Probing CPT invariance with top quarks at the LHC

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The first model-independent sensitivity to CPT violation in the top-quark sector is extracted from ATLAS and CMS measurements of the top and antitop kinematical mass difference. We find that the temporal component of a CPT-violating background field interacting with the top-quark vector current is restricted within the interval $[-0.13, 0.29]$ GeV at 95% confidence level.

CPT invariance is a symmetry of the Standard Model (SM) and generic prediction of local, unitary, and Lorentz invariant quantum field theories in Minkowski spacetime [1]. Among its consequences are the equalities of particle and antiparticle masses and lifetimes.

Connecting theoretical predictions of CPT invariance violation to particle–antiparticle CPT tests has been carried out for all particle species of the SM with exception of the top quark. This work addresses this gap, establishing the first sensitivity to top-sector CPT violation from top and antitop mass reconstructions in ATLAS and CMS Collaboration measurements.

Kostelecký and Potting demonstrated that spontaneous CPT violation in string theory may result in remnant observables (likely suppressed by the energy scale of this violation) which can be possibly tested in current experiments [2]. The subsequent development of effective field theory (EFT) descriptions [3] generated intense interest in testing fundamental spacetime symmetries and have produced hundreds of constraints across a variety of systems [4]. Within this EFT framework, known as the Standard Model Extension (SME), are operators involving top-quark fields.

Lorentz- and CPT-violating effects described by the SME can be viewed as generalized tensor background fields. In view of the discovery of the Higgs boson [5, 6] described by a homogeneous and isotropic scalar background with $SU(2) \times U(1)$ quantum numbers, searching for new physics in the form of additional backgrounds is well motivated.

In this study, we suggest using measurements of the kinematically reconstructed top and antitop mass difference, $\Delta m^{\rm kin}_{t\bar{t}}$, an observable which is uniquely sensitive to CPT violation, to extract the first constraints on various coefficients responsible for it in the top-quark sector of the SME. Dedicated measurements of the kinematically reconstructed mass difference have been performed by DØ [7], CDF [8], ATLAS [9], and CMS [10, 11].[1] All results are consistent with SM expectations within the experimental uncertainties, and may be translated into constraints on top quark coefficients for CPT violation.

In our study, we aim to test gauge invariant and renormalizable CPT-violating SME operators of the form [3, 15]

$$\begin{aligned}\mathcal{L}^{\rm CPT-} = &-(a_Q)_{\mu AB}\bar{Q}_A\gamma^\mu Q_B - (a_U)_{\mu AB}\bar{U}_A\gamma^\mu U_B \\ &-(a_D)_{\mu AB}\bar{D}_A\gamma^\mu D_B.\end{aligned} \tag{1}$$

The odd number of operator Lorentz indices implies a change of sign under a CPT transformation. Therefore, $\mathcal{L}^{\rm CPT-}$ is odd under CPT, which is reflected in its superscript. We are interested in probing operators involving the third generation ($A = B = 3$), where

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

The relevant coefficients for CPT-violating operators are therefore $(a_Q)_{\mu 33}, (a_U)_{\mu 33}$, and $(a_D)_{\mu 33}$. Note that the Lagrangian mass parameter m_t remains identical for top and antitop quarks in the presence of CPT violation, in accordance with Greenberg's theorem [16].

A reduction of the number of independent coefficients in Eq. (1) is possible under suitable approximations. In the limit of a zero bottom quark mass m_b (in comparison with m_t), the phases of D_3 and Q_3 fields can be independently changed. Thus, the position-dependent field redefinition $D_3 \to \exp[-i(a_D)_{\mu 33}x^\mu]D_3$ can be used to remove the last term in Eq. (1). An analogous redefinition of Q_3 and U_3 with the same phase $\exp[-i(a_Q)_{\mu 33}x^\mu]$ allows to eliminate the term with Q_3 and shifts the coefficient $(a_Q)_{\mu 33}$ into the U_3 term, such that $(a_U)_{\mu 33} \to (a_U)_{\mu 33} - (a_Q)_{\mu 33}$. This transformation preserves the structure of all SM terms and yields an equivalent Lagrangian density expressed in the mass eigenstate basis:

$$\mathcal{L}^{\rm CPT-}_{\rm top} = b_\mu \bar{t}_R\gamma^\mu t_R, \tag{3}$$

[1] In Ref. [12], earlier DØ and CDF top mass measurements [13, 14] were used to place a conservative upper limit on the top and antitop mass difference.

where $b_\mu \equiv [(a_Q)_{\mu 33} - (a_U)_{\mu 33}]$ and only t_R fields appear. Under these field redefinitions, CPT violation is isolated to the top-quark sector and quantified through the differential propagation of t_R relative to t_L. [2]

Performing the variational procedure including the conventional top kinetic terms results in a modified Dirac equation

$$\left[i\not{\partial} + \tfrac{1}{2}(1-\gamma_5)\not{b} - m_t\right] t = 0. \tag{5}$$

Plane-wave solutions imply a quartic equation in $p^\mu = (E_t, \vec{p})$ with four distinct solutions linear in b_μ:

$$p^2 = \begin{cases} m_t^2 - p\cdot b \pm [(p\cdot b)^2 - m_t^2 b^2]^{1/2} & \text{(top)} \\ m_t^2 + p\cdot b \pm [(p\cdot b)^2 - m_t^2 b^2]^{1/2} & \text{(antitop)} \end{cases} \tag{6}$$

neglecting higher-order terms in b_μ. The first and second unconventional terms in each row are associated with the vector and pseudovector pieces of Eq. (3), respectively, and the $\pm$ signs denote states of opposite helicities. The difference between particle and antiparticle solutions is obtained by $b_\mu \to -b_\mu$, reflecting the CPT-odd property of Eq. (3) and the effect of CPT conjugation on the plane-wave solutions. Note that potential CPT-violating corrections to top and antitop decay widths are suppressed relative to free-propagation effects (6) by the square of the weak coupling constant and are neglected.

The presence of b_μ implies both charge- and helicity-dependent energy eigenvalues. Top p and antitop $\bar{p}$ momenta and kinematical masses $m_t^{\rm kin} \equiv \sqrt{p^2}, m_{\bar{t}}^{\rm kin} \equiv \sqrt{\bar{p}^2}$ are reconstructed through the charge and four-momentum conservation of final-state decay products. In the conventional CPT-invariant case, $m_t^{\rm kin} = m_{\bar{t}}^{\rm kin} = m_t$. The kinematical mass difference

$$\Delta m_{t\bar{t}}^{\rm kin}(p, \lambda_p, \bar{p}, \lambda_{\bar{p}}, m_t, b) \equiv m_t^{\rm kin} - m_{\bar{t}}^{\rm kin} \tag{7}$$

parametrizes a CPT-violating asymmetry, where λ_p ($\lambda_{\bar{p}}$) are the top (antitop) helicities. In principle, measurements of $\Delta m_{t\bar{t}}^{\rm kin}$ could be used to extract b_μ. However, this is generically non-trivial because $\Delta m_{t\bar{t}}^{\rm kin}$ is time dependent. Implicit time dependence enters via event-by-event reconstructions of the top and antitop four-momenta. Explicit time dependence enters through b_μ directly since the relevant experiments are performed in non-inertial Earth-based laboratories. As a result, the coefficient b_μ is modulated as a function of the laboratory velocity and rotation rate [17]. It is convenient and standard practice to introduce the approximately inertial sun-centered frame (SCF) where the coefficients for CPT violation carry indices $\mu = \{T, X, Y, Z\}$ and may be approximated as constants [18]. In this setting, the leading laboratory signatures are given by single harmonics of the Earth's sidereal rotation frequency $\omega_\oplus \approx 2\pi/(23\ \text{h}\ 56\ \text{min})$. Despite these complications, we demonstrate that suitably averaged observables permit analyses involving distinct proper subsets of $\{b_T, b_X, b_Y, b_Z\}$.

The ATLAS and CMS Collaborations have reported measurements of $\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle$ [9–11], where $\langle\rangle$ indicates averaging over all events. ATLAS used a sample of $t\bar{t}$ events in the single charged lepton + jets decay mode, selected from 4.7 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV [9]. The data were regularly collected over several months in 2011 [19]. The kinematical mass difference $\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle$ was determined from a maximum likelihood fit to the per-event top and antitop candidate mass difference, reconstructed in the ATLAS detector frame. The reported result

$$\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle^{\rm ATLAS} = 0.67 \pm 0.61_{\rm stat} \pm 0.41_{\rm syst}\ \text{GeV} \tag{8}$$

is consistent with zero within uncertainties. The measurement involved averaging over several sidereal days and sampling of the full $t\bar{t}$ phase space. This measurement therefore has negligible sensitivity to the top polarizations and spatial components of b_μ. The invariance of the temporal component b_0 under the rotation connecting the ATLAS detector and SCF frames implies $b_0 = b_T$ and Eq. (7) takes the form

$$\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle^{\rm ATLAS} \approx -\frac{b_T}{m_t}\frac{\langle E_t + E_{\bar{t}}\rangle}{2}, \tag{9}$$

where $\langle E_t + E_{\bar{t}}\rangle$ is the average over the phase space of the sum of top and antitop energies characteristic to the dataset. To leading order in b_μ the energies $E_t, E_{\bar{t}}$ are the conventional eigenenergies.

The CMS analyses also selected events where one W boson decays hadronically and the other leptonically. The data were split into ℓ^+ and ℓ^- samples. Using the ideogram likelihood method [20], $m_t^{\rm kin}$ and $m_{\bar{t}}^{\rm kin}$ were reconstructed from the two samples, respectively, in the CMS collider frame, from which their difference was obtained. The 2017 analysis used a data sample [21] corresponding to pp collisions at $\sqrt{s} = 8$ TeV and an integrated luminosity of 19.6 ± 0.5 fb^{-1}. The data were collected over several months in 2012, yielding [22]

$$\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle^{\rm CMS} = -0.15 \pm 0.19_{\rm stat} \pm 0.09_{\rm syst}\ \text{GeV}. \tag{10}$$

Since the tops and antitops were selected from different events, CMS is sensitive to a sum of the averages, $\langle E_t\rangle + \langle E_{\bar{t}}\rangle$, and therefore

$$\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle^{\rm CMS} \approx -\frac{b_T}{m_t}\frac{\langle E_t\rangle + \langle E_{\bar{t}}\rangle}{2}. \tag{11}$$

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[2] One could have chosen $\exp[-i(a_U)_{\mu 33}x^\mu]$ as phase shift for both Q_3 and U_3 which would lead to

$$\mathcal{L}'^{\rm CPT-}_{\rm top} = b'_\mu \bar{t}_L \gamma^\mu t_L, \tag{4}$$

with $b'_\mu \equiv [(a_U)_{\mu 33} - (a_Q)_{\mu 33}] = -b_\mu$ and only t_L fields involved. For this equivalent formulation the experimental limits on b_μ will be identical to those for Eq. (3).

	$t\bar{t}$	$t\bar{t} \to \ell\nu jjbb$ tot	$t\bar{t} \to \ell\nu jjbb$ fid
$\langle E_t + E_{\bar{t}}\rangle_{@7\text{ TeV}}$	706.3	708.9	658.4
$\langle E_t + E_{\bar{t}}\rangle_{@8\text{ TeV}}$	738.9	742.2	674.4
$\langle E_t + E_{\bar{t}}\rangle_{@13\text{ TeV}}$	878.8	883.7	725.2
$\langle E_t + E_{\bar{t}}\rangle_{@13.6\text{ TeV}}$	892.5	898.7	729.1

TABLE I. The values of $\langle E_t + E_{\bar{t}}\rangle$ in GeV at various LHC energies for $pp \to t\bar{t}$ processes: a) $pp \to t\bar{t}$ ($t\bar{t}$); b) $pp \to t\bar{t} \to \ell\nu jjb\bar{b}$ with no cuts applied (tot); c) $pp \to t\bar{t} \to \ell\nu jjb\bar{b}$ with fiducial CMS cuts applied (fid). See further details in the text. The events here are generated with CalcHEP.

In order to extract an upper bound on b_T, we need to calculate the average $\langle E_t+E_{\bar{t}}\rangle$ for $t\bar{t}$ events in the fiducial region considered by the two experiments. For the same set of cuts, however, there will be no difference between the sum of the averages $\langle E_t\rangle + \langle E_{\bar{t}}\rangle$ and average of the sum $\langle E_t + E_{\bar{t}}\rangle$. The evaluation of $\langle E_t + E_{\bar{t}}\rangle$ for $t\bar{t}$ events at various center-of-mass energies is performed with the aid of the Monte Carlo (MC) generator CalcHEP [23] and cross-checked using Madgraph [24] (interfaced with Pythia8 [25] and the detector simulator Delphes [26]). The results we find are summarized in Table I.
The value of b_T including uncertainty reads

$$b_T = -\frac{2\langle \Delta m_{t\bar{t}}^{\text{kin}}\rangle m_t}{\langle E_t + E_{\bar{t}}\rangle} \times \left[1 \pm \sqrt{\left(\frac{\delta\langle \Delta m_{t\bar{t}}^{\text{kin}}\rangle}{\langle \Delta m_{t\bar{t}}^{\text{kin}}\rangle}\right)^2 + \left(\frac{\delta\langle E_t + E_{\bar{t}}\rangle}{\langle E_t + E_{\bar{t}}\rangle}\right)^2}\,\right]. \tag{12}$$

We estimate the uncertainty $\delta\langle E_t + E_{\bar{t}}\rangle$ on the predicted value $\langle E_t + E_{\bar{t}}\rangle$ from our MC simulations by varying the factorization scale within $m_t/2$ and $2m_t$, as well as using different PDF sets. We find it to be below 5% for each uncertainty. We have also evaluated the effect of the top-quark width on the $\langle E_t + E_{\bar{t}}\rangle$ value by comparing the results for $2 \to 2$ versus $2 \to 6$ processes at parton level (the second versus the third column in Table I) and find an increase of only about +0.5% on $\langle E_t + E_{\bar{t}}\rangle$ when the width is taken into account, which is simply related to a kinematical effect. A more detailed analysis of these uncertainties is not relevant for this study since the uncertainty on b_T is completely dominated by the experimental uncertainty on $\delta\langle \Delta m_{t\bar{t}}^{\text{kin}}\rangle$, which is of order 100%. Therefore, even a very conservative value of $\delta\langle E_t + E_{\bar{t}}\rangle$ of order 10% will affect the overall uncertainty for b_T determination at the level of only 1%, as one can see from Eq. (12).

Combining experimental statistical and systematic uncertainties in quadrature and using Eq. (12), we find the following exclusion limits on b_T:

$$b_T \in \begin{cases} [-1.10, 0.41]\text{ GeV} & \text{ATLAS @ 7 TeV} \\ [-0.13, 0.29]\text{ GeV} & \text{CMS @ 8 TeV} \end{cases}. \tag{13}$$

Outside of these intervals b_T is excluded at 95% confidence level.

	7 TeV tot	7 TeV fid	8 TeV tot	8 TeV fid	13 TeV tot	13 TeV fid	13.6 TeV tot	13.6 TeV fid
$\langle\lvert\Delta_Z\rvert\rangle$	72	68	76	70	97	79	100	80
$\langle\lvert C_X\rvert\rangle$	74	69	79	70	103	84	103	81
$\langle\lvert S_X\rvert\rangle$	418	329	451	361	590	416	603	405

TABLE II. Phase space averages (both in the whole phase space and in the CMS fiducial region) for the quantities described in the text in units of GeV. The events here are generated with MadGraph and showered/hadronized with Pythia8. Finally, Delphes is used to simulate detector effects.

The spatial components $b_{X,Y,Z}$ can be constrained with the same dataset but require dedicated analyses. To good approximation, the laboratory-frame coefficients for both ATLAS and CMS are related to the SCF coefficients via the rotation

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} -b_Z \sin\chi\cos\psi + \cos(\omega_\oplus T_\oplus)(b_X\cos\chi\cos\psi + b_Y\sin\psi) + \sin(\omega_\oplus T_\oplus)(b_Y\cos\chi\cos\psi - b_X\sin\psi) \\ b_Z\cos\chi + \sin\chi[b_X\cos(\omega_\oplus T_\oplus) + b_Y\sin(\omega_\oplus T_\oplus)] \\ -b_Z\sin\chi\sin\psi + \cos(\omega_\oplus T_\oplus)(b_X\cos\chi\sin\psi - b_Y\cos\psi) + \sin(\omega_\oplus T_\oplus)(b_Y\cos\chi\sin\psi + b_X\cos\psi) \end{pmatrix}, \tag{14}$$

where the colatitude is $\chi = 43.7^o$ and the beamline orientation north-of-east is $\psi = -11.3^o$. The time $T_\oplus$ is identified with the event time. Note that this choice of laboratory frame is identical for ATLAS and CMS: the 2-axis points in the upward vertical direction and the 1-axis points towards (away from) the center of the LHC ring for ATLAS (CMS).

The kinematical mass difference for single event in terms of the SCF coefficients is given by

$$\Delta m_{t\bar{t}}^{\rm kin} = -\frac{1}{2m_t}\left[b_T\Delta_T + b_Z\Delta_Z + \sum_{A=X,Y} b_A\Big(C_A\cos(\omega_\oplus T_\oplus) + S_A\sin(\omega_\oplus T_\oplus)\Big)\right] \;, \tag{15}$$

$$\Delta_T = E_t + E_{\bar{t}} \;, \tag{16}$$

$$\Delta_Z = -\sin\chi\cos\psi(p_1+\bar{p}_1) + \cos\chi(p_2+\bar{p}_2) - \sin\chi\sin\psi(p_3+\bar{p}_3) \;, \tag{17}$$

$$C_X = \cos\chi\cos\psi(p_1+\bar{p}_1) + \sin\chi(p_2+\bar{p}_2) + \cos\chi\sin\psi(p_3+\bar{p}_3) \;, \tag{18}$$

$$S_X = -\sin\psi(p_1+\bar{p}_1) + \cos\psi(p_3+\bar{p}_3) \;, \tag{19}$$

$$C_Y = -S_X \;, \tag{20}$$

$$S_Y = C_X \;, \tag{21}$$

where p_i ($\bar{p}_i$) are the top (antitop) three-momentum components in the laboratory frame. The symmetry of the pp collisions guarantees $\langle p_i + \bar{p}_i\rangle = 0$, and hence $\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle = -\frac{b_T}{2m_t}\langle E_t + E_{\bar{t}}\rangle$ when averaging over the whole phase space. This means that the coefficients $b_{X,Y,Z}$ can only be constrained by dedicated analyses. Moreover, note that the coefficients b_X and b_Y induce effects that vanish also when averaged over time.

A strategy to build an observable sensitive exclusively to b_Z is to consider

$$\langle \Delta m_{t\bar{t}}^{\rm kin\,\prime}\rangle = \langle \Delta m_{t\bar{t}}^{\rm kin}\,{\rm sgn}[\Delta_Z]\rangle = -\frac{b_Z}{2m_t}\langle|\Delta_Z|\rangle. \tag{22}$$

In fact, $\langle\Delta_T\,{\rm sgn}[\Delta_Z]\rangle = 0$ and time averaging eliminates $b_{X,Y}$. This quantity can be measured by first calculating $\Delta m_{t\bar{t}}^{\rm kin}\,{\rm sgn}[\Delta_Z]$ on an event-by-event basis (Δ_Z is a simple function of the top and antitop three-momenta) and then studying its distribution. Since it is not possible to simply convert the measured $\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle$ distribution into the corresponding $\langle \Delta m_{t\bar{t}}^{\rm kin\,\prime}\rangle$ one, a constraint on b_Z can only be obtained via a dedicated re-analysis of the data. The b_Z sensitivity of this analysis is straightforward to assess because, in absence of a signal, we expect the experimental $\langle \Delta m_{t\bar{t}}^{\rm kin}\rangle$ and $\langle \Delta m_{t\bar{t}}^{\rm kin\,\prime}\rangle$ distributions to be very similar. In order to get an upper limit on b_Z, one should consider the statistical uncertainty of the 8 TeV CMS analysis but adopt the larger ATLAS systematic uncertainty, which has been calculated from a scheme where the top and antitop masses are determined simultaneously on a per-event basis, and center the distribution on zero: $\langle \Delta m_{t\bar{t}}^{\rm kin\,\prime}\rangle \sim [0 \pm 0.19 \pm 0.41]$ GeV. Combining these sensitivities with the MC results for $\langle|\Delta_Z|\rangle$ presented in Table II we obtain the expected sensitivity

$$|b_Z|_{\rm expected} \lesssim 4.6 \text{ GeV}. \tag{23}$$

For the transverse components, b_X and b_Y, the situation is more complicated because a sidereal-time analysis is required. A possible strategy is to divide the sidereal period in a number N of bins. Focusing on the coefficient b_X, the kinematical mass difference for events in the n-th bin is given by:

$$\Delta m_{t\bar{t}}^{\rm kin} = -\frac{b_X}{2m_t}\Delta_X^{(n)}, \tag{24}$$

$$\Delta_X^{(n)} = C_X\langle\cos(\omega_\oplus T_\oplus)\rangle_n + S_X\langle\sin(\omega_\oplus T_\oplus)\rangle_n, \tag{25}$$

where $\langle\rangle_n$ indicates the time average over bin n. For each bin we can then proceed exactly as for b_Z and average over all events in the bin weighting $\Delta m_{t\bar{t}}^{\rm kin}$ by ${\rm sgn}[\Delta_X^{(n)}]$. In order to obtain the sensitivity to the coefficients b_X and b_Y we simply calculate the phase space average $[\langle|C_A|\rangle + \langle|S_A|\rangle]/\sqrt{2}$, where $A = X, Y$, and the factor $1/\sqrt{2}$ is the root-mean-square of the sin and cos functions. Following the same procedure as for the b_Z case (but using the appropriate averages from Table II), we find the following expected of the sensitivity to $b_{X,Y}$:

$$|b_{X,Y}|_{\rm expected} \lesssim 0.8 \text{ GeV}. \tag{26}$$

To summarize, we have established the first model-independent sensitivity to CPT violation in the top-quark sector using LHC measurements of the top and antitop kinematical mass difference. The constraint on b_T (13) is about two orders of magnitude stronger than those expected from single-top production [15]. We have also suggested dedicated analyses which would lead to constraints on $|b_Z|$ (23) and $|b_{X,Y}|$ (26) of the same order.

Regarding prospects, let us note that an analysis of the the entire Run-2 dataset (140 fb^{-1}), assuming a factor of two improvement on the systematic uncertainty and taking into account the larger $\sqrt{s} = 13$ TeV center-of-mass energy, is expected to yield a sensitivity to b_T at the 0.05 GeV level (with similar fractional improvements for $b_{X,Y,Z}$). Further accumulation of data will lead to a systematically dominated total uncertainty.

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