Parity violation in QCD process

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Abstract

Parity violation in QCD process is studied using helicity dependent top quark pair productions at Large Hadron Collider experiment. Though no violation can be found in the standard model (SM), new physics beyond the SM predicts the violation in general. In order to evaluate the violation, we utilize an effective operator analysis in a case that new particles predicted by the new physics are too heavy to be directly detected. By using this method, we try to discriminate supersymmetric SM from universal extra-dimension model via an asymmetry measurement of the top quark pair production. We also discuss the asymmetry from the SM electroweak top pair production process and that from the little Higgs model.

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I. INTRODUCTION

The standard model (SM) successfully describes almost all experiments below $O(100)$ GeV. However, there are some difficulties in the SM, for example, a hierarchy problem in the Higgs sector as a quantum field theory. It is also a problem that the SM does not contain natural candidate of dark matter. People believe an existence of underlying theory beyond the SM above a scale of $O(1)$ TeV, and its discovery is strongly expected at Large Hadron Collider (LHC) experiment. A lot of candidates beyond the SM have been suggested until now. The first promising candidate is supersymmetry (SUSY), in which the gauge hierarchy problem is naturally solved as well as gauge coupling unification is achieved. In the SUSY with $R$-parity, the lightest SUSY particle is stable which can be a dark matter. The second candidate is extra-dimension theory, which might be related to string theory. Solutions of the hierarchy problem have been suggested in various setup in the extra-dimension (see, for example, Ref.\textsuperscript{[1]}). Here we consider an universal extra-dimension (UED) model as the simplest example of the extra-dimension theory.
The UED model is a naive extension of the SM, where SM particles have extra-dimensional modes, i.e., Kaluza-Klein (KK) particles, and their spins are the same as SM particles. The lightest KK particle is stable and can be a dark matter. Both SUSY and UED predict new heavy particles as superpartners and KK-particles, respectively.

For those models, it is important to experimentally distinguish one from the other, not only by the mass spectrum but also by the kinematic feature in the production. Actually, the production processes between SUSY and UED models are similar at hadron colliders, so that the study of the kinematic properly will become more important role to determine it. The spin correlation will be the direct probe to determine the model, although we meet a difficulty how to measure the spin-correlation in production.

The aim of this paper is to discriminate SUSY from UED at the LHC by focusing on the parity violation in QCD processes without discovering any new particles. We investigate the determination of underlying theory through the parity violation in QCD, even if new particles are too heavy to be detected directly in the experiments. Of cause the SM has no parity violation in QCD, and it can be happened through the effects of new physics. In SUSY, gluino-quark-squark interactions can violate parity, since a mass of left-handed squark $\tilde{q}_L$ is different from that of right-handed squark $\tilde{q}_R$ in general. While the UED has no parity violating QCD interactions (at least in tree level). Therefore, we could distinguish SUSY from UED through the QCD-parity violation. An asymmetry measurement of the helicity dependent cross sections of the top pair production will suggests the violation. The SM effect will be also estimated, where the asymmetry is caused by electroweak interactions in a tree-level. This is the background of the discovery of parity violation in the QCD. We will also consider a little Higgs (LH) model as the third candidate beyond the SM, where no parity violation exists in QCD but weak interactions are modified from the SM. This will cause the asymmetry in the helicity dependent cross sections of the top pair production.

In this paper, we study parity violation in QCD process by using helicity dependent top quark pair productions at the LHC experiment. Though no violation can be found in the SM, new physics beyond the SM predicts the violation in general. In order to evaluate the violation, we utilize an effective operator analysis in a case that new particles predicted by the new physics are too heavy to be directly detected. By using this method, we try to discriminate SUSY SM from UED model via an asymmetry measurement of the top quark pair production. We also discuss the asymmetry from the SM electroweak top pair production process and that from the LH model.

II. TOP PAIR PRODUCTION WITH HELICITY DEPENDENCE

We investigate helicity dependent top pair production at LHC experiment. The helicity of top pair can be measured, since top quark immediately decays before hadronization differently from other quarks. The observed property in the decay products assessed the helicity information of the top quarks. Then a measurement of the cross section depending on helicities of top and anti-top is possible. Here, at first, we show how to determine the helicity of top quark through an angular distribution of charged lepton and momentum of multi-jets experimentally. As for a spin direction of a top quark, we focus on a case that top quark decays into $l^+ \nu b$ and anti-top is fully hadronic decay with jets. The top quark decays into...
where a helicity of $b$ is identified as a chirality of $b$ (i.e., $b_L$) since $m_b$ is negligible in this energy. In a rest frame of the top, this $W^+$ almost goes along the top spin axis and its polarization is longitudinal or $-1$, since the weak interaction is chiral. In this frame, longitudinal $W^+$ goes to $+1/2$ spin direction of the top, while left-handed $b$ goes to the opposite direction. On the other hand, $-1$ polarized $W^+$ almost goes to $-1/2$ spin direction of the top. In both cases, $l^+$ almost emits in the $W^+$ polarization direction due to angular momentum conservation. Next step, we consider how to know the direction of motion of the top. It can be measured since the anti-top quark decays into 3-jets which can be reconstructed. Therefore, we can determine the helicity of the top quark, and the helicity of anti-top can be also measured in a similar way.

If parity is violated in QCD through the effects of new physics, there must appear asymmetry in the cross section depending on helicities of top and anti-top. For the asymmetry with the helicity dependence in the $t\bar{t}$ mass system, $m_{t\bar{t}}$ distribution is defined as

$$\delta A_{LR}^0(m_{t\bar{t}}) = \left( \frac{d\sigma_{++}}{dm_{t\bar{t}}} + \frac{d\sigma_{--}}{dm_{t\bar{t}}} \right) - \left( \frac{d\sigma_{+-}}{dm_{t\bar{t}}} + \frac{d\sigma_{-+}}{dm_{t\bar{t}}} \right),$$

(II.1)

where $\sigma_{\lambda_t\lambda_f}$ denotes the production cross section with a top (anti-top) helicity $\lambda_t$ ($\lambda_f$). We apply an effective operator analysis to the top pair production up to orders of $\alpha_s^2$. We neglect a chirality flip via a top Yukawa coupling ($y_t$) that suggests an order of $\alpha_s^2 y_t$ in 1-loop diagrams. The analysis of this paper is the first step, and we will regard the effects of top Yukawa coupling in the next work[18]. Then $\sigma_{+-}$ and $\sigma_{-+}$ in $\delta A_{LR}^0$ of Eq. (II.1) are irrelevant, since $\sigma_{+-}$ and $\sigma_{-+}$ are caused by chiral flip of top or anti-top quark. Namely, the helicity of anti-top quark is automatically determined by that of top quark up to the order of $\alpha_s^2$. For example, when top quark helicity is $+$, helicity of the anti-top is also $+$ due to the no chirality flip. Then $\sigma_{+-}$ and $\sigma_{-+}$ are redundant, and it is useful to define $\delta A_{LR}$ as

$$\delta A_{LR}(m_{t\bar{t}}) = \frac{d\sigma_{++}}{dm_{t\bar{t}}} - \frac{d\sigma_{--}}{dm_{t\bar{t}}}. \quad (II.2)$$

We do not have to measure the helicity of anti-top for $\delta A_{LR}$, and we estimate $\delta A_{LR}$ of parton level in the following analyses of investigating the parity violation in QCD.

As for a numerical calculation of quark and anti-quark annihilation and gluon fusion processes, we use GR@PPA event generator[10], where in calculation, we use the CTEQ6L1. The cross section is given by

$$\sigma(pp \to t\bar{t}) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 \sigma(ab \to t\bar{t}; \hat{s}, x_1, x_2, \mu_R)D_{a/p}(x_1, M_Z)D_{b/p}(x_2, M_Z), \quad (II.3)$$

where $D_{a/p}(x, \mu_F)$ is a parton distribution function with a factorization scale of $\mu_F$, which is chosen for $Z$ boson mass, for simplicity. The $a$ and $b$ stand for gluon and quark flavor in the proton. The $\hat{s}$ is a parton level cross section with an invariant mass of $a$

and $b$ as $\hat{s} = (p_a + p_b)^2$ and scaling parameter $x$. The $\mu_R$ is a renormalization scale which we take $M_Z$. 
III. SUSY AND UED DISCRIMINATION VIA QCD PARITY VIOLATION

At first, we represent parity violating dimension 6 operators, and, next, we investigate the QCD parity violation in SUSY and UED. Let us try to discriminate SUSY from UED through the parity violation even when masses of sparticles or KK-particles are too heavy to be detected at direct searches. We also estimate effects of weak parity violation in the SM and LH.

A. Dimension 6 operators

We use an effective theory where particles of new physics, such as, sparticles and KK-particles, are integrated out. The QCD parity violation is represented by the SM field contents with dimension 6 operators as a leading order. These irrelevant operators in QCD are shown by \( O_{qqq}^{(1)} \), \( O_{qqq}^{(8)} \), \( O_{qqGG} \), and \( O_{qqGG} \), which represent color-singlet 4 fermi, color-octet 4 fermi, quark-quark-gluon, and quark-quark-gluon-gluon operators, respectively. They are listed in Ref\[1\], and given by

\[
O_{qqq}^{(1)} = \frac{12g_4^4}{192\pi^2} \sum_{i,j=L,R} \int \frac{d^4k_1 d^4k_2 d^4k_3 d^4k_4}{(2\pi)^4(2\pi)^4(2\pi)^4(2\pi)^4} (2\pi)^4\delta^4(-k_1 + k_2 - k_3 + k_4)
\]

\[
	imes C_{ij} \left[ q(k_1) \gamma^\mu P_i q(k_2) \right] \left( \bar{q}'(k_3) \gamma_\mu P_j q'(k_4) \right), \tag{III.1}
\]

\[
O_{qqq}^{(8)} = \frac{12g_4^8}{192\pi^2} \sum_{i,j=L,R} \int \frac{d^4k_1 d^4k_2 d^4k_3 d^4k_4}{(2\pi)^4(2\pi)^4(2\pi)^4(2\pi)^4} (2\pi)^4\delta^4(-k_1 + k_2 - k_3 + k_4)
\]

\[
	imes D_{ij} \left[ q(k_1) T^a \gamma^\mu P_i q(k_2) \right] \left( \bar{q}'(k_3) T^a \gamma_\mu P_j q'(k_4) \right), \tag{III.2}
\]

\[
O_{qqGG} = \frac{g_3^4}{96\pi^2} \sum_{i=L,R} \int \frac{d^4k_1 d^4k_2 d^4k_3 d^4k_4}{(2\pi)^4(2\pi)^4(2\pi)^4(2\pi)^4} (2\pi)^4\delta^4(-k_1 + k_2 + k_3) q(k_1) T^a E_i^\mu G_\mu^a(k_3) P_i q(k_2), \tag{III.3}
\]

\[
O_{qqGG} = \frac{g_4^4}{192\pi^2} \sum_{i=L,R} \int \frac{d^4k_1 d^4k_2 d^4k_3 d^4k_4}{(2\pi)^4(2\pi)^4(2\pi)^4(2\pi)^4} (2\pi)^4\delta^4(-k_1 + k_2 + k_3 + k_4)
\]

\[
	imes \bar{q}(k_1) \left[ F_i^{\mu\nu} \delta^{ab} + H_i^{\mu\nu} T^a T^b \right] G_\mu^a(k_2) G_\nu^b(k_3) P_i q(k_4), \tag{III.4}
\]

where \( P_i \) (\( i = L, R \)) is the chirality projection, \( P_L = \frac{1 - \gamma^5}{2} \) \( P_R = \frac{1 + \gamma^5}{2} \), and \( E_i^\mu \), \( F_i^{\mu\nu} \), \( H_i^{\mu\nu} \) are defined as

\[
E_i^\mu = \{ e_1 \gamma_1 + e_2 \gamma_2 \} k_1^\mu + \{ e_3 \gamma_2 + e_4 \gamma_1 \} k_2^\mu + \{ e_5 \gamma_3 + e_6 \gamma_4 \} k_3^\mu - e_8 i e^{\alpha\beta} \gamma_5 \gamma_\mu k_1 \alpha k_2 \beta, \tag{III.5}
\]

\[
F_i^{\mu\nu} = f_{1I\alpha} i e^{\alpha\beta\gamma\delta} \gamma_5 \gamma_\beta + f_{2\alpha} g^{\nu\gamma} \gamma_\alpha + f_{3\alpha} g^{\mu\nu} \gamma_\alpha + f_{4\alpha} g^{\nu\gamma} \mu, \tag{III.6}
\]

\[
H_i^{\mu\nu} = h_{1\alpha\beta} i e^{\alpha\beta\gamma\delta} \gamma_5 \gamma_\beta + h_{2\alpha} g^{\nu\gamma} \gamma_\alpha + h_{3\alpha} g^{\mu\nu} \gamma_\alpha + h_{4\alpha} g^{\nu\gamma} \mu. \tag{III.7}
\]

In Eqs.\[III.2\] and \[III.3\], \( C_{ij}, D_{ij}, e_{11}, \ldots, e_{8i} \) are Wilsonian coefficients which have mass dimension \( M_{NP}^{-2} \), where \( M_{NP} \) stands for a scale of new physics characterized by new particles’ masses. In Eqs.\[III.6\] and \[III.7\], coefficients \( f_{1\alpha}, \ldots, f_{11\alpha}, \ldots \) are some combination of the quark and the gluon momentum, e.g.

\[
f_{1L\alpha} = f_{1L}^{(k_1)} k_1 + f_{1L}^{(k_3)} k_3 + f_{1L}^{(k_4)} k_4 \tag{III.8}
\]
for left-handed quarks, and $f_{1i}^{(k_1)}, \cdots, j_{4i}^{(k_4)}$, $h_{1i}^{(k_1)}, \cdots, h_{4i}^{(k_4)}$ are Wilsonian coefficients with mass dimension $M_{NP}^2$. The QCD interactions in Eqs. (III.1)-(III.4) become chiral in the SUSY SM, since their coefficients are different between left- and right-handed quarks. We can see explicit coefficients of these operators in the SUSY SM and UED model (and also LH model) in Ref. [17].

**B. SUSY**

In the SUSY SM with R-parity, SUSY particles can propagate only inside loop diagrams, and the maximal contributions of the parity violation come from 1-loop induced dimension 6 operators. There were some estimations previously, where SUSY particles have masses of $O(100)$ GeV [18, 19, 23]. Especially, in Ref. [19], the asymmetry was estimated as $|\Delta A_{LR}(m_{\tilde{t} R})| \simeq 2.0\%$ with $O(100)$ GeV sparticles. Here we show a similar estimation by use of dimension six operators by integrating out heavy SUSY particles. We neglect the left-right mixing in the stop mass matrix, which corresponds to neglect top Yukawa in the loop level.

We should take mass bounds of gluino and squarks constrained by LHC experiment [24]. Cross sections from SUSY dimension 6 operators at a center-of-mass energy $E_{CM} = 7$ TeV are listed in Table I. Where we take some sample points of sparticle masses as $(m_{\tilde{g}}, m_{\tilde{L}}, m_{\tilde{R}}) = (2000, 2100, 1000)$, (2000, 1200, 1000), and (400, 1200, 410) GeV. Cases of (i) and (ii) show heavy sparticles consistent with LHC data [24]. In case of (iii), parameter set shows gluino and one of stop are degenerate within 30 GeV, which is not excluded experimentally, too. It is because there are experimental cut for $p_T$s of multi-jets with missing transverse momentum in SUSY search at LHC (Tevatron), where an event selection for jets is $p_T > 40$ GeV [24] ($p_T > 30$ GeV [25]), and $p_T$ of jets are roughly estimated as the mass difference of gluino and squarks. For calculating a cross section, we should pay attention to the cut of collision energy at parton level. In the effective operator approach, operators are expanded by sparticle masses. This means the parton level invariant mass $\sqrt{s}$ can not be larger than sparticle mass, $\sqrt{s} < M_{SUSY}$. Here, we estimate the cross section under the limit of $\sqrt{s} \leq 0.95 \times M_{SUSY}$, where $M_{SUSY}$ stands for $\text{Min.}[m_{\tilde{g}}, m_{\tilde{L}}, m_{\tilde{R}}]$.

Note that top and anti-top are mainly produced in QCD process in collider experiment and the experimental data shows $\sigma^{exp}(pp \rightarrow t\bar{t}) = 179$ pb [26], where the magnitude of $\sigma^{exp}$ is almost same as that induced from the SM QCD processes, $\sigma^{SM}$. Table II shows cross sections of (i) and (ii) are (roughly) $10^{-6}$ smaller than $\sigma^{SM}$. Even if gluino mass is $O(100)$ GeV as the case of (iii), the cross section does not drastically increase.

We show the numerical calculation of the asymmetry $\delta A_{LR}$ for the case of (i) together with UED result in subsection 3.5.

Table II shows cross sections at $E_{CM} = 7$ TeV with various magnitudes of $m_{\tilde{L}}$, fixing $m_{\tilde{g}}$ and $m_{\tilde{R}}$. In Table II $\Delta \sigma$ is defined as $\Delta \sigma = \sigma^{SM+SUSY} - \sigma^{SM}$, where $\sigma^{SM+SUSY}$ stands for a cross section including QCD, SM electroweak (SMEW), and SUSY contributions. The SUSY contribution is small, i.e., cross section is $O(10^{-4})$ pb and $|\Delta \sigma| \simeq O(10^{-2})$ pb. The values of $\delta A_{LR}$ depending on the masses are shown in Fig. II. Apparently, the larger the mass difference between $\tilde{q}_L$ and $\tilde{q}_R$ becomes, the larger magnitude of $\delta A_{LR}$ becomes.

**C. UED**

In the UED with KK-parity, KK particles can propagate only inside loop diagrams, and the max-
Table I. Sample points of sparticle masses and their cross sections at $E_{CM} = 7 \, \text{TeV}$

\[\begin{array}{|c|c|}
\hline
(m_\tilde{b}, m_{\tilde{t}_1}, m_{\tilde{t}_2}) \, [\text{GeV}] & \sigma^{\text{SUSY}}(pp \rightarrow t\bar{t}) \times 10^{-4} \, \text{pb} \\
\hline
(2000, 2100, 1000) & 2.2 \\
(2000, 1200, 1000) & 1.5 \\
(400, 1200, 410) & 8.8 \\
\hline
\end{array}\]

Table II. Sparticles masses and corresponding cross sections are listed. $\sigma^{\text{SUSY}} \equiv \sigma^{\text{SUSY}}(pp \rightarrow t\bar{t})$ and $\Delta \sigma \equiv \sigma^{\text{SM+SUSY}} - \sigma^{\text{SM}}$

\[\begin{array}{|c|c|c|}
\hline
(m_\tilde{b}, m_{\tilde{t}_1}, m_{\tilde{t}_2}) \, [\text{GeV}] & \sigma^{\text{SUSY}} \times 10^{-4} \, \text{pb} & \Delta \sigma \times 10^{-2} \, \text{pb} \\
\hline
(2000, 1010, 1000) & 2.5 & -5.2 \\
(2000, 1100, 1000) & 2.3 & -5.0 \\
(2000, 1200, 1000) & 2.2 & -4.9 \\
(2000, 1300, 1000) & 2.3 & -4.7 \\
(2000, 1400, 1000) & 2.0 & -4.6 \\
(2000, 1500, 1000) & 1.9 & -4.5 \\
(2000, 1600, 1000) & 1.8 & -4.3 \\
(2000, 1700, 1000) & 1.8 & -4.1 \\
(2000, 1800, 1000) & 1.7 & -4.0 \\
(2000, 1900, 1000) & 1.6 & -3.8 \\
(2000, 2100, 1000) & 1.5 & -3.6 \\
(2000, 2200, 1000) & 1.5 & -3.6 \\
(2000, 2300, 1000) & 1.5 & -3.5 \\
\hline
\end{array}\]

D. SM electroweak background and LH

Here we estimate $\delta A_{LR}$ induced from not QCD but weak interactions, which is the SMEW background. The SMEW background is not negligible, although it was not estimated in Ref. [19]. The asymmetry from the SMEW, $\delta A^{\text{SMEW}}_{LR}$, is induced by electroweak interactions at a tree-level, and the cross section of the SMEW is estimated as $\sigma^{\text{SMEW}}(pp \rightarrow$
\[ t\bar{t} \simeq 3.4 \times 10^{-1} \text{pb} \]  

The SMEW contribution is larger than the SUSY contribution comparing to Table I. It is worth noting that a magnitude of \( \sigma^{QCD+\text{SMEW}}(\approx 125 \text{ pb}) \) is smaller than that of only QCD contribution \( \sigma^{QCD}(\approx 138 \text{ pb}) \). The SMEW contributions in \( pp \rightarrow t\bar{t} \) process is studied in Ref. 20-22.

As for the LH, there is no QCD parity violation as in the SM. The effects of the LH is summarized as deviated weak interactions from the SM. Integrating out new heavy particles in the LH, the effective 4 Fermi operators are induced as \[ \mathcal{O}^{\text{LH}} = \frac{g^2}{2} \cos^2 \beta \frac{1}{k_\text{W} - M_\text{W}^2} (\tilde{t} \gamma^\mu P_L b)(\tilde{b} \gamma^\mu P_L t) \]

\[
+ \sum_q \frac{g^2}{3} \tan^2 \theta_W \cos^2 \beta \frac{1}{k_Z^2 - M_Z^2} (\tilde{q} \gamma^\mu P_L q)(\tilde{t} \gamma^\mu P_L t),
\]

\[(\text{III.}11)\]

where \( \cos \beta \sim 1 - \frac{v^2}{27\pi} \), \( g \) is the SU(2)_L coupling, and \( v \) (\( f \)) is a vacuum expectation value (VEV) of the Higgs in the SM (LH), respectively. \( k_\text{W} \) and \( k_Z \) stand for momenta of \( W \) and \( Z \) bosons, respectively. When the LH takes VEV as \( f = 2 \text{ TeV} \), the angle \( \beta \) becomes \( \cos \beta = 0.992 \). We will estimate the helicity asymmetry in the LH in Figs. 2 and 3. Note that the cross section of the LH model is the same order of that of the SMEW processes as \( \sigma^{\text{LH}}(pp \rightarrow t\bar{t}) = 2.4 \times 10^{-1} \text{ pb} \).

E. Discriminate SUSY from UED

Figures 2-5 show results of numerical analyses of the magnitude of \( \delta A_{LR} \) in the SUSY, UED, SMEW, and LH depending on \( m_{t\bar{t}} \) and \( p_t \), respectively. For example, \( \delta A_{LR} \) in SUSY, denoted by \( \delta A_{LR}^{\text{SUSY}} \), is defined by \( \delta A_{LR}^{\text{SUSY}} = \frac{d\sigma_{\text{SUSY}}}{dm_{t\bar{t}} - d\sigma_{\text{SM}}^{LR}} \), while an observable magnitude of \( \delta A_{LR} \) in the experiments is given by \( \delta A_{LR}^{\text{exp}} = \frac{d\sigma_{\text{exp}}^{LR}}{d\sigma_{\text{SM}}^{LR} - d\sigma_{\text{exp}}^{LR}} \), where \( \sigma^{\text{exp}} \) is the total cross section.

The magnitude of \( \delta A_{LR}^{\text{SUSY}} \) in Figs. 2 and 3 does not include an interference of SM and SUSY. \( \delta A_{LR} \) of UED, SMEW, and LH in Figs. 2 and 3 are defined in the same way. We input SUSY mass parameters as \((m_{\tilde{g}}, m_{\tilde{q}_L}, m_{\tilde{q}_R}) = (2 \text{ TeV}, 2.1 \text{ TeV}, 1 \text{ TeV})\), and \((2 \text{ TeV}, 1 \text{ TeV}, 2.1 \text{ TeV})\). Parameters of UED model are taken as \((R^{-1}, \Lambda) = (2 \text{ TeV}, 20 \text{ TeV})\). Apparently, the helicity asymmetry in the SUSY SM can be larger than that in UED model, which is of cause due to the squark mass splitting. For example, when \( m_{\tilde{q}_L} \gg m_{\tilde{q}_R} \), left-handed top pair production should be suppressed, and then the sign of \( \delta A_{LR}^{\text{SUSY}} \) becomes positive because \( \sigma_{++} \) is larger than \( \sigma_{--} \). The opposite case is similarly understood. However, we should notice that the SUSY cross section is much smaller than that of the SM QCD, and unfortunately, once the SM interferes the SUSY contribution, the asymmetry could not seen by the large SM QCD contribution.

Figures 4 and 5 show \( \delta A_{LR} \) including the interference of SM and the new physics (SUSY, UED and LH), where \( \delta A_{LR}^{\text{SM+SUSY}} \) is around \( 3 \times 10^{-3} \), and a deviation of \( \delta A_{LR}^{\text{SM+SUSY}} \) from \( \delta A_{LR}^{\text{SM}} \) is roughly estimated as \( 1 \times 10^{-3} \). Here SM means QCD + SMEW. As for LH, there is a large contribution as \( \delta A_{LR}^{\text{LH}} \sim 5 \times 10^{-3} \). Since the helicity asymmetry is measured by a spin correlation, \( \delta A_{LR}^{\text{exp}} \) should be larger than an error of the spin correlation for observation. Thus, \( \delta A_{LR}^{\text{SM+SUSY}} \) is difficult to be observed. For example, in Ref. 28, a correlation coefficient in a helicity basis is represented, and the statistic and the systematic errors are of order 0.1. However, we could expect that the statistic error reduces about 1/3 by 10 times events in the future LHC experiments and the systematic error reduce about ⌃\[ (g_s, g_s') = (1.3, 0.65, 0.31), M_Z = 91 \text{ GeV}, m_t = 173 \text{ GeV} \]
1/10. In the rest of this section, we discuss a potential to observe $\delta A_{LR}$.

Note that the cross section of the SM QCD decreases comparing to that of the SUSY SM in high $m_{t\bar{t}}$ and $p_T$ region, since SUSY interactions are represented by irrelevant operators. So the SUSY signal could be significant, if we select the phase space (final states) as well as take cut to focus on high $m_{t\bar{t}}$ and $p_T$ region, where the SM QCD contribution should be suppressed. Tables III and IV show fractions of $(\lambda_t, \lambda_{\bar{t}}) = (+, -), (-, +), (+, +),$ and $(-, -)$ for SM QCD, SMEW, SUSY-L, and SUSY-R at $E_{cm} = 7$TeV. Where SUSY-L and SUSY-R
stand for \((m_{\tilde{g}}, m_{\tilde{q}_L}, m_{\tilde{q}_R}) = (2\text{TeV}, 2.1\text{TeV}, 1\text{TeV})\) and \((2\text{TeV}, 1\text{TeV}, 2.1\text{TeV})\), respectively. Notice that SM QCD contribution of \((+, +)\) and \((-,-)\) are suppressed in \(gg \rightarrow t\bar{t}\) process. Moreover, when top

| Helicities | SM QCD | SMEW | SUSY-L | SUSY-R |
|------------|--------|------|--------|--------|
| \((+, -)/(−, +)\) | 0.222  | 0.181 | 0.022  | 0.023  |
| \((+, +)\)    | 0.385  | 0.178 | 0.570  | 0.402  |
| \((-,-)\)     | 0.393  | 0.641 | 0.408  | 0.575  |

TABLE III. Helicity fractions in \(q\bar{q} \rightarrow t\bar{t}\) process

Yukawa coupling is large, the parity violation could be enhanced since 1-loop diagrams with a charged Higgs(ino) inside the loop has the top Yukawa couplings, which have \(t_R\) and \(\bar{t}_R\) in the external lines (while bottom Yukawa couplings have \(t_L\) and \(\bar{t}_L\) in the external lines). This effect is order of \(\alpha_s y_t^2\), which could be the same order as \(\alpha_s^2\) in small \(\tan\beta\) region. Then, if the SUSY cross section is enhanced as \(\sim 10^{-2}\) pb at the high \(m_{t\bar{t}}\) and \(p_T\) region with the specific phase space (where the SM QCD cross section could be suppressed as \(\sim 1\) pb), \(\delta A_{LR}^{\text{SUSY}}\) could be large enough as 0.05. In this case, \(\delta A_{LR}\) can be observed when the statistic error is of order 0.01. We need \(10^4\) events for this statistic error. This number of events is the difference between \((+, +)\) and \((-,-)\) in \(t\bar{t}\) production. Then, the total event should be \(2 \times 10^5\) to obtain \(\delta A_{LR} \simeq 0.05 \pm 0.01\), and an integrated luminosity is roughly estimated as \(10^2\) fb\(^{-1}\). Therefore, we should take reanalyses of \(\delta A_{LR}\) up to \(\mathcal{O}(\alpha_s y_t^2)\) with no use of dimension 6 operators, and we need more detailed studies for the discrimination between the SUSY SM and UED model.

As for the LH model, \(\delta A_{LR}^{\text{LH}}\) is the same order as \(\delta A_{LR}^{\text{SMEW}}\) as shown in Figs. 2 and 3. Their asymmetries could be observable when the SM QCD cross section is suppressed, where the LH might be also discriminated from the SMEW in a specific value of \(f\).

IV. SUMMARY AND DISCUSSIONS

In this paper, we have studied parity violation in QCD process by using helicity dependent top quark pair productions at the LHC experiment. Though no violation can be found in the SM, new physics beyond the SM predicts the violation in general. In order to evaluate the violation, we have utilized an effective operator analysis in a case that new particles predicted by the new physics are too heavy to be directly detected. By using this method, we have tried to discriminate SUSY SM model from UED model via an asymmetry measurement of the top quark pair production. In spite of the tiny asymmetries of the SUSY and UED, there are still possibilities of the discrimination to succeed, i.e., we will take the analyses of order \(\alpha_s y_t^2\) in the small \(\tan\beta\) region, and investigate without use of the effective operators in the specific phase space\([15]\). We have also estimated the asymmetries from the SMEW background and the LH model. They are the same order and could be observable in the specific phase space. For other models, which might suggest significant \(\delta A_{LR}\), such as gauge-Higgs model\([29]\) with tree level parity violation we will also analyze them.

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