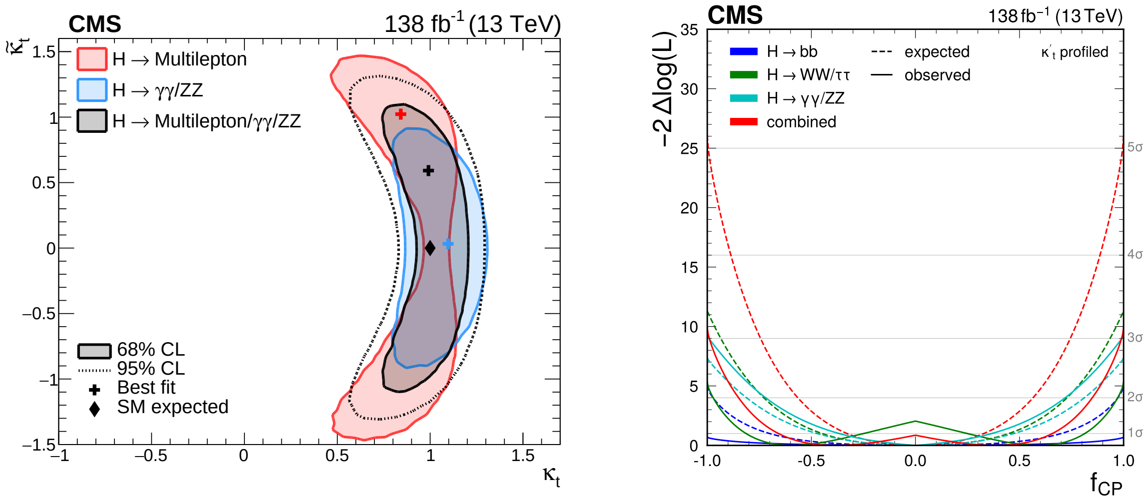

Figure 3: Likelihood scan as a function of κ_t and $\tilde{\kappa}_t$ for $t\bar{t}H, H \to \gamma\gamma$ and multilepton channels [22] (left); and likelihood ratio test statistic as a function of f_{CP} including as well $H \to b\bar{b}$ final state [23] (right).

4. Summary

The most precise measurement of the top quark and antiquark mass difference at CMS has a precision of 0.21 GeV, and was recently interpreted as a constraint on a parameter governing CPT-violation. The first search for violation of Lorentz invariance with $t\bar{t}$ process at the LHC, within the Standard Model Extension, was presented. By measuring the differential normalized cross section for $t\bar{t}$ production with time, spacetime anisotropy in special relativity is tested at the 0.1–0.8% level. The CP symmetry is tested in the coupling of the top quark to the gluon with a precision of 0.2–0.3 TeV^{-2}, to the Z boson with a precision of 0.4 TeV^{-2}, and to the Higgs boson where the CP fraction is observed (expected) to be lower than 0.85 (0.6) at 95% confidence level. All of those parameters would profit from a measurement at the LHC Run 3 or at the HL-LHC.

References

[1] O. W. Greenberg, “CPT violation implies violation of Lorentz invariance,” Phys. Rev. Lett. **89** (2002), 231602 [arXiv:hep-ph/0201258 [hep-ph]].

[2] CMS Collaboration, “The CMS Experiment at the CERN LHC,” JINST **3** (2008), S08004

[3] CMS Collaboration, “Development of the CMS detector for the CERN LHC Run 3,” JINST **19** (2024) no.05, P05064 [arXiv:2309.05466 [physics.ins-det]].

[4] V. A. Kostelecky and S. Samuel, “Spontaneous Breaking of Lorentz Symmetry in String Theory,” Phys. Rev. D **39** (1989), 683 doi:10.1103/PhysRevD.39.683

[5] R. Gambini and J. Pullin, “Nonstandard optics from quantum space-time,” Phys. Rev. D **59** (1999), 124021 [arXiv:gr-qc/9809038 [gr-qc]].

[6] CMS Collaboration, “Measurement of the mass difference between top quark and antiquark in pp collisions at $\sqrt{s} = 8$ TeV,” Phys. Lett. B **770** (2017), 50-71 [arXiv:1610.09551 [hep-ex]].

[7] CMS Collaboration, “Review of top quark mass measurements in CMS,” Accepted by Physics Reports [arXiv:2403.01313 [hep-ex]].

[8] A. Belyaev, L. Cerrito, E. Lunghi, S. Moretti and N. Sherrill, “Probing CPT Invariance with Top Quarks at the LHC,” Phys. Rev. Lett. **133** (2024) no.22, 221601 [arXiv:2405.12162 [hep-ph]].

[9] D. Colladay and V. A. Kostelecky, “CPT violation and the standard model,” Phys. Rev. D **55** (1997), 6760-6774 [arXiv:hep-ph/9703464 [hep-ph]].

[10] D. Colladay and V. A. Kostelecky, “Lorentz violating extension of the standard model,” Phys. Rev. D **58** (1998), 116002 [arXiv:hep-ph/9809521 [hep-ph]].

[11] CMS Collaboration, “Searches for violation of Lorentz invariance in top quark pair production using dilepton events in 13 TeV proton-proton collisions,” Phys. Lett. B **857** (2024), 138979 [arXiv:2405.14757 [hep-ex]].

[12] D0 Collaboration, “Search for violation of Lorentz invariance in top quark pair production and decay,” Phys. Rev. Lett. **108** (2012), 261603 [arXiv:1203.6106 [hep-ex]].

[13] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, “Dimension-Six Terms in the Standard Model Lagrangian,” JHEP **10** (2010), 085 [arXiv:1008.4884 [hep-ph]].

[14] CMS Collaboration, “Measurement of the top quark polarization and $t\bar{t}$ spin correlations using dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV,” Phys. Rev. D **100** (2019) no.7, 072002 [arXiv:1907.03729 [hep-ex]].

[15] CMS Collaboration, “Search for CP violation using $t\bar{t}$ events in the lepton+jets channel in pp collisions at $\sqrt{s} = 13$ TeV,” JHEP **06** (2023), 081 [arXiv:2205.02314 [hep-ex]].

[16] CMS Collaboration, “Search for CP violating top quark couplings in pp collisions at $\sqrt{s} = 13$ TeV,” JHEP **07** (2023), 023 [arXiv:2205.07434 [hep-ex]].

[17] CMS Collaboration, “Measurement of top quark pair production in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV,” JHEP **03** (2020), 056 [arXiv:1907.11270 [hep-ex]].

[18] CMS Collaboration, “Measurement of the inclusive and differential $\mathrm{t}\bar{t}\gamma$ cross sections in the single-lepton channel and EFT interpretation at $\sqrt{s} = 13$ TeV,” JHEP **12** (2021), 180 [arXiv:2107.01508 [hep-ex]].

[19] CMS Collaboration, “Measurement of the inclusive and differential $\mathrm{t\bar{t}}\gamma$ cross sections in the dilepton channel and effective field theory interpretation in proton-proton collisions at $\sqrt{s}$ =13 TeV,” JHEP **05** (2022), 091 [arXiv:2201.07301 [hep-ex]].

[20] A. Kobakhidze, L. Wu and J. Yue, “Electroweak Baryogenesis with Anomalous Higgs Couplings,” JHEP **04** (2016), 011 [arXiv:1512.08922 [hep-ph]].

[21] CMS Collaboration, “Measurements of $\mathrm{t\bar{t}}H$ Production and the CP Structure of the Yukawa Interaction between the Higgs Boson and Top Quark in the Diphoton Decay Channel,” Phys. Rev. Lett. **125** (2020) no.6, 061801 [arXiv:2003.10866 [hep-ex]].

[22] CMS Collaboration, “Search for CP violation in ttH and tH production in multilepton channels in proton-proton collisions at $\sqrt{s} = 13$ TeV,” JHEP **07** (2023), 092 [arXiv:2208.02686 [hep-ex]].

[23] CMS Collaboration, “Measurement of the $\mathrm{t\bar{t}}$H and tH production rates in the H $\rightarrow \mathrm{b\bar{b}}$ decay channel using proton-proton collision data at $\sqrt{s} = 13$ TeV,” JHEP **02** (2025), 097 [arXiv:2407.10896 [hep-ex]].