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Search for W′ bosons decaying to a top and a bottom quark at $\sqrt{s} = 13$ TeV in the hadronic final state with CMS

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A search is performed for W′ bosons decaying to a top and a bottom quark in the all-hadronic final state, in proton-proton collisions at a center-of-mass energy of 13 TeV using data collected by the CMS experiment between 2016 and 2018 and corresponding to an integrated luminosity of 137 fb^{-1}. Deep neural network algorithms are used to identify the jet initiated by the bottom quark and the jet containing the decay products of the top quark when the W boson from the top quark decays hadronically. No excess above the estimated standard model background is observed. Upper limits on the production cross sections of W′ bosons decaying to a top and a bottom quark are set. Both left- and right-handed W′ bosons with masses below 3.4 TeV are excluded at 95% confidence level, and the most stringent limits to date on W′ bosons decaying to a top and a bottom quark in the all-hadronic final state are obtained.

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1. Introduction

The CERN LHC has strengthened the validity of the standard model (SM) of particle physics by delivering a large volume of data and providing a significant amount of evidence matching its theoretical predictions. The existence of new physics beyond the SM, however, is needed in order to explain several observed phenomena and theoretical quests in particle physics. Extensions of the SM, conceived to overcome these limitations, include theories proposing a new spin-1 gauge boson W′, a color singlet with an electric charge of ±1 [1–3]. Some theoretical models, for example [4–6], assume a preferential coupling of a W′ boson to the third-generation fermions, which motivates the search for a W′ boson decaying to a top and a bottom quark.

In this note, we discuss the search performed by the CMS experiment [7] for a W′ boson decaying to a top and a bottom quark in the all-hadronic final state, where the signature is an excess of events over a smoothly falling background in the invariant mass spectrum of top and bottom quark candidates (m_{tb}) in the range 1–4 TeV [8].

2. Objects used

For each event, hadronic jets are clustered from the particles, reconstructed with particle-flow algorithm [9], using the infrared- and collinear-safe anti-k_{T} algorithm [10] with distance parameters 0.4 (AK4 jets) and 0.8 (AK8 jets), as implemented in the FastJet package [11]. The AK4 and AK8 jets are used to identify the bottom quark and the hadronically-decaying top quark, respectively, from a W′ boson decay.

Two deep neural network (DNN) based algorithms are used to identify ("tag") jets initiated by bottom quark and top quark decay products. The use of DNNs reduces the background from multijet production in quantum chromodynamics (QCD) in the case of an all-hadronic final state. The DeepJet [12] tagger is used for the b tagging of AK4 jets, utilizing information from the tracks, neutral particles, and the secondary vertices within the jet. The top quark arising from the decay of a heavy W′ boson has a large Lorentz boost, and its decay products are expected to be captured within an AK8 jet. The jet mass after soft drop grooming (m_{SD}) [13], is required to be within a window of 105–210 GeV for a jet to be t-tagged. Specific features of particle distribution within the jet arising from top quark decay are utilized using a DNN-based t tagging algorithm, DeepAK8 [14].

3. Event selection and background estimation

Events with at least one AK8 and one AK4 jet, both within the tracker volume, satisfying transverse momentum $p_{\mathrm{T}} > 550$ GeV and separated by distance $\Delta R > 1.2$ in the rapidity-azimuth plane, are considered for the analysis. The AK8 jet with the highest t tagging score is taken as the top quark candidate jet, and the AK4 jet with the highest p_{T} which satisfies $\Delta\phi > \pi/2$ with respect to the top quark candidate jet is taken to be the bottom quark candidate jet.

The main SM background processes from LHC proton-proton collisions that can mimic the final state sought in this search are the production of multijet events due to QCD interactions, the production of a top quark-antiquark pair ($\mathrm{t\bar{t}}$), and the electroweak production of a single top quark associated with a bottom quark or W boson.

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The signal region SR is defined by requiring the top quark candidate jet to pass both the m_{SD} and the t tagging score requirement and the bottom quark candidate jet to pass the threshold on the b tagging score. Multijet background in the SR is estimated using the event yield in a control region satisfying same conditions in the SR, except the bottom quark candidate jet is required to fail the requirement on the b tagging score, multiplied with the b tagging pass-to-fail ratio of the bottom quark candidate jet obtained from the orthogonal control regions where the top quark candidate jet has $m_{SD} < 105$ GeV. The technique used to estimate the multijet background is cross-checked in a validation region VR, which differs from the SR in the t tagging condition on the top quark candidate jet. The estimated multijet m_{tb} spectrum agrees with the one observed in data in the VR within statistical and systematic uncertainties, thus validating the background estimation.

Background estimates for $t\bar{t}$ events are taken primarily from simulation, but also include a correction derived from data as follows. A control region is selected that satisfies all of the criteria in the SR, but requires that the AK8 jet associated with the bottom quark candidate jet has m_{SD} in the [105, 210] GeV window and passes the threshold on the DeepAK8 tagger score. Events with $t\bar{t}$ production, where both the top quarks decay hadronically, constitute approximately 80% of the events in this region. The ratio between the m_{tb} spectra in data and simulation is fitted with a first-order polynomial to derive a correction that is applied to the simulated $t\bar{t}$ background.

The smallest background considered is from single top quark events, and it is estimated purely from the simulation.

4. Results and interpretation

We consider several sources of systematic uncertainty that cover experimental effects, uncertainties due to the extraction of the multijet background, and uncertainties in the predicted $t\bar{t}$ and single top quark backgrounds. Since the multijet background is dominant, the uncertainties in b tagging pass-to-fail ratio and jet energy scale are the dominant sources of systematic uncertainty.

The signal and expected background m_{tb} distributions are compared with data, and a binned maximum-likelihood fit is applied to measure the W′ boson yield. Each source of systematic uncertainty is treated as a nuisance parameter [15].

The expected numbers of events from different background and signal hypotheses and the observed yields in data after the binned maximum-likelihood fit is performed are shown in Fig. 1 in the SR for the three years of data taking. No significant excess is observed over the SM background. Upper limits on the product of W′ on the production cross section and branching fraction to a top and a bottom quark, $\sigma_{W'}\mathcal{B}(W' \to tb)$, are obtained at 95% confidence level (CL) using the asymptotic CL_s method [16, 17] and are shown in Fig. 2 The theoretical cross section for the production of left-handed W′ bosons saturates at high mass because of the interference with single top quark production in the SM, which causes the signal shape to be asymmetric with a pronounced tail at low m_{tb}. This results in a substantial difference between the upper limits on the production cross section of left- and right-handed W′ bosons at high m_{tb}. Both right- and left-handed W′ bosons of masses less than 3.4 TeV are excluded at 95% CL. The expected limits are 3.7 and 3.6 TeV for the right- and left-handed W′ bosons, respectively.

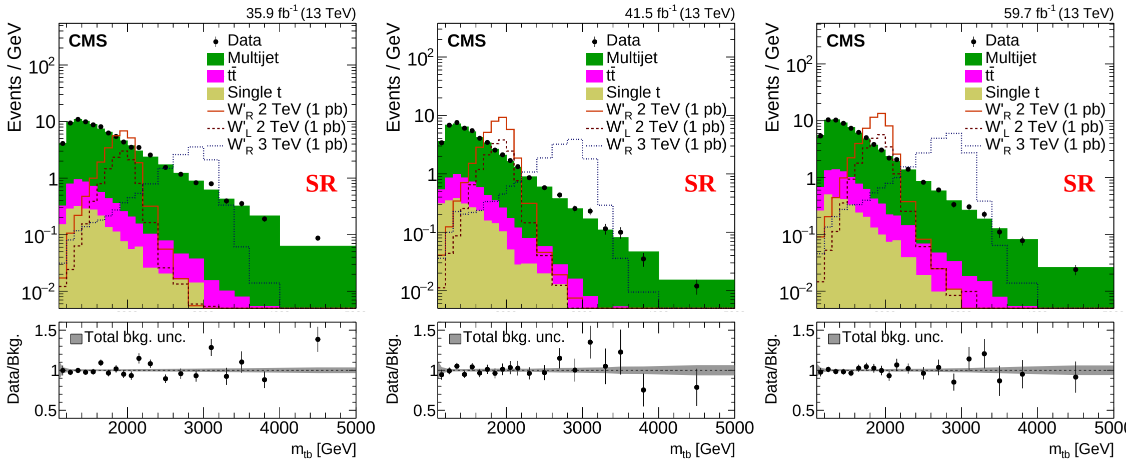

Figure 1: The reconstructed m_{tb} distributions in data (black points with error bars), and backgrounds in the SR for three data-taking periods. The yield in each bin is divided by the corresponding bin width. Distributions expected from W′ bosons of different masses and chiralities are shown. The lower panel in each plot shows the ratio of data to the background prediction. The shaded band indicates the total uncertainty in the estimated background, including both statistical and systematic components.

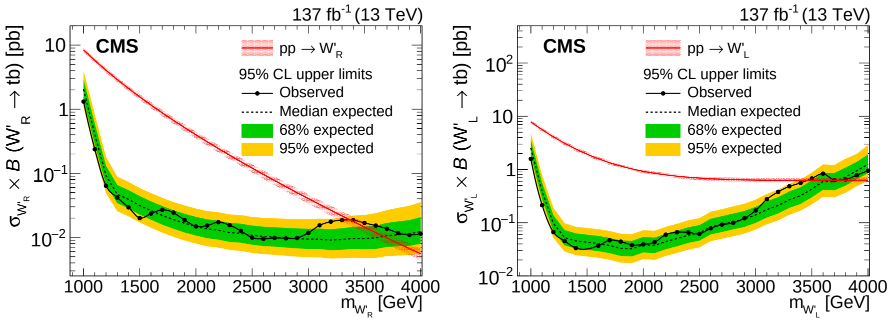

Figure 2: Upper limits at 95% CL on the production cross section and branching fraction of a W'_{R} boson (left) and a W'_{L} boson with the SM interference (right) decaying to a top and a bottom quark, using combined 2016–2018 data and backgrounds. The observed and median expected limits are shown with the black solid and dashed lines, respectively. The inner green and outer yellow bands represent the 68 and 95% confidence level intervals, respectively, of the expected limit, computed using the background-only hypothesis. The theoretical prediction and its uncertainty due to the choice of QCD scale and PDF set are indicated by the red curve and associated red shaded band, respectively.

5. Summary

A search has been performed for heavy W′ bosons decaying to a top and a bottom quark in the hadronic final state using data corresponding to an integrated luminosity of 137 fb^{-1} collected by the CMS experiment during the data taking period from 2016 to 2018. Left- and right-handed W′ bosons with masses below 3.4 TeV are excluded at 95% confidence level. The limits provided on W′ bosons decaying to a top and a bottom quark in the all-hadronic decay mode are the most stringent to date over the explored mass spectrum between 1.2 and 4.0 TeV.

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