

## Top quark decay in the Aligned two-Higgs-doublet Model

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### Abstract

We compute the one loop right and left anomalous tensor couplings ( $g_R$  and  $g_L$ , respectively) for the top quark, in the aligned two-Higgs-doublet model. They are the magnetic-like couplings in the most general parameterization of the  $tbW$  vertex. We find that the aligned two-Higgs doublet model, that includes as particular cases some of the most studied extensions of the Higgs sector, as Type I and II 2HDM, introduces new electroweak contributions and provides theoretical predictions that are very sensitive to both new scalar masses and the neutral scalar mixing angle. The model can account for new CP violation effects via the introduction of complex alignment parameters that have important consequences on the values for the imaginary parts of the couplings. The top anomalous tensor couplings will be measured at the LHC and at future colliders providing a complementary insight on new physics, independent from the bounds in top decays coming from B physics and  $b \rightarrow s\gamma$ .

**Keywords:** Top anomalous couplings, New physics, Two-Higgs-doublet models

For on-shell particles, the amplitude for the top quark decay can be written:

$$\mathcal{M}_{tbW} = -\frac{e}{\sin\theta_w\sqrt{2}}\epsilon^{\mu*}\bar{u}_b\left[\gamma_\mu(V_L P_L + V_R P_R) + \frac{i\sigma_{\mu\nu}q^\nu}{M_W}(g_L P_L + g_R P_R)\right]u_t \quad (1)$$

In the Standard Model (SM) the tree level anomalous couplings are  $g_R = g_L = 0$ . Recent calculations including one loop QCD and EW corrections give:  $g_R^{SM} = -(7.85+1.23i)\times 10^{-3}$  and  $g_L^{SM} = -(1.220+0.014i)\times 10^{-3}$  [1, 2]. Experimental measurements of the anomalous couplings take place both at Tevatron and the LHC. Recent publications combine ATLAS and CMS results for top helicity fractions [3, 4, 5], giving  $-0.142 \leq g_R \leq 0.023$  and  $-0.081 \leq g_L \leq 0.049$  at 95% CL [6]. Indirect bounds were obtained in Refs.[7, 8] from the  $Br(B \rightarrow X_s\gamma)$  branching ratio, measured at B factories. These results represent the strongest bounds on the

anomalous tensor couplings. In our notation, they get:  $-0.07 < Re(g_R) < 0.27$ , and  $-0.001 < Re(g_L) < 0.0003$  which is in slight tension with the predicted SM value given in Ref.[2]. The measurement of an asymmetry between the forward and backward decay fractions in the normal direction can put bounds on the value of the imaginary part of  $g_R$ :  $A_{FB}^N = 0.64P Im(g_R)$  [9]. Recent measurements made in Ref.[10] give:  $A_{FB}^N = 0.031 \pm 0.065(stat.)_{-0.031}^{+0.029}(syst.) \rightarrow Im(g_R) \subset [-0.20, 0.30]$ .

The 2HDMs extend the SM Higgs sector by adding a scalar doublet. The doublets  $\Phi_1$  and  $\Phi_2$  contain five physical degrees of freedom: two charged scalars  $H^\pm$  and three neutral scalars which must be rotated to obtain the mass eigenstates  $\varphi_i = (H, h, A) = R_{ij}(\gamma)S_j$ . In the Yukawa sector, the model allows for flavour changing neutral currents (FCNC), due to the coupling of both doublets to fermion fields through two a priori non simultaneously diagonalizable matrices. Alignment in flavour space is required to avoid tree level FCNC. Then both matrices are proportional, and therefore si-

multaneously diagonalizable:  $Y_d = \zeta_d M_d$ ,  $Y_u = \zeta_u M_u$ . The complex parameters  $\zeta_u$  and  $\zeta_d$  are called the *alignment parameters* [11]. The Yukawa lagrangian of the A2HDM can be written as:

$$\mathcal{L}_Y = \frac{e}{\sqrt{2}M_w \sin \theta_w} H^+ \bar{u} (\zeta_d V M_d P_R - \zeta_u V M_u P_L) d + \frac{e}{2M_w \sin \theta_w} \sum_{\varphi, f} \varphi_i \mathbf{y}_f^{\varphi_i} \bar{f} M_f P_R f + h.c. \quad (2)$$

where the neutral couplings are  $\mathbf{y}_d^{\varphi_i} = R_{i1} + (R_{i2} + iR_{i3})\zeta_d$  and  $\mathbf{y}_u^{\varphi_i} = R_{i1} + (R_{i2} - iR_{i3})\zeta_u^*$ . Bounds on the alignment parameters have been explored in  $B$  meson and low-energy physics in Refs.[12, 13, 14, 15], giving  $|\zeta_u| < 0.91(1.91)$  for  $m_{H^\pm} = 80(500)$  GeV, and  $|\zeta_u||\zeta_d| \lesssim 20$ , for  $m_{H^\pm} \in (80, 500)$  GeV, assuming  $|\zeta_u| < 3$ .

The contributions to the top quark anomalous tensor couplings  $g_{R,L}$  in the A2HDM have been calculated in Ref.[16]. The Feynman diagrams in the calculation are identified by naming the particles in the loop as ABC, as in Fig.1. The results depend on the alignment parameters:  $\zeta_u = \rho_u e^{i\theta_u}$  and  $\zeta_d = \rho_d e^{i\theta_d}$ , involving two modules and two complex phases; and the neutral scalars mixing angle  $\gamma$ .

We compare the new contributions from the A2HDM with the values from the EW contribution of the SM (SM- EW) to the  $g_R$  and  $g_L$  top couplings, studying the quotients:  $Q_{R,L}^{Re} \equiv Re(g_{R,L}^{A2HDM})/Re(g_{R,L}^{EW})$  and  $Q_{R,L}^{Im} \equiv Im(g_{R,L}^{A2HDM})/Im(g_{R,L}^{EW})$  for the real and imaginary part, respectively.

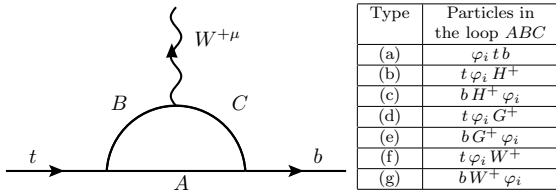


Figure 1: The  $t \rightarrow bW^+$  vertex: one loop diagrams.

We chose different scenarios for the masses of the new particles (Table 1): two with three light neutral scalars (**I** and **Ii**), two with  $h$  as the only light scalar (**II** and **IIi**) and two more with the CP-odd scalar  $A$  being the lightest one (**III** and **IIIi**). The mass  $m_H$  is chosen to be higher and lower (types **i**) than the top quark mass:

For the six different mass scenarios considered, we study how the quotients  $Q_{R,L}^{Re,Im}$  depend on the four alignment parameters  $\rho_{d,u}$ ,  $\theta_{u,d}$ , and on the mixing angle  $\gamma$ . In general, we will show the results for conservative values of the modulus, *i.e.* for  $\rho_{u,d} \sim 1$ , for greater values

Scalar mass scenarios (in GeV)				
I	$m_h = 126, m_H = 173, m_A = 150, m_{H^\pm} = 320$			
Ii	$m_h = 126, m_H = 173, m_A = 150, m_{H^\pm} = 150$			
II	$m_h = 126, m_H = 865, m_A = 865, m_{H^\pm} = 320$			
IIi	$m_h = 126, m_H = 865, m_A = 865, m_{H^\pm} = 150$			
III	$m_h = 865, m_H = 865, m_A = 126, m_{H^\pm} = 320$			
IIIi	$m_h = 865, m_H = 865, m_A = 126, m_{H^\pm} = 150$			

Table 1: Different scalar mass scenarios taken for the analysis. Each scenario is identified by a different color and type of line.

will certainly produce larger deviations from the SM-EW predictions.

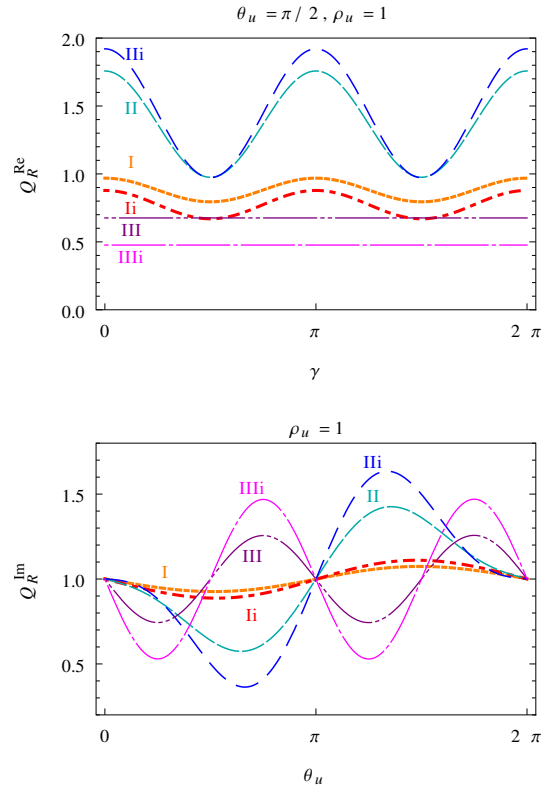


Figure 2: The right coupling  $g_R$  is very sensitive to the mixing angle  $\gamma$  and the  $\theta_u$  phase.

The right coupling  $g_R$  is very sensitive to the mixing angle  $\gamma$  and the  $\theta_u$  phase, as shown in Fig. 2. The quotient  $Q_R^{Im}$  can take values from 0.5 up to 1.5, for  $\rho_u = 1$  and for several values of  $\theta_u$ .  $Im(g_R)$  has already been measured at the LHC [10], taking advantage of the recently investigated asymmetries in the normal direction [9], and future measurements may show sensitivity to new physics. A significant deviation of this mea-

surement from the electroweak SM value would point to new CP-violation mechanisms such as the non-zero phases  $\theta_{u,d}$ .

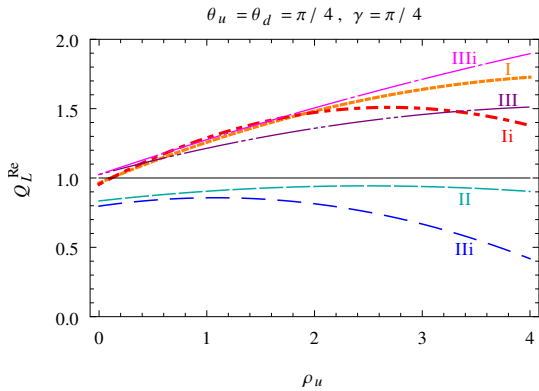


Figure 3: The current SM prediction for  $Re(g_L)$  (Ref.[2]) is below the lower bound suggested in Ref.[8]. The A2HDM can only give a positive contribution for  $\rho_u > 2$ .

For  $Re(g_L)$  there are some values of the  $\rho_u$  parameter where this magnitude can change sign with respect to the SM-EW prediction. Then, the total one loop QCD plus A2HDM prediction for this coupling is 18% lower than the SM one. Besides, this fact could produce contributions that may elucidate the tension between the indirect bounds put on  $Re(g_L)$  by  $b \rightarrow s\gamma$  decays and the SM prediction (Fig.3). The imaginary part of  $g_L$  is extremely sensitive to  $\rho_u$  and to both complex phases  $\theta_{u,d}$ . It can deviate from the SM prediction up to 400%, even for low values of the  $\rho_u$  parameter ( $\approx 1$ ).

The study of the A2HDM in this unexplored context of top quark physics shows that the precise measurement of the anomalous top couplings may allow for a discrimination among the different scalar mass scenarios and the value of the mixing angle  $\gamma$ . The measurement of the anomalous couplings (real and imaginary parts) for the top quark can also reveal new CP-violation mechanisms that can be accounted for in the A2HDM by the the complex alignment parameters  $\zeta_{u,d}$ . The observables considered in the literature, taken together with the results presented in Ref.[16] can help in finding new physics and also in restricting the range of the allowed regions of the parameter space in the A2HDM. High precision measurements of the top quark anomalous tensor couplings are expected in the next high energy runs at the LHC and in the next generation of colliders. These measurements, the flavor constraints and the collider searches for new scalar resonances are complementary insights and will illuminate this up to now almost unexplored physics.

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## References

- [1] C. S. Li, R. J. Oakes, T. C. Yuan, QCD corrections to  $t \rightarrow W^+b$ , Phys. Rev. D 43 (1991) 3759–3762. doi:10.1103/PhysRevD.43.3759.
- [2] G. A. González-Sprinberg, R. Martínez, J. Vidal, Top quark tensor couplings, JHEP 1107 (2011) 094. arXiv:1105.5601, doi:10.1007/JHEP07(2011)094.
- [3] S. Chatrchyan, et al., Measurement of the W-boson helicity in top-quark decays from  $t\bar{t}$  production in lepton+jets events in pp collisions at  $\sqrt{s} = 7$  TeV, JHEP 1310 (2013) 167. arXiv:1308.3879, doi:10.1007/JHEP10(2013)167.
- [4] Combination of the ATLAS and CMS measurements of the W-boson polarization in top-quark decays, ATLAS-CONF-2013-033, ATLAS-COM-CONF-2013-004 (2013).
- [5] Measurement of W-helicity fractions in single top events topology, CMS-PAS-TOP-12-020 (2013).
- [6] M. Fabbrichesi, M. Pinamonti, A. Tonero, Limits on anomalous top quark gauge couplings from Tevatron and LHC data, Eur.Phys.J. C74 (12) (2014) 3193. arXiv:1406.5393, doi:10.1140/epjc/s10052-014-3193-8.
- [7] B. Grzadkowski, M. Misiak, Anomalous Wtb coupling effects in the weak radiative B-meson decay, Phys. Rev. D 78 (2008) 077501. arXiv:0802.1413, doi:10.1103/PhysRevD.78.077501.
- [8] J. Drobnak, S. Fajfer, J. F. Kamenik, Probing anomalous  $tWb$  interactions with rare B decays, Nucl. Phys. B 855 (2012) 82–99. arXiv:1109.2357, doi:10.1016/j.nuclphysb.2011.10.004.
- [9] J. Aguilar-Saavedra, J. Bernabeu, W polarisation beyond helicity fractions in top quark decays, Nucl. Phys. B 840 (2010) 349–378. arXiv:1005.5382, doi:10.1016/j.nuclphysb.2010.07.012.
- [10] Search for  $C\mathcal{P}$  violation in single top quark events in  $pp$  collisions at  $\sqrt{s} = 7$  tev with the atlas detector, Tech. Rep. ATLAS-CONF-2013-032, CERN, Geneva (Mar 2013).
- [11] A. Pich, P. Tuzon, Yukawa Alignment in the Two-Higgs-Doublet Model, Phys. Rev. D 80 (2009) 091702. arXiv:0908.1554, doi:10.1103/PhysRevD.80.091702.
- [12] M. Jung, A. Pich, P. Tuzon, Charged-Higgs phenomenology in the Aligned two-Higgs-doublet model, JHEP 1011 (2010) 003. arXiv:1006.0470, doi:10.1007/JHEP11(2010)003.
- [13] A. Celis, M. Jung, X.-Q. Li, A. Pich, Sensitivity to charged scalars in  $B \rightarrow D^{(*)}\tau\nu_\tau$  and  $B \rightarrow \tau\nu_\tau$  decays, JHEP 1301 (2013) 054. arXiv:1210.8443, doi:10.1007/JHEP01(2013)054.
- [14] X.-Q. Li, J. Lu, A. Pich,  $B_{s,d}^0 \rightarrow \ell^+\ell^-$  Decays in the Aligned Two-Higgs-Doublet Model, JHEP 1406 (2014) 022. arXiv:1404.5865, doi:10.1007/JHEP06(2014)022.
- [15] M. Jung, A. Pich, Electric Dipole Moments in Two-Higgs-Doublet Models, JHEP 1404 (2014) 076. arXiv:1308.6283, doi:10.1007/JHEP04(2014)076.
- [16] L. Duarte, G. A. González-Sprinberg, J. Vidal, Top quark anomalous tensor couplings in the two-Higgs-doublet models, JHEP 1311 (2013) 114. arXiv:1308.3652, doi:10.1007/JHEP11(2013)114.