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Search for Lepton Flavor Violation in Z and Higgs decays with the CMS Experiment

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Abstract

The standard model of particle physics explicitly conserves lepton flavor in particle interactions in spite of the absence of an underlying symmetry. The observation of neutrino oscillation proves neutral lepton flavor violation (LFV) and thus motivates a search for violations in charged lepton interactions. Here, searches for LFV performed by the CMS collaboration in leptonic decays of the Z and Higgs boson are presented. The data analyzed contains 19.7 fb^{-1} (2.3 fb^{-1}) of proton-proton collisions at $\sqrt{s} = 8$ (13) TeV delivered by the LHC during 2012 (2015).

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Search for Lepton Flavor Violation in Z and Higgs decays with the CMS Experiment

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Abstract

Searches for charged lepton flavor violation in decays of the Z and Higgs boson using data corresponding to an integrated luminosity of $19.7 (2.3) \text{ fb}^{-1}$ collected by the CMS detector in proton-proton collisions at $\sqrt{s} = 8 (13) \text{ TeV}$ are described.

Keywords: Lepton flavor violation, Z boson, Higgs boson, CMS

1. Introduction

Lepton flavor is a conserved quantity in the standard model (SM) of particle physics. This conservation is not a consequence of an underlying gauge symmetry, however, and from neutrino oscillation we know of its violation in the neutral sector. Neutrino oscillation allows in principle for charged lepton flavor violation (LFV) but the large mass difference between neutrinos and heavy gauge bosons suppresses such interactions to orders of magnitude immeasurable by experiments [1]. However, extensions of the SM can lead to significant enhancements of processes involving charged LFV. While the probability of Z boson decays to leptons of different flavor can be enlarged by supersymmetric models and models with heavy Dirac or Majorana neutrinos [1, 2], LFV Higgs boson decays can become amplified already in models assuming the validity of the SM only up to a finite scale [3]. Other possibilities are models involving more than one Higgs doublet [4].

Here, the search for LFV in decays of the Z boson to an electron and a muon [5] as well as in Higgs boson decays to any combination of different lepton flavors [6, 7, 8] with the CMS Experiment [9] is described.

2. Search for Lepton Flavor Violation in Z decays

2.1. Background estimation and event selection

This analysis looks for a peak in the invariant mass spectrum of selected electron-muon pairs at the nominal Z mass using 19.7 fb^{-1} of data collected in pp collisions by CMS at $\sqrt{s} = 8 \text{ TeV}$ [5]. Main backgrounds arise from dileptonic $t\bar{t}$ and WW decays, as well as from $Z \rightarrow \tau\tau$ with subsequent tau decays into an electron and a muon. Other backgrounds come from jets being misidentified as leptons (e.g. from W+jets or multijet production), single top and other diboson production. While the component of the background stemming from misidentified jets is estimated using a data-driven technique, the remaining backgrounds as well as the signal hypothesis are modeled using simulation. Simulated background samples are normalized to previously calculated cross sections except for $t\bar{t}$ production which is normalized to the cross section measured by CMS. The signal sample is normalized to the production cross section of the Z boson and scaled to a branching fraction $\mathcal{B}(Z \rightarrow e\mu) = 10^{-6}$ for the purposes of finding appropriate selection criteria and visualization.

In order to reduce the background contribution around the nominal Z mass, topological selection criteria are introduced in addition to basic trigger, lepton identification and isolation requirements. These include the transverse momentum of the leading jet in the event,

Figure 1: Distribution of the invariant mass reconstructed from the electron and muon after the full selection. The signal is stacked on top of the background estimate.

the transverse mass of the muon and the transverse momentum of the Z boson candidate reconstructed from the selected muon and electron. The thresholds used in the selection are determined through optimization of the quantity $S/\sqrt{S+B+\Delta B}$ in the signal region between 88 – 94 GeV. Here, S and B are defined as the signal and total background yields, respectively, and ΔB denotes the uncertainty in the background estimate. The distribution of the invariant electron-muon mass after the full selection is depicted in figure 1.

2.2. Systematic uncertainties

The dominant systematic uncertainties in the signal region are attributed to the finite number of simulated background events (10.6%) and the normalization of both signal and background (3.3% and 6.8%, respectively). Uncertainties of the order of 1 – 3% arise from the mismeasurement of the electron energy, the transverse momentum of the muon, the luminosity, knowledge of the parton density functions as well as the number of simultaneous collisions in a single bunch crossing (pileup). Uncertainties in trigger, identification and isolation efficiencies, as well as in the jet energy and the missing transverse energy are typically below 1%.

2.3. Results

After the full selection, 87 events are found within the signal region in data, while 83 ± 9 (stat.) from background and 43.8 ± 0.5 (stat.) from signal using a branch-

ing fraction of 10^{-6} are expected. Given these numbers, an observed (expected) upper limit on the branching fraction of $\mathcal{B}(Z \rightarrow e\mu) < 7.3 \cdot 10^{-7}$ ($6.7^{+2.8}_{-2.0} \cdot 10^{-7}$) at 95% confidence level (CL) is obtained. This result is similar to that obtained by the ATLAS Collaboration [10].

3. Search for Lepton Flavor Violation in decays of the Higgs boson

3.1. Background estimation and event selection

Three different final states are investigated in the search for LFV in decays of the Higgs boson: $e\mu$, $e\tau$ and $\mu\tau$ [6, 7, 8]. The $e\tau$ ($\mu\tau$) final state is further split into $e\tau_\mu$ and $e\tau_h$ ($\mu\tau_e$ and $\mu\tau_h$) where the subscripts denote the decay of the tau lepton into leptons (e/μ) or hadrons (h). The final observable in the $e\tau$ and $\mu\tau$ final states is the collinear mass m_{col} . It is constructed from the two leptons and the projection of the missing transverse energy on the direction of the visible decay products of the tau under the assumption that the decay products are heavily boosted along the tau flight direction. In the $e\mu$ final state the invariant mass of electron and muon is used as the final observable. While for the all final states 19.7 fb^{-1} of data collected in pp collisions by CMS at $\sqrt{s} = 8 \text{ TeV}$ are analyzed, additional 2.3 fb^{-1} of data collected at $\sqrt{s} = 13 \text{ TeV}$ are analyzed in case of the $\mu\tau$ final state.

The dominant backgrounds in final states with a hadronically decaying tau come from $Z \rightarrow \tau\tau$ and jets being falsely identified as tau leptons (e.g. W+jets and multijet production). To estimate the $Z \rightarrow \tau\tau$ background, an embedding technique is used in which the muons of $Z \rightarrow \mu\mu$ events measured in data are replaced by simulated taus. Background from jets identified as taus is estimated by using control regions based on the electric charges of the leptons and whether or not they are isolated in the detector. The extrapolation to the signal region is done with the probability for leptons being misidentified as jets measured in $Z \rightarrow ee/\mu\mu + X$ events. Other backgrounds coming from $H \rightarrow \tau\tau$, $t\bar{t}$, diboson and single top quark production as well as the signal are estimated using simulation and in case of $t\bar{t}$ a normalization measured in a control region. Backgrounds in final states with leptonically decaying taus are estimated in a similar manner.

In case of the $e\mu$ final state a combination of fit functions is used to model the total background. The functions depend on the region of the detector where the leptons were reconstructed and on the categories which are described later in the text. They consist of polynomials

of order 4, exponential functions and power laws. The signal is modeled using the sum of two Gaussians with resolutions depending again on the detector region in which the leptons were reconstructed. These functions are determined from simulation.

While in all three final states trigger, lepton identification and isolation requirements are imposed, additional criteria are used to reduce backgrounds which differ depending on the final state. Variables used in $e\tau$ and $\mu\tau$ final states are the transverse lepton momenta, their transverse mass and the azimuthal angles between the two leptons as well as the angles between lepton and missing transverse energy. The numerical values of the selection criteria are determined by maximizing the quantity $S/\sqrt{S+B}$ in the interval $100 \text{ GeV} < m_{\text{col}} < 150 \text{ GeV}$ with the signal scaled to a LFV branching fraction of 1%. In the $e\mu$ final state the missing transverse energy is used to suppress backgrounds with significant true missing energy from neutrinos. Finally, in all final states with one reconstructed electron and one muon ($e\mu$, $e\tau_\mu$ and $\mu\tau_e$) events are rejected that feature jets initiated by b quarks.

In order to make use of the different Higgs boson production mechanisms, categories are introduced. These categories mainly use the number of jets present in the event. The 0-jet and 1-jet categories primarily contain signal events produced via gluon fusion while the 2-jet category is dominated by Higgs boson production via vector boson fusion (VBF). In the 2-jet category additional requirements on the pseudorapidity difference and the invariant mass of the dijet system are made.

3.2. Systematic uncertainties

Systematic uncertainties in the normalization in the $e\tau$ and $\mu\tau$ final states in 8 TeV data range from 9–100% for estimated backgrounds and are of order 10% for the signal. Trigger, identification, isolation, luminosity and b-tagging uncertainties are between 1–6.7%. Uncertainties affecting the shape of the signal and background distributions come from energy mismeasurements (τ_h , jet and unclustered energy) and are in the range of 3–10%. Furthermore the observation of a shift of the m_{col} peak by 1–2% with respect to the simulation is corrected and associated with a 100% uncertainty. In 13 TeV data the normalization uncertainties are estimated to be between 10–41% for backgrounds while for the signal they remain the same. Luminosity, b-tagging, trigger, identification and isolation uncertainties are now in the range 2.7–10% and uncertainties in the shape from mismeasured energies are between 3–20%. In the $e\mu$ final state the largest systematic

uncertainties come from the jet energy scale and resolution (up to 78%), theory (2.6–7.8%) and acceptance (0.8–5.1%). Lepton energy scale and dilepton mass resolution uncertainties are between 1–5%. Other uncertainties in the normalization from trigger, lepton identification, luminosity, b tagging, pileup and the background model range from 1–2.6%.

3.3. Results

In the $e\mu$ and $e\tau$ final states no excess is observed within the signal region. Thus, 95% CL upper limits on the respective branching fractions are set: $\mathcal{B}(H \rightarrow e\mu) < 0.035\%$ and $\mathcal{B}(H \rightarrow e\tau) < 0.69\%$. While the limit on $\mathcal{B}(H \rightarrow e\mu)$ is far less stringent than that determined from $\mu \rightarrow e\gamma$ search results, $O(10^{-6})$ [3], the limit on $\mathcal{B}(H \rightarrow e\tau)$ is improved by an order of magnitude from $O(10\%)$ [3] to $O(1\%)$ by this analysis.

The data collected at 8 TeV show an excess over the background estimate in the $\mu\tau$ final state (see fig. 2). This excess results in a best fit value for the branching fraction of $\mathcal{B}(H \rightarrow \mu\tau) = (0.84^{+0.39}_{-0.37})\%$ corresponding to a 2.4σ deviation from the SM hypothesis. Because of this excess, the observed 95% CL upper limit on the branching fraction is considerably worse than the expected one: $\mathcal{B}(H \rightarrow \mu\tau) < 1.51\%$ compared to $\mathcal{B}(H \rightarrow \mu\tau) < (0.75 \pm 0.38)\%$. The analysis of 2.3 fb^{-1} of data collected at 13 TeV does not reveal an excess and an observed upper limit on the branching fraction of $\mathcal{B}(H \rightarrow \mu\tau) < 1.20\%$ is set. The best fit value for the branching fraction is measured to be $\mathcal{B}(H \rightarrow \mu\tau) = (-0.76^{+0.81}_{-0.84})\%$, which is consistent with zero. It is however important to point out that the best fit value of the branching fraction measured at 8 TeV cannot be excluded by the result of this analysis. Nevertheless, also in the $\mu\tau$ final state the limit is an improvement of an order of magnitude over those from indirect measurements [3].

The limits on the branching fractions enable us to also set upper limits on the LFV Yukawa couplings [3] themselves via

$$|Y_{\ell^\alpha \ell^\beta}|^2 + |Y_{\ell^\beta \ell^\alpha}|^2 = \frac{8\pi}{m_H} \Gamma_{\text{SM}} \frac{\mathcal{B}(H \rightarrow \ell^\alpha \ell^\beta)}{1 - \mathcal{B}(H \rightarrow \ell^\alpha \ell^\beta)}, \quad (1)$$

where ℓ^α and ℓ^β ($\ell^\alpha \neq \ell^\beta$) denote the lepton flavors, m_H the mass of the Higgs boson and Γ_{SM} the decay width of the SM Higgs boson. The limits are determined to be

- $\sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 5.4 \cdot 10^{-4}$
- $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.4 \cdot 10^{-3}$
- $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.16 \cdot 10^{-3}$.

Figure 2: Distribution of the collinear mass reconstructed from the muon and tau after the full selection combined for all categories and weighted by $S/(S+B)$. The signal is stacked on top of the background estimate and scaled to the best fit branching fraction.

4. Summary

Searches for lepton flavor violating decays of the Z and Higgs boson have been presented. An upper limit on the branching fraction $\mathcal{B}(Z \rightarrow e\mu)$ similar to that measured by the ATLAS Collaboration was set. An excess of 2.4σ observed in the dataset collected in 2012 in decays of the Higgs boson to a muon and a tau could not be confirmed with data taken in 2015. However, the best fit branching fraction measured with 2012 data could not be excluded either. The absence of an observed signal lead to upper limits on the respective branching fractions in all final states considered as well as on the lepton flavor violating Yukawa couplings. Limits on $\mathcal{B}(H \rightarrow e\tau)$ and $\mathcal{B}(H \rightarrow \mu\tau)$ constitute improvements by an order of magnitude over those from indirect measurements.

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