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H →τ+τ−γ as a probe of the τ magnetic dipole moment

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Journal

Journal of High Energy Physics, 2016(12)

ISSN

1126-6708

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Publication Date

2016-12-01

DOI

10.1007/jhep12(2016)111

Peer reviewed

$H \to \tau^+\tau^-\gamma$ as a Probe of the τ Magnetic Dipole Moment

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Abstract

Low energy observables involving the Standard Model fermions which are chirality-violating, such as anomalous electromagnetic moments, necessarily involve an insertion of the Higgs in order to maintain $SU(2) \times U(1)$ gauge invariance. As the result, the properties of the Higgs boson measured at the LHC impact our understanding of the associated low-energy quantities. We illustrate this feature with a discussion of the electromagnetic moments of the τ-lepton, as probed by the rare decay $H \to \tau^+\tau^-\gamma$. We assess the feasibility of measuring this decay at the LHC, and show that the current bounds from lower energy measurements imply that 13 TeV running is very likely to improve our understanding of new physics contributing to the anomalous magnetic moment of the tau.

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I. INTRODUCTION

The discovery of the Higgs boson by the LHC [1, 2] in the $\sqrt{s} = 7$ and 8 TeV datasets represents a key milestone in the ongoing study of the Standard Model (SM). The fact that the observed boson has features which, at least in the broad brush, match with the SM expectations confirms that it is the principle agent of electroweak symmetry breaking. A major focus of the LHC run II is to establish its properties to high precision to either confirm the SM vision for electroweak breaking or to find the influence of new physics [3–6].

As the agent of the electroweak breaking, the observed Higgs boson is connected to any process for which the chirality of a SM fermion must flip. To maintain $SU(2) \times U(1)$ gauge invariance, such processes must contain an insertion of an electro-weak breaking vacuum expectation value (VEV), and the Higgs boson, as the fluctuations around the electroweak vacuum, has interactions connected with all such terms. A particularly interesting class of such observables are the electroweak dipole moments of the SM fermions, dimension five operators which can be sensitive probes of physics beyond the Standard Model. In fact, a long-standing mystery surrounds the magnetic dipole moment of the muon, whose experimental determination defies the best available theoretical predictions of the SM at more than two sigma [7].

The anomalous magnetic dipole moment of a fermion ψ is usually written in terms of the mass m_ψ and the electromagnetic coupling e as:

$$a_\psi \; \frac{e}{2m_\psi} \; \bar{\psi}\sigma^{\mu\nu}\psi \; F_{\mu\nu} \tag{1}$$

where $F_{\mu\nu}$ is the electromagnetic field strength tensor and the real quantity a_ψ parameterizes the size of the anomalous magnetic moment. The chiral structure of $\sigma^{\mu\nu}$ demands that one of ψ or $\bar{\psi}$ be left-chiral (and thus part of an $SU(2)$ doublet), and the other right-chiral (and thus an $SU(2)$ singlet). In the UV theory, it descends from a pair of dimension six operators combining $\bar{\psi}_L\sigma^{\mu\nu}\psi_R$ with an additional Higgs doublet (and field strengths for the $U(1)$ and $SU(2)$ gauge bosons). This obscured dependence on electroweak symmetry breaking is the origin of the well known fact that, in a theory where the SM Yukawa interactions account for all of the chiral symmetry breaking, the anomalous magnetic moment is proportional to m_ψ itself. It also implies that a_ψ maps uniquely (in a theory with a single source of electroweak breaking) to an interaction between the Higgs boson, $\psi\bar{\psi}$, and a photon.

In this article, we focus on the magnetic dipole moment of the τ lepton. As the heaviest of the SM leptons[1], the τ is a natural place to search for new physics, and the fact that neutrino masses imply some kind of physics beyond the Standard Model may be a further indication that the lepton sector is a good place to look for its influence. Indeed, if the anomalous magnetic moment of the muon is indeed a manifestation of such physics, one could hope that even larger relative deviations could be present in the τ sector. At the same time, measurements of the τ dipole moment are currently relatively mildly constrained, leaving room for large deviations.

Higgs decays thus furnish an opportunity to study the τ magnetic dipole, through the rare decay,

$$h \to \tau^+\tau^-\gamma \tag{2}$$

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[1] Quark dipole moments are more subtle, manifesting as properties of the hadrons into which they are bound.

which we find is potentially observable during high luminosity running of the LHC. As explained above, this process is related through gauge invariance to the more traditional probes of the τ's electroweak interactions via precision measurements of its production and/or decay [8–23], and we will see that Higgs decays provide both an opportunity to discover physics beyond the Standard model, or to provide some of the best constraints on an anomalous contribution to the τ magnetic moment.

This work is structured as follows. In Section II we discuss the operators which parameterize new physics contributions to the τ magnetic moment, and review the existing constraints. In Section III, we outline the search strategy and discuss backgrounds, and in Section IV we discuss the potential for discovery or limits in the case no excess of signal events is found. We conclude in Section V.

II. DIPOLE OPERATORS OF THE τ LEPTON: CURRENT CONSTRAINTS

Anomalous contributions to the electroweak dipole moments of the tau (at low-energy scales) originate from dimension six operators:

$$c_1 \ \bar{\tau}_R \sigma^{\mu\nu} B_{\mu\nu} \ H^\dagger L_3 + c_2 \ \bar{\tau}_R \sigma^{\mu\nu} \ H^\dagger W_{\mu\nu} L_3 + h.c. \tag{3}$$

where L_3 is the third family left-handed $SU(2)$ doublet, H is the Higgs doublet, $B_{\mu\nu}$ and $W_{\mu\nu}$ are the field strengths for the hypercharge and $SU(2)$ gauge bosons, and c_1 and c_2 are complex numbers with units of (energy)$^{-2}$. After electroweak symmetry-breaking, linear combinations of these operators lead to anomalous magnetic and electric dipole interactions, and analogous terms involving the Z boson.

Currently, the most stringent constraints on the τ dipole operators are from LEP2, where the DELPHI collaboration searched for $e^+e^- \to e^+e^-\tau^+\tau^-$ events, at various collision energies between 183 GeV and 208 GeV with a dataset corresponding to an integrated luminosity of 650 pb^{-1} [24]. The results were found to be consistent with the SM expectations, leading to the constraint

$$-0.052 < a_\tau^\gamma < 0.013, \quad 95\% \text{ CL.} \tag{4}$$

Similarly, the ALEPH collaboration searched for $e^+e^- \to \tau^+\tau^-$ events on the Z-pole with a dataset corresponding to an integrated luminosity of 155 pb^{-1} [25], and obtained the limit

$$a_\tau^Z < 1.14 \times 10^{-3}, \quad 95\% \text{ CL.} \tag{5}$$

Since the Z magnetic dipole interaction is much more severely constrained, we choose to focus on a_τ^γ from here on.

The combination related to the magnetic moment is described by,

$$\frac{1}{\Lambda^2} \left\{ v \ \bar{\tau}\sigma^{\mu\nu} \ \tau F_{\mu\nu} + h \ \bar{\tau}\sigma^{\mu\nu} \ \tau F_{\mu\nu} \right\} \tag{6}$$

where h is the Higgs boson and Λ^2 is a real parameter with dimensions of (energy)^2. The anomalous magnetic moment a_τ^γ is related to Λ and the Higgs VEV v via:

$$a_\tau^\gamma = -\frac{4m_\tau}{e} \ \frac{v}{\Lambda^2}. \tag{7}$$

3

In terms of Λ, the LEP bound (4) implies

$$|\Lambda| > \begin{array}{l} 333 \text{ GeV} \\ 666 \text{ GeV} \end{array} \qquad \text{for}: \quad \begin{array}{l} \Lambda^2 > 0 \\ \Lambda^2 < 0 \end{array}. \qquad (8)$$

The second term of Eq. (6) leads to the rare Higgs decay $h \to \tau^+\tau^-\gamma$. Measurements of this decay therefore translate into measurements of the dipole moment. In fact, the SM contribution to this decay mode has the same chirality structure as the dipole operator, allowing for constructive interference, and resulting in a relative enhancement of the new physics contribution compared to the direct search by LEP.

It is worth mentioning that the imaginary parts of c_1 and c_2 would also lead to a CP-violating electric dipole moment (and its Z analogue) for the τ. While interesting in their own right [26–34], CP symmetry prevents these new physics amplitudes from interfering with the SM contribution to $h \to \tau^+\tau^-\gamma$, thus leading to greatly decreased LHC sensitivity (see also [35]). For this reason, we choose here to focus on the magnetic dipole moment for which Higgs decays are a more sensitive probe.

III. $h \to \tau^+\tau^-\gamma$ AT THE LHC

In this section we estimate the LHC sensitivity reach to the τ magnetic dipole moment through the decay $h \to \tau^+\tau^-\gamma$. This is a challenging signal to reconstruct at a hadron collider for a number of reasons. First, τ leptons decay promptly, producing missing momentum along with either a charged lepton or a handful of hadrons. Events containing more than one of them can at best be incompletely reconstructed. Decays involving neutral pions also contain energetic photons, which can potentially fake the additional γ which distinguishes our rare decay mode from background associated with $h \to \tau^+\tau^-$. Photons themselves receive non-perturbative contributions to their production from QCD, which are not very well understood. Minimizing these uncontrolled contributions to photon production typically requires tight isolation cuts, which can be inefficient for events with dense angular population of energy in the detector. In addition, jets can fake both taus and photons at a rate which is intimately tied to the detector response, which is beyond our ability to reliably estimate. To work around these difficulties, we base our $h \to \tau^+\tau^-\gamma$ on the existing CMS search for $h \to \tau^+\tau^-$ [36], allowing us to draw from its detailed background study. We augment this search by requiring an additional energetic final state photon that along with the $\tau^+\tau^-$ system reconstructs the Higgs.

A.   Signal Selection

The CMS search analyzes multiple signal categories, based on the τ-pair decay modes, the decay products transverse momentum (p_T) spectrum, and N_j, the number of high p_T jets in the event. It is inclusive with regard to photons. The background estimates in each category are useful in deducing the dominant background components when an additional photon is required. Moreover, the results for the $N_j + 1$ categories can be used in estimating the backgrounds from jets faking photons by scaling the yields with the appropriate fake factor.

We focus on categories which have one hadronic tau (τ_h), and one leptonic tau decaying

Decay Mode	CMS Cuts	Additional Cuts
$\tau_h\tau_e$	$p_T^e > 24, \quad |\eta^e| < 2.1$ $p_T^{\tau_h} > 30, \quad |\eta^{\tau_h}| < 2.4$ $m_T < 30$ GeV	$p_T^\gamma > 30$ GeV, $\quad |\eta^\gamma| < 2.5$ $p_T^{\tau_h} < 45$ GeV $m_{\tau\tau} < 60$ GeV
$\tau_h\tau_\mu$	$p_T^\mu > 20, \quad |\eta^\mu| < 2.1$ $p_T^{\tau_h} > 30, \quad |\eta^{\tau_h}| < 2.4$ $m_T < 30$ GeV	$p_T^\gamma > 30$ GeV, $\quad |\eta^\gamma| < 2.5$ $p_T^{\tau_h} < 45$ GeV $m_{\tau\tau} < 60$ GeV

TABLE I: Baseline cuts for the signal categories (middle column, from [36]) and additional cuts (right column) for search categories with $\tau_h\tau_e$ and $\tau_h\tau_\mu$ tau decays.

either to an e or a μ (τ_e and τ_μ, respectively). This is motivated by the fact that the efficiency of the τ-pair reconstruction method is larger for the $\tau_h\tau_\ell$ modes than for purely leptonic modes which have more neutrinos, as well as for purely hadronic modes which suffer from uncertainties related to τ-tagged jets [36].

We select the "low-p_T" categories, for which the selection criteria for the τ candidates are close to the trigger threshold. This category is particularly sensitive to the $h \to \tau^+\tau^-\gamma$ decay because: the additional photon in the Higgs decay implies that the $\tau^+\tau^-$ pairs are on average less energetic than in the two-body decay; we expect our additional selection requirements to substantially reduce backgrounds, and low-threshold signal categories are likely to result in a larger signal sample to start with. We further select the $N_j = 0$ categories because a Higgs produced recoiling against additional jets has its acceptance reduced because its boosted decay products become more collimated, and tend to fail the isolation criteria more often.

CMS also employs a transverse mass cut, $m_T < 30$ GeV, which substantially reduces W-boson related backgrounds. The final selection cuts for the two search categories ($\tau_h\tau_e$ and $\tau_h\tau_\mu$) are shown in Table I. For completeness, we also include the additional cuts of our analysis which are discussed in subsequent sections.

It is worth mentioning that one could also consider different production topologies for the Higgs in searching for $h \to \tau^+\tau^-\gamma$, such as the vector boson $+ h$ (VH) [37] or vector boson fusion (VBF) [36] production modes, which show good sensitivity to $h \to \tau^+\tau^-$. These modes yield a richer final state, and thus are somewhat more fragile with respect to tight photon and tau isolation criteria. While it would be worthwhile to pursue them as part of a multi-channel analysis of $h \to \tau^+\tau^-\gamma$, we leave their detailed investigation for future work.

B. Backgrounds

A detailed study of the backgrounds contributing to the search for $h \to \tau^+\tau^-$ is presented in the CMS study, Ref. [36]. In this section, we use these results to infer the most important backgrounds for $h \to \tau^+\tau^-\gamma$ in the $\tau_h\tau_\ell$, $N_j = 0$ topology. The dominant background for $h \to \tau^+\tau^-$ arises from production of a Z boson which subsequently decays into $\tau^+\tau^-$. There are also much smaller contributions from electroweak and QCD processes. We further require an additional energetic isolated photon to be present, which can either correspond to real electromagnetic radiation or a jet which is misidentified as a photon.

The contributions to the real photon backgrounds can be roughly estimated from the

$N_j = 0$ backgrounds studied in [36] scaled[2] by $\sim \alpha$. This scaling suggests that of the backgrounds considered, only the $Z \to \tau^+\tau^-$ is large enough to be relevant. Thus, the real photon background can be approximated as coming entirely from $Z + \gamma$ diboson production.

The size of the background from jets misidentified as a photon can be estimated based on the $N_j = 1$ analysis of [36] scaled by the fake rate of $f_{j\to\gamma} \sim 10\%$ [38]. To make a fair comparison, we apply a cut of $p_T > 30$ GeV and $|\eta^\gamma| \leq 2.5$ on signal photons in order to match the jet cut in the $N_j = 1$ categories. Once again, the only relevant background after applying the fake rate is Z+jet production, where the Z decays into taus and the jet fakes a photon.

The backgrounds can be reduced by applying further cuts on top of the CMS analysis. First, we require $p_T^{\tau_h} < 45$ GeV (see also [39]), which reduces contributions from Z (and W) boson decays, while having negligible effects on the signal yield. Second, we impose a cut on the $\tau^+\tau^-$ invariant mass, $M_{\tau\tau} < 60$ GeV in order to reduce the Z-background which is narrowly centered around $m_Z \sim 91$ GeV. In a realistic setting, the $M_{\tau\tau}$ distribution is smeared out by the imperfect τ reconstruction; nonetheless we will see below that an upper cut $M_{\tau\tau} < 60 - 75$ GeV removes most of the Z background, while still preserving a large part of the signal.

C. Monte Carlo Simulation

To assess future LHC sensitivity to the dipole operator from searches for the $h \to \tau_\ell \tau_h \gamma$ decay mode, we perform a Monte Carlo simulation of the signal and $Z + \gamma$ and Z+jet backgrounds described above. All three processes are simulated in MadGraph5_aMC@NLO (MG5) [40], with showering and hadronization by Pythia6 [41, 42], and jet matching under the CKKW prescription [43–45]. Tau decays are handled at the generator level [46] (as opposed to by Pythia), as discussed below. The hard matrix elements are derived from FeynRules implementations [47, 48], supplemented by higgs effective vertices with gluons and photons and the tau dipole operators [49]. For the Z+jet background, we include a K-factor of $K_{Zj} \sim 1.5$ representing the enhancement of the cross-section from higher order QCD corrections [50].

The detector reconstruction is simulated by the Delphes 3.3.0 [51] detector emulator with parameters from its default CMS card. At the detector level, anti-k_T jets [52] are reconstructed with FastJet [53]. Electrons, muons, and photons are required to be isolated within a cone of size $\Delta R = 0.5$, where an object is considered to be isolated if the ratio of the sum of p_T depositions within the cone around it to its own p_T is smaller than 0.1. Photon isolation, is applied in MG5 using the built-in Frixione prescription [54] with parameters $\Delta R = 0.4$ and $p_T^{\gamma \, min} = 10$ GeV. We decay the taus at the generator level in order to include the pions from their decay in this isolation cut.

The tau pair kinematics are reconstructed using the public stand-alone version of the package, SVFitStandAlone [55], employing a likelihood based method [36, 56, 57] which improves on the collinear approximation [58]. We calibrate this package with the Delphes-level covariance matrix of the transverse missing-energy two-vector $\vec{\slashed{E}}_T$ using a Monte Carlo sample of Z+jet in the CMS fiducial region. By comparing the "truth"-level missing energy information (neutrinos) with the reconstructed $\vec{\slashed{E}}_T$, we deduce the covariance matrix

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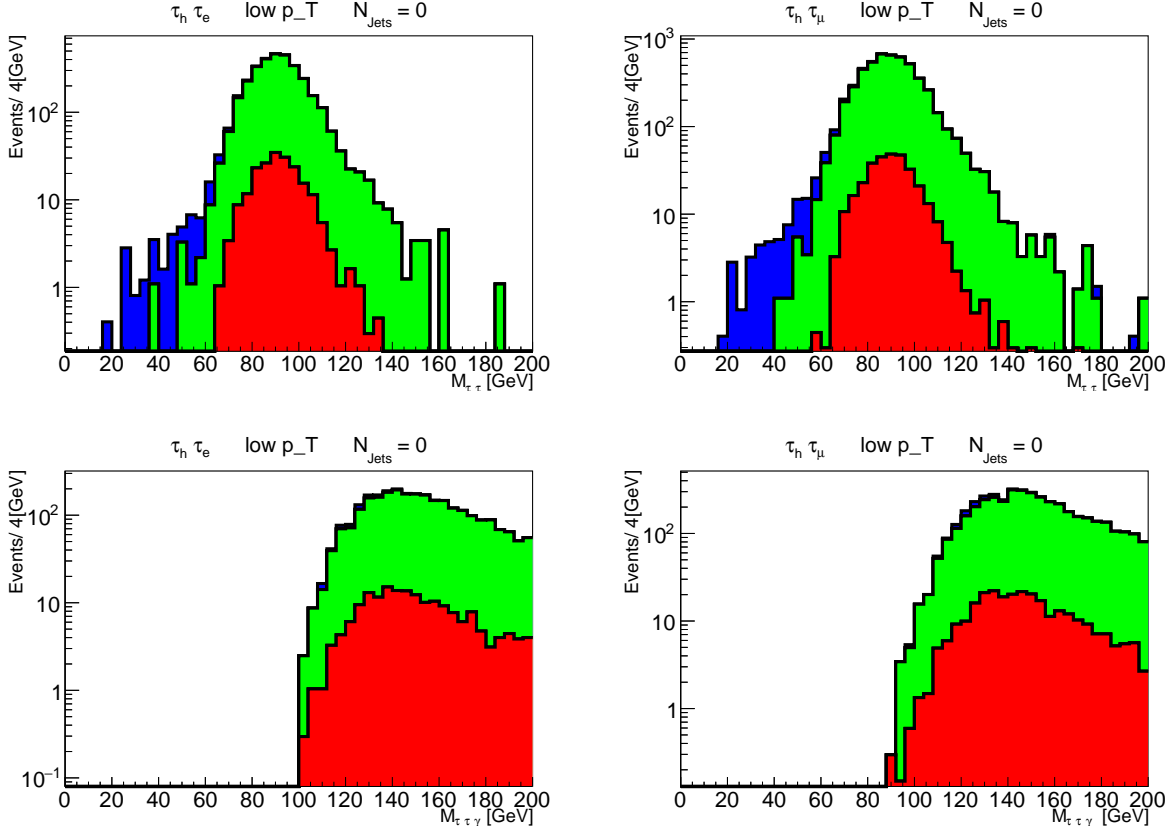[2] Note that the required stringent isolation cuts control large collinear logarithms.

FIG. 1: The $M_{\tau\tau}$ (upper plots) and $M_{\tau\tau\gamma}$ (lower plots) distributions for the two signal categories $\tau_h\tau_e$ (left) and $\tau_h\tau_\mu$ (right) at $\sqrt{s} = 13$ TeV and $\mathcal{L}_{\rm int} = 300$ fb^{-1}, before applying the $M_{\tau\tau} < 60$ GeV cut. Contributions from the signal $gg \to h \to \tau\bar{\tau}\gamma$ (blue), $pp \to Z + \gamma$ (red), and $pp \to Z + j(\gamma)$ (green) are indicated.

parameters. We find that SVFitStandAlone reconstructs masses for the h and Z that are systematically somewhat higher than their pole masses. As a result, the Higgs peak is smeared into the range $120 - 140$ GeV. We thus define 120 GeV $\leq M_{\tau\tau\gamma} < 140$ GeV as the signal region of our analysis.

We note that Ref. [36] also imposes a cut on the energy deposited near the hadronically decaying tau. This cut is not possible to implement via our work-flow, and thus is neglected. However, because of the strong isolation cuts already imposed on the other hard final state objects in the event, we expect this omission has little effect on our final conclusions.

IV.   RESULTS AND PROJECTED LIMITS

We analyze the reach of the LHC running at $\sqrt{s} = 13$ TeV, with the reconstruction strategy outlined above. In Fig. 1 we show the expected $M_{\tau\tau}$ and $M_{\tau\tau\gamma}$ distributions for the signal (with $\Lambda = 343$ GeV, $\Lambda^2 > 0$) and $Z + \gamma$ and $Z + j$ background processes, in the $\tau_h\tau_e$ and $\tau_h\tau_\mu$ topologies, for an integrated luminosity of $\mathcal{L}_{\rm int} = 300$ fb^{-1}. All analysis cuts with the exception of the $M_{\tau\tau} < 60$ GeV cut are applied. Evident from the upper plots is the motivation for the $M_{\tau\tau} < 60$ GeV cut to separate the signal from the backgrounds. The $M_{\tau\tau\gamma}$ distributions after this cut are presented in Fig. 2, and demonstrate its dramatic
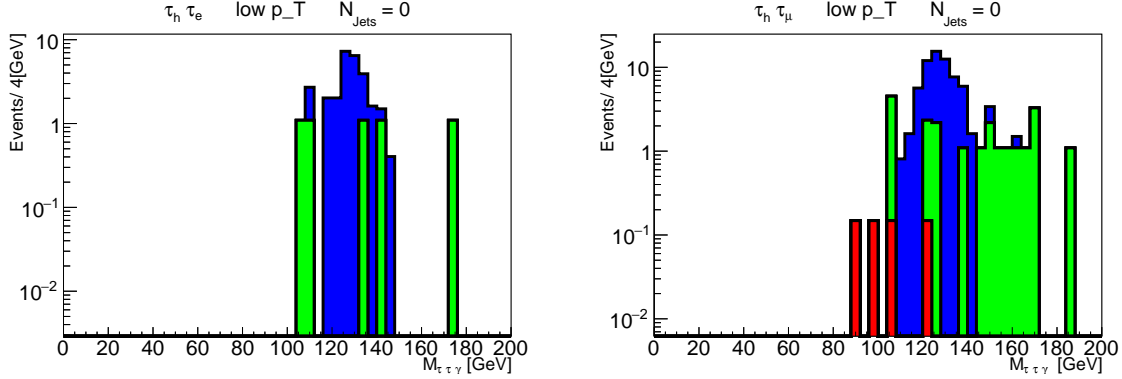
FIG. 2: The $M_{\tau\tau\gamma}$ distributions of the two signal categories, $\tau_h\tau_e$ (left) and $\tau_h\tau_\mu$ (right), after applying the $M_{\tau\tau} < 60$ GeV cut, with color coding as in Fig. 1.

Signal Region	N_{SM}	$\hat{N}_{\mathrm{INT}}$	$\hat{N}_{\mathrm{NP}}$
$\tau_h\tau_e$	0.124	-8.19×10^4 GeV^2	2.88×10^{11} GeV^4
$\tau_h\tau_\mu$	0.371	-5.88×10^5 GeV^2	7.31×10^{11} GeV^4

TABLE II: Sizes of the three coefficients, N_{SM}, $\hat{N}_{\mathrm{INT}}$, and $\hat{N}_{\mathrm{NP}}$, corresponding to $\mathcal{L}_{\mathrm{int}} = 300$ fb^{-1}.

efficacy, with only a handful of background events left in the 120 GeV $\leq$ M$_{\tau\tau\gamma} <$ 140 GeV signal region.

To estimate the eventual sensitivity of the high luminosity LHC to new physics in the tau magnetic dipole, we write the amplitude for the signal process as

$$\mathcal{M}_{\mathrm{sig}} = \mathcal{M}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\mathcal{M}_{\mathrm{NP}} \tag{9}$$

with the Λ dependence explicitly factored out. The yield of signal events (for $\mathcal{L}_{\mathrm{int}} = 300$ fb^{-1}) after cuts is:

$$N_{\mathrm{sig}} = N_{\mathrm{SM}} + \frac{2}{\Lambda^2}\hat{N}_{\mathrm{INT}} + \frac{1}{\Lambda^4}\hat{N}_{\mathrm{NP}}. \tag{10}$$

The sizes of these three coefficients, after all analysis cuts, are shown in Table II. We present N_{sig} as a function of Λ for both signs of Λ^2 in Fig. 3, including the $\tau_h\tau_e$ and $\tau_h\tau_\mu$ channels, and also the combined number of events in both signal categories, $\tau_h\tau_\ell$.

Under the Assumption that no signal is observed, and the mean number of background events, 6.7, is obtained, one may place a lower limit on the new physics scale Λ. The 95% CL bound on Λ in that case would be given by:

$$|\Lambda| > \begin{matrix} 634 \text{ GeV} \\ 739 \text{ GeV} \end{matrix} \qquad \text{for}: \qquad \begin{matrix} \Lambda^2 > 0 \\ \Lambda^2 < 0 \end{matrix}. \tag{11}$$

which translates into a projected limit on the anomalous moment of

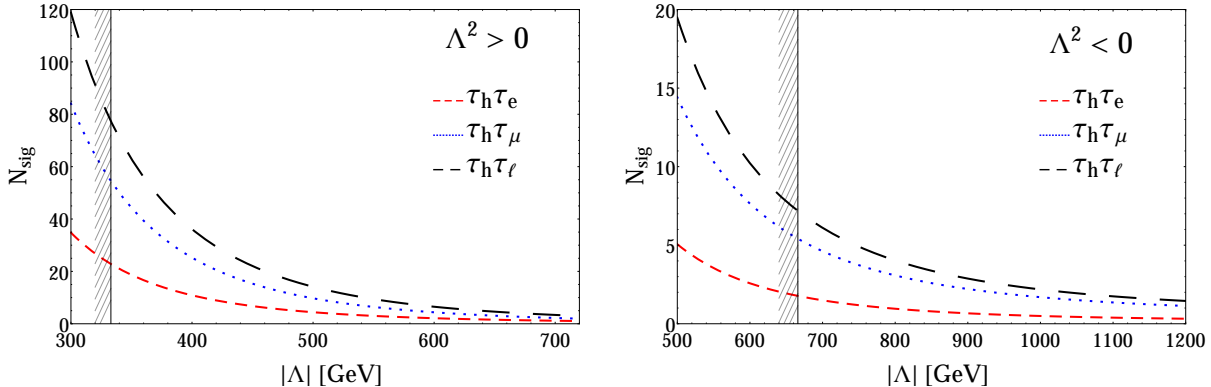$$-0.0144 < a_\tau^\gamma < 0.0106. \quad (95\% \text{ CL}), \tag{12}$$

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FIG. 3: The expected number of signal events, $N_{\rm sig}$, as a function of Λ in the two signal categories, $\tau_h \tau_e$ (red), $\tau_h \tau_\mu$ (blue), and their combination $\tau_h \tau_\ell$ (black), for $\Lambda^2 > 0$ (left plot) and $\Lambda^2 < 0$ (right plot), for $\mathcal{L}_{\rm int} = 300$ fb^{-1}. The LEP exclusion limits are indicated by the hatched vertical lines.

approximately a factor of two improvement on Λ for $\Lambda^2 > 0$ or 10% for $\Lambda^2 < 0$.

V. CONCLUSIONS AND OUTLOOK

As measurements of the Higgs boson become more sophisticated, we move into a regime where it becomes a tool in its own right to search for new physics. In particular, low energy observables involving a chiral flip of the SM fermions necessarily invoke electroweak symmetry-breaking, and thus imply a modification of the properties of the Higgs. In this work, we have examined the possibility that one can place bounds on the electromagnetic moments of the τ by searching for the rare decay of the Higgs into $\tau^+ \tau^- \gamma$. Given the longstanding discrepancy between measurements of the muon's magnetic moment and SM predictions, one could hope that a_τ^γ might also be a likely target for which to search for manifestations of new physics.

We find the promising result that the LHC with a large data set should be sensitive to modifications of the τ magnetic dipole moment beyond the current bounds extracted from LEP – by about a factor of two on the new physics scale if $\Lambda^2 > 0$. Given these promising results, it would be worthwhile to follow up with a study based on more realistic detector simulations and including effects beyond our ability to reliably simulate, such as pile-up. We hope that our study will motivate the experimental collaborations to carry out this effort.

Another interesting direction for the future would be to study the prospects at a future $e^+ e^-$ collider such as the ILC or a future circular collider [59]. While the rate for hZ production at such colliders is considerably smaller than the inclusive Higgs production at the LHC, new physics saturating the LEP bound nonetheless allows for a handful of events, and the prospects depend sensitively on the ability to efficiently reconstruct the signal events and reject backgrounds.

The discovery of the Higgs is a triumph of run I of the LHC. We look forward to run II and beyond to follow up with precision measurements that reveal the deep secrets that reflect its character.

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