Unravelling the non-standard top and Higgs couplings in associated top-Higgs production at the High-luminosity LHC

Saurabh D. Rindani
Theoretical Physics Division, Physical Research Laboratory,
Navrangpura, Ahmedabad 380 009, India,
E-mail: saurabh@prl.res.in

Pankaj Sharma[*]
Center of Excellence in Particle Physics (CoEPP),
The University of Adelaide, Adelaide, Australia
E-mail: pankaj.sharma@adelaide.edu.au

Ambresh Shivaji
INFN, Sezione di Pavia,
Via A. Bassi 6, 27100 Pavia, Italy
E-mail: ambresh.shivaji@pv.infn.it

We study the sensitivities of non-standard top and Higgs couplings in the $pp \to thj$ process at the 14 TeV high-luminosity run of Large Hadron Collider (HL-LHC). We calculate top polarization and construct various lab-frame observables to study their sensitivities on anomalous couplings at HL-LHC. Both anomalous Wtb and hVV couplings contribute in the production process. However, only the former contributes in top decay and only the latter takes part in Higgs decay. We study this interesting interplay of couplings in the production and decay observables. In production, these couplings significantly affect the top polarization. As a measure of top polarization, we look at decay-lepton angular distributions in the laboratory frame and study the effect of anomalous couplings on these distributions. We construct certain asymmetries to study the sensitivity of these distributions to top quark couplings. In particular, real and imaginary parts of an hVV coupling and real part of a Wtb coupling f_{2R} significantly alter the top polarization and, in turn, affect the decay-lepton distributions in laboratory frame.

---

[*]Speaker.

1. Introduction

To characterize the new boson discovered at the Large hadron Collider (LHC), we need to study its couplings with a high precision with the SM particles. In the presence of CP violation, it would have both scalar and pseudoscalar couplings. To determine the composition of the Higgs, in this work, we study the polarization of the top quark when it is produced in association with Higgs and a forward jet. This process would receive the contributions of various anomalous couplings of the Higgs and top quark. But the most important one is top-Higgs Yukawa coupling. Direct determination of this coupling is one of the important goal of high-luminosity LHC (HL-LHC).

Top polarization as a probe of this coupling in associated production of top and Higgs has been proposed in [1, 2]. In this work, we propose an azimuthal asymmetry in the laboratory frame to probe and determine the CP-phase of $t\bar{t}h$ coupling. The azimuthal distribution of charged lepton in lab frame shows sensitivity to top polarization and thus to other anomalous couplings. More details about top polarization and azimuthal asymmetry can be found in [3, 4] and references therein. It has been studied extensively in the context of constraining top chromo-dipole couplings in top pair production [6], in tW production [5]; and anomalous Wtb couplings [7] and CP violation [8] in single-top production at the LHC. In the context of two Higgs doublet models (2HDM), it has been used to determine $\tan\beta$ [9, 10] and distinguish different 2HDMs [11].

The most general $t\bar{t}h$ coupling is written as:

$$\mathscr{L}_{t\bar{t}h} = \frac{m_t}{v}\bar{t}\,(\cos\zeta_t + i\sin\zeta_t)t\,h \tag{1.1}$$

ζ_t is the CP-violating phase. $\zeta_t = 0$ corresponds to pure scalar state while $\zeta_t = \pi/2$ to pure pseudoscalar state. Current LHC data on $h \to \gamma\gamma$ and $h \to gg$ constrains $|\zeta_t| < 0.6\pi$

Using only Lorentz and gauge invariance, the WWh couplings up to dimension-5 can be written as:

$$\mathscr{L}_{WWh} = g_{h1}(G^+_{\mu\nu}W^{-\mu} + G^-_{\mu\nu}W^{+\mu})\partial^\nu h + g_{h2}(G^-_{\mu\nu}G^{+\mu\nu})h \tag{1.2}$$

$$- g_{h3}\frac{m_W^2}{v}(W^+_\mu W^{-\mu})h + g_{h4}(G^+_{\mu\nu}\tilde{G}^{-\mu\nu} - G^-_{\mu\nu}\tilde{G}^{+\mu\nu})h \tag{1.3}$$

where $G^{\mu\nu}$ and $\tilde{G}^{\mu\nu}$ are the field strength tensor and its dual respectively. Using only Lorentz invariance, the tbW coupling can be written as:

$$\Gamma^\mu = \frac{-g}{\sqrt{2}}V_{tb}\left[\gamma^\mu(f_{1L}P_L + f_{1R}P_R) - \frac{i\sigma^{\mu\nu}}{m_W}(p_t - p_b)_\nu(f_{2L}P_L + f_{2R}P_R)\right] \tag{1.4}$$

These couplings were studied in the context of associated-single top and Higgs production process in ref. [12].

2. Top polarization and angular asymmetries of charged lepton

Top polarization can be determined through the angular distribution of its decay products. In this work, we study the decay-lepton azimuthal distribution, in the lab frame, as a qualitative measure of top polarization. In the lab frame, we define the lepton azimuthal angle with respect to

the top-production plane chosen as the *x-z* plane, with the convention that the *x* component of the top momentum is positive.

In Fig. 1, we show the lepton azimuthal distribution for different anomalous top couplings at the 14 TeV LHC. We find that this distribution is sensitive to the CP phase of top Yukawa coupling; and to the real and imaginary parts of the coupling g_{h1}. To quantify the sensitivity of these distributions, we further define an asymmetry in terms of partially integrated cross sections

$$A_\phi^\ell = \frac{\sigma(\cos\phi_\ell > 0) - \sigma(\cos\phi_\ell < 0)}{\sigma(\cos\phi_\ell > 0) + \sigma(\cos\phi_\ell < 0)}, \tag{2.1}$$
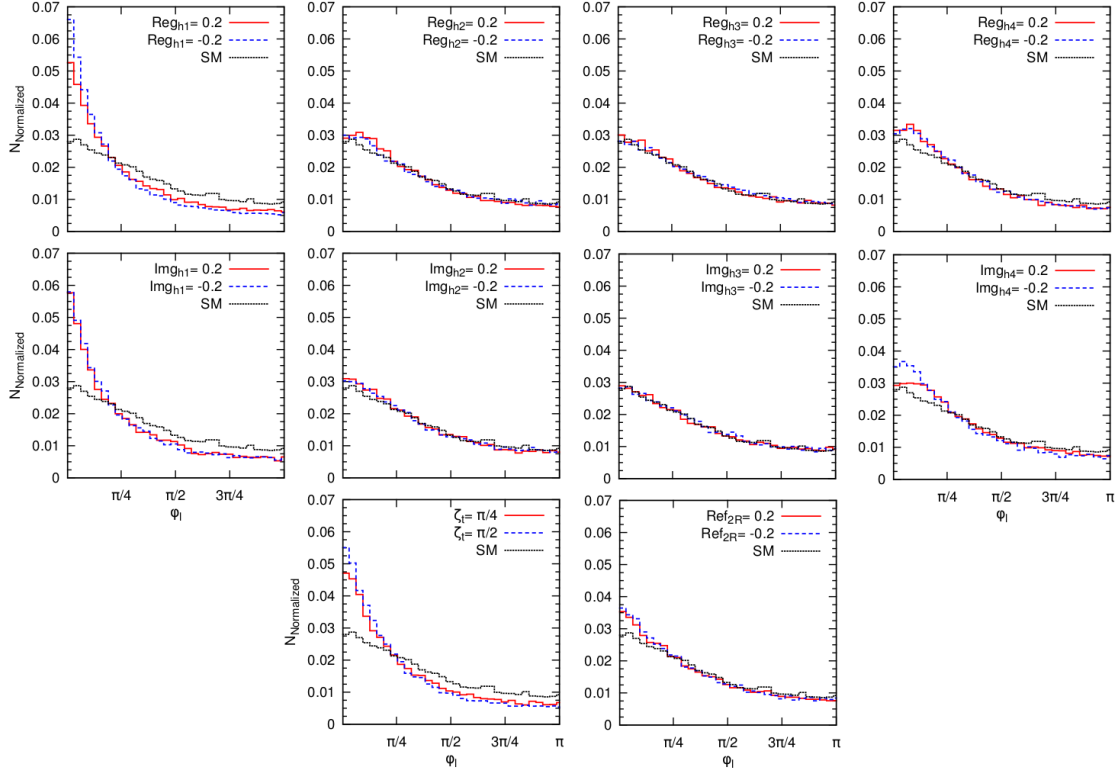

Figure 1: The normalized azimuthal distribution of the charged lepton in *thj* production at the LHC14 for anomalous *WWh*, *Wtb* and *tth* couplings. Also shown in each case is the distribution for the SM.

In Fig. 2, we display the top polarization and azimuthal asymmetry for different anomalous top couplings at the 14 TeV LHC. One can easily notice from the top and bottom panel of fig. 2 the fact that the asymmetry, A_ϕ^ℓ, reconstructs the qualitative behaviour of the top quark polarization. The A_ϕ^ℓ is quite sensitive to real and imaginary parts of gh_1 and CP-phase of top-Yukawa coupling as can be seen from the fig. 2. After the HL-LHC run, the total integrated luminosity is expected to be about 3 ab^{-1}. With that amount of data, this asymmetry would determine the CP phase to within $\pi/16$.

3. Conclusions

In conclusion, we find that the azimuthal asymmetry, which is defined in the lab frame, would be a better probe to determine the CP-structure of the newly-discovered boson than the rest-frame
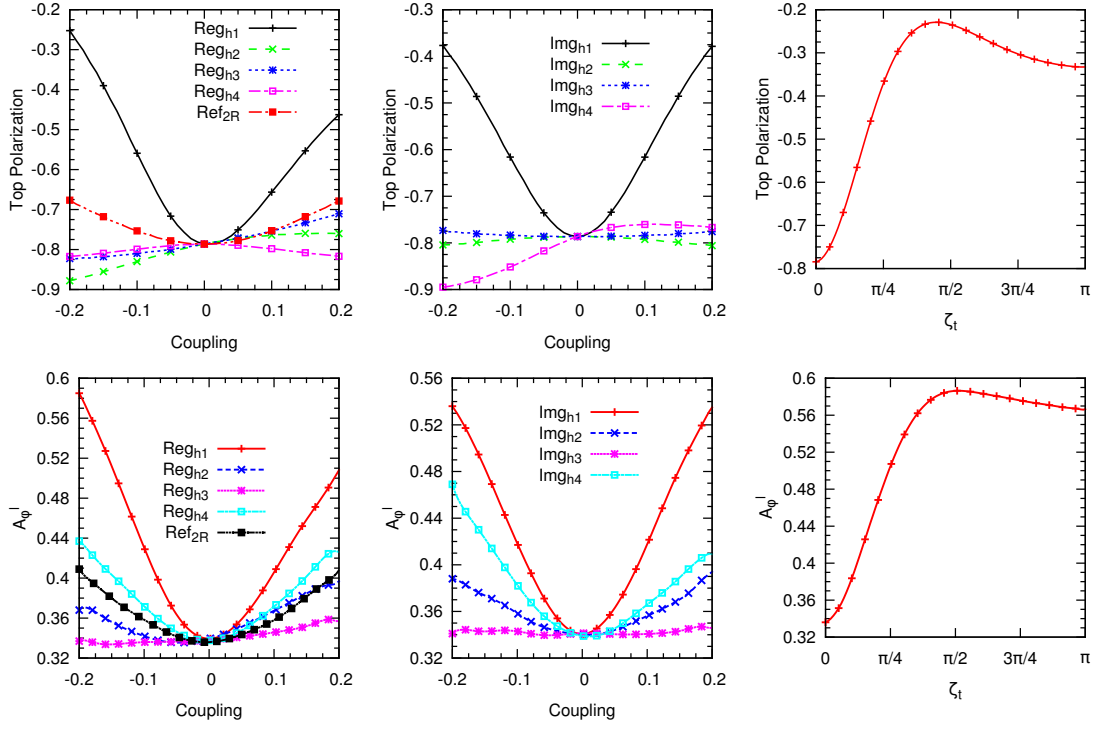
Figure 2: The top polarization and azimuthal asymmetry A_ϕ for $pp \to thj$ production as a function of top- and Higgs-anomalous couplings.

asymmetries. The top polarization and the azimuthal asymmetry is sensitive to CP phase in the parameter space where cross section is not much sensitive.

References

[1] J. Ellis, D. S. Hwang, K. Sakurai and M. Takeuchi, JHEP **1404**, 004 (2014).

[2] J. Yue, Phys. Lett. B **744**, 131 (2015).

[3] V. del Duca and E. Laenen, arXiv:1510.06690 [hep-ph].

[4] R. M. Godbole, K. Rao, S. D. Rindani and R. K. Singh, JHEP **1011**, 144 (2010).

[5] S. D. Rindani, P. Sharma and A. W. Thomas, JHEP 10 (2015) 180; arXiv:1510.08959.

[6] S. S. Biswal, S. D. Rindani and P. Sharma, Phys. Rev. D **88**, 074018 (2013).

[7] S. D. Rindani and P. Sharma, JHEP **1111**, 082 (2011)

[8] S. D. Rindani and P. Sharma, Phys. Lett. B **712**, 413 (2012).

[9] K. Huitu, S. Kumar Rai, K. Rao, S. D. Rindani and P. Sharma, JHEP **1104**, 026 (2011).

[10] R. M. Godbole, L. Hartgring, I. Niessen and C. D. White, JHEP **1201**, 011 (2012)

[11] S. D. Rindani, R. Santos and P. Sharma, JHEP **1311**, 188 (2013).

[12] P. Agrawal, S. Mitra and A. Shivaji, JHEP **1312**, 077 (2013).