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Polarization of the top quark as a probe of its chromomagnetic and chromoelectric couplings in single-top production at the Large Hadron Collider

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We study the sensitivity of the Large Hadron Collider (LHC) to top quark chromomagnetic (CMDM) and chromoelectric (CEDM) dipole moments and Wtb effective couplings in single-top production in association with a W^- boson, followed by semileptonic decay of the top. We calculate the top polarization and the effects of these anomalous couplings on it at two centre-of-mass (cm) energies, 8 TeV and 14 TeV. As a measure of top polarization, we look at decay-lepton angular distributions in the laboratory frame, without requiring reconstruction of the rest frame of the top, and study the effect of the anomalous couplings on these distributions. We construct certain asymmetries to study the sensitivity of these distributions to top-quark couplings. The Wt single-top production mode helps to isolate the anomalous ttg and Wtb couplings, in contrast to top-pair production and other single-top production modes, where other new-physics effects can also contribute. We determine individual limits on the dominant couplings, viz., the real part of the CMDM $\mathrm{Re}\rho_2$, the imaginary part of the CEDM $\mathrm{Im}\rho_3$, and the real part of the tensor Wtb coupling $\mathrm{Re}f_{2R}$, which may be obtained by utilizing these asymmetries at the LHC. We also obtain simultaneous limits on pairs of these couplings taking two couplings to be non-zero at a time.

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1. Introduction

The top quark is the heaviest fundamental particle discovered so far, with mass $m_t = 172.99 \pm 0.91$ GeV [1]. Because of its large mass, the top-quark life time is very short and it decays spontaneously before any non-perturbative QCD effects can force it into a bound state. So by studying the kinematical distributions of top decay products, it is, in principle, possible to measure the top polarization in any top production process.

Top quark couplings to a gluon can be defined in a general way as

$$\Gamma^\mu = \rho_1 \gamma^\mu + \frac{2i}{m_t} \sigma^{\mu\nu} (\rho_2 + i\rho_3\gamma_5)\, q_\nu, \tag{1.1}$$

where ρ_2 and ρ_3 are top quark CMDM and CEDM form factors. Of these, the ρ_2 term is CP even, whereas the ρ_3 term is CP odd. In the SM, both ρ_2 and ρ_3 are zero at tree level. Similarly, Wtb couplings can be written as

$$\Gamma^\mu = \frac{-g}{\sqrt{2}} V_{tb} \left[\gamma^\mu (\mathrm{f_{1L}P_L} + \mathrm{f_{1R}P_R}) - \frac{i\sigma^{\mu\nu}}{m_W} (p_t - p_b)_\nu (\mathrm{f_{2L}P_L} + \mathrm{f_{2R}}P_R) \right] \tag{1.2}$$

where $\mathrm{f_{1L}} = 1$ and $\mathrm{f_{1R}} = \mathrm{f_{2L}} = \mathrm{f_{2R}} = 0$ in the SM.

In this work, we study Wt production at the LHC in the presence of top CMDM and CEDM. In particular, we examine the possibility of using top polarization and angular observables, constructed from top decay products in the laboratory frame, to measure these couplings. We construct an asymmetry out of the azimuthal distribution of charged leptons in the lab frame and show that it has all the characteristics of top polarization. More details about top polarization and azimuthal asymmetry can be found in [2] and references therein. This asymmetry was first defined in [3]. Subsequently, it has been studied extensively in the context of constraining top chromo-dipole couplings in top pair production [4], in tW production [5]; and anomalous Wtb couplings [6] and CP violation [7] in single-top production at the LHC. In the context of two Higgs doublet models (2HDM), it has been used to determine $\tan\beta$ [8, 9] and distinguish different 2HDMs [10].

2. Top polarization and angular asymmetries of charged lepton

Top polarization can be determined through the angular distribution of its decay products. The angular distribution of a decay product f for a top-quark ensemble has the form

$$\frac{1}{\Gamma_f} \frac{\mathrm{d}\Gamma_f}{\mathrm{d}\cos\theta_f} = \frac{1}{2}(1 + \kappa_f P_t \cos\theta_f). \tag{2.1}$$

Here θ_f is the angle between the momentum of fermion f and the top spin vector in the top rest frame. κ_f and P_t are the spin analysing power of decay product f and polarization of the top quark respectively. In this work, we study the lepton azimuthal distribution, in the lab frame, as a qualitative measure of top polarization. In the lab frame, we define the lepton azimuthal angle ϕ_ℓ 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 top couplings at the 14 TeV LHC. We find that these distributions show the best sensitivity to $\mathrm{Re}\rho_2$ and $\mathrm{Ref_{2R}}$. To quantify the sensitivity of these distributions, we further define an asymmetry in terms of partially integrated cross sections

$$A_\phi = \frac{\sigma(\cos\phi_\ell > 0) - \sigma(\cos\phi_\ell < 0)}{\sigma(\cos\phi_\ell > 0) + \sigma(\cos\phi_\ell < 0)}, \tag{2.2}$$

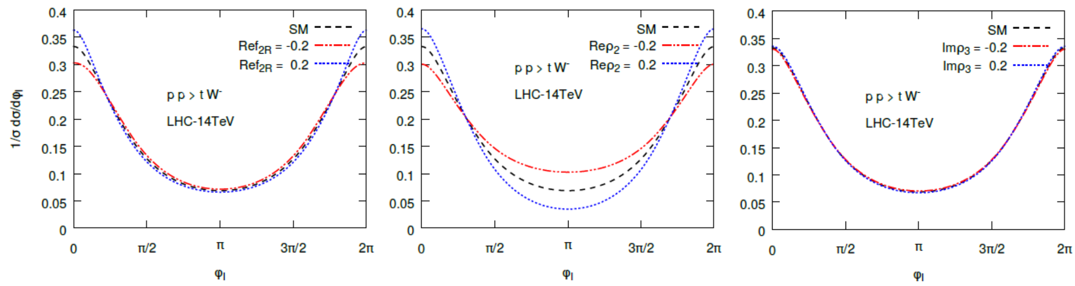

Figure 1: The normalized azimuthal distribution of the charged lepton in associated-Wt single-top production at the LHC14 for anomalous couplings Ref$_{2R}$, Reρ_2 and Imρ_3.

In Fig. 2, we display the top polarization and azimuthal asymmetry for different top couplings at the 8 and 14 TeV LHC. We also study the sensitivity of the observables to the measurement of the anomalous couplings. The 1σ limits on Ref$_{2R}$, Reρ_2 and Imρ_3 are given in Table 1 for LHC8 and LHC14, where we assume only one anomalous coupling to be non-zero at a time. We have assumed measurements on a tW^- final state and only one leptonic channel. Including the conjugate process and other leptonic decays of the top would improve the limits further.

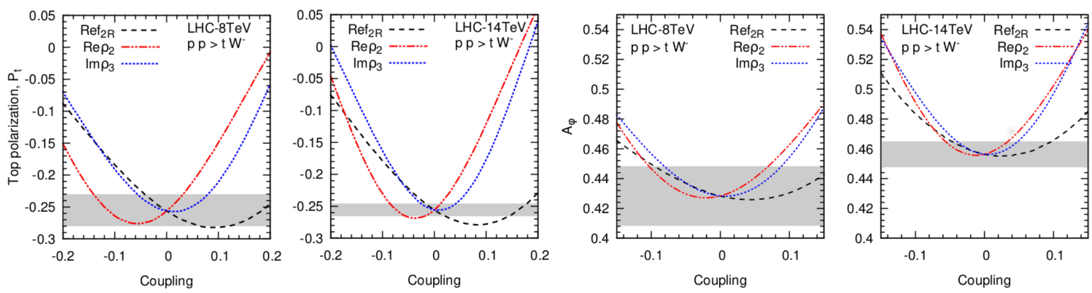

Figure 2: The top polarization and azimuthal asymmetry A_ϕ for tW^- production as a function of top-anomalous couplings.

Apart from the 1σ limits shown in Table 1 there are other disjoint intervals which could be ruled out if no deviation from the SM were observed for P_t and A_ϕ. This is apparent from Fig. 2. The additional allowed intervals for Ref$_{2R}$ and Reρ_2 from P_t measurement are [0.158, 0.205] and [-0.80, -0.65] for LHC14, respectively[1]. It is seen that the top polarization, P_t, and azimuthal asymmetry, A_ϕ, of the charged lepton are more sensitive to negative values of the anomalous couplings Ref$_{2R}$ and positive values of Reρ_2.

We also obtain simultaneous limits (taking two couplings out of Ref$_{2R}$, Reρ_2 and Imρ_3 non-zero simultaneously) on these anomalous couplings that may be obtained by the measurements of

[1] [a, b] denotes the allowed values of the coupling f at the 1σ level, satisfying $a < f < b$.

	Observable	Ref_{2R}	Reρ_2	Imρ_3
8 TeV	P_t	[−0.030, 0.032]	[−0.028, 0.019]	[−0.038, 0.065]
	A_ϕ	[−0.060, 0.140]	[−0.080, 0.050]	[−0.055, 0.070]
14 TeV	P_t	[−0.010, 0.010]	[−0.009, 0.009]	[−0.020, 0.035]
	A_ϕ	[−0.031, 0.081]	[−0.045, 0.020]	[−0.030, 0.040]

Table 1: Individual limits on anomalous couplings Ref_{2R}, Reρ_2 and Imρ_3 which may be obtained by the measurement of the observables at 8 and 14 TeV with integrated luminosities of 20 and 30 fb^{-1} respectively.

asymmetries. For this, we perform a χ^2 analysis to fit all the observables to within $f\sigma$ of statistical errors in the measurement of the observable. In Fig. 3, we show the 1σ, 2σ and 3σ regions in Ref_{2R} − Reρ_2 plane, Ref_{2R} − Imρ_3 plane and Reρ_2 − Imρ_3 plane allowed by the measurement of the asymmetry A_ϕ. From the plots shown in Fig. 3, we find that the strongest simultaneous limits are [−0.03, 0.08] on Ref_{2R}, [−0.05, 0.02] on Reρ_2 and [−0.03, 0.03] on Imρ_3, at the 1σ level.

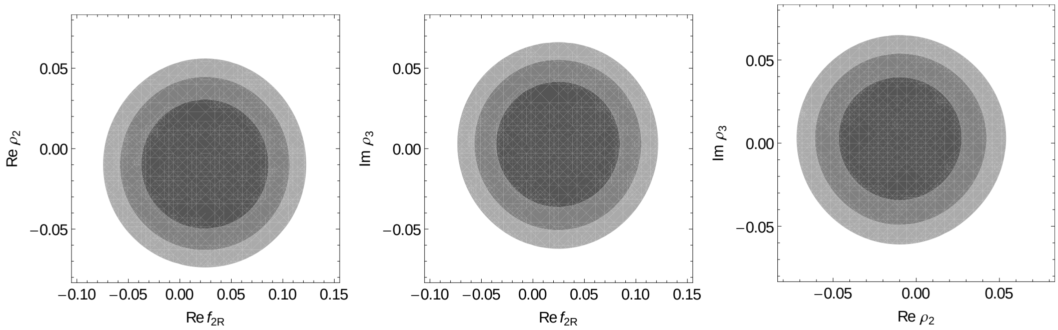

Figure 3: The 1σ (central), 2σ (middle) and 3σ (outer) CL regions in the Ref_{2R}-Reρ_2 plane (left), Ref_{2R}-Imρ_3 plane (center) and Reρ_2-Imρ_3 plane (right) allowed by the measurement of A_ϕ at the LHC14.

3. Conclusions

In conclusion, we have shown that top polarization, and subsequent decay-lepton distributions can be used to obtain fairly stringent limits on chromomagnetic and chromoelectric top couplings from the existing 8 TeV run of the LHC. The limits could be improved by the future runs of the LHC at 14 TeV.

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