

Latest constraint on nonstandard top-gluon couplings at hadron colliders and its future prospectZenrō Hioki^{1,*} and Kazumasa Ohkuma^{2,†}¹*Institute of Theoretical Physics, University of Tokushima, Tokushima 770-8502, Japan*²*Department of Information Science, Fukui University of Technology, Fukui 910-8505, Japan*

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Constraints on the nonstandard top-gluon couplings composed of the chromomagnetic- and chromoelectric-dipole moments of the top quark are updated by combining the latest data of top-pair productions from the Tevatron, 7-TeV LHC, and 8-TeV LHC. We find that adding the recent 8-TeV data to the analysis is effective to get a stronger constraint on the chromoelectric-dipole moment than the one from the Tevatron and 7-TeV LHC alone. We also discuss how those constraints on the nonstandard couplings could be further improved when the 14-TeV LHC results become available in the near future.

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The Large Hadron Collider (LHC) has discovered a new particle which seems to be the standard-model Higgs boson [1,2]. This discovery means the standard model is nearing completion and the LHC has achieved one of its important aims to operate. On the other hand, however, there have been no positive signals suggesting the existence of new particles which are not belonging to the framework of the standard model. That indicates that nonstandard particles, if any, might be too heavy to be created at the present LHC energies. Therefore, the top quark, the heaviest particle that can appear in real experiments, is expected to play an important role in searching for new physics beyond the standard model [3,4].

In this situation, an approach in terms of the effective Lagrangian composed of only the standard-model fields is one of the most promising and general ways to parametrize quantum effects of nonstandard particles and derive constraints on them. Therefore, quite a number of authors have so far studied top-quark physics at the Tevatron and LHC using this effective-Lagrangian procedure [5–31]. Among those works, what we performed in [20,24,26] was to combine the Tevatron and LHC data on $t\bar{t}$ productions to get a strong restriction on possible nonstandard top-gluon couplings, i.e., the chromomagnetic- and chromoelectric-dipole moments of the top quark.

Now that the LHC has been shut down for an upgrade to increase its colliding energy after its successful operations at $\sqrt{s} = 7$ TeV (hereafter LHC7) and $\sqrt{s} = 8$ TeV (LHC8), it will be meaningful to update those constraints by using the latest results of the Tevatron and LHC experiments in order to clarify the current status of new-physics search through top-gluon interactions in the effective-Lagrangian approach. This is what we aim to perform here, which is going to be our first analysis taking the LHC8 results into account.

The effective Lagrangian which we have adopted so far is the one proposed by Buchmüller and Wyler [32]

(see also [33–35]). In this framework, we have the following top-gluon couplings for the top-pair productions in $pp/p\bar{p}$ collisions:

$$\begin{aligned} \mathcal{L}_{t\bar{t}gg}^{\text{eff}} = & -\frac{1}{2}g_s \sum_a \left[\bar{\psi}_t(x) \lambda^a \gamma^\mu \psi_t(x) G_\mu^a(x) \right. \\ & \left. - \bar{\psi}_t(x) \lambda^a \frac{\sigma^{\mu\nu}}{m_t} (d_V + id_A \gamma_5) \psi_t(x) G_{\mu\nu}^a(x) \right], \end{aligned} \quad (1)$$

where g_s is the $SU(3)$ coupling constant, and d_V and d_A are nonstandard couplings corresponding to the chromomagnetic- and chromoelectric-dipole moments, respectively. Using this Lagrangian for top-gluon interactions and the usual standard-model Lagrangian for all the other interactions, the total cross section of top-pair productions is derived straightforwardly and expressed as

$$\sigma(pp/p\bar{p} \rightarrow t\bar{t}X) = \sigma_{\text{SM}} + \Delta\sigma(d_V, d_A), \quad (2)$$

where σ_{SM} denotes the standard-model cross section and $\Delta\sigma(d_V, d_A)$ expresses the remaining $d_{V,A}$ -dependent part.¹ The explicit form of Eq. (2) is found at the parton level in Ref. [20]. As for the parton distribution functions, we have been using CTEQ6.6M (NNLO approximation) [36].

Recently, new data of top-pair productions at the Tevatron and LHC experiments were presented by combining those from the CDF and D0 collaborations at the Tevatron, and those from the ATLAS and CMS collaborations at the LHC7 [37,38] as

¹There are also some standard-model loop effects which generate dipole couplings. In our preceding articles [20,24,26], we already have taken into account the QCD contributions to them by using corrected cross sections for σ_{SM} (as mentioned below), while we have so far neglected the electroweak (EW) contributions. It will, however, be required eventually to include the EW part into the analysis, which we discuss later before the summary.

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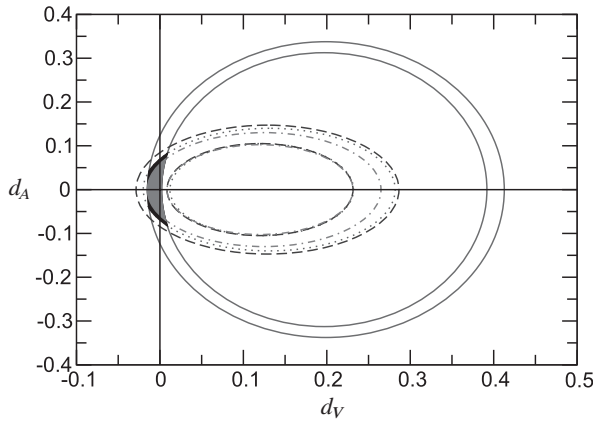


FIG. 1. The $d_{V,A}$ region allowed by the Tevatron, LHC7, and LHC8 data.

$$\begin{aligned}\sigma_{\text{exp}} &= 7.65 \pm 0.41 \text{ pb} \quad (\text{CDF plus D0 at the Tevatron}), \\ &= 173.3 \pm 10.1 \text{ pb} \quad (\text{ATLAS plus CMS at the LHC7}).\end{aligned}$$

Furthermore, ATLAS and CMS gave new data at $\sqrt{s} = 8$ TeV [39,40] as

$$\begin{aligned}\sigma_{\text{exp}} &= 241 \pm 32 \text{ pb} \quad (\text{ATLAS at the LHC8}), \\ &= 227 \pm 15 \text{ pb} \quad (\text{CMS at the LHC8}).\end{aligned}$$

There, the following standard-model cross sections including higher-order QCD corrections were used for comparison based on [41–45]

$$\begin{aligned}\sigma_{\text{SM}}^{\text{QCD}} &= 7.24_{-0.27}^{+0.24} \text{ pb} \quad \text{for the Tevatron}, \\ &= 167_{-18}^{+17} \text{ pb} \quad \text{for the LHC7}, \\ &= 220_{-13}^{+14} \text{ pb} \quad \text{for the LHC8}.\end{aligned} \quad (3)$$

Treating the center values of these $\sigma_{\text{SM}}^{\text{QCD}}$ as σ_{SM} in Eq. (2), and comparing the whole σ with the above experimental data, the resultant allowed regions of d_V and d_A are shown in Figs. 1 and 2. In those figures, the ellipsoidal regions given by the solid curves, the dotted curves, the dashed curves, and the dash-dotted curves are those from the combined Tevatron (CDF and D0), combined LHC7 [ATLAS (7 TeV) and CMS (7 TeV)], ATLAS (8 TeV) and CMS (8 TeV) data.² In addition, the shaded regions mean

²Note that readers might encounter a similar figure in which, however, all the curves got turned over about $d_V = 0$ (i.e., the d_A axis) as if they had performed the analysis with opposite-sign d_V . In that case, compare not only the sign of their nonstandard coupling but also the one of their standard coupling with ours, since the interference between these two contributions would make this seeming difference. Concerning d_A , on the other hand, any difference does not appear because there is no such interference and the leading term is proportional to d_A^2 . This is why all the curves in the figures are symmetric about the d_V axis.

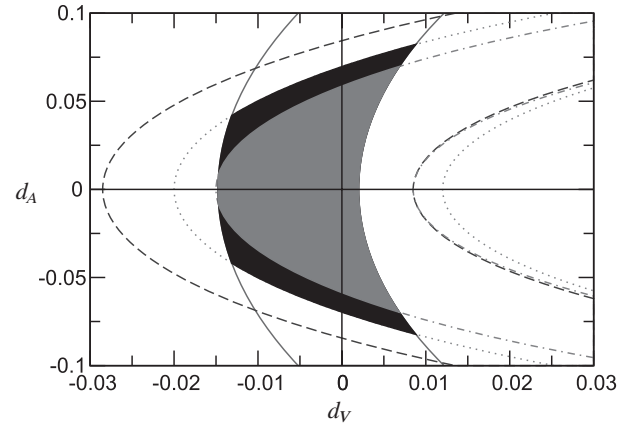


FIG. 2. The enlarged view of the allowed region in Fig. 1.

the common $d_{V,A}$ regions allowed by all the data. More specifically, the part allowed by the combined Tevatron and LHC7 is the whole shaded, i.e., the black plus gray regions, while the gray part is the allowed one estimated by the Tevatron and LHC7 data *plus* the ATLAS and CMS data at $\sqrt{s} = 8$ TeV. This shows that the black region was excluded by taking into account the LHC8 data. Although d_V is still mainly limited by the Tevatron and LHC data in the positive region, the latest Tevatron and LHC data are becoming dominant in its negative region.

Since the LHC with $\sqrt{s} = 14$ TeV (LHC14) is planned to operate in the near future, the constraint of d_V and d_A could be much more improved. In order to estimate what improvement is expected with the increasing colliding energy, we also perform a virtual analysis according to the above method for the LHC14. Let us use the following theoretical prediction on the top-pair productions for $m_t = 173$ GeV [45], assuming 10% and 5% errors³ as the virtual-experimental value:

$$\begin{aligned}\sigma(\sqrt{s} = 14 \text{ TeV}) &= 920 \pm 92 \text{ pb} \quad (10\% \text{ error case}), \\ &= 920 \pm 46 \text{ pb} \quad (5\% \text{ error case}).\end{aligned}$$

The results of this virtual analysis are shown in Fig. 3. There, the dash-dot-dashed curves and the dot-dash-dotted curves, which indicate the allowed region estimated from the 10% and 5% error cases, respectively, are added to Fig. 2. Moreover, the allowed regions combining the current constraint derived here and constraints from the 10% and 5% error cases are described as the middle-lighter and lighter gray regions. As seen in Fig. 3, the LHC14 has a potential to strengthen both of the current individual constraints on d_V and d_A about twice, i.e., the allowed area could become almost quarter its size, if the errors are controlled at about the 5% level.

³We mean those errors as combinations of the theoretical one in σ_{SM} and experimental one.

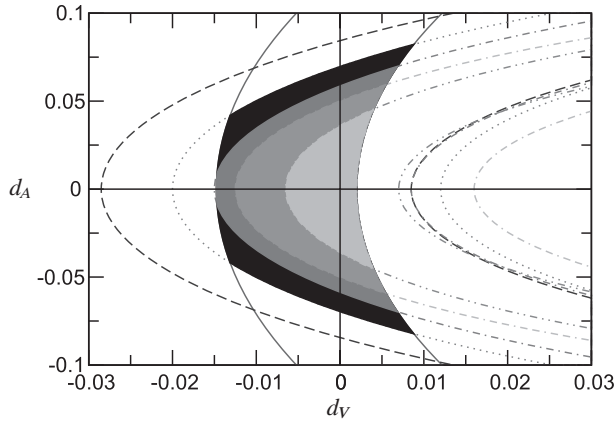


FIG. 3. The expected allowed regions of $d_{V,A}$ when the LHC14 data become available.

Finally, let us briefly discuss standard-model loop effects. Within the standard model, a top-quark chromoelectric-dipole-moment term can only arise at three-loop level through CP -violating electroweak interactions and its contribution may be safely neglected. On the other hand, a chromomagnetic-dipole-moment term is generated at one-loop level as both QCD corrections (denoted as Δd_V^{QCD}) and EW corrections (Δd_V^{EW}). Here, we used the standard-model cross sections including higher-order QCD corrections $\sigma_{\text{SM}}^{\text{QCD}}$ presented in Eq. (3) for σ_{SM} in Eq. (2), that is, the Δd_V^{QCD} contribution is included in σ_{SM} implicitly with other QCD corrections, while we have not taken account of Δd_V^{EW} . Therefore, strictly speaking, the constraint on d_V shown in our figures should be understood as the one not on d_V alone but on

$$d_V + \Delta d_V^{\text{EW}}. \quad (4)$$

At present, this does not cause any serious problem, considering the size of Δd_V^{EW} and the precision of our analysis: According to Ref. [46], $|\Delta d_V^{\text{EW}}| = 9.4 \times 10^{-4}$ (for $m_{\text{Higgs}} = 120$ GeV), which moves the origin of the d_V axis in our figures by only about 0.001. We, however, will have to take it into account carefully in the near future when the LHC14 starts, which our virtual analysis is telling us.

In summary, using the latest data of top-pair productions at the Tevatron and LHC, the current bound on the chromomagnetic-dipole moment (d_V) and chromoelectric-dipole moment (d_A) of the top quark was updated. Although the main contribution to constraining d_V , especially in its positive region, still comes from the Tevatron data, the LHC data are now giving almost the same constraint as the Tevatron in the negative region. For constraining d_A , on the other hand, the LHC8 data, which were taken into account for the first time here, were effective to exclude some area allowed by the Tevatron and LHC7 data alone. In addition, it was pointed out via a virtual analysis that the current allowed area on the d_V - d_A plane could get almost quarter the size if the errors were controlled at the 5% level for the measured $t\bar{t}$ cross section at the LHC with $\sqrt{s} = 14$ TeV.

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