Constraining τ-lepton dipole moments and gluon couplings at the LHC

Alper Hayreter and German Valencia*

Department of Physics, Iowa State University, Ames, Iowa 50011, USA
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We study the constraints that can be placed on anomalous τ-lepton couplings at the LHC. We use an effective Lagrangian description for physics beyond the standard model which contains the τ-lepton anomalous magnetic moment, electric dipole moment, and weak dipole moments in two operators of dimension 6. We include in our study two additional operators of dimension 8 that directly couple the τ leptons to gluons and are therefore enhanced at the LHC. We consider the two main effects from these couplings: modifications to the Drell-Yan cross section and to the τ-lepton pair production in association with a Higgs boson. We find that a measurement of the former at the 14% level can produce constraints comparable to existing ones for the anomalous dipole couplings and that a bound on the latter at a sensitivity level of 500 $\sigma_{\rm SM}$ or better would produce the best constraint on the τ-gluonic couplings.

I. INTRODUCTION

The study of τ leptons by the ATLAS and CMS collaborations has matured to the point where they have a very active program. Among the many studies, we can cite examples of standard model (SM) physics with the reconstruction of the Z resonance in the ditau mode [1,2], beyond standard model physics (BSM) where heavy resonances such as Z' bosons have been excluded in this channel up to masses around 1 TeV [3,4]. Of course there is also an active program to observe the recently discovered 126 GeV state in the ditau channel in order to confirm it as the SM Higgs boson [5,6] as well as searches for additional neutral scalars that decay to $\tau^+\tau^-$.

In order to study BSM physics in a model independent way, we can use the effective Lagrangian and the complete catalog of operators up to dimension 6 that exists in the literature [7,8]. In this paper we will focus our attention on the τ-lepton dipole-type couplings, its anomalous magnetic moment and electric dipole moment given by a_τ^γ and d_τ^γ, respectively,

$$\mathcal{L} = \frac{e}{2}\bar{\ell}\sigma^{\mu\nu}(a_\ell^\gamma + i\gamma_5 d_\ell^\gamma)\ell F_{\mu\nu}, \tag{1}$$

and its corresponding weak dipole moments a_τ^Z and d_τ^Z,

$$\mathcal{L} = \frac{g}{2\cos\theta_W}\bar{\ell}\sigma^{\mu\nu}(a_\ell^Z + i\gamma_5 d_\ell^Z)\ell Z_{\mu\nu}. \tag{2}$$

These usual definitions, Eqs. (1) and (2), can be generalized to operators that respect the symmetries of the SM

$$\mathcal{L} = g\frac{d_{\ell W}}{\Lambda^2}\bar{\ell}\sigma^{\mu\nu}\tau^i e\phi W_{\mu\nu}^i + g'\frac{d_{\ell B}}{\Lambda^2}\bar{\ell}\sigma^{\mu\nu}e\phi B_{\mu\nu} + \text{H.c.} \tag{3}$$

The fully gauge invariant operators contain, among other terms, the anomalous magnetic moment, the electric dipole

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*valencia@iastate.edu

moment, and the weak dipole moment of the leptons with the correspondence

$$a_\ell^\gamma = \frac{\sqrt{2}v}{\Lambda^2}\,\text{Re}(d_{\ell B} - d_{\ell W}),$$

$$d_\ell^\gamma = \frac{\sqrt{2}v}{\Lambda^2}\,\text{Im}(d_{\ell B} - d_{\ell W}),$$

$$a_\ell^Z = -\frac{\sqrt{2}v}{\Lambda^2}\,\text{Re}(d_{\ell B} + d_{\ell W}),$$

$$d_\ell^Z = -\frac{\sqrt{2}v}{\Lambda^2}\,\text{Im}(d_{\ell B} + d_{\ell W}), \tag{4}$$

where v is the Higgs vacuum expectation value $v \sim 246$ GeV and Λ is the scale of new physics. The gauge invariant operators in Eq. (3) also relate the anomalous dipole-type couplings to new couplings among the τ lepton, the respective gauge boson and the Higgs boson. Effectively, Eqs. (1) and (2) get multiplied by a factor of $(1 + h/v)$.

In general BSM operators in the effective Lagrangian with dimension larger than six are further suppressed at low energy by additional powers of the new physics scale. However, for LHC physics, this power counting is altered for dimension 8 operators that couple a lepton pair directly to gluons due to the larger parton luminosities [9]. This motivates us to include in our study the so called "lepton-gluonic" couplings for the τ which take the form

$$\mathcal{L} = \frac{g_s^2}{\Lambda^4}(d_{\tau G}G^{A\mu\nu}G_{\mu\nu}^A\bar{\ell}_L\ell_R\phi + d_{\tau\tilde{G}}G^{A\mu\nu}\tilde{G}_{\mu\nu}^A\bar{\ell}_L\ell_R\phi) + \text{H.c.} \tag{5}$$

Here $G_{\mu\nu}^A$ is the gluon field strength tensor and $\tilde{G}^{A\mu\nu} = (1/2)\epsilon^{\mu\nu\alpha\beta}G_{\alpha\beta}^A$ its dual. If we allow for CP violating phases in the coefficients, $d_{\tau G}$ and $d_{\tau\tilde{G}}$, the resulting gluon-lepton couplings take the form

$$\mathcal{L} = \frac{v}{\sqrt{2}} \frac{g_s^2}{\Lambda^4} (\mathrm{Re}(d_{\tau G}) G^{A\mu\nu} G^A_{\mu\nu} + \mathrm{Re}(d_{\tau\tilde{G}}) G^{A\mu\nu} \tilde{G}^A_{\mu\nu}) \bar{\ell}\ell$$
$$+ i \frac{v}{\sqrt{2}} \frac{g_s^2}{\Lambda^4} (\mathrm{Im}(d_{\tau G}) G^{A\mu\nu} G^A_{\mu\nu}$$
$$+ \mathrm{Im}(d_{\tau\tilde{G}}) G^{A\mu\nu} \tilde{G}^A_{\mu\nu}) \bar{\ell}\gamma_5\ell. \qquad (6)$$

The related couplings that include the Higgs boson are obtained by multiplying Eq. (6) with the factor $(1 + h/v)$ as before.

The anomalous couplings in Eqs. (3) and (5) (as well as the leptons ℓ) in these equations are understood to carry a generation index and are in principle different for electrons, muons, or τ leptons. They could be lepton number violating as well, but in this paper, we restrict our attention to the case of τ leptons. The study of the τ-lepton dipole moments has a long history that includes constraints from both cross sections and T-odd asymmetries [10–21]. At the LHC, we find that the cross sections are the more interesting observables because the T-odd asymmetries are suppressed by the mass of the τ.

II. DRELL-YAN PRODUCTION OF τ-LEPTON PAIRS

We begin by considering the cross section for Drell-Yan production of τ-lepton pairs. The new couplings will modify this cross section and can be probed in one of two ways: by comparing the measured cross section with its value in the SM or by looking for deviations from lepton universality in measured cross sections. With the aid of MadGraph5 [22] and FeynRules [23], we compute the contribution of the new couplings to $pp \to \tau^+\tau^-$ at 14 TeV. We distinguish between two different regions of $m_{\tau\tau}$ invariant mass: the high energy region and the Z-resonance region. Our numerical results for sample values of the new couplings,

as well as fits to these Monte Carlo (MC) points that can be used to interpolate between them are presented in the Appendix.

Our first study corresponds to the high energy region, defined by $m_{\tau\tau} > 120$ GeV. This is the most interesting region at the LHC for several reasons: it probes phase space not covered by Large Electron Positron Collider (LEP) or LEP2, and it excludes the Z resonance and therefore significantly reduces the SM background. The results of our numerical simulations are displayed in Fig. 6 and the fits are given in Eq. (A1) for the electric and weak dipole moments and in Fig. 7 and Eq. (A2) for the lepton-gluonic couplings. Our resulting cross sections are approximately quadratic in the anomalous couplings indicating that the interference with the SM is small. An analytic calculation reveals that the interference terms between the SM and the dipole-type couplings in Eq. (A1) are small due to a suppression by the τ mass. We have checked that these interference terms do scale linearly with m_τ in our MC simulation. For the τ-gluonic couplings, there is of course no interference with the SM, as the two contributions arise from different parton level processes.

The Drell-Yan cross section for dimuons and di electrons above the Z resonance has been measured at the LHC [24], so we can expect that in the future it will be possible to compare it to the ditau mode. We would expect the largest uncertainty in such a comparison to occur in the ditau channel, so we turn to the CMS search for heavy resonances in this mode for guidance. In Ref. [3] it is estimated that the main systematic uncertainty in ditau events with high invariant mass, $m_{\tau\tau} > 300$ GeV, results from the estimation of background and is in the range 6%–14%. To estimate the sensitivity of the LHC to the anomalous couplings, we will assume that a comparison between the ditau and the other dilepton modes at the 14% level will be possible. To this effect, in Fig. 1, we use
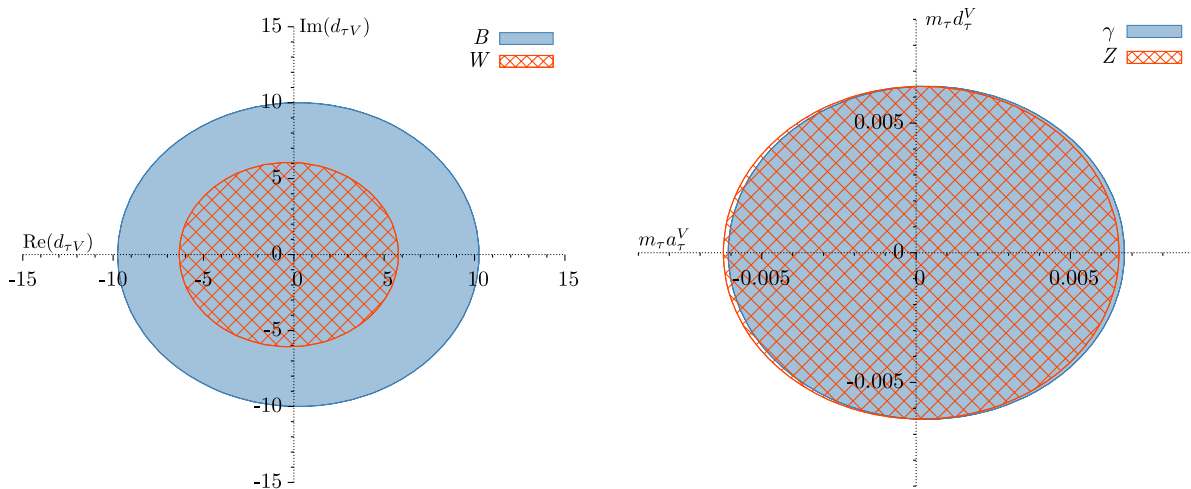

FIG. 1 (color online). Parameter space allowed at 1σ by requiring the total cross section $pp \to \tau^+\tau^-$ at 14 TeV with $m_{\tau\tau} > 120$ GeV to deviate from its SM value by at most 14%.

Eq. (A1) to illustrate the region of parameter space allowed at 1σ by requiring the total ditau cross section to deviate from its SM value (equivalently from the dimuon cross section) by at most 14%.

The best bounds from Fig. 1, taken one coupling at a time and converting to the γ, Z basis, are given by

$$-0.0064 \lesssim (m_\tau d_\tau^\gamma, m_\tau d_\tau^Z) \lesssim 0.0064$$
$$-0.0061 \lesssim m_\tau a_\tau^\gamma \lesssim 0.0068 \qquad (7)$$
$$-0.0063 \lesssim m_\tau a_\tau^Z \lesssim 0.0066.$$

The best existing limit for the τ-lepton anomalous magnetic moment $(g_\tau - 2)/2 = 2m_\tau a_\tau^\gamma$ comes from the process $e^+ e^- \rightarrow e^+ e^- \tau^+ \tau^-$ as measured by Delphi at LEP2 [25]. At the 95% C.L., it is

$$-0.052 < (2m_\tau a_\tau^\gamma) < 0.013, \quad \text{or}$$
$$\qquad (8)$$
$$-0.026 < m_\tau a_\tau^\gamma < 0.007.$$

The best existing limit for the tau-lepton electric dipole moment comes from the study of $e^+ e^- \rightarrow \tau^+ \tau^-$ by Belle [26] that constrains both the real and imaginary parts of $d_\tau(0)$, where $\mathrm{Re}(d_\tau(0)) \equiv -e d_\tau^\gamma$. Again, at the 95% C.L., it is

$$-2.2 \lesssim \mathrm{Re}(d_\tau(0)) \lesssim 4.5 \times 10^{-17} \text{ e cm}, \quad \text{or}$$
$$\qquad (9)$$
$$-0.002 < m_\tau d_\tau^\gamma < 0.0041.$$

Belle also quotes a bound for an absorptive part of the form factor (which we do not consider here) $-2.5 \lesssim \mathrm{Im}(d_\tau(0)) \lesssim 0.8 \times 10^{-17}$ e cm. As far as the weak dipole moments, Aleph has obtained the best existing bound from studying $e^+ e^- \rightarrow \tau^+ \tau^-$ close to the Z mass [27] [our couplings can be expressed in terms of theirs as $(d_\tau^Z, a_\tau^Z) = (2m_\tau \sin \theta_W \cos \theta_W) \times (d_\tau^W, \mu_\tau)$]. At the 95% C.L., they quote

$$\mathrm{Re}(d_\tau^W) < 5.0 \times 10^{-18} \text{ e cm}, \quad \text{or} \quad m_\tau |d_\tau^Z| \lesssim 6.7 \times 10^{-4}$$
$$\mathrm{Re}(\mu_\tau) < 1.1 \times 10^{-3}, \quad \text{or} \quad m_\tau |a_\tau^Z| \lesssim 1.6 \times 10^{-3}. \qquad (10)$$

A proposal to improve on the result for a_τ^γ by an order of magnitude with high luminosity B factories exists [28].

With the aid of Eq. (A2), we can find the region of parameter space in the τ-gluonic couplings that is allowed at 1σ by requiring the total ditau cross section to deviate from its SM value (equivalently from the dimuon cross section) by at most 14%, we find

$$(|d_{\tau G}|^2 + |d_{\tau \tilde{G}}|^2) \lesssim 0.93. \qquad (11)$$

Note that these bounds are about five times better than those for $d_{\tau W}$ for $\Lambda = 1$ TeV, corroborating the impact of the much higher gluon parton luminosities. The result, Eq. (11), is very close to what was obtained in Ref. [9] requiring 3σ statistical sensitivity with an integrated luminosity of 10 fb^{-1}. Of course, since these couplings originate at dimension 8, their impact drops significantly

faster than that of the anomalous dipole couplings for higher new physics scales.

It may be interesting to consider the Z-resonance region as well given the very large number of events expected there. A simulation for $60 < m_{\tau\tau} < 120$ GeV is presented in Fig. 8 and the corresponding fit in Eq. (A3). In this case the reported systematic error in the measurement of the Z cross section using the ditau channel by CMS is 8% [1], and it is the main source of error already. Assuming a comparison to the theoretical cross section at 10% will be possible at 14 TeV, we find constraints only slightly weaker than Eq. (7), by about 30%.

III. HIGGS PRODUCTION IN ASSOCIATION WITH A τ-LEPTON PAIR

We now turn our attention to the associated production of a Higgs boson with a τ-lepton pair. The motivation to study this process is simple: gauge invariance of the effective Lagrangian relates the dipole couplings of the τ lepton to couplings involving the Higgs boson. At the same time, a similar study of top-quark dipole couplings in Ref. [29] suggests that the two processes can yield comparable constraints. From the experimental perspective, there are Higgs boson searches in the HV, $V = Z$, W modes underway [30,31]. Although at the moment they follow a different analysis, they can in principle also be conducted for the case $Z \rightarrow \tau^+ \tau^-$.

To estimate the event rates that can be expected, we take the SM prediction for $m_h = 125$ GeV at 14 TeV from CERN Report 2011-002 [32], $\sigma(pp \rightarrow Zh) = (0.8830^{+6.4\%}_{-5.5\%})$ pb, and multiply it by $\mathrm{Br}(Z \rightarrow \tau^+ \tau^-)$ to find $\sigma(pp \rightarrow Zh \rightarrow \tau^+ \tau^- h) = (29.8^{+1.9}_{-1.6})$ fb. In Fig. 2 we show the distributions $d\sigma(pp \rightarrow \tau^+ \tau^- h)/dm_{\tau\tau}$ for the SM, for $d_{\tau W} = 5$, and for the case $d_{\tau G} = 1$ which correspond to what can be constrained in Drell-Yan according to Fig. 1 and to Eq. (11). The distributions show that, whereas the SM is sharply peaked at the Z resonance as is the $d_{\tau W}$ induced rate, the $d_{\tau G}$ case is not. Of course the contribution to the rate beyond the scale Λ (which we have chosen to be 1 TeV for this study) is not physical and simply reflects the nature of the effective theory. This could be addressed by rescaling the bounds on the anomalous couplings by increasing the new physics scale if desired.

Since the contribution of $d_{\tau W}$ is largest at the Z resonance, we first consider its constraints from $60 < m_{\tau\tau} < 120$ GeV. The numerical cross sections obtained for sample values of the anomalous couplings, along with the corresponding fit are displayed on the right of Fig. 8 and in the second Eq. (A3). If the cross section can be constrained to be at most twice the SM value (or below 26 fb), one would obtain the bounds shown in Fig. 3.

In view of Fig. 2, we limit our study for the $d_{\tau G}$ coupling to the high ditau invariant mass region, $m_{\tau\tau} > 120$ GeV, where the SM background is smallest. The numerical cross sections obtained for sample values of the anomalous
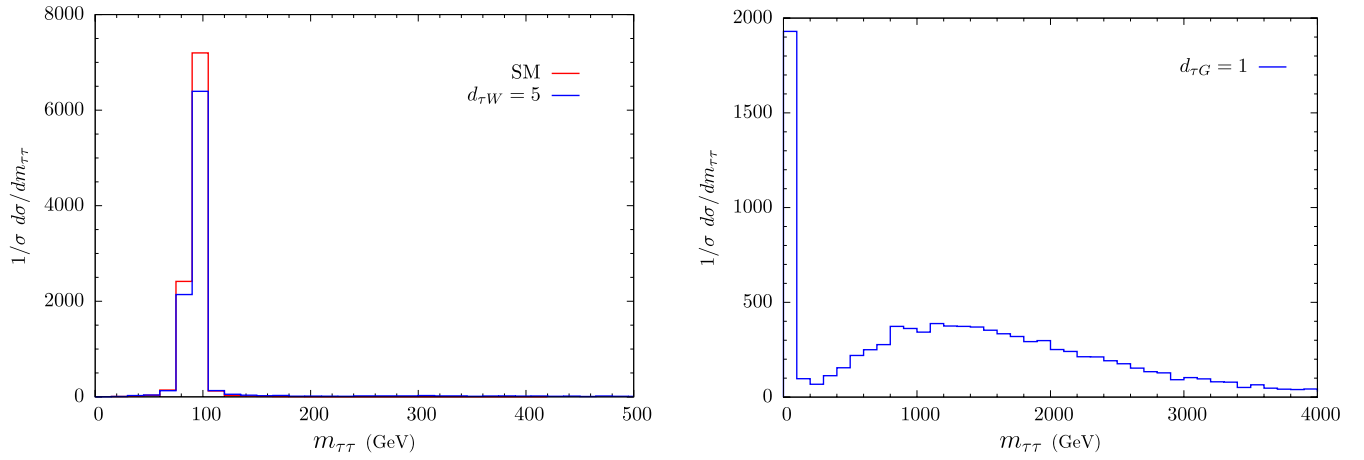
FIG. 2 (color online). Differential decay distribution $d\sigma(pp \to \tau^+\tau^-h)/dm_{\tau\tau}$ for (left plot) the SM and for $d_{\tau W} = 5$ and (right plot) $d_{\tau G} = 1$.

couplings, along with the corresponding fit are displayed on the right of Fig. 6 and in the second Eq. (A1), respectively for anomalous dipole couplings and in Fig. 7 and in the second Eq. (A2) for the gluon-leptonic couplings. Assuming that $\sigma(pp \to \tau^+\tau^-h)$ with $m_{\tau\tau} > 120$ GeV is measured to within a factor of fifty of its SM value (that is, the cross section can be bounded by 5 fb) yields an allowed region for the anomalous dipole couplings displayed in Fig. 4. The bounds from Fig. 4 are comparable to those in Fig. 1, indicating that a 14% measurement of the Drell-Yan ditau cross section yields similar bounds to a constraint $\sigma(pp \to \tau^+\tau^-h) \lesssim 5$ fb in the region $m_{\tau\tau} > 120$ GeV.

The situation is different for the lepton-gluonic couplings where Eq. (A2) implies that an experimental constraint on $\sigma(pp \to \tau^+\tau^-h)$ at the 50 fb level (500 times larger than the SM) is enough to match the constraints on the tau-gluonic couplings from the Drell-Yan process, Eq. (11),

$$(|d_{\tau G}|^2 + |d_{\tau \tilde{G}}|^2) \lesssim 20 \times \text{experimental upper bound on}$$

$$\frac{\sigma(pp \to \tau^+\tau^-h)}{1 \text{ pb}}. \tag{12}$$

IV. ANALYSIS AT THE τ DECAY LEVEL

The constraints that we have obtained in the previous section rely on a measurement of the ditau cross section and on the level at which background can be controlled. In this section we explore this in somewhat more detail by including the τ-lepton decay in our analysis as well as the physics backgrounds that exist at that level following the guidelines used in Ref. [33]. We will consider only two cases. First the dilepton mode in which both τ-leptons undergo leptonic decay into muons or electrons is $pp \to \tau^+\tau^- \to \ell^+\ell'^- \not{E}_T$, $\ell = \mu$, e. The background for this mode includes:
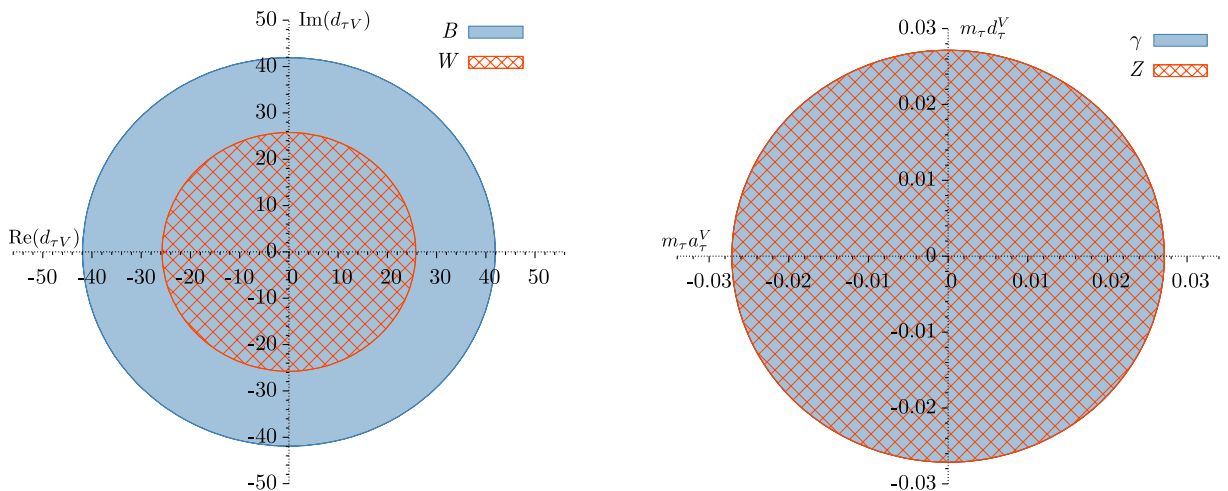

FIG. 3 (color online). Parameter space allowed at 1σ by requiring the total cross section $pp \to \tau^+\tau^-h$ at 14 TeV with $60 < m_{\tau\tau} < 120$ GeV to deviate from its SM value by at most a factor of 2 (or remain below 26 fb).
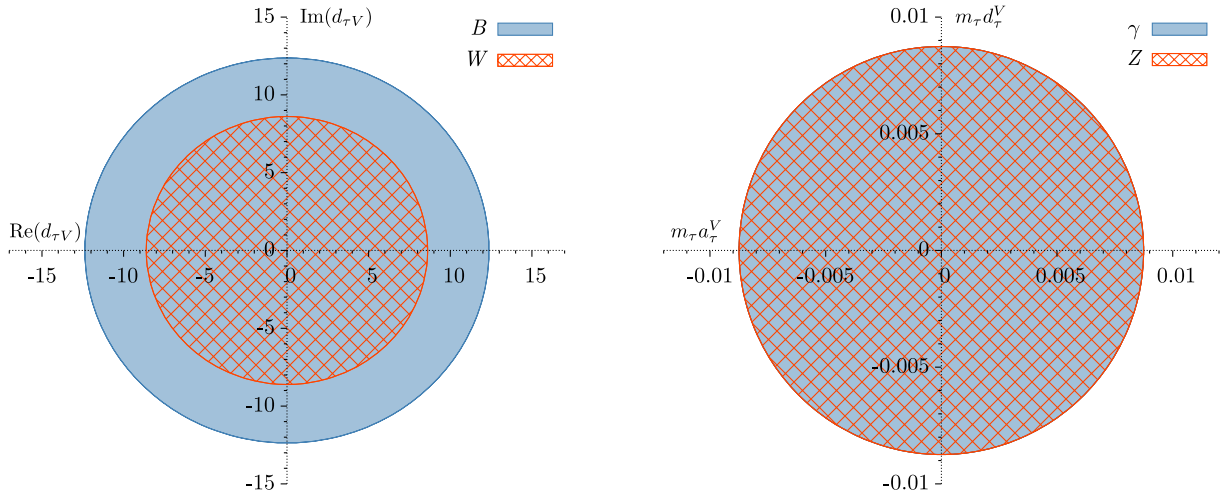
FIG. 4 (color online). Parameter space allowed at 1σ by requiring the total cross section $pp \rightarrow \tau^+\tau^- h$ at 14 TeV with $m_{\tau\tau} > 120$ GeV to be at most 5 fb (50 times the SM value).

(i) $t\bar{t}$ pairs in which both b jets are missed. We model this by requiring $p_{Tb} < 20$ GeV.

(ii) ZZ pairs in which one Z decays to charged leptons and the other one to neutrinos. This background can be suppressed considerably by requiring the dilepton mass to be above 120 GeV.

(iii) W^+W^- pairs.

(iv) for same flavor pairs, we also have direct Drell-Yan production of $\ell^+\ell^-$. This background can be eliminated with the requirement that the events have a minimum missing E_T of 10 GeV.

Second we consider modes in which one τ lepton decays leptonically to a muon or an electron and the other one hadronically. The background for these modes consists of the $t\bar{t}$, W^+W^-, or ZZ as in the previous modes and in addition the more important of W plus one jet (Wj) production. We will limit our analysis to the two hadronic decay modes $\tau^\pm \rightarrow \pi^\pm\nu$ and $\tau^\pm \rightarrow \rho^\pm\nu$ which together account for a branching ratio near 36%. For the Wj background that meets our selection cuts, we assume a probability of 0.3% that the QCD jet will fake a τ jet and

reduce these events accordingly. This number is taken from studies by ATLAS and CMS [34].

In all cases we generate the signal and background events using MadGraph5 and implement the τ-lepton decay modes with the package DECAY [35]. We use the following basic cuts on the leptons and the jets: $p_T > 6$ GeV, $|\eta| < 2.5$ and $\Delta R_{ik} > 0.4$, where the indices $i, k = \ell, j$. In addition we require the high invariant mass region with the cuts $m_{\ell\ell'} > 120$ GeV or $m_{\ell j} > 120$ GeV. We suppress the backgrounds with the cuts detailed above. The results for several values of the anomalous dipole couplings as well as the corresponding fits are presented in the Appendix in Fig. 9 and Eq. (A4). The latter show two numbers for the case of vanishing anomalous couplings: the first number is the remaining background after the cuts, and the second number is the SM contribution to the process. If we assume again that comparison between theory and experiment will be limited by the 14% systematic error mentioned before, we obtain allowed regions shown in Fig. 5. We see that the limit that can be obtained with dilepton modes is comparable to that one quoted
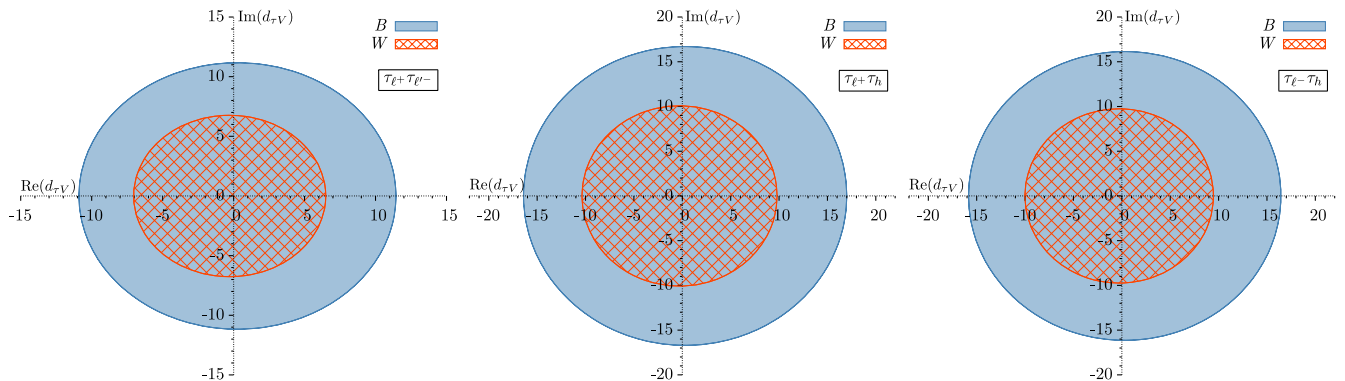

FIG. 5 (color online). Limits that can be obtained on the anomalous dipole couplings of the τ lepton assuming a comparison between theory and experiment at the 14% level in the modes $\tau_{\ell^+}\tau_{\ell'^-}$ (left), $\tau_{\ell^+}\tau_h$ (center), and $\tau_{\ell^-}\tau_h$ (right).

before at the ditau level. The limits in the $\tau_\ell \tau_h$ modes are about a factor of 2 worse.

V. SUMMARY

We have examined the possible limits that can be placed on certain anomalous couplings of τ leptons at the LHC. We have considered the four dipole-type couplings that appear at dimension 6 in the effective Lagrangian as well as the two τ-gluon couplings that appear at dimension 8. We have found the constraints that can be placed from a measurement of the high invariant mass region $m_{\tau\tau} > 120$ GeV Drell-Yan ditau cross section. We have assumed that the comparison between theory and experiment will be limited by the current 14% maximum error in background estimation for high invariant mass ditau pairs in CMS. Under this assumption, for the dipole-type couplings, we find limits that are comparable to the best existing limit on $(g - 2)$ for the τ, within factors of 2 of the best limit for the τ-electric dipole moment and 5–10 times worse than the Belle limits on the dipole couplings of the τ to the Z. For new physics at the TeV scale, we find that comparable or slightly better constraints can be placed on the dimension 8 τ-gluonic couplings.

Using the fully gauge invariant effective Lagrangian, we related these couplings to new contributions to the associated production of a τ-lepton pair and a Higgs boson. The cross section for this process is very small, of order 0.1 fb. We find that in order to extract constraints on the dipole couplings that are competitive with those from Drell-Yan, one needs to bound $\sigma(pp \to \tau^+ \tau^- h)$ at the 5 fb level. On the other hand, one only needs to bound it at the 50 fb level (or 500 times the SM) to constrain the τ-gluonic couplings at the same level as with a 14% measurement of the Drell-Yan cross section.

Finally we have repeated our study of the Drell-Yan ditau cross section allowing for ditau decay into dileptons (muons or electrons) or into lepton plus jet channels keeping the $\pi\nu$ and $\rho\nu$ modes. We find that there is not much loss in sensitivity, mostly because the limitation of the measurement had already been assumed to be due to systematics.

APPENDIX: EVENTS WITH τ-LEPTONS AS FINAL STATES

In this Appendix we present our numerical results. We begin our calculation by implementing the Lagrangian of Eqs. (3) and (5) into MadGraph5 with the aid of FeynRules [23]. We use the resulting Universal FeynRules Output model file to generate τ-lepton pair events as well as $\tau^+\tau^- h$ events for several values of $d_{\tau W}$, $d_{\tau B}$, $d_{\tau G}$, and $d_{\tau \tilde{G}}$ in a range that changes the $\tau^+\tau^-$ SM cross section by factors of a few. We then fit the numerical results to obtain approximate expressions for cross sections in terms of the new couplings. We repeat this procedure for two different invariant mass regions.

1. τ-lepton pairs at the high invariant mass region

Our first study is for the high energy region defined by $m_{\tau\tau} > 120$ GeV, and the results are shown in Fig. 6. We fit the MC points to a quadratic equation in the anomalous couplings since they occur linearly in the amplitudes. The result of this fit, normalized to the SM for the case of
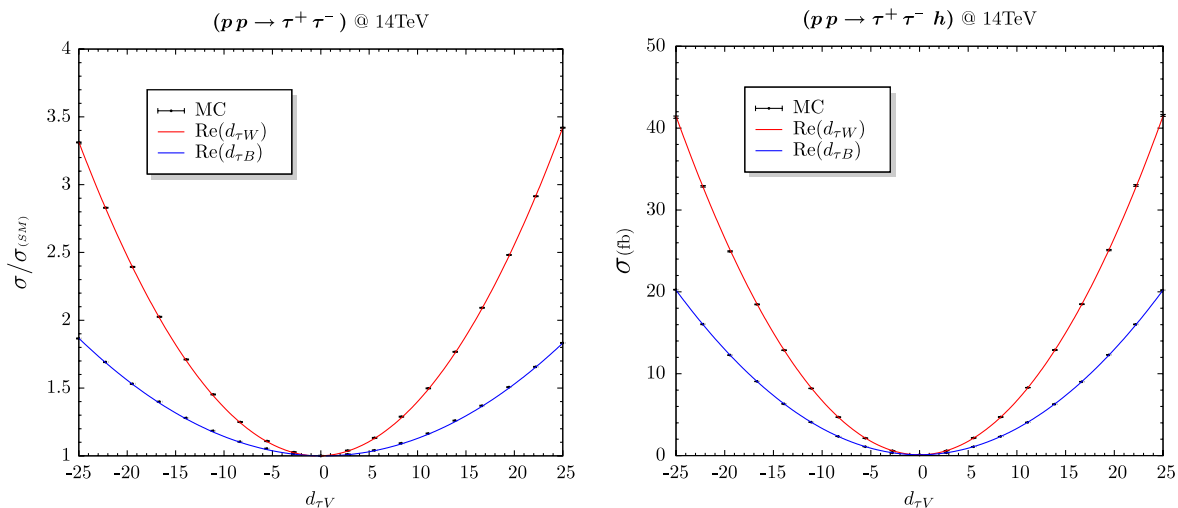

FIG. 6 (color online). Cross section for the processes $pp \to \tau^+\tau^-$ (left) and $pp \to \tau^+\tau^- h$ (right) at 14 TeV as calculated with MadGraph5 for different values of the anomalous coupling $d_{\tau V}$ with $m_{\tau\tau} > 120$ GeV and the corresponding fits.
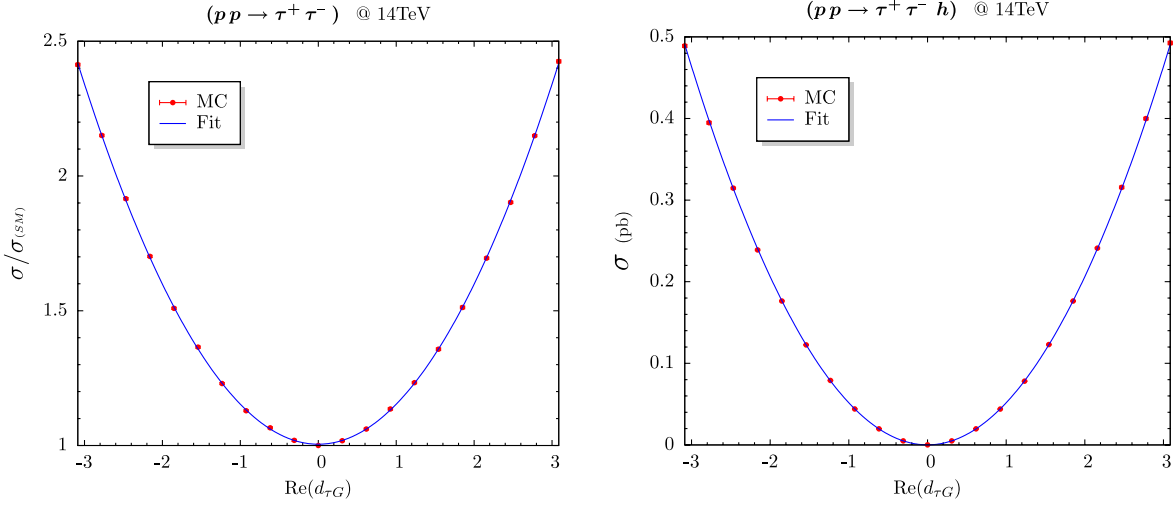
FIG. 7 (color online). Cross section for the processes $pp \to \tau^+\tau^-$ (left) and $pp \to \tau^+\tau^- h$ (right) at 14 TeV as calculated with MadGraph5 for different values of the anomalous coupling $d_{\tau G}$ with $m_{\tau\tau} > 120$ GeV and the corresponding fits.

τ-lepton pair production (which is calculated by MadGraph5 to be $\sigma(pp \to \tau^+\tau^-)_{SM} = (9.03 \pm 0.02)$ pb) is

$$\frac{\sigma(pp \to \tau^+\tau^-)}{\sigma_{SM}}$$
$$= 1 + 2.1 \times 10^{-3} \, \mathrm{Re}(d_{\tau W}) + 3.8 \times 10^{-3}|d_{\tau W}|^2$$
$$- 7.2 \times 10^{-4} \, \mathrm{Re}(d_{\tau B}) + 1.4 \times 10^{-3}|d_{\tau B}|^2$$
$$\sigma(pp \to \tau^+\tau^- h)$$
$$= (0.1 + 6.6 \times 10^{-2}|d_{\tau W}|^2 + 3.2 \times 10^{-2}|d_{\tau B}|^2) \text{ fb}.$$
$$\text{(A1)}$$

The last cross section is to be compared to the very low SM cross section $\sigma(pp \to \tau^+\tau^- h)_{SM} = 9.6 \times 10^{-5}$ pb.

Our results for the tau-gluon couplings are shown in Fig. 7. As expected from the results of Ref. [9], the effect on the cross section from $\mathrm{Re}(d_{\tau G})$, $\mathrm{Re}(d_{\tau \tilde{G}})$, $\mathrm{Im}(d_{\tau G})$, and $\mathrm{Im}(d_{\tau \tilde{G}})$ is the same, so we show only one of them in the figure. The corresponding (quadratic again) fit is given by

$$\frac{\sigma(pp \to \tau^+\tau^-)}{\sigma_{SM}} = 1 + 0.15(|d_{\tau G}|^2 + |d_{\tau \tilde{G}}|^2)$$
$$\sigma(pp \to \tau^+\tau^- h)$$
$$= (1 \times 10^{-4} + 5.15 \times 10^{-2}(|d_{\tau G}|^2 + |d_{\tau \tilde{G}}|^2)) \text{ pb}.$$
$$\text{(A2)}$$

We generated 10^4 events for each of our sample coupling values, and the errors in the cross sections are the statistical error calculated by MadGraph5. For the $\tau^+\tau^-$ samples, 0.02 pb, and for the $\tau^+\tau^- h$ samples, 4×10^{-4} fb.

2. τ-lepton pairs near the Z-resonance region

We next consider the Z-resonance region, defined by $60 < m_{\tau\tau} < 120$ GeV. Our results for this case are shown in Fig. 8.

The SM cross section in this case is calculated by MadGraph5 to be $\sigma(pp \to \tau^+\tau^-)_{SM} = (692.1 \pm 1.3)$ pb and $\sigma(pp \to \tau^+\tau^- h)_{SM} = (12.78 \pm 0.04)$ fb, and the fit to the new physics is given by

$$\frac{\sigma(pp \to \tau^+\tau^-)}{\sigma_{SM}}$$
$$= 1 + 3.78 \times 10^{-4} \, \mathrm{Re}(d_{\tau W}) + 1.4 \times 10^{-3}|d_{\tau W}|^2$$
$$+ 7.64 \times 10^{-5} \, \mathrm{Re}(d_{\tau B}) + 5.33 \times 10^{-4}|d_{\tau B}|^2$$
$$\sigma(pp \to \tau^+\tau^- h)$$
$$= (12.78 + 1.9 \times 10^{-2}|d_{\tau W}|^2 + 7.3 \times 10^{-3}|d_{\tau B}|^2) \text{ fb}.$$
$$\text{(A3)}$$

3. $\tau_\ell \tau_{\ell'}$ and $\tau_\ell \tau_h$ modes

We perform a partial study of what happens at the tau decay level using the $\tau_\ell \tau_{\ell'}$ and $\tau_\ell \tau_h$ channels. After starting with τ-lepton pair samples, we allow the τ leptons to decay either leptonically to a muon or electron plus two neutrinos or into a τ jet. For the hadronic decay, we only include the $\pi\nu$ and $\rho\nu$ modes. All these decays are performed with the DECAY package. The results are shown in Fig. 9. We do not show figures for the imaginary parts of the couplings as they are indistinguishable from these ones. The corresponding fits are given by (the statistical error computed by MadGraph5 is 0.032 pb for dilepton case)
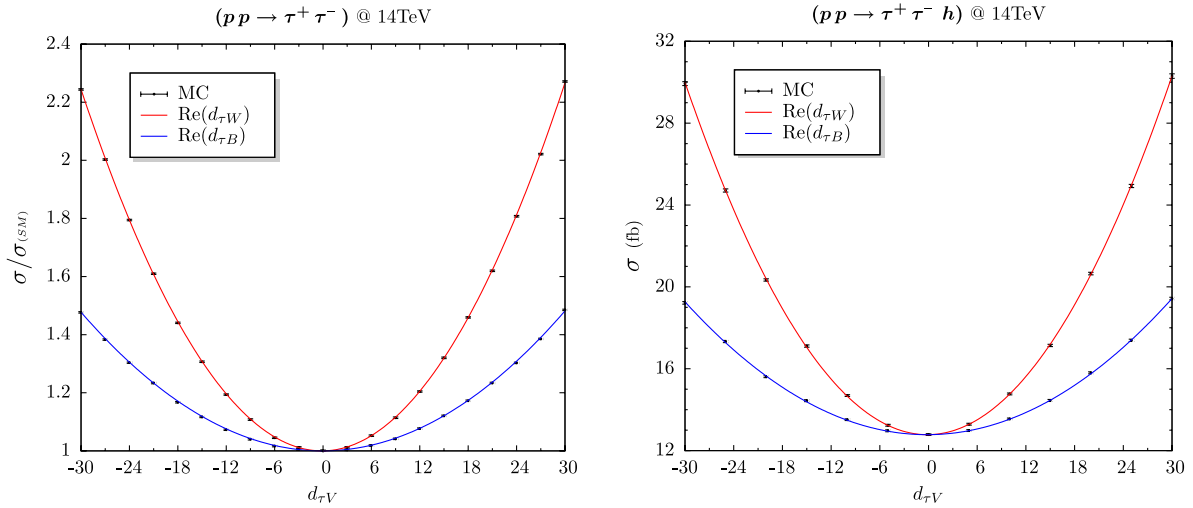
FIG. 8 (color online).   Cross section for the processes $pp \to \tau^+\tau^-$ (left) and $pp \to \tau^+\tau^- h$ (right) with $60 < m_{\tau\tau} < 120$ GeV at 14 TeV as calculated with MadGraph5 for different values of the anomalous coupling $d_{\tau V}$ and the corresponding fits.
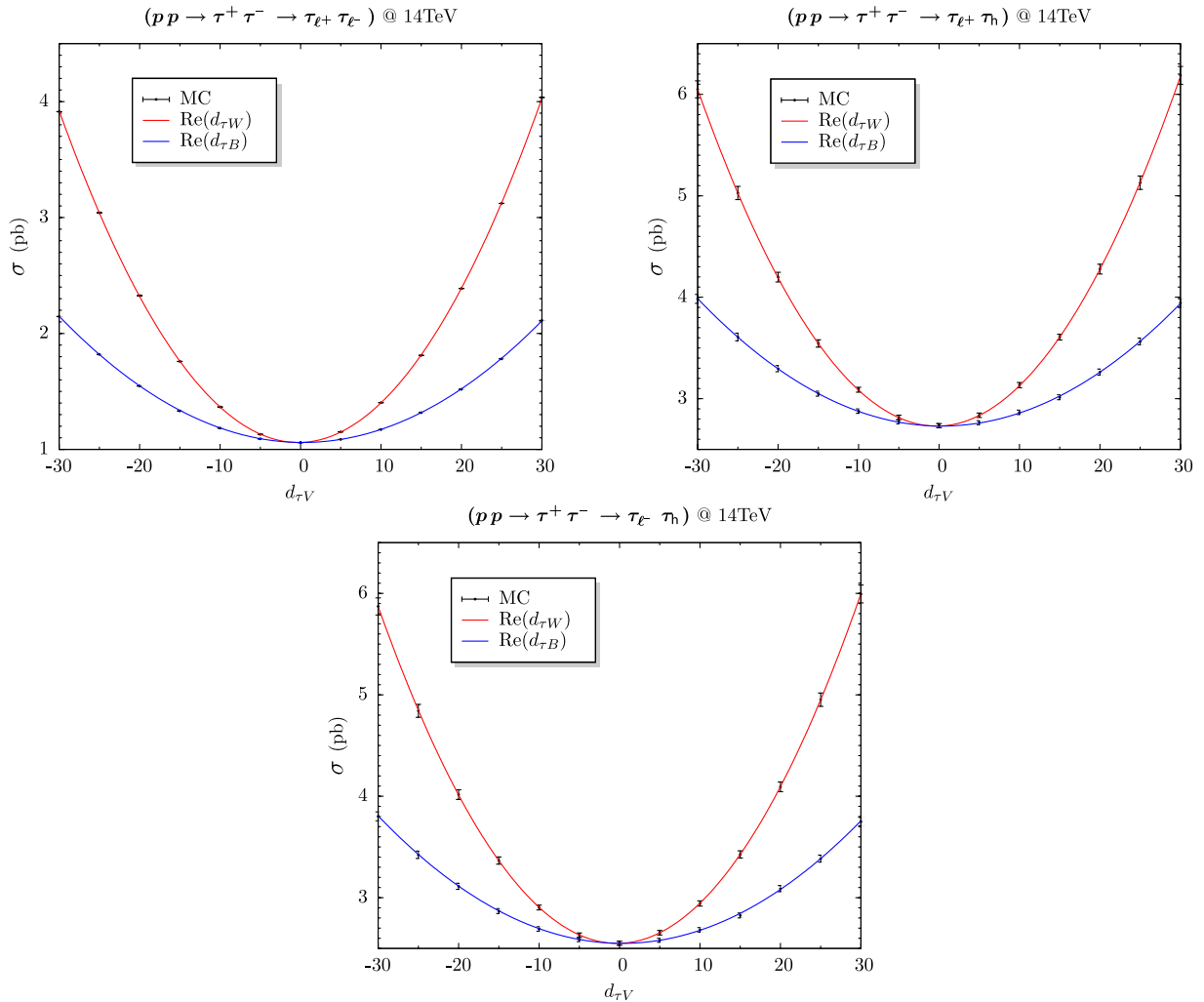

FIG. 9 (color online).   Cross section for the processes $pp \to \tau_{\ell^+}\tau_{\ell'^-}$, $pp \to \tau_{\ell^+}\tau_h$, and $pp \to \tau_{\ell^-}\tau_h$ with cuts described in the text at 14 TeV as calculated with MadGraph5 and DECAY for different values of the anomalous coupling $d_{\tau V}$ and the corresponding fits.

$$\sigma(pp \to \tau_{\ell^+} \tau_{\ell'^-}) = 0.27 \text{ pb} + (0.79 + 1.80 \times 10^{-3} \text{Re}(d_{\tau W}) + 3.24 \times 10^{-3} |d_{\tau W}|^2$$
$$- 6.44 \times 10^{-4} \text{Re}(d_{\tau B}) + 1.19 \times 10^{-3} |d_{\tau B}|^2) \text{ pb}$$

$$\sigma(pp \to \tau_{\ell^+} \tau_h) = 1.80 \text{ pb} + (0.95 + 2.15 \times 10^{-3} \text{Re}(d_{\tau W}) + 3.76 \times 10^{-3} |d_{\tau W}|^2$$
$$- 8.07 \times 10^{-4} \text{Re}(d_{\tau B}) + 1.37 \times 10^{-3} |d_{\tau B}|^2) \text{ pb}$$

$$\sigma(pp \to \tau_{\ell^-} \tau_h) = 1.60 \text{ pb} + (0.93 + 2.07 \times 10^{-3} \text{Re}(d_{\tau W}) + 3.76 \times 10^{-3} |d_{\tau W}|^2$$
$$- 8.22 \times 10^{-4} \text{Re}(d_{\tau B}) + 1.37 \times 10^{-3} |d_{\tau B}|^2) \text{ pb}. \tag{A4}$$

In these equations we have separated the contribution from the background as described in the main section (first number) and the signal.

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