Probing $Zt\bar{t}$ couplings using $Z$ boson polarization in $ZZ$ production at hadron colliders

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We propose to utilize the polarization information of the $Z$ bosons in $ZZ$ production, via the gluon-gluon fusion process $gg \to ZZ$, to probe the $Zt\bar{t}$ gauge coupling. The contribution of longitudinally polarized $Z$ bosons is sensitive to the axial-vector component ($a_t$) of the $Zt\bar{t}$ coupling. We demonstrate that the angular distribution of the charged lepton from $Z$ boson decays serves well for measuring the polarization of $Z$ bosons and the determination of $a_t$. We show that $ZZ$ production via the $gg \to ZZ$ process complement to $Zt\bar{t}$ and $tZj$ productions in measuring the $Zt\bar{t}$ coupling at hadron colliders.

1. Introduction.

Top quark, the heaviest fermion in the Standard Model (SM), is commonly believed to be sensitive to new physics (NP) beyond the SM. The top quark often plays a key role in triggering electroweak symmetry breaking (EWSB) in many NP models, and as a result, the gauge couplings of top quarks, e.g. $Wtb$ and $Zt\bar{t}$, may largely deviate from the SM predictions [1–5]. The $Wtb$ couplings have been well measured in both the single top quark production and the top-quark decay [6–17]. The $Zt\bar{t}$ couplings can be measured in $t\bar{t}Z$ and $tjZ$ productions [18–22], which are, unfortunately, difficult to separately determine the vector and axial-vector components of the $Zt\bar{t}$ coupling. The chiral structure of the $Zt\bar{t}$ coupling would reveal the gauge structure of NP models [20–23], therefore, measuring and distinguishing the vector and axial vector components of the $Zt\bar{t}$ coupling is in order.

In this work we explore the potential of measuring the $Zt\bar{t}$ coupling using the polarization information of the $Z$ bosons in $ZZ$ production, at the CERN Large Hadron Collider (LHC). The $Zt\bar{t}$ coupling contributes to $ZZ$ production through top-quark loop effects in the gluon fusion channel. The process, $gg \to ZZ$, has been used to constrain the Higgs boson width through the interference of box and triangle diagrams and it has been shown to be sensitive to many NP effects [24–57]. In particular, the polarization of the $Z$ boson pair highly depends on the $Zt\bar{t}$ coupling. The polarizations of $Z$ bosons in $ZZ$ pair production can be categorized as: TT (transverse-transverse), TL (transverse-longitudinal), and LL (longitudinal-longitudinal). Figure 1 shows the fraction of the three polarization modes of $ZZ$ pairs in the processes of $gg \to ZZ$ (red) and $q\bar{q} \to ZZ$ (blue) at the 13 TeV LHC. The TT mode dominates in both production processes as a result of that, owing to the Goldstone boson equivalence theorem, the interaction of the longitudinal mode to light quarks is highly suppressed by the small mass of the light quarks. The suppression of the LL mode in the $gg \to ZZ$ channel arises from the cancellation between the box and triangle diagrams due to unitarity, and the cancellation is sensitive to the axial-vector coupling of $Zt\bar{t}$ [38]. In the high energy limit, the contribution of top-quark loops to the LL mode is given by

$$M_{+/+,0,0} \sim \frac{m_t^2}{m_Z^2} \left( a_t^2 - \frac{1}{4} \right) \left[ \log^2 \left( \frac{\delta}{m_t^2} \right) - 2i\pi \log \left( \frac{\delta}{m_t^2} \right) \right],$$

(1)

where $a_t$ is the axial-vector component of the $Zt\bar{t}$ coupling, $m_t$ and $m_Z$ denotes the mass of the top quark and $Z$ boson, respectively. The subscript +, − and 0 denote the right-handed, left-handed and longitudinal polarization of the gluons or $Z$ bosons, respectively. In the SM, $a_t = 1/2$, and it yields a strong cancellation in the LL mode scattering. However, in the NP model the value of $a_t$ can deviate from its SM value, so that the above-mentioned cancellation is spoiled and the
fraction of the LL mode contribution would be enhanced. Therefore, the polarization information of the Z boson pairs in ZZ production, via $gg \rightarrow ZZ$, can be used to probe the axial-vector coupling of $Zt\bar{t}$ interaction at hadron colliders.

2. ZZ production via Gluon fusion.

Here, we consider the case that the NP effects modify only the four-dimensional $Zt\bar{t}$ coupling. The effective Lagrangian of the $Zt\bar{t}$ interaction is

\[
\mathcal{L} = \frac{g_W}{2c_W} \bar{t}(v_t - a_t\gamma_5)\gamma^\mu t,
\]

where $g_W$ is the electroweak gauge coupling and $c_W$ is the cosine of the weak mixing angle $\theta_W$. In the SM,

\[
v_t^{\text{SM}} = \frac{1}{2} - \frac{2}{3}s_W^2 = 0.3526, \quad a_t^{\text{SM}} = \frac{1}{2},
\]

where $s_W \equiv \sin \theta_W$. We calculate the helicity amplitudes of the channel $g(\lambda_1)g(\lambda_2) \rightarrow Z(\lambda_3)Z(\lambda_4)$ using FeynArts and FeynCalc \cite{Seymour:2000hs, Jetzer:1999iz} where $\lambda_i$ labels the helicity of particle $i$. The contribution of the box diagram (□) to each helicity amplitude can be parametrized as \cite{FNLSYM3, FNLSYM4},

\[
M_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} = \left( v_t^2 + a_t^2 \right) A_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} + \left( v_t^2 - a_t^2 \right) B_{\lambda_1,\lambda_2,\lambda_3,\lambda_4} + a_t^2 C_{\lambda_1,\lambda_2,\lambda_3,\lambda_4},
\]

where $\lambda_i = \pm$ and 0. Both $B_{\lambda_1,\lambda_2,\lambda_3,\lambda_4}$ and $C_{\lambda_1,\lambda_2,\lambda_3,\lambda_4}$ vanish for (massless) light quark loops. In the limit of $\hat{s} = -\hat{t}/2 = -\hat{u}/2 \gg m_t$, where $\hat{s}, \hat{t}$ and $\hat{u}$ are the usual Mandelstam variables, the coefficients $A, B$ and $C$ are

\[
A \sim \text{Constant}, \quad B \sim 0,
\]

\[
C_{\pm,0,0} \sim -\frac{m_t^2}{m_Z^2} \left[ \log^2 \left( \frac{\hat{s}}{m_t^2} \right) - 2\pi \log \left( \frac{\hat{s}}{m_t^2} \right) \right].
\]

Here, the constant in the coefficient $A$ is a combination of gauge couplings and loop factor. Furthermore, The contribution of the triangle diagram (△) to each helicity amplitude is

\[
M_{\pm,\pm,0,0} \sim -\frac{m_t^2}{4m_Z^2} \left[ \log^2 \left( \frac{\hat{s}}{m_t^2} \right) - 2\pi \log \left( \frac{\hat{s}}{m_t^2} \right) \right],
\]

which cancels with the coefficient $C$ in the contribution of the box diagram $M^{\pm\pm}$ for each helicity amplitude. The sensitivity of the cancellation on $a_t$ can be understood from the fact that the axial current is not conserved for the top quark, whose mass is at the weak scale.

Below, we consider the impact of the non-standard $Zt\bar{t}$ coupling to the differential cross sections of $gg \rightarrow ZZ$ by changing only one parameter at a time. Define $\delta v_t$ and $\delta a_t$ as the amount of deviation of the vector and axial-vector couplings from the SM values, i.e.,

\[
\delta v_t = v_t - v_t^{\text{SM}}, \quad \delta a_t = a_t - a_t^{\text{SM}}.
\]

Figure 2(a) shows the differential cross sections of $gg \rightarrow ZZ$, normalized to the SM prediction, as a function of $m_{ZZ}$ at the 13 TeV LHC; the polarization fraction of the LL mode (b) and the TT mode (c).
their fractions in the SM; cf. the blue and black curves. Therefore, the polarization information of the $Z$ bosons in $ZZ$ production can be utilized to provide a good probe of the anomalous $a_t$ coupling.

The polarization information of the final state $Z$ boson can be inferred from the angular distribution ($\cos \theta$) of the charged lepton in the rest frame of the $Z$ boson from which the charged lepton is emitted. The angular distributions for various polarization states of the $Z$ boson are given as

$$
\phi_L(\cos \theta) = \frac{3}{4}(1-\cos^2 \theta), \quad \phi_T(\cos \theta) = \frac{3}{8}(1+\cos^2 \theta),
$$

where $\phi_L$ denotes a longitudinally polarized $Z$ boson, and $\phi_T$ a transversely polarized $Z$. The angle $\theta$ is defined as the opening angle between the charged lepton three-momentum in the rest frame of the $Z$-boson and the $Z$-boson three-momentum in the center of mass frame of the $ZZ$ pair.

To determine the value of $a_t$, we compare the angular distributions ($\cos \theta$) predicted by the Monte Carlo (MC) simulation to the theory template obtained by the analytical calculation. The theory template of $\cos \theta$ distribution, of the processes $gg, q\bar{q} \rightarrow ZZ \rightarrow 4\ell$ with $\ell = e^+, \mu^+$, is approximated by multiplying the fraction of each polarization mode of the $ZZ$ boson pair with the corresponding $\phi_{L,T}$ distributions. Though the spin correlation between the two final-state $Z$ bosons is not strictly maintained in this approximation, the prediction of the theory template (solid curves) on the $\cos \theta$ distribution, via either the $q\bar{q}$ or $gg$ scattering process, in the SM agrees very well with that obtained by the MC simulation (dashed curves), as clearly shown in Figure 3 without imposing any kinematic cut.

3. Collider simulation.

Next we perform a detailed Monte Carlo simulation to explore the potential of probing $a_t$ via the signal process $gg \rightarrow ZZ \rightarrow 4\ell$ at the 13 TeV LHC and a 100 TeV proton-proton (pp) hadron collider. Its major background comes from the process $q\bar{q} \rightarrow ZZ$, while the other backgrounds are negligible [41]. We generate both the signal and background events by MadGraph5 [42] at the parton-level and pass events to PYTHIA [43] for showering and hadronization. The Delphes package is used to simulate the detector smearing effects [44]. The QCD corrections are taken into account by introducing a constant $\kappa$ factor, i.e. $\kappa_{gg} = 1.8$ and $\kappa_{q\bar{q}} = 1.7$ [45–50]. At the analysis level, both the signal and background events are required to pass the kinematic cuts: $|\eta_\ell| < 2.5$ and $P_{T\ell} > 15$ GeV. We further require the invariant mass window cut for same flavor leptons as $80 < m_{4\ell} < 100$ GeV and demand $m_{4\ell} > 600$ GeV to enhance the LL mode.

The kinematic cuts inevitably modify the lepton kinematics and the polarization fractions of the $ZZ$ bosons. Figure 4(a) displays the $\cos \theta$ distribution after imposing the kinematic cuts for the processes $gg \rightarrow ZZ$ (black) and $q\bar{q} \rightarrow ZZ$ (red). The shapes of the $\cos \theta$ distributions of the theory template agree with those of the MC simulation except near the edge region. Focusing
on the central region with $|\cos \theta| < 0.8$, we plot the ratio between the normalized theory template and the MC simulation in Fig [4(b)], which shows good agreements between the two calculations.

The total event number of the signal ($N_s$) and background ($N_b$) processes are

$$N_s = \sigma(gg \to ZZ) \times 4B^2 \times \epsilon_{\text{cut}}^g \times L_{\text{int}},$$

$$N_b = \sigma(q\bar{q} \to ZZ) \times 4B^2 \times \epsilon_{\text{cut}}^q \times L_{\text{int}},$$

(9)

where $\epsilon_{\text{cut}}^g$ is the cut efficiency for the signal and background process, respectively. $L_{\text{int}}$ is the integrated luminosity, and

$$\text{Br} \equiv \text{Br}(Z \to e^+e^-) = \text{Br}(Z \to \mu^+\mu^-).$$

(10)

In the SM (with $\delta v_t = \delta a_t = 0$), the total cross section of the signal ($\sigma_s$) and background ($\sigma_b$) processes are,

$$\sigma_s = \sigma(gg \to ZZ) \times 4B^2 \times \epsilon_{\text{cut}}^g \simeq 0.032 \text{ fb},$$

$$\sigma_b = \sigma(q\bar{q} \to ZZ) \times 4B^2 \times \epsilon_{\text{cut}}^q \simeq 0.2 \text{ fb}$$

(11)

at the 13 TeV LHC, while at a 100 TeV pp collider

$$\sigma_s = \sigma(gg \to ZZ) \times 4B^2 \times \epsilon_{\text{cut}}^g \simeq 1.26 \text{ fb},$$

$$\sigma_b = \sigma(q\bar{q} \to ZZ) \times 4B^2 \times \epsilon_{\text{cut}}^q \simeq 1.72 \text{ fb}.$$  

(12)

There are roughly about 700 and 9000 events of $ZZ$ pairs produced at the 13 TeV LHC and a 100 TeV pp collider with an integrated luminosity of 3000 fb$^{-1}$.

For probing the $Zt\bar{t}$ coupling, we divide the $|\cos \theta|$ distribution into 8 bins and use the binned likelihood function to estimate the sensitivity for the hypothesis of NP with non-vanishing $(\delta v_t, \delta a_t)$ versus the hypothesis of SM at the $q$-sigma ($q\sigma$) level.

$$F^{q,q}_{N,s,b} \int_{-0.8}^{0.8} d\cos \theta \left[ R_L^{q,q} \phi_L + (1 - R_L^{q,q})\phi_T \right] = 1.$$  

(14)

Explicitly,$$F^{q,q}_{N,s,b} = 1/(0.728 + 0.216R_L^{q,q}).$$

Define the likelihood function ratio as following,

$$q^2 = -2\frac{L(\delta v_t, \delta a_t)}{L(0,0)},$$

(15)

which describes the exclusion of the hypothesis of NP with non-zero $(\delta v_t, \delta a_t)$ versus the hypothesis of SM at the $q$-sigma ($q\sigma$) level.

Figure [4] displays the projected regions of the parameter space in which $(\delta v_t, \delta a_t)$ can be measured at the $2\sigma$ level, at the 13 TeV LHC and a 100 TeV pp hadron collider with an integrated luminosity of 3000 fb$^{-1}$. The cyan and gray regions denote the constraints provided by the measurement of $tZj$ [52, 53] and $Zt\bar{t}$ [54, 55] productions at the 13 TeV LHC, respectively. The horizontal black line represents the upper limit of $\delta a_t$ derived from the strength of the off-shell Higgs-boson signal in $ZZ$ production [41]. The purple region denotes the projected parameter space obtained from measuring the degree of polarization of the $Z$ bosons in $gg \to ZZ$ production, at the $2\sigma$ level, at the 13 TeV LHC, while the orange region is the projected parameter space for a 100 TeV pp collider.

It is evident that the measurement of $Zt\bar{t}$ production, as compared to $ZZ$ and $tZj$ productions, yields the strongest constraint on values of $\delta v_t$ and $\delta a_t$ at the 13 TeV LHC. However, the drawback of this measurement is that the bounded region contains a degeneracy of $\delta a_t$ and $\delta v_t$, i.e.,

$$0.77 \leq 3.05 (\delta a_t + 0.5)^2 + 1.71 (\delta v_t + 0.19)^2 \leq 1.14.$$  

(16)

Taking into account the $tZj$ production can partially resolve the degeneracy, found in analyzing the $Zt\bar{t}$ events. The $ZZ$ production is sensitive only to $a_t$, and it alone yields a twofold constraint $\delta a_t \in [-0.25, 0.15] \cup [-1.16, -0.75]$ at the 13 TeV LHC, and $\delta a_t \in [-0.08, 0.06] \cup [-1.00, -0.92]$ at a 100 TeV pp collider, cf. the two purple and orange regions. With a larger data sample in the future runs of the LHC and a 100 TeV pp collider, it is possible to precisely determine first the axial-vector component $a_t$, and then the vector component $v_t$ of the $Zt\bar{t}$ coupling. The measurement of $tZj$ production is particularly important for the determination of its vector component from the combined analysis. Furthermore, the results could be potentially improved if one utilizes advanced technologies such as Boosted Decision Tree or Multi-Variable Analysis [33, 56].

### 4. Summary.

We propose to measure the axial-vector component of the $Zt\bar{t}$ coupling by utilizing the polarization information of the $Z$ bosons in the process $gg \to ZZ$, at the 13 TeV LHC and a 100 TeV proton-proton collider.
When the final-state Z-bosons are both longitudinally polarized, the cross section for $gg \rightarrow ZZ$ is sensitive to the axial-vector coupling $a_t$, because the axial current is not conserved for massive top quarks. We demonstrate that the fraction of longitudinal-longitudinal (LL) mode increases with a non-vanishing anomalous coupling $a_t$, when the invariant mass of the Z-boson pair becomes larger. From the angular distribution of the charged leptons from the Z-boson decay, one can determine the polarization of the Z bosons and in turn to probe the anomalous $a_t$ coupling, regardless of the value of the vector component ($v_t$) of the $Zt\bar{t}$ coupling. By comparing the theory template and Monte Carlo simulation, we find the parameter space of $\delta a_t \equiv a_t - a_t^{SM}$ which can be probed at the $2\sigma$ level, from the measurement of $ZZ$ production at hadron colliders. It is $\delta a_t \in [-0.25, 0.15] \cup [-1.16, -0.75]$ at the 13 TeV LHC, and $\delta a_t \in [-0.08, 0.06] \cup [-1.00, -0.92]$ at a 100 TeV pp collider. We emphasize that the $ZZ$ production is complementary to the $Zt\bar{t}$ and $tZj$ productions in the measurement of the $Zt\bar{t}$ coupling.

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