One-loop effects on top pair production in the littlest Higgs model with T-parity at the LHC

Bingfang Yang\textsuperscript{1,2} and Ning Liu\textsuperscript{1*}

\textsuperscript{1}College of Physics \& Electronic Engineering, Henan Normal University, Xinxiang 453007, China
\textsuperscript{2}Basic Teaching Department, Jiaozuo University, Jiaozuo 454000, China

Abstract

In this work, we systematically investigate the one-loop corrections to $t \bar{t}$ production in the littlest Higgs model with T-parity (LHT) at the LHC for $\sqrt{s} = 8, 14$ TeV. We focus on the effects of LHT particles on $t \bar{t}$ cross section, polarization asymmetries, spin correlation and charge asymmetry at the LHC. We also study the top quark forward-backward asymmetry at Tevatron and its correlations with the LHC observables. We found that: (1) the contributions of the LHT particles to $t \bar{t}$ production can only reach about 1\% at the 14 TeV LHC. Meanwhile, the anomalous top quark forward-backward asymmetry at Tevatron is also hardly to be explained in the LHT model. (2) the parity violating asymmetries in $t \bar{t}$ production, such as left-right asymmetry $|A_{LR}|$ and the polarization $|P_t|$ can respectively reach 1.1\% and 0.5\%, which may have the potential to provide a signal of LHT at the LHC.

PACS numbers: 14.65.Ha,12.15.Lk,12.60.-i,13.85.Lg

\textsuperscript{*} corresponding author: wlln@mail.ustc.edu.cn
I. INTRODUCTION

Due to a heavy mass, top quark has been widely considered as a window of unveiling the new physics at TeV-scale. In particular, the recent anomalous top quark forward-backward asymmetry observed at the Tevatron \cite{1} may be a strong hint of new physics beyond the Standard Model (SM) \cite{2}, although many measurements from the Tevatron are consistent with the SM predictions. Besides, because of the small statistics, the study of top-quark properties is limited at the Tevatron. As a new generation of top quark factory, the LHC will copiously produce the top events via top pair productions and single top productions, which provides a good opportunity to scrutinize the top quark properties and to search the new physics signals \cite{3}.

Notwithstanding the SM have been confirmed by the various experiments from the LEP to the LHC, it still has some drawbacks, such as the hierarchy problem. In order to solve this problem, the little Higgs model was proposed \cite{4}, where the Higgs boson is treated as a pseudo-Goldstone boson. The littlest Higgs (LH) model \cite{5} is an economical approach to implement the idea of the little Higgs, however, this model suffers strong constraints from electro-weak precision tests \cite{6} and will reintroduce the fine-tuning problem in the Higgs potential \cite{7}. A feasible way to overcome these difficulties is to impose a discrete symmetry called T-parity \cite{8} in the littlest Higgs model, it prevents the tree-level contribution from the heavy gauge bosons to the electro-weak observables and also forbids the interactions that induce the triplet scalars to develop the VEV in the LH model. This resulting model is referred to as the littlest Higgs model with T-parity (LHT). One aspect of the LHT phenomenology in top-quark sector is that the top quark can have interactions with the LHT particles, such as heavy gauge bosons, mirror fermions, and heavy quarks $T^\pm$. These new interactions can contribute to the $t\bar{t}$ production at the loop level.

Since the new particles beyond the SM have not been discovered at the LHC, the scale of the new physics may be higher than the expected. In this situation, the indirect searches through the loop effect become important. Furthermore, compared with other light quarks the produced top quarks can decay before the hadronization, and the spin information of top quarks will be inherited and manifested by its decay daughters. Therefore, spin polarization and spin correlation of top quark can be used to probe the mechanisms of top quarks productions and decays \cite{9}, and unveil the new physics \cite{10} related to the top quark.
In this paper, we calculate the complete one-loop corrections to the process $pp \rightarrow t \bar{t}$ in the LHT at the Tevatron and at the LHC with $\sqrt{s} = 8$ TeV and 14 TeV. We also study the correlation behaviors among the top quark forward-backward asymmetry, top charge asymmetry, polarization asymmetry and the spin correlation.

This paper is organized as follows. In Sec.II we give a brief review of the LHT model related to our work. In Sec.III we calculate the (un)polarized $t \bar{t}$ production and the correlation of the observables in the LHT model. Finally, we give our conclusions in Sec.IV.

II. A BRIEF REVIEW OF THE LHT MODEL

The LHT is a non-linear $\sigma$ model based on the coset space $SU(5)/SO(5)$, with the global group $SU(5)$ being spontaneously broken into $SO(5)$ by a $5 \times 5$ symmetric tensor at the scale $f \sim \mathcal{O}(\text{TeV})$, the gauged subgroup $[SU(2) \times U(1)]^2$ of $SU(5)$ is broken into the SM gauge group $SU(2)_L \times U(1)_Y$. From the $SU(5)/SO(5)$ breaking, there arise 14 Goldstone bosons which transform under the electroweak gauge group as follows:

$$1_0 \oplus 3_0 \oplus 2_{1/2} \oplus 3_{\pm 1}. \quad (1)$$

where the subscripts indicate the hypercharges. We can denote the fields in these four representations as $\eta, \omega, H$ and $\phi$, respectively. After EWSB, $H$ can be decomposed as $H = (-i\pi^+\sqrt{2}, (v + h + i\pi^0)/2)^T$. Explicitly, they are described by the “pion” matrix $\Pi$, given by

$$\Pi = \begin{pmatrix}
-\frac{\omega^0}{2} & -\frac{\eta}{\sqrt{20}} & -\frac{\omega^+}{\sqrt{2}} & -\frac{\pi^+}{\sqrt{2}} & -\frac{\phi}{\sqrt{2}} & -\frac{\phi^+}{\sqrt{2}} \\
-\omega^0 & \frac{\omega^0}{2} & \frac{\eta}{\sqrt{20}} & \frac{\omega^+}{\sqrt{2}} & \frac{\pi^+}{\sqrt{2}} & \frac{\phi}{\sqrt{2}} \\
\frac{\eta}{\sqrt{20}} & \frac{\eta}{\sqrt{20}} & v + h + i\pi^0 & \frac{1}{5\eta} \sqrt{4} & \frac{1}{5\eta} \sqrt{5} & \frac{1}{5\eta} \sqrt{5} \\
\frac{\omega^0}{\sqrt{2}} & \frac{\omega^0}{\sqrt{2}} & \frac{\eta}{\sqrt{20}} & \frac{\omega^+}{\sqrt{2}} & \frac{\pi^+}{\sqrt{2}} & \frac{\phi}{\sqrt{2}} \\
\frac{i\phi^-}{\sqrt{2}} & \frac{i\phi^-}{\sqrt{2}} & \frac{i\phi^-}{\sqrt{2}} & \frac{\pi^-}{\sqrt{2}} & \frac{\omega^-}{\sqrt{2}} & \frac{\omega^-}{\sqrt{2}} \\
\frac{i\phi^-}{\sqrt{2}} & \frac{i\phi^-}{\sqrt{2}} & \frac{i\phi^-}{\sqrt{2}} & \frac{i\phi^-}{\sqrt{2}} & \frac{\pi^-}{\sqrt{2}} & \frac{\omega^-}{\sqrt{2}} \\
\frac{i\phi^0 + \phi_P}{\sqrt{2}} & \frac{i\phi^0 + \phi_P}{\sqrt{2}} & \frac{i\phi^0 + \phi_P}{\sqrt{2}} & \frac{i\phi^0 + \phi_P}{\sqrt{2}} & \frac{\pi^0 + \pi_P}{\sqrt{2}} & \frac{\omega^0 + \phi_P}{\sqrt{2}}
\end{pmatrix} \quad (2)$$

Where $\omega^\pm, \omega^0, \eta$ are eaten respectively by 4 new heavy gauge bosons $W_H^\pm, Z_H, A_H$ whose masses up to $\mathcal{O}(v^2/f^2)$ are given by

$$M_{W_H} = M_{Z_H} = gf (1 - \frac{v^2}{8f^2}), M_{A_H} = \frac{gf}{\sqrt{5}} (1 - \frac{5v^2}{8f^2}) \quad (3)$$

3
with \( g \) and \( g' \) being the SM \( SU(2) \) and \( U(1) \) gauge couplings, respectively. In the 't Hooft-Feynman gauge, the would-be Goldstone-Boson mass is the same as its corresponding gauge boson.

When T-parity is implemented in the fermion sector of the model we require the existence of mirror partners for each of the original fermions. For each SM quark, a copy of mirror quark with T-odd quantum number is added. We denote them by \( u_i^H, d_i^H \), where \( i = 1, 2, 3 \) are the generation index, whose masses up to \( \mathcal{O}(v^2/f^2) \) are given by

\[
m_{d_i^H} = \sqrt{2}\kappa_i f, \quad m_{u_i^H} = m_{d_i^H}(1 - \frac{v^2}{8f^2})
\]  

(4)

where \( \kappa_i \) are the diagonalized Yukawa couplings of the mirror quarks.

In order to cancel the one-loop quadratic divergent radiative corrections to Higgs mass parameter induced by top quark, an additional heavy T-even partner of the top quark \( T^+ \) is introduced. The implementation of T-parity then requires its own mirror quark \( T^- \), which is T-odd under T-parity. Their masses up to \( \mathcal{O}(v^2/f^2) \) are given by

\[
m_{T^+} = \frac{f}{v} m_t \left[ \frac{1}{\sqrt{x_L(1 - x_L)}} \left[ 1 + \frac{v^2}{f^2} \left( \frac{1}{3} - x_L(1 - x_L) \right) \right] \right]
\]  

(5)

\[
m_{T^-} = \frac{f}{v} m_t \left[ \frac{1}{\sqrt{x_L}} \left[ 1 + \frac{v^2}{f^2} \left( \frac{1}{3} - \frac{1}{2} x_L(1 - x_L) \right) \right] \right]
\]  

(6)

where \( x_L \) is the mixing parameter between the SM top-quark \( t \) and the new top-quark \( T^+ \).

In the LHT model, the flavor structure is richer than the one of the SM due to the presence of the mirror fermions and their weak interactions with the ordinary fermions\[11\]. The mirror quark sector exists two CKM-like unitary mixing matrices as follows:

\[
V_{H_u}, V_{H_d}
\]  

(7)

Note that \( V_{H_u} \) and \( V_{H_d} \) are related through the SM CKM matrix:

\[
V_{H_u}^\dagger V_{H_d} = V_{CKM}.
\]  

(8)

These mirror mixing matrices are involved in the flavor changing interactions between the SM fermions and the mirror fermions which are mediated by the T-odd gauge bosons \( (W^\pm_H, Z_H, A_H) \) or T-odd Goldstone bosons\( (\omega^\pm, \omega^0, \eta) \). One cannot completely turn off the new mixing effects except with a universally degenerate mass spectrum for the T-odd
mirror fermions. The mixing matrix $V_{Hd}$ can be conveniently parameterized, we follow Ref.\cite{12} to parameterize $V_{Hd}$ with three angles $\theta_{12}^d, \theta_{23}^d, \theta_{13}^d$ and three phases $\delta_{12}^d, \delta_{23}^d, \delta_{13}^d$ as follows

$$V_{Hd} = \begin{pmatrix}
    c_{12}^d c_{13}^d & s_{12}^d c_{13}^d e^{-i\delta_{12}^d} & s_{13}^d e^{-i\delta_{13}^d} \\
    -s_{12}^d c_{23}^d e^{i\delta_{12}^d} - c_{12}^d s_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{23}^d)} & c_{12}^d c_{23}^d - s_{12}^d s_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{23}^d)} & s_{23}^d c_{13}^d e^{-i\delta_{23}^d} \\
    s_{12}^d s_{23}^d e^{i(\delta_{12}^d + \delta_{23}^d)} - c_{12}^d c_{23}^d s_{13}^d e^{i\delta_{23}^d} & -c_{12}^d s_{23}^d e^{i\delta_{23}^d} - s_{12}^d c_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{12}^d)} & c_{23}^d c_{13}^d
\end{pmatrix}$$

(9)

III. NUMERICAL RESULTS AND DISCUSSIONS

In our calculation, we neglect the high order $O(v^2/f^2)$ terms in the masses of new particles and the higher order couplings between the scalar triplet $\Phi$ and top quark, the amplitudes are performed at the order $O(\alpha_s^2)$. In the 't Hooft-Feynman gauge, we use the dimensional regularization scheme to regulate the ultraviolet divergences in the virtual corrections and adopt the on-shell renormalization scheme to remove them. The relevant Feynman diagrams for process $gg \to t\bar{t}$ and $q\bar{q} \to t\bar{t}$ in the LHT are depicted in Fig.1. The black dot and grey ellipse appearing in Figs.1 represent the renormalized vertexes $\hat{\Gamma}_{qt\bar{t}}^\mu, \hat{\Gamma}_{gg\bar{q}}^\mu$ and top quark self-energy at one-loop level respectively, whose diagrams are displayed in Fig.2 and Fig.3. We list the explicit expressions of these amplitudes in Appendix. We analytically and numerically checked that the divergences in the renormalized vertex and propagator have been canceled. We also find that there are no divergences in the box diagrams.

The relevant LHT parameters are the scale $f$, the mixing parameter $x_L$, the Yukawa couplings $\kappa_i$ and the parameters in the matrices $V_{Hu}, V_{Hd}$. For the mirror fermion masses, we get $m_{u_H}^U = m_{d_H}^U$ at $O(v/f)$ and assume that the masses of the first two generations are degeneracy.

$$m_{u_H}^U = m_{u_H}^D = m_{d_H}^U = m_{d_H}^D = M_{12}, m_{u_H}^L = m_{d_H}^L = M_3$$

(10)

For the matrices $V_{Hu}$ and $V_{Hd}$, we follow Ref.\cite{16} to choose the following scenario: $V_{Hu} = 1, V_{Hd} = V_{CKM}$. In this scenario, the contribution of the mirror quarks will come entirely from the third family ones and the additional heavy quarks $T^+, T^-$. We note that both of the CMS and ATLAS collaborations have reported their null results of searching for the fermionic top partner and respectively excluded the masses regions below 557 GeV.
FIG. 1: Feynman diagrams of the one-loop correction to the process $pp \rightarrow t\bar{t}$ in the LHT model.

The black dot and gray ellipse represent the renormalized vertexes $\hat{\Gamma}_{g_{tt}}^{\mu}$, $\hat{\Gamma}_{gq}^{\mu}$ and top quark self-energy respectively, whose diagrams are displayed in Fig.2 and Fig.3.

and 656 GeV at 95% CL. In our calculations, we scan the parameter regions: $f = 500 \sim 2000$ GeV, $x_{L} = 0.1 \sim 0.9$, $\sqrt{2}\kappa_{i} = 0.6 \sim 3$ and require our samples to satisfy direct search constraints from the LHC and the flavor constraints in Refs. \[19\]. Since the new parity violating interactions between top quark and LHT particles can not only affect the $t\bar{t}$ production rate but also the spin polarization, we will discuss the LHT corrections to the (un)polarized top pair production by using the following observables.

(i) For the unpolarized $t\bar{t}$ production, we calculate the relative corrections for total $t\bar{t}$ production cross section ($\delta \sigma/\sigma$), charge asymmetry ($A_{C}$) \[20\] at the LHC and the top quark forward-backward asymmetry ($A_{FB}^{t}$) \[21\] at the Tevatron, which are defined
FIG. 2: The effective $gt\bar{t}$, $ggq$ vertex diagrams at one-loop level in the LHT model.

FIG. 3: The effective fermion propagator diagrams at one-loop level in the LHT model.

as:

$$\frac{\delta \sigma}{\sigma} = \frac{\sigma_{tot} - \sigma_{SM}}{\sigma_{SM}},$$  \hspace{1cm} (11)$$

$$A_C = \frac{\sigma(\Delta |\eta_t| > 0) - \sigma(\Delta |\eta_t| < 0)}{\sigma(\Delta |\eta_t| > 0) + \sigma(\Delta |\eta_t| < 0)},$$  \hspace{1cm} (12)$$

$$A_{FB}^{t} = \frac{\sigma(\Delta y_t > 0) - \sigma(\Delta y_t < 0)}{\sigma(\Delta y_t > 0) + \sigma(\Delta y_t < 0)},$$  \hspace{1cm} (13)$$

where $\Delta y_t$ ($\Delta \eta_t$) is the (pseudo)rapidity difference of the top and anti-top quark in the laboratory frame. In the following, when we calculate $A_C$ and $A_{FB}$, we only consider the contribution from the interference between the SM and the LHT model.
For the polarized $t\bar{t}$ production, we calculate the spin correlation($\delta C$)\cite{9}, the polarization asymmetry($P_t$)\cite{22} and the left-right asymmetry($A_{LR}$)\cite{22}, which are given by:

\[
C = \frac{(\sigma_{RR} + \sigma_{LL}) - (\sigma_{RL} + \sigma_{LR})}{\sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}}, \quad (14)
\]

\[
\delta C = \frac{C_{tot} - C_{SM}}{C_{SM}}, \quad (15)
\]

\[
P_t = \frac{(\sigma_{RL} + \sigma_{RR}) - (\sigma_{LR} + \sigma_{LL})}{\sigma_{RL} + \sigma_{RR} + \sigma_{LL} + \sigma_{LR}}, \quad (16)
\]

\[
A_{LR} = \frac{\sigma_{RL} - \sigma_{LR}}{\sigma_{RL} + \sigma_{LR}}. \quad (17)
\]

Here, the subindices $L(R)$ represent left($\lambda_{t(\bar{t})} = -1/2$) and right-handed($\lambda_{t(\bar{t})} = +1/2$) top(antitop) quarks, respectively.

The SM parameters input in our numerical calculations are taken as\cite{14}

\[
G_F = 1.16637 \times 10^{-5} \text{GeV}^{-2}, \quad s_W^2 = 0.231, \quad \alpha_s = 0.1076,
\]

\[
\alpha_e = 1/128, \quad M_{Z_L} = 91.2 \text{GeV}, \quad m_t = 172.9 \text{GeV}. \quad (18)
\]

Recently the ATLAS and CMS collaborations at the LHC have independently discovered a Higgs-like resonance with mass about 125 GeV\cite{15}. So we take $m_h = 125 \text{GeV}$ in our numerical calculations. We use the parton distribution function CTEQ10\cite{13} with renormalization scale and factorization scale $\mu_R = \mu_F = m_t$. In table I, we give the dependence of our observables on renormalization/factorization scale by taking $\mu$ as $\mu_0/2$, $\mu_0$ and $2\mu_0$ respectively. The benchmark point used in the calculation is: $f = 1250 \text{GeV}$, $x_L = 0.5$, $\sqrt{s} = 14 \text{TeV}$ (where $A_{FB}^l$ for $\sqrt{s} = 1.96 \text{TeV}$). From the table, we can see that the LHT corrections will mildly reduce the scale dependence of LO $t\bar{t}$ cross section.

For other observables, we find that they have weak dependence on the unphysical scale because of the cancellation of scale between numerator and denominator.

A. Unpolarized top quark pair production

In Fig.4, we show the LHT correction $\delta\sigma/\sigma$ versus $f$ and $x_L$ at the LHC when $\sqrt{s} = 8, 14 \text{ TeV}$ respectively. On the left panel, we can see that the maximum value of the relative correction to the $t\bar{t}$ cross section can reach $-0.25\%$ for $\sqrt{s} = 8 \text{ TeV}$ and $-0.2\%$
TABLE I: Dependence of observables in $t\bar{t}$ production on renormalization/factorization scale with $\mu_0 = m_t$.

| $\mu_0/2$ | $\sigma$(pb) | $\delta\sigma/\sigma$(%) | $A_C$(%) | $A_{FB}$(%) | $\delta C$(%) | $P_t$(%) | $A_{LR}$(%) |
|----------|--------------|--------------------------|----------|-------------|-------------|----------|------------|
|          | 595.14       | -0.0385                  | -0.153   | -0.173      | -0.0416     | -0.311   | -0.768     |
| $\mu_0$  | 487.38       | -0.0385                  | -0.154   | -0.173      | -0.0415     | -0.310   | -0.770     |
| 2$\mu_0$ | 416.18       | -0.0386                  | -0.154   | -0.174      | -0.0416     | -0.310   | -0.769     |

FIG. 4: The relative correction of the top-quark pair production cross section $\delta\sigma/\sigma$ as the function of $f, x_L$ for $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV, respectively.

for $\sqrt{s} = 14$ TeV, respectively. We also notice that the process $gg \rightarrow t\bar{t}$ are more sensitive to the LHT particles than $q\bar{q} \rightarrow t\bar{t}$. When the scale $f$ increases, the relative corrections $\delta\sigma/\sigma$ become small. This indicates that the effects of the LHT particles on $t\bar{t}$ cross section will decouple at the high cutoff scale $f$. Since heavy top quark $T^+$ and $T^-$ masses have a strong dependence on the mixing parameter $x_L$, we can see that when $x_L$ tends to 0, the masses of $T^+$ and $T^-$ will become heavy and their contribution is very small. When $x_L$ tends to 1, the masses of $T^+$ will become heavy but the masses of $T^-$ will become light. As a result, the effect of $T^-$ will still reside in the $t\bar{t}$ production. On the right panel of Fig.4, we can see that the maximum value of the relative correction $\delta\sigma/\sigma$ occurs in the region of $x_L \sim 0.56$.

In Fig.5 we show the charge asymmetry $A_C(t\bar{t})$ versus $f$ and $x_L$ at the LHC, where $A_C(t\bar{t})$ only includes the LHT contributions. We can see that the LHT contribution to
FIG. 5: The top quark charge asymmetry $A_C(t\bar{t})$ as the function of $f, x_L$ for $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV, respectively. The $A_C(t\bar{t})$ plotted therein correspond to the LHT contributions.

charge asymmetry $A_C(t\bar{t})$ are negative and small for $\sqrt{s} = 8, 14$ TeV. Considering the uncertainty of $t\bar{t}$ measurement, we can infer that it will be very difficult to observe the LHT effects on $A_C(t\bar{t})$ at the LHC[20, 24]. We also notice that since both numerator and denominator of $A_C$ in Eq.(13) decouple with the cutoff scale $f$, $A_C(t\bar{t})$ has a weak dependence on the scale $f$ and show a slow decoupling behavior. We checked that when $f$ was taken very large, the LHT effects on $A_C(t\bar{t})$ will disappear. The similar behavior can be seen in $A_{FB}^t$ in Fig.6.

FIG. 6: The forward-backward asymmetry in rapidity $A_{FB}^t$ as the function of $f, x_L$ at the Tevatron. The $A_{FB}^t$ plotted therein correspond to the LHT contributions.

In Fig.6 we show the forward-backward asymmetry $A_{FB}^t$ versus $f, x_L$ at the Tevatron, where $A_{FB}^t$ only includes the LHT contributions. We can see $A_{FB}^t$ in the LHT is negative
and small. So LHT model will be not helpful to alleviate the large discrepancy between the SM prediction and the measurement of $A_{FB}$ from Tevatron.

B. Polarized top quark pair production

(i) The correction to the spin correlation

![Graph showing the correction to the spin correlation $\delta C$ as the function of $f, x_L$ for $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV.]

FIG. 7: The correction to the spin correlation $\delta C$ as the function of $f, x_L$ for $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV, respectively.

Recently, the CMS collaboration reported their measurement of the $t\bar{t}$ spin correlation coefficient $C$, that is, $C = 0.24 \pm 0.02$ (stat.) $\pm 0.08$ (syst.) in the helicity basis[27], which is consistent with the SM predictions. In Fig.7, we show the relative correction to the spin correlation $\delta C$ versus $f, x_L$ for the LHC with $\sqrt{s} = 8, 14$ TeV, respectively. We can see $\delta C$ decouple fast with the increase of scale $f$. The maximum value of $\delta C$ can reach $-0.5\%$ for $\sqrt{s} = 8$ TeV and $-0.6\%$ for $\sqrt{s} = 14$ TeV, which is difficult to be detected at the LHC[28].

(ii) Top quark polarization asymmetry

In Fig.8 we show the polarization asymmetry $P_t$ versus $f, x_L$ for the LHC with $\sqrt{s} = 8, 14$ TeV, respectively. From Fig.8, we can see the large effects come from the region of small $f$ and large $x_L$. Comparing with the results of $\sqrt{s} = 8$ TeV, we can see that the $P_t$ is enhanced greatly for $\sqrt{s} = 14$ TeV. The maximum value of $P_t$ can respectively reach about $-0.3\%$ for $\sqrt{s} = 8$ TeV and about $-0.5\%$ for $\sqrt{s} = 14$ TeV.
FIG. 8: The top quark polarization asymmetry $P_t$ as the function of $f, x_L$ for $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV, respectively.

Compared to $|P_t| = 0.5\%$ predicted in the SM at the 14 TeV LHC\cite{29}, the $t \bar{t}$ polarization asymmetries in the LHT model may be accessible at the LHC.

(iii) Top quark left-right asymmetry

FIG. 9: The top quark left-right asymmetry $A_{LR}$ as the function of $f, x_L$ for $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV, respectively. The $A_{LR}$ plotted therein correspond to the LHT contributions.

In Fig. 9, we show the left-right asymmetry $A_{LR}$ versus $f, x_L$ for the LHC with $\sqrt{s} = 8, 14$ TeV. We can see that $A_{LR}$ can maximally reach about $-0.8\%$ and about $-1.1\%$ for $\sqrt{s} = 8, 14$ TeV respectively. In order to estimate the statistical observability of $A_{LR}$, we use the significance $N_S$ defined in Refs.\cite{22} and find that the maximal significance of $A_{LR}$ can be $3\sigma$ for $\sqrt{s} = 8$ TeV and $9.3\sigma$ for $\sqrt{s} = 14$ TeV.
with an assumption of integrated luminosity \( L = 5.0 \, fb^{-1} \). It has also been pointed in Ref. [22] the appropriate cuts on \( t\bar{t} \) invariant mass and on the angle between the lepton and top quark can further enhance the significance at the LHC. Therefore, the left-right asymmetries in \( t\bar{t} \) production may have the potential to probe LHT at the LHC and may deserve further studies by including the top quark decay and detector response.

### C. The correlation of the observables in \( t\bar{t} \) production

In Fig. 10, we present the correlations among \( \delta C, \delta \sigma/\sigma, A_C(t\bar{t}), P_t \) and \( A_{LR} \) at the LHC with \( \sqrt{s} = 8 \) TeV and \( \sqrt{s} = 14 \) TeV. We can see that the correlation behaviors of these observables at \( \sqrt{s} = 8 \) TeV are similar to the ones at \( \sqrt{s} = 14 \) TeV. Since the new chiral interactions can simultaneously affect \( \delta C, P_t \) and \( A_{LR} \), we can see that there is strong correlation among the three observables. Besides, we notice that correlation among \( \delta C, P_t \) and \( A_{LR} \) in LHT model are different from those in other new physics models, such as axigluon model, left-right symmetric models [30]. So we can use these correlation behaviors to distinguish the LHT model from other new physics models.

### IV. CONCLUSIONS

In this paper, we systematically studied the one-loop LHT corrections to \( t\bar{t} \) production at the LHC for \( \sqrt{s} = 8, 14 \) TeV. We presented the numerical results for the relative correction to \( t\bar{t} \) cross section, polarization asymmetries, spin correlation and charge asymmetry at the LHC. Besides, we also investigated the top quark forward-backward asymmetry at Tevatron and its correlations with the LHC observables. We found that the effects of the LHT particles are significant only when they are light and the largest relative correction from these particles to \( t\bar{t} \) production can only reach about 1%. So it will be difficult to observe such small loop-induced LHT effects through the measurement of \( t\bar{t} \) cross section at the LHC. Meanwhile, the anomalous top quark forward-backward asymmetry at Tevatron is also hardly to be explained in the LHT model. However, we noticed that the contribution from LHT to left-right asymmetry \( |A_{LR}| \) and the polarization \( |P_t| \) can respectively reach 1.1% and 0.5%, compared to \( |A_{LR}| = 1.2\% [29] \) and \( |P_t| = 0.5\% \) within
FIG. 10: The correlations between $\delta C$ and $\delta\sigma/\sigma$, $A_{C}(tt)$, $P_t$, $A_{LR}$ for $\sqrt{s} = 8$ TeV and $\sqrt{s} = 14$ TeV, respectively.
the SM at the 14 TeV LHC. These parity violating asymmetries in $t\bar{t}$ production may have
the potential to probe LHT at the LHC and may deserve further studies by including the
top quark decay and detector response and optimizing the cuts on $t\bar{t}$ invariant mass and
on the angle between the lepton and top quark to enhance the significance at the LHC.

Acknowledgments
We would like to thank Lei Wu for useful discussions and suggestions. This work is
supported by the National Natural Science Foundation of China (NNSFC) under grant
No.11305049, the Startup Foundation for Doctors of Henan Normal University under con-
tract No.11112, the National Natural Science Foundation of China (Grant No. 11147167),
the key project of science and technology research of the Education Department of Henan
province under Grant Nos. 13A140113 and 12A140011, the Program of ISTTCP un-
der Grant No. 114100510021, and the Natural Science Research Project of Education
Department of Henan Province (Grant No. 2011A140007).

Appendix: The explicit expressions of the renormalized vertex $\hat{\Gamma}^\mu_{gif}$ and the
renormalized propagator $-i\hat{\Sigma}^f(p)$ \[31\]

They can be represented in form of 1-point, 2-point and 3-point standard functions
$A, B_0, B_1, C_{ij}$. Here $p_t$ and $p_t'$ denote the momenta of the top and antitop respectively,
and they are assumed to be outgoing.

(I)Renormalization vertex

\[
\hat{\Gamma}^\mu_{gif} = \Gamma^\mu_{gif} - ieQ_f\gamma^\mu(\delta Z_V^f - \gamma_5\delta Z_A^f - \frac{S_W}{2C_W}\delta Z_{ZA}) + ie\gamma^\mu(v_f - a_f\gamma_5)\frac{1}{2}\delta Z_{ZA}
\]
where

\[ v_f \equiv \frac{I_f^3 - 2Q_f S_W^2}{2C_W S_W}, \quad a_f \equiv \frac{I_f^3}{2C_W S_W} \]

\[ \delta Z_{ZA} = 2\frac{\Sigma_{AZ}^{(0)}}{M_{ZL}^2} \]

\[ \delta Z_L' = Re[\Sigma_L'(m_f^2) + m_f^2 \frac{\partial}{\partial P_f} Re[\Sigma_L(P_f^2) + \Sigma_R(P_f^2) + 2\Sigma_f(P_f^2)]]|_{P_f^2 = m_f^2} \]

\[ \delta Z_R' = Re[\Sigma_R'(m_f^2) + m_f^2 \frac{\partial}{\partial P_f} Re[\Sigma_L(P_f^2) + \Sigma_R(P_f^2) + 2\Sigma_f(P_f^2)]]|_{P_f^2 = m_f^2} \]

\[ \delta Z_V' = \frac{1}{2}(\delta Z_L' + \delta Z_R'), \delta Z_A = \frac{1}{2}(\delta Z_L' - \delta Z_R') \]

\[ \hat{\Gamma}_{AHT} = \hat{\Gamma}_{glt}(\eta) + \hat{\Gamma}_{glt}(\omega^0) + \hat{\Gamma}_{glt}(\omega^\pm) + \hat{\Gamma}_{glt}(\pi^0) + \hat{\Gamma}_{glt}(h) + \hat{\Gamma}_{glt}(A_H) + \hat{\Gamma}_{glt}(Z_H) + \hat{\Gamma}_{glt}(W_H) + \hat{\Gamma}_{glt}(Z) \]

\[ \hat{\Gamma}_{uH} = \frac{g^2 g_s T_{\alpha \beta}^a(V_{Hu})_{i3}^a(V_{Hu})_{33}^a}{100 M_{AH}^2} \frac{i}{16\pi^2} \]

\[ \left\{ m_{uH}^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_L + m_{uH}^2 (\psi_i^f + \psi_i) \gamma^\mu \gamma^\alpha C_{\alpha \gamma} P_L + m_{uH}^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R + m_{uH}^2 (\psi_i^f + \psi_i) \gamma^\mu \gamma^\alpha C_{\alpha \gamma} P_R 
+ m_{uH}^2 m_{t} (\psi_i^f + \psi_i) \gamma^\mu \gamma^\alpha C_{\alpha \gamma} P_L - m_{uH}^2 m_{t} (\psi_i^f + \psi_i) \gamma^\mu \gamma^\alpha C_{\alpha \gamma} P_R 
- m_{uH}^2 m_{t} \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_L - m_{uH}^2 m_{t} \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R 
- m_{uH}^2 m_{t} \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_L + m_{uH}^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R 
+ \gamma^\mu [m_{uH}^2 B_1 P_L + m_{uH}^2 B_1 P_R + \frac{1}{2}(m_t^2 + m_{uH}^2) B_0 (-p_t, m_{uH}, m_{uH}) 
+ \frac{1}{2}(m_t^2 + m_{uH}^2)(m_t^2 + m_{uH}^2 - m_{\omega}^2) \frac{\partial}{\partial p_t} B_0 - 2m_t^2 m_{uH}^2 \frac{\partial}{\partial p_t} B_0] \right\} \] (19)

\[ \hat{\Gamma}_{uH}^{\omega^0} = \frac{g^2 g_s T_{\alpha \beta}^a(V_{Hu})_{i3}^a(V_{Hu})_{33}^a}{4M_{ZL}^2} \frac{i}{16\pi^2} \]

\[ \left\{ m_{uH}^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_L + m_{uH}^2 (\psi_i^f + \psi_i) \gamma^\mu \gamma^\alpha C_{\alpha \gamma} P_L + m_{uH}^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R + m_{uH}^2 (\psi_i^f + \psi_i) \gamma^\mu \gamma^\alpha C_{\alpha \gamma} P_R 
+ m_{uH}^2 m_{t} (\psi_i^f + \psi_i) \gamma^\mu \gamma^\alpha C_{\alpha \gamma} P_L - m_{uH}^2 m_{t} (\psi_i^f + \psi_i) \gamma^\mu \gamma^\alpha C_{\alpha \gamma} P_R 
- m_{uH}^2 m_{t} \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_L - m_{uH}^2 m_{t} \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R 
- m_{uH}^2 m_{t} \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_L + m_{uH}^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R 
+ \gamma^\mu [m_{uH}^2 B_1 P_L + m_{uH}^2 B_1 P_R + \frac{1}{2}(m_t^2 + m_{uH}^2) B_0 (-p_t, m_{uH}, m_{\omega}) 
+ \frac{1}{2}(m_t^2 + m_{uH}^2)(m_t^2 + m_{uH}^2 - m_{\omega}^2) \frac{\partial}{\partial p_t} B_0 - 2m_t^2 m_{uH}^2 \frac{\partial}{\partial p_t} B_0] \right\} \] (20)
\[
\dot{\Gamma}_{dH,\omega z} = \frac{g^2 g_s T_{\alpha \beta} (V_{H u})^* (V_{H u})}{2 M_{W H}^2} \frac{i}{16\pi^2} \left\{ m_{d_h}^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_L + m_{a \mu}^2 (\bar{\phi}_t^* + \bar{\phi}_t) \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_L + m_t^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R + m_{d_h}^2 m_t (\bar{\phi}_t^* + \bar{\phi}_t) \gamma^\mu C_{\alpha \beta} P_R \\
- m_{d_h}^2 m_t \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_L - m_{a \mu}^2 m_t (\bar{\phi}_t^* + \bar{\phi}_t) \gamma^\mu C_{\alpha \beta} P_L - m_{d_h}^2 m_t \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R - m_{d_h}^2 m_t (\bar{\phi}_t^* + \bar{\phi}_t) \gamma^\mu C_{\alpha \beta} P_R \\
\right. \\
\left. + \alpha^\mu[m^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_L + m_{d_h}^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R + m_{d_h}^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R (\bar{\phi}_t^* + \bar{\phi}_t, p_t, m_{a \mu}, m_{\omega z}, m_{a \mu}) \\
+ \frac{1}{2} (m_t^2 + m_{d_h}^2)(m_t^2 + m_{d_h}^2 - m_{\omega z}^2) \frac{\partial}{\partial p_t^2} B_0 - 2 m_t^2 m_{d_h}^2 \frac{\partial}{\partial p_t^2} B_0 \right\} 
\] (21)

\[
\dot{\Gamma}_{T,\eta} = \frac{4 g^2 m_t^2 f^2}{25 M_{A H}^2 v^2} \left\{ \frac{1}{2} - \frac{u^2}{f^2} + \frac{x_L^2}{2} + \frac{1}{6} \right\} g_s T_{\alpha \beta} \frac{i}{16\pi^2} \left\{ \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R + (\bar{\phi}_t^* + \bar{\phi}_t) \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_L + m^2 \gamma^\mu - \gamma^\mu C_0 (\bar{\phi}_t^* + \bar{\phi}_t, p_t, m_{T -}, m_{\eta}, m_{T -}) P_R \\
+ \gamma^\mu B_1 P_L + \frac{1}{2} B_0 + \frac{1}{2} (m_t^2 + m_{T -}^2 - m_{\eta}^2) \frac{\partial}{\partial p_t^2} B_0 \right\} 
\] (22)

\[
\dot{\Gamma}_{T,\omega} = \frac{g^2 m_t^2}{4 M_{Z H}^2} \left( \frac{v^2}{f} \right) g_s T_{\alpha \beta} \frac{i}{16\pi^2} \left\{ \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R + (\bar{\phi}_t^* + \bar{\phi}_t) \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_L + m^2 \gamma^\mu - \gamma^\mu C_0 (\bar{\phi}_t^* + \bar{\phi}_t, p_t, m_{\omega}, m_{T -}) P_R \\
+ \gamma^\mu B_1 P_L + \frac{1}{2} B_0 + \frac{1}{2} (m_t^2 + m_{T -}^2 - m_{\omega}^2) \frac{\partial}{\partial p_t^2} B_0 \right\} 
\] (23)

\[
\dot{\Gamma}_{T,\pi^0} = \frac{g^2 x_L^2}{4 M_{Z H}^2} \cos^2 \theta \left( \frac{v^2}{f} \right) g_s T_{\alpha \beta} \frac{i}{16\pi^2} \left\{ m_{T +}^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_L + m_{T +}^2 (\bar{\phi}_t^* + \bar{\phi}_t) \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_L + m_t^2 \gamma^\alpha \gamma^\beta C_{\alpha \beta} P_R + m_{T +}^2 m_t \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_R \\
+ m_t^2 (\bar{\phi}_t^* + \bar{\phi}_t) \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_R - m_{T -}^2 m_t \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_R - m_t^2 \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_R \\
+ m_{T +}^2 \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_L + m_{T +}^2 \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_R + m_{T +}^2 \gamma^\mu \gamma^\alpha C_{\alpha \beta} P_R (\bar{\phi}_t^* + \bar{\phi}_t, p_t, m_{T +}, m_{\pi^0}, m_{T +}) P_R \\
+ \gamma^\mu B_1 P_L + \gamma^\mu B_1 P_R + \frac{1}{2} (m_t^2 + m_{T +}^2) B_0 \right\} \\
+ \frac{1}{2} (m_t^2 + m_{T +}^2) (m_t^2 + m_{T +}^2 - m_{\pi^0}^2) \frac{\partial}{\partial p_t^2} B_0 + 2 m_t^2 m_{T +}^2 \frac{\partial}{\partial p_t^2} B_0 \\
+ \gamma^\mu B_1 P_L + \frac{1}{2} (m_t^2 + m_{T +}^2) B_0 \\
+ \frac{1}{2} (m_t^2 + m_{T +}^2) (m_t^2 + m_{T +}^2 - m_{\pi^0}^2) \frac{\partial}{\partial p_t^2} B_0 + 2 m_t^2 m_{T +}^2 \frac{\partial}{\partial p_t^2} B_0 \right\} 
\] (24)
\[
\dot{\Gamma}_{T+h} = m_t^2 g_s T_{a} \frac{i}{16\pi^2} \\
\{ \frac{c_2^2}{s_\chi^2 v^2} \gamma^\alpha \gamma^\mu \gamma^\beta C_{\alpha\beta} P_L + \frac{c_2^2}{s_\chi^2 v^2} (\phi_t^\dagger + \phi_t^\gamma) \gamma^\mu \gamma^\alpha C_{\alpha} P_L + \frac{s_\chi^4}{f^2} \gamma^\alpha \gamma^\mu \gamma^\beta C_{\alpha\beta} P_R \\
+ \frac{s_\chi^4}{f^2} (\phi_t^\dagger + \phi_t^\gamma) \gamma^\mu \gamma^\alpha C_{\alpha} P_R - \frac{c_\chi m_{T+h}}{v f} \gamma^\alpha \gamma^\mu C_{\alpha} P_R - \frac{c_\chi m_{T+h}}{v f} (\phi_t^\dagger + \phi_t^\gamma) \gamma^\mu C_{0} P_R \\
- \frac{c_\chi m_{T+h}}{v f} \gamma^\alpha \gamma^\mu C_{\alpha} P_R - \frac{c_\chi m_{T+h}}{v f} (\phi_t^\dagger + \phi_t^\gamma) \gamma^\mu C_{0} P_R - \frac{c_\chi m_{T+h}}{v f} \gamma^\alpha \gamma^\mu C_{\alpha} P_R \\
+ \gamma^\mu \frac{s_\chi^4}{f^2} B_1 P_L + \frac{c_2^2}{s_\chi^2 v^2} B_1 P_R + \frac{1}{2} (\frac{s_\chi^4}{f^2} + \frac{c_\chi^2}{s_\chi^2 v^2}) B_0 (-p_t, m_{T+h}, m_h) \\
+ \frac{1}{2} (\frac{s_\chi^4}{f^2} + \frac{c_2^2}{s_\chi^2 v^2}) (m_t^2 + m_{T+h}^2 - m_h^2) \frac{\partial}{\partial p_t^\alpha} B_0 - 2 \frac{s_\chi^4}{f^2} m_{T+h}^2 \frac{\partial}{\partial p_t^\alpha} B_0 \} \\
\tag{25}
\]

\[
\dot{\Gamma}_{u_{uH}} = \frac{g^2 g_s T_{a} (V_{Hu})_{i3} (V_{Hu})_{i3} i}{100} \frac{i}{16\pi^2} \{ 2 \gamma^\sigma \gamma^\mu \gamma^\lambda C_{\lambda\sigma} P_L \\
+ 2 \gamma^\mu P_L - \gamma^\rho (\phi_t^\dagger + \phi_t^\gamma) \gamma^\mu \gamma^\rho C_{\lambda} P_L + 2 m_{u_{uH}}^2 \gamma^\mu C_0 (p_t^\dagger, p_t, m_{u_{uH}}, M_{A_{H}}, m_{u_{uH}}) P_L \\
+ \gamma^\mu [2 B_1 P_R + B_0 + (m_t^2 + m_{u_{uH}}^2 - M_{A_{H}}^2) \frac{\partial}{\partial p_t^\alpha} B_0 (-p_t, m_{u_{uH}}, M_{A_{H}}) - P_L] \} \\
\tag{26}
\]

\[
\dot{\Gamma}_{u_{uZ_H}} = \frac{g^2 g_s T_{a} (V_{Hu})_{i3} (V_{Hu})_{i3} i}{4} \frac{i}{16\pi^2} \{ 2 \gamma^\sigma \gamma^\mu \gamma^\lambda C_{\lambda\sigma} P_L \\
+ 2 \gamma^\mu P_L - \gamma^\rho (\phi_t^\dagger + \phi_t^\gamma) \gamma^\mu \gamma^\rho C_{\lambda} P_L + 2 m_{u_{uH}}^2 \gamma^\mu C_0 (p_t^\dagger, p_t, m_{u_{uH}}, M_{Z_{H}}, m_{u_{uH}}) P_L \\
+ \gamma^\mu [2 B_1 P_R + B_0 + (m_t^2 + m_{u_{uH}}^2 - M_{Z_{H}}^2) \frac{\partial}{\partial p_t^\alpha} B_0 (-p_t, m_{u_{uH}}, M_{Z_{H}}) - P_L] \} \\
\tag{27}
\]

\[
\dot{\Gamma}_{d_{W_H}} = \frac{g^2 g_s T_{a} (V_{Hu})_{i3} (V_{Hu})_{i3} i}{2} \frac{i}{16\pi^2} \{ 2 \gamma^\sigma \gamma^\mu \gamma^\lambda C_{\lambda\sigma} P_L \\
+ 2 \gamma^\mu P_L - \gamma^\rho (\phi_t^\dagger + \phi_t^\gamma) \gamma^\mu \gamma^\rho C_{\lambda} P_L + 2 m_{d_{W_H}}^2 \gamma^\mu C_0 (p_t^\dagger, p_t, m_{d_{W_H}}, m_{d_{W_H}}) P_L \\
+ \gamma^\mu [2 B_1 P_R + B_0 + (m_t^2 + m_{d_{W_H}}^2 - M_{W_H}^2) \frac{\partial}{\partial p_t^\alpha} B_0 (-p_t, m_{d_{W_H}}, M_{W_H}) - P_L] \} \\
\tag{28}
\]

\[
\dot{\Gamma}_{T-A_{H}} = \frac{4 g^2 g_s T_{a} i}{25} \frac{i}{16\pi^2} \{ 2 \gamma^\sigma \gamma^\mu \gamma^\lambda x_{L} C_{\lambda\sigma} P_R + 2 x_{L} \gamma^\mu P_R + 2 \gamma^\sigma \gamma^\mu (\phi_t^\dagger + \phi_t^\gamma) x_{L} C_{\lambda}(p_t^\dagger, p_t, m_{T-}, M_{A_{H}}, m_{T-}) P_R \\
- 8 m_{T-} x_{L} \sqrt{x_{L} v} \frac{v}{f} C^{\mu} - 4 (\phi_t^\dagger + \phi_t^\gamma) m_{T-} x_{L} \sqrt{x_{L} v} \frac{v}{f} C_0 + 2 m_{T-}^2 x_{L} \gamma^\mu C_{0} P_R \\
+ \gamma^\mu [2 x_{L} B_1 P_R + x_{L} B_0 + x_{L}(m_t^2 + m_{T-}^2 - M_{A_{H}}^2) \frac{\partial}{\partial p_t^\alpha} B_0 - P_L \\
- 8 x_{L} \sqrt{x_{L} v} m_{T-} \frac{\partial}{\partial p_t^\alpha} B_0 - \frac{\partial}{\partial p_t^\alpha} B_0 (-p_t, m_{T-}, M_{A_{H}}) - x_{L} P_R] \} \\
\tag{29}
\]
\[
\hat{\Gamma}^\mu_{T^+} = \frac{g^2 g_s T^\alpha_{\beta} x^2}{4 \cos^2 \theta} \int \frac{i}{f^2 16 \pi^2} \left\{ 2 \gamma^\rho \gamma^\mu C^\lambda_{\sigma} P_L + 2 \gamma^\mu P_L \\
- \gamma^\rho (\not{\pi} + \not{\phi} + \not{\rho} C^\lambda_{\sigma} P_L + 2m_{T^+}^2 + \gamma^\mu C^0 (p_L, p_t, m_{T^+}, M_T, m_{T^+}) P_L \\
+ \gamma^\mu [4B_1 P_R + 2B_0 + 2(m_t^2 + m_{T^+}^2 - m_Z^2) \frac{\partial}{\partial p_t^2} B_0 (-p_t, m_{T^+}, M_Z) - 2P_L] \right\}
\]

(II) Renormalization fermion propagator

\[
-\iota \hat{\Sigma}^f (p) = -\iota \Sigma^f (p) + (-\iota \delta \Sigma^f (p))
\]

where

\[
\Sigma^f (p) = m_f \Sigma^f_L (p^2) + \not{\pi} P_L \Sigma^f_L (p^2) + \not{\rho} P_R \Sigma^f_R (p^2)
\]

\[
\delta \Sigma^f (p) = \delta m_f \left[ \Sigma^f_L (m_f^2) + \frac{1}{2} \Sigma^f_L (m_f^2) + \frac{1}{2} \Sigma^f_R (m_f^2) \right]
\]

\[
\delta Z^f_L = Re \Sigma^f_L (m_f^2) + m_f \frac{\partial}{\partial p^2} Re [\Sigma^f_L (p^2) + \Sigma^f_R (p^2) + 2\Sigma^f_S (p^2)]_{|p^2 = m_f^2}
\]

\[
\delta Z^f_R = Re \Sigma^f_R (m_f^2) + m_f \frac{\partial}{\partial p^2} Re [\Sigma^f_L (p^2) + \Sigma^f_R (p^2) + 2\Sigma^f_S (p^2)]_{|p^2 = m_f^2}
\]

\[
\hat{\Sigma}^f = \hat{\Sigma}^f (\eta^0) + \hat{\Sigma}^f (\omega^+ \omega^0) + \hat{\Sigma}^f (\pi^0) + \hat{\Sigma}^f (h^0) + \hat{\Sigma}^f (A_H) + \hat{\Sigma}^f (Z_H) + \hat{\Sigma}^f (W^+_H) + \hat{\Sigma}^f (Z)
\]

\[
-\iota \hat{\Sigma}^{\eta_H} (p) = -\frac{g^2 (V_{H^+})_{i3} (V_{H^+})_{i3}}{100 M_{A_H}^2} \frac{i}{16 \pi^2} \left\{ m_{a_{H^+}}^2 \phi B_1 P_L + m_{a_{H^+}}^2 \phi B_1 P_R + m_{a_{H^+}}^2 B_0 (-p_t, m_{a_{H^+}}, m_{\eta}) \\
- m_{a_{H^+}}^2 B_0 + m_f \frac{\partial}{\partial p_t^2} (m_{a_{H^+}}^2 B_1 + m_f^2 B_1 + 2m_{a_{H^+}}^2 B_0) \\
- \rho P_L [m_{a_{H^+}}^2 B_1 + m_f \frac{\partial}{\partial p_t^2} (m_{a_{H^+}}^2 B_1 + m_f^2 B_1 + 2m_{a_{H^+}}^2 B_0)] \\
- \rho P_R [m_{a_{H^+}}^2 B_1 + m_f \frac{\partial}{\partial p_t^2} (m_{a_{H^+}}^2 B_1 + m_f^2 B_1 + 2m_{a_{H^+}}^2 B_0)] \right\}
\]

(31)
\[-i\tilde{\Sigma}^{\omega u_H}(p) = -\frac{g^2 (V_H u)_3 (V_H u)_3}{100 M^2_{\tilde{A}_H}} \frac{i}{16\pi^2} \]
\{m^2_{u_H} \phi_1 B_1 P_L + m^2_{u_H} \phi_1 B_1 P_R + m_t m^2_{u_H} B_0 (-p_t, m_{u_H}, m_{\omega^0}) \}
\{-m_t m^2_{u_H} B_0 + m^2_t \frac{\partial}{\partial p_t} (m^2_{u_H} B_1 + m^2_t B_1 + 2 m^2_{u_H} B_0) \}
\{-p_L m^2_{u_H} B_1 + m^2_t \frac{\partial}{\partial p_t} (m^2_{u_H} B_1 + m^2_t B_1 + 2 m^2_{u_H} B_0) \}
\{-p_R m^2_{u_H} B_1 + m^2_t \frac{\partial}{\partial p_t} (m^2_{u_H} B_1 + m^2_t B_1 + 2 m^2_{u_H} B_0) \} \}

\(-i\tilde{\Sigma}^{\omega d_H}(p) = -\frac{g^2 (V_H u)_3 (V_H u)_3}{100 M^2_{\tilde{A}_H}} \frac{i}{16\pi^2} \]
\{m^2_{d_H} \phi_1 B_1 P_L + m^2_{d_H} \phi_1 B_1 P_R + m_t m^2_{d_H} B_0 (-p_t, m_{d_H}, m_{\omega^0}) \}
\{-m_t m^2_{d_H} B_0 + m^2_t \frac{\partial}{\partial p_t} (m^2_{d_H} B_1 + m^2_t B_1 + 2 m^2_{d_H} B_0) \}
\{-p_L m^2_{d_H} B_1 + m^2_t \frac{\partial}{\partial p_t} (m^2_{d_H} B_1 + m^2_t B_1 + 2 m^2_{d_H} B_0) \}
\{-p_R m^2_{d_H} B_1 + m^2_t \frac{\partial}{\partial p_t} (m^2_{d_H} B_1 + m^2_t B_1 + 2 m^2_{d_H} B_0) \} \}

\(-i\tilde{\Sigma}^{\eta T^-}(p) = -\frac{2g^2 m t f}{5 M_{A_H} v} \frac{i}{16\pi^2} [1 - \frac{v^2}{f^2} \frac{x}{2} + \frac{1}{6}] [\phi_1 B_1 P_R \]
\{m^2_t \frac{\partial}{\partial p_t} B_1 - \phi_1 P_L m^2_t \frac{\partial}{\partial p_t} B_1 - \phi_1 P_R (B_1 + m^2_t \frac{\partial}{\partial p_t} B_1) (-p_t, m_{T^-}, m_{\eta}) \}

\(-i\tilde{\Sigma}^{\omega_0 T^-}(p) = -\frac{g m t f}{2 M_{Z_H} v} \frac{i}{16\pi^2} \]
\{\phi_1 B_1 P_R + m^2_t \frac{\partial}{\partial p_t} B_1 - \phi_1 P_L m^2_t \frac{\partial}{\partial p_t} B_1 - \phi_1 P_R B_1 (-p_t, m_{T^-}, m_{\omega_0}) \}

\(-i\tilde{\Sigma}^{\pi_0 T^+}(p) = -\frac{g^2 x^2 v^2}{4 M^2_2 \cos^2 \theta f^2} \frac{i}{16\pi^2} \]
\{m^2_{\pi^+} \phi_1 B_1 P_L + m^2_{\pi^+} \phi_1 B_1 P_R + m_t m^2_{\pi^+} B_0 (-p_t, m_{T^+}, m_{\pi^0}) \}
\{-m_t m^2_{\pi^+} B_0 + m^2_t \frac{\partial}{\partial p_t} (m^2_{\pi^+} B_1 + m^2_t B_1 + 2 m^2_{\pi^+} B_0) \}
\{-p_L m^2_{\pi^+} B_1 + m^2_t \frac{\partial}{\partial p_t} (m^2_{\pi^+} B_1 + m^2_t B_1 + 2 m^2_{\pi^+} B_0) \}
\{-p_R m^2_{\pi^+} B_1 + m^2_t \frac{\partial}{\partial p_t} (m^2_{\pi^+} B_1 + m^2_t B_1 + 2 m^2_{\pi^+} B_0) \} \}

(34)

(35)

(36)
\[-i\hat{\Sigma}^{HT^+}(p) = m_1^2 \frac{i}{16\pi^2} \left( \frac{x_L}{(1 - x_L)^2} \right) \phi_L B_I P_L - \frac{(1 - x_L)^2}{f^2} \phi_R B_I P_R \]
\[-s\lambda\sqrt{x_L m_{T^+}} \frac{B_0}{f v} + s\lambda\sqrt{x_L m_{T^+}} \frac{B_0}{f v} (-p_t, m_{T^+}, m_h) \]
\[+m_t \frac{\partial}{\partial p_t^2} \frac{x_L m_t^2}{(1 - x_L)^2} B_I - \frac{(1 - x_L)^2 m_t^2}{f^2} B_I - \frac{2s\lambda\sqrt{x_L m_{T^+} + m_t}}{f v} B_0 \]
\[-\phi_L P_L \frac{x_L}{(1 - x_L)^2} B_I + \frac{\partial}{\partial p_t^2} \frac{x_L m_t^2}{(1 - x_L)^2} B_I - \frac{(1 - x_L)^2 m_t^2}{f^2} B_I - \frac{2s\lambda\sqrt{x_L m_{T^+} + m_t}}{f v} B_0 \]
\[-\phi_R P_R \frac{x_L}{(1 - x_L)^2} B_I + \frac{\partial}{\partial p_t^2} \frac{x_L m_t^2}{(1 - x_L)^2} B_I - \frac{(1 - x_L)^2 m_t^2}{f^2} B_I - \frac{2s\lambda\sqrt{x_L m_{T^+} + m_t}}{f v} B_0 \] (37)

\[-i\hat{\Sigma}^h u (p) = -\frac{g^2 (V_{Hu})_3 (V_{Hu})_3}{100} \frac{i}{16\pi^2} [2\phi_t (B_1 + \frac{1}{2}) P_L \]
\[+2m_3 \frac{\partial}{\partial p_t^2} B_1 - \quad 2G_m P_L (B_1 + \frac{1}{2} + m_3 \frac{\partial}{\partial p_t^2} B_1) - 2G_m P_R m_3 \frac{\partial}{\partial p_t^2} B_1 (-p_t, m_{uH}, M_{Au}) ] (38)\]

\[-i\hat{\Sigma}^h u (p) = -\frac{g^2 (V_{Hu})_3 (V_{Hu})_3}{4} \frac{i}{16\pi^2} [2\phi_t (B_1 + \frac{1}{2}) P_L \]
\[+2m_3 \frac{\partial}{\partial p_t^2} B_1 - \quad 2G_m P_L (B_1 + \frac{1}{2} + m_3 \frac{\partial}{\partial p_t^2} B_1) - 2G_m P_R m_3 \frac{\partial}{\partial p_t^2} B_1 (-p_t, m_{uH}, M_{Zu}) ] (39)\]

\[-i\hat{\Sigma}^W (p) = -\frac{g^2 x_L^2 v^2}{4\cos^2 \theta f^2 16\pi^2} \frac{i}{2} [2\phi_t (B_1 + \frac{1}{2}) P_L \]
\[+2m_3 \frac{\partial}{\partial p_t^2} B_1 - \quad 2G_m P_L (B_1 + \frac{1}{2} + m_3 \frac{\partial}{\partial p_t^2} B_1) - 2G_m P_R m_3 \frac{\partial}{\partial p_t^2} B_1 (-p_t, m_{T^+}, M_{Z}) ] (40)\]

\[-i\hat{\Sigma}^{ZT^+}(p) = -\frac{4g^2 x_L^2 v^2}{25} \frac{i}{16\pi^2} [2x_L \frac{v^2}{f^2} \phi_t (B_1 + \frac{1}{2}) P_L + 2x_L \phi_t (B_1 + \frac{1}{2}) P_R \]
\[+2m_3 \frac{\partial}{\partial p_t^2} \frac{x_L^2 v^2}{f^2} B_1 + x_L B_1 + 4x_L \sqrt{x_L} \frac{v m_{T^-}}{f} B_0 (-p_t, m_{T^-}, M_{Au}) ] \]
\[-2G_m P_L \frac{x_L^2 v^2}{f^2} (B_1 + \frac{1}{2}) + m_3 \frac{\partial}{\partial p_t^2} (x_L^2 \frac{v^2}{f^2} B_1 + x_L B_1 + 4x_L \sqrt{x_L} \frac{v m_{T^-}}{f} B_0 ) \]
\[-2G_m P_R \frac{x_L^2 v^2}{f^2} (B_1 + \frac{1}{2}) + m_3 \frac{\partial}{\partial p_t^2} (x_L^2 \frac{v^2}{f^2} B_1 + x_L B_1 + 4x_L \sqrt{x_L} \frac{v m_{T^-}}{f} B_0 ) ] (42)\]
[1] G. Stricker et al., CDF note 9724 (2009); T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 101: 202001 (2008); V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 100: 142002 (2008).

[2] A. Djouadi, G. Moreau, F. Richard, R.K. Singh, Phys. Rev. D 82: 071702 (2010); S. Jung, H. Murayama, A. Pierce, J.D. Wells, Phys. Rev. D 81: 015004 (2010); J. Shu, T. M. P. Tait, K. Wang, Phys. Rev. D 81: 034012 (2010); A. Arhrib, R. Benbrik and C. H. Chen, Phys. Rev. D82: 034034 (2010); D. W. Jung, P. Ko, J. S. Lee and S. h. Nam, Phys. Lett. B 691: 238 (2010); I. Dorsner, S. Fajfer, J.F. Kamenik, N. Kosnik, Phys. Rev. D 81: 055009 (2010); V. Barger, W.-Y. Keung, C.-T. Yu, Phys. Rev. D 81: 113009 (2010); C. H. Chen, G. Cvetic and C. S. Kim, Phys. Lett. B 694: 393-397 (2011); J. A. Aguilar-Saavedra, Nucl. Phys. B 843: 638 (2011); C. Degrande, et al., JHEP 1103: 125 (2011); B. Xiao, Y. K. Wang, S.H. Zhu, Phys. Rev. D 82: 034026 (2010); J. Cao, Z. Heng, L. Wu, J. M. Yang, Phys. Rev. D 81: 014016 (2010); P. H. Frampton, J. Shu and K. Wang, Phys. Lett. B 683: 294-297 (2010); R. S. Chivukula, E. H. Simmons, C.-P. Yuan, Phys. Rev. D 82: 094009 (2010); Junjie Cao, Lin Wang, Lei Wu, Jin Min Yang, Phys. Rev. D 84: 074001 (2011); Cédric Delaunay et al., Phys.Lett.B 703:486-490 (2011); Kfir Blume et al., Phys.Lett.B 702:364-369 (2011); Cédric Delaunay et al.,JHEP 1108:031(2011); Leandro Da Rold, Cédric Delaunay, Christophe Grojean, Gilad Perez,JHEP 1302:149 (2013).

[3] W. Bernreuther, J. Phys. G 35: 083001 (2008) D. Chakraborty, J. Konigsberg, D. Rainwater, Ann. Rev. Nucl. Part. Sci. 53: 301 (2003); E. H. Simmons, hep-ph/0211335; C.-P. Yuan, hep-ph/0203088; S. Willenbrock, hep-ph/0211067; M. Beneke, et al., hep-ph/0003033; T. Han, arXiv:0804.3178; C. T. Hill and S. J. Parke, Phys. Rev. D 49: 4454 (1994); K. Whisnant, J.M. Yang, B.L.Young, X. Zhang, Phys. Rev. D 56: 467 (1997); J. M. Yang, B.-L. Young, Phys. Rev. D 56: 5907 (1997); K.I. Hikasa, K. Whisnant, J.M. Yang, B.L. Young, Phys. Rev. D 58: 114003 (1998); R.A. Coimbra, et al., Phys. Rev. D 79: 014006 (2009); Jin-Yan Liu, Zong-Guo Si, Chong-Xing Yue, Phys. Rev. D 81: 015011 (2010).

[4] N. Arkani-Hamed, A. G. Cohen, and H. Georgi, Phys. Lett. B 513: 232 (2001); N. Arkani-Hamed, et al., JHEP 0208: 020 (2002); JHEP 0208: 021 (2002); I. Low, W. Skiba, and D.
Smith, Phys. Rev. D 66: 072001 (2002); D. E. Kaplan and M. Schmaltz, JHEP 0310: 039 (2003).

[5] N. Arkani-Hamed, A. G. Cohen, E. Katz, and A. E. Nelson, JHEP 0207: 034 (2002); S. Chang, JHEP 0312: 057 (2003); T. Han, H. E. Logan, B. McElrath, and L. T. Wang, Phys. Rev. D 67: 095004 (2003); M. Schmaltz and D. Tucker-smith, Ann. Rev. Nucl. Part. Sci. 55: 229 (2005).

[6] C. Csaki, J. Hubisz, G. D. Kribs, P. Meade, J. Terning, Phys. Rev. D 67: 115002 (2003); Phys. Rev. D 68: 035009 (2003); J. L. Hewett, F. J. Petriello, and T. G. Rizzo, JHEP 0310: 062 (2003); M. C. Chen and S. Dawson, Phys. Rev. D 70: 015003 (2004); M. C. Chen, et al., Mod. Phys. Lett. A 21: 621 (2006); W. Kilian, J. Reuter, Phys. Rev. D 70: 015004 (2004).

[7] G. Marandella, C. Schappacher and A. Strumia, Phys. Rev. D 72: 035014 (2005).

[8] H. C. Cheng and I. Low, JHEP 0309: 051 (2003); JHEP 0408: 061 (2004); I. Low, JHEP 0410: 067 (2004); J. Hubisz and P. Meade, Phys. Rev. D 71: 035016 (2005).

[9] J. H. Kuhn, Nucl. Phys. B 237: 77 (1984); V. D. Barger, J. Ohnemus and R. J. N. Phillips, Int. J. Mod. Phys. A 4: 617 (1989); G. Mahlon and S. J. Parke, Phys. Lett. B 411: 173 (1997); Phys. Rev. D 53: 4886 (1996); Phys. Rev. D 81: 074024 (2010); T. Stelzer and S. Willenbrock, Phys. Lett. B 374: 169 (1996); Bernreuther, W., Brandenburg, A., Si, Z.G., Uwer, P., Phys. Rev. Lett. 87: 242002 (2001); W. Bernreuther and Z. G. Si, Nucl. Phys. B 837: 90 (2010); G. Mahlon, arXiv:1007.1716 [hep-ph].

[10] K. Cheung, Phys. Rev. D 55: 4430 (1997); B. Holdom and T. Torma, Phys. Rev. D 60: 114010 (1999); M. Arai, N. Okada, K. Smolek, V. Simak, Phys. Rev. D 70: 115015 (2004); M. Arai, N. Okada, K. Smolek, V. Simak, Phys. Rev. D 75: 095008 (2007); Acta Phys. Polon. B 40: 93 (2009); M. Arai, N. Okada and K. Smolek, Phys. Rev. D 79: 074019 (2009); C. Yue, T. T. Zhang and J. Y. Liu, J. Phys. G 37: 075016 (2010); Chengcheng Han, Ning Liu, Lei Wu, Jun Min Yang, Phys. Lett. B 714: 295-300 (2012); Lei Wang, Lei Wu, Jun Min Yang, Phys. Rev. D 85: 075017 (2012); Junjie Cao, Lei Wu, Jun Min Yang, Phys. Rev. D 85: 014025 (2012); Chengcheng Han, Ning Liu, Lei Wu, Jun Min Yang, Phys. Lett. B 714: 295-300 (2012); Ning Liu, Lei Wu, Commun. Theor. Phys. 55: 296-302 (2011).

[11] Jay Hubisz, Seung J. Lee, Gil Paz, JHEP 0606: 041 (2006); M. Blanke, et al., Phys. Lett.
B 646: 253 (2007).

[12] M. Blanke, et al., Phys. Lett. B 646: 253 (2007); M. Blanke, et al., JHEP 0701: 066 (2007).

[13] H. L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin, C. P. Yuan, Phys. Rev. D 82: 074024 (2010).

[14] K. Nakamura et al. (Particle Data Group), J. Phys. G 37: 075021 (2010).

[15] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716:1-29 (2012); S. Chatrchyan et al. [CMS Collaboration], CMS-HIG-12-028, arXiv:1207.7235.

[16] M. Blanke, et al., JHEP 0705: 013 (2007).

[17] CMS Collaboration, arXiv:1203.5410.

[18] ATLAS Collaboration, arXiv:1210.5468.

[19] J. Hubisz, P. Meade, A. Noble, and M. Perelstein, J. High Energy Phys. 0601: 135 (2006); A. Belyaev, C.-R. Chen, K. Tobe, and C. P. Yuan, Phys. Rev. D 74: 115020 (2006); Q.-H. Cao and C.-R. Chen, Phys. Rev. D 76: 075007 (2007); Luca Fiorini, ATL-PHYS-PROC-2012-029, arXiv:1201.5844.

[20] CMS Collaboration, Phys. Lett. B 709: 28-49 (2012); The ATLAS Collaboration, Eur. Phys. J. C 72: 2039 (2012).

[21] J. H. Kuhn, G. Rodrigo, Phys. Rev. D 59: 054017 (1999); M. T. Bowen, S. D. Ellis and D. Rainwater, Phys. Rev. D 73: 014008 (2006); V. Ahrens et al., JHEP 1009: 097 (2010); N. Kidonakis, Phys. Rev. D 84: 011504 (2011); W. Hollik and D. Pagani, Phys. Rev. D 84: 093003 (2011).

[22] C. Kao and D. Wackeroth, Phys. Rev. D 61: 055009 (2000); K.I. Hikasa, J.M. Yang, B.L. Young, Phys. Rev. D 60: 114041 (1999); P. Y. Li, et al., Eur. Phys. J. C 51: 163 (2007); David Krohn, Tao Liu, Jessie Shelton, Lian-Tao Wang, Phys. Rev. D 84: 074034 (2011).

[23] Qing-Hong Cao, Chuan-Ren Chen, F. Larios, C.-P. Yuan, Phys. Rev. D 79: 015004 (2009).

[24] Johann H. Kuhn, German Rodrigo, arXiv:1109.6830.

[25] http://www-cdf.fnal.gov/physics/new/top/2011/AfbComb/

[26] T. Aaltonen, et al, CDF Collaboration, Phys. Rev. Lett. 101: 202001 (2008).

[27] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP12004; https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-117/.

24
[28] F. Hubaut, et al., Eur. Phys. J. C 44: 13 (2005).

[29] C. Kao and D. Wackeroth, Phys. Rev. D 61: 055009 (2000).

[30] Junjie Cao, Lei Wu, Jin Min Yang, Phys. Rev. D 83: 034024 (2011).

[31] W. F. L. Hollik, Fortschr. Phys. 38: 165-260(1990); A. Denner, Fortschr. Phys. 41: 307-420 (1993).