The Compact Muon Solenoid Experiment
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Search for new physics with tau final states at 13 TeV

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Searches for four new particles: Sequential Standard Model W' and Z' bosons, right-handed W bosons and third-generation leptoquarks; are performed using pp collision data at $\sqrt{s} = 13$ TeV recoed by the CMS detector at the LHC. The events observed are found to be in good agreement with the SM predictions. At 95% confidence level, new mass exclusions are set for W'_{SSM} between 1 to 3.3 TeV, for Z'_{SSM} up to 2.1 TeV, for W_R up to 3.2 TeV, when the N_τ mass is half the mass of W_R , and for third-generation leptoquarks up to 900 GeV.

Keywords: new physics, tau lepton

1. Introduction

The standard model (SM) of particle physics is a successful theory that can explain many experimental observations of particle processes involving weak, electromagnetic, and strong interactions. However, the fact that it fails to incorporate the gravitational force and lacks a description in which the gauge interactions are unified has lead to the proposal of many new models of physics. Such models often manifest themselves as new heavy particles that could be observed at the Large Hadron Collider (LHC). We present searches for four new particles, each of which would decay to one or two taus, performed by the CMS Collaboration [1] at $\sqrt{s} = 13$ TeV.

2. SSM W' and Z'

New heavy gauge bosons are predicted by various extensions of the SM. The charged and charge neutral version of such heavy gauge bosons are generally referred to as W' and Z' . In this report, we present searches for W' and Z' interpreted in the context of the Sequential Standard Model (SSM), where the W' and Z' bosons have the same coupling to quarks and leptons as their SM partners.

2.1. $W' \rightarrow \tau\nu$ Strategy and Results [2]

The SSM W' search is performed in the $W' \rightarrow \tau\nu$ decay channel, where we further require the tau lepton to decay hadronically (τ_h). Leptonically decaying taus such as $W' \rightarrow \tau\nu \rightarrow e\nu_e\nu_\tau\nu_\tau$ cannot be distinguished from $W' \rightarrow e\nu_e$ and are covered by the corresponding leptonic W' searches.

Events are selected by requiring the τ_h to have at least 80 GeV in transverse momentum (p_T) and the missing transverse energy of the event (E_T^{miss}) greater than 120 GeV. To further separate signal from background events, we require $0.7 < p_T/E_T^{\text{miss}} < 1.3$ and the separation angle between the τ_h and E_T^{miss} to be greater than 2.4.

The results are shown in Fig 1 using the transverse mass (M_T) of the τ_h and E_T^{miss} :

$$M_T = \sqrt{2p_T^\tau E_T^{\text{miss}}(1 - \cos \Delta\phi(\tau, \vec{p}_T^{\text{miss}}))} \quad (1)$$

where p_T^τ denotes the p_T of the τ_h and $\vec{p}_T^{\text{miss}}$ is $-\sum \vec{p}_T$ of all reconstructed particles. No significant deviations from the SM prediction are observed.

As shown in Figure 2, at 95% confidence level (CL), the SSM W' boson, when decaying to a tau lepton and a neutrino, is excluded in the range of $1 < M_{W'} < 3.3$ TeV.

Figure 1: The MT distribution after the final selection.

2.2. $Z' \rightarrow \tau\tau$ Strategy and Results [3]

The SSM Z' search is performed in the $Z' \rightarrow \tau\tau$ channel. With two taus in the decay chain, one can have in total six possible final states: $\tau_l\tau_l, \tau_l\tau_h, \tau_h\tau_h$, where τ_l refers to when the tau decays to an electron or muon and neutrinos. Four final states, $\tau_e\tau_\mu, \tau_e\tau_h, \tau_\mu\tau_h$ and $\tau_h\tau_h$ are considered in this analysis, as the remaining two are explored in the relevant $Z' \rightarrow ee$ and $Z' \rightarrow \mu\mu$ searches.

Figure 2: Limits on the product of cross section and branching fraction into $\tau\nu$ for a SSM W' boson. The dotted and the long-dashed lines show the cross section prediction in the SSM as a function of the W' boson mass, at NNLO and LO, respectively.

To improve signal acceptance and reduce background contamination, reconstructed events are selected to contain two leptons (four possible pairs, as mentioned above) with: $p_T > 20$ or 60 GeV depending on the channel, back-to-back, and carrying opposite electric charge. To further reduce $t\bar{t}$ and W backgrounds, se-

lections based on b-tagging and the correlation between the direction of E_T^{miss} and the leptons are applied.

The final discriminator is the constructed using the visible decay products of the tau leptons and E_T^{miss} as the following:

$$m(\tau_1, \tau_2, E_T^{\text{miss}}) = \sqrt{(E_{\tau_1} + E_{\tau_2} + E_T^{\text{miss}})^2 - (\vec{p}_{\tau_1} + \vec{p}_{\tau_2} + \vec{p}_T^{\text{miss}})^2} \quad (2)$$

where $\vec{p}_T^{\text{miss}}$ is $-\sum \vec{p}_T$ of all reconstructed particles.

Figure 3: $m(\tau_1, \tau_2, E_T^{\text{miss}})$ distribution for the $\tau_e\tau_h$ channel. The right-most bin includes events with a reconstructed mass greater than 900 GeV.

Figure 3 shows the reconstructed mass in the $\tau_e\tau_h$ channel. For all four channels, no evidence of new physics decaying into tau lepton pairs is seen. As shown in Fig. 4, by combining all four final states, we exclude Z'_{SSM} models with masses less than 2.1 TeV at 95% CL.

Figure 4: 95% CL upper limits on the product of the cross section and branching fraction into tau lepton pairs as a function of Z'_{SSM} mass for the four final states combined.

3. Right-handed W Searches

The observation of neutrino oscillation [4] implies that neutrinos have mass and is often considered as evidence of physics beyond the SM. Among several models proposed to explain this phenomenon, the left-right (L-R) symmetric extensions [5] to the SM predict the existence of heavy charged (W_R) and neutral (Z_R) gauge bosons with heavy neutrinos that could be produced at LHC energies.

Of particular interest here is the decay channel where the right-handed W (W_R) decays to a tau and a heavy neutrino (N_τ). The N_τ further decays to a tau lepton and two quarks resulting: $W_R \rightarrow \tau + N_\tau \rightarrow \tau + \tau qq'$. As mentioned previously, due to the possible decay channels of the tau lepton, one can further separate events into those where both taus decay hadronically ($W_R \rightarrow \tau_h \tau_h qq'$) and those where one tau decays hadronically and the other decays leptonically ($W_R \rightarrow \tau_l \tau_h qq'$).

3.1. $W_R \rightarrow \tau_h \tau_h qq'$ Strategy and Results [6]

The $\tau_h \tau_h$ channel is performed using 2.1 fb^{-1} of data collected by the CMS experiment in 2015 at $\sqrt{s} = 13 \text{ TeV}$. Events are selected by requiring the presence of at least two τ_h candidates with $p_T > 70 \text{ GeV}$, at least two jets with $p_T > 50 \text{ GeV}$ and $E_T^{\text{miss}} > 50 \text{ GeV}$.

To successfully distinguish between signal and background events, we use the reconstructed mass defined below as the final discriminator:

$$m(\tau_1, \tau_2, j_1, j_2, E_T^{\text{miss}}) = \sqrt{(E_{\tau_1} + E_{\tau_2} + E_{j_1} + E_{j_2} + E_T^{\text{miss}})^2 - (\vec{p}_{\tau_1} + \vec{p}_{\tau_2} + \vec{p}_{j_1} + \vec{p}_{j_2} + \vec{p}_T^{\text{miss}})^2} \quad (3)$$

Figure 5 shows the background predictions as well as the observed $m(\tau_1, \tau_2, j_1, j_2, E_T^{\text{miss}})$ where no significant deviation from SM predictions is seen. Due to the lack of knowledge on the mass of N_τ , as shown in Fig 6, the expected and observed limits are shown as a function of $m(W_R)$ and $m(N_\tau)/m(W_R)$. At 95% CL, W_R masses below 2.35 (1.63) TeV are excluded, assuming the N_τ mass is 0.8 (0.2) times the mass of W_R boson.

3.2. $W_R \rightarrow \tau_l \tau_h qq'$ Strategy and Results [7]

Analysis of the $\tau_l \tau_h$ channel is performed using 12.9 fb^{-1} of data collected by the CMS experiment in 2016 at $\sqrt{s} = 13 \text{ TeV}$. Similar to the selections in Section 3.1, events are selected by requiring one τ_h candidates with $p_T > 60 \text{ GeV}$, one electron or muon candidate with $p_T > 50 \text{ GeV}$, at least two jets with $p_T > 50 \text{ GeV}$ and the $E_T^{\text{miss}} > 50 \text{ GeV}$. To further reduce electroweak backgrounds introduced by the acceptance of electron or

Figure 5: $m(\tau_1, \tau_2, j_1, j_2, E_T^{\text{miss}})$ distribution. The last bin in the mass plot represents the yield for $m(\tau_1, \tau_2, j_1, j_2, E_T^{\text{miss}}) > 2.25 \text{ TeV}$

muons, the invariant mass of the light lepton and the τ_h is required to be greater than 150 GeV.

Figure 6: Observed and expected 95% CL upper limits on the production cross section for the ratio between $m(N_\tau)$ and $m(W_R)$ as a function of $m(W_R)$.

After the final selection, the scalar sum of the transverse momentum (S_T) of all final state objects as well as the E_T^{miss} is used to search for the presence of signal.

$$S_T = p_T(l) + p_T(\tau_h) + p_T(j_1) + p_T(j_2) + E_T^{\text{miss}} \quad (4)$$

Figure 7 shows the S_T distribution in the $e\tau_h$ channel, where no excess is seen above the SM expectations within the uncertainties. Assuming the mass of the N_τ is half the mass of W_R , as shown in Fig. 8, W_R of masses below 3.2 TeV are excluded at 95% CL.

Figure 7: Distribution in S_T observed in the $e\tau_h$ channel

4. Leptoquark Searches [6] [7]

The $\tau\tau jj$ final state described in Section 3 can also be used to probe other extensions of the SM. For example, a number of extensions of the SM predict particles, called leptoquarks (LQ), that carry color charge, fractional electric charge and both lepton and baryon quantum numbers [8]. Thus, the analysis described in Section 3 is modified as a search for a pair of third-generation LQs that decays into $\tau\tau bb$. Event selections for the LQ searches are very similar to those of the W_R searches, with optimizations focused on requiring the two leptons to carry opposite electric charge and requiring the presence of b jets.

Figure 8: Observed and expected upper limits at 95% CL on the product of cross section and branching fraction for combined $e\tau_h$ and $\mu\tau_h$.

The S_T variable is used as the final discriminator. No significant deviation from SM predictions is observed. Figure 9 shows the expected and observed limit for $\tau_h\tau_h$ channel. At 95% CL, third-generation leptoquarks, with 100% branching fraction of decay to a tau lepton and a b quark, of masses below 740 (900) GeV are excluded

using the $\tau_h\tau_h$ ($\tau_l\tau_h$) channel.

Figure 9: Expected and observed limits, at 95% confidence level, as functions of LQ mass in the $\tau_h\tau_h$ channel.

5. Summary

Searches of four new particles through the decays of tau leptons are performed using pp collision data at $\sqrt{s} = 13$ TeV recorded by the CMS detector at the LHC. The events observed are found to be in good agreement with the SM predictions. At 95% CL, new mass exclusions set on the proposed new particles are:

- SSM W' : $1 \text{ TeV} < M_{W'} < 3.3 \text{ TeV}$,
- SSM Z' : 2.1 TeV ,
- $W_R(\tau_h\tau_h)$: $2.35(1.63) \text{ TeV}$, $\frac{m(N_\nu)}{m(W_R)} = 0.8(0.2)$,
- $W_R(\tau_l\tau_h)$: 3.2 TeV , $\frac{m(N_\nu)}{m(W_R)} = 0.5$,
- $LQ_R(\tau_h\tau_h)$: 740 GeV ,
- $LQ_R(\tau_l\tau_h)$: 900 GeV .

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