LORENTZ VIOLATION IN TOP-QUARK PHYSICS

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Lorentz and CPT violation can affect the rates for $t$-$\bar{t}$ production and decay. The Lorentz-violating coefficients in the Standard-Model Extension responsible for modifying the top-quark events have recently been bounded by the D0 Collaboration. To extend the analysis to the LHC the calculations need to be extended to include the gluon fusion production mechanism. Some of the first results of this program were presented at the Meeting.

1. Introduction
The possible existence of Lorentz and CPT violation has been increasingly studied in recent years. Many efforts toward developing a theory of quantum gravity contain Lorentz violation as a generic physical consequence although the size of the effects are usually quite small in realistic experiments with attainable energies much smaller than the Planck scale. A systematic approach for parametrizing the possible forms of Lorentz violation in the context of an effective field theory called the Standard-Model Extension (SME)\textsuperscript{1–3} has been developed. The Lorentz- and CPT-violating physical effects are encoded in the form of coefficients. A Lorentz-violating term is an observer scalar density formed by contracting the Lorentz-violating operator with the associated coefficient. Diverse kinds of experiments can place bounds on the same coefficients, so that the experimental sensitivities can be directly compared.\textsuperscript{4}

The Lorentz-violating coefficients provide the possibility of preferred frames and directions in space and could in principle have an effect on collider physics experiments. If the coefficient is constant in space then one expects there to be a sidereal time variation as the Earth rotates through this constant background. Collider physics scattering events naturally have access to many Lorentz frames since produced particles and their decay
products are distributed with many different boosts and orientations relative to the laboratory frame and beam direction.

2. Top quark Lorentz-violating coefficients in the SME

Top quark production and decay involves many fields so the overall rates and the distributions could be affected by many different Lorentz violating coefficients in the SME. In this discussion we will focus on coefficients which involve the top quark field \( t \). Then the relevant coefficients arise from the matrices \((a_Q)_{\mu ij}, (a_U)_{\mu ij}, (c_Q)_{\muij}, (c_U)_{\muij}, (H_U)_{\muij}\) contained in the SME, where \( i \) and \( j \) are flavor indices, and the \( Q \) and \( U \) indices correspond to the left- and right-handed fields of the Standard Model. Of these five coefficients, the first two control CPT-odd operators, while the last three control CPT-even ones. At present bounds have been placed on the \( c \)-type coefficients,\(^5\) so we will concentrate on those in the following. The coefficients relevant to the top quark production and decay have \( i = j = 3 \) (in general there will be flavor mixing in the Lorentz-violation sector that does not have to align with the CKM matrix of the Standard Model), so for convenience one can define \((c_L)_{\mu\nu}^3 = (c_Q)_{\mu33} \) and \((c_R)_{\mu\nu}^3 = (c_U)_{\mu33} \) to simplify the notation.

The Standard-Model terms involving the \( t \) and \( b \) quark fields and their interactions with the \( W_\mu^- \) boson are

\[
\mathcal{L}_{t,b}^{SM} = \frac{i}{2} \bar{t} \gamma_\mu \gamma_5 \gamma_\nu \partial^\mu t - \frac{g}{\sqrt{2}} W^-_\mu b_L \bar{t} \gamma_\mu t_L + \frac{1}{2} \bar{b} \gamma_\mu \gamma_5 \gamma_\nu \partial^\nu b - m_b \bar{b} b + \text{h.c.}. \tag{1}
\]

The additional terms in the SME corrections involving the \( c \)-type coefficient can be written in equivalent forms,

\[
\mathcal{L}_{t,b}^{\text{CPT-even}} = \frac{i}{2} (c_L)_{\mu\nu} \bar{t} \gamma_\mu \gamma_5 \gamma_\nu t_L + \frac{i}{2} (c_R)_{\mu\nu} \bar{t} \gamma_\mu \gamma_5 \gamma_\nu t_R \\
+ \frac{1}{2} i (c_L)_{\mu\nu} \bar{t} \gamma_\mu \gamma_5 \gamma_\nu b_L + \left(\frac{g}{\sqrt{2}} (c_L)_{\mu\nu} W^-_\mu \bar{b} \gamma_\mu t_L + \text{h.c.}\right) \\
= \frac{i}{2} c_{\mu\nu} \bar{t} \gamma_\mu \gamma_5 \gamma_\nu t_L + \frac{i}{2} d_{\mu\nu} \bar{t} \gamma_\mu \gamma_5 \gamma_\nu t_L \\
+ \frac{1}{2} i (c_L)_{\mu\nu} \bar{t} \gamma_\mu \gamma_5 \gamma_\nu b_L + \left(\frac{g}{\sqrt{2}} (c_L)_{\mu\nu} W^-_\mu \bar{b} \gamma_\mu t_L + \text{h.c.}\right), \tag{2}
\]

where \( c_{\mu\nu} = (c_L)_{\mu\nu} + (c_R)_{\mu\nu} \) and \( d_{\mu\nu} = (c_L)_{\mu\nu} - (c_R)_{\mu\nu} \). These terms give rise to additional Feynman rules which can be treated as insertions in diagrams. By working in leading order in the Lorentz-violating coefficients, it is
a straightforward procedure to enumerate diagrams and calculate contributions to the amplitudes which depend on them. At the Tevatron top quark production is dominated by the $q\bar{q} \rightarrow t\bar{t}$ process for which the Lorentz-violating corrections are known.

3. Bounds

The Lorentz violating coefficients are defined as constant in a Sun-centered frame ($X, Y, Z, T$). The coefficients in the laboratory frame ($x, y, z, t$) then change with sidereal time because the Earth is rotating. Nonzero Lorentz-violating coefficients thus produce sidereal time-dependent signals with frequency an integer multiple of $\omega_\oplus \simeq 2\pi/(23 \text{ h 56 min.}).$ The D0 Collaboration has used data collected at the Fermilab Tevatron Collider from 5.3 fb$^{-1}$ of integrated luminosity to place the first bounds on the top-quark Lorentz-violating coefficients:

\begin{align}
(c_Q)_{XX33} &= -0.12 \pm 0.11 \pm 0.02, \\
(c_Q)_{YY33} &= 0.12 \pm 0.11 \pm 0.02, \\
(c_Q)_{XY33} &= -0.04 \pm 0.11 \pm 0.01, \\
(c_Q)_{XZ33} &= 0.15 \pm 0.08 \pm 0.02, \\
(c_Q)_{YZ33} &= -0.03 \pm 0.08 \pm 0.01, \\
(c_U)_{XX33} &= 0.1 \pm 0.09 \pm 0.02, \\
(c_U)_{YY33} &= -0.1 \pm 0.09 \pm 0.02, \\
(c_U)_{XY33} &= 0.04 \pm 0.09 \pm 0.01, \\
(c_U)_{XZ33} &= -0.14 \pm 0.07 \pm 0.02, \\
(c_U)_{YZ33} &= 0.01 \pm 0.07 \pm < 0.01. \tag{3}
\end{align}

The experimental events used in the analysis contain lepton + jets final states, and a candidate signal would be expected to exhibit sidereal or twice-sidereal variations. These bounds are at roughly the 10% level, and all coefficients are consistent with zero. It is expected that the much larger top sample at the LHC could improve these bounds by at least an order of magnitude.

4. Gluon Fusion

Top-quark production is dominated by the gluon-fusion mechanism at the LHC. There are three contributing diagrams ($s$-channel gluon and $t$- and
In the Standard Model, the cross section for the $u$-channel top quark is well-known.\textsuperscript{11–13} The calculation of the Lorentz-violating corrections is somewhat more involved than the one for $qar{q} \rightarrow tar{t}$ because of the number of diagrams and the presence of external gluons which must be taken to be transverse. The first results of this calculation were presented at the Meeting.

5. Summary

The first bounds on the top-quark SME coefficients have been obtained by the D0 Collaboration using data collected at the Tevatron. The measurements are consistent with zero. Top quark production at the LHC is dominated by gluon fusion, and it is expected that the bounds can be improved to the percent level.

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