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A first constraint on CPT violation in top quarks

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In this talk, I discuss the how the first model-independent constraint on CPT violation in top quarks was extracted from ATLAS and CMS Collaboration measurements of the top-antitop kinematical mass difference.

9th Symposium on Prospects in the Physics of Discrete Symmetries (DISCRETE2024)
2–6 Dec 2024
Ljubljana, Slovenia

https://pos.sissa.it/

PoS(DISCRETE2024)003

1. Introduction

The CPT theorem roughly states that local, unitary, and Lorentz-invariant quantum field theories in Minkowski spacetime are invariant under the simultaneous application of charge-conjugation (C), parity (P), and time-reversal (T) transformations [1–3]. This CPT invariance ensures that particles and corresponding antiparticles share some identical properties, including masses and lifetimes. Though presently observed as an exact symmetry, violations of CPT invariance appear admissible in some approaches to quantum gravity, e.g., string models [4, 5]. If present, these violations will produce deviations from the Standard Model (SM) and General Relativity that might be detectable in sensitive experiments.

The model-independent Standard-Model Extension (SME) is an effective field theory widely used to search for violations of CPT invariance and other fundamental symmetries [6–9]. Application of the SME to phenomenological studies and experimental searches has led to numerous constraints on parameters controlling CPT violation [10]. Within this body of work are CPT tests involving particle–antiparticle comparisons. These proceedings report on recent work that tests CPT violation in the top sector of the SME for the first time [11]. We demonstrate that proper interpretation of the top–antitop mass difference measured by the ATLAS and CMS collaborations [12–14] implies a model-independent constraint on CPT violation.

2. Setup

The relevant gauge-invariant and renormalizable CPT-violating effects are given by [6, 15]

$$\mathcal{L}^{\text{CPT}-} = -(a_Q)_{\mu AB}\bar{Q}_A\gamma^\mu Q_B - (a_U)_{\mu AB}\bar{U}_A\gamma^\mu U_B - (a_D)_{\mu AB}\bar{D}_A\gamma^\mu D_B. \quad (1)$$

An odd number of operator Lorentz indices introduces a sign flip under the CPT transformation, which is indicated in the superscript on $\mathcal{L}^{\text{CPT}-}$. We are interested in flavor-diagonal effects in the third quark generation, thus $A = B = 3$. The fields have the standard definitions

$$Q_3 = \begin{pmatrix} t \\ b \end{pmatrix}_L, \quad U_3 = t_R, \quad D_3 = b_R, \quad (2)$$

and the coefficients for CPT violation are $(a_Q)_{\mu 33}, (a_U)_{\mu 33}$, and $(a_D)_{\mu 33}$. A reduction of the number of independent coefficients is possible when neglecting the bottom-quark mass relative to the top-quark mass m_t. Note that m_t remains identical for top and antitop quarks in the presence of CPT violation, in accordance with Greenberg's theorem [16]. The phases of D_3 and Q_3 fields can be independently transformed by position-dependent field redefinitions that leave the physics invariant. $D_3 \to \exp[-i(a_D)_{\mu 33}x^\mu]D_3$ removes the a_D-type term in Eq. (1) and a similar redefinition involving the phase $\exp[-i(a_Q)_{\mu 33}]$ applied to Q_3 and U_3 eliminates the a_D-type term such that $(a_U)_{\mu 33} \to (a_U)_{\mu 33} - (a_Q)_{\mu 33}$. Under these assumptions, Eq. (1) expressed in the mass-eigenstate basis reads

$$\mathcal{L}^{\text{CPT}-}_{\text{top}} = b_\mu \bar{t}_R\gamma^\mu t_R, \quad (3)$$

where $b_\mu \equiv [(a_Q)_{\mu 33} - (a_U)_{\mu 33}]$. CPT-violating effects are then isolated to the top sector and involve only the right-handed field $t_R = P_R t$.

Including Eq. (3) with the conventional kinetic terms yields a modified Dirac equation

$$\left[i\partial\!\!\!/ + \tfrac{1}{2}(1-\gamma_5)b\!\!\!/ - m_t\right] t = 0, \tag{4}$$

where $b\!\!\!/ = b_\mu \gamma^\mu$. The plane-wave ansatz results in a quartic equation in $p^\mu = (E_t, \vec{p})$ with distinct solutions

$$p^2 = \begin{cases} m_t^2 - p\cdot b \pm [(p\cdot b)^2 - m_t^2 b^2]^{1/2} & \text{(top)} \\ m_t^2 + p\cdot b \pm [(p\cdot b)^2 - m_t^2 b^2]^{1/2} & \text{(antitop).} \end{cases} \tag{5}$$

Note that by assumption CPT-violating effects are small, so higher-order terms in b_μ are neglected here. The first and second CPT-violating terms in each row are tied to the vector and pseudovector pieces of Eq. (3), respectively. The $\pm$ signs denote the helicity of the state and $b_\mu \to -b_\mu$ connects the particle and antiparticle solutions, reflecting the CPT-odd property of Eq. (3). CPT-violating corrections to the top and antitop decay widths are also neglected since they are suppressed relative to these free-propagation effects by the square of the weak coupling constant.

In the conventional CPT-invariant case, $m_t^{\rm kin} = m_{\bar{t}}^{\rm kin} = m_t$. However, the top ($p$) and antitop ($\bar{p}$) *kinematical masses* $m_t^{\rm kin} \equiv \sqrt{p^2}$ and $m_{\bar{t}}^{\rm kin} \equiv \sqrt{\bar{p}^2}$, respectively, generically differ in the presence of CPT violation. The kinematical masses are reconstructed via charge and four-momentum conservation of the final-state decay products. The kinematical mass difference

$$\Delta m_{t\bar{t}}^{\rm kin}(p, \lambda_p, \bar{p}, \lambda_{\bar{p}}, m_t, b) \equiv m_t^{\rm kin} - m_{\bar{t}}^{\rm kin} \tag{6}$$

parametrizes a CPT-violating top-antitop asymmetry, where λ_p ($\lambda_{\bar{p}}$) are the top (antitop) helicities.

In principle measurements of $\Delta m_{t\bar{t}}^{\rm kin}$ can be used to extract all components of b_μ. However, in practice, this is nontrivial because b_μ acts as a background vector field that also violates Lorentz invariance [16]. Any relevant Earth-based experiment would thus observe b_μ modulated as a function of the laboratory velocity and rotation rate [17]. The standard approach involves introducing an inertial Sun-centered frame (SCF) wherein the coefficients for CPT violation carry indices $\mu = \{T, X, Y, Z\}$ and whose components may be taken as constants [18–21]. The dominant time-dependent signatures are then given by single harmonics of the Earth's sidereal rotation frequency $\omega_\oplus \approx 2\pi/(23\text{ h } 56\text{ min})$.

3. ATLAS and CMS data

The ATLAS and CMS Collaborations have reported time-averaged measurements of (6), which we denote as $\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle$ [12–14]. These measurements use samples of $t\bar{t}$ events in the lepton + jets decay mode. The ATLAS events were collected regularly over several months in 2011 at a center-of-mass energy $\sqrt{s} = 7$ TeV, totaling 4.7 fb^{-1} of integrated luminosity [22]. By performing a maximum likelihood fit, $\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle$ was determined from the per-event kinematical mass difference reconstructed in the ATLAS detector frame [12]. The result

$$\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle^{\rm ATLAS} = 0.67 \pm 0.61_{\rm stat} \pm 0.41_{\rm syst}\ \text{GeV} \tag{7}$$

was obtained and is consistent with zero within uncertainties. Averaging over months-long timescales yields negligible sensitivity to the spatial components $\vec{b}$ from (6), leaving b_0. The invariance of b_0 under the rotation connecting the ATLAS-detector and SCF frames implies $b_0 = b_T$. The relevant kinematical mass difference (6) to be compared with (7) is thus

$$\langle \Delta m_{t\bar{t}}^{\mathrm{kin}} \rangle^{\mathrm{ATLAS}} \approx -\frac{b_T}{m_t} \frac{\langle E_t + E_{\bar{t}} \rangle}{2}, \tag{8}$$

where $\langle E_t + E_{\bar{t}} \rangle$ denotes the average of the sum of top and antitop energies. Working at first order in b_μ means these can be taken as the conventional CPT-invariant energies in Eq. (8).

The CMS analyses [13, 14] split the data into positively (ℓ^+) and negatively (ℓ^-) charged lepton samples. The ideogram likelihood method [23] was applied in determining $\langle \Delta m_{t\bar{t}}^{\mathrm{kin}} \rangle$ in the CMS-detector frame. The most recent analysis [14] used data collected over several months in 2012 at a CM energy $\sqrt{s} = 8$ TeV, totaling 19.6 ± 0.5 fb^{-1} of integrated luminosity [24]. The result

$$\langle \Delta m_{t\bar{t}}^{\mathrm{kin}} \rangle^{\mathrm{CMS}} = -0.15 \pm 0.19_{\mathrm{stat}} \pm 0.09_{\mathrm{syst}} \ \mathrm{GeV} \tag{9}$$

was obtained and is consistent with zero within uncertainties. Since tops and antitops were reconstructed from different lepton samples, the relevant form of Eq. (6) is instead

$$\langle \Delta m_{t\bar{t}}^{\mathrm{kin}} \rangle^{\mathrm{CMS}} \approx -\frac{b_T}{m_t} \frac{\langle E_t \rangle + \langle E_{\bar{t}} \rangle}{2}. \tag{10}$$

	$t\bar{t}$	$t\bar{t} \to \ell \nu j j b \bar{b}$ (tot)	$t\bar{t} \to \ell \nu j j b \bar{b}$ (fid)
$\langle E_t + E_{\bar{t}} \rangle_{\sqrt{s}=7\ \mathrm{TeV}}$	706.3	708.9	658.4
$\langle E_t + E_{\bar{t}} \rangle_{\sqrt{s}=8\ \mathrm{TeV}}$	738.9	742.2	674.4
$\langle E_t + E_{\bar{t}} \rangle_{\sqrt{s}=13\ \mathrm{TeV}}$	878.8	883.7	725.2
$\langle E_t + E_{\bar{t}} \rangle_{\sqrt{s}=13.6\ \mathrm{TeV}}$	892.5	898.7	729.1

Table 1: $\langle E_t + E_{\bar{t}} \rangle$ in units of GeV at various values of $\sqrt{s}$ for $pp \to t\bar{t}$ processes: a) $pp \to t\bar{t}$ ($t\bar{t}$); b) $pp \to t\bar{t} \to \ell \nu j j b \bar{b}$ (lepton + jets) with no cuts applied (tot); and c) $pp \to t\bar{t} \to \ell \nu j j b \bar{b}$ with fiducial cuts applied (fid).

In deducing b_T, we calculated $\langle E_t + E_{\bar{t}} \rangle$ and $\langle E_t \rangle + \langle E_{\bar{t}} \rangle$ for $t\bar{t}$ events in the ATLAS and CMS experimental fiducial regions, respectively. However, we note that for the same set of cuts there is no difference between $\langle E_t \rangle + \langle E_{\bar{t}} \rangle$ and $\langle E_t + E_{\bar{t}} \rangle$. The evaluation of $\langle E_t + E_{\bar{t}} \rangle$ for $t\bar{t}$ events at various CM energies was performed with the aid of the Monte Carlo (MC) generator CalcHEP [25]. We cross-checked these results using Madgraph [26] interfaced with Pythia8 [27] and the detector simulator Delphes [28]. Our results are summarized in Table 1.

The value of b_T including uncertainty propagation reads

$$b_T = -\frac{2 m_t \langle \Delta m_{t\bar{t}}^{\mathrm{kin}} \rangle}{\langle E_t + E_{\bar{t}} \rangle} \left[1 \pm \sqrt{\left(\frac{\delta \langle \Delta m_{t\bar{t}}^{\mathrm{kin}} \rangle}{\langle \Delta m_{t\bar{t}}^{\mathrm{kin}} \rangle} \right)^2 + \left(\frac{\delta \langle E_t + E_{\bar{t}} \rangle}{\langle E_t + E_{\bar{t}} \rangle} \right)^2} \right]. \tag{11}$$

We estimated the uncertainty $\delta \langle E_t + E_{\bar{t}} \rangle$ on $\langle E_t + E_{\bar{t}} \rangle$ from our MC simulations by varying the factorization scale and using different parton distribution function (PDF) sets. In all cases we found

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the relative uncertainty to be less than 5%. We also evaluated the effect of the top-quark decay width by comparing $pp \to t\bar{t}$ versus $pp \to t\bar{t} \to \ell\nu jjb\bar{b}$ processes at parton level (see the second and third columns of Table 1). Taking the width into account, we observed a small increase of $\sim 0.5\%$ on $\langle E_t + E_{\bar{t}} \rangle$. In contrast, the uncertainty $\delta\langle \Delta m_{t\bar{t}}^{\text{kin}} \rangle$ on $\langle \Delta m_{t\bar{t}}^{\text{kin}} \rangle$ is of order 100% and thus completely dominates the uncertainty on b_T. We argued an in-depth analysis of uncertainties on $\langle E_t + E_{\bar{t}} \rangle$ was unnecessary since even a conservative $\sim 10\%$ contribution produces an overall uncertainty on b_T at the $\sim 1\%$ level.

By combining experimental uncertainties in quadrature and using Eq. (11), we found b_T to excluded outside of the following 95% confidence-level intervals

$$b_T \in \begin{cases} [-1.10, 0.41]\ \text{GeV} & \text{ATLAS } (\sqrt{s} = 7\ \text{TeV}) \\ [-0.13, 0.29]\ \text{GeV} & \text{CMS } (\sqrt{s} = 8\ \text{TeV}) \end{cases} . \tag{12}$$

4. Conclusions

In these proceedings, we have discussed the how the first model-independent sensitivity to CPT violation in top quarks was extracted [11]. Our approach relied on the SME framework and previous measurements of the top and antitop kinematical mass difference by the ATLAS and CMS Collaborations. It is also noteworthy that our constraints (12) are at least two orders of magnitude more stringent than what would be achievable in an analysis based on single-top production [15].

We project a future analysis using the entire Run-2 dataset ($\sqrt{s}$ = 13 TeV with 140 fb^{-1} of integrated luminosity) with a factor of two improvement on the systematic uncertainty would yield sensitivity to b_T at the 0.05 GeV level. By defining suitable modified kinematical masses, we also outlined how the remaining vector components $\vec{b}$ can be extracted via a re-analysis of existing datasets [11].

Acknowledgments

This work is supported by by the Deutsche Forschungsgemeinschaft under the Heinz Maier Leibnitz Prize BeyondSM HML-537662082.

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