

Recent results on lepton flavor violation from CMS*

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Abstract

Lepton flavor is a conserved quantity in the standard model of particle physics. It does not follow from an underlying gauge symmetry however, and from neutrino oscillation we know of its violation in the neutral sector. Charged lepton flavor violation induced by neutrino oscillation is heavily suppressed by the small neutrino and heavy gauge boson masses making its discovery extremely unlikely. Extensions of the standard model are able to enhance the branching fractions of such decays to levels observable at the LHC. Here, three searches for lepton flavor violation with the CMS experiment are presented: the decay of the Higgs boson into a muon and a tau lepton, and the decay of heavy resonances as well as the Z boson into an electron and a muon.

LEPTON FLAVOR VIOLATION IN HIGGS DECAYS

Introduction

Flavor-violating Yukawa couplings become possible for example in case the standard model (SM) is valid only until a finite scale [1]. Other possibilities for their introduction are theories with more than one Higgs doublet [2]. While the decay of the Higgs boson to an electron and a muon is strongly constrained by $\mu \rightarrow e\gamma$ searches ($\mathcal{B}(\text{H} \rightarrow e\mu) < \mathcal{O}(10^{-8})$), $\mathcal{B}(\text{H} \rightarrow e\tau)$ and $\mathcal{B}(\text{H} \rightarrow \mu\tau)$ are constrained to upper limits of only $\mathcal{O}(10\%)$ [1] making these channels especially interesting for a direct search.

Analysis

Based on an integrated luminosity of 19.7 fb^{-1} collected with the CMS detector [3] in pp collisions at $\sqrt{s} = 8 \text{ TeV}$, a search for lepton flavor violation (LFV) is performed in the two final states $\text{H} \rightarrow \mu\tau_e$ and $\text{H} \rightarrow \mu\tau_h$ where H corresponds to a standard model Higgs boson of mass $m_{\text{H}} = 125 \text{ GeV}$ and τ_e as well as τ_h denote the decays of tau leptons into electrons and hadrons [4]. The main background in the $\text{H} \rightarrow \mu\tau_e$ channel is $\text{Z} \rightarrow \tau\tau$ while subdominant background originates from jets misidentified as tau leptons in $\text{W}+\text{jets}$ and multijet events. In the $\text{H} \rightarrow \mu\tau_h$ channel the latter is the dominant background and $\text{Z} \rightarrow \tau\tau$ as well as $\text{Z}+\text{jets}$ are less important. These backgrounds are estimated using data-driven methods while smaller contributions from standard model $\text{H} \rightarrow \tau\tau$ decays as well as $t\bar{t}$ and diboson production are estimated by simulation. The simulation are normalized the integrated luminosity and theory calculation whereas for $t\bar{t}$ a control region in data is used. The signal is estimated using simulation and theory calculations.

Categorization, Mass Reconstruction and Event Selection

Depending on the final state, events are triggered by requiring a single muon ($H \rightarrow \mu\tau_h$) or a muon and an electron ($H \rightarrow \mu\tau_e$) fulfilling loose kinematic and identification criteria. The leptons in these two final states are then subject to tighter kinematic and identification requirements and must be isolated from other activity in the event. Events are further categorized based on the number of high energetic jets to enhance the sensitivity in the different production mechanisms. Signal events in the zero jet category are predominantly from Higgs bosons produced via gluon-gluon fusion while the two jet category is mostly populated by Higgs bosons produced through vector boson fusion. The one jet category contains signal events both from gluon-gluon fusion and production in association with a vector boson.

The variable of interest is the collinear mass (M_{col}) reconstructed from the muon, the visible part of the tau lepton and the component of the missing transverse energy pointing in the direction of the tau lepton. This technique is based on the collinear approximation which assumes that because the tau lepton mass is much smaller than that of the Higgs boson its decay products are highly boosted in the direction of the τ .

In order to reduce background contribution, discriminating variables are defined. These variables are based on the transverse momenta of the final state leptons, the transverse mass $M_T^\ell = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos \Delta\phi)}$ of lepton ℓ ($= e, \mu, \tau$), and the azimuthal angles between the leptons and between one lepton and the missing transverse energy. p_T^ℓ denotes the transverse momentum of lepton ℓ , E_T^{miss} the missing transverse energy in the event, and $\Delta\phi$ the azimuthal angle between p_T^ℓ and E_T^{miss} . The selection criteria for these discriminants are chosen such that $S/\sqrt{S+B}$ is maximal. S and B are the number of expected signal and background events in the region $100 < M_{\text{col}} < 150 \text{ GeV}$, and $\mathcal{B}(H \rightarrow \mu\tau) = 10\%$. Furthermore, the jets in the vector boson fusion category must have an invariant mass $m_{jj} > 550 \text{ GeV}$ and must be separated by a pseudorapidity gap of $\Delta\eta > 3.5$. In order to reduce contamination from $t\bar{t}$, events with at least one b-tagged jet are vetoed in the $H \rightarrow \mu\tau_e$ channel.

Systematic Uncertainties

Normalization uncertainties range from 9–100% for the different background estimations while for the signal they are of the order of 10% depending on the parton density functions,

renormalization and factorization scales, and the modeling of both the underlying event and parton showering. Uncertainties from the trigger, identification and isolation of the individual leptons, luminosity and b-tagging range between 2 – 3% and are small compared to the others. Uncertainties affecting the shape of signal and background distributions come from the energy scale of hadronically decaying tau leptons (3%), the jet energy scale (3 – 7%) and the unclustered energy scale affecting the missing transverse energy (10%). The observation of a 1% shift of M_{col} between data and simulation in $Z \rightarrow \tau\tau$ events is associated with an uncertainty of 100%.

Results

A binned likelihood is used to extract the event yields of signal and individual backgrounds from the collinear mass distribution for every category and channel. Using these values, an observed upper limit on the branching fraction of $\mathcal{B}(H \rightarrow \mu\tau) < 1.51\%$ at 95% confidence level (CL) is set while $\mathcal{B}(H \rightarrow \mu\tau) < (0.75 \pm 0.38)\%$ is expected. The best fit value of the branching fraction is $\mathcal{B}(H \rightarrow \mu\tau) = (0.84_{-0.37}^{+0.39})\%$ corresponding to an excess of 2.4 standard deviations. These results are consistent with those obtained by the ATLAS collaboration [5]. Given the observed upper limit on the branching fraction, an upper limit on the flavor-violating Yukawa couplings $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$ can be set at 95% CL [1]. The distribution of the combination of the collinear mass in all channels and categories is shown in figure 1 together with the 95% CL upper limits per channel and category and the constraints on the flavor-violating Yukawa couplings.

DECAYS OF HEAVY STATES TO ELECTRON-MUON PAIRS

Introduction

Several extensions of the standard model predict lepton-flavor-violating decays of heavy states to an electron-muon pair. This analysis describes a search for three of these models with the CMS experiment [6]. The first model is R-parity violating supersymmetry with a tau sneutrino ($\tilde{\nu}_\tau$) as the lightest supersymmetric particle decaying to the $e\mu$ final state [7]. The other models describe lepton flavor violation in decays of Z'/a' bosons [8] and quantum black holes (QBH) [9–11] to electron-muon pairs. Similar searches have also been performed by the CDF [12, 13] and D0 [14] collaborations at the Tevatron, and the ATLAS Collaboration [15] at the LHC.

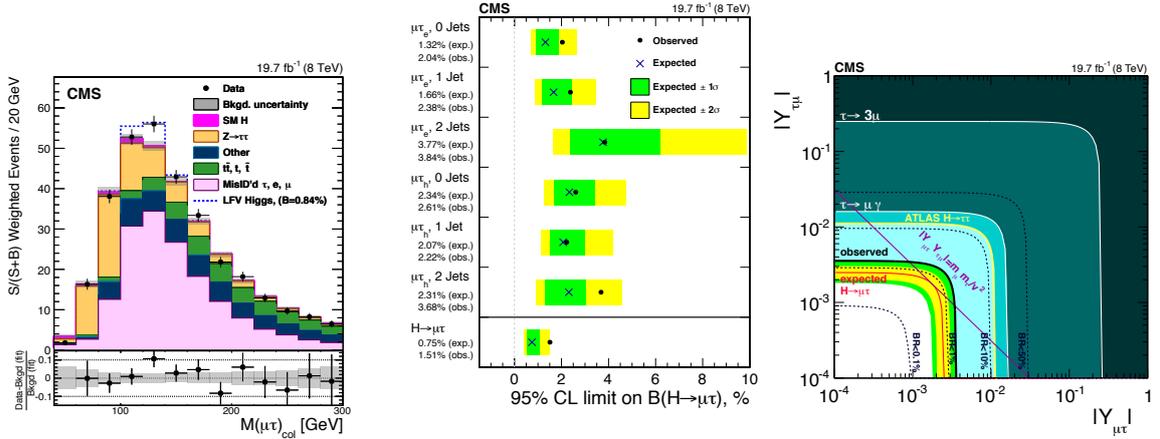


FIG. 1. Left: Distribution of M_{col} combined for all categories and channels individually weighted by $S/(S + B)$. Center: 95% CL upper limits on branching fractions split into categories and channels. Right: Constraints on $|Y_{\mu\tau}|$ and $|Y_{\tau\mu}|$. The red line depicts the expected limit together with its one and two sigma uncertainty bands in yellow and green, respectively. The solid black line shows the observed upper limit while the dashed black lines are reference values. The shaded regions come from null searches for the decays shown and the purple line shows the theoretical naturalness limit.

Analysis

In this search, an excess over the background expectation of electron-muon pairs with high invariant mass ($M_{e\mu} \geq 200 \text{ GeV}$) is sought. The data sample used corresponds to an integrated luminosity of 19.7 fb^{-1} collected in pp collisions by CMS at $\sqrt{s} = 8 \text{ TeV}$. For this analysis $t\bar{t}$ is the dominant background at low invariant masses while above $M_{e\mu} \sim 1 \text{ TeV}$ also WW production becomes important. Other background processes are diboson (e.g., WZ, ZZ and $W\gamma$) as well as single-top production, $Z \rightarrow \tau\tau$, and W+jets, Z+jets and multijet production where jets are misidentified as leptons. While background from W+jets and multijet production is estimated using a data-driven technique, all other processes are modeled using simulation and normalized to theory calculations and integrated luminosity.

Event Selection

This analysis uses a single muon trigger to select events and then further requires at least one muon and one electron satisfying kinematic as well as identification and isolation requirements. Electrons are rejected if there is a muon with low transverse momentum in

its vicinity to reduce background from high p_T muons misidentified as electrons. If there is more than one electron-muon pair, the one with the higher invariant mass is chosen. The invariant mass distribution is shown in figure 2 (left). In order to keep this search as model independent as possible there are no further requirements imposed.

Systematic Uncertainties

The total systematic uncertainty on the background expectation lies between 10% and 35% increasing with the invariant mass. It includes uncertainties in the luminosity, lepton identification and isolation efficiencies, muon momentum as well as electron energy scale, parton distribution functions, cross sections, top- p_T , renormalization and factorization scale, and the limited amount of simulated events in the high invariant mass part of the distribution.

Results

No significant discrepancies between the SM expectation and the data collected by CMS are seen. The result is interpreted in terms of upper limits on different models: resonant tau sneutrino, Z'/a' and QBH production for different numbers of extra dimensions (see figure 2). While there is no sensitivity to lepton-flavor-violating Z'/a' decays when fixing the couplings to the upper bounds obtained in previous experiments [8, 16], yet, limits are set on the tau sneutrino mass depending on the couplings ($M_{\tilde{\nu}_\tau} < 1.21$ (2.11) TeV for $\lambda_{132} = \lambda'_{311} = 0.01$ ($\lambda_{132} = 0.05, \lambda'_{311} = 0.1$)) as well as on the threshold mass of quantum black holes depending on the number of extra dimensions ($M_{\text{th}} < 1.99 - 3.63$ TeV for $n = 0 - 6$). The exclusion limit on the tau sneutrino mass for coupling strengths $\lambda_{132} = 0.05, \lambda'_{311} = 0.1$ is similar to that obtained by the ATLAS collaboration [15].

LEPTON FLAVOR VIOLATION IN Z DECAYS

Introduction

Decays of the Z boson into leptons of different families are forbidden in the SM. Although neutrino oscillation does allow for non-zero branching fractions of lepton-flavor-violating decays, these fractions are unobservably small (e.g., $\mathcal{B}(Z \rightarrow e\mu) < 4 \cdot 10^{-60}$ [17]). Several supersymmetric models and models with massive Dirac or Majorana neutrinos are able to enhance these decay rates to observable levels [17, 18]. There are stringent indirect limits from low-energy $\mu \rightarrow 3e$ conversion experiments on the decay $Z \rightarrow e\mu$ [19, 20] which are

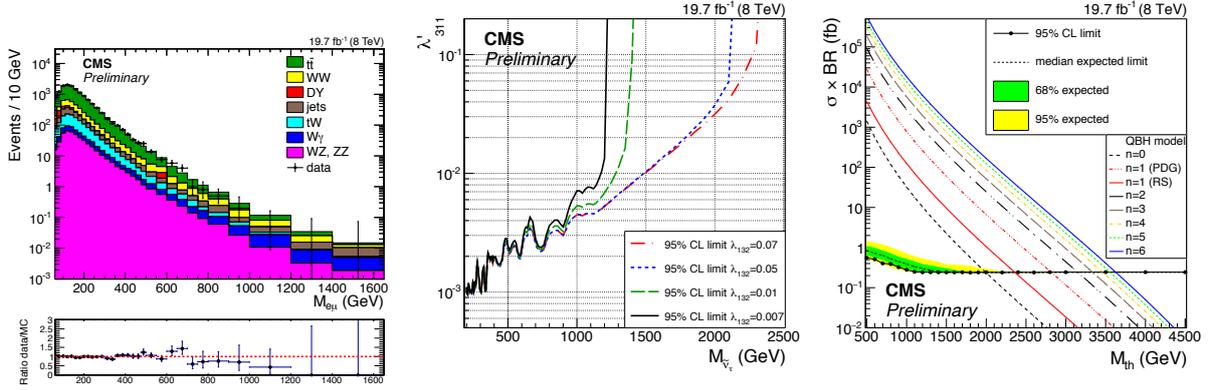


FIG. 2. Left: Invariant mass of electron-muon pairs passing the selection. ‘jets’ refers to the data-driven background estimate of W +jets and multijet production. Center: 95% CL limit contours in the $M_{\nu\tau}$ - λ'_{311} plane. Regions above the curves are excluded. Right: 95% CL exclusion limit on the signal cross section times branching fraction for QBH production as a function of the threshold mass.

complemented by direct searches from the LEP experiments [21] and recently the ATLAS Collaboration [22].

Analysis

The analysis [23] looks for a deviation from the background expectation in the invariant mass distribution of electron-muon pairs at the Z pole using 19.7 fb^{-1} of data collected in pp collisions by CMS at $\sqrt{s} = 8 \text{ TeV}$. The main backgrounds come from dileptonic $t\bar{t}$ decays, WW production and $Z \rightarrow \tau\tau$. Other backgrounds are jets being misidentified as electrons or muons (e.g., from W +jets and multijet production) as well as single top and other diboson production (e.g., ZZ and WZ). Background from jets misidentified as leptons is estimated using a data-driven approach while the shapes of the other backgrounds are estimated using simulation. Simulated samples are normalized to calculated cross sections except in case of the top-antitop sample where a CMS cross section measurement is used. The signal is estimated using simulation and normalized to the production cross section of Z bosons and a branching fraction of 10^{-6} .

Event Selection

Events are preselected by an electron-muon trigger. Apart from basic kinematic as well as identification and isolation requirements on the electron and muon, the leptons must match

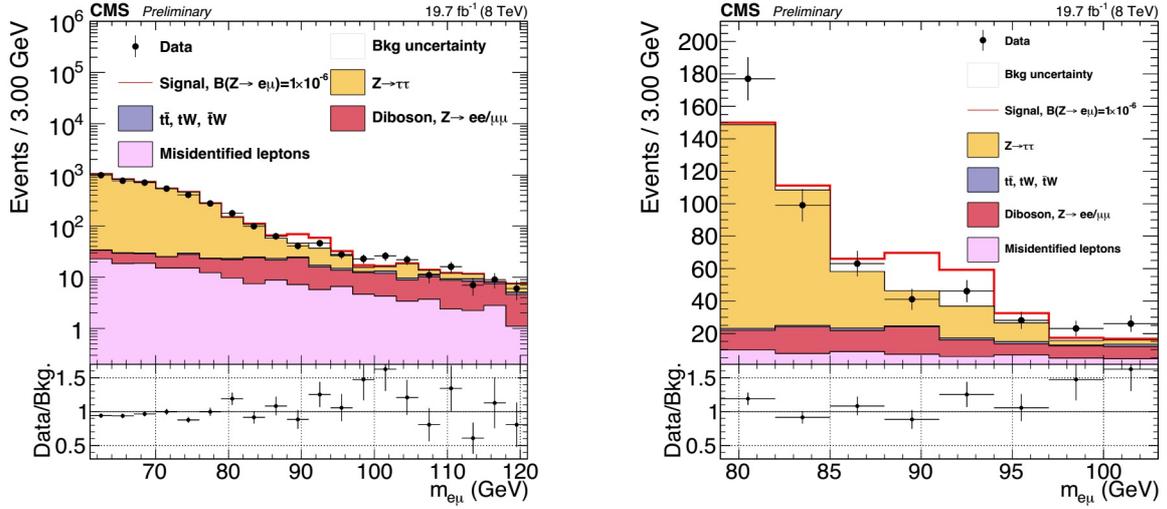


FIG. 3. Distributions of the invariant mass reconstructed from the electron and muon after the full selection for different mass ranges (left: 60 – 120 GeV, right: 79 – 103 GeV). The signal is stacked on top of the background estimate.

the trigger objects and further selection criteria are applied to reduce the large background from standard model processes. First, events with any second electron or muon are rejected in order to diminish background from diboson production and the invariant mass of the remaining events must satisfy $60 < m_{e\mu} < 120$ GeV. Second, three kinematic variables are used to control the main backgrounds. The first is the transverse momentum of the leading jet, the second the transverse mass of the muon M_T^μ and the third the transverse momentum of the Z reconstructed from the selected electron and muon. The requirements on the variables are determined by optimizing the discovery potential $S/\sqrt{S+B+\Delta B}$ in the signal region of 88 – 94 GeV with S and B being the signal and background yields, respectively, and ΔB representing the uncertainty in the background estimate. The distribution of the invariant mass after the full selection is depicted in figure 3.

Systematic Uncertainties

The dominant systematic uncertainty in the background estimate stems from the limited amount of simulated events (10.6%) followed by the normalization uncertainty (6.8%). Other uncertainties come from the electron energy and muon p_T scale as well as from influence of additional collisions in the same bunch crossing, the luminosity measurement and parton density functions (1 – 3%). Uncertainties in trigger, identification and isolation efficiencies

are small ($< 1\%$) as are uncertainties introduced by the jet energy scale and resolution as well as the missing transverse energy. For the signal estimate the systematic uncertainties mentioned above range between 0.1 and 3.3% with the normalization uncertainty being the dominant one.

Results

After the selection, 87 events are found in data within the mass range 88–94 GeV agreeing well with the background expectation of 83 ± 9 (stat.). Assuming a branching fraction of 10^{-6} , 43.8 ± 0.5 (stat.) signal events are expected. Using these numbers, an observed (expected) 95% CL limit on the branching fraction of $\mathcal{B}(Z \rightarrow e\mu) < 7.3 \cdot 10^{-7}$ ($6.7_{-2.0}^{+2.8} \cdot 10^{-7}$) is obtained which is similar to the result from the ATLAS Collaboration [22].

SUMMARY

The searches for lepton flavor violation in decays of the Higgs boson to a muon and a tau lepton and in decays of high mass resonances and the Z boson to electron-muon pairs have been presented. While a 2.4σ excess was observed in the process $H \rightarrow \mu\tau$, no evidence was found in the other searches. Thus, for lepton-flavor-violating Higgs and Z decays, upper limits were set on the respective branching fractions as well as on the Yukawa couplings in case of the Higgs. The absence of a signal in the high mass resonance search was interpreted in terms of three different standard model extensions and model dependent limits were set.

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